Contrasting Pre-Mei-Yu and Mei-Yu Extreme Precipitation in the Yangtze River Valley: Influencing Systems and Precipitation Mechanisms

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ABSTRACT

The mei-yu season over the Yangtze–Huai Rivers basin, typically occurring from mid-June to mid-July, is one of three heavy-rainfall periods over China and can contribute 50% of the annual precipitation. In this study, the first and second heaviest daily precipitation events at the Wuhan station have been selected to represent typical mei-yu and pre-mei-yu precipitation events where the differences in the atmospheric thermodynamic characteristics, precipitation nature, influencing systems, and mechanisms are investigated. During the mei-yu case, moist air mainly came from the South China Sea. Precipitation occurred south of the mei-yu front where abundant moisture and favorable thermodynamic conditions were present. The main influencing systems include a stable blocking pattern and strong and stable western Pacific subtropical high in the midtroposphere, and a small yet intense mesoscale cyclonic vortex in the low troposphere. Rainfall in Wuhan was continuous, caused by a well-organized convective line. A heavy rainband was located along the narrow band between the elongated upper-level jet (ULJ) and the low-level jet (LLJ) where the symmetric instability was found in the midtroposphere near Wuhan. Quite differently, for the pre-mei-yu precipitation case, moist air primarily came from the Beibu Gulf and the Bay of Bengal. Precipitation happened in the low-level convective instability region, where a short-wave trough in the midtroposphere and a mesoscale cyclonic vortex in the low-troposphere were found. Precipitation in Wuhan showed multiple peaks associated with independent meso- β -scale convective systems. A rainstorm occurred at the exit of the LLJ and the right entrance of the ULJ, where convective instability existed in the mid- to low troposphere.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) suggests that extreme precipitation events will become more intense as a result of global warming (IPCC 2007). This phenomenon is particularly important over land at middle

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to high latitudes (Trenberth and Fasullo 2010). During recent years, floods have caused billions of dollars in property damage within the United States, China, India, Pakistan, and other countries (Zhou et al. 2018). Changes in extreme weather and climate events have significant impacts and are among the most serious challenges to scientists (Seneviratne et al. 2012; Qin et al. 2015).

The mei-yu season over the Yangtze–Huai Rivers basin, typically occurring from mid-June to mid-July, is one of three heavy-rainfall periods over China (Ding 1992; Luo et al. 2014; Cui et al. 2015). In some years, mei-yu precipitation can contribute 50% of the annual precipitation (Liu and Wang 2006). The mei-yu period is characterized by the presence of a quasi-stationary cloud band extending from southern Japan to southern China (Geng 2014), in association with an abrupt northward migration and maintenance of the East Asian summer monsoon (Ding 2005; Sampe and Xie 2010). At the surface, the cloud band is associated with a quasi-stationary front (the mei-yu front; Hsu and Sun 1994). To the south side of the mei-yu front, winds are from the southwest in the lower troposphere, carrying much warm and moist air. To the north side of the front, the northwesterly flow dominates, carrying much cooler air from northern China. The low-level convergence enhances lifting, resulting in a narrow band of convection on the warm side (south side) of the front (Lin et al. 1992; Cui et al. 2015).

Rainstorms during the mei-yu period are usually formed under certain favorable environmental conditions, such as the interaction of multiple scales of systems (Ninomiya and Akiyama 1992; Ni 2001; Zhang et al. 2002; Cui et al. 2015). Zhang and Tao (1998) found that precipitation anomalies during the mei-yu period are closely related to the establishment of blocking patterns in the middle and high latitudes, which affect precipitation by modulating the southward invasion of cold air masses. The western Pacific subtropical high (WPSH; enclosed by the 5880-gpm contour) also plays an important role in the variability of rainfall within the middle and lower reaches of the Yangtze River valley (Ren et al. 2013; Wang et al. 2000). A cyclone, trough, low pressure disturbance, horizontal wind shear line, and vortex are the typical synoptic systems causing the precipitation over the Yangtze River valley during the mei-yu period (Zhang et al. 2004; Ding and Chan 2005). The meso- β -scale (20–200 km) and meso- γ -scale (2–20 km) convective systems are the key direct factors of heavy precipitation during the mei-yu period (Ninomiya and Kurihara 1987). About 60%–70% of mei-yu precipitation can be associated with the meso- β -scale convective systems (Zhang et al. 2004).

Quite often, there is a low-level jet (LLJ; wind speed greater than 12 m s^{-1} at 850 or 700 hPa) with a scale of hundreds of kilometers located on the south side of the mei-yu front, which advects great amounts of warm, moist air into the mei-yu frontal zone and increases instability energy. Statistical results reveal that 79% of LLJs are accompanied by rainstorms during the mei-yu period (Wang et al. 2003), while 83% of the rainstorms are accompanied by LLJs. In early summer, an upper-level jet (ULJ; wind speed greater than 28 m s^{-1} at 200 hPa) usually extends from southern China to the northern Pacific (Wang and Zuo 2016). The right side of the ULJ stream entrance region is dominated by divergence and positive vorticity advection, leading to a secondary vertical circulation with warm updrafts up to 0.2 m s^{-1} (Lu and Yang 2004).

In recent decades, there have been many severe rainstorms and floods in the Yangtze River valley. In the summer of 1998, the rainband persisted over the Yangtze River basin, causing frequent rainfall on the upper, middle, and lower reaches of the Yangtze River valley. The average areal precipitation amount in the Yangtze River valley reached 670 mm, 37.5% above the climatological mean during the same period, causing more than 1562 deaths. During the mei-yu period of 1991, 7 days exceeded 50 mm day^{-1} of precipitation amount, and 5 days exceeded 100 mm day^{-1} in Wuhan, causing more than 240 deaths. During the mei-yu period of 2016, Wuhan City received a record-breaking weekly rainfall of 574 mm, reaching a maximum of 1087.2 mm in the downtown areas from 30 June to 6 July. This intense rainfall resulted in a disastrous flood that killed 237 people, left 93 people missing, and caused at least \$22 billion (U.S. dollars) in damage (Zhou et al. 2018).

Heavy rainfall in the Yangtze River valley, especially in Hubei province, happens not only during the mei-yu period but also prior to the mei-yu period. For example, a heavy rainfall event occurred in Hubei province before the mei-yu period (began on 10 July 1982). The precipitation amount within 15 h reached 312.9 mm in Wuhan on 20 June. The storm center was located in a downtown area, seriously affecting the traffic and normal life of citizens. The mei-yu period started on 19 June 2016. Another heavy rainfall event occurred on 1 June 2016 (the mei-yu period started on 19 June) with a daily accumulated precipitation amount of 115 mm in the urban area of Wuhan city, causing severe waterlogging.

Hubei province is located in the center of the Yangtze River valley, which is a key region relating to the mei-yu front. In this area, the precipitation occurs frequently during the mei-yu period and prior to the mei-yu period, causing serious impacts on economic development and people's lives. Many studies have focused on the

precipitation during the mei-yu season in China (Chen and Yu 1988; Chen et al. 1998; Qian et al. 2004; Ding and Chan 2005; Luo et al. 2010, 2013; Cui et al. 2015). Luo et al. (2013) investigated the differences of rainfall characteristics and convective properties over the entire Yangtze River valley between the mei-yu period and the pre-mei-yu period from a climatological point of view. However, the differences in the influencing systems and precipitation mechanisms between the heavy rain cases during these two periods need to be explored in depth.

The first and second heaviest daily precipitation events since 1985 in Wuhan happened on 18 June 2011 (193.8 mm, Case I) and 6 June 2013 (166.1 mm, Case II). These two heavy precipitation events occurred during the mei-yu period (Case I) and prior to the mei-yu period (Case II), respectively. Here we use these two events to provide a preliminary assessment of the differences and similarities between the mei-yu and pre-mei-yu extreme precipitation in terms of the precipitation nature, atmospheric thermodynamic characteristics, multiple scales influencing systems, and the precipitation mechanisms.

This paper is organized as follows. Section 1 introduces the data used in the study. Section 2 describes the differences of thermodynamic characteristics and the precipitation nature between the mei-yu period and the pre-mei-yu period (~2 weeks prior to the mei-yu) and the reasons for selecting these two cases. Furthermore, section 2 also discusses the differences of influencing systems, atmospheric water vapor transport, ULJ and LLJ, instability energy, wind convergence and energy frontal zone between the two cases. A summary and discussion are presented in the final section.

2. Datasets

In this study, a comprehensive analysis on the two cases is conducted through observations of the surface rain gauges, the Climate Forecast System Reanalysis (CFSR) data, the Doppler radar, and the wind profiler radar (WPR) data. Daily precipitation collected from the surface rain gauges at weather stations over China from 1985 to 2013 has been used in this study. Hourly precipitation and wind fields during two cases recorded from surface automatic weather stations (AWSs) over Hubei province in China are also used in this study. These three datasets are provided by the National Meteorological Information Center (NMIC) of China.

The CFSR data (Saha et al. 2010; available online at <https://rda.ucar.edu/pub/cfsr.html>) were obtained on a 0.5° latitude $\times$ 0.5° longitude grid globally with 37 isobaric levels at 6-h temporal resolution [0000, 0600, 1200, and 1800 UTC, corresponding to 0800, 1400, 2000, and 0200 Beijing standard time (BST) at 120°E].

The temperature, relative humidity (RH), geopotential height, and wind field of the CFSR data, as well as the equivalent potential temperature θ_e , absolute zonal momentum M , and water vapor fluxes computed from the CFSR data were utilized to study the two cases of heavy rainfall.

Analysis of convective systems is based on the Doppler radar mosaic of composite reflectivity (MCR) with a resolution of $1\text{ km} \times 1\text{ km}$, which is produced by the Severe Weather Automatic Nowcast (SWAN) system via the Doppler raw radar data collected from NMIC (Han and Wo 2018). The WPR is primarily used to detect wind speed and direction at different altitudes (Cui et al. 2015). The altitudes covered by the WPR observations range from 28 to 9620 m with a vertical resolution of 58 m within the planetary boundary layer, 116 m in the lower troposphere, and 232 m in the middle and upper troposphere at 3-min intervals. The data of WPR, which was located at Wuhan weather station, are provided by the Institute of Heavy Rain (IHR), China Meteorological Administration. These data have been proven reliable (Wan et al. 2011) and been used for research on a short-term severe precipitation process in Wuhan (Wang et al. 2012).

3. The differences between mei-yu precipitation and pre-mei-yu precipitation

a. Thermodynamic characteristics

High temperature, high RH, and a deep moist layer are favorable conditions for the formation of rainstorms. Equivalent potential temperature θ_e is a comprehensive variable that encapsulates information of atmospheric temperature and humidity and is equivalent to atmospheric moist static energy. The horizontal distributions and vertical profiles of RH and θ_e are examined to help the understanding of similarities and differences in the atmospheric thermodynamic characteristics during the mei-yu period and the pre-mei-yu period.

Figure 1 shows the averaged RH and θ_e in the mei-yu period, the pre-mei-yu period, and the differences between these two periods during 2000–13 from the CFSR data. As shown in Figs. 1a and 1b, during the mei-yu period, the Yangtze River valley and its southern region are the centers of high RH and θ_e , the averaged RH and θ_e are over 70% and 340 K in the most part of Hubei province. Figures 1c and 1d show the averaged RH and θ_e of 50%–70% and 330–340 K, respectively, over the middle and lower reaches (east of Yichang) of the Yangtze River valley during the pre-mei-yu period. The maximum positive centers of the RH and θ_e differences between the mei-yu period and the pre-mei-yu

FIG. 1. The RH (shaded; %) and temperature (black solid lines; K) averaged from 925 to 500 hPa in (a) the mei-yu period of each year, (c) the pre-mei-yu period (within 2 weeks prior to the mei-yu period of each year), and (e) the differences between the mei-yu period and the pre-mei-yu period during 2000–13 from the CFSR data. The θ_e (shaded; K) averaged from 925 to 500 hPa in (b) the mei-yu period, (d) the pre-mei-yu period, and (f) the differences between the mei-yu period and the pre-mei-yu period during 2000–13 from the CFSR data. The blue lines represent the Yellow River and the Yangtze River. The black triangle indicates Wuhan (114.13°E, 30.62°N), which is located at southeastern Hubei province (black thick solid line). The red triangle, circle, and square represent Yibin, Yichang, and Hukou, respectively. They represent the upper (Yibin–Yichang), middle (Yichang–Hukou), and lower (east of Hukou) reaches of the Yangtze River. The profiles of averaged (g) RH (%) and (h) θ_e (K) during the mei-yu period (red lines) and the pre-mei-yu period (blue lines) in Wuhan during 2000–13 from the CFSR data.

period were located in the middle and lower reaches of the Yangtze River valley (Figs. 1e,f). The increased temperature (black solid lines in Fig. 1e) in this area was also obvious. Focusing on Wuhan, the RH and θ_e during the mei-yu period are significantly greater than those during the pre-mei-yu period at all altitudes (Figs. 1g,h). Specifically, the averaged RH and θ_e between 1000 and 200 hPa were 77.2% and 346.5 K, respectively, during the mei-yu period and 59.7% and 338.3 K, respectively, during the pre-mei-yu period at Wuhan. Therefore, the study on the precipitation in Wuhan is very useful for the understanding of general precipitation characteristics in the middle and lower reaches of the Yangtze River valley.

Before mei-yu precipitation (Case I), a zonal band of relatively high RH and θ_e was located at the Yangtze River valley (Figs. 2a,c) including Wuhan (indicated by the black triangles). In contrast, prior to pre-mei-yu precipitation (Case II), the high θ_e and RH area was mainly located at the west and south side of the upper reach (Yibin–Yichang) of the Yangtze River valley (Figs. 2b,d). The middle reach (Yichang–Hukou) of the Yangtze River valley had large RH and θ_e gradients. In the vertical, the RH below 350 hPa and the θ_e for all levels before Case I was larger than before Case II (Figs. 2e,f), indicating the abundant moisture and energy of Case I. Comparing Fig. 2 with Fig. 1, the differences between Case I and Case II were similar to the differences between the mei-yu period and the pre-mei-yu period. Therefore, the study on these two cases can basically represent the atmospheric thermodynamic and the precipitation characteristics during these two periods.

It is noteworthy that θ_e increased with height below the 925-hPa layer over Wuhan before Case I, while decreased before Case II (Fig. 2f). This phenomenon illustrated that the layers below 925 hPa in Case I (mei-yu precipitation) appeared to be convectively stable while Case II (pre-mei-yu precipitation) appeared to be convectively unstable despite the fact that in climatology both cases appeared to be convectively unstable throughout the lower troposphere (below the 650-hPa layer during the mei-yu period and below the 700-hPa layer during the pre-mei-yu period).

b. Precipitation nature and atmospheric water vapor transport

Li et al. (2018) defined the mei-yu front as a regional center, where the north–south gradient of equivalent potential temperature at the 850-hPa layer is greater than 0.04 K km^{-1} while extending over more than 10° longitude. According to this definition, a mei-yu front started at 112.5°E and extended eastward into the

East China Sea in Case I, with a center latitude around 31.5°N (Fig. 3a). There was no mei-yu front in the Yangtze River valley during Case II (Fig. 3b). The characteristic differences of precipitation nature and water vapor transport with and without the mei-yu front will be discussed in this section.

As shown in Fig. 3a, the spatial distributions of the rainstorm (over 50 mm in 24 h) in Case I were zonally elongated, along the middle and lower reaches of the Yangtze River valley, mainly within 2° latitude south of the mei-yu front. This rainstorm band corresponded well with the region of enhanced RH and θ_e seen in Figs. 2a and 2c. However, this rainstorm band was quite different from the low-level convective instability region (the region of negative θ_e difference between the 925- and 1000-hPa layers in Fig. 3a), especially the eastern part and around Wuhan, where significant convective stability (the region of positive θ_e difference) was found. As shown in Fig. 3b, the rainstorm region of Case II was more concentrated in the zonal direction, mainly between 111° and 119°E . Most of the rainstorm bands corresponded to the low-level convective instability region, except for a small range of precipitation in central Hubei, where its RH and θ_e values were larger than those over the eastern part of the rainstorm band.

Figure 4 shows time series of hourly accumulated precipitation from the surface rain gauges at Wuhan weather station and an average of AWSs over the entire Wuhan area (94 stations in 2011, 103 stations in 2013). As shown in Fig. 4a, the continuous heavy rain (over 15 mm h^{-1} at Wuhan station) was primarily concentrated in about 8 h in Case I with a peak of 34.7 mm h^{-1} at Wuhan during 1100–1200 BST 18 June, while the average AWSs rainfall intensity was 9.7 mm h^{-1} . This continuous heavy rain was caused by a well-organized convective line. From 0400 to 0800 BST 18 June, a convective line with several embedded small cells moved eastward toward Wuhan and gradually developed into a well-organized zonally oriented meso- α -scale (200–2000 km) convective line. Then, this well-organized mesoscale convective line moved eastward slowly, affecting Wuhan until 1400 BST 18 June (figure not shown). In the vertical distribution (Fig. 5a), this convective line was pronounced and continuous with strong radar reflectivity (over 35 dBZ) extending to 7 km, corresponding to the continuous surface precipitation. The echo center during 1100–1200 BST caused by an intense meso- β -scale convective system in the convective line centered on Wuhan corresponded to the heaviest surface precipitation in Wuhan. As shown in Fig. 4b, the precipitation of Case II lasted longer and exhibited the characteristics of multiple peaks. The heaviest hourly precipitation at the Wuhan weather station (50 mm h^{-1}) occurred during 0000–0100 BST.

FIG. 2. (a) The averaged RH (shaded; %) and temperature (black solid lines; K) and (c) θ_e (shaded; K) from 925 to 500 hPa during the period from 2000 BST 17 Jun to 0800 BST 18 Jun 2011 (the beginning of Case I) from the CFSR data. (b),(d) As in (a) and (c), but averaged during the period from 2000 BST 5 Jun to 0800 BST 6 Jun 2013 (the beginning of Case II). The blue lines represent the Yellow River and the Yangtze River and the black thick solid line denotes the boundary of Hubei province. The black triangle indicates Wuhan. The red triangle, circle, and square represent Yibin, Yichang, and Hukou, respectively. The profiles of averaged (e) RH (%) and (f) θ_e (K) within 12 h prior to the precipitation of Case I (red lines) and Case II (blue lines) in Wuhan from the CFSR data.

FIG. 3. The difference of θ_e (shaded; K) between 925 and 1000 hPa within 12 h prior to the precipitation and rainstorm (over 50 mm in 24 h, black lines; mm) collected by surface rain gauges during (a) Case I and (b) Case II. The thick red line outlines the area where the north-south gradient of equivalent potential temperature at 850 hPa is bigger than 0.04 K km^{-1} . The blue solid line represents the Yangtze River. The dark gray solid line denotes the boundary of Hubei province. The red triangle indicates Wuhan.

During Case II, a meso- α -scale convective system was located in the eastern Hubei province, moving slowly eastward. Within this convective system, several independent meso- β -scale convective systems developed and affected Wuhan. In the vertical (Fig. 5b), the echo had high-value centers around 1200–1700 and 1900–2000 BST 6 June and 2300 BST 6 June–0100 BST 7 June, corresponding to the peaks of surface precipitation in Wuhan (Fig. 4b), respectively.

Case I was formed by a well-organized convective line and Case II was formed by several independent meso- β -scale convective systems. This difference has resulted in larger variations in radar reflectivity (convective intensity) near ground surface and surface rainfall amount in Case II than in Case I.

To reveal the difference of water vapor transport, the horizontal and vertical distribution of atmospheric water vapor flux and the divergence of water vapor flux

FIG. 4. Hourly precipitation amount (mm) recorded by the surface rain gauge at Wuhan weather station (blue bars) and averaged hourly precipitation amount (mm) recorded by surface rain gauges at AWSs over the entire Wuhan area (purple bars; 94 stations in 2011, 103 stations in 2013): (a) for Case I from 0000 BST 18 Jun to 0000 BST 19 Jun 2011 and (b) for Case II from 0800 BST 6 Jun to 0800 BST 7 Jun 2013.

before and during the two cases were analyzed. In Case I, strong southerly winds transported huge amounts of moist air to the middle and lower reaches of the Yangtze River valley (Fig. 6a), causing significant water vapor convergence there (Fig. 6e). The water vapor mainly came from the South China Sea, crossing over the southern boundary of the mainland, and was roughly uniform in the meridional. The water vapor flux was concentrated blow 500 hPa, centered at 950 hPa around 120°E (Fig. 6c). In Case II, southwesterly winds transported plenty of moist air from the Beibu Gulf and the Bay of Bengal to the middle reach of the Yangtze River valley (Figs. 6b,f). The water vapor flux was deeper than Case I, centered at 900–850 hPa and 106°E–109°E (Fig. 6d).

As mentioned above, mei-yu precipitation occurred along the south of the mei-yu front, and the rainstorm band corresponded well with the region of enhanced RH and θ_e . Huge amounts of moist air were transported from the South China Sea with a lower center of water vapor fluxes to the middle and lower reaches of the Yangtze River valley. Heavy rain around Wuhan was continuous, caused by a well-organized convective line. Pre-mei-yu precipitation mainly corresponded to the region of low-level convective instability. The water vapor

source over the middle reach of the Yangtze River valley was primarily advected from the Beibu Gulf and the Bay of Bengal with a higher center of water vapor fluxes. Heavy rain around Wuhan exhibited the characteristics of multiple peaks associated with independent meso- β -scale convective systems and was likely related to multiple accumulations and releases of unstable energy.

Note that the different water vapor sources for these two cases could also attribute their water vapor convergence differences and precipitation differences. As demonstrated in Fig. 6a, the major water vapor source for Case I was the South China Sea, whereas the Beibu Gulf and the Bay of Bengal were major water vapor sources for Case II (Fig. 6b). For Case I, the large water vapor convergence area was located in the middle and lower reaches of the Yangtze River (Fig. 6e), while for Case II, it was located in the middle reach of the Yangtze River (Fig. 6f). The large water vapor convergence areas in these two cases are consistent with the locations of their rainstorm zones.

c. Influencing systems

The large-scale synoptic pattern before Case I (shown in Fig. 7a) was similar to a well-known rainstorm case,

FIG. 5. Time–height cross section of radar reflectivity (a) during 0400–1600 BST 18 Jun 2011 and (b) from 0800 BST 6 to 0200 BST 7 Jun 2013, from the surface to 14 km, and averaged over the $0.2^\circ \times 0.2^\circ$ area around Wuhan weather station. The empty area between 1600 and 1700 BST 19 Jun 2013 indicates missed data during this period.

called the “August 1975” extreme heavy rainfall event (Ding 2015; Yang et al. 2017). A deep trough (point B) was located near the Okhotsk Sea, and a ridge (point A) was located at the southeast of Lake Baikal and extended northeastward. The WPSH (point C) was zonally distributed with its ridgeline (connecting the points of the greatest anticyclonic curvature along the isohypses, or the boundary line between easterly and westerly winds within the high pressure region) located at around 25°N . The combination of wind field (vectors) and temperature field (green solid lines) was favorable for the transport of the warm air masses by southerly and southeasterly winds along the west side

of the WPSH (point C) and cold air by northerly winds along the east side of the ridge (point A), with both converging to the middle and lower reaches of the Yangtze River valley. Figure 7c shows the differences in the 500-hPa circulation pattern between Case I and the climatic means. The trough over the Okhotsk Sea and the ridge on the southeast of the Lake Baikal are both stronger in Case I as demonstrated by the positive center and negative center around 50°N . The stable blocking pattern resulted in more cold air being transported to eastern China.

The average circulation pattern prior to Case II (shown in Fig. 7b) indicates that the high pressure ridge (point A)

FIG. 6. Height (1000–300 hPa) and time (from 12 h prior to the initiation of the heavy precipitation to the end of the precipitation) averaged water vapor fluxes (arrows; unit length represents $10 \text{ g cm}^{-1} \text{s}^{-1} \text{hPa}^{-1}$; color represents the magnitude of the water vapor flux) from the CFSR data in (a) Case I and (b) Case II. The black thick solid line denotes the boundary of Hubei province, and the black triangle represents Wuhan. The black thin straight lines denote the range of the cross section in (c) and (d). Time-averaged vertical cross section of the magnitude of the water vapor flux ($\text{g cm}^{-1} \text{s}^{-1} \text{hPa}^{-1}$) along 22°N in (c) Case I and (d) Case II. Height and time averaged divergence of water vapor fluxes ($10^{-7} \text{g cm}^{-2} \text{s}^{-1} \text{hPa}^{-1}$; negative values represent water vapor convergence) from the CFSR data in (e) Case I and (f) Case II.

FIG. 7. The 500-hPa geopotential height (shaded; dagpm), temperature (green solid lines; K), and wind fields (black arrows; m s^{-1}) from the CFSR data. (a) Averages during the period from 2000 BST 17 Jun to 0800 BST 18 Jun 2011 (within 12 h prior to the precipitation in Case I) and (b) averages during the period from 2000 BST 5 Jun to 0800 BST 6 Jun 2013 (within 12 h prior to the precipitation in Case II). The letter “A” denotes the ridge to the southeast of the Baikal Lake, “B” indicates the trough over the Okhotsk Sea, and “C” represents the western Pacific subtropical high (WPSH). The black thick solid line denotes the boundary of Hubei province. The blue triangle indicates Wuhan. (c) The differences between (a) and the climatic means on the same day from 2000 to 2010; (d) the differences between (b) and the climatic means on the same day from 2000 to 2010.

and the low-pressure trough (point B) were weaker than Case I. The cold northerly wind between the ridge and trough was located east and north compared to Case I. The zonal ridge line of the WPSH (point C) was located at around 20°N, 5° south of Case I. A short-wave trough, much deeper than that in Case I, was located in the upper and middle reaches of the Yangtze River valley. As the wind barbs shown, the convergence of warm and cold air masses was weaker than Case I. On the contrary, the short-wave trough was active in midlatitudes where the multiple positive and negative centers around 30°N were presented in Fig. 7d.

The mesoscale cyclonic vortex is an important system that is favorable for precipitation in the middle and lower reaches of the Yangtze River valley (Hu and Pan 1996; Xu et al. 2006; Yue 2008; Zhang et al. 2013). During Case I, the lowest value of closed isobaric line around the vortex center is 143 dagpm at 850 hPa. This small but intense vortex located over the middle reach of the Yangtze River valley, just on the western side of Wuhan (Fig. 8a). During Case II, the lowest value of closed isobaric lines around the vortex center is 144 dagpm at 850 hPa. This large-size vortex was located on the upper reach of the Yangtze River valley, corresponding to the

FIG. 8. The geopotential height (red lines; dagpm) and wind fields (wind barbs; a long barb represents 4 m s^{-1} while a short one is 2 m s^{-1}) at 850 hPa from the CFSR data during (a) Case I and (b) Case II. The black thick solid line denotes the boundary of Hubei province. The blue triangle indicates Wuhan.

short-wave trough in the midtroposphere. Wuhan was affected by a weak warm shear line (a shear line between southwesterly and southeasterly winds) extending from the east side of the vortex (Fig. 8b).

In summary, a stable blocking pattern, the WPSH, persistent wind convergence between warm air and cold air in the midtroposphere, and an intense mesoscale cyclonic vortex located over the middle reach of the Yangtze River valley in the low troposphere characterize the large-scale circulation pattern and synoptic systems of mei-yu precipitation. A short-wave trough in the midtroposphere and a mesoscale cyclonic vortex located on the upper reach of the Yangtze River valley in the low troposphere constitute the main influencing systems of pre-mei-yu precipitation.

Through an integrative analysis of Figs. 6a and 6b and Figs. 7a and 7b, we found that the paths of water vapor transport were along the west side of WPSH in both cases. The difference in water vapor transport was closely related to the difference in the WPSH location.

d. Upper-level jet and lower-level jet

Figure 9 shows the horizontal distribution (Figs. 9a,b) and vertical cross section (Figs. 9c,d) of the time-averaged ULJ and LLJ during the two cases. During Case I, a southwesterly LLJ and westerly ULJ both spanned from about 114°E eastward to the East China Sea. The rainstorm band was located just along the narrow band of the south edge of ULJ and the north edge of LLJ (Fig. 9a). In the vertical cross section (Fig. 9c), the ascending flow (red and purple lines) on the south side of the mei-yu front (convergence line in Fig. 9c) was the link between the LLJ (dark blue shadow) and the ULJ (dark red shadow). The strong updraft (vertical speed $< -0.4 \text{ Pa s}^{-1}$, within the purple lines) was located

in the middle and upper layers (550–200 hPa), between the LLJ and the ULJ.

During Case II (Fig. 9b), the southwesterly LLJ was located over the middle reach of the Yangtze River valley. The ULJ was located over the lower reach of the Yangtze River valley. The two jets were oriented nearly orthogonally. Rainstorm over the middle reach and the west part of the lower reach of the Yangtze River valley corresponded with the exit of the LLJ and the right side of the ULJ entrance region. In the vertical cross section (Fig. 9d), compared to Case I, more intense and deeper ascending motion was centered over Wuhan and extended from the lower level to the upper level (approximately 900–250 hPa), above the bottom layer of the LLJ.

As mentioned above, a ULJ and LLJ were observed in both cases, but they had different interaction modes. In Case I, Wuhan was within the left side of the LLJ entrance, where the ascending branch of the secondary circulation of the LLJ was superimposed on the ascending branch of the ULJ. The strong updraft was located between the LLJ and the ULJ. In Case II, Wuhan was located at the exit of the LLJ, where convergence was produced due to the wind speed differences. The convergence in the low layers caused by the LLJ was superimposed on the divergence on the right side of the ULJ. The strong updraft stretched from the bottom layer of the LLJ to the upper troposphere.

e. Atmospheric instabilities

Symmetric instability is a kind of atmospheric instability. If parcels are displaced along slantwise paths rather than vertical or horizontal paths, it is possible under certain conditions for the displacements to be unstable even when the conditions for ordinary static and inertial

FIG. 9. The ULJ (blue lines; wind speed at 200 hPa greater than 28 m s^{-1}) and the LLJ (wind barbs in red are $12\text{--}14 \text{ m s}^{-1}$, and purple are over 14 m s^{-1} ; a long barb represents 4 m s^{-1} while a short one is 2 m s^{-1} ; contours represent the region with mean wind speed greater than 12 m s^{-1} between the 850- and 700-hPa layers) from the CFSR data, and rainstorm (shaded; mm) collected by surface rain gauges for (a) Case I and (b) Case II. The purple solid lines illustrate the north-south section across Wuhan in (c) and (d). The vertical cross section of airflow field (southerly wind and vertical wind), jets (shaded; magnitude of horizontal wind; m s^{-1}), and vertical speed (red lines: -0.1 Pa s^{-1} , purple lines: -0.4 Pa s^{-1} , and blue lines: 0.1 Pa s^{-1}) during (c) Case I and (d) Case II.

stability are separately satisfied (Holton and Hakim 2012). Symmetric instability illuminated in the zonal-vertical cross section of θ_e and M [absolute zonal momentum ($M \equiv fy - u_g$, where $\partial M/\partial y = f - (\partial u_g/\partial y)$ is the zonal mean absolute vorticity)], where the θ_e surfaces and the M surfaces both slope upward toward the pole, while the θ_e surfaces slope more than the M surfaces (Holton and Hakim 2012; Schultz and Schumacher 1999). According to this definition, before Case I (Fig. 10a), a symmetric instability area was located between 750 and 650 hPa north of Wuhan. There was no obvious symmetric instability near Wuhan before Case II (Fig. 10b).

Convective instability is illuminated by the vertical gradient of equivalent potential temperature. A negative vertical gradient [$(\partial\theta_e/\partial z) < 0$] indicates the presence of convective instability, while a positive vertical gradient [$(\partial\theta_e/\partial z) > 0$] indicates the presence of convective stability. Before Case I, θ_e increased with height below the 925-hPa layer, then decreased slowly from 354 to 348 K from the 925- to 600-hPa layer. This phenomenon illustrated that the layers below 925 hPa were convectively stable, and the layers between 925 and 600 hPa were convectively unstable. Before Case II, significant convective instability appeared in the middle and lower troposphere over Wuhan. The θ_e decreased rapidly from

FIG. 10. Vertical cross section of θ_e (red lines; K) and M (black lines; m s^{-1}) 12 h prior to (a) Case I and (b) Case II along 114.13°E . The blue triangle represents Wuhan.

344 to 324 K within the 150-hPa layer between 800 and 650 hPa, showing significant convective instability in the mid- to low troposphere over Wuhan. Under the influence of deep and strong ascending motion (shown in Fig. 9d) convective instability may easily cause a rainstorm. The vertical distribution of convective stability continued until the beginning of precipitation in the two cases (as shown in Fig. 2f).

In a word, symmetric instability and weak convective instability prior to mei-yu precipitation and intense convective instability prior to pre-mei-yu precipitation were found in the mid- to low troposphere.

f. Convergence line of wind and frontal zone of energy

Figure 11 shows the temporal variation of θ_e and vertical-longitudinal wind in the two cases. A wind convergence line between southerly wind and northerly wind and a frontal zone marked by sharp gradients of θ_e appeared at all times from 12 h before the precipitation of Case I to its end. At the beginning (Fig. 11a), this energy front and convergence line tilted poleward with height. Northerly winds were present in the low levels over Wuhan, while southerly winds were present aloft (Fig. 13c). Then, cold northerly winds developed further south, pushing the wind convergence line in the middle and upper troposphere southward. In lower layers, high-energy southerly winds stopped the southward advance of northerly winds. The energy front became more and more upright (Figs. 11b–d). Over Wuhan (Fig. 13c), northerly winds near the surface intensified and extended upward, corresponding to a sustained enhanced convergence on the ground surface. Meanwhile, southerly winds in the high levels intensified and extended downward. Strong wind shear between northerly winds in the low levels and southerly winds in the

high levels appeared in the layers between 0.5–1.5 km just before the precipitation of Case I. After rainfall (Fig. 11e), the wind convergence line and energy front was tilted equatorward with height.

At the beginning of Case II, the southerly winds occupied the middle and lower troposphere so there was no wind convergence line (Figs. 12a,b). Oscillation of the southerly airflow was presented in the lower troposphere over Wuhan. Then, a northerly wind first appeared to the south side of the potential temperature minimum in the middle troposphere (Fig. 12c), corresponding to the northerly wind above 3.5 km around 2000 BST 6 June over Wuhan from the WPR data (Fig. 13d). The northerly wind on the ground surface appeared at about 0000 BST 7 June. Then, the northerly wind on the ground surface and in the middle troposphere developed upward and downward, respectively (Figs. 13b,d). At the heaviest rainfall time (0200 BST 7 June); northerly winds extended over almost the entire troposphere (Figs. 12d and 13d). After rainfall (Fig. 12e), the wind convergence line and energy front also was tilted equatorward with height.

As mentioned above, in Case I, the wind convergence line and energy front extended over almost the entire troposphere and lasted from 12 h before the precipitation to its end. The convergence line was pushed southward by the cold dry northerly winds. Strong vertical wind shear appeared near an altitude of 1 km over Wuhan. While in Case II, during daytime precipitation, fluctuations in the southerly wind were present in the lower troposphere. At night, northerly winds appeared in the middle troposphere, causing convective instability together with southerly wind below. The convergence of cold and warm air only occurred around the time of the strongest precipitation. In both cases, the precipitation ended while the wind convergence line and energy front tilted equatorward.

FIG. 11. Vertical cross sections of θ_e (shaded; K) and streamlines along Wuhan (114.13°E, 30.62°N; the blue triangle) from the CFSR data. (a) 2000 BST 17 Jun, (b) 0200 BST 18 Jun, (c) 0800 BST 18 Jun, (d) 1400 BST 18 Jun, and (e) 2000 BST 18 Jun 2011.

FIG. 12. Vertical cross sections of θ_e (shaded; K) and streamlines along Wuhan (114.13°E, 30.62°N; the blue triangle) from the CFSR data. (a) 0800 BST 6 Jun, (b) 1400 BST 6 Jun, (c) 2000 BST 6 Jun, (d) 0200 BST 7 Jun, and (e) 0800 BST 7 Jun 2013.

FIG. 13. Hourly time series of wind divergence (red lines; s^{-1} ; positive and negative values represent wind divergence and convergence) and northerly wind component (blue lines; $m s^{-1}$; positive and negative values represent southerly and northerly winds) from Wuhan AWS data. (a) Case I from 2000 BST 17 Jun to 2000 BST 18 Jun 2011 and (b) Case II from 2000 BST 5 Jun to 0800 BST 7 Jun 2013. Time–height cross sections (from 0.028 to 6.143 km) from the WPR data at Wuhan weather station (positive and negative values represent southerly and northerly winds). (c) Case I from 0000 BST to 1200 BST 18 Jun 2011 and (d) Case II from 0400 BST 6 Jun to 0400 BST 7 Jun 2013. The empty areas indicate the data were either missing or unreliable (confidence level below 50%).

4. Summary and conclusions

In this study, a comprehensive study of the first and second heaviest daily precipitation in Wuhan since 1985 has been conducted through an integrative analysis of surface rain gauge measurements, the CFSR data, the Doppler radar, and the WPR data. These two cases represent typical mei-yu precipitation and pre-mei-yu precipitation characteristics, respectively, with the following conclusions.

- 1) There have been many studies on mei-yu precipitation. For example, [Luo et al. \(2013\)](#) investigated the differences of rainfall characteristics and convective properties over the entire Yangtze River valley between the mei-yu and pre-mei-yu period from a climatological point of view. However, detailed analysis of pre-mei-yu precipitation is relatively rare and the differences between pre-mei-yu and mei-yu periods have not been discussed extensively, especially over the middle

reach (Yichang–Hukou) of the Yangtze River valley. This study focuses on the heavy precipitation in Wuhan and its surrounding area and the discussion is mainly based on a weather point of view. Specifically, the mei-yu period is defined based on the precipitation data from the surface rain gauges at weather stations in the Hubei province east of $110^{\circ}E$. The pre-mei-yu period is defined within 2 weeks prior to the onset of the mei-yu.

- 2) During the mei-yu precipitation case, a zonally oriented band of enhanced RH and θ_e was located in the middle and lower reaches of the Yangtze River valley. A rainstorm corresponded with this band and was located 2° latitude south of the mei-yu front. Rainfall at the Wuhan weather station was continuous, caused by a slowly moving well-organized mesoscale convective line. Whereas for the pre-mei-yu precipitation case, a region of enhanced of RH and θ_e gradient was located over the middle reach of the Yangtze River

valley. The rainstorm mainly corresponded to the low-level convective instability region. The precipitation at the Wuhan weather station was caused by several independent meso- β -scale convective systems and exhibited the multipeak feature.

- 3) During the mei-yu precipitation case, a stable blocking pattern at high latitudes resulted in transporting plenty of cold air masses to eastern China, and the WPSH favors the transport of moist and warm air masses along its west side. A small but intense mesoscale cyclonic vortex was found over the middle reach of the Yangtze River valley. Strong southerly winds transported huge amounts of warm, moist air centered at 950 hPa from the South China Sea to the middle and lower reaches of the Yangtze River valley, causing significant water vapor convergence there. In contrast, for the pre-mei-yu precipitation case, a short-wave trough was located over the upper and middle reaches of the Yangtze River valley in the midtroposphere, corresponding to a mesoscale cyclonic vortex in the low troposphere. Significant water vapor convergence over the middle reach of the Yangtze River valley was mainly caused by the transportation of water vapor primarily from the Beibu Gulf and the Bay of Bengal, centered at 900–850 hPa. There was very good consistency between water vapor convergence in mid- to low layers and the rainstorm in both cases.
- 4) During the mei-yu precipitation case, a rainstorm band was located just along the narrow band between the elongated ULJ and LLJ. The ascending branches of the secondary circulation of the LLJ and the ULJ were superimposed over Wuhan, causing a strong updraft over there. Before the precipitation, symmetric instability in the midtroposphere was identified near Wuhan. A wind convergence line and a frontal zone appeared at all times and extended over almost the entire troposphere. For the pre-mei-yu precipitation case, the intersection angle of the two jets was nearly orthogonal. The rainstorm band was concentrated in the exit of the LLJ and the right entrance of the ULJ. The strong updraft stretched from the bottom layer of the LLJ to the upper troposphere. Significant wind speed convergence caused intense and deep ascending motion centered over Wuhan. Before the precipitation, regions of significant convective instability were detected in the mid- to low troposphere near Wuhan. Northerly winds first appeared to the south side of the potential temperature minimum in the midtroposphere. The convergence of cold and warm air only occurred around the time of the strongest precipitation.

Results of this study provide some preliminary knowledge on the differences of atmospheric thermodynamic characteristics, the precipitation nature, influencing systems, and the precipitation mechanisms between mei-yu and pre-mei-yu extreme precipitation events in the middle and lower reaches of the Yangtze River valley. Atmospheric circulation anomalies of multiple temporal and spatial scales and the interactions among them appear to be critical for the formation of the precipitation extremes. The differences of circulation anomalies between mei-yu and pre-mei-yu extreme precipitation caused the differences of water vapor and thermodynamic conditions, including water vapor transport and convergence, warm and cold air convergence, and environmental temperature and humidity conditions. These differences between the two cases further led to the difference of instability conditions, and eventually triggered two extreme heavy precipitation events with different precipitation natures. This increases the level of difficulty in achieving accurate representations of the associated moisture transport and instability processes, and therefore skill predictions, for both types of precipitation in a regional model such as the Weather Research Forecasting (WRF) Model.

It is well known that abundant moisture, instability, and dynamic lifting are the three basic conditions for producing heavy rainfall. The accumulated rainfall amounts for these two selected cases are comparable, however, their environmental conditions, including relative humidity and equivalent potential temperature, are significantly different. This result suggests that under dry environmental conditions, the occurrence of a rainstorm requires higher instability and more favorable dynamical factors such as mechanical lifting, while in moist and warm environmental conditions, the dependence of a rainstorm on instability and dynamical factors is relatively small. We do recognize that this conclusion is based on only two typical cases, and a further investigation of more rainstorm cases during the mei-yu period and pre-mei-yu period is necessary to draw a more robust conclusion.

One might suspect that rainfall rates from one station and from a multiple-station average can be different, and two extreme cases do not seem to be sufficient to clearly represent the heavy rainfall difference between pre-mei-yu and mei-yu season. However, the two cases used in this study demonstrated that they indeed represent typical mei-yu precipitation and pre-mei-yu precipitation, and the differences between the two cases are significant, meteorologically meaningful, and consistent with the seasonal cycle in the region. The differences between the two selected cases can thus reflect the differences between the two periods to a certain extent.

Future studies are needed to corroborate the findings presented here by considering more rainstorm cases, more data, and resorting to numerical modeling where observations are limited.

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