Environmental Conditions for Nighttime Offshore Migration of Precipitation Area as Revealed by In Situ Observation off Sumatra Island

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ABSTRACT

The diurnal cycle over tropical coastal waters is characterized by offshore migration of precipitation area during nighttime. This study analyzes in situ observational data collected during the YMC-Sumatra 2017 field campaign around the western coast of Sumatra Island, Indonesia, to examine the offshore migration phenomenon during 5–31 December 2017, when the Research Vessel *Mirai* was deployed about 90 km off the coast to perform observation. The offshore migration is observed in only less than a half of the 27 days. A comparison of radiosonde data at the vessel between days with and without the offshore migration reveals that vertical wind shear in the lower troposphere is a key environmental condition. In late afternoon of the days with the offshore migration, offshore (northeasterly) wind shear with height with considerable magnitude is observed, which is due to weaker daily mean southwesterly wind in the lower free troposphere, stronger southwesterly wind in the boundary layer, and sea breeze. As this condition is considered favorable for regeneration of convective cells to the offshore side of old ones, these results support an idea that the regeneration process is critical for the offshore migration. The Madden–Julian oscillation and cold surges play some roles in the weakening of the free-tropospheric wind. The migration speed is estimated at $2\text{--}3\text{ m s}^{-1}$, which is lower than that observed in another field campaign conducted in 2015 (Pre-YMC 2015). This difference is partly due to the difference in the environmental wind in the lower to midtroposphere.

1. Introduction

In the tropics, the diurnal cycle of convective activity and precipitation is one of the dominant sources of atmospheric variability and exhibits complicated behavior over coastal regions. While precipitation over coastal land is maximal in the afternoon and early evening, the variability over adjacent seas is characterized by offshore

migration of precipitation areas during nighttime and early morning from near the coast to sometimes several hundred kilometers off the coast (Yang and Slingo 2001). Typical examples can be found in coastal regions in the Maritime Continent such as those of Sumatra Island (Mori et al. 2004, 2011; Sakurai et al. 2005, 2009; Wu et al. 2009; Fujita et al. 2010, 2011), Malay Peninsula (Fujita et al. 2010), Borneo/Kalimantan Island (Houze et al. 1981; Ichikawa and Yasunari 2006; Wu et al. 2008), Java Island (Mori et al. 2018; Katsumata et al. 2018), and New Guinea Island (Liberti et al. 2001; Zhou and Wang 2006; Ichikawa and Yasunari 2008), as well as in other tropical regions such as the Bay of Bengal (Zuidema 2003) and

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Pacific coast of Panama and Columbia (Mapes et al. 2003a). To understand the diurnal cycle is of scientific importance, as it affects the behavior of intraseasonal variability (Wang and Li 1994; Ichikawa and Yasunari 2007; Sobel et al. 2010; Hagos et al. 2016) and the climatological radiation budget, as well as the local energy and water cycles.

Previous studies have addressed physical processes of the offshore migration and proposed possible mechanisms based on analyses of available observational data such as those from satellites, weather radars, and radiosondes launched from land sites, as well as numerical experiments. Warner et al. (2003) and Mapes et al. (2003b) proposed that gravity waves excited by nighttime radiative cooling of the elevated terrain of the Andes propagated offshore in the lower troposphere and destabilized the offshore atmosphere, contributing to the migration of the precipitation area. Love et al. (2011) and Hassim et al. (2016) also argued the role of the gravity waves that propagated in the lower troposphere, which were excited by evaporative cooling associated with convection over land, rather than by the radiative cooling. Several studies focused on diurnally excited gravity currents, such as land breeze and convective cold outflow, which trigger new convective cells to the offshore side of old ones via horizontal convergence with environmental winds or the gravity currents excited over another landmass (Houze et al. 1981; Mori et al. 2004; Wu et al. 2009; Fujita et al. 2010; Wapler and Lane 2012). Other studies such as Ichikawa and Yasunari (2006, 2008) and Yanase et al. (2017) focused on advective effect of environmental winds.

To help verify these proposed mechanisms, high-frequency observations of dynamic and thermodynamic conditions of the offshore atmosphere can provide useful information. However, routine upper-air observation is usually performed twice a day at the utmost, and there is no routine site over the sea, so it is necessary to perform special observation campaigns to collect such data. Therefore, as a pilot field campaign activity of an international overarching research initiative known as Years of the Maritime Continent (YMC), the Japan Agency for Marine–Earth Science and Technology (JAMSTEC), the Indonesian Agency for the Assessment and Application of Technology (BPPT), and the Meteorological, Climatological, and Geophysical Agency of Indonesia (BMKG) jointly conducted a field campaign, named Pre-YMC 2015 campaign, in the western coastal area of Sumatra Island in November and December of 2015. As part of the campaign, the Research Vessel (R/V) *Mirai* of JAMSTEC was deployed at a station located approximately 50 km off the coast from 23 November to 16 December. Various kinds of observation items

including 3-hourly radiosonde soundings and continuous weather radar observation were performed on board the vessel. Yokoi et al. (2017, hereafter Y17) analyzed the data collected during this campaign and demonstrated that the offshore migration was observed almost every day during the period from 23 November to 12 December, whereas the offshore migration could not be seen during 13–16 December when a convectively active phase of the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) arrived at the study area. Kamimera et al. (2012) and Peatman et al. (2014) also reported this relationship between the amplitude of the diurnal cycle and the MJO phase. Based on the analyses of the radiosonde data over the R/V *Mirai* in the former period, Y17 presented evidence that supported the idea proposed by Love et al. (2011) and Hassim et al. (2016). Specifically, Y17 found that the lower free troposphere started cooling and moistening a couple of hours before the precipitation area reached the vessel's position, playing a role in destabilization of the atmosphere. These tendencies were found to be mainly caused by vertical advection due to ascent. Y17 argued that this ascent might be associated with ascending wave front of shallow gravity waves excited by evaporative cooling caused by the convection over land and propagating offshore in the lower free troposphere ahead of the migrating precipitation area.

The Pre-YMC 2015 campaign offered a unique opportunity to examine the migration phenomenon in great detail, and Y17's argument was an important step toward the understanding of its physical processes. On the other hand, the diurnal cycle examined by Y17 took place under an easterly lower-tropospheric wind environment, and the behavior of the diurnal cycle is known to strongly depend on environmental wind conditions. Ichikawa and Yasunari (2006) examined the diurnal cycle over and around Borneo/Kalimantan Island using satellite and reanalysis datasets and revealed that the offshore migration was observed off the western (eastern) coast of the island under the environment of easterly (westerly) lower-tropospheric wind. A similar relationship was found around New Guinea Island (Ichikawa and Yasunari 2008). As for the western coastal waters of Sumatra Island, Yanase et al. (2017) found that the direction of the migration of convective precipitation systems was determined by the lower-tropospheric wind, while that of stratiform precipitation systems was modulated by upper-tropospheric wind. From these previous studies, we realized that other field campaigns in periods with different environmental conditions were required to fully understand the nature of the offshore migration. This is one of the purposes of our YMC-Sumatra 2017 field campaign conducted in the 2017/18 boreal winter

FIG. 1. Maps of (a) the Indonesian Maritime Continent and (b) the study area of the YMC-Sumatra 2017 field campaign. The square in (a) indicates the location of (b). In (b), the filled circle and square represent the positions of the R/V *Mirai* and the Bengkulu site, respectively, and the two open circles represent the 100-km range from weather radars installed at these sites. The blue rectangle shows the area where radar-estimated precipitation intensity is examined, and the blue dashed line represents the simplified coastline. Color shadings represent topography.

with similar configuration to Pre-YMC 2015. As discussed in section 3a, the environmental conditions in YMC-Sumatra 2017 were totally different from those in Pre-YMC 2015. Therefore, it seems fruitful to examine the diurnal cycle observed in YMC-Sumatra 2017 and compare its behavior with that in Pre-YMC 2015. In particular, this study focuses on the impacts of horizontal wind and thermodynamic environments over coastal waters.

The remainder of the paper is organized as follows. Section 2 presents an overview of the YMC-Sumatra 2017 campaign, observation strategy, and description of observational data analyzed in this study. Following a brief description of the large-scale environmental conditions during the campaign period in section 3a, section 3b presents observed diurnal cycle of precipitation. Sections 3c and 3d examine horizontal wind and thermodynamic profiles, respectively, to discuss what environmental conditions are critical for the offshore migration. Finally, section 4 presents a summary of the paper.

2. Data and methods

The YMC-Sumatra 2017 field campaign was conducted in the western coastal area of Sumatra Island, located in the western part of the Indonesian Maritime Continent (Fig. 1a), in the 2017/18 boreal winter, through international collaborative efforts of JAMSTEC, BPPT, and BMKG. The campaign consisted of two observation sites located on coastal water and coastal land (Fig. 1b)

where a variety of atmospheric and oceanographic observations were performed. Over the coastal water, the R/V *Mirai* was deployed at 4.24°S, 101.52°E, approximately 90 km off the coast, from 0000 UTC 5 December 2017 to 0600 UTC 1 January 2018. Note that the vessel's position is different from that in Pre-YMC 2015 (4.07°S, 101.90°E). Intensive observations were also performed at BMKG observatory in Bengkulu city (3.86°S, 102.34°E), located several kilometers from the coast, for 2 months from 16 November 2017 to 15 January 2018. Among the items of the observations, this study will examine reflectivity data of weather radars and radiosonde data for the 27-day period of 5–31 December 2017.

The reflectivity data were obtained by two weather radars installed at both sites. The R/V *Mirai* is equipped with a dual-polarized C-band Doppler radar, with which volume scan observations were performed at 6-min intervals with a ray and gate spacing of 0.7°–1° (depending on elevation angles) and 150 m, respectively, at 17 elevation angles from 0.5° to 40°. There is an operational C-band Doppler radar at the BMKG observatory, which has performed volume scan observations at 10-min intervals with a ray and gate spacing of 1° and 250 m, respectively, at 11 elevation angles from 0.5° to 19.5°.

From radar reflectivity at 2-km altitude above sea level calculated via interpolation of the volume scans, precipitation intensity was estimated with the use of a conventional reflectivity–precipitation relationship of $Z = \alpha R^\beta$, where Z indicates reflectivity (in $\text{mm}^6 \text{m}^{-1}$)

and R precipitation intensity (in mm h^{-1}). Data within a 100-km range of the radars (indicated by black circles in Fig. 1b) were used. The parameters α and β were determined through comparison of reflectivity with precipitation intensity measured by a rain gauge on-board the vessel following a method described by Yokoi et al. (2012), and comparison between reflectivity of the two radars, as done by Y17. We decided to use (α, β) of (59.0, 1.28) for the vessel's radar, and (100.4, 1.28) for the Bengkulu radar. The parameter values in principle should not be different between the two C-band radars as long as they observe the same precipitation events. The difference in the chosen parameter values between the two radars may result from those in specification of the radars, scan strategy, and data correction methods such as ground clutter elimination and attenuation correction. Although we acknowledge that this estimation method is simplistic, we believe it sufficient for examining spatiotemporal precipitation variability, and not absolute amount. More sophisticated and accurate estimation using polarimetric information obtained by the vessel's radar is left for our future study.

Because the observation intervals of the two radars are different, the estimated precipitation intensity was averaged temporally to hourly mean data for the two radars separately. Then the hourly mean data of the two datasets were averaged where they overlapped with each other. The blue rectangle in Fig. 1b is the area where the precipitation variability is examined, with long sides that run in the northeast–southwest direction of a 45-km length over the land and a 150-km length over the sea, and short sides of 130 km. We assume that characteristics of the diurnal cycle did not vary significantly for the direction parallel to the coastline and the mountain range that have quasi-linear configuration (Fig. 1b). Therefore, the precipitation intensity averaged in the northwest–southeast direction, i.e., the direction parallel to the simplified coastline, as shown by thick dashed blue line in Fig. 1b, will be examined to describe characteristics of precipitation as a function of distance from the coastline. This approach was also adopted by Mori et al. (2004), Kamimera et al. (2012), and Y17.

The radiosonde observations were performed at the two sites with 3-h intervals, with launch time 30 min before nominal time [0100, 0400, ..., and 2200 local time (LT); LT = UTC + 7 h]. The sensors used at the vessel were RS41-SGP manufactured by Vaisala Ltd., and those at Bengkulu were iMS-100 manufactured by Meisei Electronic Co. Ltd. The component of horizontal wind normal to the simplified coastline (u_n), with positive values indicating onshore (southwesterly) wind, temperature, humidity, and geopotential height are analyzed in

FIG. 2. Anomalies of 850-hPa horizontal wind (vector) and SST (color shadings) in (a) December 2015 and (b) December 2017 from December climatology (1985–2014 mean). The reference vectors at the lower right of the panels represent 5 m s^{-1} . Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) is used for the wind, and COBE-SST (Ishii et al. 2005) dataset is used for SST.

this study. The vertical resolution of the data analyzed is 10 hPa.

Two-sided Welch's t test and Student's t test are employed to assess statistical significance of results. The 95% confidence level is used to judge the significance.

3. Results and discussion

a. Overview of the large-scale conditions

Before examining the diurnal cycle, we briefly describe the overall large-scale conditions in the campaign periods. Figure 2 shows monthly sea surface temperature (SST) and 850-hPa horizontal wind anomalies in December 2015 and 2017 from December climatology, which represent different El Niño–Southern Oscillation (ENSO) phases between Pre-YMC 2015 and YMC–Sumatra 2017. In Pre-YMC 2015 (Fig. 2a), positive SST anomalies exceeding +3 K were observed in the tropical eastern Pacific and accompanied by westerly wind anomalies over the tropical central Pacific, which are typical of mature El Niño condition. Weak easterly wind anomalies were found over the study area, presumably associated with weakening of the ascending branch of the Walker circulation over the Indonesian Maritime Continent during El Niño. In contrast, in YMC–Sumatra 2017 (Fig. 2b), negative SST anomalies elongated along the tropical eastern Pacific, suggestive of mature La Niña condition, and strong westerly wind

FIG. 3. (a) Longitude–time cross section of precipitation of the Global Satellite Mapping of Precipitation (GSMaP; Okamoto et al. 2005) standard product version 7, averaged between 10°S and the equator for the period from November 2017 to January 2018. Vertical lines indicate the longitude and the period of the intensive observation, with squares (circles) representing the start and end dates of the observation at Bengkulu (the R/V *Mirai*). Dashed lines indicate MJO convective envelopes. (b) As in (a), but for zonal wind at the 850-hPa level of the JRA-55 dataset. (c) The RMM index phase diagram for November 2017 (blue), December 2017 (red), and January 2018 (green). Numbers over the trajectory indicate day of the month for every 5 days.

anomalies dominated over and around the Maritime Continent.

Figure 3a shows a longitude–time cross section of satellite-based precipitation data averaged between 10°S and the equator, from November 2017 to January 2018. Precipitation occurred mostly in the longitudinal band from 60°E and 180°, whereas the equatorial eastern Pacific (180°–120°W) was dry. In intraseasonal time scales, two large precipitation events were found over the eastern Indian Ocean (60°–90°E) in late November and late December and moved eastward toward 180° at speeds of 3–4 m s⁻¹, as indicated by dashed lines. These events were accompanied by lower-tropospheric westerly wind (Fig. 3b). Based on these characteristics, these eastward-propagating events can be regarded as MJO convective envelopes. This view is supported by Real-time Multivariate MJO (RMM) index (Wheeler and Hendon 2004) shown in Fig. 3c. The RMM index rotated counterclockwise from phase 3 to 6 in two periods from late November to early December, and from middle to late January. This corresponds to the MJO convective envelope moving from the eastern Indian Ocean to the western Pacific. As shown by filled circles in Figs. 3a and 3b, observation activity at the coastal water site using the vessel was performed during the period between the passages of the two

convective envelopes, when the RMM index progressed from phase 6 to 2.

b. Precipitation diurnal cycle

Figure 4 shows time series of precipitation during the 27-day period in the blue rectangle plotted in Fig. 1b as a function of the distance from the simplified coastline. The offshore migration is represented in the figure as a band with large amount of precipitation extending from upper right to lower left. Several migration events can be seen. For example, on 18, 19, and 21 December, precipitation peaks appeared over inland in early afternoon and then migrated offshore, reaching approximately 80 km from the coast. Migration phenomena were also found on 11, 29, and 31 December, although they were less obvious with some gaps. In contrast, several cases of onshore migration on 13, 15, 23, and 26 December were noted; however, they occurred at different times of the day and thus seemed not to be associated with the diurnal cycle. In summary, the offshore migration phenomena were observed in only less than a half of the 27 days. Such less regular feature of the offshore migration is in contrast to the Pre-YMC 2015 case; Y17 reported that the offshore migration was observed almost every day during the period from 23 November to 12 December 2015, as discussed in section 1.

FIG. 4. Time series of radar-estimated precipitation (mm h^{-1}) as a function of distance from the simplified coastline for 5–31 Dec 2017. The horizontal axis represents the distance defined as the direction toward land being positive, and the vertical axis represents time. Vertical dashed lines represent the positions of the vessel (left) and the coast (right), and horizontal dashed lines indicate 0700 LT on each day.

Figure 5 shows mean diurnal cycle (MDC) of precipitation, which is calculated by making composites of the data at each hour of the day during the 27 days, as done in Y17. Despite being a less regular feature, the offshore migration signal is recognizable in the MDC, suggesting that this is a dominant feature of diurnal variability during the period. Over the southwestern slope of the mountain range (Fig. 1b), precipitation is inactive in the predawn and morning, and then it starts increasing around noon and reaches a maximum at 1400 LT. Then the precipitation peak appears to migrate seaward and cross the coastline at around 2200 LT. Over the coastal waters, while precipitation is inactive in the afternoon and early evening, the peak moves offshore in the late evening and predawn, reaching 60 km off the coast at 0600 LT. Farther away from the coast, the offshore migration

phenomenon is much less clear, whereas some hint of the onshore migration from the open sea can be found. Note that precipitation over the mountain slope occurs over a much shorter time period than that over the sea, implying smaller day-to-day variability over land in terms of precipitation time. Over waters within 60 km from the coast, the average speed of the front of the offshore-migrating area, which is defined here as an edge of the dark blue shadings in Fig. 5, can be estimated at $\sim 3 \text{ m s}^{-1}$, and the precipitation peak seems to migrate at a slightly lower speed ($2\text{--}3 \text{ m s}^{-1}$).

The MDC of precipitation during Pre-YMC 2015 exhibited faster offshore migration. According to Y17, precipitation over the inland part of the study area started increasing around noon and reached a maximum at 1500 LT, which is very similar to the YMC-Sumatra 2017

FIG. 5. MDC of radar-estimated precipitation (mm h^{-1}) as a function of distance from the simplified coastline for 5–31 Dec 2017. Plots in 0700–1900 LT are repeated for clarity. Vertical dashed lines represent the positions of the vessel (left) and the coast (right), and the thick dashed line represents offshore migration speed of 3 m s^{-1} . Parallelograms with the symbols A to C are used for the determination of OM and NoOM days (see text for details).

case. Then the precipitation peak also migrated seaward, crossed the coastline as early as 1800 LT, and passed over the vessel's position of Pre-YMC 2015 ($\sim 40 \text{ km}$ off the coast) at around 2100–2200 LT. Y17 estimated the migration speed of the front of the precipitation area at 8 m s^{-1} , and that of the precipitation peak at $3\text{--}3.5 \text{ m s}^{-1}$. A possible reason for the difference in the migration speed between the two periods will be discussed in next subsection.

What environmental conditions are responsible for the occurrence of the offshore migration will be examined in the following sections. For this purpose, days with clear offshore migration are identified by the following procedure. First precipitation is averaged over three domains represented in Fig. 5 as parallelograms A, B, and C, for individual days (P_A , P_B , and P_C). Then the geometric mean of P_A and P_B (P_{AB}) is defined as a precipitation measure in the migrating area. After removing days with $P_C \geq 0.3 \times P_{AB}$ (i.e., days with active precipitation hours before the offshore migration takes place), we choose

9 days in descending order of P_{AB} as the clear offshore migration days (OM days). The selected days are 10, 11, 16, 18, 19, 20, 22, 29, and 31 December. The other 18 days are referred to as non-OM days (NoOM days). Note that 21 December is categorized into a NoOM day, although the offshore migration can be seen in Fig. 4. This discrepancy is associated with onshore migrating areas just before the appearance of the offshore migration, which leads to $P_C \geq 0.3 \times P_{AB}$.

To check whether this approach works well, Fig. 6 compares the MDC of precipitation of the 9 OM days with that of the 18 NoOM days, from 0700 LT of the OM and NoOM days (Day 0) to 1900 LT of the following day (Day +1). It seems that the characteristics of the offshore migration of the OM-day composite (Fig. 6a) are qualitatively similar to the MDC of all the 27 days (Fig. 5), including the migration speed. The magnitude of precipitation is much larger, and the difference between the OM days and the NoOM days is statistically significant over most parts of the waters within 60 km from the coast during nighttime. These results imply that the above method determines the days with the clear offshore migration fairly well. On the other hand, the precipitation amount of the onshore-migrating signal from the open sea is also larger in the OM days than in the NoOM days, particularly between 1900 LT of Day 0 and 0700 LT of Day +1, although the difference is not significant. It may be interesting to examine how the offshore-migrating and onshore-migrating systems interact, but this subject is beyond the scope of this paper and thus left for our future study.

c. Wind environment

As argued in the last subsection, the mean migration speed of the front (peak) of the offshore migration in YMC-Sumatra 2017 were lower than that in Pre-YMC 2015 by $\sim 5 \text{ m s}^{-1}$ ($\sim 1 \text{ m s}^{-1}$). To examine factors responsible for this difference, Fig. 7 compares mean vertical profile of u_n between Pre-YMC 2015 (23 November to 12 December 2015) and YMC-Sumatra 2017 (5–31 December 2017). Note that for the Pre-YMC 2015 mean, we examine the 20-day period when the offshore migration was regularly observed and thus Y17 focused on. By definition, positive u_n indicates southwesterly (onshore) wind, while negative u_n indicates northeasterly (offshore) wind. While northeasterly wind dominates in the free troposphere above the 900-hPa level in Pre-YMC 2015, southwesterly wind prevails in the lower half of the troposphere from the surface to the 300-hPa level during YMC-Sumatra 2017, at both the vessel and Bengkulu. In the lower to middle free troposphere (850–500-hPa layer), the difference is $5\text{--}7 \text{ m s}^{-1}$ and statistically significant (Fig. 7c). This difference is consistent with the

FIG. 6. (a) MDC of radar-estimated precipitation (mm h^{-1}) of the 9 OM days, from 0700 LT of the OM days (Day 0) to 1900 LT of the following day (Day +1). Circles (crosses) indicate that the OM-day composite is larger (smaller) than the NoOM-day composite with statistical significance at the 95% confidence level, as assessed by Welch's t test. (b) As in (a), but for the 18 NoOM days. Circles (crosses) indicate that the NoOM-day composite is larger (smaller) than the OM-day composite with statistical significance.

difference in the speed of the front, suggesting that the difference in the migration speed is in part due to the advection of the convective systems by the environmental winds. The impact of the lower-tropospheric wind on the speed, and even the direction, of the migration has also been reported in previous studies, such as Ichikawa and Yasunari (2006, 2008) and Yanase et al. (2017).

The difference in u_n in the lower troposphere is due mostly to the zonal wind component rather than the meridional wind component; easterly wind dominated in Pre-YMC 2015 (Figs. 2a and 8 of Y17) whereas westerly wind dominated in YMC-Sumatra 2017 (Figs. 2b and 3b). As stated in Y17 and section 3a, during Pre-YMC 2015, El Niño was developing (Fig. 2a) with active convection in the central tropical Pacific, and the MJO was inactive

FIG. 7. (a) Mean vertical profile of u_n at the vessel (blue) and Bengkulu (red) for 23 Nov–12 Dec 2015 (Pre-YMC 2015 period). (b) As in (a), but for 5–31 Dec 2017 (YMC-Sumatra 2017 period). (c) As in (a), but for the difference of u_n for the Pre-YMC 2015 period from that for the YMC-Sumatra 2017 period. Light blue and light red lines indicate that the differences are smaller than the 95% confidence level, as assessed by Welch's t test.

FIG. 8. As in Fig. 7, but for (a) the OM days, (b) the NoOM days, and (c) the difference of u_n in the OM days from that in the NoOM days.

or had its convective envelope over the Indian Ocean during the period when the diurnal cycle was active, both of which led to the easterly wind in the lower troposphere. In contrast, during YMC-Sumatra 2017, La Niña was established (Fig. 2b), leading to the westerly wind in the lower troposphere.

Another difference in u_n can be found in the vertical shear below the 700-hPa level. In Pre-YMC 2015, southwesterly wind is observed in the boundary layer below the 900-hPa level, with a positive maximum of u_n around the 950-hPa level, while northeasterly wind is found in the lower free troposphere. These constitute offshore wind shear with height (positive $\partial_p u_n$), or equivalently, southeastward horizontal vorticity. On the other hand, in YMC-Sumatra 2017, u_n increases monotonically (i.e., negative $\partial_p u_n$) from the surface up to the 700-hPa level. The magnitude and direction of the environmental shear over the coastal waters are important for the proposed mechanism that the low-level horizontal convergence due to the cold outflow and the environmental wind generates new convective cells to the offshore side of old ones and thus contribute to the offshore migration (Houze et al. 1981; Mori et al. 2004; Sakurai et al. 2009, 2011). This is because this regeneration process favors the condition that the environmental vertical shear is in opposite direction and has comparable magnitude to the vertical shear induced by the cold outflow (Rotunno et al. 1988). As the cold outflow to the offshore side of the convective cells have onshore vertical shear (negative $\partial_p u_n$), the positive $\partial_p u_n$ environment is favorable for the regeneration process to trigger new convection there.

While $\partial_p u_n$ averaged over the 27 days in YMC-Sumatra 2017 is negative, its sign is different between the OM and NoOM days. Figure 8 shows composite u_n profile of the OM and NoOM days. The composite u_n of the NoOM days increases monotonically from the surface to the 750-hPa level at both sites, as in the 27-day average (Fig. 7b). In contrast, the composite u_n of the

OM days at the vessel has a positive maximum at the 950-hPa level and positive $\partial_p u_n$ in the 950–800-hPa layer, which is rather qualitatively similar to the Pre-YMC 2015 mean (Fig. 7a). The differences at the vessel between the two composites (Fig. 8c) are positive and statistically significant in the boundary layer below the 950-hPa level and negative and significant in the lower free troposphere (850–750-hPa level), and thus the difference in $\partial_p u_n$ is also significant (not shown). On the other hand, at Bengkulu, while the difference in the lower free troposphere is similar to that at the vessel, the difference in the boundary layer is negligible.

Interestingly, similar contrasts in the wind shear were observed also in Pre-YMC 2015. As revealed in Fig. 4 of Y17, which shows time series of precipitation in Pre-YMC 2015, there were 2 days (26 November and 8 December 2015) when the offshore migration was not clear, in addition to 13–16 December as mentioned in section 1. The time–vertical cross section of u_n during the Pre-YMC 2015 period (not shown) reveals that $\partial_p u_n$ in these 6 days was negative.

While these results suggest that the direction of the daily mean environmental wind shear in most of the Pre-YMC 2015 period and the OM days is favorable for the regeneration process to contribute to the offshore migration, the magnitude of the daily mean shear does not seem to be large enough. According to LeMone et al. (1998), over tropical oceanic regions, squall lines, in which the regeneration process is essential, are generally observed in the environment of low-level wind shear stronger than $2 \text{ m s}^{-1} (100 \text{ hPa})^{-1}$ in the 1000–800-hPa layer. From Fig. 7a, $\partial_p u_n$ averaged over the Pre-YMC 2015 period is $+1.9 \text{ m s}^{-1} (100 \text{ hPa})^{-1}$ between the 950- and 810-hPa levels, slightly smaller than this threshold value. The composite $\partial_p u_n$ of the OM days is as small as $+0.9 \text{ m s}^{-1} (100 \text{ hPa})^{-1}$ between the 940- and the 820-hPa levels.

However, it is premature to conclude that the regeneration process did not take place, because vigorous

FIG. 9. (a)–(c) Vertical profile of MDC of u_n at the vessel in (a) the OM days and (b) the NoOM days, and (c) the difference of u_n in OM days from that in NoOM days. The contour interval is 0.5 m s^{-1} . Warm (cold) colors represent positive (negative) values. In (c), yellow and pale blue shadings represent that the difference is statistically significant at the 95% confidence level, as assessed by Welch's t test. (d)–(f) As in (a)–(c), but at Bengkulu.

sea- and land-breeze circulations may affect the vertical structure of u_n during the course of the day. According to Finkle (1998), while the sea breeze circulation first appears in the morning near the coast, the area with the sea breeze circulation extends offshore as well as onshore during daytime. As the sea breeze circulation leads to positive $\partial_p u_n$, it can increase the magnitude of the shear over the coastal waters in the afternoon of the OM days. The MDC of u_n over the vessel in the OM days (Fig. 9a) and the NoOM days (Fig. 9b) actually has positive temporal maxima at 1600 or 1900 LT in the boundary layer, indicative of the sea breeze. In the OM days, while the low-level $\partial_p u_n$ is negative in the predawn and morning, positive $\partial_p u_n$ is observed in the afternoon and early evening, a couple of hours before the migrating precipitation area reached the vessel's position (Fig. 6a). The magnitude of the shear at 1900 LT is $+2.4 \text{ m s}^{-1} (100 \text{ hPa})^{-1}$ between the 960- and the 820-hPa levels, which is above the threshold value proposed by LeMone et al. (1998). Note that similar analysis for the Pre-YMC 2015 period (not shown) reveals that

the composite $\partial_p u_n$ reached $+2.7 \text{ m s}^{-1} (100 \text{ hPa})^{-1}$ at 1600 LT. In contrast, in the NoOM days, the diurnal cycle does not change sign of the shear; $\partial_p u_n$ is negative from the surface to the 750-hPa level throughout the day.

The difference of composite u_n of the OM days from that of the NoOM days (Fig. 9c) is positive in the boundary layer and negative in the lower free troposphere throughout the day, which is consistent with Fig. 7c. Furthermore, the difference in the afternoon and early evening is statistically significant with a larger magnitude than in the predawn and morning, which means that the diurnal cycle has larger amplitude in the OM days. These results suggest that not only the daily mean feature but also the diurnal cycle are responsible for the difference in the vertical structure of u_n and positive $\partial_p u_n$ in the late afternoon with large enough magnitude in the OM days. Note that the daily mean feature can be considered as a background environmental condition for the offshore migration, while the diurnal cycle in u_n and the offshore migration are possibly interrelated.

At Bengkulu, the MDC of u_n (Figs. 9d,e) in the boundary layer is characterized by clear replacement between southwesterly wind during the daytime and northeasterly wind during the nighttime, which is arguably due to the sea- and land-breeze circulations, respectively. Interestingly, the impact of the diurnal cycle on the vertical structure of u_n is similar between the OM and NoOM days, at least in the boundary layer. The fact that the qualitative difference between the OM and NoOM days is evident only at the vessel's position suggests an advantage of conducting intensive observation over the coastal waters. In the lower free troposphere, on the other hand, the difference between the OM and NoOM days (Fig. 9f) is similar to that over the vessel.

It seems reasonable to imagine that variability in large-scale circulation may cause the difference in the daily mean u_n between the OM and NoOM days. As stated in section 3a, the RMM index progressed from phase 6 to 2 during the 27 days. A statistical analysis using the Japanese 55-year Reanalysis (JRA-55; Kobayashi et al. 2015) data and the RMM index over the 20-yr (1997–2016) December seasons (Fig. 10) reveals that the 850-hPa u_n near the study area has the positive maximum at phase 5 and the negative maximum at phase 2. Therefore, the MJO phase progression tended to cause weaker southwesterly wind in the second half of the 27-day period than in the first half. As majority of the OM days were in the second half, it can be said that the MJO circulation probably played some roles in the difference in the daily mean u_n in the lower free troposphere between the OM and NoOM days. On the other hand, the stronger boundary layer southwesterly in the OM days is not due to the MJO circulation, as the 1000-hPa u_n varies with the MJO phase in a quite similar manner to the 850-hPa u_n .

Figure 11 further compares 850- and 1000-hPa horizontal wind fields averaged over the OM days with those over the NoOM days. At both levels, while westerly or northwesterly wind prevails in the Southern Hemisphere, strong northeasterly wind is found over the South China Sea (SCS), which is a typical feature in December as a component of Asian winter monsoon circulation. This SCS northeasterly wind is stronger in the OM days than in the NoOM days (Figs. 11c,f). It is well known that the variability of the SCS northeasterly wind in boreal winter is caused mainly by the cold surge, a cold mid-latitude air mass progressing southward over the eastern Eurasian Continent and adjacent seas. The cold surge signal first appears around 40°N in association with a trough–ridge system, and then expands to low latitudes within a few days (Compo et al. 1999). After arriving at the SCS, the cold surge tends to intensify the convective activity over the SCS, Vietnam, and windward side of

FIG. 10. The u_n at 850-hPa (solid) and 1000-hPa (dashed) levels at 5°S, 100°E in 20-yr (1997–2016) December seasons as a function of the MJO phase.

Borneo Island and Java Island (Chang et al. 1979, 2005; Johnson and Priegnitz 1981; Yokoi and Matsumoto 2008; Hattori et al. 2011).

At the 850-hPa level, the influence of the stronger cold surge seems to reach the Indian Ocean across Sumatra Island (Fig. 11c), although the surge itself recurves southeastward at around the equator toward the Java Sea (Fig. 11a). The difference of u_n in the OM days from that in the NoOM days (color shadings in Fig. 11c) shows that an area with negative values greater than -1 m s^{-1} extends from the SCS to the west of Sumatra Island, where the radiosonde observations also exhibited negative values (Fig. 8c). This suggests a possibility that the cold surge also plays some roles in the occurrence of the offshore migration, via modulating the environmental wind in the lower free troposphere, although the physical process behind this is unclear at this moment. To examine further the relationship between the cold surge and the offshore migration, Fig. 12 shows the time series of a cold surge index over the SCS, defined by Yokoi and Matsumoto (2008) as the 3-day running mean of meridional wind anomaly at the 925-hPa level averaged over 110°–120°E along 20°N, with respect to the monthly average in December 2017. Days with the index negatively larger than minus one standard deviation are considered as those with cold surges. There were 9 days when the index passed this threshold, all of which were in the second half of the month (17–23 and 29–31 December). Among the 9 surge days, 6 days are categorized into the OM days, which suggests that the cold surge might occasionally play some role in the offshore migration. On the other hand, there are 3 OM days when the cold surge is weak or absent, all of which are in the first half of the 27 days. This implies that large-scale atmospheric disturbances other than the

FIG. 11. (a)–(c) Composite horizontal wind at the 850-hPa level in (a) the OM days and (b) the NoOM days, and (c) the difference of the OM-day composite from the NoOM-day composite. Unit vector on the right of each panel represents 10 m s^{-1} . The red circle and square represent the positions of the R/V *Mirai* and the Bengkulu site, respectively. In (c), color shadings indicate differences of u_n in the OM days from that in the NoOM days. (d)–(f) As in (a)–(c), but for the 1000-hPa level.

MJO and cold surge might contribute to these offshore migration events.

In contrast to the 850-hPa level, at the 1000-hPa level, while the u_n difference over the SCS is negative and greater than -1 m s^{-1} , the area of large negative values does not extend beyond Sumatra Island (Fig. 8f). On the contrary, the difference around the vessel's position is slightly positive. Although the sign is consistent with the radiosonde data (Fig. 8c), the difference in the reanalysis data is only marginal, whereas that in the radiosonde data is much larger and statistically significant. Presumably, the significant positive difference is caused by processes not represented by the atmospheric reanalysis system of JRA-55. At this moment, it is unclear what caused this positive difference in the boundary layer, and we want to leave this topic for future work.

d. Thermodynamic profile over the R/V *Mirai*

Besides the wind environments examined thus far, thermodynamic environments may also play roles in the offshore migration. In particular, thermally unstable condition for cumulus convection is considered to be favorable for the offshore migration. Hassim et al. (2016) analyzed their numerical simulations of the offshore migration

north of New Guinea Island and compared the thermodynamic conditions between days when the offshore migration was simulated and those when the simulated precipitation was found only over the island. They reported that convective available potential energy (CAPE)

FIG. 12. Time series of a cold surge index defined as the 3-day running mean of meridional wind anomaly at the 925-hPa level averaged over 110° – 120° E along 20° N, with respect to the monthly average in December 2017. Dashed line represents minus one standard deviation. Arrows indicate the OM days.

FIG. 13. (a) Mean vertical profile of equivalent potential temperature (solid) and saturated equivalent potential temperature (dashed) at the vessel at 1600 LT for 23 Nov–12 Dec 2015 (red) (Pre-YMC 2015) and 5–31 December 2017 (blue) (YMC-Sumatra 2017). (b) As in (a), but at 1900 LT of the OM days (red) and the NoOM days (blue). (c),(d) As in (a), (b), respectively, but for relative humidity, and the vertical axis ranges from the 1000- to 500-hPa levels.

was higher and middle troposphere was moister in the days with the offshore migration. Figure 13a shows vertical profiles of equivalent potential temperature (θ_e) and saturated equivalent potential temperature (θ_e^*) at the vessel at 1600 LT averaged over the Pre-YMC 2015 period and over the YMC-Sumatra 2017 period. The reason why the profiles at 1600 LT are examined is because the migrating precipitation area reached the vessel's position by 1800 LT on average in Pre-YMC 2015 (Y17). It is shown that θ_e^* , and thus temperature, are higher through the depth of the troposphere in Pre-YMC 2015 than in YMC-Sumatra 2017, with larger difference in the lower troposphere below the 700-hPa level. The mean CAPE at 1600 LT in Pre-YMC 2015 is 2042 J kg^{-1} while that in YMC-Sumatra 2017 is 1644 J kg^{-1} , and the difference

(398 J kg^{-1}) is statistically significant at the 95% confidence level.

Figure 13b compares the thermodynamic profiles between the OM and NoOM days at 1900 LT, a couple of hours before the migrating precipitation area reached the vessel's position on average. While the differences between the OM and NoOM days are smaller than those between Pre-YMC 2015 and YMC-Sumatra 2017, the midtroposphere (600–300-hPa layer) is cooler in the OM days than in the NoOM days, while the boundary layer below the 950-hPa level is warmer in the OM days. The mean CAPE at 1900 LT of the OM days is 2250 J kg^{-1} while that of the NoOM days is 1816 J kg^{-1} , and the difference (434 J kg^{-1}) is also statistically significant at the 95% confidence level.

Potential temperature tendency

FIG. 14. (a) Vertical profile of MDC of potential temperature tendency at the vessel for 5–31 Dec 2017. Contour intervals are 0.2 K (3h)^{-1} , and yellow (pale blue) shadings indicate that the tendency is positive (negative) and statistically significant at the 95% confidence level, as assessed by Student's t test. (b) Potential temperature tendency at the vessel at 1900–2200 LT of the OM days (red) and the NoOM days (blue). Circles indicate that the tendency is statistically significant at the 95% confidence level.

While these results indicate thermally more unstable conditions in the OM days, the mean CAPE in the NoOM days seems to be high enough to sustain convective activity, so it is difficult to say that the thermodynamic conditions determine whether the offshore migration occurred. Note that the difference in CAPE is smaller than that presented by Hassim et al. (2016), which estimated daily mean CAPE averaged over a coastal area at $\sim 2100 \text{ J kg}^{-1}$ in the days with the offshore migration and $\sim 1400 \text{ J kg}^{-1}$ in the days without it.

In contrast to θ_e and θ_e^* , relative humidity profiles (Figs. 13c,d) are not so different between Pre-YMC 2015 and YMC-Sumatra 2017, and between the OM and NoOM days. An increase of relative humidity with height in the boundary layer and gradual decrease in the lower free troposphere are found in all the four profiles. Column relative humidity (vertically integrated specific humidity divided by vertically integrated saturated specific humidity) is about 80% for all the cases.

As mentioned in section 1, Y17 found that, in Pre-YMC 2015, cooling and moistening in the lower free troposphere were observed a couple of hours before the arrival of the migrating precipitation area and associated with ascent, and argued that this ascent might be associated with the shallow gravity waves. It is interesting to examine whether such tendencies can also be found in YMC-Sumatra 2017. Figure 14a shows the MDC of potential temperature tendency over the 27 days. Lower-tropospheric negative tendencies in the late afternoon

and early evening exhibit vertically tilted structure as in Pre-YMC 2015 (Fig. 11a of Y17). At 1900–2200 LT, negative tendencies with statistical significance are observed in the 900–800-hPa layer, while the tendency is marginal in the boundary layer, which is a quite similar feature to that found at 1600–1900 LT in Pre-YMC 2015. Examination of the water vapor mixing ratio tendencies (not shown) reveals that this cooling is accompanied by moistening with magnitude fairly consistent with the assumption that these tendencies are caused by ascent. Interestingly, both of the OM-day and NoOM-day composite exhibits cooling at 1900–2200 LT in this layer with statistical significance, although the cooling rate is higher in the OM days than in the NoOM days (Fig. 14b). These results suggest that the cooling and associated ascent in the lower free troposphere may not be sufficient conditions for the offshore migration.

4. Summary

The diurnal cycle over the tropical coastal waters is characterized by the offshore migration of areas with large precipitation during the nighttime and early morning. While a number of studies have addressed the main causes of the migration and proposed a variety of mechanisms, detailed observation data of the offshore atmosphere that are considered to be of particular importance for verifying the proposed mechanisms have been lacking. With one of the purposes being to obtain

such data, JAMSTEC, BPPT, and BMKG jointly conducted an intensive observation campaign in the western coastal area of Sumatra Island in the 2017/18 boreal winter, named YMC-Sumatra 2017. This campaign consisted of two observation sites; one is over the coastal waters using the R/V *Mirai* and the other is the BMKG observatory in a coastal city Bengkulu. This study examined observed characteristics of the diurnal cycle in the 27-day period of 5–31 December 2017, when the R/V *Mirai* was on station, and argued what environmental factors were responsible for the occurrence of the offshore migration and its speed, via a comparison between days when the offshore migration was observed (OM days) and the other days (NoOM days), and a comparison with observed characteristics in another field campaign (Pre-YMC 2015) with similar configuration to YMC-Sumatra 2017. The ENSO phases were completely different in the two campaigns that led to different environmental wind conditions: La Niña (El Niño) phase in the YMC-Sumatra 2017 (Pre-YMC 2015) period (Fig. 2).

The major findings of this study are summarized as follows:

- 1) The offshore migration phenomenon was observed in only less than a half of the 27 days. This was in contrast to the Pre-YMC 2015 period, when the migration phenomenon was found almost every day (Y17).
- 2) Mean migration speed was also different between the two campaigns, and this difference was partly due to the difference in the environmental wind field in the lower to midtroposphere.
- 3) The component of horizontal wind normal to the simplified coastline (u_n) over the coastal waters was remarkably different between the OM and NoOM days. In the afternoon and early evening of the OM days, southwesterly (onshore) wind was stronger in the boundary layer than in the lower free troposphere, leading to the offshore wind shear (positive $\partial_p u_n$) in the lower troposphere, while $\partial_p u_n$ is negative in the predawn and morning hours. In contrast, in the NoOM days, $\partial_p u_n$ was negative during the course of the day.
- 4) Both the daily mean feature and the diurnal cycle were responsible for the difference in the vertical structure of u_n between the OM and NoOM days and positive $\partial_p u_n$ in the afternoon and early evening of the OM days.
- 5) The MJO circulation and the cold surge over the SCS played some roles in the difference in u_n in the lower free troposphere between the OM and NoOM days.
- 6) The thermodynamic environmental conditions of the offshore atmosphere did not exhibit qualitative differences between the OM and NoOM days. Convective available potential energy (CAPE) is considerably high even in the NoOM days, and relative humidity profiles are almost the same between the OM and NoOM days.
- 7) The cooling in the lower free troposphere in the late afternoon over coastal waters, which was observed in Pre-YMC 2015 (Y17), was also found in both the OM and NoOM days, and was probably associated with the ascent. This implies that the preconditioning by the shallow gravity waves might not be a sufficient condition for the offshore migration.

Our findings suggest that the direction and magnitude of the environmental low-level wind shear over the coastal waters are important for the offshore migration. This is in line with an idea that the regeneration process of the convective cells is the major physical mechanism for the offshore migration off Sumatra Island (e.g., Mori et al. 2004; Sakurai et al. 2009, 2011). As the cold outflow to the offshore side of the developed convective cells induces negative $\partial_p u_n$ (or northwestward vorticity), positive $\partial_p u_n$ (southeastward vorticity) with adequate magnitude is a key to the regeneration process to trigger new convective cells. A comparison with the threshold value proposed by LeMone et al. (1998) suggests that the environmental shear in the late afternoon of the OM days is strong enough for the regeneration process to take place. Note that not only the daily mean wind profile but also the sea breeze are important for the adequate offshore shear environment for the regeneration process.

It should also be noted that some of the above results were obtained precisely because we performed the radiosonde observation over the coastal water for as long as nearly a month, which is one of the advantages of the two field campaigns. As far as we know, there is no study that presents the vertical structure of horizontal wind to the offshore side of the diurnally migrating precipitation area in the tropics using in situ observational data.

In recent years, high-resolution numerical models that explicitly represent cumulus convection are used to simulate the migration phenomena, assisting in examining the physical processes for the migration (e.g., Peatman et al. 2015; Birch et al. 2016; Hassim et al. 2016; Vincent and Lane 2016, 2017). These studies realized that the simulated diurnal cycle still had some biases, such as those in the migration speed, time, and magnitude of the precipitation peak. It seems interesting to examine whether these models successfully simulate the contrast between the OM and NoOM days and dependency of the migration feature on the lower-tropospheric u_n profile over the coastal waters that this study revealed via the analysis of the in situ observations.

This study is the first step of research activity to investigate the diurnal cycle and the offshore migration via

analyses of the observational data obtained in YMC-Sumatra 2017, and several research issues still need to be considered, in addition to those already mentioned above. For example, relationship between the diurnal cycle and the MJO should be examined more in detail. While lots of studies examined how the behavior of the diurnal cycle depends on the MJO phase, it seems also interesting to examine whether we can see evidence of the impact of the diurnal cycle on the MJO behavior in the observational data. In addition to the MJO and the cold surge, equatorial waves and tropical cyclones over the Indian Ocean may also modulate the behavior of the diurnal cycle, which is another topic of interest. We will pursue analyses of the YMC-Sumatra 2017 and Pre-YMC 2015 observational data to address these issues in our future study.

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