Diurnal Variations of Warm-season Precipitation East of the Tibetan Plateau over China

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Abstract

This study explores the diurnal variations of the warm-season precipitation to the east of the Tibetan Plateau over China using the high-resolution CMORPH precipitation data and the GFS gridded analyses during mid-May to mid-August of 2003-2009. Complementary to the past studies using satellite or surface observations, it is found that there are strong diurnal variations in the summertime precipitation over the focus domain to the east of the Tibetan Plateau. These diurnal precipitation cycles are strongly associated with several thermally driven regional mountain-plain solenoids due to the differential heating between the Tibetan Plateau, the highlands, the plains, and the ocean. The diurnal cycles differ substantially from region to region and during the three different month-long periods, namely, the pre-Meiyu period (May 15-June 15), the Meiyu period (June 15-July 15), and the post-Meiyu period (July 15-August 15).

In particular, there is substantial difference in the propagation speed and eastward extent of the peak phase of the dominant diurnal precipitation cycle that is originated from the Tibetan Plateau. This diurnal peak has a faster (slower) eastward propagation speed, the more (less) coherent propagation duration, and thus covers the longest (shortest) distance to the east during the pre-Meiyu (post-Meiyu) period than that during the Meiyu period. The differences in the mean midlatitude westerly flow and in the positioning and strength of the Western Pacific Subtropical High (WPSH) during different periods are the key factors in explaining the difference in the propagation speed and the eastward extent of this dominant diurnal precipitation cycle.
1. Introduction

The diurnal cycle of precipitation plays an important role in the local weather and climate (Dai 2001; Yang and Slingo 2001; Liang et al. 2004). The diurnal variations of precipitation are often induced by differential diabatic heating between regions with different surface topography including the contrast between mountains and plains and/or between land and sea. Recent studies have examined the diurnal variations of precipitation over several mountain ranges and adjacent plains or basins over different continents (e.g., Carbone et al. 2002; Wang et al. 2004, 2005; Yu et al. 2007a, b; Fitzjarrald et al. 2008; Levizzani et al. 2010; Huang et al. 2010; He and Zhang 2010, hereafter referred to as HZ10). Many of these studies have found that the warm-season rainfall often generates over the highlands in the local mid-afternoon hours and then propagates\(^1\) eastward or southeastward to adjacent lowland in the night or early morning such as over North America (Carbone et al. 2002) and East Asia including different regions of China (Wang et al. 2004, 2005; Yu et al. 2007a, b; Huang et al. 2010; HZ10). Carbone et al. (2002) suggest that the fixed timing, areal coverage, and longevity of these diurnal precipitation cycles may be potentially used to extend the predictability of the warm-season rainfall forecasts if these diurnal cycles can be properly captured in numerical weather prediction models.

The terrain elevations over China change drastically from the high Tibetan Plateau (TP) on the west to highlands in the middle and the low-lying plains on the east (Figure 1a). The strong contrast in terrain elevations is responsible for the occurrence of warm-season diurnal precipitation cycles (Wang et al. 2004, 2005; Chen et al. 2010). The vast majority of areas in China east of the TP are under the influence of the East Asia summer monsoon with the primary monsoon rain belt advancing northward from mid-May to mid-August (Tao and Chen 1987). The

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\(^1\) In this study, propagation is loosely defined as the speed of movement in space with time of a feature such as the peak or the minimum that includes pure translation in space and mean flow effect.
TP and other mountain ranges are important factors in organizing and modulating precipitation during the Asian summer monsoon period (Xie et al. 2006). The dual influence of complex topography and the summer monsoon on the diurnal variations of warm-season precipitation over this region have been noted in many recent studies (e.g., Geng and Yamada 2007; Wang et al. 2004, 2005; Yu et al. 2007a, b; Chen et al. 2009a, b; Chen et al. 2010). Some of these studies also examined the regional difference of diurnal precipitation variations and propagation (e.g., Wang et al. 2004, 2005, and Hirose and Nakamura 2005). Most recently, through the case study of an individual episode on the leeside of TP, Huang et al. (2010) found that a solenoidal circulation between TP and its leeside lowlands contributes to the longevity and further downstream propagation of the diurnal precipitation peak.

Some studies also examined the diurnal variations of precipitation over East Asia over one or several sub-periods of the warm season (Asai et al. 1998; Chen et al. 2009; Xu and Zipser 2011). Under the monsoon influence, climatologically the primary rain belt over China moves from south to north with the rainy season in South China during mid-May and mid-June, the Meiyu season in the Yangtze-Huai River Valleys (YHRV) of Central and East China during mid-June and mid-July, and the rainy season in North China during mid-July and late August. According to the climatological mean positions of the primary rainband, the current study divides the warm-season in the focus domain (areas east of TP over China) into three periods, namely, the pre-Meiyu period (May 15 - June 15), the Meiyu period (June 15 - July 15), the post-Meiyu season (July 15 - August 15).

Complementary to past studies which mostly analyzed the characteristics of the diurnal precipitation cycle on the entire warm season, this study explores the diurnal variations in the warm-season precipitation to the east of the TP over China with a focus on the difference during
three different month-long periods, each of which represents a different rainy season in China. Section 2 provides a description of the dataset and methodology. Section 3 describes the overview of the warm-season precipitation east of the TP over China. Characteristics and the variations in the diurnal precipitation, along with the connection with several regional mountain-plains solenoidal circulations, are examined in Section 4. Section 5 discusses on the difference in diurnal variation during different periods. Concluding remarks are given in Section 6.

2. Data and Methodology

As in HZ10, the high-resolution global precipitation dataset from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC) morphing technique (CMORPH, Joyce et al. 2004) is used for this study. Seven warm seasons of the CMORPH dataset during 2003-2009 (mid May-mid August) will be examined. The CMORPH has a spatial resolution of 0.7277° available every 30 minutes between 60°N and 60°S produced since December 2002. It combines precipitation estimates derived exclusively from several low-orbit satellite microwave sensors. The CMORPH dataset uses the spatial propagation information that is obtained from geostationary satellite infrared data to transport the microwave-derived precipitation features during periods when microwave data are not available at a location. Recently, Shen et al. (2010) compared the spatial distribution and seasonal variations of six satellite-based precipitation estimates, including CMORPH, with over 2000 rain gauge measurements during 2005-2007. They found the CMORPH rainfall estimates had the best agreement with the rain gauge observations, especially during warm-season months (May-August) over East and South China. They also found that the CMORPH dataset depicted well the diurnal variations and propagation of the warm-season precipitation, despite some
underestimation of early morning rainfall maxima over the plains. The reliability of the CMORPH dataset on warm-season and annual rainfall estimation has also been demonstrated in several other recent studies (Fitzjarrald et al. 2008; Hirpa et al. 2010; Pereira et al. 2010).

Besides the CMORPH dataset, the NOAA Global Forecast System (GFS) 1°×1° operational analyses every 6 hours over the same period are used to provide the corresponding environmental conditions. Our analysis domain is over a 33°×20° longitude-latitude domain (95°E-128°E, 20°N-40°N; Figure 1a) that covers most areas of China with the focus area on a 27°×8° to the east of the TP including the Sichuan Basin sandwiched by the Qinling and Wushan Mountain Ranges, as well as the low-lying middle-to-lower ranges of the YHRV and the adjacent oceans. The focus area is home to more than a third of China’s population that includes several of the most populous provinces and cities in China. On average, the terrain elevation decreases from west to east (Figure 1b). The latitude-averaged highest step of the TP has mean elevations above 3500 m. The second step is the highlands in Southwest and Central China that includes the Sichuan Basin and the surrounding mountain ranges (hereafter refer to as “the highlands”) with average elevations ~1000 m. The third step is the plains over Central and East China along the mid-to-lower ranges of the YHRV (hereafter referred to as “the plains”) that have average terrain elevation less than 300 m with the ocean to the east.

To highlight the larger-scale variations in the diurnal precipitation cycles and to directly compare with a coarse GFS analysis, as in HZ10, this study also uses a two-dimensional spectral decomposition technique developed in Lin and Zhang (2008) to truncate signals with horizontal scales less than 300 km. The spectral filtering is performed on the latitude-longitude grid over the entire domain of Figure 1a though only plotted in a subset of this domain in subsequent figures.
3. Overview of warm-season precipitation in the focus domain

The warm-season precipitation (mid-May through mid-August) accounts for most of the annual rainfall in China with the highest amount over South China and gradually decreasing to the north and west (Figure 2a). Accompanied by the northward progression of the East Asian summer monsoon, there are three distinguished phases of warm-season precipitation with quasi-stationary rainfall belts on average situated over South China during mid-May to mid-June, over middle-to-lower ranges of the YHRV in Central and East China during mid-June to mid-July, and over North China from mid-July to mid-August (Tao 1980; Tao and Chen 1987).

The northward movement of the quasi-stationary quasi-linear east-west-oriented rain belt is strongly linked to the position and strength of the Western Pacific Subtropical High (WPSH) and the midlatitude westerly flow (Figure 3). The quasi-stationary rain belt over the focus domain during mid-June to mid-July is typically called the Meiyu season in this area2. For simplicity, this study will characterize the duration between May 15 and June 15 as the pre-Meiyu period, between June 15 and July 15 as the Meiyu period, and between July 15 and August 15 as the post-Meiyu period over the focus area to the east of the TP over China. Given strong differences in the climatological mean of the synoptic environment for these three different periods (Figure 3b-d), this study will examine the changes in the diurnal variations of precipitation over these three different warm-season periods over the focus domain. This will complement past studies of the diurnal variations in precipitation over this area that focused broadly over the entire summer seasons (e.g., Wang et al. 2005a, b; Yu et al. 2007a, b) or

2Meiyu is also called Baiyu in Japan and sometimes may refer broadly to all quasi-stationary precipitation belts associated with the East Asian summer monsoon during all warm seasons.
exclusively over the Meiyu season (e.g., Geng and Yamada 2007). Moreover, this study will also seek to understand the similarities and differences in propagation and diurnal variation mechanisms during different rainfall periods.

From the CMORPH dataset averaged over 2003-2009, the maximum monthly mean precipitation totals of 250-450 mm are located over South China (south of 27°N outside of the focus domain) during the pre-Meiyu period (May 15-June 15). Within the focus domain, local maxima with monthly total precipitation between 100 and 200 mm are observed in the eastern edge of the TP, as well as over the highlands east of the Sichuan Basin and the southern portion of the East China plains (Figure 2b). During the Meiyu period (June 15-July 15), although precipitation over South China especially along the coastal areas remains strong (but weakened compared to the pre-Meiyu period), nearly all areas in the focus domain encounter increased precipitation. The primary rain belt with monthly total maxima over 300 mm moves over to the East China plains along the mid-to-lower ranges of the YHRV oriented mostly along the west-east direction (Figure 2c). During the post-Meiyu period, this primary rain belt continues moving northward to the North China plains across the northern boundary of the focus domain while rainfall decreases substantially along the YHRV over most of the southern half of the focus domain (Figure 2d).

Differences in the large-scale flow regimes and weather patterns not only leads to large differences in the amount and distribution of the precipitation in the focus domain during different periods but also results in significant differences in the diurnal variations and propagation of the rainfall as evidenced from the averaged plots in Figure 4 and the time-longitude Homovöller diagrams in Figure 5 for different periods. Figure 4 shows the spatial
distribution of the diurnal percentage of the total precipitation during different periods over the focus domain and surrounding areas. As in HZ10, the diurnal percentage (DP) is defined as:

\[
DP = \frac{\sum_{t=1}^{24} |r_t - \bar{r}|}{r_d}
\]  

(1)

Here, \( r_t \) is the mean precipitation rate at each hour, \( \bar{r} \) is the mean hourly precipitation rate and \( r_d \) is the mean daily precipitation.

Different from the total rainfall distribution in Figure 2a, the highest percentage in diurnal precipitation with values between 30-50% occurs on the eastern TP including the adjacent sharpest terrain slope and the Sichuan Basin to the east; the diurnal percentage of precipitation drops to below 20% for most of the high and low plains to the east except for the mountainous areas in the southeast edge of the focus domain (Figure 4a). The distribution of the diurnal precipitation percentage varies from period to period, with the Meiyu period most similar to the warm-season average (Figure 4c). Among the three warm-season months, the pre-Meiyu (post-Meiyu) period has the highest (lowest) diurnal percentage over the Sichuan Basin but the lowest (highest) on the plains (Figures 4b, 4d). It is worth noting that our definition of DP includes the variations of precipitation during different hours of the day besides the pure diurnal cycle, which differs from a more strict definition used in Carbone and Tuttle (2008). The DP calculation using their definition yields similar distribution patterns as in Figure 4 (not shown) though the absolute percentage value is smaller without higher frequency modes.

Following the methodology of Figure 12 of Carbone et al. (2002) and Figure 4 of HZ10, Figure 5a shows the distance-time Homovöller diagram of the normalized hourly precipitation deviations averaged along the cross section from west to east. The map distributions of the normalized hourly precipitation deviations at different hours are shown in Figure 6. Precipitation
over the eastern TP shows obvious characteristics of diurnal variations with a dominant peak in the afternoon hours (around 9-12 UTC or 17-20 BJT\(^3\); Figures 5a, 6d, and 6e) and a minimum in the morning (around 0-3 UTC or 8-11 BJT; Figures 5a, 6a, and 6b). The maximum diurnal precipitation peak over the TP (near 100°E) begins to migrate eastward and downslope around 12 UTC (20 BJT; Figures 5a, 6e) starting from around 102°E that arrives at the highlands (near 105°E) around 15-21 UTC (23-05 BJT; Figures 5a, 6f-h). The maximum rainfall in the Sichuan Basin area occurs mainly in the nighttime and early morning hours (nocturnal) consistent with previous studies (Wang et al. 2004; Kurosaki and Kimura 2002). The diurnal precipitation maximum continues moving eastward at similar phase speed (~13 m/s) but gradually slows and weakens in relative magnitude that co-exists and may interact with other diurnally varying precipitation modes. The dominant diurnal precipitation peak persistent over all land areas to the east of 108°E occurs between 07 and 10 UTC (or 15-18 BJT, mid-afternoon) while a secondary propagating maximum, as a continuation of the signal from the TP and the Sichuan Basin, peaks at approximately 15-18 UTC (or 23-02 BJT, around midnight the second day) between 112 and 114°E.

Further eastward propagation of this diurnal peak is hard to track east of 115°E in the latitudinal average (Figure 5a) as the eastward propagating diurnal peak interacts with other modes, resulting in a more complex diurnal precipitation variation pattern over the plains (Figures 5a, 6). One such mode is the southeastward propagating diurnal precipitation peak that originated from a northeast-southwest-oriented terrain slope between the mountain ranges and plains in North China (Figures 6c-g) that was examined previously in HZ10. Another is a non-propagating, quasi-stationary oscillatory mode typical of summertime precipitation over land that

\(^3\)Note that the local standard time (LST) over areas east of TP is within 2 hours of Beijing standard time (BJT). BJT is 8 hours ahead of the coordinated universal time (UTC).
has a peak in the afternoon and a minimum in the morning. The non-propagating oscillatory diurnal mode becomes the dominant signal over land east of 114°E in the latitudinal average of Figure 5a while the southeastward propagating mode is most evident in the map plot of Figure 6.

Over the ocean (east of 122°E), the diurnal cycle phase is nearly opposite to that over the land: there is a late night and early morning maximum (18-03UTC or 02-11 BJT) and a late afternoon and early night minimum (09-15UT or 17-23 BJT) (Figure 5a). The late-evening to early-morning rainfall maximum over the ocean is consistent with past observational studies (e.g., Dai 2001; Yang and Smith 2006).

The diurnal evolution of summertime precipitation revealed from the CMORPH dataset in Figure 5a is broadly consistent with Wang et al. (2004, 2005), who used hourly infrared (IR) brightness temperature derived from the Geostationary Meteorological Satellite (GMS). One noticeable difference between this study and Wang et al. (2004, 2005) is that the averaged eastward propagation speed derived from the CMORPH dataset is ~13 m/s and is slower than 17 m/s found in their study. This difference may be due to the difference in the averaging latitude range (20-40°N versus 27-35°N), the difference in the data sources (GMS satellite IR brightness temperature versus CMORPH rainfall), and/or the period of the dataset (May 1-August 31, 1998-2001 versus May 15-August 15, 2003-2009). Tuttle et al. (2008) noted that the infrared(IR)-based propagation speeds are on average ~4 m/s faster than that of radar-measured suggesting that the IR-based phase speeds are faster than the typical deep westerly shear.

The diurnal cycle originating from the eastern edge of the TP has the fastest and most coherent propagation all the way to the east coast of China during the pre-Meiyu period (Figure 5b). The WPSH is weak and farther south and east while the focus area is well within the midlatitude westerly flow at 500 hPa (Figure 3b). The slowest and least coherent propagating
diurnal precipitation peaks are observed during the post-Meiyu period that is confined mostly to the eastern slope of the TP and adjacent highlands (Figure 5d) while most of the focus area is within the westward extent of the WPSH (Figure 3d). The East China plains during this period are controlled mostly by the same phase non-propagating diurnal variation that peaks in the late afternoon around 09 UTC (17 BJT; Figure 5d). During the Meiyu period, the rainfall diurnal variation and propagation is the most complicated with the coexistence of both the stationary and eastward propagating modes over the Central and East China plains (Figure 5c) while the focus area becomes the transition zone of the WPSH and the westerly flows (Figure 3c).

Figure 7 shows the latitudinally averaged daily and diurnal rainfalls as well as the diurnal percentage of the daily rainfall averaged during different periods. As in Figure 2, the averaged maximum rainfall is found in the Meiyu period, followed by the post-Meiyu period, and the lowest is during the pre-Meiyu period. There are two primary local rainfall maxima present in each of the three periods with the weaker and narrower peak located on the eastern edge of the TP and the stronger and broader peak on the plains between 113-122°E (Figure 7a). These two local maxima are most noticeable during the Meiyu period and least apparent during the pre-Meiyu period.

The diurnal percentage of the daily rainfall (defined in equation 1), on the other hand, shows greater difference from period to period, especially over the plains east of 112°E (Figure 7b). During the pre-Meiyu period, the diurnal precipitation contributes as much as 60% on the lee slope of the TP (near 102.5°E) which drops nearly linearly to ~30% at 110°E. A secondary peak of ~35% is observed at the second terrain slope (~112°E) that further declines over the East China plains and reaches less than 20% on the coast.
The latitudinally averaged diurnal percentage of the precipitation during the Meiyu and post-Meiyu periods west of 113°E (Figure 7b) is more or less similar to the pre-Meiyu period though the primary peak on the eastern edge of TP becomes slightly weaker (~50-55%) and 2-3 degrees more to the west along with a more noticeable enhancement at the foothills of TP (i.e., over the Sichuan Basin and surroundings). Although the diurnal percentage increases at the second terrain slope (~112°E) for both the Meiyu and post-Meiyu periods, there is no obvious secondary peak in this longitude range. The diurnal percentage over the plains east of 112°E stays at similar values between 25-30% until an enhancement to nearly 40% on the coastal area. The diurnal percentage during the post-Meiyu period, on the other hand, increases steadily over the plains from a minimum of ~25% at 110°E to a peak above 45% on the coast (Figure 7b). Correspondingly, the averaged daily diurnal rainfall during the pre-Meiyu period is similar to the Meiyu and post-Meiyu periods west of 110°E (over the TP and adjacent highlands) but significantly smaller over the plains east of 110°E (Figure 7c).

To further elucidate the difference of total precipitation and the period-mean synoptic environment, the following subsections will examine separately the characteristics and dynamics of the summertime rainfall diurnal variations during each of the three periods.

4. Diurnal variations of summertime precipitation during different periods

4.1 The pre-Meiyu Period (May 15-June 15)

Figure 8 shows the normalized diurnal precipitation deviations at different hours during the pre-Meiyu period (May 15-June 15). As in HZ10, to highlight the larger-scale variations of the diurnal precipitation cycles and to directly compare with a coarse GFS analysis, a two-dimensional spectral decomposition (Lin and Zhang 2008) has been used to truncate signals with
horizontal scales less than 300 km in Figure 6 (as well as in Figures 8, 11 and 14). Consistent with Figure 5b, a diurnal precipitation peak starts at 06 UTC (14 BJT; Figure 8c) over the eastern edge of the TP (98-100°E). The strongest diurnal peak is observed on the sharpest terrain slope east of the TP at 15 UTC (23 BJT; Figure 8f). This diurnal peak subsequently moves downslope reaching the Sichuan Basin (105-108°E) between 18 and 21 UTC (02 and 05 BJT; Figures 8g-h) corresponding to the nocturnal and early morning rainfall maximum widely observed in this area. The peak phase continues moving eastward arriving at the Qinling and Wushan Mountain Ranges at 06 UTC (14 BJT; Figure 8c) on the second day, which is locally enhanced near 110-112°E as it moves down the eastern slope of these mountain ranges at around 9 UTC (17 BJT; Figure 8d). The peak phase front becomes less north-south oriented and less coherent thereafter during its continuous eastward propagation reaching the East China plains in the later evening and early morning hours (15-21UTC or 23-05BJT; Figures 8f-h) corresponding to another nocturnal precipitation maximum also well-observed in this area. The remnant of this diurnal peak has traceable eastward propagation even during the third day until it reaches the east coast, albeit even lesser coherent and weaker (Figures 8a-c).

From the eastern edge of the TP to the coastal plains, this diurnal precipitation peak is clearly traceable for nearly two days with an average eastward propagation speed of approximately 15 m/s (Figure 5b). In general, the diurnal precipitation peaks in the afternoon hours on the high mountains or their eastern slopes and in the late evening or early morning on the plains or the basins. In addition, the diurnal peaks usually weaken as they propagate away from the terrain slopes suggesting the differential heating between highland and lowland (or between land and sea) is essential in controlling the diurnal cycles along with the influence of the large-scale environment.
As discussed in HZ10, the speed of phase propagation and the relationship between the local diurnal precipitation peak and minimum may be related to the diurnal variations of several regional-scale Mountain-Plains Solenoid (MPS) circulations induced by differential heating between the plateaus, highlands, and plains over this region. Following HZ10 which focused on North China, this study examined the mean GFS analysis available every six hours averaged through the warm-season months of 2003-2009 as shown in Figures 9-10 over the focus domain from the TP to the coastal plains. The evolution of the MPS circulation over many places of the world along with its impacts on summertime precipitation and other weather phenomena have been extensively studied (e.g., Tripoli and Cotton 1989; Dai et al. 1999; Zhang and Koch 2000; Koch et al. 2001; Carbone et al. 2002; Wang et al. 2004, 2005; Hirose and Nakamura 2005; Laing et al. 2008; Carbone and Tuttle 2008).

Figure 9 shows the low-level (850-hPa) vertical motion deviations and perturbation wind vectors of each GFS analysis during the pre-Meiyu period averaged over 2003-2009. Figure 10 shows the corresponding latitudinally averaged vertical motions and the perturbation vertical circulation vectors along the west-east cross section. At 06 UTC (14BJT) in the early afternoon (Figures 9a, 10a), there are three distinct west-east solenoidal circulations in the lower-to-mid troposphere of the latitude-averaged vertical cross section. These solenoidal circulations are apparently driven by the differential diabatic heating due to the difference in surface terrains with the upward branches on the highland/plateau slopes and the downward branches over the low basins, plains, or oceans. The western most and strongest solenoid (S1) has the westward tilted rising branch over the eastern slope of the TP and the sinking branch over the Sichuan Basin. The second solenoid in the middle (S2) has a rather shallower rising branch over the highlands along the Qinling and Wushan Mountain Ranges and a more extended and broader sinking branch over
the East China plains. The third solenoid (S3) has the rising branch along the coastal lands and
the weak sinking branch over the nearby oceans. Each of the upward branches of the solenoids
corresponds to a diurnal precipitation peak. On a larger scale, though not marked in Figure 10a,
there also exists a broader domain-wide vertical solenoid circulation (S0) across all three
solenoids with the upward branch on the eastern TP and the downward branch over the plains.

At 12 UTC (20 BJT) in the early evening (Figures 9b, 10b), the S0 becomes the dominant
mode in the cross section with the upward motion strengthened at the eastern slope of the TP and
the downward motion over most of the areas eastward except for the weak upward branch of the
S2 in the lower troposphere on the eastern slope of the Qinling and Wushan Mountain Ranges
(\sim 112^\circ E). Both the upward branches of S1 and S2 continue to be associated with local diurnal
precipitation maxima at this hour while the broader and stronger sinking branch over the East
China plains corresponds to a broad local precipitation minimum phase in these regions at this
hour. The coastal solenoid S3 is mostly absent in this early evening hour though the sinking
branch over the ocean is considerably stronger than over the coastal land.

At 18 UTC (02 BJT) in the early morning (Figures 9c, 10c), the nighttime vertical
circulation is nearly a complete reversal of the daytime circulation at 06 UTC (14 BJT in Figures
9a, 10a) with the downward branches over the highland/plateau slopes and the upward branches
over the low-lying plains/basins. Consequently, strong diurnal precipitation peaks (nocturnal
rainfall maxima) are observed over the Sichuan Basin (part of S1) and over the East China plains
(part of S2). However, according to the diurnal evolution of the rainfall shown in Figure 8h, the
nocturnal circulation pattern may be further strengthened to peaked maximum at 21 UTC at a
time when the GFS analysis is not available. On the other hand, as discussed in HZ10 and other
studies (e.g., Higgins et al. 1997; Carbone and Tuttle 2008), the nocturnal precipitation peak
phase over the plains is also coincidental with a developing low-level southerly jet that transports more warm moist air to this area and contributes to the enhancement of nighttime precipitation. The strongest positive anomaly of meridional wind (as an indication of the strength of the low-level jet anomaly) at 18 UTC (02 BJT) is indeed situated over the plains east of 115°E. Boundary layer processes associated with the reduced turbulence diffusion due to ceased daytime heating are believed to be responsible for the development of the low-level nocturnal jet (Blackadar 1957; Holton 1967).

At 00 UTC (08 BJT) a few hours after sunrise (Figures 9d, 10d), the vertical circulation transitions from the nocturnal pattern in Figures 9c and 10c to the daytime pattern in Figures 9a and 10a, and is again dominated by the domain-scale broad solenoid (S0) as a reversal of that in Figures 9b and 10b with the downward motion maximized at the eastern slope of the TP and the upward motion in a broad area to its east maximized at the mid troposphere. S1 becomes even stronger than the nocturnal phase 6 hours previous as it moves eastward corresponding to the mid-morning precipitation peaks in the northeastern Sichuan Basin (Figures 5b and 8), while S2 becomes weaker. Future research will conduct mesoscale reanalysis and forecast at higher spatial and temporal resolutions than GFS analysis for the region to examine in greater detail the diurnal variations of these MPS.

In summary, during the pre-Meiyu period, the diurnal precipitation peak moves eastward from the eastern edge of the TP to the coastal plains in about two days, and the averaged propagation speed (estimated between 101°E and 112°E) is approximately 15 m/s (Figure 5b). This diurnal peak is strengthened twice in its eastward propagation, once on the eastern slope of the Qinling and Wushan Mountain Ranges (110-112°E), and again along the east coast (118-120°E). From Figures 8a and 9a, these two local enhancements appear to be a result of the local
solenoids (S2 and S3) that are in phase with the propagating diurnal precipitation peak originating from S1 on the second and the third day respectively. In other words, the local enhancements by S2 and S3 may have contributed substantially to the longevity and coherence of diurnal phase propagation during the pre-Meiyu period. A recent modeling study by Huang et al. (2010) on an individual event revealed that in addition to the eastern TP acting as a heat source for convection, the diurnal solenoid circulation also contributes to the longevity and propagation of episodes. Another recent study of Chen et al. (2010) also examined the diurnal variations of summertime long-duration nocturnal rainfall down the Yangtze-River Valley. They found that the diurnal clockwise rotation of the low-tropospheric circulation might explain the eastward-delayed initiation of the long-duration nocturnal rainfall events while the upward motion belt moves eastward in time. However, both of these studies only identified the broad vertical circulation driven by the TP thermal forcing (S0) without discussing the three individual contributing solenoids (S1, S2, and S3) likely due to the even coarser spatial resolution dataset they used (2.5°x2.5° versus 1°x1°).

4.2 The Meiyu period (June 15-July 15)

During the Meiyu period (June 15-July 15), the WPSH moves northward (Figure 3c); consequently, the primary summer-time rain belt in China shifts north to the focus area and then becomes quasi-stationary over Central and East China (Figure 2c). The period-mean synoptic environment is different from what is during the pre-Meiyu period (Figure 3b), as are the diurnal variations of precipitation (Figures 4b, 5b). The red dashed box in Figure 2c indicates the main rain belt of this period (east of 112°E, 30-34°N). Figure 11 shows the normalized diurnal precipitation deviations at different hours during the Meiyu period. In comparison to the pre-
Meiyu period, it is found that most of the diurnal variations and propagation west of 114°E are more or less similar to those in Figure 8 while differing greatly east of 114°E. More specifically, the diurnal precipitation peak still starts in the early afternoon hours over the eastern edge of the TP, which propagates continuously eastward across the Sichuan Basin and arrives at the eastern slope of the Qinling and Wushan Mountain Ranges in the afternoon hours on the second day. The averaged eastward propagation speed during this period is ~13 m/s (estimated between 101°E and 111°E in Figure 5c), slightly slower than that during the pre-Meiyu period. The propagating diurnal precipitation peak weakens in the foothills of these mountain ranges (around 114°E) in the morning hours on the third day (Figures 5c, 11h). To the east of 114°E, the diurnal peak phase front changes from north-south oriented to a northeast-southwest orientation over the plains (and more parallel to the Meiyu frontal rain belt highlighted by a red dashed box)\(^4\). Coincidentally, there is also a local oscillating quasi-stationary mode (in contrast to the continuous spatial phase propagation) overlapped with elements of eastward propagating diurnal signals from west to east. More specifically, along the Meiyu rain belt, positive anomalies of the precipitation deviation are observed in the morning hours (21-03 UTC or 05-11 BJT; Figures 11a, b, h) and negative anomalies from the afternoon to the evening hours (09-15 UTC or 17-23 BJT; Figures 11d-f). The diurnal precipitation variations to the south and north sides of this primary Meiyu frontal rain belt overall are similar but in a nearly opposite phase to that within the red box.

Nevertheless, there is about a 6-hour phase lag between the south and north sides; the south sub-region diurnal precipitation reaches a peak (minimum) around 06-09 UTC or 14-17 BJT (18-

\(^4\) It is possible that there may be a resonance of speed/distance propagation among these three local MPS circulations S1-S3 and the timing of their regeneration which was pointed by Laing et al. (2008) for their study over the African continent.
21 UTC or 02-05 BJT) while the north peaks between 12-15 UTC (20-23 BJT). The characteristics of the diurnal variations along the Meiyu frontal rain belt and adjacent areas are broadly consistent with Geng and Yamada (2007). A more complex diurnal evolution in different areas of this region is also discussed in Yu et al. (2007a).

Figure 12 shows the low-level (850-hPa) vertical motion deviations and perturbation wind vectors for each GFS analysis during the Meiyu period averaged over 2003-2009. Figure 13 shows the corresponding latitudinally averaged vertical motions and the perturbation vertical circulation vectors along the west-east cross section. Despite differences in the details of relative size and strength, the three localized solenoidal circulations (S1-S3) as well as the domain-wide large-scale vertical circulation S0 (Figures 12 and 13) are mostly similar in phase and location to those observed during the pre-Meiyu period (Figures 9 and 10). Comparison of the vertical circulations between Figures 10 and 13 suggests that the lack of clearly identifiable eastward diurnal precipitation phase propagation east of 114°E (in Figures 5c and 11) is likely due to the presence of the strong Meiyu front precipitation that has a predominant quasi-stationary north-south diurnal oscillation as described above.

4.3 The post Meiyu-period (July 15 – August 15)

During the post-Meiyu period (July 15- August 15), the WPSH moves further northward and extend more to the west (Figure 3d) while the primary rain belt only overlaps the northern edge of the focus domain. The East China plains are now under the dominance of the quasi-stationary high-pressure system resulting in an even weaker midlatitude westerly flow over the focus domain and much reduced precipitation during this period (Figure 2d) except for occasional occurrences of tropical cyclones. Consequently, on average, the eastward propagation
of the diurnal precipitation peak originating from the eastern TP is further slowed and becomes barely traceable over the plains (Figures 5d). The averaged eastward propagation speed during this period is \( \sim 9 \) m/s (estimated between 102°E and 110°E in Figure 5d), which is substantially slower than that during the previous two periods. The diurnal precipitation, averaged latitudinally over the Central China highlands and East China plains during this period, has a dominant peak in the late afternoon and a minimum in the morning with little or no spatial phase propagation in the latitudinal average (Figure 5d).

However, this latitudinal average apparently does not capture some of the relatively weaker and less coherent diurnal propagations that are not strictly oriented north-south as illustrated in the normalized diurnal precipitation deviations at different hours (Figure 14). For example, a secondary diurnal precipitation peak originating at top of the Taihangshan Mountain Ranges in North China in the early afternoon (Figure 14c) propagates southeastward into this study’s focus domain. This secondary diurnal peak reaches the northern plain area of the focus domain in the later evening and early morning hours corresponding to secondary nocturnal precipitation maxima in this region (Figure 14f-h). Evolution of this secondary peak is similar to HZ10 where possible mechanisms for the nocturnal rainfall maximum were discussed in details.

On the other hand, the spatial propagation of the diurnal precipitation peak from the TP to the highlands (Figure 14) remains more or less similar to the previous two periods (Figures 8 and 11). Figure 15 shows the 850-hPa vertical motions deviations and perturbation wind vectors at each GFS analysis during the post-Meiyu period averaged over 2003-2009. Figure 16 shows the corresponding latitudinally averaged vertical motions and the perturbation vertical circulation vectors along the west-east cross section. Both the low-level anomaly plots and the latitudinally averaged longitude-height diagrams in Figures 15 and 16 are also similar to those of the previous
periods that show three local vertical circulations (S1-S3) most discernible at 06 and 18 UTC (14 and 20 BJT) as well as a domain-wide broader scale mountain-plains solenoid (S0) most apparent at 00 and 12 UTC (08 and 20 BJT). Again, the detailed diurnal phase variations and propagation of these solenoids cannot be fully resolved in the rather coarse temporal resolution of the GFS analysis.

5. Discussion of the difference in diurnal variations during different periods

Analyses of the diurnal variation during different summer months in the previous sections show (1) there are strong diurnal variations in the summertime precipitation over the focus domain to the east of the TP; (2) these diurnal precipitation cycles are strongly associated with several thermally driven regional mountain-plains solenoids due to the differential heating between the TP, the highlands, the plains, and the ocean; (3) the diurnal cycles differ greatly from region to region and during different rainy periods. In particular, there is substantial difference in the propagation speed and eastward extent of the dominant diurnal precipitation peak that is originating from the TP. This diurnal peak has a faster (slower) eastward propagation speed, more (less) coherent propagation duration, and thus covers the longest (shortest) distance to the east during the pre-Meiyu (post-Meiyu) period than that during the Meiyu period.

What causes the difference in the propagation speed and the eastward extent of this dominant diurnal precipitation peak originating from the TP? The above analysis suggests that even though the diurnal precipitation cycles are strongly associated with several mountain-plains solenoids, these regional solenoidal circulations between different periods are more or less similar in the coarse temporal resolution GFS analysis whose difference is not enough to explain the difference in the diurnal propagation during different period.
More likely mechanisms to explain the propagation difference are the difference in the mean midlatitude steering-level westerly flow and the difference in positioning and strength of the WPSH during different periods (Figure 3). The steering level is defined at the level where the phase propagation speed of the features equals the speed of the background flow. Over the TP and the adjacent highlands, the steering level is at approximately 500-350 hPa and over the plains at approximately 600-450 hPa. Figure 17 further shows the time-latitude diagrams of averaged mid-tropospheric zonal winds diagnosed with the GFS analyses from May 15 to August 15 averaged over two subdomains, one between 102° and 110°E for pressure levels between 500-350 hPa (Figure 17a), and the other between 112° and 120°E for between 600-450 hPa (Figure 17b). Indeed, consistent with the gradual decrease in the eastward propagation speed of the diurnal precipitation peak, the averages of the zonal winds in the mid-troposphere over both subdomains are decreasing with time and latitude. The southern parts of both subdomains begin to see the reversal of zonal winds at the start of the post-Meiyu period while nearly one third of the domain is under the easterlies toward the end of the post-Meiyu period. The decrease of the westerly flow throughout these summer months and the emergence of the easterly flow will likely lead to the decrease in the eastward propagation of the diurnal precipitation peak and prevent it from advancing farther eastward to the plains during the later months of the summer. As discussed in Section 3, the decrease in the mid-tropospheric zonal flow is due to the strengthening of the WPSH which shifts north and protrudes more inland at the start of the Meiyu period and again at the start of the post-Meiyu period (Figure 3). Note that the difference in the eastward propagation of the diurnal rainfall signals during different summer months was also noted in Wang et al. (2004, 2005, 2011) though without explanation of the difference.
6. Concluding remarks

This study explores the diurnal variations of the warm-season precipitation to the east of the TP over China using the high-resolution CMORPH precipitation data and the GFS gridded analyses during mid-May to mid-August of 2003-2009. Warm-season rainfalls account for most of the total annual precipitation in this focus area and thus have very important impacts on the water cycles and climate of the region that includes several of the most densely populated cities and provinces of China. Also investigated are the differences in diurnal variations and propagation among the three different month-long periods, namely, the pre-Meiyu period (May 15-June 15), the Meiyu period (June 15-July 15) and the post-Meiyu period (July 15-August 15).

Averaged over the entire 3-month period, it is found that the local peak phase of the diurnal precipitation usually begins in the mid-to-late afternoon on the eastern edge of the TP which subsequently propagates eastward and downslope at an average speed of ~13 m/s. The primary diurnal precipitation peak reaches the Sichuan Basin and adjacent highlands to its east around midnight and the early morning hours, and coincides with well-observed nocturnal rainfall maximum in this region. The diurnal precipitation maximum continues to move eastward at a slightly slower phase speed and gradually weakens in relative magnitude that may co-exist and interact with other diurnally varying precipitation modes. The most dominant diurnal precipitation peak persistent over all land areas to the east of 108°E occurs in the mid-afternoon (with maximum solar heating) while a secondary propagating maximum, as a continuation of the signal from the TP and the Sichuan Basin, peaks around midnight on the second day over the East China plains. These diurnal precipitation cycles are strongly associated with several thermally driven regional mountain-plains solenoids due to the differential heating between the plateaus, the highlands, the plains, and the ocean.
It is also found that the diurnal cycles differ greatly from region to region and in the propagation speed and eastward extent during different rainy periods. This diurnal peak originating from the eastern edge of the TP during the pre-Meiyu period propagates eastward at an average velocity of \( \sim 15 \text{ m/s} \). It reaches all the way to the east coast on the third day (\( \sim 45 \) hours) covering a distance of \( \sim 2000 \) km. The average eastward speed of this diurnal precipitation peak is \( \sim 13 \text{ m/s} \) during the Meiyu period which is clearly traceable only to the western edge of the plains (\( \sim 114^\circ\text{E} \)) in \( \sim 32 \) hours. The post-Meiyu period features the slowest propagation speed of \( \sim 9 \text{ m/s} \) which is mostly confined to the west of 113 °E and barely reaches the plains.

The differences in the mean midlatitude westerly flow and in the positioning and strength of the WPSH during different periods are the key factors in explaining the difference in the propagation speed and the eastward extent of this dominant diurnal precipitation cycle. Compared with the other two periods, the WPSH during the pre-Meiyu period is situated over the ocean that is the farthest south and east while the mid-latitude westerly flow is the strongest and farthest south resulting in the highest eastward propagation speed of the diurnal precipitation peak that also has the most eastward extent. The opposite is true for the post-Meiyu period while the diurnal cycle during the Meiyu period is in between the two periods and this also is closest to the three-month warm-season mean.

Similar to what discussed in HZ10, the following mechanisms may be responsible for the nocturnal precipitation maximum over the East China Plains. These nocturnal precipitation peaks may have been initiated first or enhanced on the eastern slopes of the TP during peak solar heating hours which subsequently move eastward and reach the plains at the nighttime following the mid-tropospheric mean flow. The nocturnal precipitation peaks over the plains could also be due to the local initiation or enhancement of precipitation by the upward branch of a mountain-
plains solenoid induced by differential heating between the TP and the highlands or between the
highlands and the plains. The nighttime precipitation peaks can be initiated or enhanced by a
nocturnal low-level jet over the plains which brings warmer, moister air to the area during the
nighttime. Future studies will examine the respective contributions different mechanisms, as
performed in Trier et al. (2006, 2010) for the continental United States, or through high temporal
and spatial resolutions regional-scale reanalysis that better resolves the evolution of the regional
mountain-plains solenoids and their impacts on the diurnal precipitation variations over this
region.

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References:


Figure Captions

Figure 1. (a) Map plot of terrain elevations (shaded every 250 m) over China with the focus domain (98°E-125°E, 27°N-35°N) highlighted in the black box. (b) The average terrain elevations (m) along the west-east cross section in the focus domain with characteristic terrain types separated by black dashed lines.

Figure 2. Distribution of mean monthly total precipitation (mm) during (a) the entire warm season, (b) the pre-Meiyu period, (c) the Meiyu period, and (d) the post-Meiyu period averaged over all hours during 2003-09 estimated with the CMORPH dataset. The bold lighter gray lines denote the terrain elevation of 500-m, and the bold darker gray lines denote the elevation of 2000-m. These two terrain contours mark the approximate locations of the two steepest terrain slopes, Slope 1 and Slope 2, marked in Figure 1b, respectively. The red dashed box in (c) denotes the primary Meiyu front rain belt during the Meiyu period.

Figure 3. Spatial distribution of the 500 hPa horizontal wind vectors, geopotential height (2 dam intervals) and negative vorticity (shaded, 10^{-5} s^{-1}) averaged over (a) the entire warm season, (b) the pre-Meiyu period, (c) the Meiyu period, and (d) the post-Meiyu period.

Figure 4. Percentage (%) of the diurnal contributions of the total precipitation averaged over (a) the entire warm season, (b) the pre-Meiyu period, (c) the Meiyu period, and (d) the post-Meiyu period.

Figure 5. Longitude-time Homovöller diagrams of the normalized hourly precipitation deviation without filtering averaged from 27°N to 35°N and over (a) the entire warm season, (b) the pre-
Meiyu period, (c) the Meiyu period, and (d) the post-Meiyu period. The solid lines denote the eastward propagation of the primary coherent diurnal precipitation peak while the dashed lines denote other secondary or less-coherent eastward propagation modes.

**Figure 6.** Normalized diurnal precipitation deviations at (a) 00, (b) 03, (c) 06, (d) 09, (e) 12, (f) 15, (g) 18, and (h) 21 UTC averaged over the entire warm season. Scales smaller than 300 km are truncated by a 2-D spectral decomposition technique as in Lin and Zhang (2008).

**Figure 7.** Map plots of (a) the daily rainfall (mm), (b) the diurnal percentage of the daily rainfall (%), and (c) the daily diurnal rainfall (mm) latitudinally averaged from 27°N to 35°N during different periods. The gray solid curves show the average terrain elevation (m).

**Figure 8.** Same as Figure 6 but for the pre-Meiyu period.

**Figure 9.** Spatial distribution of the 850 hPa vertical motions deviation (unit: cm/s, colored) and perturbation wind vectors diagnosed with the GFS analyses at (a) 06, (b) 12, (c) 18, and (d) 00 UTC averaged over the pre-Meiyu period.

**Figure 10.** Vertical profiles of the vertical motion deviations (unit: cm/s, colored), the perturbation vertical circulation vectors (zonal wind and 100 times of vertical velocity) and the perturbation meridional winds (0.2 m/s; solid blue, positive; dashed, negative) latitudinally averaged between 27°N-35°N diagnosed with GFS analyses at (a) 06, (b) 12, (c) 18 and (d) 00 UTC during the pre-Meiyu period. The pink solid curves show the averaged normalized diurnal precipitation deviations with the pink dashed straight line as the zero value. The black solid curves show the averaged terrain elevations. The green solid lines show the zonal wind is equal
to the mean diurnal propagation speed of 15 m/s. S0, S1, S2, S3 show the approximate solenoidal centers.

**Figure 11.** Same as Figure 6 but for the Meiyu period. The red dashed box denotes the primary Meiyu front rain belt.

**Figure 12.** Same as Figure 9 but for the Meiyu period.

**Figure 13.** Same as Figure 10 but for the Meiyu period with the green solid lines showing the zonal wind is equal to the mean diurnal propagation speed of 13 m/s during the Meiyu period.

**Figure 14.** Same as Figure 6 but for the post-Meiyu period.

**Figure 15.** Same as Figure 9 but for the post-Meiyu period.

**Figure 16.** Same as Figure 10 but for the post-Meiyu period.

**Figure 17.** Time-latitude diagrams of averaged mid-tropospheric zonal wind speed (shaded; m/s) diagnosed with the GFS analyses from May 1 to August 15 over (a) the west subdomain averaged between 102-110°E and for pressure levels between 500-350 hPa, and (b) the east subdomain averaged between 112-120°E and for pressure levels between 600-450 hPa. The gray solid curves show the area-mean zonal wind speed (m/s) averaged over (a) the west subdomain (27-35°N, 102-110°E) and (b) the east subdomain (27-35°N, 112-120°E).
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