Mechanisms for the Dipolar Patterns of Rainfall Variability over Large Islands in the Maritime Continent Associated with the Madden–Julian Oscillation

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ABSTRACT

Before the eastward-propagating rainy envelope of a Madden–Julian oscillation (MJO) arrives at the Maritime Continent (MC), some islands in the MC experience dipolar patterns of rainfall variability with opposite signs of rainfall anomalies in two neighboring regions within an island. Similar incoherent rainfall anomalies are also observed after the MJO passed the MC. The mechanisms for these dipolar patterns of rainfall anomalies are investigated by using observed and reanalysis data. It is found that the response of rainfall in the MC depends on the direction of wind anomalies and the availability of atmospheric moisture in different phases of the MJO. The low-level wind anomalies over the MC are easterlies in MJO phases 1–3, which cause above-normal rainfall over the mountainous areas in Java, and in western Borneo, western Sumatra, and western Malay Peninsula, respectively. In phases 5–6, the low-level wind anomalies are westerlies and the positive rainfall anomalies are over the eastern part of the islands. Two physical mechanisms are responsible for this phenomenon of the dipolar patterns of rainfall anomalies: 1) the monsoonal damping effect on rainfall over elongated narrow islands—an inverse relationship between the intensity of the diurnal cycle of sea breezes and valley breezes and the large-scale monsoonal wind speed, and 2) the wake effect on rainfall over large and wide islands—above-normal rainfall on the downwind wake side of an island or mountain range with respect to large-scale wind anomalies.

1. Introduction

The Madden–Julian oscillation (MJO) (Madden and Julian 1971, 1972; Zhang 2013; Wang et al. 2016), which is most manifested in precipitation in the equatorial section of Indian Ocean, the “Maritime Continent” (MC), and the western Pacific Ocean, has a strong impact on rainfall and wind variability in the MC at sub-seasonal time scale (Rauniyar and Walsh 2011). The MJO is composed of a pair of rainy and dry envelopes at the scale of several thousand kilometers (zonal wavenumbers 3–5 in the precipitation field), propagating eastward at a speed of about 5 m s^{-1} (or $400\text{--}500 \text{ km day}^{-1}$), and having periods of 30–80 days (Wang et al. 2016). Depending on the longitudinal location of the rainy envelope in its eastward propagation, Wheeler and Hendon (2004) developed a real-time multivariate MJO (RMM) index with eight phases. Even though the

variation of equatorial circulation field associated with the MJO is circumglobal with a zonal wavenumber-1 structure, the rainfall variation of the MJO is concentrated in the Indo-Pacific Ocean section of the tropics. It is in MJO phase 1 that above-normal rainfall is initiated in the western Indian Ocean, and in phase 2 that the rainy envelope moves to the central Indian Ocean. The maximum rainfall in the Maritime Continent corresponds to phases 3–5. In phases 6–7, the rainy envelope moves to the western Pacific Ocean, and phase 8 corresponds to its location in the central Pacific. However, besides the large-scale structure, it is observed that some land areas in the MC experience the early signal of above-normal rainfall before the main rainy envelope arrives in the MC, which was called the “vanguard” pattern of rainfall anomalies by Peatman et al. (2014). Sakaeda et al. (2017) studied satellite estimated precipitation and multilevel cloud fraction data and also noticed that the diurnal cycle amplitude in the coastal area tends to increase 5–10 days before the arrival of the main MJO rainy envelope, but the signals are weak in the interior of large islands. Similarly, there are late signals of incoherent rainfall anomalies (trailing pattern)

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FIG. 1. Terrain heights (m) over the Maritime Continent based on the U.S. Geological Survey 2-min data.

in the MC after the MJO rainy phase passed the MC, as will be shown shortly. The current study aims to understand the mechanisms for these vanguard and trailing signals of the MJO impacts in the MC from the perspective of multiscale climate processes.

Located in the deep tropics with strong solar radiation, the diurnal cycles of surface temperature, winds and rainfall over the MC are strong. The complex topography of the islands and seas in the MC also makes the variability of rainfall different among the islands. Figure 1 shows the topography of the MC, the archipelago between the Indian and Pacific Ocean. The latent heating in the MJO rainy envelope is accompanied by the Matsuno–Gill-type wind pattern (Matsuno 1966; Gill 1980). The passing of the MJO through the MC results in the change of winds corresponding to the eastward propagation of the rainfall center with the sequential progress of MJO phases 1–8. These changes of winds may either strengthen or weaken the monsoonal winds, depending on whether the MJO-caused wind anomalies are in the same direction of or opposite to the seasonal mean winds (as shown in Fig. 2). Then, the regional synoptic winds are expected to modulate the intensity of the local thermally driven diurnal cycle of land–sea breezes and mountain–valley winds and further affect the precipitation associated with the sea-breeze convergence. It seems that the mechanisms are somewhat like the El Niño–Southern Oscillation (ENSO) impacts on rainfall anomalies studied in Qian et al. (2010, 2013). We will examine if the multiscale processes responsible for the formation of the dipolar pattern of rainfall variability (i.e., opposite signs of rainfall anomalies in the neighboring regions within an island) proposed in those previous studies may also be applied to the MJO impacts on the rainfall in the MC, and be used to interpret the observed vanguard and trailing patterns of rainfall anomalies.

The spatial and temporal rainfall variability over the MC will be analyzed using observational data. The datasets used for the analysis are briefly described in section 2. Results are given in section 3, for various islands in the eight MJO phases in the boreal winter in detail, and other seasons briefly. Conclusions are drawn in section 4.

2. Datasets used

We used the historical dates corresponding to the eight MJO phases of Wheeler and Hendon (2004), obtained from the Australian Bureau of Meteorology (<http://www.bom.gov.au/climate/mjo/graphics/rmm.74toRealtime.txt>), for composite analyses. Other datasets used in this study are similar to those used in Qian et al. (2013), which are described briefly below.

The satellite estimated 3-hourly precipitation data of NOAA Climate Prediction Center (CPC) morphing technique (CMORPH; Janowiak et al. 2005; $0.25^\circ \times 0.25^\circ$; December 2002–12) are used to study the diurnal cycle of rainfall. The data cover both land and seas, and are good for analyzing coastal weather and climate, such as precipitation associated with land–sea breezes.

The daily 850-hPa winds of NCEP–DOE Reanalysis II Project 1979–2012 (NRP; Kalnay et al. 1996; Kanamitsu et al. 2002) were also used for composite analysis of winds and their anomalies for different phases of the MJO.

The seasonal averaged CMORPH precipitation and the 850 hPa NRP winds in the MC are shown in Fig. 2. The most prominent feature is the Asian–Australian monsoon: the annual migration of rainband between Southeast Asia and Australia and the associated low-level winds blowing from winter hemisphere toward summer hemisphere, that is, northeasterly winds over the South China Sea and then northwesterly winds in southeast MC in December–February (DJF), and then southeasterly winds in the southeast MC, and then southwesterly winds in the South China Sea in June–August (JJA). The second prominent feature is the concentration of rainfall over the islands in the MC, which is caused by the sea-breeze convergence (sea breezes blow from the coast toward the center of an island from noon to evening), reinforced by the valley-breeze convergence and the cumulus-merger process [the process similar to the conditional instability of the second kind (CISK)] (Qian 2008). Moisture availability and wind direction change with the seasons are the two most important factors determining the MJO impact on rainfall in this region.

The twice-daily Quick Scatterometer (QuikSCAT) sea wind data (around 10 m above ocean only, $0.25^\circ \times 0.25^\circ$, available starting from 19 June 1999 and decommissioned on 21 November 2009, with evening passes and morning passes; Liu 2002) have been used to roughly illustrate the

FIG. 2. The averaged (2003–13) CMORPH seasonal precipitation (mm day^{-1} ; shaded) and the climatology (1971–2000) of the NRP horizontal winds (m s^{-1} ; red arrows) at 850 hPa in the Maritime Continent for (a) DJF, (b) MAM, (c) JJA, and (d) SON.

land–sea breezes. The estimated sea breezes and land breezes more or less correspond to the winds in the evening pass and morning pass (minus the daily mean), respectively. Since the daily mean is estimated as $(\text{morning pass} + \text{evening pass})/2$, the sea breeze is equal to the evening pass minus the daily mean, which results in $(\text{evening pass} - \text{morning pass})/2$. It was shown that the estimated sea breezes seem reasonable over the coastal seas around Borneo (Qian et al. 2013).

3. Results

a. Incoherent rainfall variability in the MC associated with MJO

Large-scale features of the MJO have been reported in many papers (Wang et al. 2016; Moron et al. 2015; Zhang and Ling 2017; to name a few) and are briefly

described below. Figure 3 shows the composite anomalies of the CMORPH precipitation and low-level winds (at 850 hPa) of the NRP for the eight phases of MJO in the Indian Ocean–Maritime Continent–western Pacific Ocean section of the tropics in DJF. In the current study, the anomaly field for each MJO phase is defined as the composite mean in that phase [with the radius in the RMM phase diagram being larger than 1 according to Wheeler and Hendon (2004)] minus the seasonal mean. The rainfall anomaly pattern of the MJO is mostly manifested in the Indo-Pacific region, even though the perturbation of the circulation field propagated eastward along the equator circumglobally (Wang et al. 2016). The MJO rainy envelope is initiated in the western Indian Ocean in phase 1, moves to the central Indian Ocean in phase 2, arrives in the eastern Indian Ocean and western MC in phase 3, expands to the

FIG. 3. Composite anomalies of CMORPH precipitation (mm day^{-1} , shaded) and the NRP winds at 850 hPa (red arrows) in MJO phases 1–8 in DJF. Shaded (nonwhite) areas are statistically significant by the two-sided Student's t test above 95%.

eastern MC in phases 4–6, and propagates to the Pacific in phases 7 and 8 (Zhang 2013). The winds at 850 hPa show a typical Matsuno–Gill-type circulation pattern (Matthews 2000; Wang et al. 2016) with easterly and westerly winds on the east and west side of the major rainy envelope respectively and converging to the maximum rainy area.

Figure 3 also shows that the rainfall anomalies in the MC are spatially incoherent, with pockets of positive and negative anomalies located in neighboring areas, even in the early phases of the MJO—this was called the “vanguard” pattern of rainfall variability in the MC by Peatman et al. (2014). For example, rainfall anomalies are positive over Java Island but negative over the Java

Sea in phase 2; while in phases 1–3, positive and negative rainfall anomalies are found in southwestern and northeastern Borneo, respectively. There are also some late trailing patterns of incoherent rainfall anomalies over the islands in phases 5–8, after the main rainy envelope passed to the east of the MC, especially over those large islands in the central and eastern MC. These rainfall anomaly patterns are very much like the dipolar rainfall anomaly patterns found in Java (Qian et al. 2010) and Borneo (Qian et al. 2013) associated with ENSO. The Java Island dipolar pattern is the north–south contrast pattern with positive rainfall anomalies over the central and south mountainous areas versus the negative rainfall anomalies over the northern coastal plains in El Niño years (and vice versa in La Niña years) (Qian et al. 2010). The Borneo Island dipolar pattern is the east–west contrast pattern with positive rainfall anomalies over southwest part and negative rainfall anomalies in the central and northeast part of Borneo in El Niño years (and vice versa in La Niña years) (Qian et al. 2013). Therefore, it is reasonable to speculate that these dipolar patterns of rainfall variability associated with the MJO might be caused by similar mechanisms to those of the ENSO impacts discussed in Qian et al. (2010, 2013). These MJO-related mechanisms will be examined in detail for Java, Sumatra and Malay Peninsula (SMP), Borneo, and other islands, respectively, in the following subsections. Since DJF is the wet season for most areas in the MC and the rainfall anomalies associated with the MJO are expected to be large, we will first focus on the analysis of MJO impacts in this season, and then briefly check the MJO impacts in other seasons. Because the width, length and location are very different among the islands in the MC, the impact of sea breezes on rainfall over the islands are also different. Therefore, we will analyze the MJO impacts on rainfall variability for the major islands, respectively.

Because the diurnal cycle is the key factor for understanding the climate variability in the MC, the diurnal cycle of the CMORPH rainfall in the MJO phase 2 is shown by Fig. 4, as an example. In general, in the morning just after sunrise (0700–1000 LT), positive rainfall anomalies are over the seas, while negative rainfall anomalies are over the islands. In the early afternoon (1300–1600 LT), rainfall is concentrated over narrow islands such as Java, Malay Peninsula, and Sulawesi, and over the coastal land of large and wide islands such as Sumatra, Borneo and New Guinea. In the later afternoon (1600–1900 LT), maximum rainfall remains over narrow islands, and expands from coastal to inland areas of wide islands, especially over the central mountain range in New

Guinea. In the evening after sunset, maximum rainfall still occupies part of the wide islands such as central and west Sumatra and Borneo, and the north and south slope of the central mountain range of New Guinea. After midnight, the coastal rainband propagated from island offshore to the seas (such as west Sumatra or northwest Borneo), or from mountain slopes to the valleys (such as south Borneo or southwest New Guinea). Negative rainfall anomalies prevail over narrow islands from midnight to morning. Note that the timing of peak rainfall is earlier over very narrow island (such as Timor Island, shared by Indonesia and East Timor) than narrow island (such as Java), because sea-breeze fronts from the opposite coasts of the very narrow island meet earlier than those over the narrow islands. These important features of the diurnal cycle of rainfall are useful for interpreting the rainfall variability over the islands in the MC associated with the MJO.

b. MJO impacts on rainfall in Java—The monsoonal damping effect

Java Island is an elongated narrow island of about 150 km in width, so the sea breezes from the north and south coast of Java can converge at the center of the island in the afternoon to promote precipitation (Qian 2008; Qian et al. 2010). Figure 5 shows the anomalous fields of rainfall, 850-hPa winds, and sea breezes (derived from the twice daily QuikSCAT surface winds over the oceans, calculated as the evening pass minus the daily mean) over Java Island and the vicinity. In the following, I will show that the above-normal rainfall occurs over Java before the main rainy envelope arrives in the MC, and this is caused by the monsoonal damping effect—the inverse relationship between the intensity of the diurnal cycle and the magnitude of the low-level wind speed. Because the monsoonal damping effect depends on the low-level wind speed, which varies with MJO phases, the results are discussed one by one in the order of eight MJO phases.

In MJO phase 1, the precipitation anomalies over Java and the surrounding seas are all negative, except a small area of positive rainfall anomalies over the mountains near the south coast of west Java. The 850-hPa wind anomalies are easterlies, opposite to the seasonal mean northwesterly monsoonal winds as shown in Fig. 2a. The anomalies of sea breezes are away from the island (in opposite direction to the sea breezes), meaning that the sea breezes are weakened. As shown in Qian (2008) and Wang and Sobel (2017), the convergence flow toward the center of islands in the afternoon in the MC is caused by combined sea breezes and valley breezes,

FIG. 4. Diurnal cycle of CMORPH rainfall (mm day^{-1} ; the daily mean is subtracted) for MJO phase 2; LT is the local time at 105°E (Jakarta time). The 3-hourly CMORPH data are from DJFs of 2003–13.

and strengthened by latent heating over the islands–cumulus merger process (Simpson et al. 1993), which in essence is similar to the CISK. The weakening of the sea breezes in phase 1 (Fig. 5a) is due to small latent heating associated with low humidity and light rainfall over Java in this dry phase of the MJO, even though the sensible heating of solar radiation is strong. Geographically, west Java is closer to the incoming MJO from the Indian

Ocean, so it feels the impacts of the MJO earlier than eastern Indonesia. Also note that the southern part of west Java is mountainous (Qian et al. 2010). Therefore, combined sea breezes and valley breezes converge toward the mountains to produce above-normal rainfall over the southwest mountains, as shown in Fig. 5a.

When the main rainy envelope is in the central Indian Ocean, thousands of kilometers away from the MC,

FIG. 5. Composite anomalies of CMORPH precipitation (mm day^{-1} ; shaded), the NRP winds at 850 hPa (red arrows), and the QuikSCAT sea breezes (black arrows) in MJO phases 1–8 in DJF over Java Island and the vicinity. Shaded areas are statistically significant by the two-sided Student's t test above 95%.

above-normal rainfall appear over Java, as shown in Fig. 5b for the MJO phase 2. Blowing toward the main rainy envelope over the central Indian Ocean, the low-level wind anomalies are easterlies over Java. The rainfall anomalies are positive over the central and southern Java Island, especially over the mountainous areas in southwest Java, central Java, and southeast

Java; but the rainfall anomalies are slightly negative along the north coast of Java. Corresponding to the dipolar pattern of rainfall anomalies (dry north coast vs wet south coast) over Java, the anomalous sea winds of the QuikSCAT data show onshore convergence along the south coast, but offshore divergence along the north coast of the Java Island. Over the Java Sea, the rainfall

anomalies are still negative. This rainfall anomaly pattern over the Java Island mimics the dipolar pattern of rainfall anomalies in DJF associated with El Niño, as shown and interpreted in [Qian et al. \(2010\)](#). In this early phase of the MJO, the lower atmosphere over the western MC starts to moisten up ahead of the arrival of the major rainy envelope of the MJO ([Zhang 2013](#)), and the low-level winds are weakened due to opposite signs of seasonal mean winds (northwesterly in DJF; see [Fig. 2a](#)) and the MJO-related wind anomalies (easterly; [Figs. 3b](#) and [5b](#)). The weakened large-scale winds [corresponding to the quiescent weather type in [Qian et al. \(2010\)](#)] favors stronger local thermally driven diurnal cycle, therefore, the sea breezes and valley breezes are stronger, especially near the mountainous south coast of west Java, central Java and south coast of east Java. The physical process of the MJO impact discussed here is essentially the same as the monsoonal damping effect on the diurnal cycle (an inverse relationship between the synoptic wind speed and the intensity of diurnal cycle of land-sea breezes and mountain-valley winds) found in [Qian et al. \(2010\)](#). Therefore, it is confirmed that the phenomenon of the vanguard pattern of early signal of positive rainfall anomalies over Java associated with MJO is not really a vanguard of the MJO entity but is actually caused by this damping effect of large-scale winds on the local diurnal cycle over the island (i.e., the weaker large-scale winds cause the stronger diurnal cycle of sea and valley breezes; or say in the other way, the stronger large-scale winds would damp the diurnal cycle of sea and valley breezes—i.e., the monsoonal damping effect).

When the MJO propagates eastward and approaches the MC in phase 3, the low-level wind convergence at 850 hPa is over the eastern Indian Ocean off the coast of Sumatra Island, and the positive rainfall anomaly is over the eastern Indian Ocean and western MC ([Fig. 3c](#)). Note that rainfall anomalies are positive over Java Island (statistically significant, including the north coast) and only slightly positive (statistically insignificant) over the Java Sea and over the waters off the south coast of Java ([Fig. 5c](#)). Rainfall anomalies are also positive in other small islands east of Java, such as Bali (a small island next to Java) and Timor (an elongated island shared by Indonesia and East Timor) (as can be seen in [Fig. 3c](#)). The wind anomalies are still easterlies in phase 3. So the monsoonal winds over Java are weakened by the arrival of the MJO rainy envelope. Because the atmosphere becomes very humid in this rainy phase of the MJO over the western MC, it is easy to trigger convection by the sea-breeze convergence over the islands. The cumulus-merger process (or the CISK mechanism) would further enhance low-level convergence over the

islands by latent heating. Hence, the positive rainfall anomalies are even more pronounced over the islands than over the seas.

The diurnal cycles of winds and rainfall are caused by the solar radiation that reached the land surface. Therefore, the diurnal cycles of the island should become weaker in cloudy and rainy days. This is indeed observed in phase 4 ([Fig. 5d](#)) when the rainfall envelope is centered over the MC. The rainfall anomalies over the Java Sea and over the Indian Ocean off the south coast of Java are positive, but the rainfall anomalies over the Java Island become small and mixed in signs: negative in a small mountainous area in west Java, positive in some coast areas, and insignificant over most of the Java Island. The anomalies of sea breezes direct away from the Java Island, so the diurnal cycle of sea breezes is weaker than normal in this MJO phase. Even though the moisture is plentiful in this phase, the rainfall and cloudy sky in this region reduce the incident solar radiation thus suppressing the diurnal cycle of sea breezes. So the mountainous region in west Java has negative rainfall anomalies. This result is consistent with that of [Rauniyar and Walsh \(2011\)](#) and [Oh et al. \(2012\)](#) in that the diurnal cycle is suppressed over islands in the peak rainy phase of the MJO over the MC.

When the rainy envelope moves to the central and eastern MC, rainfall over Java Island and the vicinity continues to decrease in phase 5 ([Fig. 5e](#)). Rainfall anomalies are negative over almost whole Java Island, especially in the central and south areas. The rainfall anomalies over the seas in the vicinity of the Java Island are small, and slightly positive. The 850-hPa wind anomalies are westerly ([Fig. 5e](#)), in the same direction of seasonal mean winds (see [Fig. 2a](#)), acting to increase the wind speed. The sea breezes on the northwest coast are weakened, but the impact of large-scale winds on sea breezes in other coastal places is not clear. The strengthened winds may also disrupt the local thermally driven diurnal cycle of valley breezes. The reduced valley-breeze convergence toward the mountain peak may reduce the rainfall over the mountains in the Java Island (as indeed seen in [Fig. 5e](#)), according to the monsoonal damping effect on valley breezes proposed in [Qian et al. \(2010\)](#).

In phase 6, when the main rainy envelope moves to the western Pacific ([Fig. 3f](#)), the rainfall anomalies over Java Island are negative, except over the flat plains along the north coast ([Fig. 5f](#), even though statistically insignificant). The 850-hPa wind anomalies are westerly, in the same direction as the mean seasonal winds ([Fig. 2a](#)), thus enhancing the mean winds. According to [Qian et al. \(2010\)](#), the monsoonal damping effect makes the diurnal cycle weaker, and the weakened

sea-breeze (and valley-breeze) convergence over the Java Island (especially over the mountainous areas near the south coast of Java) makes the rainfall decrease over the island (especially in its southern part), as observed in Fig. 5f. In comparing phases 2 and 6 (Figs. 5b,f), it is seen that the wind anomalies are in opposite direction, and the north–south rainfall anomaly dipolar patterns are also opposite to each other between the two phases. This is very similar to the dipolar pattern of rainfall anomalies over Java associated with El Niño shown in Qian et al. (2010).

When the main rainy envelope moves farther east to the western Pacific in the South Pacific convergence zone (SPCZ) in phase 7, the whole MC becomes dry (Fig. 3g). However, the rainfall anomalies are positive along the north coast of Java (only statistically significant over the north coast of west Java), and negative in the south coast of Java (Fig. 5g). The wind anomalies are westerly, strengthening the northwesterly mean winds and disrupting the local diurnal cycle. Therefore, this is again consistent with the monsoonal damping effect on sea breezes proposed by Qian et al. (2010).

In phase 8, the major rain pocket should be farther east in the SPCZ and in the tropical rain forests in South America and Africa (Amazon and Congo rain forests, respectively), the MC should generally be drier than normal. However, the rainfall anomalies along the center and south of the Java Island is positive (only significant over the mountains in west and east Java), except along the north coast lowlands (Fig. 5h). The wind anomalies are easterlies at 850 hPa (Fig. 5h), opposite to the direction of the northwesterly seasonal mean winds (see Fig. 2a), thus the wind speed is reduced in this phase. Therefore, the monsoonal damping effect on the diurnal cycle is weakened, and the thermally driven diurnal cycle of valley winds are stronger, enhancing convergence to the mountainous areas in Java Island and producing more rainfall there, leaving a trailing mark of the MJO impact on rainfall over Java in this late phase. Once again, the monsoonal damping effect of Qian et al. (2010) can be used to interpret the late signal of rainfall anomalies over Java in phase 8.

Figure 6 shows latitude–time cross sections of the diurnal cycle of rainfall and its anomalies along the longitude of 110°E in MJO phase 2 and 6. The terrain height and the DJF seasonal mean diurnal cycle across central Java along 110°E are shown in Fig. 6e. A mountain peak with elevation about 1500 m is at 7.3°S. Different from West Java and East Java where mountains are closer to the south coast than the north coast, the mountain in Central Java is roughly over the center of the island, as seen in the cross section of Fig. 6e (green line). The diurnal cycle of rain rate reaches the maximum intensity of

25 mm day^{−1} in the afternoon (1500–1800 LT) over the mountain top, then attenuates and propagates away to the north and south coast. In MJO phase 2 (Figs. 6a,b), maximum rain rate of 40 mm day^{−1} occurs in the afternoon from 1500 to 1800 LT between 7.6° and 7.8°S over the southern slope of the mountain, where the maximum rainfall anomaly is located. The above-normal rainfall over south Java (Fig. 5b) is caused by the increase of the diurnal cycle over the south slope of the mountain. In phase 6, rainfall over the mountain top and southern slope is much reduced by over 10 mm day^{−1}. There is, however, a maximum rainfall center at the north coast and over the Java sea (with peak rain rate of 20 mm day^{−1}) at night. Therefore, when the main rainy envelope propagates to eastern MC in phase 6, rain lingers longer over the coastal Java Sea.

In summary, for Java Island, large positive rainfall anomalies occur in phase 2, from one to two phases ahead of the major rain envelope arriving in the MC. The driest phases in Java are phases 5 and 6, which are from one or two phases ahead of the large-scale dry envelope over the MC (Peatman et al. 2014). For all eight of the phases of the MJO, the vanguard and trailing signals of rainfall anomalies can be interpreted with the monsoonal damping effect on sea and valley breezes, that is, an inverse relationship between the large-scale wind speed and the intensity of the diurnal cycle of land–sea breezes and mountain–valley winds (Qian et al. 2010). The change of anomalous wind direction and moisture availability with the progress of MJO phases are the major large-scale factors, while the monsoonal damping effect and the cumulus-merger process in the converging sea- and valley-breeze fronts are the key local thermodynamic processes used to interpret the observed rainfall anomalies over Java associated with the MJO. In other words, the seemingly “vanguard” pattern of rainfall variability over Java Island is actually the opposite signs of rainfall anomalies (a north–south dipolar pattern) caused by the modulation of the local diurnal cycle by large-scale wind anomalies associated with the MJO.

c. MJO impacts on rainfall in SMP

The SMP located in the westernmost part of the MC, adjacent to the Indian Ocean, thus experiences the earliest impact from the eastward-propagating MJO from the Indian Ocean. Some MJOs terminate near Sumatra (i.e., no propagation farther east), which is the so-called barrier effect of the MC on the MJO (Zhang and Ling 2017). In boreal winter, both the MJO from west and cold surges from high latitudes of East Asia have strong impacts on the rainfall in the SMP region. But the MJO has a stronger impact on the Indian Ocean

FIG. 6. Latitude-time (diurnal cycle) diagrams of the CMORPH observed rainfall (mm day^{-1}) in DJF along 110°E for MJO phases (a) 2 and (c) 6 and (b),(d) the corresponding anomalies. (e) The DJF mean diurnal cycle of rainfall (black) and the cross section of terrain height (m; green) over Java Island along 110°E .

coastal areas than the cold surges do (Lim et al. 2017). The parallel land-sea-land topography of northern Sumatra, the Malacca Strait, and Malay Peninsula in this deep tropical region can promote a strong diurnal cycle of sea breezes (Qian 2008, 2020; Teo et al. 2011; Birch et al. 2016). There is a long and narrow mountain

range along the west coast of Sumatra. These geographical and climatological backgrounds are important for understanding the MJO variability and impact in this region.

In phase 1 (Fig. 7a), wind anomalies at 850 hPa are easterlies, the leeward side over western Sumatra garners above-normal rainfall, and correspondingly the sea

FIG. 7. As in Fig. 5, but over Sumatra, Malay Peninsula (SMP), and Borneo Islands.

breezes are stronger along the west coast of Sumatra, that is, west of the coastal mountain range, which is similar to the wake effect discussed in Qian et al. (2013) and in the next subsection. Rainfall anomalies are positive in the narrow southern part of the Malay Peninsula, especially over the western half of this region, downwind of the 850-hPa wind anomalies. The positive rainfall anomalies may also be caused by the enhanced sea-breeze convergence, especially over southwestern Malay Peninsula

(near the Kukup Island, which is off the southwestern tip of the Malay Peninsula) where the diurnal cycle is strong [see the large magnitude of the diurnal cycle shown in Figs. 3a and 3d in Birch et al. (2016)].

In phase 2, before the main rainy envelope of the MJO arrives in the MC, above-normal rainfall expands in the SMP (Fig. 7b). Negative rainfall anomalies cover a narrow coastal land along the east coast of the Malay Peninsula north of 3.5°N and a small area in the

southeastern coastal lowlands of Sumatra, connecting to the negative rainfall anomalies in the Java Sea. In the central South China Sea, rainfall anomalies are still negative. Positive rainfall anomalies are especially large over the southwestern coast of Sumatra, downwind of the 850-hPa wind anomalies. Therefore, even though the center of the major rain envelope of the MJO is still in the central Indian Ocean in phase 2 from the large-scale perspective, it seems the SMP should also be included in the eastern tip of this rainy envelope based on the observed results shown in Fig. 7b. The cause for the early signal of positive rainfall anomalies could be the enhanced sea-breeze convergence as seen from the onshore sea-breeze anomalies on the west coast of Sumatra. (Positive rainfall anomalies are also observed over western Borneo in phase 2, but this will be discussed separately in the next subsection.) The above result is consistent with Vincent and Lane (2017, 2018), who reported that convective heating peaks in MJO phases 2 and 3 in the TRMM Precipitation Radar over Sumatra.

When the main rainy envelope of the MJO has arrived in the eastern Indian Ocean and western MC in phase 3 (Fig. 7c), the whole SMP, including the surrounding South China Sea and Java Sea, is occupied by positive rainfall anomalies. Actually, the positive rainfall anomalies over the ocean, such as those over the southern South China Sea between Sumatra and Borneo, are larger than those over Sumatra. The reduced solar radiation under the cloudy sky, especially in the morning hours, in this wet MJO phase, as compared to the dry phases of the MJO in which the sky is usually clear in the morning, would reduce the intensity of the diurnal cycle, which peaks in the afternoon (Hagos et al. 2016; Birch et al. 2016). This might be the reason for less pronounced positive rainfall anomalies over Sumatra. However, some narrow parts of the islands, such as the southern Malay Peninsula (and Java as shown in section 3b), still have very large positive rainfall anomalies, indicating the enhanced sea-breeze convergence by the amplifying effect of the cumulus-merger process (Qian 2008).

In phase 4 (Fig. 7d), even though rainfall over the eastern Indian Ocean, southern South China Sea, and Java Sea is still above normal (but to a lesser extent relative to phase 3), the rainfall anomalies over Sumatra become very small, and the rainfall anomalies over Malay Peninsula become slightly negative. So the positive rainfall anomalies over land areas in the SMP come earlier, and go earlier as well, relative to those over the surrounding seas.

When the main MJO rainy envelope moves to the central-eastern MC in phase 5 (Fig. 7e), rainfall anomalies

over the SMP are negative, especially over the southern Malay Peninsula and western Sumatra. The sea breezes are weaker than normal, indicated by the offshore wind anomalies in the QuikSCAT sea winds. Phase 5 is very special in the regional rainfall anomaly map (Fig. 3e). While the rainy envelope is right over the center of the Indo-Pacific warm pool, above-normal rainfall is over the seas on both the north and south sides of the MC, with maximum intensity of positive rainfall anomalies (Fig. 3e), but the rainfall over the islands in the MC is below normal, especially over the western MC, as seen in Fig. 7e.

When the MJO rainy envelope is leaving the MC in phase 6 (Fig. 7f), rainfall anomalies in the SMP are small. There is a small area of slightly positive rainfall anomalies over northeastern Sumatra, downwind of the 850-hPa wind anomalies, which are now weak westerlies in the region.

When the main rainy envelope propagates east to the Pacific in phases 7 and 8, the SMP becomes dry. In phase 7 (Fig. 7g), rainfall anomalies are negative but very small over the Malay Peninsula. Rainfall anomalies over Sumatra are very small too. Rainfall anomalies over the seas around SMP are negative, which is expected in this dry phase of the MJO from the large-scale perspective. In phase 8 (Fig. 7h), rainfall anomalies over the seas in the SMP region are still negative, especially over the South China Sea and Java Sea. Rainfall over the eastern coast of the Malay Peninsula is below normal. Over Sumatra, rainfall anomalies are small and mixed in sign in this dry MJO phase over the MC.

In summary, positive rainfall anomalies start to show up in MJO phase 1 in the southern Malay Peninsula and Sumatra, when the MJO rainy envelope is still in the western India Ocean, far away from the MC. Most land areas of the SMP become wetter than normal in phase 2, when the MJO rainy envelope is still in the central Indian Ocean. These early signals of positive rainfall anomalies in the SMP are caused by sea-breeze convergence of low-level moisture ahead of the main MJO rainy envelope to enhance local precipitation over the islands. In phase 3, the moistening related to the cumulus-merger process may contribute to the rather large positive rainfall anomalies in narrow parts of the islands such as the southern Malay Peninsula (and the narrow island of Java as well.)

d. MJO impacts on rainfall in Borneo—The monsoonal wake effect

The eastern half of the panels in Fig. 7 is Borneo, the fifth largest island of the world, with four Kalimantan provinces of Indonesia in the south, two states of Malaysia in the north, and the country of Brunei. Borneo island is

wide. In the current study, “wide” is defined in the sense that the sea breezes from the opposite coasts of an island cannot travel far enough to meet at the center of the island, which is usually wider than about 300 km. The wake effect proposed in Qian et al. (2013) works for wide islands with a central mountain range in the tropics. The impact of the MJO on Borneo rainfall is also incoherent (Fig. 7) with a remarkable feature of opposite signs of variability between southwest Borneo and northeast Borneo in MJO phases 1–6, very similar to the regional dipolar pattern of rainfall anomalies over Borneo (between southwest Borneo and northeast Borneo) associated with ENSO that was studied in Qian et al. (2013).

In phase 1 (Fig. 7a), when the 850-hPa wind anomalies over Borneo are easterlies, positive rainfall anomalies are on the lee side (i.e., western side) of the island with respect to the wind anomalies. The rainfall anomalies in the seas around Borneo (South China Sea and Java sea) are still negative, because the major rainy envelope is still far away in the western Indian Ocean. However, the rainfall variability starts to show this east–west bipolar pattern of opposite signs of rainfall anomalies over Borneo even in this early phase of the MJO.

When the main rainy envelope is still in central Indian Ocean in the MJO phase 2 (Fig. 7b), there is a very clear dipolar pattern of rainfall anomalies over Borneo: positive rainfall anomalies over western Borneo (downwind of the 850-hPa wind anomalies), and negative rainfall anomalies over eastern Borneo. The magnitude of the positive rainfall anomalies is quite large over southwest Borneo. Note that the 850-hPa easterly wind anomalies in this region are quite strong, so the large positive rainfall anomalies are located downwind of the wind anomalies (i.e., on the lee side of the wind anomalies—the wake effect). As discussed in Qian et al. (2013) by using the daily weather types, the shielded lee side of the island (or similarly, the lee side of the central mountain range) has stronger diurnal cycle, which favors more rainfall. On the other hand, the propagation of gravity waves (Mapes et al. 2003; Wu et al. 2009) and/or horizontal advection of thunderstorm-scale precipitation are affected by large-scale wind anomalies associated with large-scale oscillations such as ENSO and MJO, which also favor more rainfall on the lee side of the island or the central mountain range (Qian et al. 2013). These are the factors responsible for the dipolar pattern of rainfall anomalies over Borneo in this early phase of the MJO. This may be seen more clearly from the diurnal cycle of rainfall across Borneo in phase 2, which will be shown shortly in Fig. 8.

In phase 3 (Fig. 7c), the 850-hPa wind anomalies are still easterly but with smaller magnitude, the rainfall anomalies over Borneo are still of a dipolar pattern:

positive in central and western Borneo, and negative in east Borneo in the North Kalimantan Province of Indonesia. Even though it looks like the MJO convective envelope “caught up” with the Borneo convection and the rainfall over the island is just a part of MJO convective phase, but actually the dipolar pattern of rainfall anomalies is a separate entity caused by the monsoonal wake effect on the diurnal cycle, similar to that in phase 2.

Wind anomalies over Borneo at 850 hPa become westerly in phase 4 (Fig. 7d), but the magnitude of the wind anomalies is very small. The rainfall anomalies become slightly negative (statistically insignificant) on the southwest coast of Borneo, and positive in the Indonesian part of central and east Borneo (East and North Kalimantan Provinces of Indonesia).

In phases 5 and 6 (Figs. 7e,f), the main rainy envelope has moved to the eastern MC and western Pacific Ocean, the wind anomalies over Borneo at 850 hPa are westerly. The pattern of rainfall anomalies is negative in western Borneo and positive in eastern Borneo. Therefore, the rainfall anomalies are still of a dipolar pattern with positive rainfall in the downwind direction of the 850-hPa wind anomalies. In phases 7 and 8 (Figs. 7g,h), the rainfall anomalies over Borneo are small with mixed signs, which is expected in these dry phases of MJO in the MC.

In summary, rainfall anomalies have dipolar patterns in phases 1–6, with positive rainfall anomalies on the lee side of the island with respect to the direction of the 850-hPa wind anomalies, which can be similarly interpreted to that in Qian et al. (2013), from the perspective of multiscale physical processes. In other words, the early signal of positive (negative) rainfall anomalies over the western (eastern) Borneo in MJO phases 1–3 is actually the dipolar pattern of rainfall anomalies corresponding to easterly low-level wind anomalies. So is the trailing signal of a dipolar pattern of dry west versus wet east Borneo in terms of rainfall anomalies in MJO phases 5 and 6 corresponding to westerly low-level wind anomalies.

To quantify the regional dipolar pattern of rainfall anomalies over Borneo, the zonal-time cross sections of rainfall and its anomalies along the latitude of 2.5°N for the MJO phases 2 and 6 are plotted in Fig. 8. The 850-hPa winds and their anomalies are plotted at the bottom of each panel. The terrain heights of the central mountain range are plotted in Fig. 8e. The mountain effect on the airflow is roughly determined by the Froude number $F_r = U/(Nh)$, where U is the mean wind speed (on the order of 1 m s^{-1} as shown in Fig. 8e), N is the Brunt–Väisälä frequency, which is about 0.02 s^{-1} , and h is the height of the mountain, which is about 2000 m here

FIG. 8. Longitude–time (diurnal cycle) diagrams of the CMORPH observed rainfall (mm day^{-1}) in DJF along 2.5°N for MJO phases (a) 2 and (c) 6 and (b), (d) the corresponding anomalies. Red arrows are 850-hPa zonal winds and their anomalies (m s^{-1}). (e) The DJF mean diurnal cycle of rainfall (black) and the cross section of terrain height (m; green) over Borneo Island along 2.5°N . Small blue marks denote the locations of coastlines.

(Fine et al. 2016). When $F_r > 1$, the flow has enough kinetic energy to rise over and pass the mountain, which usually causes lifted condensation and precipitation in the windward side of the mountain and less precipitation in the lee side of the mountain, the so-called rain shadow

effect. However, when $F_r < 1$, the airflow does not have enough momentum to be lifted over the mountain, which is usually the case in the deep tropics (tropical doldrum region with light winds). In the case of Borneo, in rough terms, $F_r = 1/(0.02 \times 2000) = 0.025$, which

supports flow blocking and the wake effect. Thus the mechanic lifting by large-scale circulation is not very important, but the thermally driven diurnal cycle of land–sea breezes and mountain–valley winds become more important, as can be seen in the diurnal cycle across the Borneo Island along the latitude of 2.5°N .

First, let us check the DJF mean shown in the bottom panel of Fig. 8, the 850-hPa winds are very light easterlies of about 1 m s^{-1} . Rainfall starts to build up around noon and reach maximum in the evening. More rainfall is over the lee side of the mountain (western side). Then the rainfall propagates from the slopes of the central mountain range toward the east and west coast, respectively. There are secondary rainfall maxima along the coasts in the morning, around 0600–0900 local time (LT), especially over the west coast.

In MJO phase 2 (Figs. 8a,b), the wind anomalies are easterly, the leeside (western side) has much more rainfall than the windward side. So there is a clear dipolar pattern of the opposite signs of rainfall anomalies in the east–west cross section over Borneo. In the MJO phases 6 (Figs. 8c,d), the wind anomalies are westerly, and the total winds are also westerly, more rain falls on the lee side (eastern side) than the windward side of the central mountain range. Hence, there is also a dipolar pattern of rainfall anomalies in phase 6, but the magnitude of the rainfall anomalies is smaller than that in phase 2. Hung and Sui (2018) also noted that advective moistening in the MC tends to be positive (negative) on leeside (windward side) of the major islands, consistent with the dipolar pattern of rainfall anomalies shown in the current study.

e. MJO impacts on rainfall in other islands in the eastern MC

MJO impacts on some other islands in the central and eastern MC, such as Sulawesi (the K-shape island east of Borneo; central Sulawesi is mountainous where rainfall is heavier than surrounding areas; Qian 2008) and New Guinea, can also be seen from Fig. 3. In general, the positive and negative rainfall anomalies are located downwind and upwind of the 850-hPa wind anomalies, respectively, similar to that over Borneo. In phases 1, 2 and 3, when the wind anomalies are easterlies, positive rainfall anomalies are in the western Sulawesi, and the west and southwest coast of New Guinea. In phase 4, wind anomalies are westerlies, positive rainfall anomalies are east of Sulawesi; but positive rainfall anomalies cover most of New Guinea when the rainy envelope of the MJO is right over the central and eastern MC. In phases 5–6, positive rainfall anomalies are over the northeast coast of New Guinea, downwind of the 850-hPa wind anomalies. In general, the MJO impact on

Sulawesi and New Guinea is very similar to that over Borneo, in that the positive rainfall anomalies are on the leeside of the island with respect to low-level wind anomalies. But because Sulawesi is smaller in size than Borneo, the positive rainfall anomalies are shifted to the waters offshore of Sulawesi. The location of positive rainfall anomalies on the wake side of islands seems to be a common feature among the large islands in the MC.

Having checked the MJO impact on rainfall in western MC in detail and eastern MC briefly in DJF, it may be concluded that the monsoonal-damping effect and wake effect proposed in Qian et al. (2010, 2013) for the ENSO impact also works here for the MJO impact. The opposite signs of rainfall anomalies in the early phases of the MJO, looking like a vanguard pattern of rainfall anomalies, actually result from the modulation of the diurnal cycle by the MJO-induced wind anomalies, as discussed above. Similarly, the trailing impact of the MJO on the MC in its late phases is just the dipolar pattern of rainfall anomalies associated with westerly wind anomalies at 850 hPa. Because of the large lower-atmospheric moisture convergence ahead of the MJO rainy envelope (Zhang 2013), the vanguard pattern looks stronger than the trailing pattern of the MJO impact in terms of the magnitude of rainfall anomalies.

f. Seasonality of the dipolar patterns of rainfall variability in the Maritime Continent associated with the MJO

The latitudinal position of the intertropical convergence zone (ITCZ) generally migrates following the sun in the annual cycle. So should the location of MJO impacts on regional rainfall in different seasons; that is, the rainfall anomalies are large where the mean seasonal rainfall is heavy. Therefore, the MJO impact is regionally and seasonally dependent (Zhang and Dong 2004; Masunaga 2007; Haertel and Boos 2017). In the following, we check the common features and differences among the MJO impacts on the rainfall in the MC in the four seasons: March–May (MAM), JJA, September–November (SON) and DJF. The timing of the seasons in any given area in Southeast Asia depends on the annual migration of the ITCZ passing by that location, the characteristics of the local topography, as well as the mean monsoonal flow in the region, therefore, the onset and demise of the seasons are location dependent. We will not discuss the delimitation of the seasons here in the current study, but still use the conventional four 3-monthly seasons DJF, MAM, JJA, and SON for convenience. We will not discuss the cause of the global features of the seasonality of the MJO itself either. Rather we will primarily focus on the response of the local climate in the MC to the MJO in its eight phases.

Nevertheless, this study may provide some general guidance for subseasonal to seasonal (S2S) climate forecasts in the MC region corresponding to the MJO phases predicted by major global climate prediction centers.

Wind direction and speed and moisture availability are among the key factors that affect the MJO impact on rainfall in the MC. Because the MC is in the deep tropics, the annual cycle of the latitudinal location of the ITCZ and the associated moisture convergence is an important factor for analyzing the MJO impact on rainfall. Moreover, since the MC is in the center of the Asian–Australian monsoon region, mean winds change direction and magnitude with the seasons. As can be seen from the DJF case analyzed above, anomalous winds blow toward the rainy envelope of the MJO (which propagates eastward with the progression of MJO phases 1–8), with the Matsuno–Gill-type flow pattern (Matsuno 1966; Gill 1980). Therefore, the combination of the MJO related wind anomalies and the seasonal mean winds may either strengthen or weaken the winds, according to whether the MJO-related wind anomalies are in the same direction of or opposite to the seasonal mean winds.

MAM is a season frequent of extremely active MJOs (Lafleur et al. 2015; Kikuchi et al. 2012). In MAM (Fig. 9), the ITCZ moves northward slightly as compared with that in DJF. The magnitudes of rainfall anomalies and wind anomalies also become slightly smaller in the tropics. The spatial pattern of the early signals of MJO impacts on rainfall variability is quite similar to that in DJF, but with some noticeable differences. The positive rainfall anomalies in the southern Malay Peninsula do not appear in phase 1, and only slightly in phases 2–5. The positive rainfall anomalies on Sumatra are on the leeward side of the islands with respect to 850-hPa wind anomalies in phase 2 (wetter on the west side). The dipolar pattern of rainfall anomalies over Borneo with positive rainfall anomalies on the wake side of the central mountain range occur in phases 1–3 (wetter on the west side) and phases 5 and 6 (wetter on the east side). In phases 3–4, when the major rainy envelope is over the eastern Indian Ocean and the MC, respectively, most of the land and seas are of positive rainfall anomalies over the region, but still see larger positive rainfall anomalies over land downwind of the 850-hPa wind anomalies than that in the upwind direction, similar to that in DJF. One exception is over Java in phase 3, which is of slightly negative rainfall anomalies, unlike the positive rainfall anomalies in DJF. The reason could be that in MAM, both the seasonal mean winds and wind anomalies are weak, so that the monsoonal damping effect by large-scale winds over Java Island is

not as strong as that in DJF, rendering the rainfall anomalies in MAM over Java under the large-scale influence of the MJO, similar to those over the seas around Java.

The mean climate of JJA is very different from that of DJF, and so is the MJO impact on rainfall in the MC (Zhang and Dong 2004). This is the season with least frequent extremely active MJOs (Lafleur et al. 2015). The maximum rainfall in JJA is north of the MC. It is the dry season in most areas in the MC. Therefore, the rainfall and wind anomalies associated with the MJO are larger in the Northern Hemisphere than in the Southern Hemisphere, as shown in Fig. 10. The MJO in JJA (and SON as well) is sometimes called the boreal summer intraseasonal oscillation, with a large variability of rainfall in the Northern Hemisphere tropics (Lawrence and Webster 2002; Kikuchi et al. 2012). The MJO impact on rainfall on Java and other islands in southern Indonesia is very small in magnitude in this dry season (but negative rainfall anomalies are still statistically significant in some MJO phases, especially in phase 6), very different from the case in DJF and MAM, indicating that the MJO impact on rainfall is strongly seasonally dependent over Java. In phases 1 and 2, the easterly wind anomalies at 850 hPa in the Northern Hemisphere in the MC are very large, and the positive rainfall anomalies are located in the downwind direction of big islands such as Borneo or the topographically complex area of the SMP. In phase 3, when the wind anomalies are weak in the western MC, the positive rainfall anomalies are over both islands and seas, without a clear dipolar pattern (in Borneo, the negative rainfall anomalies are only over the North Kalimantan State of Indonesia located in eastern Borneo). In phases 4 and 5, large positive rainfall anomalies are over the oceans in the Bay of Bengal, South China Sea and Northwest Pacific, and the wind anomalies are westerly; a small area of positive rainfall anomalies is also observed in northeast Borneo (on the lee side of the wind anomalies, not significant in phase 5). In phases 6–8, the MC is drier than normal, but the western Pacific Ocean (north of the MC) is wetter than normal. As for New Guinea, positive rainfall anomalies are also on the lee side of the 850-hPa wind anomalies, such as on the southwestern slope of the central mountain range in phases 2 and 3, and on the northeastern slope of the central mountain range in phases 5–7.

In SON (Fig. 11), the center of the ITCZ moves south but still stays in the Northern Hemisphere tropics, and the magnitude of wind anomalies is still larger in the Northern Hemisphere than in the Southern Hemisphere. In phase 1, positive rainfall anomalies are along the west and

FIG. 9. As in Fig. 3, but for MAM.

southwest coast of Borneo, on the lee side of the 850-hPa wind anomalies. Positive rainfall anomalies are along the west coast of the wide part of the Malay Peninsula (lee side of the 850-hPa wind anomalies), and over southern Thailand in the narrow part of the Malay Peninsula (statistically insignificant) and the east coast of northern Malay Peninsula (statistically significant). It may be worthwhile to also noted that significant positive rainfall anomalies are over the narrow part of the Malay

Peninsula in southern Thailand and northern Malaysia in MJO phase 2. The seasonal mean wind in the SON in this area of the Malay Peninsula is northwesterly (see Fig. 2d), therefore, the easterly wind anomalies (Figs. 11a,b) act to reduce the synoptic wind speed in the area, which helps to enhance the local sea-breeze convergence and promote rainfall in this narrow part of the Peninsula. The mechanism in action here is similar to the monsoonal damping effect discussed in section 3b for the MJO impact on Java

FIG. 10. As in Fig. 3, but for JJA.

Island and in [Qian et al. \(2010\)](#) to interpret the impact of El Niño on rainfall over Java Island. In phases 2–3, positive rainfall anomalies are also located in western Borneo, on the lee side of the central mountain range (and also on the lee side of the island) with respect to the direction of wind anomalies. In phases 4–7, positive rainfall anomalies are located in the eastern or north-eastern part of Borneo, again downwind of the 850-hPa westerly wind anomalies. The major area of positive

rainfall anomalies in phases 4–7 in SON is located in the ocean in the Northern Hemisphere, similar to that in JJA. In phase 8, positive rainfall anomalies are over the western Malay Peninsula, downwind of the 850-hPa easterly wind anomalies.

In summary, even though the rainfall anomalies in MAM, JJA and SON are not as large as those in DJF over the MC, the general patterns of the MJO impact over the islands are similar, with a dipolar pattern of

FIG. 11. As in Fig. 3, but for SON.

rainfall variability: positive (negative) rainfall anomalies located downwind (upwind) of the 850-hPa wind anomalies. For large and wide islands such as Borneo, the early signal of the “vanguard pattern” seen in the early phases of the MJO is simply the manifestation of the dipolar pattern of rainfall anomalies closely related to the direction of wind anomalies of the approaching MJO. The trailing signal of the MJO impact on rainfall in its late phases can also be interpreted accordingly by

the monsoonal damping effect on elongated narrow islands and the wake effect on large and wide islands.

4. Conclusions and discussion

The vanguard pattern of the MJO impact on rainfall in the MC, that is, the early signals of dipolar patterns of rainfall anomalies in the MC before the main rainy envelope arrives in the MC, has been studied with rainfall

and wind data over various major islands in the MC. Similarly, the trailing signal of incoherent rainfall anomalies in the MC after the convective phase of the MJO passed the MC has also been analyzed. It is found that the dipolar patterns of rainfall anomalies associated with the MJO can be interpreted by the monsoonal damping effect in narrow islands and wake effect in large and wide islands, which were discussed in [Qian et al. \(2010, 2013, respectively\)](#), as well as the advection or propagation of the local rainfall system by low-level atmospheric winds or gravity waves ([Mapes et al. 2003; Wu et al. 2009](#)). These two effects are summarized as follows. With the eastward propagation of the MJO, the wind anomalies in the MC change direction accordingly, with anomalous winds in the lower atmosphere blowing toward the main convective body of the MJO. The positive rainfall anomalies are usually found downwind of the 850 hPa wind anomalies, that is, on the lee side of a large and wide island or the central mountain range of an island, similar to the wake effect over Borneo proposed by [Qian et al. \(2013\)](#). Over an elongated narrow island, when the wind speed is reduced (with the opposite direction between the mean seasonal winds and the MJO-associated wind anomalies), the local sea breezes and valley breezes are strengthened to produce stronger sea- and valley-breeze convergence and more rainfall over the narrow islands or a narrow part of the Malay Peninsula, especially over the mountains. Vice versa, when the MJO-related wind anomalies are in the same direction as the seasonal mean winds, the monsoonal wind speed is increased to damp the local thermally driven diurnal cycle of sea breezes and valley breezes, and the weakened sea- and valley-breeze convergence in the lower atmosphere acts to reduce rainfall over narrow islands, especially over the mountains, which is consistent with the monsoonal damping effect proposed in [Qian et al. \(2010\)](#) to explain rainfall anomalies over Java associated with El Niño.

The impact of the MJO on rainfall in the MC depends on both the seasonal mean climate and the wind anomalies in each of the MJO phases. The wake effect is at work for all seasons, especially for Borneo, with positive (negative) rainfall anomalies in the downwind (upwind) direction of low-level wind anomalies associated with MJO phases. The monsoonal damping effect is only manifested in the seasons when sufficient moisture is available in the lower atmosphere, such as in DJF over Java and in SON over the northern Malay Peninsula.

[Nakazawa \(1988\)](#) noticed the multiscale precipitation system in the western Pacific with different directions of propagation for different scales. From the results of the current study, the major large-scale rainy envelope of the MJO propagates eastward, within

which the synoptic/thunderstorm-scale precipitation associated with the local diurnal cycle propagates in the direction following the lower-atmospheric winds, which are usually the easterly trade winds. However, when the low-level winds are northwesterly in the boreal winter, or in whatever direction, the downwind direction should get more rainfall. Weather forecasters pay special attention to the propagation of precipitation by the low-level winds in their operational day-to-day weather forecasts ([Cheong and Zheng 2018a](#)), while long-term climate forecasters focus on larger-scale phenomena such as MJO, ENSO and Indian Ocean dipole (IOD). To understand precipitation variability in a given location, one actually needs to consider all these multiscale processes. Low-level wind anomalies associated with large-scale teleconnection patterns (such as MJO, ENSO, and IOD) are very important for understanding the incoherent regional climate variability in the tropics. However, one needs to keep in mind that every MJO event is somewhat different, just like no ENSO events are exactly the same. Nevertheless, these kind of climate studies may provide some general guidance for regional weather and climate forecasters.

The current study indicates that the impact of the MJO on rainfall in the MC is season and location dependent. For example, the impact of the MJO on Singapore (Malay Peninsula) and Jakarta (Java Island) is different; and the impact on the western and eastern Borneo is also different. Therefore, even for a specific location, scrutiny on the MJO impact in different seasons is needed for understanding and improvement of the S2S forecasts. For Singapore as an example, [Cheong and Zheng \(2018b\)](#) studied a seasonal perspective of the MJO's impact on bimonthly rainfall and found that strong impact occurs in different convective phases of the MJO in different months. We can also imagine that the MJO impact in the wet early northeast monsoon season (late November–January) should be different from the dry late northeast monsoon season (February–early March), therefore, further scrutiny should be interesting and useful for weather and climate forecasts from daily to seasonal time scale. For mainland Southeast Asia, even though DJF is the dry season, the impact of the MJO on rainfall is significant in some phases ([Fig. 3](#)); and the impact of MJO on rainfall is stronger and significant in some areas in other seasons ([Figs. 9–11](#)). These problems are worth further investigation.

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