ANALYSIS OF VARIATION CHARACTERISTICS OF EXTREME PRECIPITATION EVENTS IN HETAO AREA, CHINA BASED ON FUZZY CLUSTERING CLIMATE ZONING

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Abstract. This paper adopts the meteorological data from 1951 to 2014 provided by 73 national ordinary stations in Hetao area, China, combines Kendall-tau non-parametric test method and Sen's slope estimation method based on sub-regions divided by fuzzy clustering method and analyses the variation trend of extreme precipitation indexes in the area. The results show that: (1) In the arid and semi-arid sub-region (located in the upper reaches of the Yellow River) and humid and semi-humid sub-region (located in the middle and lower reaches of the Yellow River) in Hetao area, extreme precipitation events have different variation trends, and the spatial distribution of precipitation is unbalanced. (2) Except the precipitation of extreme wet days has significantly increased (R99p is 32.01 mm /10a), other indexes do not increase significantly in the arid and semi-arid sub-region of Hetao area. (3) In the humid and semi-humid sub-region of Hetao area, the variation trends of the other 9 indexes are negative except the indexes consecutive days with rain (CWD) which showed upward trend (0.03d/10a). (4) There is an upward trend of extreme precipitation events in Bayinmaodao, but other regions in Hetao area have not increased.

Keywords: *fuzzy C-means, climate division, Kendall-tau, extreme precipitation*

Introduction

In more than half a century in the past, Scholars all over the world have conducted a lot of research work on extreme climate events in different regions of the world and have achieved research results of different depths. In early 2014, Science published 7 papers in a row to discuss the "the Challenge of Climate Science" and elaborate on some core issues of current climate and hydrology sciences, including the issue of "regional climate and extreme events". The paper believes that an important trend of warming research is to reflect global warming in the research on regional climate and extreme events, but the research needs to be further developed, where also exists great difficulties (Wang et al., 2014). At present, domestic and international researches focus mainly on the observational facts of extreme climate. The assessment report (IPCC-AR4) of the UN Intergovernmental Panel on Climate Change (IPCC) has summed up the observations and research findings of extreme temperature and precipitation events in full length, pointing out that extreme precipitation events are very sensitive to the global climate change, and minor changes in the climate may cause greater changes in

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the frequency and intensity of extreme climate (Zhai et al., 2003; Zhou et al., 2010; Wang et al., 2013; Shen et al., 2012).

Scholars all over the world have done a lot of research work on extreme precipitation events on different spatial and temporal scales in different regions, which mainly includes four aspects: determination of representative values of extreme precipitation, characteristics of temporal and spatial distribution and evolution trend of extreme precipitation, factor of influence of extreme precipitation and simulation and prediction of extreme precipitation based on the climate change mode. With regard to the arid area in northwestern China and even the entire country, the research findings are given that the variation of extreme precipitation events in China is extremely complex with obvious regional and local characteristics. The micro-precipitation in the North significantly decreased, the drought continued in North China and the summer monsoon precipitation in the basin of the Yangtze and Huaihe Rivers increased significantly; heavy precipitation decreased significantly in North China, extreme precipitation events showed a significant upward trend in most parts of Northwest China and western part of Northeast China, but that showed a significant downward trend in the eastern part of Northeast China (Wang et al., 2012). the temperature in the northwestern region has shown an overall upward trend in the past 50 years, during which extreme high temperature events have increased and extreme low temperature events decreased; precipitation has shown a slight increase and extreme precipitation events was on the rise (Qi et al., 2015). The precipitation in the Yellow River basin showed a downward trend year by year, while extreme precipitation events in winter showed an upward trend, which mainly centralized in the upper reaches, while the downward trend was mainly seen in the middle and lower reaches, and spatial differences can be found in the Yellow River Basin in terms of precipitation and precipitation variation trend (Zhao et al., 2015). The precipitation in Xinjiang increased, extreme precipitation also showed an upward trend and continuous drying index dropped under the impact of climate warming (Li et al., 2015). The extreme precipitation indexes in the semi-arid region in the north such as maximum precipitation of 5 days, heavy precipitation, precipitation intensity, consecutive wet days, consecutive dry days, heavy rain days and annual total precipitation have shown a downward trend (Wang et al., 2016).

From previous research findings, it can be seen that extreme precipitation events on different scales have different rules or characteristics. The research area in this paper is Hetao area in China, which refers to the “T-shaped” bend of the Yellow River and its surrounding river basins. The whole area is located in the confluence of the Loess Plateau, Ordos Plateau and Inner Mongolia Plateau and the transitional zone of China’s arid, semi-arid and semi-humid regions, where plains, deserts, mountains, platforms, lakes and wetlands are intertwined, topography and landform are complex, terrain changes greatly and the structure of the underlying surface is complex. They have a temperate continental climate with low precipitation, strong evaporation and sensitivity to climate change. At the same time, the area relies on the irrigation of the Yellow River passing through, which is known as the major producing area of grain and cash crops in China and an emerging industrial cluster. It thus can be seen that the economic development in the area requires the sound development of precipitation resources and even extreme precipitation events. If extreme precipitation events occur frequently, it will have an adverse impact on the industrial and agricultural production and urban development in the area. Therefore, it is of both scientific and practical significance to

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study the characteristics and evolution trend of extreme precipitation events in Hetao area.

Predecessors have already conducted some researches on extreme precipitation events in Hetao area. The precipitation within the year in Hetao area was unevenly distributed with about 80% of the precipitation concentrated in the period from June to September, while the precipitation was less in winter. The annual total precipitation in Hetao area has shown an upward trend in the past 50 years, but the trend is not obvious, which is less than 10 mm (Tao et al., 2011). The extreme precipitation threshold in summer in northern Hetao area showed an upward trend from northwest to southeast, and the extreme precipitation events in summer showed a slight upward trend in the past 45 years (Huang et al., 2013). The rainstorm days in Hetao area showed an insignificant downward trend. In addition, the rainstorm is characterized by less rainy day, heavy precipitation, more local rainstorm and less regional rainstorm in terms of distribution (Cai et al., 2014; Zhang et al., 2014). At present, the variation trend and characteristics of extreme precipitation events in Hetao area still need to be further studied to enhance systematic understanding.

Therefore, this paper, based on the daily precipitation data of 73 meteorological stations in Hetao area from 1951 to 2014, uses the extreme precipitation event index recommended by ETCCDMI and the climate change reference period and reference value of 30 years (1981-2010) recently recommended by WMO, and divides the sub-regions for study using fuzzy clustering method (FCM) to conduct an in-depth research on the variation of extreme precipitation events in Hetao area from differential temporal and spatial scales, reveal the variation characteristics and trend and answer the key issue that if the extreme precipitation events tend to increase in the area, hoping to provide a reference for water resource management, ecological vulnerability assessment and hydrogeological hazard warning in the area.

Data and methodology

Data information

When it comes to the research on the variation of extreme precipitation events, this paper usually uses the observed values of precipitation provided by meteorological stations distributed in the research area as data information. This paper adopts the daily precipitation data from 1951 to 2014 of 73 national ordinary stations in Hetao area provided by China Meteorological Data Network (http://data.cma.cn/). Prior to research, the meteorological data selected in this paper has been pretreated, including homogenization inspection; inspection of climate threshold and abnormal value; inspection of station extremum; internal consistency inspection of set value, daily average and daily extremum; temporal and spatial consistency inspection and so on, and the data has been corrected based on the inspection results. In addition, the distribution of meteorological stations is shown in *Figure 1*.

Research method

Fuzzy clustering analysis

Clustering analysis is a multivariate statistical analysis method, which classifies individuals based on their several characteristics, so that individuals of the same category have a higher homogeneity while individuals of different categories have a

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higher heterogeneity. Since the boundaries of individual categories are not always clear and exact, varying degrees of fuzziness is always seen in practical classification problems. When clustering involves fuzzy boundaries between individuals, a fuzzy clustering analysis method is usually used, which is established on fuzzy mathematics. The commonly used fuzzy clustering analysis method is Fuzzy C-Means (FCM for short), which was proposed by Bezkek in 1981. The impact of different number of categories *c* on classification results is highly significant. To evaluate the classification effect under different *c* values in a scientific way, the predecessors have done a lot of research work and defined a number of evaluation indexes to guide the specific classification process. Assuming that different *c* values are determined according to those indexes, the smaller *c* value shall prevail if different *c* values have similar classification effect (Qi et al., 2015).

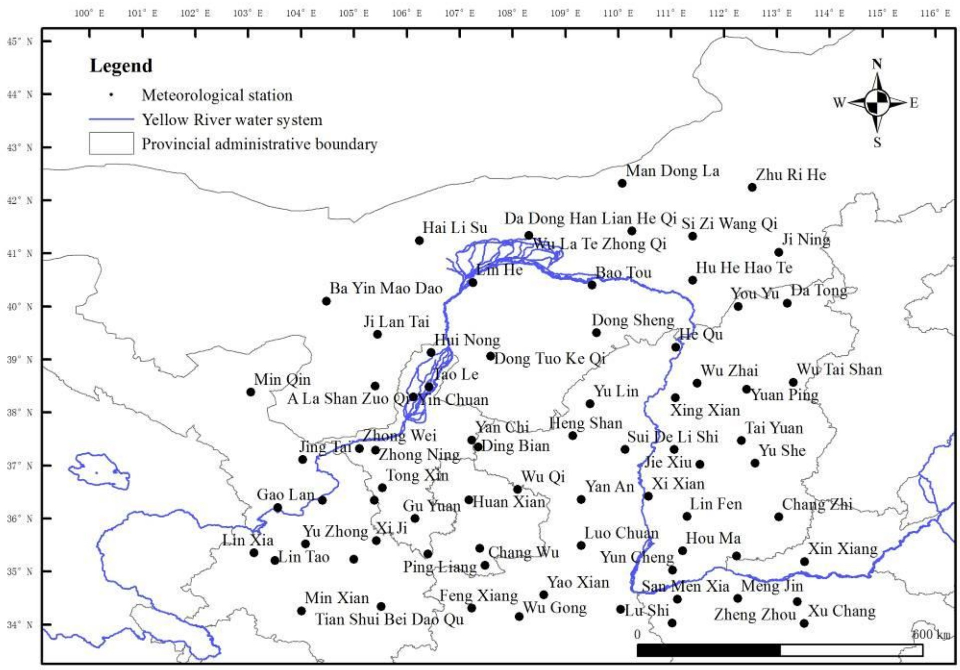

Figure 1. *Diagram of distribution of meteorological stations in Hetao area*

Definition and calculation of extreme precipitation indexes

The extreme precipitation indexes used in the research are “climate change detection and indexes” defined and recommended by CCI, WCRP, CLIVAR and ETCCDMI. These indexes and their calculation methods have been widely used in the world, and the research results also reflect that these indexes in this series are characterized by good regional adaptability, and low noise (Zhao et al., 2015; Li et al., 2012).

There are 29 indexes in this series, including temperature and precipitation. This paper selects 11 indexes of precipitation to analyze the extreme precipitation events in Hetao area, and specific indexes and meanings are shown in *Table 1*. The indexes are calculated using RClimDex1.1 software. In the process of calculation, quality inspection and control is conducted on the said meteorological data including outliers and error

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values. Meanwhile, this paper also adopts the climate change reference period and value of 30 years (1981-2010) recently recommended by WMO (Zhang et al., 2014).

Table 1. *Definitions of extreme precipitation indexes*

S.N.	Abbreviation of index	Index name	Index definition	Index unit
1	CWD	Continuous moisture index (consecutive days with rain)	Maximum stay with daily precipitation greater than or equal to 1 mm	d
2	R10mm	Heavy precipitation days	Total days with annual daily precipitation greater than or equal to 10 mm	d
3	R20mm	Very heavy precipitation days	Total days with annual daily precipitation greater than or equal to 20 mm	d
4	R25mm	Strong precipitation days	Total days with annual daily precipitation greater than or equal to 25 mm	d
5	PRCPTOT	Annual total precipitation	Daily cumulant with precipitation greater than or equal to 1 mm	mm
6	R99p	Precipitation of extremely wet days	Sum of heavy precipitation with the tantile greater than 99%	mm
7	Rx5day	5-day maximum precipitation	Annual/quarterly/monthly/daily maximum precipitation in 5 days in a row	mm
8	SDII	Ordinary daily precipitation intensity (daily precipitation intensity)	Ratio of total precipitation greater than or equal to 1 mm and number of days	mm/d

Analysis method of variation trend of extreme precipitation indexes

Meteorological data belong to time series. For the trend analysis of time series, a linear regression method is usually used, but such method directly calculates the slope based on the actual data value, which is greatly affected by the abnormal value. Sen’s slope estimation algorithm has strong anti-noise performance, but it cannot be used to make a significant judgement of sequence trend. The Kendall-tau non-parametric test method does not require the sample to follow a certain distribution, allows the existence of missing values and can achieve significant judgments, but it cannot be used to obtain the slope of the sequence (Zhai et al., 2003). Therefore, Kendall-tau non-parametric test method and Sen’s slope estimation method are combined in this paper to analyze the variation trend of extreme precipitation indexes, and since they are subject to no abnormal value, they are more suitable for the time sequence trend analysis in the research of extreme climate changes. In addition, the area weighted average method shall be adopted for zone leveling.

Homogeneity test method for meteorological data

Data quality is the primary condition for drawing the correct conclusion in research and is also one of the decisive conditions. Affected by factors such as the replacement of observation instrument, changes in station position, changes in observation procedures and subjective biases of observers, meteorological data is found to have problems such skewness, lack of observation and outliers, thereby resulting in inhomogeneity of the sequence of meteorological data, which shall be homogenized. In

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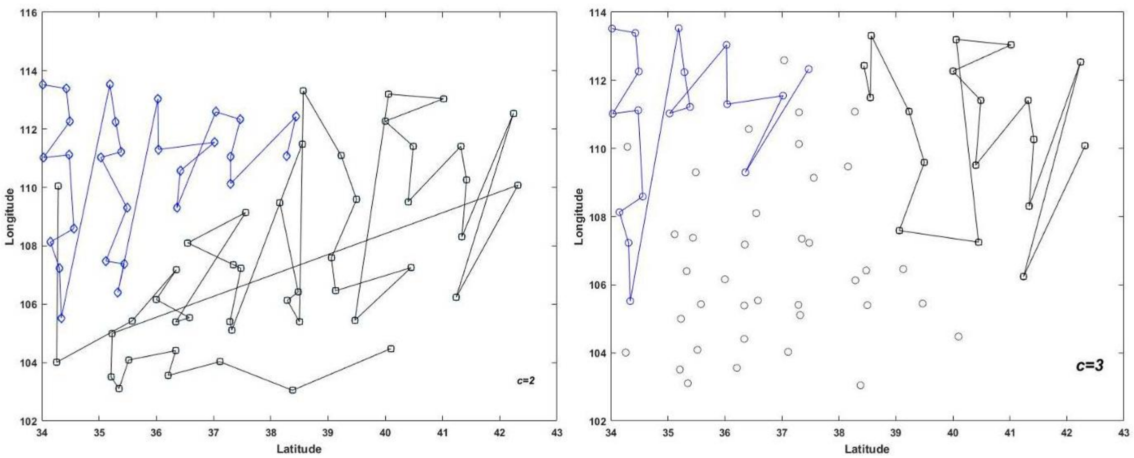
this paper, the RHtest method is used to carry out homogenization and correction of the meteorological data sequence in Hetao area. The method was established by Wang et al. from Climate Research Center of Environment Canada to test the entire sequence of meteorological data based on a two-stage linear regression model (Wang et al., 2007; Zhang et al., 2005), whose feasibility and rationality has been widely verified (Zhang et al., 2012; Zhang, 2012).

Results and discussion

FCM-based climate division

Combined with the natural conditions of the geographical location of the research area, latitude and longitude, altitude, average temperature and maximum and minimum temperature of the meteorological stations are regarded as characteristic values to perform clustering analysis on 73 meteorological stations in Hetao area. The number of divisions is preliminarily estimated to be c = 2 or c = 3. By selecting different c values, FCM can obtain corresponding membership matrix. According to the relationship reflected in the matrix, the classification results shall be plotted when c = 2 or c = 3 (see *Fig. 2a, b*). On this basis, the most reasonable number of divisions shall be analyzed. In addition, it can be seen from *Figure 2* that more stations are not classified in Hetao area when c = 3; while the classification shows good results when c = 2.



a **b**

Figure 2. *FCM analysis of meteorological stations in Hetao area: c = 2 (a) and c = 3 (b)*

To more intuitively express the FCM climate divisions in Hetao area, the classification results are represented in a map (see *Fig. 3*). It can be clearly observed that 73 stations are classified into 2 different climate divisions along the line of "Yuanping—Xing County—Suide—Yan'an—Pingliang—Tianshui", and the line is very close to China's 400 mm equivalent precipitation line, which also fully indicates that it is reliable and reasonable to apply the fuzzy clustering algorithm to climate division in this paper. By referring to the significance of the 400 mm equivalent precipitation line, this paper defines 2 different climate divisions in Hetao area obtained by FCM clustering analysis as "arid and semi-arid sub-region" and "humid and semi-humid sub-region", respectively.

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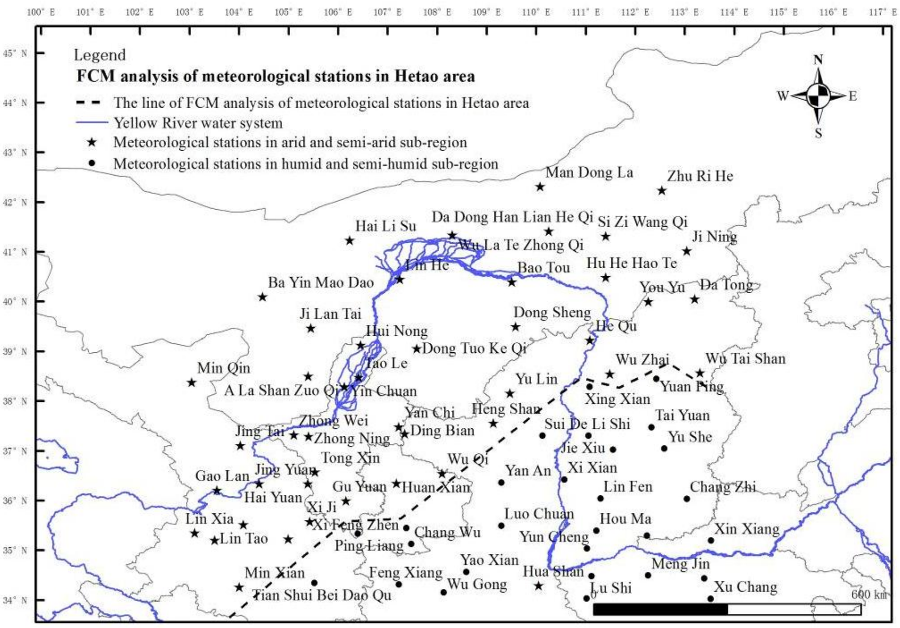

Figure 3. FCM analysis results of meteorological stations in Hetao area

Variation characteristics of extreme precipitation indexes in Hetao area

Variation of CWD, R10mm, R20mm and R25mm indexes

There is no station with significant upward trend of CWD; stations with significant downward trend include Linhe, Taiyuan, Wutaishan, Yan'an and Lushi (see *Fig. 4*, *Table 2*). In addition, the interannual change process of CWD in the entire Hetao area, CWD index have shown an upward trend whether in arid and semi-arid sub-region or humid and semi-humid sub-region (see *Table 2* and *Fig. 5*), but this upward trend is not significant.

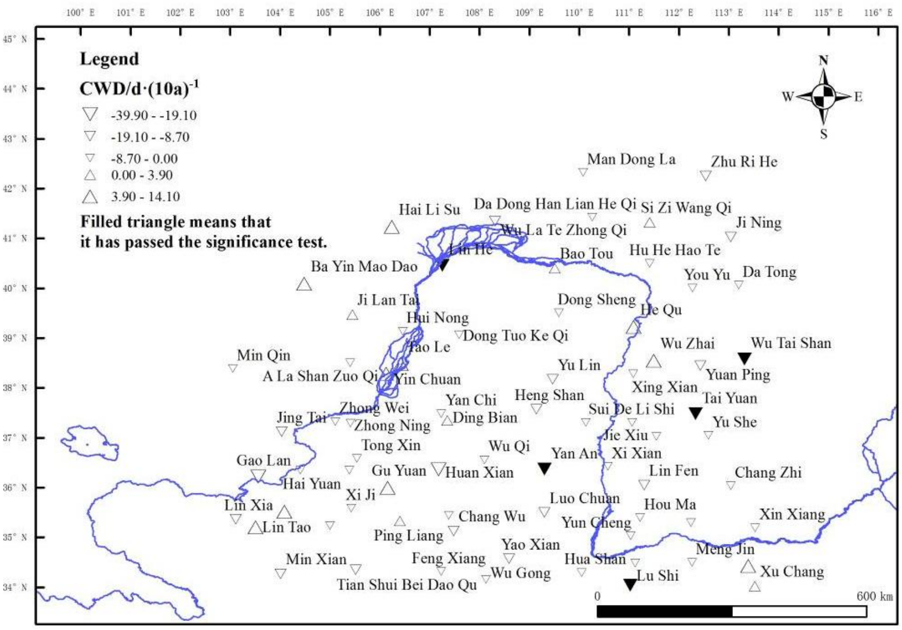

Figure 4. Space variation of CWD index in Hetao area

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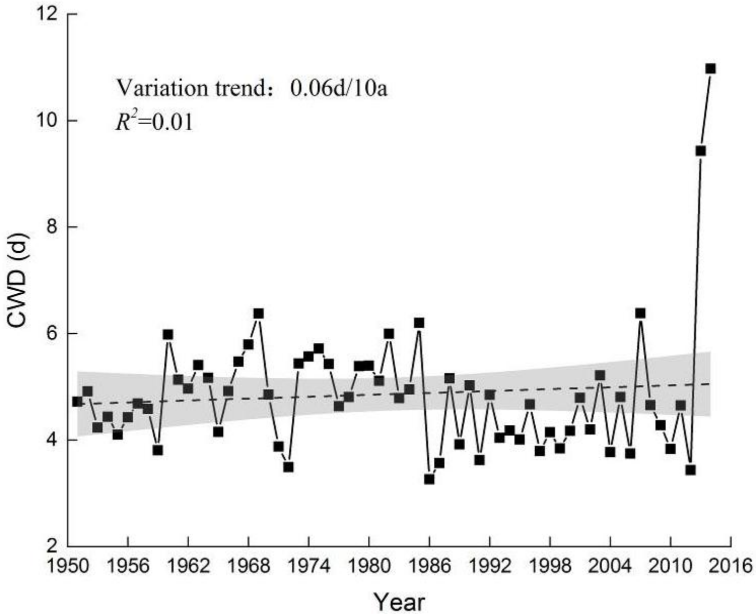

Figure 5. *Interannual variation of CWD index in Hetao area (73 stations involved)*

Stations with significant upward trend of R10mm include Bayinmaodao and Zhongwei; those with significant downward trend include Linhe, Wutaishan and Huashan (see *Fig. 6; Table 2*). Stations with significant upward trend of R20mm include Bayinmaodao and those with significant downward trend include Linhe, Wutaishan and Huashan (see *Fig. 7; Table 2*). There is no station with insignificant upward trend of R25mm; those with significant downward trend include Gaolan, Linhe and Wutaishan (see *Fig. 8; Table 2*).

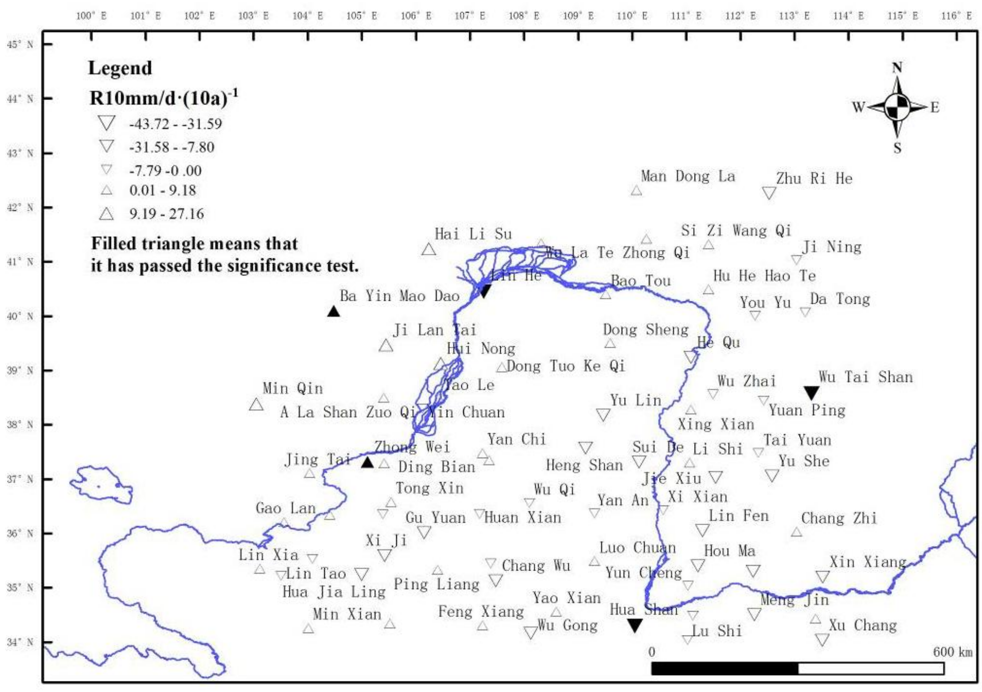

Figure 6. *Space variation of R10mm index in Hetao area*

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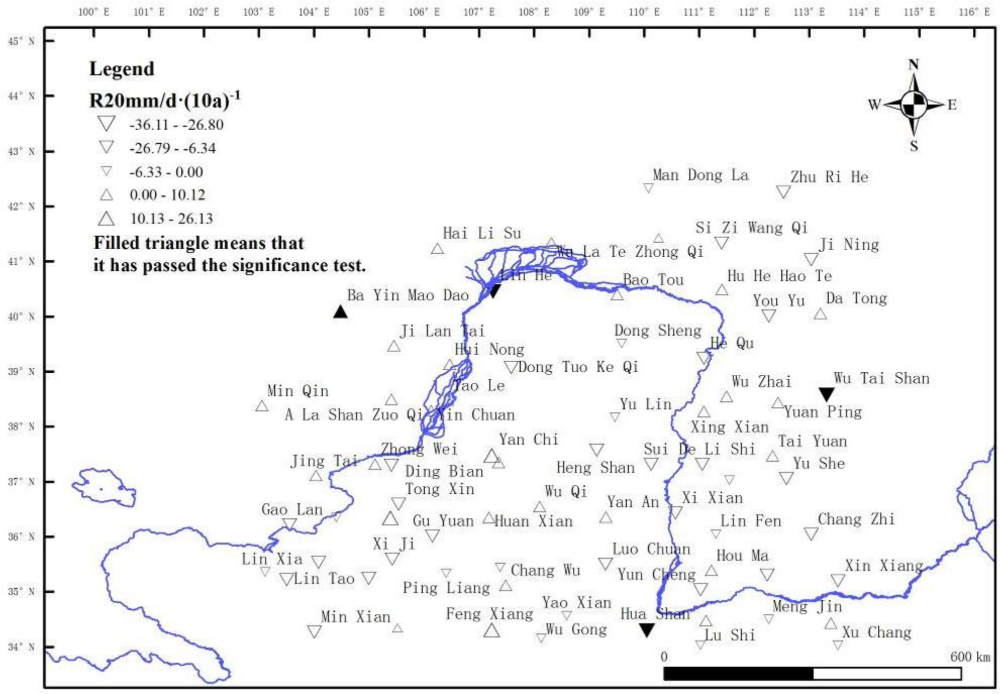

Figure 7. *Space variation of R20mm index in Hetao area*

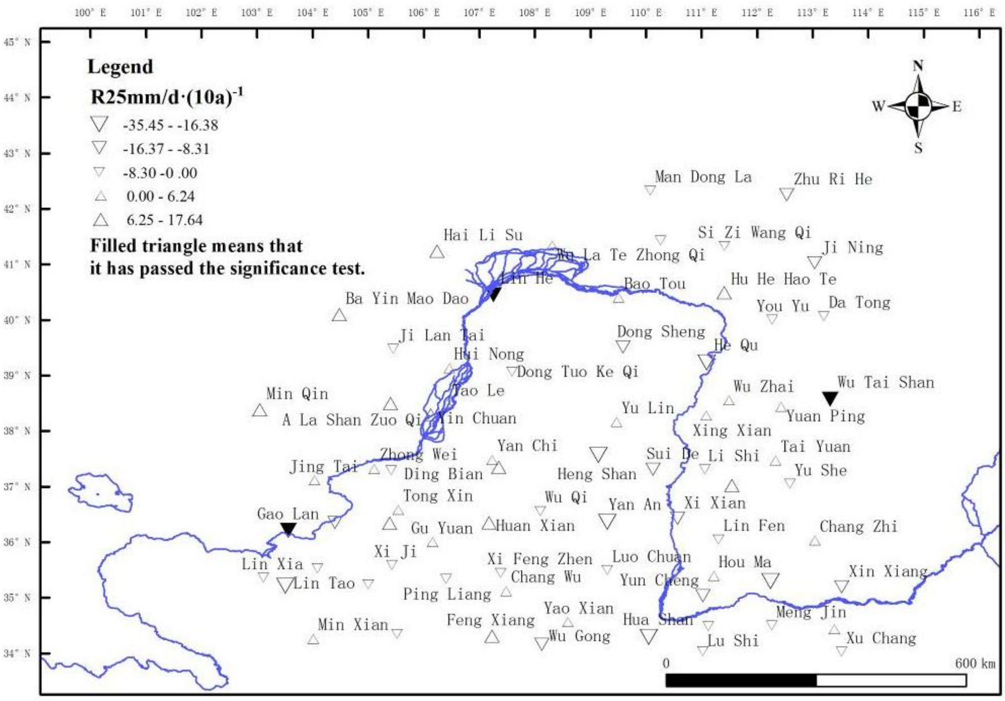

Figure 8. *Space variation of R25mm index in Hetao area*

There is an upward trend in interannual variation of the following indexes in the entire Hetao area, such as heavy precipitation days (R10mm), very heavy precipitation days (R20mm) and strong precipitation days (R25mm) (see *Figs. 9*, *10* and *11*), but the

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upward trend is not significant. On the scale of sub-regions, the variation trend is quite different in two sub-regions. The arid and semi-arid sub-region is positive while humid and semi-humid sub-region is negative (see *Table 3*).

Table 2. *Meteorological site with significant variation trend in extreme precipitation indexes*

Extreme precipitation index	Meteorological station	Variation trend (d/10a)
CWD	Lin He	-39.90*
CWD	Wu Tai Shan	-29.50*
CWD	Tai Yuan	-20.20*
CWD	Yan An	-20.10*
CWD	Lu Shi	-22.00*
R10mm	Ba Yin Mao Dao	27.16*
R10mm	Lin He	-31.59*
R10mm	Wu Tai Shan	-43.72*
R10mm	Zhong Wei	22.36*
R10mm	Hua Shan	-31.61*
R20mm	Ba Yin Mao Dao	26.13*
R20mm	Lin He	-36.11*
R20mm	Wu Tai Shan	-26.80*
R20mm	Hua Shan	-28.88*
R25mm	Gao Lan	-22.43*
R25mm	Lin He	-35.45*
R25mm	Wu Tai Shan	-21.89*

* means that it passed the 95% confidence level test

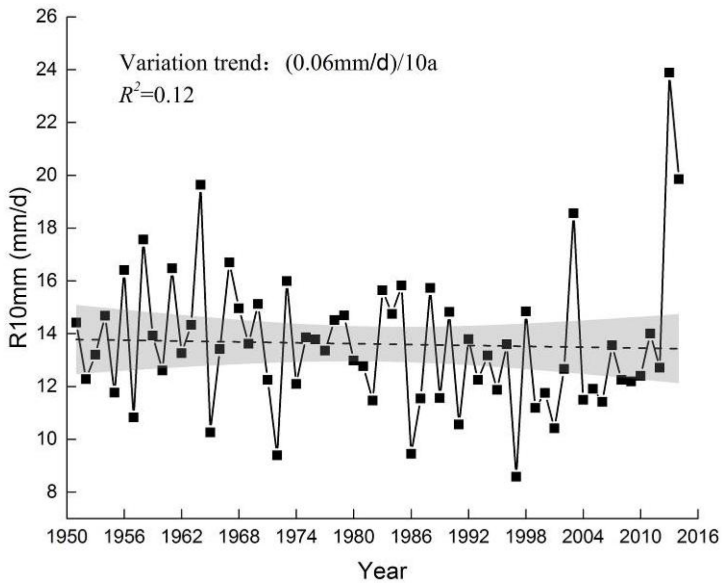

Figure 9. *Interannual variation of R10mm index in Hetao area (73 stations involved)*

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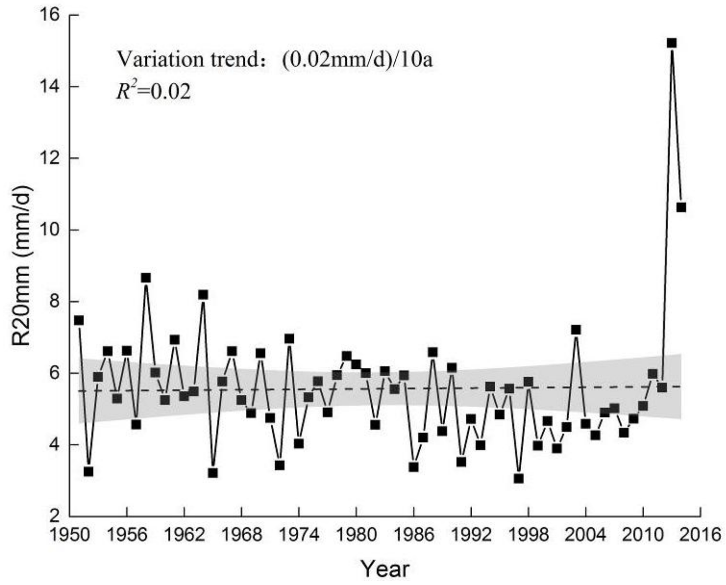

Figure 10. *Interannual variation of R20mm index in Hetao area (73 stations involved)*

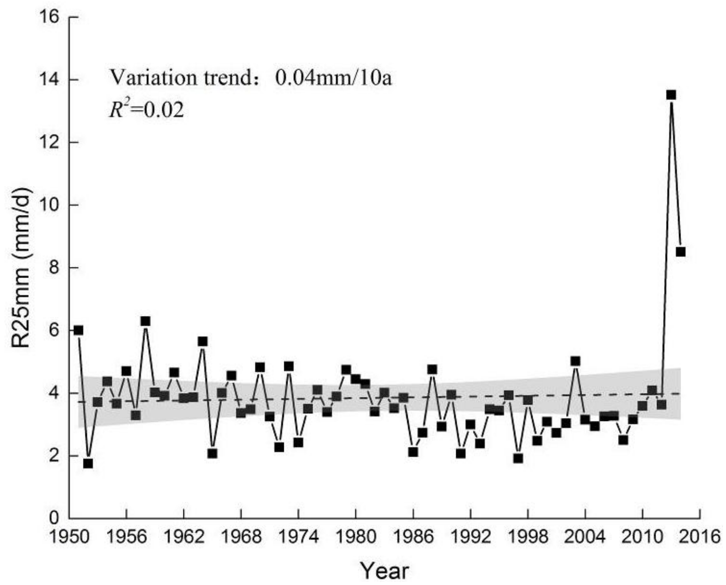

Figure 11. *Interannual variation of R25mm index in Hetao area (73 stations involved)*

Table 3. *Variation trend of extreme precipitation indexes in Hetao area from 1951 to 2014*

Extreme precipitation index	Arid and semi-arid sub-region			Humid and semi-arid sub-region		
	F-statistics	Significance	Variation trend (d/10a)	F-statistics	Significance	Variation trend (d/10a)
CWD	1.45	n.s.	0.18	0.20	n.s.	0.03
R10mm	0.04	n.s.	0.05	0.63	n.s.	-0.16
R20mm	0.77	n.s.	0.16	1.03	n.s.	-0.12
R25mm	1.18	n.s.	0.19	1.24	n.s.	-0.11

n.s. means that the variation trend is not significant

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It is analyzed in this paper that there is a significant upward trend in heavy precipitation days in Bayinmaodao, Inner Mongolia. According to the records and related literature of the local meteorological department, heavy precipitation occurred in the area in 2010, 2013, 2014, 2015 and 2016 (Sun et al., 2013; Song et al., 2015; Ma, 2016; Lv, 2015; Man, 2015; Sun, 2018; Song, 2016). In order to detect whether there is extreme precipitation event at this station, this paper analyses the decades average precipitation and dynamic precipitation averages of Bayinmaodao meteorological station (see *Tables 4* and *5*).

Table 4. *Decades precipitation averages of Bayinmaodao meteorological station*

S.N.	Decades	Average precipitation (mm/year)
1	1957-1960	91.15
2	1961-1970	80.78
3	1971-1980	114.57
4	1981-1990	96.32
5	1991-2000	112.21
6	2001-2010	123.18
7	2011-2014	131.225

Table 5. *Dynamic precipitation averages of Bayinmaodao meteorological station*

S.N.	Periods of time	Average precipitation (mm/30 years)
1	1957-1980（24 years）	95.5
2	1961-1990（30 years）	97.22
3	1971-2000（30 years）	98.99
4	1981-2010（30 years）	107.7
5	1991-2014（24 years）	122.21

Based on statistical evaluation, the upward trend of decades precipitation averages and dynamic precipitation averages passed the 95% confidence level test in Bayinmaodao.

The above four indexes illustrate the extreme precipitation events from the perspective of time duration. Based on comprehensive analysis of the variation trend of the said indexes, this paper believes that the imbalance of precipitation in Hetao area is prominent, there is an extreme trend in Bayinmaodao, but extreme precipitation events in other regions have not increased.

Variation of PRCTOT, R99p, Rx5day and SDII indexes

Stations with significant upward trend of PRCTOT include Hailinsu and Bayinmaodao; those with significant downward trend include Linhe, Wutaishan and Huashan (see *Fig. 12*). There is no station with significant upward trend of R99p, while stations with significant downward trend include Sanmenxia and Gaolan (see *Fig. 13*). Stations with significant upward trend of Rx5day include Bayinmaodao; those with

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significant downward trend include Linhe and Wutaishan (see *Fig. 14*). In addition, stations with significant upward trend of SDII include Bayinmaodao and Luochuan; station with significant downward trend is Linhe (see *Fig. 15*). Based on the comprehensive analysis of the information, it also reinforces the conclusion drawn in the preceding part of this paper that the extreme precipitation events in Bayinmaodao.

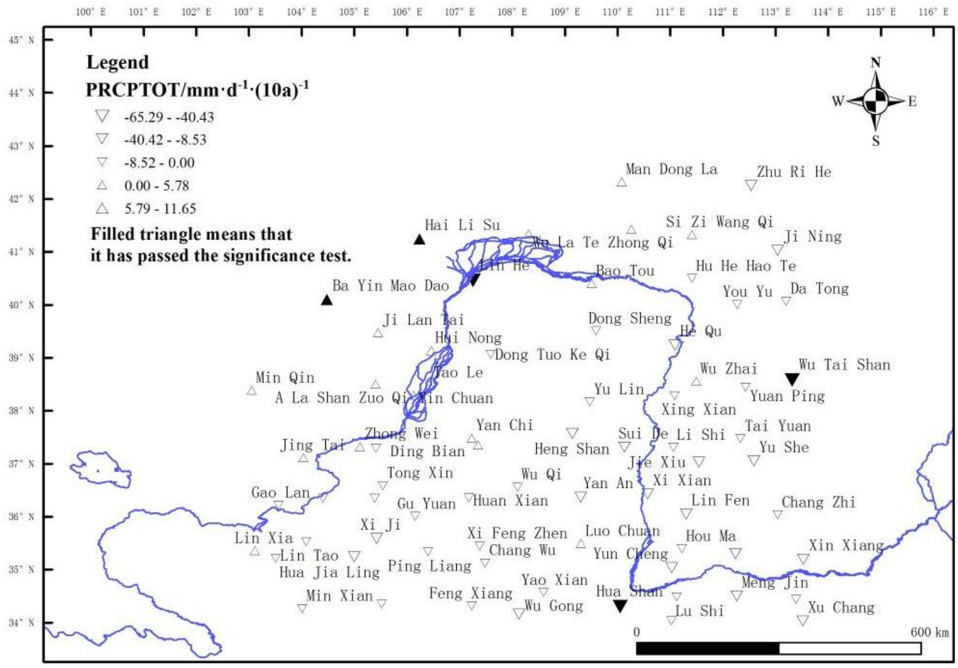

Figure 12. *Space variation of PROCTOT index in Hetao area*

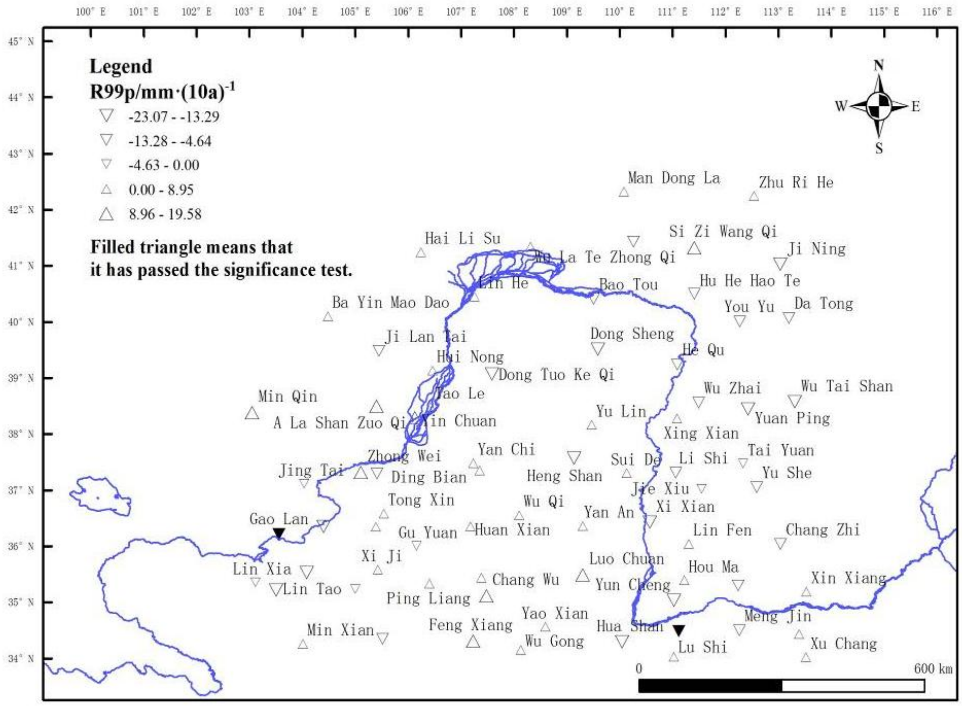

Figure 13. *Space variation of R99p index in Hetao area*

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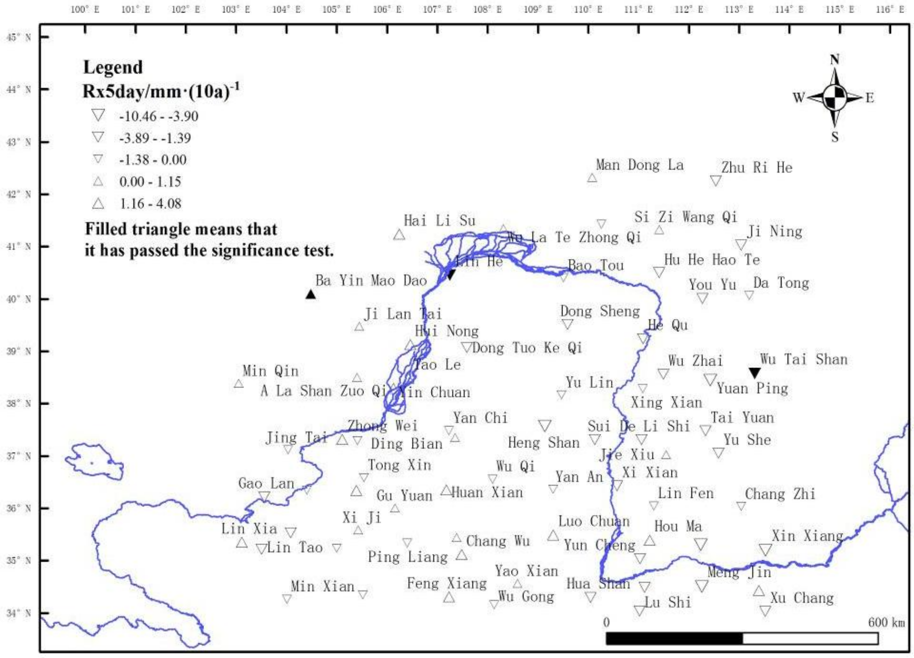

Figure 14. *Space variation of Rx5day index in Hetao area*

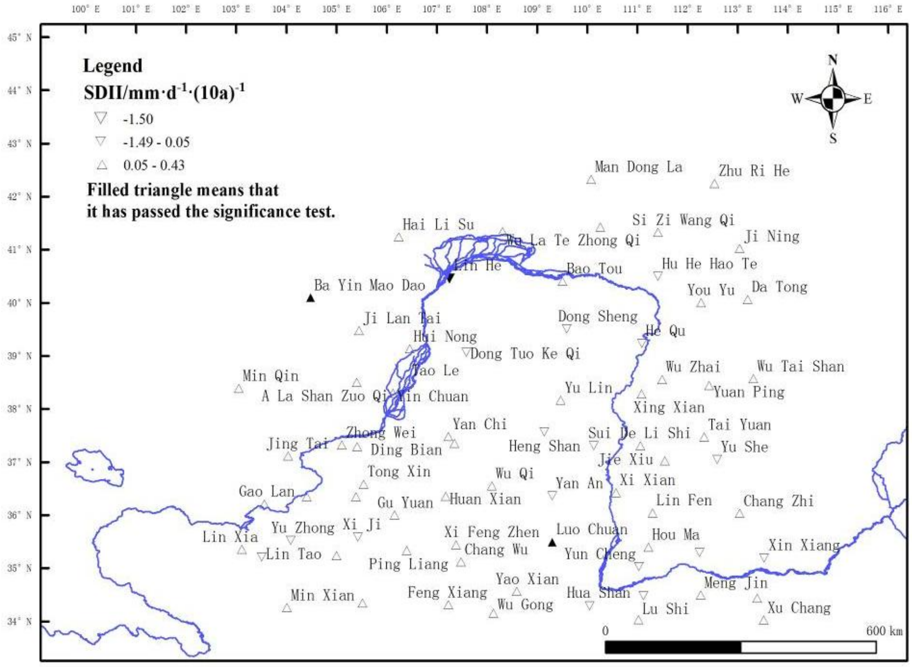

Figure 15. *Space variation of SDII index in Hetao area*

Viewed from interannual variation, the extreme precipitation events in the entire Hetao area have shown an upward trend, but it is not significant (see *Figs. 16, 17, 18, 19* and *Table 6*). However, the variation trend is different on sub-regions scale. The 4 indexes above in arid and semi-arid sub-region are positive, especially the index R99p (32.01 mm/10a) trend is significant; while the 4 indexes above in humid and semi-

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humid sub-region are negative (see *Table 6*). This highlighting that the precipitation in the entire Hetao area is spatially unbalanced.

Table 6. *Variation trend of extreme precipitation indexes in Hetao area from 1951 to 2014*

Extreme precipitation index	Arid and semi-arid sub-region			Humid and semi-humid sub-region		
	F-statistics	Significance	Variation trend (/10a)	F-statistics	Significance	Variation trend (/10a)
PRCPTOT	1.07	n.s.	18.28 mm	2.88	n.s.	-12.24 mm
R99p	4.37	*	32.01 mm	1.45	n.s.	-5.94 mm
Rx5day	0.37	n.s.	1.04 mm	0.63	n.s.	-0.43 mm
SDII	2.01	n.s.	0.26 mm/d	0.15	n.s.	-0.03 mm/d

* means that it passed the 95% confidence level test; n.s. means that the variation trend is not significant

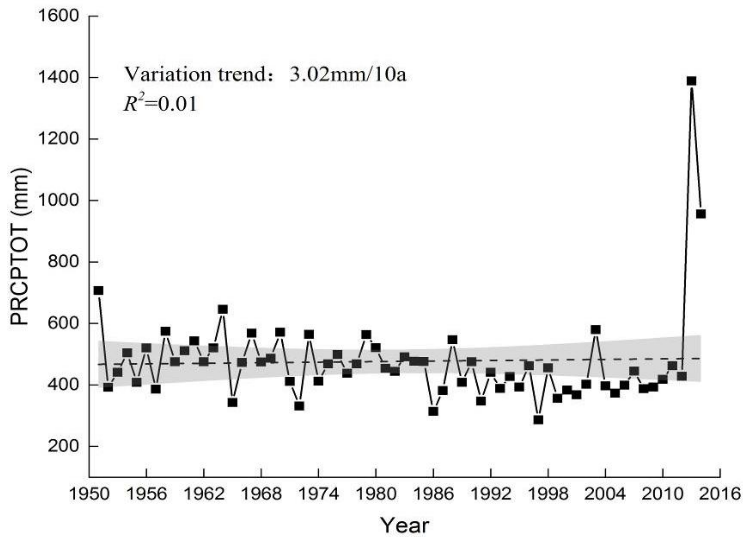

Figure 16. *Interannual variation of PROCTOT index in Hetao area (73 stations involved)*

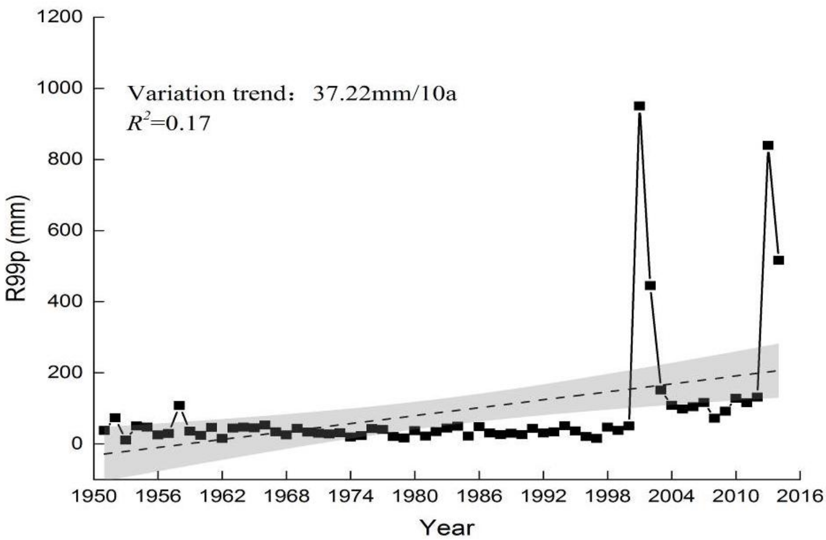

Figure 17. *Interannual variation of R99p index in Hetao area (73 stations involved)*

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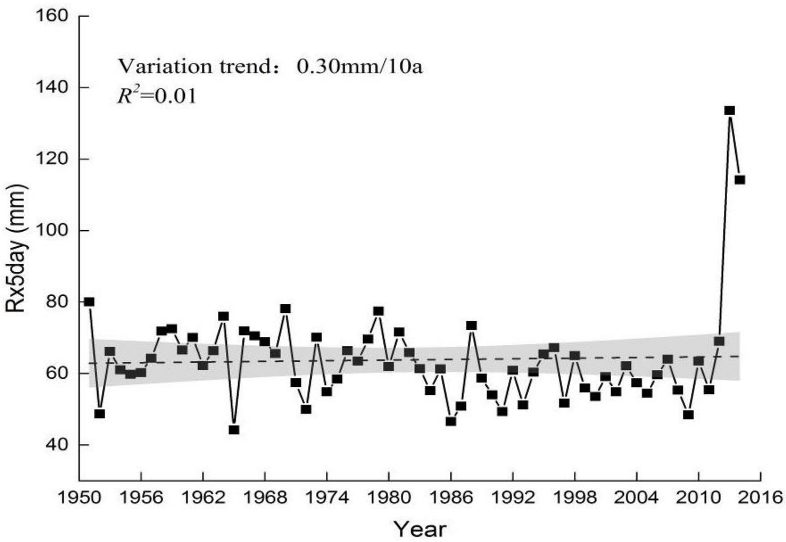

Figure 18. *Interannual variation of Rx5day index in Hetao area (73 stations involved)*

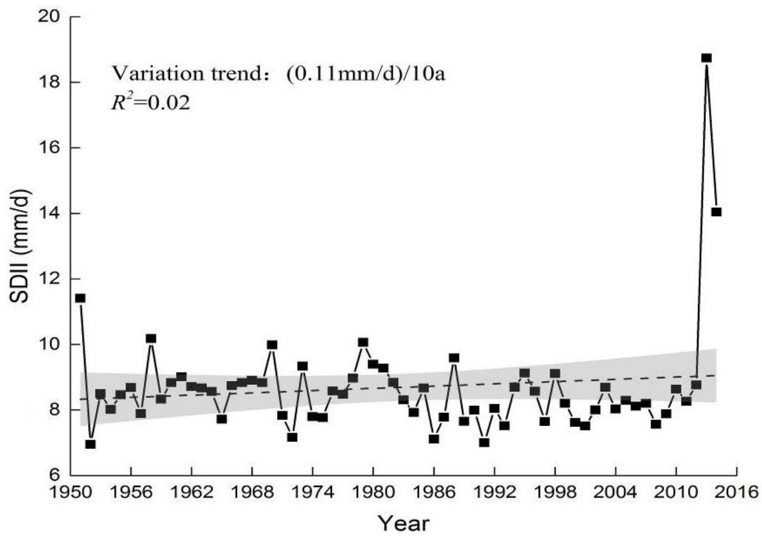

Figure 19. *Interannual variation of SDII index in Hetao area (73 stations involved)*

Conclusion

It is a focused issue for many scholars to probe into the evolution rule and its reasons of extreme precipitation events. Other studies have shown an increasing trend in extreme precipitation in China. The trend of annual precipitation changes in northwestern China showed a slight upward trend, but extreme precipitation did not increase significantly. Hetao area is located in the transitional zone of arid, semi-arid and semi-humid regions in China and is sensitive to climate change. This paper analyzes 8 extreme precipitation indexes from a temporal-spatial perspective in Hetao area China from 1951 to 2014, and comes to the following conclusions:

(1) Hetao area is located in the transitional zone of arid and semi-arid climate and humid and semi-humid climate, so the variation trend of extreme precipitation events is different in arid and semi-arid sub-region (located in the upper reaches of the Yellow

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River) and humid and semi-humid sub-region (located in the middle and lower reaches of the Yellow River), and precipitation is spatially unbalanced.

(2) Although the R99p index is a significant upward trend, the trend of other indicators is not significant. Except for the Bayinmaodao, the extreme precipitation events in Hetao area has not an obvious trend

(3) In the humid and semi-humid sub-region of Hetao area, only the variation trend of CWD index is positive, the variation trend of other 7 indices are negative. Whether this situation indicates that precipitation is decreasing is yet to be further studied.

Based on the research above, this paper draws the conclusion that the extreme precipitation events in Hetao area has not an obvious trend in the past half a century. In addition, the trend has no spatial consistency due to the trend is quite different in sub-regions. The reasons for this situation is extremely complex, and reasons for such phenomenon still need to be further studied.

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