Modulation of Diurnal Rainfall Cycle by the Madden–Julian Oscillation Based on One-Year Continuous Observations with a Meteorological Radar in West Sumatera

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Abstract

One-year meteorological radar observations (from November 2006 to October 2007) over a region from the west coast of central Sumatera (Sumatra) through the Mentawai Strait (about 130-km width) to Siberut Island were analyzed, and modulation of rainfall diurnal cycle (DC) in the region by the Madden–Julian oscillation (MJO) was studied. The DC peaked in the afternoon over Sumatera and Siberut islands, and in the nighttime/early morning over Mentawai Strait between the islands. Over the strait, offshore (westward) migration of the DC peak was distinct when the MJO active phase was propagating eastward over the Indian Ocean, whereas the migration was indistinct after the active phase passed over Sumatera. When the MJO active phase was propagating eastward over the eastern Indian Ocean, the DC was amplified, and daily rainfall maximum tended to appear over western Sumatera including the strait. The DC peaks originating from Sumatera reached Siberut, and the DC over Siberut had an additional, stronger rainfall peak after midnight.

1. Introduction

Over the equatorial Indian Ocean, super cloud clusters associated with the Madden–Julian oscillation (MJO; Madden and Julian 1971) with a period of 30–60 d and a zonal wave number of 1 or 2 are dominant, but most become unclear when they arrive at the western edge of the Indonesian maritime continent (IMC) (Nitta et al. 1992). Over the IMC, including inland and surrounding seas, diurnal cycles (DCs) of convective cloud activity and precipitation are dominant. Their maxima are from afternoon to midnight over land, and from nighttime to early morning over sea (e.g., Nitta and Sekine 1994; Mori et al. 2004; Sakurai et al. 2005). These features, as well as the relationships between the MJO over the Indian Ocean and the DCs over the IMC, have been studied mainly based on satellite observations (e.g., Sui and Lau 1992; Murata et al. 2006; Shibagaki et al. 2006; Tian et al. 2006; Ichikawa and Yasunari 2007; Fujita et al. 2011). In western Sumatera (Sumatra), which is at the western edge of the IMC and is the place where the MJO first comes ashore, annual rainfall reaches 2,600–6,300 mm (year)\(^{-1}\) over land (Hamada et al. 2008, from surface rain gauges). This amount of rainfall over land is comparable with that over coastal seas, and a band of coastal heavy rain (CHeR) forms (e.g., Mori et al. 2004, with the Tropical Rainfall Measuring Mission (TRMM) satellite). Convective clouds with DC migrate between land and sea. Offshore (westward) migrations of the clouds can be observed in all seasons (Sakurai et al. 2011; Kawashima et al. 2011; Fudeyasu et al. 2011; Mori et al. 2011). This study uses one-year continuous radar observations for the first time, and shows the modulations of the rainfall DC for each MJO phase.

2. Observation and data analysis

In late October 2006, we installed an X-band Doppler radar (XDR; JMA-237B, Japan Radio Co., Ltd.) adjacent to Minangkabau International Airport (MIA), near Padang in western Sumatera (100.30°E, 0.79°S; Fig. 1). The installation was an activity under the Hydrometeorological Array for ISV-Monsoon Automonitoring (HARIMAU) project (Yamanaka et al. 2008). For estimating surface rainfall, this study used almost continuous radar reflectivity observations from October 28, 2006 to November 1, 2007. This period was the first year of a five-year operation of the XDR. During the period, the observations were made every 6 min in two scanning modes: (i) single-elevation scan at 0.6° with a 166-km range, and (ii) volume (multi-elevation) scan at 18 elevations from 0.6° to 50°, with a 83-km range. See Mori et al. (2011) for further information on the XDR operation.

A gridded data set of 6-min radar reflectivity was processed as pseudo-constant altitude plan position indicators, at 2 km above sea level and 0.02° (about 2 km) horizontal resolution, using both the single-elevation and volume scans. At each grid point, the
6-min reflectivity values were averaged every 30 min, if they were available four or five times. An empirical power-law relationship was derived between rainfall rate $R$ gauged at five surface stations (see Fig. 1) and radar reflectivity factor $Z$ above them for November 2006. The function $R = (Z/a)^b$ was fitted to 30-min values of $Z$ and $R$ using a nonlinear least squares method. This resulted in a coefficient $a = 6.21$ and exponent $b = 2.22$. Using this derived $Z-R$ relationship, the 30-min reflectivity values were converted into rainfall for the entire study region and period. If the number of 30-min rainfall values for one day was 44 or more, the values for that day were used in subsequent analyses. We omitted the grid points where radar reflectivity was consistently weak (i.e., the rainfall averaged over the entire study period was less than 6.5 mm d$^{-1}$). This weak reflectivity was probably due to the following three causes of spatially inhomogeneous errors: (i) rain attenuation of the XDR 3.1-cm electromagnetic radiation in a long range of 166 km; (ii) different sampling volume, height and timing at each location, because of the combined use of single-elevation and volume scans; and (iii) radar beam shielding by steep topography or obstacles such as trees and buildings.

The phase and amplitude of the MJO were determined by the all-season real-time multivariate MJO index (RMM1 and RMM2) proposed by Wheeler and Hendon (2004), and daily values of which are available at the Centre for Australian Weather and Climate Research website (http://cawcr.gov.au/staff/mwheeler/maproom/RMM/). When the “amplitude” $\equiv [(RMM1)^2 + (RMM2)^2]^{1/2} < 1$ for one day, we defined the MJO activity to be weak on that day. For all other days (amplitude $\geq 1$), the “phase” determined by RMM1 and RMM2 corresponds to the center of convective clouds distribution associated with the MJO, such as the Indian Ocean for phases 2 and 3, the IMC for phases 4 and 5, the western Pacific for phases 6 and 7, and the western hemisphere or Africa for phases 8 and 1. For the weak MJO condition and for each MJO phase, the mean daily rainfall and the composite DC of 30-min rainfall were calculated at each grid point. Because there was no correction for rain attenuation of radar reflectivity, 30-min rainfall values were normalized by the mean daily rainfall at each grid point, and only the phases of the DC and the MJO are discussed in subsequent sections.

To investigate the relation between the diurnal rainfall cycle and the distance from the west coast of Sumatera, we computed distance from the coastline to each grid point, using the Generic Mapping Tools (Wessel and Smith 1998, version 4.5.2) with the Global, Self-consistent, Hierarchical, High-resolution Shoreline data (Wessel and Smith 1996, version 2.0.2).

### 3. Diurnal rainfall cycle in weak MJO condition

The spatial distribution of local time (LT; UTC + 7 h for the study region) of diurnal rainfall peak in the weak MJO condition is shown in the center panel of Fig. 2. The west coast of Sumatera, diurnal rainfall peaks appearing at the same time are almost parallel to the coastline. This means that the diurnal peaks appear synchronously along the coastline, depending on distance from it. There is a peak around 16 LT over a broad land area, and another during 20–00 LT near the coastline. This feature can also be recognized in the center panel of Fig. 3, which shows a distance-time section of normalized 30-min rainfall in the weak MJO condition.

Previous studies using the TRMM PR data for three or seven consecutive years (without considering MJO activity) show that it tends to rain around 18 LT over land, and during 21–03 LT (Mori et al. 2004) or 18–22 LT (Wang et al. 2007) near the coastline. In the GMS data of brightness temperature (again without considering MJO activity), tall cloud tends to appear around 18 LT over land, and during 21–24 LT near the coastline (Sakurai et al. 2005). In weak MJO condition (and in all MJO phases, as discussed in Section 4), the diurnal peak over land from the ground-based XDR observations appears earlier than that from the satellite observations in the previous studies.

Over Mentawai Strait, diurnal rainfall peak appears during 00–04 LT in the eastern part, and during 04–08 LT in the western part. Over Sibetut Island, which locates about 130-km west of Sumatera, the peak appears in the early afternoon. This feature over Sibetut Island is similar to that over the western Sumatera. Previous studies based on the TRMM PR observations without the removal of the MJO effects (Mori et al. 2004; Wang et al. 2007) showed the peak around 05 LT over the strait but did not clearly show the early afternoon peak over Sibetut, which was confirmed using the XDR observations. As indicated by the rain gauge measurement of Wu et al. (2008), the four-month averaged DC of rainfall over Sibetut has two peaks, at around 02 and 14 LT. In the present XDR observations over Sibetut, the early afternoon peak...
can be confirmed. However, the peak after midnight was not recognized in the weak MJO condition, as shown in the center panels of Figs. 2 and 3.

4. Difference in diurnal cycle for each MJO phase

The afternoon rainfall peaks over Sumatera and Sibirut islands appear in all MJO phases (Fig. 2). However, over Mentawai Strait, the diurnal rainfall peak time changes from 20 to 08 LT with the MJO phase. During phases 8 and 1–3 of the MJO, the peak time is dependent on the distance from the coastline, similar to the weak MJO condition mentioned in the previous section. The peak is delayed offshore until midnight, and the delay for phase 3 is less than that for the weak condition and for phases 8, 1, and 2. During MJO phases 4–7, the peak time does not show a high dependency on the distance from the coastline.

Figure 3 shows distance-time sections of normalized 30-min rainfall for each MJO phase. The normalized rainfall was calculated as the 30-min rainfall divided by the mean daily rainfall at each grid point, and was averaged within each band-shaped area (10-km width), parallel to the coastline of Sumatera. During MJO phases 8 and 1–3, offshore (westward) migration of the DC peak was distinct. The migration in phase 3 was more distinct and more continuous. At each distance (band-shaped area) between Sumatera and Sibirut, the DC peak of the normalized rainfall has reached 5% in phase 3, and was larger than that in the other phases. This means that the DC peak migrating westward over Mentawai Strait was amplified in phase 3. For MJO phases 8 and 1–3, a linear function was fitted between the DC peak and the distance from the coastline of Sumatera over the strait (between −130 km and 0 km) using a least squares method. As a result, it was found that the peaks started to migrate from the west coast of Sumatera around 19–21 LT after sunset, and migrated offshore over the strait with a velocity of about 3–5 m s\(^{-1}\). This velocity agreed approximately with the average value of 4 m s\(^{-1}\) for November 2006 obtained by Mori et al. (2011).

During MJO phases 4–7, the offshore migration was relatively indistinct or discontinuous compared with that in other phases (Fig. 3). During phases 4 and 5, the DC peak migration seems to show a jump between land in the afternoon and sea at midnight. During phase 6, rainfall peaks appeared over the strait and migrated two times (starting from the coastline at 20 LT and 02 LT). During phase 7, the peak (> 2% in the normalized rainfall) near the coastline from around sunset (18 LT) until midnight (00 LT) migrated offshore after midnight, but did not reach Sibirut. These features are another aspect why the peak time distribution over the sea becomes complex during phases 4–7, as shown in Fig. 2.

Mori et al. (2004), Sakurai et al. (2005), and Ichikawa and Yasunari (2007) suggested eastward migrations of diurnal-cycle clouds over Sumatera and further east (over the Java (Java) Sea and other large islands), particularly when intraseasonal variations (including the MJO) were active. The XDR can observe only the western Sumatera. However, similar studies will be possible using other radars (under construction by the Indonesian government since 2009).

5. A “turning back” of MJO-enhanced rainfall peak from Sumatera to Sibirut

Over Sibirut Island, the diurnal rainfall peak appeared in the afternoon before sunset, in all MJO phases, and another rainfall peak appeared from 00 to 04 LT during phases 8 and 1–4 (Fig. 3). These two peaks were consistent with rain gauge and Global Positioning System (GPS) humidity observations (peaks around 02 and 14 LT), on Sibirut (Wu et al. 2008) and on other Mentawai islands (Fujita et al. 2011). This study proves that the nighttime peak over Sibirut during phases 8 and 1–4 originates from the peak after sunset on the west coast of Sumatera. The peak over Sumatera migrated across the Mentawai Strait overnight, and reached Sibirut a few hours before sunrise.

The maximum of the mean daily rainfall appeared on the west coast of Sumatera and over the strait in MJO phase 3, whereas in phase 4, the maximum appeared on the east coast of Sibirut (Fig. 4). The daily rainfall maximum over Sumatera in phase 3 is consistent with a result based on operational rain gauge observations at Padang (Hamada J.-I., personal communication). Despite the facts that Sibirut is to the west of Sumatera and that the MJO active phase propagates eastward, the mean daily rainfall over Sibirut tended to reach its maximum (in phase 4), several days after the maximum appeared over Sumatera (in phase 3). We call this effect the “turning back” of daily rainfall maximum, westward from Sumatera to Sibirut.

Concerning westward migrations, previous studies showed that the MJO propagating eastward over an open ocean or over large island may involve smaller-scale cloud clusters migrating westward (e.g., Nakazawa 1988; Shibagaki et al. 2006), although their horizontal scales are larger than the present case. This study shows that the DC peak migrating westward over Mentawai Strait was amplified at each distance between Sumatera and Sibirut (as discussed in Section 4) and the daily rainfall maximum tended to appear over the western Sumatera including the strait, when the MJO active phase was propagating eastward over the eastern Indian Ocean (in phase 3). These features are an aspect of the interaction between the eastward-propagating MJO over the Indian Ocean and the DC at the western edge of the IMC.

6. Summary

We used one-year continuous observations from a ground-based meteorological radar in western Sumatera for the first time, and analyzed the modulations of the rainfall DC caused by the MJO. The DC peaked in the afternoon over Sumatera and Sibirut islands, and in the nighttime/early morning over the Mentawai Strait between the islands. Over the strait, offshore (westward) migration of the DC peak was distinct when the MJO was propagating eastward over the Indian Ocean, but was indistinct after the MJO passed over Sumatera. When the MJO was propagating eastward over the eastern Indian Ocean (just before arriving at the western edge of the IMC), the DC was amplified, and daily rainfall maximum tended to appear over western Sumatera including the strait. When the MJO was propagating eastward over the Indian Ocean and arrived over the IMC, the DC peak originating from Sumatera reached Sibirut, and the DC over Sibirut had two peaks in the afternoon and after midnight. The additional peak after midnight was stronger than the original afternoon peak. Through such interactions with DC, the MJO may produce much greater rainfall over coastal areas of the western IMC than over the open Indian Ocean.
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