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LIGHTNING ACTIVITIES OVER THE WESTERN COASTAL AREA OF SUMATRA, INDONESIA DURING THE PRE-YMC CAMPAIGN OBSERVATION PERIOD

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Abstract In this study, we examined the diurnal and intra-seasonal variations of lightning activities over the western coastal area of Sumatra, Indonesia by the World Wide Lightning Location Network data during a pilot field campaign of the Years of the Maritime Continent project observation period (November–December, 2015). Regarding the diurnal changes, the land-sea contrast of the peak time of the day and the offshore propagation of the active lightning area predominated. The land had higher lightning activity during the day (0700–1900 LT), whereas the nearby seas experienced more lightning activity during the night (1900–0700 LT). As for the intra-seasonal variations, the lightning frequency was related to the lower-tropospheric wind variations by the Madden-Julian Oscillation (MJO) phase. When the MJO convection was convectively repressed over the area, lighting activities were more active and the offshore diurnal land-sea migration was prominent in weak or easterly wind circumstances. After the MJO convection passed over Sumatra, lightning was suppressed under the strong westerly wind conditions. The location and nocturnal fluctuations of lightning appeared to change as the center of MJO convection traveled over the area. In particular, the location of lightning changes to the east, and the timing of the initial occurrence tended to be delayed.

Keywords: lightning, convection, diurnal cycle, Madden-Julian Oscillation, Years of the Maritime Continent

1. Introduction

Indonesia’s archipelago is called a “maritime continent,” because this region consists of many islands with a complex topography and long coastlines surrounded by warmer sea water in the tropics (Ramage 1968). Over the maritime continent, convection displays a clear diurnal pattern. From space and by ground observation, a diurnal offshore migration of convective cloud system was seen in the area of major islands like Sumatra (e.g., Mori *et al.* 2004, 2011; Yokoi *et al*. 2017, 2019; Zhao *et al.* 2022). The diurnal cycle tended to be modulated by the passage of the Madden-Julian Oscillation (MJO), whereas diurnal convection affects the propagation and strength of MJO over the maritime continent. In order to comprehend local weather and climate as well as the effects on the global climate, it is crucial to research the multiscale interaction of convection over the maritime continent (Yamanaka *et al.* 2018; Yoneyama and Zhang 2020).

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Besides, the maritime continent is known as one of the active lightning regions in the globe (e.g., Ramage 1968; Christian *et al.* 2003; Virts *et al.* 2013a). A statistical analysis using a global surface lightning observation network data described that the diurnal cycle of lightning was predominant over the maritime continent and it tended to be modulated by lower-tropospheric wind variations under a different phases of the MJO (Virts *et al.* 2013b). However, because of the restricted in situ atmospheric observation over the area, a process of thunder cloud production and the modulation by MJO have not been thoroughly understood.

Years of the Maritime Continent (YMC) is organized to expedite the progress toward enhancing understanding and prediction of local multiscale variability of the maritime continent's weather climate system and its global effects through observations and numerical modeling. A pilot study of the YMC project (Pre-YMC) field campaign observation was performed in November–December 2015 in the western coastal area of Sumatra, Indonesia to examine migration processes of diurnally evolving atmospheric convection and its interactions with the MJO (see comprehensive review by Yoneyama and Zhang 2020).

In this research, we aimed to investigate diurnal and intra-seasonal variations of lightning activities over the western coastal area of Sumatra, Indonesia during November–December 2015 based on a global surface observation network lightning data. Previous studies described the land-sea convective system migration, but for lightning. Thus, we examine daily variations in the diurnal offshore migration of lightning and how the MJO passage affects these variations. By using in situ, intense atmospheric sounding data from the Pre-YMC field campaign observation, we also look at the background atmospheric conditions for the production of thunder clouds.

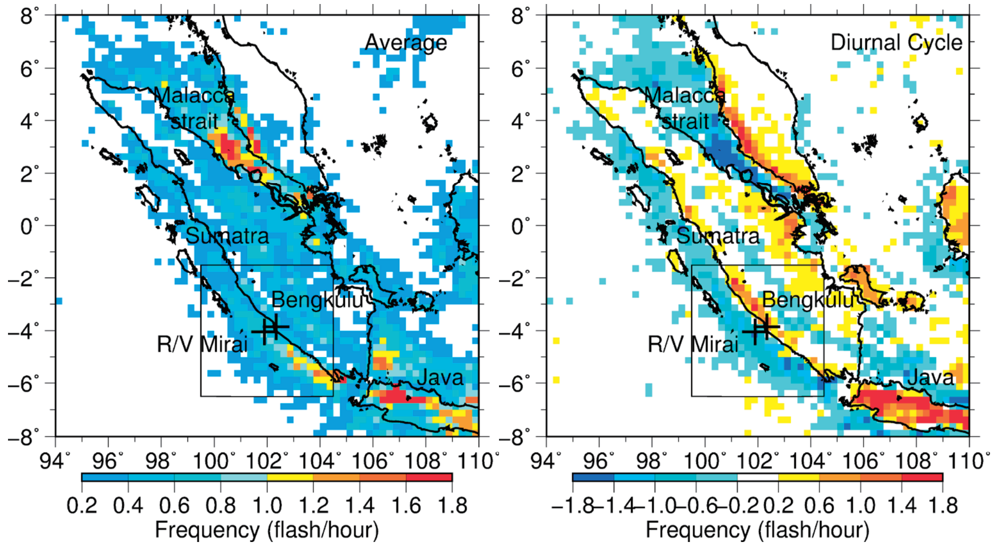

Fig. 1 Distribution of lightning frequency around Sumatra during November–December, 2015 (left). Diurnal difference of lightning frequency between daytime (0700–1900 LT) and nighttime (1900–0700 LT) (right). A positive (negative) value shows daytime (nighttime) lightning is more frequent. Cross marks indicate the position of Research Vessel (R/V) Mirai (4.07°S, 101.90°E) and Bengkulu (3.86°S, 102.34°E) observatory, respectively.

2. Data

We used lightning location data from the World Wide Lightning Location Network (WWLLN) during the Pre-YMC campaign observation period (November–December 2015) over the western coastal area of Sumatra, Indonesia. The WWLLN is a ground-based observation network that comprises of over 70 receiving sites (as of 2022) that monitor very-low-frequency (VLF) radio waves (3–30 kHz) emitted by lightning strokes. The network employs a time of the group arrival of the VLF waves detected at more than five stations to locate lightning. The spatial resolution is within about 5 km (Dowden *et al.* 2002; Abarca *et al.* 2010).

The Pre-YMC intensive observation campaign was conducted in the western coastal area of Sumatra in November–December of 2015. Intensive upper air soundings at intervals of 3 hours were conducted at the Indonesian Agency for Meteorology, Climatology and Geophysics (BMKG) Bengkulu Meteorological Observatory (3.86°S, 102.34°E) during the intensive observation period from 9 November to December 25, 2015. From November 22 to December 17, the Research Vessel (R/V) Mirai stayed at the station about 50 km offshore. The upper winds from the observations were used in the current investigation.

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

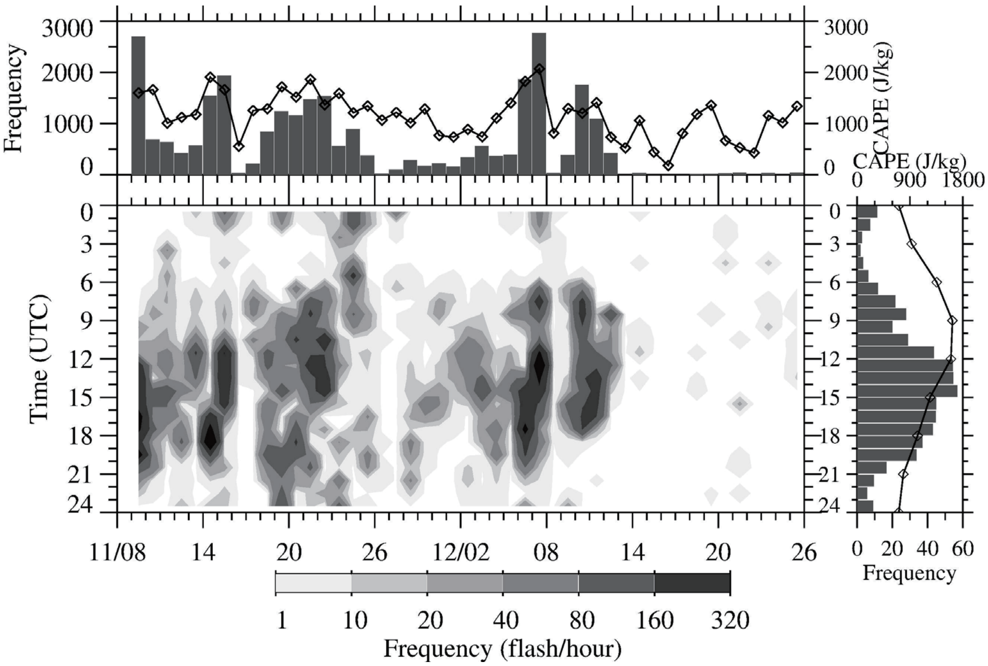

Fig. 2 Day-to-day and diurnal variations of lightning frequency over the western coastal area of Sumatra during the Pre-YMC Bengkulu intensive sounding observation period (9 November–25 December, 2015). The lightning frequency is indicated if the lightning is located within 100 km distance from the R/V Mirai fixed observation point. Day-to-day and average diurnal variations of Convective Available Potential Energy is also indicated (solid line with open diamond mark). The time difference is 7 hours between UTC and LT in the western Indonesia (LT = UTC + 7 hours).

3. Results

Firstly, we investigated the average spatial distribution of lighting and its diurnal variation around Sumatra from November–December 2015. Frequent lightning occurred over large islands and their surrounding seas especially for Java, southern coastal sea areas of Sumatra, and the Malacca strait (Fig. 1). Regarding the diurnal changes, the land-sea contrasts during the diurnal cycle's peak were predominate (Fig. 1). Over the land, lightning was more active during the day (0700–1900 LT), whereas over the nearby waters, lightning predominated at night (1900–0700 LT). The time difference is 7 hours between UTC and LT in the western Indonesia (LT = UTC + 7 hours). Nighttime lightning was also frequent on the eastern side of the steep mountains near the western coast of Sumatra. Over the western coastal area of Sumatra (Pre-YMC campaign observation area), lightning was active in the afternoon with the peak at around 2000 LT by the lightning over the sea (Fig. 2). The second small peak also appeared around 1500 LT by the lightning over land area. These diurnal lightning peaks are a few hours earlier than the diurnal rainfall peaks observed at R/V Mirai (2200 LT) and Bengkulu observatory (1800 LT), respectively (Yokoi *et al*. 2017).

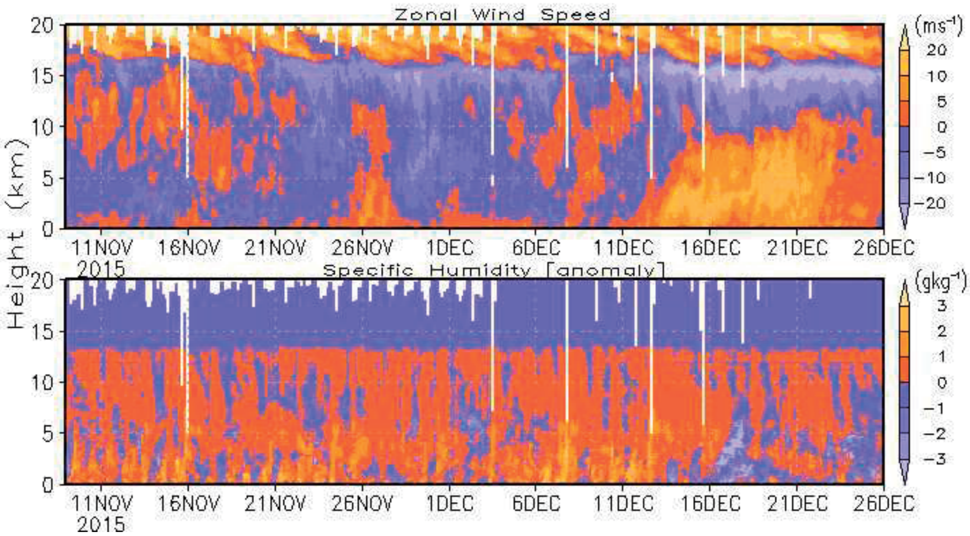

Fig. 3 Time-height variations of zonal wind (top) and specific humidity (bottom) at Bengkulu observatory during the Pre-YMC Bengkulu intensive sounding observation period (9 November 00UTC–25 December 21UTC). Specific humidity is shown as anomaly from the period mean at each height. Note that the colors are used to emphasize the difference between positive and negative values.

Background atmospheric conditions during the Pre-YMC campaign observation period were described by the intensive radiosonde observation at Bengkulu (Fig. 3). Intensive rawinsonde observation at Bengkulu shows lower-tropospheric zonal wind was weak or easterly when the MJO convection was in the Indian Ocean. After the MJO convection passed through in the middle of December, the wind was mostly westerly. Throughout the observation period, specific humidity was high, but it tended to be dry when the westerly wind was in the air.

Although the daily variation in lightning frequency was large, lightning activity tended to be more active from early November to the middle of December during the convectively suppressed phase of MJO (Fig. 2). Frequent lightning (more than a thousand in a day) was found in 8, 14–15, 19–23 November, and 7–8, 10–11 December. These frequent lightning days tended to happen on days with light or easterly lower-tropospheric winds. During convectively suppressed periods of the MJO, a noticeable offshore movement of lightning was seen from the evening through the early morning (Fig. 4). Additionally, differences in daily lightning frequency correlated with variations in atmospheric stability, as seen by Convective Available Potential Energy (CAPE). On the other side, strong westerly winds formed and lightning activity was reduced in the second part of December when vigorous MJO convection passed through the area.

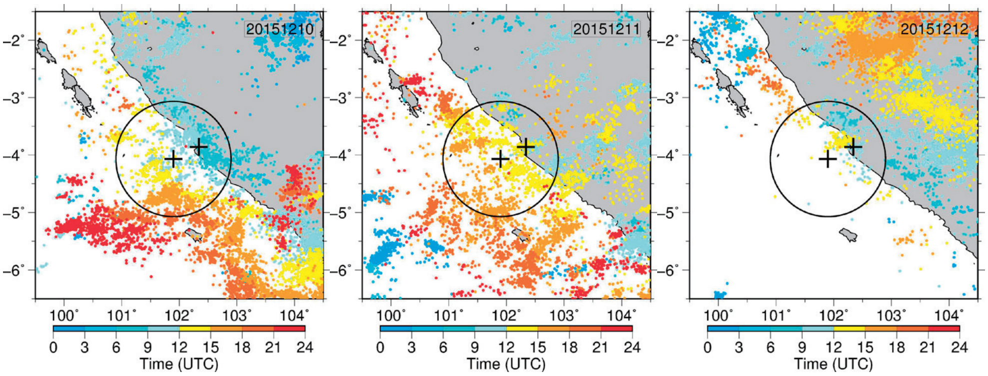

Fig. 4 Spatial distribution and the occurrence time of the lightning over the western coastal area of Sumatra during 10 (left), 11 (center), and 12 (right) December, 2015. The position and color of the circle indicate the location and occurrence time (UTC) of the lighting, respectively. The thick circle shows the 100 km distance from the R/V Mirai fixed observation point. The time difference is 7 hours between UTC and LT in the western Indonesia (LT = UTC + 7 hours).

Figure 4 depicts the modulation of diurnal lightning distribution patterns by the passages of MJO convection around 10–12 December. Land-sea lightning migration off the western coast of Sumatra was predominant on 10 December. This diurnal offshore migration pattern was also observed on 11 December, but the timing of the initial occurrence and the migration were tended to be delayed (1900–0100 LT) off the coastal sea area. On December 12, lightning activity was reduced or restricted over land in the western coastal region, and the location of active lightning tend to be on the eastern faces of steep mountains. The Bengkulu observatory recorded a daily rainfall of 144.6 mm in 12 December, the highest daily total in the previous 21 years, with an hourly rainfall of over 100 mm (Wu *et al.* 2017). The passage of MJO convection and the leading edge of the MJO westerly wind across Sumatra's western coastal area might be responsible for these changes.

4. Conclusions and study subjects

In this research we examined lightning activities over the western coastal area of Sumatra during the Pre-YMC field campaign observation period (November–December 2015). At Bengkulu, in situ radiosonde observations were used to examine the background atmospheric conditions. The region's lightning has a clear diurnal pattern. The movement of MJO modified the diurnal cycle of lightning. Day-to-day lightning frequency was active under the convectively suppressed MJO. Where ambient low-level winds are weak or easterly, the diurnal cycle of lightning is enhanced during the suppressed phase. The diurnal cycle of lightning is intensified to the east of Sumatran mountains when the active phase of MJO and low-level westerly winds pass across Sumatra. The obtained results from in situ intensive atmospheric observation support the previous study results based on the statistical analysis (Virts *et al.* 2013b). In addition, day-to-day variations of lightning frequency was related to low-level westerly wind development and atmospheric stability (CAPE). Lightning activities tended to be inactive when the thickness of the lower-tropospheric westerly wind increased and CAPE was low. Additionally, variations in lightning activity during the day (timing of the initial occurrence and the migration) was modulated by the passing of the MJO's convective center and the location of the westerly wind edge.

As for the further study subjects, thunderstorm developments should be investigated by using C-Band Doppler Radar observation by R/V Mirai and BMKG Bengkulu during the Pre-YMC field campaign, especially at the timing of the MJO passage. The microphysical observation was also done by videosondes observation near a coastal region of Sumatra (Suzuki *et al.* 2018). To discuss the modulation processes of lightning activities by the passage of the MJO, we need to consider the knowledge of the microphysical properties over the area. Furthermore, the torrential rainfall event on 12 December (Wu *et al.* 2017) and its link to thunderstorm development need to be investigated. Then, from November 2017 to January 2018, the YMC-Sumatra 2017 field campaign was held in the same configuration as the Pre-YMC (Yoneyama and Zhang 2020). As a results, we could contrast the characteristics of variations in lightning under various circumstances, including El Niño (Pre-YMC) and La Niña (YMC-Sumatra 2017).

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