Why Nocturnal Long-Duration Rainfall Presents an Eastward-Delayed Diurnal Phase of Rainfall down the Yangtze River Valley

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ABSTRACT

Hourly observational records and 6-hourly reanalysis data were used to investigate the influences of large-scale forcings on the diurnal variation of summer rainfall along the Yangtze River (YR). The results show that long-duration (more than six hours) rainfall events dominate the summer rainfall along the YR. These events tend to start during the night and to peak after several hours of development. The eastward-delayed initiation of the nocturnal long-duration rainfall events is thought to be due to the diurnal clockwise rotation of the low-tropospheric circulation, especially the accelerated nocturnal southwesterlies. In the early evening, the anomalous easterly flow toward the Tibetan Plateau (TP) causes low-level convergence over the Plateau’s eastern slope that induces the formation of rainfall in the upper YR valley. The anomalous wind sequentially rotates clockwise to a southerly flow at midnight and accelerates the meridional wind in the middle valley, resulting in the initiation of rainfall between 2300 and 0300 LST. In the early morning, the accelerated southwesterlies in southern China, when combined with decelerated winds in the north of the YR, causes a strong convergence along the YR and contributes to the early morning rainfall in the lower valley. Furthermore, the development of the convection systems is suppressed in the afternoon by the mid- and low-level warm advection downstream from the TP. This helps explain why long-duration events do not typically start in the afternoon in the upper YR valley.

1. Introduction

The diurnal cycle of precipitation is an important aspect of regional climate, because the regular occurrence of precipitation at a particular time of the day is connected with both regional and large-scale dynamical and thermal conditions (Sorooshian et al. 2002). Observational studies have demonstrated a distinctive geographical pattern of diurnal variation for precipitation during summer over contiguous China (Yu et al. 2007b). The unique nocturnal rainfall peak along the Yangtze River (YR; located at 27°–33°N, 100°–120°E, see the southern dark gray line in Fig. 1) is in contrast to the afternoon
The nocturnal rainfall downstream of the Tibetan Plateau (TP) has been recognized long before (Lu 1942; Ye and Gao 1979; Zeng et al. 1994), but the physical mechanisms involved are still not clearly understood. Based on the analyses of the nocturnal rainfall in tropical islands or North America, numerous studies have stated that the midnight–early morning rainfall maxima in land areas may be linked to the local effects, such as complex terrain and sea-breeze circulations (Oki and Musiake 1994; Yang and Slingo 2001), the interaction of mountain or land breezes with the prevailing wind (Ohsawa et al. 2001), or the long, nocturnal life cycle of mesoscale convective systems (Wallace 1975; Dai et al. 1999; Nesbitt and Zipser 2003). However, according to Yu et al. (2007a), long-duration rainfall events dominate the summer rainfall along the YR; therefore, the local effects may not adequately explain the nocturnal long-duration rain, which is closely related to the systematical rain affected by large-scale forcings (Chen 1983). The intimately coupled monsoon systems, especially the southwesterly low-level jet (LLJ), are crucial factors for maintaining the rainfall along the YR (Chen and Li 1995; Wang et al. 2000; Ding et al. 2001). As raised by Sperber and Yasunari (2006), the LLJ is of paramount importance for the monsoon precipitation, not only because it transports humidity, but also because it is related to numerous processes ranging from turbulence up to synoptic scales. Based on the intensive observations in 1998–99 mei-yu periods, Li et al. (2007) found that the enhanced transport of warm and moist air by LLJ at night may induce the nocturnal-type cloud clusters over eastern China. Recently, Yu et al. (2009) analyzed the diurnal cycle of surface winds over central eastern China and described the evident diurnal variation of wind at mountain stations. These mountain stations are all above 1200 m, and their averaged height is 1669 m. They suggested that the accelerated wind from midnight to early morning may imply the acceleration of nocturnal LLJ, which contributes to the morning peak of long-duration rainfall events. Further research into the influences of LLJ on the diurnal variation of rainfall should help to clarify the mechanisms responsible for summer nocturnal rainfall along the YR.

The eastward diurnal phase delay of summer rainfall is also a vivid characteristic along the YR (Yu et al. 2007b). Similar phenomenon has been reported over the U.S. Great Plains (GP), and a number of studies attribute it to the eastward propagation of convection systems from the upstream Rockies Mountains to the GP (Riley et al. 1987; Carbone et al. 2002; Jiang et al. 2006; Chen et al. 2009). By analyzing 4-yr hourly infrared brightness temperatures from the Geostationary Meteorological Satellite, Wang et al. (2004) found some convection systems propagate eastward from the eastern edge of the TP to downstream in May–June, and the propagation is almost ceased in July–August. Nevertheless, the IR brightness temperature is a measure of cold cloud tops and does not always represent active deep convection (Dai 2006), and the eastward diurnal phase delay still occurs in the July–August rainfall. Yu et al. (2007b) also mentioned that nocturnal rainfall in the upper valley of YR does not always follow an early
morning rainfall event in the middle valley, while early morning rainfall in the middle valley does not always suggest a preceding upstream night rainfall. Therefore, the downstream phase transition cannot be fully regarded as the eastward propagation of convection systems, and its image remains obscure to some extent.

In this study, our attention is devoted to the impacts of large-scale circulation on the nocturnal long-duration rainfall events along the YR. We mainly address the following two questions: (1) why the long-duration rainfall events tend to initialize and develop at nocturnal hours along the YR, and (2) why there is an eastward phase transition of the nocturnal long-duration rain. Our results show that the nocturnal rainfall and its eastward phase delay along the YR is significantly contributed by diurnal clockwise rotation of low-level wind. The mid- and low-level warm advection from the TP in the afternoon may also play important roles.

The rest of the paper is organized as follows: section 2 describes the datasets and analysis methods. The detailed diurnal characteristics of long-duration rain are presented in section 3. The influences of large-scale circulation on the diurnal features of long-duration rain are analyzed in section 4. Section 5 discusses the possible roles of thermal advection from the upstream TP. The summary and concluding remarks are given in section 6.

2. Data and analysis methods

a. Data description

The quality-controlled hourly and daily rain gauge records between 1991 and 2004 are obtained from the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). These records include about 626 stations covering most of contiguous China (Yu et al. 2007b). Because the precipitation over most of China mainly occurs from June to August (JJA; Tao and Chen 1987; Zhou and Yu 2005), and the diurnal cycle is strongest in summer (Dai et al. 2007); therefore, we will focus on the JJA season.

To investigate the role of large-scale forcings in the diurnal cycle of long-duration rainfall events, the 6-hourly reanalysis data taken from the cooperative research project of long-term reanalysis [Japanese 25-yr Reanalysis Project (JRA25)] by the Japan Meteorological Agency (JMA) and the Central Research Institute of Electric Power Industry (CRIEPI) are used in this study. The dataset has a spectral resolution of T106 (about 120 km) and 40 vertical layers, with the top level at 0.4 hPa. Detailed information on the JRA25 data can be found in Onogi et al. (2007). Similar analyses have been performed by the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) and the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis, and the results are similar to those of JRA25. Thus, only the results of JRA25 are shown later for its relatively higher resolution. Hourly wind records at seven mountain stations and 12-hourly wind records at 124 radiosonde stations over China are also applied. Moreover, the cloud-top pressure from the International Satellite Cloud Climatology Project (ISCCP) products (Rossow and Schiffer 1991, 1999) from 1991 to 2004 is adopted.

b. Analysis methods

The hourly rainfall events, defined as the ones with more than 0.1-mm precipitation accumulation during one hour, are classified according to their continuous durations, without any intermittence or at most 1-h intermittence during a single rainfall event (Yu et al. 2007a). The hours between the start and the end of every event are defined as the duration. In this study, we give emphasis to the long-duration rainfall events (an event lasts more than six hours), which account for more than 60% of total rainfall along the YR (Yu et al. 2007a). The hourly rainfall is normalized by the daily mean for a better comparison between the long-duration rain and the total rainfall. Because the time at which a rainfall event starts represents the initial conditions of a rainfall event, the starting times of long-duration rainfall events are also examined in this study. If a rainfall event starts at hour \(i\), it means that there are at least two hours intermittence before the hour \(i\), while the rainfall amount is greater than 0.1 mm at the hour \(i\). The starting hours of all long-duration rainfall events are counted in a 24-h cycle at each station. The hour \(i\) corresponding to the maximum number is considered as the most frequent starting hour. Similar calculations are also performed on the diurnal phase to obtain the most frequent peaking hour at each station.

3. Diurnal features of long-duration rain along the YR

The long-duration rainfall events remarkably contribute to the midnight–early morning diurnal rainfall peaks along the YR, whereas the short-duration rainfall shows an afternoon peak with no evident regional differences (Yu et al. 2007a). The percentage of accumulated nocturnal rainfall amount to total amount of summertime rainfall is shown in Fig. 1a. More than 50% of the total amount occurs in the nocturnal hours over most of central eastern China (Fig. 1a). Especially in the
upper and middle valleys of YR (100°–110°E), nocturnal rainfall contributes more than 60% of the cumulative rainfall amount. The center of percentage distribution (more than 65%) locates in the eastern slope of the TP, mainly because both short- and long-duration rainfall have a nocturnal peak in this region (Li et al. 2008). The relative small percent (about 55%) in the lower valley corresponds to the notable semidiurnal cycle (Yu et al. 2007b). Although long-duration rainfall events are taken into consideration, widespread large values appear along the YR (Fig. 1b). More than 65% of nocturnal rainfall comes from long-duration rain over this region. Comparing Fig. 1a with Fig. 1b reveals that the nocturnal rainfall, which is dominated by long-duration rain, significantly contributes to the summer rainfall along the YR.

In addition to the prominent nocturnal feature, the diurnal peak of summer rainfall displays an eastward phase transition along the YR (Yu et al. 2007b). Here, the spatial phase transition is examined in terms of rainfall duration. Figure 2 shows the Hovmöller diagrams of normalized (using the daily mean) rainfall diurnal variation averaged between 27° and 33°N. The summertime rainfall peaks late at night in the upper valley of the YR and about six hours later in the middle valley (Fig. 2a), which is consistent with previous studies (Yu et al. 2007b; Zhou et al. 2008). An eastward delay is obvious in long-duration rainfall events (Fig. 2b), suggesting that the diurnal phase delay is mainly caused by long-duration rain. Meanwhile, the phase transition of total rainfall is not evident over the regions east of 110°E, whereas it is more continuous for long-duration rainfall events from the upper to lower valleys.

The previous results demonstrate the dominance of long-duration rainfall events in determining the distinct diurnal features of summer rainfall along the YR. Besides the characteristics of nocturnal rainfall with eastward phase transition, another key factor concerning the diurnal features is the starting time. The peak time of a rainfall event may be associated with external forcings, as well as the development of the rainfall system itself, while the starting time is more suitable to represent the trigger conditions caused by forcings. To resolve the spatial distribution of the initiation hour and its relationship with diurnal phase, the most frequent starting and peaking hours of the long-duration rainfall events are displayed in Fig. 3. The preferred starting time shows an eastward delay, as that of the diurnal phase (Yu et al. 2007b), in agreement with the hypothesis that several hours of development is necessary before long-duration rainfall events peak (Yu et al. 2007a). In the upper valley of the YR (100°–105°E), the long-duration rain prefers to start in the early evening (1800–2200 LST, Fig. 3) at 17 stations (73.9% of 23 stations) and peak after more than three hours from midnight to late night (2300–0300 LST) at 16 stations (69.6%). In the middle valley (105°–110°E), the long-duration rain tends to start at midnight (2300–0300 LST) at 25 stations (78.1% of 32 stations) and peak in the early morning (0300–0700 LST) at 24 stations. In the lower valley (110°–120°E), the long-duration rain is apt to start between late night and early morning (0100–0800 LST) at 51 of 75 stations (68%) and peak in the morning (0600–1000 LST) at 42 stations, however, with less coherent distribution. To further examine the significance level of the maximum hours of the start and peak of long-duration rain, the regional mean percentages of the most frequent starting and peak hours are calculated. Results indicate that most of the starting and peak hours of long-rainfall cases occur around the maximum hours, especially in the upper and middle valleys. In the upper valley, 50.6% of the long-duration events start between 1700 and 2300 LST, with the maxima percentage (larger than 10%) at 2000 LST. The most frequent peak hour occurs at 0100 LST, five hours later than that of the starting time. In the middle valley, 43.7% (47.1%) of the long-duration events start (peak) during 2200–0400 (0200–0800 LST), and in the lower valley, 41.9% (35.2%) of the long-duration events start (peak) during 0000–0800 (0500–1100 LST).
The wind records at mountain stations are useful indicators for tropospheric low-level wind (Yu et al. 2009). To quantitatively reveal the relationship between 850-hPa wind and wind records at mountain stations, the 6-hourly 850-hPa winds around the location of mountain stations within a radius of 1.25° are averaged at each reanalysis slice in 1288 summer days during 1991–2004. The correlation coefficients are then calculated between the 850-hPa wind and station records. The calculation results are insensitive to the radius selected. As shown in Table 1, the zonal wind, meridional wind, and the wind speed between mountain station records and corresponding 850-hPa winds are all significantly correlated, with no evident differences among the four reanalysis time slices. The correlation coefficients are relatively small in the two westernmost stations, but they are still highly above the 1% significance level.

To further validate the reliability of the JRA25 data in analyzing the diurnal changes of low-level circulation, the JJA mean 850-hPa wind in JRA25 is compared with 12-hourly wind records observed at radiosonde stations. As shown in Fig. 4, the southwesterly dominates southern China in all three datasets, indicating the prevailing

### Table 1. The correlation coefficients of the zonal wind $u$, meridional wind $v$, and wind speed $s$ between wind records at mountain stations and 850-hPa wind in JRA25 at each reanalysis time slice in 1288 summer days during 1991–2004. The first three rows indicate the location and height of seven mountain stations.

| Lon (°E) | 117.10 | 110.08 | 110.23 | 119.41 | 118.15 | 112.70 | 118.10 |
| Lat (°N) | 36.50  | 34.48  | 30.78  | 30.35  | 30.13  | 27.30  | 25.72  |
| Height (m) | 1533.7 | 2064.9 | 1819.3 | 1505.9 | 1840.4 | 1265.9 | 1653.5 |
| 0200 BJT | $u$ 0.64 | 0.44  | 0.80  | 0.75  | 0.77  | 0.73  | 0.84  |
| | $v$ 0.71 | 0.54  | 0.48  | 0.48  | 0.73  | 0.70  | 0.82  |
| | $s$ 0.52 | 0.51  | 0.46  | 0.56  | 0.75  | 0.75  | 0.80  |
| 0800 BJT | $u$ 0.73 | 0.54  | 0.83  | 0.82  | 0.81  | 0.75  | 0.84  |
| | $v$ 0.80 | 0.49  | 0.59  | 0.59  | 0.79  | 0.71  | 0.87  |
| | $s$ 0.66 | 0.48  | 0.51  | 0.68  | 0.83  | 0.83  | 0.82  |
| 1400 BJT | $u$ 0.70 | 0.48  | 0.74  | 0.71  | 0.74  | 0.66  | 0.72  |
| | $v$ 0.67 | 0.58  | 0.36  | 0.55  | 0.69  | 0.66  | 0.80  |
| | $s$ 0.58 | 0.53  | 0.38  | 0.66  | 0.75  | 0.70  | 0.75  |
| 2000 BJT | $u$ 0.71 | 0.50  | 0.77  | 0.79  | 0.77  | 0.61  | 0.83  |
| | $v$ 0.72 | 0.59  | 0.39  | 0.57  | 0.76  | 0.72  | 0.85  |
| | $s$ 0.54 | 0.47  | 0.34  | 0.62  | 0.72  | 0.67  | 0.80  |
monsoon flow in summer. The southwesterlies shift westward from the morning to the evening. This feature is evident in both of the datasets. Because of the significant resemblance between wind records observed at stations and the reanalysis of 850-hPa wind fields, we employ the hourly wind records at mountain stations to reveal the diurnal evolution and the reanalysis data to resolve the spatial distribution. Since only 6-hourly reanalysis data are available, Beijing time (BJT; local time at 120°E) is used instead of LST in the following for a better comparison between station data and the reanalysis.

The analyses in section 3 demonstrated the fundamental roles of long-duration rain in determining the diurnal features of summer rainfall along the YR. As indicated by previous studies (e.g., Chen 1983; Chen and Li 1995; Ding et al. 2001), the long-duration rainfall events tend to develop in the synoptic- or large-scale disturbances. Contrarily, the short-duration rainfall events usually result from local convection, thunderstorms, and other such mesoscale phenomena, which are not necessarily related to large-scale circulation or organized convection. Therefore, we will focus on the large-scale low-level circulation in long-duration rainfall days. To facilitate analyzing the influences of the large-scale forcings on nocturnal long-duration rain, the days when nocturnal (2000–0800 LST) long-duration rainfall events start along the YR (27°–33°N, 100°–120°E) are selected for composite analyses. The results are insensitive to the region selected (figures not shown). There are 130 stations in the target region. The days when nocturnal long-duration events occur at least at 10% of the stations are defined as long-duration rainfall days. This criterion resulted in 396 of 1288 days being chosen during the 1991–2004 summers. The large-scale circulation and thermal condition on long-duration rainfall days are synthesized.

To investigate the diurnal wind evolution on long-duration rainfall days, Fig. 5 shows the JJA mean wind vectors and the diurnal variation of composite wind anomalies at 3-h intervals at seven mountain stations. The wind anomaly is defined as deviations at each hour relative to the daily mean. The composite wind speed in long-duration rainfall days is larger than that of the climatological mean at the four mountain stations in southeastern China, whereas it is much smaller at the two stations north of the YR. The enhanced
southerly over the south of the YR implies the preferred occurrences of LLJ in the long-duration rain days. The anomalous winds exhibit large diurnal variation and the amplitude reaches more than 1 m s$^{-1}$. The anomalous wind vectors generally rotate clockwise during the day. The westward component increases from the afternoon to early evening. At 2000 BJT, the wind anomaly blows to the TP at most mountain stations. The southerly anomalies at midnight (0200 BJT) enhance the mean low-level wind at the five stations south of YR, which favors the formation of nocturnal LLJ. At 0800 BJT, the southerly is still evident at the two southernmost stations, whereas the northerly appears at northern stations.

The homodromous composite mean southerly and anomalous wind vectors during midnight to early morning at the southern mountain stations imply the preferred nocturnal occurrences of LLJ. To resolve the spatial distribution of an enhanced southerly on long-duration rainfall days, the composite low-level wind reanalysis is shown in Fig. 6. The southerly prevails over southeastern China on the long-duration rainfall days, consistent with that of the composite anomalous wind at mountain stations (Fig. 5). A cyclonic circulation locates west of 110°E and a shear line lies along the YR. The combination of the southwest vortex and the shear line, as well as the low-level convergence of the warm tropical water vapor with the cold subtropical water vapor, provides a favorable environment to maintain the rainfall systems along the YR (Tao and Chen 1987; Zhou and Yu 2005). The accelerated southerly contributes to the formation of the LLJ. Because the LLJ occurs over various locations among different cases, the climatic mean wind speeds shown in Fig. 6 are much weaker than that defined as LLJ. However, some case studies indicate that in southern China, the low-level wind speed exceeds 12 m s$^{-1}$ from midnight to early morning with maxima at 850 or 700 hPa in long-duration days (figures not shown). Therefore, in the following analyses, the region controlled by the accelerated southerly in long-duration rainfall days is selected to represent the region where LLJ prefers to occur (referred to as the LLJ region in following description).

The synthesis of analyses presented previously demonstrates that the long-duration rainfall events are closely associated with the enhanced southerly in a climatic mean state. What is the relationship between the southerly and long-duration rainfall event in a diurnal time scale? To examine the roles of the low-level southerly in initializing nocturnal long-duration rain, the 850-hPa wind anomalies (relative to daily mean), averaged at four reanalysis time slices, are displayed in Figs. 7a–10a, respectively. As low-level wind has been found to develop prior to the heavy rain event (Chen and Yu 1988; Chen and Li 1995), we also show the normalized long-duration rainfall amount averaged in the subsequent six hours, relative to the reanalysis time slices. The rainfall amount is normalized by a daily mean for better comparison. To quantitatively examine the diurnal variation of the low-level southerly, the anomalous wind is projected to the composite wind, averaged over the selected LLJ region (Fig. 6). Assuming that $\mathbf{V}$ and $\mathbf{V}'$ denote the regionally averaged wind vector and anomalous wind vectors, respectively, the projected field is defined as $(\mathbf{V}' \cdot \mathbf{V})/|\mathbf{V}|$ and is shown in Figs. 7b–10b. The composite anomalous zonal circulations averaged between 27° and 33°N are displayed in Figs. 7c–10c, whereas vertical velocity averaged between 850 and 700 hPa and the anomalous low-level divergence are shown in Figs. 7d–10d, respectively. Note that the zonal and meridional wind at the sixth model level (approximately equivalent to 882.44 hPa) are used to calculate the low-level divergence to reduce the biases.

Generally, the diurnal evolution of 850-hPa wind anomalies exhibits a close resemblance to that at mountain stations. In the early evening (2000 BJT), a coherent easterly anomaly dominates most of central eastern China (Fig. 7a), and during evening–midnight (2000–0200 BJT) the rainfall anomaly locates in the upper valley. The negative-projected values over most of central eastern China stand for the anomalous wind opposite to the prevailing southerly in the early evening (Fig. 7b), suggesting a suppressed phase of the southerly over the LLJ region. The westward wind
resulting from the low-level convergence and the strong upflow in the eastern slope of the TP (Figs. 7c,d) is caused by the westward low-level flow. As a result, the long-duration rain prefers to start in early evening at most stations in the upper YR valley, and then the daily rainfall maxima occur at midnight after several hours of development (Fig. 3).

At midnight (0200 BJT), the anomalous wind rotates clockwise about 90°. The anomalous southerly and southwesterly prevails the region west of 110°E and north of the YR (Fig. 8a), where the low-level wind is accelerated (Fig. 8b). The accelerated southerly not only causes low-level convergence (Fig. 8d) but also favors the transport of warm and moist air from the lower latitude (Zhou and Yu 2005; Li et al. 2007). Both of them contribute to the frequent midnight starting rainfall events in the middle YR valley. Consequently, the midnight–morning (0200–0800 BJT) rainfall mainly locates in the mid valley of the YR (Fig. 8a). The rainfall anomaly also exists in the region east of 110°E, especially over the north of the YR. This partly explains the less coherent pattern of preferred starting times and the discontinuity of the eastward phase transition in the region east of 110°E. A low-level ascending motion exists between 105° and 110°E (Figs. 8c,d), whereas the downward movement controls most regions along the YR.

In the early morning (0800 BJT), the southwesterly anomaly dominates the region south of the YR, whereas the northeasterly anomaly prevails over the region north of YR (Fig. 9a). The southwesterly anomaly contributes to the acceleration of the low-level southwesterly in southeastern China (Fig. 9b). The enhancement of the moisture transport by the southwesterly (Li et al. 2007), combined with strong convergence caused by the asymmetric rotation of anomalous wind along the YR (Fig. 9d), provides a favorable environment for the occurrences of long-duration rain. Accordingly, the anomalous rainfall from morning to noon (0800–1400 BJT) lies in the LLJ region. The anomalous upward motion, which locates east of 110°E (Figs. 9c,d), is also in accordance with the

![Composite JJA mean of 850-hPa zonal and meridional wind anomalies (vectors; m s⁻¹) at 2000 BJT in long-duration rainfall days for the 1991–2004 period. The shading denotes the normalized long-duration rainfall amount accumulated in the six hours after 2000 BJT (i.e., 2000–0200 BJT). (b) The projections of diurnal wind anomalies on the composite regional mean winds averaged over the southwesterly region at 2000 BJT. Values >0.9 (<0.9) are shaded with dots (slashes). The selected low-level regions are shown by black dashed lines, and the regional mean composite wind is presented by black vectors. Black areas are topographic regions where surface pressure is <850 hPa. (c) The composite anomalous zonal circulation averaged between 27° and 33°N at 2000 BJT. The gray shading denotes the meridional-averaged vertical velocity (10² Pa s⁻¹), whereas the black denotes the topography. (d) Spatial distribution of composite vertical velocity averaged between 850 and 700 hPa (contours interval; 2 × 10² Pa s⁻¹) and divergence at the sixth model level (shaded, 10⁻⁵ s⁻¹) at 2000 BJT.](image-url)
predominant early morning starting events in the lower valley (Fig. 3).

In the afternoon (1400 BJT), the northerly anomaly dominates most of central eastern China (Fig. 10a). The low-level southwesterly is greatly weakened at this time (Fig. 10b), probably resulting from frictional drag caused by the strong mixing in the boundary layer (Blackadar 1957). Weak anomalous vertical motion is observed in the upper and middle valleys. An ascending flow and low-level convergence locate over the southeastern coastal
region (Figs. 10c,d), which may be associated with the afternoon development of convection systems caused by local thermal instability.

5. Discussion

As we have just documented, the diurnal clockwise rotation of the low-level wind and its interaction with the topography play important roles in modulating the nocturnal long-duration rain along the YR. Nevertheless, other factors may also play important roles in the distinct diurnal features of summer rainfall along the YR. For example, the local low-level instability caused by insolation is strongest in the afternoon in summer. The variation of the low-level southwesterly may not fully explain why the long-duration rain does not commonly initialize in the afternoon in the upper and middle valleys. As proposed by previous studies (Ye and Gao 1979; Kuo and Qian 1981; Yu et al. 2004; Li et al. 2005), the thermal advection from the TP greatly influences the downstream climate in East Asia. To reveal its impacts on the diurnal rainfall, the composite meridional-averaged (27°–33°N) potential temperature and zonal wind for long-duration rainfall events are illustrated in Fig. 11. The warm temperature trough at 700–600 hPa is evident in the afternoon and early evening over the TP. Combined with the eastward wind, an apparent warm advection locates over the upper YR valley in the afternoon. Meanwhile, the moisture advection from the TP, which modulates the vertical structure of the moist static energy, is also evident at the same time. The afternoon wetting by the moisture advection plays a similar role as the thermal advection. These advections suppress the development of afternoon local thermal convection. As a result, the afternoon rainfall system may not develop sufficiently over this region, and it tends not to last for a long duration. Although the warm trough remains until early evening, the zonal wind near the eastern edge of the TP reverses to easterly (Fig. 11b). Consequently, the advections are reduced and the low-level unstable energy accumulated during the day is able to release. Then rainfall tends to occur as a response to low-level convergence caused by westward anomalous wind. At night, weak, cold advection is observed at 0200 (Fig. 11c) and 0800 BJT (Fig. 11d), mainly resulting from the cooling of the plateau, which may also favor the development of rainfall systems in nocturnal hours.

To further identify the thermal effects of TP, the regionally averaged cloud-top pressure on long-duration rainfall days is displayed in Fig. 12. The corresponding zonal temperature advection $\frac{\partial \theta}{\partial x}$ is also shown by triangles. The diurnal cycle of the cloud-top pressure resembles the variation of long-duration rain (Yu et al. 2007a). The clouds reach their highest level in the early morning (0500 BJT). After sunrise, the cloud-top pressure decreases quickly. At 1400 BJT, the cloud-top pressure reaches the lowest while the zonal thermal advection from the TP reaches the maximum, implying that the local
Afternoon thermal convection is significantly suppressed by the upstream thermal advection. Then the cloud-top pressure increases with the decreasing warm advection resulting from the weakening of solar radiative heating. The thermal advection is relatively weak at the other three reanalysis time slices except at 1400 BJT. It is noted that the diurnal variation of the thermal advection and cloud-top pressure is not linearly correlated. For example, the cloud-top pressure decreases quickly from 0500 to 0800 BJT when warm advection remains weak at 0800 BJT. Therefore, the warm advection may mainly contribute to the suppression of the afternoon convection. Other factors may also account for the evolutions of the cloud and convections during other hours of the day. More observational data are needed to reveal the detailed role of the thermal advection from the TP on the downstream rainfall in diurnal time scale.

The nocturnal occurrences of rainfall should be the comprehensive results of several factors. Despite the dynamical and thermal forcings discussed previously, the radiative forcings caused by the deep stratus with high-cloud optical depth may also be important (Yu et al. 2004; Li et al. 2008). Generated by the TP, deep, continental stratus clouds over southwestern China hinder the solar radiation from reaching the ground and suppress the local thermal convection during the day. However, the radiative–convection interaction (Randall et al. 1991; Lin et al. 2000) may also have contributions to the preferred nocturnal occurrences of rainfall downstream of TP. The relative high cloud top (Fig. 12) implies a greater infrared cooling at the cloud top than cloud base in the night, resulting in the destabilization of the middle troposphere. Then, the cloud develops with a maximum

![Figure 11](image1.png)

**Fig. 11.** The composite longitude–vertical cross section of JJA mean potential temperature (shaded, °C), zonal wind (black contours, m s\(^{-1}\)) and specific humidity (green contours, g kg\(^{-1}\)) averaged between 27° and 33°N during long-duration rainfall days: (a) 1400, (b) 2000, (c) 0200, and (d) 0800 BJT. The topography is shaded.

![Figure 12](image2.png)

**Fig. 12.** The composite diurnal variation of cloud-top pressure from 3-hourly ISCCP D1 data (solid line, left axis) and the zonal temperature advection averaged between 600 and 700 hPa (triangular-shaped symbols, right axis) from 6-hourly JRA25 data averaged over 27°–33°N, 100°–105°E. Each triangle denotes the advection at a reanalysis slice.
height occurring in the early morning. During the day, warming at the cloud top as a result of solar absorption increases the stability; thus, convective activity is restricted during the daytime. Though the cloud radiative forcing is important downstream of the TP, further study on its diurnal features is restricted by a shortage of data. The hypothesis mentioned here should be tested in field observation campaigns and in numerical experiments.

6. Summary and concluding remarks

In this study, we present an explanation for the prominent nocturnal long-duration rain and its eastward phase delay along the YR. We demonstrate that the distinct diurnal characteristics are greatly attributed to the diurnal clockwise rotation of low-level wind. The major conclusions are summarized.

1) The summer rainfall along the YR valley is dominated by nocturnal long-duration rainfall events. These events prefer to start in the early evening and peak in the middle to late night in the upper valley of the YR and show an eastward delay along the YR. The downstream transition of preferred starting hours presents a similar distribution to that of the peaking hours.

2) The diurnal features of long-duration rain are closely related to the diurnal evolution of the low-level southwesterly. The diurnal clockwise rotation of anomalous low-level wind corresponds well to the preferred nocturnal occurrences of the long-duration rain and its eastward phase transition. The anomalous westward flow blowing to the eastern slope of TP in the evening causes the upward motion, corresponding to the frequent initiation of long-duration rainfall events around this time in the upper YR valley. The wind anomaly then rotates to southwesterly at midnight, accelerating the southward component and favoring the trigger of rainfall in the middle valley. In the early morning, the accelerated southwesterly in the south of the YR and the northeasterly anomaly in the northern converge along the YR, in favor of the early morning arising of long-duration events in the lower valley.

3) The thermal advection from the upstream TP may also influence the diurnal rainfall along the YR. In the afternoon, the mid- and low-level warm advection favors the formation of the inversion layer and suppresses the afternoon thermal convection in the upper valley.

The diurnal cycle of rainfall along the YR shows large regional differences, and its physical mechanisms are complicated. Because of the limitation of the available data, it is difficult to investigate the integrated diurnal evolution of its physical processes. By proposing the influences of large-scale circulation on the diurnal cycle of long-duration rainfall, the present study expands our knowledge in understanding the diurnal features over inland regions with complex topography. More observational data, as well as further model simulations, are needed to illustrate the detailed diurnal evolution of the dynamical and thermal forcings, and their impacts on the diurnal cycle of rainfall.

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