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Diurnal rainfall pattern observed by Tropical Rainfall Measuring Mission Precipitation Radar (TRMM-PR) around the Indochina peninsula

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[1] This study addressed the diurnal cycle of rainfall during the summer monsoon season (May to September) around the Indochina peninsula, with a focus on the diurnal cycle's relationship to terrain. The investigation used 10 year (1998–2007) Tropical Rainfall Measuring Mission Precipitation Radar (TRMM-PR) observations. Results revealed that the diurnal variations in rainfall over the Indochina region had three distinct peaks. An early afternoon maximum of rainfall occurred along the mountain ranges and on coastal land. Evening rainfall was observed near the foot of mountain ranges, in a valley, and in a basin-shaped plain; this rainfall weakened before the middle of the night. Heavy rainfall in the early morning was found around the coasts over the eastern Gulf of Thailand and the Bay of Bengal, as well as over the eastern Khorat Plateau. We found that nearly half of the total rainfall occurred in the early morning over these regions, which indicated that early morning rainfall significantly contributes to the climatological rainfall pattern. Note that the regions with early morning heavy rain did not correspond to windward faces of mountains but to the windward plain or to an offshore area apart from the mountain ranges in the windward direction. Additional examination of rainfall frequency and rainfall intensity showed that this early morning heavy rainfall was composed of frequent or long-lasting rainfall events with a strong intensity.

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1. Introduction

[2] The diurnal cycle of rainfall and convective activity is a basic characteristic of the climate over the tropics [e.g., *Wallace*, 1975; *Murakami*, 1983; *Nitta and Sekine*, 1994; *Yang and Slingo*, 2001; *Nesbitt and Zipser*, 2003]. The timing of the diurnal cycle of the convective system is generally associated with the energy budget through the radiation budget; this relationship may be an essential component of the Earth's climate. The diurnal rainfall cycle is closely associated with the land-sea distribution, the terrain, and the associated local circulation.

[3] Over the past three decades, infrared radiation (IR) and gauge-observed rainfall data have been used to examine the diurnal variations in convective activities over the southeast Asian monsoon region [e.g., *Murakami*, 1983; *Nitta and Sekine*, 1994]. These pronounced diurnal variations during the Asian summer monsoon season have been found over the Indochina peninsula, the Tibetan Plateau, the Bay of Bengal, and the South China Sea [*Nitta and Sekine*, 1994]. *Ohsawa et al.* [2001] investigated diurnal rainfall over Southeast Asia using gauge-observed rainfall data and satellite-derived IR data. The rainfall observations included a clear diurnal cycle over the Indochina peninsula, which varied somewhat from the results derived from IR. Interestingly, *Ohsawa et al.* [2001] also found that late night and early morning rainfalls were stronger than daytime rainfalls; these results were obtained from rain gauge observations from a few stations located inland of the Indochina peninsula. *Satomura* [2000] simulated an eastward (leeward) moving rainfall system using a two-dimensional cloud-resolving model. This appears to partly explain the diurnal cycle of rainfall inland of the Indochina peninsula. Recently, *Hirose and Nakamura* [2005] used 6 year PR (Precipitation Radar) data from the TRMM (Tropical Rainfall Measuring Mission) to show distinct diurnal cycles of rainfall over the entire tropical Asian monsoon region. They found diurnal patterns of rainfall that are typical for the tropics, with an evening maximum over land and an early morning maximum around the coast. The evening rain over land consisted of small rainfall systems, while the morning rain along the foothills of the Himalayan mountains were large-scale rainfall systems.

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[4] Diurnal variations in cloud activity and rainfall over the Asian monsoon region, including the Indochina peninsula, were investigated associated with the land-sea distribution; however, variations associated with regional scale orography over the Indochina peninsula have not been investigated, even though these variations are strongly affected by regional scale terrain (spatial scale ranging from several tens of kilometers to more than a hundred kilometers).

[5] Several earlier studies have used TRMM-PR data to investigate the diurnal cycle of rainfall associated with regional orography over the Asian monsoon region. For example, *Fujinami et al.* [2005] investigated the diurnal variations in rainfall over the mountain-valley terrain of the southern Tibetan plateau. They found that rainfall activity usually occurs over the mountains in early afternoon and over the valley in late evening. *Bhatt and Nakamura* [2005] showed that there was a late evening to early morning rainfall over the southward slope of the Himalayas. *Singh and Nakamura* [2009] investigated diurnal rainfall variations over the central Tibetan Plateau and found late afternoon peak rainfall over hilly regions, and late evening to early morning peak rainfall over valleys and lakes. These studies investigated the diurnal rainfall cycle associated with regional scale orography, and speculated the existence of local circulations over regions with sparse observation network. In other words, the diurnal variations of cloud and rainfall activities provide a means to visualize a portion of the local circulation, which is useful for an understanding of local circulations associated with these variations over regions with a sparse observation network.

[6] The use of long-term TRMM-PR observations from space allows the total amount of rainfall and the diurnal rainfall cycle in the tropics to be investigated. The 10 year average of these data can resolve the diurnal cycle of rainfall and can capture the climatology of total rainfall [e.g., *Hirose et al.*, 2008]. The advantage of long-term TRMM-PR observations is that they have almost uniform quality over sea, land, and mountainous areas. Conversely, gauge-observed, IR-estimated, and microwave-estimated rainfalls are less advantageous for analyzing the total amount of rainfall and diurnal rainfall cycles related to the regional scale terrain. Rain gauge observations have been inadequate for describing the diurnal cycle of rainfall over Indochina terrain and over the sea, since their locations were limited to populated and low-altitude areas. The advection of upper level clouds [e.g., *Inoue et al.*, 2006] interferes with the investigation of diurnal cloud activity related to regional scale terrain. The advection of the upper tropospheric clouds also adversely affects rainfall products from IR data. Recently, microwave imagers such as TRMM Microwave Imager have been available for rainfall estimation; they are useful for observations over oceans, but their accuracy over land is poor. Although TRMM-PR observations of rainfall over the mountain ranges may include uncertainties, possibly due to ground clutter, the ability to detect clear diurnal variations over the mountain-valley regions shows that TRMM-PR is sufficiently able to investigate diurnal variations in rainfall over the Indochina region.

[7] Prior to the present study, the pronounced diurnal variations in convective activities over the Indochina peninsula have only been analyzed using gauge-observed rainfall and IR-based convective indices. Also, the diurnal variations of rainfall related to regional scale terrain have not been previously investigated. We used 10 year TRMM-PR data to investigate diurnal rainfall cycles over and around the Indochina peninsula as they relate to the regional orography. In addition, rainfall intensity, rainfall frequency, and their diurnal cycles were investigated to understand characteristics of rainfall in this region. Previous studies have showed that the rainy season over the Indochina peninsula occurs during 5 months, from May through September [e.g., *Matsumoto*, 1997; *Takahashi and Yasunari*, 2006]; thus we focused on that period. Section 2 describes the data used in this study. Section 3 presents results of the TRMM-PR observations. Possible mechanisms for the observed phenomena are discussed in section 4, and conclusions are presented in section 5.

2. Data

[8] The primary rainfall data set used here was the TRMM-PR rainfall 3G68 product version 6, which is a gridded version of the TRMM-PR rainfall 2A25 product [*Iguchi et al.*, 2000]. Hereafter, we refer to these rainfall data as TRMM-PR. The 3G68 product includes the grid-averaged hourly rainfall amount, the grid-accumulated numbers of rainfall pixels, and the grid-accumulated total number of observation pixels every hour. These data had a 0.5 × 0.5 degree grid resolution within the tropics and subtropics (approximately 36.5°S–36.5°N). The 10 years of TRMM-PR observations spanned from 1998 to 2007. We defined a rainfall frequency and a rainfall intensity to describe the characteristics of the diurnal rainfall cycle and the spatial distribution of rainfall totals. The three parameters were calculated from the 3G68 product at each hourly time slot. The rainfall amount, RA, was the total amount for 10 years divided by the total observation number. The rainfall frequency, RF, was the number of rainfall pixels divided by the total number of pixels for the TRMM-PR observation, expressed as a percent. A rainfall pixel was identified when the 2A25 algorithm judged the existence of near-surface rainfall. The rainfall intensity, RI, was calculated as the mean rainfall amount divided by the rainfall frequency. RI is the rain rate when a near-surface rainfall exists (near-surface rain rate >0 mm h^{-1}). Because the study area was limited to the Indochina peninsula, we used unified local time along 105°E.

[9] As a second data set, we compared the amount of rainfall from TRMM-PR with gauge-observed rainfall data. We used a 30 year period of daily rainfall data (1971–2000) that was collected as part of the Global Energy and Water Cycle Experiment (GEWEX) Asian Monsoon Experiment (GAME), and the Monsoon Asian Hydro-Atmosphere Scientific Research and Prediction Initiative (MAHASRI). Less than 10% of the rain gauge data were missing at each station.

[10] To discuss the local circulation associated with diurnal variations in rainfall over the Indochina peninsula, we used 3 years of surface wind speed and direction data (1998–2000) observed at meteorological stations by the Thai Meteorological Department. Only 3 years of data were available to resolve the diurnal cycle. The wind observations were taken

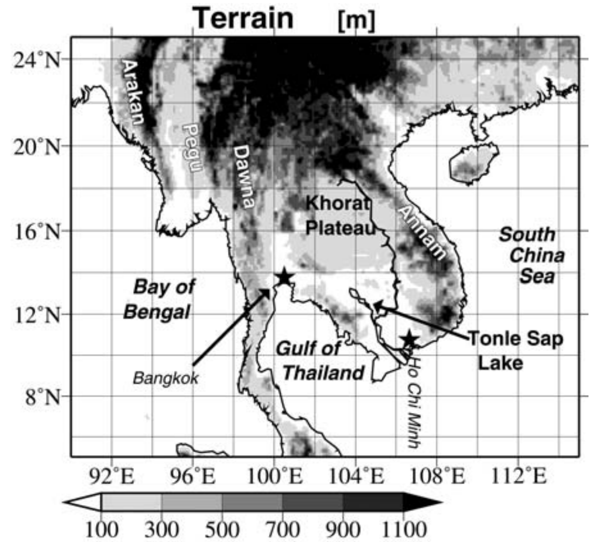

Figure 1. Terrain elevation and geography of the study area. Shading indicates terrain elevation.

at 3 h intervals. The data were also collected by the GAME and MAHASRI activities.

[11] In addition, we used monthly mean horizontal winds at 850 and 200 hPa, from the Japanese 25 year Reanalysis Project (JRA25) [*Onogi et al.*, 2007] data. This provided data availability to study the relationship between the rainfall distribution and large-scale atmospheric circulation. JRA25 data for the Indochina peninsula were taken from the 27 year period spanning from 1979 to 2005, for 5 months of the summer rainy season (May to September).

3. Results

3.1. Background Monsoon Circulations Over the Indochina Region

[12] The terrain features are shown in Figure 1, and the long-term (1979–2005) May–September mean winds are depicted in Figure 2. At 200 hPa (Figure 2a), the easterlies prevailed, associated with the circulation related to the Tibetan High. However, at 850 hPa (Figure 2b), low-level monsoon westerlies prevailed from the Bay of Bengal to the South China Sea. A large amount of rainfall was observed on the windward side of the north-south mountain ranges within the Asian monsoon region; this was suggested to be caused by the orographic lifting of the low-level monsoon westerlies [e.g., *Xie et al.*, 2006].

3.2. Spatial Distribution of TRMM-PR Rainfall

[13] Prior to analyzing the diurnal rainfall cycle, we examined the spatial distribution of the total rainfall during the rainy season over the Indochina peninsula, comparing data from TRMM-PR (Figure 3a) with 30 year (1971–2000) rain gauge climatology data (Figure 3b). The TRMM-PR data showed large amounts of rainfall occurring around the coasts of the eastern Bay of Bengal and the Gulf of Thailand, and also west of the Annam mountain ranges (Figure 3a); this agreed quite well with the peaks shown by the rain gauge observations (Figure 3b). To further examine these spatial similarities, a spatial correlation r_s was calculated using the following equation:

$$r_s = \sum_{i=1}^{N} (x_i - \overline{x})(y_i - \overline{y}) \Big/ \sqrt{\sum_{i=1}^{N} (x_i - \overline{x})^2} \sqrt{\sum_{i=1}^{N} (y_i - \overline{y})^2},$$

where N is number of stations, x_i is the 30 year average of total rainfall measured from May through September at the ith station, y_i is the 10 year average of total rainfall observed by TRMM-PR from May through September at the closest grid to the ith station, $\overline{x}$ is the average for all x_i, and $\overline{y}$ is the average for all y_i. The spatial correlation coefficient r_s was 0.78, which was significant at the 99.9% confidence limit. This suggested that the TRMM-PR observations substantially captured the climatology of the spatial distribution of rainfall over the Indochina peninsula. The TRMM-PR values were slightly underestimated relative to the rain gauge measurements at some stations on the Indochina peninsula (Figure 3). The TRMM-PR rainfall provides a grid average

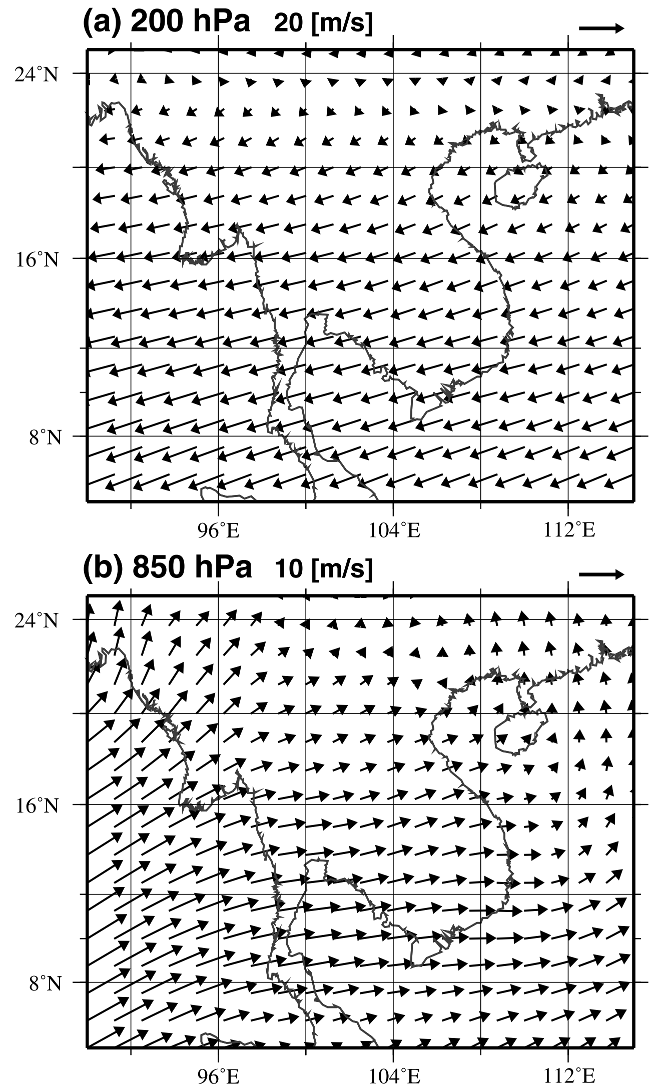

Figure 2. Long-term (1979–2005) summer rainy season (May–September) mean wind fields at (a) 200 hPa and (b) 850 hPa.

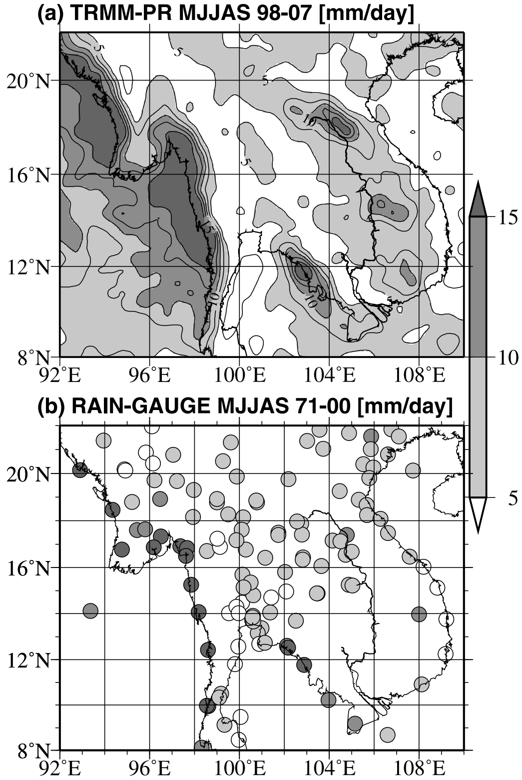

Figure 3. (a) Summer (May–September) mean amount of rainfall observed by TRMM-PR. The amount of rainfall was averaged for 10 years (1998–2007). (b) Summer mean amount of rainfall observed at meteorological stations for 30 years (1971–2000). The rain gauge stations were missing fewer than 10% of the data.

(50×50 km^2), whereas the rain gauge observations are point measurements; this could explain the differences between the values.

[14] The lowest amounts of rainfall were found along the ridges and over the leeward side of high mountains (Arakan, Dawna, and Annam mountain ranges). Their total rainfall during the summer monsoon season was less than 5 mm d^{-1}. The highest amounts of rainfall in the region (over 15 mm d^{-1}) were observed offshore in the eastern Bay of Bengal and in the eastern Gulf of Thailand, and also at the windward side of the Annam mountain range (eastern Khorat Plateau). These areas of high rainfall corresponded to the windward sides of the Indochina mountain ranges. Interestingly, this correlation did not hold everywhere; low total rainfall was observed along both the windward and leeward faces of the Dawna mountain ranges. It is notable from the mean total rainfall distribution that the maximum rainfall did not occur over the windward faces, but over the windward plain or off shore.

3.3. Diurnal Pattern of Rainfall

[15] As previous studies have found, a diurnal rainfall cycle is dominant over the Indochina peninsula [*Ohsawa et al.*, 2001; *Hirose and Nakamura*, 2005]. In this study, we examined the 3 h mean diurnal cycle of 10 year climatological rainfall occurring from May through September (Figure 4). To facilitate the examination of diurnal rainfall patterns in low-rainfall regions, the contribution rate for each 3 h period is also shown in Figure 4. The contribution rate is defined as the proportion of rainfall during a 3 h period to the total rainfall amount over 24 h.

[16] Starting at 0700–1000 local time (LT) (Figure 4, top left), little rainfall was observed over the Indochina peninsula. Early afternoon rainfall occurred along the mountain crests and over coastal land at approximately 1300–1600 LT, then weakened in the evening. At several locations where there is a plain in proximity to a mountain range (around the north of Bangkok, and over a basin-shaped plain around Tonle Sap Lake in Cambodia), evening rainfall began at approximately 1600–1900 LT. The evening rainfall was strongest at 1900–2200 LT, and weakened before the middle of the night. Heavy rainfall over the eastern Khorat Plateau in northeastern Thailand began around 2200–0100 LT. Note that the transition of rainfall activity is discontinuous from 1900–2200 LT to 2200–0100 LT. The heavy rainfall over the eastern Khorat Plateau peaked at 0400–0700 LT. In addition, early morning rainfall (0100–0400 to 0400–0700 LT) over the sea near the coasts occurred at the eastern Gulf of Thailand and at the Bay of Bengal. Heavy early morning rainfall over both land and sea weakened later in the morning. Note also that heavy rainfall was observed over the eastern Khorat Plateau during the early morning hours; this was consistent with rain gauge observations [*Ohsawa et al.*, 2001].

[17] Interestingly, we found that the spatial distribution of rainfall during the early morning hours (0100–0400 LT and 0400–0700 LT) was very similar to the distribution of total rainfall, particularly in the higher-rainfall regions (Figure 3). This similarity suggests that early morning rainfall is a significant contributor to the climatological rainfall pattern in this region. The contribution of early morning rainfall to the total amount of rainfall is shown in Figure 5. Early morning rainfall was defined as the amount of rainfall occurring over 8 h, between 0100 and 0900 LT. The regions where the proportion of early morning rainfall was nearly 50% were located near the coast of the eastern Gulf of Thailand and the Bay of Bengal, and over the eastern Khorat Plateau. The regions of high overall rainfall (Figure 3) and early morning rainfall basically coincide (Figures 4 and 5).Our results indicate that an understanding of early morning rainfall would deepen our understanding of the basic mechanism of monsoon rainfall.

3.4. Diurnal Cycle in Surface Winds

[18] An analysis of the surface winds over Thailand can be used to discuss the local atmospheric circulations associated with the diurnal rainfall variations. Diurnal components of winds are calculated as the difference between the 3 year averaged daily mean winds and the 3 year averaged 3-hourly winds (Figure 6). At 1000 LT and 1300 LT, almost all winds flow toward mountain ranges and can converge over the mountain crests. This pattern continues until 1600 LT. At 1900 LT, the diurnal components of the surface winds at almost all stations have drastically changed direction to flow toward basin-shaped plains; it is likely these are downslope winds. Also, westward winds have developed over the central Khorat Plateau at 1900 LT, and these westward winds converged with the southward winds north of Bangkok at both 1900 and 2200 LT. Along the coast around Bangkok, northward winds were observed at 1900 LT. By 0100 LT,

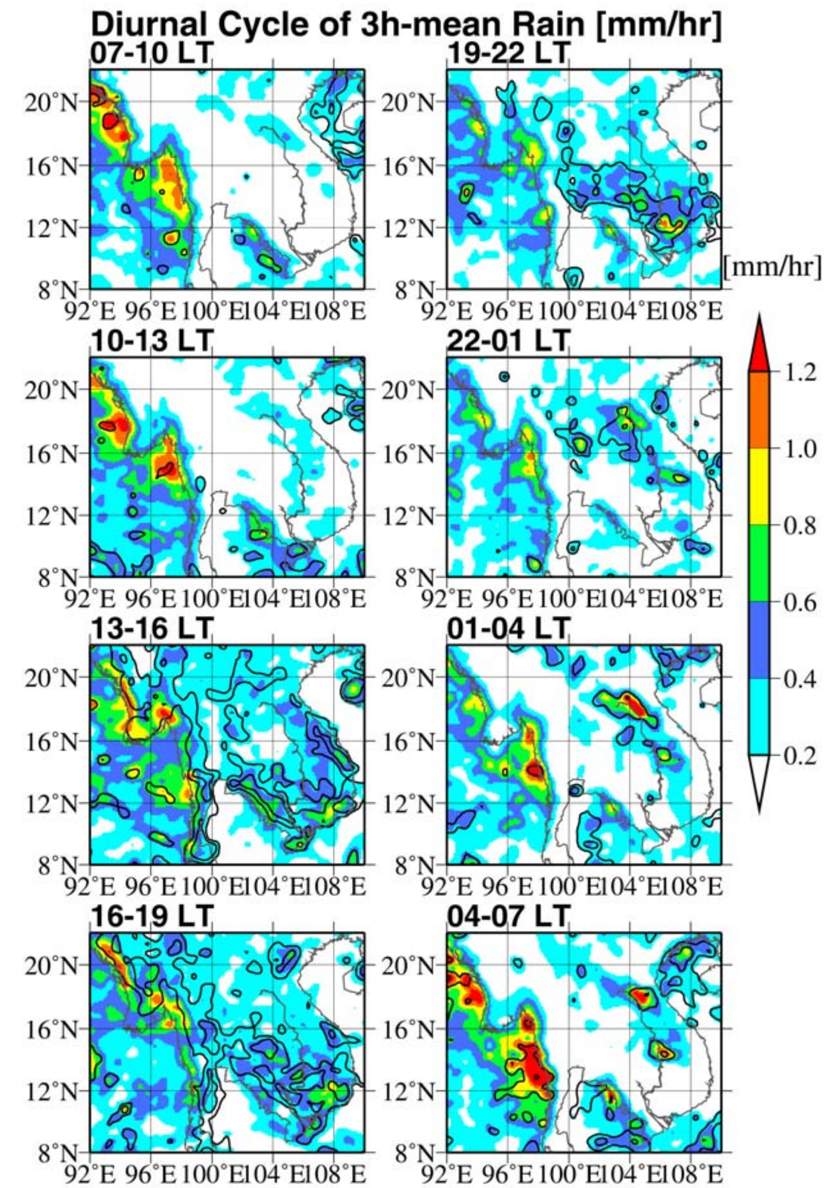

Figure 4. The 3 h mean diurnal cycle of 10 year climatological rainfall (TRMM-PR) for May–September (1998–2007). The colors indicate the intensity of rainfall (mm h^{-1}). The thick contours denote the contribution rate, which is defined as the proportion of the 3 h rainfall to the total rainfall; the 20% and 30% contours are shown.

the diurnal components in the surface winds have become southwestward over almost the entire Indochina peninsula, and they continued until 0700 LT. The southwestward winds along the coast were observed from 2200 LT to 0700 LT.

[19] The winds toward the mountain ranges explain the occurrence of rainfall over the mountain ranges during early afternoon. Also, the convergence between the westward and southward winds is consistent with the evening rainfall north of Bangkok. These results clearly indicate that there are different mechanisms for onset of the evening rainfall compared with that of the early afternoon rainfall. This difference was not discussed in previous studies which described them as afternoon-evening rainfall. Also, it is possible that the northward winds from the Gulf of Thailand enhanced the convergence and supported the trigger of evening convective activities north of Bangkok, from 1900–2200 LT. As we mentioned above, diurnal variations in rainfall have a discontinuous transition between 1900–2200 LT and 2200–0100 LT. This timing corresponded with the disappearance of the wind convergence north of Bangkok. These diurnal wind characteristics probably affect the diurnal rainfall variations over the Indochina region. However, the mechanism of early morning rainfall is still unclear, which will be discussed in section 4.

3.5. Rainfall Frequency and Rainfall Intensity

[20] Previous studies have investigated only the climatological mean diurnal rainfall pattern, but a given rainfall amount may be caused by a larger number of weaker rainfall events or a smaller number of stronger rainfall events. To

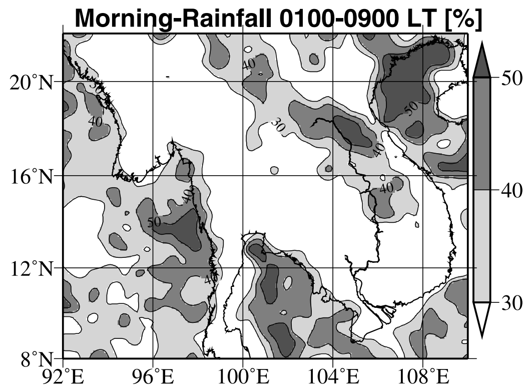

Figure 5. The contribution of the early morning rainfall to the total rainfall. Thick contours denote the proportion of the amount of rainfall over 8 h, from 0100 to 0900 LT, to the total rainfall.

understand the characteristics of the diurnal rainfall cycle and the spatial distribution of rainfall totals, we investigated the daily mean rainfall frequency and the rainfall intensity (Figure 7).

[21] The spatial distributions of both the rainfall frequency (Figure 7a) and rainfall intensity (Figure 7b) were quite similar to that of the total rainfall (Figure 3a). Over

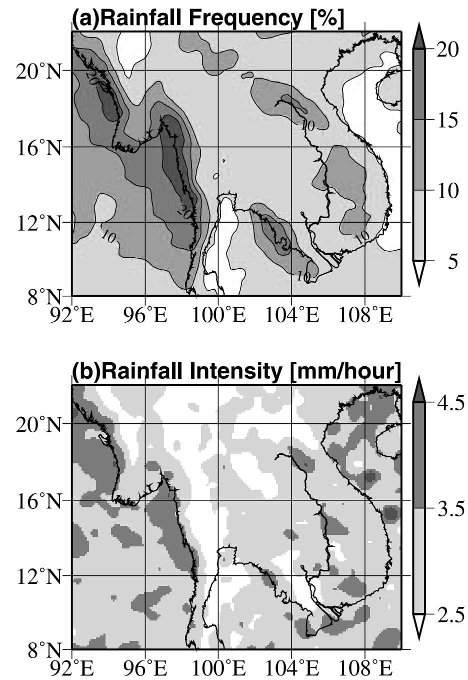

Figure 7. Spatial distribution of the daily mean (a) rainfall frequency and (b) rainfall intensity.

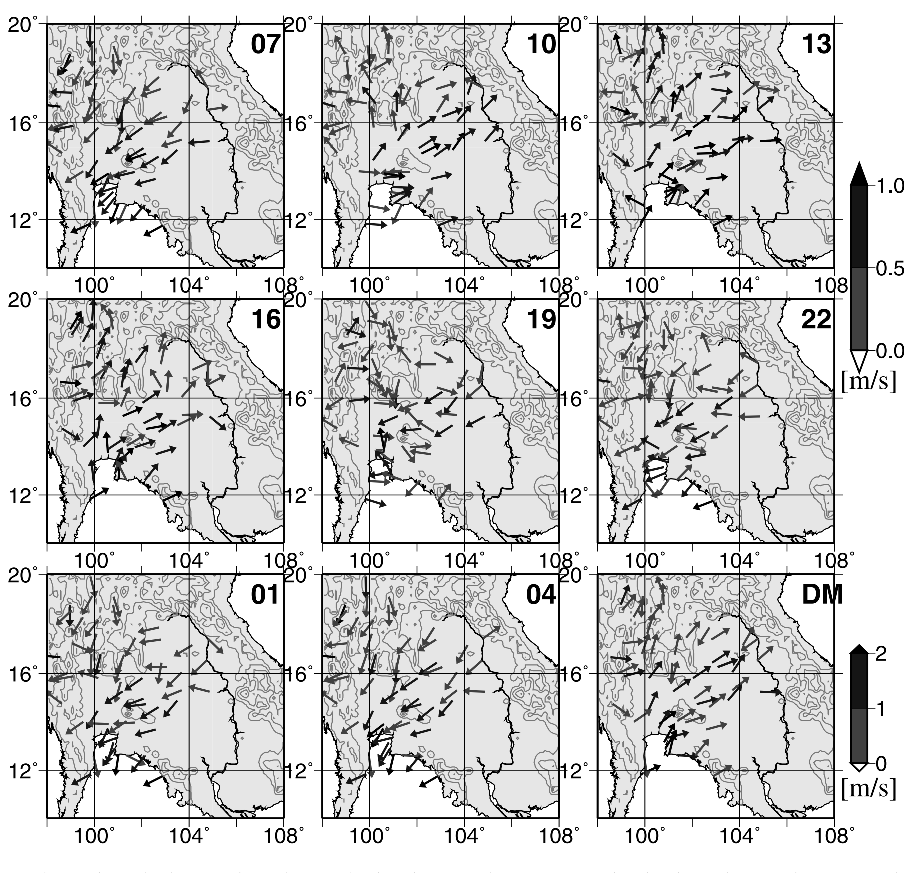

Figure 6. Diurnal variations of surface winds observed at meteorological stations of TMD. Diurnal components of wind are shown. The number in the top right corner of each plot indicates local time. The bottom right plot shows daily mean (DM) winds. The wind direction is indicated in the direction of an arrow, and wind speed is shown in gray color. The diurnal component of wind (the daily mean wind) is shown with upper (lower) shading scale.

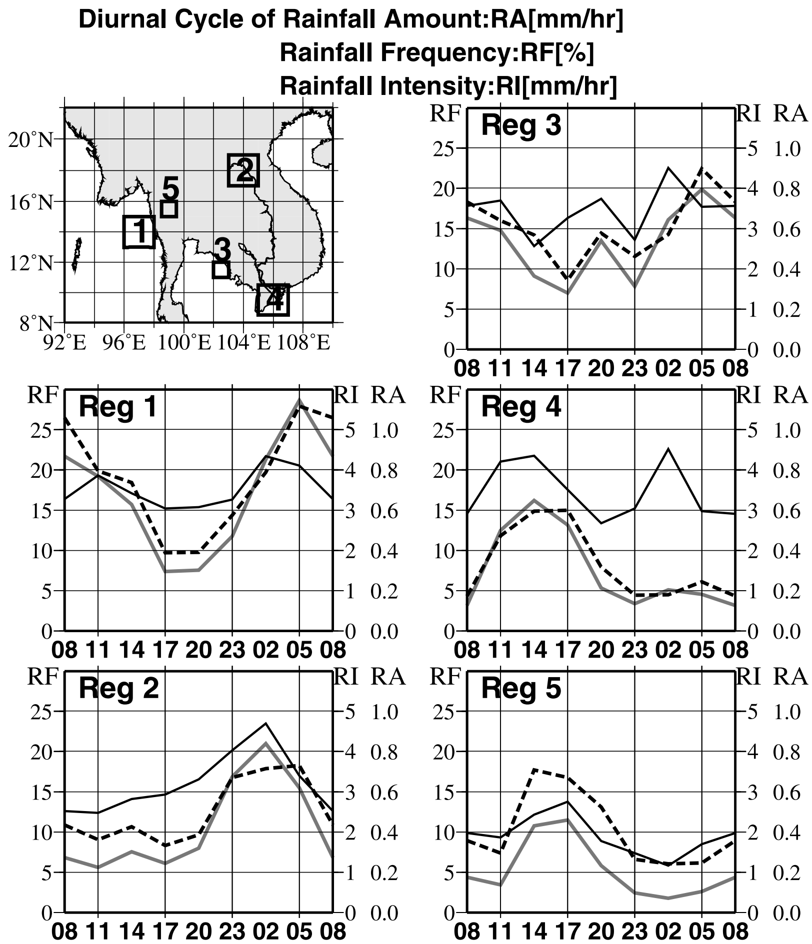

Figure 8. Diurnal cycle of total amount of rainfall, rainfall frequency, and rainfall intensity, averaged over the regions. The gray thick line indicates the diurnal cycle of total amount of rainfall. The black dashed line denotes the rainfall frequency, and the black solid line shows the rainfall intensity. The ranges of total amount, rainfall frequency, and rainfall intensity are given by RA, RF, and RI, respectively. The region locations are shown in the top left plot.

the eastern Bay of Bengal (98°E, 14°N), total rainfall was over 15 mm d^{-1}, which was approximately 4 times greater than the rainfall over the Dawna mountain range in western Indochina (99°E, 15°N). The rainfall frequency over the eastern Bay of Bengal was about 15–20%, indicating that its rainfall occurred twice as frequently as the rain over the Dawna Mountain range. The rainfall intensities over the eastern Bay of Bengal and over the Dawna Mountain range were about 3.5–4.5 mm h^{-1} and under 2.5 mm h^{-1}, respectively. Thus, both the rainfall frequency and the rainfall intensity contributed to the climatological rainfall pattern.

[22] The diurnal cycles of the total amount of rainfall, the rainfall frequency, and the rainfall intensity are shown in Figure 8. These three components are presented as averages over each of the five regions shown in Figure 8 (top left). Regions 1, 2, 3, 4, and 5 represent the coast of the eastern Bay of Bengal, the eastern Khorat Plateau, the coast of the eastern Gulf of Thailand, around Ho Chi Minh City in Viet Nam, and the Dawna mountain range, respectively. The sizes of Regions 3 and 5 were small since only the windward coast and the Dawna mountain region were examined. In Region 1, the total rainfall peaked at 0500 LT, corresponding to peaks of rainfall frequency and rainfall intensity, with the frequency providing the more significant contribution. Region 2 shows a nocturnal maximum of rainfall, with contributions from both the rainfall frequency and the rainfall intensity. In Region 3, two rainfall peaks were observed, a minor peak in the evening and a major peak in the early morning. Region 4 and Region 5 had rainy peaks occurring in the early afternoon, which could be distinguished from the evening rainfall. The rainfall intensity during the early afternoon in Regions 4 and 5 is weaker or comparable to the rainfall intensity during early morning. These results indicated that the heavy early morning rainfall over Regions 1–3 (the coast of the Bay of Bengal, the eastern Khorat Plateau, and the coast of the Gulf of Thailand) consisted of frequent or long-lasting rainfall events with heavier rainfall intensity. This is consistent with the results of *Hirose and Nakamura* [2005], who reported the frequent detection of large rainfall systems over these regions.

[23] Regions 1–3, which have dominant early morning maximums of rainfall, also showed some rainfall during the daytime. Conversely, in regions with daytime maximums, the rainfall frequency is reduced during the morning hours.

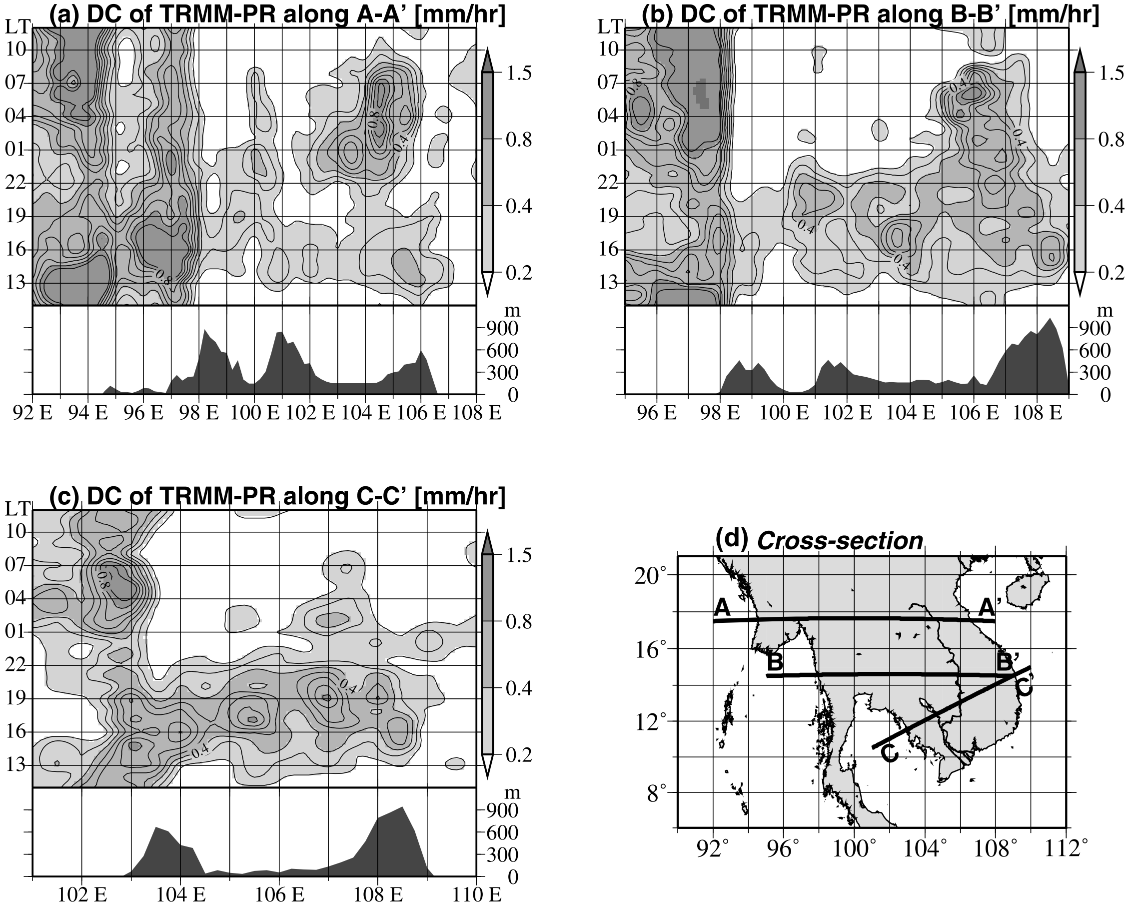

Figure 9. Time-longitude cross section of rainfall over the Indochina peninsula along (a) A–A′, (b) B–B′, and (c) C–C′ as shown in (d) cross section. The bottom of each plot in Figures 9a–9c shows the elevation of the terrain along each cross section.

Although these trends contributed to the total rainfall, the diurnal cycles of rainfall amount were prominent.

4. Discussion

[24] In this section, we discuss the mechanisms of the climatological diurnal rainfall cycle and how they relate to the Indochina terrain. Three hour running mean values of the diurnal rainfall cycle are plotted in Figure 9. Early afternoon rainfall occurred at approximately 1500 LT over the mountain ranges (106°E in Figure 9a, 108°E in Figure 9b, and 104°E, 108.5°E in Figure 9c). These rainfalls likely resulted from the convergence of thermally induced upslope winds. Evening rainfall occurred over the basin-shaped plains of Cambodia (104.5°E–107.5°E in Figure 9c) and north of Bangkok (101°E in Figure 9b), and the valley between the Pegu and Dawna mountain ranges (97°E in Figure 9a). The evening rainfall north of Bangkok was caused by the convergence between the southward downslope winds and the westward winds from the Khorat Plateau (Figure 6). These evening rainfalls that occurred over a plain in proximity to a mountain range likely come from the mountain range or relate to a downslope wind. It is possible that the evening rainfall over the plain of Cambodia is also related to a land-lake circulation over and around the Tonle Sap Lake. Rainfall activities along these sections decrease after the evening, corresponding to the discontinuous transition of rainfall from 1900–2200 LT to 2200–0100 LT (Figure 4). This suggested that the eastward traveling rainfall system suggested by *Satomura* [2000] was not climatologically observed from the TRMM-PR results. Around 0500 LT, heavy rainfall was observed over the eastern Bay of Bengal (94°E in Figure 9a, 97.5°E in Figure 9b), over the coast of the Gulf of Thailand (103°E in Figure 9c), and on the windward side of the Annam Mountain range (104.5°E in Figure 9a, 106°E in Figure 9b). Note that the evening rainfall did not persist through the middle of the night, so that the early morning rainfall was likely newly developed.

[25] Note also that the early morning rainfall does not develop over the windward faces, but develops over the windward plain or over the sea close to shore. This appeared to be related to the convective activities over the Bay of Bengal, in which the convections developed over the sea near the shore [*Zuidema*, 2003]. Observational evidence suggests that the climatological rainy peak was not caused by orographically forced upslope winds. If it were, high rainfall would occur over the windward slopes, and it would be expected that the diurnal peak in rainfall in the high-

rainfall region would occur during the daytime, due to the daytime enhancement of upslope winds caused by the superposition of the mean monsoon westerlies and the thermally induced upslope winds. Since this was not observed, it suggests that the concept of monsoon rainfall being caused by orographic lifting of the monsoon westerlies should be reconsidered to include the processes of the diurnal cycle of rainfall.

[26] *Grossman and Durran* [1984] reported that offshore convective activity peaked west of the Western Ghats Mountains of India; their results correspond to our findings of large rainfall away from windward slopes, over and around the Indochina peninsula. Also, the atmospheric structure over the Indian monsoon region, namely the low-level westerlies and the upper-level easterlies, corresponded to similar structures over the Indochina monsoon region. Although *Grossman and Durran* [1984] did not discuss the diurnal rainfall cycle, the observational evidence suggests a mechanism underlying the onset of nonwindward and early morning rainfall.

[27] The mechanism of early morning rainfall around this region is still unclear. In a classical paper, *Houze et al.* [1981] discussed the offshore rainfall during early morning, and proposed that the onset of offshore rainfall was due to a convergence of land breeze and low-level monsoon flow. This mechanism might explain the early morning windward rainfall, although the atmospheric structure was different. Because early morning rainfall was found only over the windward side of the mountain ranges, the mountain breezes may contribute to the local circulation in this region. Over the Indochina peninsula, *Satomura* [2000] simulated an eastward (leeward) moving rainfall system using a two-dimensional cloud-resolving model. This moving rainfall system might explain the peak timing in the diurnal cycle of rainfall over the eastern Khorat Plateau, although the simulated peak occurred earlier than the observed peak. *Kataoka and Satomura* [2005] used a three-dimensional cloud-resolving model to suggest a possible mechanism for a nocturnal rainfall system in Bangladesh, although the onset and peak times of their simulated rainfall were somewhat different from the early morning rainfall times in our study. The rainfall system in their study developed during the night, due to greater atmospheric instability at night than during the day. Also, in conjunction with the off-slope peak of rainfall, they simulated the onset of a rainfall system at the foot of the windward mountain ranges without katabatic winds, although katabatic winds had been considered a major candidate for the rainfall mechanism. The authors suggested another possible mechanism, in which a cold pool in front of a mountain range provides the same effect as the mountain range.

[28] Although an analysis of the surface winds could partially discuss the local circulation associated with the diurnal variations in rainfall, the discussions are limited to the surface winds. To fully understand the mechanism behind climatological early morning rainfall, additional observations of rainfall and local circulations are necessary.

5. Conclusion

[29] This study used 10 year (1998–2007) TRMM-PR data to investigate the diurnal rainfall cycle, rainfall intensity, and rainfall frequency over the Indochina peninsula during the summer monsoon season (May to September), with a focus on their relationship to the regional scale terrain. To discuss the local circulations associated with the diurnal cycle in rainfall, we also used 3-hourly surface wind observations over Thailand.

[30] We used rain gauge measurements over land to verify that the 10 year TRMM-PR observations can capture the climatological mean pattern of rainfall. We examined the detailed diurnal pattern of rainfall and its association with the Indochina terrain, using 3 h mean TRMM-PR rainfall observations. Previous studies showed an evening maximum of rainfall over land and a morning maximum over the sea. Our results revealed that the diurnal variations in rainfall over the Indochina region can be classified into three distinct peaks. We also observed early afternoon rainfall over mountain ranges and over coastal land. Evening rainfall occurred around 1900–2200 LT over the foot of mountain ranges, in a valley (north of Bangkok), and over a basin-shaped plain (Cambodia). The results of the surface wind analysis suggested that the evening rainfall was associated with downslope winds from surrounding mountain ranges, and that this evening rainfall was generated by a separate mechanism than early afternoon rainfall. Heavy early morning rainfall was observed near the coasts over the eastern Bay of Bengal and over the eastern Gulf of Thailand, as well as over the eastern Khorat Plateau. It was found that nearly half of the total rainfall occurred in the early morning over these regions. Therefore, we concluded that early morning rainfall is the primary component of the climatological mean rainfall pattern. The examination of rainfall frequency, rainfall intensity, and their diurnal cycles showed that heavy rainfall during the early morning over the higher-rainfall regions consisted of frequent or long-lasting rainfall events with a strong intensity. Note that regions with dominant early morning rainfall events also had some rain during the daytime, which contributed to the large total amount of rain. These new findings were not reported in previous studies that investigated only the diurnal phase and amplitude of rainfall.

[31] It was noteworthy that evening rainfall did not persist through the middle of the night, suggesting that the early morning rainfall may have redeveloped, although the mechanism for triggering early morning rainfall has not been clarified.

[32] Finally, heavy rainfall events were observed in the early morning, away from windward mountain faces. This cannot be explained by the traditional understanding of monsoon rainfall, that it is caused simply by the orographically forced uplifting of the monsoon westerlies. Therefore, the concept of monsoon rainfall should be reconstructed to include the processes of the diurnal cycle of rainfall.

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