Why Does Convection Weaken over Sumatra Island in an Active Phase of the MJO?

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(Manuscript received 17 September 2021, in final form 27 November 2021)

ABSTRACT: This study investigated the diurnal cycle of convection over Sumatra Island in an active phase of the Madden-Julian oscillation (MJO) during the Pre-Years of the Maritime Continental observation campaign in December 2015 based on in situ and satellite observations and a convection-permitting numerical model. Observations suggest that before the active phase of the MJO in early December, convection occurred frequently over the island during the afternoon and at midnight. By contrast, during the active phase of the MJO in mid-December, afternoon convection over the island was delayed and suppressed, and midnight convection was suppressed. Numerical experiments also successfully replicated the main features of the observed modulations. In general, during the active phase of the MJO, the troposphere became drier in the Sumatra region. While the clouds reduced the solar radiation over the land, the sea breeze was also found to be delayed and weakened. As a result, the afternoon convection initiation was delayed and weakened. Further analyses suggested that the sea breeze was weakened mainly due to the orographic stagnation effect rather than the slightly reduced land–sea temperature contrast. On the other hand, the increased stratiform-anvil clouds induced the anomalous evaporative cooling in the midtroposphere and generated island-scale subsidence during the nighttime, which finally led to the suppression of inland convection. Overall, our study reveals the modulation of diurnal convection over Sumatra Island by an active phase of the MJO and also shows the potential role of land–sea interaction in convection initiation and maintenance.

KEYWORDS: Maritime Continent; Atmosphere-land interaction; Madden-Julian oscillation; Diurnal effects

1. Introduction

The unique geographical features and location of the Maritime Continent (MC) make it a hotspot of the atmosphere–land–sea interactions, where numerous islands are surrounded by the warmest ocean on Earth (e.g., Yamanaka 2016; Yoneyama and Zhang 2020). Vigorous convective activity is the key feature of the MC due to a large amount of latent heat released from the ocean. Among the convective variabilities on different time scales, the diurnal cycle of convection is one of the dominant variabilities over the MC. It is well known that convection in this region generally occurs over islands in the afternoon and propagates offshore during the nighttime as a result of the sea–land breeze circulations (e.g., Mori et al. 2004; Sakurai et al. 2005; Wu et al. 2009; Yokoi et al. 2019). Moreover, some studies also found that the diurnal cycle has spatial variations among the different islands of the MC due to their sizes and orographic characteristics (e.g., Yang and Slingo 2001; Li and Carbone 2015; Wang and Sobel 2017).

In addition to the local diurnal cycle, the Madden–Julian oscillation (MJO), the largest element of the intraseasonal variability in the tropical atmosphere, has also been demonstrated to significantly influence the weather over the MC (e.g., Madden and Julian 1994; Matthews 2008). Numerous observational and numerical studies have shown that the MJO can modulate the diurnal convection over the MC (e.g., Fujita et al. 2011; Kanamori et al. 2013; Ajayamohan et al. 2021). For example, based on satellite observations, Rauniyar and Walsh (2011) found that the amplitude and phase of the diurnal cycle of rainfall on islands vary among the categories of the MJO. Peatman et al. (2014) showed that precipitation was enhanced over land before the main convective envelope arrived, while they further evaluated such modulation by the MJO in a high-resolution GCM (Peatman et al. 2015). On the other hand, some studies have also shown that the MJO may not greatly influence the diurnal cycle (e.g., Suzuki 2009).

Similar to the diverse effects of the MJO reported in previous studies, different mechanisms were also proposed for MJO modulation. Birch et al. (2016) and Fonseca et al. (2019) explained the reasons for the differences in the mean rainfall anomaly over the land and sea in an active phase of the MJO by the interaction between the large-scale environment and the mesoscale circulation (sea–land breezes). From another perspective, Sakaeda et al. (2017) suggested that the MJO...
modulates the diurnal cycle of rainfall and cloudiness by changing the cloud-type population distribution and associated rainfall rates, and Vincent and Lane (2018) further emphasized the importance of the modulations of convective and stratiform processes by the MJO. Besides the clouds, the related insolation also modulates the sea-breeze circulation and the diurnal cycle consequently (e.g., Natoli and Maloney 2019). More recently, Wei et al. (2020) further discussed the spatial differences in the modulations by evaluating the processes over three major islands in the MC. In addition, some recent studies also demonstrated the important role of the background states among the different phases of the MJO, such as the moisture (e.g., Lu et al. 2019) and the wind (e.g., Bai et al. 2021).

However, most previous studies evaluated the influence of the MJO on convection based on long-term measurements from satellites and simulations, but few of them focused on detailed characteristics of circulation fields due to the lack of high-resolution in situ observations. Therefore, our knowledge of the modulations of the MJO on the diurnal cycle of convection remains few.

In 2015, an intensive observation was performed as part of the Pre-Years of the Maritime Continent observation campaign (Pre-YMC 2015), and an active MJO event was successfully observed during the campaign. Observations were made at Bengkulu and from the research vessel (R/V) Mirai on the western coast of Sumatra Island (see white dots in Fig. 1) from November to December 2015, which clearly showed a weakened diurnal cycle during the MJO (e.g., Yokoi et al. 2017). On the other hand, based on the observation data obtained during the campaign, Wu et al. (2017) found that strong daytime solar radiation caused a pronounced diurnal cycle in surface air temperatures on the island in December 2015, even during an active phase of the MJO. Moreover, it is reported that the land–sea temperature contrast did not change much (Wu et al. 2018). Interestingly, previous studies suggested the MJO weakens sea breeze by reducing the solar insolation and land–sea temperature difference via the increased cloud cover, and, therefore, modulates the diurnal cycle (e.g., Qian 2008; Birch et al. 2016). Thus, the goal of this study is to investigate why the diurnal convection was suppressed over Sumatra Island during the active phase of the MJO and possible hidden mechanisms using the in situ observations obtained during the Pre-YMC campaign and numerical approaches.

This paper is organized as follows. Section 2 includes descriptions of the data sources and model settings. Section 3 documents the observed modulation of diurnal convection and atmospheric conditions before and during the active phase of the MJO in December 2015. In section 4, the possible mechanisms of the suppressed convection are presented. Section 5 discusses the weakened sea breeze. Finally, a summary of our major findings is presented in section 6. The results of the preliminary tests of microphysics schemes in our simulation, extra information of diurnal variations, and simulated atmospheric properties (correspond to the in situ observations) are presented in the supplemental material.

2. Materials and methods

a. Data

In this study, we used hourly precipitation data from the Global Rainfall Mapping Precipitation (GSMaP) dataset (Kubota et al. 2020), which has a resolution of 0.1° from 60°S to 60°N. The in situ radiosonde data were obtained aboard the R/V Mirai and at Bengkulu, Indonesia during the Pre-YMC 2015 field campaign with a 3-h interval (Yokoi et al. 2017). Note that the observation aboard the R/V Mirai ended on 16 December, while observations continued at Bengkulu until 25 December (Fig. 2). For further analyses, radiosonde data were vertically averaged within every 5 hPa. Rain gauge precipitation data, surface downward solar radiation, surface temperature, and wind were also gathered at both Bengkulu and aboard the R/V Mirai, and we used the hourly data in this study. The convective available potential energy was calculated based on the radiosonde data and the most unstable scenario using the FORTRAN code created by Dr. G. H. Bryan (e.g., Bryan and Fritsch 2004; see acknowledgments for downloadable link).

For the numerical model, we used the 0.25° ERA5 dataset from the European Centre for Medium-Range Weather Forecast (ECMWF) as the initial and lateral boundary conditions (Hersbach et al. 2020). The sea surface temperature (SST) was obtained from the 0.25° daily GHRsst Multiproduct Ensemble (GMPE; Martin et al. 2012) for the lower boundary condition.

Note that the diurnal anomalies of observations and simulations represented in this study were obtained by removing the 1-day running mean, and the cross-sectional wind was obtained by assuming that the cross-section angle is 45° (see the orientation of Sumatra Island in Fig. 1).

b. Numerical simulations

Although the field campaign successfully observed detailed characteristics of precipitation around the west coast, the
weather radars could not observe precipitation in inland areas. While the radiosonde data have high temporal resolution enough for analyzing the diurnal signals, their spatial resolution may not be sufficient for discussing mechanisms of the modulations of the MJO on the diurnal cycle. To overcome these difficulties, we conducted the numerical simulations based on the Weather Research and Forecasting (WRF) Model (WRF V4.2.2; Skamarock et al. 2019). Moreover, to reduce the potential influence of initial conditions (e.g., Bei and Zhang 2007; Singh and Mandal 2015), a set of simulations were conducted with different initial times (i.e., initial conditions) from 0000 UTC 29 November to 0000 UTC 30 November with 6-h intervals (five ensemble members in total). Since we only focused on the latter half of the period of the Pre-YMC 2015 campaign from 2 to 23 December, the period before 2 December in each member was considered the spinup time and was not used for the analyses. The simulated atmospheric properties were saved every hour.

Our model domain was to cover the whole Sumatra region with a resolution of 9 km, and it contains a 3-km two-way nested domain to obtain the high-resolution atmospheric fields around Sumatra Island (Fig. 1). Both domains have 60 sigma layers from the surface to 50 hPa. In both domains, we used the Goddard microphysics scheme (Tao et al. 2016), the Yonsei University PBL scheme (Hong et al. 2006), the revised MM5 surface layer scheme (Jiménez et al. 2012), the United Noah Land Surface Model (Tewari et al. 2004), and the New Goddard shortwave and longwave schemes (Chou and Suarez 1999; Chou et al. 2001). In coarser domain 1, we applied the Grell-Freitas ensemble cumulus scheme (Grell and Freitas 2014) following Zhao and Nasuno (2020). Note that some other microphysics schemes were also tested, and the Goddard scheme showed the best performance, especially in terms of precipitation over the

3. Observed atmospheric conditions in December 2015
   a. Pre-MJO and MJO periods

Figure 2 shows the observed zonal wind and specific humidity at Bengkulu (3.87°S, 102.35°E) and R/V Mirai (anchored at approximately 4.06°S, 101.09°E). In early December 2015, the wind in western Sumatra was generally weak in the lower troposphere, while slightly stronger easterly wind (~5 m s⁻¹) dominated at higher levels. During 13–22 December, when the enhanced convection developed and shifted east across the MC (i.e., the active phase of the MJO; Wu et al. 2017; Yokoi et al. 2017), strong westerlies (>10 m s⁻¹) were dominant in the lower- to midtroposphere (Figs. 2a,b). On the other hand, observations show that the whole troposphere was relatively moist during the period before the MJO, and then became drier (see the reduction in the total precipitable water vapor in Fig. 2). One may consider it is strange to see a drier atmosphere during an active phase of the MJO; however, this was mainly due to the specific location of Sumatra Island, which is located west of the enhanced convective envelope during the active phase of the MJO over MC. Such moisture reduction could also be seen in previous observational and numerical studies (e.g., Fujita et al. 2011; Yokoi 2015; Matsugishi et al. 2020). Note that our model well simulated the wind and moisture and their changes before and during the MJO (Fig. S3).

According to the observations, we defined the active phase of the MJO over MC from 13 to 22 December (hereafter referred to as the MJO period; also see the Real Multivariate
MJO index in Fig. S2, Wheeler and Hendon 2004). Accordingly, we defined the same 10-day period from 2 to 11 December to show the conditions prior to the active phase of the MJO (hereafter, the PRE period). Note that the data on 12 December were excluded due to phase changing (Fig. 2).

b. Response of convection

To generally show how convection responded to the phase changing of the MJO, following Zhao and Nasuno (2020), we analyzed the frequency–altitude distributions (FAD) of the relative humidity (RH with respect to ice, i.e., RH can >100%) calculated from the radiosonde observations (Fig. 3). During the PRE period, the high RH (>80%) had a higher frequency at the lower to midtroposphere rather than the upper levels at both Bengkulu and R/V Mirai (Figs. 3a,d), which can be regarded as the regular diurnal convection with a larger fraction of convective precipitation (e.g., Mori et al. 2011; Sakaeda et al. 2017). On the other hand, a clear increment of high RH (>85%) frequency at mid- to upper levels was seen in the observations at both Bengkulu and R/V Mirai during the MJO (Figs. 3b,e; also see Fig. S12 for the simulated results), which provided the favorable condition for the development of stratiform-anvil clouds. These findings are also consistent with previous studies which suggest the fraction of stratiform precipitation becomes larger during the active phase of the MJO (e.g., Morita et al. 2006; Mori et al. 2011; Sakaeda et al. 2017). Moreover, observations also showed that, compared with the R/V Mirai (i.e., over the sea), the frequency of high RH at lower to midlevels decreased more at Bengkulu during the MJO (Figs. 3c,f), suggesting the potential suppression of the diurnal convection.

c. Diurnal conditions before and during the MJO

Comparing with the general overview, our interest focused on the diurnal cycle of convection. As shown in Fig. 4, before the MJO, the precipitation mainly occurred from the late afternoon to the evening at Bengkulu and from evening to the early morning over the sea (Figs. 4a,e). These results
generally represent a canonical diurnal cycle of convection, that convection was initiated over the mountains and propagated offshore later (e.g., Yokoi et al. 2017).

As the primary drivers of the diurnal cycle, we first investigated the temperature difference between Bengkulu and R/V Mirai and the cross-sectional wind at Bengkulu, which roughly represent the land–sea temperature contrast and the land–sea breeze, respectively (Fig. 5). Before the MJO, the temperature difference started to increase after the sunrise (0000 UTC, 0700 LT), and it rapidly reached its maximum (∼2°C) at about 0400 UTC (1100 LT) and was maintained for several hours. The increasing temperature difference also induced the onshore wind (i.e., the sea breeze) from morning to the late afternoon but with 1–2-h delay (see blue lines in Figs. 5a,b). The maximum onshore wind could exceed 6 m s⁻¹ at noon, while the offshore wind dominated the nighttime but was generally weak (∼2 m s⁻¹). Interestingly, our results showed that, although the solar insolation had comparable values over the land and sea before noon, the sea received more solar heating in the afternoon, and the temperature over the sea increased during the whole daytime. In contrast, the temperature at Bengkulu decreased from 0700 UTC (1400 LT), which was likely caused by the offshore propagating diurnal convection. Consequently, the land–sea temperature contrast declined rapidly and became negative after 0800 UTC (1500 LT), and the onshore wind also declined in the afternoon.

During the MJO, the regular diurnal precipitation was no longer observed (Fig. 4). It was raining in both the morning and evening hours at Bengkulu and over the sea (green bins in Figs. 3a,c). Meanwhile, the solar radiation reduced about 30% at Bengkulu and even became only one-third of its previous level over the sea as we observed aboard the R/V Mirai (e.g., Wu et al. 2018; Suzuki et al. 2018). However, due to the larger heat capacity of the water, the temperature over the land and the sea experienced similar reductions, resulting in the similar diurnal amplitude of the land–sea temperature contrast as the PRE period (but was 1-h delayed; Fig. 5b). Unlike the slightly changed temperature contrast, the local circulation was significantly modulated. The surface onshore wind was largely weakened and was delayed about 3 h, while its duration was also reduced from 9 to 6 h (Fig. 5b). Such
weakening in the onshore wind was further confirmed under the 950-hPa level.

In addition to the modulated surface conditions, modulations were also seen in the troposphere. Before the MJO, the lower troposphere warming appeared in the morning at Bengkulu together with a negative potential temperature anomaly at the approximately 700-hPa level (Fig. 6c), leading to an unstable lower troposphere later in the afternoon (also see the increasing CAPE in Fig. 6g). Considering the weak background wind (Fig. 2), the surface onshore wind generally followed the variations of temperature (temperature contrast), while a relatively strong onshore wind dominated the lower-to midtroposphere in the afternoon when the moistening was seen over the entire troposphere (i.e., the arrival of the diurnal convection). Comparing with the land (Bengkulu), the diurnal fluctuations over the sea were generally smaller than those over land (Fig. 7), but the lower tropospheric warming and moistening also induced a large instability over the sea at 0600 UTC (1300 LT). Moreover, the landward wind was also weak over the sea in the afternoon.

After the MJO transferred to the active phase, the lower layer was less warmed in the morning and early afternoon over the land and the sea (see smaller positive $\theta$ anomaly below the 800-hPa level; Figs. 6d and 3d) due to the reduced solar insolation (Fig. 4), and the onshore wind anomaly was also weakened. Meanwhile, the low-level moistening was seen over the land at 0600 UTC (1200 LT; Fig. 6b), which was likely due to the moisture transported from the sea by the onshore wind (e.g., Fig. 5). On the other hand, while the MJO-related convective activities dominated over the sea, the diurnal variation of the tropospheric moistening became less visible in our radiosonde observation aboard the R/V *Mirai* (although there was a negative anomaly in the afternoon; Fig. 7b). Another interesting fact is that a strong onshore anomalous wind was observed in the late evening at mid-to upper levels that were absent before, and the near-surface offshore wind anomaly also became stronger.

4. Modulation of the MJO on the diurnal convection in WRF simulations

a. Overview of convection

Comparing with the radiosonde observations, satellite observation and our simulation provide a wider view of the modulated diurnal convection during the MJO (Fig. 8). Prior to the MJO, convection was initiated over the mountainous areas of the island in the afternoon (0600 UTC, 1300 LT), while the peak precipitation over mountains was observed a few hours later at approximately 0900 UTC (1600 LT; Fig. 8e). Then, mountainous convection migrated offshore toward the sea in the subsequent late afternoon to evening hours, presenting a typical pattern of the diurnal cycle of convection over the western coast of Sumatra Island (Wu et al. 2017, 2018; Yokoi et al. 2017). As a result, the precipitation over the land decreased during the evening but increased over the sea (see solid lines in Figs. 8e,f). Moreover, the second peak in precipitation over the land was observed at midnight (1800 UTC, 0100 LT), which...
FIG. 6. Composite diurnal anomalies of the (a),(b) radiosonde-observed specific humidity \(q\); (c),(d) potential temperature \(\theta\); and (e),(f) cross-sectional wind \(u^*\) together with (g) the convective available potential energy (CAPE) and convective inhibition (CIN) at Bengkulu. Black dots indicate the significant values (90% based on the Student’s t test).
FIG. 7. As in Fig. 6, but for the data observed at R/V Mirai.
likely corresponded to the eastward migration of mountainous convection (Figs. 8a,c; e.g., Sakurai et al. 2005). The inland precipitation during midnight was weak but covered a large area over Sumatra Island, especially on the eastern side of mountains, contributing to the second peak in precipitation over Sumatra Island (Fig. 8e).

After 13 December, the diurnal convection over the Sumatra region was significantly changed. The afternoon convection over mountainous areas was greatly suppressed (Figs. 8b,d), as shown by a 2–3-h lag in the peak precipitation and a large reduction in precipitation intensity. Consequently, no clear migration of convection was observed. Furthermore, the midnight inland precipitation became nearly negligible when the MJO arrived, resulting in the disappearance of the second peak (Fig. 8e). By contrast, the precipitation over the sea was enhanced during the active phase of the MJO and persisted for the whole day, although it became slightly weaker when mountainous precipitation appeared in the afternoon.

It should be mentioned that our model tends to overestimate precipitation over the mountains compared with satellite observations, while the underestimation was found over the sea, and one may, therefore, think our results lacking reliability. One fact that should be mentioned is that our simulated precipitation shows good agreement with the radar-estimated
precipitation over mountains (see Fig. 5 in Yokoi et al. 2017), suggesting the satellite observations may underestimate the precipitation over the mountainous area (e.g., Birch et al. 2015; Lu et al. 2019). Meanwhile, although the simulated eastward migration of convection was nearly invisible in the satellite observations, the reduction in midnight precipitation was clear in both simulation and observations.

In addition, despite the overestimated diurnal amplitude of the precipitation, our model well represented the changes in other diurnal signals that observed at Bengkulu and R/V Mirai, such as the temperature, moisture, and wind (see Figs. S10, S11, and S13), including the enhanced subsidence-related cross-sectional winds during the MJO period. The simulated vertical distributions of relative humidity (Fig. S12) also matched well with the observations (Fig. 3). Thus, our simulations are reliable in representing the modulations on convection by the MJO.

b. Afternoon convection

To find why the afternoon convection was delayed and suppressed, we first evaluated the atmospheric conditions of convection initiation during the PRE and MJO periods. Figure 9 shows the cross-sectional distributions of the vertical equivalent potential temperature gradient \(\frac{d\theta_e}{dz}\), vertical velocities, diurnal anomalies of cross-sectional wind, and the hourly precipitation along the cross section. During the PRE period, our simulation suggests that descending motions were dominant over the sea and the inland area of Sumatra Island during the morning (see the downward vectors in Fig. 9a). From 0200 UTC (0900 LT) to 0300 UTC (1000 LT), a weak updraft appeared over the mountainous area during the PRE (Fig. 9c), corresponding to the surface heating by the solar insolation. After that, it was further enhanced by the onshore wind (hence, the sea breeze; also see Fig. 5) and its related orographic lifting. Meanwhile, the surface warming and the moisture carried by the sea breeze destabilized the boundary layer over the mountains (see the upward tilted large negative \(\theta_e\) gradient around mountains), leading to a favorable condition for convection. Finally, at 0400 UTC (1100 LT), a much stronger updraft was seen (Fig. 9e), that extended upward over the 3000-m height, accompanied by the strong sea breeze, indicating the triggering of convection over the mountains. This mountainous convection further developed during the next few hours (Figs. 9g,i) before its offshore migration (Fig. 6), inducing the local precipitation over the mountains. Because of the weak background wind, the above convection initiation was quite conspicuous even in original composites (see Fig. S4).

During the MJO, the weakened solar insolation induced a relatively cooler surface over the mountains in the morning (Fig. 10), leading to the weakened updraft (e.g., Figs. 9d,f). In addition, the sea breeze and the related upslope wind were found to be delayed and greatly weakened during the MJO (Fig. 10c), which was also confirmed by our surface observations at Bengkulu and the sea breeze was not started until 0500 UTC (1200 LT; Fig. 5b). As a result, the atmosphere became less unstable, as shown by the weak upward titled negative \(\theta_e\) gradient (Fig. 9f). As the sea breeze started to blow and the instability grew larger at noon (Fig. 9h), the mountainous convection was finally triggered at about 0600 UTC (1300 LT; Fig. 9j), though its intensity was greatly suppressed. Overall, our results suggest that, besides the reduced solar heating, the weakened sea breeze played a key role in the suppression of afternoon convection, and its causes will be further discussed in section 5.

c. Midnight inland precipitation

Comparing with the afternoon convection that mainly developed over the mountains, the suppressed midnight inland precipitation had a larger scale (Fig. 8). Therefore, we examined the island-averaged microphysics induced heating and cooling (MP, Figs. 11a,b), which explicitly represent the moist processes. In general, variations of the heating/cooling were consistent with that of the precipitation, while the inland precipitation was delayed and reduced during the MJO. Interestingly, we found that cooling at lower- to midlevels (700–500 hPa; Fig. 11b) during the MJO, which was absent before. Moreover, subsidence was found below the upper troposphere at midnight simultaneously when the cooling appeared (Fig. 11d).

According to previous studies (e.g., Cifelli and Rutledge 1994; Virman et al. 2020), it is reasonable to link the cooling and the related subsidence to the stratiform precipitation, whose fraction would increase during the MJO (e.g., Morita et al. 2006; Sakaeda et al. 2017; also see Fig. 3 and Fig. S12). Figure 12 further revealed the close relationship between clouds and the anomalous cooling. While the regular diurnal cycle of convection induced the westward propagation (Fig. 12a), the clouds covered the coastal area all day along the MJO, and the stratiform-anvil clouds spread landward due to the background westerly wind from the late afternoon. Then, these clouds further covered the entire island during the following nighttime hours (Fig. 12b), inducing the anomalous cooling in midlevels (Fig. 12d).

Together with the drier atmosphere during the MJO (e.g., Fig. 2), this subsidence would suppress the possible convective activity over the island during the nighttime and also create an unfavorable condition in maintaining the weak eastward migration of mountainous convection (Figs. 8 and 11a). This evaporative cooling and subsidence may further induce the capping inversion as seen in the morning during the MJO (Fig. 9). In addition, convection over the sea may also provide the potential contribution via the compensation effect, as seen by the well-corresponded phases of vertical motions between land and sea (see Fig. S6 for heating terms and vertical velocity over the sea). To give a clear image of the subsidence and the suppressed precipitation over the island, Fig. 13 shows the cross-sectional horizontal and vertical velocities from the late evening to the next morning. In general, the vertical motions corresponded well with the simulated precipitation. The upward motion dominated the coastal region west of Sumatra Island during both PRE and MJO periods, but it was not the case over the island. Before the MJO, subsidence was seen over the mountain, accompanied by the landward wind at midlevels and the offshore wind at...
FIG. 9. In each panel, (top) cross sections of the vertical gradient of equivalent potential temperature ($d\theta_e/dz$, color shading), vertical velocities (cm s$^{-1}$, contours), and diurnal anomalies of cross-sectional wind (vectors with colored heads) during the mountainous convection initiation along with (bottom) the hourly precipitation. Contours are plotted every 2 cm s$^{-1}$, and solid lines and dashed lines show the positive and negative values, respectively. The orography is masked by light gray shading based on the surface pressure, and vertical velocities are amplified by a factor of 50 in vector plotting. Only values above the 95% confidence level (based on the Student’s $t$ test) are plotted. Note that vectors are rescaled smaller in (g)–(j) due to the increased sea breeze from 0500 UTC (1200 LT).
horizontal cooling-induced subsidence appeared at midnight (1700 UTC, the western coast (Fig. 13a). This weak subsidence may be regarded as a compensating downward flow because no clear horizontal component existed far away from the coast (Fig. 13h). Moreover, simulations also showed that the cooling-induced subsidence and its related anomalous winds remained visible until the next morning (Fig. 11d and Fig. 58).

Although our results represented the well corresponded cooling and subsidence, one may consider that the subsidence could also be related to the coastal convection which induced the strong upward motions. However, it is not case we found in Fig. 13. One fact is that the subsidence over the mountains was weaker during the PRE period than that of the MJO period, even the coastal convection on the western side of Sumatra Island was stronger. Thus, the island-scale subsidence was not induced by the coastal convection. On the other hand, while the causality is clear, the subsidence could still interact with the coastal convection via the compensation circulation, considering the correlated vertical motions over the land and the sea (Fig. 11d and Fig. 56d) and horizontal anomalous winds (Figs. 6f and 13). A recent study also argued such compensating effect between the land and the sea during another field campaign in 2017 (Nasuno 2021); however, some numerical sensitivity experiments are needed to further evaluate the detailed processes which are beyond the scope of the current study and should be one of our future works.

Another fact, that should be mentioned here, is the offshore wind in the morning (as we will discuss later) was not related to the compensation flow because no clear horizontal component was found in mid- to upper levels (Fig. 6f). Readers may also refer to Fig. 7 for a clear image of the cross-sectional flow with diurnal anomalies of moisture and potential temperature.

5. Impacts of orographic stagnation on sea breeze

As we mentioned in previous sections, the weakened sea breeze was one of the key factors in the suppression of afternoon convection. However, its origin remains unclear. One possible reason would be the reduced land–sea temperature contrast which was also mentioned in previous studies (e.g., Qian 2008, 2020; Birch et al. 2016). Comparing with the PRE period, observations showed that the surface temperature difference between Bengkulu and R/V Mirai reduced about 0.63°C in the morning during the MJO period (0000–0500 UTC, 0700–1200 LT; see Fig. 5b), while similar results were also found in our simulations (Fig. 10a). The reduced temperature contrast (i.e., lower temperature over the land and higher temperature over the sea) provided a favorable condition for the land breeze. However, observations also showed that the land–sea contrast was more likely being delayed rather than reduced because its diurnal amplitude remained similar before and during the MJO (Fig. 5). Moreover, it could not explain the offshore wind in the morning when the westerly wind dominated during the MJO (blue dashed lines in Figs. 5). In addition, although the westerly wind dominated the troposphere (Fig. 2), the offshore wind was observed in lower levels near the coast most of the day during the MJO (Figs. 5 and 10c), which also prevented/reduced the potential effect of the landward advection of temperature by the large-scale wind (e.g., Wang and Sobel 2017). Therefore, there must be other factor(s) enhancing the offshore wind.
Besides the land–sea temperature contrast, another factor may be the orographic stagnation effect, when the strong westerly wind blows toward the mountains on Sumatra Island. Similar with the observed wind profile (Fig. 5c), our simulations also showed the offshore wind near the surface to the southwest of the mountain range during the MJO period (Fig. 14; also see Fig. S9b for the 10-m wind), suggesting the existence of the orographic stagnation. However, the thermodynamically unstable
environment during the MJO period presents an unfavorable condition for orographic blocking. To check whether the stagnation effect worked during the MJO, two commonly used parameters could be used (e.g., Smith 1988, 1989): the aspect ratio of the obstacle ($r = L_y/L_x$; $L_x$ and $L_y$ are the terrain length scales in the cross- and along-orography directions, respectively) and the nondimensional normalized mountain height ($M = Nh_m/U$ or equivalently the inverse mountain height).
Froude number $U/Nh_m$; $N$ is the Brunt–Väisälä frequency, $h_m$ is the terrain height, and $U$ is the upstream background wind. Theoretically, the orographic stagnation effect is expected to occur when $M > 1$ and $r > 1$. Note that the stagnation effect was not clear during the PRE period because the background wind was generally weak and eastward (Fig. 2).

For the Sumatra Island, the aspect ratio $r$ is obviously larger than the critical value $1$ (Fig. 1), so we only calculated the nondimensional mountain height $M$. Following Reinecke and Durran (2008), we estimated two types of $N$ including the vertical averaged $N_u$ and the "bulk" subcrest $N_b$, as follows:

$$N_u = \frac{1}{h_m} \int_0^{h_m} N(z) dz; \quad N_b = \frac{g}{\theta_u - \theta_r} \frac{\theta_u}{h_m},$$

where $g$ is the gravitational acceleration, and $\theta_u$ and $\theta_r$ are the potential temperature at ridge crest and sea level, respectively. Then, the nondimensional mountain heights $M_u$ and $M_b$ could be obtained accordingly. In this study, the $h_m$ was set to 1400 m, and $\theta_u$ and $U$ were obtained at the upstream area (i.e., averaged over the region west of the R/V Mirai to avoid unexpected influences of potential blocked wind or land–sea breeze, e.g., Fig. 10 and Fig. S8).

Since the original concept of $M$ is available for steady, inviscid, dry, and unheated Boussinesq flow, we also estimated the cross-sectional flow-over ratio (FO = $F/f_{w}$; e.g., Kirshbaum 2017), which is defined as the momentum flux ratio between the flow across the height of mountain ridge ($F_l$) and the background flow ($F_w$):

$$F_l = \int_0^w \rho u z dx,$$

$$F_w = \int_0^w \rho U z dx,$$

where $u'$ and $w$ are cross-sectional and vertical wind, $\rho$ is the air density, $x_h$ is the lateral boundary that is far enough for representing the background flow, and $U'$ is the background cross-sectional wind. For simplicity, we assumed a constant air density for both $F_l$ and $F_w$, and $x_h$ was set to the place of R/V Mirai ($x_h \approx 83.2$ km). A schematic description can be found in Fig. 15b.

As shown in Fig. 15, $M_u$ and $M_b$ had similar diurnal variations, and both were much larger than the common-used criterion ($M = 1$) with the lowest value around 3.7. The radiosonde-based results showed even larger values (4.5–9.7). Meanwhile, the FO also indicates the blocking effect, while its value varies diurnally from 0.2 to 0.45 during the MJO. Considering the large $M$ and small FO we obtained here, our conclusion would not be changed even we applied any different $h_m$ or realistically varying air densities during the calculation. Thus, the orographic stagnation effect would likely occur and weaken the sea breeze during the MJO. Note that, the best way to explicitly confirm the above issue would be the numerical sensitivity experiments; however, it is beyond the scope of this study and will be one of the future works.

In addition, the compensating flow may also contribute to the weakening of the sea breeze during the MJO as we discussed in section 4c; however, it was unlikely the major factor when considering the canonical diurnal convection could also generate strong updraft over the coastal area (e.g., Fig. 13; also see Fig. S8).

### 6. Conclusions

In this study, we focused on the suppressed convection over Sumatra Island in an active phase of the MJO during the Pre-YMC observation campaign in December 2015. The afternoon convection over mountainous areas was suppressed and delayed when the MJO became active over the MC in mid-December, and the midnight convection nearly vanished. Since the radiosonde data showed only the changes in the atmospheric conditions at one spot, we also conducted cloud permitting WRF simulations with 5 ensemble members, which successfully replicated the main features of the modulated diurnal convection.
precipitation during the MJO. Convection, and, therefore, suppressed the midnight inland or the maintenance of the eastward migrating mountainous convective cooling due to the increased stratiform-anvil clouds. Analyses show that this subsidence was generated by the evaporative cooling and moistening during the morning hours enhanced the afternoon convection over Sumatra Island, which are consistent with the findings in a recent study on the YMC-Sumatra 2017 campaign (Nasuno 2021). Moreover, the major features of the 2015 MJO event (such as the suppressed convection over the land, strong westerlies, and increased fraction of stratiform clouds) are commonly found in other MJO events (e.g., Morita et al. 2006; Fujita et al. 2011; Peatman et al. 2015; Yokoi 2015). Therefore, it is natural to expect the similar features and related mechanisms would be found in other MJO events, which should be further examined in future studies, including the numerical sensitivity experiments on the cooling-induced subsidence, compensating flow, and the orographic stagnation effect. On the other hand, although our model well reproduced the diurnal variations as presented in this study, the model biases and the potential influences should be carefully treated. For example, the underestimated convection over the sea during the MJO period may modulate the diurnal land–sea circulation, resulting in a weaker compensation flow which may further influence the midnight subsidence over the land. Thus, our future study will also investigate the potential uncertainty induced by the model biases on convection in the future study.

To find why the afternoon convection was suppressed during the MJO in Pre-YMC 2015, we evaluated the conditions for convection initiation over the mountainous area. Results showed that, prior to the MJO, the lower tropospheric warming and moistening during the morning hours enhanced the instability over the mountainous areas, while the sea breeze and its related orographic lifting triggered convection over at 0400–0500 UTC (1100–1200 LT). After that, the migration of active convection induced the precipitation at Bengkulu in the late afternoon and precipitation over the sea during the nighttime, and its eastward component induced the second precipitation peak at midnight.

By contrast, during the active phase of the MJO, the atmosphere became colder and drier as shown by both the radiosonde data and our simulations. The cloudy conditions reduced the solar insolation and stabilized the lower troposphere. The afternoon convection was largely suppressed and delayed due to the reduced solar insolation and the weakened onshore wind. Moreover, we found the land–sea temperature contrast was more likely to be delayed because similar diurnal amplitudes were found before and during the MJO. On the other hand, based on the theoretical diagnostics, we found evidence that the orographic stagnation effect contributed to the weakening of onshore wind.

During the evening hours, island-scale subsidence was found over Sumatra Island, which was absent before the MJO. Our analyses show that this subsidence was generated by the evaporative cooling due to the increased stratiform-anvil clouds. Such conditions were not favorable for the inland convection or the maintenance of the eastward migrating mountainous convection, and, therefore, suppressed the midnight inland precipitation during the MJO.

Overall, this study reveals the modulation of diurnal convection over Sumatra Island by an active phase of the MJO via the combined effect of cloudy conditions, stagnation effect of topography and the cooling induced subsidence. Our results also show the potential role of land–sea interactions in convection initiation and maintenance over Sumatra Island, which are consistent with the finding in a recent study on the YMC-Sumatra 2017 campaign (Nasuno 2021). Moreover, the major features of the 2015 MJO event (such as the suppressed convection over the land, strong westerlies, and increased fraction of stratiform clouds) are commonly found in other MJO events (e.g., Morita et al. 2006; Fujita et al. 2011; Peatman et al. 2015; Yokoi 2015). Therefore, it is natural to expect the similar features and related mechanisms would be found in other MJO events, which should be further examined in future studies, including the numerical sensitivity experiments on the cooling-induced subsidence, compensating flow, and the orographic stagnation effect. On the other hand, although our model well reproduced the diurnal variations as presented in this study, the model biases and the potential influences should be carefully treated. For example, the underestimated convection over the sea during the MJO period may modulate the diurnal land–sea circulation, resulting in a weaker compensation flow which may further influence the midnight subsidence over the land. Thus, our future study will also investigate the potential uncertainty induced by the model biases on convection in the future study.

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Acknowledgments. The authors are grateful to all those who were engaged in the Pre-YMC 2015 field campaign. We thank Tomoe Nasuno and Shuichi Mori for their valuable discussions during the study and two anonymous reviewers for their constructive comments and suggestions. We also thank George H. Bryan for his CAPE/CIN calculation code (available at https://www2.mmm.ucar.edu/people/bryan/Code/getcape.F). All authors know of no conflicts of interest associated with this paper. This work is supported by JSPS KAKENHI (Grants 20K14560, 20H02252, and 20H05730) and by the authors’ institute (JAMSTEC) as the regular annual budget provided by the MEXT of Japan. The numerical experiments in this study were carried out on the JAMSTEC Super-Computer System (DA System).

Data availability statement. The observational data are available at www.jamstec.go.jp/ymc/jpn/ymcj_data.html (which is temporally unavailable due to the security incident and will be recovered soon; see https://www.jamstec.go.jp/e/about/informations/notification_2021_maintenance.html). We also thank the Japan Aerospace Exploration Agency for providing the GMSaP dataset (https://sharaku.eorc.jaxa.jp/GMSaP/). The data for the numerical model can be found at the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/; for the ERA5 dataset), and the GHRsst website (http://data.nodc.noaa.gov/ghrsst/; for the GMPE SST).

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