Study on temporal and spatial differences of multi-attribute characteristics of torrential rain in different months in China

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Abstract. Using the daily precipitation data of 545 meteorological stations in China from 1961 to 2016, the temporal and spatial characteristics of torrential rainfall and rain days in different months in China were detected from the three aspects of climatic state characteristics, change trend and interannual variations. The results showed that: (1) The torrential rainfall and rain days in different months in China from 1961 to 2016 had similar spatial differentiation characteristics in the corresponding months. The high-value areas of torrential rainfall and rain days gradually expanded from the southeast coast to the northwest inland from January to July, but mainly distributed in the east of the Hu Huanyong Line, and reduced from the northwest area to the southeast coastal area from August to December; The torrential rainfall and rain days were less distributed in the west of the Hu Huanyong Line in different months. (2) The temporal and spatial differentiation characteristics of torrential rainfall and rain days in different months in China from 1961 to 2016 were basically the same. The torrential rainfall and rain days in China had the most significant change trend from May to August, mainly distributed in the southeast monsoon region with an increasing trend. The torrential rainfall and rain days in the northwest have little changes in different months. (3) The interannual variations of the torrential rainfall and rain days in different months in China from 1961 to 2016 were similar. Thereinto, there was large fluctuation in the northern region from April to October, while the variations in the southern region fluctuated greatly from January to March and from November to December. The high-value areas of the torrential rainfall and rain days with large fluctuation gradually expanded from southeast to northwest, northeast and southwest with the development of month, with the fluctuation tending to decrease in the southeast, and then shrank from the northwest, northeast and southwest to the southeast, coupled with an increasing fluctuation in the southeast. The research has certain reference significance for flood control, disaster reduction, and the planning and utilization of water resources.

1. Introduction
In the context of climate warming and rapid urbanization [1-3], torrential rain events tend to increase and intensify in most region of the world [4-6], making the phenomenon of “watching the sea in city” become a new normal, which brings about a serious challenge to social and economic development and urban security operations [7-11]. In particular, through the production chain, supply chain and various types of networks, the regional waterlogging disasters induced by torrential rain and their impacts are magnified [12-18]. Torrential rains in China with long duration and large impact range occur in the southern China, Jiangnan and Jianghuai areas [18]. In the region, the regional torrential rain events in the Loess Plateau have tended to decrease in recent decades, but the process rainfall tends to increase [16]. The intensity of torrential rain in the Yangtze River Delta decreases from south to north, and the
Torrential rainfall trends to increase in summer and winter, but it decreases in spring and autumn [12]. The total amount, frequency and intensity of heavy rains in the middle and lower reaches of Yangtze River and southern China all show an increasing trend [13]. The torrential rainfall in the northeast and southwest have shown a decreasing trend [9]. Affected by the topography, the total amount and frequency of torrential rain in North China are characterized by more in the southeast and less in the northwest and concentrated from late July to early August. Both the total amount and frequency of torrential rain show a decreasing trend [16]. The total rainfall and the amount of light rain in the northwest tend to decrease, but torrential rainfall tends to increase [15]. As the urban population density continues to increase, urban construction and the impervious layer areas continue to increase, and green vegetation is reduced, and also a large amount of heat and exhaust gas are discharged by man, which has caused a significant "heat island effect", exacerbated the uplift of warm and humid air, and triggered an increase in torrential rain events potentially [7]. The current research on torrential rain is mostly carried out on the scale of year and season, while there is little research on temporal and spatial evolution on the scale of month. Affected by natural and human factors, climate change presents an integrated evolution characteristic of multi elements, multi scales and multi processes [8]. Climate change attributes include the mean, trend and fluctuation characteristics. According to the temperature and rainfall, Shi Peijun, a Chinese scholar, proposed nine climate change models, taking into account the trends (increase, invariance and decrease) and fluctuations (increase, invariance and reduction) of two main factors, and based on this, studied the regionalization of climate change in China from 1961 to 2010 [6]. The innovation of this study is to understand the original regionalization of climate mean from the perspective of dynamic change, and to carry out regionalization study under the climate dynamic change mode. Based on this idea, Wu Shaohong carried out research on risk regionalization of climate change in China under the scenario RCP8.5 [11]. Therefore, it can be seen that the climate change has multiple attribute characteristics. It is in this concept that this paper detects the characteristics of the multi-attribute evolution of torrential rain in different months in China. As the climate continues to change, there may be some variations and new features of the months and regions in which there is no torrential rain originally. From the perspective of mean, change trend and fluctuation characteristics, detecting the evolution characteristics of torrential rain in different months in China plays an important role in deeply understanding the spatial and temporal change pattern of torrential rain. At the same time, the study also has reference significance for regional flood control, disaster reduction and the planning and utilization of water resources.

2. Data and methods

2.1. Data Sources

The precipitation data from 1961 to 2016 used in this paper came from the “Daily Data Set of Basic Meteorological Elements in China's National Surface Meteorological Stations (V3.0)” provided by the National Meteorological Information Center of China Meteorological Administration. The data set includes 2482 meteorological stations, and the spatial coverage of the data is: 73°40'E-135°05'E, 4°00'N-53°31'N. The data set has undergone strict quality control, with a good quality. The data availability is above 99%, and the data accuracy is close to 100%. Since most stations in China were constructed in the 1950s, the research starting time of this paper was 1961. On this basis, the paper further carried out relevant verification: (1) If the annual missing or wrong data exceeded 0.5% of the total annual data, the station was excluded; (2) If the missing or wrong data of the total exceeded 0.5%, the station was excluded; (3) On the basis of (1) and (2), for the stations with a defect rate less than 0.5%, if there was missing data, the adjacent station and the mean data before and after the year were used to make up, and eventually 545 stations were obtained. The information of the meteorological stations in this article did not include that in China Hong Kong, Macao, and Taiwan.
2.2. Calculation method

From the three aspects of climatic state characteristics, change trend and interannual variations, the temporal and spatial characteristics of torrential rainfall and rain days in different months in China from 1961 to 2016 were detected in this paper. According to the torrential rain standard of the National Meteorological Center of China Meteorological Administration, this paper regarded the daily rainfall of 50 mm as the threshold of torrential rain, and once reaching the threshold, it was one rainstorm day. The climatic state was characterized by the sum of torrential rainfall and rain days in different months in China from 1961 to 2016. The change trend is a one-dimensional linear regression equation based on least squares, and the specific calculation method is as follows:

For the sequence $y_j$ of the torrential rainfall or rain days in one month in a station with 56 samples, $t_j$ presents the corresponding year, and a one-dimensional linear regression equation is established between $y_j$ and $t_j$:

$$\hat{y}_j = a + bt_j \quad (1)$$

Where: $a$ is the regression constant and $b$ is the regression coefficient. $a$ and $b$ can be calculated by the least square method.

$$b = \frac{\sum_{j=1}^{n} y_j t_j - \frac{1}{n} \sum_{j=1}^{n} y_j \sum_{j=1}^{n} t_j}{\sum_{j=1}^{n} t_j^2 - \frac{1}{n} \left( \sum_{j=1}^{n} t_j \right)^2} \quad (2)$$

$$a = \frac{1}{n} \sum_{j=1}^{n} y_j - b \frac{1}{n} \sum_{j=1}^{n} t_j$$

The symbol of $b$ in the regression coefficient represents the linear trend of the torrential rainfall or rain days of one station in a month in China. $b > 0$ indicates that the sequence of the torrential rainfall or rain days trends to increase (rise) with time, while $b < 0$ indicates that the sequence of the torrential rainfall or rain days trends to decrease (fall) with time. The size of $b$ reflects the rate at which the torrential rainfall or rain days increase or decrease.

Based on the coefficient of variation, this paper characterized the fluctuation characteristics of the torrential rainfall or rain days in China from 1961 to 2016, namely the interannual variation. The coefficient of variation is the ratio of the standard deviation to the absolute value of the mean, which can be used to measure the fluctuation (variation) of the data, with an advantage of eliminating the influence of difference between the unit and the mean on the variation degree of two or more data. The calculation formula is:

$$v = \frac{S}{|\bar{x}|} \quad (3)$$

Where: $S$ and $|\bar{x}|$ are the standard deviation and the mean, respectively. In this paper, the smaller (larger) the coefficient of variation, the smaller (larger) the fluctuation of the torrential rainfall or rain days in China.

3. Results and analysis

3.1. Spatial differentiation characteristics of torrential rain climate states in different months

The climatic state characteristics can reflect the climate mean state in a certain region, that is, the climate base state, which is the background state of regional long-term climate evolution. Studying the climatic characteristics of different months has a certain reference value for understanding the spatial and temporal differences of the hazard factors of urban waterlogging induced by torrential rain in the context of change. From the perspective of rainfall, the torrential rainfall from January to December in China from 1961 to 2016 increases with month. The high-value areas of torrential rainfall gradually expanded from the southeast coast to the northwest inland, but basically in the east of the Hu Huanyong Line. The torrential rainfall in the west of the Hu Huanyong Line was all below 1000 mm, in which there was little change between months, mainly because the west of the Hu Huanyong Line is deeply in the hinterland of East Asia and belongs to the non-monsoon region, where the source of water vapor is insufficient and the degree of urbanization is much lower than that of the eastern monsoon region.
Specifically, the national torrential rainfall was below 1000 mm from January to February and from November to December. The torrential rainfall in March were comparatively high only in Fujian and eastern Guangdong, most of which ranged from 1000 to 2000 mm. In April, the stations with torrential rainfall of more than 4000 mm appeared in south China coastal areas, and the stations with 1000-4000 mm were interlaced; At this time, the torrential rainfall in Jiangxi, Hunan and Hubei began to exceed 1000 mm, especially in the north of Jiangxi, there were stations with torrential rainfall of over 3000 mm. The torrential rainfall in May continued to increase in the south of the Yangtze River and east of Yunnan, and that in most stations exceeded 2000 mm; the torrential rainfall was more than 4000 mm in the coastal area of South China and the adjacent areas to Zhejiang, Jiangxi and Fujian. It is because the frontal rain belt in eastern China has risen in the Nanling region during this period. In June, the stations with more than 1000 mm of torrential rainfall began to cross the Yangtze River and extended to the north. In the meantime, the torrential rainfall in the south of the Yangtze River continued to increase, with more than 4000 mm in most regions, and further expanded to the southwest. During this period, the rain belt mainly stayed in the Jiangnan area. In July, the frontal rain belt continued to move northward, and all the torrential rainfall basically exceeded 1000 mm in the east of the Hu Huanyong Line. At this time, the torrential rainfall in central and southern China was reduced compared to June. The areas of south China coast, Guangdong, Guangxi, Sichuan and Yunnan and Bohai Rim had evolved into high-value areas of torrential rainfall, and the rainfall in most areas exceeded 4000 mm; the torrential rainfall in Shaanxi and northeast China ranged from 1000 to 2000 mm. In August, the national torrential rainfall was most distributed in the Bohai Rim, coastal areas of eastern and southern China, and eastern Sichuan, with more than 4000 mm. The torrential rainfall in coastal areas may be caused mainly by typhoon landfalls which bring lots of typhoons and rain. The torrential rainfall in central China was mostly between 2000 and 4000 mm, while that in Jiangnan region and the western region of the same latitude was mostly between 1000 and 2000 mm. The torrential rainfall in September were more concentrated in south China coast, Zhejiang coast and eastern Sichuan, with more than 2000 mm in most areas, 4000 mm in the south China, and 1000-2000 mm in the middle and lower reaches of the Yangtze River. In August, the national torrential rainfall in October was only distributed in the eastern Guangxi and western Guangdong and Hainan province, with more than 4000 mm in Hainan, mostly 1000-3000 mm in the south China coast, and mostly 1000-2000 mm in Shanghai.

In terms of time, if the time from April to September is called the summer half year, and the time from January to March and from October to December is called the winter half year, then the torrential rainfall in the summer half year is much larger in magnitude and area than that in the winter half year. In space, China's torrential rainfall has not broken through the "Hu Huanyong Line" asked by the Prime Minister, and its high-value evolution region is mainly distributed in the east of the line. In Hainan, the torrential rainfall in the months of April to November exceeds 1000 mm, and the torrential rainfall in most months exceeds 4000 mm. Similarly, we analyzed the spatial evolution characteristics of torrential rain days in different months in China from 1961 to 2016, which were basically consistent with the evolution law of the torrential rainfall. The torrential rainfall and rain days in different months in China from 1961 to 2016 were the results of the combined effects of topography, rain belt shift under the control of the western Pacific subtropical high, urbanization and typhoon.

3.2. Spatial differentiation characteristics of torrential rain change trends in different months

The change trend can reflect the directional changes of torrential rain in China under the background of warming. The increasing torrential rain means that the region is facing a high risk of waterlogging, revealing the regional variation characteristics of torrential rain change trends in different months, which has reference significance for flood control, disaster reduction and the planning and utilization of water resources. From the trend of torrential rainfall, the increasing and decreasing trends of the torrential rainfall in different months in China from 1961 to 2016 were relatively small in the west of Hu Huanyong Line; while in the east of Hu Huanyong Line, the distribution area of the trends in different months gradually proceed from the south to the north and then gradually receded to the south, dominated by an increasing trend and supplemented by a decreasing trend.
Specifically, the increase and decrease of national torrential rain were relatively small in the months of January to February and December of 1961-2016, mostly between -5 and 5 mm/10a. Since it was just in the winter, there were fewer rain events, and due to the low temperature, snowfall events are dominant. The torrential rainfall in March showed a weak increase trend in the central part of Guangdong and the adjacent areas to Zhejiang, Jiangxi, and Fujian, mainly with an increase of 5-10 mm/10a. In April, the torrential rainfall presented a decreasing trend in the adjacent areas to Guangdong and Guangxi, with a decrease of 10-20 mm/10a; In the area from the northern Hubei to Jiangxi, the torrential rainfall had a weak increasing trend with an increase range of 5-10 mm/10a. The trend of torrential rainfall in May increased and decreased alternatively in the east of the line from Tianjin to western Guangxi. In June, the torrential rainfall in the south of Huanghuai and its southern areas mainly trended to increase, among which the increases in the Yangtze River Delta, Pearl River Delta, and Guangxi were more concentrated, and the increases in the Pearl River Delta and Guangxi regions were greater than that in the Yangtze River Delta region. The torrential rainfall in July was mainly dominated by an increase trend in the south of Huanghuai, and the increase along the Yangtze River was larger than 20 mm/10a, while the Bohai Rim region mainly had a decreasing trend with a reduction of 5-20 mm/10a and had the largest decrease or decrease area of torrential rainfall in China in this period. In August, the torrential rainfall in Liaoning and the coastal provinces south of the Yangtze River increased significantly by more than 10 mm/10a, while that in the Beijing-Tianjin-Hebei region and eastern Guangxi showed a decreasing trend, with a reduction of more than 10 mm/10a. From June to August, the area of increasing and decreasing trends of the torrential rainfall in China is the largest and most significant, especially in areas with a high degree of urbanization in the southeast coast of China. The torrential rainfall in September showed a decreasing trend in Shanghai and its adjacent areas. At this time, the trend of the torrential rainfall in the coastal regions of South China was mainly increasing. In October, the torrential rainfall in central coastal areas of Guangdong showed a declining trend with a decrease of 10-20 mm/10a, while that in Hainan had an upward trend with an increase of more than 20 mm/10a in the meantime. In November, only a few stations in southern China had a weak increase in torrential rainfall. Similarly, the trend of torrential rain days in different months in China from 1961 to 2016 also showed the spatial evolution characteristics consistent with torrential rainfall.

Under the background of global warming, the atmospheric moisture saturation is increased. At the same time, the aerosol condensation nuclei in the atmosphere increase during the rapid urbanization process, and in the event of torrential rain, its intensity is bound to increase; Excessive aerosol condensation nuclei may also inhibit the occurrence of torrential rain events under appropriate water vapor conditions. This is mainly because excessive aerosols reduce the amount of water droplets that have condensed on the surface and fails to reach the torrential rain event, thus inhibiting it. In southern China, the source of water vapor is sufficient, and the increase of aerosol condensation nuclei is conducive to the increase of torrential rain events. In the north, there are fewer sources of water vapor than that in the south, and the increase of aerosol condensation nuclei inhibits the occurrence of torrential rain events. In addition, the frequency, intensity and duration of typhoon landfalls also affect the changes in torrential rainfall to some extent. Observations and studies in recent decades have shown that the number of typhoons landing in China has decreased slightly, the intensity of landfall has enhanced and the duration has increased, which provides favorable conditions for the increase of torrential rainfall in China.

3.3. Spatial differentiation characteristics of interannual variation of torrential rain in different months

Based on the coefficient of variation, the interannual variation of torrential rain in China from 1961 to 2016 were detected and could reflect the fluctuation characteristic of torrential rain events. Judging from the fluctuation characteristics of torrential rainfall, the torrential rainfall in different months in China increased with the month, and the regions with larger fluctuations first expanded from the southeast to the northwest and the northeast, while the fluctuation in the south was gradually decreased and then shrank further to the south. Specifically, the torrential rainfall in January fluctuated greatly in the south of the line from Shanghai to eastern Yunnan. In February, the regions with large fluctuations moved...
northward, mainly distributed in the south of the line from central Jiangsu Province to eastern Yunnan Province. In March, the fluctuations of the torrential rainfall began to shift to the northwest. The regions with large fluctuation were mainly in the east of the line from Tianjin to western Yunnan. The fluctuations in the south of the line from Shanghai to eastern Yunnan were smaller than that in the north. The areas with large fluctuations of torrential rain continued to move northwest in April, and among them, the fluctuations were relatively larger from the south of northeast China to the east of southwest China and in the northern part of east China, especially in western Liaoning and western Jilin, the fluctuations were the largest with agglomeration; the fluctuations in other southeastern regions were moderate; the northwest region has the smallest fluctuation. In May, the regions with strong fluctuations of torrential rainfall moved further northwest and began to break through the Hu Huanyong Line, basically distributed in the farming-pastoral ecotone. It is also the gathering area of China's climate fragile zones and key poverty counties. The northeast China, north China, and the middle and eastern parts of the Loess Plateau were the regions with the most fluctuation; at this time, the fluctuation in the south of Huanghuai was similar to that in the northwest. The areas with large fluctuations of torrential rainfall in June further pushed northward, and that in the northeast, central and eastern Inner Mongolia, north China and central and eastern Loess Plateau were larger; The southeastern region had relatively small fluctuations; There were scattered sites with large fluctuations in the northwest. The areas with the largest fluctuations of torrential rainfall in July were scattered in the northwestern region; The fluctuations in the northeast and Jiangnan were moderate; Huanghuai, Jianghuai and the west of northwest had relatively small fluctuations. The torrential rainfall in August fluctuated the most in Inner Mongolia, Ningxia and southern Gansu; The fluctuations in the northeast, north China and its south area were moderate; In northwest China, except for some stations, the overall fluctuation was relatively small. The regions with large fluctuations in September moved to the northeast, central and eastern Inner Mongolia, northern north China, and the central and eastern parts of the Loess Plateau; the areas with moderate fluctuations were concentrated in Huanghuai and its south areas; the northwest region had minimum fluctuations at this time. In October, the areas with large fluctuations of torrential rainfall began to retreat to the south, and the areas with the largest fluctuation were mainly concentrated in the Bohai Sea area and the eastern part of the southern section of Hu Huanyong Line; The south of the Yangtze River was in moderate fluctuation; The area near the west of the Hu Huanyong Line had the smallest fluctuation. The fluctuations of torrential rainfall in November and December were similar to those in March and February, respectively. The spatial correlation coefficients were 0.77 and 0.74 \((n=545)\), respectively, which passed the test at a significance level of 0.05. The fluctuation of the temporal and spatial evolution characteristics of the torrential rain days in different months in China from 1961 to 2016 were basically consistent with those of the torrential rainfall. During the winter half year, the number of torrential rainfall events in northern China, so the interannual variation was almost zero. The torrential rain events in the north in the summer half year were affected by factors such as ENSO and urbanization, so the interannual variation was large. In south China, due to the relatively small interannual difference of torrential rain events during the summer half year, the fluctuations were small; In the winter half year, the typhoons and the air-sea circulation factor were abnormal, so the fluctuations were relatively large.

4. Risk prevention and policy suggestions

(1) The variation characteristic of torrential rain events becomes more prominent in the context of warming. In the northern China, it is necessary to strengthen precautionary measures in advance for urban waterlogging induced by torrential rain in the summer half of the year, while in the south, it requires to pay close attention to the waterlogging disasters induced by torrential rain throughout the year. The government department can estimate the flood and waterlogging index insurance designed by insurance and reinsurance companies for the industries in the key fields, to rationally diversify the risk pressure through non-engineering financial measures.

(2) The number of torrential rain events in coastal areas has increased. On the one hand, there have been more extreme precipitation events due to climate warming; on the other hand, there have been new
changes in the intensity and duration of torrential rain brought by typhoons and cyclone, which require systematic assessment. Fortification in coastal cities needs to pay high attention to key time periods and key areas, enhance the weaknesses, improve the average fortification capability, and also strengthen the fortification of vulnerable points, conduct routine inspections on disaster risk, and prevent systemic risks caused by a bit of breakdown through engineering measures and strategic development inputs.

5. Conclusion and discussion

5.1. Conclusion

(1) In terms of climatic state characteristics, the climatic state characteristics of torrential rainfall and rain days in different months in China from 1961 to 2016 had similar spatial differentiation characteristics. In July, the high-value areas of torrential rainfall and rain days were the most widely distributed, mainly concentrated in the east of Hu Huanyong Line. The torrential rainfall and rain days in different months were the least distributed in the west of the Hu Huanyong Line. During the period from January to July, the torrential rainfall and rain days were increased from the southeast coast to the northwest with month; from August to December, the torrential rainfall and rain days were reduced from northwest to southeast with month. The monthly distribution of torrential rainfall in China was closely related to the shift of frontal rain belts, and was also potentially affected by factors such as water vapor and urbanization.

(2) In the trend of change, the change trend of the torrential rainfall and rain days in different months in China from 1961 to 2016 had similar spatiotemporal evolution characteristics. The change trend of torrential rain in the summer half year was more significant than that in the winter half year. Among them, the torrential rainfall and rain days in China had the most significant change trend from May to August, mainly concentrated in the southeast monsoon region. Due to the less torrential rainfall and fewer rain days, there was little obvious change in the trends in different months.

(3) In terms of interannual variation, the fluctuation characteristics of the torrential rainfall and rain days in different months in China from 1961 to 2016 were similar. From January to July, the areas with large fluctuation of the torrential rainfall and rain days expanded from southeast to northwest, northeast and southwest, and the fluctuation in the southeast was gradually decreased. From August to December, the areas with large fluctuation of the torrential rainfall and rain days were reduced from northwest, southeast and southwest to southeast, and the fluctuation in the southeast was gradually increased. The torrential rainfall and rain days in northern China fluctuated greatly from April to October; the periods from January to March and from November to December had the largest fluctuation in the south.

5.2. Discussion

As the degree of variation in torrential rain events increases, systematic assessment on the risk of waterlogging induced by torrential rain in different months has become an important issue for sustainable urban development [54-56]. Especially for the urban agglomerations in eastern Chinese, the population and wealth continue to accumulate. Sudden high-intensity torrential rain events tend to have an increasing impact on the urban safe operation and various types of disaster-bearing bodies by damaging infrastructure such as transportation networks. Once the tolerance threshold is exceeded, the urban lifeline system will be blocked, with serious consequences. Therefore, it is necessary to carry out risk assessment on urban waterlogging induced by torrential rain in different months or on more fine scale in the context of changing. On this basis, it is also urgent to explore the dynamics and thermal mechanisms of urban human activities on regional torrential rain. Especially when the depth, breadth and intensity of human activities are increasing and human activities affect regional circulation factors, it also significantly changes the stability of the hazard inducing environment, the risk of hazard factors and the exposure and vulnerability of disaster-bearing bodies. Therefore, through observation and model simulation, detecting the evolution and causes of waterlogging induced by torrential rain and determining the impact of human activities on waterlogging induced by torrential rain, have become a common scientific and management issue for academic circles including IPCC.
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