Meteorological and Environmental Research 2025, 16(4-5): 29-32, 36

Characteristics of the Rainstorm Weather System Causing Flood in the Jianjiang River Basin

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Abstract Based on the meteorological observation data from 1994 to 2023, the spatiotemporal distribution characteristics and periodic changes of extreme precipitation were analyzed. The extreme precipitation showed a fluctuating upward trend, and reached a peak of 713.5 mm in 2010. The frequency of events increased from 7 times in 1994-2000 to 56 times in 2020-2023, with significant periodicity of 3-4 and 7-8 a. In terms of spatial distribution, the precipitation intensity in the upper reaches was significantly higher than that in the middle and lower reaches, reaching 421.6 and 405.7 mm respectively. The lowest was in downstream Wuchuan City (268.3 mm), showing a decreasing trend from upstream to downstream. Extreme precipitation was mainly concentrated from July to October, especially in September (accounting for 25.8%). Typhoon was the main cause, with 80% of the TOP10 records related to typhoons, and the average precipitation intensity of typhoons reached 501.6 mm. The average precipitation intensity from 2020 to 2023 reached 442.8 mm. The correlation coefficient between 12-h rainfall intensity and flood level was 0.85, and the accuracy of flood warning based on rainfall intensity threshold was 78%, which had guiding significance for flood control and disaster reduction.

Key words Extreme precipitation; Spatiotemporal distribution; Periodicity; Typhoon; Jianjiang River basin

DOI 10.19547/j.issn2152-3940.2025.04-05.008

Extreme precipitation events often trigger floods and other disasters with their strong suddenness and catastrophic nature, seriously threatening the safety of people's lives and property[1]. Affected by monsoon climate and typhoon activity, extreme precipitation occurs frequently and shows an increasing trend[2]. In the past 60 years, the frequency and intensity of extreme weather and climate events in China have shown a significant upward trend[3]. The Jianjiang River basin originates from the northern mountainous area of Xinyi City and flows into the South China Sea in Wuchuan City, with a total length of 232 km and a drainage area of 9 540 km^2.

In recent years, research on extreme precipitation in South China has shown that the extreme precipitation in the region was mainly concentrated from May to August, with high incidence areas in the coastal areas of western Guangdong and the mountainous areas of northern Guangdong[1-2]. It was pointed out that the change of South China Sea monsoon intensity was the key factor affecting the rainstorm in South China, and the rainstorm in summer and autumn showed a significant increase trend[4]. The analysis on characteristics and cause mechanism of extreme precipitation in different regions has been deepened[5-11]. Research based on GIS showed that the risk of rainstorm caused by typhoon cannot be ignored in coastal and inland areas[12]. The short-term heavy precipitation forecasting model constructed by Zhang Hualong *et al.*[13] had good application prospects in South China, but there was still insufficient research on flood warning based on rainfall intensity threshold in the Jianjiang River basin.

In this paper, the climate characteristics and spatiotemporal variation patterns of extreme precipitation, and the relationship between extreme precipitation events and weather systems such as typhoons in the Jianjiang River basin were explored, and its periodic changes were analyzed. The meteorological data from Xinyi, Gaozhou, Huazhou, Maonan, Dianbai, and downstream Wuchuan in the basin from 1994 to 2023 were taken as the research basis.

1 Data and methods

1.1 Overview of the research area The Jianjiang River basin is one of the largest rivers in western Guangdong. The terrain within the basin is diverse, with the upper reaches consisting of medium to low mountainous areas and hills, the middle reaches dominated by hills and plains, and the lower reaches consisting of coastal plains. The basin is located in the South Asian tropical monsoon climate zone, with an annual precipitation of 1 600-2 000 mm, mainly concentrated from April to September. In this paper, the Jianjiang River basin was divided into three regions: upstream (Xinyi City, northern Gaozhou City), midstream (southern Gaozhou City, Huazhou City, Maonan District), and downstream (Dianbai District, Wuchuan City). The focus was on analyzing the spatiotemporal distribution characteristics of extreme precipitation in the basin and its relationship with hydrological processes in the river.

1.2 Data source and processing In this paper, daily and hourly precipitation observation data from six national meteorological stations (Maoming, Dianbai, Gaozhou, Huazhou, Xinyi, and Wuchuan) in and around the Jianjiang River basin from 1994 to

Received: August 12, 2025 Accepted: September 17, 2025

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2023 were used, and precipitation data from 30 regional automatic meteorological stations from 2005 to 2023 were collected as a supplement. The data underwent standardized quality control processing, including missing measurement value testing, outlier handling, and uniformity testing. Simultaneously, 12-h sliding precipitation data were extracted to analyze the time-effectiveness relationship between short-term heavy rainfall and flood occurrence, and provide data support for establishing a rapid warning model. When identifying flood-causing rainstorm events, 120 flood-causing rainstorm events were identified by comprehensively considering factors such as precipitation intensity, duration, coverage and whether flood disaster was caused. In addition, this paper also collected typhoon data affecting the Jianjiang River basin from 1994 to 2023, including typhoon paths, intensity, movement speed, and precipitation records.

1.3 Research methods In this paper, multiple analytical methods are comprehensively adopted to systematically analyze the spatiotemporal distribution characteristics and periodic changes of extreme precipitation, and its relationship with typhoons in the Jianjiang River basin. The methods such as linear trend analysis and Mann – Kendall test were used to analyze the temporal variation trend of extreme precipitation. Using wavelet analysis and power spectrum analysis, periodic features were detected. Utilizing GIS technology and Kriging interpolation, spatial distribution characteristics were analyzed.

In terms of typhoon correlation analysis, the weather system configuration analysis of TOP10 rainstorm events was carried out to reveal the synergistic mechanism between typhoon and other systems. Through the comprehensive application of the above methods, the spatial and temporal distribution characteristics and periodic variation laws of extreme precipitation, and its relationship with weather systems such as typhoons in the Jianjiang River basin were systematically analyzed, providing scientific basis for the improvement of regional extreme precipitation warning and forecasting capabilities.

2 Analysis of extreme precipitation characteristics in the Jianjiang River basin

2.1 Temporal distribution characteristics The extreme precipitation in the Jianjiang River basin showed significant interannual fluctuations from 1994 to 2023. From Fig. 1, it can be seen that the 24-h maximum precipitation has shown an overall fluctuating upward trend (Mann – Kendall test, $Z = 2.37$, $P < 0.05$). The maximum value appeared in 2010 (713.5 mm), the minimum value was in 1994 (205.2 mm), and the average was 380.5 mm. Through third-order polynomial fitting, it can be seen that extreme precipitation has gone through a cyclic process of "first rising, then falling, and then rising again", forming two distinct peaks in 2008 – 2010 and 2020 – 2023. It was worth noting that there was a trend of increasing extreme precipitation intensity after 2020.

As shown in Table 1, extreme precipitation events in the Jianjiang River basin were mainly concentrated from May to October, with September accounting for the highest proportion (25.8%), followed by October (21.7%) and August (20.8%). This distribution was basically consistent with the seasonal characteristics of typhoon activity: the active period of typhoons in the northwest Pacific is from July to October, especially in September when typhoon intensity is often high, making it the peak period of extreme precipitation in the Jianjiang River basin.

Table 1 Monthly distribution of extreme precipitation events in the Jianjiang River basin

Month	Number of extreme precipitation events	Proportion//%	Main weather systems
May	15	12.5	Frontal precipitation, monsoon trough
June	6	5.0	Frontal precipitation, early typhoon
July	17	14.2	Typhoon, monsoon
August	25	20.8	Typhoon, monsoon
September	31	25.8	Typhoon, monsoon
October	26	21.7	Typhoon, cold air
Total	120	100.0	–

The number of extreme precipitation events showed a significant upward trend at different time periods (Fig. 1): increased from 7 in 1994 – 2000 to 56 in 2020 – 2023, and the average precipitation intensity increased from 304.6 to 442.8 mm, an increase of 45.4%.

According to the wavelet analysis and power spectrum analysis, the extreme precipitation phenomenon in the Jianjiang River basin exhibited two distinct periodic changes of 3 – 4 and 7 – 8 a. The 3 – 4-a cycle was mainly related to ENSO events, while the 7 – 8-a cycle may be associated with the Pacific decadal oscillation (PDO). These periodic features were of great significance for predicting future extreme precipitation trends in the Jianjiang River basin.

2.2 Spatial distribution characteristics There were significant differences in the distribution of extreme precipitation in various districts and counties of the Jianjiang River basin (Fig. 2). From the perspective of historical maximum precipitation, Gaozhou City in the upper reaches of the basin reached 713.5 mm, ranking first, followed by Xinyi City at 529.2 mm, Maonan District and Huazhou City in the middle reaches at 513.2 and 493.4 mm respectively, Dianbai District in the lower reaches at 486.4 mm, and Wuchuan City at the estuary of Jianjiang River had the lowest at 392.0 mm. From the perspective of average precipitation intensity, Xinyi City in the upstream had the highest precipitation (421.6 mm), followed by Gaozhou City (405.7 mm), while Dianbai District, Huazhou City, and Maonan District in the midstream had relatively lower precipitation (356.8 – 374.3 mm), and Wuchuan City in the downstream had the lowest precipitation (268.3 mm). The spatial coefficient of variation was 0.35, indicating significant regional differences within the watershed.

This spatial distribution pattern was mainly influenced by the uplift of terrain. The terrain in the upstream mountainous areas was undulating, which had a significant uplift effect on air flow and was prone to form heavy precipitation. The downstream terrain was flat, the uplift effect was weakened, and the precipitation intensity was relatively low.

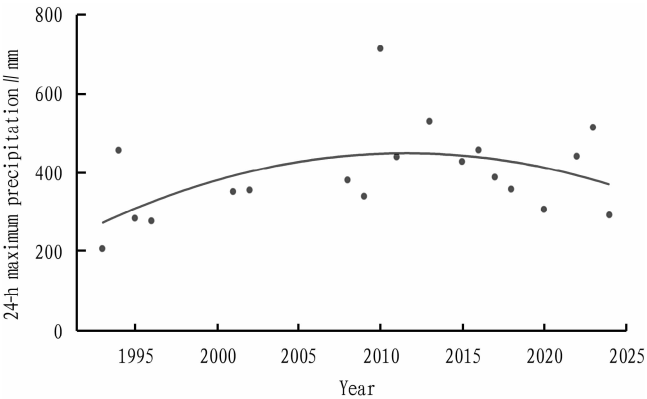


Fig. 1 Time period distribution and periodic evolution of extreme precipitation in the Jianjiang River basin

In terms of spatial and temporal distribution, extreme precipitation in the upstream mountainous areas was mainly concentrated in August – September, while in the middle and downstream areas, it was mainly in September and October, reflecting the differentiated effects of summer monsoon and autumn typhoon on different regions.

2.3 Relationship between typhoons and precipitation Typhoons were the main cause of extreme precipitation in the Jianjiang River basin. From Table 2, it can be seen that extreme precipitation in the Jianjiang River basin has shown an increasingly frequent trend: from 1993 to 2023, the top 10 records all occurred after 2009, and the frequency has been increasing since then. In the past 10 years, the frequency has accounted for 7 of the top 10 records. In the top 10 rainstorm events, the precipitation caused by typhoon accounted for 8 times, accounting for 80.0% of the total, and the non typhoon weather system only accounted for 2 times (20.0%), confirming the dominant position of typhoon in the flood-causing rainstorm in the basin. Among the 8 typhoons, only 1 typhoon was a frontal attack type, while the remaining 7 were the result of the influence of typhoon peripheral circulation and monsoon. The precipitation intensity in the upstream mountainous areas was generally higher than that in the middle and downstream areas, reflecting the interaction between typhoon circulation and terrain.

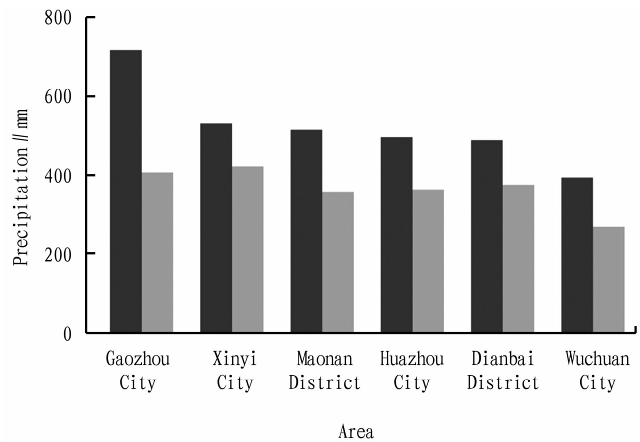


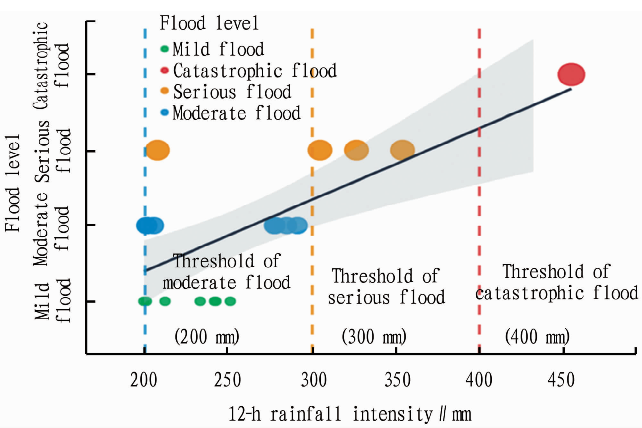
Fig. 2 Comparison of extreme precipitation differences among counties and districts in the Jianjiang River basin

Table 2 Top 10 records of maximum precipitation of rainstorm events in the Jianjiang River basin

No.	Date	Maximum precipitation // mm	Weather system	Main affected areas
1	2010 – 09 – 22	713.5	Typhoon Fanapi	Gaozhou City
2	2013 – 08 – 15	529.2	Typhoon Utor	Xinyi City, Gaozhou City
3	2023 – 10 – 21	513.2	Typhoon Sanba	Maonan District, Xinyi City
4	2023 – 09 – 09	486.4	Typhoon Haikui	Maonan District, Dianbai District
5	2016 – 05 – 21	455.4	Shear line + southwest jet stream	Xinyi City
6	2022 – 07 – 03	439.6	Southwest monsoon + shear line	Dianbai District
7	2011 – 09 – 30	438.2	Typhoon Nesat	Xinyi City
8	2015 – 10 – 05	407.9	Typhoon Mujigae	Gaozhou City
9	2018 – 09 – 17	402.4	Typhoon Mangkhut	Xinyi City, Gaozhou City
10	2009 – 09 – 16	380.9	Typhoon Koppu	Xinyi City

2.4 Correlation analysis between 24-h, 12-h precipitation and flood events The flood level prediction model based on 24-h precipitation showed that precipitation above 600 mm inevitably caused catastrophic floods, precipitation between 450 and 600 mm was prone to induce serious floods, and precipitation between 350 and 450 mm may cause moderate floods. By comparing the predicted results with the actual flood levels, it was found that the accuracy of predicting catastrophic floods was 100%, serious floods was 50%, moderate floods was 50%, and the overall prediction accuracy was 66.7%. The prediction bias mainly occurred in the critical areas of serious and moderate floods, which was related to the complexity of flood formation. In addition to precipitation intensity, it was also affected by multiple factors such as soil moisture content in the early stage, river water level, and engineering scheduling. Concentrated precipitation in upstream mountainous areas can easily lead to watershed floods, and the cumulative effect of continuous extreme precipitation processes is significant. For example, the Haikui and Sanba double typhoons in 2023 had a continuous impact, with long flood duration and wide impact range.

From Fig. 3, it can be seen that there was a significant positive correlation between 12-h rainfall intensity and flood level ($r = 0.85$, $P < 0.01$), and the correlation was significantly higher than that of 24-h cumulative rainfall ($r = 0.72$). When the rainfall intensity exceeded 400 mm within 12 h, the probability of catastrophic floods reached 95%. When the 12-h rainfall intensity was between 300 and 400 mm, the probability of serious floods was 75%. When the 12-h rainfall intensity was between 200 and 300 mm, the probability of moderate floods was 45%.



Note: The scatter color represents different flood levels, the dashed line is the rainfall intensity threshold, and the solid line is the linear fitting trend. The correlation coefficient $r = 0.85$ ($P < 0.01$) indicates a highly positive correlation between 12-h rainfall intensity and flood level.

Fig. 3 Scatter analysis of 12-h rainfall intensity and flood level

The flood warning model based on 12-h rainfall intensity showed that the accuracy of predicting catastrophic floods was 100%, serious floods was 83%, moderate floods was 65%, and the overall accuracy was 78%, which was significantly better than the prediction effect based solely on 24-h cumulative rainfall (66.7%). The core of the model lied in the determination of the rainfall intensity threshold: catastrophic flood red warning, ≥ 400 mm; serious flood, 300 – 400 mm; moderate flood, 200 – 300 mm.

3 Conclusions

(1) The extreme precipitation in the Jianjiang River basin showed a fluctuating upward trend, with the frequency of events increasing from 7 in 1994 – 2000 to 56 in 2020 – 2023. Extreme precipitation was mainly concentrated from July to October, with September accounting for the highest proportion (25.8%). It exhibited significant periodic characteristics of 3 – 4 and 7 – 8 a, closely related to ENSO events and Pacific decadal oscillation.

(2) In terms of spatial distribution, extreme precipitation in the basin showed a decreasing pattern from upstream to downstream. The average precipitation intensity in Xinyi City and Gaozhou City upstream reached 421.6 and 405.7 mm, respectively, while Wuchuan City downstream had the lowest (268.3 mm). This distribution was mainly influenced by the uplift of terrain, and the terrain amplification effect in mountainous areas was significant.

(3) Typhoons were the absolute dominant factor in extreme precipitation in the Jianjiang River basin. Among the TOP10 extreme precipitation records, 8 times (80%) were directly related to typhoons, with an average precipitation intensity of 501.6 mm, significantly higher than other weather systems.

(4) Extreme precipitation was highly correlated with flood events, with an overall correlation of 46.2%. The flood level prediction model based on 24-h precipitation indicated that precipitation above 600 mm inevitably led to catastrophic floods, while precipitation between 450 and 600 mm was prone to induce severe floods, with a prediction accuracy of 66.7%. The flood level prediction model based on 12-h precipitation showed that the probability of catastrophic floods caused by 12-h precipitation ≥ 400 mm was 95%, and the probability of serious floods caused by 12-h precipitation 300 and 400 mm was 75%. The prediction accuracy reached 78%, which can provide 6 – 12-h advance warning for watershed floods.

(5) Based on periodic analysis and climate change background, it was predicted that extreme precipitation activity may enter again from 2025 to 2026. The research results could provide important scientific basis for the comprehensive management and disaster prevention and reduction work of the basins, and have important guiding significance for ensuring flood control safety in the basins.

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