Impact of rapid urbanization on temporal and spatial pattern change of heavy rainfall in China during the past 60 years

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Abstract. Through the study of the daily heavy rainfall observation records of 659 meteorological stations in China from 1951 to 2010, we find that rapid urbanization may trigger the significant increase of large-scale heavy rainfall in China. The main conclusions are as follows: Decadal heavy rainfall amounts (HRA), heavy rainfall days (HRD) and heavy rainfall intensity (HRI) in China have increased significantly, with an increase of 68.71%, 60.15% and 11.52% respectively, and the increase of station number is 84.22%, 84.22% and 54.48% respectively, showing a time change process of "rapid slow re rapid increase" and a spatial change from Southeast Coast to Central, Southwest, North and Northeast China. The rapid urbanization factors, including the output value of the second industry (GDP2), the proportion of urban population (UP) and the annual average haze days (HD), are likely to be the main reasons for the increase of heavy rainfall in China. Their variance explanations for the HRA, HRD and HRI in China are 61.54%, 58.48% and 65.54% respectively, of which the variance explanations for the heavy rainfall rainfall, rainy day and rain intensity are respectively high only by haze 25.93%, 22.98% and 26.64% respectively, while the variance interpretation of climate factors, including WPSH, ENSO, AMO and AAO, is only 24.30%, 26.23% and 21.92% respectively. Compared with the forcing factors of rapid urbanization, the impact of these climate factors is only 1/3 of the former. The panel data of the annual mean of the total population and visibility days at the county level in China are significantly related to the HRA, HRD and HRI in China. The spatial correlation coefficient gradually increased from 1950s to 2000s, that is, the total population at the county level increased from 0.35, 0.36 and 0.40 to 0.54, 0.55 and 0.58 respectively, and the annual mean of visibility days increased from 0.36, 0.38 and 0.48 to 0.55, 0.57 and 0.58. It is further indicated that the rapid urbanization triggered the significant increase of heavy rainfall in China.

1. Introduction

Extreme heavy rainfall events have become an important factor of global environmental risks, and have attracted more and more attention from academic and social circles[1-3]. From the global and regional point of view, the existing observation and research results show that global warming causes the surface evaporation to intensify, which leads to the increase of water holding capacity of the atmosphere and the acceleration of global and regional water cycle, which will inevitably result in the increase of precipitation in some areas[4-5], in which the increase of convective precipitation is greater than that of stratiform precipitation[6]. The observational evidence since 1950 shows that, on a global scale, the number of extreme heavy rainfall events increases significantly in more regions than decreases significantly[7]. According to the fifth report of IPCC, when the greenhouse gas CO2 doubles, the extreme heavy rainfall increases significantly, which is much larger than the average intensity of precipitation[8]. The results of climate model output show that anthropogenic climate forcing may have resulted in the enhancement of global extreme precipitation
(high reliability)[4,9], and the increase in temperate regions is consistent, while the interannual variation in tropical regions is large[10]. Both observation and simulation show that the emission of greenhouse gases increases the intensity of heavy rainfall in two thirds of the land area in the northern hemisphere[11]. Using the simulation results of global climate model and regional climate model, it is found that the extreme heavy rainfall in Europe is increasing at present and in the future, and the proportion of the increase of 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 heavy rainfall in the eastern region of the United States is much more serious than the current situation, with an increase of about 107.3mm[13]. Regional atmospheric modeling system shows that the reduction of surface vegetation in Sydney Basin, Australia, affects the balance of atmospheric water and energy budget, and thus plays a role in the increase of heavy rainfall [14]. It should be emphasized that, after comparing the model results with the observation results, it is found that the actual increase of heavy rainfall under the climate warming is greater than the model results[14]. It is worth noting that the temporal and spatial patterns and changes of regional decadal heavy rainfall in China are not consistent with the warming of temperature, nor can they be reasonably explained by the dominant climate factors of atmosphere and ocean. Our statistical analysis shows that the human factors marked by rapid urbanization are likely to be the main driving factors for the significant increase of heavy rainfall in China from 1951 to 2010.

2. Data and methods

2.1. Data Sources

The precipitation data used in this paper comes from the daily precipitation of 659 meteorological stations from 1951 to 2010 in the ground meteorological data of China Meteorological Science Data Sharing Service Network. The data of WPSH, ENSO, AMO and AAO are from NOAA and China National Climate Center (74 circulation indexes). The data of atmospheric precipitable water and water vapor flux are from NCEP/NCAR reanalysis data of 1971-2010 and ECMWF reanalysis data of 1961-2010. The visibility data (1957-2005) is from the daily value data compiled by the Institute of Meteorological Sciences of China Meteorological Administration, which are all processed into the annual average days of visibility < 10 km according to the decade. The data of gross national product (GDP), the output value of the second industry (GDP2) and urban population (UP) used in this paper are from the sixty years of new China Statistics and the summary of China's county (city) socio-economic statistics; the annual average haze day. HD is from the National Meteorological Information Center of China.

2.2. Calculation method

According to the daily precipitation data of 659 stations, we calculated the annual and decadal HRA, HRD, HRI in China. Then, we took China as a plane and plotted decadal spatial distribution map of HRA, HRD, HRI. Firstly, we used the stepwise regression to screen out the factors that have an impact on heavy rainfall 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 HRA, HRD, and HRI. Finally, we carried out the spatial correlation analysis on the county-level total population and visibility days, HRA, HRD and HRI.

3. Results and analysis

3.1. Temporal and spatial changes in China's heavy rain

The HRA, HRD and HRI of 659 meteorological stations in China are calculated. The results show that China's HRA, HRD and HRI increase significantly from 1951 to 2010, and the HRI also show an increasing trend(Figure 1), and the increasing speed of each stage is uneven, showing the three-stage change characteristics of "fast increase slow increase fast increase"; compared with 1951-1960, the HRA, HRD and HRI increase by 68.71%, 60.15% and 11.52% in 2001-2010. Spatially, China's HRA, HRD and HRI gradually increase from the Southeast Coast to Central, Southwest, North and Northeast China from 1951 to 2010, in which the decadal steady expansion of HRA and HRD is particularly obvious. Compared with 1951-1960, the number of stations with increase HRA, HRD and HRI is 555, 555 and 359, respectively in 2001-
2010, accounting for 84.22%, 84.22% and 54.48% of the total number of stations, showing the characteristics of large-scale increase of heavy rainfall.

Figure 1. Variations of heavy rainfall in China from 1951 to 2010

3.2. Variance explanation rate of contribution of heavy rainfall factors

The regional precipitation is affected by many climate factors such as atmosphere and ocean. We select 29 natural climate factors that have influence on the precipitation in East Asia, and 11 human factors that represent the development of urbanization in China. Based on the stepwise regression analysis, the natural climate factors and human factors that affect the heavy rainfall in China are removed from the 40 factors that have little correlation with the heavy rainfall in China, but do not reach the significance level of 0.05. Therefore, seven heavy rainfall significant correlation factors are selected, including WPSH, ENSO, AMO, AAO, and three rapid urbanization factors, including GDP2, UP, and HD. In order to reveal the causes of the increase of HRA, HRD and HRI in China from 1951 to 2010, the correlation analysis between the above seven factors and HRA, HRD and HRI is made respectively, and it is found that there is a significant correlation between them. HRA, HRD and HRI are different degrees of negative correlation with AMO, but have different degrees of positive correlation with WPSH, ENSO, AAO, GDP2, UP and HD, and the correlation between human factors represented by rapid urbanization and heavy rainfall is very high, reaching 0.01 significant level in 100%; the correlation between natural climate factors and HRA, HRD are low, only 66% of them are at the original level reaching 0.01 significant level, and only 33% of them are at the significant level of 0.01.

In order to further reveal the degree of interpretation of human and natural influencing factors on the increase of heavy rainfall in China, we respectively conducted granger causality test with HRA, HRD and HRI in China. The results show that nine human factors for HRA, HRD and HRI have passed the significance level of 0.01, while only four natural climate factors have passed the significance level. For the test of 0.01, only 5 passed the test of 0.05 significance level, and 3 failed to pass the test of 0.05 significance level. It can be seen that a single human factor is more able to explain the increase of heavy rainfall than a single natural climate factor, and the human factor is better than the natural climate factor in explaining the increase of heavy rainfall in China as a whole. In order to quantitatively analyze the contribution of heavy rainfall factors to the increase of HRA, HRD and HRI in China, we use variance interpretation rate based on multiple linear regression to characterize the contribution of each factor. The results show that the total variance interpretation rates of the selected human factors and natural climate factors to HRA, HRD and HRI are 85.84%, 84.71% and 87.46% respectively, and the human factors are the main ones, and the variance interpretation rates to HRA, HRD and HRI are 61.54%, 58.48% and 65.54% respectively, accounting for 71.69%, 69.04% and 74.94% of the total variance interpretation rates; the natural climate factors are the auxiliary ones The variance interpretation rate of heavy rainfall is 24.30%, 26.23% and 21.92% respectively, accounting for only 28.31%, 30.96% and 25.06% of the total variance interpretation rate. HD in the human factors accounts for 25.93%, 22.98% and 26.64% of the variance interpretation rate of HRA, HRD and HRI, almost equal to the sum of the variance interpretation rate of natural climate factors, accounting for 42.14%, 33.24% and 40.65% of the variance interpretation rate of human factors, accounting for 30.21%, 27.13% and 30.46% of the total variance interpretation rate. It can be seen that HD is the leading factor in the human factors.

3.3. Spatial correlation analysis on heavy rainfall and total population and visibility days
In order to quantitatively analyze the spatial change process of China's HRA, HRD and HRI from the Southeast Coast to the Central, Southwest, North and Northeast China in recent decades, we analyzed the annual average value panel data of the total population at county level and visibility days less than 10km in different years in China, that is, the total population panel data at county level is used as the alternative data of underlying land use pattern. The results show that the correlation between the annual mean values of HRA, HRD and HRI and the total population at county level and visibility days < 10km in China increases with the passage of the years, that is, the total population at county level increases from 0.35, 0.36, 0.40 to 0.54, 0.55, 0.58, and the annual mean values of visibility days increase from 0.36, 0.38, 0.48 to 0.55, 0.57, 0.58, respectively. This result also shows that the human factors represented by rapid urbanization may play a decisive role in the increase of large-scale heavy rainfall in China.

4. Conclusion and discussion

4.1. Conclusion

HRA, HRD and HRI increased significantly of 68.71%, 60.15% and 11.52%, respectively. And spatial change of gradual increase from southeastern coast to central China, Southwest, North China, and Northeastern regions. Rapid urbanization factors, including GDP2, UP, HD, are likely to be the main causes of the increase in heavy rainfall in China. Their explanations of the variance of HRA, HRD and HRI in China reached 61.54%, 58.48% and 65.54%, respectively. However, explanation of variance of climatic factors including WPSH, ENSO, AMO, and AAO was only 24.30%, 26.23%, and 21.92%, respectively. The panel data of China's county-level total population and annual average of visibility days were significantly correlated with China's decadal HRA, HRD and HRI, indicating that rapid urbanization triggered a significant increase in decadal large-area heavy rainfall in China.

4.2. Discussion

Is the increase in annual and decadal heavy rainfall 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 rainfall is a common phenomenon, such as Europe and the United States, where urbanization is slower, and heavy rainfall are also increasing, but in India and Brazil where the urbanization is growing faster, the significant increase in heavy rainfall is much stronger than that in Europe and America. Then, what is the specific situation of increase in heavy rainfall 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 rainfall 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.

The extreme precipitation events are more sensitive to the global climate change than the average level drop. The expansion of heavy rainfall in China from Southeast Coast to Northwest Inland may be related to the northward movement of rain belt caused by global warming. After the founding of the people's Republic of China in 1949, with the continuous development of China's industry and the continuous improvement of its economic level, the emission of pollutants has also been increasing. The emission of a large number of pollutants provides the condensation needed for the formation of precipitation for cloud forming rain. In addition, most of China's densely populated and industrially developed areas are also concentrated in the area from Mohe in Heilongjiang Province to the east of Tengchong in Yunnan Province, which is exactly the middle of China. In China, the most significant area of rainfall change, the East-West differentiation of terrain and the emission of pollutants may strengthen the northwest expansion of rainstorm belt in mechanism and process, which needs further study.

Since the founding of the people's Republic of China in 1949, the level of urbanization in China has been continuously improved, and urban agglomerations in Beijing, Tianjin, Tangshan, Yangtze River Delta and Pearl River Delta have been formed. These urban agglomerations are continuous, greatly changing the original land cover changes. The urbanization of population and landscape may also have a certain impact on the northwest expansion of the rainstorm belt in terms of mechanism and process. The density of human
activities is very high in these areas, resulting in a large number of changes in human heat sources and surface roughness, changing the original distribution pattern of heat radiation, which to a certain extent will form a larger scale of heat island effect, turbid island effect, wet island effect and so on. In addition, the water vapor source in the area from Mohe in Heilongjiang Province to the east of Tengchong in Yunnan Province is relatively sufficient. Once it is conducive to the transit of precipitation weather system, coupled with the large-scale urbanization effect, it will bring extremely strong precipitation to this area. In recent years, many of the first tier cities in China have suffered heavy rain, which has led to the increase of waterlogging disaster. For example, the 7.21 heavy rainfall and waterlogging disaster in Beijing in 2012 is a typical case. It can be seen that the impact of urbanization on rainstorm is beginning to appear. However, how to quantify the impact of human activities on the rainstorm, and where to choose the breakthrough point, remains to be further strengthened in the future research.

Climate change mainly includes trend, fluctuation and extreme event change. There are obvious regional differences in time and space scales, which constitute the temporal and spatial pattern of climate change in the interannual and interdecadal. Therefore, it is very important to reveal the temporal and spatial pattern and genetic mechanism of global climate change, especially its extreme climate events, so as to further understand the temporal and spatial changes of environmental risks caused by global climate change.

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 rainfall 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 annual or decadal 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 rainfall through simulation.

In recent 60 years, the heavy rainfall 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 rain? 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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