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Spatiotemporal patterns and driving factors of flood disaster in China

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Abstract: Flood is one of the most disastrous disasters in the world inflicting massive economic losses and deaths on human society, and it is particularly true for China which is the home to the largest population in the world. However, no comprehensive and thorough investigations have been done so far addressing spatiotemporal properties and relevant driving factors of flood disasters in China. Here we investigated changes of

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flood disasters in both space and time and their driving factors behind using statistical data of the meteorological disasters from Statistical Yearbooks and also hourly rainfall data at 2420 stations covering a period of 1984-2007. GeoDetector method was used to analyze potential driving factors behind flood disasters. We found no consistent extreme rainfall trend across China with exceptions of some sporadic areas. However, recent years witnessed increased frequency of rainstorm-induced flood disasters within China and significant increase in the frequency of flood disasters in the Yangtze River, Pearl River and Southeastern coasts. Meanwhile, reduced flood-related death rates in the regions with increased flood frequency indicated enhanced flood-mitigation infrastructure and facilities. However, increased flood-induced affected rates and direct economic losses per capita were found in the northwestern China. In addition, contributions of influencing factors to the spatio-temporal distribution of flood disasters analyzed by GeoDetector are shifting from one region to another. While we found that rainfall changes play the overwhelming role in driving occurrences of flood disasters, other factors also have considerable impacts on flood disasters and flood disaster-induced losses such as topographical features and spatial patterns of socio-economy. Wherein, topography acts as the key factor behind the characteristics of spatial distribution of flood disasters in China.

Key words: Rainstorm-induced flood disasters; Heavy rainfall; Driving factors; GeoDetector

1. Introduction

China is the largest country in terms of population and is amongst the most flood-prone countries worldwide, inflicting an average of 4327 deaths per year since 1950, and 20-billion-dollar direct economic losses per year during 1990-2017 (Ye et al., 2018). Due to its special geographical location and massive impacts from the East Asian monsoon, the floods caused by heavy rains are particularly serious and strong in some regions of China (Chen and Sun, 2015). The past 50 years and in particular since 1990s China witnessed significantly enhanced frequency and intensity of extreme weather events due to warming climate (Zhang et al., 2013), thus severe floods occurred more often than before (Shi et al., 2004). Besides, rapid urbanization over China in recent years triggers spatial gathering of population and wealth over the flood plains and hence aggravated flood risk can be well expected (Li et al., 2016b; Du et al., 2018). The complex combinations of changes in hydro-meteorological extremes and increasing impacts of human activities can have paramount effects on the frequency and magnitude of flood disasters (Zhang et al., 2015b). Therefore, it is of great importance to comprehensively understand the temporal and spatial changes of flood disasters and the influencing factors behind under the context of the global warming, which provides countermeasures to flood risk management and reduces loss of life and property.

Global warming as a result of human-induced emission of greenhouse gases is accelerating the global hydrological cycle (Arnell, 1999; Allen and Ingram, 2002; Zhang et al., 2013). Meanwhile, the accelerated hydrological process is altering the spatial-temporal patterns of rainfall which can trigger increased occurrences of rainfall extremes (Easterling et al., 2000) and in turn increased occurrences of floods and droughts in many regions of the world (Easterling et al., 2000; Hu et al., 2018). Willner et al. (2018) indicated that changes in the hydrological cycle can cause a strong increase in globally aggregated direct losses due to fluvial floods. Besides, large direct losses were observed in China, the United States, Canada, India, Pakistan and various countries of the European Union (Willner et al., 2018), which implies that, with the current regional river protection level or without further adaptation efforts, large parts of densely populated areas will experience more floods in the future due to an increase in rainfall extremes (Willner et al., 2018). These findings also evidenced critical relations between rainfall extremes and flood risks over the globe. Hirabayashi et al. (2013) indicated that, in certain areas of the world, flood frequency is projected to decrease. Van Vuuren et al. (2011) indicated that the global exposure to floods would increase depending on the degree of warming, but inter-annual variability of the exposure may imply the necessity of adaptation before significant warming. Therefore, massively increasing human concerns have been attached to floods and relevant losses of human life, society property and also socio-economy (Van Vuuren et al., 2011; Willner et al., 2018). In this case, flood means much for human society and it is particularly the case for China, a country with the largest population and fast economic growth rate. This point constitutes the significance of this study.

Numerous studies have been done addressing changes of flood disasters over China. Some studies focused on the temporal and spatial changes of flood disasters based on meteorological and hydrological datasets and also historical statistical data (Zhang et al., 2015a; Zhang et al., 2018b) and impacts on social economy in provincial administrative units at national scales (Huang et al., 2012). Besides, previous studies analyzed the flood disasters from the perspective of the trends of frequency, intensity and other characteristics of extreme rainfall events (Jiang et al., 2007; Zhang et al., 2008; Lu and Fu, 2010; Zhang et al., 2015a). While, some studies focused on flood disaster risk assessment at watershed or national levels (Li et al., 2016a). However, few studies were reported addressing flood disasters at county scales in China. Wang et al. (2008) firstly investigated the spatiotemporal patterns of flood and drought disasters in county-level administrative units across China using data collected from newspapers, which provided a scientific basis for flood risk identification. Li et al. (2018) firstly adopted county-level meteorological disaster census database reported by meteorological departments across China, combined with daily rainfall observations from national meteorological stations to analyze the relationship between extreme rainfall and impacts of flood disasters, no evident relationships were found between high-value areas of heavy rain and regions of severe flood disasters. It should be clarified that flood disaster is a highly complex system involving flood hazard, disaster formative environment and exposure (Shi, 2002). Thus, a variety of environmental and human-related factors need to be included for further investigation of this subject and to better understand the mechanism behind flood disasters. This is the major motivation behind this current study.

In this study, spatiotemporal variations of flood disasters across China were analyzed. The major objectives of this study are to: (1) differentiate extreme rainfall changes and flood disasters at county-level across China based on statistical records from Statistical Yearbooks and also in situ observed rainfall; (2) to quantify fractional contribution of different influencing factors such as land use and land cover change and socio-economic characteristics to floods; and (3) to deepen human understanding of the mechanism behind the occurrence of flood disasters. What's more, we should emphasize the significance of this current study in global sense that China is the largest country in population with about 70% of population along the coastal regions (Zhang et al., 2017) and with massive exposure to natural disasters such as floods in this current study. In this sense, this current study provides a pretty typical case study for global human mitigation to floods disasters. Therefore, hydrometeorological extremes in China have been arousing increasing international concerns (Zhang et al., 2013, 2016, 2017, 2018b). Besides, China is located in the East Asia, eastern part of the largest Eurasia continent, and western edge of the largest Pacific Ocean. Furthermore, booming urbanization, fast development of water infrastructures, intensifying land use and land changes and so on, result in considerably complicated driving factors behind floods. Hence, it is of great scientific significance to develop human knowledge in flooding behaviors in a backdrop of complicated changing environment. Moreover, it is acknowledged to understand flooding behaviors from a global perspective. However, the first step is to obtain detailed information of flooding changes at regional scale. It is always useful and helpful to understand flooding behaviors at global scale based on deep understanding of flooding changes at regional scale. In this sense, this current study is theoretically and scientifically significant in development of human knowledge of flood disasters in a changing environment at regional and global scales.

2. Data

The datasets analyzed in this study included the national county-level meteorological disaster census database collected from the historical meteorological disaster dataset of the National Climate Center and Yearbook of Meteorological Disasters in China (http://data.cma.cn/data/cdcindex/cid/8e65c709b3220e70.html). The definition of flood disaster in this dataset was in accordance with Wen and Ding (2008). This dataset involves 96 indicators describing each individual severe weather-related disaster events based on the county-level administrative units from 1980-2008 with daily temporal resolution. Besides, this database includes 16 items describing the severe weather events, i.e. occurrence timing, locations, impact on society, agriculture, water resources, industry and traffic facilities as well. This database includes the data by the Ministry of Civil Affairs and the quality was firmly controlled before its release.

Based on data integrity and the continuity of time series, the flood-affected population, the flood-induced deaths and the direct economic loss during 1984 to 2007 were analyzed in this study. Besides, we sorted out and verified each flood disaster events to keep rigorousness of the dataset. Moreover, we also screened out rainstorm-induced floods that have greater impacts on human society. Specifically, the entry criteria for rainstorm-induced floods are referred to the access standards from the international disaster databases and relevant literatures (Guha-Sapir et al., 2017). The entry criteria are set as follows: (1) Deaths: 1 death or more deaths; (2) Flood-affected population: 100 or more people are affected by floods. (3) Damaged cropland: 66700 or more hectares of croplands were affected by floods (the major economic loss is caused by flood disaster events over the threshold of 66700 hectares, which is analyzed by Li and Xu (1995)). (4) Damaged reservoirs: 1 or more water reservoirs were damaged.

The hourly rainfall data were obtained from 2420 in situ observatory stations (http://data.cma.cn/). The quality of the hourly rainfall data was firmly controlled before its release (Zhang et al., 2018a). In addition, we also analyzed the total population, non-agricultural population, Gross Domestic Product (GDP), elevation and river system data for attribution analysis (shown in Fig. 1). The population data were collected from the national demographic yearbook, and the GDP data from China's county (city) socio-economic statistical yearbook. Moreover, we also used the Digital Elevation Model (DEM) obtained from the US National Atmospheric and Oceanic Administration (GLOBE Task Team et al., 1999) and also the river system data collected from the National Catalogue Service For Geographic Information (http://www.webmap.cn/commres.do?method=result100W).

3. Methods

3.1 Definition of separated rainfall events

In this study, separated rainfall events were defined using the conceptual and statistical method proposed by Gaal et al. (2014): The autocorrelation method was used to differentiate the rainless intervals by the Pearson correlation coefficient of the hourly rainfall series. When the autocorrelation coefficient dropped below a predefined significance level, i.e. 5% in this study, the time lag was taken as the waiting time between separated rainfall events. Fig. 2 illustrates the autocorrelograms of hourly rainfall series at three stations. It can be seen from Fig. 2 that the lag time is about 10 hours when the autocorrelation coefficient drops below the 5% significance level, so 10 hours were taken as the waiting time between individual rainfall events.

Stations with missing data of > 1% of the total rainfall data were excluded from the analysis. Therefore, hourly rainfall data at 1876 stations were analyzed in this study. The missing data were processed based on the procedure by Zhang et al. (2018a). Rainfall values of < 0.1 mm/h were replaced with zero (Gaal et al., 2014). The spatial patterns of stations included into/excluded from the analysis of this study were illustrated in Fig. 3. In Northern China, hourly rainfall can be observed during flooding season only. Therefore, the rainfall decadal variability during flooding season were analyzed.

3.2 Detection of trends in rainfall extremes and Kernel density estimation technique

The Modified Mann-Kendall (MMK) trend test method (Daufresne et al., 2009) was used to evaluate trends in rainfall extremes in this study. Besides, Kernel density estimation (KDE) method was used to quantify the occurrence rate of the historical flood disaster events. The KDE was used to evaluate the density function of random variables following unknown distribution and to figure out the distribution characteristics of the time series considered in this study. This method has been widely used in distribution evaluations due to the fact that this method does not need assumption of probability distributions (Mudelsee et al., 2003; Zhang et al., 2018b). Below is the estimation of occurrence rates:

$$\lambda(t) = h^{-1}\sum_{i=1}^{m} K\left(\frac{t-T_i}{h}\right) \quad (1)$$

where T_i denotes the occurrence timing of the i^{th} flood event; m denotes the total number of events; K(·) denotes the Kernel function in this study, the Gaussian kernel function was applied (Mudelsee et al., 2003); h denotes the band width. The optimal window width was determined by the unbiased cross-validation test (Cowling et al., 1996); λ(t) indicates the number of extreme events exceeding threshold given a certain time interval, t.

3.3 The GeoDetector for attribution analysis

In this study, the GeoDetector method was used to investigate influencing factors behind flood disasters. The GeoDetector is a set of statistical methods that detect the spatial variations of a variable and relevant driving forces behind (Wang and Hu, 2012; Li et al., 2013; Onozuka and Hagihara, 2017). This method follows the assumption that given an independent variable, Y, that has an important influence on a dependent variable X, the spatial distribution of Y and X should concur and hence allows for spatial similarity. The degree of the association between X and Y could be measured by q statistics:

$$q = 1 - \frac{1}{N\sigma^2}\Sigma_{h=1}^{L} N_h\sigma_h^2 \quad (2)$$

where N denotes the number of units of Y in the study area; σ^2 denotes the variance of Y; L denotes the L strata subdivided by the variable X (h = 1, 2, …, L). Different discretization schemes can modulate the q values to some extent. Thus the optimal discretization method that has the highest q value was accepted based on the procedure by Cao et al. (2013). N_h denotes the number of units of Y in the stratum h; σ_h^2 denotes the variance of Y in the stratum h. The value of $q\epsilon[0, 1]$. The higher q means the higher association between Y and X. In this study, Y denotes the indexes (flood-induced deaths, flood-affected people and flood-induced economic losses) of flood disasters, and X denotes the influencing factors as discussed in the Discussion section. Detailed introduction of the algorithms and relevant software scripts can be found at http://www.geodetector.org/.

4. Results

4.1 Trends in the annual maximum rainfall

Trends of annual maximum rainfall (AMR, the largest one-day precipitation amount during one year) were evaluated (Fig. 4). It can be observed from Fig. 4a that stations with different trends of AMR distributed in an exchangeable way. However, relatively discernable spatial pattern of stations with increasing and/or decreasing AMR can still be observed. Increased AMR was observed mainly in southeastern and central-eastern China, or specifically in the middle Pearl River basin, southeastern parts of the Yangtze River basin, the Huai River basin and the lower Yellow River basin. The AMR at 914 out of 1876 stations was in increasing tendency and significant increasing trends can be observed at 102 out of 1876 stations (Fig. 4a). Decreased AMR can be found mainly in the lower and upper Yangtze River basin, the upper Pearl River basin and Hai River basin. Besides, the northeastern China was dominated by decreased AMR. Significantly decreased AMR can be detected at 70 out of 1876 stations across China, and 790 out of 1876 stations were dominated by insignificant decreasing tendency of AMR. In this

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sense, the amount of the AMR was in moderate changes. Spatial pattern of the trends in the rainfall duration (Fig. 4b) follows the similar spatial pattern of the trends in the amount of AMR. However, few stations were dominated by significant decreasing (65)/increasing (69) rainfall duration. In this sense, rainfall duration was also subject to no significant trends across China. When it comes to spatial pattern of trends in rainfall duration, lengthening rainfall duration was found mainly in southern China and in the lower Yellow River basin, and in the Huai River basin as well. Shortening rainfall duration was observed mainly in the lower Yangtze River basin and northeastern China. Fig. 4c shows distinctly different spatial pattern of the trends in the rainfall intensity when compared to that of the AMR and rainfall durations (Figs. 4a, 4b). No confirmable and discernable spatial pattern can be identified for rainfall intensity of the AMR (Fig. 4c, the rainfall intensity of the maximum rainfall event per year). Stations with increasing rainfall intensity distributed amidst those with decreasing rainfall intensity in an even and exchangeable way. Statistically, significantly increased rainfall intensity was observed at 93 out of 1876 stations and 47 out of 1876 stations were dominated by decreased rainfall intensity. Increased rainfall intensity can be identified at 971 stations and decreased rainfall intensity can be observed at 765 stations.

The spatial and temporal evolutions of the rainstorm indexes were analyzed (Fig. 5). The rainstorm event was defined by the rainfall event with rainfall amount of > 16 mm/h in this study. We used a range of spatial interpolation methods in spatial interpolation analysis in this study and we found similar spatial patterns (figures now shown here). Besides, the Inverse Distance Weighted (IDW) interpolation method was widely used and spatial patterns by IDW are similar to the actual situation. Therefore, we accepted the IDW method in spatial interpolation analysis. It can be seen from Fig. 5 that less rainstorm amount was found mainly in the northwestern, northern and

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northeastern China. Besides, most parts of the Tibet Plateau was also dominated by less rainstorm amount, e.g. < 450 mm and even < 150 mm. However, larger rainstorm amount was observed mainly in the central and southeastern China and parts of the eastern China. Left panel graphs indicated expanding regions with smaller rainfall amount from 1980s to 2000s, and it is particularly the case in the northeastern China. While, shrunk regions with less rainstorm amount were found in northwestern China during 1991-2000. Meanwhile, regions with larger rainstorm amount during 1991-2000 were found mainly in the middle and lower Yangtze River basin and also in the Pearl River basin. However, regions with larger rainstorm amount during 2001-2007 were found mainly in the Pearl River basin. These results may imply amplification of droughts across China over the time with higher drought risks. Similar spatial and temporal evolution pattern of rainstorm duration was found (right column of Fig. 5). Regions with shorter rainstorm duration expanded during last decades and it is particularly true in recent decade. What's more, larger area of regions with longer rainstorm duration shrunk in recent years. Significant and widespread shrinking regions with longer rainstorm duration imply higher probability of intense precipitation processes and hence higher probability of floods and/or flood disasters.

4.2 Spatiotemporal variations of flood frequency

The occurrence rates of flood events were evaluated in seven sub-regions of China subdivided based on their geographical divisions (Fig. 6). Increased flood frequency can be observed during 1984-2007, the study period considered in this study. Generally, similar temporal patterns of flood frequency can be found in Northeastern China, Eastern China, Northern China and Central China, i.e. three time intervals with higher flood frequency and two time intervals with relatively lower flood frequency can be identified. Time intervals with relatively higher flood frequency are respectively 1984-

1990, 1991-2000 and 2001-2007. Two time intervals with relatively lower flood frequency are respectively 1992-1994 and 2000-2003. However, Except for the continuous increasing tendency in the Northwest and Southwest China, there was a decreasing trend during a period of 2000-2003. Larger fluctuations can be found in flood frequency changes in Northeastern, Eastern, Northern and Central China. While, relatively smaller fluctuations in flood frequency changes can be observed in Southern, Northwestern and Southwestern China. Particularly, the Southwestern China is dominated by persistently increasing flood frequency with moderate fluctuations. While, sharp increase and abrupt decrease of flood frequency can be observed at two ends of the flood series (Fig. 6), which can be attributed to boundary effects of the flood series since that fewer data are available at two ends of the time series with larger uncertainty.

Three time intervals with higher flood frequency were analyzed to calculate the annual average frequency, mortality (per million people), the flood-affected rate (%) and the economic loss per capita (unit: RMB converted into 2007 price) (Figs. 7, 8). It can be seen from Fig. 7 that Three time intervals with higher flood frequency were analyzed to calculate the annual average frequency, mortality (per million people), the flood-affected rate (%) and the economic loss per capita (unit: RMB converted into 2007 price) (Figs. 7, 8). It can be seen from Fig. 7 that higher flood frequency can be observed in the Yangtze River basin, the Yellow River basin and also in the Pearl River basin. Besides, larger flood frequency can also be detected in the northeastern China. While, higher flood frequency during 1991-2000 was significantly higher than that during 1984-1990. Increased flood frequency during 1991-2000 when compared to that during 1984-1990 was detected mainly in the middle and lower Yangtze River basin and also the Pearl River basin. Comparatively, reduced flood frequency can be found in northern and northeastern China during 1991-2000 when compared to that during 1984-1990. Besides, more regions with larger flood frequency were found during 1991-2000 than that during 1984-1990. The time interval of 2001-2007 was characterized by even higher flood frequency when compared to that during other two time intervals, i.e. 1984-1990 and 1991-2000. Specifically, high flood frequency can be found in the southwestern China, southern China, southeastern China and also almost entire Yangtze River basin. Particularly, higher flood frequency can also be observed in some counties in northwestern China.

Decadal changes in the annual number of deaths due to floods per year (Fig. 7) indicated sporadic distribution of flood-induced mortalities across China. Higher mortalities can be found in central and southern China. It is surprising to find that some counties in the northwestern China were also dominated by higher flood-induced losses (Zhang et al., 2016). Zhang et al. (2012) indicated that, after 1980, the Xinjiang region in northwestern China is exhibiting a wetting tendency, and the heavy precipitation extremes tend to occur more severely and frequently. However, the spatial pattern of the flood-induced mortalities (Fig. 7) are different from that of the flood frequency. Less counties were characterized by high mortalities during 1991-2000 when compared to that during 1984-1990. Specifically, sharp decreased flood-induced mortalities can be found in the middle and the lower Yangtze River and also in the Pearl River basin. Besides, significant decrease of flood-induced mortalities can also be found in northeastern China. It is easy to understand that the eastern and central China is highly economically developed with booming development of socio-economy, and enhanced human mitigation to floods by construction of levees and flood-mitigated infrastructure (Ye et al., 2018). However, the mortality rate of some counties in the northwestern China and northern China such as Xinjiang and Inner Mongolia was in increasing trends.

This finding can be attributed to increased rainfall and fast melting snow and ice due to warming climate (Wen and Song, 2006; Zhang et al., 2016)(…). Besides, lower development of socio-economy in these regions also make these regions susceptible to flood disasters.

Fig. 8 illustrated spatiotemporal evolutions of the flood-affected rate (ratio of the annual average flood-affected people in the study period to the totalpopulation in each county) and the direct economic loss per capita in the eastern and central parts of China. It can be easily observed from Fig. 8 that the flood-affected rate and the direct economic loss per capita are both increasing during the entire study period in both space and time (Fig. 8). The Yangtze River basin was in the dominant position in the flood-affected rate and the direct economic loss per capita. In addition, the flood-affected rate and the direct economic loss per capita are also in evident increase in the Pearl River basin. It should be noted here that the northwestern China and parts of the Tibet Plateau are also dominated by increased flood-affected rate and the direct economic loss per capita. Besides, difference was still identified in spatial pattern for the flood-affected rate and the direct economic loss per capita. Larger increase of the direct economic loss per capita than the flood-affected rate can be found in central, eastern, southern and northeastern China. Particularly, widespread and larger magnitude of increase in the direct economic loss per capita can be observed in northwestern China and in northern parts of the northwestern China in particular.

At the same time, it is worth noticing that the storm related floods in the northwest region, especially in the Northwest River Basin in Xinjiang, have continued to increase during the study period. Due to the lack of rainfall stations in the northwest, it is hard to completely determine whether this phenomenon and the increase in extreme rainfall are Related, but combined with Figure 7, it can be seen that the increase in social vulnerability is an important factor.

5. Discussions

Fig. 9 demonstrated spatial pattern of the cumulative rainfall amount and cumulative rainfall duration of each county. Relatively complicated spatial pattern can be identified for rainfall amount and rainfall duration. However, persistently increasing rainfall amount and rainfall duration can be found along the northwest to southeast and along the north to south directions. Meanwhile, Fig. 9 also clearly indicated expanding regions with smaller rainfall amount and shortening rainfall durations. This finding indicated amplifying droughts in northern and northwestern China with higher drought risks but higher flood risks in southern China and southeastern China. Besides, spatial pattern of precipitation extremes and that of flood disasters did not match well. It is easy to understand that regions for production and confluence of runoff are often not similar to those with occurrence of precipitation extremes (Zhang et al., 2015b). In addition, influences of human activities and precipitation changes on streamflow are varying for specific river basins. Damming-induced fragmentation of river basins is the major cause behind higher homogenization of flow regimes (Zhang et al., 2015b). Moreover, occurrence of floods do not always mean occurrence of flood disasters. Flooding processes are mostly natural processes. However, flood disaster is closely related to human factors such as socio-economy and population (Viero et al., 2019). All these factors trigger spatial mismatch between floods, flood disasters, and precipitation extremes. Furthermore, building of hydraulic infrastructure also modified spatial match

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of floods, flood disasters and precipitation extreme (Zhang et al., 2015b).

Besides, the results of this study indicated increased flood frequency in both space and time. Specifically, the Yangtze River basin and Pearl River basin and the coastal regions of eastern China were dominated by higher flood frequency. However, the flood-induced death rates were decreasing in both space and time. While, remarkable increase of flood-affected people percentage and flood-induced direct loss per capita can be found in central and eastern China. Closer look is necessary on other factors besides precipitation extremes behind flood disasters and flood-induced losses in human life and economy. In this study, nine factors were selected for attribution detection based on previous researches (e.g. Hu et al., 2018), i.e. urbanization rate (the proportion of non-agricultural population in the county) (UR), population density (PD), GDP per unit area (GDPD), average elevation (ELE), river network density (RD), average slope (SLP), distance of county's geometric center from shoreline (DS), annual average heavy rainfall (VR) and annual average rainstorm duration (DR) (Fig. 10). The results were evaluated by $q(q \in [0,1])$ statistics, which indicated that a factor explains the $100 \times q\%$ of the dependent variable. The larger the q, the stronger the explanatory power of an independent variable to the spatial pattern of the dependent variable. The interpretation rate of the spatial differentiation rules of the three disaster indicators of three research periods was shown in Fig. 10.

During 1984 and 1990, the interpretation of each factor to the affected population was relatively weak (Fig. 10a). During the period of 1991-2000, the influence of elevation, distance from the coast, heavy rainfall, and rainstorm duration on floods and/or flood disasters was significantly enhanced. With booming development of socio-

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economy of China and fast growing population, population density and GDP per square kilometers were growing fast and all these factors gathered along the low-lying plains and along the coastal regions as well. For example, almost all megacities in China are located along the coastal regions of China such as Jing-Jin-Ji, The Yangtze Delta and the Pearl Delta regions, and these regions are highly developed with socio-economy, high-level development of science and technology. Therefore, these regions are always densely populated. Population in eastern China accounts for more than 70% of the total population of the country (Zhang et al., 2017). Therefore, these regions are usually dominated by increased flood-induced people percentage. What's more, the middle and the lower Yangtze River basin and also the Pearl River basin are often hit by flood disasters. The Yangtze Delta and the Pearl River Delta are densely populated with highly developed socio-economy. Therefore, these regions are dominated by higher flood-affected people percentage and higher flood-induced direct loss per capita.

Furthermore, the eastern China is characterized by low-lying terrain and this kind of topographical condition is highly sensitive to flood inundation with dense river networks. Therefore, the impact of river network density in geographical factors is also increased, indicating that the influence of low-lying terrain, high population density reflected by urbanization on rainstorm-related flood disasters is increased persistently. The main factors affecting the mortality rate were the elevation, slope, population density, GDP unit area, distance from the coast, and river network density between 1984 and 2000. The geographical factors and socio-economic factors affect the spatial pattern of the flood-induced death rate. However, after 2001, the effect of above-mentioned factors on the flood-related mortality has been greatly reduced. Fig. 7 also indicated that the number of deaths due to floods has dropped significantly across the country during 1984-2007, indicating the improvement of emergency management capabilities and enhanced human mitigation to flood disasters over the country. It can be seen from Fig. 10c that the main factors affecting the per capita economic loss from 1991 to 2000 were urbanization rate, elevation and distance from the coast, which implied that social wealth mainly distributed in the coastal regions and/or low-lying areas. However, the effects of these influencing factors also decreased since 2001, reflecting to some extent the improvement of flood prevention and mitigation capabilities along the coast.

6. Conclusions

China is the largest country in terms of population, and is also the second economic body of the planet. Floods have been inflicting massive losses of human lives and socio-economy and higher flood risk can be expected in a warming climate. Therefore, thorough understanding flood disasters and related driving factors will be of paramount importance in both practical and theoretical sense. In this study, the spatiotemporal pattern of rainstorm-related flood disasters was analyzed with respect to trends during 1984-2007. The above-mentioned results can help to achieve the following interesting and important scientific viewpoints:

(1) Rainfall extremes in terms of rainfall amount and rainfall duration follow no confirmative spatial pattern. Generally, increased rainstorm amount and rainstorm duration were found mainly in the lower Yangtze River basin and the middle and the lower Pearl River basin. Besides, the Huai River basin was also dominated by increased rainstorm amount and rainstorm duration. Rainstorm intensity was in complicated spatial pattern. Stations with increased rainstorm intensity distributed sporadically with stations with decreased rainstorm intensity in an exchangeable way. Besides, regions with less rainstorm amount and shorter rainstorm duration were expanding and vice

versa. This finding implies amplifications of floods and droughts concurrently.

(2) More and more counties in the central, southern, southeastern and southwestern China were characterized by higher flood frequency. However, counties with high flood-induced deaths decreased significantly, indicating enhanced human mitigation to flood disasters. While, counties with increased flood-affected people and increased direct economic loss can be identified in central and southern and southeastern China, specifically the middle and lower Yangtze River basin, and the middle and the lower Pearl River basin as well. It is surprising to find that some counties in the northwestern China and northeastern China were also dominated by higher flood-induced mortalities, which was corroborated to be the reason of a wetting tendency in the northwestern China and the heavy precipitation extremes tend to occur more severely and frequently.

(3) There are many factors influencing spatiotemporal pattern of flood disasters and relevant impacts on society. Spatial mismatch between precipitation extremes and floods was attributed to many other factors. Besides, booming development of socio-economy and fast growing population in China triggered fast growing population density and GDP per square kilometers. Generally, the low-lying plains and coastal regions are usually densely populated with high density of GDP. Therefore, these regions are dominated by increased flood-induced people percentage and increased direct loss of economy, and increased flood-induced direct loss per capita as well. Furthermore, the eastern China is characterized by low-lying terrain and which is highly sensitive to flood inundation with dense river networks. Therefore, the impact of river network density in geographical factors also increased, indicating that the influence of low-lying terrain, high population density reflected by urbanization on rainstorm-related flood disasters increased persistently.

Author contribution: PH designed and carried out the experiments, and wrote the initial version of this manuscript. QZ and CYX reviewed and improved the main text; SS and JF helped to improve the quality of the figures.

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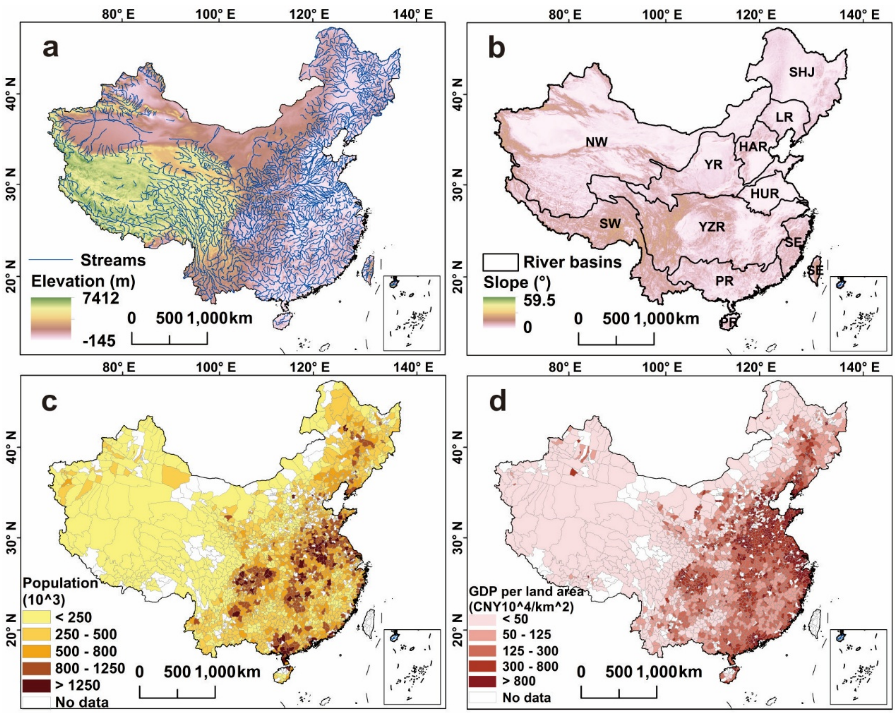

Fig. 1. Spatial distribution of (a) River streams (1:1,000,000) and elevation; (b) River basins (NW-Northwest river systems; SW-Southwest river systems; YR-Yellow River; YZR-Yangtze River; PR-Pearl River; SE-Southeast river systems; HUR-Huai River; HAR-Hai River; LR-Liao River; SHJ-Songhua River) and slope; (c) Population; (d) GDP per land area (2006).

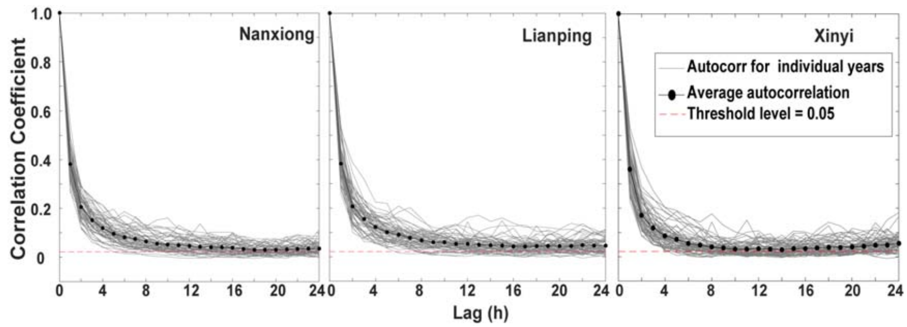

Fig. 2. Autocorrelograms for the selected three stations

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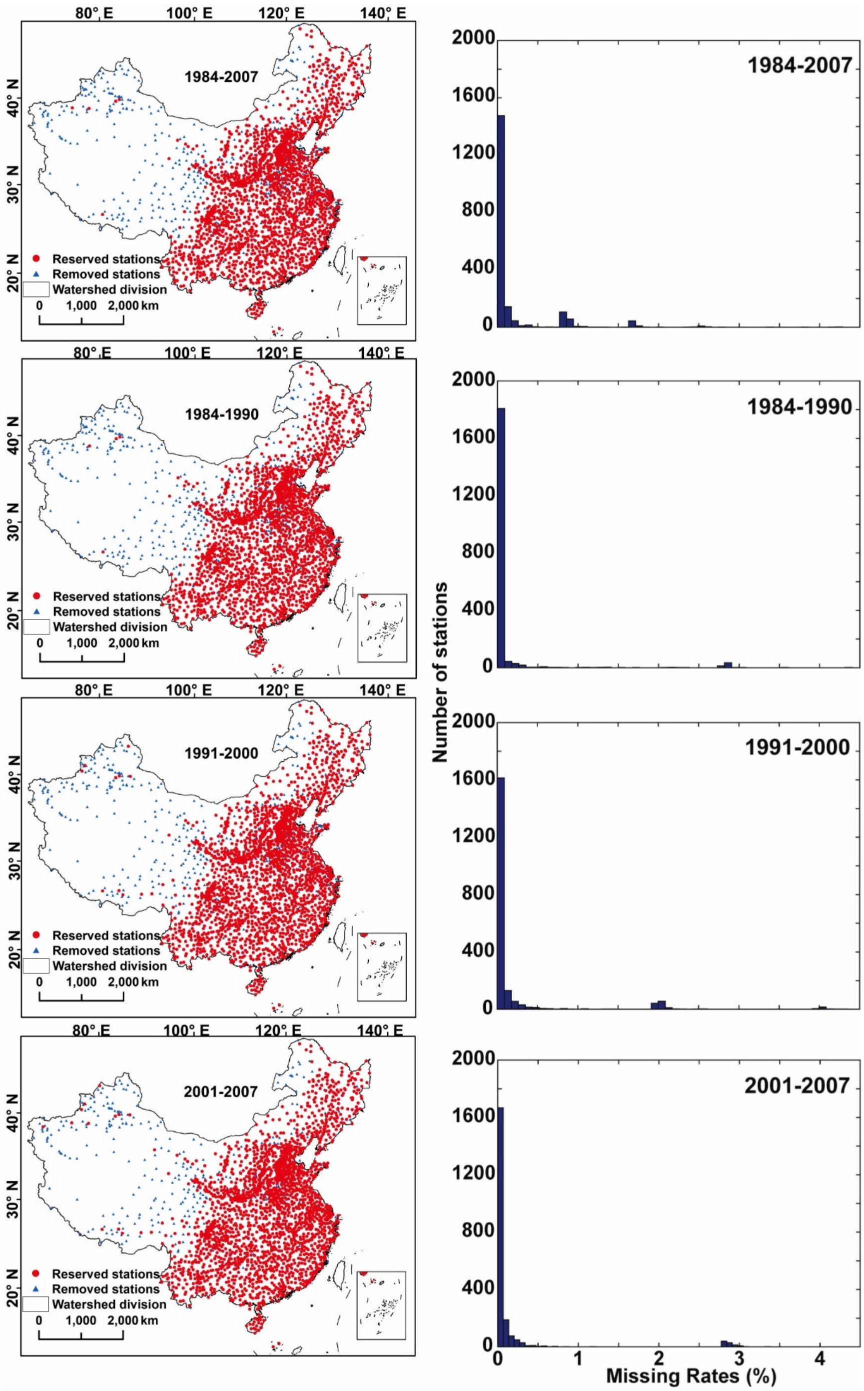

Fig. 3. Stations screened out for analysis in this study and missing rates of the data during different periods

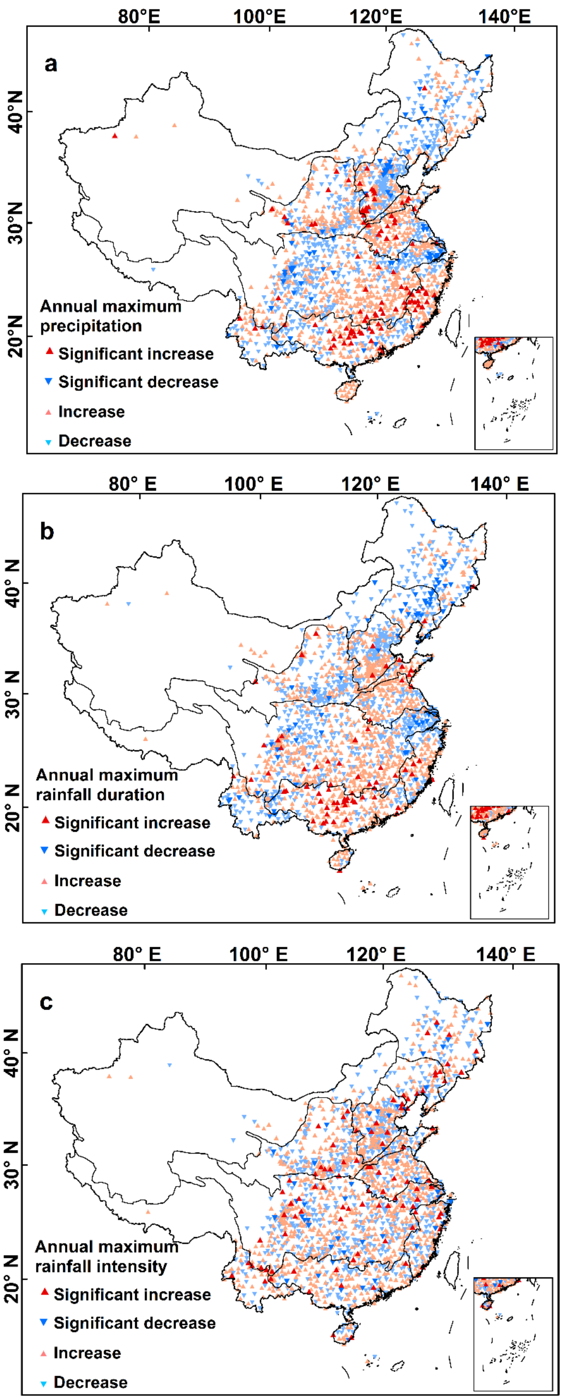

Fig. 4. Trend analysis of the maximum extreme rainfall events (a: annual maximum precipitation trend during 1984-2007; b: trend of annual maximum rainfall duration during 1984-2007; c: trend of annual maximum rainfall intensity during 1984-2007)

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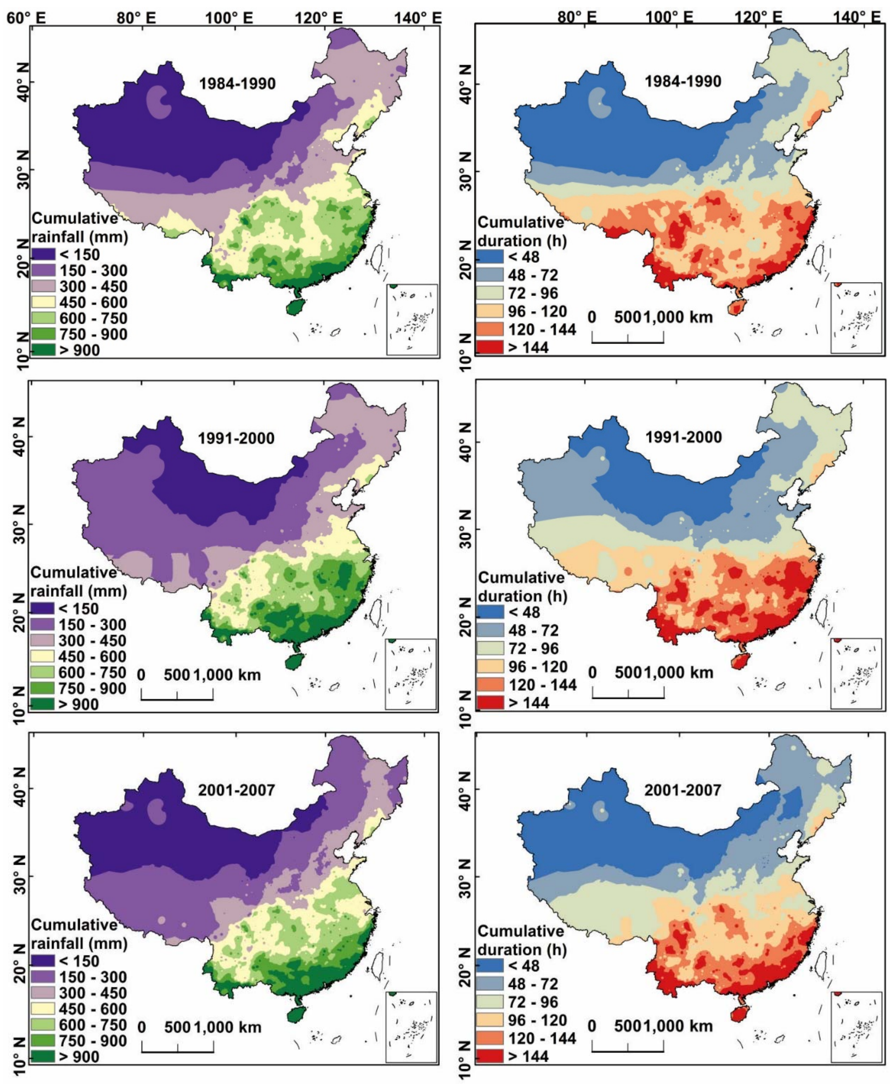

Fig. 5. Distribution of the cumulative rainfall (average annual cumulative rainfall depth of the rainstorm events) and the cumulative rainfall duration (average annual cumulative rainfall duration of the rainstorm events)

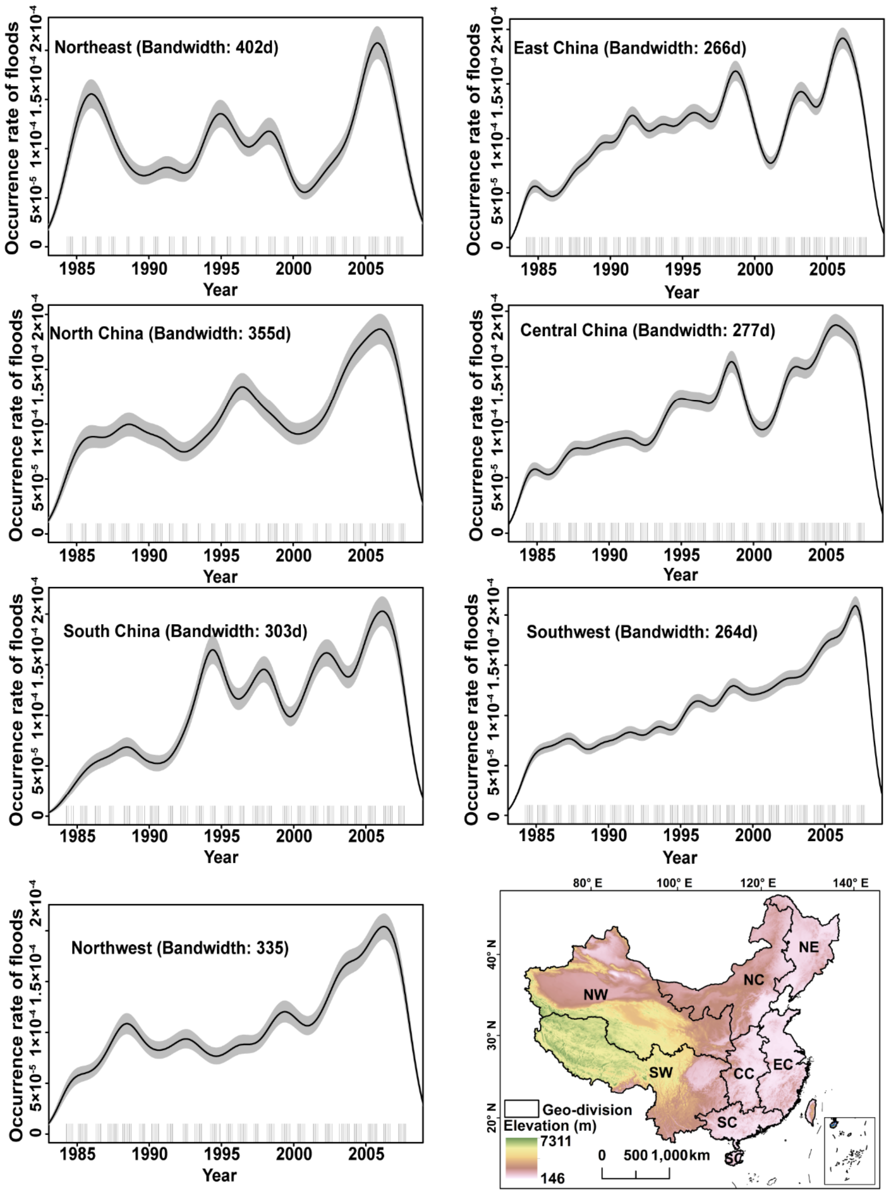

Fig. 6. Occurrence rate of flood events in seven geographical regions of China (NW-Northwest China; SW-Southwest China; SC-South China; CC-Centre of China; EC-East China; NC-North China; NE-Northeast China) in 1984-2007

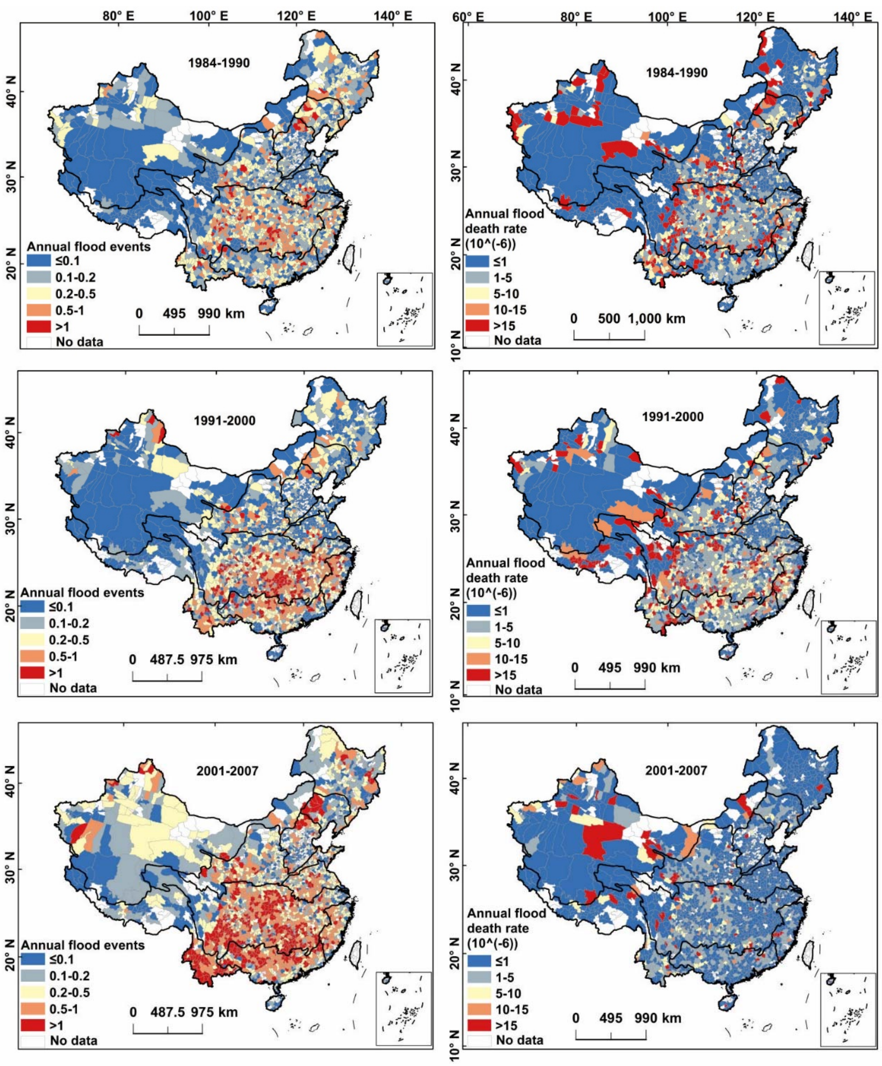

Fig. 7. Annual number of flood disasters and flood-induced death rates (ratio of flood-induced deaths to total population in each county)

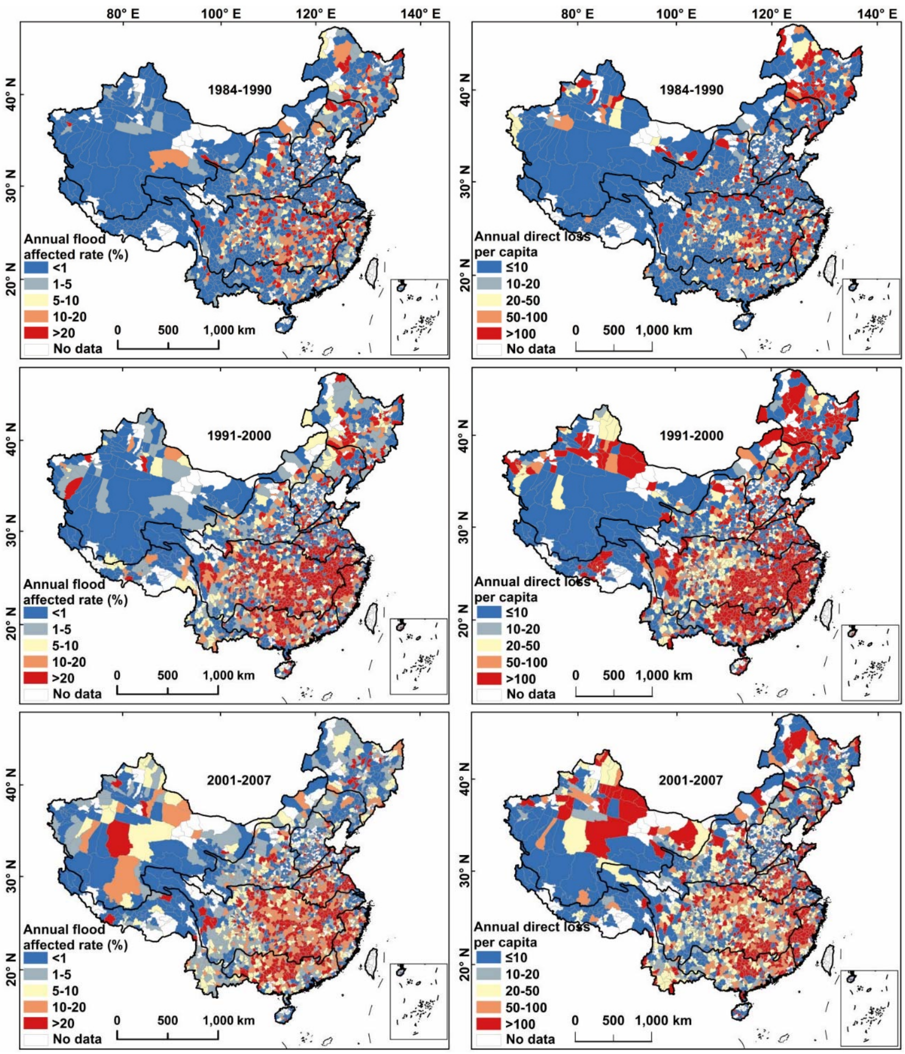

Fig. 8. Annual flood-affected rate (ratio of annual average flood affected people in the study period to total population in each county) and direct economic loss per capita (convert to the present value of 2007)

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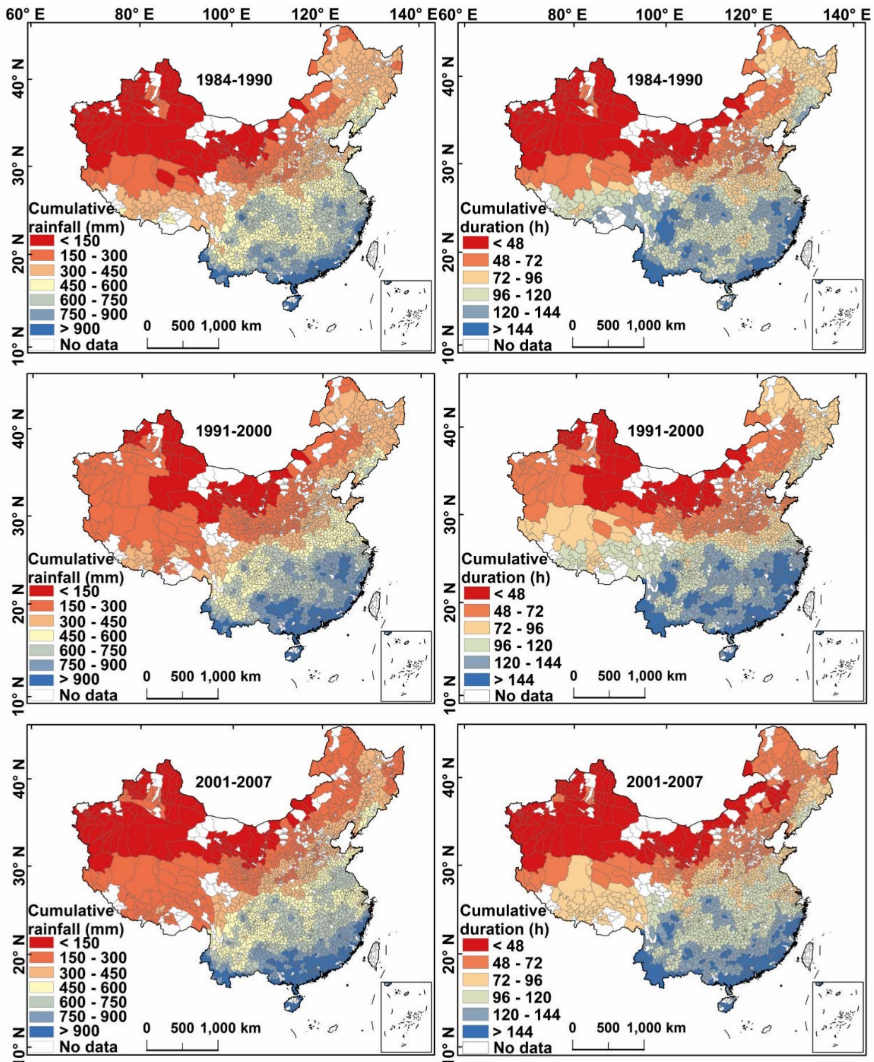

Fig. 9. Distribution of the annual cumulative intense rainfall and duration of counties (calculate average rainfall and duration of each county from results of Fig. 5)

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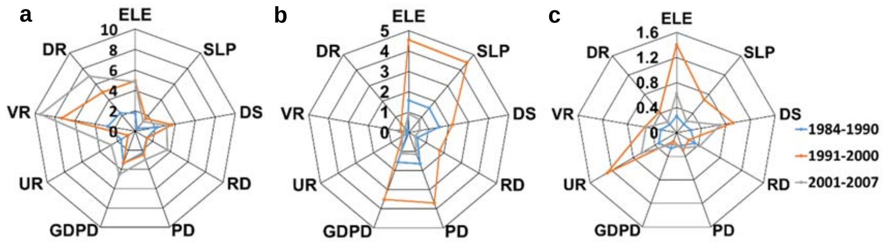

Fig. 10. Radar diagram of the contributions of meteorological and socio-economic variables (a-flood-affected people; b-flood-induced deaths; c-direct economic loss caused by flood) to the spatial distribution of flood disasters at decadal scales