Climate Factors Associated with the Midwest U.S. Floods of June 2008

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1. Introduction

In mid-June 2008, two weeks of heavy rain (Fig. 1a), combined with nearly saturated soils (Fig. 1b) and high river levels, to produce record or near-record stream flows from eastern Nebraska to northern Illinois and Michigan, and from central Illinois to eastern Indiana (black and blue dots, Fig. 1c). Widespread flooding resulted as numerous levees failed and many rivers overflowed their banks.

The most significant flooding occurred in Iowa, where nine rivers reached record levels, and 83 of 99 counties were declared disaster areas. In one instance, the Cedar River crested at over 32 feet on June 13th, flooding 1300 city blocks of Cedar Rapids. Other states affected by flooding included Illinois, Indiana, Michigan, Minnesota, Missouri, and Wisconsin. For example, the Mississippi River crested at 37 feet in the St. Louis area, seven feet above flood level (**mceer.buffalo.edu/infoservice/disasters/iowa-flood-news-statistics.asp#5)**. Flooding in some areas was greatly enhanced by breeched levees. This was especially evident along the Mississippi River, where some levees were breeched prior to being overtopped, while others were breeched when their backsides were washed away by overtopping flood waters.

Three factors likely played an important role in the Midwest floods of June 2008. These include 1) preconditioning from several months of above-av-

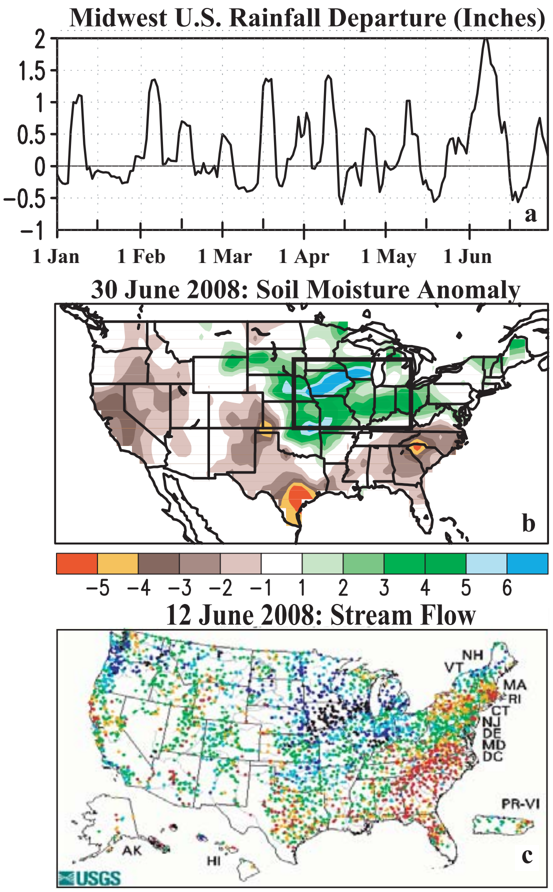

Fig. 1. (a) Time series of 5-day running rainfall departures in the Midwest U.S. during January-June 2008. Black box in (b) shows the averaging region. (b) 30 June 2008 soil moisture anomalies (inches), with green (yellow) indicating a surplus (deficit). (c) 12 June 2008 stream flows [black dots show record flows, and red dots show much below-normal flows].

erage precipitation, high soil moisture, and high river levels, 2) an atmospheric circulation pattern during the first two weeks of June that was typical of other major Midwest flood events, and 3) the combined influence of two prominent tropical climate phenomena, La Niña and the Madden-Julian Oscillation (MJO), which favored recurring jet stream patterns that contributed to several exceptionally heavy precipitation events during February-June 2008.

2. Precipitation and forecasts during January-June 2008

a. Precipitation during January-June 2008

The midwestern United States experienced well above-average precipitation (200% of normal) during January-June 2008 (Fig. 2a), with many locations recording surpluses of more than twelve inches (Fig. 2b). There were four episodes of exceptionally heavy precipitation during the period, which occurred in early February, early April, early May, and early June (Fig. 1a).

Time series of daily rainfall totals during January-June are shown for two representative cities: Indianapolis, IN (Fig. 3a) and Cedar Rapids, IA (Fig. 3b). Indianapolis recorded 32.1 inches of precipitation during the 6-month period, which is 11.8 inches above normal. Portions of Indiana experienced flooding in early February, mid-March, and mid-June. Cedar Rapids recorded 27.4 inches of precipitation during January-June, which is 11.6 inches above normal. Much of this surplus (8.5 inches) occurred during 1-15 June, providing a focus for the major flood event in mid-June.

b. NOAA's monthly and seasonal precipitation forecasts

The National Atmospheric and Oceanic Administration (NOAA) Climate Prediction Center (CPC) issues monthly and seasonal precipitation outlooks for the United States. These outlooks indicate the likelihood of above-normal and below-normal precipitation, but do not predict an exact rainfall surplus or deficit. The seasonal outlook for January-

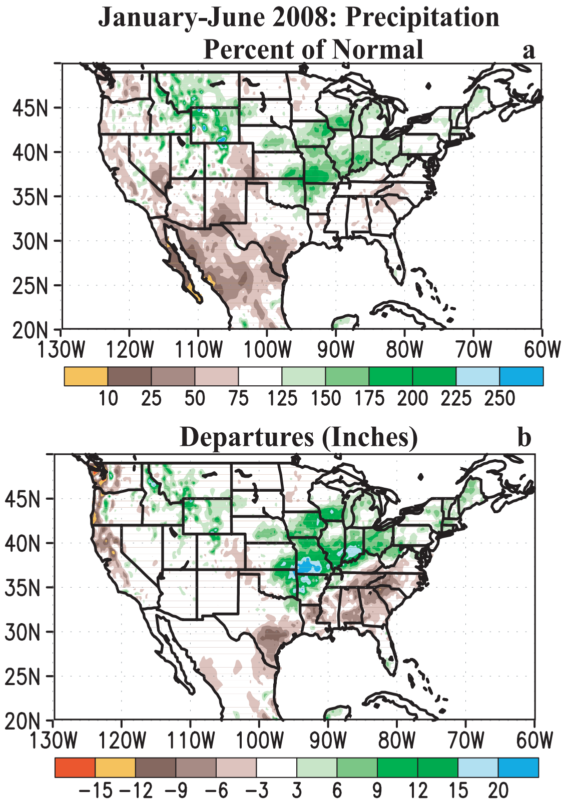

Fig. 2. January-June 2008 precipitation: (a) percent of normal and (b) departures (inches). Departures are with respect to the 1971-2000 period monthly means.

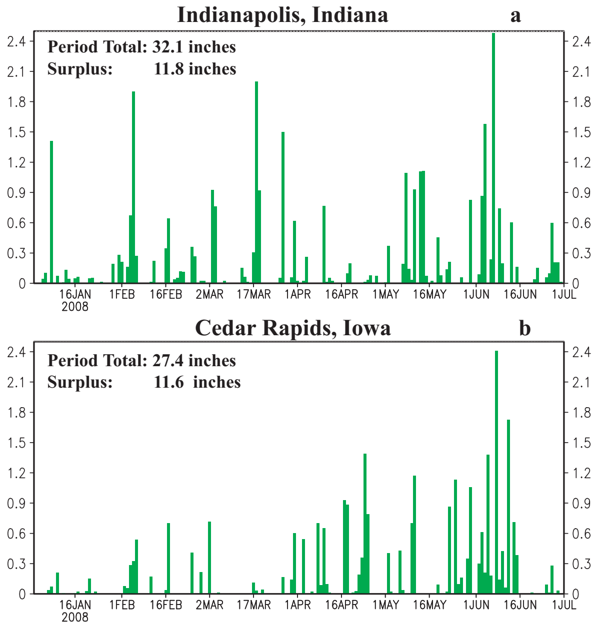

Fig. 3. Time series showing daily precipitation (inches) during January-June 2008 at (a) Indianapolis, IN, and (b) Cedar rapids, IA.

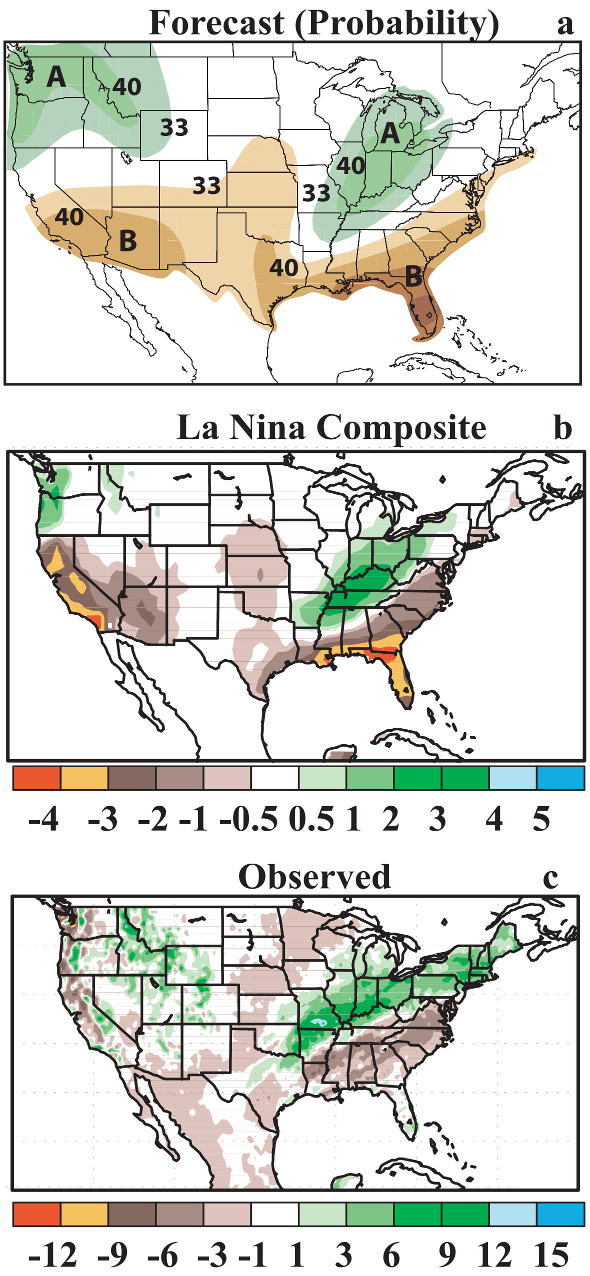

Fig. 4. January-March 2008 precipitation: (a) NOAA Climate Prediction Center seasonal forecast issued 20 Dec. 2007, (b) historical composite La Niña anomalies (inches), and (c) observed departures (inches), calculated with respect to the 1971-2000 period means.

March 2008 called for above average precipitation from Arkansas to Pennsylvania (Fig. 4a). This forecast was based primarily on the expected continuation of La Niña, which historically favors enhanced wintertime precipitation in the Midwest

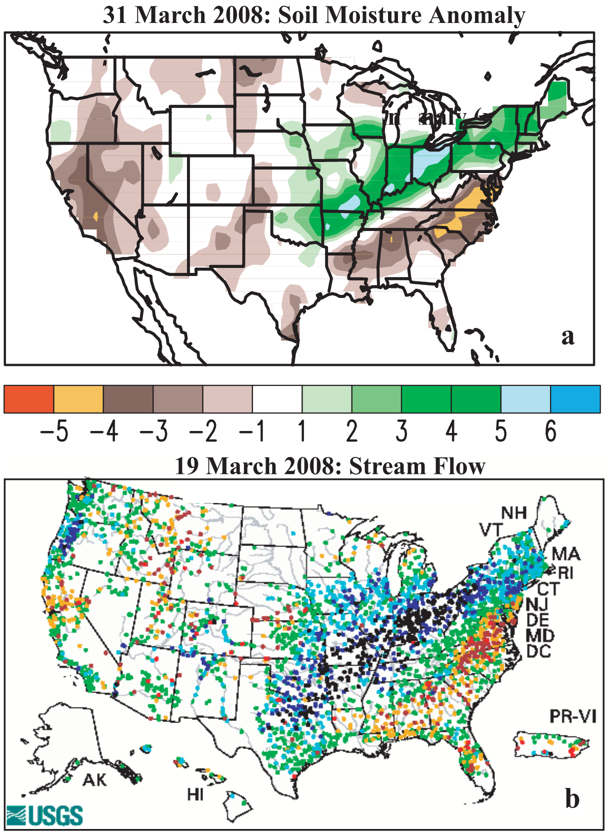

Fig. 5. (a) 31 March 2008 soil moisture anomalies (inches), with green (orange) indicating a surplus (deficit). (b) 19 March 2008 stream flows [black dots indicate record flows, red dots indicate much below-normal flows].

(Fig. 4b). The observed seasonal precipitation was indeed well above average (Fig. 4c), leading to localized flooding in both February and March.

In mid-March, the NOAA Office of Hydrology correctly predicted an above average likelihood that springtime flooding in the Midwest would continue. That forecast was based on several factors, including significant soil moisture surpluses (Fig. 5a) and exceptionally high river flows (Fig. 5b) across the Midwest during March, combined with CPC's correct forecast that above-average precipitation

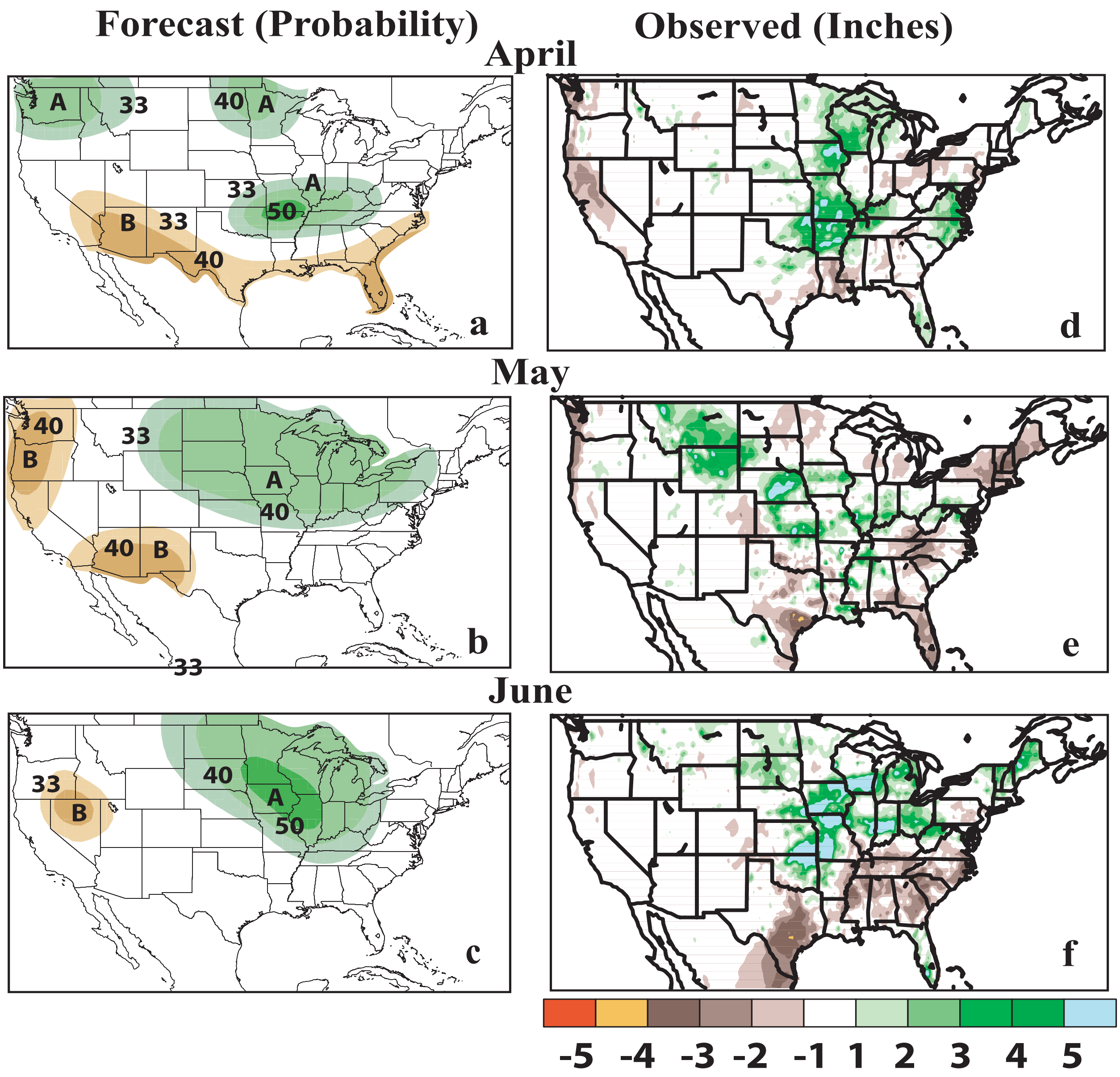

Fig. 6. Precipitation: (Left) NOAA CPC 2008 0-lead monthly probabilistic outlooks, and (Right) observed departures (inches) for (Top) April, (Middle) May, and (Bottom) June.

would continue during April (Figs. 6a, d). The flood threat indeed persisted through the spring, with CPC's monthly forecasts successfully calling for a continuation of above average rainfall during both May (Figs. 6b, e) and June (Figs. 6c, f).

3. Atmospheric conditions

a. Circulation during 2-12 June 2008

The atmospheric circulation associated with the June 2008 Midwest floods is shown in Fig. 7. During 2-12 June, a deep surface trough with well-defined cold and warm fronts was present in the central Plains (Fig. 7a). Within the warm sector, a strong low-level inflow of moist (Fig. 7b) and unstable (Fig. 7c) air overspread the impending flood region. At 500-hPa, a strong trough was located over the western U.S. (Fig. 7d). At 200-hPa, a well-defined jet

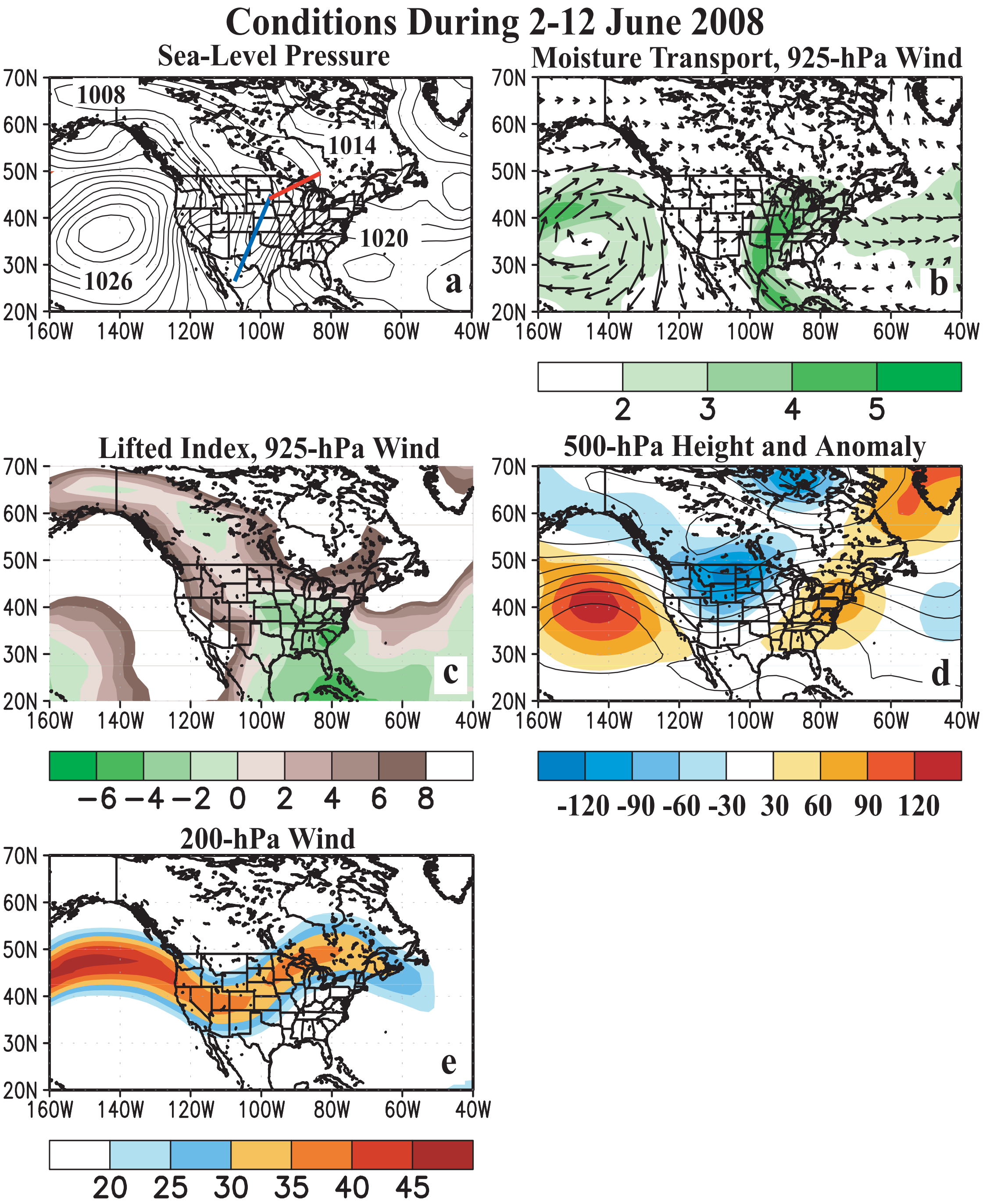

Fig. 7. Atmospheric circulation during 2-12 June 2008. (a) Sea-level pressure (interval is 2 hPa) with warm front (red) and cold front (blue) shown, (b) 1000-600 hPa moisture transport (shaded) and 925-hPa wind vectors, (c) surface-based lifted index , (d) 500-height heights (contour interval is 60 m) and anomalies (shading), and (e) 200-hPa wind speed (m s^{-1}). Height anomalies are departures from the 1971-2000 daily means.

maximum was present within the base of the trough (Fig. 7e), and divergent flow overspread the surface low and frontal boundaries. These conditions are typical of late-spring, prolonged precipitation events in the Midwest, and are similar to those associated with the Midwest floods of 1993 (Bell and Janowiak 1994).

b. Contrasting circulation between the wet and dry periods in the Midwest

During January-June 2008, the Midwest experienced heavy precipitation events in early February, early April, early May, and early June (Fig. 1a). The circulation pattern for each of these events was similar, and is summarized using composite analyses. The dates used in the composites are 31 Jan.-10 Feb., 31 Mar. -10 Apr., 30 Apr.-10 May, and 2-12 June. The composite 500-hPa height field (Fig. 8a) indicates a westward shift of the mean trough to the western United States and a westward shift of the mean ridge from its normal position over the western U.S. to well out into the eastern Pacific. As a result, southwesterly flow and upper-level divergence overspread the midwestern U.S. downstream of the mean trough axis (red shading, Fig. 8b), which made the region especially vulnerable to long periods of above-average precipitation (Fig. 8c).

In contrast, the Midwest experienced below-average precipitation during late January, early March, and mid-May. The circulation pattern for each of these dry events was similar, and is also summarized using composite analyses. The dates used for the "dry" composites are 15-25 Jan., 29 Apr. –

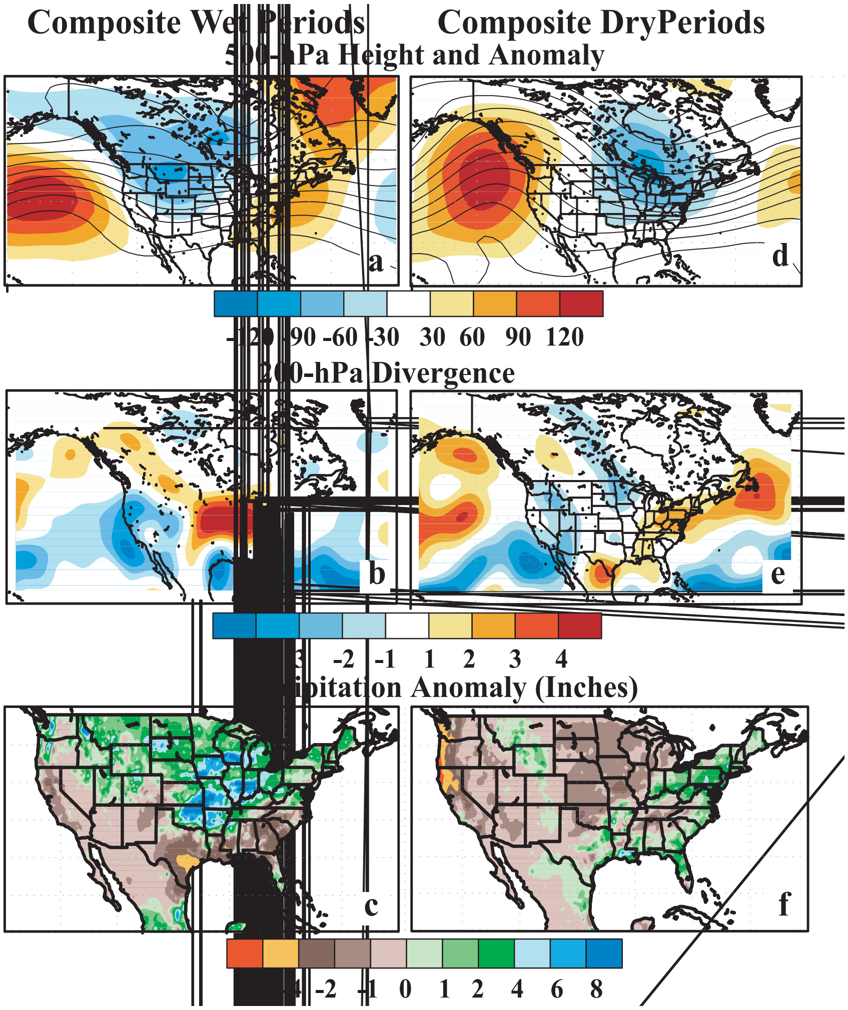

Fig. 8. Composite conditions associated with (a-c) the four main wet Midwest periods (31 Jan.-10 Feb., 31 Mar. -10 Apr., 30 Apr.-10 May, and 2-12 Jun.), and (d-f) the three dry Midwest periods (15-25 Jan., 29 Apr. – 9 Mar., and 12-22 May). Top maps (a, d) show 500-heights (contour interval is 60 m) and anomalies (shading). Middle maps (b, e) show total 200-hPa divergence field, with red indicating divergence and blue indicating convergence. Bottom maps (c, f) show total precipitation departures (inches). Anomalies are with respect to the 1971-2000 daily means.

9 Mar., and 12-22 May. During these events, the 500-hPa ridge and trough were amplified over North America, but were shifted only slightly west of their climatological mean positions (Fig. 8d). As a result, northwesterly flow and upper-level convergence (Fig. 8e) covered the north-central U.S., and the main area of above-average precipitation was shifted to the northeastern U.S. (Fig. 8f).

Therefore, the excessively wet and dry periods in the Midwest were related to recurring east-to-west shifts in the positions of the mean upper-level ridge and trough axes over North America. The climate patterns associated with these shifts are discussed in section 4.

4. Likely climate influences

a. Mean conditions and La Niña

La Niña refers to a cooling of the ocean temperatures across the central and east-central equatorial Pacific Ocean. A moderate-to-strong La Nina during 2008 (Fig. 9a) was associated with a characteristic pattern of tropical convection [indicated by anomalous Outgoing Longwave Radiation (OLR), Fig. 9b] that extended nearly one-half the distance around the global tropics. This pattern featured enhanced convection (green shading) and rainfall over Indonesia and the western equatorial Pacific, and suppressed convection and rainfall across the central and east-central equatorial Pacific (brown shading). As is typical of La Niña, this distribution of tropical convection acted to confine the deep tropospheric convective heating to the western Pacific. The result was a westward retraction of the 200-hPa ridges to the western Pacific in the subtropics of both hemispheres, and enhanced troughs over the central Pacific in the subtropics of both hemispheres

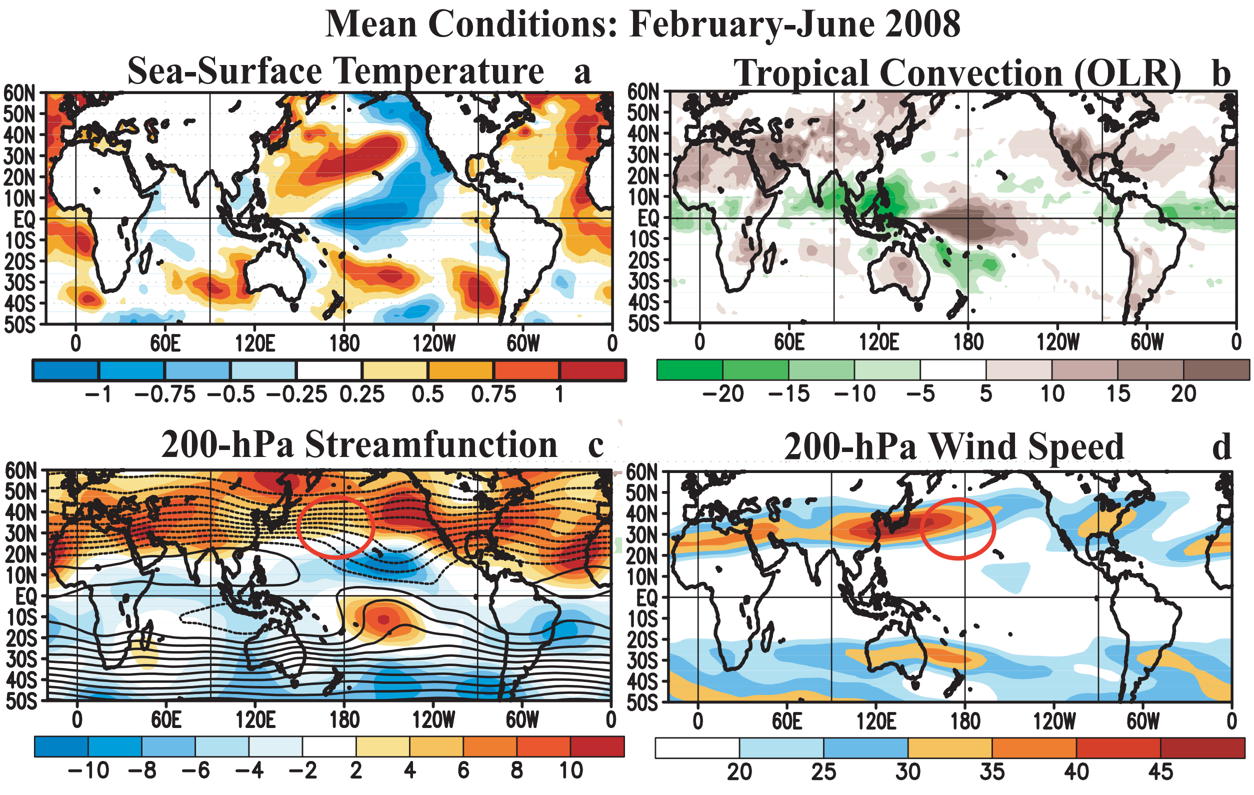

Fig. 9. Feb.-Jun. 2008 (a) sea-surface temperature anomalies (°C), (b) Outgoing Longwave Radiation (OLR, W m^{-2}) anomalies, (c) 200-hPa streamfunction (contours) and anomalies (shaded), and (d) 200-hPa wind speed (m s^{-1}). Red circles in (c) and (d) indicate the East Asian jet exit region. In (c), positive (negative) streamfunction anomalies in the NH indicate anticyclonic (cyclonic) anomalies. In the SH, negative (positive) streamfunction anomalies indicate anticyclonic (cyclonic) anomalies. SST and streamfunction anomalies are departures from the 1971-2000 monthly means. OLR anomalies are departures from the 1979-2000 monthly means.

Fig. 10. Percentage of days during February-June 2008 with positive (red) and negative (blue) height anomalies at 500-hPa. Only values exceeding ±60% of days are shaded.

Fig. 11. February-June 2008: Standard deviation of daily (a) 200-hPa zonal winds and (b) 500-hPa heights. The February-June 2008 period means and the 1971-2000 climatological means have been removed prior to calculating the standard deviation. Black arrow in (a) indicates the climatological East Asian jet.

(Fig. 9c).

The East Asian jet stream (Fig. 9d) is strongly linked to conditions in the tropics and subtropics. Situated north of the subtropical ridge, the jet core coincides with the strong gradient in 200-hPa streamfunction, while the jet exit region is defined by the area of strong diffluence between the subtropical ridge and trough axes. During 2008, La Niña contributed to a westward retraction of both the East Asian jet and jet exit region (red circle, Figs. 9c, d).

The associated 500-hPa height pattern featured persistent positive anomalies over the eastern North Pacific, and persistent negative anomalies over central North America (Fig. 10). This anomaly pattern reflected a westward shift of the mean North American ridge and trough axes, and is consistent with the westward retraction of the East Asian jet. This typical La Niña-related circulation pattern is generally most prominent during January-March, when it contributes to enhanced precipitation in the central U.S. and suppressed precipitation across the southeast (Fig. 4b). However, in 2008 these conditions lasted well into June.

b. Variability not associated with La Niña

The previous analysis indicates that La Niña can help explain the overall pattern of above-average precipitation in the midwestern U.S. during the winter and spring of 2008. However, La Niña alone cannot account for the recurring east-west shifts in the positions of the mean upper-level ridge and trough axes, with which the exceptionally wet and dry Midwest periods were associated.

To further examine these shifts, both the February-June 2008 means (similar to those shown in Fig. 9) and the climatological means were removed from the daily 200-hPa zonal wind and 500-hPa height fields. The resulting 200-hPa zonal wind anomalies exhibit maximum variability near the date line (Fig. 11a) within the exit region of the climatological mean East Asian jet (black arrow). Distinct axes of maximum variability extend upstream toward the entrance region of the East Asian jet, and downstream toward both southern California and southwestern Canada. At 500-hPa, the height anomalies exhibits maximum variability across the extratropical North Pacific in the area north of the East Asian jet stream (Fig. 11b), with much of the signal focused within and downstream of the jet exit region.

These variance maxima reflect coherent intraseasonal fluctuations in both the position of the East Asian jet exit region and the locations of the downstream 500-hPa ridge and trough axes, as was observed in Fig. 8. A more westward retraction of the jet (compared to the mean La Niña signal) is associated with a more westward shift of the North American ridge and trough axes, as was seen dring the four exceptionally wet Midwest periods. Conversely, a more eastward extension of the East Asian jet was associated with a more normal position of the ridge and trough axes over North America, and with a more southerly point at which the jet stream enters the continent. These conditions typify the three dry Midwest periods.

c. Madden-Julian Oscillation (MJO) influence on the excessively wet Midwest periods

The MJO is a tropical climate phenomenon featuring large-scale convective anomalies that propagate eastward along the equator and generally traverse the globe in 30-60 days (Madden and Julian 1971, 1972, 1994). The MJO can strongly affect the tropical and extratropical atmospheric circulation patterns, and can also sometimes produce ENSO-like anomalies (Mo and Kousky 1993, Kousky and Kayano 1994, Kayano and Kousky 1999). The MJO is seen by continuous propagation of 200-hPa velocity potential anomalies around the globe. During 2008, a time-longitude section of this parameter shows an active MJO from January through mid-April and again during May and June (Fig. 12).

Following Wheeler and Hendon (2004), eight different phases of the MJO are used to summarize the daily location of the tropical convection anoma-

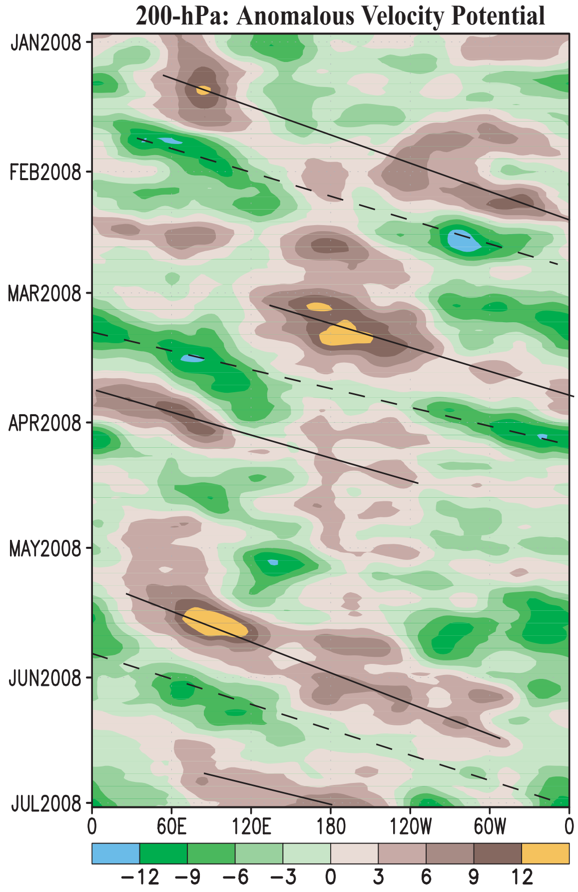

Fig. 12. Time-longitude section of 5-day running velocity potential anomalies at 200-hPa during January-June 2008 averaged between 5°N-5°S. (Green) brown shading indicates anomalous upper-level divergence (convergence). Ascending and descending phases of the MJO are indicated by dashed and solid lines, respectively. Anomalies are departures from the 1971-2000 base period daily means.

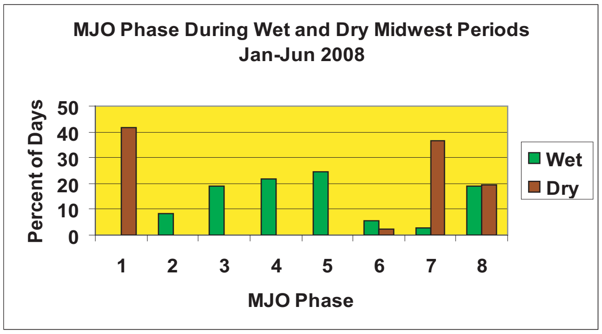

Fig. 13. Percentage of days with the MJO in each phase (phases 1 through 8) during the four wet Midwest periods (green) and the three dry Midwest periods (brown). The wet and dry periods are listed in Fig. 8.

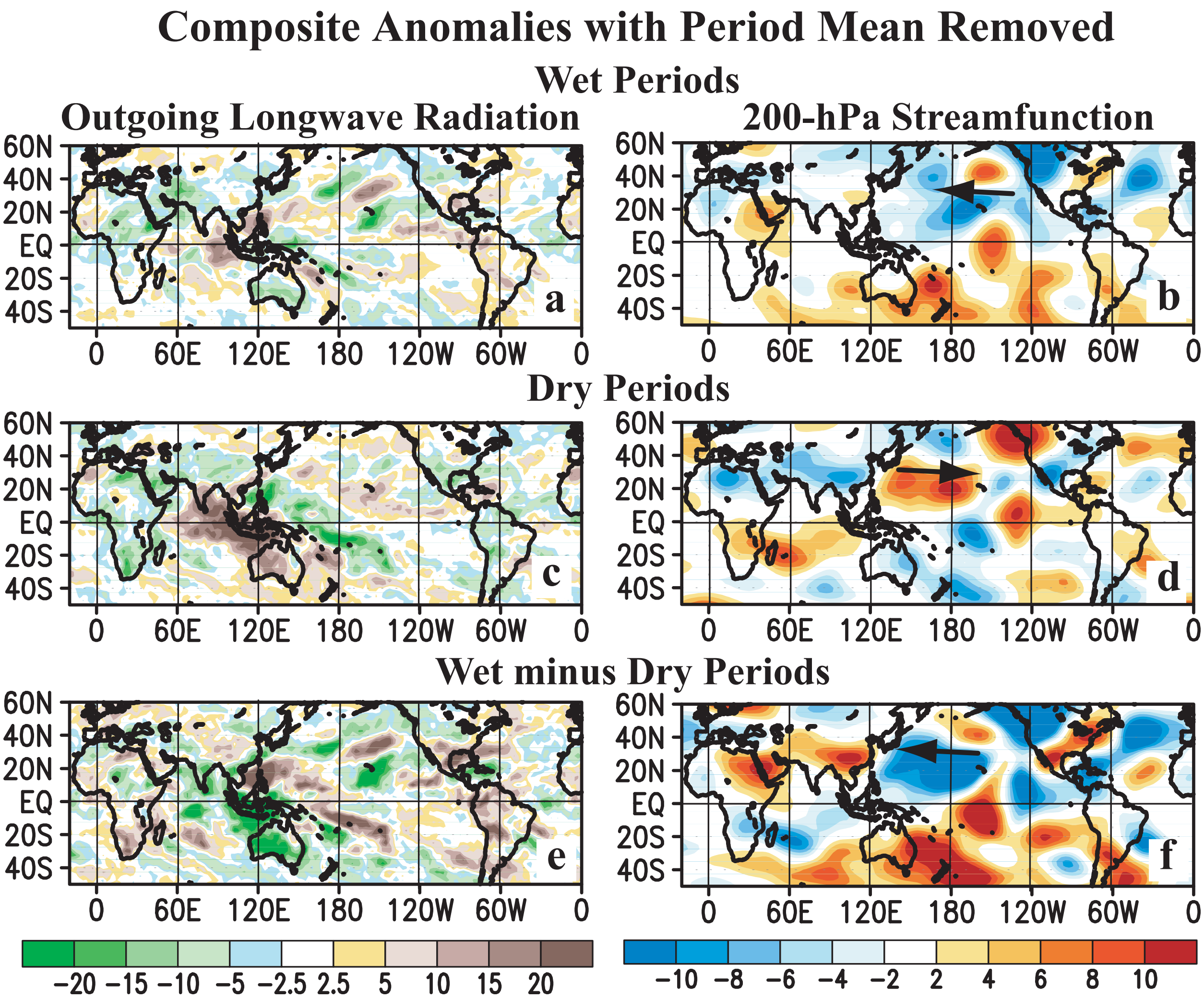

Fig. 14. Composite anomalies during February-June 2008 (period means and climatological means removed) during the four wet Midwest periods (Top), the three dry Midwest periods (Bottom), and the difference (wet minus dry). (Left) OLR and (Right) 200-hpa streamfunction with black arrows showing 200-hPa wind anomalies associated with the East Asian jet stream. The wet and dry periods are listed in Fig. 8. OLR and streamfunction are plotted as in Fig. 9.

lies. Between February and June 2008, the four main wet Midwest periods were associated primarily with MJO phases 3-5 (green bars, Fig. 13), while the three main dry periods were associated with phases 7, 8 and 1 (brown bars).

To better understand this relationship between the MJO and midwestern U.S. precipitation, both the February-June 2008 means and the climatological means were removed from the daily OLR and 200-hPa streamfunction data. The resulting analysis indicates that during the wet Midwest periods, the MJO acted to enhance convection over Indonesia (Fig. 14a), thereby accentuating the La Niña signal (Fig. 9b). Consistent with this finding, these periods featured a more westward retraction compared to La Niña of the East Asian jet exit region and a more westward shift of the circulation anomalies over the eastern North Pacific and North America (compare Figs. 14b and 9c).

Conversely, the MJO and La Niña signals offset each otherduring the dry Midwest periods, with the MJO acting to suppress convection over Indonesia and to enhance convection over the central equatorial Pacific (Fig. 14c). Consistent with this finding, these periods featured a stronger East Asian jet stream compared to La Niña, along with a more eastward position of the circulation anomalies over North America (compare Figs. 14d and 9c). Difference fields (wet minus dry Midwest) highlight these consistent relationships between the OLR (Fig. 14e) and circulation anomalies (Fig. 14f).

These results link the recurring east-to-west shifts in the positions of the North American ridge and trough axes to varying combinations of the MJO and La Niña. The excessively wet Midwest periods were associated with a reinforcement of the La Niña signal by the MJO, while the dry Midwest periods were associated with a suppression of the La Nina signal by the MJO. This link between tropical convection and the extratropical circulation anomalies remained significant even into late May and early June (Fig. 15), therein setting the stage for the return of heavy rains that ultimately produced the Midwest floods of June 2008.

5. Summary

The midwestern United States experienced well above-average precipitation during January-June 2008. NOAA's seasonal and monthly precipitation outlooks consistently called for above-average precipitation throughout the period, and their flood outlook issued in mid-March called for an above average chance of springtime flooding.

At least three factors played an important role in the Midwest floods of June 2008. These include 1) preconditioning from several months of above-average precipitation, high soil moisture, and high river levels, 2) an atmospheric circulation pattern during the first two weeks of June that was typical of other major Midwest flood events, including the Great Midwest floods of 1993, and 3) the combined influence of two prominent tropical climate factors, La Niña and the MJO, which favored recurring jet stream patterns that contributed to four exceptionally heavy precipitation events during February-June 2008.

A moderate-to-strong La Niña episode can account for the overall above-average precipitation observed in the Midwest during January-March. In addition, the four excessively heavy precipitation events during February-June all occurred while the MJO was acting to accentuate the La Niña signal. During these periods the East Asian jet exit region and the North American ridge and trough axes were shifted farther westward than would be expected for La Niña alone. As a result, the Midwest was situated downstream of the mean upper-level trough axis in an area of large-scale ascending motion, upper-level divergence, and significantly enhanced precipitation. This link to the tropical climate patterns was notable even in late May and early June, at a time when it is often difficult to link extratropical climate variability to anomalous tropical convection.

Conversely, the Midwest experienced three main periods of below-average precipitation during January-June 2008, all of which occurred while the MJO was acting to offset the La Niña signal. During

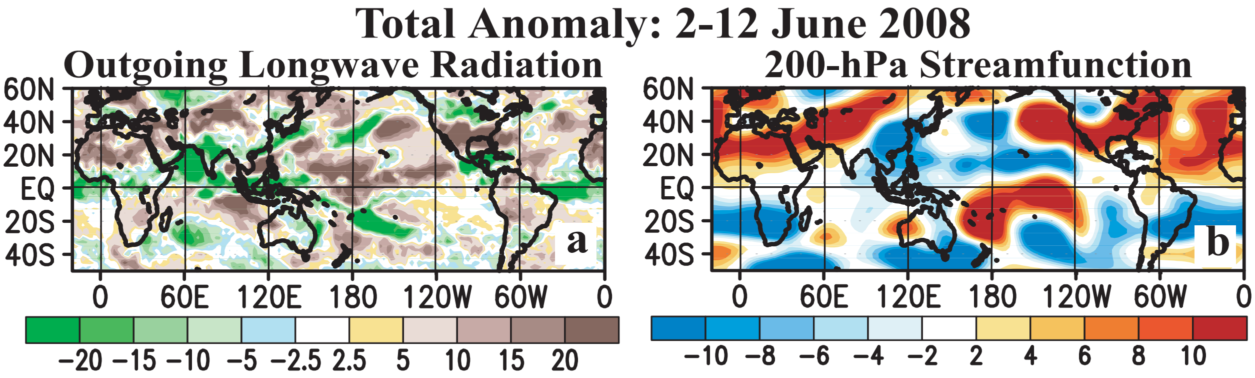

Fig. 15. Anomalous (a) OLR and (b) 200-hPa streamfunction during 2-12 June 2008. OLR and streamfunction are plotted as in Fig. 9. Period means NOT removed.

these periods, the East Asian jet stream was extended farther eastward than would be expected for La Niña alone, and the trough and ridge axes over North America were situated only slightly west of their climatological mean positions. As a result, the main area of above-average precipitation was shifted to the northeastern U.S.

These findings indicate that La Niña and the MJO can account for many aspects of the observed precipitation variability in the Midwest during January-June 2008. However, there are several reasons why these results are case-specific, meaning that they may not explain other major Midwest flood events. First, during a moderate-to-strong La Niña episode the MJO is typically much less active than was observed during 2008. Second, La Niña's impact on U.S. rainfall typically fades during the late spring. Third, other circulation features such as extratropical teleconnection patterns often significantly impact U.S. precipitation. Fourth, in any Midwest flood event, the details of the atmospheric circulation are crucial in determining exactly where the heaviest rainfall and flooding occurs. These details, which cannot generally be attributed to any climate factor, include the specific trough and jet stream configurations, the amount and location of moisture transport into the region, and the location and strength of the low-level frontal boundaries.

6. References

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