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Diurnal variations of summer precipitation over contiguous China

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[1] Diurnal variations of summer precipitation over contiguous China are studied using hourly rain-gauge data from 588 stations during 1991–2004. It is found that summer precipitation over contiguous China has large diurnal variations with considerable regional features. Over southern inland China and northeastern China summer precipitation peaks in the late afternoon, while over most of the Tibetan Plateau and its east periphery it peaks around midnight. The diurnal phase changes eastward along the Yangtze River Valley, with a midnight maximum in the upper valley, an early morning peak in the middle valley, and a late afternoon maximum in the lower valley. Summer precipitation over the region between the Yangtze and Yellow Rivers has two diurnal peaks: one in the early morning and another in the late afternoon.

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1. Introduction

[2] The diurnal cycle of precipitation is an important aspect of Earth's weather and climate. Previous analyses of surface [e.g., *Wallace*, 1975; *Higgins et al.*, 1996; *Dai et al.*, 1999; *Dai*, 2001] and satellite observations [e.g., *Yang and Slingo*, 2001; *Sorooshian et al.*, 2002; *Nesbitt and Zipser*, 2003] have shown large diurnal variations in warm-season precipitation with a maximum in later afternoon over most land areas, except for the central United States and a few other regions where the peak tends to occur in early morning. Downward propagation of atmospheric convective systems in the lee of high terrain is often associated with the morning peaks [*Carbone et al.*, 2002; *Wang et al.*, 2004]. Because of its large amplitude, coherent phase, and short-time scales, the diurnal variations of precipitation have also been used to evaluate cumulus parameterizations and other model physics in weather and climate models [e.g., *Dai et al.*, 1999; *Lin et al.*, 2000; *Davis et al.*, 2003; *Zhang*, 2003; *Liang et al.*, 2004; *Dai*, 2006].

[3] Most of the above-mentioned studies focused on the United States and the Tropics. Contiguous China occupies a large continental area over which satellite images of clouds show considerable diurnal variations [*Wang et al.*, 2004]. Surface weather reports [*Dai*, 2001] also show significant diurnal variations in precipitation frequency over the region. A few other studies also examined the diurnal variations in cloudiness and precipitation over East Asia [e.g., *Murakami*, 1983; *Kato et al.*, 1995; *Kurosaki and Kimura*, 2002; *Zhao et al.*, 2005]. Due to a lack of high-resolution precipitation data, however, a detailed picture of the diurnal cycle of precipitation over contiguous China has been unavailable. In this study, quality-controlled hourly rain-gauge records were used to quantify the diurnal variations of summer precipitation over contiguous China.

2. Data and Analysis Method

[4] In this study, hourly and daily rain gauge records during 1991–2004 from about 588 stations covering most contiguous China were analyzed to quantify diurnal variations of summer (June–August or JJA) precipitation. The hourly and daily rain-gauge data were obtained from the national climatic reference network and national weather surface network of China. Hourly precipitation was automatically recorded by siphon or tipping-bucket rain gauges, while daily precipitation was recorded by manual observations at 6 hour intervals. The rain-gauge data were collected and quality-controlled by the National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). The hourly rain-gauge data were subjected to a quality control that consists of two steps: an extreme check and an internal consistency check. The extreme check was based on the maximum of the daily precipitation series during the month. As the quality of the daily precipitation was well-controlled by the NMIC, all hourly rain-gauge data exceeding the monthly maximum of daily precipitation in the same period were rejected. The internal consistency check was used to identify erroneous data caused by incorrect units, reading, or data coding.

[5] The spatial distribution of the time when the maximum precipitation occurs is displayed to show the spatial feature of diurnal phase. Following *Dai et al.* [1999] and *Liang et al.* [2004], the time when the maximum precipitation occurs is represented by an arrow pointer on a circular 24-hours dial clock. The significance of the diurnal cycle is expressed qualitatively by comparing the amplitude to the daily mean using normalized amplitude.

[6] The diurnal variations of JJA precipitation will be discussed for the 1991–2004 mean condition. The diurnal analysis was done at each station. Note that the time used here refers to the local solar time (LST).

3. Spatial Distributions of JJA Precipitation Diurnal Phase and Amplitude

[7] Figure 1 shows the spatial distributions of the phase and amplitude (normalized by the daily mean) of the diurnal cycle of JJA precipitation by the arrows at each station and

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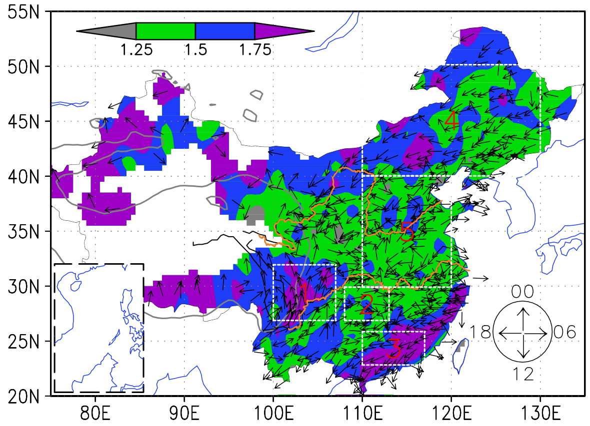

Figure 1. Spatial distributions of the phase and amplitude (normalized by the daily mean) of the 1991–2004 mean diurnal cycle of summer (June–August) hourly precipitation. Colors represent the normalized amplitude (i.e. in unit of daily mean) while unit vectors denote the local solar time (LST) of the maximum precipitation (phase clock). The solid grey line shows the 3000 m elevation contour line. The locations of the Yangtze River and Yellow River are drawn as orange lines. Five distinct regions are also labeled.

colors, respectively. The prevailing nocturnal maximum precipitation over eastern part of the Tibetan Plateau and Sichuan Basin (east to 100°E along 30°N) can be clearly identified, confirming previous studies [*Lu*, 1942; *Yeh and Gao*, 1979]. A late afternoon precipitation prevails in large part of southern China and in most northeastern China. A less coherent phase pattern is seen over the region between the Yangtze River and the Yellow River valley, which results from the two different peaks of precipitation corresponding to different prevailing precipitation systems (see next section). In addition, Figure 1 shows a clockwise diurnal phase evolution in the south of the upper and middle Yangtze River valley, which links the diurnal behaviors in the southern inland China and upper-middle Yangtze River valley together.

[8] The spatial distribution of the amplitude reveals significant diurnal variations over contiguous China. In almost all of the stations (546 over 588), the normalized amplitude is larger than 25%. There are 271 out of 588 stations having the normalized amplitude larger than 50% and 108 out of the 588 stations larger than 75%.

4. Distinctive Regional Aspects of the Diurnal Precipitation Cycle

[9] To reveal the detailed regional features, Figure 2 shows the diurnal cycle of JJA precipitation averaged over five different regions as outlined in Figure 1 by the dashed rectangles.

[10] For the eastern periphery of the Tibetan Plateau and the upper reaches of the Yangtze River valley (27°–32°N, 100°–107°E), the mean precipitation diurnal cycle (Figure 2a) shows a harmonic sinusoidal evolution with the maximum around midnight and the minimum around noon time. The feature of the precipitation diurnal cycle over the eastern Tibetan Plateau is similar to that in Region 1 (figure not shown). The diurnal cycle averaged over Region 2 (27°–30°N, 108°–113°E), i.e., the middle reaches of the Yangtze River valley, shows an early morning maximum around 0600 LST (Figure 2b). Both South (23°–26°N, 110°–117°E) and Northeast (40°–50°N, 110°–130°E) China has late afternoon maxima (Figures 2c and 2d). The diurnal cycle averaged over the domain between the Yangtze River valley and the Yellow River valley (30°–40°N, 110°–120°E) is shown in Figure 2e. As mentioned above, no coherent phase pattern is found in Figure 1 over this region. This is due to the two comparable peaks, with one in the early morning and the other in the late afternoon.

[11] Figure 3a shows a time-longitude cross section of the meridionally (27°–29°N) averaged hourly precipitation percentage relative to the daily total rainfall amount, and Figure 3b shows the corresponding result of the zonally (110°–130°E) averaged precipitation. An eastward transition of the nocturnal maximum over the eastern periphery of the Tibetan Plateau to the later afternoon peak over the lower reaches of the Yangtze River valley is evident in Figure 3a. This suggests that the maximum precipitation occurs at different local times along the Yangtze River, with a nocturnal maximum in the upper valley, an early morning peak in the middle valley, and a later afternoon maximum in the lower valley. This phase transition implies an eastward propagation of convective systems initiated over the east periphery of the Tibetan Plateau. Case analyses, however, indicate that nocturnal heavy rainfall in the upper valley is not always followed by an early morning heavy rainfall in the middle valley, while an early morning heavy rainfall in the middle valley does not always suggest that a nocturnal heavy rainfall has already happened in the upper valley. For

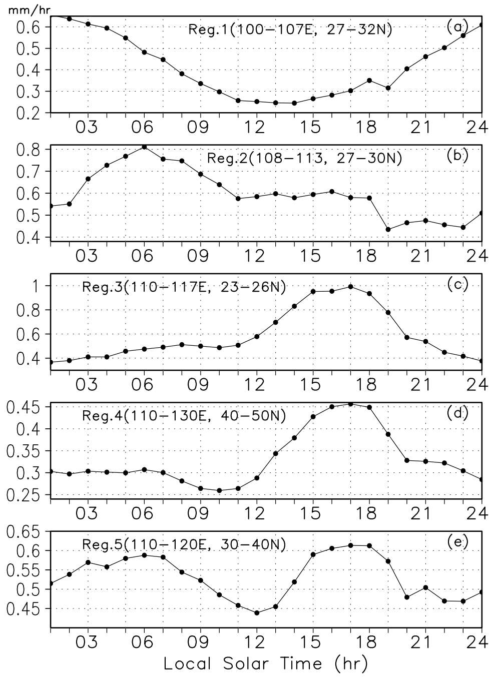

Figure 2. Diurnal variations of the 1991–2004 mean summer precipitation averaged over the five regions marked in Figure 1. The horizontal axis corresponds to the local solar time and the units of vertical axis are mm/hour.

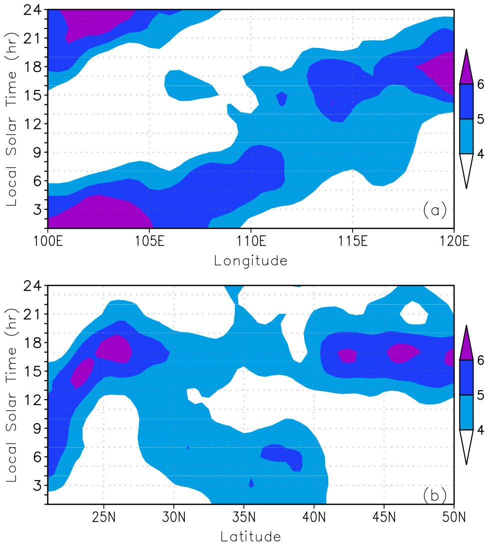

Figure 3. Hovmöller diagrams of mean diurnal variations in hourly precipitation percentage relative to the daily total rainfall amount (in unit of %). (a) Time-longitude cross section for the 27°–29°N zone. (b) Time-latitude cross section averaged over 110°–130°E. The vertical axis is local solar time in hours.

example, observations indicate that there were nine midnight heavy rainfall events over the Sichuan basin (located in the east periphery of the Tibetan Plateau) during August 2003, which occurred on 2, 3, 9, 10, 21, 22, 26, 29, and 30 August, respectively. These upper valley nocturnal heavy rainfall events were not always followed by early morning heavy rainfall events in the middle valley (figures not shown). During 20–21 July 1998, Wuhan (located in the middle valley of the Yangtze River valley) had an early morning heavy rainfall; which occurred at 7am (Beijing time) with an intensity of more than 80mm/hr, however, no preceding nocturnal heavy rainfall was observed in the upper valley, indicating it is a local convection. Further investigations are needed on this phase change.

[12] Analyzing hourly infrared (IR) brightness temperatures observed by the Geostationary Meteorological Satellite in May–August 1998–2001, *Wang et al.* [2004] found that convection is most active near the eastern edge of the Tibetan Plateau, with a clear diurnal peak in late afternoon and early morning, and some of these systems propagate eastward across East Asia. The propagation was strongest in May–June and almost ceased in July–August. This is somewhat different from the nocturnal maximum summer precipitation on the leeside of the Tibetan Plateau revealed by the rain-gauge data. According to *Wang et al.* [2004] and *Dai* [2006], this difference is not unexpected as the IR brightness temperature is a measure of cold cloud tops and does not always indicate active deep convection.

[13] Figure 3b presents vivid contrasts of the precipitation diurnal behaviors over the regions from the southern China to the northeastern China. In southern inland China and northeastern China, the diurnal cycle is dominated by a late afternoon maximum. But in the central East China between 30°–40°N, the precipitation diurnal variation exhibits two peaks, one in the late afternoon and the other occurs in the early morning, as shown in Figure 2e.

5. Summary and Discussions

[14] The diurnal cycle of summer precipitation over contiguous China is investigated using hourly rain-gauge data from 588 stations during 1991–2004. The results reveal some interesting spatio-temporal features, which can be used to evaluate numerical models. The results show a midnight maximum over the eastern part of the Tibetan Plateau and the upper-middle Yangtze River valley. The southern inland China and northeastern China have late afternoon maxima of rainfall. The diurnal cycle of summer precipitation over the middle-eastern China between the Yangtze River and the Yellow River valley is characterized by two comparable peaks. Along the Yangtze River valley around 30°N, the diurnal phase shows a coherent eastward transition from the midnight maximum in the eastern periphery of the Tibetan Plateau, to the near-dawn or early morning precipitation maximum in the middle valley and the late afternoon maximum in the lower Yangtze River valley.

[15] The late afternoon maximum can be explained by surface solar heating, which results in maximum low-level atmospheric instability and thus moist convection in the afternoon. Prevailing nocturnal precipitation over the eastern Tibetan Plateau and its eastern periphery was discussed previously [e.g., *Yeh and Gao*, 1979; *Zeng et al.*, 1994; *Kurosaki and Kimura*, 2002], but the underlying mechanisms remain unclear. The nocturnal maximum may result from the diurnal variation of local circulation forced by the complex terrain. For example, diurnal cycle in zonal winds along the eastern slopes of the Tibetan Plateau could induce diurnal variations in large-scale vertical motion, which in turn could trigger or suppress deep convection [*Zeng et al.*, 1994; *Yu et al.*, 2004; *Li et al.*, 2005]. But a detail analysis of the mechanism is out of the scope of this study. Addition work is needed to understand the midnight maximum and its downstream phase transition.

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