Impact of cold surges on the Madden-Julian oscillation propagation over the Maritime Continent

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1 | INTRODUCTION

The Madden-Julian oscillation (MJO), which plays a crucial role in affecting weather and climate over the majority of the globe (Lau and Waliser, 2011; Zhang, 2013), is featured as eastward propagation of organized convection from the equatorial Indian Ocean to the central Pacific (Zhang, 2005). However, some MJO events are blocked over the Maritime Continent (MC) and do not propagate into the western Pacific (Hsu and Lee, 2005; Matthews, 2008; Kim et al., 2014; Kerns and Chen, 2016; Zhang and Ling, 2017). Therefore, the MJO events can be categorized into those successful in crossing the MC (hereafter referred to be MJO-C, following Zhang and Ling 2017) and those blocked over the MC (MJO-B). Whether the MJO events propagate into the western Pacific or are blocked in the MC may induce the great differences in local and remote influences.

Several possible reasons are proposed to explain the distinction between MJO-C and MJO-B, including the reduction in surface heat latent flux over the MC (Hsu and Lee, 2005; Inness and Slingo, 2006; Wu and Hsu, 2009), the diurnal cycle of cloudiness and precipitation (Hagos et al., 2016; Majda and Yang, 2016; Zhang and Ling, 2017), and the moisture distribution modulated by tropical large-scale circulations (Hsu and Li, 2012; Kim et al., 2014; Feng et al., 2015; Kim et al., 2017; Zhang and Ling, 2017). All these studies indicate that the eastward propagation of MJO over the MC is a complex issue.

Previous studies have indicated that MJO has distinct tropical–extratropical interaction with some extratropical climate/weather systems. On the one hand, MJO can modulate the extratropical circulation. A specific example includes cold surges over East Asia, which can be modulated by MJO phases (Jeong et al., 2005; He et al., 2011; Abdillah et al., 2017). On the other hand, cold surges that originate in the extratropics can influence the MJO. For instance, case studies found that the cold surges over West Asia (Wang et al., 2012) or western North Pacific (Hong et al., 2017) may trigger the convective initiation of the MJO during the boreal winter. Recently, Chen et al. (2017) suggested that strong (weak) events of East Asian winter monsoonal northerlies correspond to enhanced (suppressed) convection over the
MC and equatorial western Pacific, when MJO is in phase 4. It has been long recognized that strong cold surges in East Asia can trigger the convection in the MC (Chang et al., 2005). Therefore, it is plausible to hypothesize that cold surges in East Asia may play a role in determining whether MJO can propagate into the western Pacific or is blocked over the MC. The aim of this study is to test the hypothesis.

2 DATA AND METHODS

Daily rainfall data are provided by tropical rainfall measuring mission 3B42v7 multisatellite precipitation analysis (Huffman et al., 2007) with the resolution of 0.25 × 0.25. Atmospheric variables are obtained from the European Center for Medium-Range Weather Forecasts Interim Reanalysis (ERA-Interim; Dee et al., 2011), and the horizontal resolution is 0.75 × 0.75. The analysis covers the period of 1998–2015, and the 29th February in leap years is omitted. The daily anomalies are obtained by removing 18-year mean of that particular day. Boreal winter is defined as the period from November to February when cold surges are active over East Asia following Lim et al. (2017).

The events for MJO-C and MJO-B are selected following Zhang and Ling (2017). The MJO events are objectively identified by tracking the eastward movement of 20–100-day filtered positive precipitation anomalies along the equator. Of all MJO events that formed over the Indian Ocean, MJO-C refers to those ending longitudes greater than or equal to 150°E, while MJO-B refers to those ending longitudes over the MC region (100–150°E). The detailed description of the MJO tracking method can be found in Zhang and Ling (2017).

During the analysis period of this study, 14 MJO-C and 8 MJO-B events were identified. The effective degree of freedom was calculated for each variable at each grid, and the Student’s t test was used for the significant test by comparing the MJO-C (or MJO-B) days with all other days during boreal winter.

3 RESULTS

Figure 1 shows the time-longitude diagrams of 20–100-day filtered precipitation anomalies averaged over 15°S–15°N. Here, day 0 denotes the date when the MJO convection center crosses 100°E. The MJO-C and MJO-B events can be well distinguished. The MJO-C crosses the MC and propagates eastward to the dateline (Figure 1a), while the MJO-B weakens and vanishes over the MC (Figure 1b). The MJO-C and MJO-B events do not show an apparent difference in intensity of precipitation anomalies before they approach the MC, or more exactly, before 100°E. The precipitation anomalies averaged over 15°S–15°N and 60–100°E from day −10 to day 0 are 2.5 mm day−1 both for MJO-C and MJO-B events. The spatial and temporal scopes for the average are illustrated by green diamonds in Figure 1. Therefore, initial conditions over the Indian Ocean cannot explain the different propagation characteristics over the MC between MJO-C and MJO-B events, which is in agreement with Zhang and Ling (2017), despite the difference in analysis period between the present study (November–February) and their study (the whole year).

The major difference in precipitation between MJO-C and MJO-B occurs after MJO passes 120°E (Figure 1). The precipitation anomalies averaged over 120–150°E from day 0 to day 15 are 2.3 mm day−1 for MJO-C events, similar to the values when MJO-C approaches the MC (i.e., 2.5 mm day−1), but are much smaller for MJO-B events (0.8 mm day−1). Therefore, the longitudinal scope 120–150°E was used to highlight the differences between MJO-C and MJO-B. The date when a MJO or its extension track passes to 120°E (or 150°E) was estimated by its starting date and propagating speed, following Zhang and Ling (2017). Then the composite was done over days when the MJO convection center is within this longitudinal scope. There are a total of 120 days for the MJO-C and 74 days for the MJO-B. Noted that here MJO-B days are also calculated as the period from 120 to 150°E, where the anomalous precipitation of MJO-B is still positive (Figure 1b) but fails to maintain its value over one SD.

The composite precipitation anomalies for the MJO-C events are characterized by a dipole pattern with positive anomalies over the MC and negative ones over the Indian Ocean (Figure 2a). By contrast, for the MJO-B, the positive anomalies are quite weak over the MC, with the intensity of 0.7 mm day−1 averaged over 15°S–15°N and 100–150°E (Figure 2b), which is expected since the MJO-B vanishes during crossing the MC. Besides, the precipitation anomalies for the MJO-C tend to be positive over the seas but negative over lands, in agreement with Zhang and Ling (2017).

In addition to precipitation, the lower-tropospheric winds are also distinct between the MJO-C and MJO-B. For the MJO-C, the northeasterly or northerly anomalies dominate over the subtropics and penetrate deeper into the tropics over the South China Sea and western North Pacific (Figure 2a). By contrast, for the MJO-B, there tend to be southwesterly anomalies over these regions (Figure 2b). The meridional wind anomalies averaged over 110–140°E along 15°N (red lines in Figure 2) are −1.1 and 0.8 m s−1 for the MJO-C and MJO-B, respectively. The results are also represented by compositing for the MJO-B over days when its convection center is between 120°E and ending longitude (Figure S1). This difference in meridional winds between the MJO-C and MJO-B suggests that the northerly anomalies may play a crucial role in favoring the eastward propagation of MJO over the MC.

Furthermore, as a typical phenomenon of strong northernlies, cold surges may also display a different feature between the MJO-C and MJO-B events. To test this hypothesis in a quantitative way, we define a surge index in terms of
the averaged 850-hPa meridional wind over the longitude of 110°–140°E along 15°N (red lines in Figure 2). The definition is similar to Chang et al. (2005) but with the following two modifications. Meridional wind at 850 hPa instead of 925 hPa is used to decrease the orographic effect caused by the Philippine islands, and the longitude scope is enlarged to 110–140°E to cover the key study region.

The averaged cold surge index for the MJO-C is \(-3.28\) m s\(^{-1}\), while it is \(-1.44\) m s\(^{-1}\) for the MJO-B, and they can be well separated, which is significant at the 95% confidence level using a Monte Carlo bootstrapping technique (Efron and Tibshirani, 1993) with a resampling procedure of 10,000 times. Moreover, the surge index for the MJO-C is also significantly different from the climatology \((-2.07\) m s\(^{-1}\)), but not for the MJO-B (Table 1). Here, three levels of thresholds (e.g., 1.0 SD \([\sigma]\), 0.75\(\sigma\), and 0.5\(\sigma\)) are used to examine the sensitivity of the results with the choice of criteria, and identify a cold surge day if its surge index is lower thresholds than the climatological mean. The ratio of surge days varies from 15 to 29% in climatology with the
TABLE 1 Percentages of cold surge days for the MJO-C and MJO-B events, and climatology

| Thresholds | MJO-C       | MJO-B       | Climatology, % |
|------------|-------------|-------------|----------------|
| 1σ         | 34% (±23%)  | 9% (±12%)   | 15             |
| 0.75σ      | 40%* (±26%) | 17% (±20%)  | 22             |
| 0.5σ       | 52%* (±25%) | 22% (±22%)  | 29             |

The values in brackets indicate SDs between cases, and asterisk denotes statistically significant departures from climatology at the 95% confidence levels.

decrease of thresholds from 1σ to 0.5σ. Generally speaking, the frequency of cold surge is significantly larger in the MJO-C events, while it tends to be smaller in the MJO-B events when compared to the climatology. The ratio of cold surge days for the MJO-C is approximately double, but only 2/3 for the MJO-B compared to climatology. The distinction is most prominent under the threshold of 1σ, that is, stronger cold surges tend to occur more frequently for the MJO-C in comparison with the MJO-B and climatology.

The occurrence frequency of cold surge is generally higher in the MJO-C than that in the MJO-B propagating over the MC, event by event (Figure 3; Table 1). Here, only the results by the threshold of 1σ are shown, and those by the other two thresholds exhibit similar features. The cold surges are found in 12 cases among the total 14 MJO-C events (Figure 3a), but they only occur in four MJO-B events and the proportions of surge days are generally lower for all these four events (Figure 3b).

Figure 4 shows the daily lag composite circulation associated with the cold surge events for the MJO-C event. A cold surge event is determined when surge index exceeds 1σ of the climatological mean, and the day when the surge index reaches its maximum is taken as day 0. A total of 18 cold surge events are identified during the MJO-C events propagate through the longitudinal scope (120°–150°E). The positive sea-level pressure (SLP) anomalies are strongest before cold surges reach the peak (day −2; Figure 4b). It has been well known that the amplification of the Siberian High, as the source of cold air, is a precondition for the occurrence of cold surges (Zhang et al., 1997; Takaya and Nakamura, 2005; Park et al., 2008). In comparison with these previous studies, the present results show the enhanced SLP at a relatively southward region, possibly due to the fact that cold surges are determined in this study by the tropical winds. There is a southeastward progression of the high-pressure anomalies from Siberia to Southeast China in the following 2 days, which is followed by an eastward shift at days +1 and +2. Accordingly, the lower-tropospheric northerly anomalies are found over Northeast China at days −2 and −3, and then become intensified and extend southward into the MC. The SLP index at day −2, which is defined in terms of averaged SLP over 30°–50°N and 70–120°E, shows statistically significant ($p < 0.01$) correlation ($r = −0.72$) with the cold surge index at day 0. These results indicate that cold surges occurred during the MJO-C events are triggered by the enhanced SLP at Mongolia and Northern China, at least from the view of composites, suggesting the important role of extratropical anomalies in affecting cold surges and MJO propagation.

Moreover, Figure 4 also implies that cold surges may favor the MJO propagation through the enhancement of tropical westerly anomalies. In order to remove the possible effects of MJO on westerly anomalies shown in Figure 4, a composite for all cold surge days but excluding both the MJO-C and MJO-B events is performed (Figure S2). It still shows distinct equatorial westerly anomalies over 120–150°E around day 0, consistent with previous studies (Chen et al., 2016; Hong et al., 2017), which suggest that cold surges can trigger the westerly wind bursts in the western Pacific. Those westerly anomalies may enhance convection over the equatorial western Pacific through modulating the zonal asymmetry of moist static energy, as suggested by Wang et al. (2018). However, it should be noted that the detailed mechanisms for the relationships between cold surges, equatorial westerlies, convection, and MJO propagation are complicated and require further investigation.

The MJO-related heating may modulate the extratropical circulations including cold surges. Simple general circulation models have been widely used to identify the circulation responses to prescribed tropical heating forces (Matthews et al., 2004; He et al., 2011; Guo et al., 2015; Abdillah et al., 2017). To estimate the circulation responses to heating anomalies associated with MJO-C,
we perform a numerical experiment using a simple baroclinic model with prescribed heating that is a mimic of precipitation-induced latent heating (Figure 2a), and the results are shown in Figure S3. The simulated results indicate that lower-tropospheric wind responses are generally weak over the South China Sea and western North Pacific, and thus demonstrate that the dominant part of observed northerly anomalies might not be the response to MJO heating, supporting the possibility of their extratropical sources.

**FIGURE 4** Daily lag composite sea-level pressure (shaded; units: hPa) and 850-hPa wind (vector; units: m s$^{-1}$) anomalies associated with the cold surge events for the MJO-C. Day 0 denotes the day when cold surges are the strongest. Vectors are shown as thick and black when the meridional winds being significant at the 95% confidence level, and sea-level pressure anomalies being significant at the 95% confidence level are stippled. (a) Day $-3$. (b) Day $-2$. (c) Day $-1$. (d) Day 0. (e) Day 1. (f) Day 2

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**4 | CONCLUSION AND DISCUSSION**

In this study, we have examined the extratropical circulations associated with two types of MJO events according to whether they can propagate into the western Pacific or is blocked over the MC. Distinct features are found in the extratropical regions associated with these two types of MJO events when they propagate over the MC. The northeasterly or northerly anomalies are dominant over the South China Sea and western North Pacific for the MJO-C events, while
southwesterly anomalies tend to appear over the these regions for the MJO-B. Further analyses indicate that cold surges occur much more frequently during the MJO-C event than the MJO-B events or climatology, and those cold surges is triggered by the enhanced SLP or accumulated cold air at Mongolia and Northern China.

Therefore, based on the present and previous results, we suggest that cold surges, triggered by extratropical cold air, penetrate into the MC and favor convection there, and thus provide a favorable condition for the MJO propagating through the MC and into the western Pacific. However, it should be mentioned that some MJO events can propagate across the MC without cold surges (Figure 3a), and this is true even if cold surge is defined by the thresholds of 0.5σ (not shown). Therefore, cold surges should be considered as one of the various factors that determine whether the MJO can propagate into the Western Pacific.

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