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Madden Julian Oscillation (MJO)

I. Definition:

The MJO is an intraseasonal fluctuation or "wave" occurring in the global tropics. The MJO is responsible for the majority of weather variability in these regions and results in variations in several important atmospheric and oceanic parameters which include both lower- and upper-level wind speed and direction, cloudiness, rainfall, sea surface temperature (SST), and ocean surface evaporation. The MJO is a naturally occurring component of our coupled ocean-atmosphere system and the typical length of the MJO cycle or wave is approximately 30-60 days (Madden and Julian, 1971, 1972; Madden and Julian, 1994; Zhang, 2005).

II. Characteristics:

The MJO is characterized by eastward propagation of regions of enhanced and suppressed tropical rainfall, primarily over the Indian and Pacific Oceans. The anomalous rainfall is often first evident over the Indian Ocean, and remains apparent as it propagates eastward over the very warm waters of the western and central tropical Pacific. Over the cooler ocean waters of the eastern Pacific, the pattern of tropical rainfall generally becomes nondescript, but often reappears over the tropical Atlantic and Africa. Along with these variations in tropical rainfall, there are distinct patterns of lower- and upper-level atmospheric circulation anomalies in the tropics and subtropics. These features extend around the globe and are not confined to the eastern hemisphere. Thus, they provide important information regarding the regions of ascending and descending motion associated with particular phases of the oscillation. Figure 1 illustrates an equatorial vertical cross section of the MJO showing the changes in cloudiness, rainfall, wind speed and direction, and SST as the MJO propagates eastward around the global tropics (Adapted from Madden and Julian, 1971; 1972).

By combining many MJO events together into composites, we obtain an idealized representation of the three dimensional structure of the MJO (Figure 2; Rui and Wang, 1990). When convection is active in the Indian Ocean and Indonesia, anomalous easterlies (westerlies) exit the area of enhanced convection in the upper levels of the atmosphere and associated with anti-cyclonic gyres along and behind the area of enhanced convection. Conversely, cyclonic gyres exist behind areas of suppressed convection in both hemispheres. At low levels, anomalous easterlies (westerlies) are evident ahead (behind) the area of enhanced convection. The low level gyres are generally weaker than those at upper levels. As the dipole propagates toward the central Pacific, the lower and upper level circulation anomalies become less recognizable and coherent but remain an important component in redistributing mass around the global tropics.

III. Monitoring the MJO

Due to its slowly evolving nature, accurate prediction of the MJO is fundamentally related to our ability to monitor the feature and to assess its relative position and strength. Dynamical models generally do not predict the MJO well, partly because of the inherent difficulties that still remain regarding the correct mathematical treatment of tropical convective (rainfall) processes. Meteorologists use a variety of data and analysis techniques to monitor, study, and predict the formation and evolution of the MJO. Of primary importance is information derived from NOAA's polar-orbiting and geostationary satellites. Satellite-derived data are used to indicate regions of strong tropical convective activity, and regions in which the convective activity departs substantially from the long-term mean. These departures from normal are a fundamental diagnostic tool that is used directly to monitor and predict the MJO as it propagates around the global tropics. A second fundamental data source used to monitor the MJO is the global radiosonde network which provides crucial information regarding the atmospheric winds, temperature, moisture, and pressure at many levels of the atmosphere. These data are taken twice daily, and assimilated by dynamical weather prediction models into formats that are highly efficient for climate analysis and numerical weather prediction. In combination with the satellite-derived rainfall and convection patterns, these observations provide meteorologists with the capability to routinely monitor and assess the MJO and its evolution. They also allow for a better assessment of the impacts of the MJO activity on features such as the wintertime jet streams, and the large-scale environment within which tropical cyclones develop throughout the Tropics. There are several diagnostic analysis techniques that allow us to directly monitor the MJO. These analyses are often displayed in time-longitude format so as to reveal the evolution, amplitude and location of the MJO-related features. Typical time-longitude sections are produced for (1) Outgoing Longwave Radiation (OLR), which is a satellite-derived measure of tropical convection and rainfall, (2) velocity potential, which is a derived quantity that isolates the divergent component of the wind at upper levels of the atmosphere, (3) upper- and lower-level wind anomalies and (4) 500-hPa height anomalies to represent the atmospheric responses in mid-latitudes.

IV. Interannual Variability of the MJO

There is strong year-to-year variability in MJO activity, with periods of strong activity followed by long periods in which the oscillation is weak or absent (Hendon et al. 1999; Zhang, 2005). There is evidence that the interannual variability of the MJO is partly linked to the ENSO cycle. Strong MJO activity is often observed during weak La Niña years or during ENSO-neutral years, while weak or absent MJO activity is typically associated with strong El Niño episodes. Figure 3 illustrates MJO activity for three different September through June time periods via time longitude plots of velocity potential (a measure of the divergence of air in the upper atmosphere). The first figure shows regular but generally weak to moderate MJO activity during 1989-1990 while during 1996-1997 there are periods of strong MJO episodes but with less regularity. The final panel shows virtually no MJO activity as little eastward propagation is evident with the most dominant variability being the interannual ENSO (El Nino) signal.

V. Composites of the MJO cycle

The MJO cycle results in distinct signatures in a number of atmospheric variables throughout the global tropics depending on its current phase (Knutson and Weickmann, 1987; Rui and Wang, 1990; Kayano and Kousky, 1999). Typical conditions for eight distinct phases of the MJO cycle, as the oscillation propagates from the Indian Ocean through the Pacific Ocean and into the Western Hemisphere, are illustrated by figures 4-8 that show 200-hPa velocity potential, OLR, rainfall, 850-hPa wind speed and direction, and sea level pressure. Composites are given for November through March and for May through September time periods. The figures depict mean conditions for as many characteristic MJO events as are available from the period 1979-2004. The figures clearly show the eastward propagation of the MJO. The 200-hPa velocity potential composite (Figure 4a) shows that upper-level divergence over the Indian Ocean (top panel) slowly shifts eastward over the next 30-60 days and re-enters the Indian Ocean to complete a full cycle (bottom panel). The eastward propagation is evident in all of the figures but especially for the northern hemisphere winter period (November through March). Figures 5a and 6a illustrate the disappearance of rainfall in the eastern Pacific Ocean (due to colder ocean water) and areas of enhanced (suppressed) rainfall over land areas of South America and Africa during various phases of the MJO cycle. Figure 7a shows enhanced easterlies (westerlies) ahead (behind) enhanced rainfall as the MJO propagates through the global tropics.

VI. Impacts associated with the MJO

Well established, coherent MJO activity results in key atmospheric anomalies that can potentially have wide ranging impacts. Some examples of impacts related to the MJO are listed and described below and illustrated in Figure 9.

1. In areas of upper level divergence (negative velocity potential) enhanced rainfall can occur. Favored regions over land include Northeast Brazil, Southeast Africa, and Indonesia during boreal winter (Figure 6a) and Central America/Mexico and Southeast Asia during boreal summer (Figure 6b) (Knutson and Weickmann, 1987; Rui and Wang, 1990; Kayano and Kousky, 1999).

2. The MJO can substantially modulate the intensity of monsoon systems around the globe. The Australian (boreal winter; October-March), Asian (boreal summer; June-September), South American (boreal winter, October-March) and North American (boreal summer; May-October) monsoons can all be influenced by the MJO. The enhanced rainfall phase of the MJO can affect both the timing of monsoon onset and the intensity of the monsoon. Moreover, the suppressed phase of the MJO can prematurely end a monsoon and also initiate breaks during already existing monsoons.

3. The MJO also enhances (suppresses) the intensity and extent of both the mean South Atlantic Convergence Zone (SACZ; Brazilian coast) and South Pacific Convergence Zone (SPCZ; east of Australia) (Kousky and Kayano, 1994; Matthews et al. 1996; Carvalho et al. 2004).

4. There is evidence that the MJO influences the ENSO cycle. It does not cause El Niño, but can contribute to the speed of development, and perhaps the overall intensity of El Niño episodes (Kessler and Kleeman, 2000; Zhang and Gottschalck, 2002).

5. The MJO is known to modulate tropical cyclone activity in the Indian Ocean, Pacific Ocean, Gulf of Mexico, and Atlantic Ocean (Maloney and Hartmann, 2000a; Maloney and Hartmann, 2000b; Higgins and Shi, 2001). For example, although tropical cyclones occur throughout the Northern Hemisphere warm season (typically May-November) in both the Pacific and the Atlantic basins, in any given year there are periods of enhanced / suppressed activity within the season. The MJO modulates this activity (particularly for the strongest storms) by providing a large-scale environment that is favorable (unfavorable) for development. For example, westerly wind anomalies at the surface in and just behind the area of enhanced convection of the MJO may generate cyclonic (anticyclonic) rotation north (south) of the equator respectively (Figure 2). At the same time, in the upper levels, anticyclonic (cyclonic) rotation develops along and just behind the area of convection (Figure 2) resulting in a means to reduce vertical wind shear and increase upper-level divergence – both of which are favorable for tropical cyclone development and intensification. The strongest tropical cyclones tend to develop when the MJO favors enhanced precipitation. As the MJO progresses eastward, the favored region for tropical cyclone activity also shifts eastward from the Indian Ocean to the Pacific Ocean and eventually to the Atlantic Ocean (Figure 10). While this relationship appears robust, we caution that the MJO is one of many factors that contribute to the development of tropical cyclones. For example, it is well known that SSTs must be sufficiently warm and vertical wind shear must be sufficiently weak for tropical disturbances to form and persist.

6. Enhanced tropical rainfall in the western and central Pacific can contribute to extreme rainfall events in western North America (Higgins et al. 2000). The typical scenario linking the pattern of tropical rainfall associated with the MJO to extreme precipitation events in the Pacific Northwest features a progressive (i.e. eastward moving) circulation pattern in the tropics and a retrograding (i.e. westward moving) circulation pattern in the high latitudes of the North Pacific (Figure 11).

VII. References

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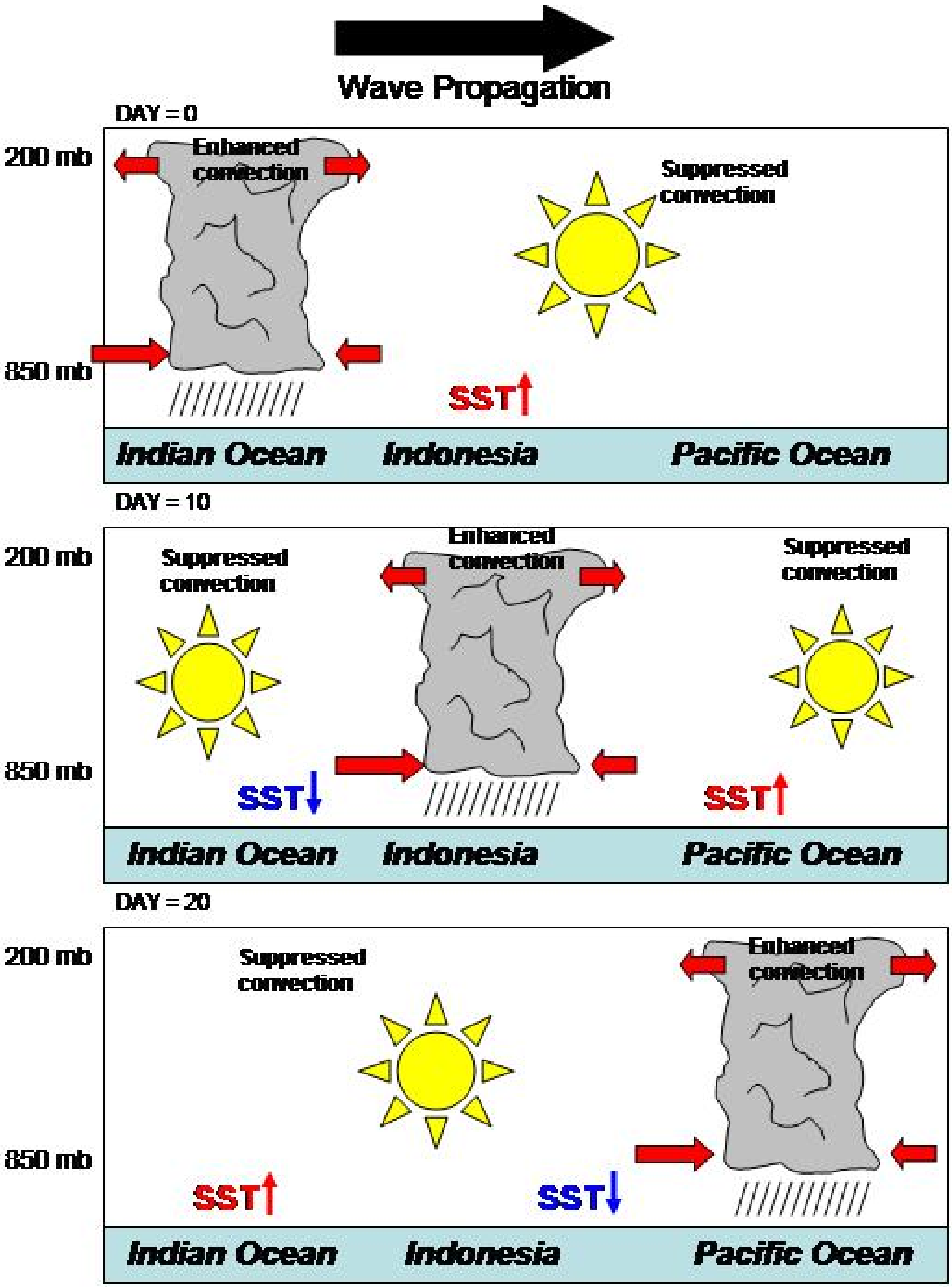


Figure 1: Equatorial vertical cross section of the MJO as it propagates from the Indian Ocean to the western Pacific. Red arrows indicate direction of wind and red (blue) SST labels indicate positive (negative) SST anomalies respectively. Figure adapted from Madden and Julian, 1971; 1972.

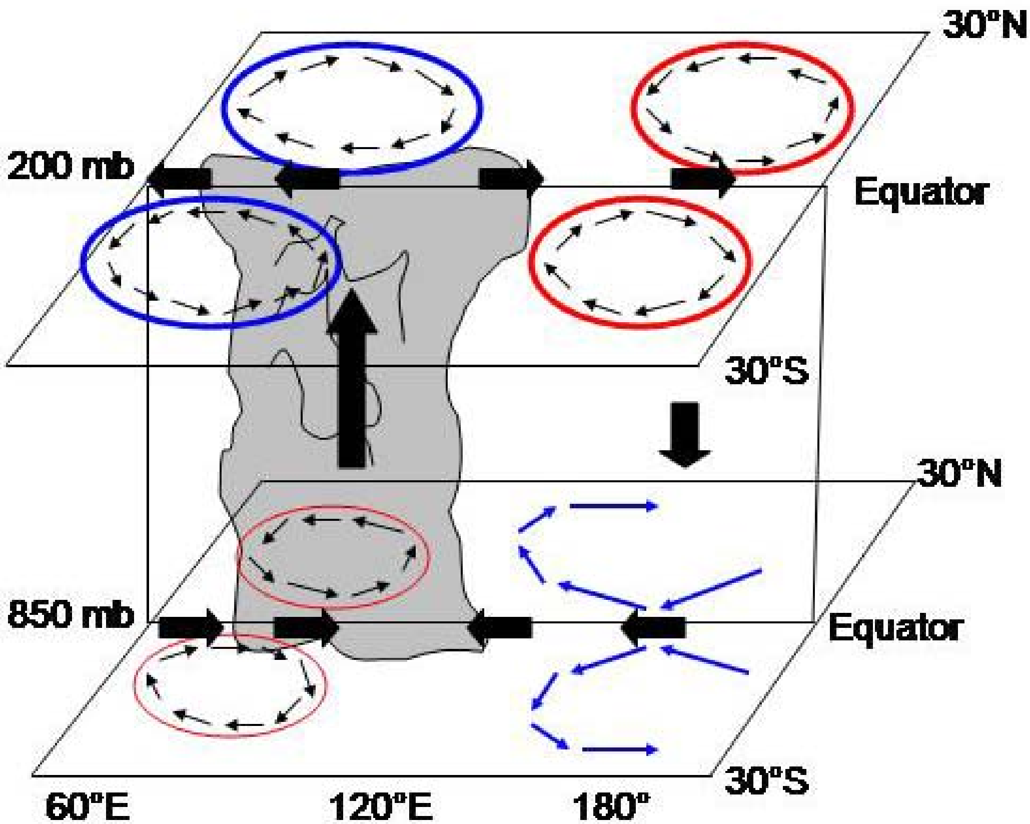


Figure 2: Schematic of the vertical three-dimensional structure of an established MJO. Figure adapted from Rui and Wang (1990). Blue (red) ovals indicate anticyclonic (cyclonic) circulations. Black arrows indicate wind direction and rising (sinking) motion.

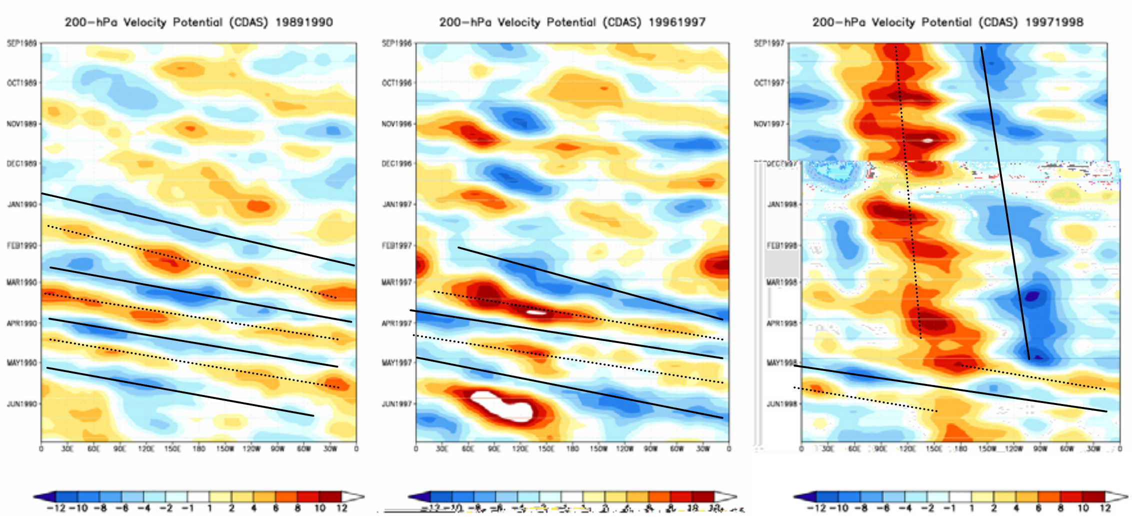


Figure 3: Time longitude plots of 200-hPa velocity potential for the June through September time period for (a) 1989-1990 (La Nina conditions), (b) 1996-1997 (ENSO neutral conditions), and (c) 1997-1998 (El Nino conditions).

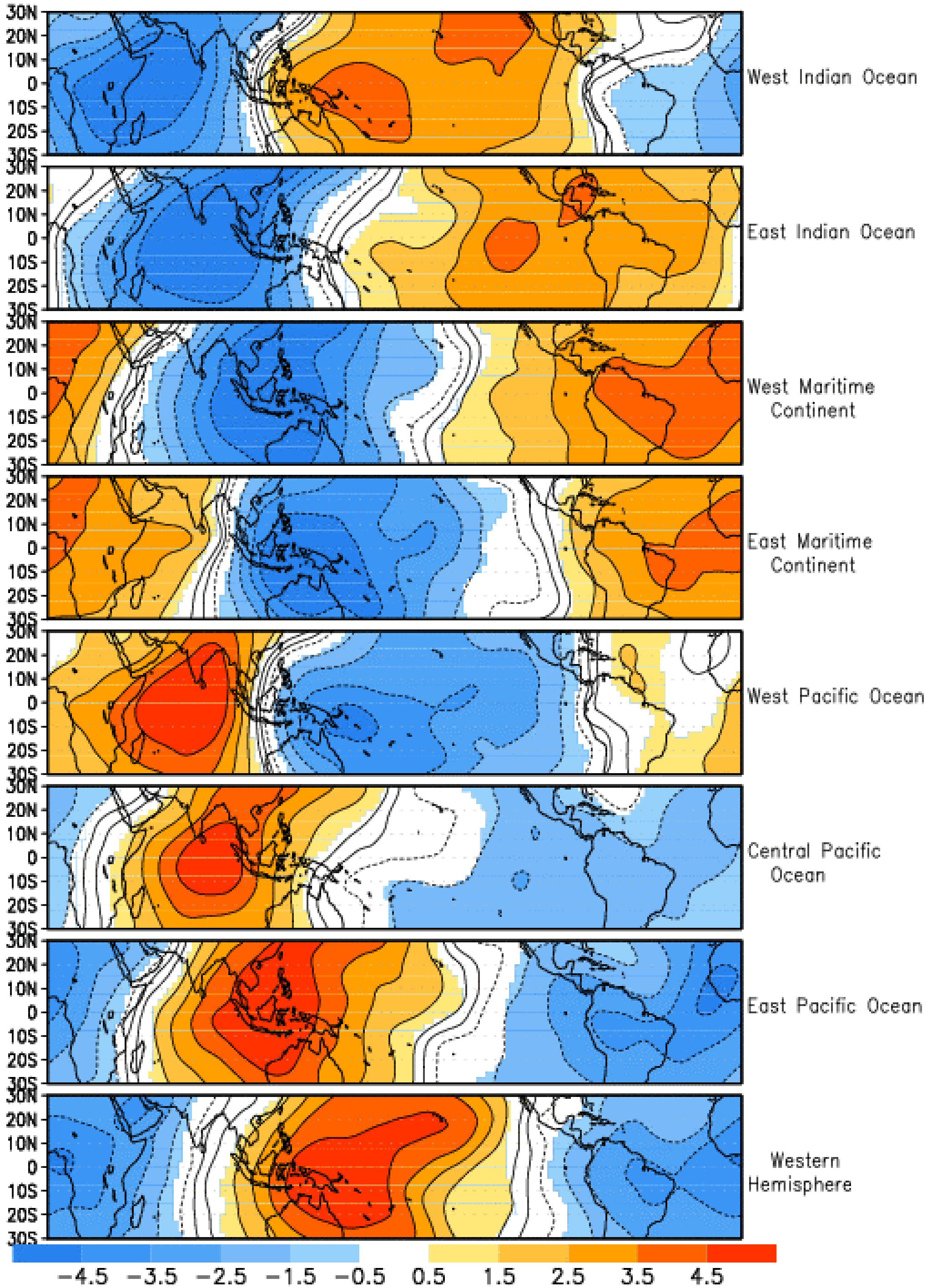


Figure 4a: Composites of 200-hPa velocity potential (m^2/s) for eight phases of the MJO cycle for the November through March time period. The anomalies are shown with contours and regions that are statistically significant (at the 95% confidence level based on a Student-t test) are shaded.

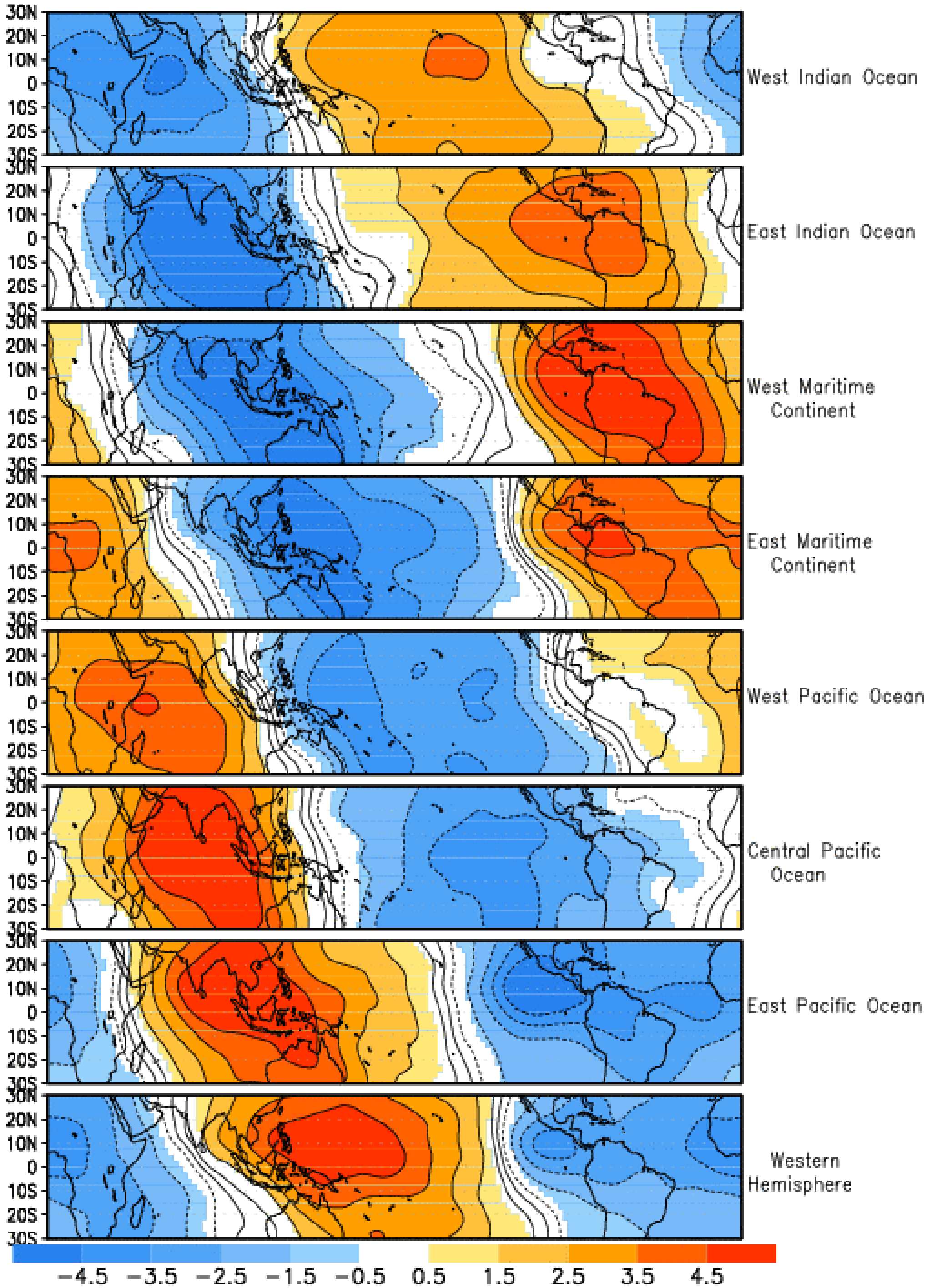


Figure 4b: Same as figure 4a except for the May through September time period.

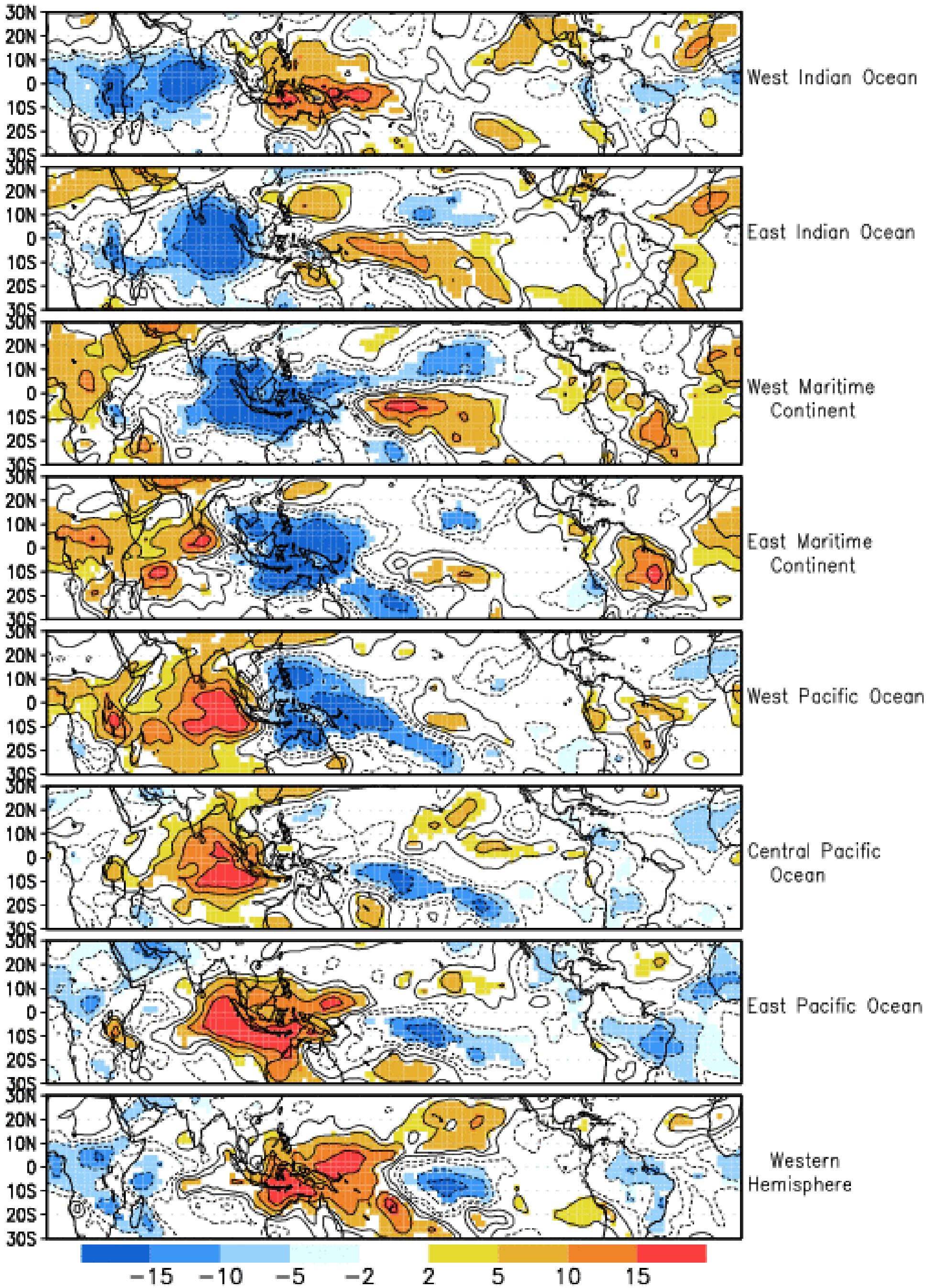


Figure 5a: Same as figure 4a except for OLR. Units are in Wm^{-2}.

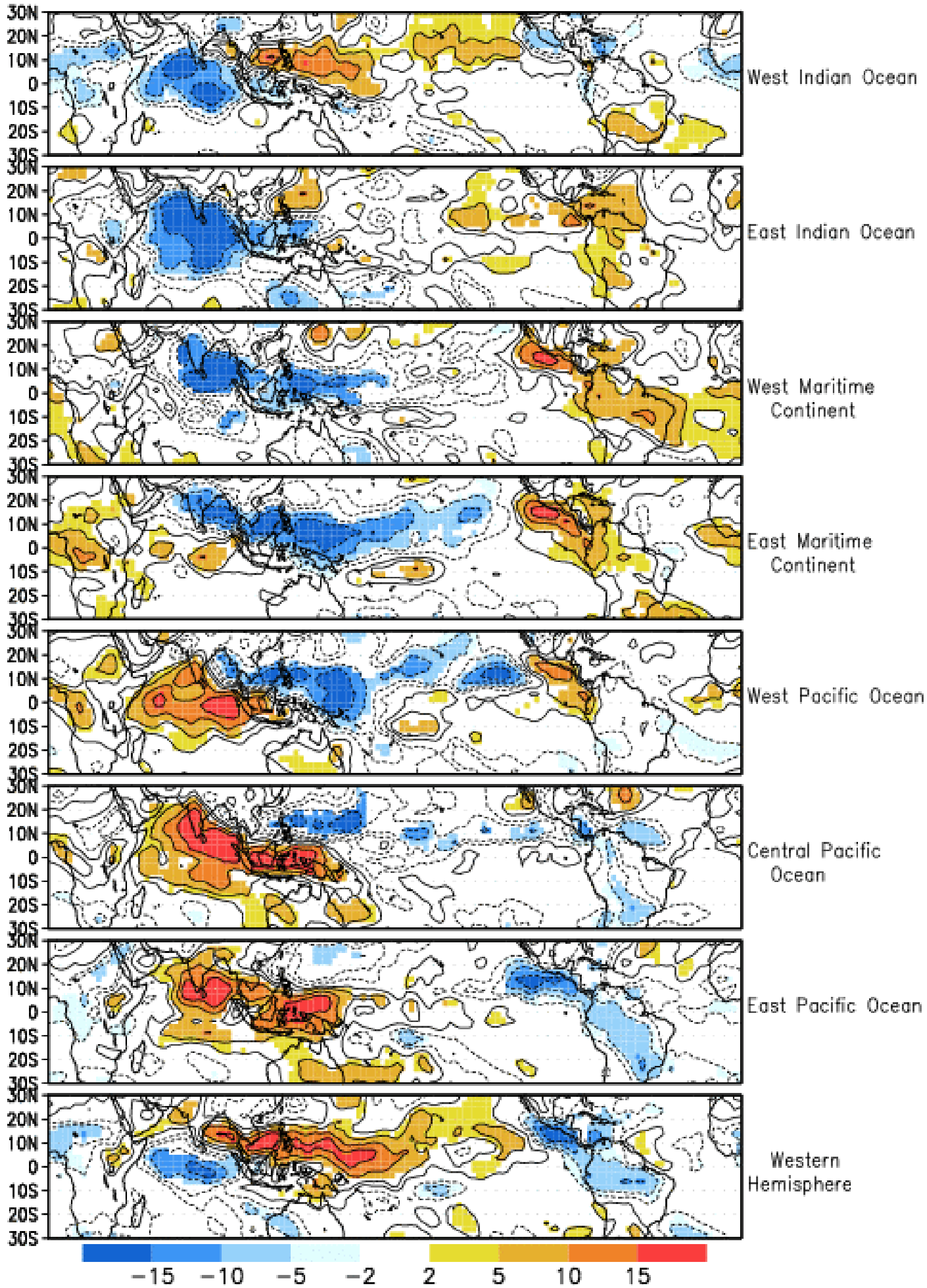


Figure 5b: Same as figure 5a except for the May through September time period.

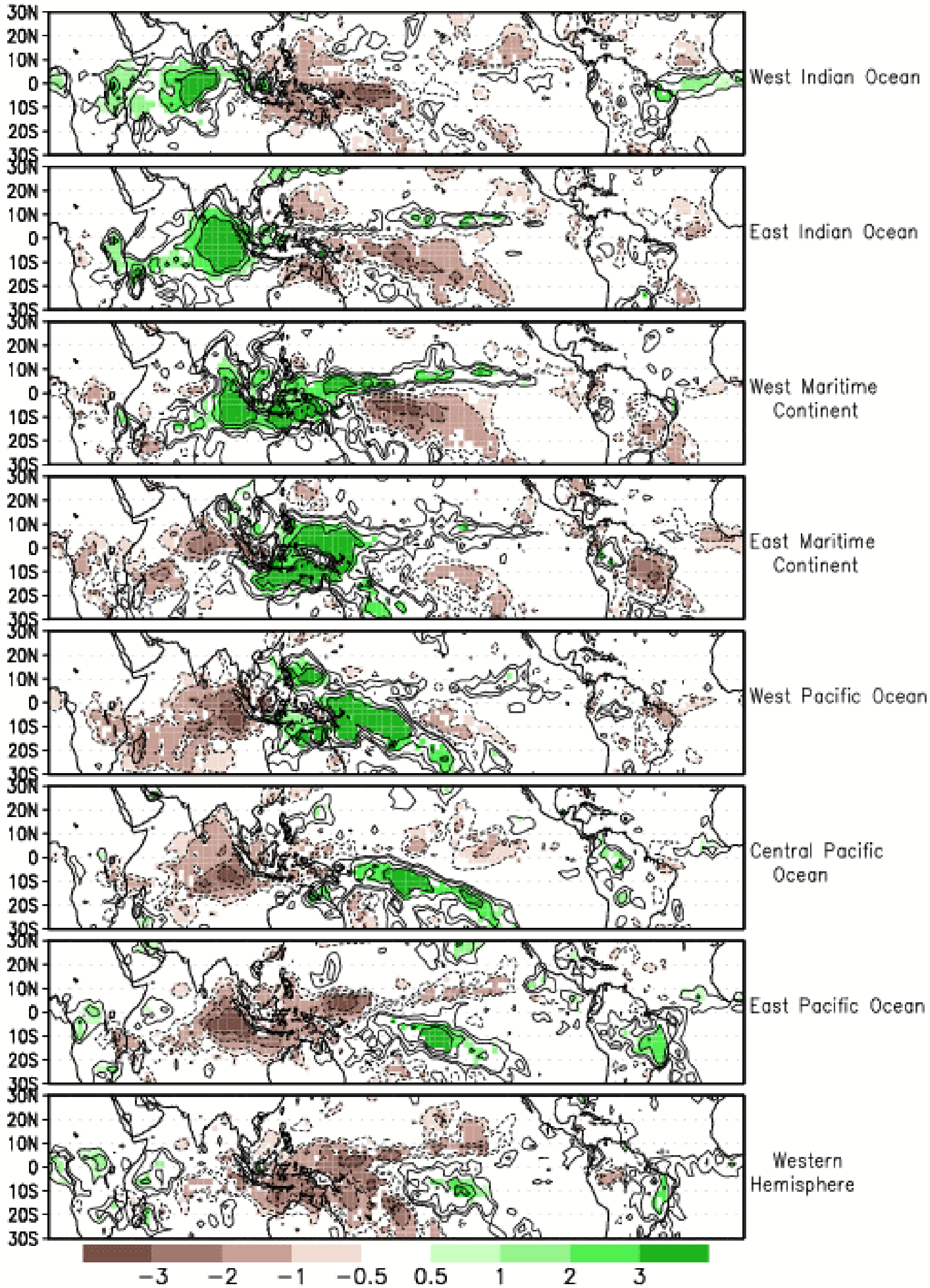


Figure 6a: Same as figure 4a except for precipitation. Units are in mm.

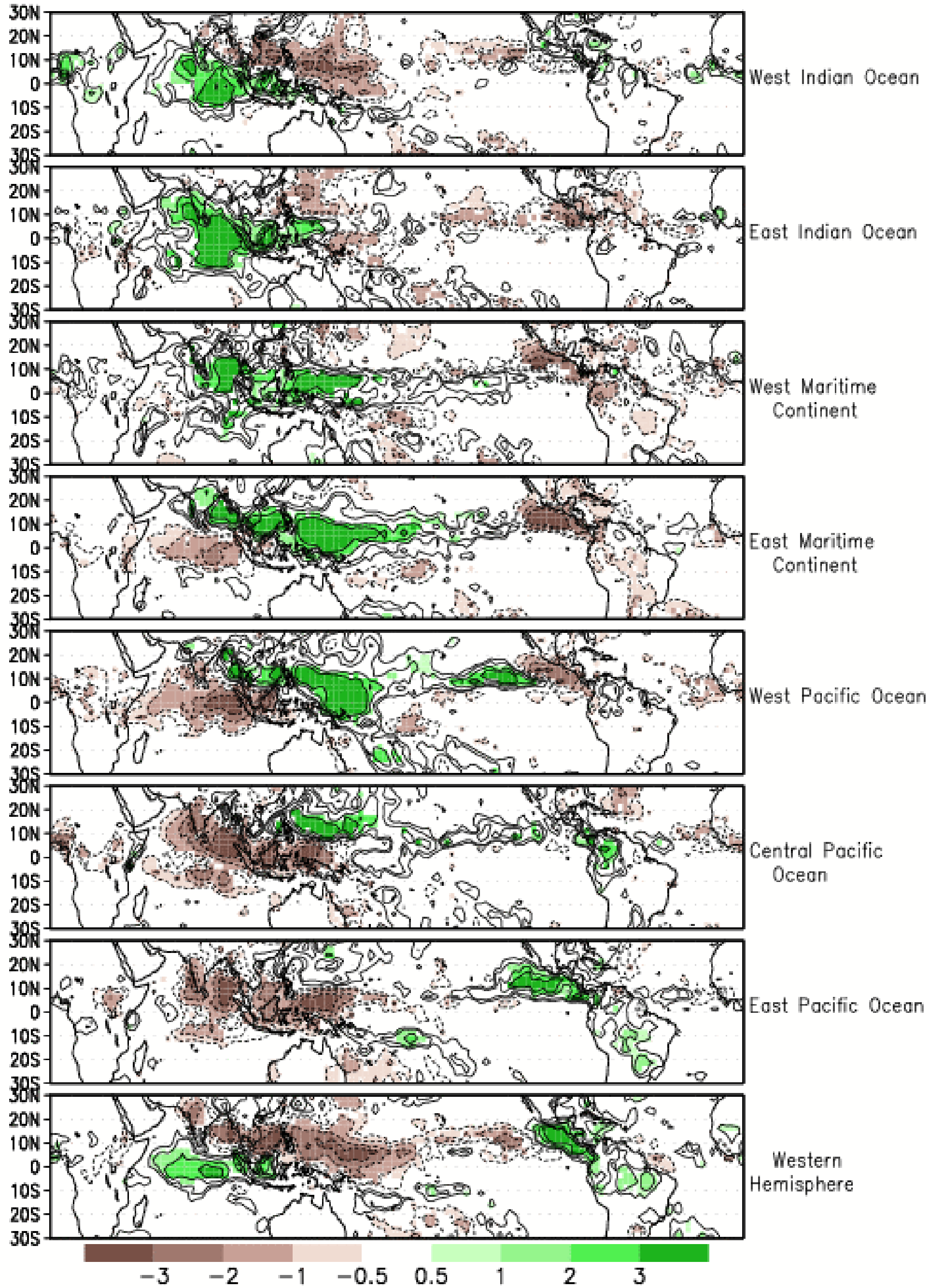


Figure 6b: Same as figure 6a except for the May through September time period.

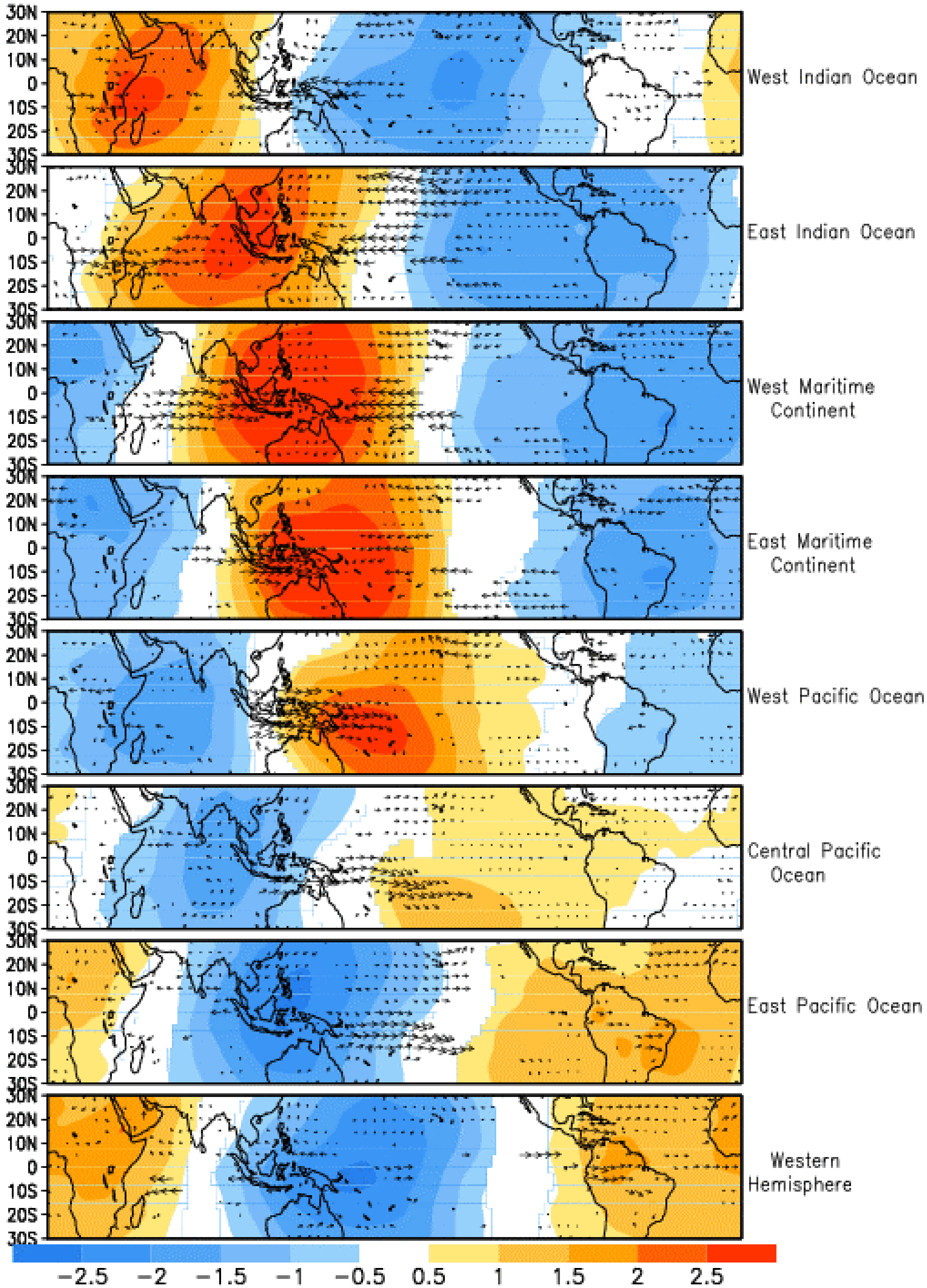


Figure 7a: Same as figure 4a except for 850 mb wind vectors and velocity potential (shading). Units for velocity potential are m^2/s.

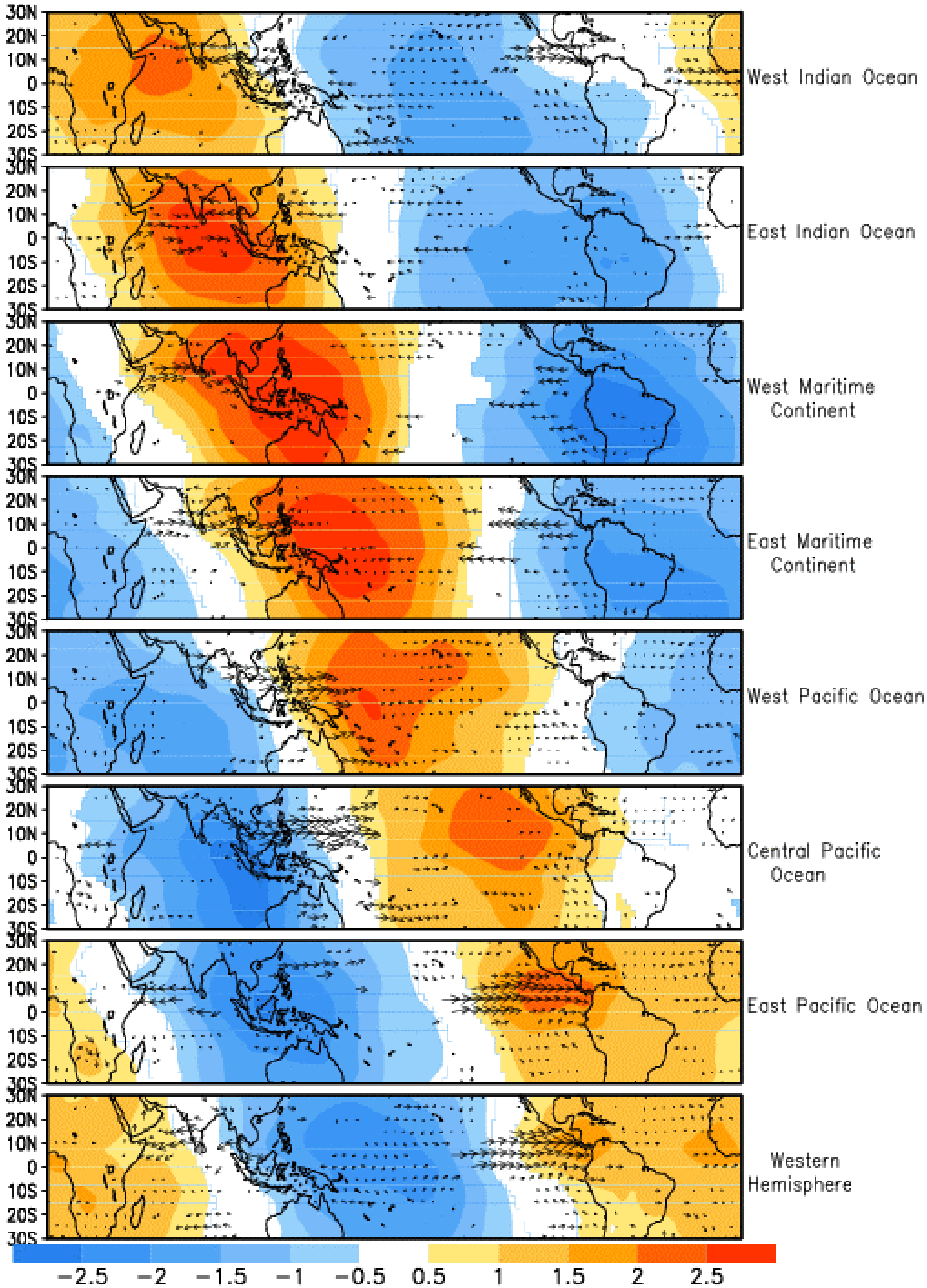


Figure 7b: Same as figure 7a except for the May through September time period.

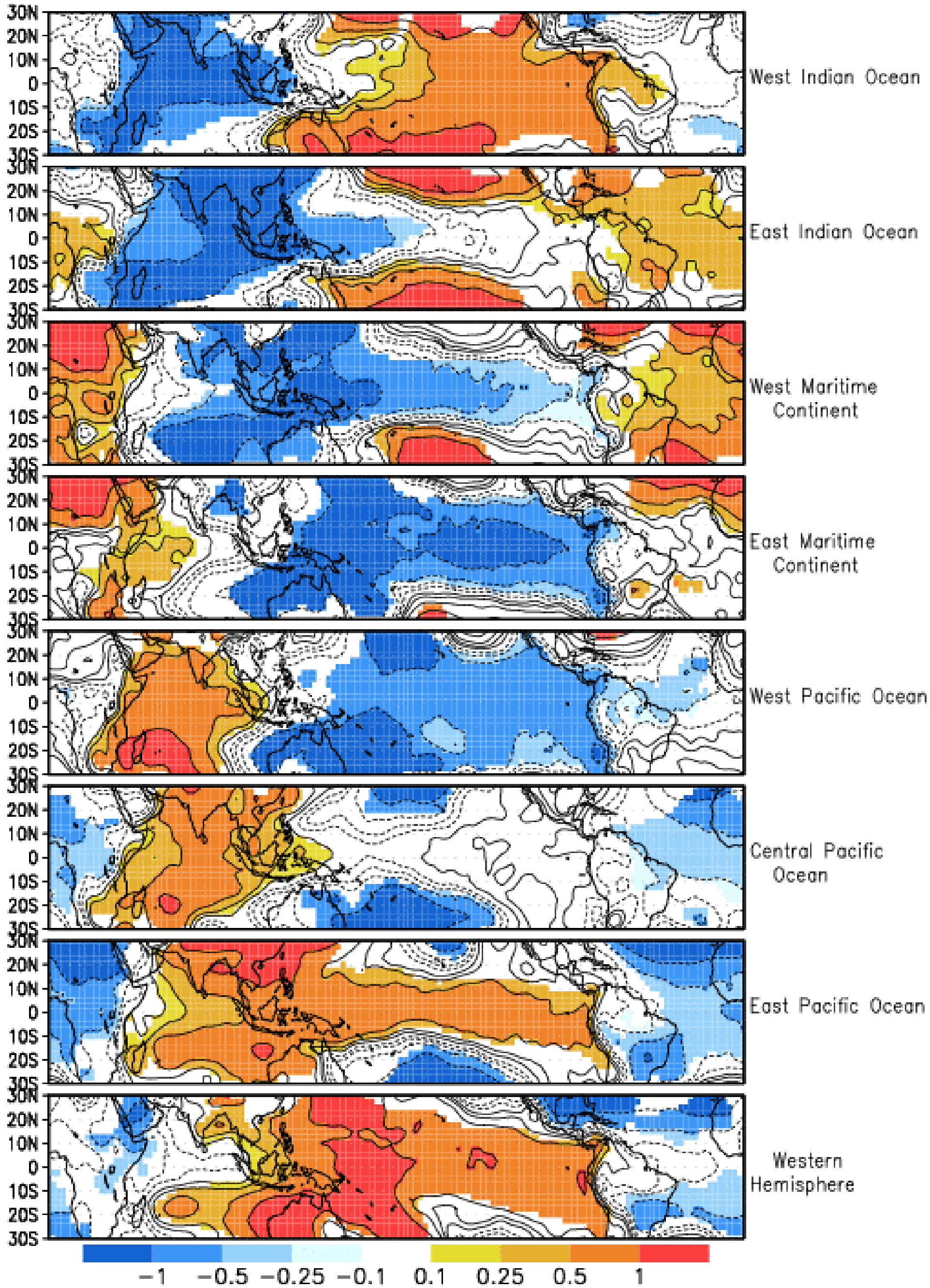


Figure 8a: Same as figure 4a except for sea level pressure. Units are in hPa.

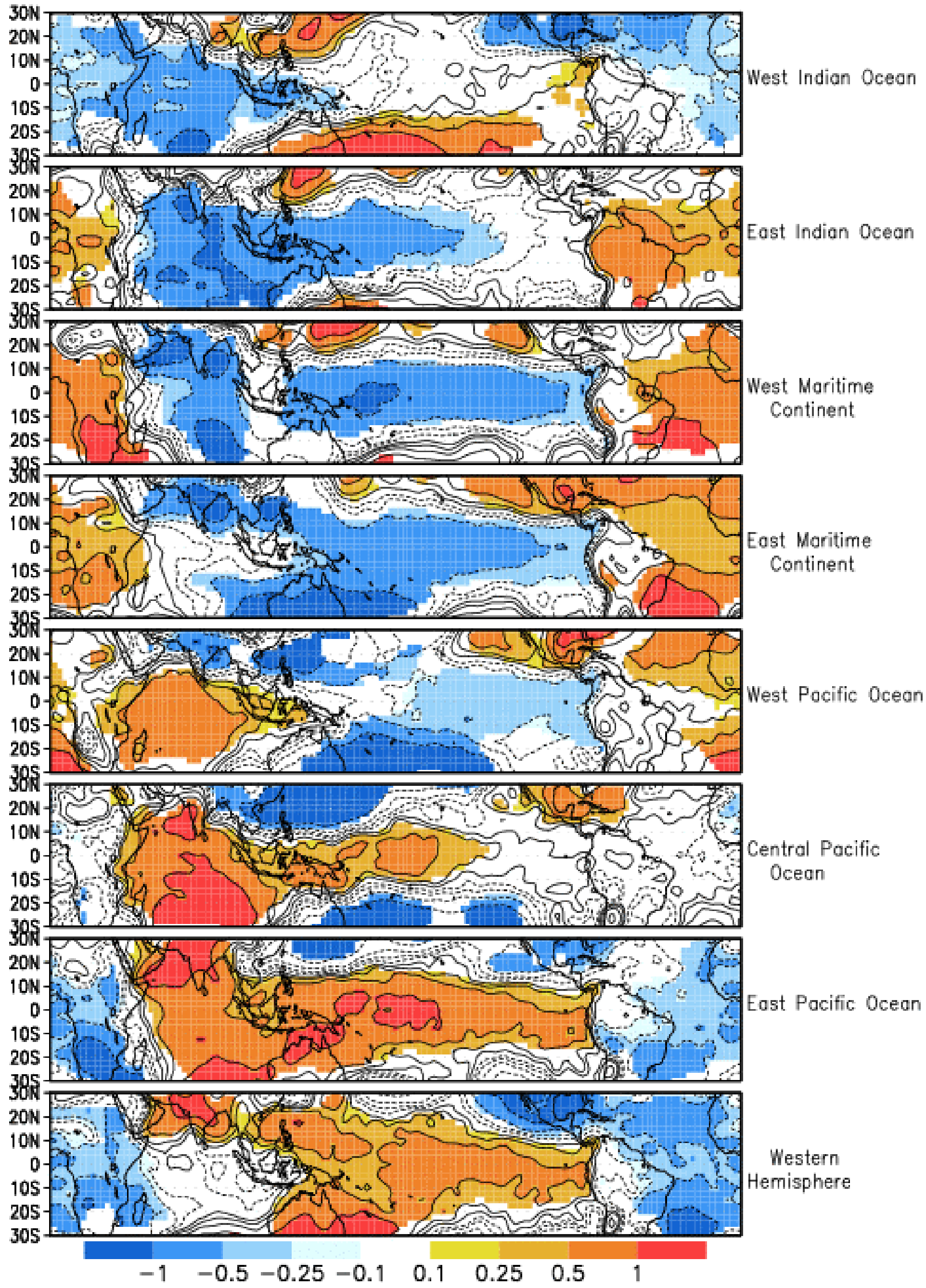
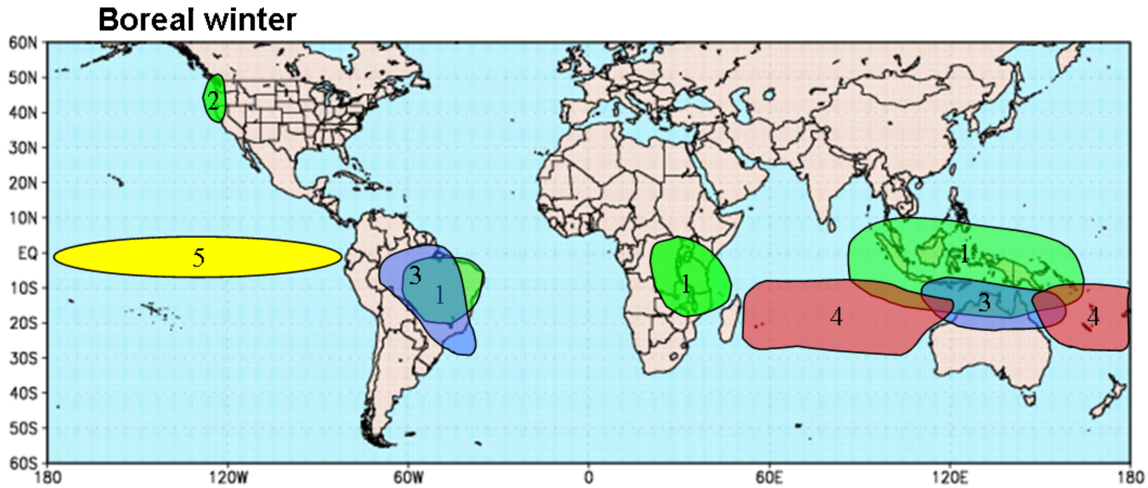
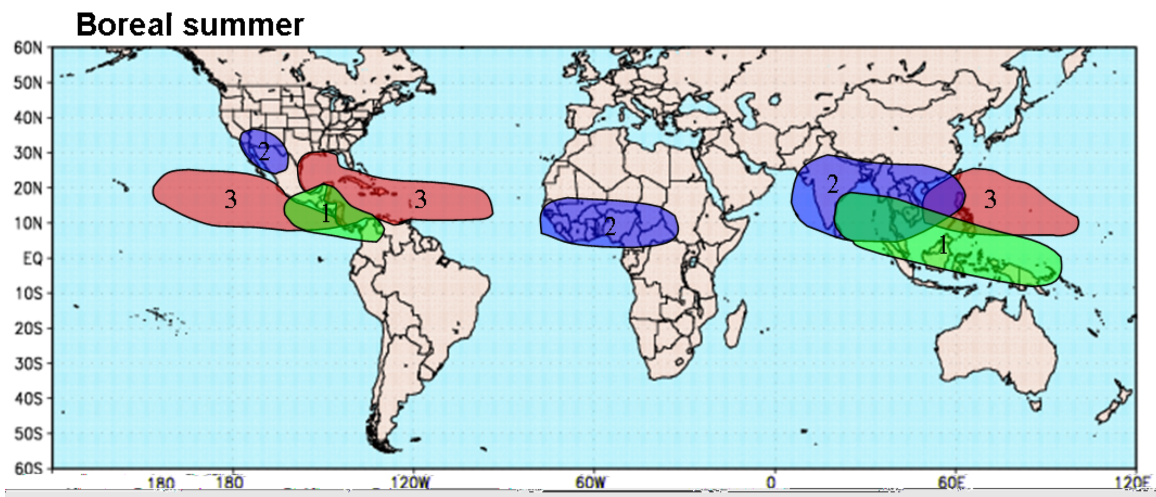


Figure 8b: Same as figure 8a except for the May through September time period.



1. Alternating periods of wetter/drier conditions in the tropics
2. ”Pineapple express” heavy rainfall events
3. Modulation of monsoon systems
4. Influence on tropical cyclone development
5. Modulation of ENSO cycle through oceanic Kelvin waves



1. Alternating periods of wetter/drier conditions in the tropics
2. Modulation of monsoon systems
3. Influence on tropical cyclone development

Figure 9: Regions and impacts where MJO activity has been shown to influence weather conditions during the 1-3 week time frame.

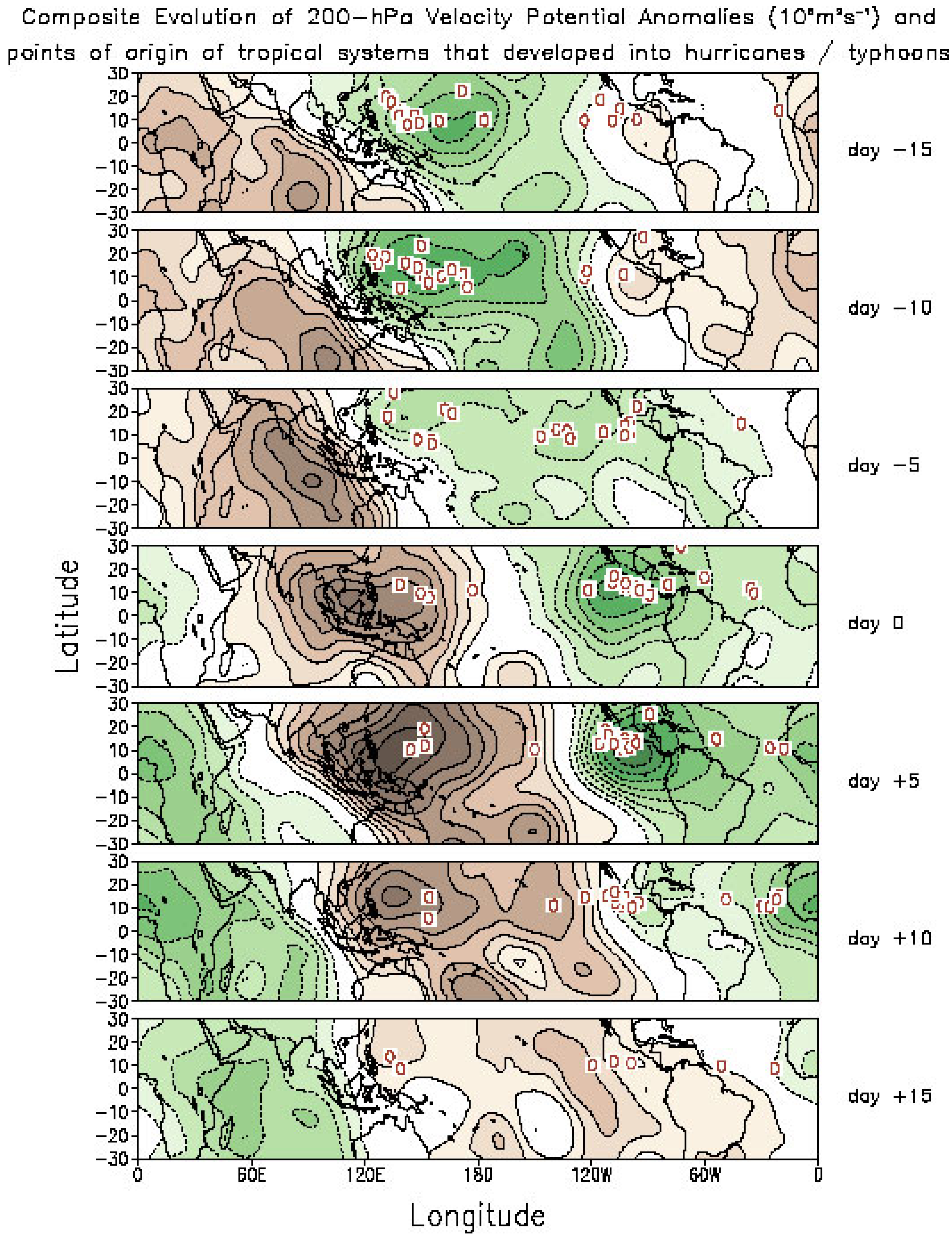


Figure 10: Velocity potential composites for different phases of the MJO cycle with hurricane/typhoon origin locations. Green shading indicates upper level divergence and brow shading indicates upper level convergence. Open circles indicate hurricane/typhoon origin centers.

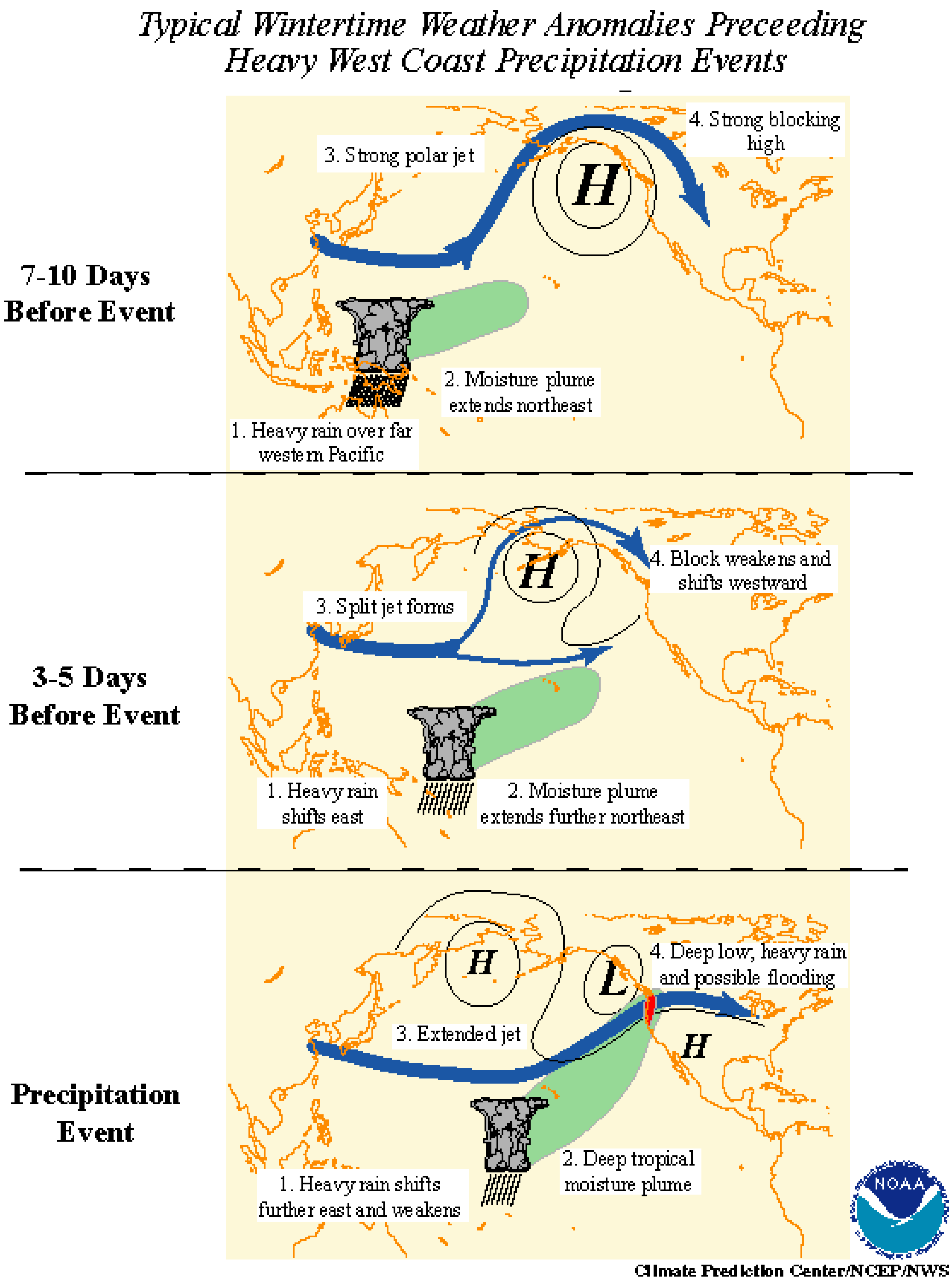


Figure 11: Schematic of circulation and moisture patterns associated with extreme rainfall events along the west coast of North America associated with the MJO.