The Impact of Trade Surges on the Madden–Julian Oscillation under Different ENSO Conditions

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Abstract

The tropical–extratropical interaction associated with the Madden–Julian Oscillation (MJO) and El Niño–Southern Oscillation (ENSO) in boreal winter is examined. When MJO convection is activated over the Indian Ocean, an anomalous extratropical high appears over the north Pacific. In this study, a zonal shift of the high is found to depend on ENSO phases, and the high shifts westward in the El Niño developing (EV) phases. Northeasterly trade surges that originate from the high intrude the tropical western north Pacific only during EV phases and moisten the area through convergence. Although convective activities are centered south of the equator in boreal winter, the moisturization by the surges results in the activation of MJO convection not only south of the equator but also north of the equator, facilitating the formation of the twin cyclonic disturbances straddling the equator. During the other ENSO phases, on the other hand, extratropical fluctuations and MJO activity do not interact each other. It has been shown in previous studies that these twin cyclonic disturbances produce westerly wind bursts, which can trigger El Niño. These results suggest that tropical–extratropical interactions between the MJO and the north Pacific high accompanied by the trade surges, occurs preferentially during EV phases, and feeds back to the development of El Niño.

1. Introduction

Although the Madden–Julian Oscillation (MJO) is the dominant tropical intraseasonal mode (e.g., Madden and Julian 1994), its signals are not restricted to the tropics. Many previous studies showed that intraseasonal fluctuations of extratropical circulation accompany the eastward propagation of MJO convection (e.g., Knutson and Weickmann 1987) though its mechanism has not been clearly explained. A significant extratropical response over the north Pacific to the MJO convection over the Indian Ocean occurs in the boreal winter associated with the Asian jet (e.g., Hsu 1996; Kim et al. 2006). With respect to forcing from the extratropics to the tropics, trade surges from an extratropical high over the north Pacific are observed at a time of active MJO convection over the central Indian Ocean (Fig. 3 of Seiki 1996). These results suggest that tropical–extratropical interactions between the MJO and the north Pacific high accompanied by the trade surges, occurs preferentially during EV phases, and feeds back to the development of El Niño.

2. Data

The primary data used in this study are daily mean values of zonal and meridional winds and sea level pressure (SLP) on 1.25° × 1.25° grids produced from four-times daily reanalysis data (JRA-25/JCICAS) prepared by the Japan Meteorological Agency (Onogi et al. 2007). Daily outgoing long-wave radiation (OLR) data derived by the National Oceanic and Atmospheric Administration (NOAA) on 2.5° × 2.5° grids are also used as a proxy for convective activity. Anomalies are defined as intraseasonal components, which are bandpass filtered with half-power frequency cutoffs at 20 and 100 days. Daily total precipitable water (TPW) data, from the Special Sensor Microwave/Imager (SSM/I) averaged for a 1° × 1° grid, are also used to represent moisture fields. Because of irregularly missing TPW data, intraseasonal components of TPW are defined as the 11-day running mean of deviations relative to a 51-day running mean. As an index of organized convection such as the MJO, bandpass filtered velocity potential data at 200 hPa (z200 anomaly) averaged at 5° × 5° are derived from JRA-25/JCICAS. Weekly 1° × 1° gridded Reynolds optimal interpolation sea surface temperature (SST) data (Reynolds et al. 2002) are also used. Monthly SST anomalies (SSTA) in Niño 3.4 are used for the El Niño index. This study focuses on boreal winter (November to March) for the period of 1992–2008 to examine the extratropical response and forcing in the northern hemisphere.

3. Analysis method

In this study, composite analysis is performed based on relatively strong MJO events in boreal winter. To determine reference days, first an empirical orthogonal function (EOF) analysis is applied to z200 anomalies in the entire tropics for 15°N to 15°S (e.g., Knutson and Weickmann 1987). The first two principle components (PCs) describe 32% and 25% of the z200 anomaly variance, and the first two eigen vectors display a divergence maximum of EOF1 and EOF2 around the maritime continent and the eastern Pacific, respectively. Some previous studies used the first two PCs as MJO signals and showed that PC1 leads PC2 by about 1/4 cycle (~10 days). In this study, the references are selected by taking the average of the preceding PC1 peak and the following PC2 peak, and the maxima greater than 1.5 standard deviations are defined as reference events. The number of MJO events selected in this study is 21. Each event is broken into five MJO phases. Phases 3 and 5 are designated as times when MJO convection develops over the maritime continent and eastern Pacific corresponding to the maxima of PC1 and PC2, respectively. Phase 1 is identified as the time when MJO convection activates over the central Indian Ocean corresponding to PC2 minima before PC1 peaks. The other
phases are placed equidistant in time between phases 1, 3, and 5. Then, we classify all the MJO events into three ENSO phases to characterize the behaviors of MJOs. First, we define El Niño developing (EV) phases as the periods from the first minimum of El Niño index preceding each El Niño to the maximum (El Niño peak), when frequent WWBs were significantly found over the western and central Pacific in ST07ab. The preceding minima approximately correspond to a 10-month lead. Then, El Niño decaying (EC) phases are defined as the periods from an El Niño peak to the following positive minimum. Note that EC phases are defined as the time when Niño 3.4 SSTA are positive, because the SSTA decrease drastically after El Niño, and the basic state changes rapidly. The rest of the events are classified into normal (NR) phases, where Niño 3.4 SSTA are around zero or negative. In general, the classification of El Niño and La Niña is more common than EV and EC phases. However, the latter classification is more suitable for this analysis, because we focus on convective disturbances of the MJO over the warm pool, i.e., the western and central Pacific, where the basic state can change drastically before and after El Niño. Therefore, even if MJO events have the same Niño 3.4 SSTA, the ENSO category in this study can be different. The number of events during the EV, EC, and NR phases is 7, 5, and 9, respectively.

4. Results

Figure 1 compares composite horizontal structures of SLP anomalies with wind anomaly vectors at the surface in MJO Phase 1, when large-scale convection lies over the central Indian Ocean. In general, similar pressure patterns are observed at the extratropics among all ENSO phases, such as north Pacific highs with anticyclonic circulations, which could be a response to the MJO over the Indian Ocean (e.g., Knutson and Weickmann 1987). While high SLP anomalies are centered around 180° and spread from northwestern to north Pacific during EV phases (Fig. 1a), they extend over the northeastern Pacific, centered around 160°W, during NR and EC phases (Figs. 1b and c). In association with the north Pacific highs, strong northeasterly outflows are found around 180° and 160°W during EV and NR phases, respectively. It is notable that the northeasterly surges reach the tropical western Pacific over the warm pool (thick dashed lines) only during EV phases. These results suggest that the subtropical trade surges impact on the equatorial Pacific depending on ENSO phases in association with the zonal shift of the north Pacific highs. On the other hand, high pressure anomalies and northeasterly surges during EC phases are obscure. Apparent differences between EV and EC phases are notable because the time lag between the two phases is at most one year.

Fig. 1. Composite sea level pressure anomalies indicated in contours with intervals of 1.5 hPa in MJO Phase 1 in EV (a), NR (b), and EC (c) phases. Zero contours are omitted. Shaded regions indicate a significance level greater than 95%. Wind anomaly fields at the surface are shown in vectors where either the zonal or meridional component is significant at the 95% level. Thick dashed lines show composite SST of 29°C. Boxes indicate the regions used for averaging of divergence anomalies in Fig. 2.

Fig. 2. Surface divergence anomalies ($10^{-7}$ s$^{-1}$) averaged for the equator−10°N, 130°E−150°E (boxes in Fig. 1) during EV (solid), NR (gray), and EC (dotted) phases. The abscissa represents the MJO phases. Error bars indicate 95% confidence limits.
anomalies found in this study can be part of the Kelvin wave response. However, amplitudes of MJO convective activities over the Indian Ocean (10°S–10°N, 60°E–100°E) during MJO Phase 1 in EV, NR, and EC phases are −16.0, −16.7, and −10.1 W m$^{-2}$, respectively. Almost the same amplitudes of OLR anomalies in EV and NR phases do not explain the stronger convergence in EV phases, suggesting the existence of external factor. These results suggest that stronger convergence over the western north Pacific during EV phases is related to the westward-shifted trade surges and prepares favorable conditions for organized convection through moisture convergence over the warm pool. In addition, southeasterlies north of the New Guinea might contribute to the convergence though they do not accompany pressure anomalies.

Along with the MJO propagation, moisture fields also vary at intraseasonal time scales. Figure 3 is the same as Fig. 1 except for TPW anomalies in Phases 1 (left panels) and 3 (right panels). Solid green contours indicate OLR anomalies of −15 W m$^{-2}$. In Phase 1 when MJO convection is observed over the Indian Ocean (Figs. 3a and c), dry anomalies are located over the southern side of the north and northeastern Pacific highs during EV and NR phases, respectively. These dry regions correspond to the origin of the trade surges. Notable is that significant anomalous moisture is found over the western north Pacific only during EV phases, corresponding to the strong convergence area. These results suggest that dry northerly surges converge over the tropical easterlies and gain plenty of moisture from the warm pool.

In Phase 3, when large-scale convection is centered over the maritime continent, the southern band around 5°S–20°S, 120°E–180° and the northeastern Pacific region around 10°N–20°N become moist generally in all ENSO phases. During EV phases (Fig. 3b), active convective region shown by solid green lines extends north of the equator to 160°E. This active convection over the western north Pacific can arise from the moisturization associated with the trade surges from Phase 1. In addition, significant moisture spreads widely over the equatorial Pacific north of the equator from 140°E to 160°W, whose eastern part can be associated with southeasterlies south of the equator. Together with the southern moist band, the western Pacific region shows widespread moisture across the equator, which is favorable for the formation of the twin cyclonic disturbances. This moisturization can facilitate the further eastward extension of MJO convection in both hemispheres (not shown). In NR phases, the trade surges are still observed in Phase 3, and the moist region over the northeastern Pacific expands widely for 8°N–20°N (Fig. 3d). However, equatorial convection is confined to the west of 140°E, unlike that in EV phases, and significant moist anomalies are not found around the equator. During EC phases (Fig. 3f), active convection propagates south of the equator, and most of the equatorial region is dry,

![Fig. 3. Same as Fig. 1 except for composite total precipitable water anomalies in shading exceeding the 95% significance level in MJO Phases 1 (left panels) and 3 (right panels). Solid (dotted) green contours represent composite OLR anomalies of −15 (+15) W m$^{-2}$.](image-url)
whereas the southern band of 10°S−20°S is substantially moist.

In all ENSO phases, the southern band becomes moist when MJO convection reaches the Pacific largely due to the seasonality. On the other hand, active convection and moist regions north of the equator can be found only in EV phases though all MJO events in this study have relatively strong amplitudes and propagate from the Indian Ocean to the Pacific. This moistening north of the equator begins when MJO activates over the Indian Ocean, and could be related to westward-shifted trade surges reaching the tropical western Pacific. The widespread convection and moisture across the equator found in EV phases may play an important role in the formation of cyclonic disturbances straddling the equator, which have been shown to generate WWBs (ST07ab).

5. Discussion and conclusions

Previous studies showed that when MJO convection is located over the Indian Ocean, the extratropical high in the lower troposphere appears over the north Pacific, which could be the extratropical response to the MJO (e.g., Knutson and Weickmann 1987). By considering their relationship under the different ENSO conditions, this study shows that the extratropical high shifts westward and the trade surges originating from the high reach the equatorial western Pacific in EV phases. These surges cause strong convergence, resulting in moisture insertion over the western north Pacific. As a result, large-scale convection north of the equator can be activated only in EV phases when MJO convection propagates eastward to the Pacific. Because convective activities, including MJO convection, shift south of the equator in boreal winter, it is unusual that convection extends meridionally across the equator in this season.

In previous studies, EV phases have been known as favorable periods for the occurrences of WWBs over the Pacific, which can trigger or enhance El Niño (ST07a and references therein). Twin cyclonic disturbances straddling the equator develop from MJO convection, and produce WWBs in association with the background westerly state and the extension of the warm pool (ST07ab). The widespread moisture across the equator through surge-induced convergence found in this study can also be one of the important factors to form the twin cyclonic disturbances, resulting in WWBs. These results suggest that interactive amplification between the MJO and the extratropical high in EV phases cause strong atmospheric forcing near the equator, which could have an impact on ENSO.

In NR phases, on the other hand, the trade surges and the north Pacific high shift eastward, and their impact does not reach the tropics. During EC phases, most extratropical signals are not significant, and equatorial regions are relatively dry. In these two ENSO phases, the extratropical response to the MJO and the MJO itself in the tropics do not interact each other. Although equatorial regions are relatively dry at a time of active MJO convection over the maritime continent, the northeastern Pacific for 10°N−20°N and the southwestern Pacific for 10°S−20°S are highly moisturized in NR and EC phases, respectively. The influence of these moist regions is an interesting topic left for future studies.

The effect of SST should be concerned to explain the active convection over the western north Pacific. Recollecting Fig. 1, the highest SST in this area is observed in NR phases. However, the strongest convergence and the most active convection are found in EV phases. Therefore, SST values are not crucial for active convection though SST above a certain level is necessary. On the other hand, since a recent study (Hendon et al. 2007) as to spring MJO cases showed that stronger MJO activity in spring precedes El Niño associated with seasonal zonal expansion of the warm pool, SST distributions as to boreal winter cases in this study need further investigation.

Previous studies indicated the extratropical response to the MJO not only in the lower but also in the upper troposphere (e.g., Knutson and Weickmann 1987). Consistent upper-level highs are also observed over the north Pacific especially north of 30°N in this study (not shown). The role of the Asian jet is noteworthy for the formation of the north Pacific highs (e.g., Kim et al. 2006). A wave train along the jet excited by MJO-related divergence winds might be an important factor (Hsu 1996; Mori and Watanabe 2008). In our ongoing study, how ENSO affects the zonal shift of the extratropical high will be examined.

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