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Does Rapid Urbanization Trigger Significant Increase of Cumulative Heavy Rains in China?

Feng KONG *

School of Public Policy and Management of Tsinghua University, Beijing 100084, China; Center for Crisis Management Research, Tsinghua University, Beijing 100084, China; China Meteorological Administration Training Centre, Beijing 100081, China

Abstract Severe disasters caused by extreme precipitation events have attracted more and more attention. The relationship between climate change and extreme precipitation has become the hottest scientific frontier issue. The study of daily torrential rain observations from 659 meteorological stations in China from 1951 to 2010 shows that rapid urbanization may have triggered a significant increase in heavy rains in China. It reached following conclusions: China's interdecadal heavy rainfall amount, rainy days and rain intensity increased significantly, with an increase of 68.71%, 60.15% and 11.52%, respectively. The increase in the number of stations was 84.22%, 84.22% and 54.48%, respectively. It showed time change of "rapid-slow- rapid increase" and spatial change of gradual increase from southeastern coast to central China, southwest, north China, and northeastern regions. Rapid urbanization factors, including secondary industry output (GDP2), urban population ratio (UP), annual average haze days (HD), are likely to be the main causes of the increase in heavy rains in China. Their explanations of the variance of heavy rainfall amount (HRA), rainy day (RD) and rain intensity (RI) in China reached 61.54%, 58.48% and 65.54%, respectively, of which only the explanation of variance of heavy rainfall amount, rainy days and rain intensity was as high as 25.93%, 22.98% and 26.64%, respectively. However, explanation of variance of climatic factors including WPSH (West Pacific Subtropical High), ENSO (El Niño – Southern Oscillation) AMO (Atlantic Interdecadal Oscillation), and AAO (Antarctic Oscillation) was only 24.30%, 26.23%, and 21.92%, respectively. Compared with the rapid urbanization forcing factor, the impact of these climatic factors was only one third of the former. The panel data of China's county-level total population and annual average of visibility days were significantly correlated with China's interdecadal heavy rainfall amount, rainy days and rain intensity. Their spatial correlation coefficient increased gradually from 1951 – 1960 to 2001 – 2010, that is, the total population of the county level increased from 0.35, 0.36, and 0.40 to 0.54, 0.55, and 0.58, respectively. The annual average of visibility days increased from 0.36, 0.38, and 0.48 to 0.55. 0.57, 0.58, further indicating that rapid urbanization triggered a significant increase in interdecadal large-area heavy rains in China.

Key words Cumulative heavy rain, Human activities, Urbanization, Triggering factors, Spatial and temporal pattern, China

1 Introduction

In recent decade, frequent occurrence of haze in China has attracted wide attention. Besides, many places were hit by heavy rains, causing floods in many urban areas, causing casualties, property damage, and serious damage to ecosystems. The extremely heavy precipitation events that occur frequently in the context of global climate change have caused great harm to economic and social development, life safety and ecosystems, and have far-reaching impact on the sustainable development of disaster areas. They have become important factors for global and regional disasters and environmental risks, and attract wide attention of both the academics and society[1 – 3]. From the global and regional perspectives, the existing findings indicate that global warming has increased surface evaporation, resulting in increased atmospheric water retention capacity and accelerated global and regional water cycles, which will inevitably lead to increased precipitation in some areas[4 – 5], of which the increase in convective precipitation was greater than that of stratiform precipitation[6]. Observation data since 1950 indicate that on a global scale, there may be more areas with a significant increase in the number of extremely heavy precipitation events than in areas with significant reductions[7]. According to the fifth report of Intergovernmental Panel on Climate Change (IPCC), when greenhouse gas CO_2 doubles, extremely heavy precipitation will significantly increase, which is much larger than the average intensity of precipitation[8]. According to results of climate model output, anthropogenic climate forcing may have led to the strengthening of global extreme precipitation (high confidence)[4,9], and the increase in temperate regions is consistent, while the inter-annual variation is greater in tropical regions[10]. Both observations and simulations showed that greenhouse gas emissions have resulted in an increase in the heavy rain intensity in two-thirds land areas of the northern hemisphere[11]. The simulation results using both global and regional climate models have found that extreme precipitation in Europe shows an increasing trend both at present and in the future, and the proportion is greater for the increase of extreme precipitation[12]. Using the Weather Research and Forecasting (WRF) model simulation, it is found that in the case of intensive fossil fuel emissions, the annual extreme precipitation in the eastern United States is much more serious than the present situation, increasing about 107.3 mm[13]. The Regional Atmospheric Modeling System (RAMS) indicates

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* Corresponding author. E-mail: kongfeng0824@foxmail.com

that the reduction of surface vegetation in the Sydney Basin in Australia affects atmospheric water and energy balance, thus promoting the increase in heavy rain[14-16]. It is important to emphasize that after comparing the model results with the observations, it is found that the actual increase in heavy rain under climate warming is greater than the model results[11, 14].

The change of total precipitation on China's national scale is not obvious, but the heavy rain intensity is increasing[15, 17-18], and the areas suffering from extremely heavy precipitation events are also increasing[19]. The increase in precipitation in the Yangtze River Basin is mainly due to the increase of precipitation intensity and the increase of extremely heavy precipitation events[20-21]; in recent years, both the heavy rainfall amount and rainy days in South China show significant increase[22-23]. The results predicted by different climate models in different cases show that there is a significant increase in the intensity and frequency of extreme precipitation in China in the future, especially in the context of global warming, extreme precipitation is showing an increasing trend in most parts of China. In the southeastern coastal areas, the Yangtze River Basin and the middle and lower reaches of the northern Chinese rivers may experience more extreme precipitation than the present[24]. In the humid region, the cloud thickness in summer is twice as high as that in the case of low pollution, which leads to a significant increase in thunderstorm weather and an increase in heavy precipitation events[25]. It should be noted that the temporal and spatial patterns and changes in the interdecadal heavy rains in China are not consistent with the warming of the temperature, and they can not be reasonably explained by the atmospheric and ocean-dominated climatic factors. According to our statistical analysis, the human factor marked by rapid urbanization is most likely the main driving factor for the significant increase in heavy rains in China from 1951 to 2010.

2 Data and methods

2.1 Data source The precipitation data used in this study were selected from the daily precipitation of the year 1951 – 2010 of 659 meteorological stations in the surface meteorological data database of China Meteorological Science Data Sharing Service Network. The natural climatic factors such as WPSH, ENSO, AMO and AAO used in this study were selected from NOAA and China National Climate Center (74 circulation indices). Atmospheric precipitable water and water vapor flux data were obtained from National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR) reanalysis data from 1971 – 2010 and European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis data from 1961 to 2010. Visibility data (1957 – 2005) were selected from the daily value data compiled by Chinese Academy of Meteorological Sciences of the China Meteorological Administration and processed into the annual average number of days with visibility < 10 km. The data used in this study, such as gross national product (GDP), secondary industry output (GDP2), and urban population (UP), were obtained from *China Compendium of Statistics 1949 – 2008 and China County Statistical Yearbook*; the annual average number of haze days (HD) were obtained from the China National Meteorological Information Center.

2.2 Calculation methods (i) We first took China as a point. According to the daily precipitation data of 659 stations, we calculated the interannual and interdecadal heavy rainfall amount, heavy rain days, heavy rain intensity in China. Secondly, we took China as a plane and plotted interdecadal spatial distribution map of heavy rainfall amount, heavy rain days, heavy rain intensity. (ii) Firstly, we used the stepwise regression to screen out the factors that have an impact on heavy rains in China. Secondly, we used Granger causality test to test the importance of the selected factors. Then, we used the variance explanation rate based on multiple linear regression to calculate the contribution rate of variance of heavy rainfall amount, rainy days, and rain intensity. Finally, we carried out the spatial correlation analysis on the county-level total population and visibility days, heavy rainfall amount, rainy days and rain intensity. The specific methods are as follows.

2.2.1 Stepwise regression. In the process of establishing multiple regression equations, the independent variables were introduced into the equation one by one according to the order of partial correlation coefficients, and the partial correlation coefficient of each independent variable in the introduced equation was statistically tested. The independent variables with significant effect were kept in the regression equation. In this way, the next independent variable was selected. At present, stepwise regression method has been widely applied in meteorology[26]. We carried out the stepwise regression of 40 heavy rain factors and China's interannual heavy rainfall amount, rainy days and rain intensity, including 29 natural climate factors proposed by the IPCC that have an impact on precipitation and 11 human social economic activity factors with the urbanization development as the representative. When the probability value of the heavy rain factor is less than 0.05 (confidence greater than 95%), it would be introduced into the model, and when it is greater than 0.1 (confidence less than 90%), it would be excluded from the model.

2.2.2 Granger causality test. The Granger causality test relies on the variance predicted by the best least squares using all the information at some point in the past. In a given information set I including the variable X and the variable Y, if the other conditions are the same, if the value before the variable X is introduced at the time t, the Y_{t+1} can be predicted better than that of non-introduction, we call the variable X is the Granger cause for the variable Y. In this study, Y is the heavy rain, and X is an influence factor explaining the heavy rain. Firstly, we examined the extent to which the current value of Y can be explained by its lag value, and then examined whether the added X one by one can enhance the explanation of heavy rain. If it can enhance the explanation, it will be deemed that X could cause Y. In this study, we classified the importance factors by the significance levels of 0.05 and 0.01, respectively. Kaufmann employed this method to test the effect of human action on the temperature of the northern and southern hemispheres[27].

2.2.3 Variance explanation rate based on multiple linear regression. For the normalized sequence, we established a multiple linear regression equation 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 $i = 1, \cdots, n$, $n = 60$ years, $b_1, \cdots, b_6$ are regression coefficients; r_1, r_2, r_3, r_4, r_5, and r_6 are correlation coefficients between heavy rain and WPSH, ENSO/AMO, AAO, GDP2, UP and HD. It can be proved that:

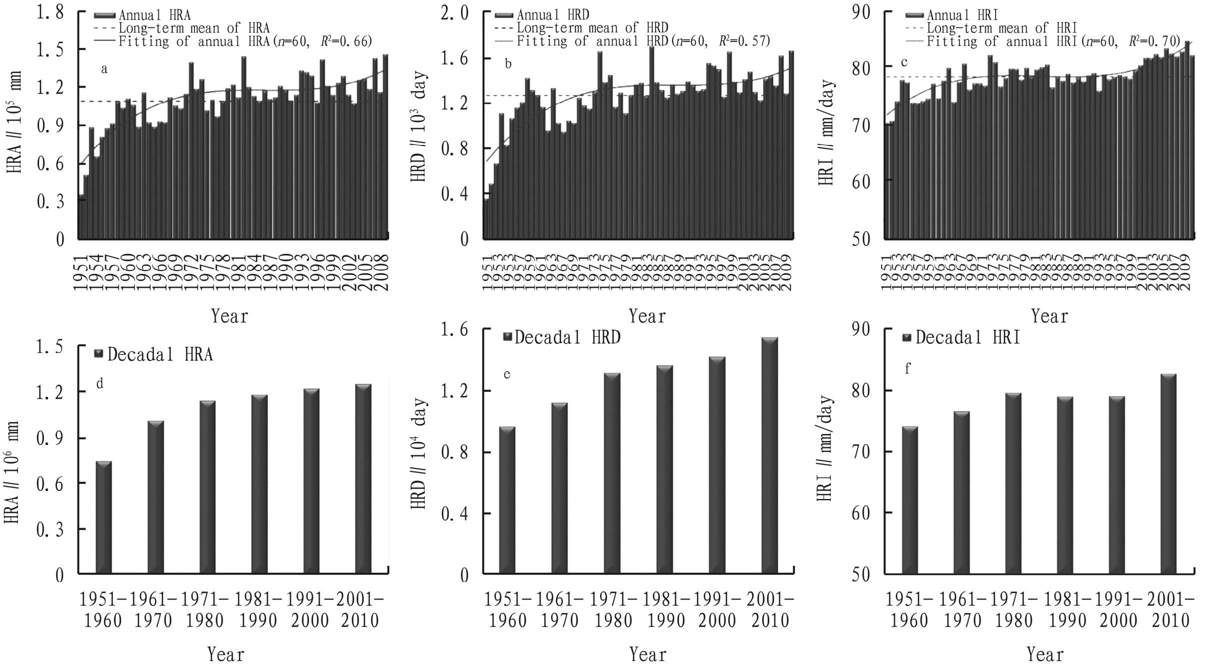
$$c^2 = b_1r_1 + b_2r_2 + b_3r_3 + b_4r_4 + b_5r_5 + b_6r_6$$

where c denotes the complex correlation coefficient, the left side represents the explanation rate of the six factors for the variance of heavy rain in China, and the right side is the independent contribution of each factor to the heavy rain variance. Using this method, Huang Jianbin *et al.* [28] analyzed the contribution of different atmospheric oscillations to the global low-level atmospheric circulation from 1958 to 1998.

2.2.4 Spatial correlation analysis. Spatial correlation analysis generally adopted panel data to determine the extent to which one or more variables are spatially correlated. The panel data based spatial correlation analysis has been widely applied[29]. Through spatial correlation analysis, it is able to quantitatively describe the spatial interdependence between multiple variable observation data. If the value of a variable becomes more similar as the distance measured by another variable becomes smaller, these two variables are spatially positively correlated; if they are more different as the measured distance of the other variable is reduced, these two variables are spatially negatively correlated. In this study, we carried out a spatial correlation analysis between the county-level total population and the annual average panel data of days with visibility less than 10 km and the corresponding heavy rainfall amount, rainy day and rain intensity panel data, and calculated the spatial correlation coefficient and performed the significance test.

3 Results and analysis

3.1 Changes in the temporal and spatial pattern of heavy rain in China We calculated the heavy rainfall amount (HRA), heavy rain days (HRD) and heavy rain intensity (HRI) of 659 meteorological stations in China. The results indicate that the HRA and HRD in China increased significantly from 1951 to 2010, and the HRI also showed an increasing trend (Fig. 1), and the speed of increase in each stage was uneven, showing a "rapid increase-slow increase-rapid increase" characteristic. Compared with 1951 – 1960, HRA, HRD, and HRI of 2001 – 2010 increased by 68.71%, 60.15% and 11.52%, respectively. In space, from 1951 to 2010, China's interdecadal accumulated HRA, HRD and HRI showed a process of gradual expansion from the southeastern coastal to the central, southwest, north China, and northeast regions (Fig. 2 and Fig. 3). The interdecadal expansion of HRA and HRD was particularly evident; compared with 1951 – 1960, the number of stations with accumulated HRA, HRD and HRI in 2001 – 2010 increased by 555, 555 and 359, respectively, accounting for 84.22%, 84.22% and 54.48% of the total number of stations, respectively, showed the characteristics of a large increase in interdecadal accumulated heavy rain.



Note: a. Annual changes of HRA in China; b. Annual changes of HRD in China; c. Annual changes of HRI in China; d. Interdecadal changes of HRA in China; e. Interdecadal changes of HRD in China; f. Interdecadal changes of HRI in China.

Fig. 1 Interannual and interdecadal changes of heavy rains in China from 1951 to 2010

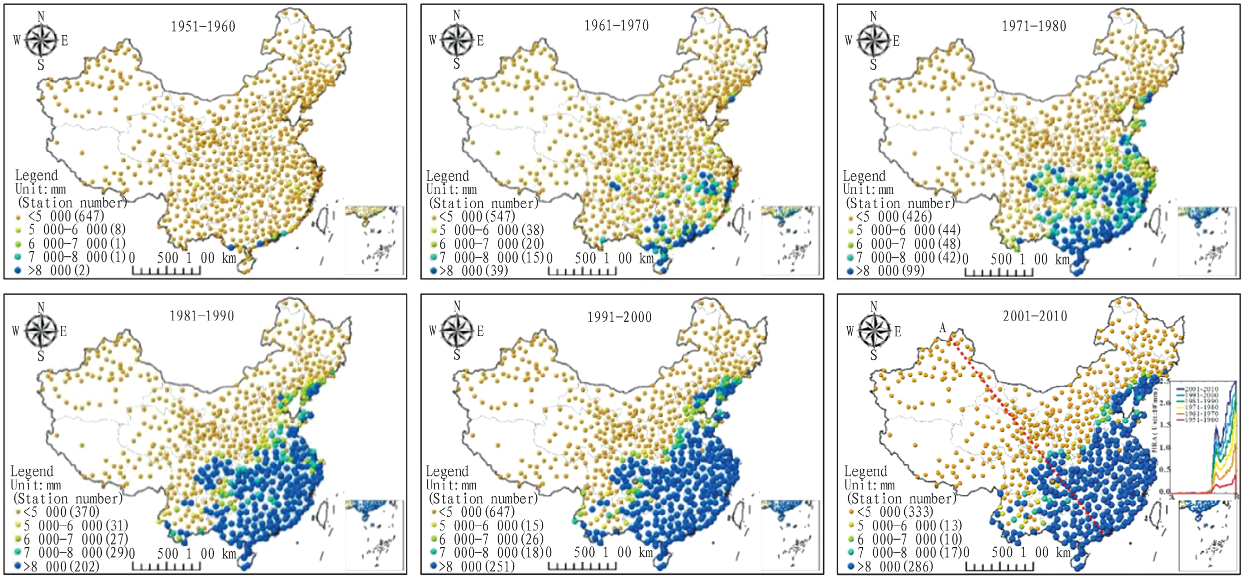


Fig. 2 Distribution of interdecadal cumulative HRA in China

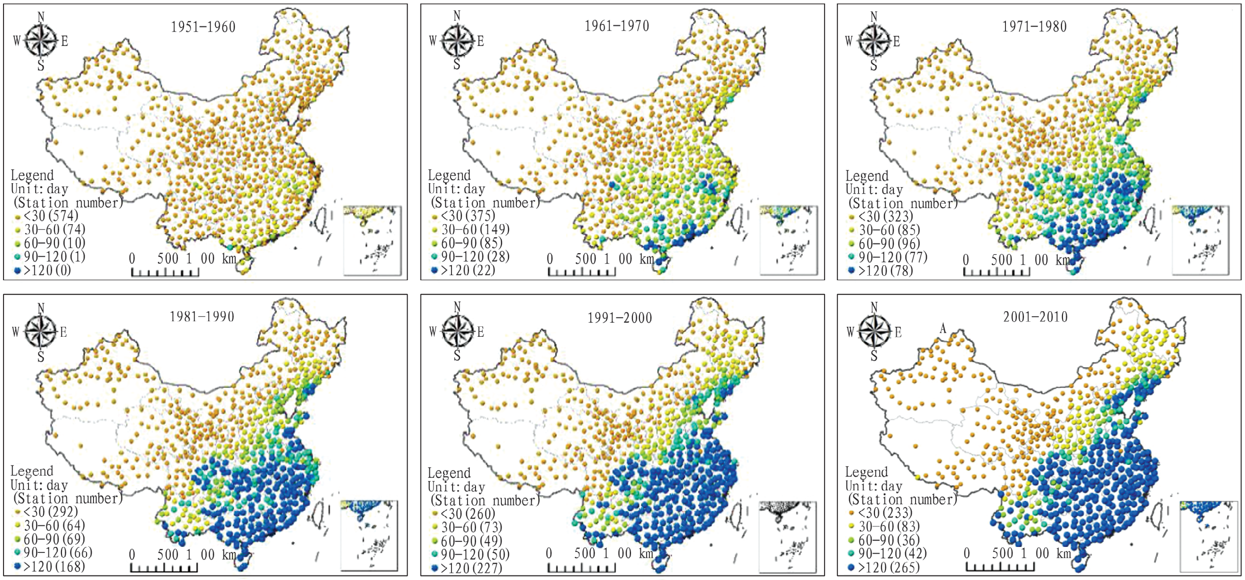


Fig. 3 Distribution of interdecadal cumulative HRD in China

3.2 Variance explanation rate of contribution of heavy rain factors to heavy rain

3.2.1 Stepwise regression screening of heavy rain factors. Regional precipitation is affected by many climatic factors such as the atmosphere and ocean. We selected 29 natural climatic factors that have an impact on precipitation in East Asia, and selected 11 human factors that characterize the urbanization development of China. Through stepwise regression analysis, from the 40 natural climatic factors and human factors affecting heavy rain in China, we rejected the factors related to the heavy rain in China with significance lower than 0.05, and selected seven factors with significant correlation, selected four natural climate factors including WPSH, ENSO, AMO, and AAO, as well as three rapid urbanization factors, namely, GDP2, UP, and HD. In order to reveal the causes of the increase in HRA, HRD, and HRI in China from 1951 to 2010, we carried out the analysis on the correlation between the above seven heavy rain factors and HRA, HRD, and HRI, and found that they had significant correlation. HRA, HRD and HRI showed different degrees of negative correlation with AMO, but had different degrees of positive correlation with WPSH, ENSO, AAO, GDP2, UP and HD. The human factors with rapid urbanization as representative showed high correlation with heavy rain, 100% reached 0.01 significance level; the correlation level between natural climatic factors and HRA and HRD was low, only 66% reached 0.01 significance level, and the correlation with HRI was lower, only 33% reached 0.01 significance level (Table 1).

3.2.2 Granger causality test of heavy rain factors to heavy rain. In order to further reveal the explanation degree of human and natural heavy rain impact factors to the increase of heavy rain in China, we performed Granger causality test with HRA, HRD and

HRI respectively. The results showed that nine human factors for HRA, HRD and HRI passed 0.01 significance level test, while only four of the natural climatic factors passed 0.01 significance level test, five passed the 0.05 significance level test, and three did not pass the 0.05 significance level test. It can be seen that a single human factor was more able to explain the increase in heavy rain than a single natural climatic factor. The human factor, on the whole, explained better the increase in heavy rain in China than the natural climatic factor (Table 1). In order to quantitatively analyze the contribution of heavy rain factors to the increase of HRA, HRD and HRI, we used the variance explanation rate based on multiple linear regression to characterize the contribution of each heavy rain factor. The results showed that the total explanation rate of the variance of HRA, HRD and HRI for the selected human factors and natural climatic factors were 85.84%, 84.71% and 87.46%, respectively, and the human factors were the main factors, and their explanation rate of the variance of HRA, HRD and HRI was 61.54%, 58.48% and 65.54%, respectively, accounting for 71.69%, 69.04% and 74.94% of the total variance explanation rate; supplemented by natural climatic factors, the explanation rate of variance for heavy rain was 24.30%, 26.23% and 21.92%, accounting for only 28.31%, 30.96% and 25.06% of the total variance explanation rate. The explanation rate of HD in human factors for HRA, HRD and HRI was 25.93%, 22.98% and 26.64%, which is almost equivalent to the sum of explanation rate of variance of natural climate factors for heavy rain, accounting for 42.14%, 33.24% and 40.65% of human factor variance explanation rate and accounting for 30.21%, 27.13% and 30.46% of the total variance explanation rate, showing that HD was the dominant factor in human factors (Table 1).

Table 1 Correlation between heavy rain factors and heavy rain parameters and explanation of variance for heavy rain

Heavy rain		Heavy rain factors									
		WPSH	ENSO	AMO	AAO	GDP2	UP	HD	Natural climatic factors	Human factors	Total explanation rate
HRA	Correlation coefficient	0.486 6**	–	−0.445 3*	0.712 9**	0.706 7**	0.785 2**	0.753 0**	0.513 4**	0.779 9**	0.780 2**
	Variance explanation rate	7.36%	–	7.32%	9.62%	17.86%	17.75%	25.93%	24.30%	61.54%	85.84%
HRD	Correlation coefficient	0.493 4**	–	−0.437 5*	0.638 1**	0.669 2**	0.640 9**	0.701 0**	0.508 5**	0.708 2**	0.731 8**
	Variance explanation rate	8.76%	–	6.24%	11.23%	16.64%	18.86%	22.98%	26.23%	58.48%	84.71%
HRI	Correlation coefficient	0.409 2*	0.388 6*	–	0.562 1**	0.724 1**	0.808 2**	0.836 0**	0.468 0*	0.843 1**	0.858 6**
	Variance explanation rate	6.46%	5.34%	–	10.12%	18.93%	19.97%	26.64%	21.92%	65.54%	87.46%

Note: * signifies that is passed 0.05 significance level, and ** signifies that it passed 0.01 significance level.

3.3 Spatial correlation analysis on heavy rain data and county-level total population and annual average panel data of visibility days In order to quantitatively analyze the spatial change process of HRA, HRD, and HRI in China from the southeastern coastal areas to the central, southwest, north China and northeast regions in recent decades (Fig. 2 and Fig. 3), we used the county-level population and the average annual days with visibility < 10 km panel data, namely, using the panel data of the county-level total population as the substitute data for the land use pattern of the underlying surface, the panel data of average annual days with visibility < 10 km as the substitute data for pollution emission. We analyzed the spatial correlation between them and the interdecadal heavy rains in China. The results show that the correlation between the interdecadal HRA, HRD, and HRI in China and the county-level total population and the annual average days with visibility < 10 km constantly increased with the chronological changes of years (Table 2). Specifically, the county-level total population increased from 0.35, 0.36, and 0.40 to 0.54, 0.55, and 0.58, respectively, and the annual average visibility days increased from 0.36, 0.38, and 0.48 to 0.55, 0.57, and 0.58, respectively. These results also show that the human factor represented by rapid urbanization may play a decisive role in the increase of heavy rains in China.

4 Discussions

4.1 Contribution of natural and human factors to the increase of heavy rains The increase of heavy rain in China from 1951 to 2010 was the joint result of human factors mainly represented by rapid urbanization and natural climatic factors in the context of global climate change.

4.1.1 Natural factors. Regional atmospheric precipitable water and water vapor flux have a certain impact on regional precipitation. Through comparing Fig. 4a with Fig. 4b, we can see the difference between the annual rainfall and the HRA in China. Specifically, after 1971, HRA, HRD and HRI continued to increase with significant decline of total rainfall and rainy days, forming a sharp contrast; comparing Fig. 4a with Fig. 4c, before 1971, the HRA, HRD and HRI in China rose rapidly with fluctuations, while natural factors decreased with fluctuations; from 1971 to 1995, HRA, HRD and HRI stabilized with fluctuations, and natural factors rose with fluctuations; after 1995, HRA, HRD, and HRI and natural factors rose rapidly with fluctuations. Through comparing Fig. 4b with Fig. 4d, we can see that both HRA and atmospheric precipitable water in China rose with fluctuation and then the two developed in the opposite direction in the fluctuation; through comparing Fig. 4b and Fig. 4d, the precipitation and atmospheric precipitable water in China showed a good corresponding relationship, that is, before 1970, the two rose with fluctuation and then declined with fluctuation. It can be seen that the changes of regional atmospheric precipitable water and water vapor flux are not favorable for the inter-annual or inter-decadal increase of HRA in China; natural factors can not reasonably explain the changes of HRA, HRD and HRI in China. We compared the proportion of heavy rains in China (two consecutive days and above) with convective heavy rains in every decade. The results show that the proportion of total

HRA to total precipitation in 2001-2010 was 7.68% higher than that in 1951-1960, the proportion of total HRD to total precipitation days increased by 0.73%, the proportion of convective HRA to total HRA correspondingly increased by 3.66%, the proportion of HRD to total HRD increased by 3.17%; at the same time, the proportion of process HRA to total HRA declined by 3.66%, and the proportion of HRD to total HRD declined by 5.18%. Therefore, it is difficult to reasonably explain the increase of HRA, HRD and HRI in China by natural climatic factors such as atmosphere and ocean.

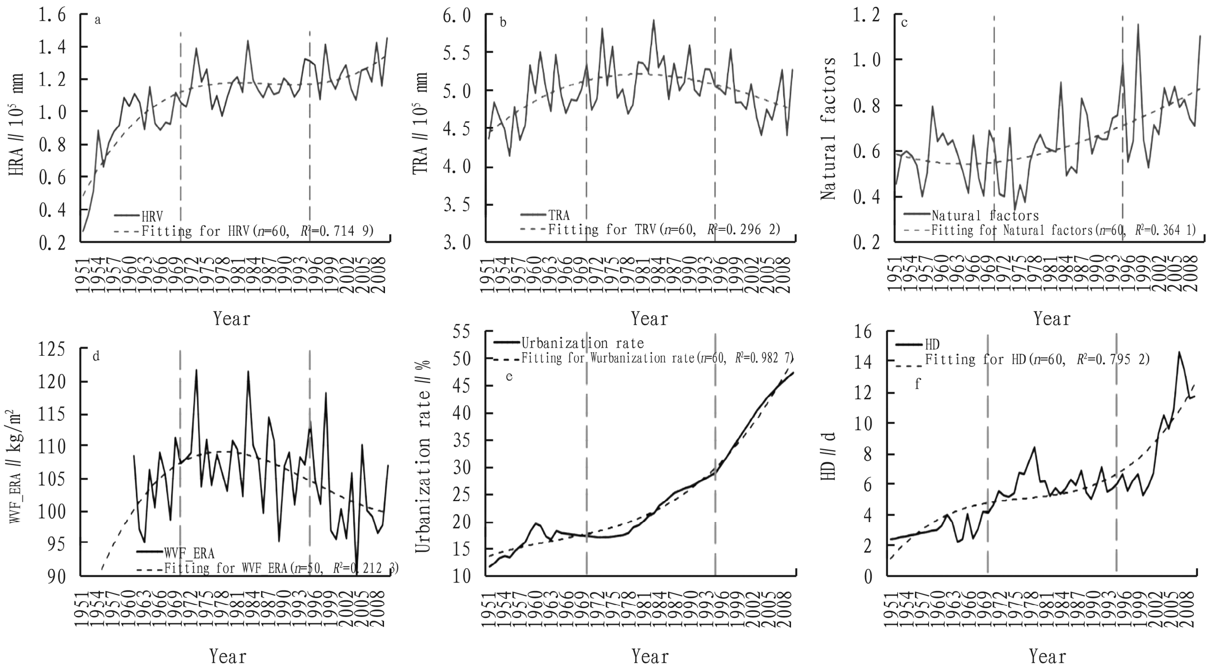
Table 2 Spatial correlation coefficient of heavy rains in China rain and county-level total population and annual average of days with visibility <10 km

Heavy rain		Year					
		1951-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
HRA	County-level total population	0.351 53**	0.364 74**	0.368 15**	0.526 88**	0.533 71**	0.535 01**
	Visibility days	0.355 94**	0.386 63**	0.437 15**	0.485 44**	0.532 78**	0.548 80**
	Built-up area	-	-	-	-	0.241 33*	0.280 15*
	Aerosol optical thickness	-	-	-	0.335 59*	0.335 97*	0.568 84**
	GDP2	-	-	-	0.161 98*	0.258 39*	0.273 08*
HRD	County-level total population	0.363 81**	0.375 72**	0.377 94**	0.540 29**	0.546 26**	0.548 20**
	Visibility days	0.374 51**	0.409 88**	0.459 93**	0.504 23**	0.549 41**	0.565 55**
	Built-up area	-	-	-	-	0.242 56*	0.293 23*
	Aerosol optical thickness	-	-	-	0.351 59**	0.360 65**	0.589 13**
	GDP2	-	-	-	0.167 69*	0.262 51*	0.277 85*
HRI	County-level total population	0.396 90**	0.399 06**	0.411 58**	0.558 51**	0.563 76**	0.581 86**
	Visibility days	0.485 05**	0.485 54**	0.549 39**	0.566 28**	0.586 83**	0.582 87**
	Built-up area	-	-	-	-	0.255 14*	0.285 45*
	Aerosol optical thickness	-	-	-	0.535 23**	0.579 61**	0.646 16**
	GDP2	-	-	-	0.237 94*	0.278 25*	0.343 52*

Note: China's county-level total population data were selected from 1953, 1964, 1982, 1990, 2000, and 2010 data; visibility data were 1957-2005 data; built-up area was data from 286 cities in China from 1993 to 2010; black carbon aerosol data were from 1980 to 2010; China county-level data GDP2 data were 1990, 2000, 2010 data; * signifies that it passed 0.05 significance level, and ** signifies that it passed 0.01 significance level.

4.1.2 Human factors. From 1951 to 2010, China's industrial structure changed substantially. 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, and the proportion of secondary industry grew at the fastest annual rate; the average annual growth rate of secondary industry and tertiary industry in China was 12.97% and 12.01%. From 1996 to 2010, the average annual growth rate of the secondary and tertiary industries was 13.16% and 14.42% respectively. Significant changes in China's industrial structure have driven rapid development of urbanization. The level of urbanization in China has been on an upward trend. In 1951-1970, 1971-1995, and 1996-2010, the annual growth rate of urbanization rate in the world was 0.37, 0.34 and 0.46 percentage points respectively, while the average annual growth rate of China's urbanization rate was 0.29, 0.49 and 1.21 percentage points respectively. These show that China's urbanization is developing rapidly, especially during the period of 1996-2010, China's urbanization is in the stage of rapid development. Rapid industrialization and urbanization have accelerated the energy demand. From 1951 to 2010, China's energy production grew at an average annual rate of 7.62%. In the same period, China's total vehicle growth rate was 12.51%. From 1996 to 2010, the annual growth rate of private cars reached 13.54%. The average annual growth rate of carbon emissions, industrial emissions and industrial soot (dust) emissions in China was 6.52%, 11.49% and 1.61%, respectively; the average annual growth rate of LPG, natural gas and gas was 6.41%, 17.22% and 9.55%, respectively.

Along with the increase in the area of urban built-up areas, major changes have taken place in the surface landscape. From 1996 to 2010, the average annual growth rate of Chinese cities was 1.01%, while the average annual growth rate of built-up areas was 7.91%. The increase in the number of large-scale cities and large-scale built-up areas contributes to the increase in convective heavy rains. With the increase in energy use, the average annual number of haze days also increases. The average annual number of haze days in China has increased from 2.3 in 1951 to 11.74 in 2010. From 1951 to 2010, the average annual growth rate was 0.16, with an average annual growth rate of 2.78%; from 1996 to 2010, the average annual growth rate was 0.37, and the average annual growth rate was 4.21%. The increase in the annual number of haze days is favorable for the increase of precipitation condensate nodules, and also favorable for the increase of convective heavy rains. Comparing Fig. 4a with Fig. 4e, before 1971 and after 1995, the HRA, HRD and HRI and urbanization rate in China rose with fluctuation, during which HRA, HRD and HRI stabilized with fluctuations, the urbanization rate first stabilized and then rose, and the heavy rain slightly lagged behind the increase of urbanization rate. Comparing Fig. 4a and Fig. 4f, the HRA, HRD, HRI and HD in China rose with fluctuation and all of them showed a high degree of consistency. Especially after 1995, the HRA, HRD and HRI and the changes in urbanization factors including the output value of secondary and tertiary production, energy consumption, and the number of private cars showed a good simultaneous growth relationship. Therefore, it is feasible to reasonably explain the increase of HRA, HRD and HRI in China by human factors represented by the urbanization.



Note: a. Annual HRA in China; b. Annual rainfall in China; c. Natural factor comprehensive value; d. Water vapor flux in central and eastern China; e. Annual urbanization rate in China; f. Annual haze days in China.

Fig. 4 Dynamic relationship between interannual rainfall of China and related factors (1951 – 2010)

4.1.3 Natural and human factors. In order to visually show the temporal correlation between human factors and natural climatic factors and HRA, HRD and HRI, we took the variance explanation rate of each factor as the weight, and integrated the normalized heavy rain actors by weight, and plotted the scatter diagram with HRA, HRD and HRI, respectively. The results show that human factors have a good correlation with HRA, HRD and HRI in time series. The correlation between human factors and HRA, HRD and HRI is better than natural climatic factors. Specifically, the correlation between human factors and natural climatic factors and HRA, HRD and HRI was 0.896 4, 0.865 9, 0.912 9 and 0.364 1, 0.404 3, 0.404 3, respectively. Besides, the synchronization in time is also superior to natural climatic factors. Synchronization of comprehensive human factors and comprehensive natural climate factors with HRI is significantly higher than HRA and HRD. Although the comprehensive natural climatic factors have certain similarities with the heavy rain changes, the synchronization of human factors and heavy rain changes is more significant and plays a leading role. This further demonstrates that human factors represented by urbanization haze play a decisive role in the increase of heavy rains in China. Therefore, the rapid urbanization changes the nature of the underlying surface, and the secondary and tertiary industries that are rapidly developing in parallel with rapid urbanization have caused a large amount of pollutant emissions, which is highly likely to be closely related to the changes in the interdecadal heavy rain in China.

4.2 Deepening the study on the causes of regional and global heavy rains In order to further confirm that rapid urbanization has triggered a significant increase in the large-scale heavy rains in China, it is urgently necessary to deepen the study on the causes of regional and global heavy rains.

4.2.1 Mode simulation verification. Based on the analysis of the atmospheric precipitation and water vapor flux in China and the climatic factors such as the atmosphere and ocean, it is necessary to make further verification of the role of human factors and natural climatic factors through high-precision regional climate model simulation, so as to reveal the mechanism and spatial and temporal characteristics of significant increase of heavy rains in China. On the one hand, under the condition of natural and anthropogenic forcing factors of given observation, it is necessary to properly reproduce and confirm the robust signals of interannual or interdecadal changes of heavy rainfall in large-scale regions. On the other hand, it is necessary to deepen the scientific understanding of the influence of human activities on the heat, power, and cloud physics of heavy rains through simulation.

4.2.2 Large-scale regional comparison. Is the increase in interannual and interdecadal heavy rains a regional phenomenon in China or a global phenomenon? For this question, we have carried out some research work, although the increase in global heavy rain is a common phenomenon, such as Europe and the United States, where urbanization is slower, and heavy rains are also increasing, but in India and Brazil where the urbanization is growing faster, the significant increase in heavy rain is much stronger than that in Europe and America. Then, what is the specific situation of increase in heavy rains in other regions of the world? In 2014, 54% of the world's people lived in cities and towns. For Africa and

Asia, there will be 56% and 64% people living in cities and towns by 2020. Are regional differences in heavy rain changes in these areas also triggered by the combination of human socioeconomic activity factors and natural climatic factors, and are mainly human factors? These issues still require more in-depth observations, diagnostic analyses, and simulation studies at global and regional scales, and need to be further explored in terms of the mechanism.

4.2.3 Analysis of the causes of stage characteristics. In recent 60 years, the heavy rains in China take on a "rapid increase-slow increase-rapid increase" characteristic, which is not quite consistent with the characteristics of the increase in socioeconomic activity factors or natural climatic factors, and showing a certain lagging characteristic. China's development in the past 60 years has shown three stages: the level of industrialization has increased rapidly, and although urbanization has surpassed industrialization, it has shown slow development, and finally both industrialization and urbanization have developed rapidly. Has the non-synchronous development of China's industrialization and urbanization triggered a three-stage change of heavy rains? And how do they affect the increase in heavy rain? It is necessary to conduct an in-depth study from the mechanism and process.

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