# Time–Space Characteristics of Diurnal Rainfall over Borneo and Surrounding Oceans as Observed by TRMM-PR

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ABSTRACT

Five years of Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) data were used to investigate the time and space characteristics of the diurnal cycle of rainfall over and around Borneo, an island in the Maritime Continent. The diurnal cycle shows a systematic modulation that is associated with intraseasonal variability in the large-scale circulation pattern, with regimes associated with low-level easterlies or westerlies over the island. The lower-tropospheric westerly (easterly) components correspond to periods of active (inactive) convection over the island that are associated with the passage of intraseasonal atmospheric disturbances related to the Madden–Julian oscillation. A striking feature is that rainfall activity propagates to the leeward side of the island between midnight and morning. The inferred phase speed of the propagation is about 3 m $s^{-1}$ in the easterly regime and 7 m $s^{-1}$ in the westerly regime. Propagation occurs over the entire island, causing a leeward enhancement of rainfall. The vertical structure of the developed convection/rainfall system differs remarkably between the two regimes. In the easterly regime, stratiform rains are widespread over the island at midnight, whereas in the westerly regime, local convective rainfall dominates. Over offshore regions, convective rainfall initially dominates then gradually decreases in both regimes, while the storms develop into deeper convective systems in the easterly regime. Aside from leeward rainfall propagation, shallow storms develop over the South China Sea region during the westerly regime, resulting in heavy precipitation from midnight through morning.

## 1. Introduction

The weather over the Maritime Continent (Ramage 1968) is characterized by heavy rainfall throughout the year. The region is a major atmospheric heat source that plays an essential role in the earth's climate system. The unique environment over the Maritime Continent includes complex land/ocean geography, surrounded by warm ocean waters. This environment favors the development of frequent deep convection on multiple temporal and spatial scales. Land–sea contrasts associated with major islands in warm oceans generate complex local circulations that play an important role in the energy and water cycle processes of the region (Neale and Slingo 2003). Much of the active deep convection occurs in response to the interactions of the several time–space-scale circulation systems over and around Borneo, which is located at the center of the Maritime Continent (Chang et al. 2005a). The linkage between island-induced convection and the large-scale circulation is crucial for convective organization over this region.

The Maritime Continent has a pronounced diurnal cycle in convection and precipitation that is influenced by surface heating. Previous studies using satellite cloud imagery have shown a distinct land–sea contrast that is characterized by late afternoon/evening convection over land, and nighttime and morning convection over the surrounding ocean (Murakami 1983; Nitta and Sekine 1994; Yang and Slingo 2001). There is also large regional variability in the diurnal cycle because of the complex forcing mechanisms related to surface inhomogeneities (Ohsawa et al. 2001). Diurnally forced

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land–sea differential heating and terrain-slope heating all initiate local circulations that can support organized cloud clusters that are characterized by a pronounced diurnal cycle (Williams and Houze 1987). Especially over coastal regions, the development of convection is dominated by the sea–land breeze (Saito et al. 2001).

One of the characteristics observed in the diurnal variability of convection over the Maritime Continent is the phase propagation of the diurnal signal. Yang and Slingo (2001), using high-resolution Cloud Archive User Service (CLAUS) brightness temperature data, showed that a widespread coherent diurnal variation in the convection peak propagates offshore around the island. This suggests that the strong diurnal signal over land moves out over the surrounding ocean as a gravity wave. Mori et al. (2004) used Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) data to examine more regional characteristics of precipitation over Sumatra and found that diurnal variation of rainfall over that island is characterized by a migration from the southwestern coastline to both inland and offshore regions. Liberti et al. (2001) examined geostationary meteorological satellite (GMS) brightness temperature data over New Guinea and showed an offshore propagation of cloud systems that moved northward toward open ocean. Numerical simulations have shown that an eastward-propagating precipitation system that develops over the lee of mountain ranges is responsible for the nocturnal rainfall maximum over inland areas of Indochina (Satomura 2000). Cold gravity currents have been shown to influence the propagation. Propagating diurnal cycles also occur over the Bay of Bengal (Webster et al. 2002; Zuidema 2003), east Asia (Asai et al. 1998), North America (Wallace 1975; Carbone et al. 2002), and the northwestern coast of South America (Mapes et al. 2003a,b; Warner et al. 2003). However, details of propagation have not yet been investigated over Borneo, which is a major island in the Maritime Continent.

Large-scale low-level winds are an important modulating factor in the diurnal cycle. Houze et al. (1981) examined nocturnal rainfall activity over the seas northwest of Borneo during the Winter Monsoon Experiment (WMONEX). Land breezes converge with northeasterly monsoons to generate offshore convection, which develops into an organized precipitation system that produces heavy rainfall between midnight and morning. Oki and Musiake (1994) found similar morning rainfall associated with offshore breezes over the Malay peninsula. They used rain gauge data to analyze the seasonal and diurnal cycles of precipitation and showed a windward shift in the coastal morning maxima in precipitation counter to the predominant monsoon wind direction. The above studies underline the importance of interactions between diurnally forced land–sea circulation and prevailing monsoon winds in generating strong diurnal variations at some locations. However, a more systematic description of the large-scale impact on convection by lower winds in the diurnal cycle has not been reported.

Since late 1997, TRMM satellite PR data have clarified some spatial and temporal variabilities in precipitation structure. Precipitation radar data yield three-dimensional rainfall distributions over the whole tropical area (e.g., Short and Nakamura 2000; Petersen and Rutledge 2001; Hirose and Nakamura 2002; Petersen et al. 2002). Nesbitt and Zipser (2003) described the complex diurnal cycle over the Maritime Continent and showed diurnal variations in individual precipitation systems identified by PR and TRMM Microwave Imager (TMI) data. Precipitation systems appeared mostly between afternoon and late evening over land, but precipitation associated with mesoscale convective systems (MCSs) lingered past midnight. The number of MCSs increased over adjacent sea regions during morning hours. In addition to these large-scale features, a more regional investigation of rainfall activity provided a more advanced understanding of the precipitation characteristics of this region of complex terrain.

This study examined temporal and spatial variations in diurnal rainfall over Borneo and adjacent oceans. A particular question addressed was how the low-level prevailing wind modulates the diurnal cycle of rainfall over the island. High-resolution PR data for 5 yr yielded precipitation characteristics and their variability. Section 2 outlines the data used in this study and the composite method. In section 3, general features of the diurnal rainfall cycle, and the time–space structure of rainfall activity during different wind regimes, are presented using the results of a composite analysis. This extracted the influence of low-level winds on the diurnal cycle. Section 4 presents a summary and discussion.

## 2. Data and methods

The data used in this study include TRMM PR for 5 yr (1998–2002). PR data provide the three-dimensional structure of a swath of rainfall from the surface to 20 km above the earth ellipsoid. The swath is 215 km wide, with a horizontal resolution of 4.3 km $\times$ 4.3 km at the nadir. Vertical resolution is 250 m. Rainfall estimate sensitivity is about 0.5 mm h$^{-1}$ (Kummerow et al. 1998, 2000). Although the data have high resolution, temporal sampling is 0.5 times day$^{-1}$ at the equator because of the satellite's orbit. It takes about 46 days for TRMM to repeat a pass over a given location at a given local time.

Because of this sampling constraint, this study examined diurnal cycles from a 5-yr composite of PR data with no less than 3-h bin temporal resolution. This resolution allows a presentation of the diurnal cycle of rainfall. The present study used near-surface rain products from the TRMM Science Data and Information System (TSDIS) 2A25 version 5 algorithm (Iguchi et al. 2000). Algorithm 2A23 (Awaka et al. 1997) classifies rainfall as convective or stratiform. Such rainfall classification is important when determining the vertical profiles of latent heating and their influence on large-scale circulation fields (Houze 1989, 1997).

Gridded TRMM PR rainfall data were produced by computing 5-yr total rainfall in $0.05° \times 0.05°$ and $0.5° \times 0.5°$ grid boxes for each local time at each grid point. This computation allowed an examination of the spatial variations in diurnal rainfall over Indonesia. Histograms of storm height, defined by the top of the highest range bins with significant reflectivity, were also constructed between the surface and 15 km, at an interval of 1 km, with the same spatial and temporal resolution as the rainfall composite. The combination of surface rainfall data from PR with information on deep and shallow storms described by storm height yielded three-dimensional convective characteristics. Hourly gridded data were smoothed with a 3-h running mean to minimize sampling errors.

The effect of the low-level prevailing wind on the diurnal cycle is discussed in this study. Changes in convection under different wind regimes were revealed through composite analyses centered on the island of Borneo. Zonal winds at 850 hPa from 5 yr (1998–2002) from the National Centers for Environmental Prediction–Department of Energy (NCEP–DOE) Atmospheric Model Intercomparison Project II (AMIP-II) reanalysis dataset (hereafter referred to as NCEP RII; Kanamitsu et al. 2002) were used to classify the wind regime. Daily, area mean zonal wind time series for a box covering Borneo shown in Fig. 1 (1.5°S∼4.0°N, 111.0°∼116.5°E) were smoothed using a 5-day running mean; the wind data were then partitioned into easterly and westerly regimes. A detailed classification definition is given in section 3b. TRMM PR surface rainfall data were composited in 0.05° grid boxes for each classified wind regime.

## 3. Results

### *a. General features of diurnal rainfall activity*

Figure 1 shows the spatial distribution of rainfall inferred from TRMM PR surface rainfall data over the Maritime Continent in the morning and during late evening. There is a pronounced diurnal cycle of rainfall

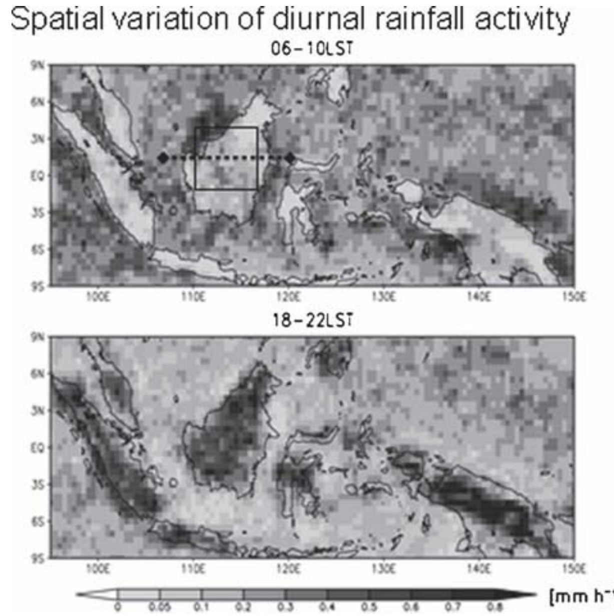


FIG. 1. Rainfall over the Maritime Continent in the morning (0600–1000 LT) and late evening (1800–2200 LT). The rectangular box is the area within which the area mean zonal wind time series are calculated. The horizontal dotted line over Borneo is a domain of calculation for the vertical distribution of storm height in Fig. 2.

between land and ocean. Rainfall is suppressed over the islands during the morning, but strong convection develops offshore, dropping much rain. The situation dramatically reverses in the evening, when rainfall activity is concentrated over Sumatra, Borneo, and New Guinea.

Borneo is located near the center of the Maritime Continent. The terrain of Borneo and the sea–land breeze creates a peculiar diurnal cycle in convection. Figure 2 shows time sequences of the vertical distribution of storm height frequency and surface rainfall (all—black solid, convective—red solid, and stratiform—black dotted) along 1°N averaged with ±0.5° in latitude (dotted line in Fig. 1) to highlight the two-dimensional structures in precipitation and convective development. Shallow storms appear over the island, over the coast, and in the central mountains, at 1100–1300 LT. By 1400–1600 LT, coastal storms have developed, enhancing surface rainfall. Between 1700 and 1900 LT, deeper storms overspread much of the island resulting in increased surface rainfall, while coastal rainfall dissipates. Most of the rain from 1100–1300 LT to 1700–1900 LT is convective. At night, convective activity is concentrated over the central part of the island. From 2000 LT through 0100 LT, deeper storms converge over inland areas, and rainfall persists until midnight over the central part of the island. The dominant

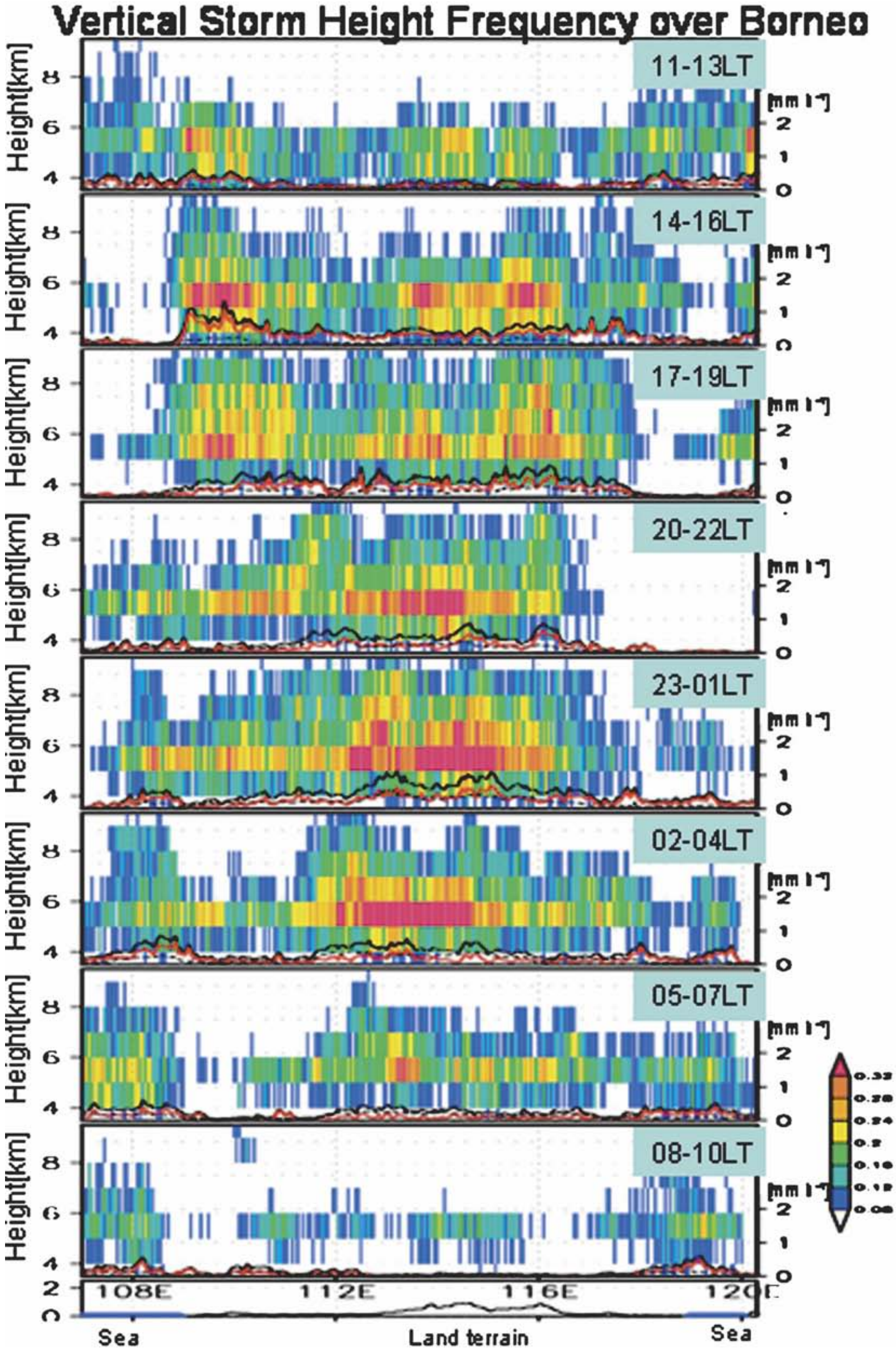


FIG. 2. Time sequence of the vertical distribution of storm height frequency from 3.5 to 9 km over Borneo along 1°N averaged with ±0.5° in latitude (horizontal line in Fig. 1). Surface rainfall amount is also noted in each time bin (black solid: all rain, red solid: convective rain, black dotted: stratiform rain). Land terrain is described along the bottom (sea is shown by blue line).

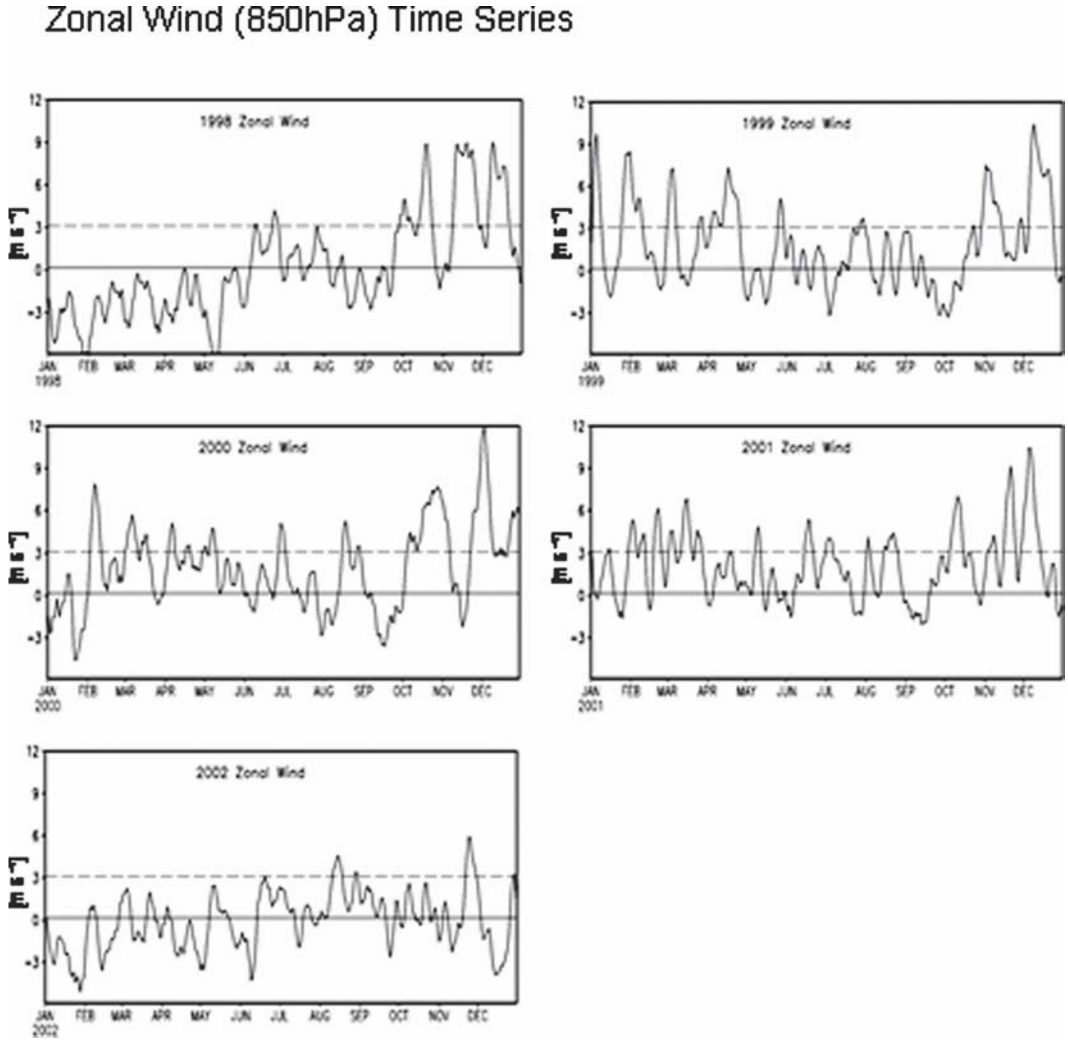


FIG. 3. Zonal wind at 850 hPa from NCEP R2 data for an area over Borneo (1.5°S–4.0°N, 111.0°–116.5°E; rectangular box in Fig. 1) and smoothed by a 5-day running mean.

rainfall type changes at night. About half of the rainfall is stratiform from 2300 LT to 0100 LT. From 0200–0400 LT until morning, offshore convection develops on both sides of the island as convection over land gradually dissipates.

### b. The low-level wind variation over Borneo and the large-scale circulation field

Oscillations in the low-level zonal wind associated with variations in the large-scale circulation field are a prominent feature over and around Borneo. Figure 3 shows a time series of zonal wind at 850 hPa from NCEP RII data averaged over Borneo (1.5°S– 4.0°N, 111.0°–116.5°E: rectangular box in Fig. 1) and smoothed by a 5-day running mean. Fluctuations in low-level flow over the island occur mainly in the intraseasonal and interannual time scales. Seasonal variations do not cause distinct variability over the island. Between January and April 1998, easterly winds persisted during an El Niño event, when submonthly scale disturbances are unlikely to dominate. A prolonged period of easterly winds, presumably due to anomalous Walker circulations, corresponded to a significant decrease in rainfall over the Maritime Continent (Lau and Wu 1999; Walsh and Newbery 1999). Wind direction changed intermittently from easterly to westerly and vice versa in association with convective variability influenced by the passage of an intraseasonal-scale disturbance such as the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972, 1994). Intraseasonal variability for the five years is most strongly dominated by the westerly phase rather than the easterly phase.

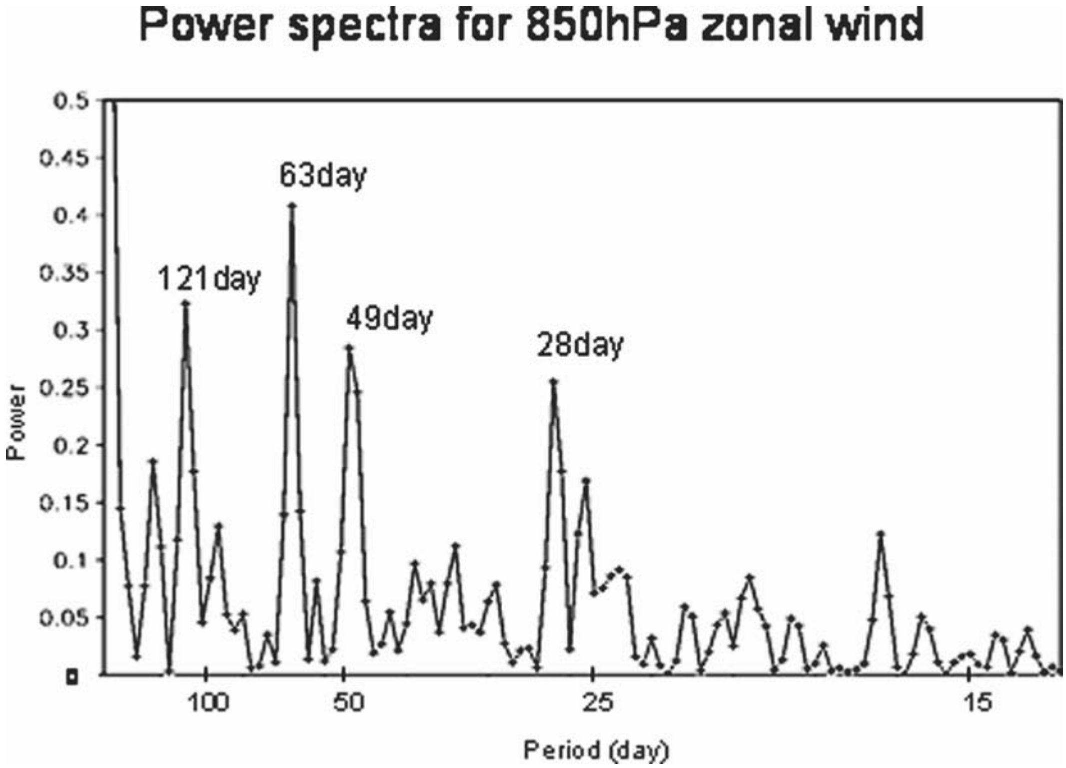


Fig. 4. Power spectra for 850-hPa zonal winds over Borneo.

This is especially true for the stronger westerly winds that prevail during boreal winter, when the MJO has a peak amplitude (Madden and Julian 1972; Madden 1986; Gutzler and Madden 1989).

A power spectrum of the zonal wind time series in Fig. 3 is shown in Fig. 4 to clarify prominent frequencies in the wind field variability. It is obvious that the intraseasonal variation is the most prominent variability in the time series of Fig. 3. Pronounced variations in zonal wind that occur with periods of about 30 and 60 days likely reflect the influence of the MJO. The spectrum shows relatively higher power at a period of 120 days, but actual changes in wind direction occur at intraseasonal frequencies, as seen in Fig. 3. As the MJO propagates eastward from the equatorial Indian Ocean toward the Pacific Ocean, low-level winds change from easterly to westerly over Indonesia as the MJO enhances or suppresses convection. Therefore, low-level equatorial westerly (easterly) winds basically correspond to periods of active (inactive) convection over the Maritime Continent because of the MJO (Chang et al. 2005a).

Three wind regimes were identified that highlight the influences of the low-level wind pattern variability on diurnal rainfall activity over the island. The smoothed time series of zonal winds (Fig. 3) were first partitioned into easterly (EE) and westerly regimes. The westerly regime was further partitioned into weak westerly (WW) and strong westerly (SW) phases based on a threshold average wind speed of 3 m $s^{-1}$. Figure 5 shows composite midtropospheric relative humidity (averaged from 700 to 400 hPa) and upper-level divergence (200 hPa) for each wind regime to depict convective activity. Despite the simple partitioning methodology, clear differences in atmospheric features for each wind regime are obvious. Westerly regimes correspond to periods of active convection over the Maritime Continent, as reflected in the large-scale upper-level divergence and wetter conditions around the Sumatra, Borneo, and Sulawesi islands. Convection is inactive when easterly winds prevail, and the regions only around Sumatra and western Borneo are rather humid. These three composites also characterize the MJO. There is enhanced convection in the Indian Ocean during the EE regime. Convection approaches the Maritime Continent in regimes WW and SW.

Although most of the variability of the wind field occurs in the intraseasonal time scale over the island, there are rather large differences of circulation field from northern winter and summer because of the seasonal reversal of the prevailing wind. To clarify the seasonal attribution of each composite, the seasonal

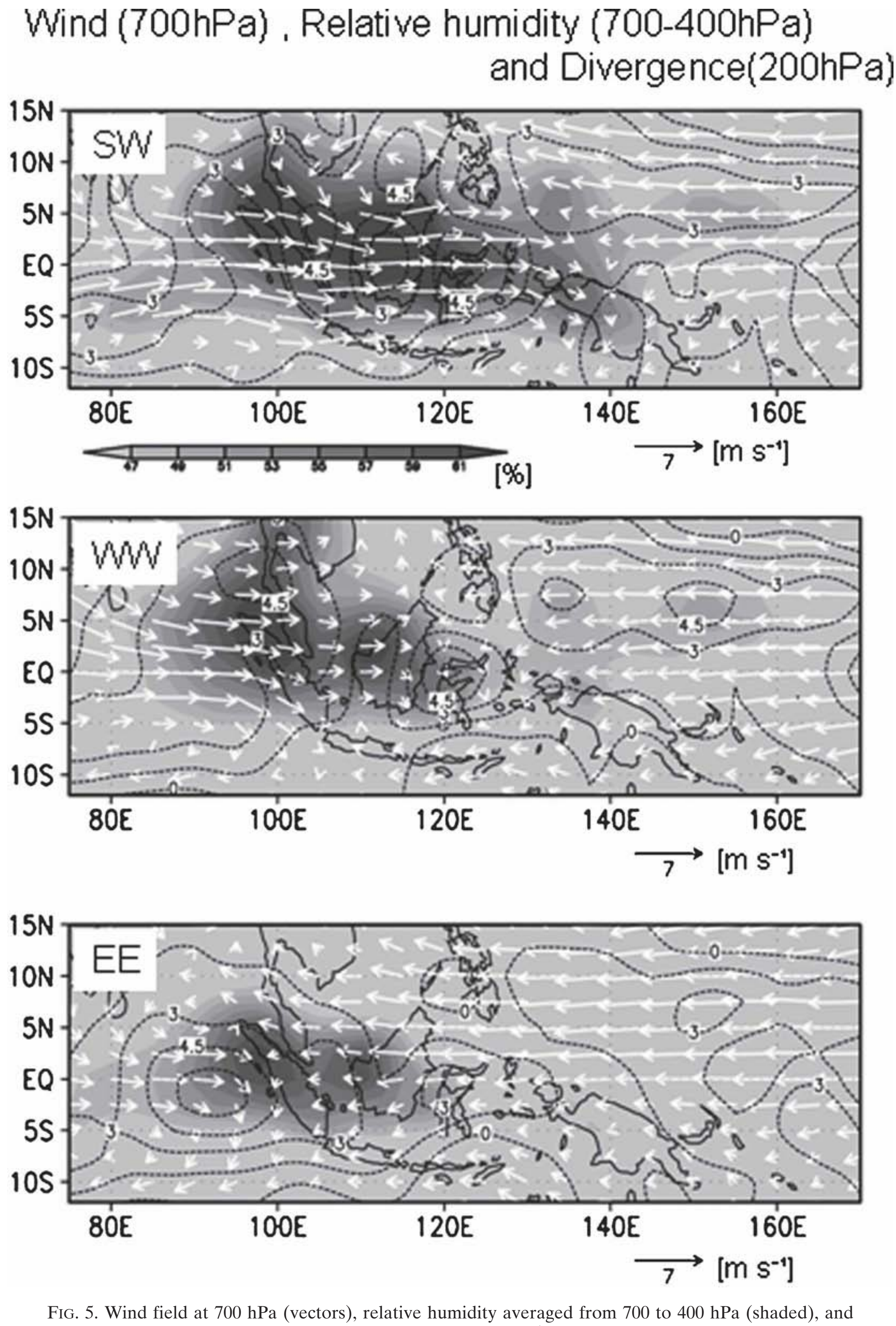


FIG. 5. Wind field at 700 hPa (vectors), relative humidity averaged from 700 to 400 hPa (shaded), and divergence at 200 hPa [contour ($\times$1 000 000 $s^{-1}$)] for each wind regime.

Table 1. The seasonal distribution of days in each wind regime over Borneo.

| | Boreal winter (October–March) | Boreal summer (April–September) | Total |
|---|---|---|---|
| SW days | 346 | 133 | 479 |
| WW days | 257 | 434 | 691 |
| EE days | 308 | 348 | 656 |

statistics of occurrence of each wind regime are examined as shown in Table 1. A strong westerly phase prevails mostly in boreal winter. On the other hand, WW tends to occur in boreal summer, while it also contains a transition period of intraseasonal variability between EE and SW in boreal winter. During the boreal summer season, the intraseasonal variation occurs between EE and WW, and the occurrence of SW is rare. Associated with this seasonality, each composite also characterizes a primary circulation pattern related to the seasonal circulation system as well as the intraseasonal variability.

Figure 6 shows composite 925-hPa wind and atmospheric instability defined by the difference of equivalent potential temperature between 850 and 500 hPa. In the SW composite, there is a strong cyclonic circulation over the South China Sea region called the Borneo vortex, which appears as a persistent feature of the boreal winter climatology (Johnson and Houze 1987). This synoptic-scale disturbance contributes to the variability of circulation field and deep convection over and around Borneo in the interaction with the MJO (Chang et al. 2005a). The cyclonic circulation of the vortex is influenced by the increased equatorial westerly associated with the MJO extended from the Indian Ocean to Borneo and the northeasterly from the South China Sea. The latter flow is partly related to the cold surges (Chang et al. 1983) associated with the Asian winter monsoon, which has an important impact in the low-level circulation patterns over the South China Sea in the synoptic time scales. In our composite, the cold surge event that is defined as the averaged 925-hPa meridional wind between 110° and 117.5°E along 15°N (horizontal line in Fig. 6) exceeds 8 $\mathrm{m\,s^{-1}}$, occurs mainly in the SW regime (SW—72 days, WW—6 days, and EE—8 days) for 5 yr. The strength of the Borneo vortex is amplified by the presence of the cold surge because of the increased shear vorticity due to the stronger northeast wind (Chang et al. 2005a). Thus, the cold surge acts to enhance the offshore activity and give much precipitation over the South China Sea. In the case of WW, the clockwise turning of the winds that cross the equator can be observed around Sumatra and Borneo. The southeasterly winds from the southern latitude turn northeastward, which extends to the Asian monsoon region. The circulation pattern that appeared in WW is similar to the wind field observed in the boreal summer (e.g., Chang et al. 2005b, their Fig. 3). Thus, all in all, the composites used in this study basically represent the intraseasonal variability, but also contain a significant feature of the seasonal circulation pattern. The atmospheric condition is more stabilized in the westerly regime compared to the easterly regime associated with the circulation and convection pattern differences over the Maritime Continent. The stable condition extends from the Indian Ocean to the west of Borneo, which changes to the rather unstable condition over the east of Borneo and around Sulawesi in SW. In contrast, the thermodaynamical instability is enhanced over and around the major islands in EE.

### c. *The influence of low-level winds on diurnal rainfall*

Figure 7 shows the composite mean wind field and rainfall distribution for each wind regime. Large-scale intraseasonal atmospheric variations primarily change the low-level flow over Borneo, as shown in Fig. 7. Prevailing westerlies over the island are, in most cases, associated with northwesterly flow from the South China Sea during the SW regime as discussed in the previous section. Weak westerly regime composites include an anticyclonic feature with the weak wind field over the island. During EE, convergence in moderate easterlies occurs over the southwestern part of the island. The daily rainfall distribution also changes associated with the three wind field patterns. The rainfall center is located over the western part of the island during the EE regime, but over the middle part in the WW regime. In the SW regime, the rainfall enhancement over the island occurs rather locally over the eastern lee foot area as compared to the other two regimes. Furthermore, during the SW regime, widespread rainfall occurs over the South China Sea northwest of Borneo. This is related to the strong cyclonic circulation of the Borneo vortex.

In addition, diurnal rainfall has different patterns in the three wind regimes. Diurnal variations in rainfall during EE and SW are shown in Figs. 8 and 9, respectively. Rainfall patterns during WW exhibit features intermediate between SW and EE (i.e., daytime rainfall persists over the central part of the island until past midnight, as shown in Fig. 2). The rainfall patterns between the EE and SW regimes are similar during the day; afternoon rainfall occurs in coastal regions and subsequently migrates inland in the evening. However, significant differences appear from midnight to morning as follows.

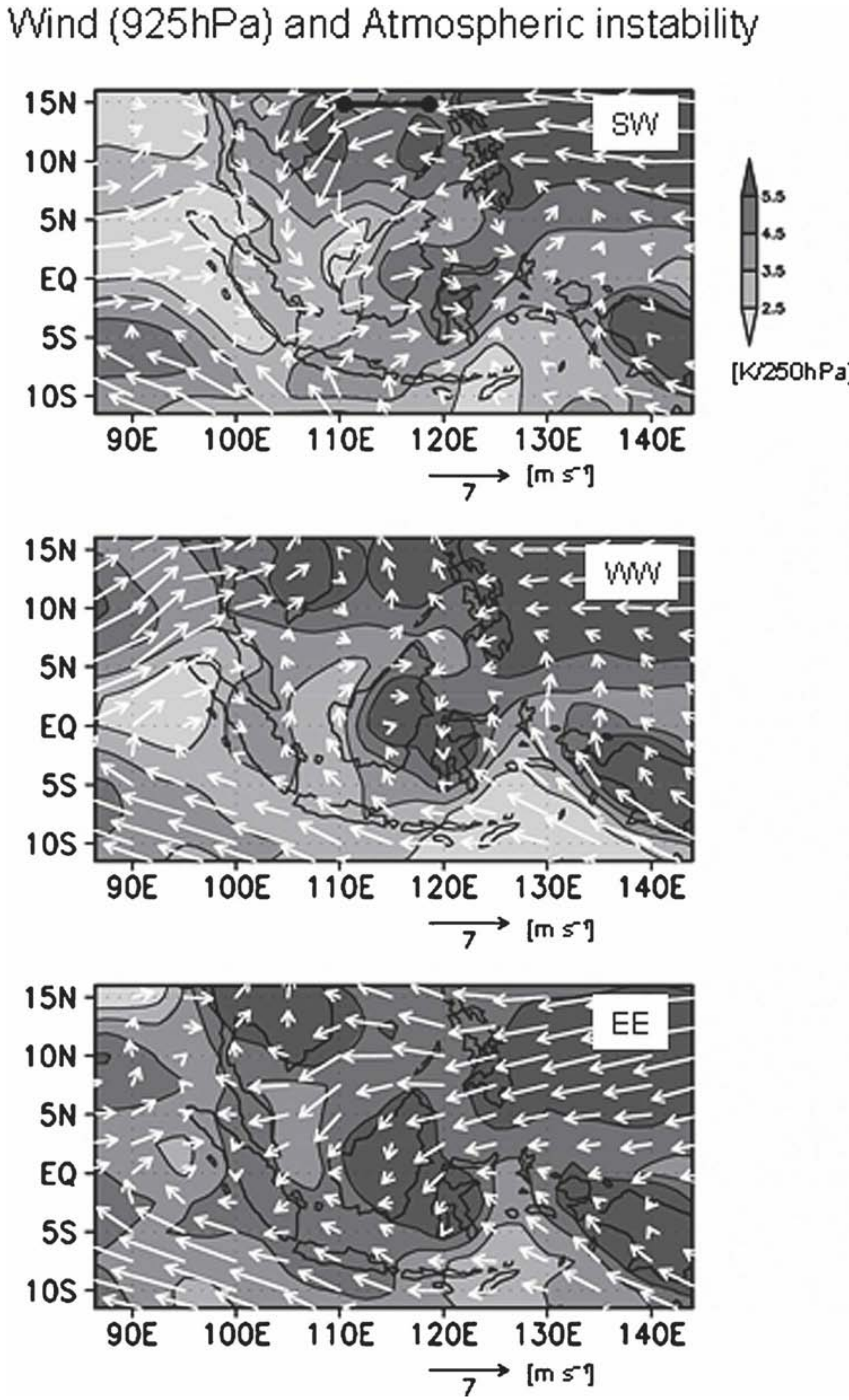


FIG. 6. Wind field at 925 hPa (vectors) and equivalent potential temperature ($\theta_e$) difference between 850 and 500 hPa [shaded; $\theta_e$(850 hPa)~$\theta_e$(500 hPa)] for each wind regime. The black horizontal line in SW is the area for the surge index (see text for details).

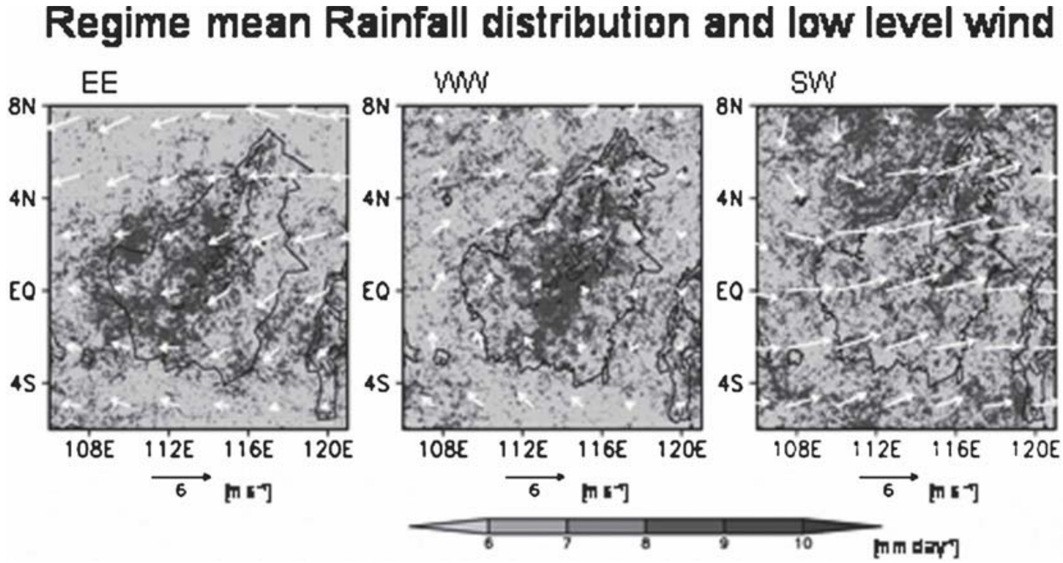


FIG. 7. Composite rainfall and 850-hPa winds for each wind regime. The black line describes island orography.

During the EE regime (Fig. 8), rainfall is suppressed on the east coast from 2000–2200 to 0200–0400 LT and is concentrated over the western half of the island. Enhanced rainfall occurs along the lee of the central mountain range and over the coastal seas, as is clearly shown at 2300–0100 and 0200–0400 LT. A relative reduction in rainfall over the eastern part of Borneo is obscured at 0500–0700 LT because convection originating over Sulawesi Island reaches coastal regions of Borneo in the morning. At 0800–1000 LT, convection over land weakens as convection off the coast strengthens.

During the SW regime (Fig. 9), the rainfall that covers the entire island at 2000–2200 LT decreases along the western coast at 2300–0100 LT. An area of suppressed rainfall expands and propagates eastward over the island from 0200–0400 to 0800–1000 LT. As in the EE regime, areas of enhanced rainfall are influenced by local terrain and occur over the eastern lee of the mountains at 2000–2200 and 2300–0100 LT, and over coastal regions at 0200–0400 LT. In addition, a convective system develops along the northwestern coast in late evening (2300–0100 LT) and overspreads the adjacent seas from late night through morning. The increased rainfall over the water northwest of Borneo (Fig. 7) is the result of this offshore convection. This nocturnal convection may be related to an organized mesoscale system that prevails during the winter monsoon over the South China Sea, as studied by Houze et at. (1981) using WMONEX data. Leeward propagation is likely to occur at larger scales over the entire island.

Figure 10 shows a time–distance cross section for a domain perpendicular to the central mountain range of Borneo to highlight the differences in the different wind regimes of the east–west propagation of rainfall activity. Interestingly, the direction of rainfall propagation changes systematically from the west during EE to the east during SW. In both regimes, rainfall occurs in the afternoon over a large area, but areas of suppressed rainfall propagate westward (eastward) during EE (SW). Thus, convection persists until midnight only over the western (eastern) side of the mountain during EE (SW), so more rainfall appears over the western (eastern) part of the island during EE (SW). During SW, a maximum in daily rainfall also appears offshore of the west coast because of a local westward-propagating rainfall system that develops at about 0000 LT (Fig. 9).

The inferred phase speed of leeward propagation for significant rainfall in Fig. 10 is $\sim -3$ m s$^{-1}$ during EE and $\sim$7 m s$^{-1}$ during SW. To reveal the relationship between the phase speeds and the surrounding wind velocity, Fig. 11 shows the vertical profile of the zonal wind velocities averaged over Borneo (1.5°S–4.0°N, 111.0°–116.5°E: rectangular box in Fig. 1) in each regime (closed circle: EE, and open circle: SW). In EE, wind condition is dominated by the easterly in all over the troposphere. The velocity increases linearly from the surface ($\sim$0 m s$^{-1}$) to the upper troposphere ($\sim$10 m s$^{-1}$ at 200 hPa). In contrast, in SW, the westerlies prevail in the lower level (>500 hPa) with its maximum (6 m s$^{-1}$) at 700 hPa, and strong easterly wind shear exists in 700 to 200 hPa. Comparing the phase speed with the wind field profile (Fig. 11), we can observe that

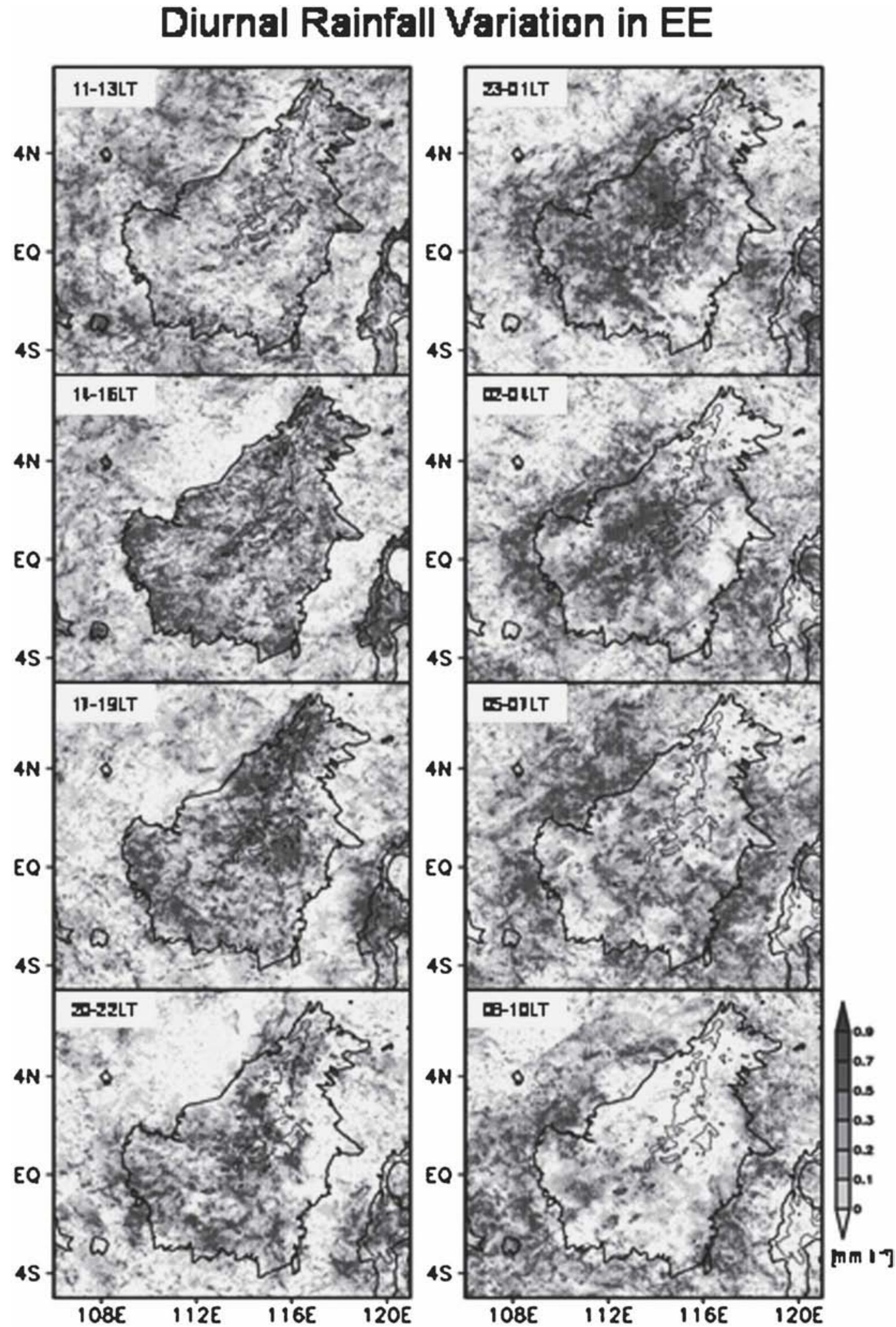


FIG. 8. Time series of rainfall distribution over Borneo in the EE regime.

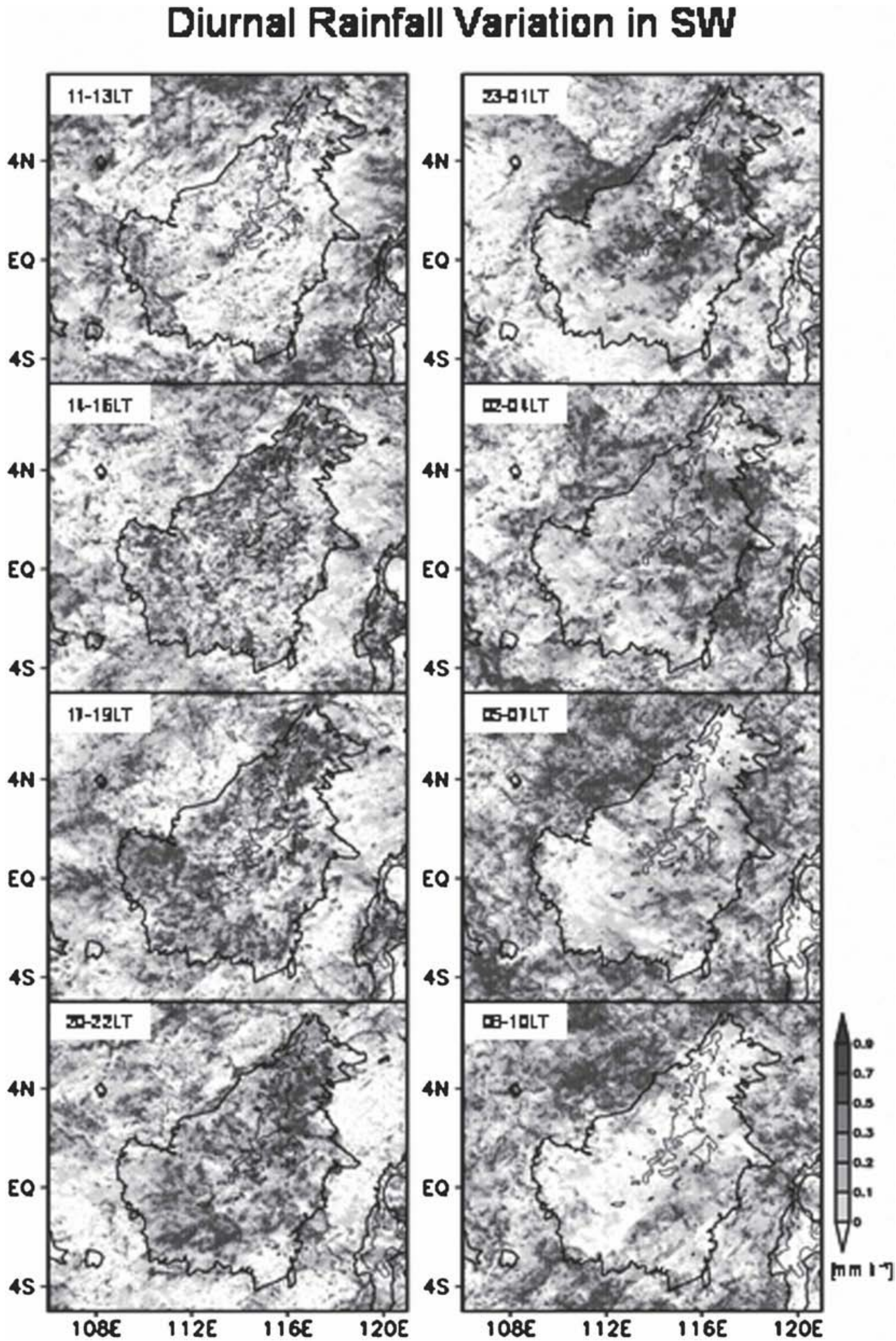


FIG. 9. Same as Fig. 8, but for the SW regime.

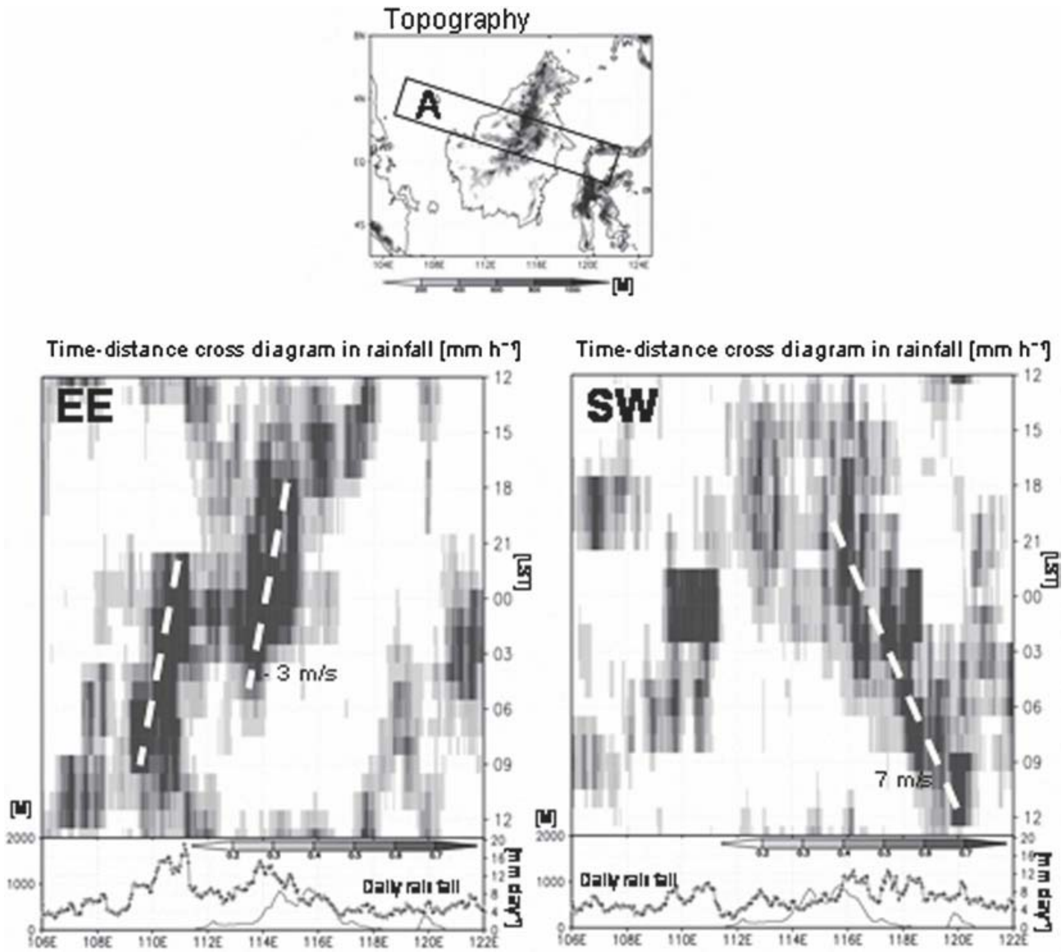


FIG. 10. Time–distance cross sections of regime rainfall along rectangle A averaged in the domain perpendicular to the central mountain range. Land terrain (solid line) and daily accumulated rainfall (crossed line) are described at the bottom of each diagram.

the leeward propagation for rainfall is closely linked to the lower-tropospheric wind in both regimes. Specifically, the inferred phase speed is roughly close to the 700-hPa wind speed in both EE and SW.

### *d. Vertical structure of diurnal rainfall activity*

The storm height characteristics of rainfall systems differ in the different wind regimes. Figure 12 shows the spatial distribution of mean storm height in each wind regime. Deeper convection is associated with rainfall propagation and occurs over the leeward side of the island. However, comparisons of Figs. 12 and 7 suggest that deeper storms do not necessarily coincide with heavy rainfall. Average storm heights are higher in EE, exceeding 7000 m, and high storms are more frequent in EE than in the other regimes associated with the conditionally unstable condition over the Maritime Continent (Fig. 6). Deeper storms tend to develop over the western coastal seas and over the southern plains in EE. Rainfall amounts differ little between coastal seas and the western lee of the mountains, but the mean storm height is lower over the lee. Higher storms, predominantly over the western part of Borneo in EE, move to eastern Borneo as the regime switches to WW and SW. Higher storm tops appear over the eastern part of the island in the SW composite, especially over the northern lee of the mountains. Offshore activity shows less vertical development in SW, with moderate storm heights from 5000–6000 m over the adjacent ocean. The rainfall distribution (Fig. 7) suggests that these relatively shallow storms nevertheless produce a lot of precipitation over the South China Sea.

Figures 13 (EE) and 14 (SW) show averaged storm height distributions in each 3 h of the day to highlight how the storm top changes diurnally. Shallow storms

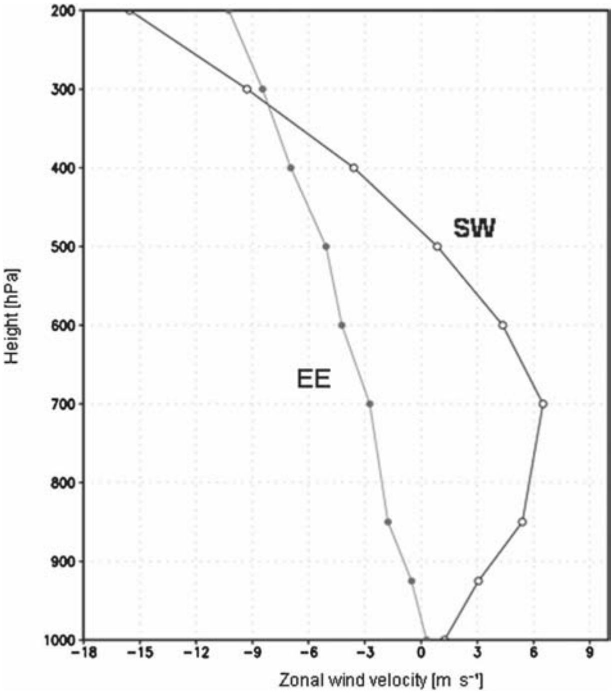


FIG. 11. Vertical profile of zonal wind velocities for an area over Borneo (1.5°S–4.0°N, 111.0°–116.5°E: rectangular box in Fig. 1) in each regime (closed circle: EE, open circle: SW).

are predominant over Borneo at 1100–1300 and 1400–1600 LT in both regimes, then rain starts over land (Fig. 8 and Fig. 9). After 1700–1900 LT, deeper storms develop and differences between EE and SW develop that are associated with the leeward propagation of rainfall. During EE (Fig. 13), deeper storms develop over western Borneo. Over land, deeper storms occur over the southern plains than over the western lee of the mountains at 2300–0100 and 0200–0400 LT. However, rainfall is heavy near the mountain range in Fig. 8. The rainfall off the west coast from midnight to morning in Fig. 8 corresponds to highly developed storms. During SW (Fig. 14), deeper storms develop over the eastern side of the island, especially over the lee of the mountains, from 2000 to 2200 LT. These deeper storms gradually weaken from 2300–0100 to 0200–0400 LT as convection propagates off the east coast. The regime mean distributions (Fig. 7; Fig. 12) suggest that the rainfall systems that develop over the South China Sea coast from 2300–0100 to 0800–1000 LT in Fig. 9 are not necessarily deeper storms.

To elucidate storm/rainfall evolution in the east–west propagation, time sequences of the vertical distribution of storm height frequency and surface rainfall (all rain—black solid, convective rain—red solid, and stratiform rain—black dotted) averaged along the rectangle A (shown in Fig. 10) are shown in Figs. 15 for EE, and Fig. 16 for SW, respectively. The data are smoothed by a 3-h running mean in each hour. The convective characteristics differ between EE and SW not only in the timing and duration of storms but also in the vertical development and rainfall type. During EE (Fig. 15), shallow convection develops, producing rainfall over the coast and central mountain range in the afternoon. This coastal convection gradually migrates toward central Borneo from 1300 to 1700 LT. Convection over the mountains develops vertically in the evening (1700–1900 LT), and deeper storms begin to appear over western Borneo from 2000 to 2200 LT. Convection over land continues until midnight with higher storm devel-

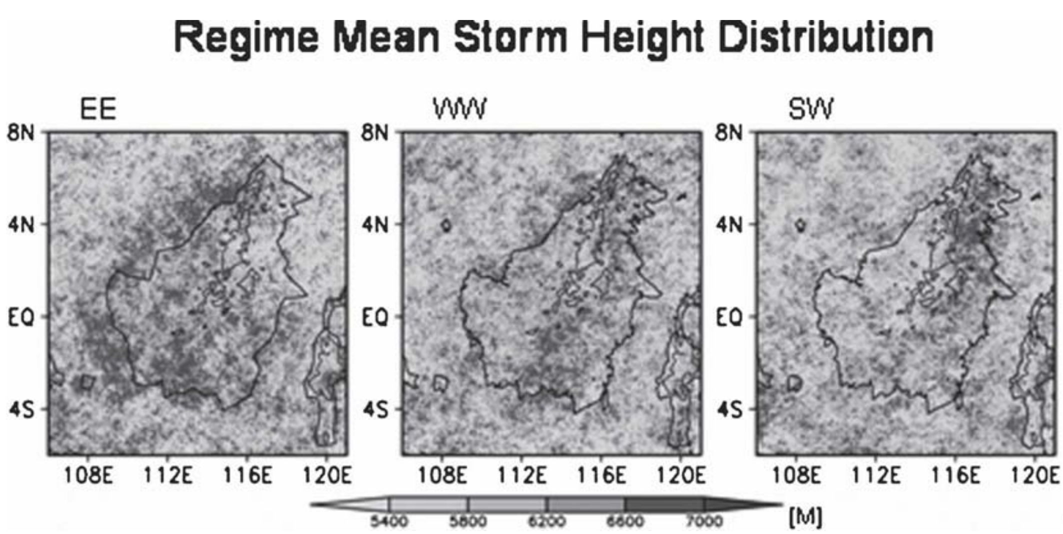


FIG. 12. Mean storm height distribution in each wind regime.

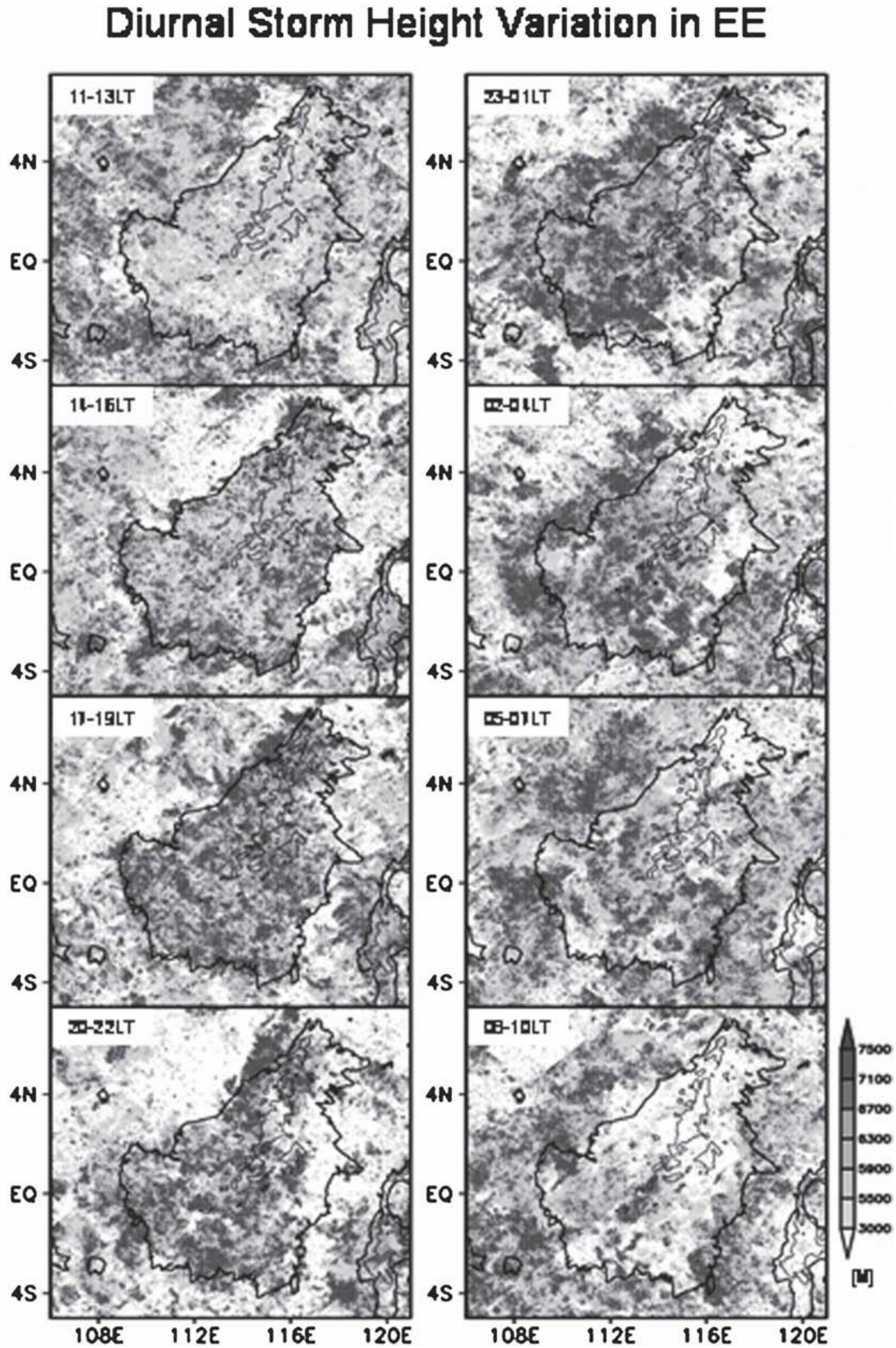


FIG. 13. Time series of mean storm height distribution over Borneo in the EE regime.

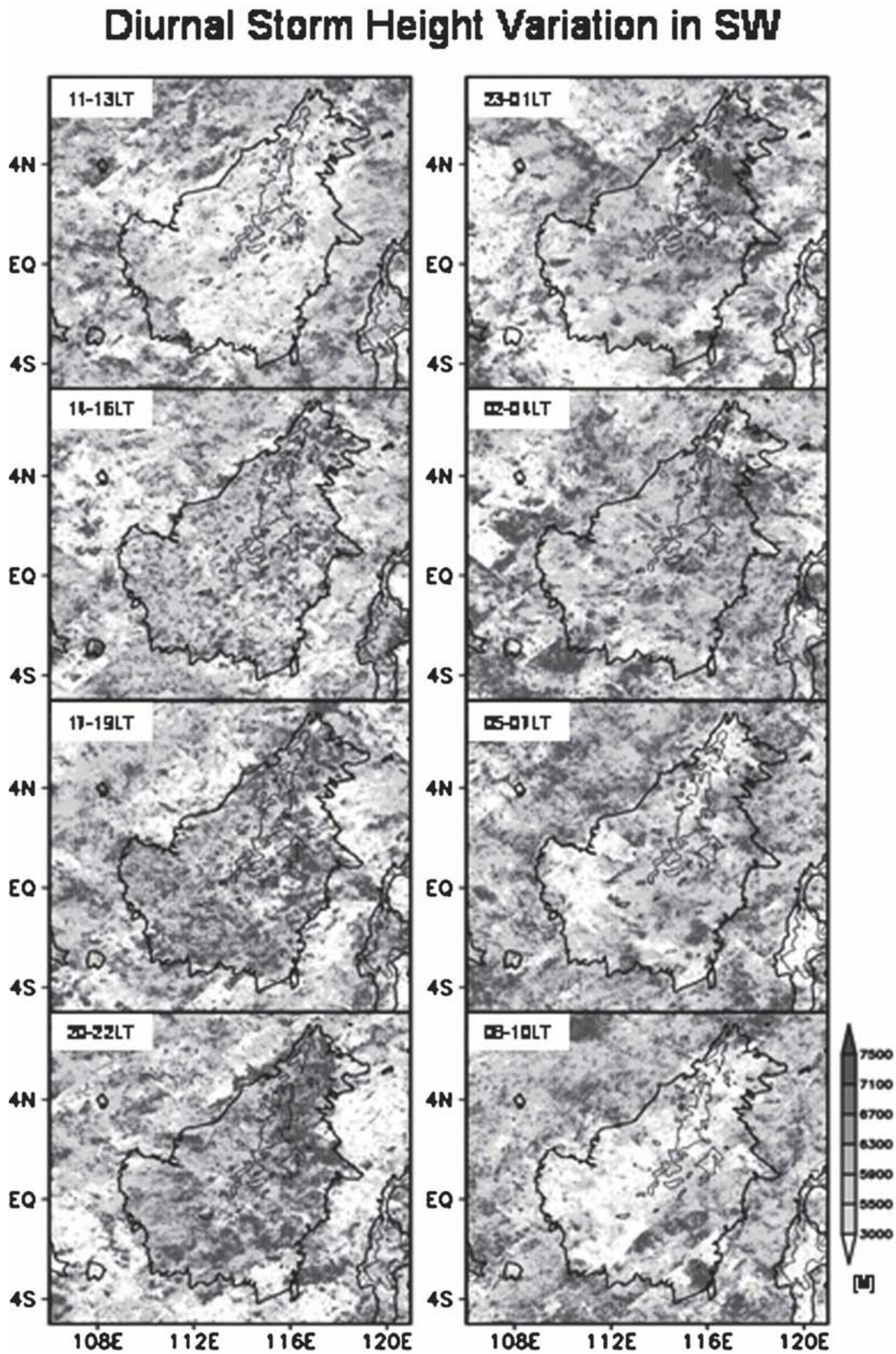


Fig. 14. Same as in Fig. 13, but for the SW regime.

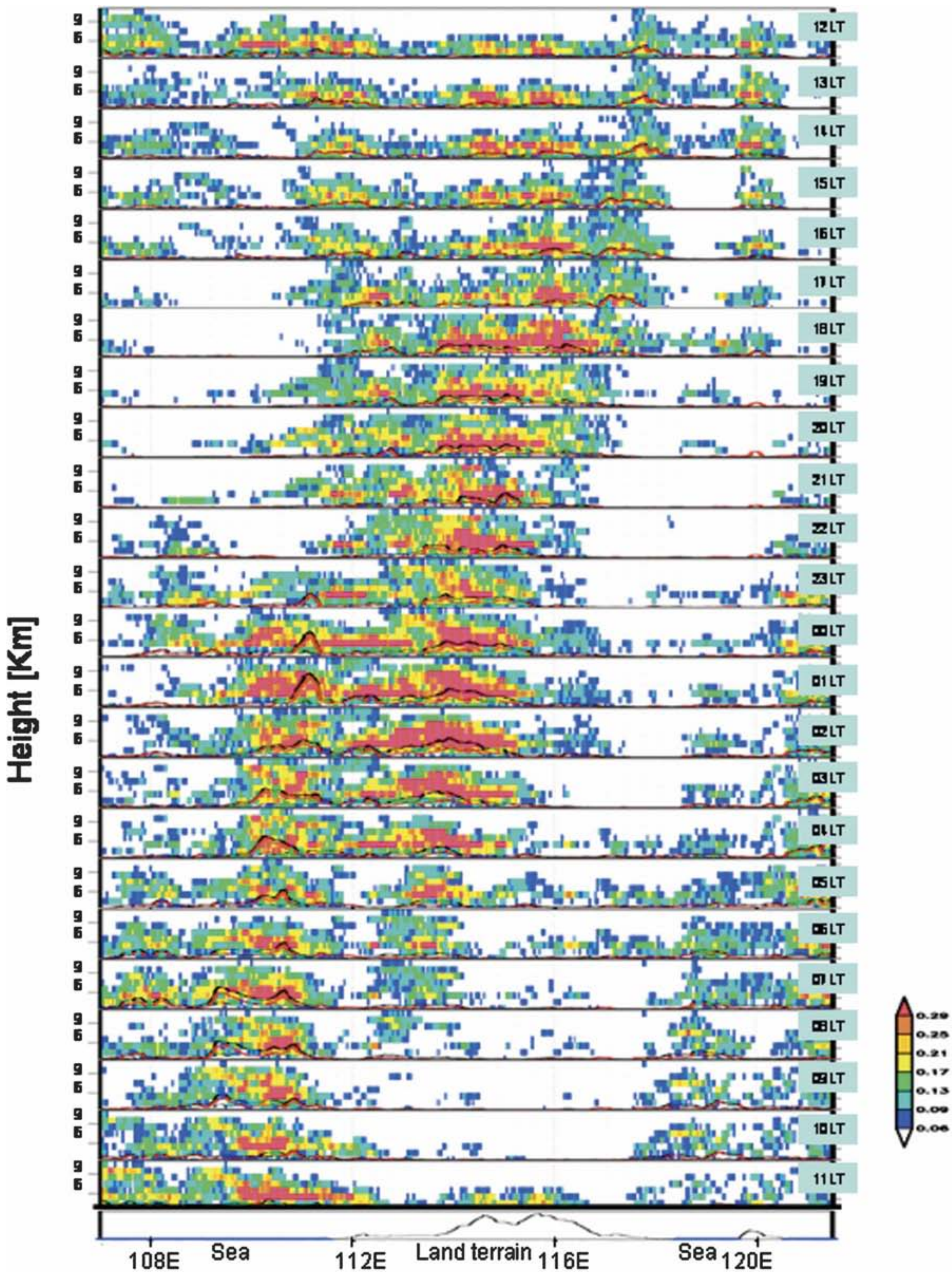


FIG. 15. Time series of vertical distribution of storm height frequency from 3.5 to 11 km over Borneo, averaged along rectangle A in the EE regime. The surface rainfall amount is indicated in each time bin (black solid: all rain, red solid: convective rain, black dotted: stratiform rain). Land terrain is described along the bottom (sea is shown by the blue line).

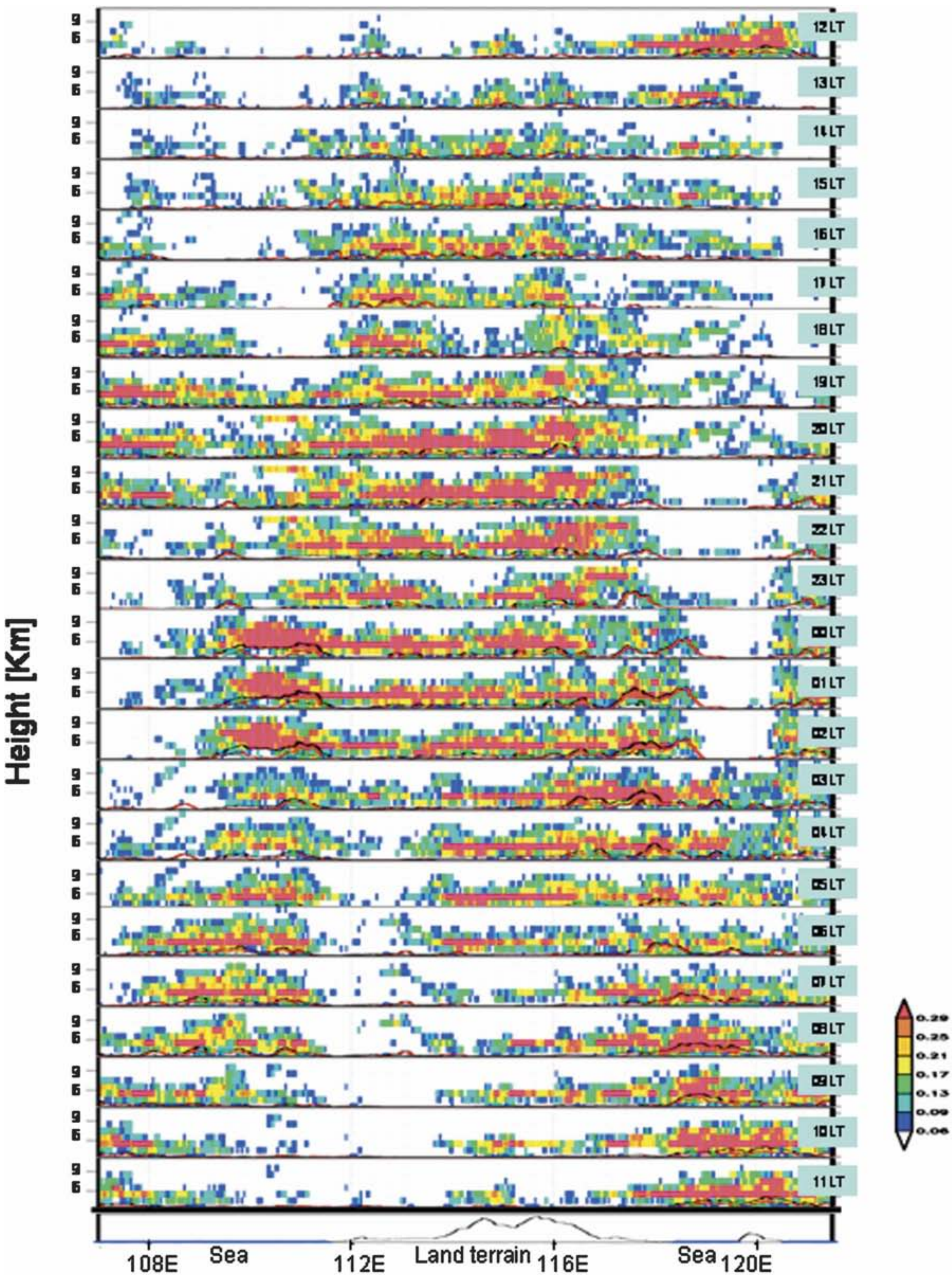


FIG. 16. Same as Fig. 15, but for the SW regime.

opment and a growing area of rainfall as the storms propagate westward. Large amounts of stratiform rainfall occur over land at night. In fact, stratiform rainfall amounts exceed convective rainfall amounts after 0100 LT. Before convection over land ceases, offshore activity starts, between 2300 and 0100 LT over the west coast. That convection rises to nearly 10 km during the morning hours. Most of the rainfall is convective, which dominates until 0800–1000 LT and gradually decreases.

In the SW regime (Fig. 16), the onset of convection is later than in EE; shallow convective clouds appear at 1400–1600 LT over the west coast and the mountain range. The coastal storms gradually evolve into widespread shallow storms at 1900–2200 LT over the western part of the island. Over the eastern part of the island, deeper storms develop at 1800–2000 LT over the mountain range. These storms evolve and propagate eastward from 2100 to 0200 LT. In contrast to the EE regime, in which stratiform rainfall overspreads much of the land (Fig. 15), rainfall in SW is predominantly convective with a sharp maximum. After 0200–0400 LT, convection over land gradually ceases, and rainfall propagates eastward, offshore of the east coast. However, these coastal storms do not develop vertically to the extent of storms over land. The dominant rain type gradually changes from convective to stratiform. Relatively shallow storms appear over regions offshore of the west coast at 0000–0200 LT. Those storms then spread to the South China Sea between midnight and morning.

## 4. Summary and discussion

The space–time characteristics of diurnal rainfall activity were investigated over the Maritime Continent using TRMM PR data for 5 yr and NCEP RII data. A prominent diurnal cycle in rainfall with a distinct land–sea contrast was obvious. Over Borneo Island, convection that starts in the afternoon over the coast and the central mountains develops vertically and subsequently covers much of the island in the evening, with enhanced rainfall. At night, convective activity converges over the central part of the island, and rainfall persists until midnight over inland areas. Convective rainfall is predominant during the daytime. Stratiform rains increase at night, producing half of the rainfall at midnight.

The annual course of daily rainfall cycle exhibits a systematic intraseasonal variability as a persistent feature of the convection over Borneo and adjacent waters. This variability can be decomposed into three regimes denoted as SW, WW, and EE, based on low-level zonal wind (850 hPa) speed values over the island. Composites of the three wind regimes have shown that the changes in zonal wind vectors over Borneo are associated with changes in large-scale circulation patterns related to intraseasonal variations. Strong westerlies tend to occur seasonally, during boreal winter, while the wind direction is most likely to change from easterly to westerly with the passage of intraseasonal atmospheric disturbances such as the MJO. Atmospheric conditions over the Maritime Continent are wet (dry) owing to the large-scale enhanced (suppressed) convection in the SW (EE) regime.

The diurnal cycle of rainfall and convective structure changes, depending on these zonal wind regimes in the lower troposphere. Figure 17 shows schematics of the diurnal cycle of convection/rainfall activity over Borneo, synthesizing the overall results of this study. After the shallow convective rainfall over the island in the afternoon, the differences in diurnal rainfall cycle between EE and SW become apparent. The most striking feature is that rainfall activity propagates to the leeward side of the island from midnight to morning in each wind regime. The inferred phase speed of the propagation is about 3 m $s^{-1}$ in EE and 7 m $s^{-1}$ in SW.

The dynamics of leeward propagation of convection/rainfall seems to differ between EE and SW. Deeper storms tend to occur in EE than SW associated with the more conditionally unstable condition. However, the structures of the developed storms are rather complicated. Over land, stratiform rainfall covers much of the island at midnight in EE. In contrast, convection in SW causes heavy local convective rainfall. A significant feature in SW is the eastward propagation of the vertically developed convective rainfall starting from the lee side of the mountain range, which suggests the development of the squall line-type convective system. The deep storms in SW appear under the strong vertical easterly wind shear condition in the upper troposphere. The propagating squall line activated at the lee foot of the mountain was simulated by Satomura (2000) over the Indochina Peninsula. In his study, the convection system is triggered by the intrusion of cold air from the windward side into the leeward side and also by the mountain wave, and propagates at the speed of the gravity current under the interaction process between the cold pool from the convection and an ambient wind near the surface. A similar mechanism may be responsible for the eastward propagation of the convection in SW. The occurrence of convection in EE is also likely to be related to the orographic forcing of the central mountain range. However, in EE, longer-lived MCSs which have wider area of stratiform rainfall tend to develop under the weaker background wind speed. The local circulation associated with complex land terrain and the land surface condition of vegetation may pre-

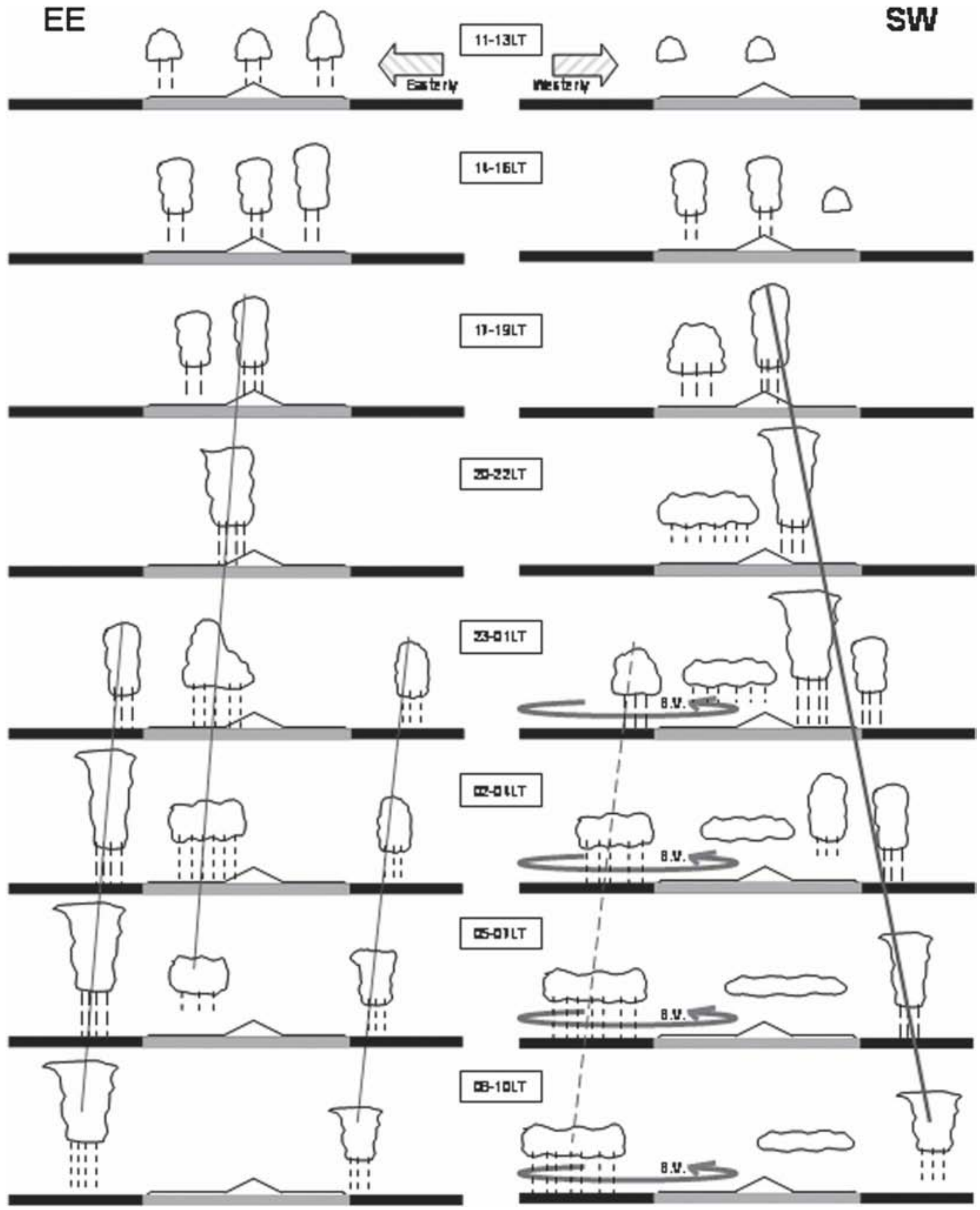


FIG. 17. Schematics of diurnal rainfall/convective activity over Borneo: (left) EE regime and (right) SW regime. Phase speed is indicated in each regime (EE : thin solid: EE, : 3 m $s^{-1}$, SW : thick solid: 7 m $s^{-1}$). Dashed line in SW denotes the evolution of shallow storm systems over the west coast. Borneo vortex (BV) in the lower level is schematically shown with a vortex-like arrow.

sumably be more important for the convection and nocturnal stratiform precipitation in EE.

Over offshore regions, initiation of convection may be associated with the land breeze for the leeward-propagating storms. Convective rainfall is predominant initially, and gradually decreases in both regimes. However, storms in EE show deeper development of convection. In addition to the conditional instability, coastline direction over the west coast, which is parallel to the prevailing wind at 925 to 850 hPa, may be an important factor for the vertical development. This may lead to produce more convergence between large-scale lower wind and land breeze blowing perpendicular to the coast, and yield deeper convection in EE.

Furthermore, over the offshore region of the northwest of Borneo, significant rainfall activity can be observed in the SW regime during nighttime to morning. The offshore activity is more shallow and stratiform as compared to the deeper convective cells in EE. The different characteristic of the nocturnal rainfall in SW is likely to be related to the presence of the Borneo vortex, which has an important impact in convection over and around Borneo (Chang et al. 2005a). As mentioned above, conditional instability is reduced during SW compared to EE around Borneo, especially over the west coast where the cyclonic circulation is dominated. In the condition, nocturnal convection is enhanced in response to large-scale convergence associated with the cyclonic circulation. Thus, shallow convection triggered by land breeze spreads its area and propagates into a large area of South China Sea, which causes widespread stratiform rainfall. On the other hand, the deeper storms developed in EE tend to stay more close to the west coast associated with the lower-level convergence enhanced by the prevailing wind and local circulations around there, which result in localized rainfall over the offshore region of the west coast.

As observed over Borneo, the leeward propagation of convection occurs also over Sulawesi in EE. The relatively shallow storms triggered by the land breeze propagate westward from the coast of Sulawesi to Borneo during nighttime to morning. The convection has an important role to enhance the rainfall amount over the eastern coastline of Borneo. When the storms reach the east coast of Borneo, the propagation of the convection is blocked by the land terrain of the island, and is ceased. However, the storms' activity is reenhanced as the convection comes close to Borneo because the land breeze intrusions from Borneo to the propagating storms make new convergence ahead of the previous convective systems from Sulawesi. Thus the rainfall persists over the east coast of Borneo until the afternoon convection develops over the coastal land area associated with the sea breeze. The shallower storms, in spite of the large atmospheric instability, may be related to the complex coastline shape of the relatively small island that may prevent convection there from organized mesoscale system.

The difference of the nocturnal convection/rainfall activity may also influence the timing and intensity of the convection following afternoon over the island. In both regimes, daytime rainfall over the island is dominated by shallow convection over the coast and mountains. However, as compared to EE, the occurrence of afternoon convection during SW is later and weaker, especially over the east coast. During the previous nighttime, in SW, shallow clouds spread over a wide range of the island and prevail until the morning hours. Increased blocking of solar insolation in the several hours after sunrise by the extensive morning clouds cover likely contributes to the delay of afternoon convection (Rickenbach 2004). Furthermore, the development of the deeper storms in the evening to nighttime would lead to stabilize the atmosphere by the convective overturning, which causes weaker afternoon convection in SW, especially over the eastern part of the island. The suppression of convection over the east in SW may also be a response to the lower-level divergence associated with the rather anticyclonic component extended from the Borneo to Sulawesi at 925-hPa winds as compared to the cyclonic circulation over the west.

A prominent feature through these results is that leeward propagation occurs over the whole of the island. A possible mechanism of the propagation may be the advection by the background low-level wind. The inferred propagation phase speed is roughly close to the 700-hPa wind speed in each regime. The actual situation is far more complicated, however, because the characteristics of the propagating rainfall activity differ between EE and SW, not only in the timing and duration of rainfall but also in dominant rain types and storm heights. The complex land terrain, which is not zonally symmetric, and differences in moist static instability of the atmosphere between SW and EE complicate the situation and its analysis. In addition to the development of the propagating storm associated with the mountain range as simulated by Satomura (2000), the occurrence of the gravity wave due to the strong diurnal signal over coastal land would be important for the propagation over the offshore region as suggested by Yang and Slingo (2001) and Mapes et al. (2003a).

Several mechanisms may be responsible for the behavior of the diurnal cycle, and a detailed investigation is needed to reveal the processes in organizing convection, including the numerical simulation of a high-resolution nonhydrostatic model. The propagating diurnal signal over the island suggests that the diurnal cycles of convection over the island are characterized not by a simple response to diurnal land–sea thermal contrast but also by the presence of propagating diurnal disturbances that are presumably embedded within the intraseasonal disturbances.

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