Propagating diurnal disturbances embedded in the Madden-Julian Oscillation

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[1] Fine structure of large-scale intraseasonal disturbance associated with the Madden-Julian Oscillation (MJO) was analyzed using the 3-hourly (3B42) TRMM rainfall data. Over the Maritime Continent, diurnal cycle becomes pronounced during the passage of MJO, and the eastward propagating diurnal disturbances (PDDs) dominate as an internal structure of large-scale convection system of MJO. Importantly, fast PDDs that penetrate through the islands are observed within the slowly propagating MJO system. This eastward penetration of PDDs through the islands result in a sudden shift of the convection center from the western part of the islands to the east, causing an overall propagation of the MJO from the Indian Ocean to the Pacific. Our results demonstrate that the diurnal cycle of convection over and around the major islands thus plays an active role in the propagation of the MJO over the Maritime Continent.
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1. Introduction

[2] The deep cumulus convection and heavy precipitation over the Maritime Continent [*Ramage*, 1968] including the Indonesian Archipelago play an essential role in the Earth's climate system through a huge latent heat release. This world convection center is subject to the intraseasonal timescale atmospheric disturbance called Madden-Julian Oscillation (MJO) [*Madden and Julian*, 1971, 1972] with a periodicity of about 30–60 days. The MJO originates in the equatorial Indian Ocean and moves eastward across the Maritime Continent into the western Pacific at about 5 m s^{-1}, accompanying deep convective activity in the eastern hemisphere. Previous studies indicates that the eastward propagation of the MJO shows a peculiar tendency over the Maritime Continent; the large-scale convection systems associated with the MJO become stationary over the islands, and exhibit a sudden shifting from the western part of the Maritime Continent to the eastern part [*Hsu and Jin*, 1990; *Weickmann and Khalsa*, 1990]. However, the detail processes of MJO propagation through the complex distributed islands has not been fully understood yet.

[3] In addition to the significant intraseasonal-timescale variability, the diurnal cycle in convection and precipitation is pronounced over the Maritime Continent that is characterized by distinct land-sea contrast. Furthermore, offshore and onshore propagation of the diurnal signal is one of the prominent features over that region [*Liberti et al.*, 2001; *Mori et al.*, 2004; *Sakurai et al.*, 2005; *Ichikawa and Yasunari*, 2006; H. Ichikawa and T. Yasunari, Intraseasonal variability in diurnal rainfall over New Guinea and the surrounding oceans during austral summer, submitted to *Journal of Climate*, 2006, hereinafter referred to as Ichikawa and Yasunari, submitted manuscript, 2006). The diurnal phase propagation is particularly significant over the major islands that vary in association with the large-scale circulation field changes, specifically associated with the low-level prevailing wind [*Ichikawa and Yasunari*, 2006; Ichikawa and Yasunari, submitted manuscript, 2006]. The pronounced diurnal cycle would be modulated by the large-scale convection associated with the MJO [e.g., *Sui and Lau*, 1992]. Recently, *Tian et al.* [2006] indicated that the significant enhancement in diurnal cycle in rainfall over the Maritime Continent during the convectively active phase of MJO. However, how the MJO propagate through the islands where the strong diurnal cycle exists has not been revealed. In this study, we investigated the fine structures associated with the diurnal variation embedded within the intraseasonal disturbances that propagated during January through February in 2001. During this particular boreal winter season, the large-scale convection was enhanced all over the Maritime Continent. Through the detailed analysis, we address the linkage between diurnal cycle and large-scale intraseasonal disturbance, and clarify the multi-scale organization in convection by the interaction process between these two.

2. Data

[4] The present study used Tropical Rainfall Measuring Mission (TRMM) 3B42 (version 6) rainfall product, containing estimated rain rate (mm h^{-1}) based on a combination of infrared radiation (IR), passive microwave, and radar data from TRMM and IR data from the geostationary satellites. The data are consecutive both temporally and spatially in the domain within the 50°S–50°N for every 3 hour, with horizontal resolution of 0.25° × 0.25°. Furthermore, in order to describe large-scale convection and circulation field, the data sets of outgoing longwave radiation (OLR) from NOAA satellite and NCEP-DOE AMIP-II reanalysis (R-2) were used, with horizontal resolution of 2.5° × 2.5° in a daily average.

3. Results

[5] An eastward propagation of large-scale anomalous convection was observed early in 2001 over the Maritime

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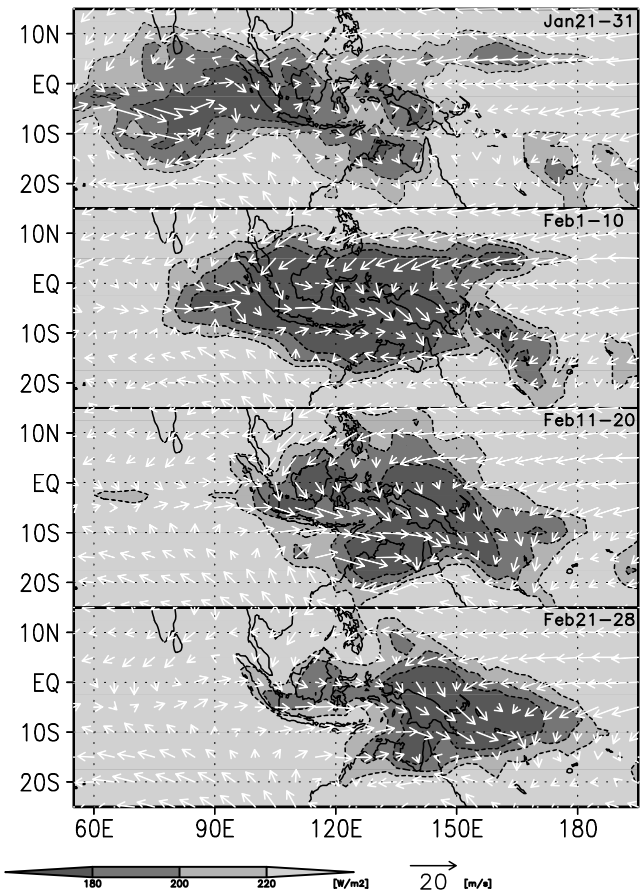

Figure 1. Time sequences of the horizontal distribution of OLR and wind at 850 hPa from late January through February, 2001.

Continent. Figure 1 shows the sequence of time-averaged OLR plots during late January to February, with daily winds at 850-hPa. As is seen in the OLR field, the center of convection was located over the Indian Ocean and extended to the western part of the Maritime Continent in late January. The large-scale convection reached the Maritime Continent on 1–10 in February, and spread over there. After February 10–20, the deeper convection propagated further eastward, and was located around New Guinea toward the Pacific Ocean on 21–28 February. In association with the enhanced convection, the anomalous westerly spread in the latitudes near the equator enclosed by the cyclonic circulation in both hemispheres (Equatorial Rossby wave pattern). In contrast to the double cyclonic circulation around the convection, the prevailing easterlies dominate at all latitude zones to the east of the convection (Kelvin wave pattern). The wind field described above is known as the 'Matsuno-Gill pattern' [*Matsuno*, 1996; *Gill*, 1980], that appears in response to the latent-heat release associated with the deep convection imposed on the Equator, and is often observed in relation to the MJO disturbance [e.g., *Madden*, 1986].

[6] In order to clarify prominent frequencies of precipitation under the large-scale convection of the MJO, the power spectrum of the TRMM merged rainfall at 6 regions near Equator were investigated during the period from January 20 to February 28 in 2001 (i.e. 320 data points were used for calculation with maximum lag number of 44 data, having a band width of 1/320 cycle per 3hours) (Figure 2, left). The time series of actual rainfall (bar), diurnal amplitude (solid line) and OLR (crossed line) were described also in Figure 2 (right). Over the Indian Ocean (Figure 2a), relatively longer time-scale (more than 5 day) variability was dominant. In contrast, it is evident that the pronounced variations in rainfall occurred with periods of about 1 day over and around the islands (Figures 2b–2f). Particularly over the islands (Figures 2c, 2d, and 2e), where strong diurnal cycle exists, the MJO low-frequency variance was greatly weakened in the spectra, and rainfall occurred continuously in the time series. Interestingly, the temporal evolution of rainfall over the islands through this active MJO period was different from island to island. Over Borneo (Figure 2c), the diurnal signal became rather amplified as the large-scale convection center reached to the island in Feb 5–15. In the case of New Guinea (Figure 2e), the diurnal cycle was prominent throughout this period while the diurnal amplitude tend to be enhanced before the MJO convection matured around the island (late January) due to the heavier diurnal rainfall over the southwestern part of the island under the lower easterly (Ichikawa and Yasunari, submitted manuscript, 2006). The diurnal cycle over the northern part of that island became strong as the MJO passed through. Over the offshore region, on the other hand, the significant signal of the MJO low-frequency variability could be observed also as well as the prominent diurnal signal (Figures 2b and 2f). This is because the occurrence of offshore rainfall was strongly related to the passage of deep convection portion of MJO, and was favored by strong diurnal cycle.

[7] In order to elucidate more detail space-time structure of MJO system, the time-longitude diagrams of 3-hourly TRMM rainfall (color contour) averaged between 4°S–1°S during the end of January through February in 2001, superimposed on the OLR (shaded) and zonal wind at 600 hPa (white contour) are shown in Figure 3. Because the diurnal cycle was the most dominant mode in rainfall variability, a high-pass filter was applied to the data in order to extract the diurnal cycle component for TRMM rainfall data. The eastward propagation of deep convection (OLR) followed by the 600-hPa level westerlies were apparent at a phase speed of about 3–4 m s^{-1}. Under the large-scale convection, the high-frequency variability in rainfall exhibited a significant eastward or westward propagation that is likely related to the background low-mid level wind. At the evolving stage of the MJO (end of January), aside from the standing oscillating rainfall over the western Indian Ocean (60°E), the westward propagating disturbances dominated to the west of the Maritime Continent (80°–120°E), intruding on the eastern Indian Ocean. These westward propagating disturbances at about 1–2 day would be associated with the previous finding [*Nakazawa*, 1988], and is presumably related to the convectively coupled inertio-gravity wave [*Takayabu*, 1994b]. Part of the westward propagating signal was triggered by each island, and is associated with the diurnal rainfall over the islands.

[8] In February, on the other hand, the eastward propagating diurnal disturbance (PDD) became pronounced over the whole Maritime Continent from the Indian Ocean to the

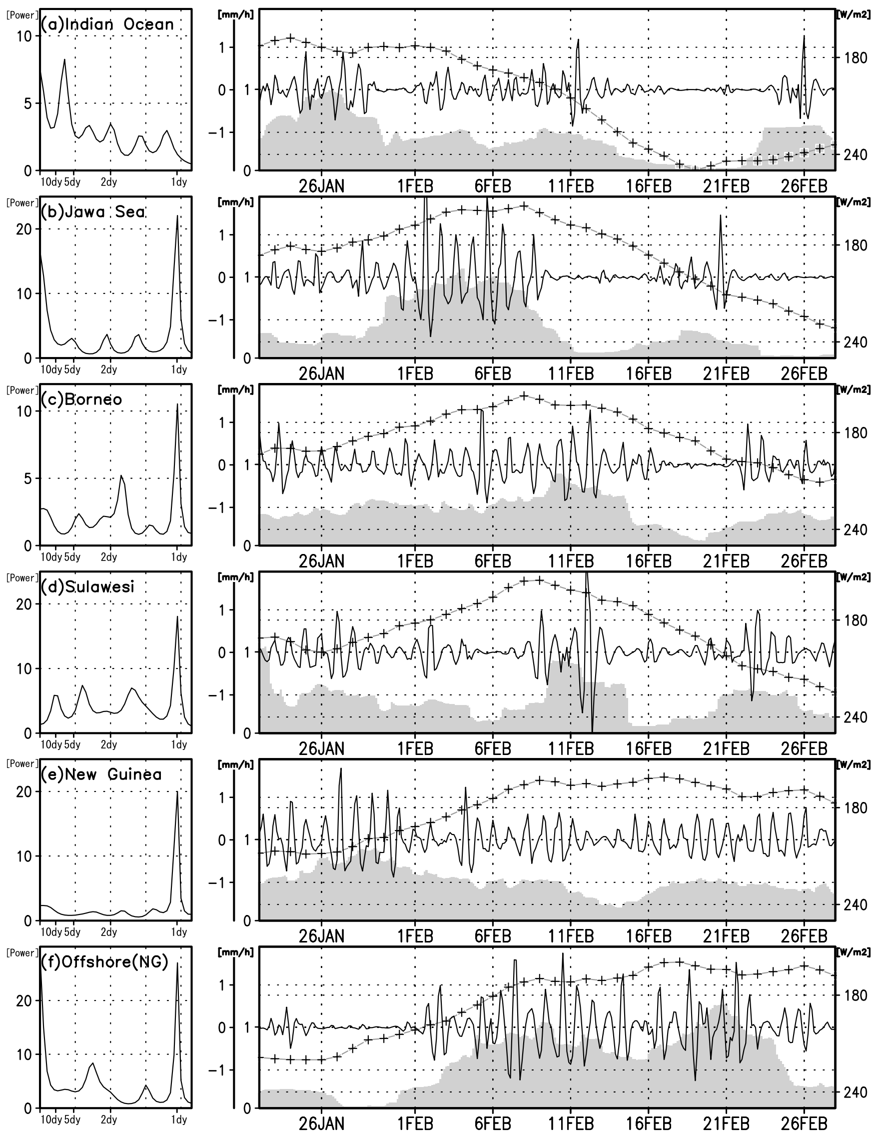

Figure 2. The power spectrum of 3-hourly TRMM rainfall from January 20 through February in 2001 by using (left) maximum entropy method and (right) time series of actual rainfall (5day running mean; bar) and diurnal cycle filtered rainfall anomaly (solid line) at 6 regions area averaged over (a) 90°E–92.5°E, 3.75°S–1.25°S, (b) 113.5°E–116°E, 6.5°S–4°S, (c) 113°E–115.5°E, 1°S–1.5°N, (d) 120°E–122.5°E, 3.75°S–1.25°S, (e) 140.5°E–143°E, 6.5°S–4°S and (f) 142.5°E–145°E, 3.75°S–1.25°S. Time series of OLR averaged over 10° × 10° grid box centered around each location are described by crossed line in the right plot also.

Pacific as the center of the large-scale convection reached the major islands and the westerlies prevailed. It should be noticed that the significant PDDs, which cut through the Maritime Continent from 100°E to 160°E, appeared during 6 to 11 February (black solid line). The inferred phase speed of the propagating disturbances was about 15–20 m s^{-1}, which were close to the 600-hPa wind speed. These eastward PDDs are likely to play an important role in the propagation of the large-scale MJO convection. In association with the penetration of PDDs through the islands, the center of rainfall activity was shifted from the western part of the Maritime Continent to the east. Associated with this, the PDDs starting from around 130°E–140°E and propagating toward the Pacific became pronounced after 16 February. On the other hand, the rainfall over the islands became rather scarce following the pervasiveness of PDDs after 10 February between the significant rainfall over the Indian Ocean and the Pacific. The other noticeable feature is that the westerly area expanded eastward incrementally over the western Pacific in association with the eastward movements of the PDDs.

[9] Figure 4 shows the composite structure of the PDDs, described by the diurnal rainfall averaged between 5–20 in February when the eastward PDDs are prominent. The PDDs appeared sequentially with the diurnal cycles in which (1) the strong diurnal signal developed in the afternoon to night (09-16UTC; 17-00LT at 125°E) over the major islands, and then (2) propagated eastward from midnight through the next day morning (16-03UTC; 00-11LT) offshore toward the neighboring islands to the east. The

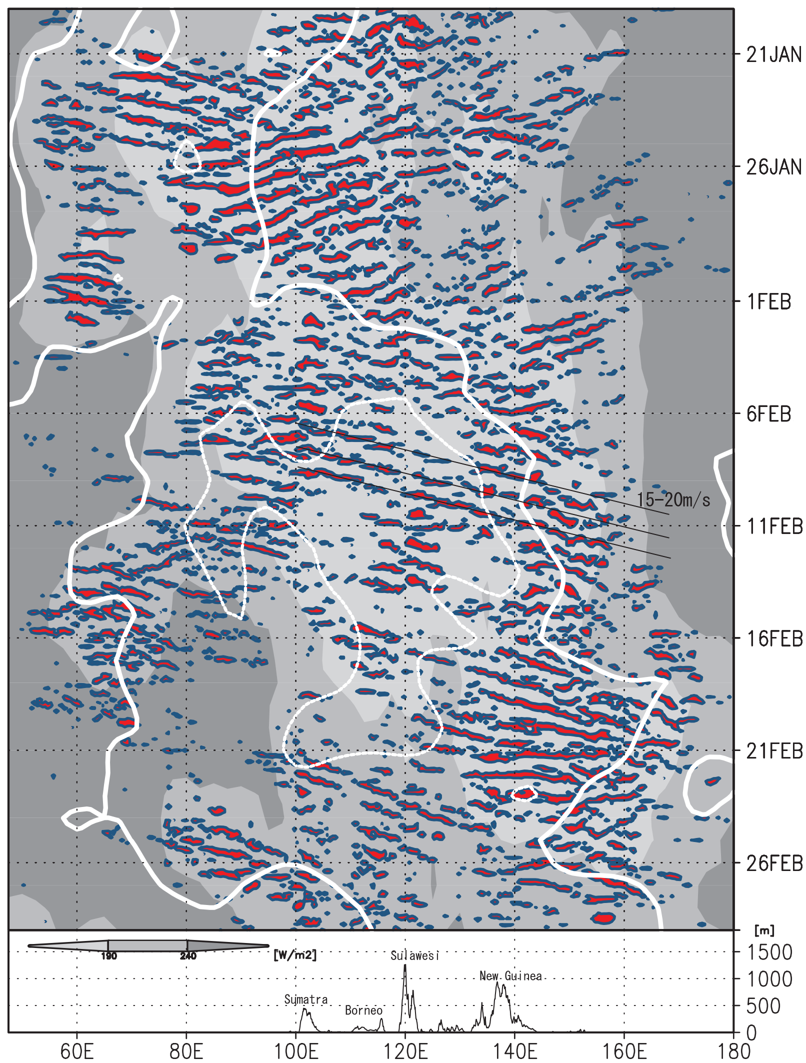

Figure 3. Time-longitude cross section of diurnal cycle filtered 3 hourly rainfall anomaly (color contour; 0.2, 0.4 mm h^{-1}) averaged between 4°S and 1°S from late of January through February, 2001. OLR (shaded) and zonal wind at 600 hPa (contour; solid-2 m s^{-1}, dashed-10 m s^{-1}) averaged between 5°S and equator are described also. The island terrain averaged between 4°S and 1°S is denoted at the bottom. Black solid line corresponds to the penetrating diurnal disturbances (see text for detail).

rainfall signals over and around the islands greatly faded out at 03-06UTC (11-14LT) as a local calm hours when the diurnal phase of rainfall shifts from sea to island areas [*Tian et al.*, 2006]. The characteristics of the developing PDDs (or diurnal rainfall) over each major island area correspond well to the previous findings [*Liberti et al.*, 2001; *Mori et al.*, 2004; *Sakurai et al.*, 2005; *Ichikawa and Yasunari*, 2006, submitted manuscript, 2006]. Over Sumatra, the northwest-southeast oriented rainfall disturbance developed along the island and propagated eastward by 12-15UTC. This PDD further progressed eastward over Jawa Sea reaching the west coast of Borneo between 18-00UTC, then gradually diminished at 03 through 06 UTC (the local calm hours). It, however, revived at 09UTC over Borneo island, which developed at local afternoon to midnight hours (09UTC to 15UTC), shifting its maximum eastward to the offshore region between Borneo and Sulawesi island. An interesting feature may be a near-synchronous evolution of rainfall over Borneo and Sulawasi but with some time lagging. The PDD over Borneo starts to develop at 09–18 UTC, whereas that over Sulawesi starts to develop at 12 to 21UTC. The PDD originating over Borneo tends to be weakened at 21 to 00 UTC, and be transferred to that over Sulawesi at 03UTC. The PDD originating over Sulawesi, once weakened at the local calm hours (03-06UTC), re-appeared over the northwestern tip of New Guinea at 09UTC, which merged with the diurnal rainfall over the central mountain range in 12-15UTC. The PDD over New Guinea gradually propagated offshore northeastward around 18UTC. The pronounced diurnal disturbance then propagated from the northern coast of New Guinea toward the western Pacific by 21UTC to 18UTC of the next day.

[10] It should be noted that the three PDD series are likely to exist as is shown in Figure 4; Sumatra series, Borneo-Sulawesi series and New Guinea series. The two pairs of the three series (i.e., Sumatra and Borneo-Sulawesi,

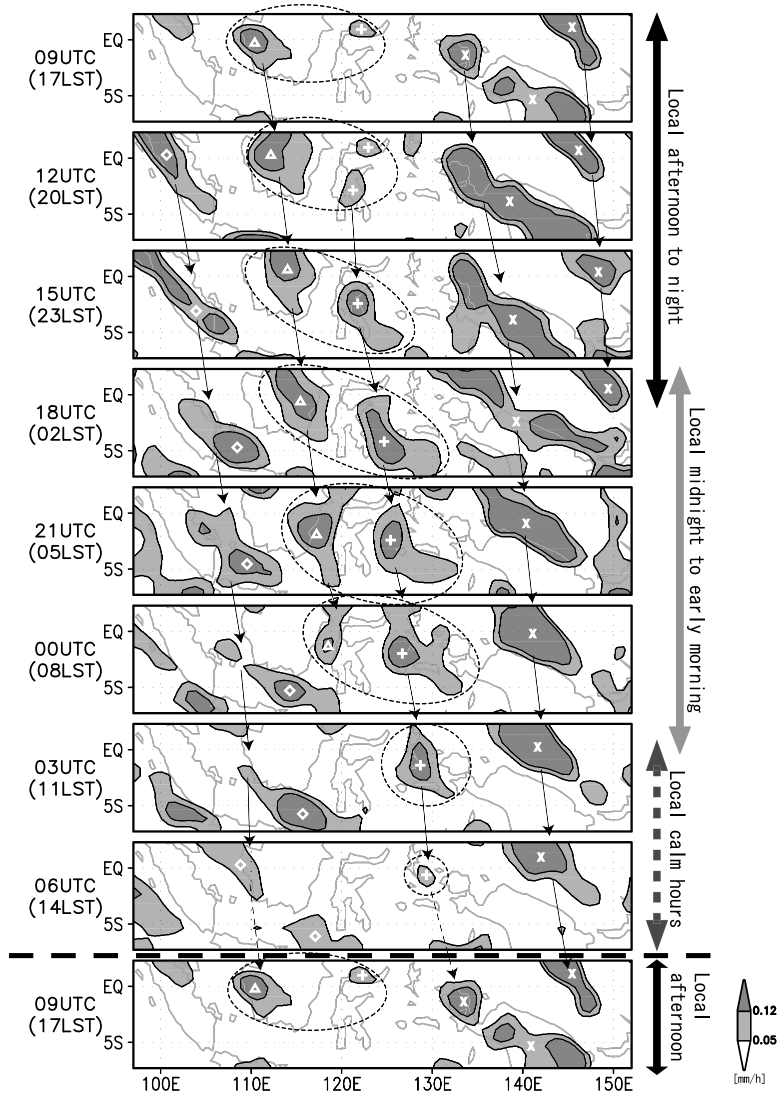

Figure 4. Spatial distribution of composite propagating diurnal disturbance described by diurnal rainfall anomaly averaged between 5–20 in February, 2001. Local standard time (LST) is at midmost longitude (125°E). The 09UTC is described at twice for both top and bottom for a reference. The rainfall disturbances are indicated by diamond (from Sumatra), triangle (from Borneo), plus (from Sulawesi), and cross (from New Guinea). Dotted circle denotes the diurnal disturbances from Borneo and Sulawesi that propagate as a packet.

and Borneo-Sulawesi and New Guinea) are connected by conveying rainfall signals in the morning (00-03UTC) eastward to rainfall signals in the afternoon (09UTC), crossing over the local calm hours. Thus, the diurnal rainfall signals appear as a long successive series of eastward propagating disturbances throughout the islands and seas in the Maritime Continent as shown in Figure 3.

4. Discussion

[11] A previous study suggested a dynamical blocking of the propagations of deep convection associated with the MJO due to the elevated orograghy over the islands, particularly over Sumatra [*Nitta et al.*, 1992]. Based on our study, the MJO disturbance, in turn, propagates through the complex orography of the Maritime Continent under the strong, highly-active diurnal cycle of convection/rainfall associated with the unique land-sea distribution. This has been supported by the recent observation of TRMM indicating the overall amplification of the diurnal cycle of rainfall over and around the Maritime Continent associated with the MJO propagation [*Tian et al.*, 2006]. The PDDs could also be identified in other cases of the MJO event during the boreal winter season (1998–2005).

[12] As shown in Figure 3, the evolution of the MJO over the Maritime Continent is characterized not by smooth propagation but by the sudden eastward shift as was also observed previously [*Hsu and Jin*, 1990; *Weickmann and Khalsa*, 1990]. Here, we note that the PDDs are likely to play a crucial role in this sudden shift of the main MJO convection system. The dynamics of these PDDs across the Maritime Continent are not clear yet, but a clue may be the advective process by the westerly wind associated with the large-scale MJO disturbances. The phase speed of the

PDDs is about 15–20 m s^{-1}, which is similar to the low-mid level (600 hPa) zonal wind speed. The long-lasting propagation of the diurnal signals for over more than a few days suggests that the atmospheric environment (e.g. moistened air) suitable for the occurrence of diurnal convection was advected by the ambient wind across the Maritime Continent. Interestingly, the significant eastward PDDs can also be observed over Indian Ocean. The pronounced appearance of PDDs over that ocean would be consistent with the results of *Tian et al.* [2006] who indicated the strong enhancement in diurnal amplitude over the Indian Ocean associated with the passage of MJO. And thus, some of the diurnal signal preferred for convection might be triggered over Indian Ocean, propagating to the islands.

[13] In addition to the advection by the background westerlies, the dynamical interaction between the diurnal cycle and the large-scale atmospheric wave trapped near equator might occur. Interestingly, as is noted by *Masunaga et al.* [2006], the timing of the PDDs (6–11 February, 2001) was consistent with a passage of the planetary-scale Kelvin wave over the Maritime Continent, suggesting that the penetration of the PDDs was triggered by the large-scale equatorial wave. Importantly, previously observed equatorial wave coupled with convection often exhibit a equivalent depth in the range of about 20–50 m [*Takayabu*, 1994a; *Wheeler and Kiladis*, 1999], corresponding to the gravity wave with phase speed of about 14–22 m s^{-1} ($\sqrt{gh}$; g: gravity acceleration, h: equivalent depth), which is similar to the phase speed of PDDs (15–20 m s^{-1}). In addition, the zonal space scale of the PDDs (of one day period) is about 20° in longitude, which would correspond to the high-frequency mode of some equatorial waves (i.e. Kelvin wave and inertio-gravity wave) in the wavenumber-frequency domain [*Takayabu*, 1994a; *Wheeler and Kiladis*, 1999]. Interestingly, this zonal scale of about 20° in longitude corresponds to the mean distance between the major islands (i.e., Sumatra, Borneo-Sulawesi, and New Guinea), which is likely to constrain the zonal scale of the PDDs. Thus, the large-scale atmospheric wave disturbance associated with the MJO might be re-organized to series of wave-packets of the PDDs through multi-scale interaction between the large-scale waves and the diurnal convection over the complex island/sea system in the Maritime Continent. Further investigation on the dynamics of this interaction is reserved for future study.

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