COMPARISON OF ATMOSPHERIC CIRCULATION PATTERNS DURING THE 2008 AND 1993 HISTORIC MIDWEST FLOODS

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Abstract

The synoptic-scale atmospheric patterns and the most extreme 13-day rainfall periods during the 1993 and 2008 historic Midwest flood events are compared. Over the north central part of the United States, these two 13-day periods were the two wettest during the warm season over the past 60 years. The 500-hPa geopotential height, mean sea level pressure, 250-hPa u-wind and 850-hPa v-wind component anomaly patterns associated with the two periods were found to be remarkably similar. A correlation of .939 was found for the 500-hPa height anomalies between the two periods. The synoptic patterns associated with both periods facilitated the development of a plume of anomalously high precipitable water and moisture flux around the periphery of the subtropical high that then intersected a quasi-stationary baroclinic zone, thereby supporting the development of frequent mesoscale convective systems (MCSs). Frequent low pressure waves along the front, as well as the presence of a nearby exit or entrance region of an upper tropospheric jet streak, enhanced synoptic scale ascent. Early detection of these extreme events might be possible by both medium and short range forecasters using ensemble guidance to ascertain the potential likelihood of similar patterns and features to the aforementioned 13-day periods. On the global climate scale, the late winter and spring season preceding both summer floods featured anomalously wet conditions over the central United States, which contributed to high antecedent soil moisture conditions. Despite the anomalously wet pre-flood periods, there were no similarities in pre-flood monthly El Nino Southern Oscillation (ENSO) anomalies, yet both years did feature a negative North Atlantic Oscillation (NAO) signal two months prior to and during the floods.

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1. Introduction

The U.S. Geological Survey classified both the 2008 and 1993 Midwest floods as being 500-year floods (Dirmeyer and Kinter 2009, henceforth DK2009). During the 2008 flood, the Cedar River at Cedar City, Iowa set a flood record by more than 11 feet above the previous record. Eighty-three Iowa counties were declared disaster areas and flooding was also reported in Illinois, Indiana, Minnesota, Missouri, Wisconsin, Nebraska and South Dakota (DK2009). The 1993 flood was the most devastating flood along the Upper Mississippi River Basin during modern times (Kunkel et al. 1994; hereafter K94) with numerous record high river levels set. The synoptic pattern and physical mechanisms associated with the 1993 flood have been well studied (e.g., K94; Bell and Janowiak 1995 (BJ95); Mo et al. 1995). The floods in 1993 and 2008 affected many of the same states making it logical to compare the two events to look for similarities and differences.

In a comparison of the floods, DK2009 showed that the rainfall during the months prior to the flooding were above normal from February through June of each year (see DK2009 Fig. 1e). The summer flood periods exhibited anomalously strong southerly winds in the lowest 300 hPa of the troposphere from the western Gulf of Mexico northward into the Midwest. DK2009 also noted anomalous evaporation across the northwestern Caribbean Sea and western Gulf of Mexico. In their study, back trajectories during both periods suggested that much of the moisture that fell as rain over the Midwest originated in the western Gulf of Mexico and was fed northward by the anomalous strong low level southerly winds along the western flank of the subtropical ridge. DK2009 concluded that large-scale floods such as the ones in the Midwest during 1993 and 2008 are due to deviations from normal that involve the atmosphere, ocean and land across large areas.

Very moist conditions were present in the months prior to each flood mainly due to synoptic scale storms, yet the worst flooding during each of the events was associated with frequent mesoscale convective systems (MCSs) that developed and tracked across the Midwest. Such corridors of heavy precipitation are a climatological feature of the summer Midwest climate (Carbone et al. 2002). Fritsch et al. (1986) showed that MCSs contribute to a large portion of warm season rainfall, and Junker et al. (1999), Moore et al. (2003), and Schumacher and Johnson (2005 and 2006) showed that many warm-season flash flood events are associated with MCSs.

During both years, the flood-producing MCSs occurred during 13-day periods. K94 identified a 13-day period (29 June -11 July 1993) as having the heaviest rains during the 1993 summer. Their study noted that during each day an MCS tracked across the region, heavy rains were produced. Using the higher resolution maximum rainfall contour data in Table 1, up to 775 mm of rainfall was recorded over parts of the domain during this 13-day period (McDonald et al. 2000). During June 2008, the active 13-day period (2-14 June 2008) featured heavy rainfall generated from MCSs over the Midwest during 11 of the 13 days. Using the data from the higher resolution maximum rainfall contour in Table 1, up to 1050 mm of rainfall was noted over parts of the domain during this 13-day period. Tuttle and Davis (2006) found that Midwest summer time corridors of heavy precipitation typically persist for two to seven days, therefore the 13-day active period is rare. Thus the longevity of the synoptic patterns associated with each of these active periods is rare.

There were similarities in the location and duration of rainfall during each flood year, as well as the anomalous wet conditions across the Midwest during the latter part of both cold seasons and the months immediately preceding the floods. But, there were differences in climate regime as indicated by opposing phases of ENSO. Coleman and Budikova (2009; hereafter CB2009) compared the large-scale circulation of the two flood events, both leading up to and during the actual flooding events. For the time frame leading up to the events, CB2009 presented the differences in ENSO signal during the late winter and early spring of each flood year. The winter and spring period of 1992-93 featured ENSO warm, or El Nino, conditions, where the same period during 2007-08 featured ENSO cold, or La Nina, conditions. This is significant from a climate regime perspective because only El Nino conditions are typically associated with wet conditions over the central plains. CB2009 indicated that a long lag association exists between ENSO and spring streamflow in the Midwest, however investigation of long lag forcing is beyond the scope of this paper. Other annular modes over the Pacific basin were examined, but they indicated opposing phases in each year. Over the Atlantic basin, CB2009 noted a negative phase of the North Atlantic Oscillation (NAO) starting two months prior to and during the floods in both years.

The purpose of this paper is to build upon the work of CB2009 by focusing on the significance of two 13-day periods when heavy rainfall occurred and describing a conceptual framework for these heavy rainfall scenarios. This was done by citing an ingredients approach to the synoptic scale features that contribute to the frequency and intensity of the rainfall associated with the MCSs. A linear correlation between 500-hPa heights over a North American domain will be shown, as well as normalized anomalies for 850 hPa meridional flow and moisture flux over the flood region each year.

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Fig. 1 (a)

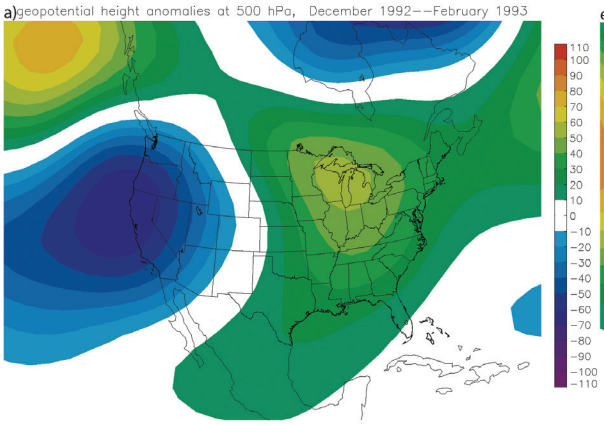


Fig. 1 (e)

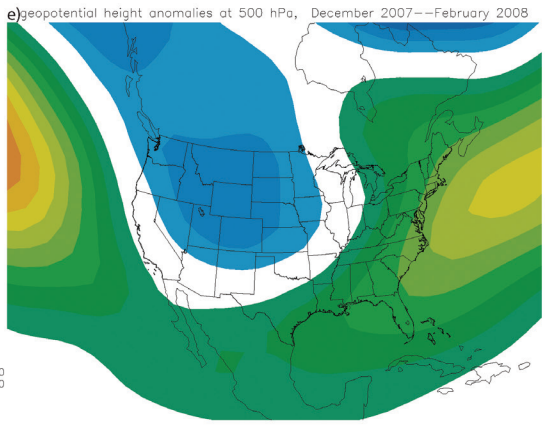
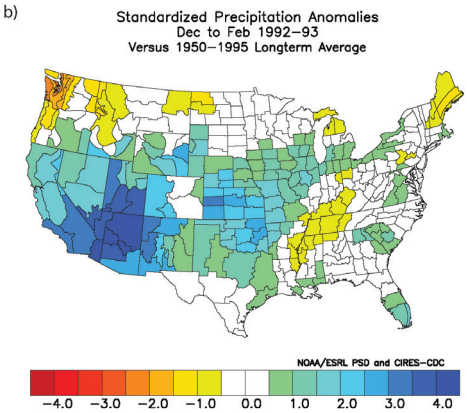


Fig. 1 (b)



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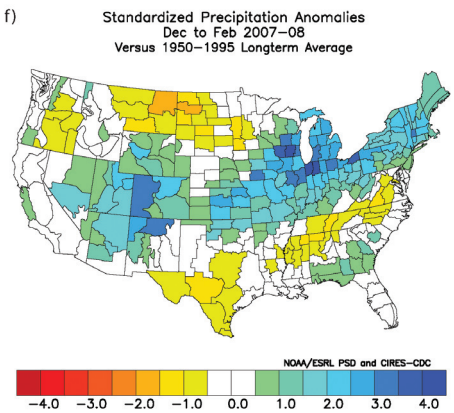

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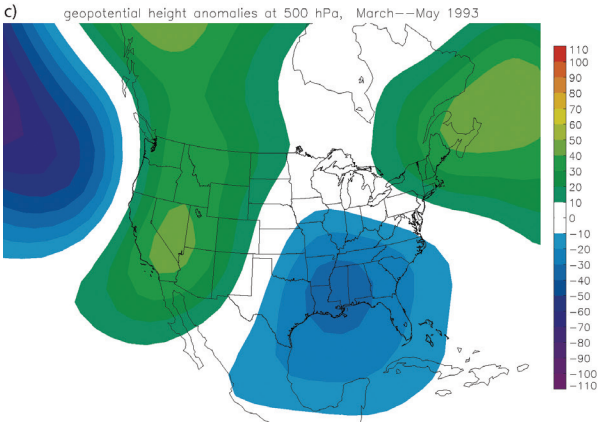

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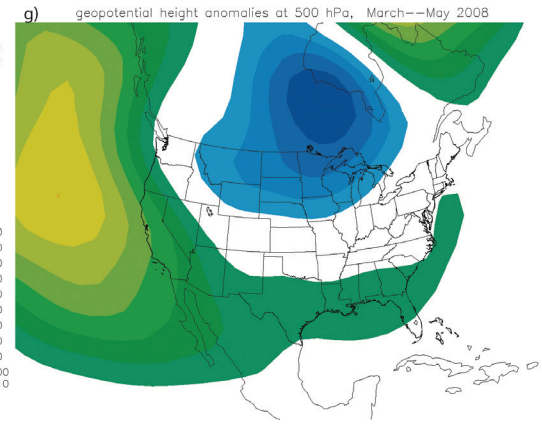

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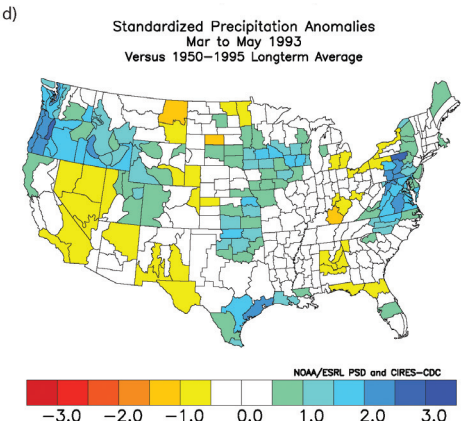

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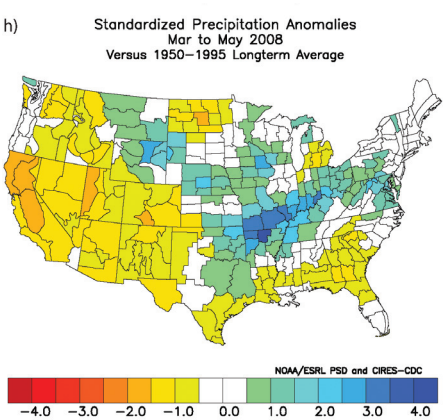

Fig. 1. a) Composite mean 500-hPa height anomaly for December 1992-February 1993, b) standardized precipitation anomalies for December 1992-February 1993, c) Same as a except March-May, d) same as b except for March-May, e) same as a except for 2008, f) same as b except for 2008, g) same as c except for 2008, h) same as d except for 2008.

Date	Locations (2-letter state ID)	Max UPD (mm)	Higher Res Max Contour (mm)	Maddox Arch-type	Wave on Front	250 hPpa Jet Streaks	850 Mflux Anom	850 v-wind a Anom	Precipita-ble water Anom	250 u-wind Anom into Plains	Negative MSLP Anom East of Rockies
1993 Data											
1-Jul	MN/WI	75	150	frontal	yes	entr/exit	3.95	2.1	2.76	yes	yes
4-Jul	MN/WI	50	75	frontal	yes	none	3.78	3.93	2.72	yes	yes
5-Jul	IA/MO	100	125	frontal	yes	entrance	4.03	3.67	3.03	yes	yes
7-Jul	MO	100	125	Synoptic/ frontal	yes	entrance	3.94	2.84	2+	yes	yes
9-Jul	IA	100	150	frontal	yes	entrance	3.37	3.29	2.39	yes	yes
10-Jul	KS/MO	50	150	frontal	no	entrance	1+	2.11*	1+	yes	yes
2008 Data											
2-3 Jun	MO/IL	50	150	frontal	Yes	No	3.61	2.53	2.11	Yes	Yes
3-4 Jun	IL/IN/OH	100	125	frontal	Yes	entr/exit	5.07	2.6	2.11	Yes	Yes
4-5 Jun	IA	100	175	frontal	Yes	entr/exit	5.36	3.65	2.48	Yes	yes
5-6 Jun	IA	75	75	continued	Yes	entr/exit	6.99	3.6	2.48	Yes	Yes
6-7 Jun	IN/IL	150	200	s/f hybrid	Yes	Entrance	5.1	3+	2.02	Yes	Yes
7-8 Jun	IA/WI/MI/IN	125	150	frontal	Yes	Entrance	6.32	3.04	2.99	yes	yes
8-9 Jun	WI	75	100	frontal	Yes	Entrance	3.94	2.89	2.69	Yes	Yes
11-12 Jun	MN/IA	75	75	synoptic	Yes	Exit	4.03	3.44	2.61	Yes	Yes

Table 1. List of important 24-hour rainfall periods (ending at 1200 UTC) and their locations during 1993 and 2008. The maximum rainfall in column 3 are the maximum contours found in the UPD site using 25 mm intervals, column 4 is the maximum contour indicated by the Stage IV data for events in 2008. HPC analysis was used in column 4 for events in 1993. Column 5 lists a subjective classification of the events based on the Maddox archetypes (Maddox et al. 1979). Column 6 states whether there was a weak surface wave on the front upstream from the rainfall maximum at the onset or during the storm. Column 7 lists whether the rainfall maximum was located along the exit or entrance region of a jet streak, the abbreviation entr/exit indicated that a double jet streak structure was present. In Columns 8-10, the highest normalized anomaly during the 24-hr period is listed. These values could come at 1200 (the beginning of the period), 1800, 0000, 0600 and 1200 UTC (the end of the period). In columns 11-12, the 250 hPa wind and mean sea level pressure (MSLP) respectively depict positive wind anomalies over the Plains and negative surface pressure anomalies east of the Rocky Mountains.

The goals of this study are to:

1) Compare the general circulation and synoptic scale features prior to and the antecedent moisture conditions for each flood through comparison of composite mean maps,

2) Compare the synoptic patterns for the two 13 day periods,

3) Compare historically how the rainfall during these two periods rank in the 60-year record (1948-2008), and

4) Investigate why the synoptic patterns associated with these periods were so conducive to MCS development, as well as the characteristics of the heavy rainfall events during the two 13-day periods.

The study data and methodology are explained in section 2. Section 3 compares the pre-flood synoptic patterns. Section 4 describes the synoptic patterns for the wettest 13-day periods each year. Also included is an analysis of how often similar 500-hPa composite mean anomaly patterns have been observed for a 13-day period. The characteristics of individual heavy rainfall events comprising the floods are examined in section 5. The conclusions of the study are given in section 6.

2. Methodology and Data

The Climate Prediction Center (CPC) latitude/longitude gridded and smoothed .25° x .25° Daily U.S. Unified Precipitation Data (UPD) set (Higgins et al., 2000) was used as the primary precipitation dataset. The data set is composed of approximately 13,000 station reports per day for dates after 1992 and about 8,000 reports in the pre-1992 years. These data were quality-checked to eliminate duplicates and overlapping stations, and standard deviation and buddy checks were applied. Stage IV data was available and used as a data set for the 2008 floods. Stage IV data is generated at NCEP and is a mosaic that synthesizes regional hourly and six hourly precipitation analysis. This precipitation analysis is derived from both gauge and radar estimated precipitation estimates. The procedure is performed at the 12 River Forecast Centers over the continental United States (Lin et al. 2005).

Sixty-year (1948-2008) daily means and standard deviations for a variety of fields were computed from the NCEP/NCAR Global Reanalysis project (GR: Kalnay et al. 1996). The data set was comprised of four six-hourly observations at 0000, 0600, 1200 and 1800 UTC. The 60-year climatology values were subtracted from the reanalysis data representing the observed time periods in the 1993 and 2008 floods respectively, and then divided by the standard deviation from the 60-year climatology to get the standardized anomaly (Hart and Grumm 2001, Grumm and Hart 2001) The standardized anomalies are computed as:

$$SD = (F - M)/\sigma$$

Where **F** is the value from the reanalysis data at each grid point, **M** is the mean for the specified date and time at each grid point, and σ is the standard deviation at each grid point. Pattern comparisons were derived from the GR data.

3. Comparison of the Synoptic Patterns and Resulting Precipitation Prior to the Floods in 1993 and 2008.

Above normal precipitation was observed over the central United States during the winter and spring seasons of 1993 and 2008. Therefore the resulting moist antecedent conditions likely contributed to the flooding in both years. Rainfall departures from normal were high across Missouri, Iowa and Northern Illinois during December 1992-February 1993 (Fig. 1b) and during March-May 1993 (Fig. 1d). A similar positive departure from normal was noted over Missouri, Illinois, Southern Wisconsin and Indiana during December 2007-February 2008 (Fig. 1f) and also during March-May 2008 (Fig. 1h).

During the wet cold seasons prior to the flooding, synoptic scale features were compared. The geopotential height regime during December 1992-February 1993 suggests a storm track further west (Fig. 1a) than during December 2007-February 2008 (Fig. 1e). Along and to the north of the storm tracks for both years, and where the summer flooding occurred, above normal precipitation was observed (Figs. 1b and 1f). A negative height anomaly over the central and upper Mississippi Valley during March-May of both 1993 and 2008 resulted in a continuation of above normal precipitation over the aforementioned regions from late winter (Figs. 1c, 1g).

ENSO signals were examined each cold season prior to the flooding and during the floods to determine if sea surface temperature (SST) forcing could be a factor in the antecedent moisture conditions and/or flooding each year. Higgins et al. (2007) noted that during boreal summer featuring a moderate or strong El Nino, there can be 15% more wet days than during a La Nina over the northern Plains and Midwest. Trenberth and Guillemont (1996: henceforth TG1996) presented evidence of a direct link between North American weather anomalies during spring and early summer and SST anomalies associated with ENSO. By highlighting both the dry summer of 1988 and the wet summer of 1993, TG1996 showed how differing SSTs altered tropical convection

each year thereby influencing the large scale storm track. The winter and spring seasons leading up to the summer flooding in 1993 featured warmer SSTs over the eastern tropical Pacific or El Nino conditions (Table 2), which is consistent with wet antecedent conditions and wet conditions during summer. However the period leading up to the floods of 2008 featured colder SSTs over the tropical Pacific or La Nina conditions, which has not been found to favor heavy precipitation over the central United States. As noted in the introduction, CB2009 presented long lag methods to further investigate a long term connection to antecedent moisture, but further examination of these topics is beyond the scope of this paper.

	ENSO 3.4 Monthly SST Normalized Anomalies	
	1993	2008
December (1992 and 2007)	0.25	-1.50
January	0.18	-1.81
February	0.28	-1.86
March	0.52	-1.08
April	0.90	-0.85
May	1.06	-0.58
June	0.79	-0.32
July	0.48	0.11

Table 2. Monthly Seas Surface Temperature (SST) anomalies for the Nino 3.4 region over the eastern Pacific. Note that the winter and spring seasons leading up to the 1993 Flood featured El Nino (ENSO warm) conditions, while La Nina (ENSO cold) conditions were observed during winter and spring prior to the 2008 Flood.

A negative phase of the NAO was noted two months prior to and during the flood events (Table 3). Weaver and Nigam (2008) found a strong correlation between negative phases of the NAO with increased strength in amplitude of the low-level jet as well as moisture inflow from the Gulf of Mexico. They attributed the link between NAO summer season variability and the low-level jet and moisture inflow over the Great Plains to variations in the positioning of the Bermuda High. Figure 2 illustrates this correlation for both June and July using the 850-hPa meridional wind. A strong Bermuda high displaced westward over the eastern United States results in increased meridional flow into the central United States.

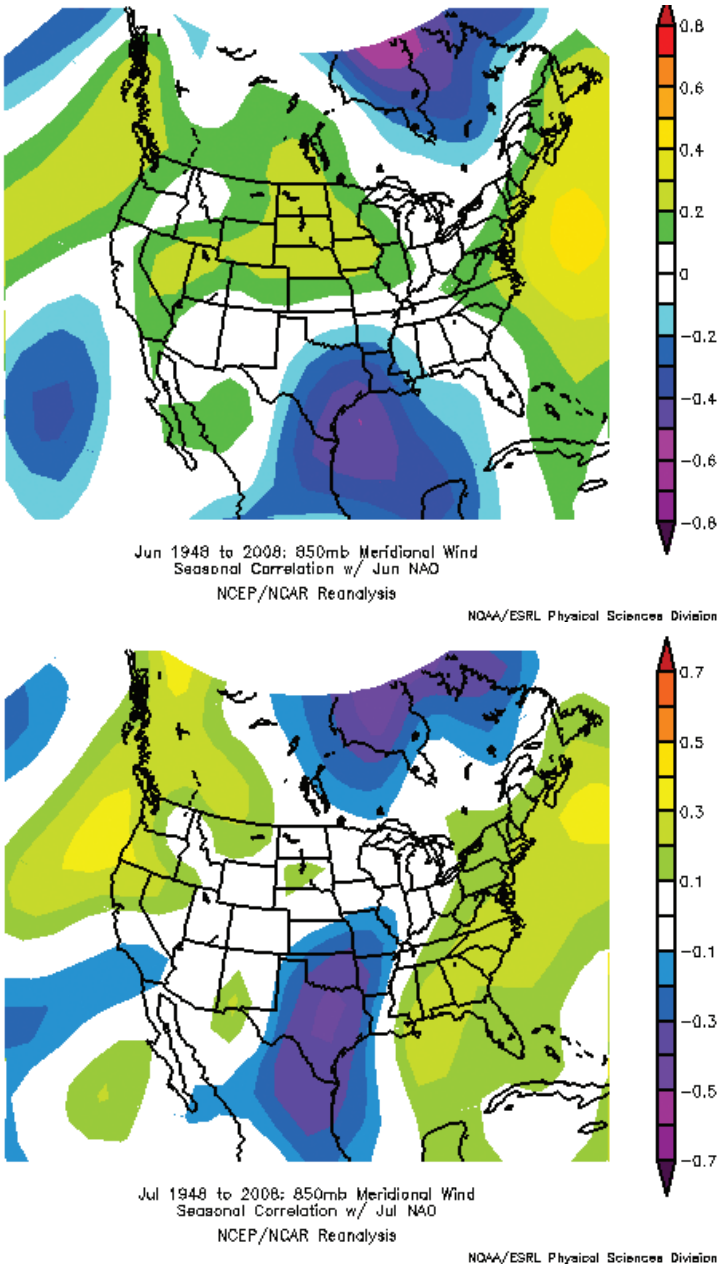

Fig. 2. Plot of correlation between NAO annular mode and 850-hPa v-wind is depicted. The top image shows the NAO and v-wind correlation for June 1948-2008 and the bottom image the correlation for July 1948-2008.

	North Atlantic Oscillation	
	Monthly Index	2008
April	0.97	-1.07
May	-0.78	-1.73
June	-0.59	-1.39
July	-3.18	-1.27

Table 3. The monthly North Atlantic Oscillation index in 1993 and 2008.

4. Comparison of the Synoptic Composites of the Rainiest 13-day periods in 1993 and 2008.

The 500-hPa geopotential height anomalies between the 13-day 1993 and 2008 periods are remarkably similar (Fig. 3c and 3g). Both had a positive anomaly center located between 40°N and 50°N, and 140°W and 150°W and strong negative height anomaly centered near the border between Montana and the Dakotas (Fig. 3d and 3h). Each period also had positive anomalies over the eastern United States. The location of the heaviest precipitation and precipitation anomalies were also similar, with the primary rainfall axis located slightly farther south and west in 1993 compared with 2008 (Fig 3b and 3f). The areal average of the precipitation within the rectangular shaped area enclosed by the dark black line in Fig. 3a and 3e was compared to every other 13-day period from May through September during the 60-year UPD record (1948-2008). The area averaged rainfall during these two periods ranked one (1993) and two (2008) during the period of record.

Two domains of differing size were used to search for analogs to the 2008 500-hPa geopotential height anomaly (Fig. 4). The first is a larger domain that includes North America as well as portions of the eastern Pacific and Atlantic oceans. The second is a smaller domain focusing primarily on the North American continent. When using the larger target domain and searching for 500-hPa geopotential height analogs to the period 2-14 June 2008, the two most highly-correlated 13-day periods are 21 June-3 July 1999 (r=0.89), and 25 June-7 July 1993 (r=0.88). The period in 1999 was associated with above-normal rainfall throughout the central United States, but not with major flooding.

When the target domain for the correlation was reduced to the area shown in Fig. 5b to focus on the conditions over North America, the maximum correlation was for 26 June-8 July 1993 (r=0.96). In addition, the 13-day periods surrounding this one, with center points from 28 June to 10 July, all have correlation coefficients greater than 0.9 with the 13-day pattern in 2008. Furthermore, there are no other 13-day periods during the entire period of record that have correlation coefficients above 0.9 with the 2-14 June 2008 anomaly pattern. The analysis was also performed in the other direction to search for analogs to the 13-day rainy period in 1993, with essentially the same results. The period with the heaviest rainfall in 1993, 29 June-11 July period had r=0.939 when correlated with the 2008 13-day period. Therefore we conclude that the only two times in the last 60 years that this 13-day average height pattern occurred for such a long period over North America were during 1993 and 2008.

The fact that the correlations were higher between the two periods for the smaller domain versus the larger is consistent with Van den Dool (1989) who found that a longer period of record was needed to identify useful analogues for larger domains than for smaller ones. In this case, the smaller domain apparently did a better job of defining the southerly gradient between the negative height anomaly over the northern Rocky Mountain area and the above normal heights to the east. The southerly gradient was determined to be the most impacting feature leading to the anomalous rainfall as it was the primary driver for deep moisture inflow.

While the smaller domain anomaly pattern was found to be unique to the 1993 and 2008 13-day periods, a study by Mo et al. (1995) using the larger domain suggests that the pattern might not be that unusual in a shorter time period. That study identified five-day flood-like periods based on correlations with the height pattern during 1993. They found that the pattern was not that unusual but typically lasted only one 5-day period as opposed to the longer periods observed in 1993 and 2008.

The negative height departures from normal across the northern Rocky Mountains eastward into the northern Plains during both periods resulted in a southward displacement of the jet stream. BJ95 noted that the jet stream over the western and central United States during June and July of 1993 was displaced well south of its mean position. The mean position for that period was very similar to the shorter 13-day period in 1993 that is discussed in this article. They noted that such an upper level wind pattern was conducive to above normal cyclone activity. The 2008 13-day period showed a similar southward displacement of the jet and an enhancement of the jet across the upper Midwest. Both periods featured an anomalously strong u-wind component (Fig. 5a and c) that extended across the northern Rocky Mountains with the exit region of the anomalous jet located over the Plains. The presence of an exit region of an upper-level wind maximum also is favorable for the enhancement of the low-level jet through the lower branch of the associated ageostrophic transverse circulation (Uccellini and Johnson 1979). This enhancement is evident in the 850-hPa composite mean meridional wind anomaly maps (Fig. 5b and d) for both periods, which show enhanced southerly winds from the western Gulf of Mexico across Texas and into the upper Midwest.

The anomalously strong 850-hPa winds also led to anomalously strong moisture flux across this same area during both periods (Fig 6). An axis of high 850-hPa moisture flux has been noted upstream from mesoscale convective systems that produced extreme rainfall (Rochette and Moore 1996; Junker and Schneider 1997; Junker et al. 1999). Augustine and Caracena (1994)

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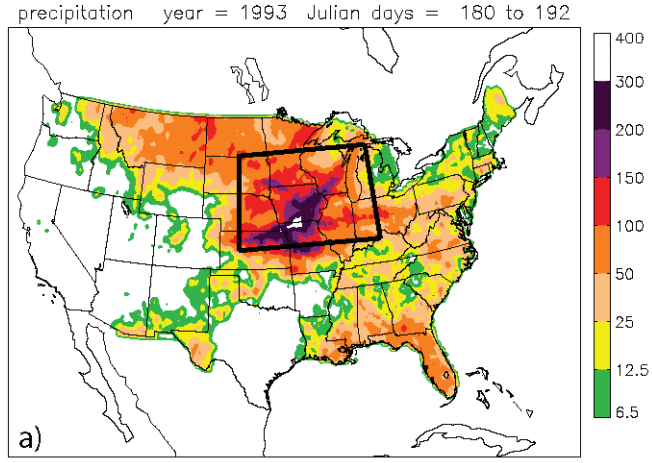
Fig. 3 (a)



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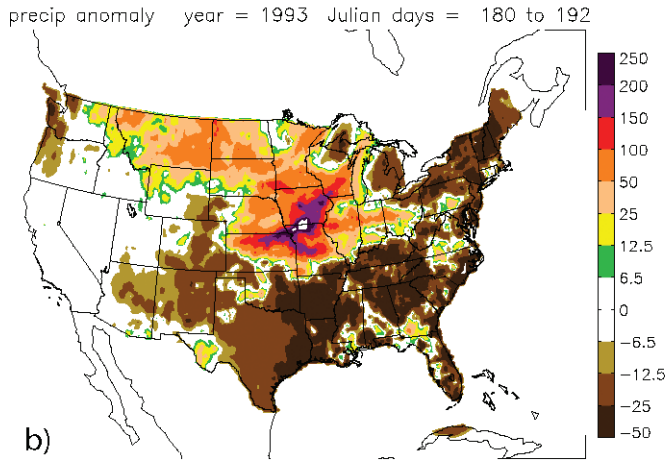

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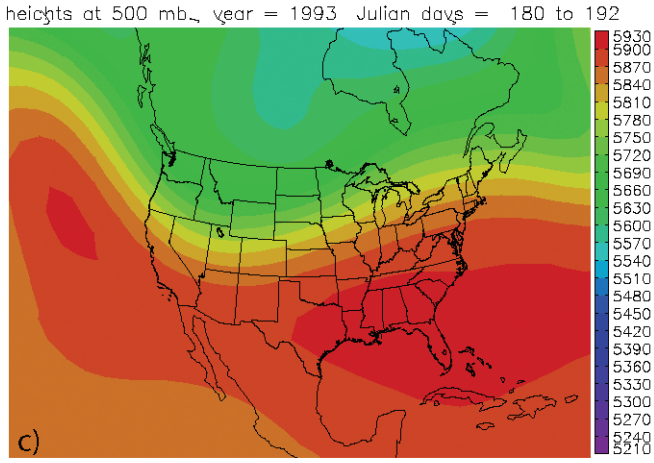


Fig. 3 (d)

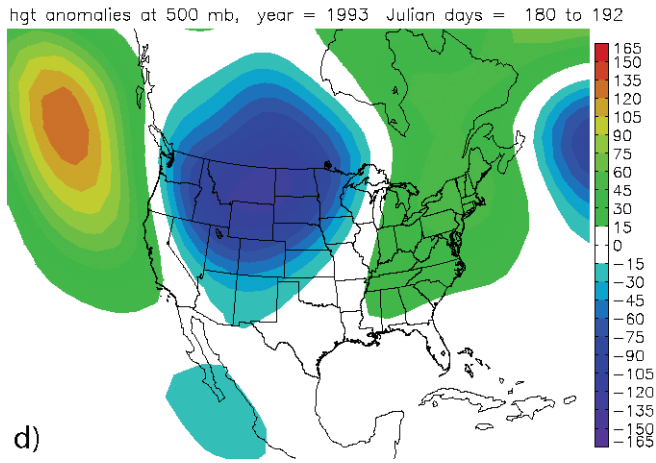


Fig. 3. Plots for the 29 June-11 July 1993, a) precipitation (mm), rectangle indicates area where rainfall was averaged for ranking, b) precipitation anomaly (mm) for each grid box, c) composite mean 500-hPa heights (m), d) composite mean 500-hPa anomalies (m) Note that blue shades are below normal heights, and green and yellow shades are above normal heights. Similar plots are shown for the 0000 UTC 2 June-0000 UTC 14 June 2008 period in panels e through h (see page 111 for e through h).

Fig. 3 (e)

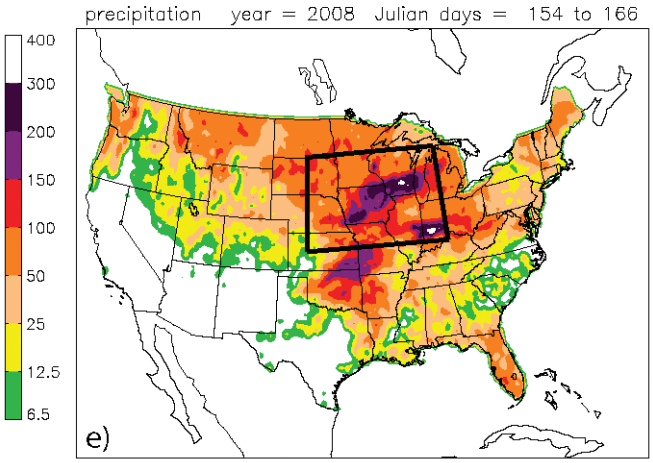


Fig. 3 (f)

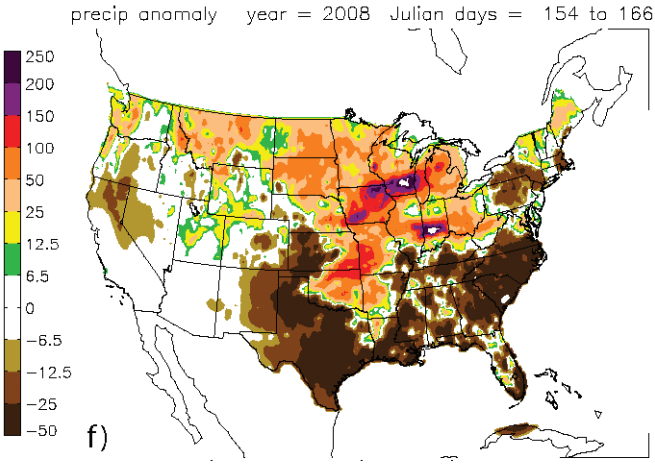
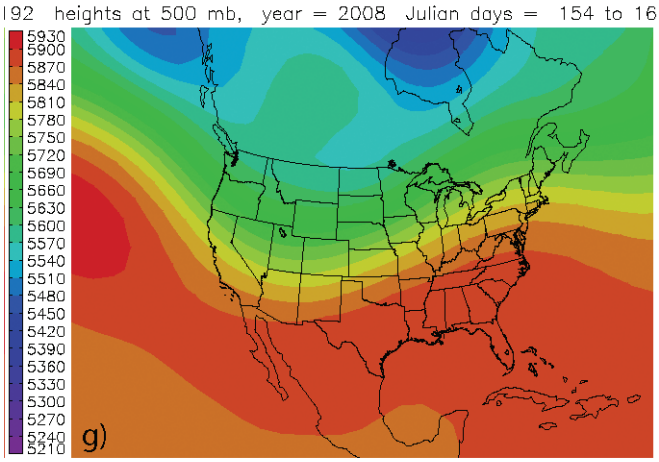


Fig. 3 (g)



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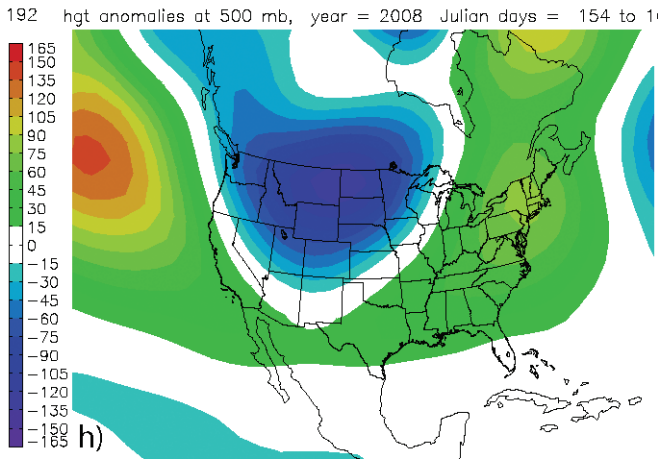


See page 110 for Figure 3 caption.

Fig. 4 (a)

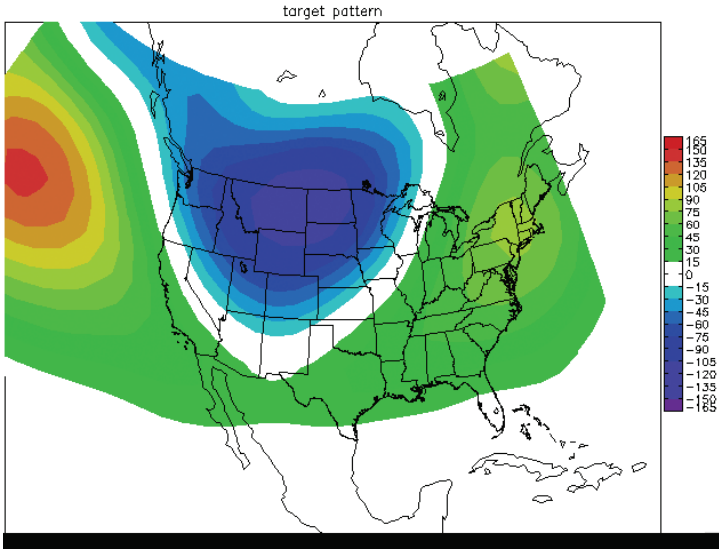


Fig. 4 (b)

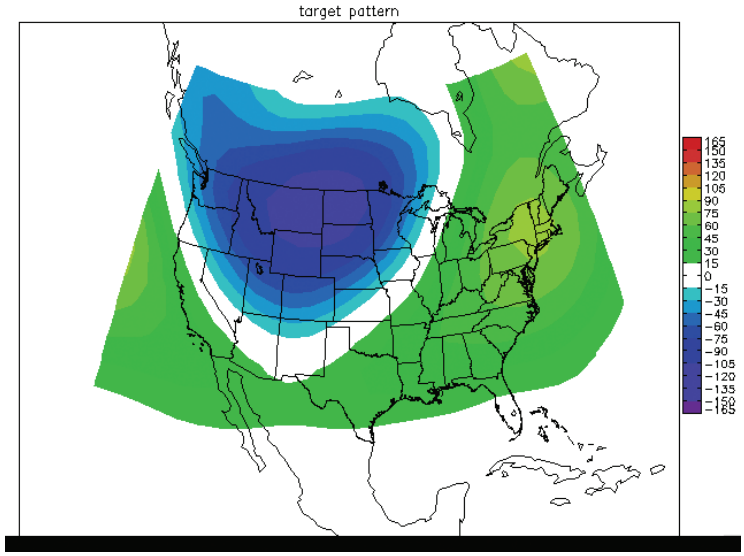


Fig. 4. Anomalies of correlated 500-hPa composite means (m) for 1993 and 2008: a) 500 hPa composite anomalies (m) for the larger domain area, b) 500-hPa composite anomalies (m) for the smaller domain area.

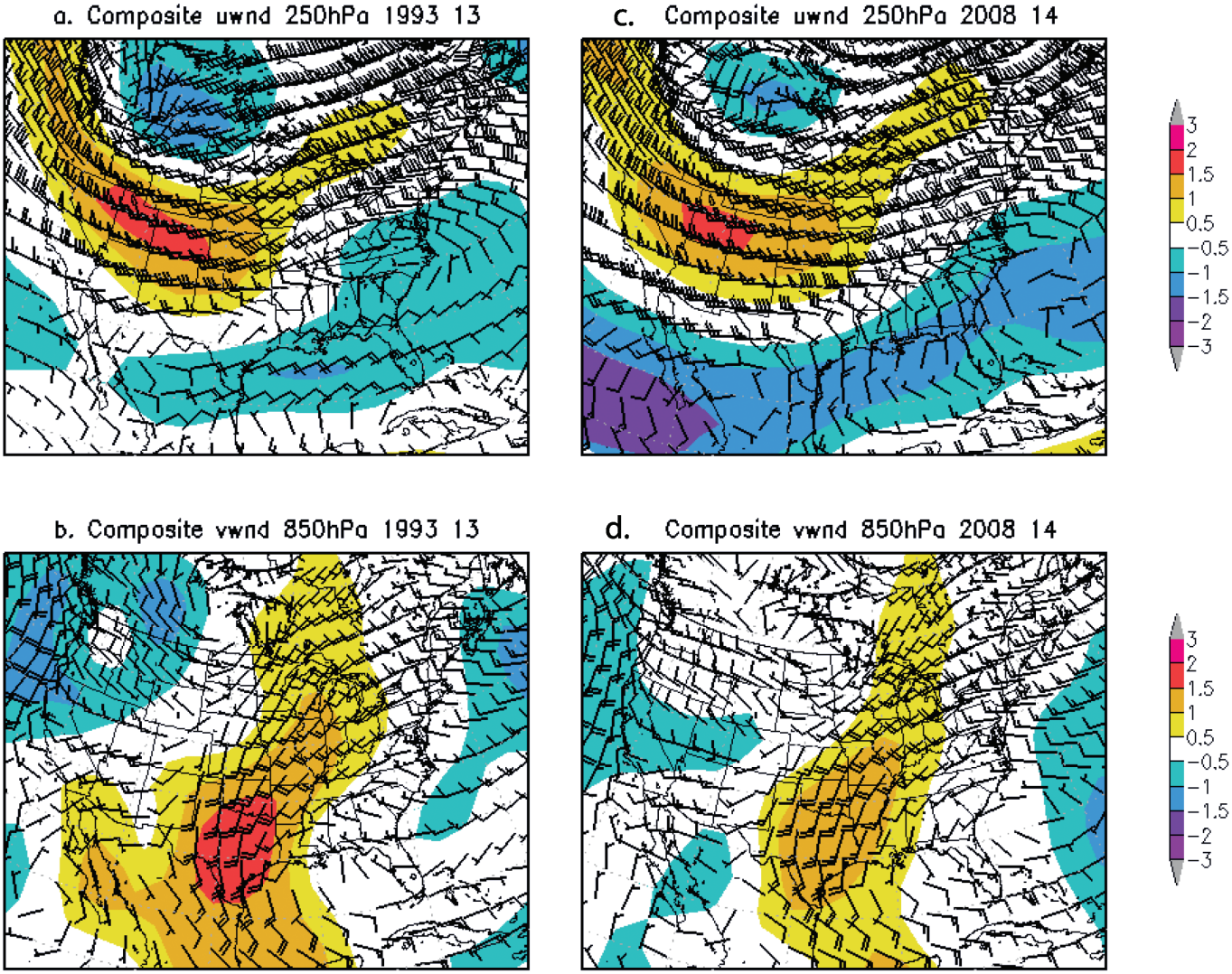


Fig. 5. Composite mean for the 29 June-11 July 1993 period of a) 250-hPa winds (plotted in knots) and the normalized u-wind component anomaly, b) same as in a except 850-hPa winds (plotted in knots) and the normalized v-wind component, c) same as in a except for 2 June-14 June 2008, d) same as in b except for 2 June-14 June 2008.

Fig. 6 (a)

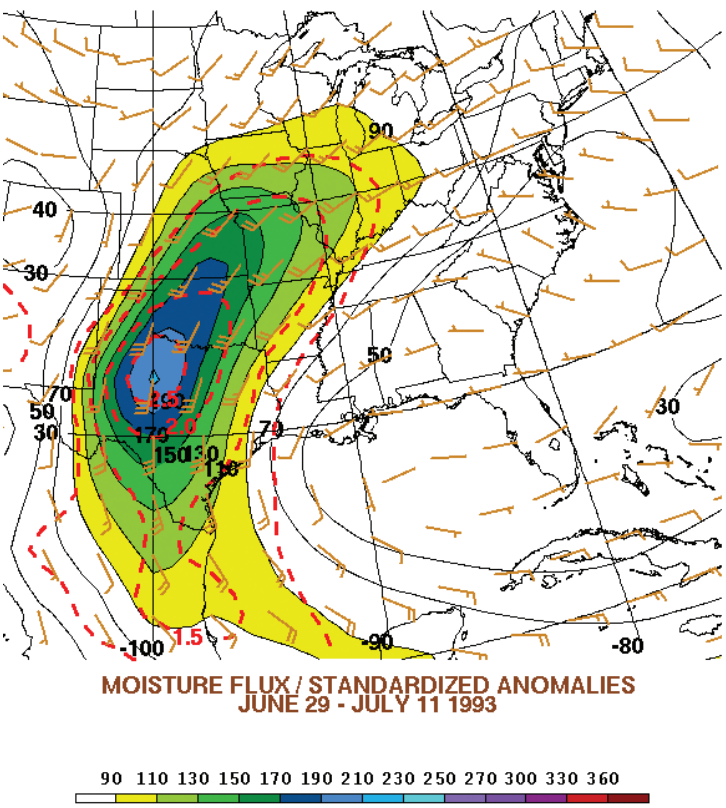


Fig. 6 (b)

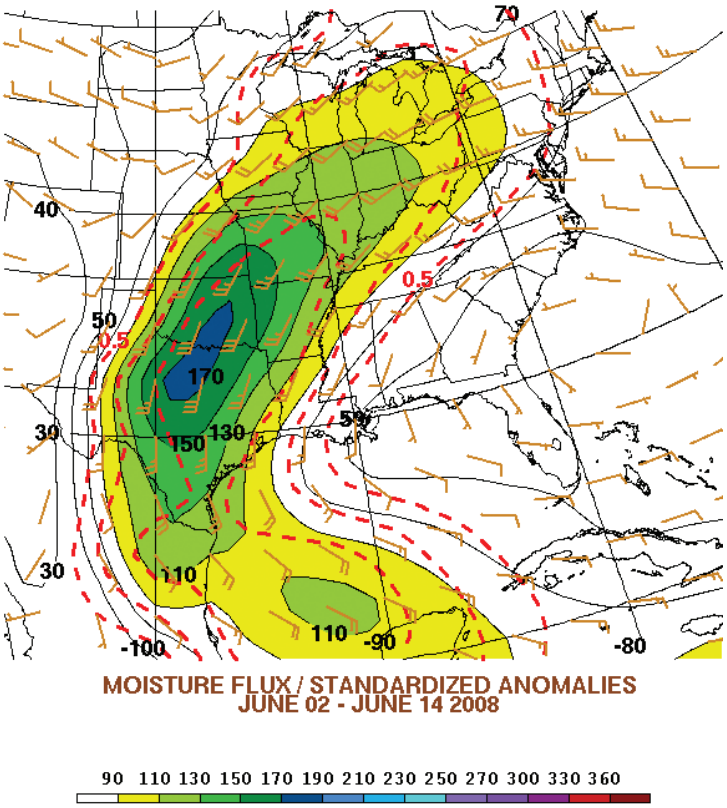


Fig. 6. Composite 850-hPa moisture flux (g m kg^{-1} s^{-1}), normalized anomalies of moisture flux and winds for 29 June-11 July 1993 and 2-14 June 2008.

have also noted that large scale, long lived nocturnal MCS development is favored downwind from a late afternoon surface geostrophic wind maximum when it is frontogenetic at 850-hPa. More recently Tuttle and Davis (2006) have shown that the corridors of warm season precipitation over the central United States are correlated to the northern terminus of the nocturnal low level jet, where speed convergence in the presence of a baroclinic zone contributes to frontogenesis.

The midlevel trough associated with the negative 500-hPa geopotential height departure (Fig. 3) and southerly displacement of the upper-level jet was also associated with below-normal mean sea level pressures and 850-hPa heights (Fig. 7) to the east of the Rocky Mountains from Texas north-northeastward across the Plains into the western portions of the upper Midwest. These below normal pressures and heights as well as the normal to above normal pressures over the east and southeast resulted in an anomalously strong pressure gradient, supporting the aforementioned low level jet. The composite mean of the 1000-hPa heights for each year is also very similar over the plains (compare Fig. 7d to 7h).

There were also similarities in the composite mean 850-hPa temperature and temperature anomaly plots during the two periods (Fig. 7c and 7g). The thermal gradient between the area of below normal temperatures across the northern Rocky Mountains into the northern Plains and the above normal temperatures over much of the eastern states implies a stronger than normal baroclinic zone over the north central United States. Figures 3a and 3e show the precipitation stretched along the respective thermal gradients (Fig.7c and 7g). Finally, during both periods, an axis of above normal precipitable water was present (Fig. 7b and 7f) and fed into the region where the heaviest rainfall was observed.

In summary, the anomalously low mean sea level pressure that was present in the composite mean plots of the 2008 and 1993 periods suggest that enhanced cyclone activity was occurring during both periods, which was one of the contributors to the heavy rainfall. The composites also suggest that the ageostrophic circulations associated with the upper-level jet may be periodically present to enhance upper level divergence (Uccellini and Johnson 1979) and may act to enhance southerly low-level winds. Ample moisture was available in these events owing to the presence of anomalously high precipitable water and 850-hPa moisture flux. Upward vertical motion was enhanced in both events by frontogenetic forcing near the strong thermal boundary in the lower troposphere.

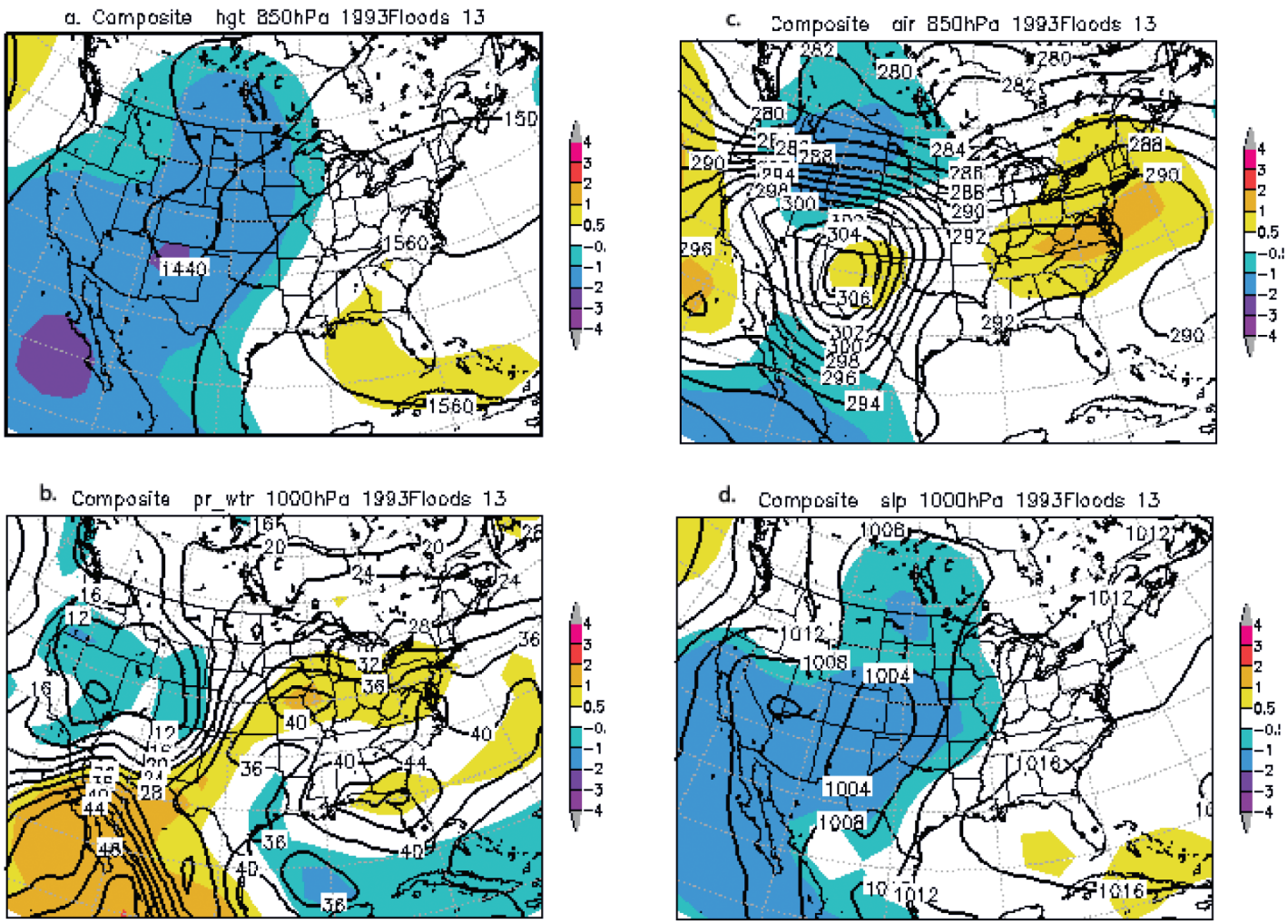


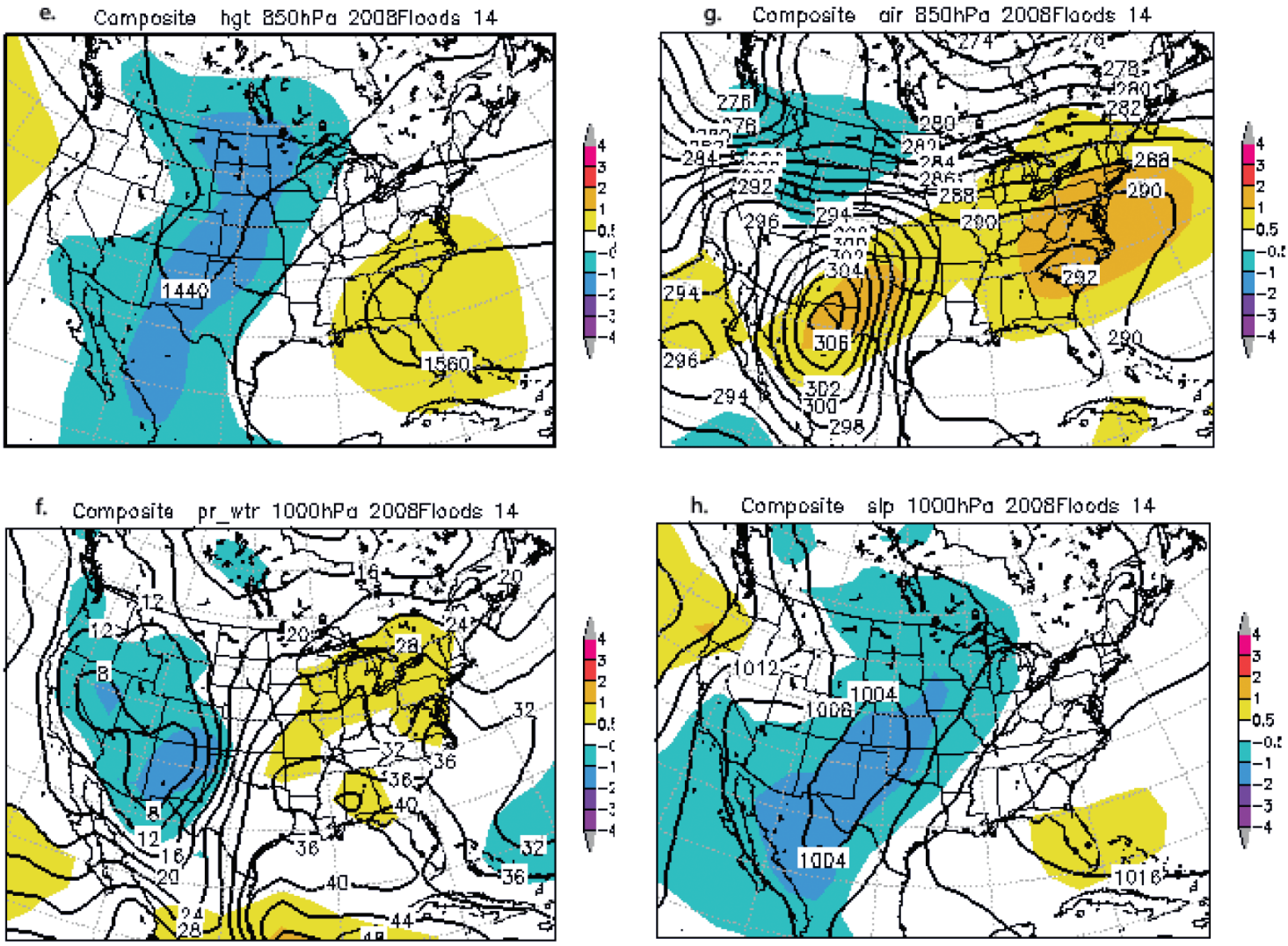
Fig. 7. Composite mean for 29 June-11 July 1993 period, a) 850-hPa heights (m) and normalized height anomaly, b) 850-hPa temperature (K) and normalized temperature anomaly, c) precipitable water (mm) and normalized precipitable water anomaly, d) mean sea-level pressure (MSLP) and normalized MSLP anomaly, e-h)same as in a-d) except for 2 June-14 June 2008. (See page 115 for e - h.)

5. Characteristics of the Heavy Rainfall Events

Table 1 summarizes the synoptic characteristics of these heavier events for both 1993 and 2008. In this table, heavy rainfall events that exhibited a maximum daily rainfall greater than 75 mm within the study domain were identified. The UPD set lacks the resolution to identify the maximum rainfall amounts observed during each event. Therefore, Stage IV precipitation data (Lin et al. 2005) were used to identify the 2008 events. However since Stage IV data were not available during 1993, the official Hydrometeorological Prediction Center (HPC) analyses (McDonald et al. 2000) were used.

Consistent with the composites in section 4, each event was associated with a southward displaced upper level jet across the Rockies and most were associated with anomalously strong u-component 250-hPa winds across eastern Colorado and Wyoming (Table 1). The placement of the negative height anomaly over the northern Rockies into the northern Plains and the stronger than normal upper-level jet across the mountains favor pressure remaining low to the east of the mountains and cyclogenesis when the exit region of a jet streak translates across the Rocky Mountains into the plains.

A subjective evaluation of events based on the NCEP North American Regional Reanalysis (Mesinger et al. 2006) data indicated that 13 of the heaviest 14 events from the combined 1993 and 2008 13-day samples were associated with a surface wave located along the frontal zone (Table 1). This result is consistent with the mean pattern, which favored a front extending across the region, and a region of lower pressure on the western end of the front. All cases were associated with a negative mean sea level pressure anomaly located to the lee of the mountains.



See page 114 for Fig. 7 caption.

Lower pressure was located south and/or west of each rainfall maximum. Such a pressure configuration would generally lead to the development of a stationary front in advance of a short wave trough moving away from the mountains.

The below normal 500-hPa heights and surface pressures to the lee of the Rocky Mountains and the ridge position located over the eastern United States contributed to a synoptic scale pattern favorable for a stronger than normal low-level jet. All the 2008 events having a rainfall maximum of over 75 mm were associated with an anomalously strong v-component of the 850-hPa wind; all had normalized anomalies that were greater than 2.5 σ above the mean located upstream from the location of the rainfall maximum. All cases were associated with a normalized precipitable water anomaly of greater than 2 σ near or upstream from the rainfall maximum. Possibly the most impressive aspect was that the maximum normalized 850-hPa moisture flux anomalies observed during these events were greater than 3.5 σ.

A return frequency graphic was produced in a manner similar to Junker et al. (2009) for a point in northwest Missouri. Figure 8 shows that a normalized 850-hPa moisture flux anomaly of 3 σ has a return frequency of around three months, and a normalized anomaly of 4 σ has a return frequency of around six months. A normalized anomaly of 6 σ has a return frequency that exceeds three years. The importance of these return frequencies is the persistence of anomalously high values that occurred within the 13-day period each year. In 1993, there were five days where the 850-hPa moisture flux exceeded 3 σ above the mean, and one day where 4 σ was exceeded. In 2008, the 850-hPa moisture flux exceeded the mean by 3 σ on eight days, 4 σ on six days, and 6 σ on two days. This information, coupled with the strong correlation of the two 13-day periods based on the 60-year climatology, further enhances the historical significance of the two flood years.

The events were subjectively classified using Maddox et al. (1979) archetypes for heavy rainfall based on the synoptic patterns associated with each one (Tables 3 and 4). Fourteen of the 19 combined events (74%) were classified as Maddox frontal-type events. The remainder appeared to be a cross between the synoptic and frontal types. The dominance of frontal type during both periods is consistent with persistence of an east-west frontal band and southerly low-level jet that is apparent in synoptic composites shown in section 3, both of which are found in the Maddox frontal schematic (see Maddox et al. 1979, Fig. 8).

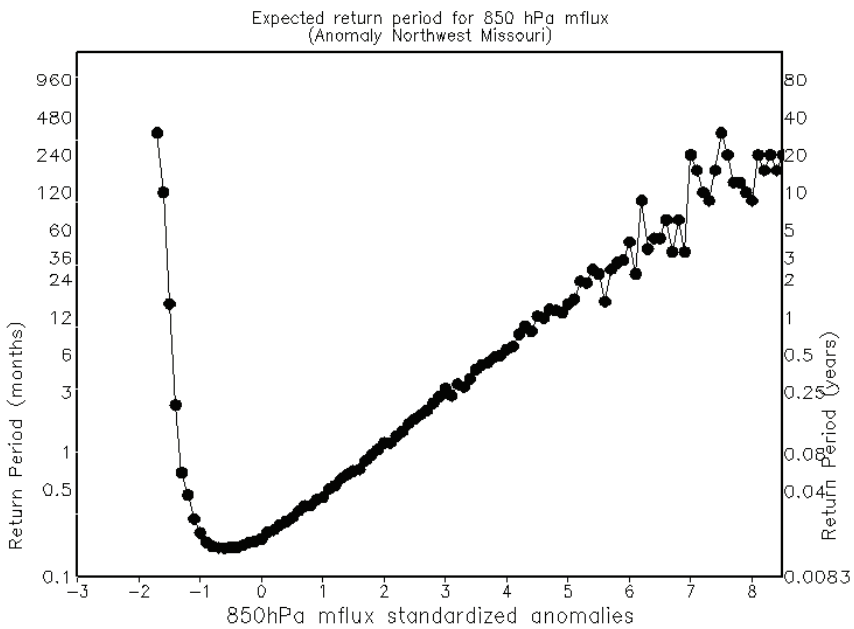


Fig. 8. Expected return period as a function of 850-hPa standardized moisture flux anomaly at a point in northeast Missouri. The x-axis shows the magnitude of the standardized anomaly and the y-axis is the return frequency in months (years) on the left (right).

6. Conclusion

A multiscale comparison of the atmospheric circulation patterns associated with the historic 2008 and 1993 floods was conducted. The synoptic pattern and tropical forcing regime during the winter and spring of 1993 and 2008 were markedly different. In the tropics, El Nino conditions were present during 1993 while La Nina prevailed in 2008. Despite these differences, above normal rain and snowfall occurred in both years, which resulted in above normal soil moisture and increased water levels along main stem rivers of the Midwest heading into summer in both years. However, by summer in both years the large scale circulation patterns were remarkably similar with high correlations of 500-hPa geopotential height noted. This pattern appears to be favorable not only for frequent development of MCSs over the upper Midwest, but also for a remarkable duration of the pattern. The high frequency of MCSs led to the two wettest 13-day periods across this area in the 60-year climatological record.

The persistent synoptic scale patterns during these two 13-day periods helped maintain below normal surface pressures to the lee of the Rocky Mountains and a stronger than normal southerly low-level jet across the region. The anomalously strong low-level jet resulted in normalized anomalies of 850-hPa moisture flux more than 3 sigma above the mean during all eight events in 2008, and during five of six events in 1993. This is an unusual number of days associated with the normalized MF anomalies of 3 σ or greater based on a relatively low return frequency. Tables 3 and 4 also depict that most of the events each year were associated with waves along a frontal boundary, and that each event was associated with high normalized anomalies of precipitable water.

Given the high correlation in large scale patterns

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Maximum rainfall totals for each 13-day period were obtained from hand analysis at HPC.

during the two 13-day periods as well as the high normalized anomalies of available moisture and low-level jet on the mesoscale with each daily event, prediction and possible early detection of these extreme events might be possible by both medium and short range forecasters using ensemble guidance to help ascertain the likelihood of a similar pattern occurring to the one associated with the two 13-day periods.

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