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The Effect of an Active Phase of the Madden-Julian Oscillation on Surface Winds over the Western Coast of Sumatra Island

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Abstract. This study examined the effect of an active phase of the Madden-Julian Oscillation (MJO) on surface winds over the western coast of Sumatra Island using surface meteorological observations, meteorological radar observations, and balloon sounding data obtained from the Years of the Maritime Continent (YMC) Sumatra 2017 field campaign. Wind gusts (sudden and large increases in surface wind speed with durations of several to tens of minutes; squall) were observed frequently at Bengkulu from late November to early December 2017 during a local active phase of the MJO. The wind gusts occurred simultaneously with heavy precipitation when the eastward propagating convection from the Indian Ocean moved over the observation site. Upper air observations showed strong northwesterly winds in the lower troposphere in the 1,000–4,000 m layer. The surface wind gusts extended from the surface up to an elevation of 560 m, with the highest wind speed occurring approximately 300 m above the ground. Small changes in surface air pressure were observed during the wind gusts. The results suggested that momentum transfer from the upper atmosphere by downdrafts was the main cause of the surface wind gusts on the western coast of Sumatra Island during an active phase of the MJO.

Keywords : MJO, surface wind, downdraft, wind gusts.

1. Introduction

Sumatra Island is located in the equatorial region, with the west of the island facing the Indian Ocean (figure 1). Convective activity over the island is generally active, with a pronounced diurnal cycle. Severe thunderstorms occur frequently over the island throughout the year. All thunderstorms have downdrafts, which cause cool air to flow out on or near the surface. A strong downdraft, which is referred to as a downburst, includes an outburst of potentially damaging winds on the ground. The sudden strong winds near the surface, that is, wind gusts, can down trees, damage buildings, and are dangerous to aviation, particularly aircraft which are on final approach or taking off.

The Madden-Julian Oscillation (MJO) [1] is the largest modulator of atmospheric intraseasonal variability in the tropics. An active phase of the MJO is characterized by an eastward progression of large areas of both enhanced and suppressed tropical rainfall, with westerly wind bursts that mainly occur between the Indian and Pacific oceans. The MJO significantly affects weather in the global tropics and subtropics. When an active phase of the MJO propagates eastwards from the Indian Ocean to the Maritime Continent, the influence of the MJO on the diurnal cycle of convection causes considerable variations in precipitation over the islands and their surroundings [2,3]. Meanwhile, convectively coupled equatorial waves (CCEWs) can significantly influence the tropical precipitation, in particular over the Indian Ocean and the Maritime continents. On average, the CCEWs can considerably affect tropical precipitation by contributing up to 16-20% of the total intraseasonal precipitation variance in the tropics [4].



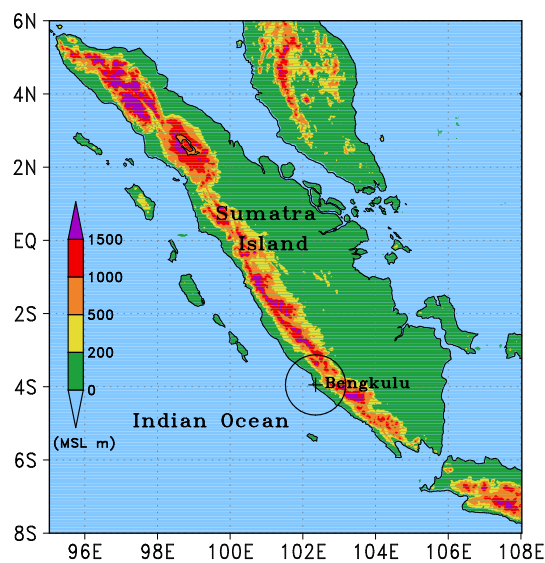


Figure 1. Topography of Sumatra Island and its surroundings, and the location of the Bengkulu Meteorological Observatory (cross). The open circles indicate the scope of the radar observations. Shading denotes terrain elevation. MSL is meters above sea level.

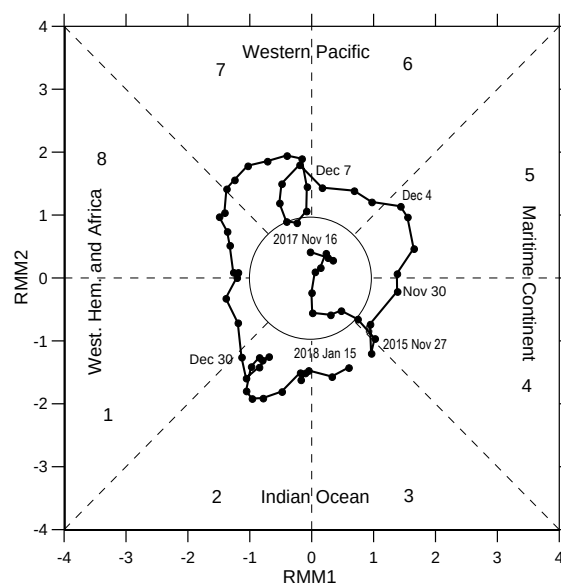


Figure 2. Phase diagrams of the Madden-Julian Oscillation (MJO) from mid-November 2017 to January 2018. The axes (RMM1 and RMM2) represent daily values of the principal components from the two leading modes. Each day within the time period is represented by a dot. The distance from the origin is proportional to MJO strength.

Wu et al. [5] investigated the effects of an active phase of the MJO on an extreme precipitation event that occurred over the western Sumatra Island in mid-December 2015 using observation data obtained from the previous Years of the Maritime Continent (YMC) field campaign. Their results showed 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 caused torrential rain on the western coast of Sumatra Island. In this way, the MJO significantly affected the diurnal cycle and development of convection on Sumatra Island, which in turn influenced winds on or near the surface. However, because field observation data are often unavailable on the island, especially the high temporal resolution data, exactly how an active phase of the MJO influenced surface winds on the island was not well understood.

To improve our understanding of convection over the Maritime Continent and its relation to the MJO and local atmospheric circulation, we performed an intensive observation, named YMC-Sumatra 2017, on the western coast of Sumatra Island from November 2017 to January 2018 as part of the YMC field campaign. Land-based observations at Bengkulu on the western coast and ship-based observations over the sea off the western coast of the island were conducted simultaneously. A surface and upper meteorological dataset with high temporal resolution was constructed for both the land and sea from these observations. The aims of the study were therefore to examine the variations of surface winds and its relation to convection, and to clarify the effect of an active phase of the MJO on strong surface winds over the western coast of Sumatra Island using the observation data obtained from the field campaign.

2. Observations and data

Surface meteorological observations, radar observations, and balloon soundings at intervals of 3 hours were performed at Bengkulu Meteorological Observatory for 61 successive days from November 16, 2017 to January 15, 2018. The observation site was located on the coastal plain approximately 4 km

from the shore (figure 1) at an elevation of 16 m above sea level. Surface meteorological variables, including atmospheric pressure, temperature, relative humidity, wind direction and speed, rainfall, and global solar radiation, were measured at 1-min intervals using an Automatic Weather Station (MAWS 201, Vaisala, Finland). Rainfall was measured by a tipping bucket rain gauge, with a sensitivity of 1 tip per 0.2 mm.

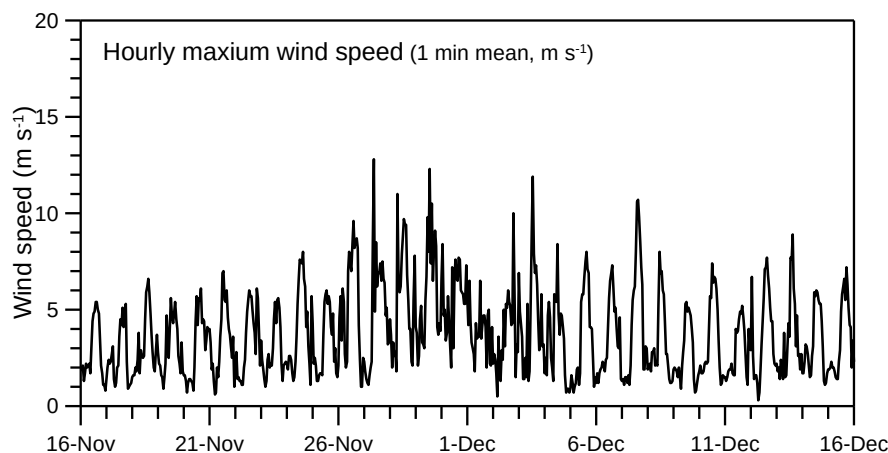


Figure 3. Time series of hourly maximum surface winds (1-minute averaged) observed at Bengkulu Meteorological Observatory on Sumatra Island from November 16 to December 15, 2017. The tick marks in the abscissa indicate 00 LT for each of the days within the time period shown.

Meteorological radar observations were conducted continuously 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 (CAPPI) were generated by Rainbow 5 software [6]. To assess the relative position and strength of the MJO, an all-season, real-time multivariate MJO index was used [7].

3. Occurrence of surface wind gusts on the Western Coast of Sumatra Island in an active phase of the MJO from November to December 2017

The oceanic and atmospheric features in November and December 2017 indicated mature La Niña conditions [8]. Sea surface temperatures were lower than normal across the central and eastern equatorial Pacific. Suppressed convection associated with the La Niña event persisted near the Date Line across the central and eastern Pacific, and enhanced convection over the Maritime Continent. Then, during late November and early December, enhanced convection developed over the eastern Indian Ocean and western Maritime Continent due to the development of an active phase of the MJO. The MJO was constructively interfering with the La Niña base state, resulting in enhanced convection over the eastern Indian Ocean and the Maritime Continent. Subsequently, enhanced convection shifted eastward across the Maritime Continent and the western-central Pacific in December.

The MJO index [7] showed a rapid increase in the MJO amplitude from November 25–27, 2017 (figure 2). On November 27, the index had an amplitude greater than 1.0, with a phase of 4 (the enhanced convective phase was centered on the western Maritime Continent). Although the position of the MJO showed little eastward propagation from November 27–29, in the subsequent five days from November 30 to December 4, an eastward propagation of the MJO over the Maritime Continent indicated a steady eastward movement of the robust MJO signal. Thereafter, the MJO index continued with amplitudes greater than 1.0 in December and propagated smoothly across the western Pacific and the Western Hemisphere.

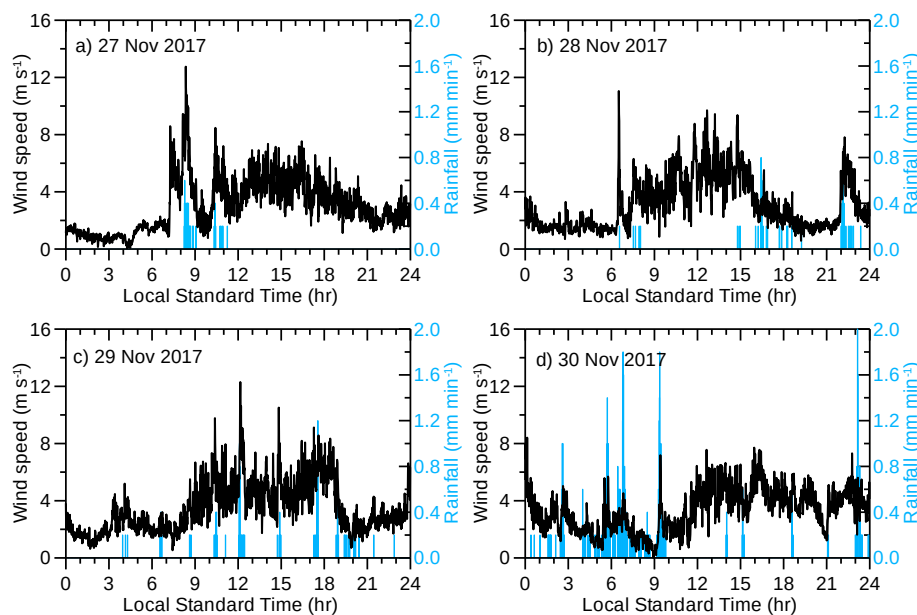


Figure 4. Time series of wind speed and precipitation observed at Bengkulu Meteorological Observatory on Sumatra Island on November a) 27, b) 28, c) 29 and d) 30, 2017 at 1-min intervals.

The time series of hourly maximum surface winds (1-min averaged) at Bengkulu on the western coast of Sumatra Island during the period from November 16 to December 15, 2017 is shown in figure 3. The surface winds were weak prior to the local active phase of the MJO until November 25. Conversely, during the local active phase of the MJO from November 27 to December 4, 2017, surface winds with maximum wind speed greater than 10 ms^{-1} were observed frequently. The surface winds showed a clear diurnal variation in wind speed throughout the period. In general, the maximum surface wind occurred in the afternoon and the minimum wind in the early morning. The strong daytime wind was largely due to the greater temperature differences between the sea and land surfaces during the day compared with at night [9]. The sea breeze on the western coast of the island in the afternoon was much stronger than the land breeze in the early morning [10]. Furthermore, the daytime enhancement of the wind speed was also partly attributable to the diurnal variation of the vertical momentum transport by turbulent fluxes, as it was much easier for fast-moving air above to mix down to the surface during the daytime [11].

4. Occurrence of precipitation and its effect on surface wind gusts

The 1-min mean wind speed and precipitation for the 4 consecutive days from November 27–30, 2017 when the MJO enhanced convective phase was centered near the western Maritime Continent are shown in figure 4. The variations of the 1-min mean winds showed that wind speed consistently displayed short time fluctuations. It was more windy during the daytime than at night. On each of the days, sudden strong surface winds, or wind gusts, occurred several times. The duration of the surface wind gusts had short time periods of 8 to 30 minutes. The World Meteorological Organization (WMO) defined the term “squall” as a sudden wind speed increase of 8 ms^{-1} or more to a speed of greater than 11 ms^{-1} , lasting for 1 min or longer in duration. Squalls occurred on November 27, 28, and 29, as the wind speed increased suddenly by more than 8 ms^{-1} , and wind speed of greater than 11 ms^{-1} were observed on these days. The surface wind speed increased simultaneously with the start of rainfall, and the highest wind speed of the wind gusts occurred during heavy precipitation at the observation site.

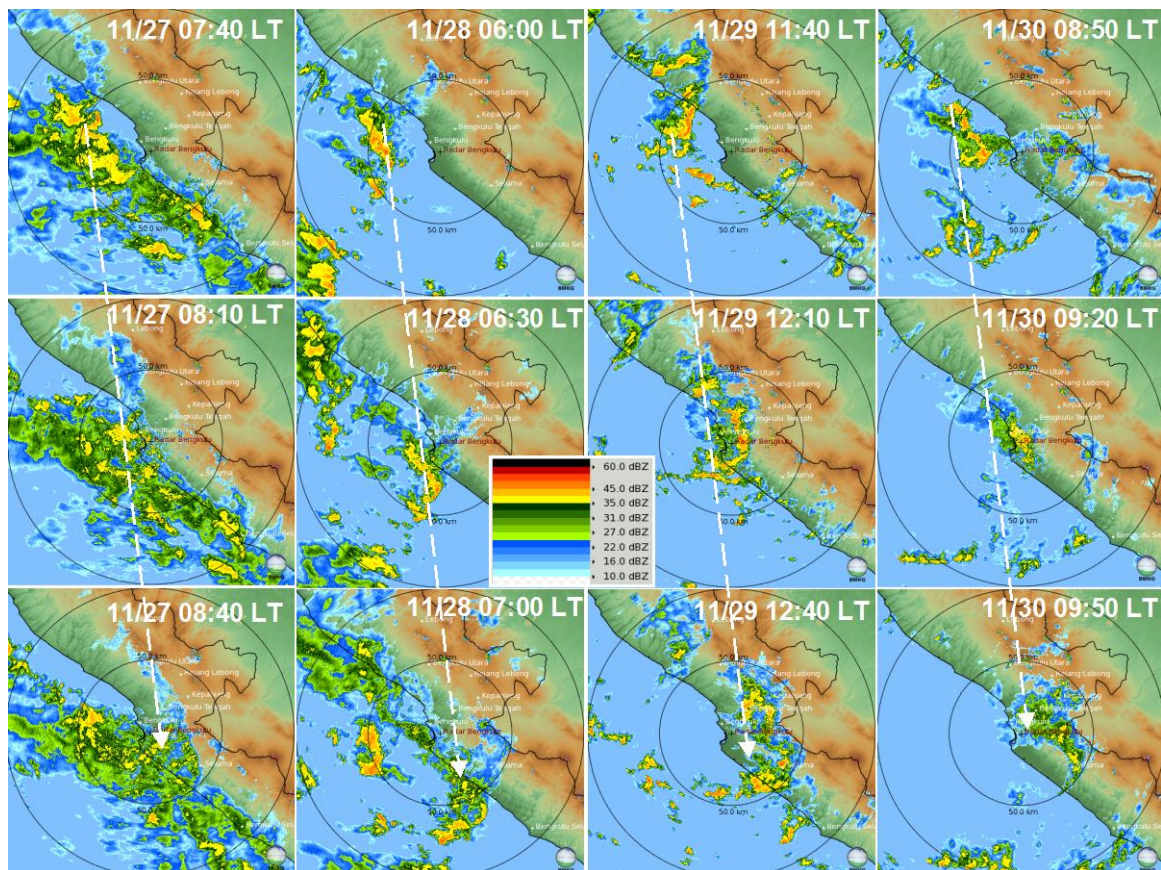


Figure 5. Reflectivity data (in dBZ) from the Constant Altitude Plan Position Indicator (CAPPI) at 2.0 km altitude obtained from the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) Bengkulu C-band Doppler radar (CDR) on November 27, 28, 29 and 30, 2017, with the end times (local time) of the volume-scan in the panels. The CAPPI is a radar display that gives a horizontal cross-section of data at a constant altitude.

The reflectivity data from the Constant Altitude Plan Position Indicator (CAPPI) at 2.0 km altitude, obtained from the Bengkulu CDR radar for the times of the strongest wind gusts on each of the four consecutive days from November 27–30, 2017, are shown in figure 5. The middle panels show CAPPI at the times when the surface winds began to increase during the wind gusts on each day. The upper panels and lower panels show CAPPI at 30 min before and after the surface winds began to increase, respectively. Thirty min before the strong surface winds were observed at the observation site, large areas of convection appeared over the eastern Indian Ocean about 30 km to the west of the radar observation site, moving southeastward toward Sumatra Island. Then, a high reflectivity area passed over the observation site during the times when the strong surface winds were observed. The convection became weaker as it moved over the island compared to when it was over the ocean.

The eastward propagation of an active phase of the MJO often causes strong northwesterly winds in the lower troposphere over Sumatra Island [5]. Upper-air sounding data have shown that strong upper westerly to northwesterly winds $20\text{--}25\text{ ms}^{-1}$ persisted over the island during the active phase of the MJO from November 27–30, 2017 (shown in Section 5). From radar observations, the migration direction of the precipitation system was almost the same as the northwesterly winds in the lower troposphere. The propagation speed of the precipitation system was estimated as approximately 20 m s^{-1} . It has been reported that the propagation of mesoscale convective complexes (MCSs) is mainly determined by the mean flow of the cloud-layer (850–300 hPa) and the development of new convective cells [12]. The above results suggested that the movement of the mesoscale convective systems from the Indian Ocean

was steered towards the west coast of Sumatra Island by the upper northwesterly winds in the cases being studied, which were caused by an active phase of the MJO. Surface wind gusts were then observed when the eastward propagating convection moved over the observation site.

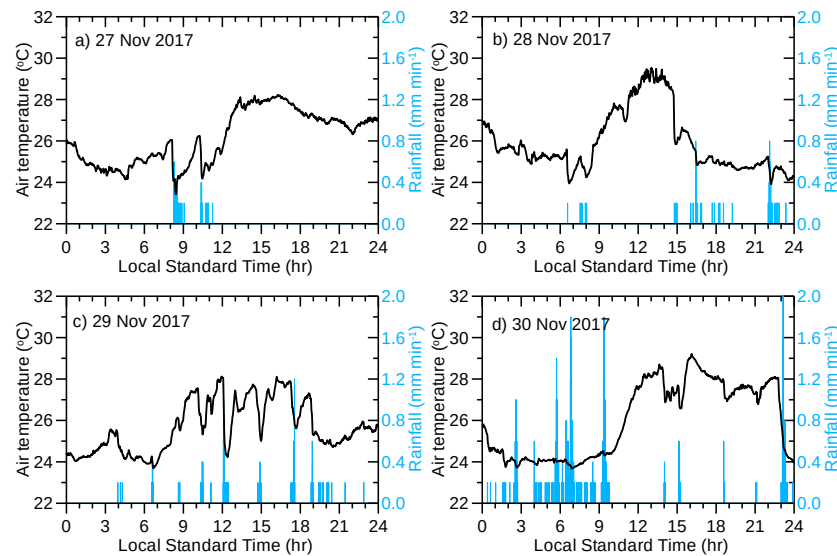


Figure 6. Time series of the surface air temperature and precipitation observed at Bengkulu Meteorological Observatory on Sumatra Island on November a) 27, b) 28, c) 29 and d) 30, 2017 at 1-min intervals.

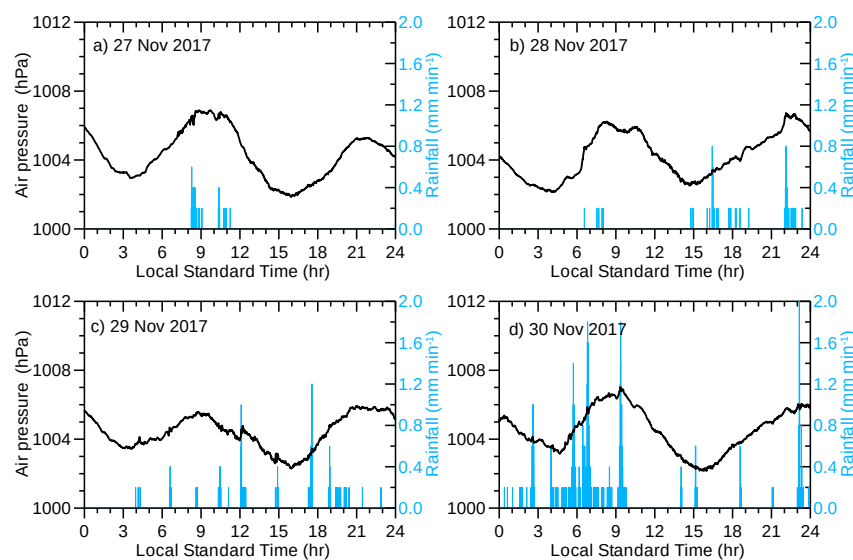


Figure 7. Time series of surface air pressure and precipitation observed at Bengkulu Meteorological Observatory on Sumatra Island on November a) 27, b) 28, c) 29 and d) 30, 2017 at 1-min intervals.

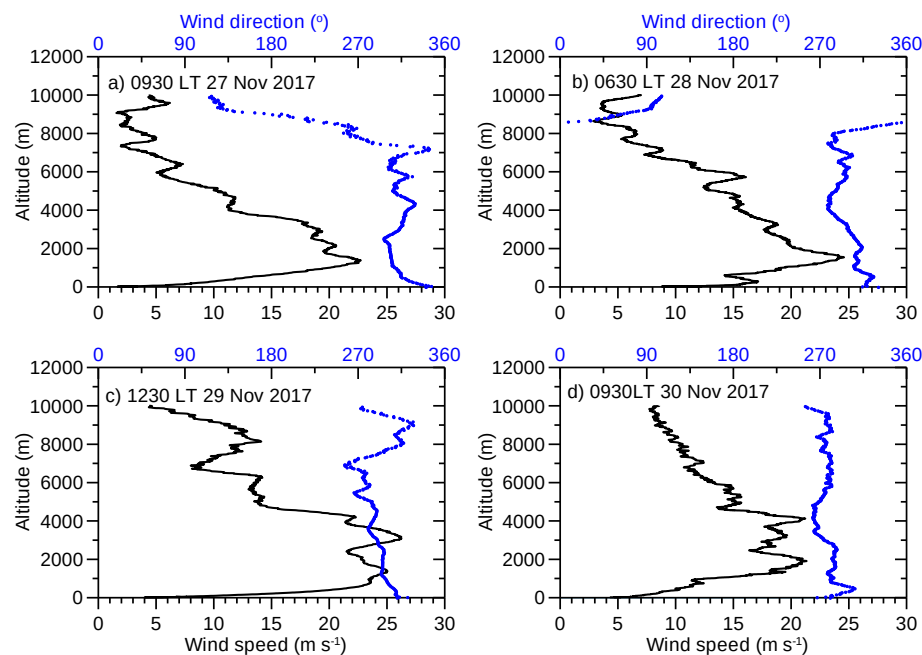


Figure 8. Profile of winds obtained from upper-air soundings at Bengkulu on November a) 27, b) 28, c) 29 and d) 30, 2017, with the balloon-release times (local time) in the panels. Wind speed is labeled along the bottom of the abscissa, while wind direction in degrees is labeled along the upper part of the abscissa.

5. Surface temperature and pressure variations, and vertical distribution of the wind of a wind gust

Continuous surface meteorological observations and balloon soundings at intervals of 3 h were performed at Bengkulu Meteorological Observatory during the YMC-Sumatra 2017 field campaign. As the wind gusts were caused by the downdraft of convection, other meteorological elements on the surface were also affected by the downdraft. In this section, we examined the variations in surface temperature and pressure, and the vertical distribution of the wind gusts.

The time series of surface air temperatures (1-min intervals) and precipitation for the four days from November 27–30, 2017 are shown in figure 6. The surface temperatures show large diurnal variations on these days, with a maximum of approximately 28°C in the afternoon and a minimum of approximately 24°C in the early morning. The diurnal cycle in surface air temperature on the island was caused by daytime solar radiation, even during a local active phase of the MJO [9]. In figure 6, abrupt decreases in surface air temperature occurred frequently, which were all accompanied by precipitation. For the four cases of the strongest surface wind gusts on each day, decreases in surface temperature varied from 0.2 to 3.9°C. Surface air temperature in the early morning on November 28 and 30 was relatively low close to 25°C, and decreases in air temperature of less than 1.0°C were observed during the wind gusts. The reason for the small changes in air temperature was probably the lower surface air temperature. Decreases in surface air temperature by downdraft on the western coast of Sumatra Island only reached a minimum of approximately 24°C [9] as the warm ground heated up the air near the surface. Furthermore, because of the lower air temperature, a layer of cold air near the surface before precipitation most likely acted as a “cushion” and weakened the downdraft near the surface [13], resulting in smaller decreases in the surface air temperature.

The time series of surface air pressure (1-min intervals) and precipitation for the four days from November 27–30, 2017 are shown in figure 7. The variations in surface air pressure were characterized by dual maxima in the morning and evening, with minima after midnight and in the afternoon. The diurnal and semidiurnal variations of pressure were the surface representation of a diurnal tide of the entire atmosphere due to the warming of the upper atmosphere by the Sun [14]. Other than the large diurnal variations from the atmospheric tide, the sudden abrupt increases in pressure coincided with

precipitation at the observation site. However, only small changes in surface air pressure of approximately 0.5–0.7 hPa occurred in the four cases of the strongest surface wind gusts on each day from November 27–30, 2017. In comparison to the cases shown above in figure 4, 6 and 7, which occurred during strong upper northwesterly winds in an active phase of the MJO, similar gusts of wind accompanied by a large decrease in surface temperatures occurred on November 22 and 24, 2017 (not shown). At this time widespread convection passed over the observation site in an inactive phase of the MJO with weak winds at the lower troposphere, whereas the wind speeds of the wind gusts were much weaker than those in the active phase of the MJO (figure 3). The above results suggested that the surface wind gusts that were observed on the western coast of Sumatra Island in an active phase of the MJO were mainly caused by momentum transfer from the upper atmosphere to the surface by downdrafts, rather than by a pressure gradient that resulted from the temperature contrast between the cold pool and air surroundings.

Figure 8 shows the wind profiles of the strongest surface wind gusts for each of the four days from November 27–30, 2017, which were obtained at the nearest balloon-release times (within 90 min) to the occurrence of the surface wind gusts. The wind speeds increased rapidly from the surface to approximately 1,000 m elevation, with maximum wind speeds ($>20 \text{ ms}^{-1}$) occurring in the 1,000–4,000 m layer. The northwesterly wind directions remained steady from near the surface up to approximately 8,000 m altitude in the lower troposphere. Above this elevation, the wind direction changed to an easterly, consistent with the passage of an active phase of the MJO. Surface winds measured on November 27, 28 and 30 (figure 8a, c, d) were weak because the balloon soundings were not carried out during the occurrence of the surface wind gusts.

On November 28, radiosonde began to ascent at 0630 LT when a surface wind gust occurred at the observation site. One min later, the largest surface wind speed of 11.0 ms^{-1} was measured at 0631 LT at the surface. The wind speed profile (figure 8b) shows that the gust winds extended from near the surface up to an elevation of 560 m, with the largest wind speed ($> 17.0 \text{ ms}^{-1}$) of the gust occurring in the 230–303 m layer.

As shown previously in section 4, on the morning of November 28, the precipitation systems propagated southeastward from the Indian Ocean to Sumatra Island. The surface wind gusts occurred when the precipitation systems passed over the observation site. In general, the highest winds in a surface wind gust in a downburst occur closer to the splashdown point near the surface when strong downdraft reaches the ground. In the present study, the highest winds of the winds gust on November 28 were not observed on the surface, but approximately 300 m from the ground. This is most likely due to the strong northwesterly winds in the lower troposphere associated with an active phase of the MJO and the fast propagation of the precipitation systems. Momentum transfer from the upper atmosphere to the surface by downdrafts caused the wind gusts near the surface. However, the surface exerts a frictional drag on the air flowing just above it, forcing the winds near the surface to slow down. As a result, the highest winds occurred close to 300 m above the ground, rather than near the surface. To reveal the detailed structure and formation mechanism of the surface wind gusts, further studies based on an analysis of the C-band Doppler radar (CDR) data and other observation data obtained from the field campaign are needed.

As previously mentioned, the oceanic and atmospheric features in November and December 2017 indicated mature La Niña conditions. Meanwhile, the Indian Ocean Dipole (IOD) remained near neutral during November to December 2017. Sea surface temperatures were close to normal across the tropical Indian Ocean; seas to the west of Sumatra Island were warm, as usual. Westerly winds prevailed in the lower troposphere. The active phase of the MJO was constructively interfering with the La Niña base state, resulting in enhanced convection over the Maritime Continent region. The effect of MJO on the development of convection and precipitation over Sumatra is expected to be highly associated with the nature of MJO itself in modulating total precipitable water (TPW/column water vapor) in the tropics, in particular during MJO phases 3 and 4, and seasonal variations of TPW modulated by the MJO are maximized in the tropics during boreal winter [15]. Therefore, it may be that the ENSO, IOD and monsoon large-scale atmospheric circulations during November to December 2017 provided favorable conditions for the development of heavy rainfall and strong surface wind gusts on the western coast of Sumatra Island.

6. Summary

We successfully performed an intensive observation, named YMC-Sumatra 2017, on the western coast of Sumatra Island from November 2017 to January 2018 as part of the YMC field campaign. During the field campaign, MJO activity took place from late November to December 2017. This study examined the variations in the surface winds and the effect of an active phase of the MJO on the occurrence of surface wind gusts over the western coast of Sumatra Island using the observation data obtained from the field campaign.

Wind gusts, or sudden and large increases in the surface wind speed with durations of several to tens of min (squall), were observed frequently at Bengkulu from late November to early December 2017 in a local active phase of the MJO. The occurrences of surface wind gusts were accompanied by heavy precipitation, when an eastward propagating convection from the Indian Ocean associated with an active phase of the MJO moved over the observation site. Upper-air observations showed strong northwesterly winds ($>20 \text{ m s}^{-1}$) in the lower troposphere in the 1,000-4,000 m layer. The gust winds extended from near the surface up to an elevation of 560 m, with the highest wind speed occurring approximately 300 m above the ground. Decreases in surface temperature varied from 0.2 to 3.9°C and small changes in air pressure were observed during the wind gusts. The results suggested that momentum transfer from the upper atmosphere by downdrafts was the main cause of the surface wind gusts on the western coast of Sumatra Island in an active phase of the MJO.

Acknowledgments

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