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Key Points:
- MJO precipitation over the Maritime Continent (MC) is dominated by diurnal convection over land and nondiurnal convection over water
- Climatological diurnal land convection acts as an intrinsic barrier effect that must be overcome for the MJO to propagate through the MC
- Increased soil moisture helps reduce the diurnal amplitude of land convection and overcome the barrier effect

Supporting Information:
- Supporting Information S1

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Possible Role of the Diurnal Cycle in Land Convection in the Barrier Effect on the MJO by the Maritime Continent

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Abstract Possible effects of the diurnal cycle in land convection on propagation of the Madden–Julian Oscillation over the Indo-Pacific Maritime Continent (MC) were investigated using satellite observations. Four features distinguishable from their respective climatology are uniquely associated with MJO events that cross the MC: strong precipitation over land as their convection centers approach the MC, subsequent increased soil moisture, reduced diurnal amplitude of land convection, and the dominance of precipitation over water by nondiurnal convection as their convection centers move over the MC. These results provide observational evidence for a proposed MAritime Continent Convective diurnal Cycle mechanism in which the diurnal cycle in land convection acts as an intrinsic barrier effect on MJO propagation over the MC.

Plain Language Summary By influencing global weather and climate, the Madden-Julian Oscillation (MJO) plays a central role in intraseasonal prediction. But when it propagates over the Indo-Pacific Maritime Continent (MC), the MJO often weakens and sometimes breaks down and ceases to exist. This is known as the barrier effect of the MC. The reason for this barrier effect is not well understood. Through diagnosing satellite data of precipitation and soil moisture, this study provides observational evidence for several steps in a MAritime Continent Convective diurnal Cycle mechanism, in which the diurnal cycle in land convection acts as an intrinsic barrier effect that must be overcome for the MJO to propagate through the MC. The observations show that increased soil moisture reduces the amplitude of diurnal convection over land, allowing convective systems over water of the MC to develop and carry MJO signals through the MC.

1. Introduction

The Madden-Julian Oscillation (MJO; Madden & Julian, 1971, 1972) serves as one of the major known sources of predictability on intraseasonal time scales (Waliser et al., 2003). As it propagates from the Indian to Pacific Oceans, the MJO influences global weather and climate (Zhang, 2013). Such influences depend upon longitudinal locations of MJO convection centers relative to the midlatitude jet stream (Adames & Wallace, 2014).

When the MJO propagates over the Indo-Pacific Maritime Continent (MC), it suffers from a barrier effect: The MJO often weakens, and sometimes completely breaks down and fails to propagate through the MC (Hendon & Salby, 1994; Kerns & Chen, 2016; Kim et al., 2014; Rui & Wang, 1990; Zhang & Ling, 2017). Most numerical models exaggerate this barrier effect (Inness & Slingo, 2003; Kim et al., 2009; Seo et al., 2009), and suffer from an MJO “prediction barrier” (Fu et al., 2013; Kim et al., 2016; Wang et al., 2014; Weaver et al., 2011). In few simulations the MC enhances MJO signals (Tseng et al., 2017).

The reasons for the MC barrier effect on MJO propagation are not well understood. Proposed mechanisms for the barrier effect include reduced surface fluxes by the islands (Maloney & Sobel, 2004; Sobel et al., 2010), distorted low-level circulations by topography (Hsu & Lee, 2005; Inness & Slingo, 2006; Tan et al., 2018; Wu & Hsu, 2009), and specific large-scale patterns of moisture and circulations (DeMott et al., 2018; Feng et al., 2015; Kim et al., 2014).

The diurnal cycle is a prominent feature of the MC (Houze et al., 1981; Mori et al., 2004; Yamanaka, 2016). Connected to the MJO over the MC (Ichikawa & Yasunari, 2008; Peatman et al., 2014; Suzuki, 2009) as well as over the open ocean (Chen & Houze, 1997; Sakaeda et al., 2017; Sui & Lau, 1992; Tian et al., 2006), the diurnal cycle has been considered a possible reason for the barrier effect (Hagos et al., 2016; Majda & Yang, 2016; Neale & Slingo, 2003; Tung et al., 2014; Wang & Li, 1994; Zhang & Hendon, 1997). One possible role of the diurnal cycle in the barrier effect is through a competition between convection over land and over water of the MC. When an MJO event moves through the MC, its signal in precipitation is carried mainly by convection over water (Sobel et al., 2010; Zhang & Ling, 2017). A strong, persistent diurnal cycle in land convection may interfere with convective development over water and weaken convective signals of the MJO. Weakening of diurnal forcing over land may help overcoming this barrier effect. Propagation of the MJO over the MC is enhanced in numerical simulations when the diurnal cycle in land convection is artificially eliminated (Hagos et al., 2016; Oh et al., 2013).

We propose a MAritime Continent Convective diurnal Cycle (MAC3) mechanism, in which the following natural processes must take place to alter the diurnal cycle in land convection and allow MJO events to cross the MC (MJO-C):

1. a strong vanguard of precipitation (increased rainfall over land of the MC before an MJO convection center enters the MC (Peatman et al., 2014)),
2. increased surface soil moisture,
3. weakened surface diurnal forcing,
4. reduced diurnal cycle in land convection,
5. weakened land-sea breezes, and
6. enhanced development of mesoscale convective systems (MCSs) over water.

In the absence of these processes, MJO events would be blocked (MJO-B) by the barrier effect of the diurnal cycle. So far, the only observational evidence for this MAC3 mechanism is greater precipitation over water for MJO-C than MJO-B (Zhang & Ling, 2017), which implies but not directly validates step 6 of MAC3.

This present study seeks additional observational evidences for MAC3. Data and method are described in section 2. Results are presented in section 3. Discussions are given in section 4.

2. Data and Method

Daily precipitation (0.25° × 0.25°) from Tropical Rainfall Measuring Mission 3B42 Multisatellite Precipitation Analysis version 7 (TMPA; Huffman et al., 2007) was used to identify individual MJO-C and MJO-B events. High-resolution (0.05° × 0.05°, 30 min) precipitation from Climate Prediction Center morphing technique (CMORPH; Joyce et al., 2004) was used to quantify the diurnal cycle. The refined temporal resolution of 30 min of CMORPH allows to better capture the precipitation variations, which may be smoothed out in the 3-hourly TMPA estimates. CMORPH exhibits superior performance in representing precipitation variations of subdaily time scales for warm season applications. Over the contiguous United States, correlation of 3-hourly precipitation from radar observations with CMORPH is significantly higher than with the TMPA data set (Xie et al., 2017).

Individual MJO events were identified by tracking their eastward propagating positive precipitation anomalies along the equator based on the known observed features of the MJO. The tracking method (Ling et al., 2014; Zhang & Ling, 2017) provides longitudinal locations of convection centers, starting and ending longitudes and dates, propagation ranges in longitude, life spans, and strength in precipitation for identified individual MJO events, which are not available from MJO indices based on empirical orthogonal functions (Kiladis et al., 2014; Lafleur et al., 2015; Liu et al., 2016; Wheeler & Hendon, 2004).

During the analysis period (1998–2015), 12 MJO-C and 12 MJO-B events were identified during October–March when MJO signals are strong. At the entrance of the MC (e.g., 100°E), both types of MJO events exhibit a similar averaged speed and comparable amplitudes and zonal scales of positive anomalies in precipitation (Zhang & Ling, 2017). Their main difference emerges after their convection centers enter the MC where MJO-B vanishes, while MJO-C continues moving into the western Pacific.

Coordinated universal time (UTC) of hourly CMORPH precipitation was converted to local solar time (LST) for every 15° longitude (roughly a time zone). An 11-day running mean was applied to eliminate signals of synoptic systems. Composites of diurnal cycles for MJO-C and MJO-B were first generated at each grid, where their daily maximum and minimum precipitation were identified. The diurnal amplitude was defined as the half value of the diurnal range, namely, the difference between the daily maximum and minimum (Kikuchi & Wang, 2008).

The daily European Space Agency Climate Change Initiative volumetric soil moisture with a horizontal resolution of 0.25° × 0.25°(Dorigo et al., 2017; Gruber et al., 2017; Liu et al., 2011) was used to explore interactions between soil moisture and land precipitation. This product captures spatial and temporal variations in soil moisture, not its absolute values compared to in situ observations (Dorigo et al., 2017).

Daily zonal and vertical wind and relative humidity from the European Centre for Medium-Range Weather Forecasts-Interim reanalysis (Dee et al., 2011) were used to demonstrate differences in large-scale circulations between MJO-C and MJO-B. Its horizontal resolution is 0.75° × 0.75° and its vertical resolutions are 25 hPa between 1,000–750 and 250–100 hPa and 50 hPa between 750 and 250 hPa.

The main results from this study (Figures 2 and 3) are presented as 12-event composites for MJO-C and MJO-B. A Monte Carlo test with resampling 1,000 times was performed to identify results that are significant at the 95% confidence level.

3. Results

During October–March, the horizontal distributions of climatological mean precipitation and its amplitude of the diurnal cycle over the MC are almost identical over land, whereas they are very different over the ocean (Figures 1a and 1b). This suggests that most precipitation over lands comes from diurnal convection, but not over water.

Daily maximum in land precipitation generally occurs around midnight inland and in the afternoon near the coasts; over water, it occurs immediately after midnight near the coasts and later away from the coasts (Figure 1c). Precipitation reaches its minimum in the morning over land and at night over water (Figure 1d). These features of the diurnal cycle over the MC agree well with previous observations (Ichikawa & Yasunari, 2008; Oh et al., 2012; Peatman et al., 2014; Yang & Slingo, 2001). The climatological diurnal precipitation averaged over land of the MC reach its maximum at 1800 LST and minimum at 0900 LST. This suggests that the time for precipitation to develop over land (from its minimum to maximum) is 6 hr shorter than its decaying time (from its maximum to minimum). A harmonic analysis for the diurnal cycle in precipitation (Peatman et al., 2014; Yang & Slingo, 2001) cannot accurately capture its phase and amplitude over the MC.

In this study, we used a different approach to isolate diurnal signals. Daily mean precipitation can be divided into two components. Had there been no diurnal cycle, precipitation would have occurred randomly during a day and climatological rainfall amount would be the same at any time of the day. On the other hand, a pure diurnal cycle in precipitation can be viewed as starting from zero at a certain hour, reaching its maximum at another hour, and returning to the same hour of zero rain. In this simple view of the diurnal cycle, the observed daily minimum represents nondiurnal precipitation. Removing this part would lead to the pure diurnal cycle. Variations in diurnal phases would, however, contribute to nonzero daily minimum in the mean. This should be negligible if variations in the diurnal phase are small.

Precipitation averaged over the MC (10°S–5°N, 100°–150°E; box in Figure 1a) increases as MJO convection centers approach and move over the MC; the increase is faster for MJO-C (black solid line in Figure 2a) than for MJO-B (black dashed line). Daily mean precipitation at its peak time over the MC is stronger (by 20%) for MJO-C than MJO-B (Figure 2a).

The evolution of MJO precipitation averaged over the MC based on the CMORPH data (Figure 2a) match well with those based on the TMPA data (Zhang & Ling, 2017). As an MJO convection center approaches the MC (e.g., at 80°E), precipitation in the MC is more over land (red lines in Figure 2a) than over water (blue lines). This early increase in land precipitation before an MJO convection center enters the MC has

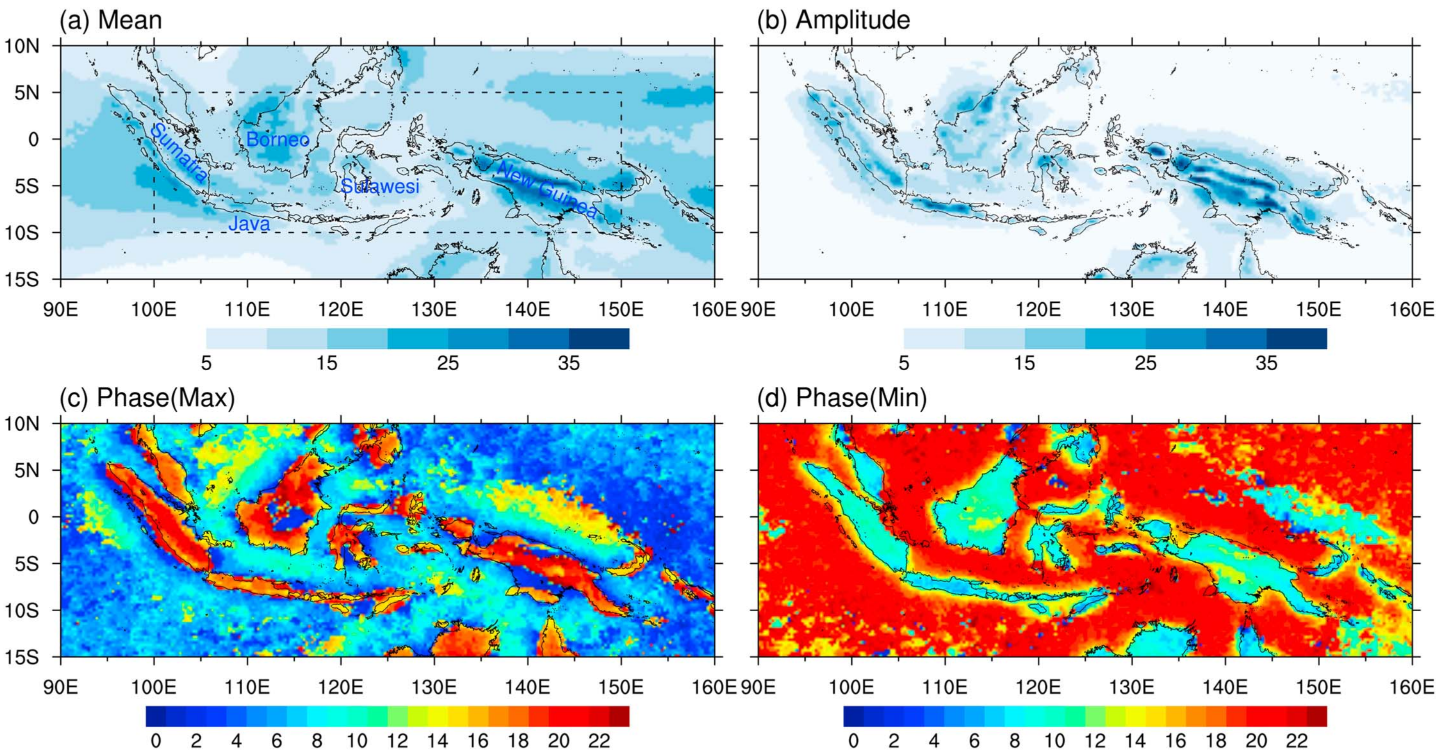

Figure 1. Climatology of the (a) mean (mm/day), (b) amplitude (mm/day), and timing (LST) for the (c) maximum and (d) minimum of the diurnal cycle in CMORPH precipitation during October–March. The names of major islands are marked in (a).

been labeled as the "vanguard of precipitation" (Peatman et al., 2014). This vanguard of precipitation is greater for MJO-C (red solid line) than MJO-B (red dashed line) for MJO convection centers west of 90°E. The evolution of land precipitation in the MC (red lines) is, however, not in phase with total precipitation (black lines). The evolution of total precipitation in the MC is dictated by that over water (blue lines). As an MJO convection center moves over the MC, precipitation over water increases (blue lines), land precipitation decreases (red lines). This is particularly evident for MJO-C (solid blue and red lines).

For MJO-C, more than 70% of the increase in precipitation over water in the MC is not related to the diurnal cycle, as measured by the ratio of the increase in daily minimum precipitation (from 3 to 11 mm/day; blue solid line in Figure 2b) to the increase in daily mean precipitation (from 11 to 22 mm/day; blue solid line in Figure 2a). The nondiurnal contribution to the increase in total precipitation is less for MJO-B (55%). Over land, nondiurnal precipitation is weak and does not vary with the MJO (red lines in Figure 2b). Nondiurnal precipitation over water mainly comes from mesoscale convective systems (MCSs), which is known to have strong two-day signals over the tropical oceans (Chen et al., 1996).

As an MJO convection center approaches the MC from the west, the vanguard of precipitation over land (red lines in Figure 2a) mainly comes from diurnal convection (red lines in Figure 2c). It is greater for MJO-C (red solid line in Figure 2c) than MJO-B (red dashed line). Once an MJO convection center is over the MC (e.g., at 140°E), the diurnal amplitude of land precipitation for MJO-C reduces by 40% and becomes weaker than that for MJO-B. The diurnal amplitudes over water are much (50–60%) weaker than those over land for both MJO-C and MJO-B (blue lines in Figure 2c), suggesting again that MJO precipitation over water is mainly from nondiurnal MCSs.

Based on the significance test, the following quantities are distinguishable at the 95% confidence level from their respective climatology only for MJO-C: the large daily mean precipitation and diurnal amplitude of land convection in the MC when MJO convection centers approach the MC and their reduced amplitude when MJO convection centers are over the MC. This implies that a strong vanguard of precipitation and a large reduction in the diurnal cycle in land convection are special features of MJO events that propagate

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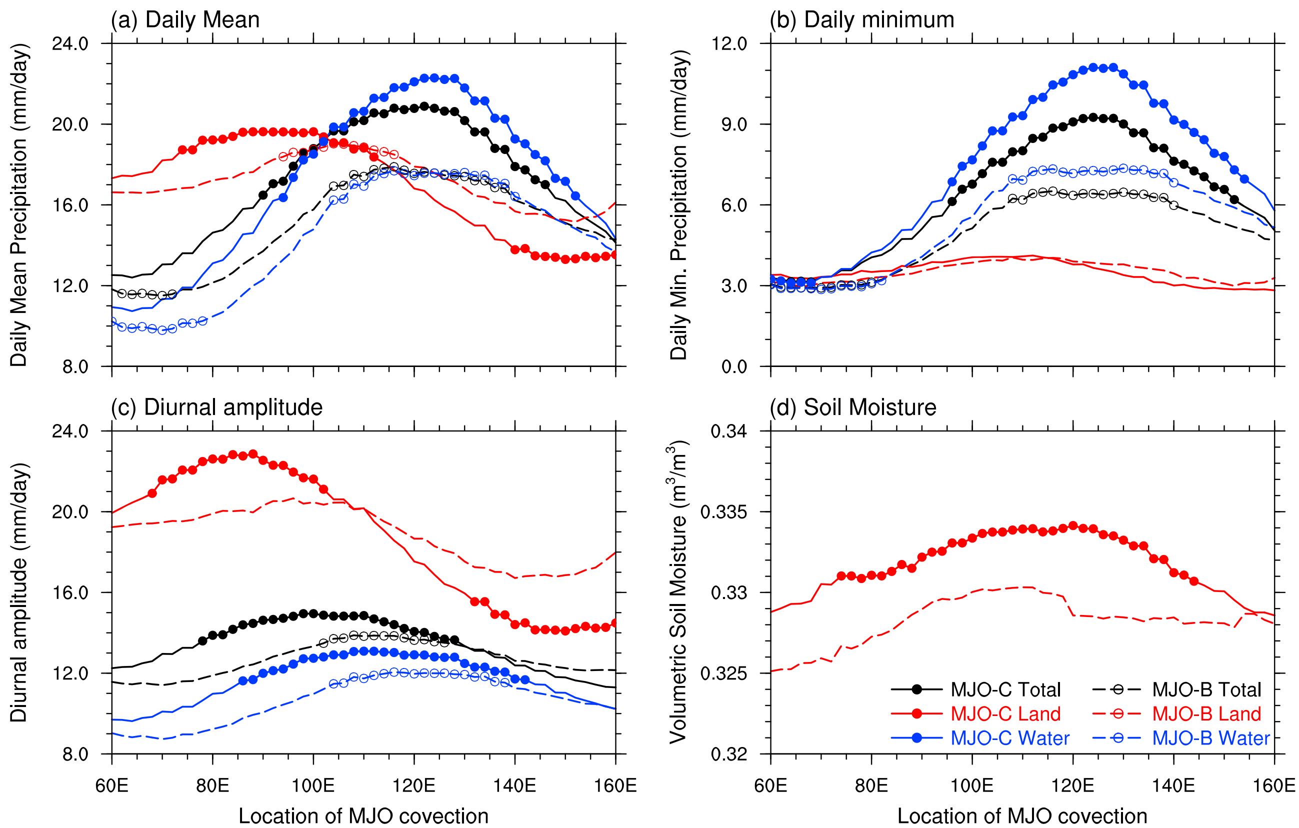

Figure 2. Evolution of (a) daily mean, (b) daily minimum, and (c) diurnal amplitude of CMORPH precipitation (mm/day) and (d) soil moisture (m^3 m^{-3}) averages over the MC (10°S–5°N, 100°–150°E) as functions of the longitudinal locations of MJO convection centers. Solid lines are for MJO-C, dashed for MJO-B. Black lines are for the entire MC, red lines over islands, and blue lines over water. Results significantly distinguishable from climatology at the 95% confidence level are marked by dots for MJO-C and circles for MJO-B.

through the MC. This implication stands even though differences in these and other quantities between MJO-C and MJO-B are not statistically significant.

As convection centers of MJO-C move over the MC, the weakening in diurnal land precipitation must be caused by a reduction in diurnal forcing. This might be caused by an increase in surface soil moisture because of the strong vanguard of precipitation (red solid line in Figure 2a). The satellite retrieval indicates that soil moisture averaged over the MC for MJO-C is significantly higher than its climatology; this is not the case for MJO-B (Figure 2d). Differences in soil moisture between MJO-C and MJO-B are not statistically significant.

The coastlines and topography of the MC determine the spatial distribution of diurnal amplitudes regardless of the condition of the MJO, namely, MJO-C versus MJO-B and longitudinal locations of their convection centers (Figures S1a–S1d). The difference in the diurnal amplitude between MJO-C and MJO-B and its dependence on longitudinal locations of MJO convection centers suggested by the MC averages (red lines in Figure 2c) can be seen over major islands, that is, Java, Borneo or Kalimantan, Sulawesi, and New Guinea (Figures S1e and S1f). But they are scattered. This plus the small sample size (12 events) might be the main reason for the differences between MJO-C and MJO-B shown in Figure 2 not passing the significance test.

4. Discussion

The barrier effect of the Indo-Pacific MC on MJO propagation may come from different factors. This study focused on the possible role of the diurnal cycle in land convection. Through diagnosing satellite retrievals of precipitation and soil moisture over the MC for MJO events that cross the MC (MJO-C) and those that are blocked by the MC (MJO-B), this study found:

Table 1
Processes of MAC3, Their Amplitudes for MJO-C Relative to Climatology, Their Amplitudes for MJO-B in Comparison to MJO-C, and Their Sources of Evidence

Steps	Processes	MJO-C	MJO-B	Evidence
1	Vanguard of precipitation	Strong	Weak	This study
2	Soil moisture	High	Low	This study
3	Surface diurnal forcing	Weak	Strong	?
4	Diurnal cycle over land	Weak	Strong	This study
5	Land-sea breezes	Weak	Strong	?
6	MCS precipitation over water	Strong	Weak	Zhang and Ling (2017) and this study[a]

[a]Indirect evidence.

1. As MJO-C events propagate over the MC, precipitation over land comes mainly from diurnal convection, while precipitation over water are mainly from nondiurnal convection. This is indirect evidence for convective signals of the MJO over the MC being carried by nondiurnal mesoscale convective systems (MCSs) over water.
2. Three other special features are distinguished from their respective climatology for MJO-C events but not for MJO-B: a strong vanguard of precipitation as their convection centers approach the MC, subsequent increased soil moisture and reduced diurnal amplitude of land convection.

These results provide observational evidence for steps 1, 2, 4, and partially for step 6 of MAC3 (Table 1). They help advance the idea that the diurnal cycle in land convection acts as an intrinsic barrier effect on MJO propagation. Meanwhile, caveats in these results should not be overlooked and remaining gaps in MAC3 need to be filled.

The vanguard of precipitation of the MJO is an outstanding feature of canonical MJO propagation through the MC (Peatman et al., 2014). It is a crucial step in MAC3. However, two fundamental issues regarding the vanguard of precipitation remain unclear: why does it exist? What makes it distinguishably stronger than climatology for MJO-C? MJO-C events tend to be mature over the central Indian Ocean, with a well-established zonal overturning circulation pattern over the equator (Figures 3a–3d). This circulation pattern includes a strong low-level easterly flow over the MC and a westward tilt structure in humidity with low-level "premoistening" (Johnson et al., 1999; Kemball-Cook & Weare, 2001; Kiladis et al., 2005; Myers & Waliser, 2003). The vanguard of precipitation appears to be associated with the low-level easterly flow and premoistening. Triggered by diurnal forcing, land convection produces the anomalously high vanguard of precipitation in place of shallow convection commonly observed to the east of MJO convection centers over the open ocean (Lau & Wu, 2003; Kikuchi & Takayabu, 2004; Del Genio et al., 2012; Barnes & Houze, 2013; Bellenger et al., 2015; Rowe & Houze, 2015; Ruppert & Johnson, 2015; Xu et al., 2015; Zermeno-Diaz et al., 2015). In contrast, MJO-B events do not establish such a well-defined zonal overturning circulation and westward title structure until their convection centers enter the MC (Figures 3e–3h). The differences between MJO-C and MJO-B shown in Figure 3 support the notions that MJO eastward propagation depends on a well-established "front Walker cell" (Chen & Wang, 2018). But the precise mechanism that links the circulation and vanguard of precipitation remains to be understood.

The meaning of surface soil moisture in step 2 of MAC3 is ambiguous in areas with heavy vegetation and canopies, which are common in the MC. Logically and conceptually straightforward, stronger precipitation would increase soil moisture, which in turn would reduce diurnal forcing at the surface (Dai et al., 1999). The exact processes involved, however, are by no means simple when surface soil is not directly exposed to the atmospheric boundary layer where turbulence leads to convection. Understanding land-atmosphere interaction on the diurnal scale in the MC region requires more sophisticated thinking and data.

Observational evidence for step 3 of MAC3 should reside in atmospheric profiles. The observed reduction in the diurnal amplitude of land convection for MJO-C suggests that this step must take place. Its direct observational evidence is still desirable. Operational twice-daily radiosonde data from the MC are insufficient for this. Satellite retrievals of temperature profiles might be useful only if they can resolve the complex land-sea distribution and the diurnal cycle.

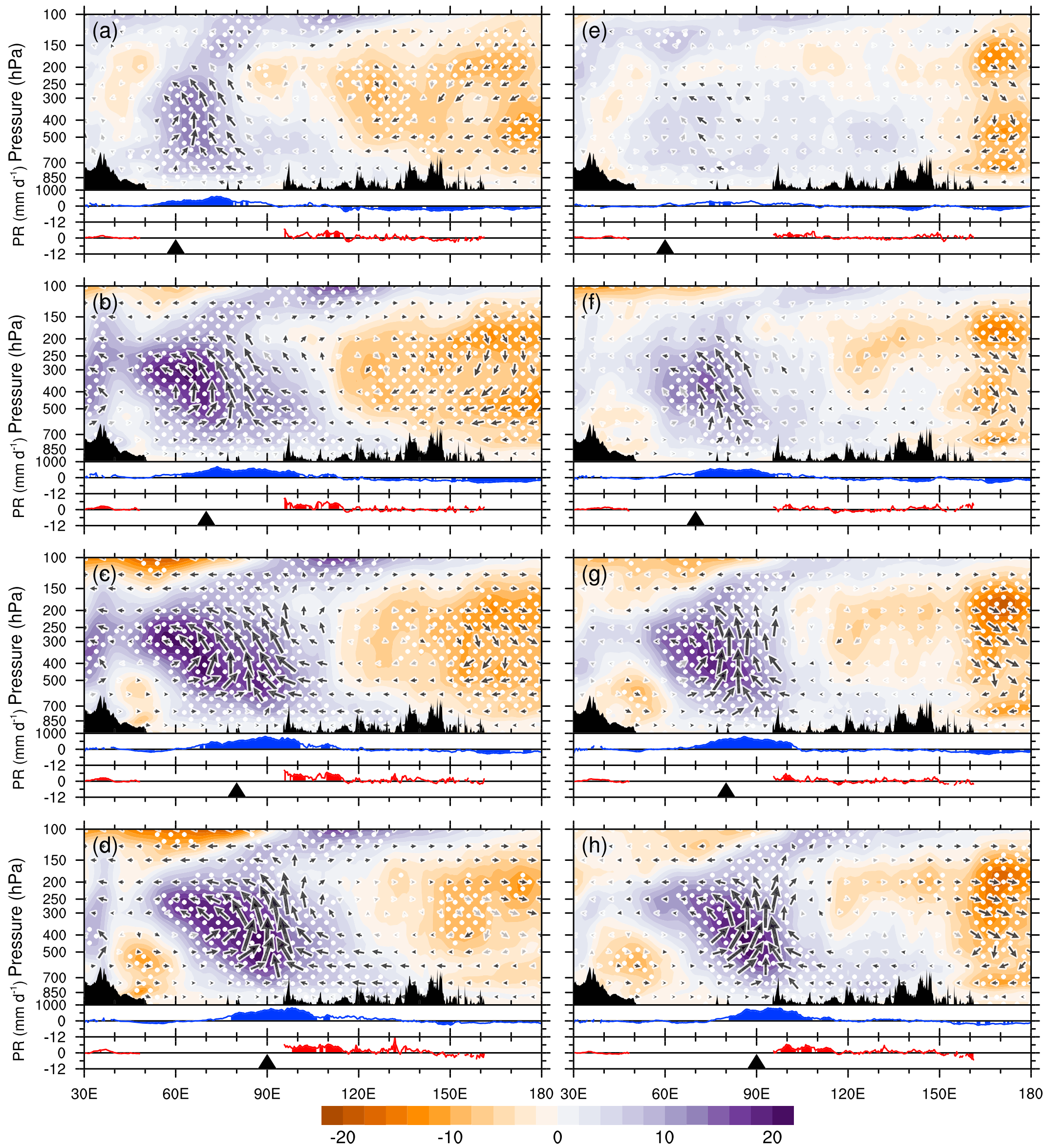

Figure 3. Composites of zonal–vertical distributions of anomalous wind vectors (u, w) overlaid with anomalous relative humidity (color, unit: %) as well as the corresponding precipitation (mm/day) over the (red curve) land and (blue curve) water, all averaged over 10°S–10°N, for (left column) MJO-C and (right) MJO-B when their convection centers are at (top to bottom) 60°, 70°, 80°, and 90°E. Results significant at the 95% confidence level are marked by black arrows for wind vectors, stipples for relative humidity, and solid color for precipitation. Black shading at the bottom of each panels indicates the averaged height of the terrain. Vertical velocities are scaled by a factor of 500 to make them visible.

Significant differences in the diurnal amplitude between MJO-C and MJO-B in step 4 of MAC3 are spatially scattered (Figures S1e and S1d). This poses an enormous challenge in validating the satellite observations against in situ observations. In addition to increased soil moisture, the observed reduction in the diurnal amplitude of land convection can be induced by other factors, such as reduced insolation due to increased cloud cover.

Observational evidence for step 5 of MAC3 is also difficult to acquire because of a lack of in situ observations and high-resolution satellite retrievals of surface wind over water of the MC. While it is known that land-sea breezes are part of the diurnal cycle (Bowman et al., 2005; Yang & Smith, 2006), the degree to which their variability may affect the development of MCSs over water is difficult to observe. High-resolution numerical models that adequately reproduce the diurnal cycle and MCSs over water of the MC can be useful tools to study this step.

The observed dominance of nondiurnal precipitation over water for MJO-C is a move forward to validate step 6 of MAC3. Complete observational evidence for this step must come from detailed information of convective structures over water, which is possible given the demonstrated capabilities of satellite observations (Houze et al., 2015).

Signals in the diurnal amplitude of land convection (step 4) and soil moisture (step 2) are significantly distinguishable from their respective climatology for MJO-C but not for MJO-B, and these signals are not significantly distinguishable between MJO-C and MJO-B. These statistics imply that if diurnal convection over land of the MC acts as a barrier effect on MJO propagation, it does so under normal conditions. In this scenario, the barrier effect of diurnal land convection is intrinsic and MJO-B events can be viewed as "normal." Only when something extraordinary (e.g., a strong vanguard of precipitation leading to reduced diurnal amplitude in land convection) happens, can an MJO event survive the barrier effect and propagate through the MC. The thinking of diurnal land convection as an intrinsic barrier effect is in line with other possible barrier effects by the fixtures of the MC, such as the presence of islands and topography. They all exist all the time and need to be overcome for the MJO to propagate through. This study presents a mechanism for overcoming the barrier effect by diurnal land convection. Mechanisms for overcoming the intrinsic barrier effects by the presence of islands and topography have yet to be investigated.

Figure 3 may lead to an impression that strong MJO events can overcome the barrier effect, whatever it is. Indeed, stronger MJO events have higher chances to survive the barrier effect than weaker ones. But all strong MJO events do not survive the barrier effect and a few weak ones do (Chen & Wang, 2018; DeMott et al., 2018; Kim et al., 2016; Zhang & Ling, 2017). Strength of the MJO alone is neither necessary nor sufficient to overcome the barrier effect. Based on the results from this study and Zhang and Ling (2017), on average, strength of the MJO over the central Indian Ocean matters more than that at the entrance of the MC to overcoming the barrier effect. This might be related to the MJO zonal circulation and suppressed convection east of its convection centers that have been suggested as a key ingredient for MJO propagation (Chen & Wang, 2018).

The thinking of diurnal land convection as an intrinsic barrier effect that must be overcome for MJO events to propagate through the MC is in contrast to an alternative thinking that MJO events normally propagates through the MC and something incidental must happen to stop them. Such incidental barrier effects may come from the large-scale conditions in sea surface temperature (Zhang & Ling, 2017; Zhu et al., 2017), background moisture distribution (Kim, 2017), and atmospheric perturbations (DeMott et al., 2018; Feng et al., 2015). An MJO event can propagate through the MC as long as no such incidental barrier effect exists at the time.

In summary, this study provides observational evidence for several steps in MAC3, in which the diurnal cycle in land convection acts as an intrinsic barrier effect that must be overcome for the MJO to propagate through the MC. To fully understand the role of the diurnal cycle in the barrier effect, in situ observations are needed not only to validate satellite observations and numerical simulations but also to discern detailed processes that cannot be credibly observed by satellites or accurately produced by numerical models. Unprecedented field observations and data from operational observing networks in the MC region are being collected by the international program Years of the Maritime Continent (https://www.jamstec.go.jp/ymc/). It is anticipated that these in situ observations may help unravel the mystery of the barrier effect.

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