Observed spatial pattern of summer extreme precipitation in China and its potential links to rapid urbanization

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Abstract. The variation and evolving tendency of extreme precipitation have received extensive concern worldwide in recent years under the background of global warming and rapid urbanization, which hold a great deal of significance for management of the risk of urban flood and waterlogging and water resources. The importance of anthropogenic factors represented by urbanization is recognized in the research of extreme precipitation variation, but its underlying mechanism and potential contribution remain unclear. Hence, the academic circles have not yet achieved consensus on this. Here we use daily precipitation dataset with 544 meteorological stations’ records to study spatial pattern of summer extreme precipitation and its potential response to urbanization from 1961 to 2010 in China. Frist, we gets each station’s threshold of extreme precipitation by using ordinary percentile method and the developed method named spatial sliding percentile. Then we define the proportion of extreme precipitation with total precipitation as the indicator to reflect extreme precipitation intensity. Based on the DMSP/OLS night light index dataset, the urbanization level of 544 meteorological stations are divided into six levels. Then we use ordinary percentile method, spatial sliding percentile and the developed method named spatial sliding anomaly to quantify the possible impact of urbanization on extreme precipitation threshold and intensity by doing a comparative analysis to 544 meteorological stations with different urbanization level. The results show that: The spatial pattern of extreme precipitation intensities derived from spatial sliding percentile is more distinguishable. Effects of urbanization make the threshold increased by 1.68% and there is a significant linear correlation between the average of extreme precipitation intensity and urbanization level, namely the intensity of extreme precipitation will increase by 0.62%, when the urbanization level increases by one grade. Therefore, effects of urbanization increase the risk of summer extreme precipitation of China.

1. Introduction
Along with the continuous expansion of cities, the greenhouse gas emissions increase, the land use rapidly changes, the urban heat island effect greatly increases, and the atmospheric boundary layer and suburb are markedly significant, so the climate condition of the city itself is quite different from that of the suburb under natural conditions. Urbanization undoubtedly becomes one of the main human factors that affect the climate [1-5].

In recent years, extreme heavy precipitation events occur frequently and they cause serious impact [6,7]. IPCC AR5 points out that the increase of global extreme precipitation since 1950 may be related to the natural change of climate and the joint influence of human activities, especially the rapid urbanization process in recent decades makes the emission of greenhouse gases and aerosols increase, and the land use coverage has greatly changed the natural landscape. Compared with natural climate
change and greenhouse gas emissions, aerosol and land use change have not drawn sufficient attention. The urbanization process is accompanied by the significant change of land use mode, and it will have a significant impact on the regional climate. In order to detect the climate effect of urbanization, researchers propose a series of methods. The most conventional and direct method is the urban-rural comparison method, the key of which is how to objectively classify the sites. Generally speaking, we can use population data [8] or satellite remote sensing data [9], and classify sites according to their geographical location, extract urban and rural sites, compare and analyse these two types of meteorological sites, analyse the impact of urbanization on a climate index.

As a type of small probability event, extreme precipitation event is highly unexpected and destructive, but the knowledge of its change rule and influencing factors is still insufficient, so the cause mechanism of extreme precipitation event is widely concerned [10]. As one of the factors that affect extreme precipitation, urbanization has drawn more attention of scholars at home and abroad. The metropolitan meteorological experiment conducted in the United States in the 1970s is a landmark study [11]. The further research results of this experiment show that the urban effect will increase precipitation by 5% ~ 25%, especially in the downwind area which is 50 ~ 70km far from the urban center in summer [12]. In addition, further research shows that urbanization and changes in suburban boundaries have a significant impact on the temporal and spatial changes of precipitation in urban areas [13]. Although many scholars have studied and confirmed the impact of urbanization on precipitation and extreme precipitation on a small scale, the quantitative evaluation on a large scale still lacks [11]. How to evaluate the impact of rapid urbanization on the threshold value and summer extreme precipitation intensity more accurately and reasonably, and whether there are regional differences in these impacts are the central issues of this paper.

2. Data and methods

2.1. Data Sources

The data used in this paper is mainly the daily precipitation data from 1961 to 2010 provided by the information center of China Meteorological Administration. In order to maintain the accuracy and scientificity of data analysis, this paper has made strict quality control over the data in the research. The selected sites must meet the following criteria: (1) the missing data days each year are less than 5% of the total days; (2) the duration of measured precipitation data is not less than 50 years. There are 544 sites that meet the above criteria. According to the spatial distribution of sites, the area in the east of 100°E and the south of 40°N is the intensive site area. The site density in the west and northeast of China is relatively small. This paper also selects the night light data observed by Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS). The satellite data comes from the National Geophysical Data Center, and the spatial resolution is 1km×1km. The data can detect low-intensity lights in urban areas and distinguish them from dark rural backgrounds. Therefore, DMSP/OLS night light images can be used as indicators of urbanization development level [14-16].

2.2. Calculation method

2.2.1. Sliding space percentile method

The percentile method is the most widely used method at present. For different regions, extreme precipitation events cannot be simply defined by a fixed daily precipitation. Therefore, the threshold value of extreme precipitation events in different regions can be determined according to the percentiles of daily precipitation at each site, usually it is the 95th percentile value of daily precipitation consequence. This paper focuses on the spatial difference of extreme precipitation, so the percentile method is more suitable. The common percentile method is inferred from each site as the basic unit. When studying the impact of urbanization on extreme precipitation, this method of determining the threshold cannot be used to analyze the impact of urbanization (so that the threshold value of urban sites in the same region under the same climate background is obviously different from that of non-urban
sites), so that all analysis based on this threshold value cannot reflect the impact of urbanization [17-19]. In order to avoid this problem, this paper designs a threshold value determination method based on spatial filtering, called sliding space percentile method. The following is its basic idea. Design a circular sliding window with a radius of R, and slide around each site as the center. When the site Si is taken as the center, extract all observation data of the site in the sliding window, and then the 95th percentile value is calculated as the extreme precipitation threshold value of the site Si. According to the spatial distribution of meteorological sites, if R is less than 1°, the site number in the sliding window is too small, so the statistical significance of this method is lost. Yang Xiuqun, etc. adopt this method and take R at 8°, 12° and 16° to analyse the impact of urbanization on the temperature in eastern China [20]. Therefore, through the analysis of 0.5°, 1°, 2°, 4°, 6° and 8° in advance, it is found that the selection of 2°, 4° and 6° is more reasonable. Therefore, this paper selects 2°, 4° and 6° windows for filtering to get the distribution of extreme precipitation threshold under different scales, and sets a control group, that is, compare the threshold value inferred from the conventional fixed percentile method without spatial sliding.

2.2.2. Index of extreme precipitation intensity
In order to objectively reflect the annual extreme precipitation intensity in different regions, this paper selects the percentage of extreme precipitation and total annual precipitation, which reflects the contribution of the precipitation of extreme precipitation event to total precipitation, and also reflects the relative intensity of extreme precipitation event in a region to some extent [17].

2.2.3. Determination of urban site and urbanization level
This paper defines the average night light value not less than 55 within the range of 5×5 around the picture element where the site is located as an urban site, and the site less than the threshold value as a non-urban site on the basis of the DMSP/OLS night light data in 2010 and according to the relevant research results of the impact of urbanization on the temperature [18-23] so as to avoid the impact of noise in the light data, so it can be judged whether urbanization has an impact on extreme precipitation. This paper further uses the above light data to divide the urbanization level of all sites in the country into six levels (Table 1), calculates the average extreme precipitation intensity under different urbanization levels on this basis, more effectively uses the information provided by this data, and then probes the mechanism of the impact of urbanization on extreme precipitation intensity in depth.

| Night light value | Urbanization |
|-------------------|--------------|
| [0,10)            | 1            |
| [10,20)           | 2            |
| [20,30)           | 3            |
| [30,40)           | 4            |
| [40,50)           | 5            |
| [50,63]           | 6            |

2.2.4. Sliding space anomaly
Similar to the sliding space percentile method, this paper calculates the extreme precipitation intensity according to the extreme precipitation threshold value inferred from different sliding windows, then calculates the difference (i.e. the sliding space anomaly) between the sliding center site and the mean value according to the extreme precipitation threshold value and the mean value of the extreme precipitation intensity of all sites in the sliding windows. If the center site is an urban site and the extreme precipitation threshold value of the site is positive anomaly, the extreme precipitation threshold value of the center urban site is higher than that of the surrounding non-urban sites. If the extreme precipitation intensity of the site is positive anomaly, it shows that the center urban site has a significant increase compared with the surrounding non-urban site, indicating that urbanization has a promoting effect on extreme precipitation. Apparently, the spatial heterogeneity of extreme precipitation variation at
different levels can be inferred from adjusting the window range. Assuming that the climate change of the sliding window and above is forced by large-scale natural climate, the spatial heterogeneity distribution after filtering can be attributed to the effect of local climate force on regional extreme precipitation change. This is the scientific significance of using sliding space percentile method and sliding space anomaly to analyse the impact of urbanization on extreme precipitation.

2.2.5. One-way ANOVA

ANOVA is a special hypothesis test, which can analyse the difference of many groups of data so as to judge whether there are significant differences among them. The most common method is one-way ANOVA. In this paper, one-way ANOVA method is used to compare whether the change of extreme precipitation intensity of each sliding window is significant under different urbanization levels [24,25].

3. Results and analysis

3.1. Spatial pattern of extreme precipitation threshold value based on sliding spatial percentile method

By using different sliding windows to calculate the extreme precipitation threshold value of 95% quantile, the results show that the extreme precipitation threshold values inferred from different sliding windows present the spatial distribution pattern which is "high in the southeast and low in the northwest". It is worth noting that the extreme precipitation threshold values inferred from the common percentile method (i.e. no sliding) are distributed in the southeast coastal areas in a crossing way, while the spatial differentiation pattern of the extreme precipitation threshold value inferred from different sliding windows becomes more and more obvious along with the increase of the sliding window. This distinct zonal feature shows that the extreme precipitation threshold value inferred from sliding window will lower the extreme precipitation threshold value of the original high threshold site, while the extreme precipitation threshold value of the low threshold station will rise.

3.2. Spatial pattern of extreme precipitation intensity based on sliding spatial percentile method

Fig.1a is the spatial pattern of extreme precipitation intensity determined by the usual percentile threshold method, in which the sites with the highest intensity level (Re > 40%) are mainly distributed in the northwest and southeast of China, followed by the north around Bohai Sea and the middle and lower reaches of the Yangtze River, while the extreme precipitation intensity in most areas of Qinghai, Tibet and Shandong is weak. Fig.1c is the intensity distribution chart under the extreme precipitation threshold when the sliding window radius is 4°. The sites with the highest intensity level are mainly distributed in the north around Bohai Sea, southeast coastal areas, Sichuan Basin and Yunnan-Kweichow Plateau, and it is also sparsely distributed in the middle and lower reaches of the Yangtze River and the north of Xinjiang. From the comparison of Fig.1a and Fig.1c, it can be found that the extreme precipitation intensity grades of many sites change, among which the intensity of the sites in the east of Sichuan Basin generally increases, the intensity of some sites in the southeast coastal area and the north of Bohai Sea also increases, while it increases and decreases in Xinjiang. In general, the distribution pattern of extreme precipitation intensity in Fig.1b is more distinct, and the spatial contrast between high-value area and low-value area is more significant. It can be seen that the sliding space percentile method can make the distribution of extreme precipitation intensity more regular in space, which also reflects the characteristics of spatial filtering. When the radius of the sliding window is 2° (Fig.1b) and 6° (Fig.1d), the result is very close to that of Fig.1c, which shows that the selection of the radius of the sliding window has no significant effect on the result, and also shows that the method is robust. From the comparison of the number of extreme precipitation intensity sites inferred from different sliding windows, along with the increase of sliding windows, the extreme precipitation intensity shows a trend of "decrease in the middle and increase at both ends", i.e., the number of extreme precipitation sites with low intensity and high intensity shows an increasing trend, while the number of extreme precipitation sites with medium intensity shows a decreasing trend (Table 2). Therefore, the spatial distribution pattern of extreme precipitation intensity calculated by sliding spatial percentile
method is more distinct. This distinct zonal feature is attributed to the fact that the extreme precipitation threshold value inferred from the sliding window reduces the original high threshold sites, while the low-threshold sites increase.

![Spatial pattern of extreme precipitation intensity (EPI)](image)

Table 2 Sites number change based on the extreme precipitation intensity (EPI) of different sliding windows

| EPI   | No sliding | 2° sliding | 4° sliding | 6° sliding |
|-------|------------|------------|------------|------------|
| < 0.11| 2 (0.4%)   | 23 (4.2%)  | 45 (8.3%)  | 69 (12.7%) |
| 0.12-0.19 | 63 (11.6%) | 87 (16.0%) | 106 (19.5%) | 105 (19.3%) |
| 0.20-0.25 | 161 (29.6%) | 140 (25.7%) | 134 (24.6%) | 113 (20.8%) |
| 0.26-0.32 | 222 (40.8%) | 186 (34.2%) | 134 (24.6%) | 123 (22.6%) |
| 0.33-0.39 | 81 (14.9%) | 70 (12.9%) | 78 (14.3%) | 86 (15.8%) |
| > 0.40 | 15 (2.8%) | 38 (7.0%) | 47 (8.6%) | 48 (8.8%) |

3.3. **Urbanization level spatial distribution features of meteorological sites**

According to the classification criteria in Table 1 and the DMSP/OLS night light data in 2010 in China, the horizontal distribution pattern of urbanization in China is shown in Fig.2a, basically showing a pattern of "point-polyline-polygon" of various forms. Point is reflected in the wide distribution of small and medium-sized cities all over the country. Polyline is reflected in the rapid development of cities along the main transportation roads and rivers. Polygon is reflected in the rapid development of city clusters in Beijing, Tianjin, Tangshan, Yangtze River Delta and Pearl River Delta. Then we can infer the urbanization development level of each site area. From Fig.2b, we can see that the urbanization level of a large number of sites in China is relatively high, among which the highly urbanized sites are mainly concentrated in the northeast, North China and southeast coastal areas, but there are also a considerable number of highly urbanized sites in the southwest and northwest. It can be seen from Table 3 that the meteorological sites with high-level urbanization account for 21.14% among all sites, and the sites with urbanization level of 4, 5 and 6 account for 48.35% among all sites. Thus, the monitoring records of many meteorological sites have included the impact of urbanization on climate.
3.4. Spatial differentiation of the impact of urbanization on extreme precipitation threshold value

Assuming that the extreme precipitation threshold value of sites in the area with high (low) urbanization level is high (low), the extreme precipitation threshold value inferred from sliding space percentile method will decrease (increase) the extreme precipitation threshold value of sites in the area with high (low) urbanization level. Based on this assumption, as regards the extreme precipitation threshold values calculated by different sliding window percentiles (experimental group) and ordinary percentiles (control group), this paper calculates their sliding space anomaly according to the corresponding windows of 2°, 4° and 6° respectively. The results are shown in Fig.3, among which Fig.3a, Fig.3c and Fig.3e are the sliding space anomaly calculated according to the windows of 2°, 4° and 6° in the control group, and Fig.3b, Fig.3d and Fig.3f are the sliding space anomaly calculated according to the windows of 2°, 4° and 6° in the experimental group. Compared with the results of the experimental group and the control group, it can be found that along with the increase of the sliding window, the spatial differences of the extreme precipitation threshold value space anomaly between the experimental group and the control group are more distinct, and the spatial distribution of the experimental group is better than that of the control group. But the difference is that the results of spatial space anomaly in the experimental group are far lower than those in the control group. It can be seen that the control group includes the influence of urbanization on extreme precipitation threshold value, so after adopting sliding space anomaly, most urban sites are featured by positive space anomaly, while the majority of non-urban sites are featured by negative space anomaly (Fig.3). It is worth noting that the positive anomaly is mainly concentrated in Beijing, Tianjin, Hebei and the Pearl River Delta and other areas with high urbanization level.

| Urbanization level | Site number | Proportion |
|--------------------|-------------|------------|
| 1                  | 105         | 19.3%      |
| 2                  | 92          | 16.9%      |
| 3                  | 84          | 15.4%      |
| 4                  | 74          | 13.6%      |
| 5                  | 74          | 13.6%      |
| 6                  | 115         | 21.2%      |
Figure 3 Effect of urbanization on the extreme precipitation threshold based on the spatial sliding anomaly (EPTA)

3.5. Spatial differentiation of the impact of urbanization on extreme precipitation intensity

In order to analyze the impact of urbanization on the extreme precipitation intensity, we calculate the extreme precipitation intensity of the extreme precipitation threshold value based on different sliding window percentiles (experimental group) and common percentiles (control group), and then calculate the sliding space anomaly according to the corresponding 2°, 4° and 6° windows respectively. By comparing the extreme precipitation intensity of the control group and the experimental group, it can be found that the positive space anomaly of extreme precipitation in the experimental group is significantly higher than that in the control group (Fig.4), and along with the increase of the sliding window, the regional differentiation of the positive space anomaly of extreme precipitation in the experimental group is getting better and better, especially in the Bohai Sea, the middle and lower reaches of the Yangtze River, Sichuan, Chongqing and the southern coastal areas. These areas are also the main distribution
areas of urban sites. The threshold value may decrease after the adoption of sliding window and the extreme precipitation intensity increase, which shows that urbanization greatly affects the intensity of extreme precipitation in China and increases the risk of extreme precipitation in China.

3.6. Quantitative analysis and test of the contribution of urbanization to extreme precipitation intensity

Fig.5a is the relationship between extreme precipitation intensity and urbanization level determined by the usual percentile threshold method. The extreme precipitation intensity values are relatively concentrated, i.e. the extreme precipitation intensity of sites at the middle and lower level of urbanization is the highest, but the extreme precipitation intensity of sites with high urbanization level is relatively small. From $R^2$ and $p$ values, they are 0.16 and 0.44 respectively, indicating the positive correlation between the extreme precipitation intensity and urbanization level is very weak, and it fails to pass the
test of 0.05 significance level. Fig. 5b is the relationship between the intensity under the extreme precipitation threshold value when the sliding window radius is 4° and the urbanization level. Similarly, from the R² and p values, they are 0.80 and 0.02 respectively, indicating that there is a significant linear relationship between the extreme precipitation intensity and the urbanization level (passing the significance level test of 0.05, almost passing the significance level test of 0.01). Furthermore, we also investigate that it is (0.64, 0.04) and (0.77, 0.03) respectively when the sliding window radius (R², p-value) is 2° and 6°, which also shows that there is a significant linear relationship between extreme precipitation intensity and urbanization level (Fig. 5c). Through the comparative analysis of fig. 5a and fig. 5b, it can be found that the extreme precipitation intensity inferred from the conventional percentile method is generally high, while the sliding space percentile method adopted in this paper can scientifically determine the threshold value of extreme precipitation, make it closer to the real situation, and quantitatively detect the impact of urbanization on extreme precipitation intensity at the national scale; i.e., the higher the urbanization level is, the higher the corresponding average intensity of extreme precipitation will be. From fig. 5c, it can be seen that from no sliding to sliding window at 6°, along with the increase of sliding window, the difference of extreme precipitation intensity of sites under different urbanization levels can be analyzed more and more. That is to say, compared with the ordinary percentile method without sliding, the method adopted in this paper plays a role of magnifying glass to a certain extent, making the impact of urbanization on extreme precipitation intensity closer to the real situation. Taking fig. 5b for example, when the sliding window is taken as 4°, the extreme precipitation intensity increases by 0.62% for each level of urbanization.

Meanwhile, we also use the corresponding urbanization level of each site to fit the extreme precipitation intensity. It is found that along with the increase of the sliding window, the goodness of fit is getting better and better, which further proves that the sliding space percentile method plays a significant role in detecting the impact of urbanization on extreme precipitation. In terms of the national average level, the higher the urbanization level of a region, the greater the intensity of extreme precipitation. It means that higher urbanization level will bring more extreme precipitation: when the scale of cities is expanding and the level of urbanization is increasing rapidly, the risk of extreme precipitation in urban areas will become more and more serious. This risk comes not only from the increase of exposure, but also from the increase of the intensity of disaster factors.

![Figure 5](image)

**Figure.5 Relationship between urbanization level and extreme precipitation intensity**
Through the method of one-way ANOVA, the relationship of extreme precipitation intensity under different urbanization levels is further analyzed. Fig.6a is a box plot of variance analysis with the common percentile method, which shows that the mean value of extreme precipitation intensity under six different levels of urbanization is basically between (0.25, 0.30) (Fig.6a), which fails to pass the test of significance level of 0.05, indicating that there is no significant difference in extreme precipitation intensity under different levels of urbanization; when the sliding window radius is 4° (Fig.6b), the extreme precipitation intensity of six different levels of urbanization is basically between (0.20,0.30) according to the box plot of variance analysis. Compared with fig.6a, the difference of extreme precipitation intensity increases, and it passes the test of 0.01 significance level, showing that the extreme precipitation intensity of different urbanization levels significantly differs. This shows that the extreme precipitation intensity inferred from sliding space percentile method and sliding space anomaly can better reveal the impact of urbanization on extreme precipitation intensity.

(a) ordinary percentile method                    (b) spatial sliding percentile with 4° sliding

Figure.6 The single factor variance analysis of urbanization level and extreme precipitation intensity

4. Conclusion and discussion

4.1. Conclusion
(1) On the national scale, the spatial pattern of the sliding space percentile threshold method proposed in this paper is more distinct than that of the usual percentile threshold method. China's most meteorological sites are affected by urbanization to some extent. Among the 544 selected meteorological sites, 48.35% of them are located in the middle and high level of urbanization, and less than 20% of them are less affected by urbanization.

(2) Urbanization has different effects on the spatial distribution of the threshold value and intensity of extreme precipitation, increased the risk of extreme precipitation, especially the extreme precipitation intensity in the Bohai Sea, the Yangtze River Delta and the Pearl River Delta.

(3) Nationwide, urbanization has increased the threshold value of summer extreme precipitation by 1.68%. Meanwhile, the average intensity of summer extreme precipitation has a significant linear positive correlation with the urbanization level. That is to say, the higher the urbanization level, the greater the average intensity of extreme precipitation. For each level of urbanization, the intensity of extreme precipitation increases by 0.62%.

(4) The results of variance analysis further verify that along with the increase of the sliding window, the extreme precipitation intensity in different urbanization level areas significantly differs. Along with the increase of the sliding window, the urbanization enlarges the difference of extreme precipitation intensity in different areas. Therefore, urbanization has had different effects on extreme precipitation in China, and increased the risk of extreme precipitation.

4.2. Discussion
Due to the internal instability of the climate system, climate catastrophe can be caused by the thermohaline circulation. Whether it is possible for human activities to trigger such a mutation and have disastrous consequences on human socio-economic system is an increasing concern. In the past more than 300 years, the population of the earth has increased rapidly, of which the total population of the world has increased nearly 10 times, and only in the 20th century, the global urban population has increased nearly 10 times. In 2015, more than 54.3% of the world's population lived in cities. In Africa
and Asia, 56.1% and 64.2% of the population will live in cities by 2020. Along with the continuous increase of global urban population, more and more human beings have penetrated into all spheres of the earth, especially the emergence of more and more urban agglomerations has had a profound impact on land use/land cover change. This type of change aggravates the concern that human factors may cause the instability of the earth’s climate system. The change of extreme precipitation is more sensitive to the response of natural climate factors and human socio-economic activity factors than the average precipitation, and the research on the impact of human social activities on extreme precipitation mainly focuses on the local scale. There is no consistent conclusion and knowledge on a large-scale regional scale. This paper verifies the linear correlation between the extreme precipitation intensity and the urbanization level in a statistical sense, and does not verify and analyze it from the perspective of genetic mechanism. Therefore, it is urgent to analyze extreme precipitation from the perspective of genetic mechanism. On the one hand, under the condition of given natural and man-made forcing factors, reasonably reproduce and confirm the robust signals of interannual or interdecadal changes of large-scale regional extreme precipitation. On the other hand, deepen the scientific understanding of the thermal, dynamic, cloud physics and other processes when human activities affect extreme precipitation through the model simulation. As the economic development is often accompanied by the increase of aerosol emissions, which may have a negative impact on sustainable development, the impact of land-use changes and aerosol emissions during urbanization can be verified through high-precision regional climate model simulation. On the one hand, understand the significance of climate change caused by land use and land cover change in the past to detect the temporal and spatial pattern change of extreme precipitation. On the other hand, understand the possible influence of land use and land cover evolution trend on the spatial-temporal pattern of extreme precipitation in the coming decades. These need to be further studied and discussed in the future work.

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