

# Multi-scale update on precipitation characteristics at Jinan, East China

Shufen Chen, Le Liu, Shuaishuai Xu, Meihong Ma, Dacheng Wang, Feng Wang and Jing Liu

## ABSTRACT

Extreme precipitation triggered by climate change is a hot issue of global concern. This study investigates changes in temporal trends of precipitation at Jinan City, Shandong Province over the last six decades. It first constructs a long series of measured daily precipitation data (1951–2017) and then exploits the relative variability, Mann–Kendall, and rescaled range analysis (R/S analysis) methods to update precipitation characteristics. Results indicate that: (1) annual precipitation varies over 116%, with 74.1% of total precipitation concentrated from June to September, especially for heavy rains and storm days; (2) at the 95% confidence level, the annual rainfall does not increase significantly ( $U = 1.15$ ), but there is a significant upward trend in the spring ( $U = 2.08$ ), whereas there is no significant downward trend in the fall ( $U = -1.03$ ); (3) precipitation sequence mutates in 1990, consistent with spring precipitation series, while there are two to four mutations in summer, autumn, and winter. The above results will provide the theoretical basis and data support for the rational development of water resources in Jinan; meanwhile, studying the law of precipitation changes in Jinan City has important practical significance for flood disaster prevention.

**Key words** | characteristics, Jinan, precipitation, update

## HIGHLIGHTS

- A latest measured long-sequence precipitation data set (over 60 years) is established;
- Precipitation characteristics in Jinan are updated;
- Annual precipitation varies over 116%, with 74.1% of total precipitation concentrated from June to September, especially for heavy rains and storm days;
- Precipitation sequence mutates in 1990, consistent with spring precipitation series;
- Future precipitation trends continue to increase.

## INTRODUCTION

Mastering the dynamic changes of climatic variables such as rainfall and evaporation, as well as the effects of induced disasters, is essential for improving disaster resilience (Roosbeh *et al.* 2018). Rainfall is an important factor affecting regional

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water resources and the eco-economic environment. Abnormal changes in rainfall will lead to droughts and floods (Wilhelmi & Morss 2013; Tarawneh 2016; Spinoni *et al.* 2017). Under the influence of global climate change, the frequency of extreme rainfall events is increasing, resulting in a more pronounced mutation in rainfall characteristics (Espinoza *et al.* 2013; Akter *et al.* 2018; Gao *et al.* 2018; Faccini *et al.* 2018; Huguet *et al.* 2018). It will cause more severe

losses to urban areas with a high population concentration and a highly developed economy. Especially in recent years, with the continuous increase of China's urbanization level, a large number of people and wealth have gathered in cities, increasing the exposure and vulnerability of natural disasters in urban areas, making their natural disaster risk situation more severe (Zhang 2020). In order to understand and predict future changes in precipitation, it is essential to formulate long-term adaptation and mitigation measures to deal with climate change (Homsí *et al.* 2020).

In recent years, the precipitation mutations and their trends have become research hotspots. Many previous studies revealed that in Brazil, the annual rainfall is evenly distributed, with the northern region having the largest rainfall in summer (Rao *et al.* 2016). Guerreiro *et al.* (2014) studied the variation characteristics of rainfall sequences in the three major Iberian watersheds. Xu & Zhang (2006) analyzed the trend of precipitation characteristics in the Yellow River Basin using 50-year precipitation data and found that the annual precipitation showed a downward trend. According to the dataset of 12 meteorological stations across the Yellow Sea western coast during 1951–2011, Wang *et al.* (2017) utilized several methods (e.g., linear regression, Mann–Kendall test) to analyze the trend of extreme precipitation events, and the results verify that in the past few decades, rainfall has become more concentrated and precipitation intensity has increased. Mo *et al.* (2018) analyzed the precipitation data of the Mayor of Guilin and revealed that the monthly rainfall has a relatively large variability and is unstable; the rainfall shows a downward trend in spring and autumn, and an upward trend in summer and winter. Using the rainfall data of Wuzhishan City for the past 60 years, Duan *et al.* (2018a, 2018b) found that the spatial variation of rainfall and the annual rainfall generally showed a significant increasing trend.

The rainfall variation characteristics have obvious regional features, and there are many methods of analysis used to study the characteristics of precipitation time series changes, including commonly used methods such as linear fitting, linear regression evaluation, relative variability, moving average, Mann–Kendall non-parametric test, etc. These methods mainly focus on analysis and the current trend of rainfall change, of which, rescaled range analysis (R/S analysis) is mainly used to judge the future change

trend; Mann–Kendall mainly analyzes the variation characteristics of precipitation sequences (Hurst *et al.* 1965; Danesh *et al.* 2016; Wang *et al.* 2016; Muthoni *et al.* 2018).

Jinan has suffered from severe water shortages for a long time. Since the summer of 2014, Jinan has faced many water shortage problems, such as the continuous decrease in precipitation, the lack of spring water spurt, and the insufficient storage capacity of major reservoirs (Chang *et al.* 2017). Meanwhile, the research on precipitation has mainly focused on the rainfall characteristics in the southern mountainous areas, the rainfall characteristics during flood season, and the cause of storm flood disasters. However, based on the long series of data, there are few studies on the characteristics of interannual and annual precipitation in Jinan urban areas (Cao & Lou 2009). Therefore, this paper mainly uses the R/S analysis method and Mann–Kendall non-parametric test method to analyze the variation characteristics of precipitation in Jinan City, and then verify its relative variability. At present, extreme rainfall events have caused severe disasters in Jinan City. The results of this paper will help Jinan to deal with the uncertainties of rainfall and flood warning management brought about by climate change. In the paper, after the Introduction, the Material and methods are presented. Results and discussion follow and, finally, a summary and the major conclusions are provided.

## MATERIAL AND METHODS

### Study area

Jinan is the capital city of Shandong Province, with the terrain high in the south and low in the north. The urban area is located in the northern part of low hills, on the micro-sloping plains, and the alluvial plains of the Yellow River. The area is located in a warm temperate continental monsoon climate zone with an annual average temperature of 14.7 °C and average annual precipitation of 671.1 mm. The summer is warm and rainy, and the winter is cold and dry with less snow. It is dry, rainless, and windy in spring and autumn.

The study area is to the east of Daxinzhuang River, to the south of the Shuangjian Mountain and Xinglong Mountain, and to the north of Yellow River and Jiqing

Expressway, covering an area of about 400 km<sup>2</sup>; the representative hydrological stations are Huangtai Bridge Station and Jinan Station (Figure 1). In recent years, the rapid development of the social economy, the continuous expansion of the city's scale, and the rapid growth of the urban built-up area, etc. have put greater pressure on the water resources, water ecological environment, and even urban security of Jinan City. Sudden rainstorms in Jinan have occurred many times, most typically, rainfall events occurred on July 13, 1962, August 26, 1987, and July 18, 2007. For instance, on July 18, 2007, the maximum hourly rainfall in the urban area reached 151 mm, at 2 h it reached 167.5 mm, and at 3 h it reached 180 mm, causing an economic loss of 1.23 billion yuan to Jinan City.

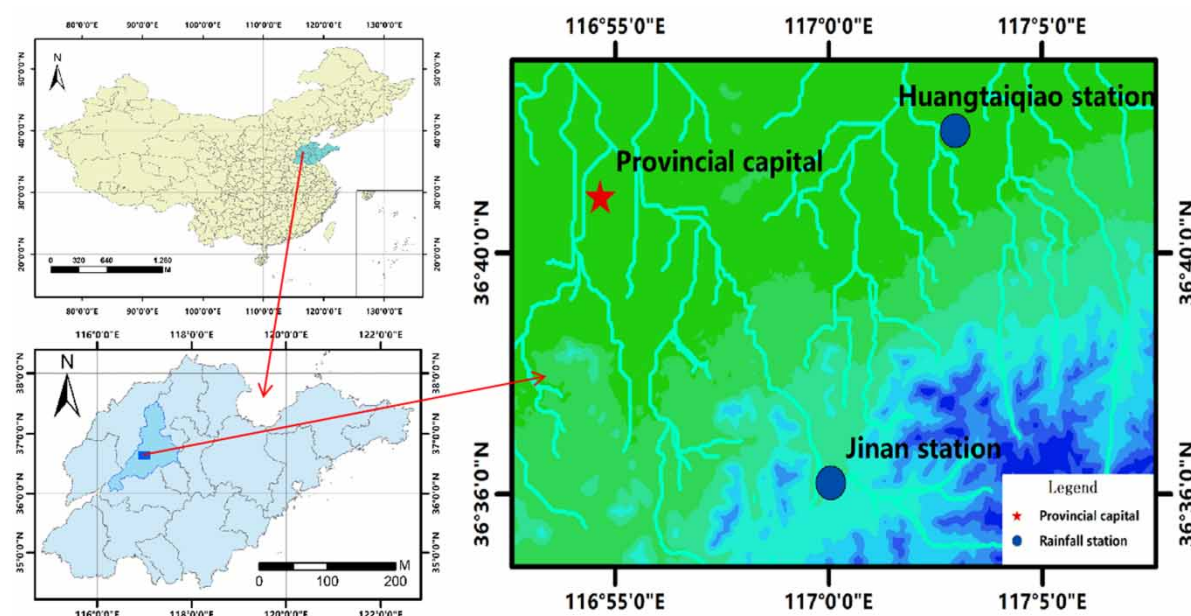
### Data collection

In order to better reflect the rainfall change trend in Jinan urban area, we comprehensively consider the representativeness, reliability, and integrity of rainfall data, as well as the long-term and consistency of data length sequence. According to the distribution of rainfall stations in Jinan City, Huangtaiqiao Station and Jinan Station were selected (Figure 1). The average measured rainfall of the two are

used as the representative data of the urban surface rainfall. The Jinan Station data is from the 'China Ground Climate Data Daily Value Data Set (V3.0)' issued by the National Meteorological Information Center. At present, due to the ongoing river landscape management of the Xiaoqing River, the Huangtaiqiao Station on the Xiaoqing River is temporarily closed, resulting in a currently available data sequence from 1951 to 2017. Meanwhile, the same time series as Huangtaiqiao Station is adopted for Jinan Station to ensure data consistency.

### Statistical analysis method

Precipitation variability refers to the magnitude of change in precipitation, reflecting the stability or reliability of precipitation. The moving average method means that the precipitation time series is affected by periodic fluctuations and random fluctuations, which has large fluctuations, and it is difficult to reflect the development trend of precipitation. However, the moving average method can make up for this defect by weakening the random factors of the original sequence, revealing the development direction and trend of precipitation (i.e., trend line), and then analyzing the long-term trend of the prediction sequence.



**Figure 1** | The study area of Jinan urban area and distribution map of the rainfall stations.

### Mann–Kendall non-parametric test

The Mann–Kendall non-parametric test mainly analyzes the changing trend of the precipitation series, and further quantitatively judges the overall trend of the series (Burn & Elnur 2002). It belongs to the non-parametric statistical method and has been recommended by the World Meteorological Organization. For hydrometeorological data with non-normal distribution, the Mann–Kendall rank correlation test has more outstanding applicability and is often used to detect the frequency trend of precipitation and drought under the influence of extreme climate. For the precipitation sequence  $x_1, x_2, \dots, x_n$ ,  $n$  is the length of the precipitation series,  $P_i$  is the number of occurrences of  $x_i < x_j$  in  $x_i, x_j (j > i)$ :

$$\begin{cases} t = 4 \sum \frac{P_i}{n(n-1)} - 1 \\ \text{Var}(t) = \frac{2(2n+5)}{9n(n-1)} \\ U = \frac{t}{[\text{Var}(t)]^{0.5}} \end{cases} \quad (1)$$

where  $t$  is the statistics of Mann–Kendall non-parametric test,  $\text{Var}(t)$  is the series sample variance,  $U$  is the rank correlation coefficient with statistical significance at  $\alpha = 0.05$  level, then  $U_{\alpha/2} = \pm 1.96$ , when  $U > 0$ , the precipitation change shows an upward trend, else downward; when  $|U| > U_{\alpha/2}$  the hypothesis test shows that the sequence change trend is significant, else not significant.

The Mann–Kendall method can analyze the significance of changes in each stage of the sequence, and extract the time, frequency, and significance of the mutation (Duan et al. 2018a, 2018b). In the mutation test,  $y_1, y_2, \dots, y_n$  are the data values in original time series,  $m_i$  is the number of  $y_i > y_j$  ( $1 \leq j \leq i \leq n$ ), the statistic  $S_k$  is calculated by using:

$$S_k = \sum_{i=1}^k m_i, \quad (2 \leq k \leq n) \quad (2)$$

Assuming that the original sequences are randomly independent, the mean and variance of  $S_k$  are:

$$E(S_k) = \frac{k(k-1)}{4} \quad (3)$$

$$\text{Var}(S_k) = \frac{k(k-1)(2k+5)}{72} \quad (4)$$

The standard normal test statistic  $S_k$  is computed as:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\text{Var}(S_k)}} \quad (5)$$

According to the reverse order of the time series:  $y: y_n, y_{n-1}, \dots, y_1$ , repeat the above steps, calculate the curve of the statistic  $UB$ , take  $\alpha = 0.05$ , draw the curve of the two statistics  $UF$  and  $UB$ , and two lines of  $\pm U_{\alpha/2}$  on the same graph, the intersection of the two curves  $UF$  and  $UB$  in the confidence interval is determined as the mutation point, and the time corresponding to the intersection point is the time to start the mutation. Whether  $UF$  exceeds the critical value is a sign to determine whether the trend change is significant, that is, if  $|UF| > 1.96$ , the changing trend is significant.

### R/S analysis

R/S analysis is a method for processing time series, mainly identifying the dynamic trend of time series; this method can not only distinguish a random sequence from a non-random sequence but also perform a search for the long-term memory process of linear systems. The Hurst index is particularly robust, has a wide range of uses for all time series, and has few assumptions about the system being studied. The basic principle is as follows:  $\{x(t)\}$  is the time series,  $t = 1, 2, \dots$ , and for any positive integer  $\tau \geq 1$ , the mean sequence is as follows:

$$x_\tau = \frac{1}{\tau} \sum_{t=1}^{\tau} x(t) \quad (6)$$

Cumulative dispersion  $X(t, \tau)$ :

$$X(t, \tau) = \sum_{i=1}^t x(i) - x_\tau \quad 1 \leq t \leq \tau \quad (7)$$

range  $R$ :  $R(\tau) = \max_{1 \leq t \leq \tau} X(t, \tau) - \min_{1 \leq t \leq \tau} X(t, \tau)$  standard deviation  $R$ ;

$$s(\tau) = \left[ \frac{1}{\tau} \sum_{t=1}^{\tau} (x(t) - x_\tau)^2 \right]^{\frac{1}{2}} \quad (8)$$

A dimensionless ratio  $R/S$  is used to rescale  $R$ . After verification, the result satisfies the following formula:

$$\frac{R}{S} = (\alpha\tau)^H (\alpha \text{ is a constant}) \quad (9)$$

where  $H$  is the Hurst index. The range of  $H$  is  $[0, 1]$ . If  $H = 0.5$ , the precipitation sequence is random, each event is random and irrelevant; if  $H > 0.5$ , the future trend of the precipitation sequence is consistent with the past, the closer  $H$  is to 1, the stronger the persistence, the closer the overall trend of future precipitation is to the past; if  $H < 0.5$ , the overall trend in the future is opposite to the past, the closer  $H$  is to 0, the stronger the anti-persistence (Zhang *et al.* 2012).

## RESULTS AND DISCUSSION

### Annual variations of precipitation

#### Stability and volatility characteristics

Many previous studies have proved that linear fitting can reflect the trend of annual precipitation over time very

clearly and intuitively. Figure 2 shows the results of statistical analysis of the annual precipitation and the five-year moving average from 1951 to 2017, and fitting its annual precipitation by linear regression. Obviously, the maximum and minimum annual precipitations are 1,143 mm (1962) and 334 mm (1968), respectively, with a difference of 809 mm and an extreme ratio of 3.42, reflecting the large interannual changes in precipitation. Meanwhile, in the two periods of 1961–1967 and 2003–2011, the five-year moving average of annual precipitation was significantly greater than the annual average, indicating that these two periods of precipitation are greater. In the two periods of 1973–1979 and 1993–2003, the five-year moving average of annual precipitation fluctuated slightly around the multi-year average precipitation, revealing that during these two periods, the annual precipitation and the multi-year average precipitation are almost consistent.

In the four periods of 1956–1961, 1967–1973, 1980–1993, and 2011–2017, the five-year moving average curves of annual precipitation all appeared below the straight line of the average annual precipitation, demonstrating that the precipitation during these four periods is relatively small, and especially in the two periods from 1967 to 1973 and 1980 to 1993, the precipitation is less and lasts longer. Based on the above analysis, the

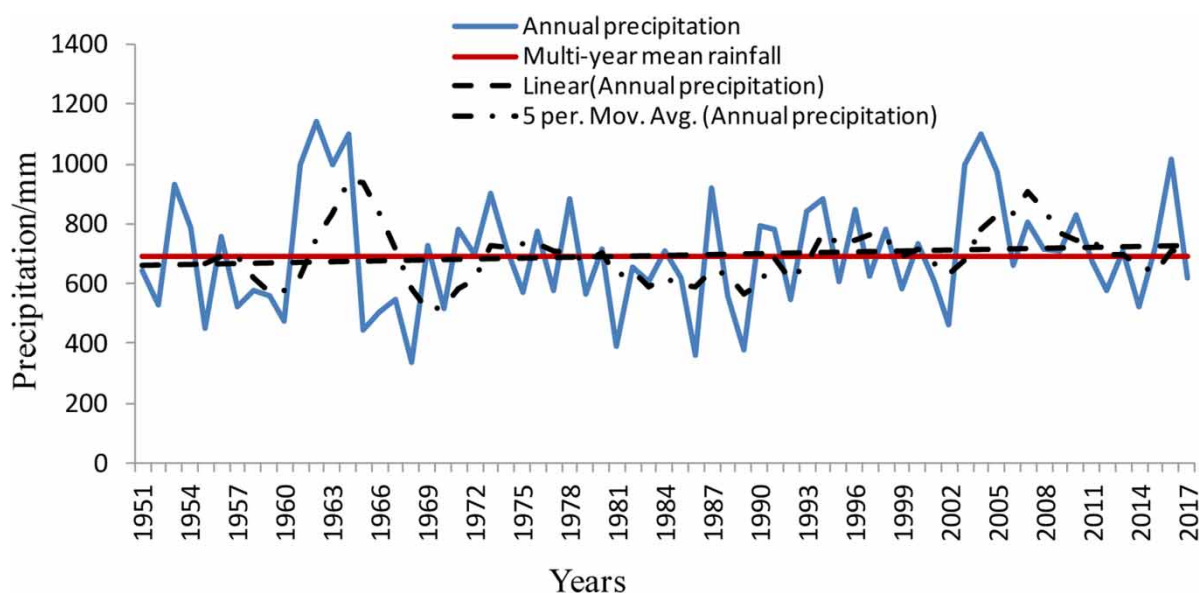


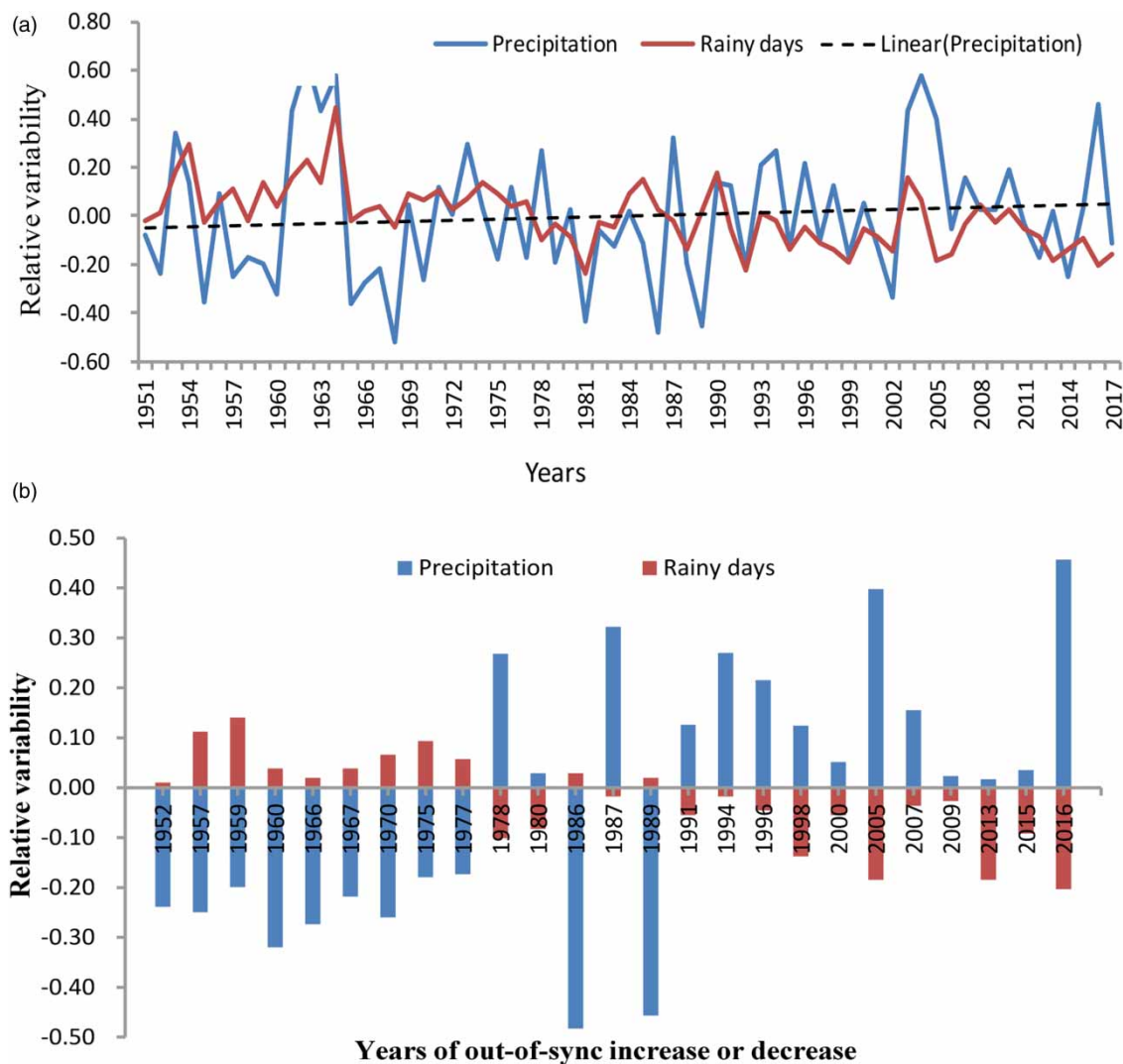
Figure 2 | Changes in precipitation from 1951 to 2017 in Jinan City.



precipitation in Jinan City has a large annual variation, with obvious volatility, and has a cyclical variation of six to nine years. Compared with the average precipitation in many years, there is an alternating pattern that annual precipitation is greater, flat, and less.

Relative variability is the abnormal percentage of a variable and its multi-year average, reflecting the annual stability or reliability of precipitation; a region with abundant rainfall and small variability indicates high water resource utilization; otherwise, it indicates that precipitation is more unstable. The relative changes of annual precipitation and annual precipitation days in Jinan were statistically

analyzed, and the relative changes of the former were linearly fitted. The results are shown in Figure 3. It can be seen from Figure 3(a) that the relative variability change in annual precipitation in Jinan is between  $-52$  and  $64\%$ , and the extreme difference in annual precipitation is  $116\%$ ; the relative variability in annual precipitation days is  $-24\%$  to  $45\%$ , and the range reached  $69\%$ ; this further indicates that the variation of precipitation changes is large. Moreover, in the 67 years (1951–2017), the changes in both the annual precipitation and annual precipitation days showed a simultaneous increase or decrease in 42 years, but there was an out-of-sync phenomenon in the



**Figure 3** | Changes in precipitation and precipitation days from 1951 to 2017.

remaining 25 years, including 14 years of annual precipitation increasing but annual precipitation days decreasing; that is, in the past 67 years, about 14 years of precipitation increased but the precipitation days decreased, accounting for 20.9% (14/67), which meant that precipitation in about one-fifth of these years was more concentrated, especially after the 1990s. Therefore, the above indicated that the concentration and the volatility of precipitation were more significant (Figure 3).

### Long-term trend and mutation characteristics

Using Mann–Kendall and linear regression to analyze the trend and mutation of annual precipitation in Jinan urban area, Figure 4 shows the statistical result of annual precipitation by the Mann–Kendall non-parametric test. Combined with the linear regression trend of Figures 2 and 3, the linear fitting slope and relative variability of annual precipitation are both greater than zero, and the linear fitting slope of the relative change of annual precipitation was less than the annual precipitation. This indicated that in the past 67 years, the annual precipitation and its relative variability in urban areas shows a growth pattern, while the relative variability of annual precipitation was not as significant as annual precipitation, and the inter-annual fluctuations in precipitation exhibited an increase but the trend was not significant. At the 95% significance level, the Mann–Kendall statistic  $U = 1.15$  of the annual precipitation series, which indicated that the annual

precipitation in Jinan urban area showed an upward trend, consistent with the above-mentioned linear regression, but the upward trend was not significant. Figure 4 shows that the curves of  $UF$  and  $UB$  intersect in 1990 and 1992, indicating that the annual precipitation series in Jinan began to change in 1990, and the annual precipitation trend also changed from a decline to an upward trend.

### Future change characteristics

The R/S analysis method is mainly to analyze whether the past changes of the annual precipitation series have the same characteristics as the future changes, and further explore the future precipitation variation trends in Jinan. The Hurst index of the annual precipitation series is calculated by R/S analysis,  $H = 0.79 > 0.5$ . The future precipitation sequence is not a stochastic process, and the future trend is positively correlated with the current trend, that is, the trend has a positive persistence.

### Characteristics of annual precipitation

#### Seasonal precipitation variation characteristics

*Stability and volatility characteristics.* According to the standards for the division of astronomical seasons in China, the four seasons are divided into spring (March to May), summer (June to August), autumn (September to November), and winter (December to February). According to the classification criteria, Figure 5 shows the calculation results of precipitation in the spring, summer, autumn, and winter from 1952 to 2017. The precipitation in the four seasons accounted for 14.2%, 65.2%, 17.0%, and 3.6% of the annual precipitation, respectively. The summer precipitation accounted for the majority of the year, the maximum reached 89.3% (1996), and the winter precipitation was the least, with a minimum of 0.14% (1996). The precipitation in spring, summer, autumn, and winter in each year is different, and the maximum difference between summer and winter in 1962 is 850.5 mm. It can be seen from the above that the annual precipitation is unevenly distributed; the difference is large in summer and winter, and not obvious in spring and autumn, mainly because spring is

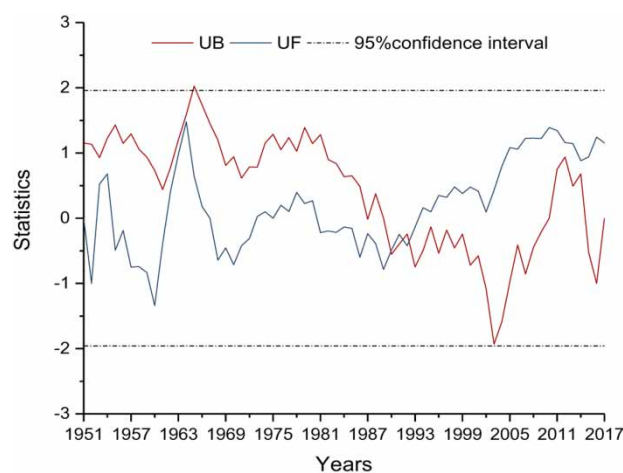
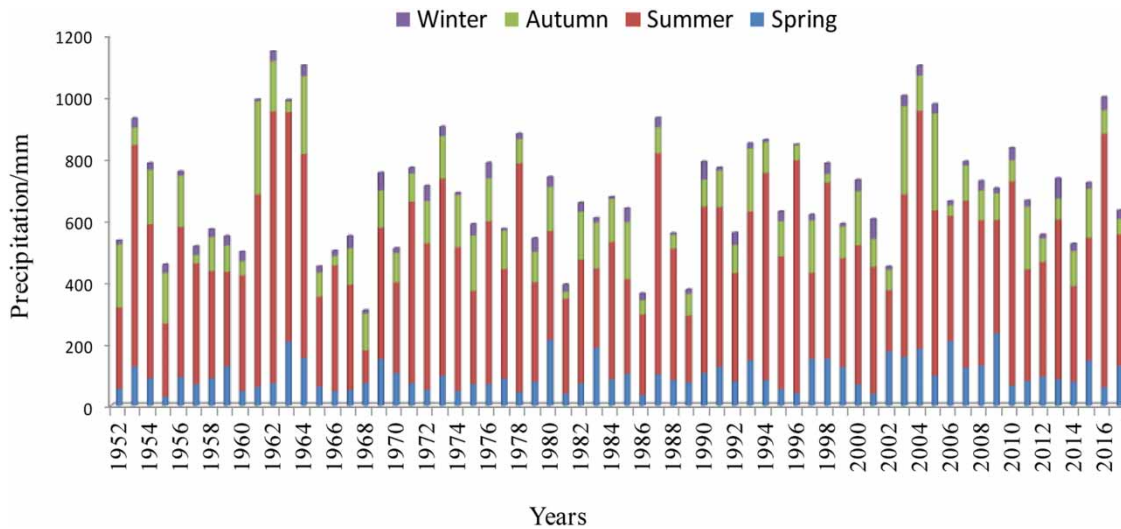


Figure 4 | Annual precipitation mutation results in Jinan City.



**Figure 5** | Precipitation changes in Jinan City from 1952 to 2017.

controlled by the northern dry continental air mass, resulting in less precipitation.

**Analysis of trend and mutation characteristics.** At the 95% significance level, the  $U$  statistics of Mann–Kendall in the four seasons of spring, summer, autumn, and winter are shown in Table 1. The Mann–Kendall in spring precipitation is  $U = 2.08$ , indicating that spring precipitation exhibited a significant upward trend;  $U = -1.03 < 0$  in autumn, illustrating that the autumn precipitation is decreasing but not significant; in summer and winter,  $U$  was 0.82 and 0.64, respectively, indicating that the summer and winter precipitation showed an insignificant upward trend, consistent with the annual precipitation trend.

Figure 6 shows the Mann–Kendall statistical curves of precipitation changes in different seasons of Jinan, revealing that the mutation time varies greatly. The intersection of  $UF$  and  $UB$  curves explains that the abrupt change of spring precipitation occurred in 1990, consistent with the annual

precipitation. Figure 6(b)–6(d) show that the  $UF$  and  $UB$  have three to five intersections, reflecting that the precipitation in summer, autumn, and winter varies greatly, with strong randomness and complexity. Considering the uncertainty of the extension data at the front and the end of the sequence, as well as the unreliability of the mutation intersection, the mutation intersection of the front end and the end of the sequence, was excluded. The mutation time was 1962 and 1992 in summer, 1961, 1981, 1990, and 2005 in autumn, and 1960, 1986, and 1996 in winter.

**Quarterly prediction of future changes.** Figure 7 shows the Hurst index  $H$  for the future variation seasonal characteristics of precipitation in Jinan City. When  $H > 0.5$  ( $0 < h$ ), it indicates that the future seasonal trend of precipitation is positively correlated with the current trend, of which the positive correlation is the strongest in spring and the weakest in winter and autumn.

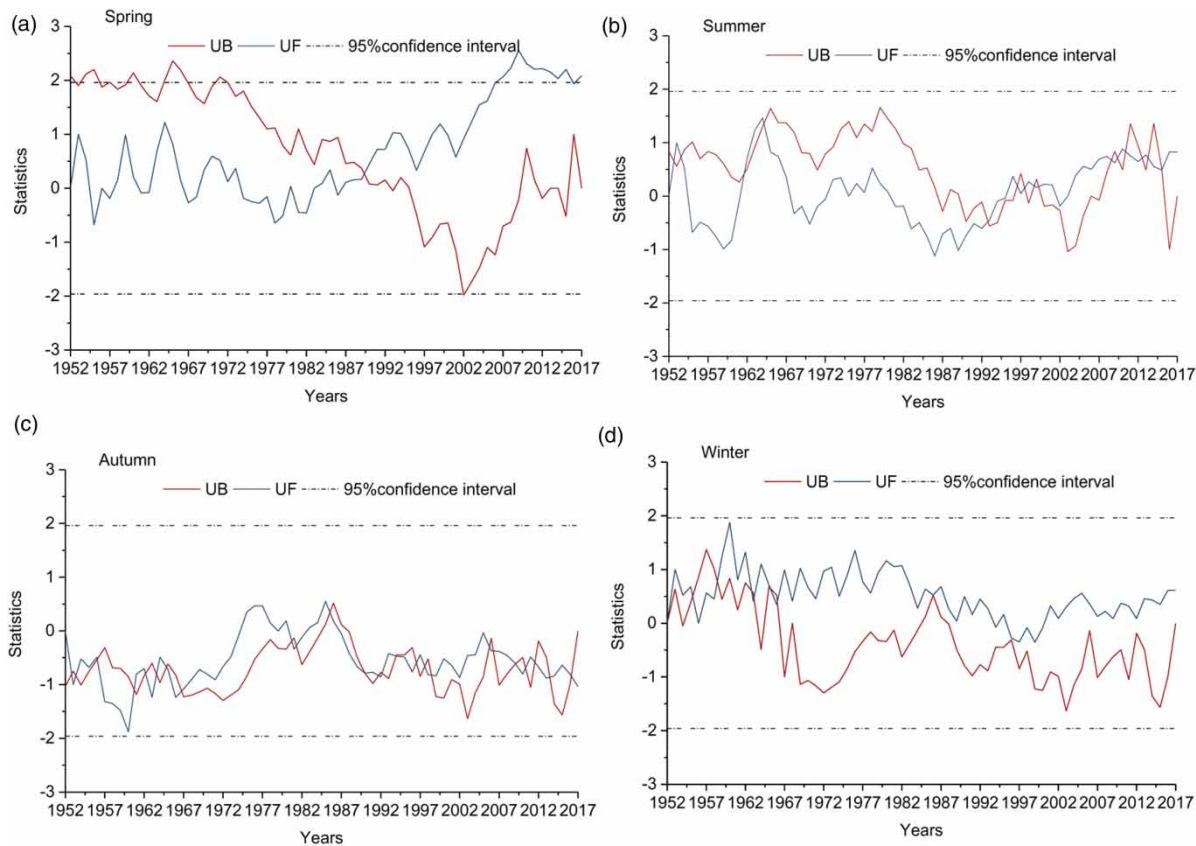
### Monthly precipitation variation characteristics

The monthly rainfall and its percentage, the standard deviation, the deviation coefficient, the maximum, the minimum, and the extreme ratio of Jinan City from 1951 to 2017 are shown in Table 2. The maximum precipitation occurred in July, with a mean of 201.1 mm and a maximum of 506.9 mm (1962). The precipitation in January and

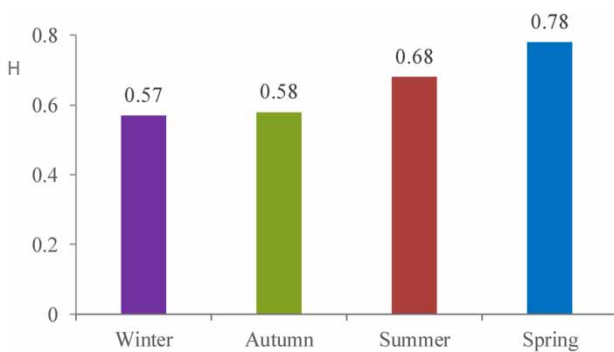
**Table 1** | Significance test of rainfall trend in Jinan City

Season	$U$	Change trend	Significance
Spring	2.08	Increase	Significant
Summer	0.82	Increase	Not significant
Autumn	-1.03	Decline	Not significant
Winter	0.64	Increase	Not significant





**Figure 6** | Mann-Kendall statistic curve of precipitation variation in various seasons.



**Figure 7** | Prediction results of seasonal variation in Jinan City.

December accounted for only 1%, and the minimum precipitation of 0 mm appeared in many years; for example, it appears six times in January (1952, 1954, 1976, 1978, 1995, 2005) and twice in December (1967, 1999). The precipitation during the flood season (June–September) accounts for 74.1% of the whole year. During the period

from January to March and December, the maximum precipitation reached 30 mm. Large-scale heavy rainfall may occur from April to May and October to November, but the number of occurrences is small and uneven. The deviation coefficient of the non-flood season is greater than that of the flood season, which is 1.2 in January and 0.51 in July. Therefore, the precipitation is large and concentrated in the flood season, but small and scattered in the non-flood season.

### Daily precipitation variation characteristics

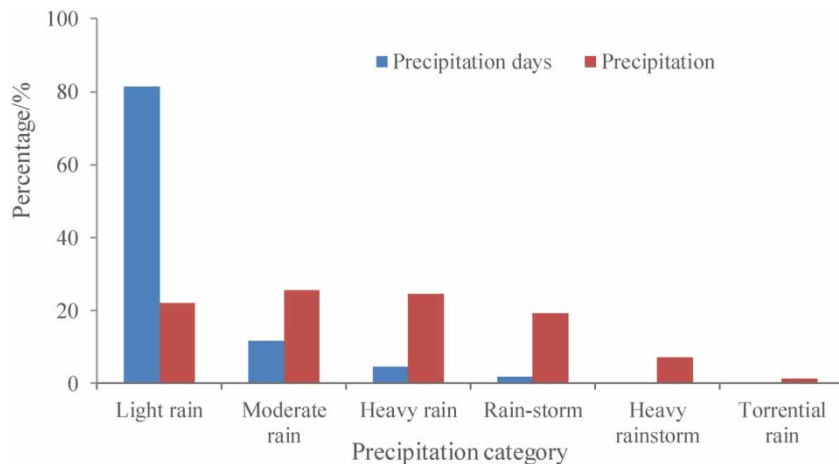
*The variation characteristics of daily precipitation.* Table 3 shows the precipitation classifications prescribed by the China Meteorological Administration. Figure 8 explains the daily rainfall from 1951 to 2017 in Jinan City. There were 7,231 precipitation days between 1951 and 2017, and the maximum daily precipitation occurred on August 26, 1987, with daily precipitation reaching 301.3 mm. Although

**Table 2** | Monthly precipitation statistics of Jinan City

Characteristic value	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean value/mm	6.19	10.69	14.40	32.59	52.07	82.50	201.10	169.88	61.91	34.74	21.49	8.18
Monthly precipitation/%	1%	2%	2%	5%	7%	12%	29%	24%	9%	5%	3%	1%
Standard deviation	7.41	8.92	11.66	26.30	38.84	56.35	101.73	99.71	49.59	29.32	21.79	8.59
Deviation coefficient	1.20	0.83	0.81	0.81	0.75	0.68	0.51	0.59	0.80	0.84	1.01	1.05
max/mm	38.40	38.20	48.30	106.30	193.60	257.20	506.90	503.50	287.50	123.50	110.90	36.00
min/mm	0.00	0.00	0.00	3.20	4.40	6.10	28.50	11.20	1.20	0.10	0.00	0.00
Extreme ratio	$\infty$	$\infty$	$\infty$	33.22	44.00	42.16	17.79	44.96	239.58	1,235.00	$\infty$	$\infty$

**Table 3** | Precipitation classification table (24 h)

Classification	Light rain	Moderate rain	Heavy rain	Rainstorm	Heavy rainstorm	Torrential rain
Precipitation/mm	<10	10–24.9	25–49.9	50–99.9	100–250	>250

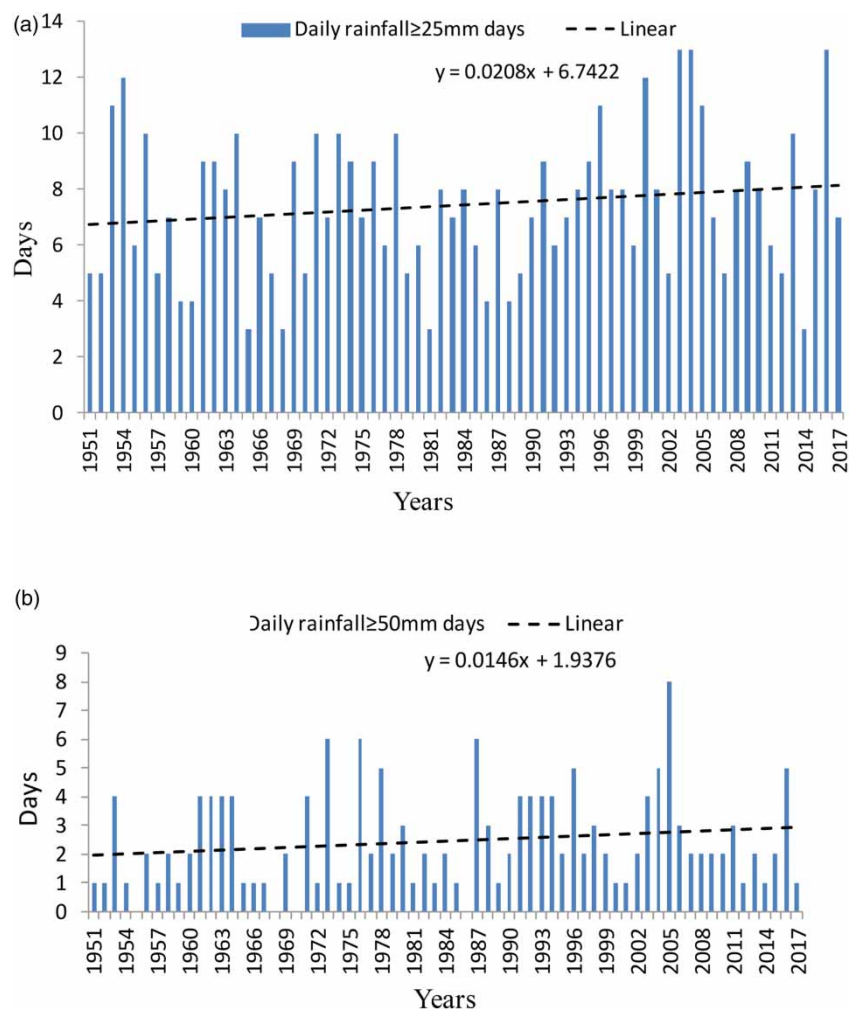
**Figure 8** | Statistical classification of daily rainfall in Jinan City from 1951 to 2017.

the number of moderate rain days with daily rainfall of 10–25 mm is not large, the rainfall accounts for 25.66%; the days with daily rainfall below 10 mm account for 81.54% of the total rainfall days, while the rainfall accounts for only 22.14%. In Jinan City, the total days of rainstorms, heavy rainstorms, and torrential rain that had the greatest impact on urban flooding were 163, accounting for 2.26% of total precipitation days.

#### *Characteristics of heavy rain and rainstorm.*

- (1) Analysis of stability and volatility results: [Figure 9](#) reveals that the precipitation days with precipitation greater than 25 and 50 mm in the different years show strong volatility

and differences. Precipitation greater than 25 mm appeared in 2003, 2004, and 2016, with a maximum of about 13 days. The minimum number of precipitation days that appeared in 1965, 1968, 1981, and 2014 was 3 days. Precipitation greater than 25 mm mainly occurred in 1953–1956, 1961–1964, 1971–1974, 1995–1998, and 2003–2005, with periodic characteristics for three consecutive years. For years with precipitation greater than 50 mm (rainstorm), the minimum is 0 days, that appeared in 1955, 1968, 1970, and 1986, respectively. Precipitation greater than 50 mm mainly occurred in 1961–1964, 1991–1994, and 2003–2005, similarly with periodic characteristics for three consecutive years.

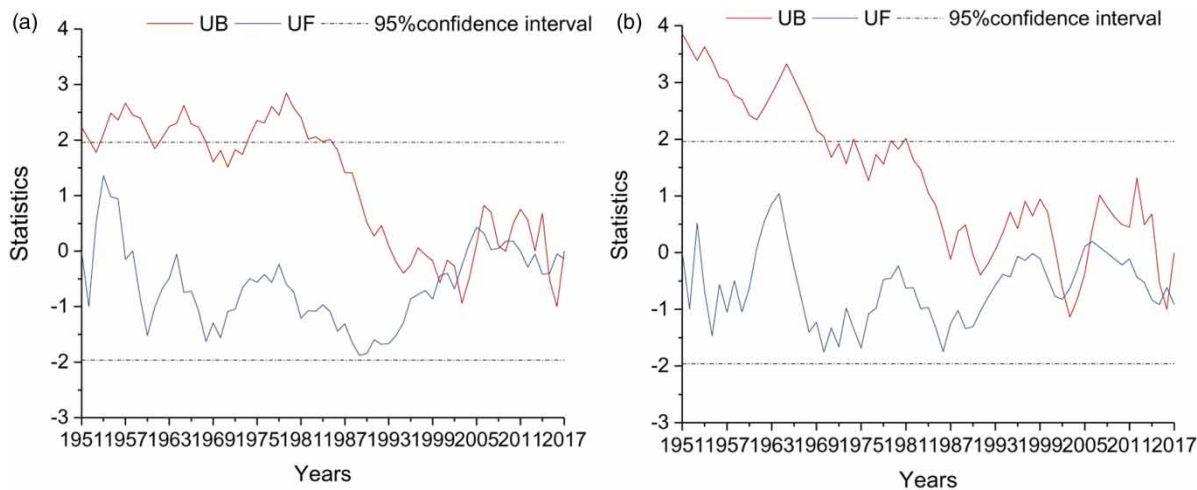


**Figure 9** | Changes in heavy rain and rainstorm from 1951 to 2017 in Jinan City.

(2) Long-term trend and mutation characteristics: [Figure 9](#) also reveals that the linear fitting trend of precipitation days with precipitation more than 25 and 50 mm exhibited an increase, but was not significant. At the 95% significance level, the Mann-Kendall statistic  $U$  of the precipitation days with precipitation greater than 25 and 50 mm was 1.04 and 1.47, respectively, with no significant upward trend, which is consistent with the linear fitting results. Combined with [Figure 10\(a\)](#), the mutation of heavy rain and rainstorm in Jinan City is the same as the  $UF$  curve of the heavy rain intersecting  $UB$  multiple times. However, due to the lack of data before 1951 and after 2017, for the mutations both on the right side of 1951 and the left side of 2017, there is

no corresponding change trend of the other side data to support, increasing the uncertainty of mutations. Therefore, taking into account the uncertainty of data front-end and the end data expansion, the mutation year of the sequence endpoint crossing is excluded, and the mutation time of the heavy rain was determined to be 2000. Besides, as also shown in [Figure 10\(b\)](#), the sudden change of rainstorm time was determined in 2002, with a two-year delay compared with the heavy rain mutation time.

(3) Prediction of future changes in heavy rain and rainstorm: in Jinan City, the Hurst index  $H$  reflecting the change in the days of heavy rain and rainstorm was 0.810 and 0.856, respectively, both of which were



**Figure 10** | Mann-Kendall statistic curve of heavy rain and rainstorm changes in Jinan city.

greater than 0.5, indicating that the future change trend was significantly positively correlated with the current change trend, and the positive correlation with the rainstorm is stronger. As anthropogenic activities have an increasing impact on the climate, extreme weather events have increased and their impact has spread all over the world. Meteorologists point out that the warming atmosphere contains more water vapor and energy. When the weather deteriorates, a lot of energy is released quickly, making the storm more ferocious, with greater precipitation intensity and more precipitation. Overall, it is foreseeable that in the context of global climate change characterized by climate warming, the future heavy rain events will continue to increase in Jinan.

## CONCLUSION

Jinan is one of the central cities in eastern China and the economic center of the lower Yellow River, with a high population density. As the impact of global climate change intensifies, the ratio of extreme precipitation to annual precipitation increases and multiple extreme rainfall events have caused severe casualties and economic losses to Jinan City. Therefore, understanding future changes is crucial for the development of adaptation and mitigation measures. Based on the statistical analysis of the

precipitation data from 1951 to 2017 in Jinan, this paper draws the following conclusions.

- (1) The precipitation varies greatly from year to year. The relative change in annual precipitation ranges from  $-52\%$  to  $64\%$ , while the precipitation days are  $-24\%$  to  $45\%$ . In the past 14 years, precipitation has increased, but the precipitation days have decreased, indicating that the precipitation concentration is stronger and more volatile, with abundance and drying regularity of six to nine years. The annual precipitation of Mann-Kendall statistic  $U = 1.15$  (significance level at  $\alpha = 0.05$ ) represents no significant increase in annual precipitation. The  $UF$  and  $UB$  curves intersected in 1990, indicating that the annual precipitation sequence began to mutate in 1990, causing precipitation to change from falling to rising. The Hurst index of the annual precipitation series is 0.79, indicating that the future precipitation pattern is the same as the current situation, and its trend and positive persistence are not significantly increased.
- (2) The annual precipitation is unevenly distributed, with significant differences in summer and winter, and slightly different in spring and autumn, but less precipitation in spring, mainly due to the influence of the dry continental air mass in the north. From June to September, the precipitation in the flood season accounted for  $74.10\%$  of the annual precipitation, with the largest proportion in July and August, and the smallest in January

and December. The Mann–Kendall statistic  $U$  for spring rainfall was 2.08, showing a significant upward trend. The increase in summer and winter is not significant, while autumn shows an insignificant downward trend. The spring mutation time was in 1990, and the summer, autumn, and winter seasons were highly volatile, with two to four mutations. The Hurst index of the four seasonal precipitation series is greater than 0, indicating that the future trend is consistent with the interannual trend.

- (3) The days with light rain, heavy rain, and above accounted for 81.54% and 6.91% of the total rainfall days, respectively, while the difference in the ratio of the rainfall to the total rainfall was relatively large, 22.14% and 52.20%, respectively; the precipitation days of heavy rain and rainstorm all showed strong volatility and difference, with an inconspicuous upward trend.

The paper analyzes Jinan's precipitation changes in detail, but it lacks in-depth attribution exploration and sensitivity analysis on important influence factors, and therefore we will conduct in-depth analysis and research in the future.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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