Intraseasonal evolution and climatic characteristics of hourly precipitation during the rainy season in the Poyang Lake Basin, China

Qiong Wu, Bin Xu, Yuanhao Wang and Mingjin Zhan

ABSTRACT

In the key flood control area of the Poyang Lake Basin (China), over 80% of annual precipitation is concentrated in the rainy season. This study investigated the intraseasonal evolution and climatic characteristics of precipitation during the rainy season in the Poyang Lake Basin under the background of climate change. On the basis of the precipitation pattern, the rainy season was divided into three stages: the spring rainy season, Meiyu season, and summer rainy season. Generally, total precipitation and precipitation hours showed no significant trends of change, whereas precipitation intensity had an obvious trend of increase. In the spring rainy season, the trend of total precipitation was downward but not significant; however, owing to substantial reduction in precipitation duration, precipitation intensity was enhanced significantly. In the Meiyu season (summer rainy season), total precipitation increased significantly because of increased precipitation duration (precipitation intensity). The spatial distributions of total precipitation in the spring rainy season and Meiyu season were similar, i.e., precipitation occurred mostly in the east and less in the west; however, the spatial distributions of the change trends were opposite. In the summer rainy season, precipitation was concentrated primarily in the surrounding mountainous areas.

1. Introduction

The monsoonal rainy season in eastern China has obvious regional and temporal characteristics (Ding 1994; Ding and Chan 2005; Wang and Ding 2008). The development and establishment of the summer monsoon over the South China Sea forms the First Flood Period in South China, the Meiyu in the basins of the Yangtze and Huaihe rivers, and the Rainy Season in North China (Wang 1981; Tao and Chen 1987; Ding 1992; Huang et al. 1992). The Poyang Lake Basin, located in the middle
and lower reaches of the Yangtze River in China, has a subtropical warm and humid monsoon climate (Figure 1). The rainy season in the Poyang Lake Basin has long been considered part of the First Flood Period in South China (Chi et al. 2005; Chen et al. 2006; Huang et al. 2014). However, it is recognized that a precipitation peak occurs in the Poyang Lake Basin before the First Flood Period in South China (Chen 1991; Chen et al. 1991). This early precipitation peak is an indicator of the onset of the rainy season in East China (Zhan et al. 2017). This precipitation period, which is called the spring rainy season in Jiangnan, is a type of hazardous weather that is a unique climatic phenomenon in East Asia (Wan and Wu 2008). He et al. (2008) suggested that the spring rainy season in Jiangnan is the “breeding stage” of the subtropical monsoonal precipitation, and that the Meiyu season that occurs after the onset of the South China Sea monsoon represents the peak of the subtropical monsoonal precipitation. Owing to its unique geographical location, the rainy season of the Poyang Lake Basin comprises three distinct periods: the spring rainy season, the Meiyu season, and the summer rainy season.

Although no significant change has been observed in the long-term trend of annual precipitation in China, the interdecadal, interannual, and regional variations
are remarkable (Zhai et al. 2005; Shang et al. 2019). Regionally, extreme heavy rainfall has shown a significant trend of increase and light rainfall has shown a significant trend of decrease over central eastern China. However, in northeastern China and the Sichuan Basin, the precipitation amount in each precipitation intensity category has shown a trend of decline (Zhai et al. 2005; Yao et al. 2008; Yu et al. 2010). Seasonally, precipitation has increased during winter and summer but has decreased during spring and autumn (Huang and Wen 2013; Wen et al. 2015; Li et al. 2016). It has been established that maximum daily precipitation is increasing in southern river basins but decreasing in northern river basins, which leads to no discernible trend of increase or decrease in maximum daily precipitation across China as a whole (Yu et al. 2011). Investigation of the interannual variability of rainfall has also revealed that the number of heavy precipitation days has increased since the 1980s in most of China, particularly in regions of southern China and areas to the south of the Yangtze River Basin (Liu 1999; Yang et al. 2013). Under the background of global climate warming, precipitation in the Poyang Lake Basin has changed significantly (Wang et al. 2009; Zhan et al. 2011). Since the 1960s, the annual number of precipitation days (daily precipitation ≥ 0.1 mm) in the Poyang Lake Basin has shown a significant downward trend, whereas the number of heavy rain days (daily precipitation ≥ 25.0 mm) has increased (Zhan et al. 2019). The trend of change of extreme precipitation is more obvious than that of annual precipitation (Gao and Ren 2016).

Recent research on precipitation in the Poyang Lake Basin has focused mainly on the climatic characteristics of the entire rainy season or the entire year, neglecting variations in different periods of the rainy season. In fact, total rainy season precipitation in the Poyang Lake Basin can often be “normal” but with drought in one period or flooding in another. Notably, precipitation in different periods has different varying degrees of impact in the Poyang Lake Basin. In spring (Mar–May), persistent rainy days have greatest influence on agriculture. For example, long periods of rain might prevent the germination of seeds. In the Meiyu season, continuous heavy rain can lead to landslides, debris flows, and basin flooding. In summer (Jul–Aug), precipitation is caused mainly by strong convection in the afternoon that can often lead to urban waterlogging. Therefore, in undertaking comprehensive research, it is very important that the intraseasonal evolution and climatic characteristics of hourly precipitation in the rainy season in the Poyang Lake Basin be analyzed.

2. Data and method

2.1. Study area

The Poyang Lake Basin (28°22′–29°45′N, 115°47′–116°45′E, area: 1.62 × 10⁵ km²; Figure 1) holds the largest freshwater lake in China. The region has a subtropical humid monsoon climate, with annual precipitation of the order of 1662 mm and annual mean temperature of 18.1 °C (1961–2019). The heavy rainfall that occurs during the major rainy season (March–September) contributes approximately 80% of the regional annual precipitation.
2.2. Meteorological data

The quality-controlled hourly precipitation data used in this study were recorded at 79 meteorological stations during 1978–2019 (black triangles in Figure 1). Prior to further analysis, this dataset was obtained from the National Climatic Reference Network and National Weather Surface Network of China, and it was collected and quality-controlled by the National Meteorological Information Center of the China Meteorological Administration. The data were tested for homogeneity and the average annual rate of missing data for the selected study period was 3.01%.

2.3. Intraseasonal evolution of the rainy season

Precipitation in the Poyang Lake Basin, which occurs mainly during March–September (the rainy season), accounts for approximately 80% of the total regional annual precipitation (Figure 2).

Precipitation in the Poyang Lake Basin has well-characterized stages during the rainy season. The main driving factors of precipitation in the different stages are not the same. In the first stage (from March to early May), the spring continuous rain, which is a unique weather and climatic phenomenon in East Asia, is the result of dynamic and thermal forcing by the high terrain of the Qinghai–Tibet Plateau. The precipitation during this stage is mainly frontal precipitation (Wan and Wu 2008). In the second stage (May–June), from the 4th to 5th pentads in May, the South China Sea monsoon breaks out. At this time, a belt of water vapor transport is established that extends from the low-latitude ocean in the Southern Hemisphere to southern China via the Arabian Sea, Indian Ocean, and Bay of Bengal (He et al. 2008). The precipitation during this stage is mainly monsoonal precipitation. In the third stage (July–September), the rainband of the East Asian subtropical monsoon extends northward to North and Northeast China. The precipitation during this stage is mainly convective precipitation (Jiang et al. 2015).

Figure 2. Monthly precipitation volume in the Poyang Lake Basin.
Precipitation duration is an important feature of any precipitation process. Compared with volume, frequency, and intensity, the duration of a precipitation event is more closely related to the characteristics of the precipitation process (Li et al. 2011). Yu and Zhou (2007) proposed that duration is the key factor for distinguishing different types of precipitation process. Precipitation events persisting for 1–6, 7–12, and $\geq 13$ h are called short-, medium-, and long-duration precipitation events, respectively (Wu and Zhan 2020). It can be seen in Figure 3 that rainy season precipitation in the Poyang Lake Basin has evident characteristic stages. In the first stage (13th to 27th pentads), i.e., the spring rainy season, the volume of precipitation begins to increase, and most precipitation events are of short and medium duration. In the second stage (28th to 36th pentads), i.e., the Meiyu season, precipitation increases and events with rainfall of $>1.6$ mm can be of short, medium, or long duration. In the third stage (37th to 49th pentads), i.e., the summer rainy season, precipitation events are mainly of short duration. The precipitation duration distribution of each stage has distinct characteristics.

2.4. Theil–Sen’s slope estimator

The Theil–Sen’s slope estimator, which is an unbiased nonparametric estimator of the true slope in simple linear regression, was used in this study to examine the long-term trends. If a given time series has a linear trend, then the level of increase or decrease per unit time can be described by the Theil–Sen’s slope (Sen, 1968). Unlike least squared linear regression, the Theil–Sen’s slope estimator is insensitive to outliers and thus the estimated linear trend is significantly more accurate and robust for skewed data. The slope of N pairs of data points can be estimated using the following relation:

![Figure 3. Precipitation duration distribution of each pentad.](image-url)
where \( x_l \) and \( x_j \) are data values at time \( l \) and time \( j \), respectively. Owing to its robustness for estimating the magnitude of a trend, this method is applied widely to hydrological and climatic time series (Cunderlik and Burn, 2003; Tabari and Talaee, 2011; Jhajharia et al. 2012; Wang et al. 2013).

### 2.5. Mann–Kendall trend test

The Mann–Kendall (M-K) test statistic \( S \) (Mann, 1945; Kendall, 1975) is calculated as follows:

\[
S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \text{sgn}(x_j - x_i),
\]

where \( n \) is the number of data points, \( x_i \) and \( x_j \) are data values in time series \( i \) and \( j \) (\( j > i \)), respectively, and \( \text{sgn}(x_j, x_i) \) is the sign function, which is given as follows:

\[
\text{sgn}(x_j - x_i) = \begin{cases} +1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \\ \end{cases}
\]

The variance is computed as follows:

\[
\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18},
\]

where \( n \) is the number of data points, \( m \) is the number of tied groups, and \( t_i \) denotes the number of ties of extent \( i \). A tied group is a set of sample data having the same value. In cases with sample size \( n > 10 \), the standard normal test statistic \( Z_S \) is computed using the following relation:

\[
Z_S = \begin{cases} \frac{S - 1}{\sqrt{\text{Var}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S + 1}{\sqrt{\text{Var}(S)}}, & \text{if } S < 0 \end{cases}
\]

Positive (negative) values of \( Z_S \) indicate increasing (decreasing) trends. Testing of trends is done at a specific \( \alpha \) significance level. When \( |Z_S| > Z_{1-\alpha/2} \), the null hypothesis is rejected and a significant trend exists in the time series; \( Z_{1-\alpha/2} \) is obtained from the standard normal distribution table. In this study, significance levels of \( \alpha = 0.01 \) and \( \alpha = 0.05 \) were used. At the 5% (1%) significance level, the null hypothesis of no trend is rejected if \( |Z_S| > 1.96 \) (\( |Z_S| > 2.576 \)).
The M-K statistical test has been used frequently to quantify the significance of trends in hydrometeorological time series (Douglas et al. 2000; Yue et al. 2002; Partal and Kahya 2006; Modarres and Silva 2007).

3. Results

3.1. Diurnal variation of precipitation

In the Poyang Lake Basin, the diurnal variation characteristics of precipitation in the three different stages are distinct (Figure 4). In the spring rainy season, precipitation presents a single-peaked distribution, and it mainly occurs during 06:00–09:00 (all times expressed as Beijing time), although afternoon precipitation does gradually increase as the rainy season progresses. In the Meiyu season, precipitation shows a bimodal distribution, with precipitation occurring mainly during 06:00–10:00 and 14:00–16:00. After the Meiyu season, precipitation starts to decrease. In the summer rainy season, precipitation is mostly convective and concentrated during 16:00–18:00.

3.2. Intraseasonal variation of precipitation

Rainy season precipitation in the Poyang Lake Basin has obvious stage characteristics.
In terms of volume (Figure 5a), precipitation in the Poyang Lake Basin begins to increase significantly after the 13th pentad, which indicates the beginning of the spring rainy season. The total volume of a pentad is more than 20 mm. The first peak appears between the 19th and 27th pentads. The pentad precipitation volume is >34.7 mm. The maximum precipitation occurs in the 27th pentad with a pentad volume of 40.6 mm. The reduction in precipitation in the 28th pentad indicates the end of the spring rainy season and the beginning of the Meiyu season. Precipitation increases rapidly after the 29th pentad. The second peak appears between the 31st and 35th pentads, and the mean pentad precipitation is 44.6 mm. After the 36th pentad, precipitation decreases rapidly, indicating the end of the Meiyu season. After the 37th pentad, the summer rainy season starts. Unlike the spring rainy season and the Meiyu season, most precipitation in the summer rainy season is associated with convective and typhoon-related processes. The third peak appears between the 42nd and 49th pentads, and the mean pentad precipitation is 22.6 mm. After the 49th pentad, pentad precipitation is <10 mm, indicating the end of the rainy season in the Poyang Lake Basin.

In terms of precipitation duration (Figure 5b), the accumulated pentad precipitation hours show a bimodal distribution. The maximum peak appears in the spring rainy season, and the mean pentad precipitation hours are 22.5 h from the 13th to 21st pentads. During the Meiyu season, the pentad precipitation hours start increasing again. The second peak appears between the 31st and 34th pentads, with mean pentad precipitation hours of 19.7 h. In the summer rainy season, the precipitation hours decrease significantly, i.e., the pentad precipitation hours are around 10 h.

In terms of intensity (Figure 5c), the precipitation also shows a bimodal distribution. In the spring rainy season, the intensity of hourly precipitation increases to reach a peak of 2.2 mm/h in the 27th pentad. After the spring rainy season, precipitation intensity first decreases and then increases again. It reaches the annual maximum
of 2.5 mm/h at the 34th pentad and it remains largely unchanged between the 34th and 48th pentads. After the summer rain season, precipitation intensity decreases to no more than 1.0 mm/h.

In the Poyang Lake Basin, precipitation in the different stages of the rainy season has distinctive features. For example, there are more precipitation hours in the spring rainy season, greater pentad precipitation in the Meiyu season, and higher precipitation intensity in the summer rainy season. In the Poyang Lake Basin, days of continuous precipitation are common in March (13th to 19th pentads). Consequently, the number of precipitation hours in March is higher in comparison with other months.

In March, a belt of water vapor transport from the Western Pacific to southern China is formed, and convergence at the front of this strong belt of water vapor transport leads to substantial increase in precipitation in the region south of the Yangtze River (including the Poyang Lake Basin) in late March (He et al. 2008). The Poyang Lake Basin is located downstream of the center of strong southwesterly winds on the southeastern side of the Qinghai–Tibet Plateau. This strong wind and moisture convergence are the direct causes of the spring rainy season. After the onset of the South China Sea monsoon, there is a period of peak precipitation in the basin as the Meiyu season arrives (Wan and Wu 2008). The precipitation in the summer rainy season is most often related to severe convective weather or typhoons; consequently, precipitation intensity is relatively high (Wang et al. 2015).

3.3. Annual variation of precipitation

The annual variation characteristics of rainy season precipitation in the Poyang Lake Basin during 1978–2019 are shown in Figure 6. Annually, precipitation volume during the entire rainy season is approximately 1240 mm, with a maximum of 1677 mm in 2010 and a minimum of 911 mm in 1978 (Figure 6a). It can be seen that
precipitation volume increases at the rate of 25.7 mm/10a during 1978–2019, but the trend is not significant (M-K value: 1.08). Annually, precipitation hours in the rainy season are 683 h, with a maximum of 864 h in 1999 and a minimum of 519 h in 2018 (Figure 6b). Unlike precipitation volume, precipitation hours during the study period decrease slightly at the rate of −4.0 h/10a, but the trend does not pass the significance test (M-K value: −0.32). Annually, precipitation intensity in the rainy season is approximately 1.82 mm/h, with a maximum of 2.26 mm/h in 1983 and a minimum of 1.52 mm/h in 1989 (Figure 6c). During the study period, precipitation intensity shows a trend of increase of 0.07 mm/h/10a, and it passes the significance test (M-K value: 3.84). Generally, during 1978–2019, precipitation in the rainy season shows a trend of increase; however, precipitation intensity is obviously enhanced owing to the reduction in precipitation hours.

Annually, precipitation in the spring rainy season is around 504 mm, with a maximum of 721 mm in 2010 and a minimum of 271 mm in 2011 (Figure 7-1a). During 1978–2019, it decreases at the rate of 10.4 mm/10a, but this trend fails to pass the 0.01 significance level test (M-K value: −0.65). Annually, precipitation hours in the spring rainy season are around 340 h, with a maximum of 440 h in 1980 and a minimum of 239 h in 2018 (Figure 7-1b). Similar to precipitation volume, precipitation hours also show a decreasing trend, with a rate of −18.6 h/10a that passes the significance test (M-K value: −3.00). Annually, precipitation intensity in the spring rainy season is around 1.48 mm/h, with a maximum of 1.91 mm/h in 2016 and a minimum of 1.07 mm/h in 2011 (Figure 7-1c). Unlike the other parameters, precipitation intensity shows an increasing trend of 0.06 mm/h/10a that passes the significance test (M-K value: 2.17). Overall, precipitation in the spring rainy season shows a trend of decrease but with a significant increase in precipitation intensity owing to the significant reduction in precipitation hours.
Annually, precipitation in the Meiyu season is around 368 mm, with a maximum of 645 mm in 1995 and a minimum of 197 mm in 1991 (Figure 7-2a). Different from the spring rainy season, it can be seen that precipitation increases at the rate of 30.6 mm/10a after 1978, which is a trend that passes the 0.01 significance level test (M-K value: 2.80). The precipitation hours in the Meiyu season also increase at the rate of 11.2 h/10a, which is a trend that also passes the significance test (M-K value: 2.19) (Figure 7-2b). Precipitation shows a trend of slight increase of 0.05 mm/h/10a (Figure 7-2c). Overall, the volume, hours, and intensity of precipitation during the Meiyu season show trends of increase, and the increase of the total precipitation is mainly attributable to the increase in precipitation hours.

![Figure 8. Spatial distribution of precipitation in (a) the entire rainy season, (b) spring rainy season, (c) Meiyu season, and (d) summer rainy season.](image-url)
Annually, precipitation in the summer rainy season is around 368 mm, with a maximum of 633 mm in 1999 and a minimum of 176 mm in 1978 (Figure 7-3a). Similar to the Meiyu season, it can be seen that precipitation volume increases at the rate of 14.0 mm/10a after 1978, but the trend fails to pass the 0.01 significance level test (M-K value: 1.34). During the study period, precipitation hours decrease at the rate of 0.5 h/10a, but this trend fails the significance test (M-K value: 0.13) (Figure 7-3b). Conversely, precipitation intensity shows a nonsignificant trend of increase of 0.06 mm/h/10a (M-K value: 1.41) (Figure 7-3c). Overall, the volume and intensity of precipitation during the Meiyu season show trends of increase, whereas precipitation hours are decreasing. The increasing precipitation intensity is the main reason for the increasing precipitation volume.

Figure 9. Spatial features of the trend of variation of precipitation in (a) the entire rainy season, (b) spring rainy season, (c) Meiyu season, and (d) summer rainy season.
3.4. Spatial distribution and variation of precipitation

It can be seen from Figure 8 that the spatial distribution pattern of precipitation in the spring rainy season is similar to that of the Meiyu season. The overall distribution indicates greater precipitation in the east of the Poyang Lake Basin than in the west. The centers of high values are concentrated in eastern central parts of the basin, while the centers of low value are mainly in northern and southwestern areas. The spatial distribution of precipitation in the summer rainy season has no obvious regularity, which might be related to topography, i.e., there is more precipitation in the mountainous areas than over the area of the central plain.

Figure 9 illustrates the spatiotemporal features of the trend of variation of precipitation at the 79 meteorological stations in Poyang Lake Basin during 1978–2019. In the spring rainy season, most stations show a trend of decreasing precipitation, especially stations in central and southern parts. Only certain stations in northern and northeastern areas show a (nonsignificant) trend of increase (Figure 9b). Conversely, in the Meiyu season, all stations show a trend of increasing precipitation, although the trend is nonsignificant for northern stations. Most southern and central stations show a significant trend of increase in precipitation (Figure 9c). In the summer rainy season, most stations show no significant trend of change in precipitation, other than two sites in the western mountainous regions where precipitation has increased significantly (Figure 9d).

4. Conclusions and discussion

On the basis of the characteristics of precipitation, the rainy season in the Poyang Lake Basin was divided into three stages: the spring rainy season (13th to 27th pentads), Meiyu season (28th to 36th pentads), and summer rainy season (37th to 49th pentads). To elucidate further details regarding changes in the rainy season in the Poyang Lake Basin, we analyzed the spatiotemporal characteristics of precipitation in the three stages. On the basis of data obtained in this study and by others, the following conclusions were drawn.

1. The diurnal variation characteristics of precipitation in the three stages are obviously different. In the spring rainy season, precipitation is concentrated mainly during 06:00–09:00. As time passes, the occurrence of afternoon precipitation gradually increases. There is a bimodal distribution of precipitation in the Meiyu season: one peak appears during 06:00–10:00 and the other appears during 14:00–16:00. After the Meiyu season, precipitation decreases and there is only one peak during 16:00–18:00 in the summer rainy season.

2. Generally, precipitation in the rainy season is increasing. Although precipitation in the spring rainy season is decreasing, precipitation in both the Meiyu season and the summer rainy season is increasing but for different reasons. In the Meiyu season (summer rainy season), the increase of precipitation is mainly due to increased precipitation hours (precipitation intensity). It is worth noting that precipitation intensity in all three stages shows an increasing trend, which will bring a greater risk of flooding in the Poyang Lake Basin.
3. The spatial distributions of precipitation in the spring rainy season and the Meiyu season are similar, with most (least) precipitation in eastern (western) parts of the Poyang Lake Basin. However, the precipitation distribution in the summer rainy season is different, i.e., most precipitation occurs in the surrounding mountainous areas and less falls over the area of the central plain. Spatially, in the spring rainy season, precipitation at most stations in the Poyang Lake Basin is decreasing, especially in the south. Conversely, in the Meiyu season, most stations show precipitation is increasing, especially in the south. In the summer rainy season, the trends of change in precipitation at most stations are not significant; only two mountain stations show a significant trend of increase.

In East China, annual precipitation shows no obvious change, but precipitation concentration shows an increasing trend. The number of days with light rain (daily rain: \( \leq 10 \text{ mm} \)) shows significant decrease, while the number of days with heavy rain (daily rain: \( \geq 50 \text{ mm} \)) shows significant increase (Zhai et al. 2005; Qian et al. 2007; Yu et al. 2011; Huang and Wen 2013; Wen et al. 2015; Li et al. 2016). Similar to East China, precipitation intensity in the Poyang Lake Basin is also increasing significantly (Zhan et al. 2013; Gao and Ren 2016). However, this study established that although precipitation in the Poyang Lake Basin might follow the general variation of precipitation in East China, it has its own characteristics. The increase in precipitation volume in the Meiyu season is greater than the decrease in volume in the spring rainy season, which means that the annual volume of precipitation in the entire rainy season is increasing. The increase in Meiyu precipitation is the primary reason for the overall increase in the volume of rainy season precipitation in the Poyang Lake Basin.

Wan and Wu (2008) suggested that the spring rainy season in the Poyang Lake Basin is the result of dynamic and thermal forcing associated with the high terrain on the Qinghai–Tibet Plateau, and its rain belt coincides with southern parts of the Wuyi Mountains, highlighting that the spring rainy season in the Poyang Lake Basin is closely related to terrain. The occurrence of heavy rainfall in summer in the Poyang Lake Basin is a positive response to regional warming (Gao et al. 2001; Tang et al. 2018). Changes in the Meiyu season might be related to variation in upper-tropospheric temperature (Yu et al. 2004; Xin et al. 2006; Yu and Zhou 2007). For example, cooling of the upper troposphere leads to weakening of the East Asian summer monsoon. Consequently, precipitation in northern China is reduced, while precipitation in the Yangtze River Basin is increased further. Thus, precipitation in the Meiyu season in the Poyang Lake Basin is increasing. The factors that influence precipitation in the Poyang Lake Basin are very complex and inconsistent throughout the rainy season, and further study is required to determine their relative importance within the context of climate change.

**Funding**

This study was supported by the Jiangxi Meteorological Bureau, Jiangxi Eco-meteorological Center, and the Natural Science Foundation of Jiangxi Province (20202BABL203036).
Data availability statement

All data used during the study were provided by the China Meteorological Administration (http://data.cma.cn/). Direct requests for these materials may be made to the provider.

References

Chen JY. 1991. The analysis and research of floods/droughts in China and long-range forecasting. Beijing: Chinese Agriculture Press.
Chen KY, Hu J, Wang QQ, Mao WS. 2006. SVD analysis of the relationship between Northern Jiangnan Meiyu precipitation and SST in the Tropical Oceans. J Nanjing Inst Meteorol. 29(2):258–263.
Chen LX, Zhu QG, Luo HB, et al. 1991., East Asian monsoon. Beijing: China Meteorological Press.
Chi YZ, He JH, Wu ZW. 2005. Features Analysis of the Different Precipitation Periods in the Pre-flood Season in South China. J Nanjing Inst Meteorol. 28(2):163–171.
Cunderlik JM, Burn DH. 2003. Non-stationary pooled flood frequency analysis. J Hydrol. 276(1–4):210–223.
Ding YH. 1992. Summer monsoon rainfall in China. J Meteorol Soc Jpn. 70(1B):373–396.
Ding YH. 1994. Monsoons over China. London: Kluwer Academic Publishers. p. 135–136.
Ding YH, Chan JCL. 2005. The East Asian summer monsoon: an overview. Meteorol Atmos Phys. 89(1–4):117–142.
Douglas EM, Vogel RM, Kroll CN. 2000. Trends in floods and low flows in the United States: impact of spatial correlation. J Hydrol. 240(1–2):90–105.
Gao B, Ren YQ. 2016. Changes of extreme precipitation events in Poyang Lake Basin from 1961 to 2010. Advances in Science and Technology of Water Resources. 36(01):31–35.
Gao X, Zhao Z, Ding Y, Huang R, Giorgi F. 2001. Climate change due to greenhouse effects in China as simulated by a regional climate model. Adv Atmos Sci. 18(6):1224–1230.
He JH, Zhao P, Zhu CW, et al. 2008. Discussions on the East Asian subtropical monsoon. Acta Meteorol Sin. 66(5):683–696.
Huang G, Wen G. 2013. Spatial and temporal variations of light rain events over China and the mid-high latitudes of the Northern Hemisphere. Chin Sci Bull. 58(12):1402–1411.
Huang RH, Yin BY, Liu AD. 1992. Intraseasonal variability of East Asia summer monsoon and its association with the convection. Proceeding of international workshop on climate variability, Beijing: China Meteorological Press.
Huang Y, Zhang RH, Gong ZQ, et al. 2014. An objectively quantitative division for rainy seasons in China. Acta Meteorologica Sinica. 72(6):1186–1204.
Jhajharia D, Dinapashoh Y, Kahya E, Singh VP, Fakheri-Fard A. 2012. Trends in reference evapotranspiration in the humid region of northeast India. Hydrof Process. 26(3):421–435.
Jiang J, Jiang DB, Lin YH. 2015. Monsoon area and precipitation over China for 1961–2009. Chin J Atmos Sci. 39(4):722–730.
Li D, Sun J, Fu S, Wei J, Wang S, Tian F. 2016. Spatiotemporal characteristics of hourly precipitation over central eastern China during the warm season of 1982–2012. Int J Climatol. 36(8):3148–3160.
Li J, Yu R, Yuan W, Chen H. 2011. Changes in duration-related characteristics of late-summer precipitation over Eastern China in the past 40 years. J Clim. 24(21):5683–5690.
Liu X. 1999. Climatic characteristics of extreme rainstorm events in China. J Catastrophol. 14(1):54–59.
Modarres R, Silva VPR. 2007. Rainfall trends in arid and semi-arid regions of Iran. J Arid Environ. 70(2):344–355.
Partal T, Kahya E. 2006. Trend analysis in Turkish precipitation data. Hydrol Process. 20(9):2011–2026.
Qian W, Lin X, Zhu Y, Xu Y, Fu J. 2007. Climatic regime shift and decadal anomalous events in China. Clim Change. 84(2):167–189.
Shang H, Xu M, Zhao F, Tijjani SB. 2019. Spatial and temporal variations in precipitation amount, frequency, intensity, and persistence in China, 1973–2016. J Hydrometeorol. 20(11):2215–2227.
Tabari H, Talae PH. 2011. Temporal variability of precipitation over Iran: 1966–2005. J Hydrol. 396(3–4):313–320.
Tang CS, Xu AH, Ma FM, et al. 2018. Spatial and temporal variations of short-duration heavy precipitation in Jiangxi during 1961–2015. Torrential Rain Disasters. 37(5):421–427.
Tao SY, Chen LX. 1987. A review of recent research on the East Asian summer monsoon in China. In: Chang PC, Krishmurti TN, editors. Monsoon meteorology. London: Oxford University Press. p. 60–92.
Wan RJ, Wu GX. 2008. Temporal and spatial distribution of the spring persistent rains over southeastern China. Acta Meteorol Sin. 66 (3):310–319.
Wang DH. 1981. Research on the division of rainy season and the change of rain belt. Acta Meteorol Sin. 32(9):252–256.
Wang HQ, Yin JM, Kong P, et al. 2015. Variation of drought and flood over the last millennium in Poyang Lake Basin by R/S analysis. Res Environ Yangtze Basin. 24(7):1214–1220.
Wang HQ, Zhao GN, Peng J. 2009. Precipitation characteristics over five major river systems of Poyang drainage areas in recent 50 years. Res Environ Yangtze Basin. 18:615–619.
Wang S, Zhang M, Sun M, Wang B, Li X. 2013. Changes in precipitation extremes in alpine areas of the Chinese Tianshan Mountains, central Asia, 1961–2011. Quat Int. 311:97–107.
Wang ZY, Ding YH. 2008. Climatic characteristics of rainy seasons in China. Chin J Atmos Sci. 32(1):1–13.
Wen G, Huang G, Hu K, Qu X, Tao W, Gong H. 2015. Changes in the characteristics of precipitation over northern. Theor Appl Climatol. 119(3–4):653–665.
Wu Q, Zhan MJ. 2020. Climatic characteristics of hourly precipitation (1978–2019) in the Poyang Lake Basin, China. Geomat Nat Haz Risk. 11(1):1679–1696.
Xin X, Yu R, Zhou T, Wang B. 2006. Drought in late spring of South China in recent decades. J Clim. 19(13):3197–3206.
Yang L, Villarini G, Smith JA, Tian F, Hu H. 2013. Changes in seasonal maximum daily precipitation in China over the period 1961–2006. Int J Climatol. 33(7):1646–1657.
Yao C, Yang S, Qian W, Lin Z, Wen M. 2008. Regional summer precipitation events in Asia and their changes in the past decades. J Geophys Res. 113(D17):D17107.
Yu C, Chen XY, Ren GY. 2011. Variation of extreme precipitation over large river basins in China. Advances in climate change research 2(2):108–114.
Yu R, Li J, Yuan W, Chen H. 2010. Changes in characteristics of late-summer precipitation over eastern China in the past 40 years revealed by hourly precipitation data. J Clim. 23(12):3390–3396.
Yu R, Wang B, Zhou T. 2004. Tropospheric cooling and summer monsoon weakening trend over East Asia. Geophys Res Lett. 31(22):L22212.
Yu R, Zhou T. 2007. Seasonality and three-dimensional structure of interdecadal change in the East Asian monsoon. J. Clim. 20(21):5344–5355.
Yue S, Pilon P, Phinney B, Cavadias G. 2002. The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol Process. 16(9):1807–1829.
Zhai P, Zhang X, Wan H, Fan X. 2005. Trends in total precipitation and frequency of daily precipitation extremes over China. J Clim. 18(7):1096–1108.
Zhan FX, Zhang KM, He JH. 2017. Intraseasonal evolution of precipitation in the Jiangnan rainy season and its interannual and interdecadal variations. Trans Atmos Sci. 40(6):759–768.
Zhan M, Zhai J, Sun H, Li X, Xia L. 2019. Observed exposure of population and gross domestic product to extreme precipitation events in the Poyang Lake Basin, China. Atmosphere. 10(12):817.
Zhan MJ, Yin JM, Kong P. 2013. Facts of climate change in Poyang Lake Basin. Meteorol Disast Reduct Res. 36(03):18–24.
Zhan MJ, Yin JM, Zhang YZ. 2011. Analysis on characteristic of precipitation in Poyang Lake Basin from 1959 to 2008. Procedia Environ Sci. 10:1526–1533.