Why Torrential Rain Occurs on the Western Coast of Sumatra Island at the Leading Edge of the MJO Westerly Wind Bursts

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Abstract

This study examined the impact of an active phase of the Madden–Julian Oscillation (MJO) on a torrential rain event that occurred on the western coast of Sumatra Island on 12 December 2015, using surface meteorological observations, meteorological radar observations, and balloon sounding data obtained from the pre-Years of the Maritime Continent field campaign. Strong MJO activity took place in mid-December 2015 into January 2016. Radar observations revealed that a convergence and convective cloud merger of mesoscale convective systems from an eastward propagating MJO and westward moving diurnal convection over the western coast of the island was the immediate cause of the torrential rain. An investigation of the occurrence of convection over the island showed that both westward moving diurnal convection from the mountains and eastward propagating convection from the Indian Ocean occurred on 12 December, because the westerly winds in the lower troposphere associated with the MJO were only just initiated and were weak on the day. The results suggest that the leading edge of the MJO westerly wind bursts provided favorable conditions for an active phase of the MJO to work with the westward moving diurnal convection and cause torrential rain on the western coast of Sumatra Island.

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1. Introduction

An extreme precipitation event occurred over Bengkulu on the western coast of Sumatra Island (Fig. 1) during the pre-Years of the Maritime Continent (pre-YMC) field campaign in December 2015. Daily rainfall of 144.6 mm, including over 100 mm of rain within a one hour period, was observed at Bengkulu Meteorological Observatory on 12 December (Fig. 2). Based on the historical data record of Bengkulu station, this was the largest daily rainfall at Bengkulu in December in 21 years.

Convective activity over Sumatra Island is generally active, with a distinct diurnal cycle on and around the island. Convection with heavy rain occurs frequently over the island in the afternoon, and over the sea off the western coast of the island at night, similar to patterns being observed throughout the tropics (e.g., Wu et al. 2003, 2008, 2009; Mori et al. 2004; Sakurai et al. 2005; Hara et al. 2009).

The Madden–Julian Oscillation (MJO) (Madden and Julian, 1994), or intraseasonal oscillation, is the largest element of 30- to 90-day intraseasonal variability in the tropical atmosphere. It is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall, with the westerly wind bursts that mainly occur between the Indian Ocean and Pacific Ocean. The MJO significantly affects weather in the global tropics and subtropics, particularly in the Maritime Continent and in western and central Pacific tropical regions.

Tangang et al. (2008) examined the role of an active phase of the MJO in the occurrence of the extreme 2006/2007 flood event in southern Malaysia Peninsula. Their results suggested that strong westerly winds over the north of Java Island caused by an active phase of the MJO can strengthen the cross-equatorial monsoonal flow, which has a strong influence on the formation of extreme heavy rain. Wu et al. (2013) investigated the effects of an active phase of the MJO on an extreme precipitation event that occurred in Jakarta during the middle of January 2013. Their re-
results showed that strong to moderate westerly winds in the lower troposphere caused by an active phase of the MJO, in conjunction with the trans-equatorial monsoonal flow, produced an intensive wind convergence at low levels near western Java Island, providing favorable conditions for heavy precipitation.

Sumatra Island is located in the equatorial region, with the west of the island facing the Indian Ocean. The MJO has a strong influence on precipitation on the island and the surroundings (e.g., Kamimera et al. 2012; Peatman et al. 2014; Birch et al. 2016). However, because field observation data are often unavailable on the island, especially the high temporal resolution data that is used to analyze the diurnal cycle of convection, exactly how the MJO influences extreme precipitation events over the island is not well understood. Therefore, the aims of the present study were to identify the factors that brought about the 12 December 2015 torrential rain event on the western coast of Sumatra Island, focusing on the effects of an active phase of the MJO.

2. Observations and data

We performed an intensive observation as part of the pre-YMC field campaign on the western coast of Sumatra Island during November to December 2015 (Fig. 1). Land-based observations at Bengkulu on the western coast, and ship-based observations over the sea 50 km off the western coast of the island were conducted simultaneously.

Surface meteorological observations and balloon soundings at intervals of 3 hours were performed at Bengkulu Meteorological Observatory for 47 successive days from 9 November to 25 December 2015. The present study employed data on rainfall and upper winds obtained from the observations.

Meteorological radar observations were conducted continuously at Bengkulu Meteorological Observatory using a C-band Doppler radar (CDR), which was operated by the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG), to obtain volume scan data at 10-min intervals with a ray and gate spacing of 1° and 250 m, respectively, at 17 elevation angles ranging from 0.5 to 40°, within a 120-km range. The reflectivity data from the Constant Altitude Plan Position Indicator (CAPP) were generated by Rainbow 5 software (Selex 2010). Stationary ship observations by a dual-polarized CDR onboard the Research Vessel Mirai were conducted at a fixed point 4°04’00”S, 101°54’00”E from 23 November to 17 December 2015. Details of the ship-based radar observations can be found in the MIRAI MR15-04 Cruise report, which are available at http://www.godac.jamstec.go.jp/catalog/data/doc_catalog/media/MR15-04_all.pdf.

To assess the relative position and strength of the MJO, an all-season, real-time multivariate MJO index was used (Wheeler and Hendon 2004; see http://www.bom.gov.au/climate/mjo/).

3. Development and eastward propagation of an active phase of the MJO in December 2015

During early December 2015, enhanced convection developed over the central Indian Ocean, while suppressed convection persisted over the Maritime Continent due to the strong 2015–2016 El Niño event. Then, in mid-December, the MJO signal overcame the El Niño-Southern Oscillation background state over the Maritime Continent, the enhanced convection developed and shifted east across the Maritime Continent and the west-central Pacific.

The MJO index had an amplitude near 1.0, with a phase of 4 (the enhanced convective phase centered on the Maritime Continent) continuing during 6 to 9 December 2015 (Fig. 3). There was an increase in the MJO amplitude from 10 to 12 December. However, the position of the MJO showed little eastward propagation. Subsequently, in the 4 days from 13 to 16 December the MJO amplitude increased from 1.5 to 2.3, with an eastward propagation over the western Maritime Continent. The MJO index continued to have an amplitude greater than 2.1, with a phase of 4 or 5 (the enhanced convective phase was centered on the Maritime Continent), for 8 days during 15 to 22 December, indicating a steady eastward propagation of the robust MJO signal. Thereafter, in late December 2015 into early January 2016, the MJO index continued to have a strong amplitude (2.1–2.8), and propagated smoothly across the western and central Pacific.

The profiles of horizontal wind vs. time from the sounding data for the period of 10–25 December 2015 (Fig. 4) showed that above the 200-hPa (~12 km) level, easterly winds prevailed throughout the period. It was observed that a change from easterly to westerly wind occurred in the lower troposphere from 11 to 12 December. A westerly began near the surface and extended gradually to the upper layers, with weak meridional winds over the two days. On 12 December, when torrential rain occurred over Bengkulu on the western coast of Sumatra Island, winds in the troposphere lower than 150 hPa (~14 km) were weak, with a weak westerly in the lower troposphere and a weak easterly in the upper troposphere. Subsequently, during 13–22 December, strong westerly winds (i.e., westerly wind bursts) were observed near the surface up to 400 hPa (~8 km), with the maximum wind speed occurring in the 900–600-hPa layer (> 10 m s⁻¹), which is consistent with the passage of the strong active phase of the MJO.

Summarizing the results of this section, strong MJO activity took place in mid-December 2015 into January 2016. During 11 to 12 December, a change from easterly to westerly wind in the lower troposphere occurred on the western coast of Sumatra Island. Therefore, the 12 December 2015 torrential rain event over the western coast of the island occurred at the leading edge of a westerly wind burst of an active phase of the MJO.

4. Convergence of convective systems from the MJO and diurnal convection over the western coast of Sumatra Island

The reflectivity from the Constant Altitude Plan Position Indicator (CAPP) at 2.0 km altitude, obtained from the Bengkulu CDR radar for 12 December 2015 is shown in Fig. 5. The results indicated that convection was initiated near noon over the mountainous areas of the island (Fig. 5, 12:03 LT), as usual. About 2 hours later, at 14:33 LT the radar images show that the convection consolidated into two cloud lines: one between 50 to 120 km to
the north of the radar observation site and extending for about 100 km, and the other to the southeast, both orientated northwest-southeast along the slope of the mountains (Fig. 5, 14:33 LT). In the subsequent 3–4 hours, the intensity of the radar reflectivity increased as the storm lines developed further, with a southwestward migration (not shown). This is a typical pattern of the diurnal cycle of convection over the island (e.g., Mori et al. 2004; Sakurai et al. 2005).

Meanwhile, convection associated with an active phase of the MJO developed over the eastern Indian Ocean. At 14:33 LT, the radar observations revealed that convection appeared over the ocean to the southwest of the radar site. The area of storms consisted of a field of many relatively small convective lines, with an eastward movement.

As the two mesoscale convective systems (MCSs) continued to move in the opposite direction both moved toward the western
coast of Sumatra Island at the same time in the afternoon. Finally, at about 17:30 LT, the convective clouds merged together near Bengkulu on the western coast. A new storm was then initiated in the area between the two existing convective systems, approximately 5 km directly east of the radar observation site. By 18:03 LT, the new storm was rapidly increasing in its intensity and areal extent. Rainfall of 102.4 mm was measured at the station within the hour of 18:10 to 19:10 LT.

The approach or collision of downdraft-induced gust fronts from adjacent cumulus clouds is the primary mechanism of cloud merger (Simpson et al. 1980). A sudden northwesterly gust (with a surface wind speed of 6 m s\(^{-1}\)) accompanied by an abrupt drop in surface temperature was observed from 17:25 at Bengkulu Observatory (see Supplement 2). Therefore, downdrafts and their associated outflow on or near the ground were induced by the preexisting systems, which might forced intense upward motion of warm moist air, resulting in the formation and rapid growth of the new convective system. Soon after the occurrence of the gust of winds, widespread heavy rain was observed by the meteorological radar (Fig. 5, 18:03 LT).

Convective cloud merging and its effect on rainfall have been documented by previous studies (e.g., Simpson et al. 1980; Wescott 1994). Merged systems generally produce larger rainfall rates, last longer, and have a larger spatial extent, so that the surface precipitation from merged systems is sometimes a factor of ten or more greater than the rain from similar, isolated systems. The results of this study showed that the convective cloud merger of an eastward propagating MCS from the Indian Ocean associated with an active phase of the MJO and a southwestward moving diurnal MCS from the mountainous areas of the island was the immediate cause of the torrential rain on 12 December. An active phase of the MJO played a crucial role in the formation of the torrential rain event.

5. Occurrence of convection over Sumatra Island prior to and during the passage of an active phase of the MJO in December 2015

As previously mentioned, the MJO is characterized by an eastward progression of large regions of both enhanced and suppressed tropical rainfall in the equatorial region. An active phase of the MJO can cause enhanced convection over Sumatra Island for a period of several days. Several studies have shown that when the MJO main convective envelope is over the Indian Ocean, rainfall and its diurnal cycle over the land in the Maritime Continent reach their maxima due to increases in atmospheric instability caused by strong solar insolation in the clearer skies and moistening environment (e.g., Kamimera et al. 2012; Peatman et al. 2014; Birch et al. 2016). So why did the torrential rain occur on the western coast of Sumatra Island prior to the occurrence of the MJO westerly wind bursts in such a short period of time on 12 December 2015, rather than the occurrence of several days of heavy rainfall ahead of the arrival of main convective envelope? To answer this question, we examined the occurrence and movement of convection over the island prior to and during the active phase of the MJO in December 2015.

The regional variation of the diurnal cycle of CAPP radar reflectivity data averaged over all pixels along lines parallel to the southwestern coastline of the island (marked by a broken white line in Fig. 5) in the scope of the radar observation. The broken lines indicate the coastline. The abscissas indicate the distance from the shore along lines perpendicular to the coastline. The tick marks in the ordinate indicate 00 UTC or 07 LT for each of the days within the time period shown.

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On 13 December, the radar observations indicated that convec-

![Fig. 6. Regional variation of the diurnal cycle of Constant Altitude Plan Position Indicator (CAPP) radar reflectivity data observed by a C-band Doppler radar (CDR) onboard the Research Vessel Mirai at 50 km off Sumatra Island for 1 to 16 December 2015. Data is averaged over all pixels along lines parallel to the southwestern coastline of the island (marked by a broken white line in Fig. 5) in the scope of the radar observation. The broken lines indicate the coastline. The abscissas indicate the distance from the shore along lines perpendicular to the coastline. The tick marks in the ordinate indicate 00 UTC or 07 LT for each of the days within the time period shown.](image-url)
oscale convective systems were unlikely to occur on the western coast of the island during the passage of an active phase of the MJO.

Note that the westward moving diurnal convection from the mountainous areas of the island, and the eastward propagating convection from the Indian Ocean associated with an active phase of the MJO occurred only on 12 December. This was made possible by the westerly in the lower troposphere associated with the MJO being only just initiated and therefore still being weak, while there was also a weak easterly in the upper troposphere over the western coast of Sumatra Island on the same day (Fig. 4). The results suggest that the leading edge of the MJO westerly wind bursts provided favorable conditions (that is, eastward moving convection and weak winds in the troposphere) for an active phase of the MJO to work with the westward moving diurnal convection, which resulted from local circulations, to cause torrential rain in the evening on the western coast of Sumatra Island.

6. Summary

We successfully performed an intensive observation as part of the pre-YMC field campaign on the western coast of Sumatra Island during November to December 2015. Strong MJO activity took place in mid-December 2015, extending into January 2016. On 12 December 2015, a torrential rain event occurred over Bengkulu on the western coast of Sumatra Island. Meteorological radar observations indicated a line of strong convection that developed along the slope of the mountains in the afternoon, which then migrated southwestward in the late afternoon on 12 December. Meanwhile, convection associated with an active phase of the MJO migrated eastward from the eastern Indian Ocean approaching Sumatra Island. The two mesoscale convective systems converged and merged on the western coast of the island in the evening, causing widespread heavy rain.

Prior to an active phase of MJO in early December, convection with heavy rain occurred regularly over Sumatra Island in the afternoon, and migrated westward to the sea west of the island in the evening. Subsequently, during the passage of the active phase of the MJO, strong westerly winds were observed near the surface up to 400 hPa. Convection frequently shifted eastward from the Indian Ocean to Sumatra Island, whereas afternoon convection over the island was suppressed because of strong westerly winds. Both westward moving diurnal convection from the mountains of the island and eastward propagating convection from the Indian Ocean then occurred on 12 December, as the westerly winds in the lower troposphere associated with the MJO were only just initiated and were weak on the day. The results suggest that the leading edge of the MJO westerly wind bursts provided favorable conditions for an active phase of the MJO to work with the westward moving diurnal convection causing torrential rain on the western coast of Sumatra Island.

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Supplement

Supplement 1 An animation of the reflectivity from the Constant Altitude Plan Position Indicator (CAPP) at 2.0 km altitude obtained from the Bengkulu C-band Doppler radar for 12 December 2015, with the end times (UTC, LT = UTC + 7) of the volume-scan in the panels.

Supplement 2 Time variations of surface wind and temperature observed at Bengkulu Observatory on 12 December 2015.

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