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Diurnal variations of summer precipitation over the Asian monsoon region as revealed by TRMM satellite data

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Climatological characteristics of diurnal variations in summer precipitation over the Asian monsoon region are comprehensively investigated based on the Tropical Rainfall Measuring Mission (TRMM) satellite data during 1998–2008. The topographic influence on the diurnal variations and phase propagations of maximum precipitation are identified according to spatiotemporal distributions of the amplitude and peak time of the diurnal precipitation. The amplitude and phase of diurnal precipitation show a distinct geographical pattern. Significant diurnal variations occur over most of continental and coastal areas including the Maritime Continent, with the relative amplitude exceeding 40%, indicating that the precipitation peak is 1.4 times the 24-h mean. Over the landside coasts such as southeastern China and Indochina Peninsula, the relative amplitude is even greater than 100%. Although the diurnal variations of summer precipitation over the continental areas are characterized by an afternoon peak (1500–1800 Local Solar Time (LST)), over the central Indochina Peninsula and central and southern Indian Peninsula the diurnal phase is delayed to after 2100 LST, suggesting the diurnal behaviors over these areas different from the general continental areas. The weak diurnal variations with relative amplitudes less than 40% exist mainly over oceanic areas in the western Pacific and most of Indian Ocean, with the rainfall peak mainly occurring from midnight to early morning (0000–0600 LST), indicating a typical oceanic regime characterized by an early morning peak. However, apparent exceptions occur over the South China Sea (SCS), Bay of Bengal (BOB), and eastern Arabian Sea, with the rainfall peak occurring in daytime (0900–1500 LST). Prominent meridional propagations of the diurnal phase exist in South Asia and East Asia. Along the eastern Indian Peninsula, there is not only the southward phase propagation with the peak occurring around 25°N but also the northward phase propagation with the peak beginning with the southernmost continent, and both reach the central Indian continent to finish. Along the same longitudes where southern China and Kalimantan are located, the diurnal phase of the former propagates from the oceanic area (northern SCS) toward the inland continent, while the phase of the latter propagates from the land area toward the outside sea, showing a landward or seaward coastal diurnal regime. A distinct zonal propagation of the diurnal phase is observed over the BOB oceanic area. The maximum precipitation zone originates from the land-sea boundary of the eastern coast of the Indian peninsula at around 0300 LST, and then propagates eastward with increasing time to reach the eastern coast of the BOB on 1800 LST, finally migrates into the Indochina continent on about 2100 LST.

TRMM, Asian monsoon region, summer precipitation, diurnal variation

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Within the global climate system, the Asian monsoon system is the most intense subsystem significantly affecting local weather and climate over a larger area. Its variations are closely related to the survival of more than 50% global population. Therefore, meteorologists all over the world have been paying much attention to studying the Asian

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monsoon variability [1–4]. The Asian monsoon includes the tropical monsoon and the subtropical monsoon, with considerable variability on a wide range of timescales from diurnal to interdecadal variations [4–7].

In fact, the most fundamental modes of variability of the atmospheric circulation along with meteorological elements are diurnal and seasonal variations due to the climate system responding to solar radiation forcing that results from the rotation and revolution of the earth. The seasonal variation has been extensively studied for several decades. However, the diurnal variation in the Asian monsoon has received less attention because of scarcity of high-frequency observational data, especially over open oceans. Exactly, the so-called diurnal variation should be the intra-daily change, indicating the alternating cycle in the intensity of a meteorological variable between daytime and nighttime.

The diurnal variations of tropical deep convection and precipitation play an important role in modulating energy budget of climate system [8]. Strong feedback exists among diurnal precipitation, shortwave radiation, and longwave radiation, modulating the global energy budget and water cycle [9, 10]. Because precipitation is a result of atmospheric circulation, it is usually used as a major index to investigate the diurnal cycle [11, 12], thereby revealing diurnal variations in related circulations and other variables [13, 14].

Wallace [15] examined the geographical pattern of diurnal variations in precipitation and thunderstorm frequency over the conterminous United States, with such an early study based on hourly precipitation data for more than 100 stations. Subsequently, some other studies have been carried out to examine the diurnal variations over different regions of the United States [16, 17]. Precipitation has been observed much more times per day over the continental areas of the United States since the 1950s, but there is no such longer observations of hourly precipitation in China. Similarly, other Asian countries also lack the hourly rainfall observations. Based on hourly rain-gauge data for the period 1991–2004, Yu et al. [5, 6] first systematically analyzed the characteristics of diurnal variations of summer rainfall over contiguous China. The considerable regionality has been found to exist in diurnal cycles of summer precipitation over China. The precipitation maximum tends to occur in the afternoon over Southern and Northeastern China and in the midnight over the eastern Tibetan Plateau; the diurnal phase changes eastward along the Yangtze River Valley with an early morning maximum in precipitation over the middle valley and a late afternoon peak in the lower valley. Two diurnal peaks exist between Yangtze and Yellow Rivers, with one in the early morning and the other in the late afternoon. Yu et al. [6] also revealed the relationship between the rainfall duration and diurnal variation in summer precipitation over central eastern China.

The launch of the Tropical Rainfall Measuring Mission (TRMM) satellite in November 1997 provides us an opportunity to examine the diurnal variations of tropical precipitation [18, 19]. The TRMM satellite is specifically devoted to observing rainfall in the tropics and subtropics of the earth by using passive microwave imager (TMI), the precipitation radar (PR), and visible and infrared sensors (VIRS). The TRMM satellite can observe the earth's surface between 40°S and 40°N, only taking 96 min to encircle the global. Therefore, the TRMM satellite has provided instantaneous rain-rate measurements with higher spatial and temporal resolution [20–22]. So far, TRMM precipitation-rate data have been archived for more than 10 years, so it is enough to use these data to study the climatological issue on diurnal variations of tropical precipitation.

Using satellite-derived precipitation estimates over tropical oceans, Janonwick et al. [23] and Chang et al. [24] found that deep convection or cold cloud frequently occurs over land between 1800 and 2100 Local Solar Time (LST) and over the tropical oceans between 0300 and 0600 LST. However, some other studies showed an afternoon peak in precipitation over some areas in the tropical oceans [25], indicating that the diurnal phase of maximum precipitation may vary from region to region in tropical oceans.

During daytime, solar radiation directly heats up the earth's surface so that sensible heating over the land surface becomes strongest in the early afternoon, leading to a reduced atmospheric hydrostatic stability and convection developing. Thus, the afternoon maximum precipitation over land is mainly a thermodynamical response of the atmosphere to diurnal cycle of solar radiative heating [26]. But the occurrence of maximum rainfall in the early morning over ocean depends on the cloud-radiation feedback such as the so-called "static radiation-convection" and "dynamic radiation-convection" mechanisms [27, 28]. Strong diurnal signal over the coastal areas is spread out over the adjacent oceans, possibly through gravity waves [29]. Some of recent studies [9, 29, 30] also showed that the diurnal cycles in convection, cloudiness and circulation and their distributions are a good test bed for the validation of the weather and climate models. Wilson and Mitchell [31] pointed out that the global climate model cannot simulate the nonlinear feedback process between convection and radiation if the diurnal cycle is not resolved adequately, resulting in degraded model simulations.

The Asian monsoon region exhibits complex geographical characteristics. Besides the land-sea contrast between the Eurasian Continent and the Indian Ocean, such planetary-scale of the land-sea contrast also exists between the Eurasian Continent and the Pacific Ocean. Moreover, in the southern part of Asia there are synoptic-scale land-sea distributions between gulf and peninsula. Because the large terrain is one of the important factors significantly affecting local precipitation, such complex geographical status certainly leads to different geographical patterns of diurnal precipitation variations. In addition to the studies of Yu et al. [5, 6] concerning diurnal variations of summer rainfall over the continental area in China, Liu and Fu [32] investigated the climatological characteristics of convective and stratiform precipitation over contiguous southern China using TRMM PR data. They found that convective precipitation tends to occur in the afternoon, exhibiting an evident diurnal variation in height of "storm top". Lu and Xu [33] noted both the maximum summer mean rainfall and the maximum variance of diurnal precipitation occur along the west coast of Indochina Peninsula and on the windward slope of the Annam Corrdillera Mountain, with rainfall peaks in the early morning over the coastal region. Besides the influence of solar radiation, the phase and amplitude of diurnal cycle of precipitation over land are significantly affected by large terrain and mountain. However, the climatological characteristics of diurnal precipitation variations have not been examined synthetically over the Asian monsoon region (especially over open oceanic areas). Therefore, the objective of this study is to reveal systematically such basic features of diurnal precipitation variations over the entire Asian monsoon region based on the TRMM precipitation data, providing evidence for validating and improving climate models.

1 Data and methods

TRMM 3B42 products are an estimate of precipitation rate based on the combined instrument rain calibration algorithm [34], which are created by blending optimally passive microwave precipitation data collected by the TMI, the Special Sensor Microwave Imager (SSM/I), the advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E), the Advanced Microwave Sounding Unit (AMSU), and the Infrared Radiation (IR) precipitation estimates collected by the international constellation of geosynchonous earth orbit (GEO). Near-global (between 50°S and 50°N) estimates of the surface precipitation rate are produced by calibrating the high quality microwave estimates to the IR brightness temperature, with the estimates being scaled to match the monthly rain gauge analyses [35]. Thus, the gridded TRMM 3B42 precipitation rates are obtained on a 3-h (refer to the mean rainfall amount accumulated every 3 h) temporal resolution and a 0.25° by 0.25° spatial resolution since January 1998. At present, the TRMM 3B42 products represent the "best" estimates for local rainfall over the tropics and subtropics.

To validate the reliability of TRMM 3B42 precipitation rates, we compare them with the rainfall reanalysis data from Global Precipitation Climatology Project (GPCP). GPCP precipitation data are monthly rainfall estimate derived from rain gauge stations, and satellite geostationary and low-orbit infrared, passive microwave, and sounding observations, with a horizontal resolution of 2.5° × 2.5° latitude-longitude grids. GPCP is reconstructing precipitation estimates at finer space on a 1° × 1° resolution, but the temporal resolution of this new version is only on daily time scale, and thus they are still not enough to examine the diurnal variations. Except for several satellite-observed precipitation estimates as TRMM data, GPCP rainfall is merged with gauge records from 6000 observational stations [36]. Since GPCP takes sufficient advantage of the strengths of each data type, especially with merged products calibrated and corrected by gauge measurements of rainfall, such data are thus able to represent actual state of rainfall systems on greater than synoptic time scales. Because the spatial resolution of TRMM 3B42 products is considerably greater than that of GPCP products, the TRMM 3B42 data are interpolated into the 2.5° × 2.5° gird points to calculate their differences.

Figure 1 shows the climatological distributions of summer (June to August) precipitation rates from TRMM 3B42 and GPCP. To be convenient for comparison, for each of these two datasets the climatology is calculated based on the period 1998–2008, although available monthly GPCP data begin with 1979. Both datasets well reflect the non-uniform rainfall characteristics over the Asian monsoon region under cooperative influences of tropical and subtropical monsoons (Figure 2(a), (b)), exhibiting remarkable accordance in rainfall pattern. Note that heavy precipitation occurs in the monsoon trough from the western coast of the Indian Peninsula through the Bay of Bengal (BOB) to the Indochina Peninsula as well as the Intertropical Convergence Zone (ITCZ) over the South China Sea (SCS) extending into the equatorial western Pacific. Precipitation maxima exist respectively over western Indian Peninsula, northern BOB-southern Tibetan Plateau, eastern Indochina Peninsula, the Philippines and the western North Pacific (130°–150°E). These several maximum centers result from three peninsula-scale monsoon troughs (over Arabian Sea, BOB, and SCS) and one planetary-scale ITCZ over the western North Pacific [37]. Note also that distinct basic feature that in China rainfall amount decreases from southeast coast to northwest area. Xie et al. [38] constructed a gauge-based daily precipitation dataset on a 0.5° latitude-longitude grid over the Asian continental area (5°–60°N, 65°–155°E) for the period from 1978 to 2003 using gauge observations at over 2200 stations (including more than 700 China meteorological stations) collected from several individual sources. Based on such daily data, Yao et al. [39, 40] investigated the regionality of occurrences of extreme rainfall events and their seasonal difference. When Figure 1(a) and (b) is compared with the results in refs. [39, 40], it is found that the rainfall patterns over land are consistent, suggesting that the TRMM 3B42 products are indeed able to reflect the precipitation situation over tropical and subtropical land surface.

Absolute positive differences greater than 1 mm d^{-1} are observed mainly over northeastern Indian Peninsula, southern Tibetan Plateau, and Indochina Peninsula (Figure 1(c)), with the differences in order of 2–3 mm d^{-1} over western Indochina Peninsula; while negative differences occur

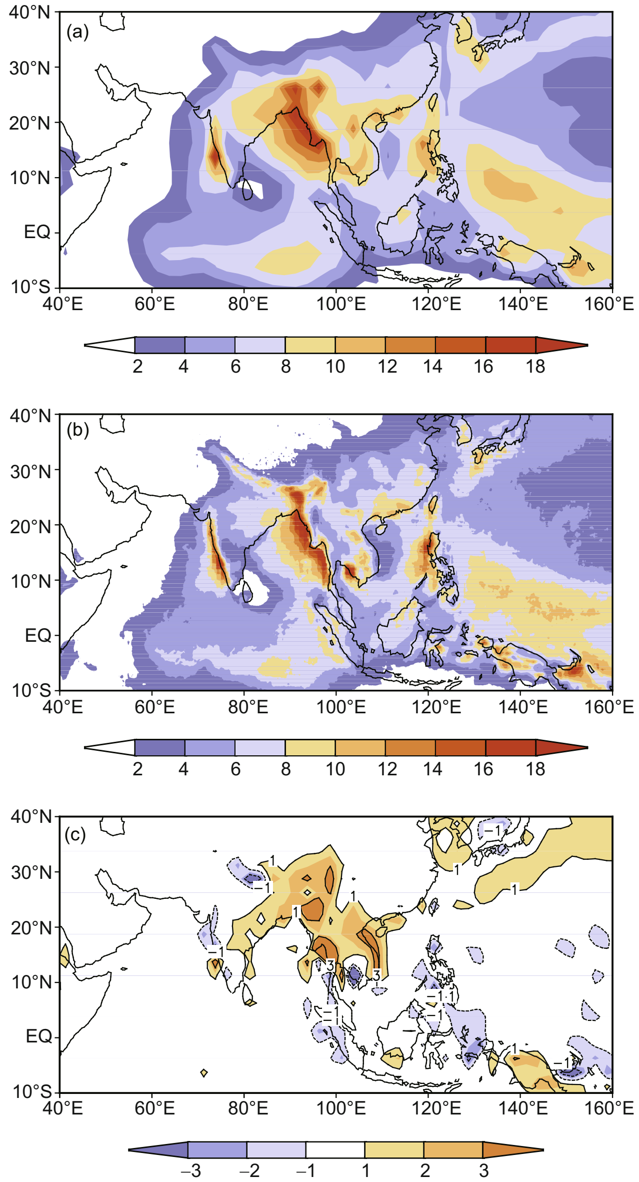

Figure 1 Climatological distributions of summer (June–August) precipitation rate (mm d^{-1}) derived from GPCP (a) and TRMM 3B42 (b). (c) Difference between GPCP and TRMM 3B42.

mostly over equatorial open oceans east of Indonesia. Relatively speaking, TRMM data merely overestimate the precipitation over some of small local areas in ocean, but evidently underestimate the rainfall over the southeastern Tibetan Plateau and Indochina Peninsula. In investigating the cause of differences between GPCP rainfall and precipitation retrieved from TRMM microwave, Liu and Fu [41] suggested that the underestimate of TRMM products are related not only to retrieval algorithm for cloud-ice content in upper troposphere over land but also to the non-uniform distribution of rain-gauge stations during GPCP assimilation. Of course, the underestimate of TRMM precipitation around Tibetan Plateau is possibly associated with topographic forcing. The "sensible heating air pump" [42, 43] of the Tibetan Plateau causes ambient airflow to converge toward the Plateau due to the sensible heating on its slopes, leading to much more rainfall over the southeastern Tibetan Plateau and western Indochina Peninsula than over other continents. However, the TRMM 3B42 algorithm is possibly difficult to identify such enhanced rainfall due to different terrain altitudes [44]. This issue needs to be further studied. As suggested by Liu and Fu [41], the TRMM microwave measurements can well represent large-scale precipitation over the Asian monsoon region. Since the TRMM 3B42 products include both microwave and high-frequency IR information, they are more suitable to investigate basic features of diurnal precipitation. Xie et al. [38] utilized their daily gridded rainfall data over China from January to July of 2003 to validate the performance of several satellite-based precipitation products. The results showed that the TRMM 3B42 precipitation exhibits the best resemblance with rain-gauge observations in terms of both temporal evolution and spatial correlation pattern. Zhou et al. [12] also found that the 3-h TRMM 3B42 products well reproduce the diurnal variations of summer precipitation over China, as are identified by hourly rain-gauge records, suggesting that the TRMM 3B42 products are indeed a reliable precipitation data on a higher temporal resolution.

Because the focus of this study is on the climatological characteristics of diurnal variations of summer precipitation over the entire Asian monsoon region, the climatological precipitation rate for each of eight observational times within a day is obtained by averaging the TRMM 3B42 precipitation rate of each corresponding observational time every day during June–August from 1998 to 2008. Since solar radiation is the dominant factor causing the diurnal cycle of meteorological variables, the calculated climatological precipitation rate for Coordinated Universal Time (UTC) is again converted as that corresponding to Local Solar Time (LST) based on the time zone where grid points are located. As such, the regional differences of diurnal precipitation can be highlighted, favorable to reveal the mechanism for the regionality. The analyzed domain is chosen to be 10°S–40°N and 40°–160°E.

There are two definitions for the amplitude of diurnal precipitation. One is the absolute amplitude, which is defined as the difference between maximum rainfall and minimum rainfall in the diurnal cycle [45]. Namely,

$$A = R_{\max} - R_{\min}, \tag{1}$$

where A is the amplitude of diurnal precipitation, $R_{\max}$ the maximum precipitation rate, and $R_{\min}$ the minimum precipitation rate.

The other is the relative amplitude of diurnal precipitation, which is defined as the normalized difference between daily maximum rainfall and daily mean [15, 17].

$$B = (R_{\max} - R_{\text{mean}})/R_{\text{mean}} \times 100\%, \tag{2}$$

where B is the relative amplitude of diurnal precipitation,

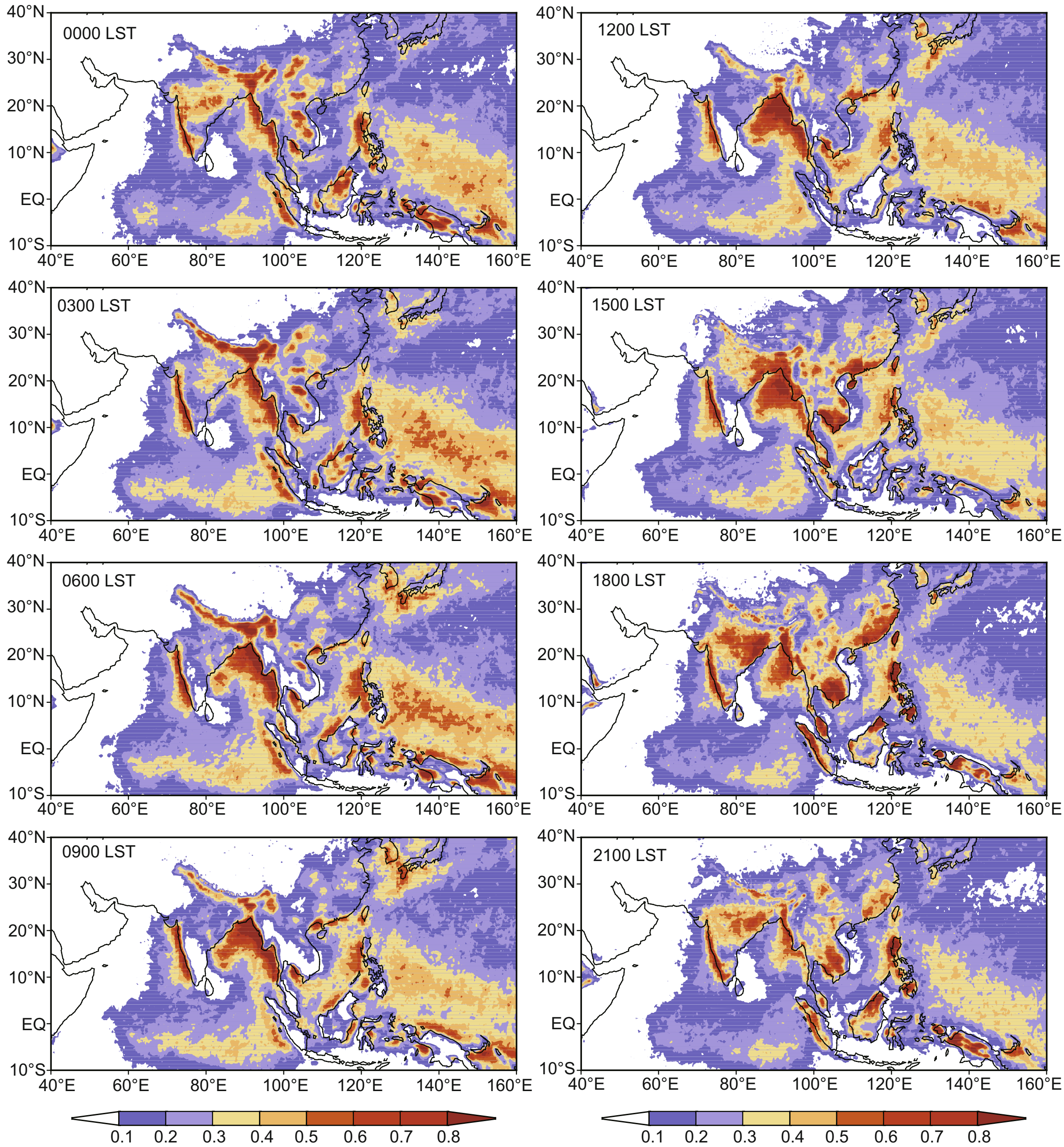

Figure 2 The diurnal cycle of climatological summer precipitation rate (mm h^{-1}) indicated by different LSTs (h).

R_{max} the maximum precipitation rate, and R_{mean} the daily mean of precipitation rate. Note that such normalized amplitude can decrease the impact of different climate backgrounds on the diurnal range, but it is not suitable for the area with very small daily mean of precipitation rate.

The diurnal phase is defined as the LST when the maximum precipitation occurs in the diurnal cycle.

2 Diurnal variability of precipitation

2.1 Day-night variations

Figure 2 shows the diurnal cycle of climatological summer precipitation rate over the Asian monsoon region. The precipitation rate over western Pacific east of Philippines is evidently stronger in midnight-to-early morning hours (0000–0600 LST) than in afternoon-to-late evening hours (1500–2100 LST), indicating an oceanic diurnal regime for open ocean areas characterized by an midnight-to-early morning peak [27, 45]. In contrast, the maximum precipitation is observed over land areas including the Indochina Peninsula and southern China from 1500 to 2100 LST, with almost no rainfall for the period 0000–0600 LST, representing a typical continental regime characterized by an afternoon-late evening peak [28]. Note that over the central and northern Indian continent, pronounced rainfall mainly occurs from afternoon to midnight (1500–0000 LST), while over the oceanic area of the northeastern BOB rainfall maximum seems to arise till noon. Over the coastal areas, the intensities of precipitation are different from different observational times. Kikuchi and Wang [45] suggested that there are two kinds of coastal diurnal regime, with the precipitation peaks propagating seaward or landward (as discussed in sections 3 and 4).

At the diurnal time scale, the day-night variation is the prominent variability mode over most regions. Figure 3 displays the distributions of daytime and nighttime rainfall accumulations as well as the ratios of daytime to nighttime rainfall accumulations. At the planetary space scale, although the daytime and nighttime rainfall distribution patterns are similar, significant regional day-night variations exist in the climatologically heavy precipitation zones such as the BOB, SCS, equatorial western Pacific, and Maritime Continent (Figure 3(a), (b)). On the other hand, the ratios of day-night variations are evidently different for some specific regions (Figure 3(c)). Over oceanic areas, the ratios are less than 1.0 over the western Pacific ITCZ zone (indicating less rainfall in daytime than in nighttime), while the ratios are greater than 1.0 over the SCS, BOB, and eastern Arabian Sea, signifying more rainfall in daytime than in nighttime over these areas. The daytime rainfall is also more than the nighttime precipitation over the major western Pacific under the influence of the subtropical high, although the precipitation amounts are usually not much larger there. These facts demonstrate that the characteristics of diurnal variations of precipitation over the tropical oceans in the Asian monsoon region (e.g. the SCS, BOB, and eastern Arabian Sea) are different from over other oceans. Over continental areas, the rainfall occurs more frequently in daytime than in nighttime over most of eastern China, while opposite situation appears over the Indian continent and central Indochina Peninsula. Note that the ratios are less than 1.0 over the central and eastern Tibetan Plateau, but large errors also appear in precipitation data over there, suggesting that such results need to be further validated. Fu et al. [14] found that the TRMM algorithm might have misclassified weak convections as stratiform rains over the Tibetan Plateau. It is thus obvious that the features of diurnal precipitation around the Tibetan Plateau are more complicated than over other low-altitude regions. The above facts indicate that large regional differences of diurnal precipitation also exist over the Asian monsoon continents.

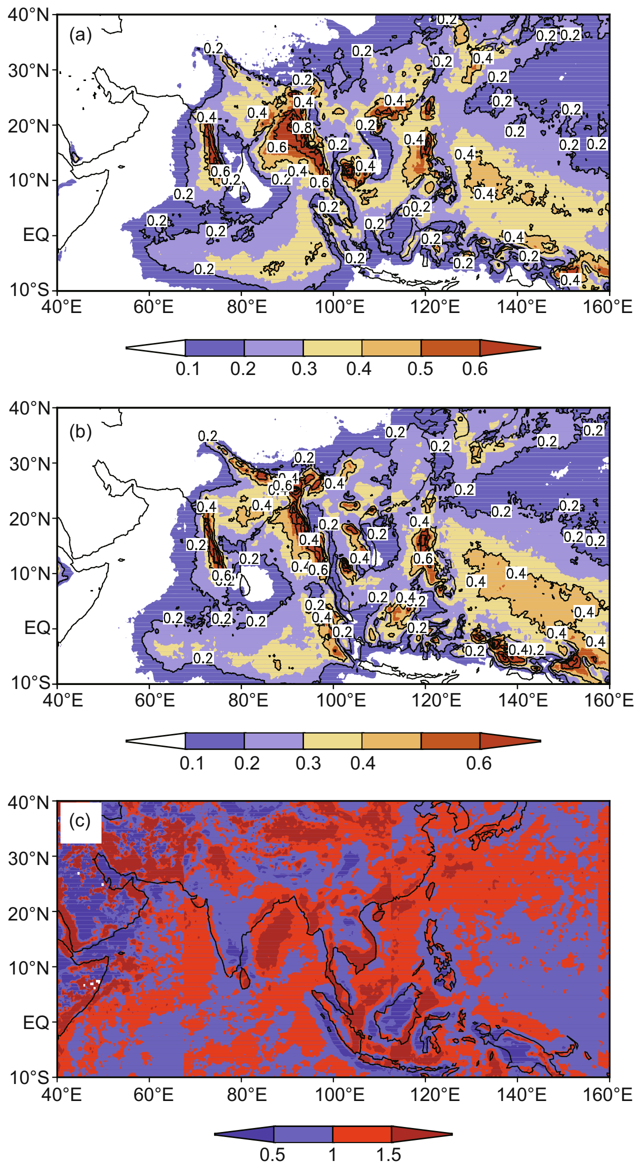

Figure 3 (a) Accumulated precipitation rate (mm h^{-1}) for daytime (0900 – 1800 LST); (b) accumulated precipitation rate (mm h^{-1}) for nighttime (2100–0600 LST); (c) the ratio of daytime to nighttime precipitation accumulations, with the magnitude of such a unitless ratio indicated by color bar.

2.2 Amplitude and phase of diurnal precipitation

To elucidate the timing of the maximum rainfall occurrence, Figure 4 shows the spatial distributions of amplitude and phase of diurnal precipitation. Strong diurnal variations with relative amplitudes greater than 40% are observed over most of continental and coastal regions including Indonesian archipelago and adjacent oceans, in which the relative amplitudes even exceed 100% over coastal continents such as southeastern China and Indochina Peninsula (Figure 4(a)). Note that the weak diurnal variations with relative amplitudes less than 40% exist mainly over the western Pacific and most of Indian Ocean except for BOB. Topographic impacts on diurnal amplitudes will be discussed in section 3.

The spatial distributions of diurnal phase of precipitation (Figure 4(c)) show that the early morning rainfall peak (0000–0600 LST) exists primarily over the oceanic ITCZ in western Pacific, Kalimantan Island, western and southern Sumatra, equatorial Indian Ocean, southern and central Indian Peninsula, southern Tibetan Plateau and Sichuan Basin in China. From late morning to early afternoon, rainfall

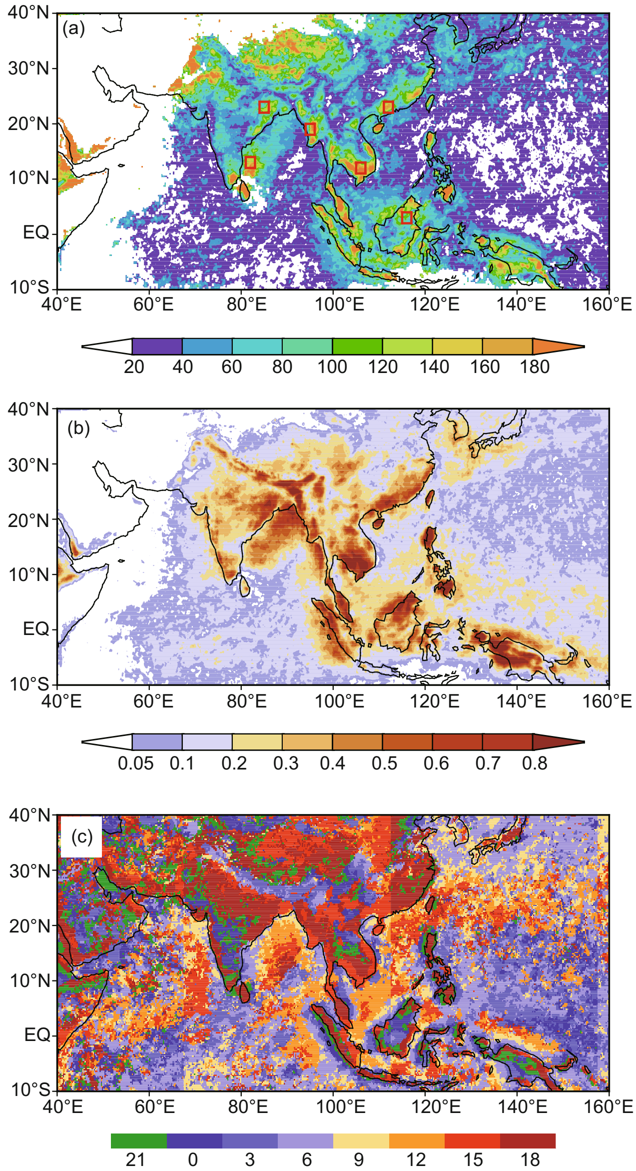

Figure 4 Climatological distributions of amplitude and phase of diurnal precipitation. (a) Relative amplitude (%), with the red square denoting the selected subarea used in Figure 5 to take area-average and the geographical location; (b) absolute amplitude (mm h^{-1}); (c) phase (LST (h)) when maximum precipitation occurs.

maximum mainly occurs over the oceanic regions of the SCS, northern BOB, and eastern Arabian Sea. The afternoon peak (1500–1800 LST) of the continental regime is particularly evident over the eastern China, northern and central Tibetan Plateau, coasts of the Indochina Peninsula and northern Indian Peninsula, and this feature is similar to the situation over the southeastern United State [17]. However, over the central Indochina Peninsula and central and southern Indian Peninsula the diurnal phase is delayed to late evening-midnight (2100–0000 LST). Note that the phase is earlier over the northern India than over the central India, implying that the diurnal phase of rainfall possibly propagates southward.

Absolute amplitudes (Figure 4(b)) exhibit a similar distribution to the relative amplitudes (Figure 4(a)). As suggested by Kikuchi and Wang [45], the pattern of absolute amplitudes essentially follows the distribution of the climatological summer rainfall (Figure 1(b)). But the absolute amplitude distribution highlights the land-sea contrast in the atmospheric response to solar radiation forcing. Generally, absolute amplitude is much large over coastal land areas (e.g. southeastern China, southern Indochina peninsula, northeastern India). Note that some ocean areas adjacent to continents also have relatively large absolute amplitude such as the northwestern BOB and the Indonesian Maritime Continent, indicating the offshore phase propagation with rainfall peak expanding from land to adjacent ocean [29, 45].

To further examine the regional difference of diurnal precipitation, six sub-regions with strong diurnal variations of the relative amplitude greater than 100% are selected to analyze the timing of the minimum rainfall occurrence. The time series (Figure 5) of precipitation rate show that the diurnal cycle for most sub-regions is characterized by a sinusoidal curve containing a maximum value and a minimum value. Daily mean rainfall over the oceanic area of southwestern BOB is not much larger (about 0.2 mm h^{-1}), with maximum rainfall rate being only 0.4 mm h^{-1} (Figure 5(a)), which is due mainly to that this area is located east of southern Indian Peninsula (the leeward side of the continent), unfavorable for large-scale monsoonal precipitation. Note that the maximum rainfall occurs in the morning (0600 LST), while the minimum rainfall appears in the late afternoon to evening (1800–2100 LST). This is typical situation resulting from local land-sea breezes, in which cloud-radiation feedback possibly plays a dominant role [28]. Although the precipitation peaks all occur in the late afternoon (1800 LST) over land areas on both western and eastern sides of the northern BOB (Figure 5(b), (c)), the minimum rainfall over the northeastern Indian continent (Figure 5(b)) appears in the morning (0900 LST), with the weakest rainfall keeping above 0.2 mm h^{-1} over the northwestern Indochina Peninsula (Figure 5(c)). The largest amplitude is present over the southern Indochina Peninsula (Figure 5(d)), with the minimum precipitation occurring in the morning (0900 LST) and with the heaviest rainfall in magnitude of 0.9 mm h^{-1} occurring in the late afternoon (1800 LST). The diurnal cycle over the southern China (Figure 5(e)) is similar to that over the northwestern Indochina Peninsula (Figure 5(c)), except that the occurrence of the maximum is earlier over the former (1500 LST) than over the latter. These facts reflect the common feature of the diurnal precipitation over the tropical continents that the maxima occur from afternoon to evening, but the phases of the minimum rainfall occurrence are different. Over the northern Kalimantan (Figure 5(f)), the heaviest rainfall occurs in the midnight (0000 LST), while the weakest precipitation appears in the noon (1200 LST).

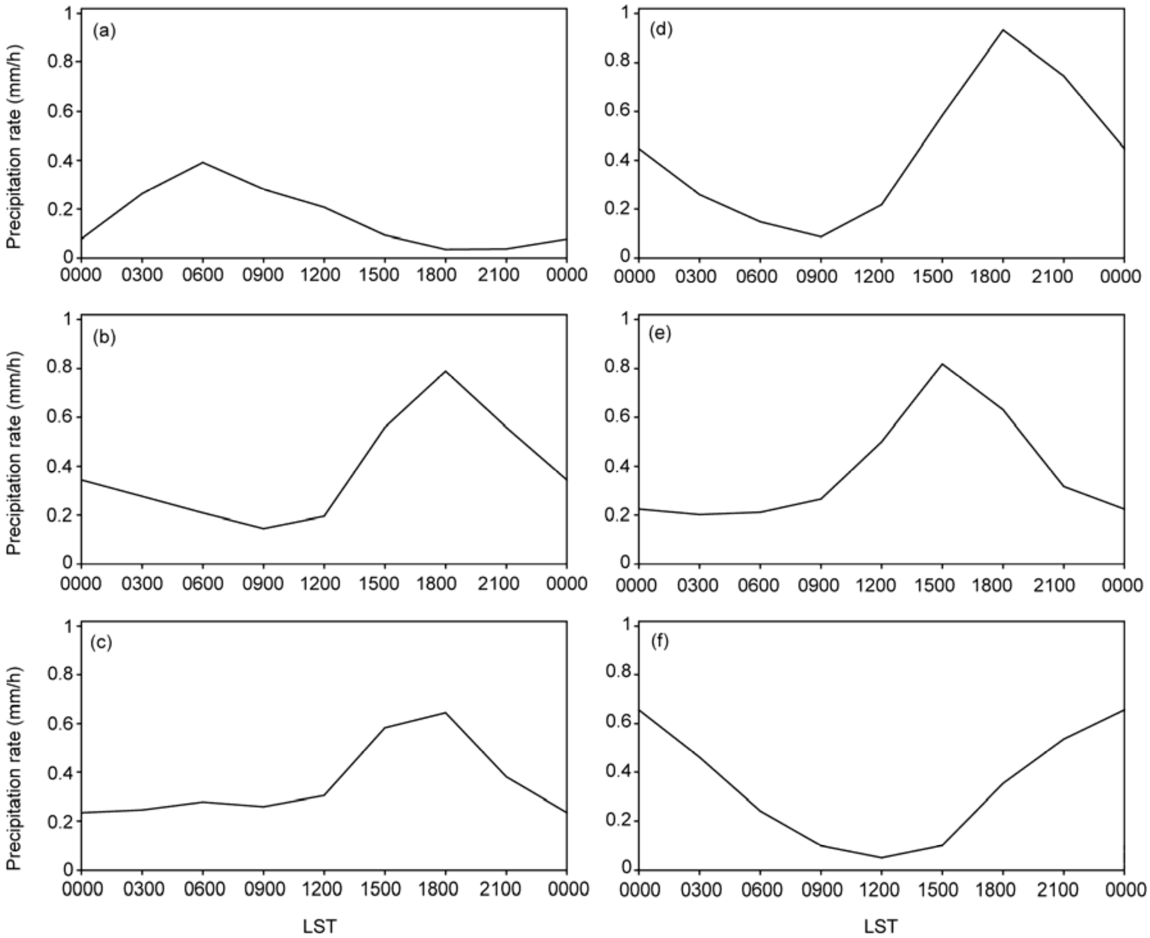

Figure 5 Diurnal cycles of area-averaged precipitation rate (mm h^{-1}) over the selected subareas outlined in Figure 4. (a) Oceanic region of southwestern Bay of Bengal (12°–14°N, 81°–83°E); (b) continental region of northeastern Indian Peninsula (22°–24°N, 84°–86°E); (c) continental region of northwestern Indochina Peninsula (18°–20°N, 94°–96°E); (d) continental region of southern Indochina Peninsula (11°–13°N, 105°–107°E); (e) continental region of southern China (22°–24°N, 111°–113°E); (f) continental region of northern Kalimantan (2°–4°N, 115°–117°E).

3 Topographic influences on the diurnal variations of precipitation

Figure 1 (a) and (b) shows a heavy precipitation center over the western coasts of the Indian Peninsula and over the Indochina Peninsula, respectively. Such a phenomenon is also pronounced in 3-h precipitation evolutions (Figure 2), although the rainfall intensity varies with time. This feature is obviously related to the unique geographical state in the southern portion of Asia. Here there are not only planetary-scale meridional and zonal land-sea thermal contrasts (between the Eurasian Continent and the Indian Ocean and between the Eurasian Continent and the Pacific Ocean) but also the synoptic-scale land-sea thermal contrasts between gulfs and peninsulas. The Arabian Sea, Indian Peninsula, BOB, Indochina Peninsula, and SCS are located alternately in the southern portion of Asia (10°–25°N), producing remarkable in situ land-sea breezes, thereby leading to significant diurnal variations of precipitation. Moreover, the modifying effect of such local land-sea breezes on large-scale monsoonal southwesterlies may also be different due to different terrain altitudes. To highlight orographic influences on diurnal precipitation variations, Figure 6 presents the longitude-time cross section of precipitation rate averaged between 14°–16°N. Along the land-sea boundary (about 75°E) of the western Indian Peninsula and the western coast (about 120°E) of Philippines, the rainfall rate for each 3-h is very large, but the amplitude of diurnal variation is weak. However, along the land-sea boundary (about 95°E) of the western Indochina Peninsula, both rainfall intensity and amplitude in the diurnal cycle are very large, with strong precipitation sustaining for a longer period (0000–1200 LST). Over the Indian continent (75°–80°E), although the rainfall rate for each 3-h is very small, the diurnal variations are pronounced, with peak phase occurring from 2100 to 0000 LST. Over the central Indochina continent (100°–105°E), almost no rainfall arises in the morning, while moderate precipitation (about 0.3 mm h^{-1}) occurs in the afternoon. For the eastern Indochina continent (105°–110°E), the diurnal variations are very prominent, with heavy rainfall occurring mainly in late afternoon-to-midnight period (1800–0300 LST) and with the weakest rainfall in the morning (0600–1200 LST). Over the oceanic longitudes of the SCS (110°–120°E), the precipitation rate decreases eastward, and the diurnal variation is not evident.

Noteworthy is the eastward phase propagation of the diurnal precipitation over the BOB (80°–95°E) (Figure 6). The rainfall maximum greater than 0.3 mm h^{-1} is observed to originate from the eastern coast of the Indian peninsula, and then propagates eastward with increasing time to reach the eastern coast of the BOB, and finally migrates into the Indochina continent. This reflects the typical landward coastal regime of the diurnal variations [45]. Actually, strong precipitation starting from 2100 LST over the western Indochina Peninsula is related to such diurnal phase propagation.

The topographic impact on the amplitude of the diurnal variations can be illustrated in Figure 7 more clearly. Except for the western BOB oceanic area, the relative amplitudes are mostly larger over continents than over oceans. Though the relative amplitude over the Indian Peninsula is less than those over the Indochina Peninsula and Philippine Island, it also exceeds 60%. The largest relative amplitudes above 160% occur over the high-terrain windward slopes of the western and eastern coasts of the Indochina Peninsula, which possibly results from the local topographic forcing superimposed on the peninsula-scale BOB monsoon trough [33, 37]. Note that weak amplitudes appear over the inland area located on the leeward slope of the western Indochina Peninsula.

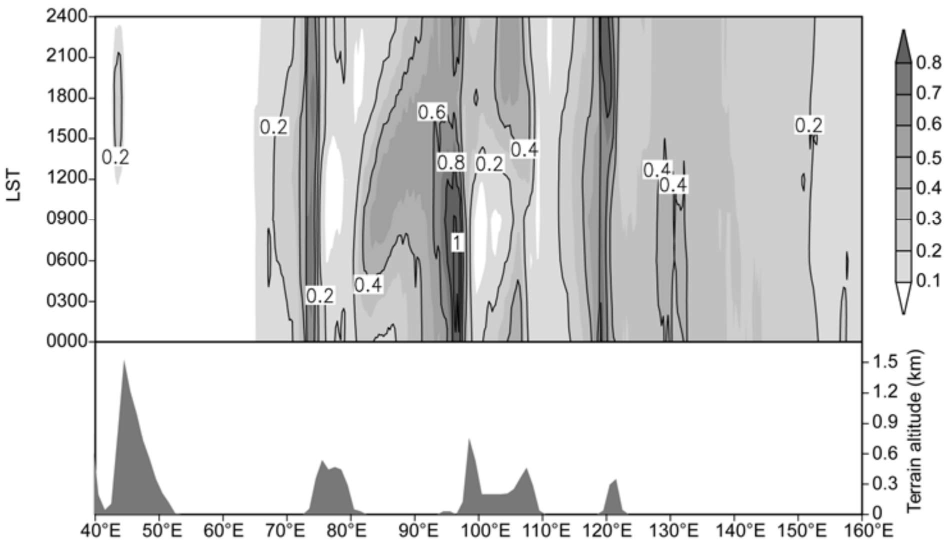

Figure 6 Longitude-time (LST) cross section of diurnal precipitation (mm h^{-1}) averaged between 14°–16°N. The bottom panel shows the terrain altitude of corresponding longitudes.

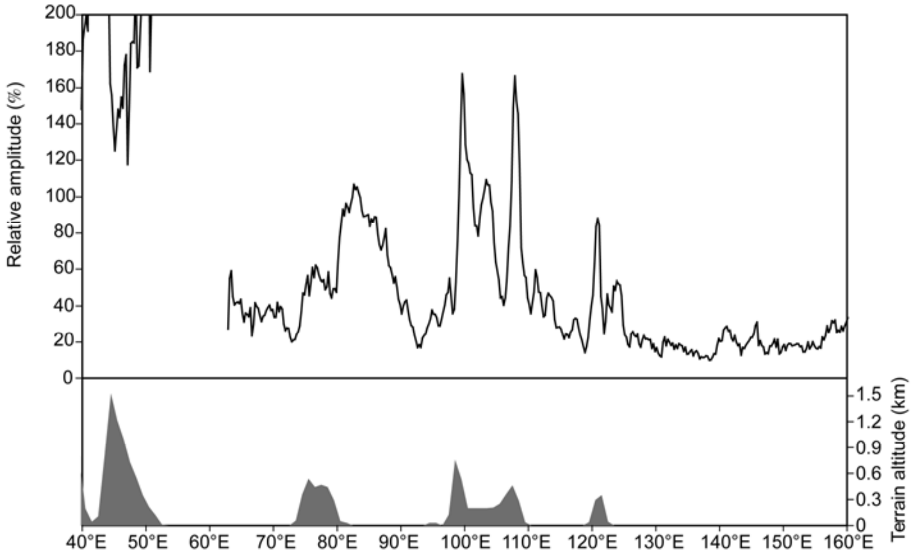

Figure 7 Longitudinal distribution of relative amplitude of diurnal precipitation averaged between 14°–16°N. The bottom panel shows the terrain altitude of corresponding longitudes.

4 Meridional propagation of the diurnal phase of maximum precipitation

In addition to the distinct zonal propagation of diurnal phase, there are prominent meridional propagations somewhere in South Asia and East Asia. Figure 8 shows the latitude-time cross section of diurnal precipitation averaged over the longitudinal band of the eastern Indian Peninsual. Note that the terrain altitudes in most of the Indian continent (south of 30°N) are lower than 1 kilometer, with higher terrain to the north associated with the Himalayas. There is a maximum rainfall zone above 0.4 mm h^{-1} in the latitudinal band between 15°N and 25°N, which tilts southward with increasing time, indicating southward phase propagation. Actually, heavy precipitation (greater than 0.4 mm h^{-1}) first occurs around 25°N at 1500 LST, and then propagates to around 18°N till 0300 LST. Besides ascending motions caused by solar radiation heating up the local continent, the reason for the earliest occurrence of this rainfall maximum in the afternoon may be due mainly to mountain-valley breezes that result from the dynamical and thermal forcing of the high Himalayas [29]. The maximum rainfall over the eastern Indochina Peninsula starting at 2100 LST shown in Figure 5 is possibly associated with such phase propagating southward to 15°N. Another maximum rainfall zone with intensity greater than 0.3 mm h^{-1} is present in the south Indian Peninsula. The precipitation above 0.2 mm h^{-1} is noted to arise first over the southmost continent of the Indian Peninsula on around 1400 LST (possibly caused by land-sea breezes). In contrast with the counterpart to the north, this maximum zone expands northward with increasing time.

Figure 9 displays the time-latitude cross section of diurnal precipitation averaged for the same longitudes where southern China and Kalimantan are located. There is a remarkable maximum precipitation zone (with intensity exceeding 0.4 mm h^{-1}) over southern China (20°–25°N) lasting from 0600 to 2100 LST. This heavy rainfall zone tilts northward with increasing time, representing a northward phase propagation. In fact, the maximum greater than 0.4 mm h^{-1} first occurs over the oceanic area in the northern SCS in nocturnal hours (0000–0300 LST). With inland areas getting more solar radiation, the continental rainfall also increases, which causes heavy rainfall zone to systematically move inland, reaching the maximum value till 1500 LST. Hereafter, the peak value decreases and migrates to around 25°N. Such landward phase propagation is consistent with the result of Yu et al. [5]. Note that increased rainfall is obviously related to the elevated terrain forcing, which may result from large-scale monsoon circulation superimposed in phase with local land–sea breezes.

Over land areas of the Kalimantan, the rainfall starts from the afternoon, and the maximum occurs around midnight (2100–0300 LST). Subsequently, the rainfall peak gradually propagates toward northern slope of the island and gets to outside ocean on 0900 LST. Over the ocean area the maximum reduces slightly. Thus, this offshore phase propagation begins with the landside coast in the midnight, lasting propagating toward ocean till 1200 LST. Thereafter, the northward propagating signal becomes less evident, and its intensity diminishes further. These facts represent typical seaside coastal regime of diurnal precipitation with peaks propagating from land to ocean [45].

5 Summary and discussion

In this study, the 3-hourly tropical rainfall measuring mission (TRMM) satellite-based precipitation data (3B42) dur-

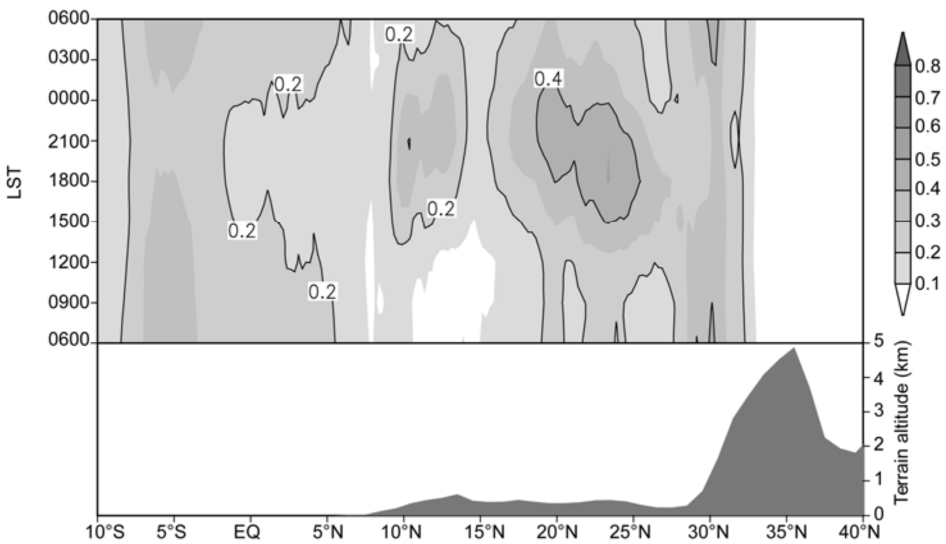

Figure 8 Latitude-time (LST) cross section of diurnal precipitation (mm h^{-1}) averaged between 75°–80°E. The bottom panel shows the terrain actitude of corresponding latitudes.

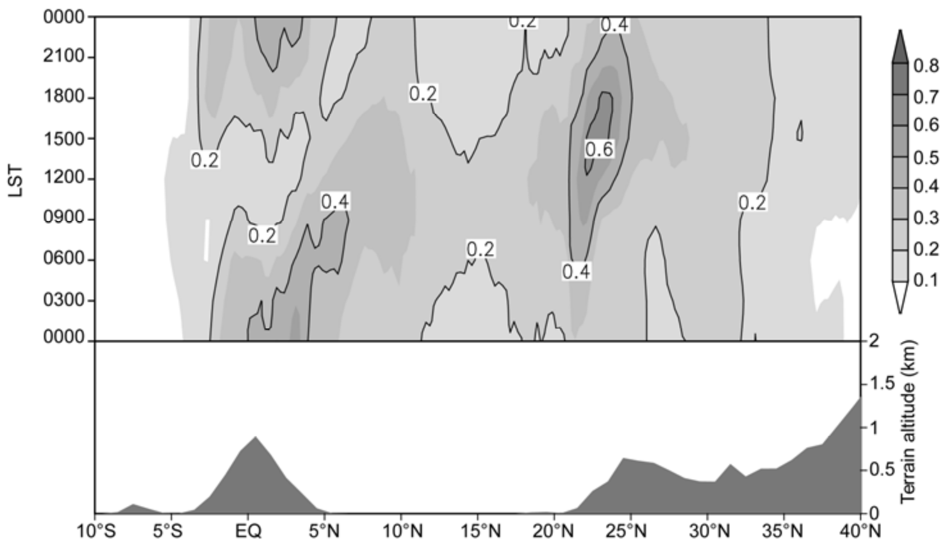

Figure 9 Latitude-time (LST) cross section of diurnal precipitation (mm h^{-1}) averaged between 110°–115°E. The bottom panel shows the terrain altitude of corresponding latitudes.

ing 1998–2008 are used to systematically investigate climatological characteristics of diurnal variations in summer precipitation over the Asian monsoon region. According to spatiotemporal distributions of the amplitude and peak time of the diurnal precipitation, the topographic impacts on the diurnal variations and the phase propagation of maximum precipitation have been identified. Main findings of the present study are summarized as follows:

(1) Significant regional day-night variations exist in the oceanic convergence zones and landside coastal areas including southern China, Indochina Peninsula and Indian Peninsula. Over the western Pacific ITCZ region, the rainfall is less in daytime than in nighttime. On the contrary, over other oceanic areas (SCS, BOB, and eastern Arabian Sea) the rainfall in daytime is more than that in nighttime. Over continental areas, the rainfall occurs more frequently in daytime than in nighttime over most of eastern China while opposite situations arises over the Indian continent and central Indochina Peninsula.

(2) The amplitude and phase of diurnal precipitation variations exhibit a distinct geographical pattern. Strong diurnal variations with relative amplitudes greater than 40% are present over most of continental and coastal regions including Indonesian archipelago and adjacent oceans, in which the relative amplitudes even exceed 100% (implying that the precipitation maximum is at least twice the 24-h mean) over coastal continents such as southeastern China and Indochina Peninsula as well as the oceanic area in the northwestern BOB. The rainfall peak over tropical continents generally occurs in late afternoon (1500–1800 LST). However, over the central Indochina Peninsula and central and southern Indian Peninsula the diurnal phase is delayed to late evening-midnight (2100–0000 LST). The weak diurnal variations with relative amplitudes less than 40% are noted to exist mainly over oceanic areas in the western Pacific and most of Indian Ocean other than the BOB, with the rainfall peak mainly occurring from midnight to early morning (0000–0600 LST), indicating a typical oceanic regime characterized by an early morning peak. Apparent exceptions occur over the SCS, BOB, and eastern Arabian Sea, with the peak occurring in daytime (0900–1500 LST).

(3) The diurnal phase of the maximum precipitation over the BOB oceanic area exhibits a distinct zonal propagation. The maximum precipitation zone originates from the land-sea boundary of eastern coast of the Indian peninsula at around 0300 LST, and then propagates eastward with increasing time to reach the eastern coast of the BOB on 1800 LST, and finally migrates into the Indochina continent on about 2100 LST. Actually, strong precipitation starting from 2100 LST over the western Indochina Peninsula is related to such diurnal phase propagation. Prominent meridional propagations of the diurnal phase exist in South Asia and East Asia. Along the eastern Indian Peninsula there are not only the southward phase propagation starting from around 25°N but also the northward phase propagation beginning with the southmost Indian continent, and both arrive at the central Indian land area to finish. Along the same longitudinal band where southern China and Kalimantan are located, the diurnal phase of the former propagates from the oceanic area (northern SCS) toward the inland continent, while the phase of the latter propagates from the land area toward the outside sea.

In this study, the diurnal variations have been examined only from the perspective of precipitation amount without analyzing the situations in the frequency and intensity of rainfall. According to the results of Dai et al. [17], although diurnal behaviors of these thee elements are similar, the differences among them still need to be explored. In addition, we have not investigated the mechanisms responsible for the diurnal variations in terms of wind fields, especially of how to separate the local land-sea breezes forced by peninsula-scale land-sea thermal contrasts and the mountain-valley breezes due to different height terrains from the planetary-scale monsoon circulation, whereby understanding the role of the individual spatial-scale circulation system on the diurnal precipitation. The associated mechanism responsible for diurnal phase propagation also deserves to be investigated. These issues will be studied in the subsequent research.

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