

DIURNAL VARIATION OF SUMMER RAINFALL OVER THE TIBETAN PLATEAU AND ITS NEIGHBORING REGIONS REVEALED BY TRMM MULTI-SATELLITE PRECIPITATION ANALYSIS

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Abstract

This paper investigates the diurnal variation of summertime precipitation over the Tibetan Plateau and its neighboring areas using the TMPA (TRMM Multi-satellite Precipitation Analysis) data during 2002~2006. The TMPA precipitation product is compared with rain gauge observations from 643 meteorological sites in China to confirm its applicability and fidelity. Both composite and harmonic analyses are applied to quantify the diurnal cycles of precipitation intensity and frequency. The harmonic amplitude indicates pronounced daily variability over the Tibetan Plateau and its nearby regions, with the strongest diurnal signal over the central Plateau and Indian Peninsula southwest of the Plateau. The harmonic phase displays that the timing of the maximum precipitation amount and frequency has considerably geographical dependence. Overall, a late-afternoon-evening maximum and a morning minimum are dominant in the central Plateau, whereas a late-night maximum is prevalent around the Plateau and in the Sichuan Basin, and a morning and afternoon maximum appear in the upper and mid-lower reaches of the Yangtze River, respectively. There is a coherent diurnal variation pattern east of the Plateau, characterized by systematically delayed precipitation away from the Plateau. The significant nocturnal rainfall in the Sichuan Basin is likely associated with eastward-propagating convective systems originated over the Tibetan Plateau.

Key words TMPA, Diurnal variation, Harmonic analysis, Tibetan Plateau

1 INTRODUCTION

One of well-known features in continental convection and precipitation during warm seasons is the significant diurnal variability associated with the well defined daily solar heating cycle. Diurnal variation of rainfall is an important aspect of both regional and global climate. When precipitation occurs regularly during particular periods of a day the atmospheric system is usually characterized by conditions and physical processes that suggest strong convection during the favored periods^[1]. Due to limited observations of precipitation, studies on diurnal variability of weather have been focused only on some specific regions in the tropics, and are mostly performed on cloud, rainfall, temperature and water vapor, using various satellite data (CLAUS, TRMM, Meteosta-5, and so on). It is generally accepted that precipitation over tropical regions has pronounced diurnal variability. In the tropics, the precipitation over oceans tends to peak in the early morning, while over continents it tends to get an afternoon-evening maximum^[2~5]. For example, using the brightness temperature data observed from CLAUS satellite, Yang and Slingo^[2] analyzed the diurnal variability of convection over tropical regions and concluded that oceanic deep convection tends to reach its maximum in the early morning, but continental convection generally peaks approximately in the evening. Using the precipitation data from TRMM (Tropical Rainfall Measuring Mission) satellite, Nesbitt and Zipser^[3] found that over oceans, the diurnal cycle of rainfall has a small amplitude and the maximum contribution to total rainfall from meso-scale convective

systems appears in the early morning, but land areas have a more significant diurnal cycle than oceans, with a minimum in the mid-morning and a maximum in the afternoon. Using the buoys data on oceans Bowman et al.^[5] confirmed the foregoing conclusions^[2,3].

Moreover from the studies in the tropics, it is found that some distinct diurnal patterns of the tropics have been documented due primarily to topography, sea-land contrast, and surface heterogeneity. For instance, Zuidema^[6] investigated the diurnal cycle of summertime cloud in the Bay of Bengal with 3-hourly Infrared data retrieved from Meteosat-5. He found that the land-water interface is very important for the convection genesis, and thereby affects the spatial distribution of convection. In addition, the strength of diurnal cycle in convection shows great special variability, with the highest amount of very cold cloud and the strongest diurnal cycle on the northwest side of the Bay and the strongest diurnal cycle. Yang and Slingo^[2] examined the tropical convective cloud systems, and pointed out that the strong diurnal signal over land spreads out to the adjacent oceans probably through gravity waves of varying depths. They also found that there is a good correspondence between the maxima in the amplitude of the diurnal harmonic and the elevated terrain of the Ethiopian Highlands and the Cameroon Highlands, implying that orography may play an important part in modulating the phase of the diurnal cycle. The coherent diurnal variations around the islands are widespread and ubiquitous, indicative of the impacts of diurnally forced sea-land breezes and organized convection. Consequently, all of the studies suggest that topography may drive the diurnal variability of convection, which is an important component of the global hydrological cycle and energy budget.

The Tibetan Plateau is one of the most prominent geographical features on the earth, with an average height of roughly 4500 m, and an area of 2.4 million km² complex topography (especially on its edges) and large land-surface contrast between the western and eastern parts. Because of the unique altitude and horizontal extent, the Plateau is of considerable importance to the Asian monsoon and global general circulation via its mechanical and thermal forcing, and exerts a striking influence on the climate change in China. For a long time, the Tibetan Plateau attracts much attention for its effects on the weather and climate over Eurasia, however the efforts into quantifying the diurnal variation of precipitation over the Plateau and its nearby areas are hampered due to poor sampling and inadequate observations at both temporal and spatial scales. With the development of remote sensing technology, satellite and radar observations have been increasingly applied to studies of the rainfall diurnal cycle over the Plateau. Murakami^[7] studied the phase and amplitude of rainfall diurnal variability over the Plateau and found that convection strengthens in the afternoon and weakens in the early morning. Yanai and Li^[8] applied the satellite data during GAME/QXPMEEX to analyze the diurnal cycle of water vapor over the Plateau, and showed that cloud amount increases in the evening and night, but decreases from morning to noon. Wang et al.^[9] analyzed the summer season cloud variation over the Plateau with the infrared brightness temperature data from GMS-5 (Geostationary Meteorological Satellite-5), and reported that there are marked diurnal signals around the eastern edge, and the cloud amount usually gets its maximum from noon to evening. In terms of the data acquired in GAME, Kuwagata et al.^[10] showed that during the daytime, water vapor decreases in valleys, but increases in the ridge. On the basis of the Precipitation Radar data of TRMM, Bhatt and Makamura^[11] examined the diurnal cycle of precipitation over the Himalayas and surrounding areas. Their results suggested that daytime precipitation is concentrated on south-facing slopes, ridges and the areas with strong ridge-valley gradients, whereas the midnight-early-morning intense rainfall is concentrated in valleys. Using the hourly precipitation observations from 14 rain gauges in the Naqu Basin, Liu et al.^[12] analyzed the diurnal variation features over the central Plateau. The results displayed the remarkable diurnal rainfall, characteristics of a morning minimum and an evening maximum. Due to the limitation of rain gauges spatial coverage, however, all of the aforementioned studies did not address the diurnal variability over the entire Plateau, especially its peripheral regions, as well as the surrounding areas.

Because of poor observations over the Tibetan Plateau, none of the previous studies applied continuous high temporal resolution data for the investigation of diurnal variations of convection. What is the intensity of the diurnal cycle in precipitation over the Plateau? How the huge topography of the Plateau affects on

convective development? Whether are the highland's effects on convection comparable to tropical highlands, or sea-land interfaces? Therefore a systematic study is much needed on the diurnal variations, development and propagation of precipitation and convection systems over the Plateau, in addition to the topographical impacts on the weather and climate over China, as well as Eurasian Continent.

Aiming to inspect and measure the precipitation and energy exchange in tropical and sub-tropical regions, the TRMM meteorological satellite was launched in 1997 by NASA (National Aeronautical and Space Administration) of USA and NASDA (National Space Development Agency) of Japan. The Precipitation Radar and the TRMM Microwave Imager, main sensors on TRMM satellite, give a mass of high time-space scale resolution products, which provide us with detailed information to analyze the precipitation, lighting and cloudiness amount, and so on [13,14]. The TMPA (TRMM Multi-satellite Precipitation Analysis) product, with high resolution, long time continuity and high accuracy, can remedy deficiencies of rain gauge observations on the ground and make it possible to examine the diurnal variability of convection over the whole Plateau. This study is intended to analyze the diurnal features of precipitation during summer seasons over the Plateau and its neighboring areas using the high time-space resolution TMPA rainfall data. This systematic examination will build a basis for future numerical modeling and understanding of orographical and heterogeneous land-surface impacts on convection and precipitation.

2 DATASETS AND METHODS

2.1 Datasets

The 3B41RT rainfall data of TMPA product used in this paper are the precipitation estimate of infrared observation from GEO (Geostationary Earth Orbit), calibrated by the TRMM real time high-quality merged passive microwave precipitation measurement. This kind of data is designed to emulate the microwave results as closely as possible, so known deficiencies in the microwave will likely be reflected in the infrared as well [15]. Along with the high spatial resolution, the hourly temporal resolution can satisfy our requirement to analyze the diurnal variability of precipitation.

This product has a $0.25^\circ \times 0.25^\circ$ latitudinal and longitudinal resolution and hourly temporal resolution in a global belt from 60°S to 60°N . The product and its narration documents can be reached in website of <http://trmm.gsfc.nasa.gov/>. The domain in the present study is $7.5^\circ\text{S} \sim 42.5^\circ\text{N}$ in the meridional direction $67.5^\circ\text{E} \sim 122.5^\circ\text{E}$ in the zonal direction, covering the Eurasia continent and the Tibetan Plateau. This analysis focuses on all of the operational five available summer seasons, June through August for 2002~2006. Huffman et al. [15] have conducted an extensive validation, and showed that the diurnal variations from TMPA are quite similar to those from the data of NERN (North-American-Monsoon-Experiment Event Raingauge Network), which suggests that the TMPA data can capture the fundamental diurnal variability of convection in mid-latitudinal regions. The precipitation data of 643 meteorological sites (see Fig.1) provided by National Meteorological Information Centre of China are also used in our study to evaluate the TMPA precipitation data.

2.2 Methods

Two methods are adopted to quantify the diurnal characteristics of precipitation intensity and frequency.

2.2.1 Mean diurnal cycle of precipitation

We first examine the diurnal cycle of rainfall amount and frequency based upon the composite or averaged daily distribution of hourly time series during five summer seasons. According to Ref.[1], the mean diurnal cycle is expressed by the following equation:

$$\bar{R}(x, y, t) = \sum_{d=1}^{d=\text{day}} R(x, y, t, d) / \text{day},$$

where $R(x, y, t, d)$ is the hourly precipitation amount at t o'clock of one day ($t = 1, 2, \dots, 24$) at grid (x, y) , the day is the total number of days with observation data during five summers; $\bar{R}(x, y, t)$ is the averaged precipi-

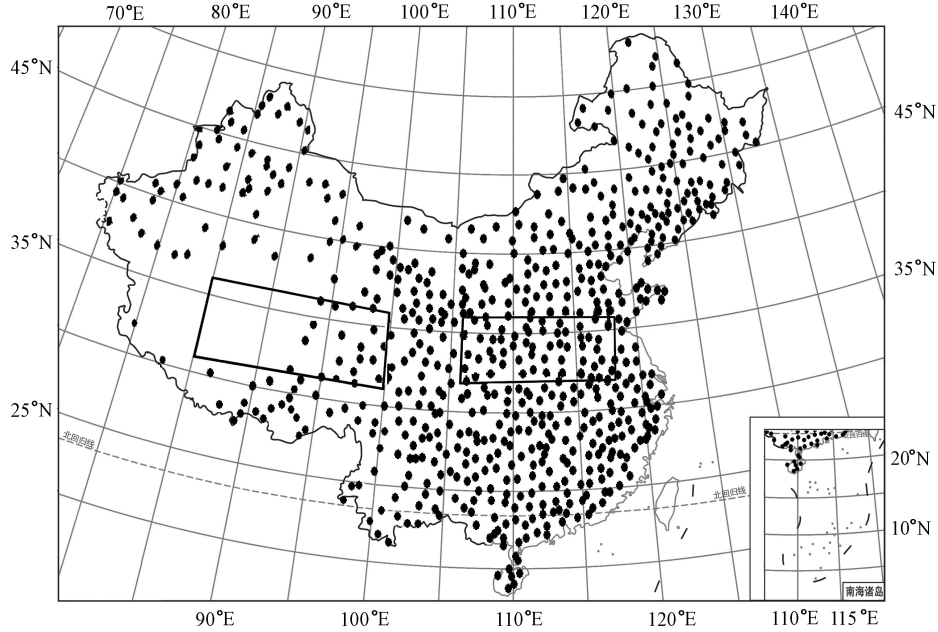


Fig. 1 Geographical locations of 643 meteorological stations in China Mainland
The frames in the left and right indicate the central Tibetan Plateau and the southern part of North China, respectively. See the text for details.

tation at t o'clock. The calculation for the mean diurnal cycle of frequency is similar to that of precipitation amount, but if the precipitation at t o'clock and grid (x, y) is more than 0.0 mm, $R(x, y, t, d)=1$, otherwise 0. By this method, the mean 24-hour time series of precipitation amount and frequency can be obtained at each grid point.

2.2.2 Harmonic analysis

Harmonic analysis is an effective way to capture the information of time series of precipitation amount and frequency. Through this method, the amplitude and phase of diurnal variation can be obtained, corresponding to the strength of diurnal variability and the timing of the maximum, respectively. The basic formula of harmonic analysis is

$$P = \bar{P} + \sum_{r=1}^{N/2} A_r \cos(r\theta - \Phi_r),$$

when r is truncated at 2, the formula is $P = \bar{P} + A_1 \cos(\theta - \Phi_1) + A_2 \cos(2\theta - \Phi_2)$, where P is the hourly precipitation amount or frequency, \bar{P} is the averaged 24-hour value, A_1 and A_2 are the amplitudes of diurnal cycle or semi-diurnal cycle, respectively, $A/\bar{P}/2$ is defined as the normalized amplitude, $\theta = 2\pi X/N$, where N is 24, and X is the hour of one day, Φ_1 and Φ_2 are the phases of diurnal or semi-diurnal cycle, namely the hours of the maximum. See Refs.[1] and [16] for the detailed Presentation.

3 PRECIPITATION FEATURES OVER THE PLATEAU AND DATA EVALUATION

3.1 Summer Precipitation Distribution

Summertime is the main rain season in Asia and also is the main precipitation season in the Tibetan Plateau. The multi-year averaged hourly precipitation (Fig. 2a) shows that the summer precipitation amount in the southern edge of the Plateau is significantly greater than that in other areas. Along the southern edge the mean hourly precipitation amount can reach about 0.3 mm and is about 0.1~0.3 mm in other southern areas. In the central and northern Plateau, however, the value is only about 0.1 mm. High precipitation frequency (Fig. 2b) appears near the southwestern edge and in the broad eastern Plateau, where rainfall occurs in more

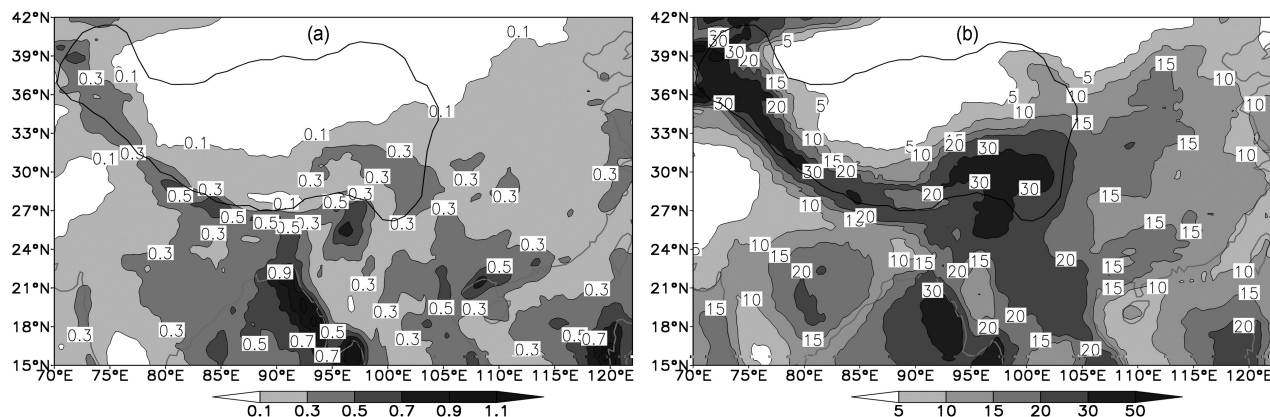


Fig. 2 Distributions of summer-mean hourly rainfall amount (a, unit: mm/h) and rainfall frequency (b, unit: %) in the summer season over the Tibetan Plateau and its nearby regions

The dark line represents the 2500 m terrain contour.

than 30% of the time. In contrast, the rain frequency is less than 5% in the central and northern part of the Plateau. For the whole domain, the precipitation amount and frequency get their maxima in the northwestern part of the Bay of Bengal and the southern slope of the Plateau.

3.2 Evaluation of the TMPA Data

Huffman et al.^[15] had tested the fidelity of the TMPA data with raingauge data in several regions and noted that the distribution of precipitation from TMPA is very similar to that from meteorological observations on the surface, even though there are some detailed difference. As a result, they believed that the TMPA data can be adopted for diurnal cycle studies. Although Huffman et al.^[15] have confirmed the applicability and fidelity of TMPA data in other mid-latitudinal areas, it is still necessary to check their applicability in China, especially over the Plateau. In the following, the long-term wet spell in 2003 in eastern part of Northwest China and North China is selected for the validation of the TMPA product.

This long-term rain episode in Shaanxi, Shanxi, Hebei and Shandong provinces persisted from 24 August to the first 10 days of September 2003. In this period the mid-lower reaches of the Yellow River suffered from the most serious flood since 1954, which caused huge economical losses in these regions. The comparison between the TMPA date and meteorological site observations during this multi-day period shows comparable rainfall areas south of 36°N on 28 August, and also similar locations of strong precipitation on 29 August (Fig. 3). Even though there are some discrepancies north of 35°N, the TMPA data reasonably capture the broad rainfall pattern in the upper reaches of the Yangtze River and mid-lower reaches of the Yellow River. The overall agreement demonstrates that the TMPA data can adequately display the observed precipitation features in the mid-latitudinal region, including the highland of the Plateau.

This long-term precipitation spell mainly occurred in the southern part of North China (32°N~36°N, 106°E~118°E). We chose 51 meteorological stations in this domain, and calculated the station-averaged daily precipitation, as well as the grid-averaged TMPA daily precipitation. As indicated in Fig. 4a, although the precipitation amounts from TMPA are somewhat weaker than the surface observations, the two time series exhibit similar temporal variations. This comparison illustrates that the TMPA product can roughly capture the observed rainfall intensity and evolution episode in the southern part of North China. However, surprisingly, large differences are present between the two datasets in the central Plateau (31°N~36°N, 85°E~100°E), where there are only 20 raingauge sites. The large differences likely result from the sparse meteorological sites which are not sufficiently representative of the true precipitation distribution over the Plateau. Huffman et al.^[15] have compared the daily precipitation variation from raingauge observations with the corresponding TMPA data result, and found that the quality of precipitation analysis highly relies on the density of sites. The more sparse the sites, the greater differences between the two products. Therefore, the high resolution TMPA data seem to

Fig. 3 Comparisons of rainfall amount (mm) over central and eastern China between surface meteorological site observations (left panels) and TMPA (right panels) on 28 August 2003 (upper panels) and 29 August 2003 (lower panels)

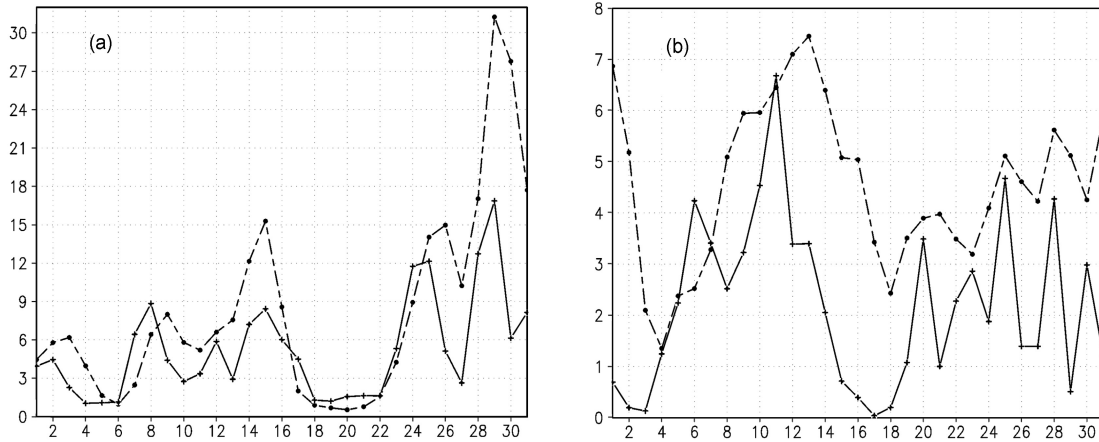


Fig. 4 Time series of daily rainfall (mm) in August 2003 over (a) southern part of North China and (b) the central Plateau

The solid and dashed lines correspond to TMPA and surface site observations, respectively. The X axis is date from August 1.

have desirable quality for the study of the diurnal cycle over the Tibetan Plateau. Additionally, besides of the diurnal variation of rainfall amount we will examine the diurnal variation in precipitation frequency, which has relatively less strict requirement for the precipitation data quality.

4 DIURNAL VARIATIONS OF PRECIPITATION OVER THE PLATEAU

4.1 Composite Analysis

The previous studies^[11~13] have revealed evident diurnal signals over the Plateau and nearby areas. Fig. 5a and 5c display the daily timing of the precipitation amount and frequency maximum derived from the mean diurnal cycles during the five seasons. It is readily seen that with an exception of the Plateau periphery, both rainfall intensity and frequency over the Plateau peak around 12~14 UTC, approximately equivalent to the evening of the local standard time (LST), in resemblance with the counterparts over the continent south to the Plateau. At the edges of the Plateau, especially along the eastern edge, the precipitation peaks between 20~24 UTC, roughly in the late night. In contrast, over the coastal water such as the Bay of Bengal, precipitation tends to peak at 02~06 UTC, namely in the morning. By and large, the maximum rainfall typically occurs at 10~14 UTC in East China.

Fig. 5 The time when the maximum of rainfall amount (left panels) and frequency (right panels) and minimum of rainfall amount (upper panels) frequency (lower panels) appear (unit: UTC)

The daily timing of the precipitation and frequency minimum (Fig. 5b and 5d) occurs at noon (around 04~08 UTC) for the Plateau and the southern continent, whereas an evening-early-night minimum (around 16~20 UTC) dominates over oceanic areas. A nocturnal minimum also appears in most regions east of the Plateau. These results demonstrate distinct difference in rainfall diurnal behaviors between ocean and land. Noticeably, the Plateau periphery and the eastern part of China share a similar minimum timing with ocean.

As an example, Fig. 6 presents the averaged daily evolution of precipitation amount and frequency, as well as the corresponding harmonic analysis over the central Plateau. The result shows that in the central Plateau the precipitation attains its minimum around the local noon, then increases in the afternoon, and eventually reaches the peak in the evening, subsequently followed by rapid weakening throughout nighttime till early morning. In our result the late-afternoon-evening preference of precipitation in the central Plateau is broadly consistent with the previous study by Liu et al.^[13], who reported that rainfall increases in the afternoon and peaks in the evening. At the same time, the dominant late-afternoon-evening convective activity over land largely consistent with the studies by Yang and Slingo^[2] and Wang et al.^[9]. The striking conclusion of the nocturnal maximum rainfall in the Sichuan Basin is very consist with the reality of rainfall in the late-evening.

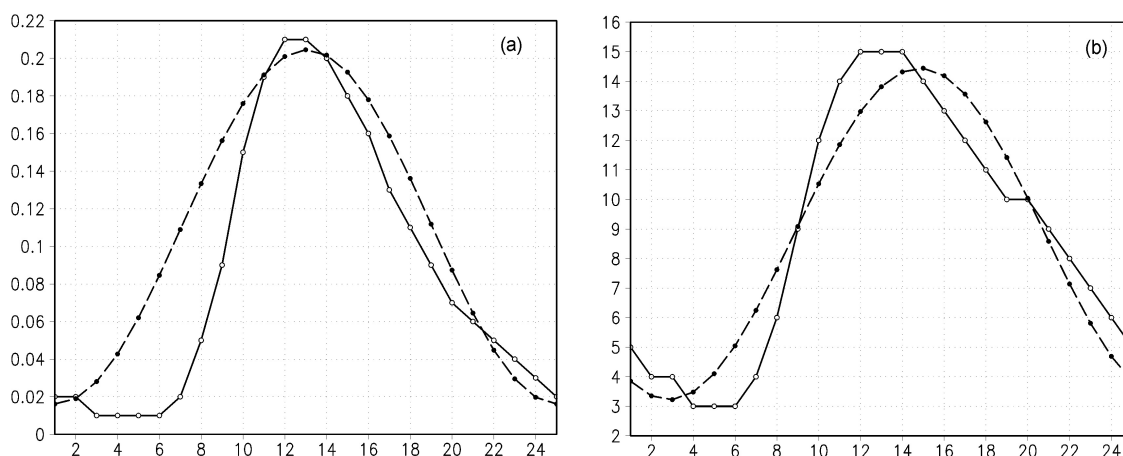


Fig. 6 Diurnal variations of precipitation amount (a, mm/h) and rainfall frequency (b, %) over the central Plateau

The solid and dashed lines correspond to the diurnal composite and the harmonic analysis, respectively.

4.2 Harmonic Analysis

To a certain extent, the amplitude of diurnal harmonic analysis is dependent on precipitation intensity. However, the harmonic amplitude normalized by the daily mean can better reflect the strength of diurnal signals and also take advantage of the regional comparisons. As evinced in Fig. 7a, the largest rainfall diurnal amplitudes appear in the sea-land interface, and the southern edge of the Plateau. Additionally, the stronger diurnal signal occurs in northwest of the Bay of Bengal and Indian Peninsula. For the most part, the continental diurnal variation is greater than the oceanic counterpart. In terms of the normalized amplitude (Fig. 7b), the most apparent diurnal variations are present in the central and eastern Plateau, and Indian Peninsula is in the next. Comparatively the weaker diurnal variations are in the western Plateau, most areas east and southeast of the Plateau. As a result, the remarked diurnal signals from the rainfall harmonic analysis are in resemblance with the studies of convective clouds by Zuidema^[6] and Wang et al.^[9].

The phases of the diurnal harmonic analysis in Fig. 7c stand for the hours of the maximum precipitation. Evidently, the maximum timing of diurnal cycle is geographically dependent. In the central Plateau, precipitation usually favorably occurs at 12~14 UTC, correspondent to a later-afternoon-evening maximum. In the neighborhood of the Plateau, rainfall is concentrated from the late night to the early morning. In East China, precipitation preferentially occurs around 08~12 UTC, namely the afternoon-evening hours. In contrast, an early-morning maximum is discernible over the Bay of Bengal and coastal region of the South China Sea. The most particularly interesting feature is progressively delayed precipitation maximum over the Plateau, characteristic of a late-night maximum in the Sichuan Basin and an early-morning maximum in the upper reaches of the Yangtze River, as well as an afternoon maximum in the mid-lower reaches. Similar phase coherence has been documented in the climatological study of summertime clouds by Wang et al.^[9].

The amplitude and phase of the diurnal harmonic analysis for rainfall frequency (Fig. 8) are generally comparable to the respective counterpart of precipitation intensity, and show a preferred late-afternoon-evening maximum over the Plateau. The largest amplitude of rainfall diurnal variation is over the southern and western Plateau. The normalized amplitude of rainfall frequency indicates that the strongest diurnal cycle is located in the central Plateau and Indian Peninsula. Prominent diurnal signals also appear in the Bay of Bengal and Indian Peninsula. In comparison, the amplitude of diurnal frequency is somewhat weaker than that of the precipitation amount.

4.3 Propagation of Diurnal Cycle

The phases in the foregoing diurnal harmonic analysis of both rainfall amount and frequency reveal a

coherent diurnal variation pattern associated with systematically delayed timing for the maxima downstream in several locations, such as the land-sea interface and areas around the Plateau periphery. The most remarkable example is in the eastern slope of the Plateau.

By zooming the phase of diurnal cycles in precipitation amount and frequency at the eastern leeside of the Plateau (Fig. 9), we can see that meridional-oriented constant phase lines spread out from the Plateau, indicative of a gradual phase lag toward the eastern Plateau. For example, along the latitude of 31°N, rainfall frequency peaks around 12~14 UTC at 100°E (near the Plateau periphery), about 22 UTC at 105°E (Sichuan Basin), and 08~10 UTC at 110°E. A similar coherent transition of cloudiness has been reported by Wang et al.^[9].

In order to further illustrate the propagating feature of diurnal signals in the eastern slope of the Plateau, Fig. 10 presents the time series of mean diurnal precipitation amount and frequency in 7 locations roughly along the zonal direction. Clearly, the diurnal evolution is characterized by progressively later rainfall and frequency peaks off the Plateau. The time of maximum precipitation ranges from 12 UTC to 00 UTC, with about 12 hour

difference between west and east. Note that some locations, such as points 2, 3, 4 and 7, have a double-peak pattern, suggestive of a semi-diurnal cycle of precipitation.

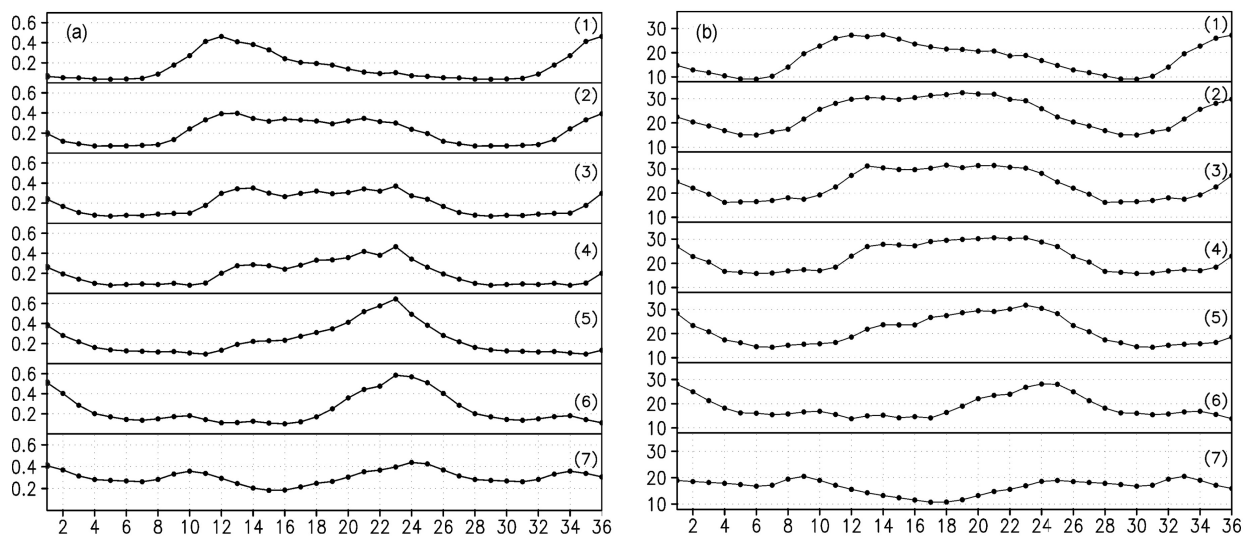


Fig. 10 Diurnal changes of rainfall amount (a, mm/h) and frequency (b, 100%) at seven sites from eastern Plateau to the lee of the Plateau (see Fig. 9a)

The phase transition between the Plateau, the slope, and the farther downstream suggests that convection tends to travel away from the Plateau and then causes gradually delayed precipitation toward the downstream as evinced by zonally-moving episodes in the meridionally-averaged rain rate diagrams.

On the basis of the phase of the diurnal harmonic analysis of rainfall amount and frequency in figure 9, the propagating signature has a speed of the order of 10 m/s, comparable to the zonal speed of coherent cloud signatures^[9]. This estimated diurnal rainfall propagation in the eastern of the Plateau is slower than the southeastward-translating cloud signatures over the Bay of Bengal^[2].

4.4 Semi-Diurnal Cycles

From both the normalized and non-normalized amplitude of the semi-diurnal harmonic in precipitation amount and frequency (not shown), it can be shown that the semi-diurnal signal over the Plateau is stronger than that in the surrounding areas, even though it is considerably weaker than the diurnal signal. On average, the amplitude of the semi-diurnal cycle in rainfall amount is roughly 50% of the diurnal amplitude, and the amplitude in frequency is less than 30% of the diurnal counterpart. By and large, the semi-diurnal variation is characteristic of a maximum between 01~03 UTC in the western Plateau and between 10~12 UTC in the central and eastern Plateau. As pointed out earlier, the semi-diurnal cycle of precipitation in east of the Plateau is clearly manifested by the dual peaks in the averaged 24-hour time series in Fig. 10.

5 CONCLUSIONS

The unique height and horizontal extents of the Tibetan Plateau as well as the complex landscape possibly result in a rich variety of precipitation. Herein, we focus on the diurnal features in rainfall amount and frequency using a new high temporal and spatial resolution rainfall dataset. The fidelity and applicability of the satellite-derived TMPA precipitation data over the Plateau and adjacent mid-latitude continent are quantified with available surface meteorological observations. The characteristics of precipitation diurnal cycle in summer over the Plateau are examined based on both the diurnal composite and harmonic analysis. The major conclusions are as follows.

(1) Strong diurnal variations are documented in both precipitation amount and frequency over the Plateau and surrounding areas, and the most significant signal is over the central Plateau and Indian Peninsula.

(2) The harmonic phase displays that the timing of the maximum precipitation amount and frequency has considerably geographical dependence. In the central Plateau the diurnal variation is broadly featured by a later-afternoon-evening maximum and a morning minimum, whereas a late-night maximum is prevalent around the Plateau and in the Sichuan Basin, and a morning and afternoon maximum appear in the upper and mid-lower reaches of the Yangtze River, respectively. On the whole, the distinct coherent diurnal patterns occur in those regions, characteristic of systematically delayed eastward-propagating signals in the downstream, causing significant nocturnal precipitation in the Sichuan Basin.

(3) In addition to the marked diurnal cycle, less significant semi-periodical diurnal cycles are also present over the Plateau. Overall, the semi-diurnal oscillation of precipitation is relatively more intensive in the Plateau than that in the neighboring regions.

These findings are generally consistent with the results documented in the earlier studies of diurnal cycles in cloud and precipitation over the Plateau and adjacent areas, and provide a basis for numerical modeling and exploration of underlying dynamical processes.

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