Diurnal Lightning Variability over the Maritime Continent: Impact of Low-Level Winds, Cloudiness, and the MJO

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ABSTRACT

Lightning over the Maritime Continent exhibits a pronounced diurnal cycle. Daytime and evening lightning occurs near coastlines and over mountain slopes, driven by sea and valley breezes. Nocturnal and morning thunderstorms are touched off where land breezes or mountain breezes converge or by gravity waves propagating away from regions of vigorous afternoon convection. In this study, the modulation of the diurnal cycle of lightning and precipitation by 850-hPa winds, cloudiness, and the Madden–Julian oscillation (MJO) is investigated using observations from the World Wide Lightning Location Network (WWLLN) and the Tropical Rainfall Measuring Mission (TRMM) satellite. The 850-hPa wind speed and area-averaged cloudiness are shown to be negatively correlated with day-to-day lightning frequency over land, and thunderstorm occurrence is suppressed windward of, and enhanced leeward of, mountain ranges. Lightning and environmental conditions are similarly related in the MJO. During break periods, the regular diurnal cycle of lightning is enhanced where ambient low-level winds are easterly but abnormally weak—in the Strait of Malacca, over western and southern Borneo and the adjacent seas, and in the region of nocturnal thunderstorms to the west of Sumatra and Java. When the active, cloudy phase of the MJO, accompanied by low-level westerly winds, passes over the Maritime Continent, the regular diurnal cycle of lightning is enhanced leeward (to the east) of the mountains of Java, Borneo, and the Malay Peninsula. The spatial patterns of lightning and rainfall anomalies are broadly similar, but lightning anomalies tend to be more concentrated near coastlines.

1. Introduction

The term “Maritime Continent” is used in meteorological literature to denote the region between southeastern Asia and Australia that contains numerous islands, including three of the six largest noncontinental landmasses in the world (New Guinea, Borneo, and Sumatra; see Fig. 1a). The diurnal variability of convection over the Maritime Continent has been described based on satellite infrared imagery (Mori et al. 2004; Sakurai et al. 2005), satellite-based rainfall data from the Tropical Rainfall Measuring Mission (TRMM; Nesbitt and Zipser 2003; Mori et al. 2004; Kikuchi and Wang 2008; Wu et al. 2009; Fujita et al. 2010; Teo et al. 2011; Oh et al. 2012), lightning observations from the World Wide Lightning Location Network (WWLLN; Virts et al. 2013), and model simulations (Wu et al. 2009; Fujita et al. 2010; Teo et al. 2011). On sunny days, the land tends to be warmer by virtue of its smaller heat capacity. The stronger land–sea temperature contrast gives rise to seaward pressure gradients along the coasts of the islands, which drive sea breezes that propagate inland during the afternoon. Convection firing along the sea-breeze fronts produces rainfall and lightning in coastal areas. Solar heating also causes warm air to rise along the mountain slopes (Fig. 1a), producing convection during the late afternoon and evening. Figures 1c and d, in the format of Teo et al. (2011) but based on WWLLN data, show the climatological diurnal evolution of lightning along a transect across Sumatra and the Malay Peninsula and another across Borneo. In both sections, afternoon and evening lightning is clearly visible over the coastlines and mountain slopes. At night, the local circulation patterns reverse:
cooler air subsides down the mountain slopes, producing convergence and convection over the adjacent lowlands during the early morning. Land breezes from Sumatra and the Malay Peninsula converge in the Strait of Malacca, producing frequent thunderstorms during the night and morning hours (Fig. 1c). In addition, gravity waves, as suggested by the numerical simulations of Mapes et al. (2003), appear to propagate away from the regions of afternoon convection and touch off nocturnal convection along the coastlines of the major islands, which subsequently propagates out to sea, as indicated by the white arrows in Figs. 1c and d. Convection triggered by these processes over the islands and surrounding seas frequently becomes organized into mesoscale convective systems (MCSs; Houze et al. 1981; Houze 2004, and references therein). The annual-mean distribution of lightning over the Maritime Continent (Fig. 1b) reflects the mechanisms that govern its diurnal cycle: maxima are observed over coastlines, mountain slopes, and adjacent coastal waters and valley floors.
The climatological-mean pattern of convective variability is modulated by transient variability. For example, convective rainfall over the Maritime Continent is comparatively enhanced during La Niña years and suppressed during El Niño years (Ropelewski and Halpert 1987), as the rising branch of the Walker circulation shifts between the Maritime Continent and the central Pacific. Lightning, in contrast, tends to be more frequent during El Niño years, particularly over western Borneo and Java and to the west of Sumatra (Hamid et al. 2001; Yoshida et al. 2007). In contrast, rainfall and lightning frequency of occurrence vary in phase with one another in association with the climatological-mean annual cycle (Chang et al. 2005; Virts et al. 2011).

The Madden–Julian oscillation (MJO) dominates atmospheric variability over the Maritime Continent on the intraseasonal (~30–80 day) time scale. During a typical cycle of the MJO, an area of enhanced cloudiness and precipitation, accompanied by low-level convergence, develops over the central equatorial Indian Ocean, propagates eastward across the Maritime Continent, and dissipates in the western or central equatorial Pacific (Zhang 2005). Analyses of data from the Lightning Imaging Sensor (LIS), which is carried aboard the TRMM satellite, have shown that lightning tends to be enhanced during the “break” period of MJO precipitation (Morita et al. 2006), particularly over the islands of the Maritime Continent (Kodama et al. 2006). Analyzing WWLLN data, Virts et al. (2011) also noted more frequent lightning over the ocean to the west of Sumatra during the MJO break period. The modulation of the diurnal cycle of lightning over the Maritime Continent...
by the MJO has not yet been systematically investigated. WWLLN’s continuous monitoring enables it to resolve the spatial structure of the lightning diurnal cycle in greater detail than TRMM LIS (Virts et al. 2013; their Fig. 6). WWLLN and other datasets are described in section 2. In section 3, we examine the impact of day-to-day variations in cloudiness and low-level wind on the spatial distribution of thunderstorm formation and propagation over the Maritime Continent. In section 4, we examine the spatial and temporal variability of lightning during both MJO break and active periods and the environmental conditions that drive these variations. Conclusions are presented in section 5.

2. Data

WWLLN (http://wwlln.net) is a ground-based network consisting of 70 sensors (as of January 2013) that monitor very-low-frequency (VLF) radio waves for lightning sferics, which propagate in the Earth–ionosphere waveguide with relatively little attenuation. The network uses a time of group-arrival technique (Dowden et al. 2002) on the detected sferic waveforms from at least five stations to locate lightning to within about 5 km and less than 10 ms (Abarca et al. 2010). Typically, WWLLN locates strokes 6000 km from the locating...
stations, with an average of 6.7 stations involved in each location. The global detection efficiency of the network is estimated to be about 10% of all strokes and about 30% of all strokes with a peak current greater than 50 kA, with preferential detection of cloud to ground strokes (Rodger et al. 2009; Abarca et al. 2010; Hutchins et al. 2012b; Connaughton et al. 2013). WWLLN has been locating nearly all lightning-producing storms since 2005 (Jacobson et al. 2006), and coverage over the Maritime Continent is nearly as good as over the best-instrumented regions (Hutchins et al. 2012a). For this study, WWLLN observations over the Maritime Continent from 2008–11 are averaged onto an hourly, 0.25° × 0.25° grid to create a field of lightning frequency of occurrence.

The TRMM satellite was launched in 1997 into a 35° inclination orbit carrying a Precipitation Radar (PR) and Visible and Infrared Scanner (VIRS). The TRMM 3B42 dataset contains TRMM rainfall observations supplemented with data from other satelliteborne microwave imagers and infrared sensors (e.g., Huffman et al. 2007) and is available at 3-hourly temporal resolution and 0.25° × 0.25° spatial resolution.

This study also makes use of 850-hPa wind fields from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim).
(Dee et al. 2011), which are available four times daily at 1° horizontal resolution, and cloud observations from Clouds and Earth’s Radiant Energy System (CERES; Wielicki et al. 1996). The CERES_SYN dataset contains cloud-area fractions observed by the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments aboard the polar-orbiting Aqua and Terra satellites (with equatorial crossings at 0130 LT and 1030 LT, respectively) that are supplemented by observations from geostationary satellites to create daily, 1° × 1° cloud fields (further details are at ceres.larc.nasa.gov).

The present study focuses on the day-to-day (section 3) and intraseasonal (section 4) modulation of lightning frequency. To highlight this variability, 15- or 80-day high-pass Lanczos filters are applied to the gridded datasets as indicated. When this operation is performed, the data are referred to as “15-day hp filtered” and “80-day hp filtered,” respectively. In both cases, the filtering removes the variability associated with the climatological-mean annual cycle, ENSO, and trends in the detection efficiency of WWLLN.

3. Lightning variability: Impact of clouds and low-level winds

Lightning variability over the Maritime Continent associated with the annual cycle or MJO has sometimes been represented in terms of changes to the lightning frequency averaged over the entire region, without reference to the spatial distribution (e.g., Morita et al. 2006). Daily, 80-day hp-filtered lightning at each grid point regressed onto 80-day hp-filtered lightning averaged over the Maritime Continent (12°S–8°N, 94°–159°E), shown in Fig. 2a, indicates that the domain-mean lightning frequency is dominated by lightning variability in the vicinity of the major islands (particularly the western islands of Sumatra, Borneo, and Java), where climatological-mean lightning is most frequent (Fig. 1b). On intraseasonal time scales, lightning in the Strait of Malacca and to the south and west of Sumatra, Borneo, and Java tends to vary in synchrony, as evidenced by the structure of the empirical orthogonal function (EOF) shown in Fig. 2b and verified by inspection of one-point correlation maps for these regions (not shown). The horizontal scale of the features observed for 15-day hp-filtered data (Fig. 2c) is somewhat smaller.

Because thunderstorms over the Maritime Continent are often driven by local, diurnally varying land–sea and mountain–valley wind regimes (see section 1; Virts et al. 2013), it follows that environmental conditions that modulate the strength of these wind regimes should likewise modulate lightning frequency. Numerical simulations of atmospheric circulation in the presence of coastlines and topography indicate that stronger vertical velocities occur in association with stronger heating of the land surface (Qian et al. 2012) on days with less extensive cloud cover (Segal et al. 1986). This relationship can be demonstrated by regressing 15-day hp-filtered lightning at each individual grid point onto 15-day hp-filtered domain-mean cloudiness, as shown in Fig. 2d. When cloudy conditions prevail over the Maritime Continent, lightning tends to be suppressed over land, consistent with the notion that reduced solar heating leads to weaker diurnally varying circulations.

The strength of land–sea and mountain–valley wind regimes is also modulated by the ambient, or background, winds (Miller et al. 2003, and references therein; Qian et al. 2010, 2013). Pointwise regression...
maps of 15-day hp-filtered lightning (Fig. 3a) and rainfall (Fig. 3b) onto 850-hPa scalar wind speed show a marked land–sea contrast, with negative values (i.e., less rain and lightning observed in association with stronger ambient winds) over land and positive values over the sea. We conclude from this result that strong ambient low-level winds disrupt the local land–sea and mountain–valley wind regimes, leading to less vigorous convection.
and reduced incidence of thunderstorms over land, in agreement with the observations of Fujita et al. (2011) and Qian et al. (2013).

Wind direction relative to the terrain also modulates the location and frequency of occurrence of lightning, as shown in Fig. 4. For each of the three major islands, we define a time-varying index of the 850-hPa wind component perpendicular to the crest of the mountain range, as represented by the straight line segments. We average the wind component normal to the line at all the grid points that lie along the line. In the averaging, we assign a positive sign to the grid points at which the wind anomaly crosses the range in the direction indicated in Fig. 4 and a negative sign if it crosses in the opposite direction. The 15-day hp-filtered 850-hPa wind, lightning, and precipitation fields were then regressed onto the wind index for each island. Striking contrasts are observed in each case, with lightning and precipitation suppressed windward of the mountains and enhanced in the lee. The TRMM 3B42 dataset relies primarily on the cloud ice detected by microwave radiometers to estimate rainfall and does not detect warm rainfall
Performing a composite analysis similar to Fig. 4b with TRMM 2A25 near-surface rain observations (not shown) produces a similar spatial pattern of anomalous precipitation, although the patterns in the near-surface rain observations are patchier. Hence, it does not appear that the suppression of rainfall windward of the mountains can be explained by a greater prevalence of warm rainfall over deep convective rainfall in those areas.

Previous studies have also noted this relationship between precipitation and low-level wind: TRMM precipitation in the vicinity of Borneo and New Guinea composites in accordance with synoptic low-level wind regimes shows enhanced precipitation in the lee of the mountains (Ichikawa and Yasunari 2006, 2008); cloud-top temperatures over Sumatra exhibit lee propagation in cases with low-level westerly winds (Sakurai et al. 2005).

The development of lee precipitation has also been investigated in numerical simulations (e.g., Sato and Kimura 2003; Mori et al. 2004; Sasaki et al. 2004; Wu et al. 2009). The simulations suggest that breezes blowing up valleys converge and produce a layer of moist air and convection along the length of a mountain range during the afternoon. Ambient winds above the crests then advect the moist air to the lee of the mountains,
and cold outflow and gravity waves from the daytime convection provide the lift required to trigger convection that then propagates farther leeward. Support for this interpretation is found in Fig. 5, in which the lightning regression patterns in Fig. 4 are divided into three segments by hour of the day. The dipole patterns develop during the afternoon hours, most prominently over New Guinea, and propagate away from the mountain ranges, onto the adjacent lowlands during the evening.

In this section, we have demonstrated that environmental conditions such as cloudiness and ambient wind speed and direction that affect the strength and evolution of the local diurnally varying land–sea and mountain–valley wind regimes also modulate thunderstorm occurrence on a day-to-day basis. In the following section, we turn to the particular case of the modulation of lightning by the Madden–Julian oscillation, which is associated with intraseasonal variations in both circulation and cloudiness over the Maritime Continent.

4. Lightning variability: Impact of MJO

The time-varying state of the MJO is represented by the real-time multivariate MJO (RMM) index, which is calculated by projecting daily observations onto the first two EOFs of a multivariate field made up of near-equatorial outgoing longwave radiation (OLR) and
lower- (850 hPa) and upper-tropospheric (200 hPa) zonal wind (Wheeler and Hendon 2004). The evolution and strength of the MJO is frequently represented by composite maps of atmospheric variables associated with eight linear combinations of the two RMM indices (e.g., Wheeler and Hendon 2004). In this study, each day of the observation period (2008–11 for WWLLN and ERA-Interim; 2007–10 for CERES; 1998–2011 for TRMM) was assigned to whichever of the eight phases that it projects onto most strongly. Days on which the magnitude of the MJO vector was less than one standard deviation from zero (243 days, or about 17% of the total data period) were discarded.

The mean cloud fraction, precipitation rate, and lightning frequency across the Maritime Continent during each MJO phase are shown in Fig. 6 [adapted from Fig. 12 of Morita et al. (2006)], and maps of each variable regressed onto time series representing MJO phases 1–8 are shown in Fig. 7. Patterns for phases 5–8 are identical to those for phases 1–4 but with the sign reversed. Cloudiness and precipitation increase across the domain as the region of active convection approaches from the west and then decrease as the region of active convection shifts eastward into the western Pacific. In contrast, domain-mean lightning is least frequent around the time of peak cloudiness and precipitation.

**Fig. 11.** Mean WWLLN lightning during MJO (a) break and (b) active period, and (c) difference between (a) and (b). Black contours indicate the 500-m elevation.
The spatial pattern of MJO lightning anomalies is visually complex (Fig. 7c) and will be examined in more detail (in Figs. 10 and 11). Composites of CERES cloud fraction and ERA-Interim 850-hPa wind during MJO phases 8-1-2 and 4-5-6 are shown in Figs. 8 and 9. Analogous plots based on OLR are shown in Rauniyar and Walsh (2011). Extensive cloudiness is observed over the major islands during all MJO phases, but the difference plots in Figs. 8c and 9c illustrate the overall cloudier conditions and greater prevalence of westerly winds during phases 4-5-6. Accordingly, the composites presented in the remainder of this section were generated for days during phases 8-1-2 (which we refer to as the MJO “break” period) and 4-5-6 (the “active” period).

Composites of daily TRMM precipitation and WWLLN lightning during the MJO break and active periods are shown in Figs. 10 and 11, respectively. Contrasts in rainfall rates shown in Fig. 10c [see also Rauniyar and Walsh (2011), based on TRMM data] are observed across Sumatra, Borneo, and to a lesser extent Sulawesi in association with the MJO, with more rain falling to the west of the islands during the break period. Most of the seas surrounding the islands receive more rain during the active MJO period, in agreement with results of Wu and Hsu (2009) and Oh et al. (2012), both based on TRMM data. The difference plot for lightning shown in Fig. 11c is more complicated. Western and southern Borneo experience more lightning during the MJO break period, while eastern Borneo experiences more
lightning during the active period. Contrasts are also observed across Sumatra, Java, the Malay Peninsula, and Sulawesi. Lightning is more frequent over most of New Guinea during break periods.

As described in section 1 and in Virts et al. (2013; their Fig. 6), the diurnal cycle of lightning over the Maritime Continent can be summarized as follows: afternoon thunderstorms are most frequent over the smaller islands and along the coastlines of the larger islands; evening thunderstorms are observed over the mountain slopes and near-coastal waters of the larger islands; and morning thunderstorms are most frequent over the seas surrounding the islands and over lowlands adjacent to mountain ranges. Figures 12 and 13 show the difference in precipitation rate and lightning frequency between the MJO break and active periods during these three segments of the day, and Fig. 14 shows the hourly difference in lightning between break and active periods over the same transects as Figs. 1c and 1d. Similar results (not shown) are obtained when compositing is performed separately for 2008–09 and 2010–11. Afternoon precipitation and thunderstorms associated with sea-breeze fronts tend to be more frequent over the coastal areas of Sumatra and Borneo during the MJO break period. The largest MJO-related lightning anomalies occur during evening. During the MJO break period, evening lightning and precipitation are enhanced over the western and southern mountain slopes and coastal areas of Sumatra, Java, the Malay Peninsula, Borneo, and Sulawesi.

**Fig. 13.** Difference between WWLLN lightning during MJO break and active periods, for the indicated segments of the day. Times are given in Singapore LT. Black contours indicate the 500-m elevation.
(Figs. 12b and 13b), and the offshore propagation of the thunderstorms continues into the morning hours (Figs. 13c and 14). The low-level winds during the break phase exhibit an easterly component and are weak over the major islands compared to the climatological mean (Figs. 1b and 9a). Previous studies have noted the development and leeward propagation of long-lived mesoscale convective systems (MCSs) over Borneo under weak low-level easterlies (Ichikawa and Yasunari 2006) and the correspondence between weak background winds and enhanced morning precipitation in the Strait of Malacca (Fujita et al. 2010), over western Borneo (Wu et al. 2008), and to the west of Sumatra (Fujita et al. 2011).

As the active phase of the MJO moves over the Maritime Continent, the low-level winds become more westerly and strengthen (Fig. 9b). Afternoon lightning tends to be suppressed over land, where the atmosphere is more stable than during the break period (Rauniyar and Walsh 2011). In contrast, more evening thunderstorms are observed over the northern and eastern (lee) slopes of the mountain ranges and along the eastern coasts of the major islands (Figs. 13 and 14). These and other storms touched off by gravity waves propagate offshore during the morning hours (Fig. 14; Mapes et al. 2003), resulting in enhanced lightning and precipitation over areas such as the Java Sea during the active phase (Rauniyar and Walsh 2011; Oh et al. 2012). The exception to this pattern is New Guinea, which experiences relatively lighter winds during the MJO active period compared to the break period but experiences weakly enhanced lightning over its mountains and near-coastal waters during the MJO break period.

The composites shown thus far suggest that the stronger diurnal heating of land surfaces during the less-cloudy MJO break period could lead to more intense convection and more lightning, a mechanism previously suggested by Sui and Lau (1992) and Kodama et al. (2006). To test the validity of this mechanism and extend it to wind, we attempt to predict MJO-related anomalous lightning frequency using the relationships between lightning and low-level winds and cloudiness documented in section 3. At each grid point, for each MJO phase, the following linear prediction scheme for the anomalous lightning frequency \( L \) associated with one standard deviation of the MJO index is used:

\[
L = a_{L,\overline{CF}} b_{\overline{CF},\text{MJO}} + a_{L,u} b_{u,\text{MJO}} + a_{L,v} b_{v,\text{MJO}},
\]

where \( \overline{CF} \) is the domain-mean cloud fraction, \( u \) and \( v \) are components of the 850-hPa wind at each grid point, \( a \) is the regression coefficient of 15-day hp-filtered lightning onto the indicated 15-day hp-filtered variable, and \( b \) is the regression coefficient of the indicated 80-day hp-filtered variable onto the MJO index for that phase. This linear regression analysis generates a predicted map of anomalous lightning frequency for each MJO phase based solely on the day-to-day relationships between lightning and selected environmental factors. Use of 15-day hp-filtered data in estimating the \( a \) coefficients in (1) ensures that they are not influenced by the MJO.
Maps of observed and predicted lightning for MJO phases 8-1-2 minus 4-5-6 are shown in Figs. 15a and 15b, respectively. The observed maps were generated by compositing maps of 80-day HP-filtered lightning frequency regressed onto these MJO phases. The predicted lightning field captures the enhanced lightning west of Sumatra and over the Strait of Malacca and western Borneo during the break period and over the South China and Java Seas during the active period. The observed-minus-predicted difference plot shown in Fig. 15c illustrates the areas where the prediction fails to capture the observed lightning pattern, most notably over eastern Borneo, where the residual lightning is as large or larger than the observed. Clearly, a much more sophisticated model would be needed to accurately predict lightning variability associated with the MJO. Nevertheless, the similarities between the observed and predicted lightning fields in Fig. 15 demonstrate that, to first order, MJO-related lightning variability over the Maritime Continent during the active and break periods reflects the modulation of the local, diurnally varying wind regimes by the large-scale cloud and circulation anomalies that accompany the MJO.
We have also tested an alternate prediction scheme in which multiple linear regression analysis is used to fit 15-day hp-filtered time series of $u$ and $v$ at each grid point and domain-mean cloud fraction to time series of lightning observations at each grid point. The same coefficients are then multiplied by 80-day hp-filtered time series of $u$, $v$, and cloud fraction to generate lightning time series at each grid point. When the predicted lightning time series are regressed onto the MJO and composited according to break and active periods, the results (not shown) are very similar to those shown in Fig. 15b.

MJO modulation of the strength of the diurnal cycle of lightning is illustrated by the difference map, shown in Fig. 16, between the amplitude of the first harmonic of hourly mean lightning frequency during the MJO break and active periods. Dividing this result by the amplitude of the first harmonic of climatological hourly mean lightning frequency at each grid point produces a similar result (not shown), with larger values somewhat less concentrated in areas of frequent climatological-mean lightning (Fig. 1). The strong similarity between Fig. 11c and 16 suggests that the complex spatial structure in the difference field of lightning frequency between MJO active and break periods reflects the differences in the strength of the diurnal cycle of lightning frequency; that is, that the MJO mediates lightning over the Maritime Continent mainly through its influence on the diurnal cycle.

Our analysis of MJO-related diurnal lightning variability has focused on the spatial pattern and amplitude of its diurnal cycle, as represented by lightning frequency during fixed segments of the day (Fig. 13). Analysis of phase of the diurnal cycle of lightning during the MJO cycle, which shows distinctive shifts in the timing of the peak lightning, is presented in the appendix.

5. Conclusions

Over the Maritime Continent, land–sea breezes and mountain–valley wind regimes forced by the diurnal cycle in low-level heating are the dominant mechanism for producing the strong lifting required to initiate deep convection. As noted in section 1, this convection frequently becomes organized into mesoscale convective systems. In focusing on diurnal lightning variability, we have made no attempt to distinguish the spatial scale, organization, or duration of the lightning-producing storms.

We have demonstrated that lightning over the islands is less frequent when these local, diurnally varying wind regimes are disrupted by strong ambient low-level winds (Fig. 3) or are weakened by a decrease in low-level heating because of increased cloudiness (Fig. 2d). Anomalous low-level wind components perpendicular to the mountain ranges also influence the diurnal cycle in convection, suppressing lightning and precipitation windward of the mountains and enhancing them over the lee mountain slopes during the day and over the adjacent lowlands during the evening and morning (Figs. 4 and 5).

The response of lightning to changes in cloudiness and low-level wind is observed not only on a day-to-day basis (section 3) but also in association with the intra-seasonal MJO. During the MJO break period, a time of generally suppressed cloudiness (Fig. 8a) and weak, easterly low-level winds (Fig. 9a), thunderstorms develop more frequently over the western mountain slopes and coastlines of the major islands and propagate westward over the seas during the night and morning (Figs. 11 and 12). In contrast, the enhanced cloudiness (Fig. 8b) and low-level westerly winds (Fig. 9b) observed during the MJO active period are associated with more
frequent thunderstorm development over the eastern slopes and coastlines and adjacent areas, including the Java Sea (Fig. 11). During both active and break periods, the MJO-related wind and cloudiness anomalies serve to amplify the climatological-mean diurnal cycle in some areas and weaken it in others.

Cloudiness and lightning over the Maritime Continent also vary inversely in association with the ENSO cycle (see section 1). Although our data period includes an El Niño year, 2009, and a La Niña year, 2010, a comparison of TRMM diurnal precipitation anomalies over the Maritime Continent during these years with ENSO anomalies based on the longer TRMM data record (not shown) indicates that 2009–10 anomalies are not representative of typical ENSO variability. Yoshida et al. (2007) composited LIS lightning over an interval encompassing the El Niño years of 1998 and 2002 and the La Niña year of 1999. The spatial patterns of ENSO-related lightning anomalies in their Fig. 2 and of MJO-related lightning anomalies in our Fig. 11 are similar in many respects. Enhanced lightning over and to the west of Sumatra and western Borneo is observed during El Niño years and during the MJO break period. This suggests that the reduced cloud cover over the Maritime Continent may strengthen the diurnally varying local circulations in the same manner during El Niño years as during MJO break periods. Low-level winds over the western Maritime Continent are anomalously westerly during La Niña years (Yoshida et al. 2007) and during MJO active phases, and in both cases lightning is enhanced over eastern Borneo and to the east of the Malay Peninsula, that is, on the lee side of the nearby mountains relative to the anomalous winds. The relationship between rainfall and downslope winds in the lee of the mountains of Borneo holds for both El Niño and La Niña years [Qian et al. 2013], based on National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC)-Morphing Technique (CMORPH) data.

The analysis of the dependence of lightning on day-to-day fluctuations in cloudiness and low-level wind (section 3), the usefulness of these empirical relationships for predicting the spatial pattern of lightning anomalies during the active and break periods of the MJO (section 4, particularly Fig. 15), and the similarities between these results and the previously published composites of lightning and wind associated with ENSO (Yoshida et al. 2007) confirm that thunderstorm variability over the Maritime Continent is mediated by variations in the strength of the local land–sea and mountain–valley wind regimes in response to changes in ambient atmospheric conditions.

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APPENDIX

Phase of Diurnal Cycle during the MJO Cycle

To investigate shifts in the timing of the diurnal cycle of lightning during the MJO, harmonic analysis has been applied to hourly mean lightning frequency at each grid point during the MJO break and active periods. The hour of the maximum of the first harmonic, shown in Figs. A1a and A1b, is consistent with an afternoon and evening peak in lightning over land, offshore propagation during the night, and maximum morning lightning over the seas, in agreement with the diurnal summary in section 1. Previous studies of shifts in the diurnal cycle of convection during the MJO have shown that while no shift is observed in the diurnal phase of deep convective cloud amounts averaged over the Maritime Continent region (Tian et al. 2006), the diurnal maximum in TRMM rainfall occurs 1–3 h earlier during the break (Rauniyar and Walsh 2011) and developing stages (i.e., phase 3) of the MJO than during the active period, particularly over the ocean (Oh et al. 2012). The difference plot in Fig. A1c indicates that, with some exceptions, areas with more lightning during the break period, such as the seas southwest of Sumatra and Borneo and west of Sulawesi, tend to experience an earlier lightning peak during the break period than during the active period (i.e., they exhibit negative values in Fig. A1c), in agreement with Rauniyar and Walsh (2011) and Oh et al. (2012). Anomalies in the vicinity of land, where there is sufficient lightning for harmonic analysis, range up to 2–3 h. The Java Sea and seas east of Sulawesi and the Malay Peninsula, which exhibit more lightning during the active period, tend to experience an earlier lightning peak during the active period than during the break period.
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FIG. A1. Hour of the maximum of the first harmonic of hourly mean WWLLN lightning frequency during MJO (a) break and (b) active periods, and (c) the difference between (a) and (b). Black contours indicate the 500-m elevation. Gray shading indicates areas of low annual-mean lightning or weak diurnal lightning variability.


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CORRIGENDUM

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The original caption of Fig. 8 in Virts et al. (2013) is incorrect. The correct caption is presented below. For Figs. 8–11, the convention is that composites for MJO break periods are shown in the top panels and the composites for MJO active periods are shown in the middle panels.

The authors regret any confusion caused by this error and thank Adam Sobel for bringing it to their attention.

REFERENCE


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FIG. 8. Mean CERES-MODIS cloud area during MJO (a) break and (b) active periods, and (c) difference between (a) and (b). Black contours indicate the 500-m elevation.