Diurnal Variation of Surface Heat Fluxes off the West Coast of Sumatra Island as Revealed by In Situ Observation

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Abstract

Given vigorous mean diurnal variation (MDV) of cumulus convection and surface wind over coastal waters of the Indonesian Maritime Continent, surface sensible and latent heat fluxes (SHF and LHF) are expected to also exhibit significant MDV. However, it is difficult to grasp characteristics of MDV of these fluxes due to lack of surface observation data. Recently, two intensive observation campaigns were conducted off the west coast of Sumatra Island in austral summer, which offer us a unique opportunity to examine the characteristics of convection and the fluxes. This study analyzes these observations to reveal that the MDV of both SHF and LHF has considerable amplitude compared with the average. The MDV of SHF is primarily caused by that of surface wind speed, in which both the MDV of convection and sea/land breezes play roles. Furthermore, there are qualitative differences in the MDV of the fluxes between the two campaign periods, which can be explained from the viewpoint of differences in phase and intensity of MDV of convection and the sea/land breezes.

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1. Introduction

Diurnal variation of cumulus convection is known to be vigorous in the Indonesian Maritime Continent (IMC), which consists of many islands and coastal waters surrounding them, and thus has been examined by many studies (e.g. Mori et al. 2004; Yokoi et al. 2017, 2019). As the convection can enhance surface sensible and latent heat fluxes (SHF and LHF) through spreading of convective cold outflow over the surface, these fluxes are expected to also exhibit diurnal variation. Furthermore, alternation of sea and land breezes is conspicuous (Hashiguchi et al. 1995; Short et al. 2019), which modulates surface wind speed and thus the fluxes. As these fluxes are considered to energize several types of large-scale atmospheric disturbances such as the Madden-Julian oscillation (MJO; Madden and Julian 1971, 1972), to understand variation of the fluxes is important for comprehensive understanding of the dynamics of such disturbances. In fact, interaction between the fluxes and the convection seems to play a considerable role in the MJO dynamics (Sobel et al. 2010). Furthermore, the behavior of the MJO over the IMC is very different from that over open ocean (Kim et al. 2014), which suggests the importance of examining the fluxes over the IMC.

However, it seems that conventional datasets such as satellite and routine observations are insufficient for examining diurnal variation of the fluxes. It is hard to retrieve near-surface thermodynamic parameters, which are necessary for estimating the fluxes, from satellite observations. Although there exist various global surface flux datasets, such as OAFlux (Yu et al. 2008) and atmospheric reanalysis products, these data basically rely on numerical models.

Recently, two field campaign projects were conducted in a coastal region of Sumatra Island of IMC in 2015/16 and 2017/18 austral summer, which are named Pre-YMC 2015 (YMC15) and YMC-Sumatra 2017 (YMC17), respectively. Here YMC stands for “Years of the Maritime Continent”. Research vessel (R/V) Mirai was deployed to perform intensive observations of the atmosphere and ocean at coastal waters under these projects. Observed data are expected to offer us a unique opportunity to examine the diurnal variation of the fluxes in detail, which is the main objective of this study. In particular, this study will address questions about how vigorous the diurnal variation of the fluxes was and which surface meteorological parameters caused them.

2. Data and method

As part of the YMC15 and YMC17 campaigns, the R/V Mirai stayed at points approximately 50 km and 90 km, respectively, off the west coast of Sumatra Island (Fig. 1) to perform intensive observations. This study will analyze 10-min mean surface meteorological parameters for periods from 23 November to 12 December, 2015 (20 days) for YMC15, and from 5 to 31 December, 2017 (27 days) for YMC17. The parameters include surface wind velocity at 25 m above sea level (asl), air temperature (T_{as}) and water vapor specific humidity (q_{w}) at 21 m asl, downwelling shortwave and longwave radiation and pressure at 13 m asl, precipitation intensity measured by an optical rain gauge, and sea surface temperature (SST). These data are available at http://www.jamstec.go.jp/ymc/ymc_data.html. SHF and LHF are estimated from these observations using the COARE3.0 bulk flux algorithm (Fairall et al. 2003). Detailed information of the implementation of the algorithm can be found in the Supplement. Wind velocity at Bengkulu site (Fig. 1) measured with an anemometer installed on the roof of a three-story weather station building is additionally analyzed. Hourly averages are calculated from the 10-min data, and then 1-2-1 filtering is applied to the hourly averages to remove short-scale fluctuations. To obtain mean diurnal variation
(MDV), we calculate anomalies from diurnal running averages, make composites of the anomalies at each hour of the day over the period, and then add the period average. We apply Student’s t test for assessing statistical significance of the anomaly composites, with an assumption that each of the days in the periods is independent of the others.

While both periods were in convectively suppressed phases of MJO, large-scale conditions were quite different: strong El Niño in YMC15 while moderate La Niña in YMC17 (Yokoi et al. 2019). Characteristics in precipitation diurnal cycle were also different. It is well known that, over the coastal waters, convectively active areas tend to migrate offshore during nighttime (Mori et al. 2004). This feature was observed in almost all of the 20 days in YMC15 (Yokoi et al. 2017), while it was observed in only less than half of the 27 days in YMC17 (Yokoi et al. 2019). These differences might also cause differences in the behavior of the surface meteorological parameters and the fluxes. Comparison of results in the two periods may give us a hint of how the behavior is different in different years.

### 3. Results

Figure 2 shows the MDV of the surface fluxes in the two periods. In YMC15, SHF (Fig. 2a) records the minimum in early evening at 2000 local time (LT; LT = UTC + 7h) and the maximum at midnight (0000 LT), with an abrupt increase in 2000−0000 LT and gradual decrease in most of the other hours. Anomalies from the average are positive and significant in late evening and small hours, and negative and significant in majority of daytime and early evening. In contrast to the dominance of the diurnal cycle in SHF, LHF (Fig. 2b) exhibits a semi-diurnal cycle; while a minimum and maximum at 1100 LT and 2300 LT, respectively. Three of these extrema are statistically significant. In YMC17, SHF (Fig. 2c) and LHF (Fig. 2d) exhibit qualitatively similar MDV, with smaller values in the evening and larger values in predawn and daytime hours except for 0800−0900 LT. Note that the MDV of LHF is qualitatively different between the two periods.

To examine diurnal amplitude of the fluxes, we calculate a ratio of the difference between the maximum and minimum of the MDV to the period average. The ratios for SHF are as high as 86% in YMC15 and 70% in YMC17. For LHF, the ratios are 25% in YMC15 and 23% in YMC17, which are smaller than SHF but still mean that the MDV has considerable amplitude.

Next, we will discuss what cause the MDV of the fluxes with the aid of bulk aerodynamic formulas. In these formulas, the fluxes can be represented as

\[ \text{SHF} \propto C_h \, U \, \Delta T, \]
\[ \text{LHF} \propto C_l \, U \, \Delta q \]

where \( C_h \) and \( C_l \) represent bulk coefficients for sensible and latent heat, respectively, \( U \) surface wind speed, \( \Delta T \) the difference of SST from \( T_{\text{air}} \) and \( \Delta q \) the difference of saturated specific humidity at SST \( (q_{\text{sat}}) \) from \( q_{\text{air}} \). Figure 3 shows the MDV of precipitation and some of these parameters. Nighttime precipitation dominates in YMC15 (Fig. 3a), and half of the daily precipitation occurs in late evening (2200−0000 LT), which is associated with the nighttime...
offshore migration of convectively active area. The evening precipitation maximum is accompanied by a decrease in $T_{\text{air}}$ (black line in Fig. 3b), with its rate $\sim$1 K in 2 hours, which is likely due to the convective cold outflow. Gradual increase in $T_{\text{air}}$ is observed in 0000−1600 LT. Similar features are also observed in YMC17, although less obvious. Precipitation exhibits three maxima, two in nighttime and the other in the morning (Fig. 3h). Associated with the nighttime maxima is $T_{\text{air}}$ decrease in 2200−0600 LT (Fig. 3i).

In the morning, warming is not obvious despite insolation, which is also associated with the precipitation maximum.

SST (orange line in Figs. 3b and 3i) exhibits a maximum in the early afternoon and minimum in predawn hours, with its amplitude larger in YMC15 than in YMC17. Note that the SST diurnal cycle is not specific to the coastal waters but can also be seen in tropical open ocean (Kawai and Wada 2007). As the diurnal amplitude of $T_{\text{air}}$ is larger than that of SST, the former primarily determines $\Delta T$ variation (Figs. 3c and 3j), whose amplitude is again larger in YMC15. The MDV of $\Delta T$ is very similar to that of SHF in both periods, suggesting that the former plays the dominant role in the latter.

The MDV of $q_{\text{sat}}$ (Figs. 3e and 3k) exhibits evening maxima adjacent of precipitation maxima in both periods, consistent with temporal evolution associated with the convection (Saxen and Rutledge 1998; Yokoi et al. 2014). In addition, there are afternoon maxima at 1600 LT in YMC15 and 1300 LT in YMC17, which might be associated with large moisture supply from the sea indicated by coinciding LHF maxima. The MDV of $q_{\text{sat}}$ (Figs. 3d and 3k) is qualitatively quite similar to that of SST by definition, and its diurnal amplitude is larger than that of $q_{\text{sat}}$. Resultantly, $q_{\text{sat}}$ plays the major role in $\Delta q$ variation (Figs. 3f and 3m), and both are larger than the average during daytime and smaller during nighttime with statistical significance. Note that, although the amplitude of $q_{\text{sat}}$ is apparently larger in YMC15 than in YMC17, that of $\Delta q$ is comparable between them. This is because, in YMC17, $q_{\text{sat}}$ correlates inversely with $q_{\text{sat}}$ and thus contributes to the $\Delta q$ variation in a similar manner to $q_{\text{sat}}$.

In YMC15, the precipitation maximum is also accompanied by increase in $U$ (black line in Fig. 3g), consistent with the convective cold outflow feature. There is another maximum in the afternoon, although it is not statistically significant. In YMC17, $U$ is smaller than the average in the evening with statistical insignificance. Three precipitation maxima are accompanied by either increase in $U$ or larger-than-average $U$, although not statistically significant. In both periods, the MDV of $U$ qualitatively resembles that of LHF, suggesting that $U$ plays the major role in the LHF variation.

The afternoon $U$ maximum in YMC15 and evening minima in YMC15 and YMC17 are likely associated with the sea/land breezes. Figures 4a and 4c show MDV of surface wind velocity, which is the vector mean of surface wind at each hour of the day, over the vessel. As the coastline runs roughly in the northwest-southeast direction (Fig. 1), here we decompose the wind velocity into a component normal to the coastline ($u_n$) and a component parallel to it, with positive values representing southwesterly (onshore) and southeasterly winds, respectively. Alternation between the sea and land breezes can be found in both periods. Positive and large $u_n$ is observed in the afternoon and early evening, with anti-clockwise rotation with time which is likely due to the Coriolis effect (Simpson 1996). The maximum $u_n$ is observed at 1500 LT in YMC15 and 1900 LT in YMC17. At the Bengkulu site located ~4 km inland from the coast, the hodographs (Figs. 4b and 4d) are much flatter and the $u_n$ maximum is observed at 1300 LT (1400 LT) in YMC15 (YMC17). The difference in the time of the $u_n$ maximum over the vessel between the two periods is due to that in the location of station observation, as the sea-breeze signal extends offshore from the coast during daytime (Finkele 1998; Short et al. 2019). As a result of the sea/land breezes, the magnitude of the mean wind velocity (orange lines in Figs. 3g and 3n) is larger than the average in the afternoon and smaller in the evening in both periods, explaining part of the $U$ variation. Larger amplitude of the magnitude in YMC15 than in YMC17 is due partly to the larger amplitude of the sea/land breezes, in addition to weaker period-average wind velocity.

To quantify contributions of surface meteorological parameters to the flux variation, we adopt an attribution analysis proposed by Yokoi et al. (2014). In this study, ratios of the fluxes with
4. Summary and discussion

It is important to understand variation of the surface heat fluxes in the Tropics for better understanding of various large-scale atmospheric disturbances such as MJO. Over the IMC, the diurnal variation should be one of the significant sources of variability. This study examined the MDV of the fluxes and related surface meteorological parameters off the west coast of Sumatra Island observed by the R/V Mirai as part of the YMC15 and YMC17 field campaigns during the austral summer.

The MDV of SHF exhibits considerably large amplitudes in both periods. The difference between the maximum and the minimum of the MDV is as high as 86% of the period average in YMC15 and 70% in YMC17. In contrast, the MDV of LHF is relatively weak but still non-negligible, having the maximum–minimum difference of ~25% of the average.

The analysis based on the bulk aerodynamic formulas suggest that $\Delta T$ plays the major role in the MDV of SHF while $U$ does so in the MDV of LHF. These resemble the characteristics of the flux enhancement caused by convective cold outflow (Saxen and Rutledge 1998; Chuda et al. 2008; Yokoi et al. 2014).

There are two phenomena that can cause the MDV: the diurnal variation of convection and the sea/land breeze. The MDV of $\Delta T$ and thus SHF is mainly caused by the former, while both phenomena play roles in the MDV of $U$ and thus LHF.

Characteristics of the MDV of the fluxes are qualitatively different between the two periods. In particular, LHF exhibits semi-diurnal cycle in YMC15 while diurnal cycle in YMC17. These differences are due mainly to those in the phase and intensity of the diurnal variation of convection and the sea/land breeze, which are likely caused by different large-scale conditions and the difference in the vessel’s position between the two campaigns. These results imply difficulty for comprehensive understanding of the climatological features of the diurnal variation across the IMC solely via analysis of field campaign data. Toward this goal, we acknowledge that long-term satellite observations and reanalysis products are helpful, despite their questionable accuracy regarding the MDV of the fluxes. The results of the field campaign data shown here will provide ground truth for examining the accuracy. Furthermore, recent studies (e.g., Vincent and Lane 2017; Dipankar et al. 2019) still reported difficulty in realistic simulation of the diurnal variation of convection over the IMC by numerical models. From the viewpoint of process-oriented evaluation of simulations, comparisons between the simulations and observations not only in the convection itself but also in the surface fluxes are important. We expect that the results of this study will be beneficial for model improvements in the future.

Behavior of the diurnal variation may also be different within the periods examined. Yokoi et al. (2019) compared the MDV of radiosonde profiles in nine days in YMC17 when the offshore migration of the convectively active area was clearly observed with the convection itself but also in the surface fluxes are important. From the viewpoint of process-oriented evaluation of simulations, comparisons between the simulations and observations not only in the convection itself but also in the surface fluxes are important. We expect that the results of this study will be beneficial for model improvements in the future.

**Fig. 5:** Contribution of individual terms in the bulk aerodynamic formulas to the MDV of (a, c) SHF and (b, d) LHF in (a, b) YMC15 and (c, d) YMC17. Each figure is composed of (left) MDV of the terms normalized by the diurnal running average and (right) STD of the normalized terms divided by that of the normalized heat fluxes. In a and b (and d), black line represents the normalized SHF (LHF), while orange, blue, and red lines and bars represent normalized bulk coefficients, $U$, and $\Delta T$ ($\Delta q$), respectively. In the right panels, STD of $SHF'(C_h' U' \Delta T')$ and $LHF'(C_c' U' \Delta q')$ divided by that of the normalized heat fluxes is also shown by pale blue bars (R).

\[
SHF' \approx C_h' U' \Delta T', \\
LHF' \approx C_c' U' \Delta q'
\]

where primes represent the ratio. Figure 5 plots the MDV of these terms, and standard deviation (STD) of the MDV of the terms in the rhs of the equations divided by that of respective heat fluxes. In YMC15, $\Delta T$ plays the dominant role in the SHF variation in the afternoon and nighttime, while $U$ also contributes to it in the morning (Fig. 5a). In YMC17, $\Delta T$ and $U$ tend to covary and both contribute to the SHF variation, with larger contribution by the former than by the latter (Fig. 5c). The STD of $\Delta T'$ is higher than that of $U'$ in both periods, and of $C_h'$ is the smallest. In contrast, $U$ plays the dominant role in the LHF variation in both periods; the STD of $U'$ is higher than that of $\Delta q'$ and $C_c'$. Note that, in YMC17, the temporal coherence between $\Delta T$ and $U$ is the primary reason for the coherence between SHF and LHF. The facts that $\Delta T$ primarily determines the SHF variation and $U$ primarily determines the LHF variation resemble the characteristics of the flux enhancement due to convective cold outflow (Saxen and Rutledge 1998; Chuda et al. 2008; Yokoi et al. 2014). Note that the STD of $SHF'(C_h' U' \Delta T')$ and $LHF'(C_c' U' \Delta q')$ is considerably smaller than that of $U'$, $\Delta T'$, and $\Delta q'$, confirming that the above expressions are close approximation.
paper. However, there are quantitative differences, such as larger diurnal amplitude in $\Delta T$ and $\Delta q$ for days with the clear migration while larger amplitude in $U$ for the other days, resulting in differences in the diurnal amplitude of the fluxes (figure not shown). It seems interesting to examine day-to-day differences in the diurnal variation more in detail, which will be one of our next research topics.

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Supplements

Supplement 1: Details of the implementation of the COARE3.0 algorithm.

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