Study on the contribution rate of urbanization and air-sea circulation factors to the increase of rainstorm in China

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Abstract. More and more attention has been paid to the serious disasters caused by extreme precipitation events. The relationship between climate change and extreme precipitation has become the hottest science foreland issue. Based on the study of daily rainstorm observation records of 659 meteorological stations in China from 1951 to 2010, this paper shows that rapid urbanization may trigger a significant increase in large-scale rainstorm in China. The main conclusions are as follows: (1) In terms of time, China's rainstorm rainfall, rainy days and rainfall intensity increased significantly, reaching 68.71%, 60.15% and 11.52% respectively. In space, the torrential rains in China gradually migrated from the southeastern coast to the spatial transition process of gradient expansion in Central, Southwest, North, and Northeast China. (2) The variance explanations of the rapid urbanization factors to the rainstorm rainfall, rainy days and rainfall intensity in China are 61.54%, 58.48% and 65.54% respectively, while the variance explanations of the climatic factors are only 24.30%, 26.23% and 21.92% respectively. Rapid urbanization factors are likely to trigger a significant increase in rainstorm rainfall in China. (3) The panel data of China's county-level total population and the annual average of visibility days are significantly spatially correlated with rainstorm rainfall, rainy days and rainfall intensity. The correlation coefficient gradually increases with age, further indicating that rapid urbanization has triggered a significant increase in large-scale inter-decadal rainstorm in China.

1. Introduction
Under the background of global climate change, frequent extreme precipitation events have caused great harm to economic and social development, life safety, ecosystem, and have far-reaching impacts on the sustainable development of disaster areas. They have become an important factor of global and regional disasters and environmental risks, and have attracted more and more attention from academic and social circles [1-3].

From a global and regional point of view, the existing observation and research results believe that global warming has intensified surface evaporation, resulting in an increase in atmospheric water retention capacity and accelerating global and regional water circulation, which is bound to increase precipitation in some areas [4-5], of which the increase in convective precipitation is greater than that in stratiform precipitation [6]. The observational evidence since 1950 manifests that, on a global scale, the number of extreme precipitation events may increase significantly in more regions than in regions with significant decreases [7]. In the fifth IPCC report, it is pointed out that when the greenhouse gas CO2 doubles, the extreme precipitation increases significantly, and its amplitude is much larger than the average intensity of precipitation [8]. The results of climate model output prove that man-made climate forcing may have led to the enhancement of global extreme precipitation (high reliability) [4, 9], and
the increase in temperate zone is consistent, while the inter-annual variation in tropical regions is large [10]. Both observation and simulation found that the emission of greenhouse gases increased the intensity of rainstorm in two thirds of the land area in the northern hemisphere [11]. Using the simulation results of the global climate model and the regional climate model, it is found that the extreme precipitation in Europe shows an increasing trend both at present and in the future, and the proportion of the increase in the extreme precipitation in the future is larger [12]. Using WRF model simulation, it is found that under the situation of fossil fuel intensive emissions, the annual extreme precipitation in the eastern United States is much more serious than the current situation, with an increase of 107.3mm [13]. Regional Atmospheric Modeling System (RAMS) indicates that the decrease of surface vegetation in Sydney Basin in Australia affects the balance of atmospheric water and energy budget, thus contributing to the increase of rainstorm [14-16]. It should be specially emphasized that after comparing the model results with the observation results, it is discovered that the actual increase of rainstorm under climate warming is larger than the model results [11, 14].

There is no obvious change in the trend of total precipitation on a national scale in China, but the rainfall intensity is increasing [15, 17-18], and the areas suffering from abnormal precipitation events are also increasing [19]. The increase in precipitation in the Yangtze River Basin is mainly due to the increase in rainfall intensity and the increase in extreme precipitation events [20,21]; In recent years, the rainstorm rainfall and rainy days in South China have increased significantly [22,23]. The predicted results using different climate models under different scenarios state clearly that the intensity and frequency of extreme precipitation in China will increase significantly in the future, especially under the background of global warming. The extreme precipitation in most areas of China will increase. The southeast coastal area, the Yangtze River basin and the middle and lower reaches of rivers in northern China are expected to experience more extreme precipitation than now [24]. Under the condition of serious pollution, the cloud thickness in humid areas in summer can be twice as high as that in low pollution, which will lead to a significant increase in thunderstorm weather and an intensification of extreme precipitation events [25].

It is worth noting that the temporal and spatial patterns and changes of inter-decadal rainstorm in China are not consistent with the warming of temperature, nor can they be reasonably explained by atmospheric and oceanic dominant climatic factors. The statistical analysis indicates that the human factors marked by rapid urbanization are likely to be the main driving factors for the significant increase of rainstorm rainfall in China from 1951 to 2010.

2. Data and methods

2.1. Data Sources
The precipitation data used in this paper are from the daily precipitation of 659 meteorological stations from 1951 to 2010 in the ground meteorological data database of China Meteorological Science Data Sharing Service Network. The natural climatic factors such as WPSH, ENSO, AMO and AAO used in the paper are from NOAA and China National Climate Center (74 circulation index). Atmospheric precipitable water and vapor flux data come from NCEP/NCAR reanalysis data from 1971 to 2010 and ECMWF reanalysis data from 1961 to 2010. Visibility data from 1957 to 2005 come from the daily data compiled by the meteorological science research institute of the China meteorological administration, and are all processed into annual average of visibility days less than 10km. The data used in this paper, such as GDP, GDP2 and Urban Population (UP), are from “Sixty Years of New China Statistics” and “Summary of Social and Economic Statistics of China's Counties (Cities)”. The annual average Haze Day (HD) comes from China National Meteorological Information Center.

2.2. Calculation method
In this study (a), firstly, China is regarded as a point. According to the daily precipitation data of 659 stations, the annual and inter-decadal rainstorm rainfall, rainy days and rainfall intensity in China are calculated. Secondly, China is regarded as a surface, and the spatial distribution map of inter-decadal
rainstorm rainfall, rainy days and rainfall intensity is drawn. (b) Firstly, using stepwise regression [26] to screen out the factors that have influence on the rainstorm in China; Secondly, Granger causality test [27] is used to test the importance of screening factors. Thirdly, the variance interpretation rate based on multiple linear regression [28] is used to calculate the variance contribution rate of each rainstorm factor to rainstorm rainfall, rainy days and rainfall intensity. Finally, the spatial correlation analysis [29] is used to make the annual average of the county-level total population and visibility days related to the spatial and rainy rainfall, rainy days and rain intensity. The method of variance interpretation rate based on multiple linear regression is as follows:

For the normalized sequence, a multiple linear regression equation is established according to the multiple regression theory:

\[ \hat{Y}_i = b_1X_{1i} + b_2X_{2i} + b_3X_{3i} + b_4X_{4i} + b_5X_{5i} + b_6X_{6i} \]

Where \( i = 1, ..., n, n = 60 \) years, \( b_1, ..., b_6 \) is the regression coefficient. It can be proved that:

\[ c^2 = b_1r_1 + b_2r_2 + b_3r_3 + b_4r_4 + b_5r_5 + b_6r_6 \]

Where \( r_1, r_2, r_3, r_4, r_5 \) and \( r_6 \) are the correlation coefficients of rainstorm with WPSH, ENSO/AMO, AAO, GDP2, UP and HD respectively. Where \( c \) is a multiple correlation coefficient, the left represents the interpretation rate of six factors to the rainstorm variance in China, and the right represents the independent contribution of each factor to the rainstorm variance in China.

3. Results and analysis

3.1. Temporal and spatial pattern change of rainstorm in China

From 1951 to 2010, China's rainstorm rainfall and rainy days increased significantly, and the rainfall intensity also showed upward trend. And the increasing speed of each stage is not uniform, indicating a three-stage change characteristic of "rapid increase-slow increase-rapid increase". Comparing 2001-2010 with 1951-1960, the rainstorm rainfall, rainy days and rainfall intensity increased by 68.71%, 60.15% and 11.52% year on year. In space, from 1951 to 2010, China's accumulated inter-decadal rainstorm rainfall, rainy days and rainfall intensity showed a gradual process of gradient expansion from the southeast coast to central, southwest, north and northeast China, especially the steady inter-decadal expansion of rainfall and rainy days. In 2001-2010, compared with 1951-1960, among 659 stations, 555 stations, 555 stations, 555 stations and 359 stations increased the accumulated rainstorm rainfall, rainy days and rainfall intensity in the inter-decadal period respectively, accounting for 84.22%, 84.22% and 54.48% of the total station points respectively, showing the characteristics of large-scale increase of accumulated rainstorm in the inter-decadal period.

3.2. Variance interpretation rate of contribution of rainstorm factor to rainstorm

3.2.1. Stepwise regression screening of rainstorm factors

Regional precipitation is affected by many climatic factors such as atmosphere and ocean. We have selected twenty-nine natural climatic factors that have an impact on precipitation in East Asia and eleven human factors that represent China's urbanization development. Through stepwise regression analysis, from forty natural climatic factors and human factors affecting the rainstorm in China, the factors related to the rainstorm rainfall in China and less than 0.05 significant level were eliminated, thus seven rainstorm significant correlation factors are selected, namely four natural climatic factors including WPSH (Western Pacific Subtropical High), AMO (Atlantic Multi-decadal Oscillation), AAO (Antarctic Oscillation), and three rapid urbanization factors including GDP2, UP and HD. In order to reveal the causes of the continuous increase of rainstorm rainfall, rainy days and rainfall intensity in China from 1951 to 2010, correlation analysis was made between the above seven rainstorm factors and rainstorm rainfall, rainy days and rainfall intensity respectively, and significant correlation was found between them. Rainstorm rainfall, rainy days and rainfall intensity have negative correlation with AMO to varying degrees, but have positive correlation with WPSH, ENSO, AAO, GDP2, UP and HD to varying
degrees. The correlation between human factors represented by rapid urbanization and rainstorms is very high, reaching a significance level of 0.01 for 100%. The correlation level between natural climatic factors and rainstorm rainfall and rainy days is low, accounting for only 66% of the 0.01 significance level. The correlation level between natural climatic factors and rainstorm rainfall intensity is even lower, accounting for only 33% of the 0.01 significance level.

3.2.2. Granger causality test explanation of rainstorm factor to rainstorm
In order to further reveal the explanation degree of human and natural rainstorm rainfall influencing factors on the increase of rainstorm rainfall in China, we conducted Granger causality test with rainstorm rainfall, rainy days and rainfall intensity in China respectively. The results demonstrate that: nine human factors for rainstorm rainfall, rainy days and rainfall intensity all passed the test with significance level of 0.01, while only four natural climatic factors passed the test with significance level of 0.01, five passed the test with significance level of 0.05, and three failed the test with significance level of 0.05. It can be seen that a single human factor can explain the increase of rainstorm more than a single natural climatic factor, and the overall explanation degree of human factor for the increase of rainstorm in China is better than that of natural climatic factor.

In order to quantitatively analyze the contribution of rainstorm factors to the increase of rainstorm rainfall, rainy days and rainfall intensity in China, we use variance interpretation rate based on multiple linear regression to characterize the contribution of each rainstorm factor. The results show that the overall interpretation rates of the screened human factors and natural climatic factors for the variance of rainstorm rainfall, rainy days and rainfall intensity are 85.84%, 84.71% and 87.46% respectively, and the human factors are the main ones. Their interpretation rates for the variance of rainstorm rainfall, rainy days and rainfall intensity are 61.54%, 58.48% and 65.54% respectively, accounting for 71.69%, 69.04% and 74.94% of the total variance interpretation rate. The natural climatic factors are supplemented, and their variance interpretation rates for rainstorm are 24.30%, 26.23% and 21.92%, respectively, accounting for only 28.31%, 30.96% and 25.06% of the total variance interpretation rates. Among the human factors, HD has variance interpretation rates of 25.93%, 22.98% and 26.64% for rainstorm rainfall, rainy days and rainfall intensity, which are almost equivalent to the sum of natural climatic factors and the variance interpretation rates of rainstorm, accounting for 42.14%, 33.24% and 40.65% of the variance interpretation rates of human factors, and accounting for 30.21%, 27.13% and 30.46% of the total variance interpretation rates. Thus, HD is the dominant factor in human factors.

3.3. Spatial correlation analysis on panel data of rainstorm and annual average of county population and visibility days
In order to quantitatively analyze the spatial change process of China's rainstorm rainfall, rainy days and rainfall intensity gradually expanding from the southeast coast to central, southwest, north and northeast China in recent decades, we used the county-level population panel data as the replacement data of the underlying land use pattern for China's total population in different years and the annual average of visibility days less than 10km. The annual average of visibility days less than 10km are used as substitute data for pollution emission, and their spatial correlation with China's inter-decadal rainstorm is analyzed respectively. The results show that the correlation between China's inter-decadal rainstorm rainfall, rainy days and rainfall intensity and the county-level total population and visibility days with annual average of value less than 10km increase continuously with the passage of time. Namely, the county-level total population increases from 0.35, 0.36, 0.40 to 0.54, 0.55 and 0.58 respectively, and the annual average of visibility days increases from 0.36, 0.38 and 0.48 to 0.55, 0.57 and 0.58 respectively. This result also indicates that the human factors represented by rapid urbanization may play a decisive role in the increase of large-scale rainstorm in China.

4. Conclusion and discussion

4.1. Conclusion
During 1951-2010, China's inter-decadal rainstorm rainfall, rainy days and rainfall intensity increased significantly, with increases of 68.71%, 60.15% and 11.52% respectively, and the number of stations increased by 84.22%, 84.22% and 54.48% respectively, showing a time-varying process of "rapid-slow-rapid increase" and a spatial change process of gradual expansion from the southeast coast to the central, southwest, north and northeast regions.

Rapid urbanization factors including GDP2, UP and HD are likely to be the main reasons for the increase of large-scale rainstorms in China. Their variance explanations for rainstorms, rainy days and rain intensities in China are 61.54%, 58.48% and 65.54% respectively. Among them, the variance explanations of haze to rainstorm rainfall, rainy days and rainfall intensity are as high as 25.93%, 22.98% and 26.64%, respectively, while the variance explanations of climatic factors including WPSH, ENSO, AMO and AAO are only 24.30%, 26.23% and 21.92%, respectively. Compared with the forcing factors of rapid urbanization, the impact of these climatic factors is only 1/3 of the former.

(3) The panel data of China's county-level total population and the annual average of visibility days are significantly correlated with China's inter-decadal rainstorm rainfall, rainy days and rainfall intensity, and their spatial correlation coefficients gradually increase from 1951-1960 to 2001-2010. Namely, the county-level total population increases from 0.35, 0.36, 0.40 to 0.54, 0.55, 0.58 respectively, and the annual average of visibility days increases from 0.36, 0.38, 0.48 to 0.55, 0.57, 0.58 respectively. It is further indicated that rapid urbanization has triggered a significant increase in large-scale inter-decadal rainstorm in China.

4.2. Discussion

The increase of rainstorm rainfall in China from 1951 to 2010 is the result of the combined action of human factors, represented by rapid urbanization, supplemented by natural climatic factors, and under the background of global climate change. Regional atmospheric precipitable water vapor flux and precipitable water vapor flux have certain influence on regional precipitation, however, they cannot fully explain the changes of rainstorm rainfall, rainy days and rainfall intensity in China. We compared the ratio of process rainstorm (continuous for 2 days or more) and convective rainstorm in different years in China. The results show that the ratio of total rainstorm rainfall to total rainfall in 2001-2010 increased by 7.68% compared with 1951-1960, and the ratio of total rainstorm rainfall to total rainfall increased by 0.73%. Among them, the proportion of convective rainstorm rainfall to the total rainstorm rainfall increased by 3.66%, and the proportion of rainstorm days to the total rainy days increased by 3.17%. At the same time, the proportion of process rainstorm rainfall to the total rainstorm rainfall decreased by 3.66%, and the proportion of rainy days to the total rainstorm days decreased by 5.18%. Therefore, it is difficult to explain the increase of rainstorm rainfall, rainy days and rainfall intensity in China with natural climatic factors such as atmosphere and ocean. Human factors must be considered. From 1951 to 2010, China's industrial structure underwent major changes. The proportion of primary industry, secondary industry and tertiary industry grew at an average annual rate of -0.66, 0.46 and 0.20 percentage points, while the proportion of secondary industry and tertiary industry grew fastest at an average annual rate. The output value of China's secondary and tertiary industries grew at an average annual rate of 13.16% and 14.42% respectively. Major changes in China's industrial structure have promoted rapid urbanization.

In order to intuitively express the temporal correlation between human factors and natural climatic factors and rainstorm rainfall, rainy days and rainfall intensity, weighted by the interpretation rate of each factor variance, we synthesize the normalized rainstorm factors according to the weight and draw scatter plots with rainstorm rainfall, rainy days and rainfall intensity respectively. The results demonstrate that there is a good correlation between human factors and rainstorm rainfall, rainy days and rainfall intensity in time series. The correlation between human factors and rainstorm rainfall, rainy days and rainfall intensity is better than that of natural climatic factors. Namely the correlation between human factors and natural climatic factors and rainstorm rainfall, rainy days and rainfall intensity are 0.8964, 0.8659, 0.9129 and 0.3641, 0.4043 and 0.4043 respectively; Moreover, the synchronization in
time sequence is better than that of natural climatic factors. The synchronization between comprehensive human factors and comprehensive natural climatic factors and rainstorm intensity is obviously higher than rainstorm rainfall and rainy days. Although there are certain similarities between the comprehensive natural climatic factors and the rainstorm changes, the synchronization between the human factors and the rainstorm changes is more significant and plays a leading role. This further illustrates that human factors such as urbanization have played a decisive role in the increase of rainstorm rainfall in China.

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