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Variation of Hourly Extreme Precipitation in the Three Gorges Reservoir Region, China, from the Observation Record

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Abstract: Extreme hourly precipitation is amongst the most prominent driving factors of flash floods and geological disasters. Based on the hourly precipitation data of 35 stations in the Three Gorges Reservoir Region (TGRR) from 1998 to 2020, we analyzed the spatiotemporal variation characteristics of hourly extreme precipitation indexes. The selected indicators included the frequency, intensity, period, annual maximum, trend of hourly heavy precipitation (20–50 mm/h) and hourly extreme heavy precipitation ($\geq$50 mm/h) in the TGRR. Closely related climatic factors such as the Western Pacific Subtropical High Intensity (WPSHI) were also discussed. The results showed that in 2010–2020, the cumulative frequency of heavy precipitation magnitude between 25 and 40 mm/h slightly increased, while the corresponding frequency for magnitudes $\geq$50 mm/h decreased. In summer, the frequency of both heavy and extreme heavy precipitation increased in June and decreased in August, indicating a shift of extreme events to an earlier time in the flood season. The cumulative frequency of heavy precipitation in July had a period of about 7a, and that of extreme heavy precipitation had a period of 3a. The annual average intensity of heavy precipitation and extreme heavy precipitation in the TGRR was 28.9 mm/h and 61.4 mm/h per station, respectively, and both fluctuated and insignificantly decreased from 1998 to 2020. The annual maximum hourly precipitation center in the TGRR moved downstream from west to northeast. The frequency of heavy precipitation was relatively small along the main stream of the river valley. Both the frequency and total amount of heavy precipitation in southeast of the TGRR were significantly higher than those in other regions. Heavy precipitation in the majority of stations with high elevation (higher than 500 m) showed a decreasing trend. The cumulative frequency of precipitation with an intensity of 20–50 mm/h was closely correlated with the Western Hemisphere Warm Pool (WHWP) Index in February and the WPSHI Index in January, and especially, the abnormal large annual frequency (top 20%) showed strong correlation with the two indexes, implying highly predictable factors for extreme events. The frequency of precipitation intensity above 50 mm/h was correlated with the Western Pacific Warm Pool (WPWP) Area Index in January and the WPWP Intensity Index in November of last year. The research results provide a strong and refined factual basis for the assessment and prediction of extreme precipitation, and for disaster prevention and mitigation, in the TGRR.

Keywords: Three Gorges Reservoir Region; hourly heavy precipitation; hourly extreme heavy precipitation; climate factors

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1. Introduction

The Three Gorges Reservoir Region (TGRR) is an important strategic area in China, with special geographical characteristics; it is an important area in terms of ecological function and a typical ecologically fragile area in the Yangtze River Basin [1,2]. The topography of the TGRR is mainly mountainous, with a high proportion of steep slopes, so it is easily affected by extreme weather [3]. Due to the impact of global climate change and human activities, short-term heavy precipitation in the TGRR has been more frequent and intensive in recent years, which has caused very serious impacts on the ecological environment and the economy of the TGRR [4–6]. In order to obtain early warning and better preparation for disaster alleviation, it is of great importance to analyze characteristics of extreme precipitation in terms of spatiotemporal variation in the TGRR and explore the physical factors related to extreme precipitation events.

Many studies have drawn general understandings on the spatiotemporal variation of short-term heavy precipitation in the Yangtze River Basin and TGRR at monthly and daily scales. There are three extreme precipitation centers in the Yangtze River basin, namely the Sichuan Basin, the Dongting Lake Basin and the Great Triangle region covering the Poyang Lake Basin and the southern foot of the Dabie Mountains [7]. Extreme precipitation in spring and summer showed a significant increasing trend in eastern China [8]. Regional persistent extreme precipitation events occurred more frequently after 1990, with higher mean intensity, longer mean duration, and larger affected areas [9]. Based on daily statistics, many scholars have analyzed regional trends [10], trends relating to extreme precipitation events [11], the temporal variability of daily precipitation [12], and so on. The annual average precipitation is 1000–1200 mm in most of the area of the TGRR, and more than 45% of the annual precipitation is concentrated in summer [13]. The differences in annual rainfall over the TGRR between the two periods before and after the operation of the Three Gorges Dam (TGD) are small, suggesting a weak impact of TGD on the rainfall at a yearly scale [14]. A similar dipole pattern appeared in the precipitation before the construction of the TGD, for example, from 1977 to 1984 [15]. Inter-decadal changes are obvious in the TGRR; it was wettest in the early 1980s, and dry in the first few years after 1990 [16].

In addition, there are many research studies on the physical causes of extreme precipitation events in the mentioned region. Extreme precipitation totals and durations, measured as days within a specific period, were found to be negatively correlated with the Western North Pacific Monsoon Index (WNPMI) in the TGRR [17]. The decrease in sea-land temperature difference caused by the abnormal warming of the Western Pacific Warm Pool (WPWP) Index was one of the important driving factors of the transition of summer extreme precipitation in eastern China around 1990 [18]. Summer extreme precipitation is statistically significantly correlated with the western North Pacific subtropical high (WPSH) and positive anomalies of 500 hPa geopotential heights [19]. With the ridge of the western Pacific subtropical high typically staying around the northeastern quadrant of the South China Sea, persistent extreme precipitation events that are induced by the typical East Asia/Pacific conditions will be more likely to occur in the Yangtze River Valley [19].

Based on the daily precipitation data, the spatiotemporal variation characteristics of extreme precipitation in the study area can be analyzed in general [20]. In the case of hourly precipitation data, not only can the above research be carried out, but the daily precipitation structure in the study area can also be depicted to compare the occurrence time and frequency of hourly precipitation of different magnitudes. Taking Henan Province as an example, the study of daily precipitation data shows that the extreme precipitation index in Henan Province has obvious interannual and interdecadal temporal variation, and the overall characteristics are more than in the early 1980s, but less than in the 1990s, and increased after the 21st century [21]. A study that was based on hourly precipitation data shows that the diurnal variation of hourly extreme precipitation frequency shows an obvious bimodal pattern, with the main peak appearing in the evening. The diurnal variation of extreme precipitation frequency over 80 mm/h shows a multi-peak structure, and the main peak value occurs at night [22].

Due to the characteristics of sudden, local and high intensity of extreme precipitation in the TGRR [23], the extant research on extreme precipitation at an hourly scale may be adequate to capture such short durations of heavy precipitation, and is this capable of meeting the needs of meteorological services [24].

In order to improve the monitoring and evaluation accuracy of short-term heavy precipitation process in the TGRR, hourly heavy precipitation ($\geq$20 mm/h) and hourly extreme precipitation (≥50 mm/h) indexes in the TGRR were defined based on hourly precipitation observation data in the TGRR from 1998 to 2020. Based on hourly precipitation data, we analyzed the frequency and spatial distribution of hourly heavy precipitation and hourly extreme heavy precipitation in the TGRR. In addition, we managed to seek the key climatic forcers that may be closely associated with extreme precipitation events in the TGRR.

2. Data and Methodology

2.1. Study Area

The TGD is located in the middle and upper reaches of the Yangtze River, which includes the areas inundated by the Three Gorges Project from Yichang in Hubei Province in the east to Jiangjin in Chongqing in the west. It is about 58,000 km^2, 600 km long, spanning several kilometers across the Yangtze River [25]. In order to better analyze and study the characteristics of extreme precipitation in the region of the TGD and its surrounding areas, this study defined the area including the region of the TGD across Chongqing and Hubei, starting from Jiangjin in Chongqing in the west, ending in Zhijiang in Hubei in the east, bordering Wuxi in Chongqing in the north and reaching Laifeng in Hubei in the south, as the TGRR (Figure 1). The region is mainly mountainous, with a high proportion of steep slopes and abundant precipitation, so it is easily affected by extreme weather [1]. Extreme precipitation is frequent and intense, which is one of the main sources of local disasters [7]. The study area has a subtropical continental monsoon climate, with summer rainfall accounting for more than 60% of the annual precipitation. The annual average temperature is 18 °C and annual precipitation is 1000–1800 mm. Meteorological disasters occur frequently. Because it is located at the junction of Sichuan Basin and the plain of the middle and lower reaches of Yangtze River, and beyond the mountain valley of central Hubei and the ridge valley of eastern Sichuan, earthquake, collapse, landslide, debris flow and other disasters occur frequently, and soil erosion is serious [3].

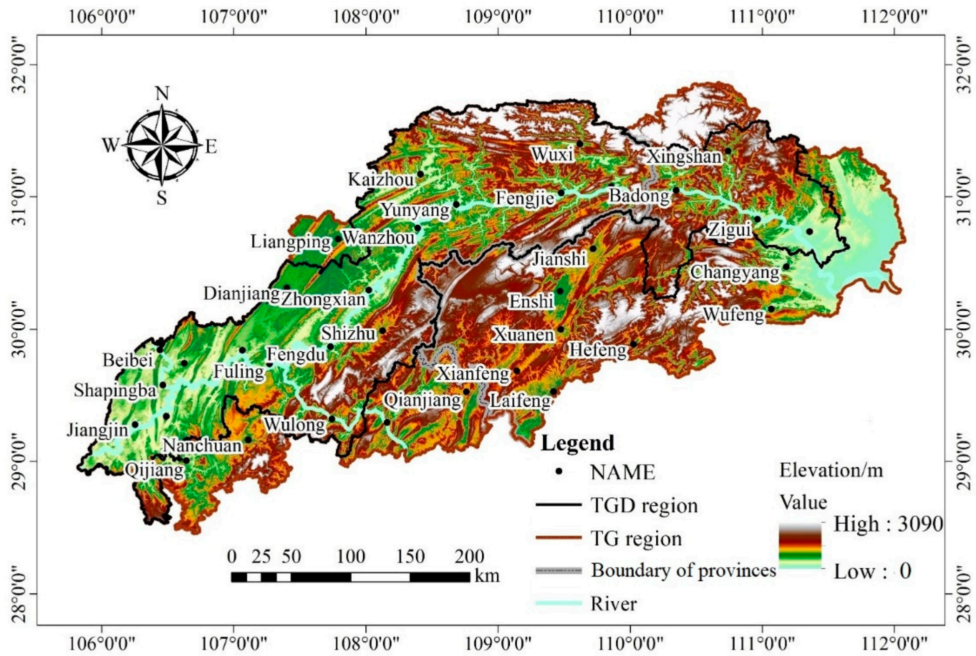


Figure 1. Elevation topography and meteorological station distribution in the TGRR.

2.2. Data

According to the hourly precipitation data of 35 meteorological stations in the TGRR from 1998 to 2020 provided by the National Climate Information Network, 12 meteorological stations such as Zigui and Hefeng in Hubei Province, and 23 meteorological stations such as Shapingba, Wulong and Qijiang in Chongqing City, were included (Figure 1). After strict quality control and inspection, the hourly rainfall data reached high reliability and accuracy.

The dataset of 40 potential predictive climatic factors that are closely related to drought and flood in flood season in China were selected according to previous research studies [26–28], out of the whole dataset of 130 indexes (including 88 circulation characteristic datasets, 26 SST datasets and 16 datasets related to other factors) from 1997 to 2020 provided by the National Climate Center of China Meteorological Administration. This subset of climatic factors covers 130 climatic factor values for each month of each year since 1956. As the drought and flood conditions in flood season of a certain year are related to the potential predictive climate factors in the autumn and winter of the previous year and the spring of the current year, the time interval of the climate factor subset adopted in this study was 1997–2020.

2.3. Study Method

2.3.1. Definition of Extreme Precipitation Duration

According to the intensity of short-term extreme precipitation, precipitation ≥20 mm/h was defined as hourly heavy precipitation, and precipitation ≥50 mm/h was defined as hourly extreme heavy precipitation [29,30]. According to the hourly extreme precipitation thresholds at different percentiles in the TGRR during 1998–2020 (Table 1), when the hourly precipitation thresholds at all stations were greater than 20 mm/h, the precipitation thresholds at the 99.98% percentile of the precipitation sequence were correlated. Therefore, the definition of extreme precipitation in China meteorological service was found to be applicable to the precipitation series in the TGRR.

Table 1. Hourly heavy precipitation thresholds at different percentiles in the TGRR from 1998 to 2020.

Percentile/%	Hourly Precipitation Threshold		
	Minimum Value	Maximum Value	Average Value
99.95	15.90	24.30	18.89
99.98	21.90	31.80	26.56
99.99	27.40	40.20	32.89

Taking the duration of extreme precipitation in the region as the index, it is specifically defined as:

Assuming that precipitation in the ith field occurs locally in the TGRR, the number of stations with precipitation ≥20 mm/h is defined as n_{Hi}, and the number of hours with heavy precipitation in the jth station is defined as m_{Hj}, then the total frequency of hourly heavy precipitation during this rainfall is defined as N_{Hj}, and the calculation formula is

$$T_{Hi} = \sum_{j=1}^{n_{H_i}} t_{Hj} \tag{1}$$

If a total of M fields of precipitation occur during a specific time, the calculation formula of the total frequency of hourly heavy precipitation of all stations is as follows

$$T_H = \sum_{i=1}^{M} T_{Hi} \tag{2}$$

In this specific time, the calculation formula of the average hourly heavy precipitation frequency $\overline{T}_H$ of 35 stations in the TGRR is

$$\overline{T}_H = \frac{T_H}{35} \tag{3}$$

Similarly, the total frequency of hourly extreme heavy precipitation (≥50 mm) of all stations T_{EH} and the average hourly heavy precipitation frequency $\overline{T}_{EH}$ of 35 stations are defined.

2.3.2. Extraction Method of Climate Forcers

The climate factors with the strongest correlation with the frequency of 20–50 mm/h precipitation are the Western Hemisphere Warm Pool (WHWP) Index in February (the spherical area where the sea surface temperature exceeds 28.5 I region at 7° N–27° N and 110° W–50° W) and the Western Pacific Subtropical High Intensity (WPSHI) Index in January (500 hPa height field; the difference between the geopotential height and the geopotential meter (gpm) of the grid points multiplied by the accumulated value of the area of the grid points in the range of 10° N–60° N and 110° E–180° N, ≥5880 geopotential meter (gpm)) [31].

The climate factor with the strongest correlation with precipitation frequency above 50 mm/h is the Western Pacific Warm Pool (WPWP) Intensity Index in November (30° S–30° N, 120° E–180° E; the difference between SST and 28.0 °C of the grid points multiplied by the cumulative value of the grid area in the region where SST exceeds 28.0 I region) and the WPWP Area Index in January (spherical area where the SST at 30° S–30° N, 120° E–180° E regions exceeds the 28.0 I region) [31].

According to Section 2.3.1, we calculated the total accumulative duration of precipitation, at each station, of 20–50 mm/h and above 50 mm/h from 1998 to 2020. After that, Pearson correlation [22] analysis was performed based on the 20 climatic factors we selected in advance from October to December of 1997 to 2019 and from January to March of 1998 to 2020. Two climatic factors with the largest Pearson correlation coefficient and their corresponding months were extracted, respectively. The specific extraction process is shown in Figure 2.

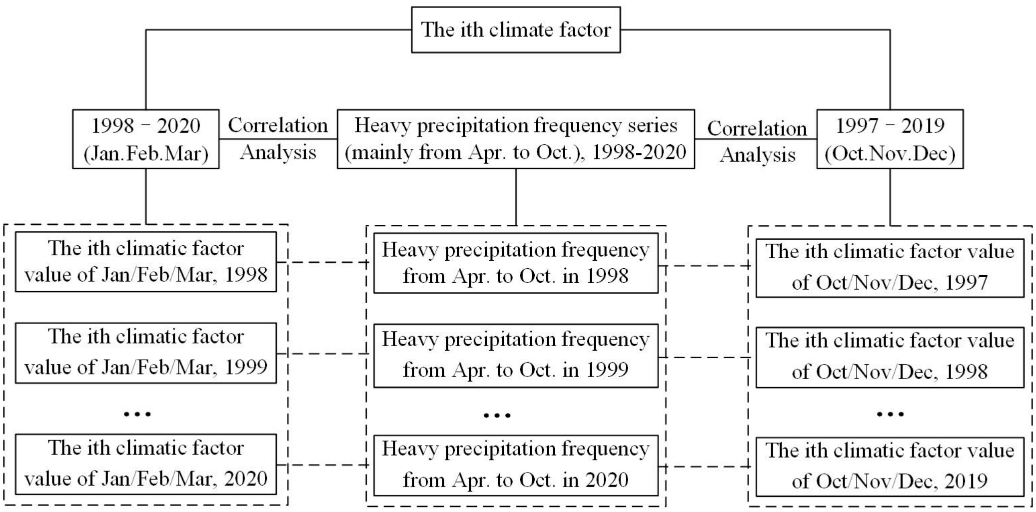


Figure 2. Schematic diagram of extraction method of climate factors.

2.3.3. Trend Calculation Method

The variation trends of the total amount, duration and rainfall intensity of heavy precipitation (≥20 mm/h) during 1999–2009 and 2010–2020 were calculated using the Sen method. As extreme heavy precipitation (≥50 mm/h) does not occur at every station every year, its variation trend was not calculated in this case. The spatial variation characteristics and evolution trend of heavy precipitation, rainfall duration and rainfall intensity in the TGRR in recent years were studied.

3. Variation of Hourly Extreme Precipitation in the TGRR

3.1. Portion of Extreme Events from Total Precipitation

The total accumulation frequency of heavy precipitation and above was compared between 1999 and 2009, and between 2010 and 2020 (Figure 3). Because the number of hours of heavy precipitation in 1998 was abnormally high, it was separately listed and also compared with the above two. The total frequency of heavy precipitation in 1998 was 257 h, 18% of which was from 1999 to 2009. In addition, the frequency of heavy precipitation of 60–65 mm/h and 70–75 mm/h in 1998 accounted for more than 50% of that which occurred from 1999 to 2009. It is worth mentioning that the heavy precipitation of 114.6 mm/h in 1998 was the highest in the TGRR in the past 23 years.

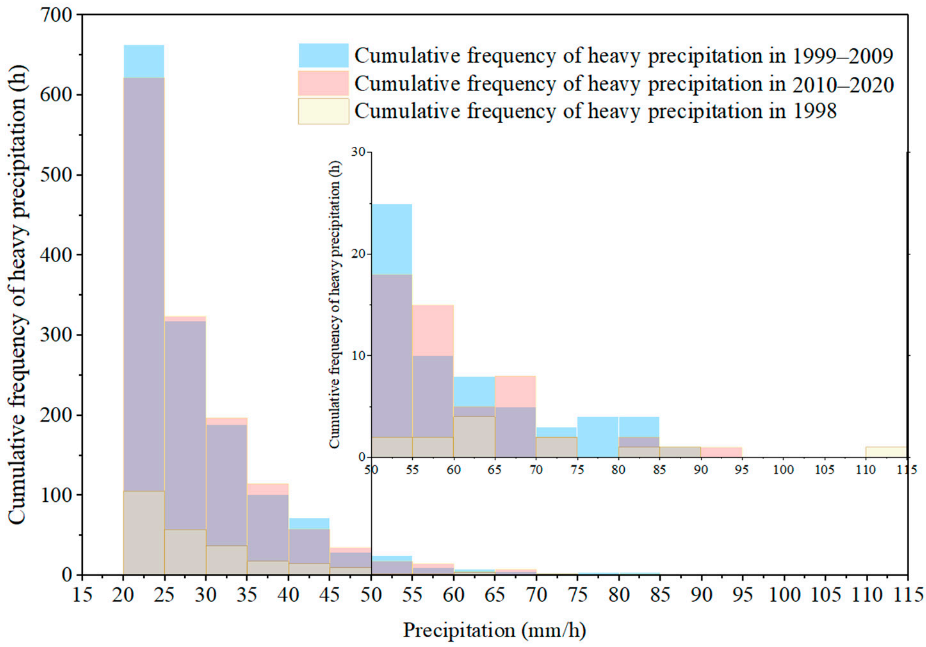


Figure 3. Vertical distribution of accumulative frequency of heavy precipitation in 1999–2009, 2010–2020 and 1998.

In general, the frequency of different levels of heavy precipitation in 1999–2009 and 2010–2020 showed a gradual decreasing trend with the increasing magnitude. From 2010 to 2020, there were 1403 h of heavy precipitation above 20 mm/h and the average frequency of hourly heavy precipitation was 127.5 h. Compared with 1999–2009, the total frequency of hourly heavy precipitation decreased by 29.0 h, and the average frequency of hourly heavy precipitation decreased by 2.6 h.

Although the total frequency and average frequency of hourly of heavy precipitation in 2010–2020 decreased compared with that of 1999–2009, the frequency of hourly heavy precipitation in different magnitudes fluctuated between increasing and decreasing trends in the two periods before and after 2010. As can be seen from Figure 3, when the hourly heavy precipitation was 25–40 mm/h, the frequency of hourly heavy precipitation in 2010–2020 was increased compared with that of 1999–2009, and the average annual occurrence of heavy precipitation in the last 11 years was 2.5 h more than that in the previous 11 years. It can be seen that in the last decade, the cumulative frequency of heavy precipitation magnitude between 25 and 40 mm/h increased slightly by 10 h of each magnitude, while the frequency for magnitudes above 70–85 mm/h decreased. However, it is worth mentioning that the maximum hourly precipitation of 90 mm/h between 1999 and 2020 occurred in 2016.

In order to better study and analyze the heavy precipitation of different magnitudes in the flood season in the TGRR, the hourly heavy precipitation was divided into two grades of 20–50 mm/h and above 50 mm/h, as shown below. Furthermore, the frequency of heavy precipitation of 20–50 mm/h and above 50 mm/h from June to August of 1998 to 2020, respectively, was statistically analyzed, which can be seen in Figure 4.

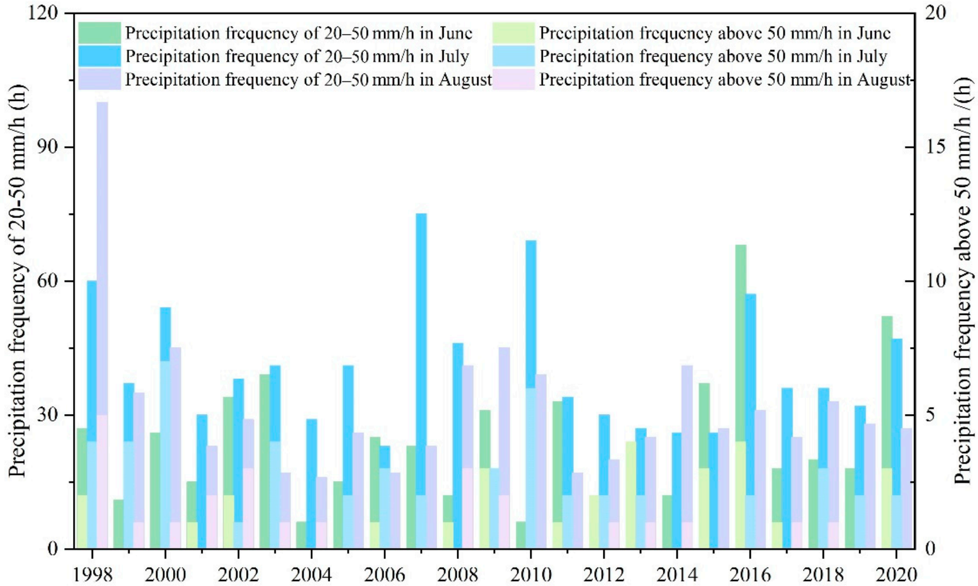


Figure 4. Statistical graph of cumulative precipitation frequency of 20–50 mm/h and above 50 mm/h from June to August, 1998–2020.

In general, the frequency of 20–50 mm/h and over 50 mm/h heavy precipitation during June to August from 1998 to 2020 showed a fluctuating trend and a periodic change rule. Due to the unusually high hourly heavy precipitation in 1998, only the frequency of hourly heavy precipitation in 1999–2009 and 2010–2020 is considered and compared here.

From 2010 to 2020, the average annual frequency of heavy precipitation in June of 20–50 mm/h and above 50 mm/h was 26.5 h and 1.6 h, respectively, which increased by 4.9 h and 0.9 h compared with the average period from 1999 to 2009. In 2016, the maximum frequency of heavy precipitation above 50 mm/h was 4.0 h. It can be seen that the frequency of heavy precipitation in June showed the characteristic of increasing fluctuation.

Compared with that of June, the condition of July was different. The average annual frequency of hourly heavy precipitation at 20–50 mm/h and above 50 mm/h in 2010–2020 was decreased by 1.1 h and 0.5 h, respectively, compared with that of 1999 to 2009. It showed a weak decreasing trend in terms of fluctuation. It is worth mentioning that except for 1998 and 2002, July was the month with the most hourly heavy rainfall of 20–50 mm/h and above 50 mm/h in all years. The average hours of heavy precipitation in August showed a trend of decreasing fluctuation. The average frequency of 20–50 mm/h and above 50 mm/h in 2010–2020 was 28.5 h and 0.5 h, respectively, which was 0.4 h and 0.8 h less than those from 1999 to 2009. In summary, the heavy precipitation in the TGRR mainly occurred in July, and the time of occurrence was in advance.

In addition, the fluctuating pattern for the duration of 20–50 mm/h and over 50 mm/h heavy precipitation in July in recent 23a was not obvious, so the interannual variation cycle of hourly heavy precipitation in July was analyzed, as shown in Figure 5. From 1998 to 2020, there was an interannual variation cycle of about 7a for the duration of 20–50 mm/h heavy precipitation in July. Similarly, the duration of extreme heavy precipitation above 50 mm/h in July from 2000 to 2020 had an interannual variation cycle of about 3a.

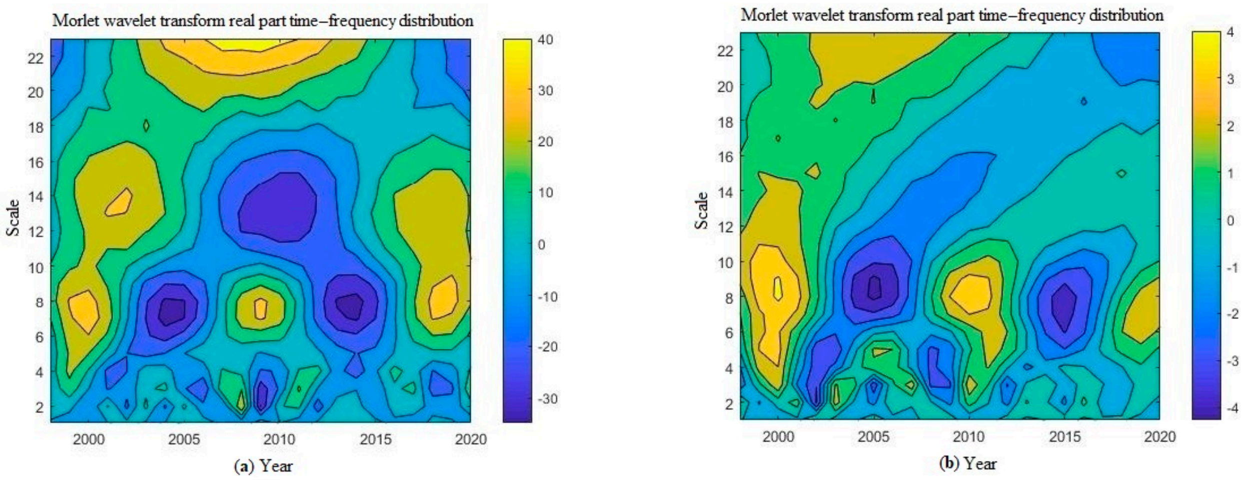


Figure 5. The wavelet model contour map of (**a**) precipitation frequency 20–50 mm/h and (**b**) precipitation frequency above 50 mm/h in July 1998–2020.

3.2. Variation of Different Intensity of Extreme Precipitation

As shown in Table 2, the average frequency of hourly heavy precipitation of each station in the TGRR during 1998–2020 was 3.8 h, and the average intensity of heavy precipitation was 28.9 mm/h. The cumulative frequency of extreme heavy precipitation in all stations was 5.5 h, and the average intensity of extreme heavy precipitation was 61.4 mm/h.

Table 2. Statistical table of precipitation frequency and average intensity of hourly heavy precipitation (≥20 mm/h) and hourly extreme heavy precipitation (≥50 mm/h) from 1998 to 2020.

Class	Hourly Heavy Precipitation (≥20 mm/h)		Hourly Extreme Heavy Precipitation (≥50 mm/h)	
Year	Average Frequency of Heavy Precipitation/h	Average Heavy Precipitation/(mm·h^{-1})	Cumulative Frequency of Extreme Precipitation/h	Average Extreme Heavy Precipitation Intensity/(mm·h^{-1})
1998	7.3	30.3	13	69.3
1999	3.6	29.1	5	65.1
2000	4.8	29.0	8	63.6
2001	2.4	27.5	2	66.6
2002	4.0	29.2	5	57.6
2003	4.0	29.1	7	61.5
2004	3.4	28.6	3	75.4
2005	3.4	27.2	4	59.4
2006	3.1	29.3	6	59.2
2007	4.4	28.0	5	55.2
2008	4.1	28.8	6	54.7
2009	3.6	30.4	9	61.3
2010	3.9	28.8	7	63.0
2011	3.1	28.0	3	60.3
2012	2.7	29.7	6	61.2
2013	3.8	28.0	7	56.5
2014	3.2	26.9	1	57.5
2015	3.5	28.2	4	56.5
2016	5.3	29.6	6	64.1
2017	3.5	29.4	4	52.0
2018	3.6	30.4	7	61.7
2019	3.0	29.0	2	57.9
2020	4.5	29.8	6	72.7
Mean value	3.8	28.9	5.5	61.4

In 1998, the average frequency of heavy precipitation was the longest, at 7 h. Except for 2001, the average frequency of heavy precipitation at each station was more than 3 h in other years. There are 3 years when heavy precipitation lasted for 5 h at each station on average, mainly after 2000. The hourly rainfall intensity of heavy precipitation was the largest in 2009 and 2018, and the average intensity of each station was 30.4 mm/h, which was 1.5 mm/h higher than the annual average. In general, the frequency of hourly heavy precipitation in the TGRR fluctuated and slightly decreased during 1998–2020, while the average hourly rainfall intensity showed no obvious fluctuation. If the abnormal year of 1998 is excluded, the hourly heavy precipitation frequency and intensity in the TGRR exhibit no obvious increasing or decreasing trend.

In addition, the largest total frequency of extreme heavy precipitation was found in 1998, which reached 13 h and is 2.4 times the annual average. In nearly 2/3 of years, the total frequency of extreme heavy precipitation at each station exceeded 5 h. The average intensity of extreme heavy precipitation in 2004 was the highest, reaching 75.4 mm/h, nearly 24% higher than the average. In general, the hourly extremely heavy precipitation duration and hourly average rainfall intensity showed a slight decreasing trend in the TGRR from 1998 to 2020.

It can be found from Table 3 that the annual average frequency of hourly heavy precipitation (≥20 mm/h) of all stations in the TGRR was 134.0 h, and the coefficient of variation was less than 30%. The annual mean of the total frequency of hourly extreme precipitation (≥50 mm/h) of all stations was 5.5 h, and the coefficient of variation was close to 50%. This shows that with the increase in hourly rainfall, the number of extreme stations decreased and the interannual variation increased, thus showing an irregular pattern.

Table 3. Annual mean, mean square error and coefficient of variation of the times of occurrence of heavy precipitation and extreme heavy precipitation.

Hourly Precipitation/mm·h^{-1}	Average Frequency/h	Mean Square of Frequency	Variable Coefficient/%
≥20	134.0	35.3	26.28
≥50	5.5	2.6	47.62

The frequency of heavy precipitation above 20 mm/h had an interannual variation period of about 3a during 1998–2005 (Figure 6). At the same time, the period from 1998 to 2015 showed an interannual variation cycle of about 8a. Similarly, the frequency of extreme heavy precipitation above 50 mm/h in 2001–2016 had an interannual variation cycle of about 2a, and the frequency of extreme heavy precipitation above 50 mm/h in 1998–2020 had an interannual variation cycle of about 8a.

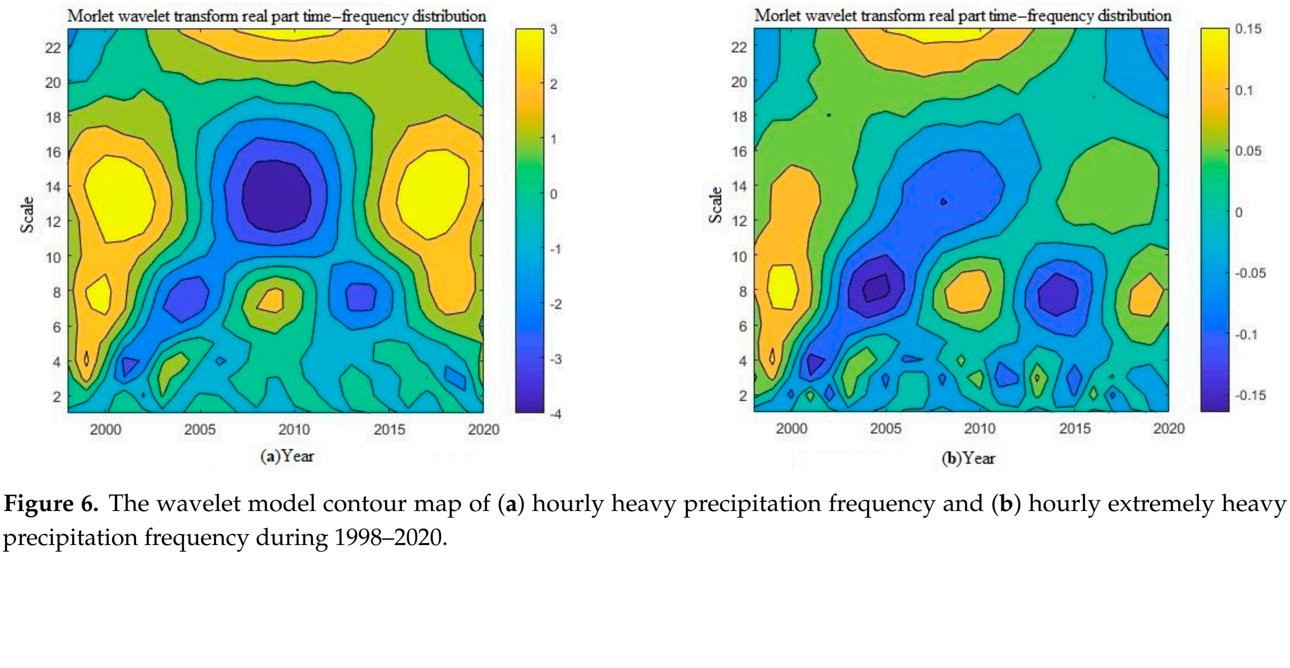


Figure 6. The wavelet model contour map of (**a**) hourly heavy precipitation frequency and (**b**) hourly extremely heavy precipitation frequency during 1998–2020.

The seasonal distribution of hourly heavy precipitation frequency (≥20 mm/h) in the Three Gorges Area during 1998–2020 is shown in Table 4. Hourly heavy precipitation mainly occurred in spring, summer and autumn, and rarely occurred in winter. Only 1.0 h hourly heavy precipitation occurred in the winter of 2004. During the 23 years, the annual mean heavy precipitation frequency in summer was the highest, reaching 100.0 h, followed by spring, which had a mean of 19.7 h, equivalent to only 19.7% of the annual heavy precipitation frequency in summer. It can be seen that summer is the season with the highest incidence of heavy precipitation.

Table 4. Statistical table of frequency of hourly heavy precipitation (≥20 mm/h) in each season from 1998 to 2020.

Year	Spring (March–May)	Summer (June–August)	Autumn (September–November)	Winter (December–February)
1998	54	198	5	0
1999	19	88	19	0
2000	8	132	28	0
2001	9	70	4	0
2002	21	106	13	0
2003	19	104	18	0
2004	30	52	36	1
2005	22	85	12	0
2006	20	69	21	0
2007	29	123	3	0
2008	25	103	16	0
2009	6	102	19	0
2010	12	120	4	0
2011	11	87	12	0
2012	11	61	22	0
2013	39	80	13	0
2014	9	80	23	0
2015	21	93	9	0
2016	13	162	9	0
2017	13	81	29	0
2018	23	93	10	0
2019	14	80	12	0
2020	24	131	3	0
Mean value of 1998–2020	19.7	100.0	14.8	0.0
Mean value of 1999–2009	18.9	94.0	17.2	0.1
Mean value of 2010–2020	17.3	97.1	13.3	0.0

Since the frequency of heavy precipitation in 1998 was abnormally high, only the variation rule of heavy precipitation frequency between 1999 and 2009, and between 2010 and 2020, is discussed here. The total frequency of heavy precipitation from 2010 to 2020 was 1404 h, 28 h less than that of 1999 to 2009. From 2010 to 2020, the annual mean annual heavy precipitation frequency in summer was 19.7 h, an increase of 3.1 h compared with that of 1999–2009. However, the average annual heavy rainfall frequency in spring and autumn in the last 10 years decreased by 1.6 h and 3.9 h, respectively, compared with that of the first 10 years. Therefore, in recent years, the frequency of heavy precipitation showed a slight decrease, and the heavy precipitation was more concentrated in summer, while it decreased in spring and autumn.

3.3. Spatial Variation of Extreme Precipitation

As shown in Figure 7, the spatial distribution of annual maximum hourly precipitation during 1999–2009 and 2010–2020 was compared and analyzed.

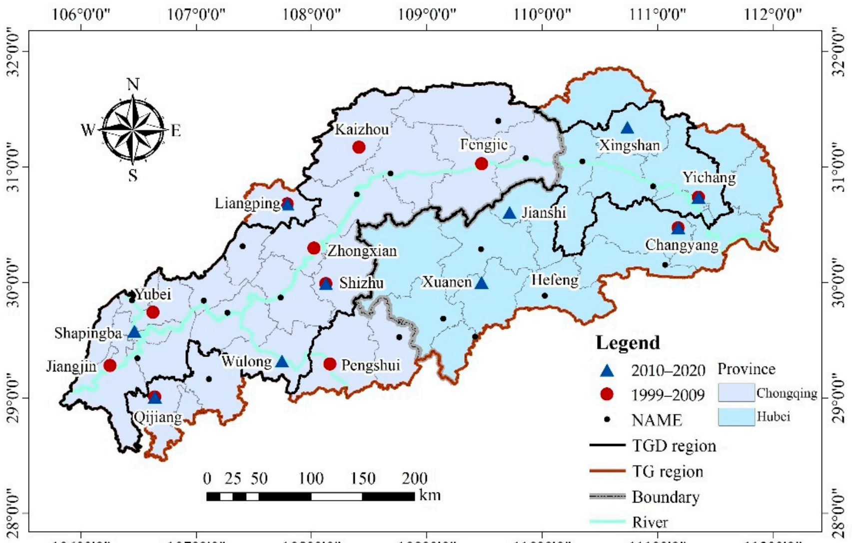
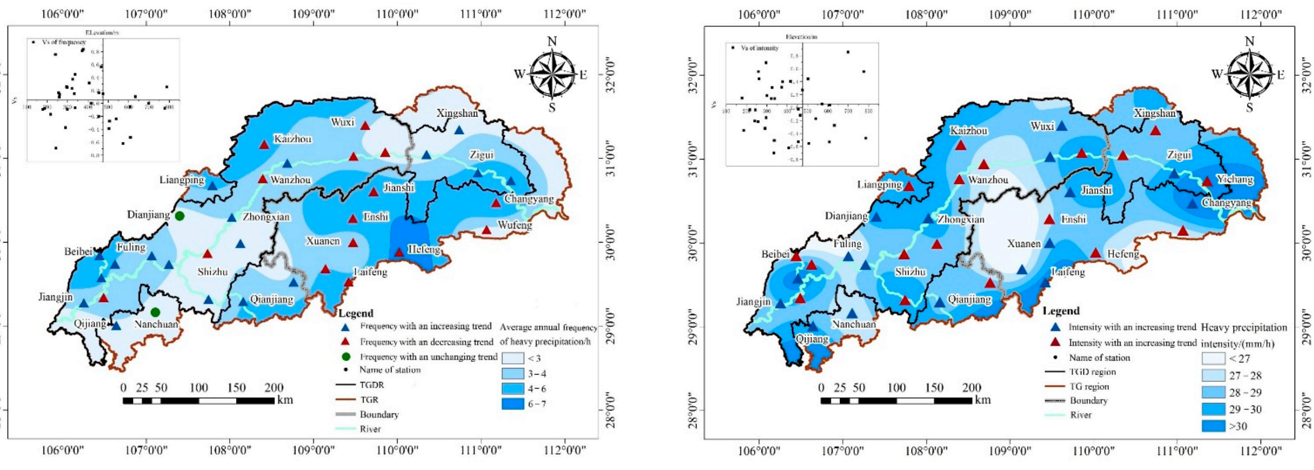


Figure 7. Spatial distribution of maximum 1 h precipitation stations in the TGRR during 1999–2009 and 2010–2020.

During 1999–2009, the annual maximum hourly precipitation was recorded within Hubei Province, Yichang and Changyang only in 2003 and 2008, respectively. In the other nine years, the maximum hourly precipitation was recorded only in Chongqing and was mostly distributed near the main stream or tributaries of the Yangtze River. In addition, the maximum hourly precipitation in the TGRR in the last 23 years was recorded at Kaizhou station in Chongqing in 1998. From 1998 to 2009, extreme heavy rainfall in the TGRR was more likely to occur in Chongqing. Furthermore, the annual maximum hourly precipitation occurred twice at Kaizhou station in the northeast of Chongqing.

From 2010 to 2020, the number of years of annual maximum hourly precipitation in the TGRR decreased to 5 years in Chongqing, and was still distributed mostly in the main stream or tributaries of the Yangtze River. Among them, three stations—Liangping, Shizhu and Qijiang—also recorded the annual maximum hourly precipitation from 1999 to 2009. In the other six years, all of the annual maximum hourly precipitation events occurred in the stations in Hubei province, Yichang and Changyang, which also recorded the maximum hourly precipitation from 1999 to 2009. In addition, the annual maximum hourly precipitation in 2020 occurred simultaneously at Shizhu station in Chongqing and Jianshi station in Hubei province. It can be seen that the annual maximum hourly precipitation in the TGRR may have moved from Chongqing to Hubei in recent years.

Figure 8 shows the spatial distribution results of the frequency of annual heavy precipitation and the average intensity of heavy precipitation in the TGRR from 1999 to 2020. The spatial distribution of frequency of annual heavy precipitation in the TGRR showed that the frequency of heavy precipitation in the northwest to southeast was longer, while that in the northeast and southwest was shorter (Figure 8a). The frequency of heavy precipitation in the central part of Hubei province was more than that of other areas, and the frequency of heavy precipitation in Hefeng station was more prominent, with the annual heavy precipitation being as long as 6.87 h, which may have been related to the topography of Hefeng station.



(**a**) (**b**)

Figure 8. Spatial distribution of (**a**) frequency of heavy precipitation and (**b**) average intensity of heavy precipitation in the TGRR from 1999 to 2020.

In addition, the frequency of heavy precipitation in nearly half of the regions (such as Wuxi and Jianshi, etc.) from 2010 to 2020 showed a decreasing trend compared with that of 1999 to 2009, mainly distributed in central Hubei and northeast Chongqing. Moreover, the distribution characteristics were related to the elevation of the sites. When the elevation of the sites was more than 500 m, the frequency of heavy precipitation at most sites in 2010–2020 showed a decreasing trend compared with that of 1999–2009. On the contrary, most sites showed an increasing trend; for some stations, such as Dianjiang and Nanchuan, the precipitation frequency of the two periods was unchanged. In addition, the spatial distribution characteristics and the pattern of annual heavy precipitation in the TGRR before and after 2010 were similar to the frequency of heavy precipitation (the figure is omitted).

Although the annual heavy precipitation and the frequency of the annual heavy precipitation in Hefeng region were both relatively large, the average intensity of the annual heavy precipitation was not outstanding, at 27.5–30.0 mm/h (Figure 8b). It can be seen that the heavy precipitation in Hefeng area had the characteristics of low intensity, long duration and large total amount. In contrast, Laifeng, Yichang, Changyang and other regions not only had large heavy precipitation and long duration, but also had large average hourly rainfall intensities of 30.00–33.5 mm/h, which were characterized by high intensity, long duration and large total amount of heavy precipitation. In addition, the average intensity of annual heavy precipitation in more than half of the regions from 2010 to 2020 showed a decreasing trend compared with that of 1999 to 2009, and the distribution was relatively scattered. The distribution characteristics were related to the elevation of the sites. When the elevation of the sites was more than 500m, the frequency of heavy precipitation at most sites during 2010–2020 showed a decreasing trend compared to that which occurred during 1999–2009. When the height of the site was less than 500m, this rule was not obvious.

According to the spatial distribution results of correlation coefficients between the annual heavy precipitation, the frequency of heavy precipitation, and the average intensity of heavy precipitation, the annual heavy precipitation in the TGRR was influenced by both the frequency of heavy precipitation and the average intensity of heavy precipitation, and the influence of precipitation frequency was stronger than that of average intensity, but there were certain regional differences.

On the whole, the correlation between annual heavy precipitation and the frequency of heavy precipitation was very good; the correlation coefficient in most areas was above 0.95. Smaller parts of the region (such as Fuling, Qijiang area) also showed relatively good correlation, with correlation coefficients above 0.9. The annual heavy precipitation in

Pengshui area was significantly affected by both heavy precipitation intensity and heavy precipitation frequency, but the influence of heavy precipitation frequency was slightly stronger. In most of the other regions, the annual heavy precipitation was mainly affected by precipitation frequency, and the impact of average intensity was weak.

4. Climatic Factor of Extreme Precipitation Events

Climate factors closely related to the frequency of the occurrence of extreme precipitation are discussed in this section. It will be demonstrated that when a climate factor is abnormally large, the frequency of extreme precipitation in the corresponding year will also be abnormally large.

As shown in Figure 9a, the precipitation frequency at the magnitude of 20–50 mm/h had a good correlation with the WHWP Index in February and the WPSHI Index in January, with correlation coefficients of 0.80 and 0.73, respectively. In the years with more precipitation of 20–50 mm/h, such as 1998, 2000, 2016, and 2020, the corresponding WHWP Index in February and WPSHI Index in January in the other three years, with the exception of 2000, were relatively high. In addition, precipitation of 20–50 mm/h only occurred in April to September of each year, which was indicative of good predictability.

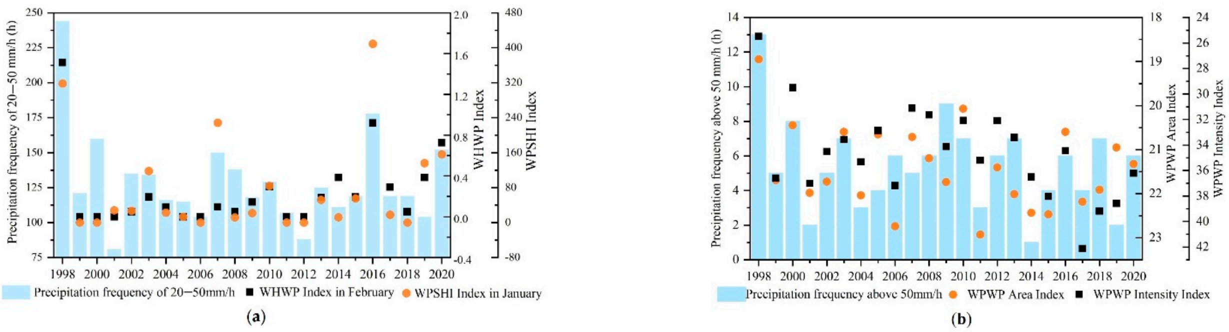


Figure 9. Schematic diagram of correlation between (**a**) heavy precipitation and (**b**) extreme heavy precipitation frequency and climate factors.

Specifically, from 1998 to 2020, when WHWP Index in February was less than 0.5, the precipitation frequency corresponding to 20–50 mm/h in all years, except for 2000, was less than 150 h. When the WHWPI Index was greater than 0.5 in February, the corresponding precipitation frequency of 20–50 mm/h exceeded 150 h in 1998, 2016 and 2020. It is worth mentioning that when the WHWPI Index exceeded 1.0 in February, the corresponding precipitation frequency of 20–50 mm/h in 1998 reached 244 h.

Similarly, when the WPSHI Index was less than 150 in January, the precipitation frequency of 20–50 mm/h in other years was less than 150 h, with the exception of 2000. When the WPSHI Index was greater than 150 in January, the corresponding precipitation frequencies of 20–50 mm/h in other years were more than 150 h, except for 2007.

As can be seen from Figure 9b, the precipitation duration with a magnitude of more than 50 mm/h exhibited a good negative correlation with the WPWP Intensity Index in November and the WPWP Area Index in January of the last recorded year, with correlation coefficients of −0.64 and −0.61, respectively. In the years with more precipitation durations above 50 mm/h, such as 1998, 2000, 2003 and 2010, the corresponding WPWP Intensity Index in November and WPWP Area Index in January of the last recorded year were smaller.

5. Conclusions and Discussion

In this study, based on hourly precipitation data of 35 stations in the TGRR from 1998 to 2020 and the set of 40 climate factors, we analyzed the frequency, intensity, total amount of hourly extreme precipitation (including $\geq$20 mm/h hourly heavy precipitation and $\geq$50 mm/h hourly extreme heavy precipitation) and their spatiotemporal variation characteristics. Then we searched for climate factors that are closely related to the occurrence frequency of extreme precipitation. The main conclusions are as follows:

From 1998 to 2020, in summer (June to August), the frequency of hourly heavy precipitation and extreme heavy precipitation showed a fluctuating trend with periodic changes. The heavy precipitation in the TGRR mainly occurred in July, and the time of occurrence showed signs of advancing to June.

1. The frequency of hourly heavy precipitation and extreme heavy precipitation in the TGRR both showed a decreasing trend from 1998 to 2020. If the year 1998, which had an abnormally high frequency of extreme precipitation, is excluded, no significant declining trend can be detected in the TGRR.
2. In recent years, the annual maximum hourly precipitation in the TGRR may have moved from upstream Chongqing to downstream Hubei. The frequency and total amount of heavy precipitation in central Hubei province were both higher than those of other regions. The precipitation frequency of the majority of stations with high elevation (higher than 500 m) showed decreasing trends for both heavy and extreme heavy precipitation.
3. When the WHWP Index in February and WPSHI Index in January were abnormally high, the frequency of hourly heavy precipitation ($\geq$20 mm/h) in the corresponding year was also likely to be high; when the WPWP Intensity Index in November and WPWP Area Index in January were abnormally low, the likelihood of extreme heavy precipitation ($\geq$50 mm/h) would also increase.

In the above study, we analyzed the characteristics of hourly extreme precipitation, based on hourly precipitation data, in the TGRR. Some more detailed spatial and temporal distribution characteristics of hourly extreme precipitation were revealed. It was previously mentioned that the topography of the TGRR is relatively complex, and is similar, in this regard, to that of the Alps in Europe. A study that focused on daily precipitation series data showed that from 1890 to 2017, heavy precipitation significantly increased in the Southern Alps region of Switzerland, while in the spring, heavy precipitation decreased in the southeastern region [32]. While based on the precipitation data of an hourly scale, a heavy precipitation process in the Alps was captured, and its related physical mechanism was explored [33].

In this research, the physical mechanism related to annual heavy precipitation frequency was also explored, and the two climate factors most closely related to heavy precipitation ($\geq$20 mm/h) and extreme heavy precipitation ($\geq$50 mm/h), respectively, were selected. Subsequent studies may select early warning indexes of the years with high incidence of extreme precipitation, and provide solid support for decision makers.

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References

1. Zhang, J.E.; Xu, Q. Changes and conservation strategies of biodiversity in the Three Gorges Reservoir area. *Trop. Geogr.* **1997**, *17*, 412–418. (In Chinese)
2. Jackson, S.; Sleigh, A. Resettlement for China's Three Gorges Dam: Socio-economic impact and institutional tensions. *Communist Post-Communist Stud.* **2000**, *33*, 223–241. [CrossRef]
3. Dong, Z.Y.; Peng, T.; Dong, X.H.; Liu, J.; Chang, W.J.; Lin, Q.X. Temporal and spatial variation of extreme precipitation events in the Three Gorges Reservoir Region from 1960 to 2016. *J. Water Resour. Water Eng.* **2020**, *31*, 93–101. (In Chinese)
4. Wang, J.Z. Three Gorges Project: The largest water conservancy project in the world. *Public Adm. Dev. Int. J. Manag. Res. Pract.* **2002**, *22*, 369–375.
5. Edmonds, R.L. The Sanxia (Three Gorges) Project: The environmental argument surrounding China's super dam. *Glob. Ecol. Biogeogr. Lett.* **1992**, *2*, 105–125. [CrossRef]
6. Gwynne, P.; You, Q.L. Yangtze project dammed with faint praise. *Nature* **1992**, *356*, 736. [CrossRef]
7. Chen, Z.; Zeng, Y.; Shen, G.; Xiao, C.; Xu, L.; Chen, N. Spatiotemporal characteristics and estimates of extreme precipitation in the Yangtze River Basin using GLDAS data. *Int. J. Climatol.* **2021**, *41*, E1812–E1830. [CrossRef]
8. Chen, S.; Liu, B.; Tan, X.; Huang, Z. Characteristics and circulation background of extreme precipitation over East China. *Nat. Hazards* **2019**, *99*, 537–552. [CrossRef]
9. Chen, Y.; Zhai, P. Persistent extreme precipitation events in China during 1951–2010. *Clim. Res.* **2013**, *57*, 143–155. [CrossRef]
10. Chen, Y.; Zhai, P. Synoptic-scale precursors of the East Asia/Pacific teleconnection pattern responsible for persistent extreme precipitation in the Yangtze River Valley. *Q. J. R. Meteorol. Soc.* **2015**, *141*, 1389–1403. [CrossRef]
11. Yang, H.W.; Gong, Z.Q.; Wang, X.J.; Feng, G.L. Interdecadal Variation Characteristics and Causes of Summer Extreme Precipitation over Eastern China. *Chin. J. Atmos. Sci.* **2021**, *45*, 683–696.
12. Mekis, E.; Hogg, W.D. Rehabilitation and analysis of Canadian daily precipitation time series. *Atmos.-Ocean.* **1999**, *37*, 53–85. [CrossRef]
13. Wu, C.G.; Lin, D.S.; Zhou, Z.X.; Wang, P.C.; Xiao, W.F.; Teng, M.J. Spatial Interpolation Methods and Temporal-Spatial Distribution of Precipitation in the Three Gorges Reservoir Area. *Resour. Environ. Yangtze Basin* **2010**, *19*, 752–758.
14. Li, Y.; Zhou, W.; Chen, X.; Fang, D.; Zhang, Q. Influences of the Three Gorges Dam in China on precipitation over surrounding regions. *J. Meteorol. Res.* **2017**, *31*, 767–773. [CrossRef]
15. Xiao, C.; Yu, R.; Fu, Y. Precipitation characteristics in the Three Gorges Dam vicinity. *Int. J. Climatol.* **2010**, *30*, 2021–2024. [CrossRef]
16. Fang, Z.; Hang, D.; Zhao, X.Y. Rainfall regime in Three Gorges area in China and the control factors. *Int. J. Climatol.* **2010**, *30*, 1396–1406. [CrossRef]
17. Sen Roy, S.; Balling, R.C., Jr. Trends in extreme daily precipitation indices in India. *Int. J. Climatol.* **2004**, *24*, 457–466. [CrossRef]
18. Wu, H.; Li, X.Y.; Qian, H. Temporal variability in extremes of daily precipitation, daily maximum and minimum temperature in Shaanxi, China. *J. Atmos. Sol.-Terr. Phys.* **2021**, *215*, 105585. [CrossRef]
19. Liu, B.J.; Chen, S.L.; Tan, X.Z. Large-scale synoptic atmospheric moisture circulation patterns associated with variability of daily precipitation over East China. *Int. J. Climatol.* **2021**, *41*, 3439–3456. [CrossRef]
20. Wang, F.; Yan, X.D.; Gu, X.P.; Li, F.G.; Zhou, S.P. Temporal and spatial characteristics of short-term heavy precipitation in early summer in southwestern Guizhou from 2006 to 2015. *Torrential Rain Disasters* **2017**, *36*, 460–466. (In Chinese)
21. Wang, L.P.; Wang, X.R.; Zhang, L.S.; Zhang, J.Z.; Wang, J.G. Exploration and application of a comprehensive intensity assessment method for regional precipitation process. *Meteorology* **2018**, *44*, 1479–1488. (In Chinese)
22. Wu, J.G.; Huang, J.H.; Han, X.G.; Gao, X.M.; He, F.L.; Jiang, M.X.; Jiang, Z.G.; Primack, R.B.; Shen, Z. The three gorges dam: An ecological perspective. *Front. Ecol. Environ.* **2004**, *2*, 241–248. [CrossRef]
23. Gao, W.H.; Li, K.F.; Jin, H.H. Analysis of extreme precipitation characteristics in Henan Province from 1960 to 2014. *J. Henan Univ. Nat. Sci. Ed.* **2020**, *50*, 253–261. (In Chinese)
24. Yang, J.Y.; Su, A.F. Temporal and spatial distribution characteristics of hourly extreme precipitation in Henan Province during warm season. *Rainstorm Disaster* **2021**, *40*, 153–159. (In Chinese)
25. Deng, Y.; Gao, T.; Gao, H.; Yao, X.; Xie, L. Regional precipitation variability in East Asia related to climate and environmental factors during 1979–2012. *Sci. Rep.* **2014**, *4*, 5693. [CrossRef] [PubMed]
26. Zhang, F.W.; Zi, L.; Qiu, H. Analysis of the climatic characteristics of rainstorm and flood in the Yangtze River. *People Yangtze River* **2017**, *48*, 62–65. (In Chinese)
27. Yuan, Y.; Gao, H.; Li, W.J.; Liu, Y.J.; Chen, L.J.; Zhou, B.; Ding, Y.H. Comparison of precipitation characteristics and physical mechanism between 2016 and 1998. *J. Meteorol.* **2017**, *75*, 19–38. (In Chinese)
28. National Climate Center, China Meteorological Administration [DB/OL]. Available online: https://cmdp.ncc-cma.net/Monitoring/cn_index_130.php (accessed on 21 December 2020). (In Chinese).
29. Chen, J.; Zheng, Y.G.; Zhang, X.L.; Zhu, P.J. Distribution and diurnal variation of short-time heavy precipitation in China during warm season and its relationship with diurnal variation of mesoscale convective system. *J. Meteorol.* **2013**, *71*, 367–382. (In Chinese)
30. Yu, X.D. Ideas and methods of short-time heavy rainfall near forecast. *Heavy Rain Disaster* **2013**, *32*, 202–209. (In Chinese)
31. Wang, J.L.; Yu, H.Y.; Hu, S.B.; Liu, W.J. A few notes on Neyman-Pearson's basic lemma. *Math. J.* **2011**, *31*, 357–361. (In Chinese)

32. Brugnara, Y.; Maugeri, M. Daily precipitation variability in the southern Alps since the late 19th century. *Int. J. Climatol.* **2019**, *39*, 3492–3504. [CrossRef]
33. Vrhovec, T.; Rakovec, J.; Gregorič, G. Mesoscale diagnostics of prefrontal and frontal precipitation in the Southeast Alps during MAP IOP 5. *Meteorol. Atmos. Phys.* **2004**, *86*, 15–29. [CrossRef]