Decadal and Interannual Variability of Persistent Heavy Rainfall Events over the Middle and Lower Reaches of the Yangtze River Valley

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ABSTRACT

This study investigates the relationship between the anomalous atmospheric circulation pattern and summertime persistent heavy rainfall (PHR) over the middle and lower reaches of the Yangtze River valley (MLYRV) on the decadal and interannual timescales. Based on the gridded daily rainfall data of the US Climate Prediction Center, the PHR events on grid-point and the regional PHR events considering both the area of PHR and regionally averaged rainfall intensity are identified over the MLYRV during the summers of 1979–2017. A PHR index (PHRI) is defined, to describe the variability of summertime PHR event number over the MLYRV. The PHRI is then divided into the decadal and interannual components. Further analysis reveals that the decadal PHR events are closely related to anomalous precipitation, intensified vertical motion, and strengthened upper-level divergence over southern China, as well as an anomalous anticyclone over the western Pacific transporting more water vapor from the South China Sea (SCS) to southern China. As for the interannual component, the above pattern still co-exists but over a narrow region around the MLYRV. By choosing the years in which the decadal and interannual components of the PHRI are simultaneously positive (SP) or negative (SN), the features of regional PHR events in SP and SN years are analyzed, respectively. The results show that there are more regional PHR events in SP years with enhanced intensity and larger affected areas compared with those in SN years. Meanwhile, the zonal oscillations of the South Asian high (SAH) and the western Pacific subtropical high (WPSH) during the regional PHR events demonstrate a better regularity in SP years than those in SN years.

Key words: middle and lower reaches of the Yangtze River valley (MLYRV), persistent heavy rainfall (PHR), decadal variability, interannual variability

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1. Introduction

The middle and lower reaches of the Yangtze River valley (MLYRV) is one of the regions with frequent meteorological disasters. Extreme persistent weather events occur over eastern China, such as the continuously heavy rainfall and the persistent heat wave in summer, as well as the continuous snow storms in winter (Wang H. J. et al., 2014; Sun et al., 2016; Chen et al., 2017). Among above, persistent heavy rainfall (PHR) over the MLYRV in summer attracted much attention during recent years (Tang et al., 2006; Wang et al., 2011; Shi and Wen, 2015; Hui and Fang, 2016). The PHR events over the MLYRV in summer often have a long duration, a large affected area, and high rainfall intensity (Ding and Hu, 2003; Liu et al., 2008; Wang et al., 2012; Wang et al., 2013). They are very likely to cause flood disasters, threatening people’s lives and social production.

The PHR occurrence over China varies greatly with time and region. Previous studies showed that after the 1990s, the PHR events over southern China present an upward trend with increasing frequency, higher intensity, longer duration, and larger affected areas (Chen and Zhai, 2013). Meanwhile, the PHR events over northern

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China undergo a downward trend (Zhai et al., 2017). Liu et al. (2014) showed that there are two main periods of more rainstorms over southern China since 1960: from the mid-1960s to mid-1970s, and from the early 1990s to 2010. Above decadal variation of PHR events over eastern China presents a coherent feature with that of the large-scale Asian summer monsoon circulation and precipitation (Ding et al., 2008; Zhang et al., 2008; Lyu et al., 2014; Zhang et al., 2018).

The PHR occurrence over China also shows interannual variation. The variation of large-scale monsoon circulation and its associated water vapor transport can contribute to droughts and floods over East China (Xue et al., 2003; Zhuo et al., 2006; Li et al., 2016; Yuan et al., 2017). For example, the atmospheric circulation anomalies stimulated by the sea surface temperature (SST) anomalies during the El Niño year, can induce the flood over southeastern Asian in the following seasons (Lin and Lu, 2009; Zhang et al., 2013). More PHR events with enhanced intensity and longer persistence occur over the MLYRV under the influence of the El Niño (Yu and Zhai, 2018).

The daily precipitation over Southeast China during summer shows a periodicity of subseasonal oscillation (Lau et al., 1988; Zhu and Xu, 2000; Zhu et al., 2003; Mao and Wu, 2006; Tang et al., 2009; Yang et al., 2010; Li et al., 2015; Song et al., 2016). The PHR events usually occur in the active phase of the subseasonal rainfall oscillation (Mao et al., 2010; Chen et al., 2015; Stephan et al., 2018). The evolution of PHR events is accompanied by a significant westward-then-eastward migration of the western Pacific subtropical high (WPSH) on the subseasonal timescale (Ren et al., 2013; Lu et al., 2014, Guan et al., 2019). Meanwhile, PHR is often associated with atmospheric circulation anomalies in the upper level, such as the eastward extension of the South Asian high (SAH) and the stable maintenance of upper level jet (Ding et al., 2010; Zhang et al., 2015). Above circulation pattern promotes the rainstorm occurrence over the MLYRV (Chen and Zhai, 2014a, b; Li and Mao, 2019).

Previous studies suggested that the frequency of PHR events over the MLYRV has variability on the decadal and interannual timescales. However, it is still unclear the anomalous atmospheric circulation pattern associated with the decadal and interannual variability of the frequency of PHR events over the MLYRV in summer. Thus, the current study focuses on the relationship between the anomalous atmospheric circulation pattern and summertime PHR over the MLYRV. The main goal is to unveil the anomalous atmospheric circulation pattern that is favorable to the PHR events on the decadal and interannual timescales over the MLYRV.

The rest of this paper is organized as follows. Data and methods are introduced in Section 2. The PHR index (PHRI) over the MLYRV in summer is defined and analyzed in Section 3. Section 4 presents the results, which include the anomalous atmospheric circulation pattern associated with the decadal and interannual components of the PHRI, and features of regional PHR events when both the PHRI’s decadal and interannual components are positive or negative, respectively. The summary and discussion are given in Section 5.

2. Data and methods

2.1 Data

The dataset of precipitation used in this study is the daily gridded data covering global land areas from the US Climate Prediction Center (CPC), at a resolution of 0.5° × 0.5°. This dataset primarily comes from rain gauge observation over global land areas (Chen et al., 2008). Following datasets are also used: a 1° × 1° daily mean outgoing longwave radiation (OLR) dataset from the Climate Data Record (CDR) project of the NOAA; daily atmospheric data from the ECMWF interim reanalysis (ERA-Interim) on a 0.75° × 0.75° spatial resolution, including geopotential height, horizontal wind (u, v), vertical wind (ω), and specific humidity (q). All datasets cover the period from 1979 to 2017.

2.2 Method

Similar to previous studies (Chen and Zhai, 2013; Ren et al., 2013), a PHR event is defined when the precipitation on a grid-point is greater than 15 mm day⁻¹ for at least three consecutive days. The parameters in the event definition is decided according to the characteristic of the persistent rainstorms over the MLYRV (Bao, 2007; Wang W. W. et al., 2014). By above criteria, we identify grid-point PHR events over eastern China during summers of 1979–2017. Averaging the grid-point PHR event number over the MLYRV (green box region in Fig. 1) in each summer, we obtain a time series from 1979 to 2017. The normalized time series is used as an index to judge the frequency of PHR events during every summer, referred to as the PHRI.

The PHR event is usually not a single grid-point event. It is often associated with a weather process that occurs in a wide area. Thus, we define a regional PHR event through taking the area and the regionally averaged rainfall intensity into account (Tang et al., 2006; Sun et al., 2016). There is a total of 160 grid-points in the MLYRV.
When a ratio of grid-number for grid-point PHR to the total number (160) is higher than 15%, the averaged rainfall over the MLYRV is greater than 10 mm day\(^{-1}\), and this state lasts for three days or more, it is defined as a regional PHR event. In the current study, the regional PHR events are used in Subsection 4.3, to investigate the subseasonal evolution of atmospheric circulation during the PHR events.

In addition, we also used the daily precipitation at more than 2000 gauge stations provided by the Climate Data Center, China Meteorological Administration to obtain a China Station PHRI (CNS-PHRI). The CNS-PHRI has a high correlation coefficient (0.88) with the PHRI from the CPC gridded data, and there regressed fields of atmospheric circulation to the CNS-PHRI are also similar to those to the PHRI (figure omitted). For convenience, we use the CPC data in this study.

3. PHR index and its decadal and interannual components

Figure 1a shows the distribution of climatological summer (JJA) rainfall over East Asia averaged from 1979 to 2017, as well as the locations of 12520-gpm isoline (12520-line) at 200 hPa and 5880-gpm isoline (5880-line) at 500 hPa. It can be seen that relatively large precipitation appears over southeastern China, South Korea, western Japan, Indo-China Peninsula, and Philippines. In particular, there are two precipitation centers over southeastern China: the MLYRV and South China. The eastern part of the SAH, which is represented by 12520-line, occupies northern Indo-China Peninsula and southern Tibetan Plateau. Its easternmost point reaches 113\(^{\circ}\)E. The WPSH represented by 5880-line is zonally elongated over the western Pacific, with the west point located around 132\(^{\circ}\)E. Its northern edge lies near 30\(^{\circ}\)N. Figure 1b plots distribution of total number of grid-point PHR events during the summers from 1979 to 2017. It can be seen that PHR events occur mainly over South China, Sichuan Province, and the MLYRV. The number of summertime PHR events in most grids over the MLYRV exceeds 30 during 1979–2017. Besides, the rainfall during PHR events over the MLYRV accounts for 15% or more to the total summer precipitation.

The time series of the PHRI during summers of 1979–2017 is plotted in Fig. 2a. Power spectrum analysis for the PHRI shows that the predominant peaks in the PHRI are around 3 and 15 yr (Fig. 2b). This result indicates that the PHRI has both decadal and interannual variability. Therefore, the PHRI is divided into two components: the decadal component by low pass filtering (more than 10 yr) of the PHRI time series (Fig. 2c), and the interannual component by high pass filtering (less than 10 yr) (Fig. 2d). Positive (negative) phases of decadal component are picked according to above (below) 0.4 (−0.4) standard deviations in Fig. 2c. In this way, we get 10 positive (1979, 1980, 1997, 1998, 1999, 2000, 2014, 2015, 2016, and 2017) and 10 negative (1984, 1985, 1986, 1992, 1993, 1994, 2004, 2005, 2006, and 2007) PHRI years for the decadal component. As for the interannual component, there are six positive (1980, 1998, 1999, 2002, 2008, and 2017) and six negative (1981, 1985, 1997, 2000, 2001, and 2007) PHRI years, based on ± 1 standard deviations (Fig. 2d).

To understand the anomalous atmospheric circulation pattern associated with the decadal and interannual variability of summertime PHR events over the MLYRV, anomalous fields are regressed separately onto the decadal

![Fig. 1.](image)
and interannual components of PHRI in the following part. The effective degree of freedom of the decadal and interannual regression signals has reduced (Sun et al., 2015; Wang et al., 2017). Thus, the significance of the regression is evaluated by using the two-tailed Student’s t test, with the new effective degree of freedom calculated as $N_{\text{new}} = N (1 - r_1 r_2)/(1 + r_1 r_2)$, where $N$ is the sample size, and $r_1$ and $r_2$ are the lag-1 autocorrelations of the two time series (Bretherton et al., 1999).

4. Results

4.1 Anomalous atmospheric circulation pattern: decadal component

Figure 3 displays the regressed fields of precipitation, OLR, total column integrated water vapor (IWV), integrated water vapor transport (IVT), and $\nabla \cdot \text{IVT}$ anomalies onto the decadal component of PHRI. A strengthened convective activity and an above-normal precipitation are seen over southern China (Figs. 3a, b). Those anomalies can be partly attributed to the atmospheric water vapor transport. The regressed IVT field shows a pattern that an anomalous anticyclone locates over the western Pacific with its west edge extending to the west of 110°E (Fig. 3d). The anomalous anticyclone transports water vapor from the South China Sea (SCS) to South China continuously. Then, the anomalous southwestward airflow is confluent with the northeastward airflow from North China over southern China. Therefore, more moisture converges between 20° and 30°N (Figs. 3c, d), being favorable for the occurrence of positive rainfall anomaly over southern China in Fig. 3a.

The regressed fields of divergence of horizontal winds at 200-hPa $\nabla \cdot V_{200}$ and $\omega$ at 500-hPa anomalies onto the decadal component of the PHRI are plotted in Fig. 4. The regressed field shows a negative–positive–negative tripolar pattern from North China, southern China to the SCS. Namely, the anomaly in $\nabla \cdot V_{200}$ field shows a strengthened divergence in the upper-level over southeastern China. Meanwhile, anomalous convergence appears over North China and regions from Taiwan to Philippines (Fig. 4a). The regressed 500-hPa $\omega$ anomaly presents a positive–negative–positive tripolar pattern over the region of North China–South China–SCS. Namely, an anomalous ascending motion over southern China and anomalous descending motion over northern China and the SCS are observed in the mid-level (Fig. 4b).

The composite 5880-line at 500 hPa and 12520-line at 200 hPa for the decadal positive and negative PHRI years are also plotted in Figs. 4a, b. The composite 12520-line suggests that the eastern part of the SAH stretches more eastward during the PHRI decadal positive years, compared with that during the decadal negative years. At the same time, the composite 5880-line during the decadal positive years stretches more westward, compared with
the composite during the decadal negative years. In short, the SAH and the WPSH are closer to each other during decadal positive years. According to previous studies, above condition is favorable to the anomalous mid-level ascending motion and upper-level divergence over southern China (Lu, 2001; Jiang et al., 2011). The SAH and WPSH are far away from each other during decadal negative years, which is not favorable for the ascending motion over southern China.

Figure 5 displays the latitude–height section of regressed anomalous fields in \( \mathbf{\nabla} \cdot \mathbf{v} \) and wind fields of \( \mathbf{v} \) and \( \mathbf{\omega} \) averaged over 112°–122°E. An increased water vapor convergence is seen in the mid–lower levels of troposphere over southeastern China of 20°–30°N. This anomalous pattern is due to anomalous convergence of wind fields over southeastern China in the lower level. Meanwhile, the locally strengthened ascending motion can further transport the moisture to the middle level.
4.2 Anomalous atmospheric circulation pattern: interannual component

Figure 6 displays the regressed fields of precipitation, OLR, IWV, IVT, and $\nabla \cdot \text{IVT}$ anomalies onto the interannual component of PHRI. The regression of precipitation anomaly shows an arrow rain band over the MLYRV (Fig. 6a). The OLR anomaly presents an intensified convective activity over the Yangtze River valley and adjacent East China Sea, and a depressed one over the SCS and subtropical western Pacific (Fig. 6b). Similar to the decadal component in Fig. 3d, the regressed IVT field onto interannual component of PHRI also shows a pattern with an anomalous anticyclone located over the region south of 30°N (Fig. 6d). Compared Fig. 3d with Fig. 6d, it can be seen that the anomalous anticyclone on interannual timescale is slightly stronger and more northward than that on decadal timescale. Thus, anomalous moisture convergence band is narrowly located over the MLYRV (Figs. 6c, d), providing necessary moisture conditions for the anomalous rainfall band over the MLYRV (Fig. 6a).

Figure 7 presents the regressed fields of $\nabla \cdot \mathbf{V}$ and $\omega$ at 500-hPa anomalies onto the interannual component of the PHRI. The composite 5880-line and 12520-line for the interannual positive and negative PHRI years are also showed in Fig. 7a, b. A divergence anomaly is observed in the upper-level over the MLYRV. Meanwhile, an anomalous ascending motion appears in the middle troposphere over the MLYRV. Similar to the decadal component in Fig. 4, the SAH and WPSH are closer to each other during interannual positive years, which contribute to the anomalous mid-level ascending motion and upper-level divergence over the MLYRV. While they are far away from each other during interannual negative years, which suppress the local vertical circulation over the MLYRV region.

Figure 8 displays the latitude–height sections of regressed anomalous fields in $\nabla \cdot \text{IVT}$ and wind fields of $v$ and $\omega$ averaged over 112°–122°E. An anomalous water
vapor convergence appears in the mid–lower levels of troposphere around the Yangtze River valley between 27° and 32°N. This is mainly the result of strengthened convergence of wind fields over the MLYRV. Meanwhile, the anomalously ascending motion over the MLYRV in the lower-level helps the water vapor rise to the mid–upper levels.

### 4.3 Features of regional PHR events when both the PHRI’s decadal and interannual components are positive or negative

Figure 9 shows the distribution of regional PHR events over the MLYRV for every summer of 1979–2017. The numbers of regional PHR events and the corresponding duration over the MLYRV vary from year to year. For example, there is no regional PHR event in several years (e.g., 1985, 1994, 2004, 2005, and 2007). During these years, both the interannual and decadal components of PHRI are simultaneously negative (SN). In some other years, there are 3–4 events occurring within one summer (e.g., 1980, 1996, 1998, 2002, 2008, 2012, and 2017). During these years except 2008, both the interannual and decadal components of PHRI are simultaneously positive (SP).

The specific SP and SN years are listed in Table 1. SP years include most of the years with strong positive interannual component of PHRI in Fig. 2d (e.g., 1980, 1998, 1999, 2002, and 2017). Within these five years, four years (1980, 1998, 1999, and 2017) are robustly decadal positive years in Fig. 2c. During these four years, the regional PHR is featured by 3–4 events or stronger intensity and prolonged duration. Most of the robustly decadal negative years are included in SN years. However, there are four strong negative interannual years out of SN years (e.g., 1981, 1997, 2000, and 2001). Both the four years and SN years are featured by only 0–1 regional PHR event or weaker intensity and shorter duration. Above asymmetry results indicate that both strong positive decadal and positive interannual PHRI signals are important to the occurrence of regional PHR events. While the mild-to-strong negative interannual PHRI signals are unfavorable to the occurrence of PHR. The influence of negative decadal signal is relatively limited.

Table 1 shows the features of regional PHR events in SP and SN years. There are more events and longer durations in SP years than those in SN years. Furthermore, the events in SP years have a higher rainfall intensity and larger affected area, compared with the events in SN years. To further demonstrate above features, Fig. 10 plots composite fields of precipitation intensity and total duration of regional PHR events over East China in SP and SN years. Indeed, the regional PHR events in SP years show the features of slightly stronger intensity and significantly longer duration days compared to those in SN years.

The subseasonal zonal movement of the SAH and WPSH also exhibits a difference between SP and SN years. The difference can be seen in the lagged composites of 12520-line (Fig. 11) and 5880-line (Fig. 12) for the regional PHR events. In the leading/lags, the 0 day represents the composite of the whole regional PHR
events. In SP years, the eastward movement and westward retreat of 12520-line during the event are orderly. While in SN years, the 12520-line shows the trajectory of firstly eastward, then westward, and again eastward and westward. Namely, the regularity of SAH’s zonal oscillation in SN years is relatively poor. At day $-8$, the position of 5880-line in SP years is more eastward than that in SN years. The WPSH in SP years has a larger amplitude of westward movement before lag $= 0$ day and a weaker amplitude of eastward retreat after day 0. In addition, the WPSH oscillates several times during the retreat phase in SN years, indicating a poor regularity.

In short, the SAH and the WPSH show a more significant bi-weekly oscillation feature in SP years than in SN years. The lagged composite of $\omega$ at 500 hPa and divergence at 200 hPa over the MLYRV region during the regional PHR events (Fig. 13) also shows the characteristic of bi-weekly oscillation in SP years and an irregular oscillation cycle in SN years. Though the positive peaks of divergence at 200 hPa and negative peaks of $\omega$ at 500 hPa in Figs. 13a, b are similar, they show differences in persistent time. The mid-level ascending motion and upper-level divergence field maintain from days $-9$ to 9 in SP years (Fig. 13a). This dynamical circulation is favorable to the regional PHR over the MLYRV in SP years. In contrast, a convergence field at 200 hPa and weak ascend motion at 500 hPa from days $-6$ to $-2$ are located over the MLYRV in SN years (Fig. 13b), which
Fig. 10. Composite fields of (a, b) precipitation intensity (shaded; mm day$^{-1}$) and (c, d) total duration (shaded; day) of regional PHR events over East China. (a, c) SP years and (b, d) SN years.

Fig. 11. Lagged composites of 12520-line at 200 hPa from (a, c) days $-8$ to 0, and (b, d) days 0 to +8 with interval of 2 days for the regional PHR events. The 0 day means the composite of whole complete events. (a, b) SP years and (c, d) SN years.
5. Summary and discussion

The study focuses on the relationship between the anomalous atmospheric circulation pattern and summertime PHR over the MLYRV on the decadal and interannual timescales. The PHRI is obtained by averaging the PHR events number over the MLYRV during the summers of 1979–2017. The decadal and interannual components of the PHRI are separated through filtering. The anomalous atmospheric circulation patterns associated with the PHRI’s decadal and interannual components are investigated, respectively. The features of regional PHR events are analyzed in SP and SN years. The main results include:

1. The frequency of summertime PHR events over the MLYRV has significant decadal and interannual variability. Power spectrum analysis for the PHRI shows that the predominant peaks in the PHRI are around 3 and 15 yr.

2. The decadal variability of PHR over the MLYRV is associated with the enhanced/decreased precipitation over southern China. The large-scale circulation pattern favorable to the PHR on the decadal timescale includes: the intensified vertical motion and strengthened divergence in the upper levels over southeastern China, and the anomalous anticyclone over the western Pacific transporting more water vapor from Philippines to southern China.

3. The interannual variability of PHR is associated with the enhanced/decreased precipitation over a narrow region around the MLYRV. The anomalous anticyclone over southeastern Asia between 10° and 30°N, together with the cyclone over northern China, produces the anomalous moisture convergence over the MLYRV. Mean-
while, the intensified vertical motion and strengthened divergence in the upper-level are all located over the MLYRV. Above pattern is favorable to the PHR over the MLYRV on the interannual timescale. It is suggested that the interannual variability predominates in PHRI, compared with the decadal variability. The SAH and WPSH are closer to each other during decadal or interannual positive years. They are far away from each other during decadal or interannual negative years.

(4) Compared to those in SN years, the regional PHR events over the MLYRV occur more frequently in SP years with enhanced intensity and larger affected area. The subseasonal zonal oscillations of the SAH and WPSH during the regional PHR events show a better regularity in SP years than those in SN years.

The current study defines the PHRI to quantify the frequency of grid-point PHR over the MLYRV. The index mainly describes the number of PHR events, but may not consider the events with prolonged duration. Besides, the present PHRI depicts the PHR event occurring mostly over the MLYRV. It is not suitable for the precipitation outside the region. An example is the relatively low value of PHRI in 1991. Previous study showed that a long-lasting rainfall season occurs over the Yangtze and Huaihe River basins in 1991 summer (Lu and Ding, 1996; Hu and Ding, 2003). The present grid-point PHR index fails to describe these events.

This study focuses on the atmospheric circulation pattern, which is favorable to the occurrence of PHR events over the MLYRV during summer. The impact of external forcing on the decadal and interannual variability of PHR over the MLYRV is not analyzed in the current study. For example, the impact of the oceanic decadal and interannual signals (e.g., the Pacific decadal oscillation and ENSO) on the PHR is unclear yet. Further investigations are needed in the future.

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