Pentad Evolution of Wintertime Impacts of the Madden-Julian Oscillation on the Contiguous United States

Stephen Baxter and Scott Weaver

Abstract. Lagged pentad composites of surface air temperature and precipitation are analyzed for the winter season (DJF) to assess the influence of the Madden-Julian Oscillation (MJO) on the contiguous United States. Significant positive temperature anomalies develop in the eastern United States 5-20 days following Wheeler and Hendon MJO Phase 3, which corresponds to enhanced convection centered in the eastern Indian Ocean. At the same lag, positive precipitation anomalies are observed from the Southern Plains to the Great Lakes region. Negative temperature anomalies appear in the central and eastern US 10-20 days following MJO Phase 7. These impacts are supported by an analysis of the evolution of 200-hPa geopotential height and zonal wind anomalies. Furthermore, impacts are assessed by analyzing composites based on a velocity potential index of the MJO. This analysis suggests that MJO-related velocity potential anomalies can be used without the Wheeler and Hendon index to predict MJO impacts.

1. Introduction

The Madden-Julian Oscillation (MJO) is the dominant mode of sub-seasonal climate variability in the tropics, consisting of propagating patterns of convection coupled with oscillating patterns in upper- and lower-level winds (Madden and Julian 1971, 1994). Studies indicate that the MJO has a strong impact on climate variability in the extratropics through a Rossby wave train associated with the anomalous tropical convection (Mo and Higgins, 1998; Matthews et al., 2004). The extratropical impacts of the MJO can also be understood in terms of the relationship between the MJO and major modes of extratropical climate variability such as the Arctic Oscillation (AO) (Zhou and Miller, 2005; L'Heureux and Higgins, 2007). Lin and Brunet (2008) show that the MJO has significant impacts on Canadian wintertime surface air temperature (SAT). Therefore, understanding the effects of MJO-related convection on the extratropics provides a useful tool in improving short term climate forecasts (~2-3 weeks).

Our purpose here is to investigate wintertime impacts of the MJO on the United States using lagged pentad composites. Additionally, we analyze composites that employ both the commonly used MJO index developed by Wheeler and Hendon (2004) and a velocity potential index used for real-time monitoring at NOAA's Climate Prediction Center (CPC). Comparing and contrasting the impacts captured by using both indices enables an assessment of which index is better suited for operations.

Section 2 describes in more detail the two MJO indices as well as the hydroclimate and circulation data used in the study. Section 3 discusses the methodology. The results of the composite analysis are discussed in section 4, followed by conclusions in section 5.

2. Data and MJO Indices

This study spans a period of 30 years (1979-2008). US SAT is derived from gridded co-op data at a 1° by 1° resolution. The CPC-unified precipitation data is used with a resolution of 0.25° by 0.25°. A square-root transformation is performed to bring the precipitation data closer to a normal curve for the purpose of significance testing. For atmospheric circulation we use the latest data available from the Climate Forecast System Reanalysis (CFSR). This global data (200-hPa zonal wind and geopotential height) is gridded at a longitudinal/latitudinal resolution of 2.5° by 1.25°. At the same resolution, we employ OLR data from NOAA's polar-orbiting satellites as a proxy for tropical convection.

In order to isolate sub-seasonal climate variability, the data is averaged over 5 days to construct the pentad data. For this wintertime study, winter is defined by the months December, January, and February. The winter season consists of 19 pentads beginning November 27. Pentad anomalies are then constructed by removing the pentad climatology. Finally, the seasonal mean anomaly is removed to eliminate interannual variability.

As previously mentioned, two MJO indices are used in the composite analysis. The Wheeler and Hendon (WH) index (Wheeler and Hendon, 2004) is a combination of the two leading principal components of a multivariate (outgoing longwave radiation (OLR), 850- and 200-hPa zonal wind) EOF analysis. These two PCs make up the two-dimensional Wheeler-Hendon diagram which is divided into eight phases.

The CPC MJO index is constructed by calculating the EEOF of 200-hPa velocity potential for 15 ENSO-neutral and weak ENSO winters during 1979-2000. The first EEOF consists of ten, time-lagged patterns. Ten MJO indices are constructed by regressing unfiltered pentad 200-hPa velocity potential onto each of the ten patterns.

3. Methodology

Pentad composites are constructed by WH MJO phase and amplitude. Pentads are selected when the pentad amplitude of the WH index is greater than or equal to 1.0. Likewise, composites based on the CPC MJO indices are constructed by selecting pentads where there the index is greater than or equal to 1.0. We do not attempt to constrain the composites by assessing propagation of the convective anomaly.

Composites are made of OLR to assess where both the WH MJO index and the CPC index agree on the location of MJO-related tropical convection. WH phases 3 and 7 coincide the active phases of CPC indices 1 and 6, respectively. Figure 1 shows the dipole of tropical convection/subsidence between the Indian Ocean and the western Pacific that occurs during WH phase 3 and CPC index 1 (spatial correlation of approximately 0.95). This dipole reverses during WH phase 7 and CPC index 6 (not shown). Additionally, WH phases 3 and 7 are the most frequently occurring phases during DJF.

In this study, we focus on the time-lagged, wintertime response of US temperature and precipitation, as well as global 200-hPa circulation, to WH phases 3 and 7 (CPC indices 1 and 6). Furthermore, composites are constructed for pentads in which CPC index 1 is greater than 1.0, but the WH index has amplitude less than 1.0 or is not in phase 3. This method allows for a deeper analysis of the manner in which the two different indices capture MJO-related convection and its US impacts. Statistical significance of the composites is calculated using a student's t-test on standardized anomaly composites.

4. Composite Analysis

a.) United States SAT anomalies

In order to analyze MJO impacts on wintertime US SAT, lagged composites are constructed for each WH MJO phase. This analysis reveals two primary findings: a) the development of a substantial positive SAT anomaly in the eastern US following WH MJO phase 3, and b) the development of a negative SAT anomaly across much of the US following phase 7. The corresponding CPC MJO indices (1 and 6, respectively) reveal nearly identical SAT anomalies. However, the CPC MJO composites contain significantly more pentads than the WH composites (WH3, n=58; WH7, n=52; CPC1, n=96; CPC6, n=79). Figure 2 shows the lagged SAT composite with respect to CPC MJO index 1. The SAT anomaly reaches a maximum at a three pentad lag, centered over the Ohio Valley and Great Lakes with a magnitude in excess of 2^{o} C. Likewise, the negative SAT anomaly that develops following a convective anomaly captured by CPC MJO index 6 (not shown) maximizes at lags three and four.

This distinct evolution of a SAT anomaly following the development of an Indian Ocean/West Pacific convective anomaly dipole suggests that the convection captured by WH phases 3 and 7 (CPC MJO indices 1 and 6) are mainly responsible for MJO-related impacts in the US. This is supported by Lin et al. (2007) which suggested that extratropical response to tropical forcing fully develops in approximately two weeks.

b.) United States precipitation anomalies

In addition to the substantial SAT anomalies that develop in response to MJO forcing, significant precipitation anomalies occur. Several studies (Mo and Higgins, 1998; Higgins et al., 2000) have established connections between MJO-related tropical convection and US West

Coast precipitation. Our contemporaneous composites of precipitation agree with this well-known relationship, namely, a positive West Coast precipitation anomaly during WH MJO phase 3.

Of greater importance to this study are the precipitation impacts that occur one to four pentads following a tropical convective anomaly. Figure 3 shows lagged (lag 1-3) precipitation composites with respect to WH MJO phase 3 and CPC MJO index 1 side-by-side. Three pentads out both composites agree on enhanced precipitation from the southern Plains to the Great Lakes, and decreased precipitation in the Southeast, mainly Florida. Lin et al. (2010) used a different analysis to show that convection in the Indian Ocean and subsidence in the West Pacific forces a similar precipitation response in the eastern half of the US. A physical explanation for this precipitation response will be explored in the next subsection.

Another interesting result of our analysis is the difference in West Coast precipitation, especially at lags of two and three pentads. The WH MJO composite places a significant negative anomaly over northern California at a two pentad lag, while the larger CPC MJO index 1 composite is statistically insignificant at that lag. This difference will be explored later as well.

c.) Circulation anomalies

In order to physically explain the MJO's US winter hydroclimate impacts, composites of 200-hPa geopotential height and zonal wind are constructed. A contemporaneous positive height anomaly exists over India and in the North Pacific (a modulation of the Aleutian Low) in both the WH MJO phase 3 composite and CPC index 1 composite. These height anomalies teleconnect to a developing height anomaly over eastern North America (Figure 4). This teleconnection is supported by Lin and Brunet (2008) who indicated a Rossby wave train results in circulation anomalies over North America in response to MJO-related convection. Furthermore, results from Bader and Latif (2005) suggest that a height anomaly over India is teleconnected to a height anomaly over eastern North America.

These large-scale circulation impacts can also be seen in the 200-hPa zonal wind composites. Convection in the eastern Indian Ocean and subsidence in the Western Pacific is associated with a retraction of the East Asian jet. Figure 5 shows the lagged (lag 1-4) composites of 200-hPa zonal wind against the winter climatology. Coinciding with the developing height anomalies over North America, a tripole of zonal wind anomalies develops at lags of two to four pentads across eastern North America and the North Atlantic.

Combining the 200-hPa geopotential height and zonal wind anomalies infers a northward-moving and weakening eastern North American jet stream two to four pentads after a substantial positive convective anomaly in the eastern Indian Ocean. Synoptically, this moves the right entrance region associated with enhanced upward motion north of its climatological position resulting in the observed precipitation anomalies (discussed in section 4b) at the same lag.

Subsidence in the Indian Ocean and convection in the Western Pacific (WH MJO phase 3; CPC MJO index 6) produces a similar, but opposite extratropical response (not shown). The response is not perfectly linear, but this is not surprising given that multiple studies (Lin and Derome, 2004; Hoerling et al., 1997) have shown that there is a substantial nonlinear component to the extratropical response to tropical forcing.

d.) Differences in impacts between WH and CPC indices

So far we have shown that using composites based on the WH MJO index and those based on CPC MJO indices are very similar when they separately capture the same tropical convective anomaly. In order to assess which index might be a better operational tool, composites were made of hydroclimate and circulation fields when CPC MJO index 1 indicated an upper-level divergence anomaly over the eastern Indian Ocean, but the WH index was either out of phase 3 or had amplitude less than 1.0. There are 56 such pentads over the 30-year period, in most of which the WH index indicated a different phase. Interestingly, the composite of OLR is nearly identical to composites of OLR based on WH phase 3 and CPC index 1 individually.

At a lag of two to four pentads, very similar hydroclimate impacts are observed across the eastern two-thirds of the US (Figure 6). A major difference in precipitation occurs in northern California at a two pentad lag, where the WH phase 3 composite (Figure 3) shows a dry anomaly but the composite based on CPC index 1 when the WH index is not in phase 3 shows a substantial positive precipitation anomaly.

These results suggest that a significant convective anomaly dipole (greater than one standard deviation) between the eastern Indian Ocean and the West Pacific forces a substantial climate response in the US. The CPC MJO index provides a simpler means through which to observe the patterns of convection that force US climate variability.

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Figure 1.

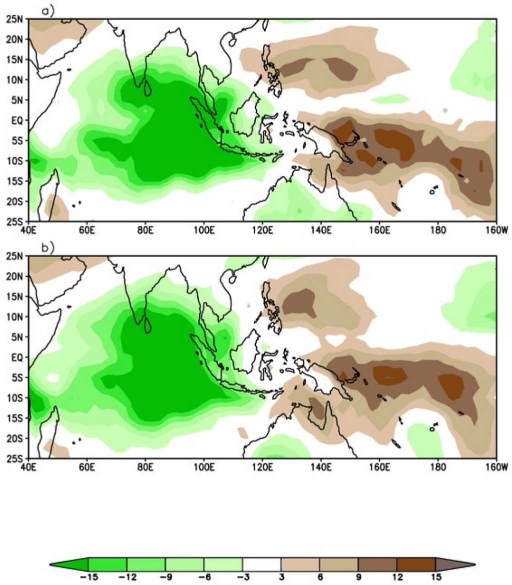

Figure 1: a) DJF pentad OLR composite during WHMJO phase 3 (n=58). b) DJF pentad OLR composite when CPC MJO index 1 is less than one standard deviation (n=96).

Figure 2.

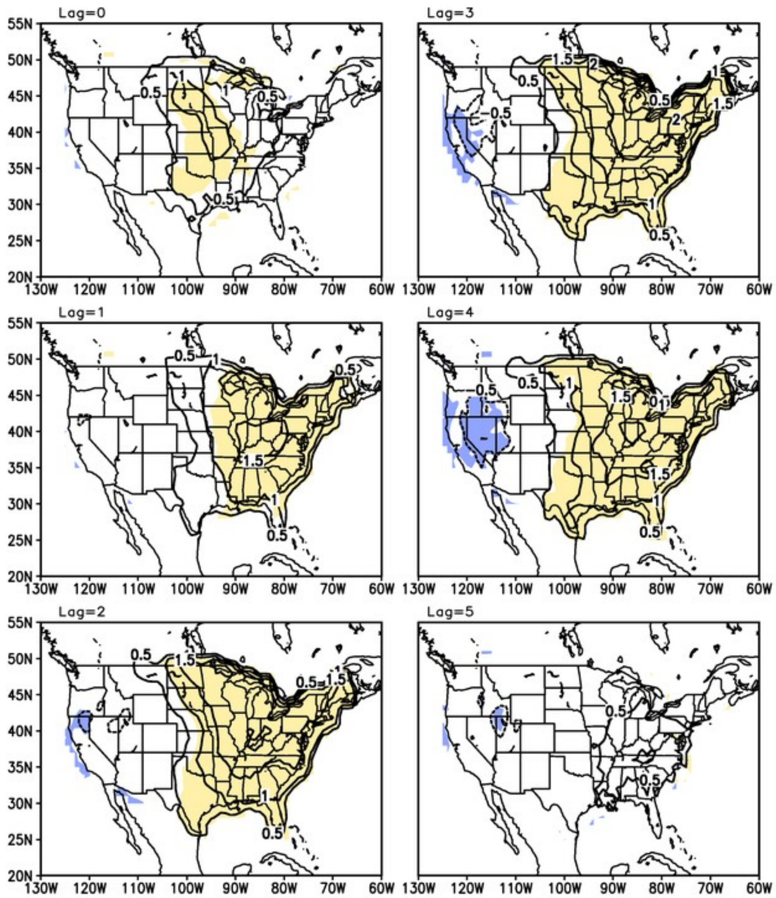

Figure 2: Contoured DJF SAT lagged (lag 0-5) pentad composite when CPC MJO index 1 is less than one standard deviation (contour interval=0.5°C). Shaded area represents significance at the 95% confidence limit.

Figure 3.

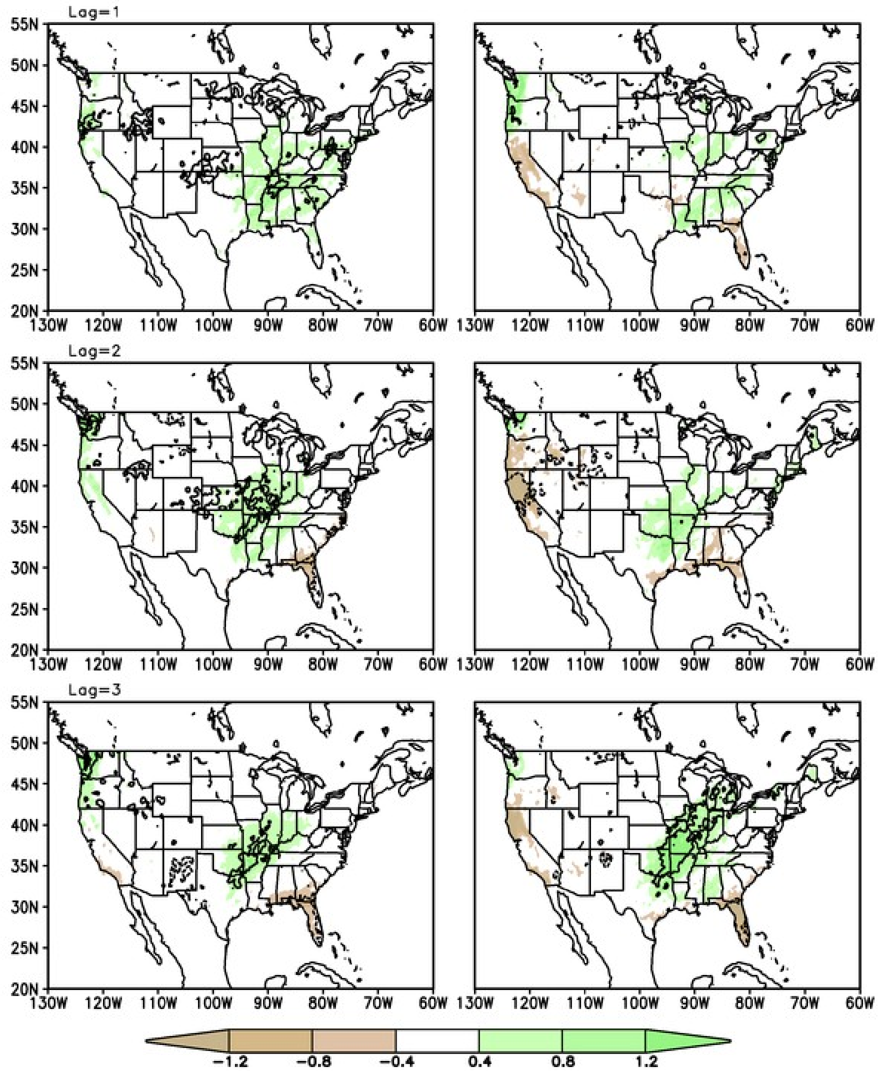

Figure 3: Left: Lagged pentad (lag 1-3) CPC MJO index 1 precipitation composite (mm/day). Right: Lagged pentad (lag 1-3) WHMJO phase 3 precipitation composite. Contour represents significance at the 95% level.

Figure 4.

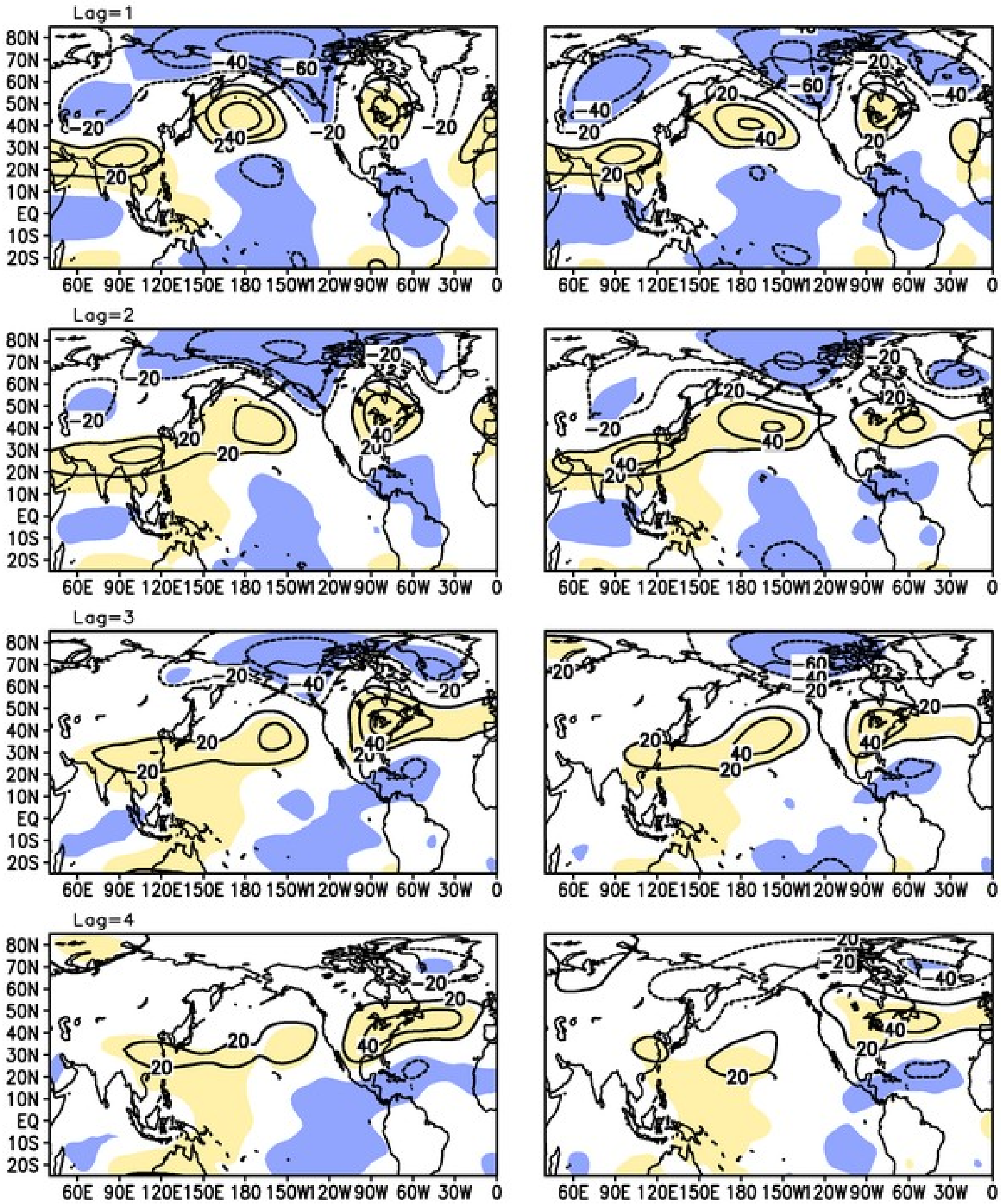

Figure 4: Left: Contoured CPC MJO index 1 lagged (lag 1-4) composite of 200-hPa geopotential height (m). Right: Same as left but for WHMJO phase 3. Shading represents significance at the 95% confidence limit.

Figure 5.

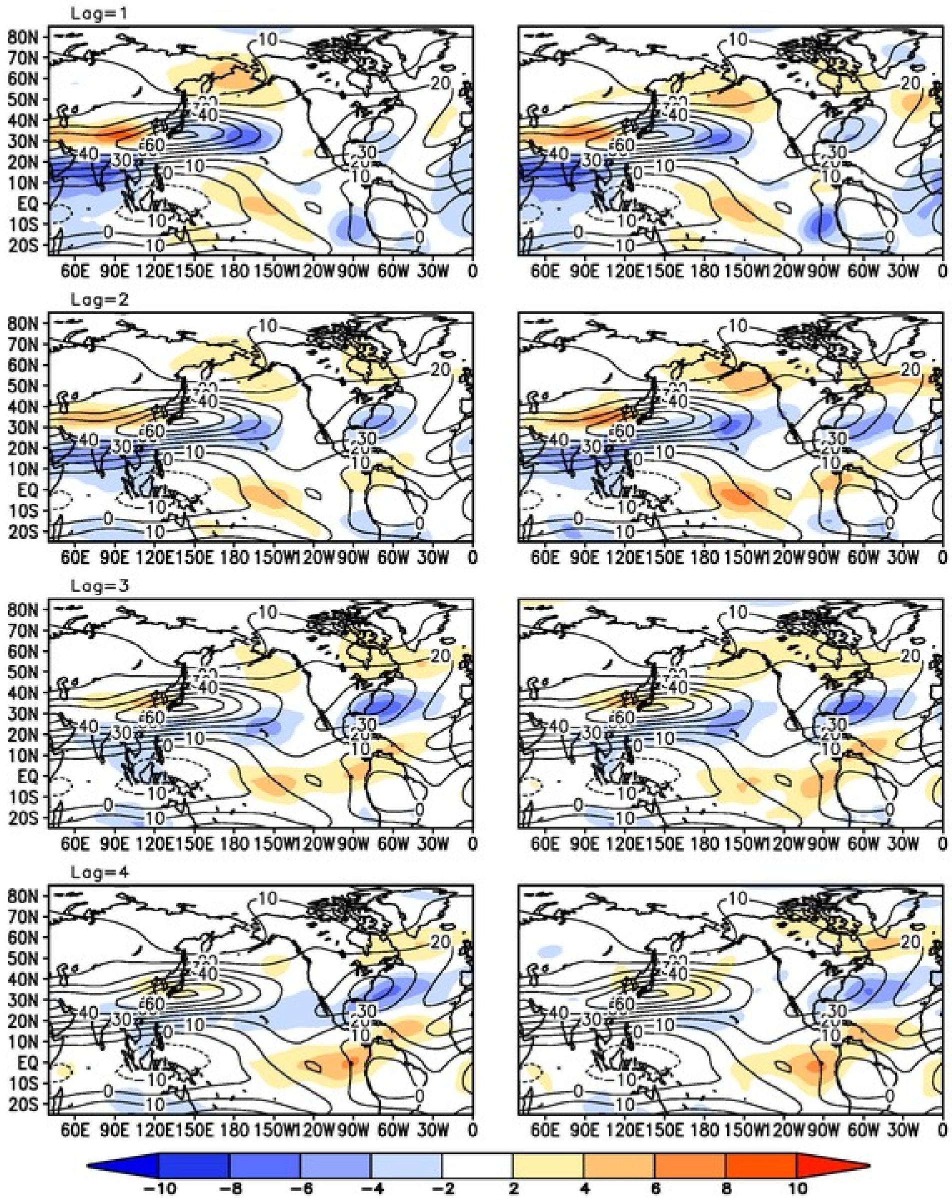

Figure 5: Left: Shaded lagged pentad composite of 200-hPa zonal wind (m/s) for CPC MJO index 1. Right: Same as left but for WHMJO phase 3. DJF climatology is contoured.

Figure 6.

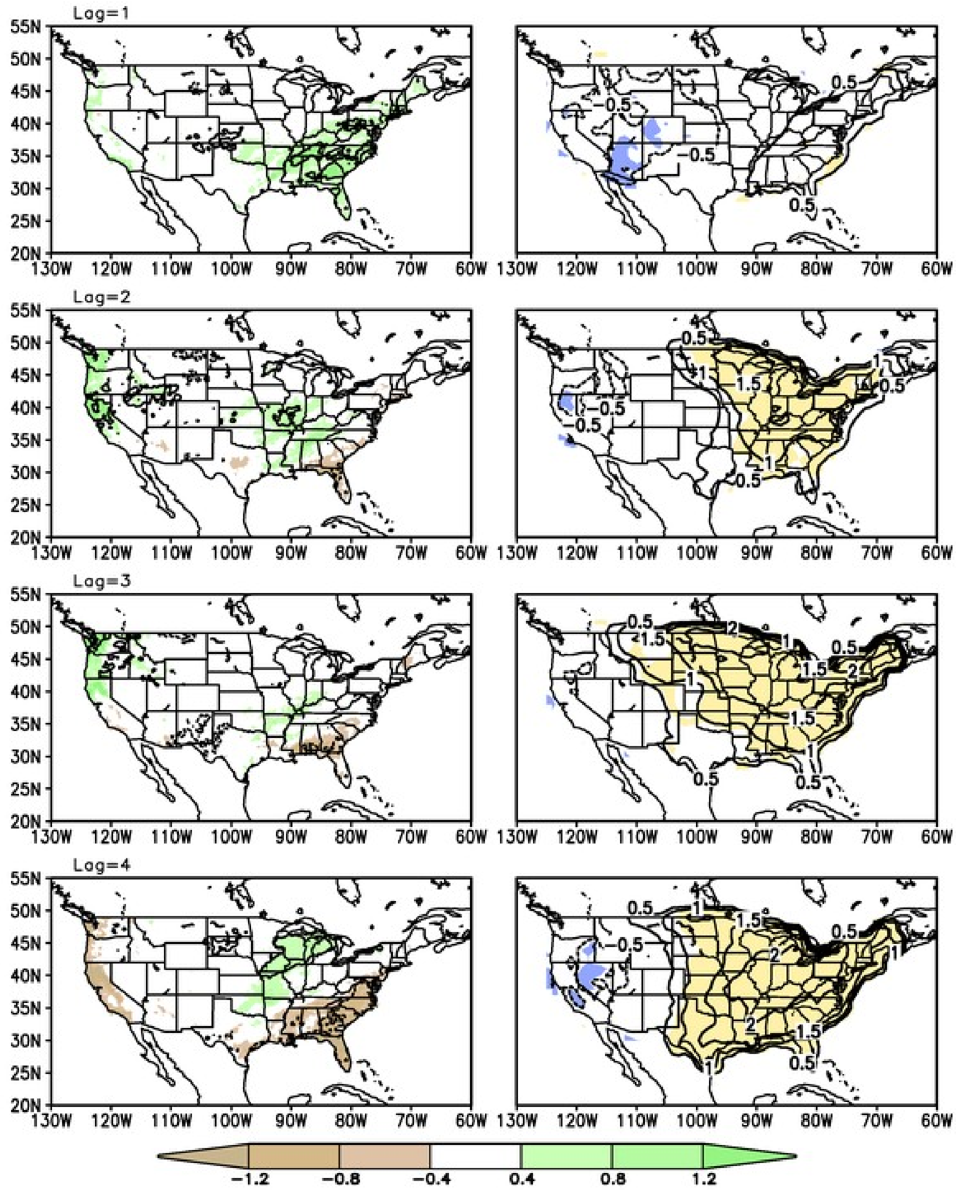

Figure 6: Left: Lagged (lag 1-4) pentad composite of precipitation (mm/day) when CPC MJO index 1 threshold is met, but the WHMJO index is not in phase 3. Significance at the 95% limit is contoured. Right: Lagged pentad composite of SAT is contoured at 0.5°C interval when CPC MJO index 1 threshold is met, but the WHMJO is not in phase 3. Significance at the 95% limit is shaded. (n=56)

Figure 7.

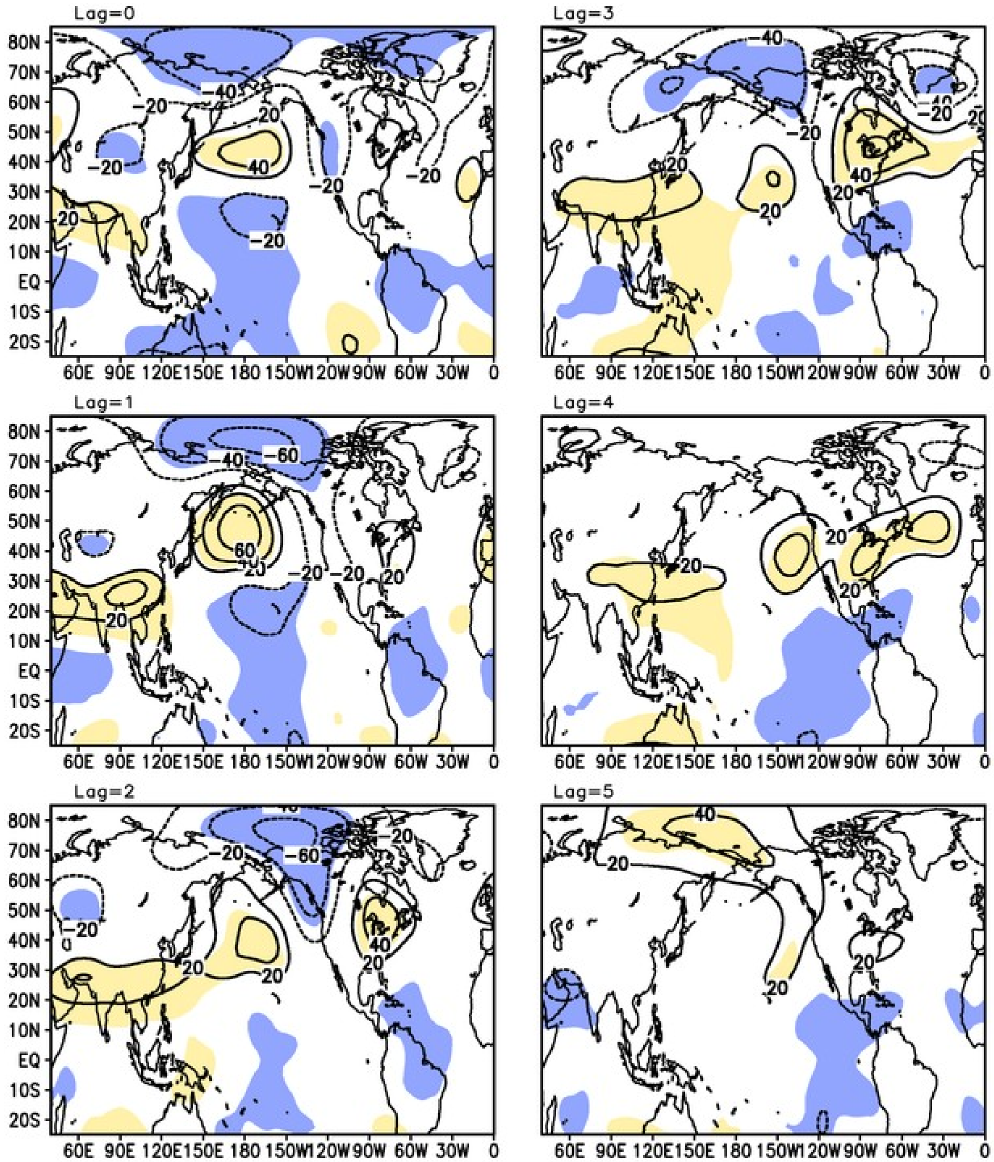

Figure 7: Contoured lagged (lag 0-5) pentad composite of 200-hPa geopotential height (m) when CPC MJO index 1 threshold is met, but WHMJO index is not in phase 3 (n=56). Shading represents significance at the 95% limit.