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ANALYSIS OF BEIJING RAINFALL PATTERNS, BASED ON 68 YEARS OF RAINFALL DATA

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ABSTRACT

Trends in Beijing rainfall behaviour are examined using peaks-over-threshold and annual maxima data in this paper. The analysis focuses on changes that have occurred in the 68-year period 1941-2008. Four annual series are examined which are annual rainfall, grades rainfall, extreme rainfall with 120 minutes and annual maximum data with short duration. Three main statistical methods which are Mann-Kendall non-parametric tests, locally weighted regression smoothing and linear trend estimates are applied to trend analysis.

Test results showed that the annual rainfall of Beijing have an insignificant downward trend between 1941 and 2008, but increased gradually after 2003. It mainly caused by addition of increasing moderate-rain and heavy-rain. The occurrence frequency and total rainfall of extreme storm events also experienced an insignificant downward process. The annual maximum rainfall with short duration showed fluctuations over 5-10 year periods and a slight downward trend in the overall. From 2003, it has been in a transitional period from decreasing to increasing.

KEYWORDS
Urban local flooding; rainfall patterns; annual maximum rainfall.

1. INTRODUCTION

With city expansion and climate change, urban local flooding occurred frequently in Beijing in recent years. For instance, large areas were inundated during the storm events on June 23rd, 2011 and July 21st, 2012, which caused road inundated, vehicles flooded and even leaded to personal injury and death. In the aftermath of a major food event, it is common to question whether rainfall is generally becoming more frequent or more severe in Beijing.

This paper concentrates on changes that have taken place since 1941 and considers whether there have been trends in Beijing rainfall. Analysis is focused on the annual rainfall, six grades rain of traditional meteorological definition, extreme rainfall with 120 minutes and annual maxima data with short durations.

2. METHODOLOGY

2.1 The data resource

In this paper, the raw rainfall data come from the Beijing Weather Observatory Station, which is the earliest and a national reference climatological stations always have been as Beijing representative sites. Currently, the station is located in Beijing's southern suburbs – DaXingJiuGong and has the longest time series of rainfall data of Beijing.

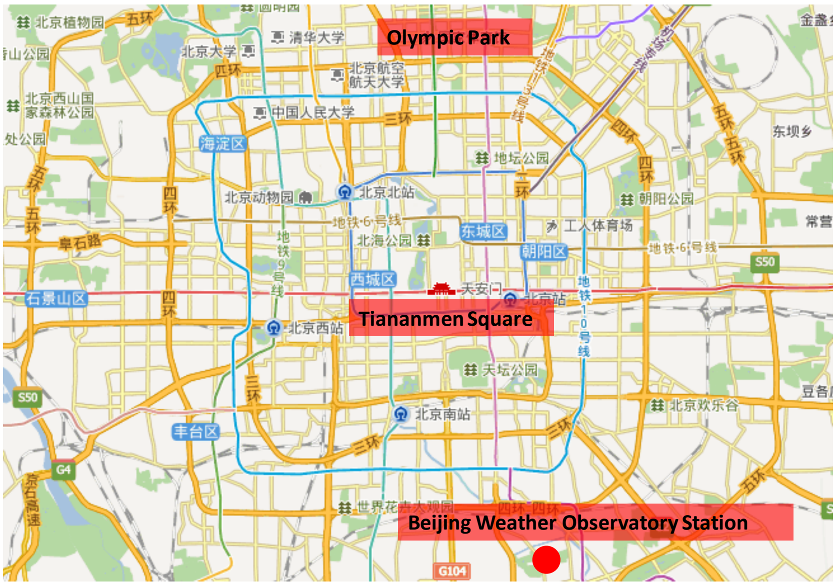


Figure 1 Location of Beijing Weather Observatory Station.

Since 1941, by-minute rainfall data has been well recorded and carefully quality controlled, and until now 68 years of data has been accumulated. Therefore, basic data used in this paper is continuous, credible and capable of representing Beijing rainfall patterns.

2.2 Statistical methods

2.2.1 Tests for trend

Mann-Kendall non-parametric rank correlation test method (MK test) is recommended by the World Meteorological Organization and widely used in trend analysis for hydrological, meteorological and other non-normally distributed data, which does not require observations to comply with a certain distribution, but also interference by a few outliers, and is not necessary for statistical analysis.(Kendall, 1970; Mann, 1945) Applying the MK test for trend analysis, time series can be judged whether the data has increasing or decreasing trend and used for mutation analysis.

During practical application, the observations can constitute a time sequence, which is represented chronologically as $x_t = (x_1, x_2 \cdots x_n)$. In the trend analysis with MK, a random time series with size of n needs to be constructed as an order sequence firstly:

$$S_K = \sum_{i=1}^{k} r_i, (k = 2,3\ldots n)$$

In the above formula:

$$r_i = \begin{cases} +1, if\ (x_i > x_j) \\ & (j = 1,2\cdots i) \\ 0, else \end{cases}$$

As can be seen, the order sequence S_k represents the cumulative number of data in time of j which are smaller than the value in time of i. Under the assumptions of independence of observations, statistics UF_k can be defined as follow:

$$UF_k = \frac{[S_k - E(S_k)]}{\sqrt{Var(S_k)}}, (k = 1,2\cdots n)$$

In the above formula: $UF_1 = 0$, $E(S_k), Var(S_k)$ are the mean and variance of S_k . Under the assumptions of independence and same continuous distribution of $x_1, x_2 \ldots x_n$, $E(S_k), Var(S_k)$ can be calculated by the following formula:

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

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

With the increase of n (n>10), UF_k quickly converges to standard normal distribution. Under the null hypothesis of no change, bilateral test was used to determine whether the trend is significant or not. The specific process is as follows: Given a level of significance marked as a , the critical value of the confidence interval $Z(a/2)$ can be obtained, when $|UF_k| < Z(a/2)$, accepting the null hypothesis that the trend was not significant, if $|UF_k| > Z(a/2)$, then reject the null hypothesis that the trend is remarkable.

Make the chronological sequence in reverse order ($x_t = (x_n, x_{n-1} \cdots x_1)$) and repeat the above procedure, while meeting the following requirement: $UB_k = -UF_k, k = n, n-1, \cdots 1, UB_1 = 0$, We can get the UB_k curve. When the UF_k or UB_k exceeds the threshold, it will indicate a significant upward or downward trend. Meanwhile, the intersection of two curves, which located between the two threshold lines, has indicated the start time of mutation.

2.2.2 Graphical presentation

Graphical presentation of the data forms an important component of the analysis. Many of the graphs make use of a smoothing technique known as locally weighted regression smoothing (loess). This is a widely used and relatively robust method (Cleveland, 1979; Cleveland et al., 1992, Cleveland and Loader, 1996). The level of smoothing is controlled by a $f(0 < f \le 1)$ parameter which dictates the proportion of data used within the smoothing window. For the 68-year series rainfall data of Beijing, f of 0.12 is used, which means 8 nearest independent variables (the years) are used to estimate value of the dependent variables (the rainfall).

The method of Linear Trend Estimate has been commonly used for trend analysis of time series data, which construct a unitary linear regression equation $x_i = a + bt_i, (i = 1,2,\cdots n)$ to express the relationship between x_i and t_i . In the equation, a is known as regression constant and b is regression coefficient. These two parameters can be calculated by the least squares method, same as the correlation coefficient R. The value of b is used to determine the increasing or decreasing trend, and by determining the level of significance, the R value is for significance judgment.

3. RESULTS AND ANALYSIS

3.1 Annual rainfall

According to the data from the Weather Observatory Station, the average precipitation is 369 mm per year with 25 m in total over a period from 1941 to 2008. The evolution of annual rainfall pattern during this time is shown in Figure 1. Figure 2 shows the M-K test results of annual rainfall.

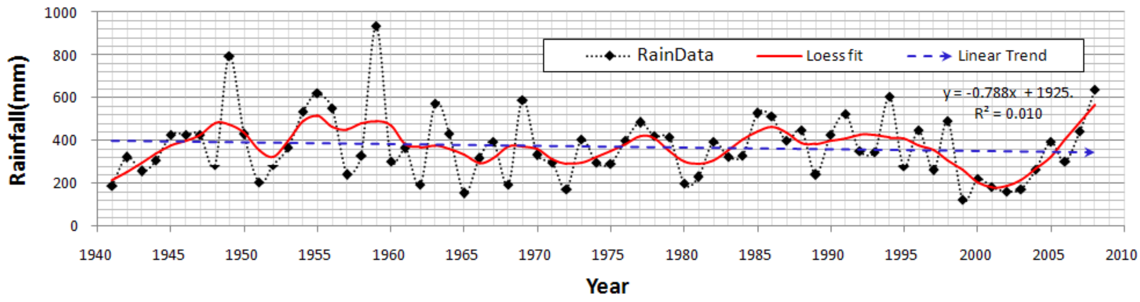


Figure 2 Yearly rainfall curve and trend line.

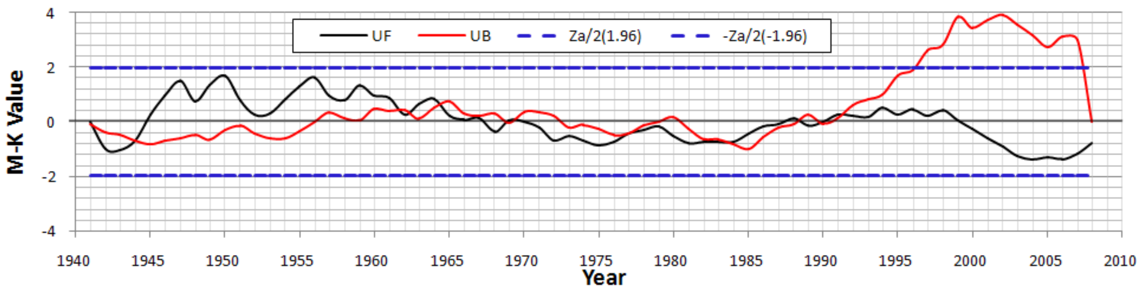


Figure 3 M-K test of yearly rainfall

As shown in Figure 2, between 1941 and 2008, the series showed a slight decrease trend. The maximum value appeared in 1959, which is 935.37mm, and the sub-maximum with a value of 793.8mm taken place in 1949. The linear trend rate is calculated as -0.8 mm/a and with a judgment of significant level of 0.05 which indicates the confidence interval is between -0.2875 and 0.2875, the downward trend is insignificant. The UF curve in MK test which is shown in Fig 3 also illustrates a downward trend in annual rainfall sequence, but not exceeds the confidence interval(between -1.96 to 1,96) under the significance level of 0.05(which means $|UF_k| < Z(a/2)$). As a result, the trend can be judged as not significant, which same as the results taken from Linear Trend Estimate. Although the overall slightly decreasing trend exits, the conclusion that the rainfall starts to increase gradually by year after 2003 can be obtained from the loess fit in Fig 2 and UB curve in Fig 3.

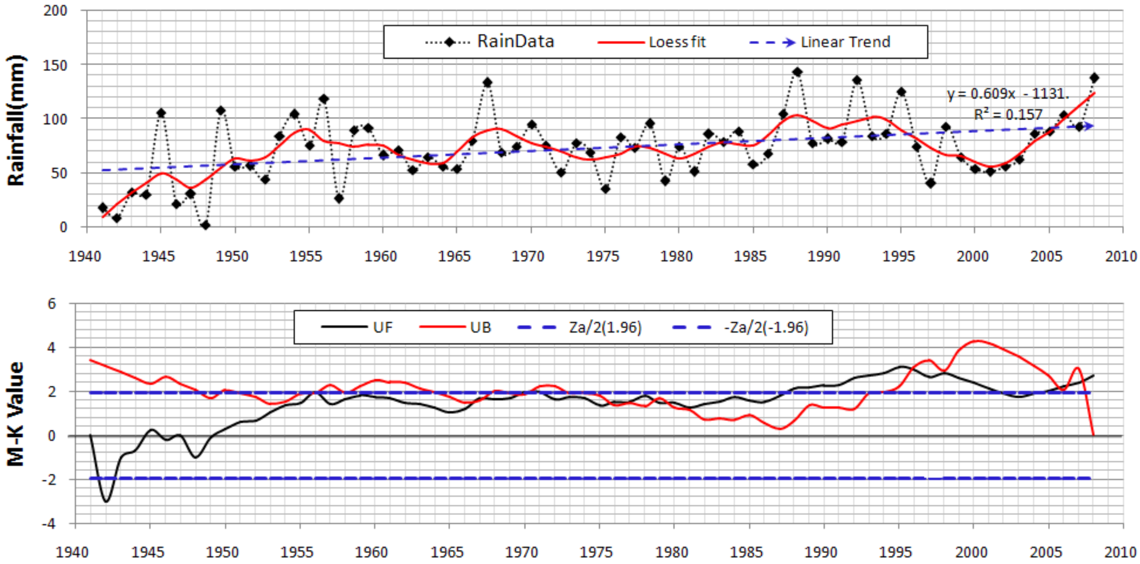
3.2 Various grades rainfall

Based on traditional meteorological definition, rainfall events can be divided into six grades termed as light-rain, moderate-rain, heavy-rain, storm, heavy-storm and extra-heavy-storm (greater than or equal to 250 mm/d). The detailed data for various grades is demonstrated in Table 1, from which we could conclude that heavy-rain and moderate-rain occupies the majority, followed by light-rain, storm and heavy-storm, and extra-heavy-storm has never happened.

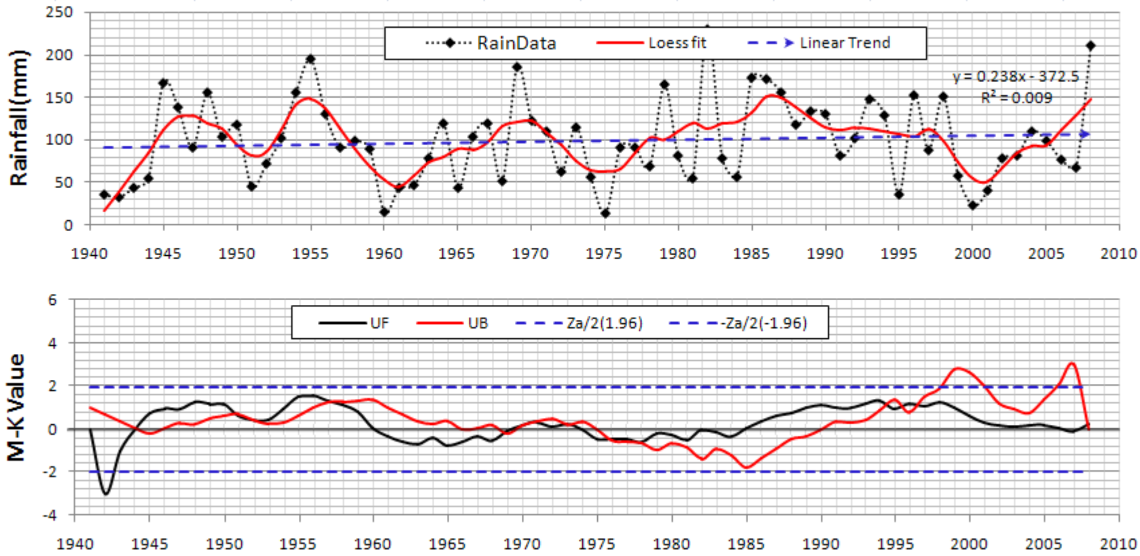
Table 1 Statistics of rainfall at various grades

Grade	Definition	Frequency	Total rainfall	Average	Proportion
Light-rain	0.1~9.9 mm/d	1836	4932.05 mm	2.69mm	19.6%
Moderate-rain	10~24.9 mm/d	419	6735.4 mm	16.07mm	26.8%
Heavy-rain	25~49.9 mm/d	198	6864.52 mm	34.67mm	27.3%
Storm	50~99.9 mm/d	70	4570.3 mm	65.29mm	18.2%
Heavy-storm	100~249.9 mm/d	16	2026.8 mm	126.68mm	8.1%

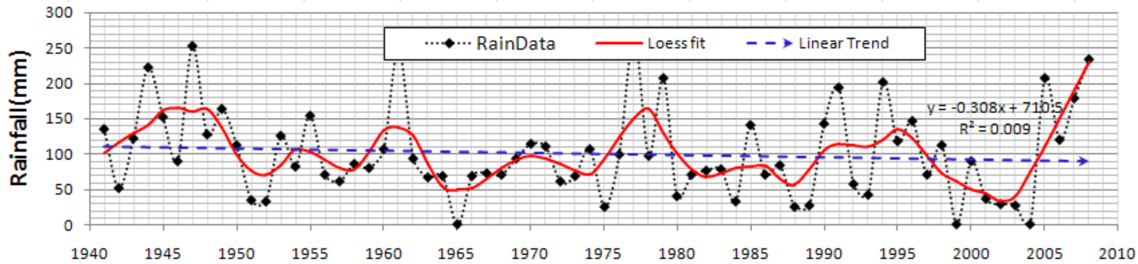
Figure 4 illustrates yearly variation of rainfall for different grades, which includes the trend analysis and M-K test results

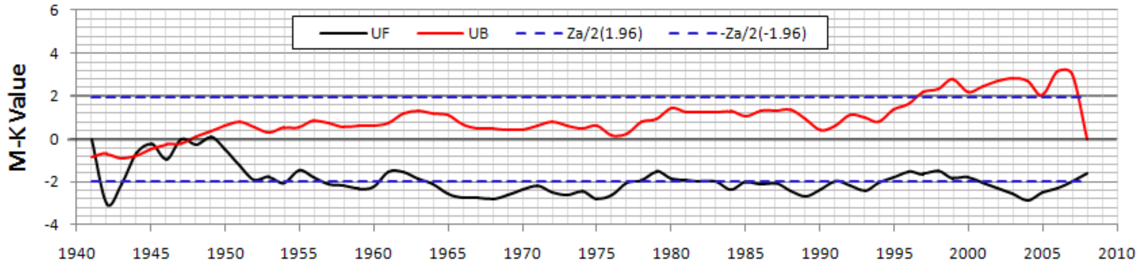


(a) Light-rain

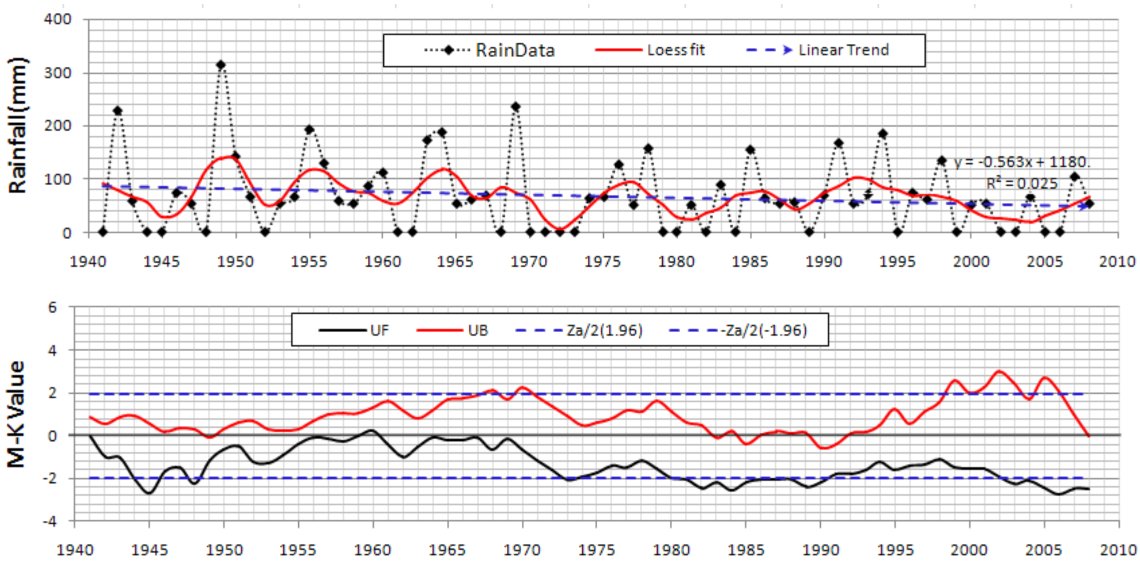


(b) Moderate-rain

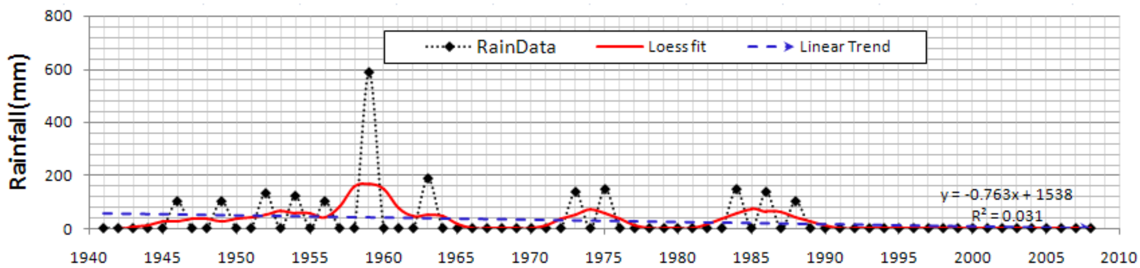




(c) Heavy-rain



(d) Storm



(e) Heavy-storm

Figure 4 Yearly variation of grades rainfall, Loess fit and linear trend are shown in the first Fig, M-K test together with 95 percent confidence intervals are shown in next Fig.

The detailed results of MK test and trend analysis are shown in Table 2:

Table 2 M-K tests and trend analysis results for grades rainfall

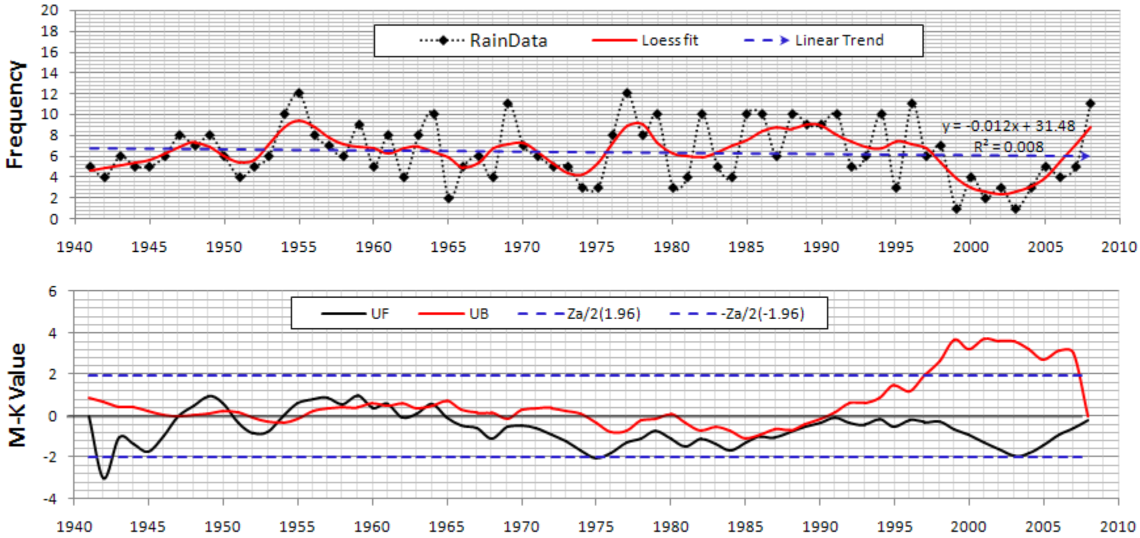
Grade	Mann-Kendall Test			Linear Trend		
	UF_n	Trend	Is significant	Slope inclination	Trend	Is significant
Light-rain	2.7	rising	Yes	0.609mm/a	rising	Yes
Moderate-rain	0.24	rising	No	0.238mm/a	rising	No
Heavy-rain	-1.61	decreasing	No	-0.308 mm/a	decreasing	No
Storm	-2.51	decreasing	Yes	-0.563mm/a	decreasing	No
Heavy-storm	-1.06	decreasing	No	-0.763mm/a	decreasing	No

Table 2 indicates rising in light-rain and moderate-rain, while decreasing in others. Especially for the heavy-storm, it only occurred before 1990. From the loess fit and UB curve which is shown in Fig 4, light rain, moderate rain, and heavy rain have also experienced a similar increasing process with the annual rainfall sequence after 2003.

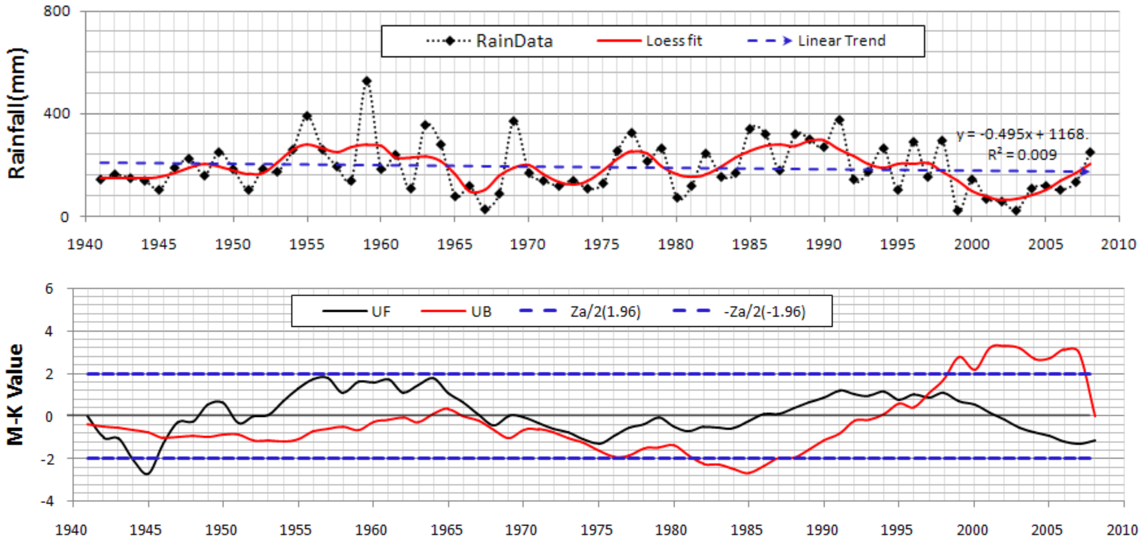
3.3 Extreme rainfall with 120 minutes

Extreme rainfall index is defined as the precipitation which exceeds 99% rainfall with same duration (Easterling, 2000). Index with 120 minutes is 16.21 millimetres in Beijing, which means that rainfall exceeds the threshold value should be defined as an extreme event.

As shown in Figure 5, the occurrence frequency and annual rainfall of extreme events (120 min) showed an insignificant downward trend and bottomed out in 2003. Since then, it experiences an upward trend. In 2008, the occurrence reached 11 times, rainfall reached 249.6 mm, has been more than 68-year average.



(a) Frequency



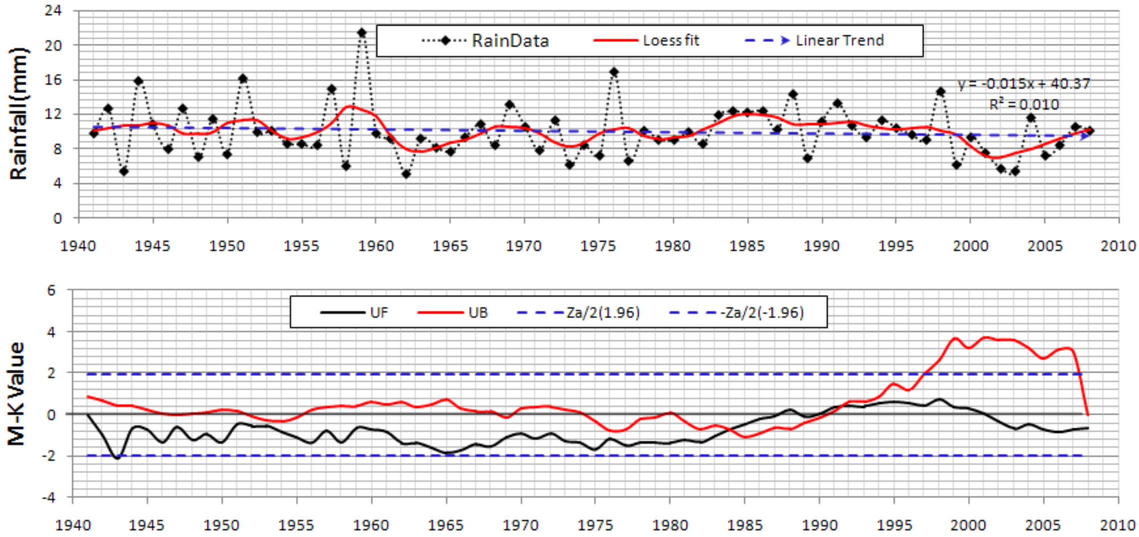
(b) Annual rainfall

Figure 5 Annual rainfall and frequency for short-duration (120 min) extreme events, Loess fit and linear trend are shown in the first Fig, M-K tests together with 95 percent confidence intervals are shown in next Fig.

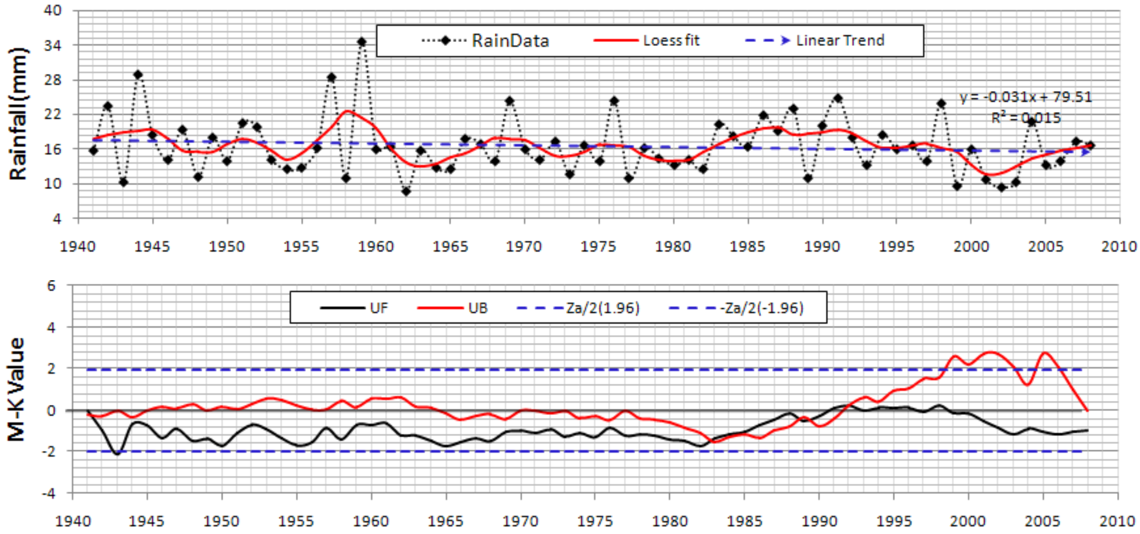
Obviously, between 1941 and 2008, annual rainfall and frequency have experienced an upward trend, and then in 1959 annual rainfall reached its peak which is 526.4mm, after that, the data gradually declined in fluctuation. From 1999 to 2003, the downward trend becomes apparent, and the minimum data with a rainfall of 23.96mm and frequency of one times appeared in 2003. Since then, the trend converts to a significant rising which is shown in UB curve.

3.4 Annual maximum rainfall with short duration

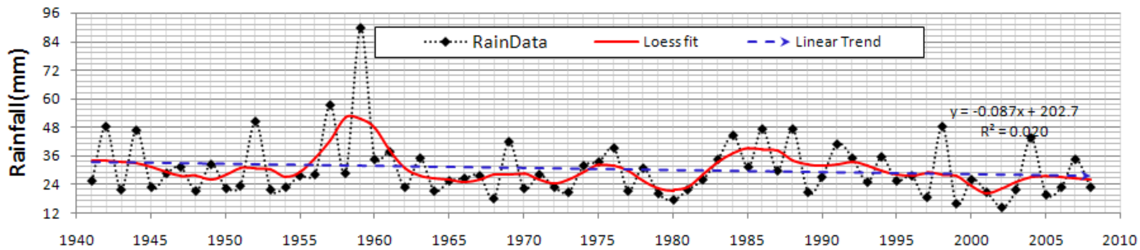
From 1941 to 2008, the trends of annual maximum rainfall with various durations (5min, 10min, 30min, 60min) are displayed in Figure 6.

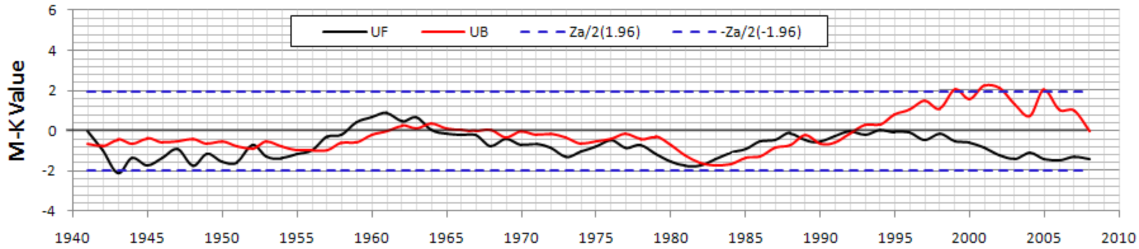


(a) 5min

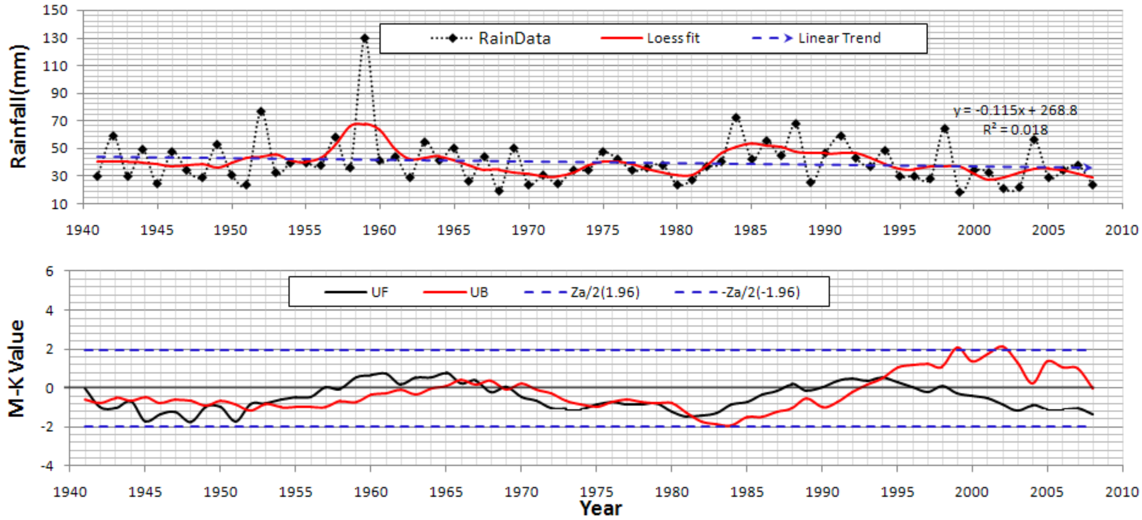


(b) 10min





(c) 30min



(d) 60min

Figure 6 Annual maximum rainfall with different durations, Loess fit and linear trend are shown in the first Fig, M-K test together with 95 percent confidence intervals are shown in next Fig.

The detailed results of MK test and trend analysis are shown in Table 3:

Table 3 M-K tests and trend analysis results for annual maximum rainfall

Duration	Average precipitation	Mann-Kendall Test			Linear Trend		
		UF_n	Trend	Is significant	Slope inclination	Trend	Is significant
5 min	9.97mm	-0.68	decreasing	No	-0.015mm/a	decreasing	No
10 min	16.53mm	-0.96	decreasing	No	-0.031mm/a	decreasing	No
30 min	30.34mm	-1.39	decreasing	No	-0.087 mm/a	decreasing	No
60 min	40.30mm	-1.33	decreasing	No	-0.115mm/a	decreasing	No

As shown in Figure 6 and Table 3, the short concentrated heavy rainfall slightly descended within 68 years. The heavy precipitation mainly occurred before 1970 and all maximum values appear in 1959 which is 21.42mm for 5min, 34.58mm for 10 min, 89.62mm for 30min and 129.72mm for 60min. The trends experienced a visible decreasing since 1990 while demonstrates transitional period from decreasing to increasing starting from 2003.

4. CONCLUSIONS

(1) The annual rainfall of Beijing showed an insignificant downward trend between 1941 and 2008, but increased gradually after 2003. It mainly caused by addition of increasing moderate-rain and heavy-rain, while Beijing has never suffered a heavy-storm in the past 20 years.

(2) The occurrence frequency and total rainfall of extreme storm events also experienced an insignificant downward process, but bottomed out in 2003. Since then, it experiences an upward trend.

(3) The annual maximum rainfall with short duration showed fluctuations over 5-10 year periods and a slight downward trend in the overall. From 2003, it has been in a transitional period from decreasing to increasing.

(4) In the last decade，rainfall of Beijing has experienced a significant upward trend. The conclusions above may partly explain the occurrence of frequent urban local flooding of Beijing in recent years. However, there is no evidence that the rainfall is generally becoming more frequent or more severe in 68-year period.

5. ACKNOWLEDGEMENTS

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