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Statistical Analysis of Influencing Factors of Temporal and Spatial Variation Patterns of Decadal Accumulative Heavy Rainfall in China

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Abstract: Daily precipitation analyses for 659 Chinese meteorological stations from 1951 to 2010 show that the rapid urbanization may have triggered the significant increase of heavy rainfall in China. During the last decades, HRAs (Heavy Rainfall Amounts), HRDs (Heavy Rainfall Days) and HRI (Heavy Rainfall Intensity) in China have increased. Impressively, the upward trends are not randomly observed among stations, but of robust consistency with quite large regional scale over large widely and significantly. Compared to the 1950s, the HRA, HRD, and HRI increased by 68.71%, 60.15% and 11.52% during the 2000s. The significant increase of accumulative heavy rainfall appears firstly in the southeastern coasts in the early period, and then gradually expands to the central, southwest, north and northeast China. Rapid urbanization is very likely the main cause of large-scale heavy rainfall increase in China. The urbanization indicators including the industrial production output (GDP2), UP (Urban Population) and annual average HDs (Haze Days) are in good agreement with the heavy rainfall variations, and these indicators can statistically explain the variance of HRA, HRD and HRI by 61.54%, 58.48% and 65.54%, respectively. Meanwhile, the explained variance by leading climate indices including WPSH (Western Pacific Subtropical High), ENSO (El Nino-Southern Oscillation), AMO (Atlantic Multi-decadal Oscillation) and AAO (Antarctic Oscillation) are respectively 24.30%, 26.23% and 21.92%, being only about 1/3 of the urbanization-related variance. Panel data analysis of county-level total population and annual average visibility days less than 10 km also show that these two indicators have significant correlation with decadal HRA, HRD & HRI and the spatial correlation coefficient increases gradually with time. These consistent temporal and spatial features strongly suggest that rapid urbanization most likely triggered the steady increase of heavy rainfall over China during the recent decades.

Key words: Climate change, accumulated heavy rainfall, urbanization, natural factors, China.

1. Introduction

Frequent occurrence of haze in China has been widely concerned in the past decades. In the meantime, many regions are pounded with heavy rainfall, causing flood, casualties and property damage in many urban areas [1]. Frequent extreme precipitation events under the background of global climate change have caused terrible harm to economic and social development, life security, ecosystem, etc., which have brought profound impact on sustainable development of disaster area. Heavy rainfall has became a key factor of global & regional disasters and environmental risk and has been widely concerned by academic community and most sectors of the society [2-4].

Global and regional observations show that under a warming condition the earth's surface evaporation and the atmospheric capability of holding moisture tend to be enhanced. The accelerated hydrological cycle results in more precipitation in some regions [1, 5], particularly, the increase of convective precipitation is

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greater than the stratiform precipitation [6]. Observations since 1950 show that the regions with dramatic increase in the number of extreme precipitation events may be more than those with dramatic decrease [7]. IPCC AR5 (The Fifth Assessment Report of Intergovernmental Panel on Climate Change) indicates that, in a CO_2 doubling scenario, the extreme precipitation would increase more significantly than the mean precipitation intensity [1]. Climate model simulation shows that anthropogenic forcings may have resulted in the intensifying (high reliability) of global extreme precipitation [8, 9], while the interannual variability is somewhat large in tropical zones [10]. Observation and modeling suggest that the heavy rainfall intensity tends to be intensified over 2/3 of northern hemispheric land due to anthropogenic greenhouse gases [11]. Global and regional climate model simulated the present increasing of extreme precipitation in Europe and projected an even larger proportion of extreme precipitation in the future [12]. Simulation in WRF (Weather Research and Forecasting Model) shows that, with the intensive greenhouse gas emission, annually extreme precipitation in US-East region is much more serious than that at present, with an approximate increase of 107.3 mm [13]. According to results of the RAMS (Regional Atmospheric Modeling System), surface vegetation decrease of Sydney Basin produces an impact on the balance between atmospheric moisture and energy, making heavy rain more possible [14]. It should be noted that the heavy rainfall may be underestimated in the simulation [11, 15].

China as a whole, the precipitation amounts have no obvious trend. On the contrary, the HRI (Heavy Rainfall Intensity) increases [16-18], and the regions suffering extreme precipitation events are also increasing [19]. At regional scale, the increasing precipitation in Yangtze River Basin mainly results from the increase of precipitation intensity and extreme precipitation frequency [20, 21]; precipitation amounts and days in south China also increase significantly in recent years [22, 23]. Simulations with prescribed scenarios indicate that the intensity and frequency of extreme precipitation in China would increase significantly under the background of global warming. In the southeastern coastal areas, Yangtze River Basin and middle and lower reaches of rivers in north China, it is predicted that more extreme precipitation will occur compared with that at present [24]. The cloud thickness with severe pollution may be two times larger compared with that of low pollution condition in humid region in summer, indicating increasing possibility of thunderstorm days as well as the extreme precipitation events [25].

It should be pointed out that the spatial-temporal features of the heavy rainfall in China during the last decades are obviously inconsistent with the warming temperature, and cannot be reasonably explained by the leading atmospheric and oceanic climate indices. The statistical analysis in this study indicates that social and ecological indicators marked by rapid urbanization are most likely the major indicators resuting in significant increasing of heavy rainfall in China from 1951 to 2010.

2. Materials

2.1 Data Source

Precipitation data for 659 meteorological stations and annual haze days are obtained from China Meteorological Administration and this dataset covers period from 1951 to 2010. The large-scale climate indices including WPSH (Western Pacific Subtropical High), ENSO (El Nino-Southern Oscillation), AMO (Atlantic Multi-decadal Oscillation) and AAO (Antarctic Oscillation) are employed, which are available from NOAA (National Oceanic and Atmospheric Administration) and Chinese National Climate Center. Atmospheric precipitable water and water vapor flux data of NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data and

ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis data are also used. Horizontal visibility for 753 meteorological stations comes from Chinese Academy of Meteorological Sciences, which is handled as annual average days with the visibility less than 10 km, and this dataset covers period from 1957 to 2005. The urbanization-related social indices including GDP, industrial production output (GDP2) and UP (Urban Population) are taken from 60-year Statistics of New China and Prefectural (Municipal) Social and Economic Statistics Summary of China.

2.2 Method

The annual and decadal heavy rainfall amounts, days and intensity are calculated from 659 meteorological stations. Stepwise regression is used to screen out factors impacting heavy rainfall in China; Granger causality test is performed to test the causality between the chosen factors and heavy rainfall indices; Variance explanation rates are calculated using MLR (Multiple Linear Regression) to determine level of contribution of the chosen factors towards heavy rainfall; and finally, spatial correlation analysis is performed to obtain spatial correlation between urbanization and heavy rainfall indices. All methods are summarized as below.

(1) Stepwise regression: When the multiple regression equation is established, independent variables will be introduced one by one into the equation in the order of coefficient of partial correlation. Each introduced independent variable will undergo statistical test for their coefficient of partial correlation, and only those with remarkable effect will stay in the equation before moving on to select the next one. Such a method has been prevailed in meteorology [26]. In this study, stepwise regression was performed on 40 heavy rainfall factors and rainfall, rain days and rain intensity of interannual heavy rain in China, including 29 natural climate factors impacting precipitation proposed by IPCC and 11 human social and economic factors. Heavy rainfall factors with probability value less than 0.05 (confidence coefficient more than 95%) were introduced into the model while those with probability value more than 0.1 (confidence coefficient less than 90%) ruled out form the model.

(2) Granger causality test: Granger causality test relies on variance of the best LS (Least Squares) prediction that uses all information in certain past time points. Granger causality is defined as such: in a given information set I, including variables X and Y, and all other things being equal, if Y_{t+1} gets better predicted when the previous X is introduced into t time than when it is not, then X is called as a Granger cause of Y. In this study, Y referred to heavy rain and X to heavy rain factors. First of all, it was studied how much the current Y got explained by its lagged value. Then X was introduced in one by one to see how they could enhance explanation of heavy rain. Any X that could do so was deemed as helping cause Y. In this study, selected factors have been classified as per importance according to significance levels of 0.05 and 0.01 respectively. Kaufmann, R. K. and Stern, D. I. [27] used to use this method to test how human actions affected temperatures in southern and northern hemispheres.

(3) MLR-based variance explanation rate: A MLR equation was established for standardized sequence based on the multiple regression theory:

$$\widehat{Y_i} = b_1X_{1i} + b_2X_{2i} + b_3X_{3i} + b_4X_{4i} + b_5X_{5i} + b_6X_{6i} \quad (1)$$

Wherein, i = 1, …, n, n = 60 years and $b_1 \ldots b_6$ are regression coefficients.

Wherein, 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 (Haze Day), respectively. It was proved in Eq. (2) that:

$$c^2 = b_1r_1 + b_2r_2 + b_3r_3 + b_4r_4 + b_5r_5 + b_6r_6 \quad (2)$$

Wherein, c is multiple correlation coefficient, the left side represents the six factors' rate of variance explanation of heavy rain in China and the right side represents individual contributions of each factor to heavy rain in China [28].

(4) Spatial correlation analysis: Spatial correlation analysis aims at determining spatial correlation degree of one or more variables. Using panel data to spatial correlation analysis has been widely used [29]. Spatial correlation coefficient is used to measure spatial correlation between distribution characteristics of a physical or ecological variable and another. If a variable' value gets more similar with that of another one whose measuring distance is getting closer, the two present positive spatial correlation; if it gets more different from that of another one whose measuring distance is getting closer, the two present negative spatial correlation. In this research, spatial correlation analysis is carried out between the CLTP (County-Level Total Population) & AAVD (Annual Average Days of Visibility) panel data and corresponding HRA (Heavy Rainfall Amount), HRD (Heavy Rainfall Day) & HRI panel data, calculating the spatial correlation coefficient and performing significance test.

3. Results and Discussion

3.1 Spatial-Temporal Patterns of the Changing Accumulated Heavy Rainfall in China

HRA, HRD and HRI of 659 meteorological stations are calculated year by year. Their time series show that HRA (Fig. 1) and HRD from 1951 to 2010 increase significantly, with uneven increase rate at different stages. Simply comparing decade of 2000s with 1950s, authors found that the HRA, HRD and HRI respectively increased by 68.71%, 60.15% and 11.52%. Correspondingly, the number (percentage) of stations with increasing accumulated HRA, HRD and HRI is 555 (84.22%), 555 (84.22%) and 359 (54.48%). As shown in Figs. 2 and 3, an outstanding spatial feature can be found that high values of accumulated HRA and HRD steadily span from southeast coast to central, southwest, north and northeast China during the last 60 years. These features are indicative of large-regional increase of accumulated heavy rainfall in China.

3.2 Explained Variance of Heavy Rainfall by Urbanization and Climate Indices

3.2.1 Stepwise Regression and Screening of Candidate Variables

The regional precipitation is greatly affected by atmosphere, ocean and other climatic factors [1]. Hereby 29 climate indices that exert influence on East Asian precipitation in East Asia is considered and meantime selected 11 urbanization-related factors. A stepwise regression analysis then is carried out by taking these factors as candidate predictors and the heavy rainfall as the target variable. Both the variable selecting and removal are judged by a threshold of 0.05 significance level. Finally, 7 factors that are statistically related to heavy rainfall variations, including 4 climate indices as WPSH, ENSO, AMO and AAO and 3 urbanization-related factors as GDP2, UP and HD are screened out. In order to show their relationship with HRA, HRD and HRI, their Pearson correlations for the period from 1951 to 2010 are computed. The HRA, HRD and HRI have negative correlation with AMO at different degrees and positive correlation with WPSH, ENSO, AAO, GDP2, UP and HD at different degrees. Urbanization-related factors have very high correlation with heavy rainfall (all significant at the 0.01 significance level) (Table 1).

3.2.2 Granger Causality Test for Heavy Rainfall

To further reveal the explanation degree of human and natural factors to the heavy rainfall changes in China, authors carry out Granger causality test for the above selected climate and human factors. And the results show that all the 9 urbanization factors exceed the 0.01 significance level. Meanwhile, only 4 of the 12 climate factors exceed the 0.01 significance level, only 5 thereof pass the test of 0.05 significance level and 3 thereof fail to pass the test of 0.05 significance level. It can be seen that statistically urbanization-related factors can better explain the heavy rainfall increasing than climate indices.

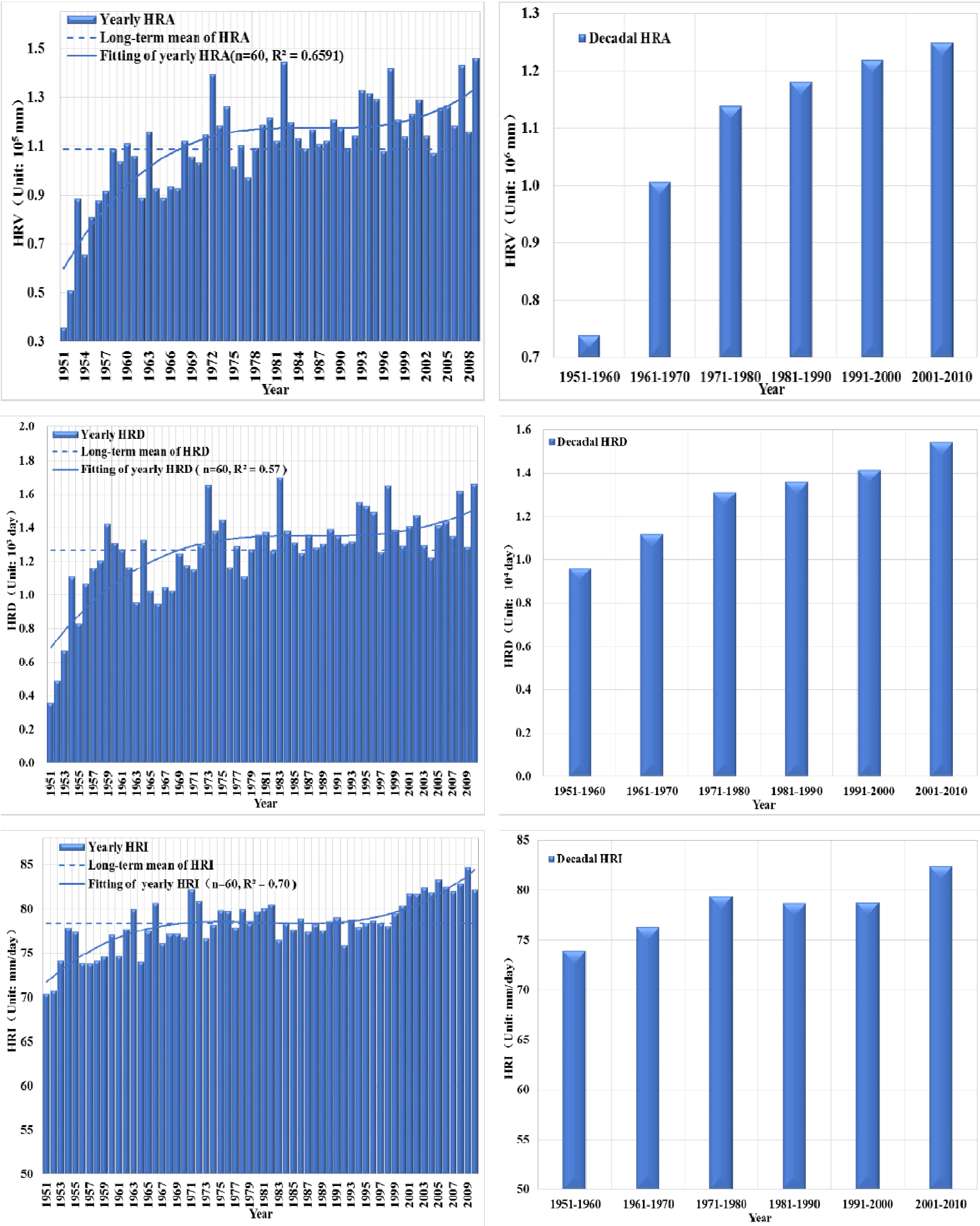


Fig. 1 Change of HRA, HRD and HRI in China from 1951 to 2010.

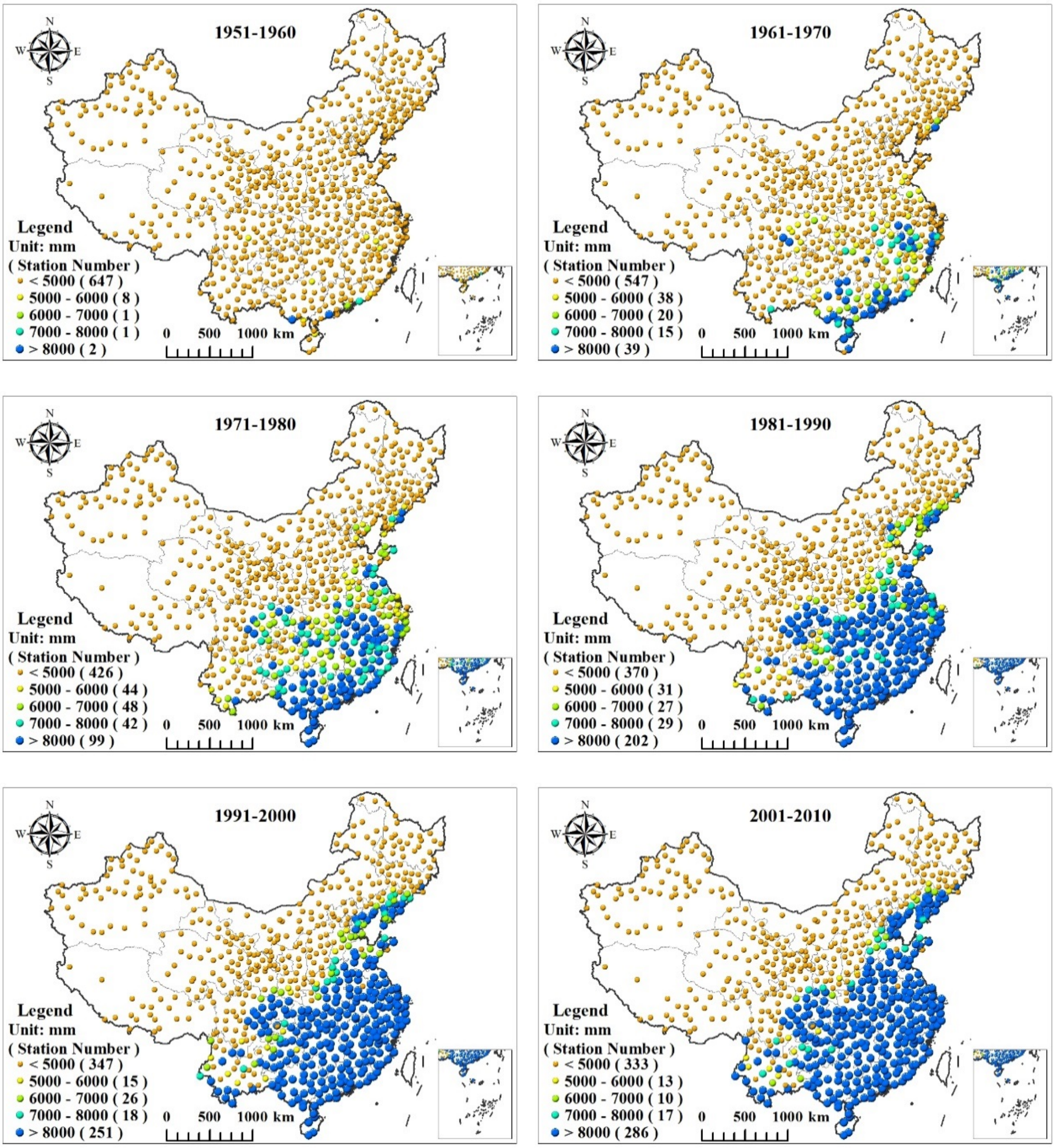


Fig. 2 Distribution of accumulated HRA for consecutive 10-year segments.

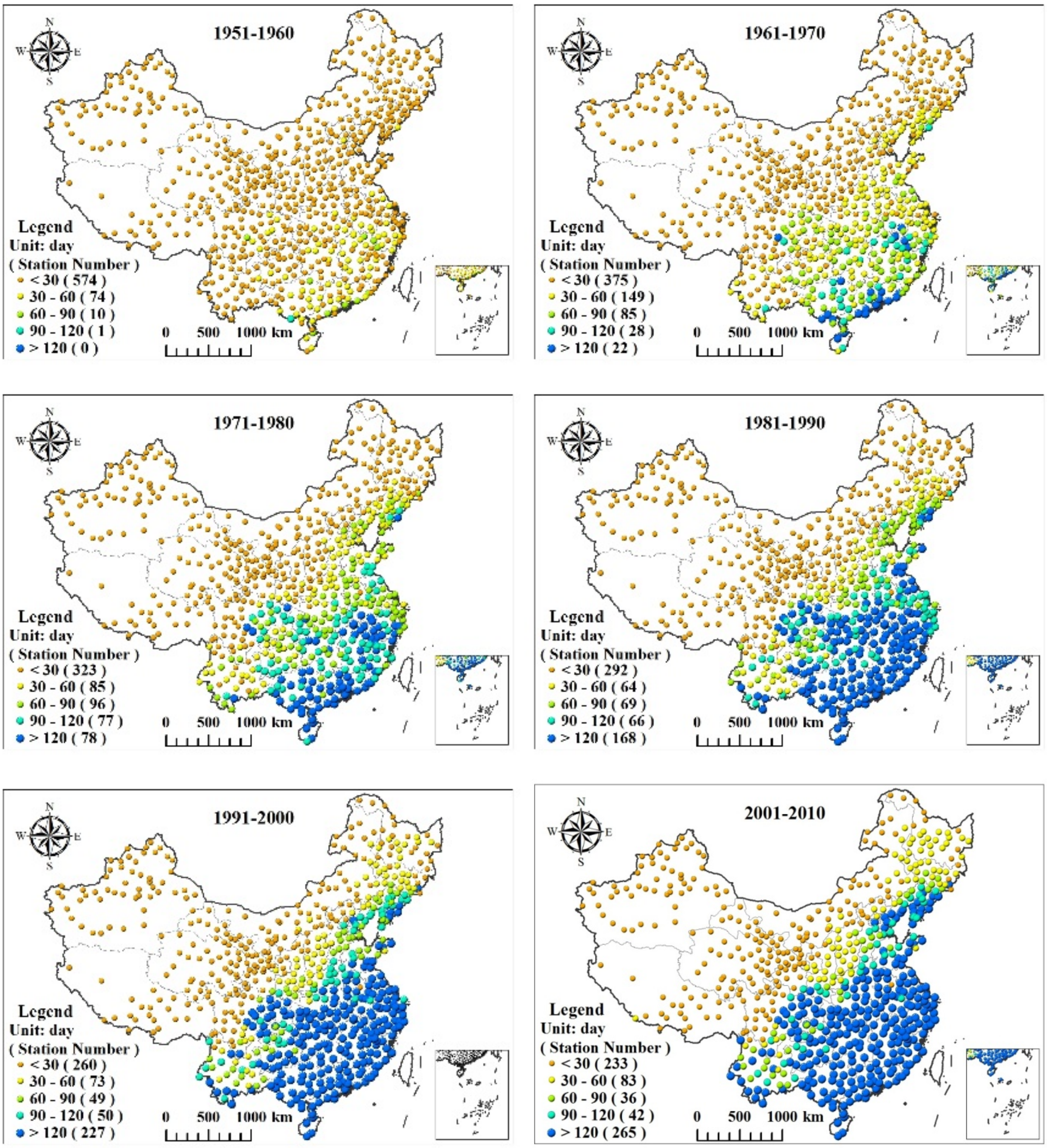


Fig. 3 Distribution of accumulated HRD for consecutive 10-year segments.

Table 1 Correlation between heavy rainfall and candidate factors.

Heavy rainfall		Factors									
		WPSH	ENSO	AMO	AAO	GDP2	UP	HD	Natural factors	Human factors	Total
HRV	VER	7.36%	-	7.32%	9.62%	17.86%	17.75%	25.93%	24.30%	61.54%	85.84%
	r	0.4866**	-	-0.4453*	0.7129**	0.7067**	0.7852**	0.7530**	0.5134**	0.7799**	0.7802**
HRD	VER	8.76%	-	6.24%	11.23%	16.64%	18.86%	22.98%	26.23%	58.48%	84.71%
	r	0.4934**	-	-0.4375*	0.6381**	0.6692**	0.6409**	0.7010**	0.5085**	0.7082**	0.7318**
HRI	VER	6.46%	5.34%	-	10.12%	18.93%	19.97%	26.64%	21.92%	65.54%	87.46%
	r	0.4092*	0.3886*	-	0.5621**	0.7241**	0.8082**	0.8360**	0.4680*	0.8431**	0.8586**

Note: VER means variance explained percentage; r means correlation coefficient; * means correlation is significant at the 0.05 level; and ** at the 0.01 level.

To quantitatively estimate the contribution of 7 factors to HRA, HRD and HRI, multiple linear regression is performed and results show that the total variance of HRA, HRD and HRI explained by 7 factors is respectively 85.84%, 84.71% and 87.46%, where the urbanization factors are the main contributors (accounting for 71.69%, 69.04% and 74.94% of the total explained variance, while the climate indices' contributions are 28.31%, 30.96% and 25.06%) (Table 1). The variance explanation of HD for HRA, HRD and HRI is 25.93%, 22.98% and 26.64%, almost the sum by all climate indices. HD alone explained 25.93%, 22.98% and 26.64% of variances in HRA, HRD and HRI respectively, equivalent to the sum of all the climate factors. In summary, urbanization factors explain the heavy rainfall variances more than 3 times the climate indices (Table 1).

3.2.3 Spatial Correlations with Population and Visibility

In order to quantitatively analyze the spatial expanding of high value accumulated HRA, HRD and HRI from southeast coast to central, southwest, north and northeast China (Fig. 2), analyses of spatial correlation based on panel data of county-level total population and annual average days of visibility less than 10 km (AAVD) are conducted. And the results (Table 2) show that the decadal correlations between the accumulated HRA, HRD & HRI and CLTP and AAVD steadily increase with time. During the 1950s, the correlations of CLTP with rainfall amounts, days and intensity are 0.35, 0.36 and 0.40. In the 2000s, the values increase notably to 0.53, 0.55 and 0.58. For AAVD, the correlations increase from 0.36, 0.38 and 0.48 for 1950s to 0.55, 0.57 and 0.58 for 2000s. The high coincidence of the spatial features of accumulated heavy rainfall variations and urbanization is strongly indicative of driving roles of human activities.

3.3 Discussion on Impact of Natural and Human Factors on the Heavy Rainfall

Increases of heavy rainfall from 1951 to 2010 in China are the result bright jointly by human activities with fast urbanization as a typical factor and by climate change as an auxiliary factor in the background of global warming.

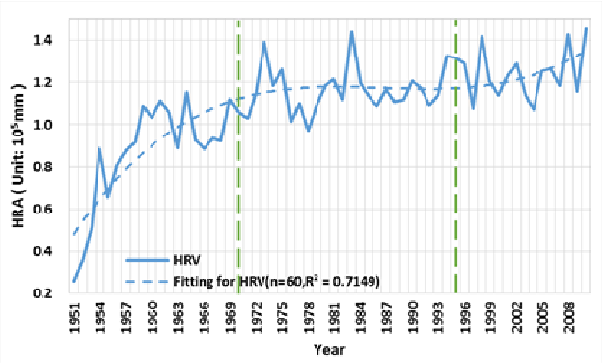
3.3.1 Natural Factors

Regional atmospheric precipitable water and water vapor flux produce a specific impact on regional precipitation. As shown in Figs. 4-a, b, there are sharp contrasts between TRAs (Total Precipitation Amounts) and HRAs. In detail, HRA, HRD and HRI have robust secular rising trends but TRA and TRD (Total Rain Days) have declined greatly after 1971. Comparing Fig. 4-a with Fig. 4-c, it can be found that HRA, HRD and HRI in China went up but natural factors went down in fluctuation before 1971. During 1971-1995, HRA, HRD and HRI have tended to steady amid fluctuations after 1971 but the natural factors went up. After 1995, HRA, HRD and HRI and natural factors went rapidly rising in fluctuation. As shown by results

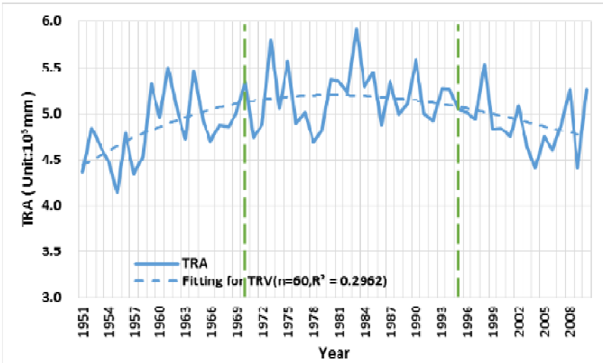
Table 2 Spatial correlation coefficients between accumulated heavy rainfall and CLTP & AADV less than 10 km.

Heavy rainfall		Decade					
		1951-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010
Amounts	CLTP	0.35**	0.36**	0.37**	0.53**	0.53**	0.54**
	AADV	0.36**	0.39**	0.44**	0.49**	0.53**	0.55**
Days	CLTP	0.36**	0.38**	0.38**	0.54**	0.55**	0.55**
	AADV	0.37**	0.41**	0.46**	0.50**	0.55**	0.57**
Intensity	CLTP	0.40**	0.40**	0.41**	0.56**	0.56**	0.58**
	AADV	0.49**	0.49**	0.55**	0.57**	0.59**	0.58**

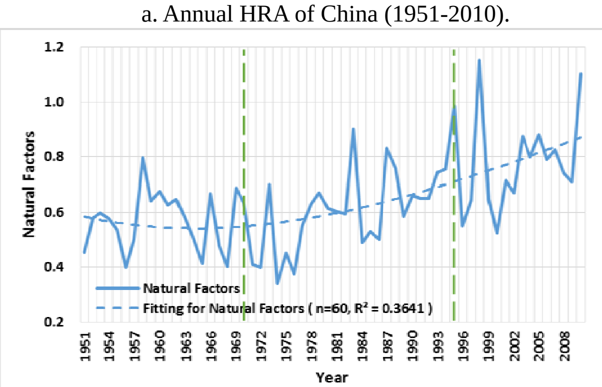
Note: The data of total population of county in China was collected in 1953, 1964, 1982, 1990, 2000 & 2010, respectively; the horizontal visibility data is from 1957-2005; * means correlation is significant at the 0.05 level; ** means correlation is significant at the 0.01 level.



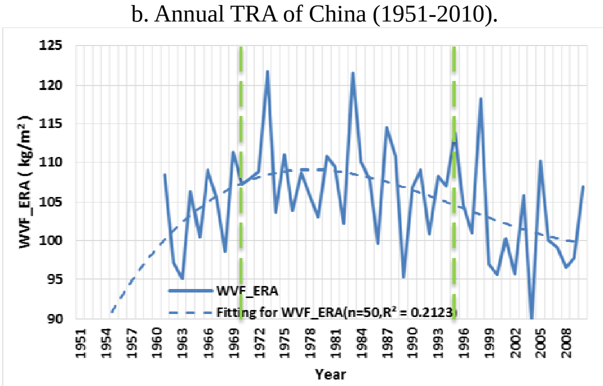
a. Annual HRA of China (1951-2010).



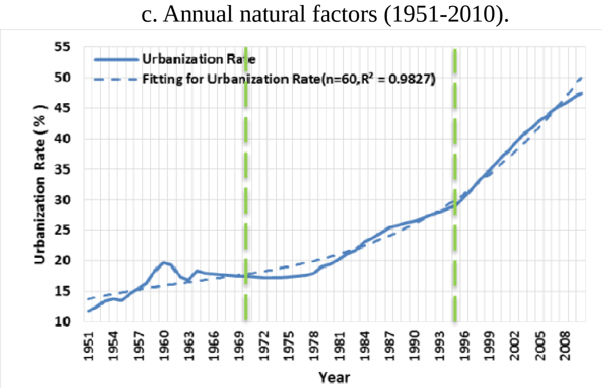
b. Annual TRA of China (1951-2010).



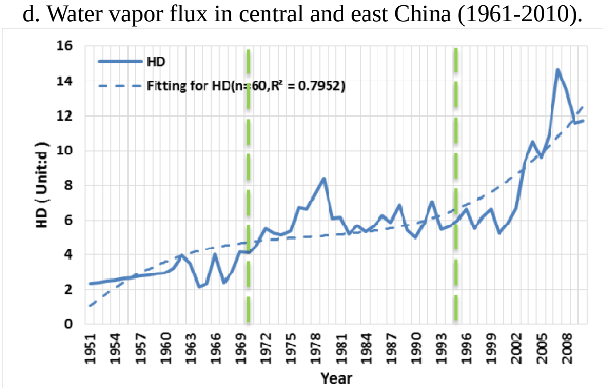
c. Annual natural factors (1951-2010).



d. Water vapor flux in central and east China (1961-2010).



e. Annual urbanization rate in China (1951-2010).



f. Annual average HD in China (1951-2010).

Fig. 4 Dynamic relations of annual precipitation and heavy rainfall of China with natural factors, atmospheric precipitable water, urbanization rate and HD.

of comparing Fig. 4-a with Fig. 4-d, HRA and water vapor flux were rising amid fluctuations and then evolving towards directions opposite to each other. After Fig. 4-b is compared with Fig. 4-d, favorable correspondence is shown between TRA and water vapor flux in China. In other words, they have been rising regardless of fluctuations before 1970 but declining amid fluctuations. In this view, regional water vapor flux goes against annual or decadal rise of HRA in China. Here, natural factor is not a reasonable factor to explain variations of HRA, HRD and HRI in China.

3.3.2 Human Factors

Industrial structures of China have witnessed drastic changes from 1951 to 2010. The agricultural industry production output (GDP1), industrial industry production output (GDP2) and the service industry production output (GDP3) experienced the annual average growth of -0.66%, 0.46% and 0.20%, respectively. Among them, GDP2 achieved the fastest growth. Annual average output value growth rate of GDP2 and GDP3 was 12.97% and 12.01%, respectively. Both GDP2 and GDP3 have witnessed the fastest annual average growth respectively at the rate of 13.16% and 14.42% from 1996 to 2010. Significant changes in industrial structure of China have greatly accelerated urbanizations. Urbanization is rising in China all the time. The global urbanization rate has respectively increased by 0.37%, 0.34% and 0.46% from 1951 to 1970, from 1971 to 1995 and from 1996 to 2010 with corresponding average urbanization rate of 0.29%, 0.49% and 1.21% respectively in China. As indicated by these data, China is being urbanized fast. In particular, China has undergone fast urbanizations from 1996 to 2010 in particular [29]. Fast industrialization and urbanization pose an increasing demand for energy. The annual average growth rate of energy production in China was 7.62% from 1951 to 2010. In this period, annual average growth rate of vehicle quantity in China was 12.51%. From 1996 to 2010, the annual average growth rate of private cars has gone to 13.54%. Carbon emissions, industrial emissions and industrial soot emissions have realized annual average growth rate of 6.52%, 11.49% and 1.61% respectively in this period. Annual average growth rate of liquefied petroleum gas, natural gas and coal gas consumptions per capita in China respectively reached 6.41%, 17.22% and 9.55%.

With increasing urban areas, surface landscapes have undergone drastic changes. From 1996 to 2010, the quantity of city in China has realized annual average growth rate of 1.01% and urban area has been increasing at the rate of 7.91% year on year. Large quantity and area of city will help bring convective heavy rainfall. As more and more energies are consumed, haze days are increasing year on year. HD in China have increased from 2.3 days in 1951 to 11.74 days in 2010 with 0.16 day increased ever year at the annual average rate of 2.78% from 1951 to 2010 and with 0.37 day increased every year at the annual average rate of 4.21%. Great increase of HD helps increase condensation nuclei and brings more convective heavy rain.

According to results of comparing Fig. 4-a with Fig. 4-e, HRA, HRD and HRI in China have been rising along fluctuating urbanization rate but tended to be steady amid fluctuations before 1971 and after 1995 and the urbanization rate was steady at first and went up then. HRA increase is slightly later than the rise of urbanization rate. After comparing Fig. 4-a with Fig. 4-f, results show that three indexes mentioned above and HD are rising amid fluctuations, thus showing high consistency between two types of variation. In particular, favorable growth has been realized by three indexes as above in pace with urbanization-related factors, such as GDP2 and GDP3, energy consumption and car quantity. In this view, it is believed that the increase of these three indexes in China can be properly explained by human factors with urbanization as a typical factor.

3.3.3 Natural and Human Factors

In order to visually present the correlativity of natural and human factors with HRA, HRD and HRI in time series, authors cite explanation rate of variance of every factor as weight and sum up normalized heavy rainfall factors according to related weights to draw scatter diagram with these three indexes respectively (Fig. 5). According to related results, favorable relation is established for human factors with these three indexes in time series. Human factors have a stronger correlativity than natural factors with these three indexes. The correlativity with these indexes is 0.8964, 0.8659 and 0.9129 respectively for human factors and 0.3641, 0.4043 and 0.4043 respectively for natural factors. Moreover, human factors have stronger correlativity than natural factors in time series. The synchronism of integrated human factors and integrated human factors with HRI is notably higher than that with HRA and HRD. Regardless of specific similarity between integrated natural factor and heavy rainfall change, the synchronism between human factor and heavy rainfall change is more remarkable and plays a leading role. This has further explained that urbanization factors with HD as a typical factor play a decisive role in heavy rainfall increase in China. Changes brought by fast urbanization to natures of underlaid surfaces and massive pollutant emissions of GDP2 and GDP3 developing fast in pace with fast urbanization may have a close relation with changes of decadal heavy rainfall in China.

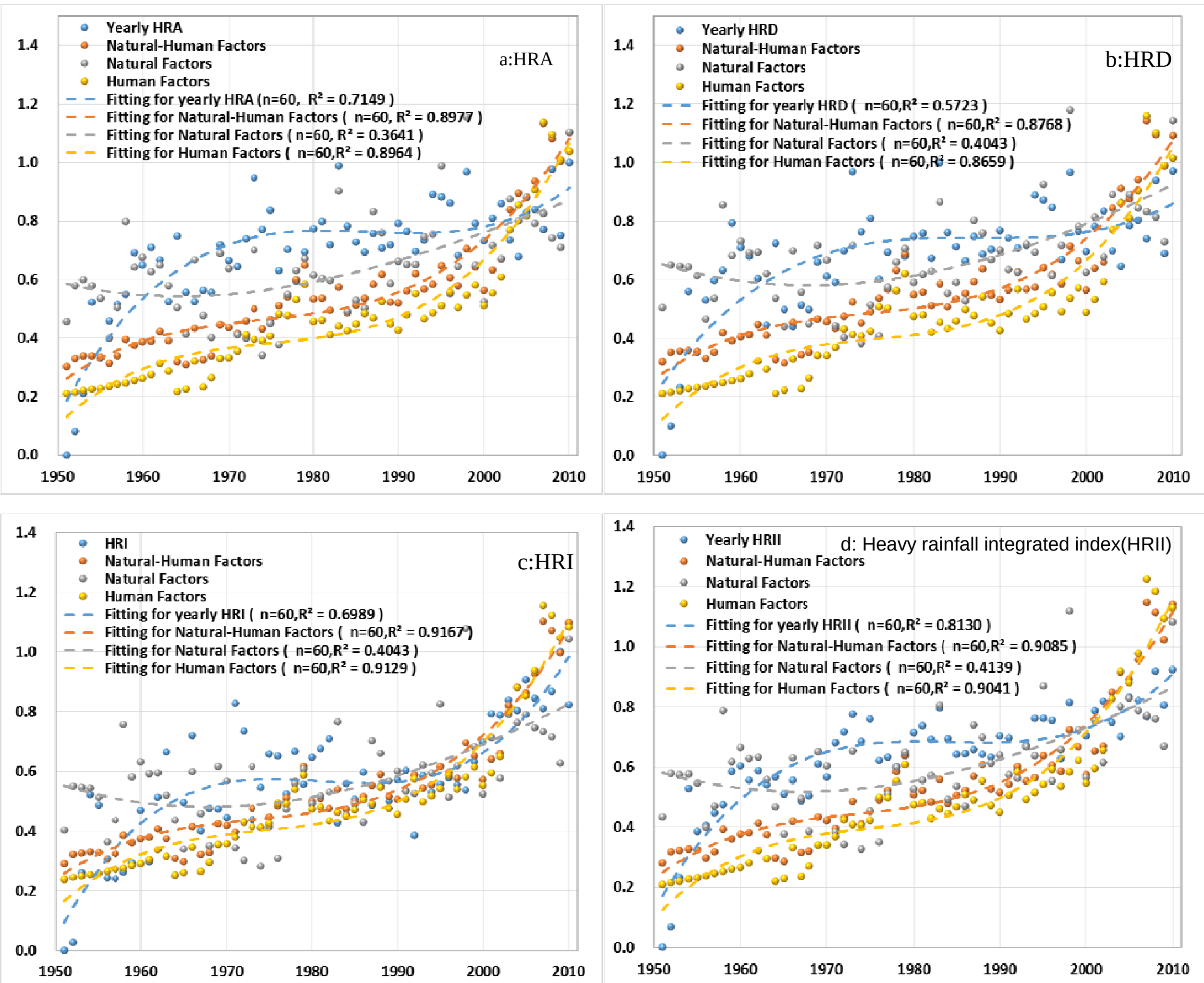


Fig. 5 Correlation between natural and human-related factors and heavy rainfall over time.

3.4 Discussion on Heavy Rainfall's Cause-and-Effect Studies

It is very urgent to deepen the studies on the cause of regional and global heavy rainfall increase to further prove that large-area drastic decadal heavy rainfall increase in China is triggered off by fast urbanizations.

3.4.1 Model Simulation and Verification on Heavy Rainfall

Temporal features of the regional precipitable water, water vapor flux and leading atmospheric and oceanic indices are examined and found to be different from the long-term changes of the heavy rainfall in China. Furthermore, through the simulation of the high precision regional climate model, the role of human factors and natural climate factors can be verified to further reveal the mechanism of heavy rainfall in China [30]. On the one hand, under the condition of given natural and human forcing factors, the strong signal of interannual or interdecadal variation of large-scale regional heavy rainfall can be reasonably reproduced and confirmed; On the other hand, through simulation, the scientific understanding of human activities affecting the thermal, dynamical and microphysical processes of rainstorms is deepened.

3.4.2 Large-scale Regional Comparisons on Heavy Rainfall

Is the heavy rainfall increase as observed in China a regional phenomenon or global phenomenon? Authors have addressed this issue. Global heavy rainfall increase is a common phenomenon. For example, Europe and the US with slow urbanization speed have also experienced heavy rainfall increasing. The rate of heavy rainfall increase in India and Brazil with fast urbanization is far greater than that in Europe and the US. How about the exact performance of the heavy rainfall in other parts of the world? In 2014, 54% of total population in the world is urban residents. In addition, 56% of African population and 64% of Asian population will live in city by 2020. Global and regional observations, diagnosis, analysis, simulations and studies as well as the responsible mechanisms are required for further studies.

3.4.3 Features for Different Periods on Heavy Rainfall

Heavy rainfall increase in China have been evolving in three stages over the past six decades, viz. fast increase in the early and recent periods and a relatively small increase in between. This kind of temporal variation does not coincide with the features of urbanization and climatic factors, which are also virtually slightly lagged behind the heavy rainfall. Development of China over the past six decades is divided into three stages. The industrialization rate was rising fast at first and urbanization exceeded industrialization then, but both of them were developing slowly. At last, industrialization and urbanization were developing fast. It is very urgent to study in mechanism and process whether asynchronous development of industrialization and urbanization in China is a cause of the three-section evolution for heavy rainfall increase and how it influences rainstorm increase.

4. Conclusions

In this study, based on daily heavy rainfall observations from 659 meteorological stations in China, results show that large-scale, rapid urbanization may have been the primary cause for the significant increase of heavy rainfall and its shifting spatial pattern across the country from 1951 to 2010. The HRA, HRD and HRI in China increased substantially, with increase rates of 68.71%, 60.15% and 11.52%, respectively. Stepwise regression analysis identified 4 out of 29 climate indices, namely WPSH, ENSO, AMO and AAO, and 3 out of 11 socio-economic factors namely GDP2, UP and annual average HD, all of which are closely related to urbanization in China, as important factors for the increased heavy rainfall in China. Granger causality test shows the urbanization factors are stronger causal to the increased heavy rainfall than the climate indices. Urbanization factors explained 61.54%, 58.48% and 65.54% of the variance in HRA, HRD and HRI respectively, while natural factors only explained 24.30%, 26.23% and 21.92% respectively. Spatially, the distributions of HRA and HRD demonstrate a clear expanding pattern, which show statistically significant correlation with spatial distribution of population density and annual low-visibility days. Authors' results strongly suggest that the significant increase in heavy rainfall across large area in China during the past 60 years may have been mainly a consequence of large-scale, rapid urbanization. Authors' results suggest the importance of a better understanding of the role of human activities in regional climate change, and thus the importance of integration them into climate modeling.

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