Spring Barrier to the MJO Eastward Propagation

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Abstract The Maritime Continent (MC) often exerts barrier effect on the eastward propagation of the Madden-Julian Oscillation (MJO), and the strongest (weakest) effect occurs in spring (winter). After passing over the MC, the MJO slightly weakens by approximately 10% in winter and it sharply decays by more than 50% in spring. The physics for this spring barrier are understood from the perspective of the frictionally coupled Kelvin-Rossby wave theory. In spring, the abrupt reduction in the boundary layer moisture convergence that occurs at the MC causes the decoupling of the Kelvin-Rossby wave packet associated with the MJO: Kelvin waves emit from the major convection, while Rossby wave component rapidly decays in the Indian Ocean. An intermediate atmospheric model involving both the fundamental dynamics of the frictionally coupled Kelvin-Rossby wave theory and the mean states confirms that the spring barrier is determined primarily by the mean surface moisture, particularly by its zonal distribution.

Plain Language Summary Madden-Julian Oscillation (MJO) has been considered as the major source of subseasonal predictability. However, one of the largest uncertainties in MJO simulations and predictions is the complexity of MJO behavior around the Maritime Continent. The MJO usually weakens as it propagates across the Maritime Continent; this phenomenon is known as the barrier effect. In this paper, a distinct seasonal difference is revealed regarding the barrier effect, wherein the strongest (weakest) effect occurs in spring (winter). The physics responsible for the strongest spring barrier are described based on both observation and model. The results indicate that the spring barrier to the MJO eastward propagation is determined primarily by the zonal distribution of the mean surface moisture. This improved understanding of the spring MJO potentially benefits studies of the climate systems, for example, the Asian monsoon and the El Niño-Southern Oscillation.

1. Introduction

As one of the prominent modes in the tropical atmosphere, the Madden-Julian Oscillation (MJO) significantly modulates global weather and climate systems (Zhang, 2013), thereby playing as the major source of subseasonal predictability (Vitart, 2014). The MJO, in the form of a slowly eastward moving convection-circulation complex, is characterized by a coupled Kelvin-Rossby wave horizontal pattern and a rearward-tilted baroclinic vertical structure (Benedict & Randall, 2007; Hendon & Salby, 1994; Jiang et al., 2011; Kiladis et al., 2005; Wang et al., 2018). The zonal asymmetry of MJO moisture processes associated with, for example, boundary layer (BL) convergence, horizontal advection, and air-sea interaction is highlighted in driving the MJO eastward propagation (e.g., Benedict & Randall, 2007; Hsu & Li, 2012; Jiang et al., 2018; Li & Wang, 1994; Maloney, 2009; Tian et al., 2010).

When the MJO convection moves over the Indo-Pacific warm pool, the embedded Maritime Continent (MC) usually exerts a barrier effect on its eastward propagation; that is, the convection substantially weakens or even vanishes at the MC (e.g., Kerns & Chen, 2016; Kim et al., 2014; Zhang & Ling, 2017). This phenomenon results in large uncertainties in simulating and predicting the MJO; consequently, numerous studies have addressed this issue. Among the mechanisms proposed for this MC barrier effect, the majority emphasize land processes such as topographic blocking (Hsu & Lee, 2005; Inness & Slingo, 2006), decreased surface fluxes (Maloney & Sobel, 2004; Sobel et al., 2010), and an enhanced diurnal cycle (Ling et al., 2019; Neale & Slingo, 2003). From a moisture mode standpoint, the moisture processes attributable to the interactions between MJO perturbations and background moisture may dampen or deflect MJO convection upon
encountering the MC (Jiang et al., 2019; Kim et al., 2017). Additionally, some dry precursors from the western Pacific Ocean (WPO) were found to be responsible for the termination of the MJO at the MC (DeMott et al., 2018; Feng et al., 2015; Kim et al., 2014). In terms of frictionally coupled Kelvin-Rossby wave theory (Hendon & Salby, 1994; Maloney & Hartmann, 1998; Wang, 1988), strong coupling between the Kelvin wave response and major convection is considered to be critical for the ensuing eastward propagation of the MJO upon being established over the eastern Indian Ocean (EIO; Wang et al., 2018, 2019). In some sense, frequent Kelvin wave emissions from MJO convections observed across regions from the EIO to the MC (Sobel & Kim, 2012) may be closely related to the MC barrier effect.

The previously mentioned understandings of the MC barrier effect were generally derived from composite analyses regarding two distinct archetypes: MJO events that propagate across the MC and those that do not during winter half year (e.g., DeMott et al., 2018; Feng et al., 2015; Ling et al., 2019; Zhang & Ling, 2017). Indeed, seasonal difference is nonnegligible in many MJO behaviors, even between winter and the following spring. For example, given that the MJO prevails in both seasons, extreme events mostly occur in spring (Lafluer et al., 2015; Lu & Hsu, 2017). Recently, a striking regional difference is observed in MJO seasonality between the two basins separated by the MC, that is, the EIO and WPO (Li et al., 2019), as also depicted in Figure 1a. Provided that the zonal contrast between the WPO and the EIO generally reflects the MC barrier effect, notable seasonality is shaped, wherein the strongest (weakest) effect appears in spring (winter; Figure 1b). Accordingly, the dramatic seasonal difference between winter and spring should not be overlooked in studies relevant to the MC barrier effect.

Based on both observations and model experiments, this paper aims to understand the essential physics regarding the strongest MJO spring barrier from the perspective of the frictionally coupled Kelvin-Rossby wave theory.

2. Data and Method

To monitor the MJO convective signal, daily mean outgoing longwave radiation (OLR) data (Liebmann & Smith, 1996) from the National Oceanic and Atmospheric Administration (NOAA) are utilized. Daily mean horizontal winds, specific humidity, and sea level pressure data are derived from the fifth reanalysis produced by the European Centre for Medium-Range Weather Forecast (ERA5; Hersbach & Dee, 2016). The above daily parameters are employed on a 2.5° spatial grid spanning 1979–2016, and the MJO-related 30–to 60-day anomalies (hereafter referred to as “anomalies”) are isolated by applying a second-order Butterworth band-pass filter to the raw daily data.

An intermediate atmospheric model involving both the framework of the frictionally coupled Kelvin-Rossby wave theory and the mean states is employed to investigate the MJO spring barrier. The model consists of a two-level free atmosphere and a well-mixed BL (Li & Wang, 1994; Wang & Xie, 1997) and covers the global tropics between 40°S and 40°N with a spatial resolution of 5° longitude × 2° latitude. The prescribed mean states in the model are derived from the ERA5 monthly three-dimensional velocities, air temperature, and surface specific humidity (represented by values at 1,000 hPa). Text S1 in the supporting information briefly describes the convective parameterization scheme, and Table S1 in the supporting information lists the selected model parameters. Details of this model are shown in Wang and Xie (1997).

3. Results

3.1. Observed Characteristics of the MJO Spring Barrier

Figure 1a illustrates the annual evolution of the MJO intensity along the equatorial belt. During boreal winter, the active MJO is observed across the broad Indo-Pacific warm pool. However, with the seasonal transition from winter to spring, the downstream and upstream basins with respect to the MC present vastly different images. In the WPO, the MJO remarkably decays, while in the EIO, the MJO is significantly strengthened and reaches its annual maximum. Considering that the zonal difference in the MJO intensity between the WPO and EIO generally reflects the MC barrier effect on the MJO, the ratio of the MJO intensity between these two regions is calculated and shown in Figure 1b, wherein a smaller (larger) value indicates a stronger (weaker) barrier effect. Obviously, the MC barrier effect is minimized in January–February (JF), becomes abruptly strengthened in March, and reaches its maximum in May. During JF, the MJO intensity

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The ratio is approximately 1, which implies a smooth eastward transition at the MC. Subsequently, the ratio quickly decreases to 0.6 in May, suggesting that the MJO substantially decays after passing over the MC. Here, revealing the physics responsible for this undeniable seasonal difference constitutes the motivation of the present work. For this purpose, composite analysis is conducted during the strong barrier period (April–May, AM) in comparison with a parallel analysis during the weak barrier period, that is, JF. To determine the individual MJO events used for the composite analysis, the domain-averaged OLR anomalies within 80°–100°E and 15°S–15°N are adopted as a reference index. First, the standard deviations of the reference index are calculated in time windows of 1 January to 28 February and 1 April to 31 May. Then, events with minima below one standard deviation that fall into the corresponding time window are selected. Since the present paper focuses on the MC barrier effect on the eastward propagation of the MJO, each qualified MJO event is double-checked through a time-longitude diagram along the equatorial belt (15°S–15°N) to exclude the events with westward or ambiguous eastward propagation over the EIO. Eventually, 28 (27) samples are chosen in JF (AM) and composited according to the dates when the reference index reaches its minimum (day 0).

Figures 1c and 1d show the time-longitude evolution of the composite MJO in JF and AM, respectively. The OLR patterns show one negative and two adjacent positive anomalies that share greatly similar zonal evolution characteristics. Therefore, the following discussion mainly emphasizes the negative anomalies, that is, the convectively enhanced MJO phase, while the opposite is naturally obtained for the convectively suppressed MJO phase. In both figures, it is clear that the MJO initiates and intensifies in the Indian Ocean, and the maximum amplitude appears rightly before arriving at the MC. Both MJO events substantially weaken as they move across the MC (100°–120°E) and then reintensify after entering the WPO. However, the WPO counterpart in AM is much weaker than that in JF, suggesting that the barrier effect is stronger in AM than in JF. To quantitatively compare the seasonal difference in the barrier effect, the MJO
intensity ratios of the WPO to the EIO are calculated in both periods. Here, the MJO intensity is represented by the standard deviation of the 61-day (days −30 through 30) OLR anomalies. The calculations show that the MJO intensity ratio is 0.87 (0.43) in JF (AM), which means that MJO slightly (dramatically) decreases by 13% (57%) in JF (AM) after passing over the MC.

Previous observations and simulations have indicated that the essential dynamics of the MJO are rooted in a convectively coupled Kelvin-Rossby wave packet (e.g., Kang et al., 2013; Seo & Kim, 2003; Wang & Rui, 1990) and that the coupling between the Kelvin wave and major convection is of vital importance for the eastward propagation of the MJO (e.g., Wang et al., 2018, 2019). In Figures 1c and 1d, Kelvin waves are clearly identified as the prevailing easterlies collocated with low-pressure areas east of the negative OLR anomalies. At the early stage, the tightly coupled convection-circulation system moves slowly eastward over the Indian Ocean, and the OLR and pressure minima are nearly coincident. Subsequently, a pressure minimum associated primarily with easterlies is separated from the OLR minimum and moves eastward much more rapidly. These fast-moving disturbances are probably interpreted as the decoupling and emission of Kelvin waves from the major MJO convection (Sobel & Kim, 2012). In JF, the behavior described above occurs after the MJO passes over the MC (approximately 140°–160°E) between day 0 and +10, while in AM, this behavior is observed at approximately 100°E between days −10 and 0. To the east of the critical longitudes that involve frequent Kelvin wave decoupling, the MJO weakens and vanishes rapidly. Such observations are in accordance with previous arguments that highlight the role of Kelvin-Rossby wave packet in the evolution of the MJO.

The detailed evolution of the MJO near the MC is further examined in Figure 2. At day −5, MJO convection is centered at the equator, and the low-level circulation exhibits a Gill-like pattern with prominent easterlies (westerlies) associated with the Kelvin (Rossby) wave. However, distinct evolution is observed during JF and AM in the following days. In JF, the organized convection-circulation system slowly propagates towards the MC; then, the main body detours southward when it encounters the western MC and tends to move along the Australian monsoon trough. In contrast, the AM MJO behaves differently when it encounters the western MC. A convection front quickly separates from the main body, as we previously described as the decoupling of the Kelvin wave. Coincident with the separation of the Kelvin wave, the main body in the EIO ceases its eastward propagation and sharply decays. Two secondary centers residing to the north and south of the equator gradually evolve at the two cyclonic gyres associated with Rossby waves. Note that the convection does not exhibit clearly westward movement (as the convectively coupled Rossby waves do) but preferably decays locally. At day +10, when the organized JF MJO is moving along the MC, the convection associated with the AM MJO completely disappears in the EIO, and only a weak remnant survives in the WPO. Thus, the physics responsible for the spring MC barrier effect on the MJO eastward propagation are related primarily to the separation of the Kelvin-Rossby packet along the western MC.

Theoretically, the MJO structure is shaped by complex interactions among convective heating, moisture, and equatorial wave-BL dynamics (Liu & Wang, 2017; Wang et al., 2016; Wang & Lee, 2017). Among these interactions, it is the BL moisture convergence that ties the Kelvin-Rossby wave packet and convection together. Both the Kelvin wave and Rossby wave contribute to the equatorial BL convergence ahead of the convective heating and favor the eastward propagation of the MJO (Matthews, 2000; Wang et al., 2016). When the MJO is located in the EIO, it is clear that positive BL moisture convergence occurs beneath and to the east of the convection center in both events, and the relatively moist BL in AM preconditions a stronger MJO (Figures 2 and 3). Prior to the MJO convection center, the BL moisture convergence associated with the AM event reaches 0.7 g · kg⁻¹ · day⁻¹, while that associated with the JF event is nearly 0.3 g · kg⁻¹ · day⁻¹. The above moisture source corresponds to a maximum convective anomaly at approximately −18.5 W/m² (−15.5 W/m²) in AM (JF). However, along the MJO pathway within 100°–110°E, the BL moisture convergence associated with the AM MJO suddenly drops to 0.2 g · kg⁻¹ · day⁻¹ (a decrease of approximately 70%), which is similar to that associated with the weak JF MJO. On this basis, an insufficient moisture supply at that longitude cannot maintain a continuous extension of convection that matches the stronger AM MJO. This abrupt reduction in moisture would suppress local convection and reduce the degree of coupling between Rossby and Kelvin waves. It is worth noting that the above longitudinal band coincides well with the frequent Kelvin wave emissions observed in AM (Figure 1d). Consequently, in tandem with the separation of the
wave packet, the wave-induced BL convergent flow would substantially weaken. A weaker convergent flow corresponds to a weaker moisture supply and weaker convection. Accordingly, the nonlinear feedback among the BL moisture, convection, and wave dynamics at the MC cause the observed strong barrier effect on the eastward propagation of the AM MJO.

3.2. Understanding the MJO Spring Barrier in Atmospheric Model

These observations provide physical interpretations of the MJO spring barrier in terms of the frictionally coupled Kelvin-Rossby wave theory. The most likely reason for this seasonality may be the mean state in which the MJO is embedded. Accordingly, a 2.5-layer intermediate model, which incorporates both the fundamental dynamics of the frictionally coupled Kelvin-Rossby wave theory and the 3-D mean flows, is employed to support our argument. This simple atmospheric model has been successfully used in many studies on MJO dynamics (e.g., Deng et al., 2016; Liu et al., 2016; Wang & Xie, 1997).

To examine the model performance in reproducing the seasonal difference in the MC barrier effect, two control runs are carried out under the mean states of JF and AM, which are derived from the ERA5 reanalysis. The two experiments are specified with an identical initial perturbation comprising a theoretical Kelvin wave structure centered at 40°E over the equator (Figure 4a). This perturbation quickly develops into an MJO-like Kelvin-Rossby wave structure.

Figure 2. Composite spatial-temporal evolution of the Madden-Julian Oscillation during (a) January–February (JF) and (b) April–May (AM). The shaded areas represent 925-hPa moisture convergence anomalies; the contours represent outgoing longwave radiation anomalies (only negative values are plotted with a contour interval of 3 W/m²), and the vectors represent the 850-hPa wind anomalies. Only values that are statistically significant at the 95% confidence level using a Student’s t test are plotted. AC (C) in each panel denotes the center of the anticyclonic (cyclonic) circulation anomaly.
with low-level westerlies (easterlies) west (east) of the convection (Figures 4b and 4c). In JF (AM), the organized convection-circulation system moves eastward as far as 140°–160°E (100°–120°E), where a clear decoupling of the Kelvin-Rossby wave packet (characterized by the separation of precipitation branch collocated with easterlies and that collocated with westerlies) is observed. These critical longitudinal bands show agreement with the observations (Figures 1c and 1d), although the simple model produces an overestimated Kelvin wave strength. Likewise, the MJO intensity ratio between the WPO and the EIO is calculated in each model experiment to reflect the MC barrier effect. Here, the modeled MJO intensity is represented by the cumulative precipitation induced by the initial perturbation, and the accumulation during days 1–11 (3–13) is utilized for the EIO (WPO) according to the areal precipitation time series (Figure S1 in the supporting information). The calculations show that the intensity ratio in JF is approximately 1.2, which is twice larger than that in AM (approximately 0.5). This finding implies that when the MJO passes across the MC, its intensity increases (decays) by approximately 20% (50%) in JF (AM). Therefore, the above evidence suggests that the model is capable of describing the essential physics of the spring MC barrier effect.

Next, the dominant factor responsible for the seasonality in the MC barrier effect is recognized by conducting a series of sensitivity runs regarding the five prescribed background fields in the model: surface moisture ($q$), 3-D winds ($u$, $v$, and $w$), and air temperature ($T$). First, the differences in the five variables between AM
and JF are calculated, that is, q\_diff\_xy, u\_diff\_xy, v\_diff\_xy, w\_diff\_xy, and T\_diff\_xy. Then, in reference to the JF control run, we conduct five sensitivity runs (SR1–SR5; Table S2), in which one of the seasonal differences is added to the JF state, while the remaining four are kept as JF states. Therefore, by comparing the sensitivity run with the JF control run, we can estimate the importance of a certain background field in causing the barrier effect. As shown in Figure 4d, the remarkable seasonal difference in the barrier effect is primarily due to the difference in the surface moisture (SR1). In JF, rich moisture concentrates in the WPO near the northern Australia, while in AM, the high center shifts westward to the EIO (Figure S2). It is suggested that this change in the zonal distribution of mean moisture significantly influences the MC barrier effect, because the sensitivity run that considers only the zonal variation of q\_diff\_xy successfully captures the spring barrier (SR6). This finding accords with the existing knowledge that the variability of the Kelvin-Rossby wave packet is determined mainly by the low-level moisture field (e.g., Kang et al., 2013; Wang & Xie, 1997).

In fact, the MJO spring barrier is produced by the different seasonality in mean moisture between the WPO and the EIO. In the WPO, the moisture content is higher in winter and lower in summer, while in the EIO, the surface moisture exhibits a strong peak in spring (Figure S3). With the transition from JF to AM, a seasonal difference of more than 1 g/kg appears in the Indian Ocean, whereas this seasonal difference is negligible in areas east of the MC (Figure 4e). This finding probably explains why the difference in the BL moisture convergence anomalies between the two MJO events is evident in the Indian Ocean but suddenly vanishes near the MC (Figure 3). Accordingly, the abrupt reduction in the BL moisture convergence anomalies around the MC, which is primarily due to the sharp zonal gradient in the mean moisture (Figure S2c), induces the decoupling of Kelvin-Rossby wave packet and weakens the eastward propagation of the spring MJO.

4. Summary

One of the most challenging issues facing the simulation and prediction of the MJO is the complex behavior encountered in the vicinity of the MC. The MJO usually suffers from a barrier effect when passing over the MC, and notable event-to-event variability exists. Consequently, previous findings regarding the MC barrier effect are typically derived from a comparison of two distinct archetypes: MJO events that propagate across the MC and those that do not. Indeed, seasonality is one of topics that cannot be avoided when investigating the behavior of the MJO. Given that the MJO is active during both the winter and the spring seasons, distinct seasonal differences exist regarding the barrier effect, wherein the strongest (weakest) occurs in spring (winter). After passing over the MC, the MJO slightly weakens by approximately 10% in winter, while the MJO dramatically decays by more than 50% in spring.

The essential physics responsible for the spring MC barrier effect are understood from the perspective of the frictionally coupled Kelvin-Rossby wave theory based on both observations and model experiments. In spring, the abrupt reduction in the BL moisture convergence anomalies that occur at the western MC causes the separation of the Kelvin-Rossby wave packet: Kelvin waves are emitted eastward from the major convection, while the Rossby wave component rapidly decays in the Indian Ocean. In contrast, the winter MJO maintains an organized moisture-convection-circulation form that detours southward when it encounters the western MC and tends to move along the Australian monsoon trough into the WPO. An intermediate atmospheric model involving both the fundamental dynamics of the frictionally coupled Kelvin-Rossby wave theory and the mean states successfully reproduces the seasonal difference in the MC barrier effect. Sensitivity experiments further indicate that the spring barrier is determined primarily by the zonal distribution of the mean surface moisture, which is basically due to the differences in the seasonality between the two basins on both sides of the MC.

This paper provides a general description and understanding of the MJO spring barrier. More detailed examinations are needed, since the observed MJO involves complex atmosphere–ocean–land processes, which surpass the dynamic framework of the frictionally coupled Kelvin-Rossby wave theory. The improved knowledge of the spring MJOs may benefit studies of climate systems because these events play an important role in triggering the Asian summer monsoon (Li et al., 2013) and initiating the El Niño-Southern Oscillation event (Hendon et al., 2007).
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