Diurnal Variations of Convective Activity and Rainfall in Tropical Asia

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Abstract

The diurnal variations of convective activity and rainfall in tropical Asia are investigated using hourly equivalent black body temperature ($T_{BB}$) data from the Japanese Geostationary Meteorological Satellite (GMS-5), and hourly (or 3-hourly) rainfall data from Bangladesh, Thailand, Vietnam and Malaysia. As an index of convective activity, we use the frequency of occurrence of the difference in $T_{BB}$ between the infrared-1 and the water vapor channel $\Delta T_{BB} (= T_{BB}(IR1) - T_{BB}(WV))$ of less than 3K. By using this index, the diurnal variations of convective activity and rainfall have approximately the same phase.

The time when convective activity reaches its maximum and minimum is examined in the domain of 80–120°E and 0–30°N. As a result, it is found that the largest number of grids exhibits the maximum at 17LT (local time) and 14LT, and the minimum at 11LT and 21LT over land and sea, respectively. Moreover, without using the harmonic analysis, which is a conventional method of analyzing the diurnal variation, areas with the maximum during the late night-early morning hours are clearly separated from those with the afternoon-early evening maximum. This late night-early morning maximum is mostly found in the windward areas of mountains, in basins and valleys, and in coastal areas. Therefore, this kind of maximum is most likely associated with terrain or its induced local circulations such as mountain and land breezes.

From the analysis of rainfall data, it is also shown that the late night-early morning maximum is found at stations with high rainfall. The number of stations with the late night-early morning maximum is less than that with the afternoon-early evening maximum. But, the mean daily rainfall at the former stations is on average a few times greater than that at the latter stations. Thus, the diurnal variation averaged for all stations in the four countries has two nearly equal maxima at 05LT and 16LT. This result suggests a strong possibility that the late night-early morning maxima of convective activity and rainfall have a great effect on energy and water cycles in tropical Asia.

1. Introduction

The latent heat and rainfall caused by convective activity in the tropics are principal factors in energy and water cycles, regionally and globally. Thus, the investigation of convection activity and rainfall in tropical Asia is one of the main purposes of GAME*-Tropics. Up to now, many studies on

* GEWEX (Global Energy and Water Cycle Experiment) Asian Monsoon Experiment
the tropical convection and rainfall have shown the prominence of the diurnal variation in their variabilities. This fact suggests that the diurnal variations of convective activity and rainfall greatly influence the energy and water cycles on a daily basis.

However, because of the lack of data, there are few comprehensive studies on the diurnal variation of rainfall in tropical Asia. The study is limited for some areas such as Malaysia (Ramage 1964; Nieuwolt 1968; Oki and Musiake 1994), some parts of India (Prasad 1970; Prasad 1974; Bhattacharya and Bhattacharyya 1980; Harilder et al. 1991), and the Indochina Peninsula (Harada et al. 1998). To understand the diurnal variation of rainfall in the whole of tropical Asia, it is necessary to obtain rainfall data with a sufficient temporal resolution from a broad region including several countries.

In this sense, satellite data covers a broad region and its derived information on convective activity can be used as a proxy for the surface rainfall with high temporal and spatial resolutions. Thus, using satellite data, many researchers have investigated the diurnal variation of convective activity in tropical Asia (e.g., Murakami 1983; Nitta and Sekine 1994; Chen and Takahashi 1995). In these previous studies, 3-hourly TBB data with a 1° × 1° resolution were used to show the geographical distribution of the diurnal variation patterns of convective activity. Their results suggested that local circulations caused by terrain (including the land-sea contrast) strongly influence the diurnal variation of convective activity. However, the resolution of the data they used is not sufficient to resolve the diurnal variation affected by the local circulations. Thus, data with a higher resolution is necessary to clarify the local topographic effects in detail.

Harada et al. (1998) analyzed the TBB data with a fine resolution (hourly 0.1° × 0.1° grid data) for one year, and showed the features of the diurnal variation of convective activity over the Indochina Peninsula. They stated that their results need to be verified by the data of other years, and that the relationship between convective activity and rainfall should be examined in further works. As they pointed out, the phase of the diurnal variation of convective activity dramatically changes with the index (threshold temperature) of convective activity used in the analysis. In general, it is known that the diurnal variation of convective activity evaluated by the index with a colder threshold temperature exhibits its maximum at earlier time in the day (e.g., Minnis and Harrison 1984; Janowiak et al. 1994). Thus, when discussing the diurnal variations of convective activity and rainfall together, it is desirable that the index of convective activity is defined so that their diurnal variations have the same phase.

As a useful method of analyzing the diurnal variation, harmonic analysis has been used in many studies (e.g., Horn and Brison 1960; Wallace 1975; Augustine 1984; Minnis and Harrison 1984; Riley et al. 1987; Fujibe 1988; Negri et al. 1993). This method has the advantage of obtaining the phase of the diurnal variation with a higher temporal resolution than that of the original data. Thus, many previous studies used the first harmonic derived from 3-hourly data (e.g., Meisner and Arkin 1987; Janowiak et al. 1994; Nitta and Sekine 1994; Chen and Takahashi 1995; Asai et al. 1998; Ohsawa et al. 1999). However, since the diurnal variation of convective activity or rainfall is essentially governed by complicated thermodynamics and cloud microphysics, it is doubtful whether each of the harmonic components has a physical meaning. That is, it may be merely a computational mode. This is also pointed out by Murakami (1983) and Oki and Musiake (1994). In this sense, the application of the harmonic analysis for the diurnal variation of convective activity or rainfall is obviously different from that for other atmospheric phenomena consisting of harmonic components governed by a restitutive force.

Taking the above problems into account, the following improvements are made in this study.

1. Rainfall data from four countries (Bangladesh, Thailand, Vietnam and Malaysia) are analyzed using the same method.

2. Satellite data for four years with higher temporal and special resolutions than previous studies (hourly 0.2° × 0.2° grid data) are used.

3. The index of convective activity is defined to be most correlated with surface rainfall.

4. The time of the maximum and the minimum convective activity or rainfall is directly derived from the diurnal variation, instead of using harmonic analysis.

This paper describes climatological features of the diurnal variations of convective activity and rainfall during the Asian summer monsoon season. The period of the analysis is limited to three months, from June to August (hereafter abbreviated as JJA).
2. Methods of analysis

2.1 Procedure for rainfall data

The rainfall data from 101 stations in four countries (Bangladesh, Thailand, Vietnam, Malaysia) are used. The number of years for which the rainfall data are available is different among the stations. It is 1 year for the data from Bangladesh, 6 years for Thailand, 10 years for Malaysia, and it ranges from 4 to 11 years for Vietnam. The temporal resolution of the data is 3-hourly for Thailand and most of Bangladesh, while it is hourly for Vietnam, Malaysia and part of Bangladesh. Moreover, the time of the 3-hourly rainfall observation is different among these countries, due to the difference of their local standard time.

In order to deal with such various kinds of data together, the following method is adopted. For the explanation of this method, a sample is shown in Fig.1. If the rainfall at a station is observed at 1-hour and 3-hour intervals, the JJA averaged hourly and 3-hourly rainfalls are as shown in Figs. 1a and

Fig. 1. (a) Hourly rainfall averaged for June to August of 1995, at Sylhet (Shahjral Univ.) in Bangladesh.
(b) The same rainfall expressed in the form of 3-hourly rainfall.
(c) Diurnal variations defined from the two kinds of data shown in (a) and (b). The solid line indicates the 3-hour running mean for (a), and the dashed line indicates the spline-interpolated hourly rainfall calculated from (b).
(d) Parameters used to evaluate the diurnal variation.
1b, respectively. First, taking a 3-hourly running mean for the hourly rainfall shown in Fig. 1a yields the solid line in Fig. 1c. Second, one third of the 3-hourly rainfall shown in Fig. 1b is defined as a tentative hourly rainfall at the center of this 3-hour period. Taking a spline interpolation for these 8 tentative hourly rainfalls yields the dashed line in Fig. 1c. By this method, the amount of daily rainfall is conserved. In addition, the time of the maximum rainfall remains unchanged; that is, it appears within the 3-hour period of the original 3-hourly rainfall maximum. In Fig. 1c, it is found

![Graphs](image)

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**Fig. 2.** (a) The relationship between $T_{BB}$ (IR1) and 3-hourly rainfall at 36 stations in Thailand for June to August of 1996–97. The 3-hourly rainfall is compared with the lowest value of $T_{BB}$ (IR1) during the 3 hours. (b) Same as in (a) but between $\Delta T_{BB}$ and the 3-hourly rainfall. (c) The relationship between $T_{BB}$ (IR1) and $\Delta T_{BB}$. (d) The correlation between the 1996–97 JJA averaged daily rainfall at 36 stations and the frequency of occurrence of low $T_{BB}$ (IR1) (dashed line) and $\Delta T_{BB}$ (solid line) for various threshold values. The $0.2\degree \times 0.2\degree$ grid values of $T_{BB}$ including the stations are used to calculate the correlation coefficients.
that this method can produce similar patterns of the diurnal variation from two kinds of data. We thus apply this method to the data from all stations, and calculate the diurnal variation of rainfall at each station.

2.2 Procedure for satellite data

The information on convective activity is derived from the data from GMS–5. We use hourly equivalent black body temperature (TB) of the infrared-1 channel (11 μm) TB (IR1) and the water vapor channel (6.7 μm) TB (WV) with a 0.2° × 0.2° resolution within the domain of 80°–120°E and 0°–30°N. This data is prepared for JJA of 4 years from 1996 to 1999.

Most of the previous studies have used the index of convective activity based on TB (IR1) that approximately corresponds to the cloud-top temperature. In addition to TB (IR1), TB (WV) data has been available since GMS–5, which was launched in 1995. Tokuno and Tsuchiya (1994) showed that the temperature difference between the infrared-1 and the water vapor channel, TB (IR1) − TB (WV) (hereafter, written as ΔTB), can be used for the classification of clouds. Their method utilizes an atmospheric characteristic such that the amount of water vapor, which causes the difference in temperature between the infrared and the water vapor channel, decreases with height. Although this method was originally designed for the polar-orbiting Marine Observation Satellite-1 (MOS-1), it is expected that the method can be applied to the data from GMS–5. We thus compare the values of both TB (IR1) and ΔTB with rainfall. The 3-hourly rainfall data at 36 stations in Thailand are compared with both TB (IR1) and ΔTB at each grid including these stations for two years of 1996 and 1997.

Comparing Figs. 2a and 2b, the value of ΔTB is found to be more sensitive to rainfall than TB (IR1). This is closely associated with the fact that the ΔTB of clouds with extremely low TB (IR1) concentrates around zero, as shown in Fig. 2c. Figure 2d shows the correlation between the surface rainfall and the frequency of occurrence of low TB (IR1) or ΔTB for various threshold temperatures. The correlation for TB (IR1) has the maximum of 0.54 at a threshold value of 220 K, while that for ΔTB has the maximum of 0.63 at a threshold temperature of 3 K. That is, the frequency of occurrence of ΔTB ≤ 3 K yields the best correlation with the surface rainfall.

The clouds represented by ΔTB ≤ 3 K have a cloud-top temperature colder than about 230 K (Fig. 2c), and tend to have an intensive rainfall (Fig. 2b). This implies that these clouds are cumulonimbus or subsequent thick stratiform clouds caused by deep convection. Thus, in this study, the frequency of occurrence of ΔTB ≤ 3 K is used as the index of convective activity. It is noted that the corresponding threshold temperature of 230 K is colder than that used in many previous studies (e.g., Murakami 1983; Nitta and Sekine 1994; Chen and Takahashi 1995; Asai et al. 1998; Harada et al. 1998; Ohsawa et al. 1999).

3. Time of the maximum and minimum in diurnal variations

3.1 Convective activity

To represent patterns of the diurnal variation in the whole domain, the hourly frequency of occurrence of ΔTB ≤ 3 K is calculated at each 1° × 1° grid. The time of the maximum and the minimum frequency of occurrence of ΔTB ≤ 3 K is shown in Fig. 3. Each time of these extremes is indicated by the orientation of a vector, and its length corresponds to the deviation of the frequency of occurrence at the time from the daily mean frequency of occurrence.

It is found that a large part of the domain shown in Fig. 3a exhibits the maximum convective activity in the afternoon or early evening over both land and sea. Over land, this maximum is undoubtedly caused by the solar radiative heating on the surface during daytime. It is also known that the solar radiative heating can enhance convective activity even over the sea (e.g., Chen and Houze 1997). Consequently, the afternoon maximum widely seen over the sea is most likely caused by the daytime solar radiative heating on the sea surface. On the other hand, the time of the minimum is considerably different between land and sea (Fig. 3b). It mostly occurs in the late morning over land, while in the late evening over the sea.

To show the time of the maximum and the minimum in detail, we statistically examine it at all 0.2° × 0.2° grids in the domain. Figure 4 represents the number of grids with the maximum and the minimum at each local time. 22% of all grids over land exhibit the maximum convective activity at 17LT, and the grids with the maximum at 14LT to 21LT (during 8 hours from 13:30LT to 21:30LT) occupy about 75% (Fig. 4a). Most of these grids with the afternoon-early evening maximum have
Fig. 3. Time of (a) the maximum and (b) the minimum frequency of occurrence of $\Delta T_{BB} \leq 3$ K at each $1^\circ \times 1^\circ$ grid for June to August of 1996 to 1999. The orientation of a vector indicates the time of the maximum or the minimum frequency of occurrence. Pointing to the north, east, south and west mean 00LT, 06LT, 12LT and 18LT, respectively. The length of the vector corresponds to the deviation of the frequency of occurrence at the time from the daily mean. The light and dark shadings indicate elevations higher than 0 m and 1,000 m, respectively.
Fig. 4. Number of grids with the maximum (solid lines) and the minimum (dashed lines) frequency of occurrence of $\Delta T_{\text{an}} \leq 3$ K at each hour. The number of grids is expressed as a percentage of the total number of grids (TNG) over (a) land (13,804) and (b) the sea (16,196).

Fig. 5. (a) Number of stations with the maximum (solid line) and the minimum (dashed line) rainfall at each hour. (b) The relationship between the time of the maximum rainfall and the JJA averaged daily rainfall. The solid line indicates the daily rainfall averaged for the stations with the maximum at each hour.
the minimum in the late morning or around noon, centered at 11LT. About 12% of all grids over land have the maximum at 02LT to 05LT. In Fig. 3, this late night-early morning maximum can be found along the foot of the Himalayas, in the upper Brahmaputra Valley in India, in the Sichuan Basin in China, and so on. Those in the Brahmaputra Valley and in the Sichuan Basin have also been shown by Murakami (1983) and Asai et al. (1998), respectively. Over the sea, the largest number of grids has the maximum at 14LT and the minimum at 21LT (Fig. 4b). About 75% of all grids over the sea exhibit the maximum at 11LT to 17LT. In addition, some grids are found to have the maximum at around 06LT to 07LT.

3.2 Rainfall

As in Fig. 4, Fig. 5 shows the number of stations with the maximum and minimum rainfall at each local time. Most stations exhibit the maximum rainfall in the afternoon or the early evening, especially concentrated at 16LT to 18LT. At 57 stations, of all 101 stations, the maximum rainfall appears at 14LT to 21LT. In addition, there are some stations with the maximum in the late night or the early morning, and 21 stations have the maximum at 03LT to 06LT. On the other hand, the minimum rainfall tends to appear in the late morning, centered at 11LT. These features are in good agreement with those of convective activity over land shown in Fig. 4a. This means that the diurnal variations of rainfall and convective activity represented by $\Delta T_{BB} \leq 3$ K have the same phase, as a whole.

In Fig. 5b, a significant relationship is found between the time of the maximum rainfall and the daily rainfall averaged from June to August. The most outstanding feature in Fig. 5b is a small amount of the JJA averaged daily rainfall at stations with the maximum rainfall in the afternoon or evening. These stations have a daily rainfall of 5 to 10 mm/day, on average. In contrast, stations with the maximum rainfall in the late night or early morning tend to have a daily rainfall of more than 10 mm/day. The stations with the maximum at 04LT to 06LT have especially high daily rainfall, which is a few times greater than that of the stations with the maximum in the afternoon or evening. It should be noted that this result is in marked contrast with Garreau and Wallace's (1997) speculation that, in South America, regions with afternoon-early evening maxima tend to receive more daily rainfall than regions with maxima at other times of day.

From Fig. 5, it is concluded that the number of stations with the late night-early morning maximum is less than that with the afternoon-early evening maximum, but the daily rainfall at the former stations is on average a few times greater than that at the latter stations. Therefore, as shown in Fig. 6, the composite diurnal variation for all the 101 stations exhibits two maxima at 05LT and 16LT and two minima at 09LT and 23LT. That is, the amount of rainfall during the late night-early morning hours is comparable to that during the afternoon-early evening hours.

At a first glance, Fig. 6 may seem to be the semi-diurnal variation associated with the solar atmospheric tide, as suggested by Brier and Simpson (1969). However, the important fact in Fig. 6 is that the composite diurnal variation primarily consists of two kinds of diurnal variation with the afternoon-early evening maximum and the late night-early morning maximum. Such a semi-diurnal variation is not always found at each station. In other words, different stations contribute to the two maxima of the composite diurnal variation in Fig. 6, as will be discussed later.

3.3 Comparison with harmonic analysis

The time of the maximum convective activity indicated by Figs. 3 and 4 is partly different from previous studies (e.g., Nitta and Sekine 1994). This
Fig. 7. Similar to Fig. 4, but for the time of the first harmonic peak over (a) land and (b) the sea.

Fig. 8. (a) Daily rainfall averaged for June to August of 1995 in Bangladesh. The area of a circle is proportional to the amount of the daily rainfall. Topographic contours are drawn at an interval of 400 m, beginning from 200 m. (b) Time of the maximum rainfall is represented in the vector form similar to Fig. 3, although, in this figure, the area of the circle is proportional to the deviation from the daily mean. Areas labeled ‘A’ to ‘C’ are explained in the text.
difference in time primarily arises from two reasons. One is the difference in the index of convective activity, as mentioned in Section 2.2. The other is the difference in the method of analysis; that is, the difference in time between the first harmonic peak and the actual maximum.

Figure 7 shows the number of grids with the first harmonic peak at each local time, and it can be compared with the actual maximum shown in Fig. 4. In Fig. 7a, the largest number of grids exhibits the maximum at 19LT, which is delayed by 2 hours compared with the actual maximum. In contrast, over the sea, the first harmonic peak is centered at around 11LT to 12LT (Fig. 7b), which is earlier than the actual maximum by about 3 hours.

As seen in Fig. 4, over most of land, the time from the minimum to the maximum is only 6 hours, which corresponds to one third of the time from the maximum to the minimum. In contrast, over most of the sea, the time from the minimum to the maximum (about 16 hours) is twice as long as that from the maximum to the minimum. Therefore, it is found that the first harmonic with a period of 24 hours essentially does not fit the actual pattern of diurnal variation. As a result, over land, its peak appears a few hours after the actual maximum and its minimum 3 or 4 hours before the actual minimum. The opposite is true over the sea.

In Fig. 4, the late night-early morning maximum can be clearly distinguished from the afternoon-early evening maximum, by representing the time of the maximum directly without using the harmonic analysis. It is obvious from Fig. 7 that this late night-early morning maximum can be hardly detected by means of the harmonic analysis.

4. Late night-early morning maxima

In this section, we focus on the late night-early morning maximum and show its geographical distribution in and around the four countries (Bangladesh, Thailand, Vietnam and Malaysia). Figures 8 to 11 show the JJA averaged daily rainfall and the time of the maximum rainfall at each station in the four countries. Figures 12 to 14 show the time of the maximum convective activity over areas covering the four countries.

![Diagram](a) JJA AVERAGED DAILY RAINFALL THAILAND  
(b) TIME OF MAXIMUM RAINFALL THAILAND

Fig. 9. Similar to Fig. 8, but for Thailand. In addition to a primary maximum, a secondary maximum is also displayed in (b).
4.1 Geographical distribution

a. Bangladesh

As seen in Figs. 8 and 12, in Bangladesh, the late night-early morning maximum is found at stations on the windward of the Shillong Plateau (labeled ‘A’ in Fig. 8b) and along the coast of the Bay of Bengal (‘B’). In sharp contrast to the area ‘A’, the maximum appears in the afternoon at around 16LT in the area ‘C’. This south-north contrast between ‘A’ and ‘C’ suggests that the late night-early morning maximum found in the area ‘A’ is associated with the Shillong Plateau working as a topographic barrier to the southerly monsoon wind.

The late night-early morning maximum in the area ‘A’ is consistent with Prasad’s (1970) findings that the maximum rainfall occurs during the late night-early morning hours at an Indian station Cherrapunji (‘CHE’ in Fig. 8a), which is well known for the world record of the highest annual rainfall. Prasad (1974), and Bhattacharya and Bhattacharyya (1980) also found the late night-early morning maximum of rainfall at the Indian stations in the Brahmaputra Valley. Figure 12 clearly shows the spatial distribution of the late night-early morning maxima of convective activity in and around the Brahmaputra Valley.

b. Thailand

In Thailand, the late night-early morning maximum is found in two areas, ‘D’ and ‘E’ (Fig. 9b). Khlong Yai (‘KHL’) and Chanthaburi (‘CHA’) in the area ‘D’ exhibit the maximum at 06LT and 03LT, respectively. It is noted that these two stations are located not only near the coast, but also on the windward side of mountains with an eleva-
tion of more than 1,000 m.

In the northeastern part ('E'), three stations have the maximum at 01LT to 06LT. At Nong Khai ('NON'), which is one of the intensive observation stations of GAME-Tropics, the maximum occurs at 03LT. These stations are located on the windward side of the northern Annam Mountains, ranging parallel to the border with Laos. In the area 'F', the maximum appears twice a day, and this seems to be a transitional feature with both the afternoon-evening maximum and the late night-early morning maximum.

c. Vietnam

In Vietnam, there are five stations with the late night-early morning maximum (Fig. 10b). One is Pleiku ('PLE') with the maximum at 01LT, which is on the windward side of the southern Annam Mountains. The remaining four stations are in the northern part of the country; two stations are in a mountainous area ('G'), and the other two are in coastal area near the mouth of the Song Hong River ('H').

According to Fig. 13, the time of the maximum convective activity in the area 'G' is similar to
those found in the areas ‘A’ in Bangladesh and ‘E’ in Thailand. In contrast, in the coastal area ‘H’,
the maximum occurs a few hours later than the
mountainous area ‘G’. Thus, the physical mech-
nanism causing the late night-early morning max-
imum seems to be slightly different between the
mountainous area and the coastal area.

d. Malaysia

The late night-early morning maximum can be
found at four stations on the west coast of the
Malay Peninsula (‘I’) and Bintulu (‘BIN’) on
Borneo (Kalimantan) Island (Fig. 11b). Unlike the
other three countries, these stations do not always
have more daily rainfall than other stations (Fig.
11a). This may be associated with the fact that
the period from June to August corresponds to a
relatively dry season in Malaysia.

e. Coastal waters

As seen in Figs. 12 to 14, the late night-early
morning maximum is especially found over coastal
waters with a concave coastline. The typical ar-

eas are the mouth of the Ganges River, the An-
daman Sea, the Gulf of Thailand, the Gulf of Tong
King, the Malacca Strait and the northwest coast
of Borneo Island. Moreover, over these coastal
waters, there is a clear tendency that the time of
the maximum convective activity is gradually de-
layed offshore. The onshore convection generally
has the maximum in the early morning, while the
maximum of the offshore convection appears in the
late morning. This late morning maximum of the
offshore convection is continuously connected with
the afternoon maximum prevailing over the open sea.

In summary, the late night-early morning maximum is found in the windward areas of mountains, in basins and valleys, and in coastal areas. These areas have a common characteristic that they are the place where a low-level convergence is expected during nighttime due to local circulations such as mountain and land breezes or their interaction with a prevailing wind. The whole distribution of the late night-early morning maximum is shown in Fig. 15.

4.2 Relationships with local circulations

According to Ramage (1964), Nieuwolt (1968), and Oki and Mustake (1994), the contrast of the
Fig. 14. Similar to 12, but over (a) the Malay Peninsula and (b) Borneo Island.
diurnal variation between the west and the east coast of the Malay Peninsula in summer can be explained by the interaction of a prevailing southwesterly wind with a land and sea breeze. During daytime, the sea breeze blows against the southwesterly wind on the east coast. Thus, the low-level convergence between them produces the afternoon maximum of rainfall. On the west coast, the land breeze during nighttime converges with the southwesterly wind, causing the late night–early morning maximum. It seems that this explanation can be applied to other coastal areas open to the west such as the areas ‘B’ in Bangladesh and ‘D’ in Thailand. As Houze et al. (1981) stated, in the coastal area with a concave coastline, the low-level convergence tends particularly to occur, due to the concentration of land breezes.

Prasad (1974) suggested that the late night–early morning maximum of rainfall found in the Brahmaputra Valley is mainly due to the low-level convergence of mountain breezes from both sides; that is, the Himalayas and the Shillong Plateau. However, in Fig. 12, the late night–early morning maximum can be found all along the foot of the Himalayas and even on the opposite (south) side of the Shillong Plateau. This implies that the mountain breeze from one side is sufficient to cause the low-level convergence during nighttime, especially in the case with a prevailing wind blowing against the mountain breeze.

The same discussion can be applied to the late night–early morning maximum seen in coastal areas. Ramage (1964) referred to the diurnal variation with the late night–early morning maximum found around the Malacca Strait (Figs. 11 and 14), and explained that it is caused by the low-level convergence of land breezes from both sides; that is, the Malayan Peninsula and Sumatra Island. It is true that the late night–early morning maximum exhibits a larger deviation over the Malacca Strait than over other sea areas (Fig. 14). But, in addition to the Malacca Strait, the late night–early morning maximum is widely seen around the peninsula and relatively large islands. Therefore, the land breeze, as well as the mountain breeze, solely has a possibility of triggering convection during the late night–early morning hours.

Houze et al. (1981) found a noticeable morning maximum of convective activity over the sea just off Bintulu (‘BIN’ in Fig. 11b) during the WMONEX (International Winter Monsoon Experiment) in 1978. They concluded that the low-level convergence of the land breeze with the northeasterly monsoon wind causes the morning maximum of offshore convection. However, as shown in Fig. 14, a similar maximum can be found even in summer when the prevailing wind blows in the same direction as the land breeze. Likewise, Nitta and Sekine (1994) showed that similar diurnal variations are found there all through the year except March. Thus, these facts also support the hypothesis that the land breeze can solely trigger the offshore convection with the morning maximum, even without its interaction with the prevailing wind.

4.3 Inconsistency of maxima between convective activity and rainfall

In coastal areas open to the west, such as the areas ‘B’, ‘D’ and ‘T’ in Figs. 8, 9 and 11, respectively, the maximum rainfall occurs in the late night or early morning. However, the corresponding late night–early morning maxima of convective activity cannot be detected in Figs. 12 to 14. These areas are covered with the afternoon–early evening maxima that extend to the west from inland. On the other hand, the early morning maxima can be found several dozen kilometers off each coast, and they seem to be related with the late night–early morning maxima of rainfall found in the coastal areas.

The opposite phenomenon appears in the area ‘J’ on the east coast of the Malay Peninsula (Fig. 11). In this area, the maximum convective activity occurs during the late night–early morning hours, while the maximum rainfall appears during the afternoon–evening hours. It is obvious in Fig. 14 that this late night–early morning maxima of convective activity expand from coastal waters onto the east coast of the peninsula. After all, the above facts suggest that the pattern of the diurnal variation of convective activity shifts westward as a whole.

The same westward shift can be also seen in Harada et al. (1998). Since the westward shift, found both in their study and in Figs. 12 to 14 of this study, extends over several dozen to one hundred kilometers, it cannot be explained solely by the low elevation angle of the GMS in this region (the GMS may misunderstand the radiation coming from clouds with a high cloud-top as that coming from a farther ground to the west of the cloud, because of its low elevation angle). Moreover, it is confirmed that the grid of satellite data is placed in its proper position geographically. Thus, it is most
Fig. 15. Distribution of the late night-early morning maximum of convective activity. Areas with the maximum at 00LT to 08LT are shaded, except those with the maximum deviation from the daily mean of less than 4%. Topographic contours are drawn at 500 m and 2000 m.

Fig. 16. Climatological winds at (a) 850 hPa and (b) 200 hPa for June to August of 1979 to 1995, based on the NCEP objective analysis data. The light and dark shadings indicate elevations higher than 0 m and 1,000 m, respectively.
likely that this westward shift is caused by a westward advection of upper non-precipitating clouds such as an anvil by a strong easterly wind of about 10 to 15 m/s in the upper troposphere (Fig. 16). To prove the speculation, we need a further study using the satellite data of a winter season in which a westerly wind prevails in the upper troposphere.

5. Conclusions

General and regional features in diurnal variations of convective activity and rainfall in tropical Asia have been investigated. Hourly equivalent black body temperature ($T_{BB}$) data was applied with a 0.2° × 0.2° resolution obtained from the Japanese Geostationary Meteorological Satellite (GMS-5). Also, hourly or 3-hourly rainfall data, collected from 101 stations in Bangladesh, Thailand, Vietnam and Malaysia, was used. The satellite data was analyzed for 30,000 grids (13,804 over land and 16,196 over the sea) in the domain of 80–120°E and 0–30°N.

In this study, as an index of convective activity, we used the frequency of occurrence of the difference in $T_{BB}$ between the infrared-1 and the water vapor channel ($\Delta T_{BB} = T_{BB} (IR1) - T_{BB} (WV)$) of less than 3 K. By using this index, the diurnal variations of convective activity and rainfall approximately have the same phase. Also, we directly derived the time of the maximum and the minimum convective activity or rainfall from its diurnal variation, instead of using a conventional harmonic analysis. This is because the time of the first harmonic peak in the diurnal variation can be different from the actual maximum from a few to several hours, due to its essentially non-sinusoidal behavior.

As a result, it was found that, over land, the maximum of convective activity tends to occur during the afternoon-evening hours centered at 17LT or during the late night-early morning hours centered at 04LT. Over the sea, the maximum primarily appears during the afternoon centered at 14LT, and there are also some areas with the maximum at 07LT. It is most likely that these afternoon-early evening maxima, found over both land and sea, are caused by the solar radiative heating on the surface during daytime. On the other hand, the late night-early morning maxima, centered at 04LT over land and 07LT over the sea, seem to be closely associated with terrain or terrain-induced local circulations. This is because these maxima are limitedly found in the windward areas of mountains, in basins and valleys, and in coastal areas. In these areas, a low-level convergence tends to occur during nighttime due to local circulations such as mountain and land breezes or their interactions with a prevailing wind. In this sense, the late night-early morning maximum found over coastal waters should be distinguished from the 'predawn' or 'near-dawn' maximum of convective activity that is frequently reported over the open sea and regarded as a result of cloud-radiative interactions (e.g., Gray and Jacobson 1977; Janowiak et al. 1994; Tao et al. 1996).

The maximum of rainfall also occurs during either of two periods; that is, the afternoon-early evening hours or the late night-early morning hours. The number of stations with the late night-early morning maximum is less than that with the afternoon-early evening maximum. But, the mean daily rainfall at the former stations is on average a few times greater than that at the latter stations. Thus, the late night-early morning maximum is comparable to the afternoon-early evening maximum in the diurnal variation averaged for all stations.

One of the most important findings in this study is the fact that the late night-early morning maximum occurs in especially heavy rainfall areas in tropical Asia. This suggests that the late night-early morning maxima of convective activity and rainfall have a great effect on energy and water cycles in the Asian monsoon region. Further studies are necessary for an understanding of physical mechanisms responsible for this kind of maximum, especially in terms of the local circulation. As such a further study, we are planning the analysis of the convective activity and rainfall found in the northeastern part of Thailand, which is one of typical areas with the late night-early morning maximum, using the data of the GAME-Tropics intensive observation in 1998.

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