Multiscale Processes of Heavy Rainfall over East Asia in Summer 2020: Diurnal Cycle in Response to Synoptic Disturbances

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ABSTRACT

Multiscale processes from synoptic disturbances to diurnal cycles during the record-breaking heavy rainfall in summer 2020 were examined in this study. The heavy rainfall consisted of eight episodes, each lasting about 5 days, and were associated with two types of synoptic disturbances. The Type-1 episodes featured a northwestward extending western Pacific subtropical high (WPSH), while the Type-2 episodes had approaching midlatitude troughs with southward retreat in the WPSH. Each heavy rainfall episode had 2–3 occurrences of nocturnal low-level jets (NLLJs), in close association with intense rainfall in the early morning. The NLLJs formed partly due to the geostrophic wind by increased pressure gradients under both types of synoptic disturbances. The NLLJs were also driven by the ageostrophic wind that veered to maximum southerlies at late night due to the boundary-layer inertial oscillation. The diurnal amplitudes of low-level southerlies increased remarkably after the onset of Type-1 episodes, in which the extending WPSH provided strong daytime heating from solar radiation. By contrast, the wind diurnal amplitudes were less changed after the onset of Type-2 episodes. The NLLJs strengthened the mesoscale mean ascent, net moisture flux convergence, and convective instability in elevated warm moist air, which led to the upscale growth of MCSs at the northern terminus of the LLJ after midnight. The MCSs-induced Meiyu rainband was re-established in Central China during the Type-1 episodes with the increased diurnal variations. The findings highlight that the regional diurnal cycles of low-level winds in response to synoptic disturbances can strongly regulate mesoscale convective activities in a downscaling manner, and thus produce heavy rainfall.
1. Introduction

Persistent heavy rainfall can result in devastating disasters with enormous losses in the economy and society during the warm season (e.g. Tang et al. 2006; Groisman et al. 2012). The heavy rainfall can usually last for several days to 1-2 weeks, and are influenced by the variations in large-scale atmospheric conditions from synoptic to subseasonal time scales (Ninomiya 2000; Qian et al. 2004; Wang et al. 2012; Trier et al. 2014; Guan et al. 2020). A long-lived heavy rainfall episode may consist of successive MCSs that develop in several days following similar paths and produce torrential rainfall within a narrow latitude corridor (Fritsch et al. 1986; Carbone et al. 2002; Tuttle and Davis 2006; Carbone and Tuttle 2008; Jiang et al. 2006; Wang et al. 2014; Chen et al. 2017). Understanding the persistent heavy rainfall episodes and related multiscale processes is important for the prediction of extreme weather and prevention of flood-induced disasters (Feng et al. 2016, 2019; Schumacher and Rasmussen 2020; Clark et al. 2021; Takahashi and Fujinami 2021).

Previous studies have revealed that persistent heavy rainfall episodes are strongly influenced by the diurnal cycles (Carbone et al. 2002; Tuttle and Davis 2006; Ninomiya and Shibagaki 2007; Sun and Zhang 2012; Trier et al. 2014; Chen et al. 2017; Xue et al. 2018; Zhang et al. 2018). Persistent rainfall episodes tend to have a primary peak in the early morning due to long-lived and well organized nocturnal MCSs over East Asia (Geng and Yamada 2007; Yu et al. 2007; Guan et al. 2020; Zhang et al. 2020), which are analogous to those over North America (Carbone et al. 2002; Tuttle and Davis 2006; Jiang et al. 2006; Trier et al. 2014). These morning peak in heavy rainfall is greatly affected by the regional diurnal variabilities in low-level winds that accelerate at night and form nocturnal low-level jets (NLLJs) (Augustine and Caracena 1994; Monahan et al. 2010; Rife et al. 2010; Du and Rotunno 2014). The NLLJs can strengthen northward moisture transport at night and induce net moisture flux at their northern terminus (Ninomiya 2000; Yamada et al. 2007; Chen et al. 2013; Xue et al. 2018). The NLLJs are also conducive to mesoscale ascent and convective instability for the growth of nocturnal MCSs (Tuttle and Davis 2006; Carbone and Tuttle 2008; Chen et al. 2017; Trier et al. 2014, 2017; Schumacher and Rasmussen 2020). The heavy rainfall episodes over East Asia are also found to exhibit a secondary peak in the afternoon, which are produced by short-lived small convections due to convective instability induced by solar heating (Yu et al. 2007; Guan et al. 2020; Zhang et al. 2020).
Recent studies have noted that regional diurnal processes may change with variations in large-scale atmospheric conditions, which can regulate the detailed features of heavy rainfall (Tuttle and Davis 2006; Wang et al. 2014; Trier et al. 2014; Shin et al. 2019). Southwesterly winds over East Asia may have large or small diurnal amplitudes depending on the thermal conditions over the landmass (Guan et al. 2020; Chen G. 2020; Zhang et al. 2020). The diurnal cycle of wind at a given intensity may last for days as the subtropical high modulates background winds and low-level warming, which can determine the preferred hours and locations of repeated MCSs (Zeng et al. 2019). Such a strong coupling between regional wind diurnal variations and large-scale conditions can account for the diurnal peaks of heavy rainfall (Trier et al. 2014; Shin et al. 2019) and long-term variations in East Asian rainfall (Guan et al. 2020; Chen et al. 2021; Wu and Chen 2021). Most previous studies have investigated the large-scale conditions or diurnal cycles from climate-mean perspectives, and the diurnal cycles that evolve with the synoptic variations that influence the MCSs are less well understood in persistent heavy rainfall episodes.

The most significant rainy season over East Asia (namely, Meiyu in Chinese, Baiu in Japanese, or Changma in Korean) is characterized by frequent persistent heavy rainfall episodes that influence large populations (Tao and Chen 1987; Ninomiya and Murakami 1987; Oh et al. 1997). During the Meiyu season (June-July) of 2020, persistent heavy rainfall episodes occurred repeatedly within 29°N–34°N from Central China to Southwest Japan. These episodes yielded torrential rainfall with the maximum amount exceeding 1000 mm (Figure 1a), which became the largest Meiyu rainfall in the last 60 years (Ding Y. et al. 2021). To date, this extreme Meiyu rainfall has been recently studied from the aspects of variabilities at local, diurnal, mesoscale, synoptic, subseasonal, interannual and interdecadal time scales. For instance, the interannual/interdecadal variations in SST over tropical oceans were shown to result in anomalous anticyclonic circulation over the western North Pacific and anomalous cyclonic circulation over northeastern Asia to support 2020 Meiyu heavy rainfall (Takaya et al. 2020; Guo et al. 2021; Pan et al. 2021; Zheng and Wang 2021). Subseasonal variations, such as shifts in the NAO phase, the quasi-biweekly oscillations in the western North Pacific subtropical high and the quasi-stationary MJO over the Indo-Pacific, also played an important role in 2020 Meiyu (Liu et al. 2020; Ding L. et al. 2021; Ding Y. et al. 2021; Qiao et al. 2021; Zhang et al. 2021).
The 2020 Meiyu rainfall was also found to have variations at shorter time scales from several days to several hours. For instance, Ding Y. et al. (2021) pointed out that the 2020 Meiyu underwent six subperiods of severe rainfall, in association with several-day variations in the subtropical high, low-level southwesterly winds, and upper-level westerly jet. Qian et al. (2021) noted nine heavy rainfall episodes with durations of about one week in association with narrow belts of anomalous convergence and positive moist vorticity, which were accompanied by mesoscale disturbances along the Meiyu front. Chen T. et al. (2020) revealed morning peaks in the 2020 Meiyu heavy rainfall from a seasonal-mean perspective, which may have been related to the nocturnal increases of southwesterly winds. Figure 1b shows that, during the 2020 Meiyu season, strong southwesterly winds were prevalent on the northwestern flank of the western Pacific subtropical high (WPSH) with a large amount of warm moist air (equivalent potential temperature, $\theta_e > 350$K) over Southeast China. Such warm moist conditions over the landmass may be conducive to the nocturnal increases of southwesterly winds (Chen G. 2020). If so, we expect that the northward transport of warm moist air from the south to the rainfall area could be most efficient at night, thereby influencing the nocturnal MCSs to produce persistent heavy rainfall episodes (Augustine and Caracena 1994; Shinoda et al. 2005; Trier et al. 2006; Yamada et al. 2007; Chen et al. 2017; Xue et al. 2018). As several synoptic disturbances were noted to have occurred during the 2020 Meiyu season (Ding L. et al. 2021; Ding Y. et al. 2021; Qian et al. 2021), their evolutions could have possibly modulated regional heating conditions and thus diurnal processes (Zeng et al. 2019; Trier et al. 2014). Therefore, the repeated occurrences of Meiyu heavy rainfall episodes in 2020 offer an opportunity to study the multiscale processes linking synoptic conditions to the regional diurnal cycles and convective systems.
Figure 1. (a) Accumulated rainfall amount (mm) during June–July 2020, derived from the IMERG dataset. (b) 850-hPa equivalent potential temperature (K, shading), 850-hPa winds (short and long barbs denoting wind speeds of 2 and 4 m s$^{-1}$, respectively) and the 500-hPa geopotential height (gpm, contours), averaged during June–July 2020, derived from the ERA5 reanalysis. The black rectangle in (a) denotes the rainband in Central China (28°N–35°N, 105°E–122°E). The black rectangle in (b) denotes Southeast China (23°N–29°N, 107°E–120°E). The white areas in (b) denote topography higher than 1500 m. The white line in (b) denotes the cross section from A (21°N, 106°E) to B (34°N, 120°E) to make Figure 6.
The present study aims to explain the multiscale processes of heavy rainfall in which synoptic conditions may affect mesoscale rainfall systems by modulating regional diurnal cycles. Specifically, we examine several episodes of heavy rainfall in which the diurnal cycles and large-scale conditions underwent several-day evolutions during the 2020 Meiyu season. We emphasize how the diurnal cycle of low-level winds responds to synoptic disturbances and how such multi-scale processes influence convective systems during multiday heavy rainfall episodes. The rest of this paper is organized as follows. Section 2 introduces the dataset used in this study. Section 3 presents the characteristics of Meiyu heavy rainfall and atmospheric conditions at both synoptic and diurnal time scales. The mechanisms of the NLLJs formation linked to large-scale atmospheric conditions are investigated in Section 4. The influence of NLLJs on mesoscale rainfall systems under different synoptic disturbances are examined in Section 5. Finally, the conclusion and discussion are offered in Section 6.

2. Data used in this study

The rainfall analysis was conducted using the NASA Global Precipitation Mission Integrated Multi-Satellite Retrievals (IMERG) version 6 which merges precipitation estimations from constellation satellite and rain gauge data (Hou et al. 2014; Huffman et al. 2015). IMERG offers precipitation estimation at fine temporal intervals of 30 minutes and a spatial resolution of 0.1°, which can capture the mesoscale features and diurnal variations of rainfall systems (Cui et al. 2020). The IMERG product captures the spatial distributions, overall amount, and probability distribution of extremely heavy rainfall over China (Fang et al. 2019). The dataset also reproduces the daily mean precipitation intensity well (Tang et al. 2016), which may help to capture variations at the synoptic time scale. The diurnal cycle of rainfall amount over China estimated from the IMERG product compares well with the ground-based observations, although the rainfall intensity in the early morning is slightly overestimated (Li et al. 2018). Therefore, the new-generation IMERG product is used to show the 2020 Meiyu heavy rainfall with variations at synoptic and diurnal time scales in this study. Radar mosaics were used to characterize the convective nature of rainfall. These radar mosaic comprise observations from the China Next Generation Weather Radar network with image processing and other quality-control procedures (Bai et al. 2020a). These data were available every 6 min at a horizontal resolution of ~2 km, which can resolve well the diurnal cycle and spatial distributions of the occurrence of convection initiation over China (Bai et al. 2020b).
Atmospheric conditions are depicted using the recent fifth-generation reanalysis dataset of ERA5 from the European Centre for Medium-range Weather Forecasts (Hersbach et al. 2020). The ERA5 reanalysis has a time interval of 1 hour and horizontal grid spacing of 0.25° with 37 vertical levels, resulting in improved resolution compared with prior reanalysis products, such as the ERA-interim. The high-resolution ERA5 dataset allows a detailed investigation of severe weather environments, and is suitable for the analysis of extremely heavy rainfall (Li et al. 2020; Taszarek et al. 2020). The ERA5 reanalysis has good performance in representing diurnal processes over China (Chen et al. 2014, 2021; Du and Chen 2019). Jourdier (2020) found that the ERA5 has decreased wind speed at 17–18 LST and 05–06 LST, which may be due to 4D-Var data assimilation using the 12-hour windows of 05–17 LST and 17–05 LST (the following day). To avoid this issue, the daily mean wind is estimated as an average of 20 LST and 08 LST and the wind diurnal deviation is calculated by subtracting the daily mean. By doing so, the ERA5 dataset agrees well with the reliable performance of other mainstream reanalysis data in showing the daily mean and diurnal cycles over East Asia (Chen et al. 2021).

3. Multiscale characteristics of rainfall and atmospheric conditions

a. Synoptic episodes of heavy rainfall and related atmospheric conditions

We first examine the subseasonal and multiday variations in rainfall averaged over eastern China. Prior to mid-June, rainfall mostly occurred south of 28°N (Fig. 2a). During June 11 to July 28 (the Meiyu period), the rainfall with mean rain rates larger than 1 mm h\(^{-1}\) was confined to 28°N–35°N latitude. The Meiyu period in 2020 had a duration of up to 48 days, which was twice as long as the climate-mean Meiyu period, and caused excessive rainfall in Central China (Fig. 1a). After late July, the rainfall moved north of 34°N, and some rainfall occurred south of 23°N (Fig. 2c). These northward movements (blue rectangles) of rainfall are well-known subseasonal variations in the East Asian rainband (Ding and Chan 2005).

Figure 2a also shows that the intense rainfall during the Meiyu season was concentrated in ten episodes, as marked by E1–E10. Eight of the episodes (except for E5 and E10) lasted for 4–7 days. Each episode included several MCSs that developed on 2–3 consecutive days at similar latitudes, and the maximum rain rates exceeded 5 mm h\(^{-1}\) (the typical maximum hourly rain rate during these episodes). These multiday episodes with intense rainfall in narrow latitudinal bands can be called heavy rainfall corridors,
which occur during both the warm seasons of North America (Fritsch et al. 1986; Carbone et al. 2002; Tuttle and Davis 2006) and East Asia (Chen et al. 2017; Guan et al. 2020). The other two episodes (E5 and E10) had short durations of less than 2 days, and their longitudinally averaged rain rates were mostly weaker than 4 mm h$^{-1}$.

Figure 2. Time-latitude variations of rain rate (mm h$^{-1}$), average over 105°E–122°E, derived from the IMERG estimation. The blue contours denote a rain rate of 5 mm h$^{-1}$. The blue rectangles denote the subseasonal march of the summer rainband. The red rectangles denote the synoptic episodes of heavy rainfall during the 2020 Meiyu period.
The black vertical lines denote the beginning date (June 11) and ending date (July 28) of the 2020 Meiyu period. The gray-dashed vertical lines denote the 08 LST for each day.

To facilitate the analyses, we defined the multiday episodes of heavy rainfall using objective criteria and specified their onset days. A rainfall episode was defined if the daily rainfall averaged over Central China (28°N–35°N, 105°E–122°E) exceeds the climate-mean value by one standard deviation and persists for more than 2 days. The onset of episodes denoted the first day when the anomalous daily rainfall occurred. Each episode (Figure 3) had anomalous heavy rainfall for 2–3 days after the onset, while the rainfall was suppressed 1–2 days before the onset. Episodes had an average life cycle of about 5 days, suggesting that the Meiyu rainfall episodes were closely related to synoptic variations. We compared situations before and after the onset of these episodes to clarify the changes in synoptic disturbances and their impacts. It is also noted that the rainfall amounts, durations and locations of these rainfall episodes defined in our study generally match with those episodes defined in recent studies (Ding Y. et al. 2021; Liu et al. 2020; Qian et al. 2021), despite of a small discrepancy due to different selection criteria and periods of study.

Figure 3. Daily rainfall of 2020 (red line, mm day$^{-1}$), the climate mean (black line, mm day$^{-1}$) and the climate mean daily rainfall plus its standard deviation (blue line, mm day$^{-1}$), averaged over Central China (28°N–35°N, 105°E–122°E), derived from the IMERG estimation. The ten heavy rainfall episodes (E1-10) with the days before the onset (open circles) and after the onset (closed circles) are marked on the x-axis. The black-dashed vertical lines denote the beginning date (June 11) and ending date (July 28) of the 2020 Meiyu period.

We further examined the daily evolution of large-scale atmospheric conditions associated with rainfall episodes. Figure 4a shows that during the Meiyu season, the WPSH was well established in Southeast China. The northern boundary of the WPSH
experienced several disturbances within 25°N–32°N, as the 5880-gpm contour extended northward and then retreated southward. The WPSH moved northward by more than 5°N during the onset of four episodes (E1, E4, E7 and E9), as shown by the arrows in red. In contrast, during the onset of the other four episodes (E2, E3, E6 and E8), the WPSH tended to retreat southward (blue arrows) and the low-pressure systems in midlatitudes (35°N–40°N) intruded southward (black arrows). The onset of heavy rainfall episodes was characterized by two different types of synoptic disturbances. Figure 4a also shows that the rainfall was shifted northward remarkably after the onset of E1, E4, E7 and E9, while it maintained at similar latitudes during E2, E3, E6 and E8. Therefore, the Meiyu rainband had four occurrences of northward jumps and was re-established at ~32°N after the onset of the first group of episodes (E1, E4, E7, and E9), with an interval of about two weeks. This indicated that the synoptic episodes of the Meiyu rainfall were related to the synoptic variations (Ding L. et al. 2021) and bi-weekly oscillations of the WPSH (Ding Y. et al. 2021).
Figure 4. Time-latitude variations of daily (a) geopotential height (gpm, shading and contours) at 500 hPa, (b) temperature (K, shading) at 850 hPa, and (c) winds (short and long barbs denoting wind speeds of 2 and 4 m s$^{-1}$, respectively) and wind speed (m s$^{-1}$, shading) at 850 hPa. The wind speed larger than 12 m s$^{-1}$ is shown by white-dotted contours and thickened wind barbs. All of these variables are averaged over 107°E–120°E. In all plots, the daily rainfall of 20 (50) mm over 105°E–122°E are hatched in light (dark) blue. The ten heavy rainfall episodes (E1-10) with the days before the onset (open circles) and after the onset (closed circles) are marked on the x-axis. The black
vertical lines denote the beginning date (June 11) and ending date (July 28) of the 2020 Meiyu period.

Figure 4b shows that, along with the variations in the WPSH, Southeast China experienced lower-tropospheric warming during each of the eight episodes except for E5 and E10. The onset of four episodes (E1, E4, E7 and E9) was characterized by warming, as the 850-hPa temperature increased by more than 2K. In contrast, the temperature increase was smaller than 1K after the onset of E2, E3, E6 and E8. The warming mainly occurred in 25°N–30°N, several hundred kilometers south of the heavy rainfall, which may provide warm static energy for the Meiyu rainfall (Shinoda et al. 2005; Yamada et al. 2007). Figure 4c shows that the low-level winds in 25°N–30°N also experienced eight enhancements with the daily wind speed exceeding 12 m s\(^{-1}\). Strong southwesterly winds occurred on 2–3 consecutive days during each of the eight episodes. Strong southwesterly winds are well known to be crucial for transporting moisture and warm static energy for Meiyu heavy rainfall (Qian et al. 2004; Ding et al. 2020).

In summary, the eight episodes of heavy rainfall repeatedly occurred in Central China, with each lasting for about 5 days. They were accompanied by different synoptic variations, i.e., the northward extensions of the WPSH or the southward movements of the midlatitude low-pressure systems. These synoptic disturbances were associated with low-level warming and strong southwesterly winds over Southeast China. The evolutions of heavy rainfall and related synoptic conditions on the onset days seemed to vary among episodes, which are examined next.

b. Diurnal variations in precipitation and low-level winds

Figure 5 shows that during the Meiyu season, the daily mean southerly winds were enhanced after the onset of the eight episodes except for E5 and E10. The low-level southerly winds also exhibited large diurnal variations that were strengthened after midnight and maximized during 02–05 LST. The southerly winds attained their maximum wind speed of up to 12 m s\(^{-1}\) (white-dotted lines) and thus formed NLLJs on 2–3 consecutive days after the onset of each episode. During E1, E4, E7 and E9, the NLLJs had a maximum wind speed (NLLJ core) at ~23°N before the onset, shifted northward to ~27°N after the onset, and then retreated southward slowly (white-solid lines). These northward shifts in the NLLJ core after the onset were closely related to the movements of the WPSH (Fig. 4a). The diurnal amplitudes of wind speed were estimated...
as ~1 m s$^{-1}$ before the onset and were enhanced to ~3 m s$^{-1}$ after the onset of these episodes. On the onset days of the other episodes (E2, E3, E6, and E8), the northward shifts in the NLLJ core were relatively small, and the increases in wind diurnal amplitudes were mostly less than 1 m s$^{-1}$. This evolution of NLLJs and wind diurnal amplitudes seemed to occur with southward intrusion of the midlatitude systems and southward retreat of the WPSH (Fig. 4a). During the other two episodes (E5 and E10), the NLLJs did not form as the background winds and their diurnal amplitudes were relatively small. In the rest of this article, we excluded the E5 and E10, so that we could focus on the eight episodes to see how the NLLJs responded to different types of synoptic variations and influenced heavy rainfall.
Figure 5. Time-latitude variations of hourly meridional winds (m s\(^{-1}\), shading) at 850 hPa, averaged over 107°E–112°E. The wind speed of 12 m s\(^{-1}\) is shown by white-dotted contours. The hourly rain rate averaged over 105°E–122°E larger than 1 mm h\(^{-1}\) (5 mm h\(^{-1}\)) is hatched in medium (dark) blue. The bold-white curve denotes the latitudes of instantaneous maximum meridional wind speed. The ten episodes of heavy rainfall with the days before the onset (green sections) and after the onset (black sections) are marked on the x-axis. The black vertical lines denote the beginning date (June 11) and ending date (July 28) of the 2020 Meiyu period. The gray-dashed vertical lines denote 08 LST for each day. The black horizontal lines denote 23°N and 28°N latitude.
Figure 5 also shows that during the eight episodes with NLLJs, the rainfall was relatively weak before the onset and was intensified after the onset with maximum rain rates exceeding 5 mm h\(^{-1}\). The heavy rainfall underwent northward shifts from ~25°N before the onset to ~32°N after the onset (blue arrows) of the four episodes (E1, E4, E7, and E9). This re-establishment of the Meiyu rainband in Central China corresponded well to the large northward shifts in the NLLJ core (white-solid lines). In contrast, the rainfall was displaced northward by less than ~2°N on the onset days during the other four episodes (E2, E3, E6, and E8), which was related to the small changes in the latitudes of the NLLJs core. We investigate the rainfall diurnal cycles and their relationship with the NLLJs formation by comparing them between the two types of episodes (Type-1: E1, E4, E7, and E9; Type-2: E2, E3, E6, and E8). On the last two days of most episodes, the rainfall decayed with slight southward drifts probably due to the MCS-induced cold pools (Luo et al. 2014; Guan et al. 2020), which are beyond the scope of this study.

We further examined the detailed diurnal cycles of rainfall, convection and low-level winds during the Meiyu season. The rainfall increased after midnight, reached its peak in the early morning (~06 LST), and was sustained until noon (Figure 6a). The rainfall was relatively weak in the afternoon and evening. The convective echo (radar reflectivity above 35 dBz) also increased in the early morning (Fig. 6b), suggesting that the rainfall was mainly produced by moist convection. This dominant morning peak of rainfall and convective echo resembled the rainfall climatology in active Meiyu years (Geng and Yamada 2007; Yu et al. 2007; Chen T. et al. 2020; Guan et al. 2020; Zhang et al. 2020).
Figure 6. (a) Rain rate (mm h\(^{-1}\)) of IMERG and (b) occurrence frequency of convective echo (radar reflectivity >35 dBz), averaged over 105°E–122°E. (c-f) Time-latitude variations in rain rate (mm h\(^{-1}\), shading) and 850-hPa winds (m s\(^{-1}\), short and long barbs denoting wind speeds of 2 and 4 m s\(^{-1}\), respectively. Wind speeds larger than 12 m s\(^{-1}\) are shown by thickened barbs), and diurnal deviations of 850-hPa meridional winds (>1 m s\(^{-1}\), blue contours with intervals of 1 m s\(^{-1}\)) where the daily mean value has been removed. The black-dashed horizontal lines denote the shear lines. The rain rate was averaged over 105°E–122°E. The winds were obtained along the cross section from (21°N, 106°E) to (34°N, 120°E), as shown by the white line in Fig. 1b. The bold gray arrows denote the northward shifts of the shear line from before to after the onset.

For the Type-1 episodes (Fig. 6c), southwesterly winds were mostly seen over Southeast China, and a shear line was established ~29°N before the onset. The rainfall south of the shear line was evident during the daytime (08–19 LST), but it was suppressed during the nighttime (20–07 LST), probably due to the convective instability of daytime heating (Guan et al. 2020; Zhang et al. 2020). Figure 6d shows that, after the onset, the
shear line was displaced from ~29°N to ~34°N, and the southwesterly winds became pronounced south of 34°N. The southwesterly winds south of the shear line were strengthened by ~3 m s$^{-1}$ at late night to form NLLJs, while the wind diurnal amplitudes were negligible north of the shear line. Correspondingly, the rainfall was re-established in Central China (29°N–34°N) at the northern terminus of the NLLJs, with the maximum intensity during 00–05 LST.

During the Type-2 episodes (Figs. 6e,f), the latitude of rainfall and shear line was less changed after the onset compared with that before the onset, while the intensity of rainfall and southwesterly winds was increased slightly. The diurnal amplitudes of southwesterly winds after the onset were comparable to those before the onset, and the rainfall had similar diurnal peaks in the morning. The changes in the rainfall patterns and wind diurnal variations were small after the onset of the Type-2 episodes, in strong contrast to the pronounced changes during the Type-1 episodes. These differences are consistent for the eight individual episodes (not shown). In summary, movement and diurnal cycles of the Meiyu rainband were closely related to differing evolution of the NLLJ in two different synoptic environments.

4. Formation of NLLJs in response to large-scale atmospheric conditions

Given the close relationship between the NLLJs and rainfall diurnal cycle during the synoptic episodes, we investigated the processes governing NLLJs formation and their possible links to large-scale atmospheric conditions. The NLLJs with a maximum wind speed at late night can be decomposed into the enhancements in daily mean wind $s$ and wind diurnal deviation, which are related to different physical mechanisms.

Figure 7a shows that the daily mean southerly winds were enhanced by ~4–5 m s$^{-1}$ on the onset days of the eight episodes. Such enhancements were also found in the geostrophic wind component, while the increases in the ageostrophic wind were negligible. The variations in daily mean winds were highly related to the geostrophic wind during the Meiyu season, with a correlation coefficient of 0.87 that was significant at the 95% confidence level. Figure 7b shows that the variations in wind diurnal amplitudes resulted from the ageostrophic wind with a correlation coefficient of 0.72 that was significant at the 95% confidence level. In particular, on the onset days of Type-1 episodes, the diurnal amplitudes of southerly winds were increased by ~2 m s$^{-1}$ (refer to
the pink arrows). These increasing amplitudes matched the enhancements of ~3 m s\(^{-1}\) in diurnal amplitudes of the ageostrophic wind component, while they were negligible for geostrophic wind. During the Type-2 episodes, the diurnal amplitudes of the ageostrophic wind increased by less than 1 m s\(^{-1}\) (E3, E8) or even decreased (E2, E6) on the onset days (refer to the blue arrows), corresponding to small increases in the diurnal cycle of the total winds.

Figure 7. (a) Daily mean and (b) diurnal range (02 LST − 20 LST) of 850-hPa meridional winds averaged over 26°N–30°N, 107°E–112°E. The total wind (V), geostrophic wind (Vg) and ageostrophic wind (Va) are denoted by red, green and purple lines, respectively. The ten heavy rainfall episodes (E1-10) with the days before the onset (open circles) and after the onset (closed circles) are marked on the x-axis. The black vertical lines denote the beginning date (June 11) and ending date (July 28) of the 2020 Meiyu period.

We further examined the diurnal deviation of low-level winds in Figure 8. The wind diurnal deviation exhibited anomalous northerlies in the afternoon and veered clockwise to anomalous southerlies after midnight during both types of the episodes. This clockwise rotation was mainly seen in the ageostrophic wind deviation but was negligible in the geostrophic wind deviation. The clockwise rotation of wind deviation may be caused by inertial oscillations, which were driven by an unbalance between the pressure gradient

force and the Coriolis force due to the diurnally varying frictional effects of boundary-layer mixing (Blackadar 1957; Du and Rotunno 2014; Zeng et al. 2019). During the Type-1 episodes (cf. Figs. 8a,b), the wind diurnal deviation was ~1.2 m s$^{-1}$ before the onset and was strengthened to ~2 m s$^{-1}$ after the onset, which corresponded to enlarged diurnal deviation of the ageostrophic wind. During the Type-2 episodes (cf. Figs. 8c,d), the wind diurnal deviation after the onset had a magnitude comparable to those before the onset. Therefore, although both types of the episodes underwent enhancements in the daily mean wind (mostly the geostrophic component) after the onset, they featured remarkable differences in the diurnal amplitudes of wind (mostly the ageostrophic component).

Figure 8. The diurnal deviation of 850-hPa wind (where the daily mean value has been removed) at the hours from 18 LST to 10 LST (+1 day), which is averaged over 26°N–30°N, 107°E–112°E. The daily mean values are shown at the bottom right of each plot. The total wind (V), geostrophic wind (Vg) and ageostrophic wind (Va) are denoted by red, green and purple lines, respectively.
To explain the enhanced daily mean geostrophic wind, we investigated the zonal gradients of geopotential height. Figure 9 shows that during the Meiyu season, southerly geostrophic wind was prevalent at 23°N–30°N, where the zonal gradients of geopotential height were eastward directed (positive value). The geostrophic wind was mostly strengthened by ~4 m s⁻¹ from before to after the onset of the eight episodes, which was related to the enlarged gradients by ~3 gpm degree⁻¹. The southerly geostrophic wind was relatively small at 35°N–40°N where the gradients of geopotential height were westward directed (negative value), indicating the influence of midlatitude systems (Fig. 4a).

Figure 9. Time-latitude variations of daily mean zonal gradients of geopotential height (gpm degree⁻¹, shading), meridional geostrophic winds (>4 m s⁻¹, black contours with intervals of 2 m s⁻¹) at 850 hPa, averaged over 107°E–112°E. The daily rainfall amount of 20 (50) mm over 105°E–122°E is hatched in light (dark) blue. The ten heavy rainfall episodes (E1-10) with the days before the onset (open circles) and after the onset (closed circles) are marked on the x-axis. The black vertical lines denote the beginning date (June 11) and ending date (July 28) of the 2020 Meiyu period.

Figures 10a-d show that before the onset of the Type-1 episodes, the southwesterly geostrophic wind was relatively small in Southeast China. After the onset (Figs. 10e-h), the geostrophic wind extended to ~30°N, with the wind speed increasing to ~12.2 m s⁻¹. The geostrophic wind after the onset was ~44% larger than that before the onset, which accounted for ~90% of the enhancement in the total wind speed (not shown). This enhanced geostrophic wind was related to the eastward-directed gradients of geopotential height that were enlarged by ~45% from before the onset to ~6 gpm degree⁻¹ after the
onset. The enlarged gradients were caused by a decreased height of ~10 gpm near the Sichuan Basin (SCB) together with an increased height of ~20 gmp in Southeast China (Figs. 10i-l). The increased geopotential height in Southeast China was related to northwestward extensions of the WPSH (pink hatches in Figs. 10a-h), while the decreased height near the SCB was due to the development of troughs (contours in Figs. 10a-h).

Figure 10. Daily mean zonal gradients of geopotential height (gpm degree$^{-1}$, shading), geostrophic winds $>$8 m s$^{-1}$ (green vectors), and geopotential height (gpm, black contours with intervals of 20 gpm) at 850 hPa, which are composited on the days before the onset (a-d) and after the onset (e-h) for the Type-1 episodes (E1, E4, E7 and E9). The pink-hatched area in (a-h) denotes the 500-hPa daily mean geopotential height larger than 5880 gpm. (i-l) The differences in the daily mean geopotential height (contours with intervals of 10 gpm) with its zonal gradients (gpm degree$^{-1}$, shading), and geostrophic wind (vectors) at 850 hPa before and after the onset. The white areas denote topography higher than 1500 m. The red rectangles denote the Southeast China over 23°N–29°N, 107°E–120°E. The Sichuan Basin is labeled as SCB.
Figures 11a-h show that during the Type-2 episodes, the southwesterly geostrophic wind in Southeast China was strengthened to ~12.3 m s\(^{-1}\) after the onset, which was ~43% stronger than that before the onset. The increases in daily geostrophic wind explained ~65% of the enhancement in total wind (not shown). The enhanced geostrophic wind was due to the increase in eastward-directed gradients of geopotential height by ~32% from before to after the onset. Figures 11i-l further show that the enlarged gradients were mainly caused by the decrease in geopotential height in the eastern part of China. The height decrease was up to ~40 gpm north of 40°N but was less than ~20 gpm south of 30°N, which was related to the approaching midlatitude troughs (contours in Figs. 11a-h) with a southward retreat of the WPSH (pink hatches in Figs. 11a-h). Therefore, the enhanced daily mean geostrophic wind after the onset was mainly due to the northward extending WPSH during the Type-1 episodes, whereas it was primarily due to approaching midlatitude troughs.

Figure 11. Same as Fig.10 but for the Type-2 episodes (E2, E3, E6 and E8).

b. Diurnal variations in ageostrophic wind regulated by synoptic conditions

We examined how synoptic conditions influenced the wind diurnal variations in the NLLJs formation. Previous studies have pointed out that both the large background winds and boundary-layer heating are favorable for enhancing wind diurnal variations (Du and Rotunno 2014; Xue et al. 2018; Zeng et al. 2019; Chen G. 2020). Therefore, we compared the daily mean wind speed and boundary-layer warming under the different synoptic conditions present in the two types of episodes.

Figure 12a shows that before the onset of the Type-1 episodes, the southwesterly wind deviation at 02 LST \( \vec{V}_{02\text{LST}} - \vec{V}_{\text{daily}} \) was mostly smaller than \( \sim 2 \text{ m s}^{-1} \). After the onset (Fig. 12b), the wind diurnal deviation was strengthened to \( \sim 3 \text{ m s}^{-1} \) and extended northward to \( \sim 30^\circ\text{N} \). The daily mean southwesterly winds were strengthened from less than 10 m s\(^{-1}\) before the onset to exceed 16 m s\(^{-1}\) after the onset (black contours), in association with the northwestward extension in the WPSH (white hatches). Figures 12d,e show that during the Type-2 episodes, the southwesterly wind deviation was enhanced by less than 1 m s\(^{-1}\) after the onset compared with those before the onset. The daily mean southwesterly winds were strengthened by \( \sim 6 \text{ m s}^{-1} \) (black contours) from before to after the onset, while the WPSH retreated southward (white hatches). Figure 13a further shows that the late-night wind deviation was positively related to the daily mean wind speed both before and after the onset, with a correlation coefficient of 0.29. These features suggested that the enhanced wind diurnal amplitudes after the onset could be influenced by the enlarged daily mean wind speed under the synoptic disturbances.
Figure 12. (a), (b), (d), (e) Temperature at 18 LST (K, shading), the wind diurnal deviation at 02 LST (vectors) where the daily mean value has been removed, and the daily mean wind speed of southwesterly winds (>10 m s$^{-1}$, contours with intervals of 2 m s$^{-1}$) at 850 hPa. The white-hatched area denotes the 500-hPa daily mean geopotential height larger than 5880 gpm. These four plots are composites on the days before (P1) and after (P2) the onset during the two types of episodes. (c), (f) Differences in downward short-wave radiation at the surface at 14 LST (W m$^{-2}$, shading) and the 850-hPa temperature at 18 LST (>0K, contours with intervals of 1K) between the days after and before the onset during the two types of episodes. The white areas denote topography higher than 1500 m. The dashed rectangles denote the area of 26°N–30°N, 107°E–120°E to make Fig.13.

Figure 13b shows that the late-night wind deviation was positively related to the late-afternoon temperature with a correlation coefficient of 0.56 both before and after the onset. This strong relationship agrees with previous studies that suggested that boundary-layer heating was conducive to inertial oscillations driving the wind diurnal cycles (Du and Rotunno 2014; Zeng et al. 2019; Chen G. 2020). Figure 13b also shows the different evolutions of daytime heating and wind diurnal deviation after the onset of the two types of episodes. During the Type-1 episodes, the late-afternoon temperature mostly increased

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by more than 2K and the late-night wind deviation was enhanced by ~1.2 m s$^{-1}$ from before to after the onset. These enhancements were relatively large over 26°N–30°N (cf. Figs. 12a,b), in association with northwestward extensions of the WPSH. During the Type-2 episodes (Fig. 13b), the late-afternoon temperature only increased by less than 1K and the late-night wind deviation was increased by ~0.8 m s$^{-1}$ from before to after the onset. The small increase in daytime heating was related to the approaching troughs with the retreating WPSH (cf. Figs. 12c,d).

Figure 13. Scatterplots of (a) 850-hPa daily mean wind speed (m s$^{-1}$) with 850-hPa wind diurnal deviation at 02 LST (m s$^{-1}$) where the daily mean value has been removed, (b) 850-hPa temperature at 18 LST with diurnal deviation of 850-hPa wind speed at 02 LST (m s$^{-1}$), and (c) downward short-wave radiation at the surface at 14 LST (W m$^{-2}$) with 850-hPa temperature at 18 LST (K). The correlation coefficients are shown in the bottom right of each plot, where the single (double) star denotes that the value are above the 90% (99%) confidence level. All of these variables are averaged over 26°N–30°N, 107°E–120°E as shown by dashed rectangles in Fig.12.
Figure 13c further shows that the daytime heating was strongly dependent on the short-wave radiation with a correlation coefficient of ~0.7. During the Type-1 episodes, the short-wave radiation was strengthened from ~450 W m\(^{-2}\) before the onset to exceed 700 W m\(^{-2}\) after the onset. The strengthened radiation was most pronounced at 26°N–30°N (Fig. 12c), where the increase in afternoon temperature was larger than 1K. The greater short-wave radiation after the onset was due to less cloudiness under the extending WPSH than that before the onset. Therefore, the wind diurnal amplitudes were largely strengthened after the onset of these episodes. During the Type-2 episodes (Fig. 13c), the short-wave radiation was ~100 W m\(^{-2}\) stronger after the onset than that before the onset, and the daytime heating was slightly stronger, which was consistent with relatively small extensions in the WPSH (cf. Figs. 12d,e). As a result, the wind diurnal amplitudes were slightly enlarged during the Type-2 episodes.

5. Impacts of NLLJs on rainfall systems under two types of synoptic conditions

In this section, we examine the response of rainfall systems to the different synoptic conditions in the two types of episodes. We focus on the role of NLLJs in regulating mesoscale ascent, moisture transport, and warm moist energy, which are conducive to convection growth.

a. Low-level convergence and mesoscale ascent

Figures 14a,b show that before the onset of the Type-1 episodes, weak horizontal convergence was seen south of 28°N and was enhanced slightly in the early morning. After the onset, the horizontal convergence was enhanced and was shifted northward to ~30°N (Figs. 14c,d). The rainband was also displaced northward to 29°N–34°N. The ageostrophic wind was strengthened from ~4 m s\(^{-1}\) before onset to ~6 m s\(^{-1}\) after onset. The strengthened convergence was particularly large in the early morning when the ageostrophic wind veered to a maximum southerly wind (Fig. 14d). The early-morning convergence mostly occurred at the northern terminus of the NLLJs, where the southerly ageostrophic wind had large northward-decreasing gradients. The nocturnal convergence at the northern terminus of the NLLJs had separate maximum centers at ~107°E and ~115°E, where mid-level ascents and upper-level divergence were strong (not shown), corresponding to the locations of two nocturnal MCSs. The early-morning convergence after the onset was two times larger than that before the onset (cf. Figs. 14d,b), while the
afternoon convergence was comparable to that after the onset (cf. Figs. 14c,a). The NLLJs have been shown to induce mesoscale ascent to support nocturnal MCSs in the frontal zone (Augustine and Caracena 1994; Chen et al. 2017; Trier et al. 2017). Here, it was found to be favorable for the morning rainfall of the Meiyu rainband by the enlarged wind diurnal amplitudes under an extending WPSH.
Figure 14. The 850-hPa ageostrophic wind (m s\(^{-1}\), black vectors) and its horizontal convergence (s\(^{-1}\), shading) at 17 LST (left panel) and 05 LST (right panel). These plots are composited on the days before (P1) and after (P2) the onset during the two types of episodes. The blue hatches denote rainfall with rain rates larger than 1 mm h\(^{-1}\). The green-dotted area denotes the 850-hPa southwesterly wind speed larger than 12 m s\(^{-1}\). The white areas denote topography higher than 1500 m.

During the Type-2 episodes with the approaching trough, the horizontal convergence increased from afternoon to early morning both before (cf. Figs. 14e,f) and after the onset (cf. Figs. 14g,h). The diurnal variations of convergence at 30°N were less changed between the two stages of the episodes, which was related to the ageostrophic wind that had a comparable magnitude of 2–3 m s\(^{-1}\). Nevertheless, the early-morning convergence and rainfall after the onset of the Type-2 episodes were weaker than those of the Type-1 episodes (cf. Fig.14h,g). This feature suggested that an extending WPSH was favorable to pronounced nocturnal MCSs by mesoscale ascent due to the NLLJs with large diurnal amplitudes, which has also been noted in other cases (Xue et al. 2018; Zeng et al. 2019).

b. Moisture transport and convective instability

Figures 15a,b show that before the onset of the Type-1 episodes, the northeastward moisture flux and its convergence mostly occurred south of 28°N and increased slightly from the afternoon to the early morning. Figures 15c,d show that, after the onset, the northeastward moisture flux and its convergence were enhanced and shifted to north of 30°N. The moisture flux was ~400 kg m\(^{-1}\) s\(^{-1}\) in the afternoon and strengthened to more than ~600 kg m\(^{-1}\) s\(^{-1}\) in the early morning (cf. Figs. 15d,c). The moisture flux convergence had two local maxima at ~107°E and ~115°E, matching the locations of nocturnal MCSs (Fig. 15d). The early-morning moisture flux convergence after the onset was nearly twice that before the onset (cf. Figs. 15d,b), indicating that the NLLJs were highly efficient in regulating moisture transport and convergence at night. The NLLJs have also been found to strengthen moisture transport in the development of nocturnal MCSs in the other persistent heavy rainfall episodes (Augustine and Caracena 1994; Tuttle and Davis 2006; Chen et al. 2013, 2017; Xue et al. 2018).
Figure 15. The rain rate larger than 1 mm h$^{-1}$ (orange contours with hatches) at 17 LST (left panel) and 05 LST (right panel), water vapor flux (kg m$^{-1}$ s$^{-1}$, vectors) and its horizontal divergence ($10^{-4}$ kg m$^{-2}$ s$^{-1}$, shading) at 1 hour prior to the rainfall. These plots are composited on the days before (P1) and after (P2) the onset during the two types of episodes. The water vapor flux is vertically integrated from the surface to 700 hPa. The white areas denote topography higher than 1500 m.
Figures 15e-h show that during the Type-2 episodes, the moisture flux convergence was sustained at 29°N–34°N both before and after the onset. The moisture flux and its convergence were strengthened from late afternoon to late night by ~30% (cf. Figs. 15e,f and cf. Figs. 15g,h). The early-morning moisture flux and its convergence were slightly stronger after the onset of Type-2 episodes (cf. Figs. 15h,f), in contrast to the greater changes during the Type-1 episodes (cf. Figs. 15b,d). Overall, the early-morning moisture convergence after onset of the Type-2 episodes was weaker than that of the Type-1 episodes (cf. Fig. 15d,h). These differences were highly similar to those of the wind diurnal variations and resultant convergence. Therefore, the wind diurnal variations, which were regulated by different synoptic conditions, could influence the diurnal variations in moisture flux and thus influence the nocturnal MCSs.

The NLLJs have been recognized as an important conveyer of warm moist air for Meiyu rainfall and become more efficient in moisture transport at night as the winds speed up (Chen et al. 2013; 2017; Xue et al. 2018; Zeng et al. 2019). Thus, we investigated the diurnal variations of warm moist air. Figure 16a shows that before the onset of the Type-1 episodes, the boundary-layer warm moist air (θₑ >350K) was mostly concentrated south of 28°N. The warm moist air in the afternoon had large θₑ near the surface and decreased upward (Fig. 16a), forming convective instability for daytime convection. The warm moist air had reduced θₑ at late night (Fig. 16b) due to radiative cooling. The warm moist air north of 28°N had relatively small θₑ with little diurnal variation. Figures 16c,d show that, after the onset, the warm moist air was extended northward to 33°N due to the enlarged warming area under an extending WPSH (Fig. 12b). In particular, in 29°N–34°N, the maximum θₑ was considerably elevated to ~900 hPa in the early morning (Fig. 16d), in strong contrast to that before the onset (Fig. 16b). The elevated θₑ maximum in the early morning was located at the northern terminus of the NLLJs (black contours), where low-level ascent was evident (blue contours). These features suggest that the NLLJs-advected warm moist air from Southeast China was fed into the Meiyu frontal zone and was tilted up with local ascent at night (Chen et al. 2017; Zeng et al. 2019). Such elevated warm moist air produced convective instability with a CAPE of ~1600 J kg⁻¹ (not shown). This unstable condition was favorable for the growth of nocturnal MCSs and helped the rainband to re-establish in Central China.
Figure 16. The latitude-vertical sections of equivalent potential temperature (K, shading), southerly winds (>4 m s$^{-1}$, black contours with intervals of 2 m s$^{-1}$) and vertical velocity (<0.2 Pa s$^{-1}$, blue-dashed contours with intervals of 0.2 Pa s$^{-1}$) along 115°E. These plots are composited on the days before (P1) and after (P2) the onset during the two types of episodes. The white dashed rectangles denote the warm moist air.
Figures 16e-h show that during the Type-2 episodes, the warm moist air was mainly located south of 30°N both before and after the onset. Strong ascending motion was maintained in the frontal zone of 29°N–32°N (as indicated by relatively large meridional gradients of $\theta_e$). The warm moist air had relatively large $\theta_e$ near the surface in the afternoon (Figs. 16e,g). The warm moist air in the frontal zone had an elevated $\theta_e$ maximum at ~900 hPa in the early morning, in association with relatively strong southwesterly winds and ascending motion (Figs. 16h). Nevertheless, the early-morning elevated $\theta_e$ maximum after the onset was less changed (or slightly enhanced) than that before the onset (cf. Figs. 16h,f). Such elevated warm moist air in the early morning led to a moderate CAPE of ~1200 J kg$^{-1}$ (not shown), which produced convective instability to facilitate the nocturnal MCSs for both before and after the onset of the Type-2 episodes.

6. Conclusion and discussion

In this study, we examined multiscale processes in several heavy rainfall episodes during the 2020 Meiyu season, with emphasis on the diurnal cycles regulated by different synoptic disturbances. The connections of large-scale atmospheric conditions to regional wind diurnal cycles and their impacts on MCSs were clarified. The major findings were summarized as follows:

The 2020 Meiyu rainfall included eight heavy rainfall episodes, each lasting for about 5 days. The eight episodes were associated with two types of synoptic disturbances, including the northwestward extending WPSH (Type-1) or the approaching midlatitude troughs (Type-2). These heavy rainfall episodes exhibited significant diurnal variations. The low-level southwesterly winds strengthened at night and formed NLLJs on 2–3 consecutive days during each episode. During the Type-1 episodes, the southwesterly winds and their diurnal amplitudes were relatively weak before the onset of heavy rainfall. Daytime rainfall occurred in the warming area south of 28°N due to convective instability from heating. After the onset, when the WPSH extended northward, the wind diurnal amplitudes were enhanced to ~3 m s$^{-1}$ and the NLLJs formed. The rainband was re-established at 29°N–34°N with peaks in the early morning. During the Type-2 episodes, the NLLJs had smaller latitudinal shifts with comparable wind diurnal amplitudes before and after the onset. The rainfall was maintained in Central China with morning peaks, which was strengthened after the onset.
NLLJ intensity was influenced by enhanced daily mean wind speed and diurnal amplitudes from before to after the onset, which were associated with two types of synoptic variations. Both types of episodes had similar enhancements in the daily mean wind speed that was related to strengthened geostrophic wind after the onset. The strengthened geostrophic wind resulted from the increased eastward directed gradients of geopotential height by the northwestward extending WPSH during the Type-1 episodes or by approaching midlatitude troughs during the Type-2 episodes. The enlarged diurnal amplitudes in the NLLJs formation were due to the clockwise rotation of ageostrophic wind that was driven by boundary-layer inertial oscillations. The increase in wind diurnal amplitudes after the onset was pronounced during the Type-1 episodes, in which the daytime heating by solar radiation was strongly enhanced under an extending WPSH. During the Type-2 episodes, the enlarged wind diurnal amplitudes were mainly due to enhanced background winds rather than daytime heating because the WPSH retreated.

The NLLJs were favorable for the development of nocturnal MCSs and thus coincided with early-morning peaks of heavy rainfall. The NLLJs enhanced the horizontal convergence or mesoscale ascent at late night due to the southerly ageostrophic wind, which helped to trigger several MCSs at their northern terminus. The NLLJs efficiently transported moisture and warm air from the southern warming area to the Meiyu frontal area at night, inducing moisture convergence and convective instability to support the growth of nocturnal MCSs. These impacts of NLLJs gave rise to nocturnal MCSs on 2–3 consecutive days during each episode and thus produced heavy rainfall at similar latitudes. The NLLJs with morning rainfall were more pronounced during the Type-1 episodes than those during the Type-2 episodes, and were associated with greater diurnal amplitudes of horizontal wind speed under the northwestward extending WPSH. The morning rainfall during the Type-2 episodes was slightly strengthened after the onset due to relatively strong ascending motions between the approaching troughs and the WPSH.

The heavy rainfall episodes during the 2020 Meiyu season resembled the climatology of rainfall corridors over East Asia that reoccurred in latitudinal bands over 29–34°N (Guan et al. 2020), though they occurred southward of those found in North America (Carbone et al. 2002; Tuttle and Davis 2006). The dominant early-morning peaks of rainfall during these episodes were also consistent with rainfall corridor climatology over East Asia (Chen et al. 2017; Guan et al. 2020) and North America (Tuttle and Davis 2006; Carbone and Tuttle 2008; Trier et al. 2014). Anomalous synoptic patterns with
pronounced diurnal cycles have been found to exist in other heavy rainfall corridors (Carbone and Tuttle 2008; Trier et al. 2014; Guan et al. 2020). The linkages between synoptic variations and diurnal cycles were examined in this study, and further comparisons among persistent heavy rainfall episodes in other flooding years are needed (Ding et al. 2020; Clark et al. 2021; Chen et al. 2021; Ding L. et al. 2021; Pan et al. 2021; Wang et al. 2021). Moreover, cloud-radiation forcings could be one of the key processes linking the large-scale conditions to regional diurnal cycles as noted in this study and others (Yamada et al. 2007; Chen G. 2020; Wu and Chen 2021). Our ongoing studies will focus on thermodynamic forcings of large-scale circulation that provide warm moist conditions to support diurnal cycles in heavy rainfall episodes.

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Data Availability Statement

The Integrated Multi-Satellite Retrievals (IMERG) final run data used during this study are openly available from the Global Precipitation Mission of NASA at https://gpm.nasa.gov/data/directory. The radar mosaic maps over China used in this study are available online at http://www.nmc.cn/publish/radar/huadong.html. The image processing and quality-control procedures were conducted on the radar mosaic maps as following Bai et al. 2020a. The fifth-generation reanalysis dataset of ERA5 from the European Centre for Medium-range Weather Forecasts is openly available at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels.

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