Spatial-temporal Characteristics of Rainstorm, Flood Disaster Losses and Disaster-inducing Factors in Sichuan Province of China

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Keywords: Rainstorm and flood disasters, disaster losses, percentile method, rainstorm intensity, Sichuan Province of China

Abstract: Analysis of spatial-temporal distributions and variation trend of meteorological disasters and disaster-inducing factors can shed new light on meteorological disaster prevention and control, disaster relief planning and adaptation to climate change. Rainstorm and associated flood disasters are among the most frequent and serious meteorological disasters in Sichuan Province of China which spans part of the Qinghai-Tibet Plateau. In this study, daily precipitation data at 42 weather stations in Sichuan Province from 1973 to 2012 were collected and utilized along with statistics on rainstorms, flood disasters and socioeconomic status of 21 cities and prefectures from 1985 to 2012. Indicators characterizing the losses caused by rainstorm and flood disasters and rainstorm features were chosen. Critical disaster-causing precipitations were determined using the percentile method. Thus, a comprehensive analysis was conducted over the spatial-temporal distribution of the losses caused by rainstorms, flood disasters and the disaster-inducing factors in Sichuan Province, with a thorough characterization of precipitation during the rainstorms. The results showed from 1985 to 2012, the loss of crop area caused by the rainstorm and flood disasters and the loss rate showed a large fluctuation. The increasing trend of annual average rainstorm intensity was more obvious than that of the annual average rainstorm frequency. In the context of global warming, although the overall precipitation of Sichuan decreases, both the probability and intensity of extreme precipitation events increase. The annual average rainstorm volume and annual average rainstorm frequency shared similar spatial distribution patterns in the past 40 years. The overall frequency and the frequency of rainstorm processes of five intensity grades decreased from east to west. The frequencies were much higher in the basin of eastern Sichuan than in the mountainous south-western region and in the north-western plateau. The smallest frequency was found in the plateau of north-western Sichuan. Within the basin, the frequency of rainstorm intensity in the west was higher than that in the east.

1 INTRODUCTION

An analysis of 1970-2009 EM-DAT (Emergency Events Database) data reveals 7,870 hydro-meteorological related global disasters, causing the loss of 1.86 million lives and economic damages of US$ 1.954 trillion (adjusted to 2011 US$ exchange rate), among which storms and floods account for 79% of the total number of disasters and cause 56% of life losses and 85% of the economic losses (World Meteorological Organization, 2013). Recent years have witnessed a growing number of extreme weather and meteorological events along with accelerating urbanization and industrialization in many countries the general context of global warming. This directly results in a surge of losses related to meteorological disasters. Among various types of meteorological disasters, rainstorm and flood disasters are more frequent and cause greater losses than other disasters. Rainstorms are the primary cause of flood disasters and are also the related primary disaster-inducing factor. Many studies have been conducted at home and abroad concerning spatial-temporal distribution of rainstorms and associated losses. On basis of available rainfall data from 1891 to 2000, Kulkarni et al (2010) analyzed severe rainstorm characteristics of the Godavari Basin in Peninsular India. The results showed that 22 severe rainstorms affected the Godavari Basin in the past 110 years, mostly during the monsoon months of July and August. Hitchens

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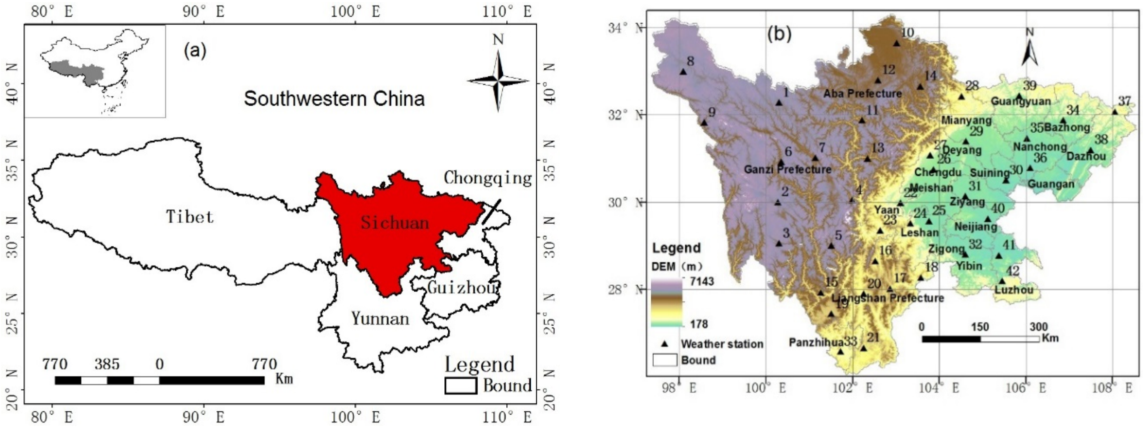
and Brooks studied the spatial and temporal distributions of heavy hourly rainfalls in the United States by using two high-resolution precipitation datasets (Hitchens & Brooks, 2013). Higgins and Kousky examined the changes in observed daily precipitation over the United States between 1950-1979 and 1980-2009 by using several simple measures including mean, frequency, intensity and return period. The results showed that multi-day heavy precipitation events are increasing in the more recent period (Higgins & Kousky, 2013). Wu analyzed the changing characteristics of precipitation during 1951-2013 for the contiguous United States (CONUS). Results showed a strong increase of heavy precipitations with extreme events increasing for most of the CONUS with the exception of the west region (Wu, 2015). Dauji (2019) discussed the monsoon rainstorm characteristics for varying inter-event intervals at a site on the western coast of India. Shakeel et al. applied a mix research approach to analyze the 2010-flood generating factors and damages in districts Muzaffar Garh. The analysis indicated that the flood was generated by extreme rainfall event in the last week of July 2010 in the upper catchment areas of River Indus. And the analysis showed that the inundation incurred total estimated economic loss of about 9.85 million US$ (Shakeel et al., 2021).

China is one of the countries with the highest frequency of rainstorm and flood disasters and it suffers enormous economic losses (Yu et al., 2018). According to statistics, the annual average area of crops covered by rainstorm and flood disasters from 1951 to 2015 was 12.07 million ha; the annual average economic loss caused by rainstorm and flood disasters from 1984 to 2018 was 103.8 billion RMB. Therefore, factors inducing the rainstorm and flood disasters and assessment of related losses have been a research hotspot (Huang et al., 2021; Zhao et al., 2014; Wu et al., 2014; Lin & Yang, 2014; Wang et al., 2014; Zou & Ren, 2015; Zhao et al., 2017; Jiang & Gao, 2019; Luo et al., 2020). Rainstorms are the primary source of floods in Sichuan of China and the most serious meteorological disasters in Sichuan Basin. A major trigger mechanism for rainstorms in basin regions is the coupling of vertical vorticity in the Qinghai-Tibet Plateau and Sichuan Basin. Extreme rainstorms can easily lead to floods, mountain torrents and debris flows, causing high casualties and economic losses. For example, from June 8th to 11th, 2013 western Sichuan Basin underwent an episode of extreme rainstorm. During this rainstorm, the precipitation at Dujiangyan Station from 20:00 of 8th to 20:00 of 9th was 415.99mm, and the maximum at a local station exceeded 700mm. Extreme precipitation triggered extreme natural disasters, causing 59 deaths, 174 missing people and direct economic losses of 20.3 billion RMB (Xiao et al., 2017). In 2018, according to the statistics of Sichuan Climate Center, there were 8 local rainstorms within the province. The average precipitation was by 21% higher than in normal years. From July 8th to 20:00 of 12th, an extreme rainstorm was observed at Guanghan Station of Deyang City. The maximum daily precipitation was 321.9mm, and the event rainfall was 488.8mm, both of which were the largest throughout the province. In mid-August 2020, there was continuous rainstorm and heavy rainstorm in the west of Sichuan Basin, and severe rainstorm occurred in some areas. Among them, the hourly rainfall intensity generally reached 50-80mm, and some places exceeded 100mm. Focusing on the losses caused by rainstorm and flood disasters and on the spatial-temporal distribution features, Deng studied the features of flood disasters in Sichuan and disaster countermeasures taken since the founding of New China. It was concluded that the major reasons for extreme rainstorms and flood disasters in Sichuan from 1952 to 1998 were abnormal climate changes (Deng, 2001). Zhou et al (2011) used the daily precipitation data of 133 weather stations in Sichuan Province from 1961 to 2008 and analyzed variation and influence of atmospheric precipitation in Sichuan in the past 50 years. It was found that from the west to the east of Sichuan Province, the annual average number of rainstorm days showed the overall trend of increase, decrease, and again increase. Qing et al (2013) implemented statistical methods and wavelet analysis to disaster census database from 1985 to 2009 and discussed the spatial-temporal distribution features of losses caused by rainstorm and flood disasters in Sichuan Province. The results showed that the basic change trend of losses caused by rainstorm and flood disasters was increasing, and the proportion of direct economic loss caused by rainstorm and flood to GDP (Gross Domestic Product) and the disaster area of crops had a change cycle of about 8a and 13-14a, respectively. Li and Mu (2014) used daily precipitation data of 102 weather stations from 1961 to 2010 in south-western Sichuan. They analyzed the spatial-temporal distribution features of rainstorms in south-western Sichuan in a period of 50 years by using trend analysis, Mann-Kendall mutation test and wavelet analysis. Deng et al (2017) investigated the rainstorm and flood disaster-inducing features in the past 30 years using rainstorm and flood disaster-related economic loss questionnaire forms for Sichuan from 1984 to 2010, daily precipitation data of Sichuan from June to September in the period from 1981 to 2010 and NCEP (National Centers for Environmental Prediction) reanalysis data. Thus, they derived the circulation background for disaster-inducing rainstorms in Sichuan during major flood periods in flood years. Based on the above studies, we selected Sichuan as the study area. Sichuan, located in south-western China, has diversified geomorphic types and frequently occurring meteorological disasters.



(a) Geographical location of Sichuan Province

(b) Digital Elevation Model and Weather Stations

Figure 1: Overview of study area and administrative division of Sichuan Province and geographic locations of weather stations.

As reported in this paper, daily precipitation data at 42 weather stations in Sichuan Province from 1973 to 2012 were collected and utilized along with statistics on rainstorm and flood disasters and socioeconomic status of 21 cities and prefectures from 1985 to 2012. Indicators characterizing the losses caused by rainstorm and flood disasters and rainstorm features were used. The critical disaster-causing precipitation was determined using the percentile method. The purpose was to conduct a comprehensive analysis over the losses caused by rainstorm and flood disasters in Sichuan Province and over the spatial-temporal distribution of disaster-inducing factors, with a thorough characterization of rainfall of rainstorm events. The research findings can shed new light on rainstorm and flood disaster prevention and control, disaster relief planning and adaptation to climate change for Sichuan Province in the context of global warming.

2 MATERIALS AND METHODS

2.1 Study Area

Sichuan Province is located in southwestern China beside the upper reaches of the Yangtze River (97°21'～108°33'E, 26°03'～34°19'N) (Figure 1a). Sichuan is featured by complex terrain and large difference in elevation between the west and east, the range being 178-7,143m (Figure 1b). There are a variety of climate types with frequent occurrence of meteorological disasters. The annual precipitation of the province is smaller in the west and larger in the east, smaller in the plateau than in the basin, and smaller in the hilly area inside the basin than in the mountainous regions around it (Zhou et al., 2011). By topography and landform, Sichuan Province is divided into basin in the east, plateau in the northwest (mainly referring to Ganzi Prefecture and Aba Prefecture), and mountainous regions in the southwest (mainly referring to Liangshan Prefecture and Panzhihua City). According to statistics supported by the meteorological disaster database from 1985 to 2009, among the areas affected by meteorological disasters, the drought area is the largest one. However, rainstorm and flood disasters cause the greatest losses, because they not only affect agricultural production, but also the transportation and industry sectors (Qing et al., 2013).

2.2 Data Sources

The meteorological data used in this paper mainly came from daily precipitation dataset available on the website of China Meteorological Administration (http://data.cma.cn/). A total of 42 representative weather stations were selected throughout Sichuan Province, and the time period was from 1973 to 2012. Before formal data processing, daily precipitation data within 40 years were first inspected. Interpolation was performed for the missing values, so as to ensure the continuity and accuracy of data. Statistics on disasters and socioeconomic status were collected from Encyclopedia of China Meteorological Disasters (Sichuan Volume), Sichuan Flood and Drought Disasters, Sichuan Disaster Relief Yearbook, Sichuan Statistical Yearbook and related literature (Deng et al., 2017). Since the disaster statistics before 1984 were unavailable, the time span of statistics on disasters and socioeconomic status was from 1985 to 2012. Figure 1b shows the administrative division of Sichuan Province and geographic locations of 42 weather stations; Table 1 presents the administrative affiliation of these weather stations. There are 18 prefecture-level cities and 3 autonomous prefectures affiliated to Sichuan Province. As to the distribution of weather stations, there are 14 stations (No. 1-14) located in the plateau of north-western Sichuan, 7 (No. 15-21) in the mountainous region of south-western Sichuan and 21 (No. 22-42) in the basin of eastern Sichuan.

Table 1: Detailed information of weather stations in Sichuan Province used in the study.

Prefectures and Cities	Numbers and names of weather stations
Ganzi Prefecture	1 Seda, 2 Litang, 3 Daocheng, 4 Kangding, 5 Jiulong, 6 Xinlong, 7 Daofu, 8 Shiqu, 9 Dege
Aba Prefecture	10 Ruoergao, 11 Maerkang, 12 Hongyuan, 13 Xiaojin, 14 Songpan
Liangshan Prefecture	15 Muli, 16 Yuexi, 17 Zhaojue, 18 Leibo, 19 Yanyuan, 20 Xichang, 21 Huili
Ya'an City	22 Ya'an, 23 Hanyuan
Leshan City	24 Emeishan, 25 Leshan
Chengdu City	26 Wenjiang, 27 Dujiangyan
Mianyang City	28 Pingwu, 29 Mianyang
Suining City	30 Suining
Ziyang City	31 Ziyang
Yibin City	32 Yibin
Panzhihua City	33 Panzhihua
Bazhong City	34 Bazhong
Nanchong City	35 Langzhong, 36 Gaoping
Dazhou City	37 Wanyuan, 38 Daxian
Guangyuan City	39 Guangyuan
Neijiang City	40 Neijiang
Luzhou City	41 Naxi, 42 Xuyong

2.3 Main Research Methods

2.3.1 Measurement Indicators of Rainstorm and Flood Disaster Losses and Rainstorm Features

Frequency of rainstorm and flood disasters and degree of damage caused are important factors for characterizing the impact of disasters. To measure the degree of damage caused by rainstorm and flood disasters, we use the following indicators: area of crops covered by natural disasters (the sown area of crops reduced by more than 10% due to disasters), area of crops affected by natural disasters (the sown area of crops reduced by more than 30% due to disasters), area of total crop failure (the sown area of crops reduced by more than 80% due to disasters), absolute and relative values of direct economic losses. Relative indicators included loss rate (i.e., direct economic loss caused by rainstorm and flood disasters of the year concerned/GDP of the year concerned) and ratio of crop loss area to total farmland area. Rainstorms are the primary reason for flood disasters. The following measures are used to characterize the rainstorms: annual average rainstorm volume, annual average contribution rate of rainstorms (ratio of annual average rainstorm volume to annual average total precipitation), annual average rainstorm frequency (ratio of cumulative number of rainstorm days to actual length of time period concerned) and annual average rainstorm intensity (ratio of annual average rainstorm precipitation to annual average frequency of rainstorms). The regional rainstorm value is expressed as the integrated arithmetic mean at all weather stations in this region.

2.3.2 Percentile Method

Percentile, as a position indicator, is used to describe the distribution of a group of sample values. The combined use of several percentiles can comprehensively describe the distribution of samples. Percentile can be calculated using the empirical formula below (Wang et al., 2011):

$$Q_i(p) = (1-\gamma)X_{(j)} + \gamma X_{(j+1)} \tag{1}$$

$$j = \mathrm{int}\left(p \times n + (1+p)/3\right) \tag{2}$$

$$\gamma = p \times n + (1+p)/3 - j \tag{3}$$

where, $Q_i(p)$ is the i^{th} percentile; X is the sample sequence in an ascending order; p is the percentile rank; n is the number of sequences; j is the j^{th} sequence; *int* is the integer-valued function, the return value is the closest integer by rounding downwards; γ is the weight of $(j+1)^{th}$ sequence.

2.3.3 Precipitation during the Rainfall Process and Critical Disaster-causing Rainfall

The higher the precipitation intensity and the higher the frequency of heavy precipitation, the more severe losses are caused by rainstorm and flood disasters. Hence, the more destructive the rainstorm and flood disasters, the higher is the hazard degree of disaster-inducing factors. The hazard degree of rainstorm and flood disaster-inducing factors can be characterized by rainstorm frequency and intensity, using the following method: (1) A rainstorm process is taken into consideration if it lasts several consecutive days with rainfalls, and it is required that the precipitation is larger than 50mm on at least one day; (2) Precipitations for these processes spanning up to 10 days or more at each weather station over the years are determined. Precipitations of each episode at all weather stations constitute a sequence, and 10 such sequences with varying time lengths are built. For each sequence, the precipitations are ranked in an ascending order and the precipitations in the 98th, 95th, 90th, 80th and 60th percentiles are calculated. These values are taken as the critical disaster-causing precipitations (rainstorm intensity); (3) Based on these percentiles, rainstorm intensity is divided into 5 grades: precipitations in the 60th-80th percentile are of grade 1 (flood-inducing); those in the 80th-90th percentile are of grade 2 (mild flood); those in the 90th-95th percentile are of grade 3 (moderate flood), those in the 95th-98th percentile are of grade 4 (severe flood) and those above 98th percentile are of grade 5 (extreme flood); (4) According to the index, the frequencies of annual rainstorm and flood processes with different intensity are determined at each station, and the spatial distribution maps of rainstorm frequency are plotted for each intensity grade (Li et al., 2013).

3 RESULTS AND DISCUSSION

3.1 Spatial-temporal Distribution Features of Losses Caused by Rainstorm and Flood Disasters

3.1.1 Interannual Variation and Monthly Distribution Features

Sichuan is located in southwestern China, where agriculture accounts for a large proportion of the national economy. Due to lower economic development level, Sichuan is susceptible to natural disasters. Every year, huge economic losses and casualties are caused by rainstorms and floods, and the losses involve mostly the agricultural production. Figures 2 and 3 show the loss of crop area caused by the rainstorm and flood disasters and the ratios of such losses to local GDP (loss rate) in Sichuan from 1985 to 2012. The area of crops covered and affected by the rainstorm and flood disasters all fluctuated greatly in the past 28 years, and the changing trend follows the polynomial distribution law of the fifth power (Figure 2). Among the area of crops covered by the rainstorm and flood disasters, the greatest losses of occurred in 2010, the area of crops covered by the disaster being 1.508 million ha; the second largest loss occurred in 1998, the area of crops covered by the rainstorm and flood disasters being 1.416 million ha; the loss was the smallest in 1994, the area of crops covered by the rainstorm and flood disasters being 0.192 million ha. Among the area of crops affected by the rainstorm and flood disasters, the greatest loss occurred in 1998, the crop area affected was 0.819 million ha; the second largest loss occurred in 2003, the crop area affected being 0.786 million ha; the loss was the smallest in 2008, the crop area affected being only 16 thousand ha. Taken together, 1998 was the year with the largest loss of crop area affected by rainstorm and flood disasters, and 2008 was the year least affected. In 1998 catastrophic floods occurred in the entire drainage basin of the Yangtze River. Sichuan, located in the upper reaches of the Yangtze River, suffered from 15 rainfall events as well as floods, landslides and debris flows in different cities and prefectures from May to September 1998. These natural disasters caused direct economic loss of about 12.3 billion RMB, and 1998 was the year with most severe crop loss in Sichuan in the 20th century (Feng & Luo, 1995).

From 1985 to 2012, the direct economic loss caused by rainstorm and flood disasters fluctuated within the range from 45.08 to 0.087 billion RMB; the loss was the greatest in 2010 and the smallest in 1985. GDP increased continuously from 1985 to 2012, the variation range being from 42.115 to 2,382.78 billion RMB. The loss rate calculated on this basis also showed a larger fluctuation, and the changing trend follows the polynomial distribution law of the third power (Figure 3). The interannual variation was considerable, the loss rate was the highest in 2010, the value being 26.23‰; the second highest was found in 1989, the value being 18.73‰; the smallest was found in 2006, the value being 1.44‰ and the average 8.97‰. Over the 28 years, the values were above the averages in 9 years, and were below the averages in 19 years; the values were all below the averages in 11 consecutive years from 1999 to 2009, showing an apparent decreasing trend. Thus, the loss caused by rainstorm and flood disasters was not only closely related to disaster itself, but also to the economic development level and the disaster defense ability.

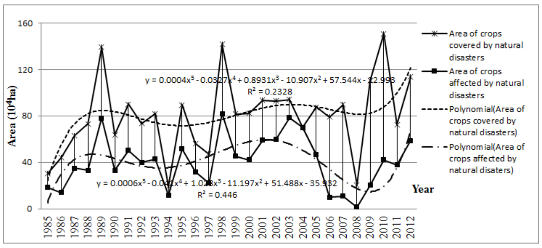


Figure 2: Loss of crop area due to rainstorm and flood disasters from 1985 to 2012.

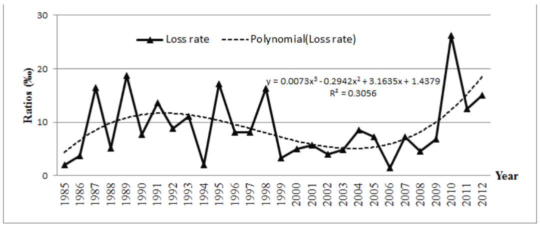


Figure 3: Ratios of loss caused by rainstorm and flood disasters to GDP from 1985 to 2012 (loss rate).

Figure 4 shows the percentages of monthly average loss caused by rainstorm and flood disasters to annual average loss related to disasters from 1985 to 2012. Rainstorm and flood disasters mainly occurred in the time span from March to November in Sichuan, and most of them in the period from June to September. The ratios of direct economic losses, areas of crops covered and affected by the rainstorm and flood disasters and areas of total crop failure in these four months to the corresponding annual averages were 95.8, 86.6, 85.4 and 90.6, respectively. These values were especially higher in July, accounting for 42.8%, 38%, 40.5% and 43.6% of the annual total, respectively. The second highest economic loss and crop loss area were found in August and June, while those of March, April and October accounted for the smallest percentages. This was especially true in March, where the percentages were all below 0.03%. Figure 5 shows the percentages of monthly average crop loss area due to rainstorm and flood disasters to total farmland area from 1985 to 2012. Most of the crop loss occurred in the time from June to August, especially in July. The ratios of area of crops covered and affected by the disasters to total farmland area were 5.87 and 2.16, respectively; the highest percentages occurred in July, the values being 2.19% and 0.88%, respectively.

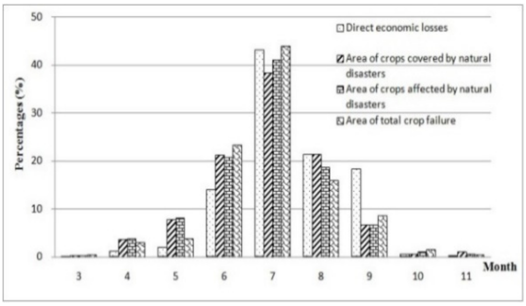


Figure 4: Percentages of monthly average loss caused by rainstorm and flood disasters to annual average loss related to disasters from 1985 to 2012.

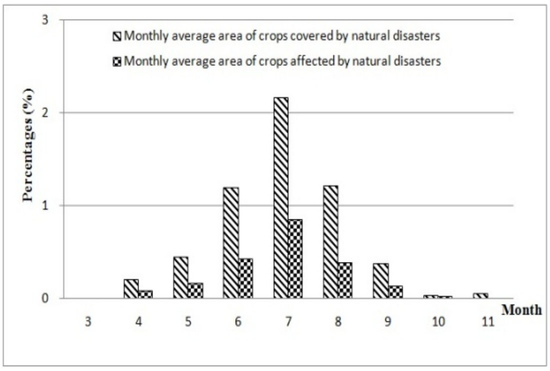


Figure 5: Percentages of monthly average crop loss area due to rainstorm and flood disasters to total farmland area from 1985 to 2012.

3.1.2 Spatial Distribution Characteristics of Losses in Cities and Prefectures

Sichuan is featured by high diversity of terrain and climate types, and there are large variations in socioeconomic development level across the cities and prefectures. Rainstorm and flood disasters had therefore a varying impact on different regions. Figure 6 shows the spatial distributions of average direct economic loss and loss rate due to rainstorm and flood disasters in 21 cities and prefectures from 1985 to 2012. The average direct economic loss due to rainstorm and flood disasters (Figure 6a), was higher in Dazhou, Mianyang and Nanchong City, which are located in the north-eastern Sichuan Basin. The average direct economic losses were 0.483, 0.434 and 0.214 billion RMB. Regions with the lowest average direct economic loss were Ya'an, Aba Prefecture and Neijiang City, the values being 48, 34 and 14 million RMB, respectively. Due to difference in economic aggregate in 21 cities and prefectures, the absolute direct economic loss cannot fully reflect the degree of loss caused by rainstorm and flood disasters in different regions. Figure 6b shows the spatial distribution of loss ratio. It can be seen that the absolute average direct economic loss was smaller in Ganzi Prefecture in the plateau of north-western Sichuan, the value being 76 million RMB. Ganzi Prefecture ranked 15th among 21 cities and prefectures. However, while the annual average GDP (6.007 billion RMB) of Ganzi Prefecture was the smallest of the 21 cities and prefectures, its loss rate was the highest (12.63‰). The loss rates of Dazhou, Guangyuan and Mianyang City, located in the north-eastern Sichuan Basin, were also relatively high, the values being 12‰, 9.12‰ and 8.18‰, respectively; by contrast, the loss rates of Ziyang, Chengdu and Neijiang City in the middle and eastern Sichuan Basin were smaller, the values being 1.73‰, 0.43‰ and 0.42‰, respectively.

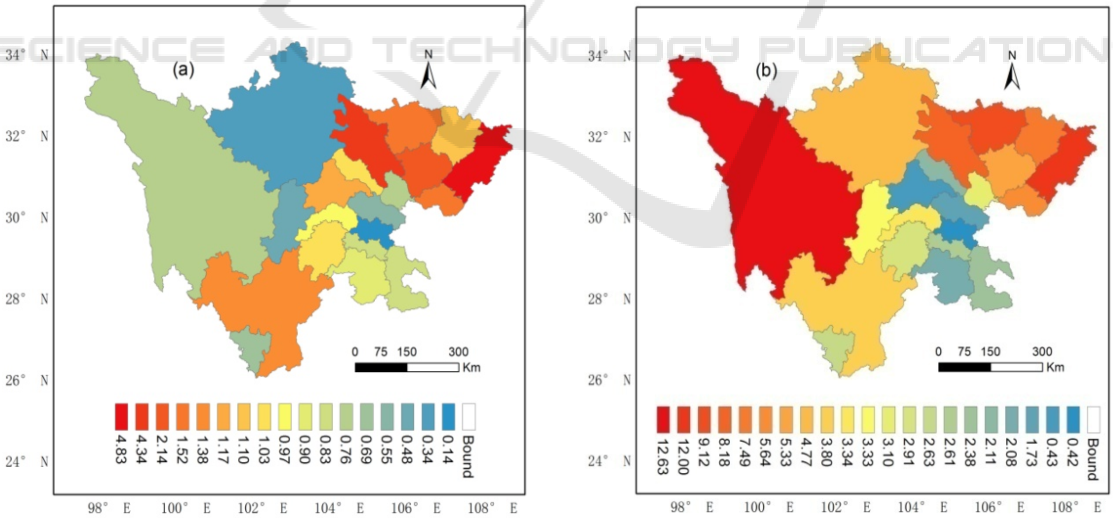


Figure 6: Average direct economic loss (100 million RMB) (a) and loss rate (‰) (b) due to rainstorm and flood disasters in 21 cities and prefectures from 1985 to 2012.

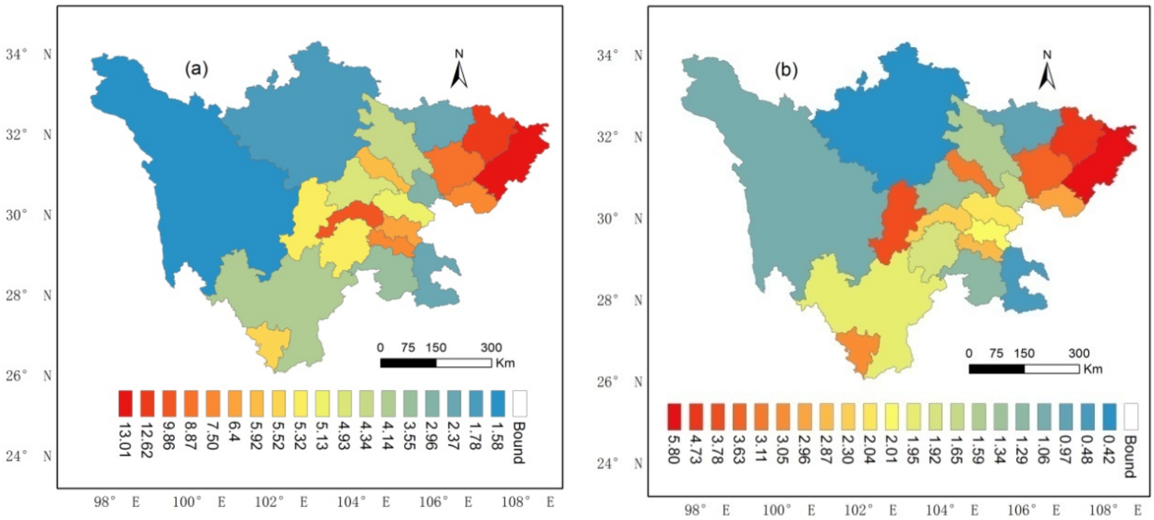


Figure 7: Percentages of average area of crops covered (a) and affected (b) by rainstorm and flood disasters to total farmland area in 21 cities and prefectures from 1985 to 2012 (%).

Figure 7 shows the ratios of average areas of crops covered and affected by rainstorm and flood disasters to total farmland area in each city and prefecture from 1985 to 2012. Dazhou, Bazhong and Meishan located in the north-western or south-western Sichuan Basin were the top three cities with the highest ratio of average area of crops covered by the rainstorm and flood disasters to total farmland area (Figure 7a). The percentages were 13.01%, 12.62% and 9.86%, respectively; the last three locations were Guangyuan, Aba Prefecture and Ganzi Prefecture in northern Sichuan Basin or plateau of north-western Sichuan. The percentages were 2.37%, 1.78% and 1.58%, respectively. Dazhou and Bazhong in north-eastern Sichuan Basin and Ya'an in south-western Sichuan Basin were the top three cities with the highest ratio of average area of crops affected by rainstorm and flood disasters to total farmland area (Figure 7b). The percentages were 5.80%, 4.73% and 3.78%, respectively; the last three locations were Guangyuan and Luzhou in eastern Sichuan Basin and Aba Prefecture in north-western Sichuan Basin. The percentages were 0.97%, 0.48% and 0.42%, respectively.

The agriculture sector accounts for a considerable proportion of Sichuan provincial economy. Among various losses caused by the rainstorm and flood disasters and secondary disasters, the loss caused to the agricultural production is most direct and significant. Based on the crop loss area and ratio of such loss to total farmland area, Dazhou and Bazhong City in north-eastern Sichuan Basin and Meishan and Ya'an City in south-western Sichuan suffered the most from severe rainstorm and flood disasters; by contrast, Ganzi Prefecture and Aba Prefecture in the plateau of north-western Sichuan, Guangyuan City in northern Sichuan Basin and Luzhou City in southern Sichuan Basin suffered the least. The results observed are basically in agreement with other research previously carried out in the southwestern China (Zhao et al., 2017; Li & Mu, 2014) and Sichuan Province (Xiao et al., 2017; Deng, 2001; Qing et al., 2013; Deng et al., 2017; Deng, 1999; Feng & Luo, 1995). However, the year with the least loss of crop area affected by rainstorm and flood disasters, as well as the loss rate due to rainstorm and flood disasters in 21 cities and prefectures are different. The discrepancies may be caused by the data with different time periods used in the different studies.

3.2 Spatial-temporal Distribution Features of Factors Inducing Rainstorm and Flood Disasters

From the viewpoint of their cause, flood disasters can be divided into rainstorm, barrier and snowmelt types. Rainstorm-induced flood is the most important type of flood in Sichuan, and most of the flood disaster events belong to this type which is prevalent all over the province. Heavy rainstorms often cause flood disasters, and intensive precipitation in a certain region at a certain time is usually the result of one or several rainstorms. Thus, rainstorms are considered the most important flood-inducing factor.

3.2.1 Analysis of Interannual Variation Features of Rainstorms

Rainstorm refers to high-intensity rainfalls or rainfalls with high cumulative volume within a certain time period. According to the standard for heavy precipitation developed by China Meteorological Administration, rainfalls with precipitation volume of 50mm or more within 24h are considered rainstorms. Annual average rainstorm volume can comprehensively reflect the general size of daily rainfall and the amount of rainstorm in a certain region. This study analyzed the variation trends of annual average rainstorm volume, annual average contribution rate of rainstorms, annual average rainstorm frequency and annual average rainstorm intensity over the years at 42 weather stations in Sichuan from 1973 to 2012 (figure omitted).

The results showed that although the annual average precipitation of time series in Sichuan demonstrated a mild decreasing trend over the years, the annual average rainstorm volume, annual average contribution rate of rainstorms, annual average rainstorm frequency and annual average rainstorm intensity increased, but insignificantly. Within the 40 years, the annual average rainstorm volume was the largest in 1981, the value being 200.4mm; the years 1983 and 1998 came next, with values of 196.2 and 191.3mm, respectively; the year 1976 had the smallest annual average rainstorm volume, 81.3mm. The annual average contribution rate of rainstorms had the largest value (20.7%). The year 1976 was the smallest (9.5%) and the difference between the two was 11.2%. The annual average rainstorm frequency was the highest in 1998 with 2.6 days, followed by the years 1981 and 1983, with values of 2.5 days and 2.4 days, respectively; the lowest occurred in 1976, with the value of 1.2 days. The annual average rainstorm intensity had the highest value of 91.5mm/d in 2010, followed by the years 1985 and 1989, with 83.7 and 83.1mm/d, respectively; the lowest occurred in 1976, with 65.6mm/d. The increasing trend of annual average rainstorm intensity was more obvious than that of the annual average rainstorm frequency. This means that the composition of rainstorm intensity was more extreme. In other words, in the context of global warming, although the overall precipitation of Sichuan decreases, both the probability and intensity of extreme precipitation events increase. The temporal trends in our work are similar to previous studies in reporting variation trends of precipitation and rainstorm over the past few decades in Sichuan Province (Xiao et al., 2017; Zhou et al., 2011; Li & Mu, 2014; Zhang et al., 2019; Li et al., 2019).

Rainstorm occurrences in Sichuan are mainly influenced by circulation factors on three large scales. The first are the southwest and southeast monsoons from India and western Pacific, which mainly influence rainstorm intensity and variation; the second are the activities of subtropical high in the western Pacific and Qinghai-Tibet Plateau, which mainly control the seasonal variation of rainstorms; the third are abnormal atmospheric circulations in the northern hemisphere, especially in the middle and high latitudes of East Asia. For example, the locations of Ural high, Okhotsk Sea high and Balkashi Lake low trough are key large-scale circulation backgrounds controlling rainstorm occurrences (Zhan & Wen, 2006). Many studies have shown that under the circulation background conducive to rainstorm occurrence, there are four major types of weather systems that influence rainstorm occurrences in Sichuan: southwest vortex, low trough and low vortex and shear line above the Qinghai-Tibet Plateau that work with cool surface air, southwest low-level jet, and western Pacific subtropical high (Li et al., 2014). From May to September 1981, 6 episodes of catastrophic precipitations occurred in Sichuan. Due to the joint influence from 500hPa low trough, southwest vortex and southeast low-level jet that work with cool surface air, the extreme rainstorm in Sichuan Basin from 9th to 14th of July was the most severe. It caused the heaviest losses of the 6 episodes. The rainstorm affected 141 cities and counties of Sichuan. During the 6 days precipitation process, the regions with precipitation above 100mm spanned over an area of 173.6 thousand km^2. This rainstorm episode was the largest rainstorm and flood disaster in Sichuan Basin in the 20th century and also one of the extreme floods since the founding of New China. Therefore, the year 1981 presents the highest annual average rainstorm volume and also the highest annual average contribution rate of rainstorms within the period from 1973 to 2012 (Sichuan Water Conservancy and Electricity Department, 1996).

3.2.2 Spatial Distribution Features of Rainstorms

Spatial kriging interpolation was performed for the annual average rainstorm volume and annual average rainstorm frequency registered at 42 weather stations of Sichuan from 1973 to 2012. The spatial distribution diagrams of annual average rainstorm volume and annual average rainstorm frequency in Sichuan over the years are shown in Figure 8.

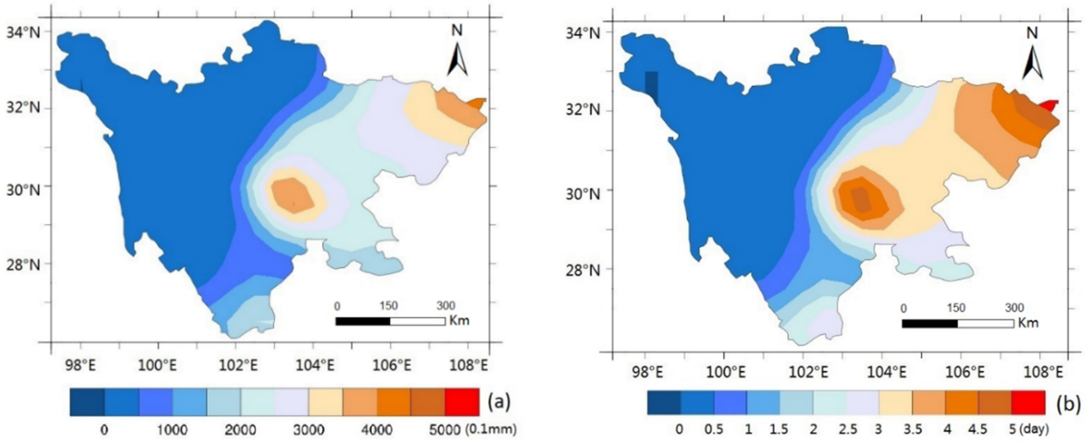


Figure 8: Spatial distribution diagrams of annual average rainstorm volume (a) and annual average rainstorm frequency (b) over the years from 1973 to 2012.

The annual average rainstorm volume and annual average rainstorm frequency in Sichuan shared similar spatial distribution patterns over the years. Both were higher in the east region than in the west region. The lowest was observed in the plateau of north-western Sichuan, followed by the mountainous region of south-western Sichuan; the highest was found in Sichuan Basin in the east. The annual average rainstorm volume was above 200mm in the entire Sichuan Basin. The annual average rainstorm frequency was over 2 days, and there were large differences in rainstorm volume and rainstorm frequency within the basin. Rainstorms were fewer in Neijiang, Ziyang and Suining City in the middle of the basin, where the annual average rainstorm volume was below 250mm and the annual average rainstorm frequency was below 3.5 days. Regions with high rainstorm volume and frequency were mostly found in western and north-eastern basin. Ya'an, Leshan and Meishan City in the western part of the basin had an annual average rainstorm volume above 500mm and annual average rainstorm frequency above 5 days. These were obviously regions with frequent rainstorms. Dazhou and Bazhong City in the north-eastern basin, where the annual average rainstorm volume was above 400mm and annual average rainstorm frequency above 4 days, were also regions with frequent rainstorms. In addition, southern Liangshan Prefecture and Panzhihua City in the mountainous regions of south-western Sichuan were also afflicted by frequent rainstorms, with annual average rainstorm volume of about 200mm and annual average rainstorm frequency of 3 days.

Spatial kriging interpolation was performed for the monthly average rainstorm volume and monthly average rainstorm frequency based on data registered at 42 weather stations of Sichuan from 1973 to 2012 (figure omitted). The results showed that the spatial distribution of monthly average rainstorm volume and monthly average rainstorm frequency was similar in Sichuan over 40 years; the months with larger rainstorm volume also had higher rainstorm frequency. Rainstorm in Sichuan showed apparent seasonal features, with no rainstorms occurring in winter. Rainstorms were fewer from March to May and from October to November, and were uniformly distributed. The months from June to September were the major season of rainstorms, and local rainstorms were more frequent from July to August. The monthly average rainstorm volumes of western and north-eastern basin were all above 100mm/month from July to August, and the monthly average rainstorm frequency reached over 2d/month.

Comprehensively, the influence of terrain on rainstorm occurrences in Sichuan was identified. There was a clear-cut boundary between the high- and low-value regions of annual average rainstorm volume, annual average rainstorm frequency over the years, as well as monthly average rainstorm volume and monthly average rainstorm frequency from July to August. This boundary coincides with the boundary of eastern Qinghai-Tibet Plateau in Sichuan. Two conditions have to be met for rainstorms to occur: one is the presence of abundant water vapor, and the other is the rising air current. The plateau in north-western Sichuan has high altitude and the air, thinner than in the plains, has lower water vapor content. Under the joint effect of plateau terrain and south Asia high, East Asian monsoon and India monsoon can hardly transport water vapor to the plateau of north-western Sichuan. As a result, both the annual and monthly average rainstorm volume and frequency are low in this region. The basin, by contrast, has lower altitude and more abundant water vapor in the air. Besides, the basin is surrounded by mountains on the four sides, and the water vapor produced by evaporation and transpiration within the basin is not likely to mix with that outside the basin. Thus, the basin has more abundant water vapor. When a strong disturbance is given by the convergence of external conditions, precipitation is more likely to erupt in the form of rainstorm. Moreover, due to the terrain effect, rainy centers are mostly distributed on the windward slopes of the mountainous region. For this reason, Ya'an, Leshan and Dujiangyan City in the western part of the basin are regions which not only have the highest annual average rainstorm volume and frequency, but also the highest rainstorm volume and frequency from July to August. Besides the terrain factor, the southwest vortex weather process has also an impact on precipitation and acts in the basin as an important and special weather system inducing rainstorm.

3.2.3 Analysis of Rainstorm Precipitation Process

Using the above statistical methods for rainstorm precipitation process and critical disaster-causing precipitation, we constructed 10 rainfall sequences of rainstorm process at 42 weather stations in Sichuan from 1973 to 2012. Then, precipitations in the 98th, 95th, 90th, 80th and 60th percentiles were calculated for different sequences, and the critical disaster-causing precipitation was determined. Finally, the rainstorm intensity was divided into 5 grades based on percentiles. Table 2 shows the scope and frequency of each grade of rainstorm intensity for rainstorms lasting for different days according to rainstorm volume thresholds determined by percentiles.

Table 2: Scope and frequency of rainstorm processes with different intensity grades and lasting for different days.

Days	Grade 1 (0.1mm)	Grade 2 (0.1mm)	Grade 3 (0.1mm)	Grade 4 (0.1mm)	Grade 5 (0.1mm)	Frequency (times)	Rainstorm value (0.1mm)
1	703≤R<860	860≤R<1035	1035≤R<1222	1222≤R<1438	R>1438	339	500
2	858≤R<1080	1080≤R<1305	1305≤R<1603	1603≤R<1933	R>1933	602	500
3	947≤R<1197	1197≤R<1491	1491≤R<1863	1896≤R<2360	R>2360	538	500
4	1054≤R<1383	1383≤R<1792	1792≤R<2020	2020≤R<2403	R>2403	429	500
5	1253≤R<1615	1615≤R<1969	1969≤R<2307	2307≤R<2709	R>2709	313	500
6	1402≤R<1898	1898≤R<2177	2177≤R<2600	2600≤R<3034	R>3034	184	500
7	1394≤R<1833	1833≤R<2254	2254≤R<2723	2723≤R<2960	R>2960	160	500
8	1634≤R<2087	2087≤R<2694	2694≤R<2965	2965≤R<3357	R>3357	132	500
9	1712≤R<2204	2204≤R<2507	2507≤R<2752	2752≤R<3437	R>3437	78	500
≥10	2376≤R<3162	3162≤R<3958	3952≤R<4569	4569≤R<4935	R>4935	149	500

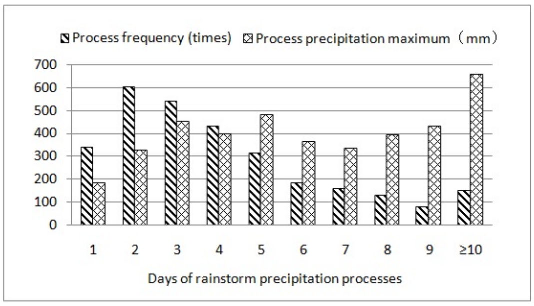


Figure 9: Process frequency and maximum precipitation in 10 rainfall sequences.

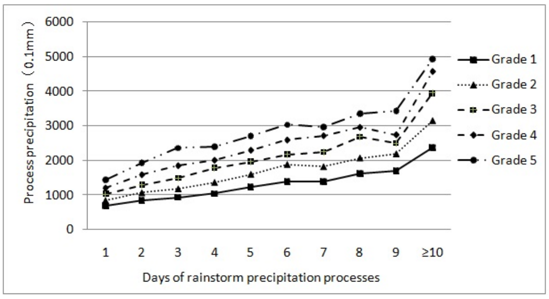


Figure 10: Precipitation for different grades of rainstorm intensity in 10 rainfall sequences.

(1) Frequency distribution and maximum precipitation of rainstorm precipitation processes

During 40 years (1973-2012), a total of 2,924 rainstorm precipitation processes lasting for different days occurred. The frequency and maximum precipitation of the 10 rainfall sequences are shown in Figure 9. Using the duration of 5 days as the demarcation point, it was found that the rainstorm frequency decreased significantly if the duration was above this threshold. The first and last five sequences were treated as two separate entities. Rainstorms lasting for a few days accounted for a greater proportion. There were 2,221 rainstorm processes shorter than 5 days, accounting for 75.98% of the total, while there were only 703 rainstorm processes longer than 5 days, accounting for 24.02% of the total. From 1973 to 2012, the number of rainstorm processes lasting for 2 days was the greatest. The frequency and therefore the probability of rainstorm processes lasting longer than 2 days decreased. Generally, rainstorms shorter than 2 days occurred more frequently than those lasting longer.

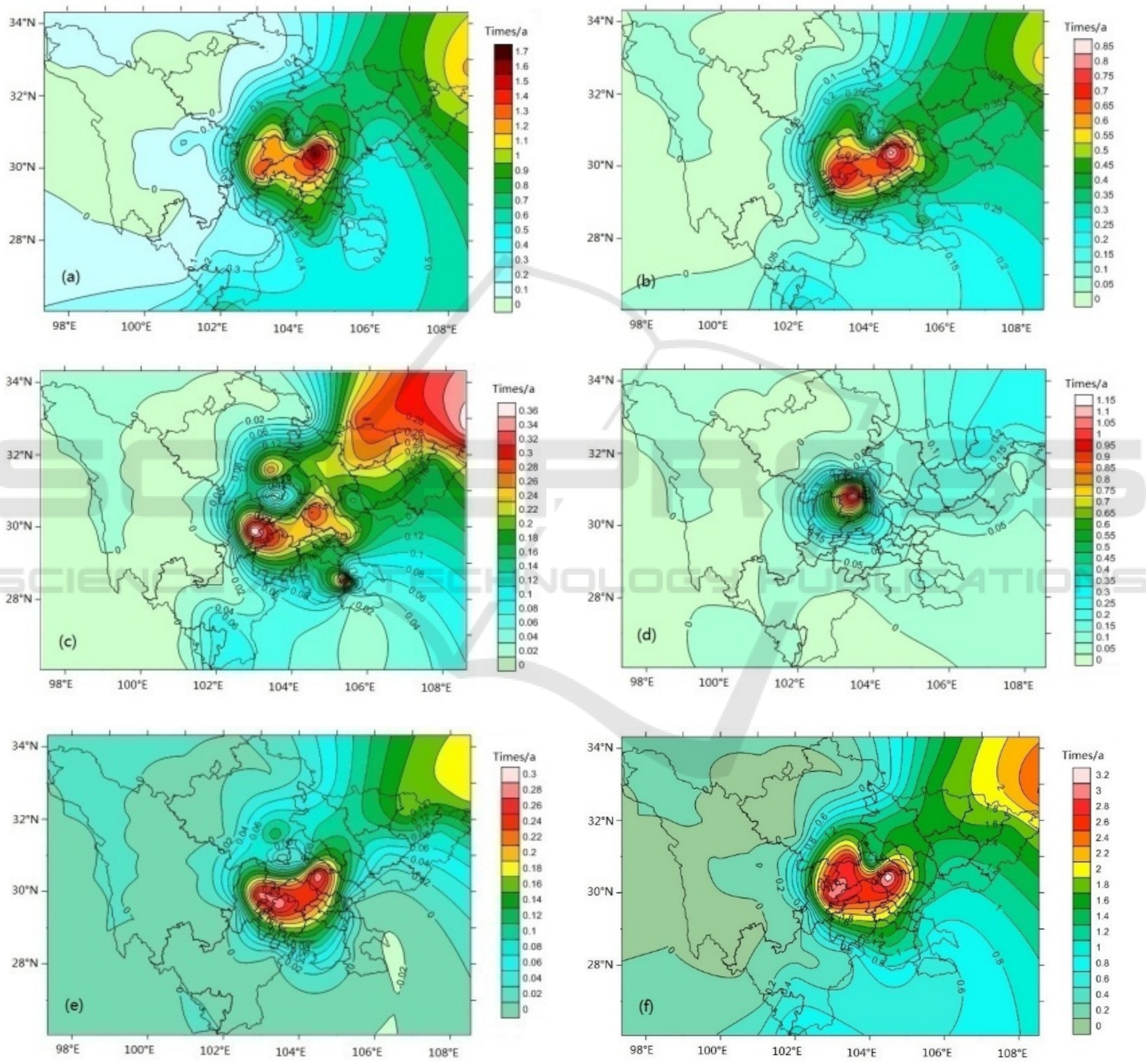


Figure 11: Spatial frequency distribution of overall rainstorm intensity and each grade of rainstorm intensity (a) Grade 1 (b) Grade 2 (c) Grade 3 (d) Grade 4 (e) Grade 5 (f) Overall.

Among rainstorm rainfall processes lasting for several days, the maximum precipitation also varied significantly in different sequences. The maximum precipitations of rainstorm processes lasting for 1 to 10 days and above were as follows: 185.9mm (1 day), 328mm (2 days), 449.6mm (3 days), 398.8mm (4 days), 481.1mm (5 days), 365mm (6 days), 333.1mm (7 days), 393.1mm (8 days), 430.7mm (9 days) and 657.4mm (≥10 days). We concluded that except for large difference in maximum precipitation between rainstorm processes lasting for 1 day and for more than 10 days, the maximum precipitation of other rainstorm processes was mostly about 400mm.

(2) Spatial frequency distribution of overall rainstorm intensity for each grade of rainstorm intensity

The maximum precipitation varied a little for rainstorm processes in different sequences. In some cases, the maximum precipitation of rainstorm processes lasting for longer days was smaller than that of shorter rainstorms. However, maximum precipitations are only extreme cases which cannot reflect the general rule. Figure 10 shows the precipitations of 5 intensity grades of rainstorm processes in 10 sequences. As the duration of rainstorms increased, the precipitation of each rainstorm intensity grade increased as well. For 42 weather stations in Sichuan, the frequency of rainstorms of each intensity grade was calculated over the years from 1973 to 2012 according to the critical disaster-causing precipitation (Table 2). The average total number of episodes of each intensity grade in every 10 years span was calculated as the frequency at that station. The overall frequency of rainstorm at the station was the sum of frequencies of rainstorms of different intensity grades. The spatial distributions of frequencies of rainstorms for each intensity grade and overall rainstorm intensity and frequency at each station are shown in Figure 11.

The results showed that the overall frequency and the frequency of rainstorm processes of different intensity grades decreased from east to west of Sichuan Province. The frequencies were much higher in the basin of eastern Sichuan than in the mountainous south-western region and in the north-western plateau. The smallest frequency was found in the plateau of north-western Sichuan. Within the basin, the frequency of rainstorm intensity in the west was higher than that in the east. The high-value regions of overall rainstorm intensity frequency were mainly found in the western and north-eastern basin. Ya'an, Leshan and Meishan City in the western part of the basin were high-frequency regions, followed by Bazhong and Dazhou City in the north-western basin. The frequency of 5 rainstorm intensity grades (Figure 11a-e), decreased from grade 1 to grade 3, the maximum decreasing from 17 times/10a for grade 1 to 3.6 times/10a for grade 3. The rainstorm frequency increased slightly for grade 4 intensity and decreased for grade 5 intensity. The frequency for grade 5 intensity was the smallest of all grades, with a maximum of 3 times/10a. The overall rainstorm frequency (Figure 11f) varied within the range of 0-30 times/10a. Within the years covered by statistical data, the overall rainstorm intensity frequency was 0 in most part of the plateau of western Sichuan. Ya’an, Leshan and Meishan City in the western part of the basin were regions with high overall rainstorm intensity frequency, the maximum being 30 times/10a. Figure 12 shows the distribution of stations with overall rainstorm intensity frequency above 10 times/10a. The high-value regions were mainly found in Ya’an (Ya'an and Hanyuan Station), Dazhou (Wanyuan and Daxian Station), Leshan (Emeishan and Leshan Station), Chengdu (Wenjiang and Dujiangyan Station), Bazhong (Bazhong Station) and Guangyuan (Guangyuan Station) City in western and north-eastern basin. In these regions, the overall rainstorm intensity frequency was above 15 times/10a, which agreed with the spatial distribution features of rainstorms discussed in the above section. In terms of spatial distribution features of rainstorms and rainstorm precipitation process, our results are also consistent with the previous studies in Sichuan Province or neighboring regions (Xiao et al., 2017; Li & Mu, 2014; Zhang et al., 2019), but our analysis is more comprehensive.

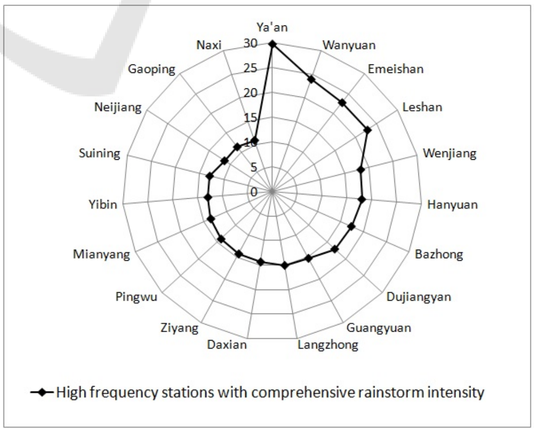


Figure 12: Radar map of stations with overall rainstorm intensity frequency above 10 times/10a.

4 CONCLUSIONS

Global climate warming and urbanization have conducted to intensity and frequency changes of meteorological disaster-inducing factors. Therefore, it emphasized the challenge in the management of meteorological disasters. This challenge has become the high-priority issue for different countries in coping with climate change. Analysis of spatial-temporal distributions and variation trend of meteorological disasters and disaster-inducing factors can shed new light on meteorological disaster prevention and control, disaster relief planning and adaptation to climate change. We chose Sichuan Province which spans part of the Qinghai-Tibet Plateau as the research area because the region is affected by heavy rainfall and increased flood frequency. The daily precipitation data of 42 weather stations in Sichuan from 1973 to 2012 were used, along with statistics on rainstorm and flood disasters and socioeconomic status of 21 cities and prefectures from 1985 to 2012. The following main conclusions were deduced:

(1) From 1985 to 2012, the loss of crop area caused by the rainstorm and flood disasters and the loss rate in Sichuan showed a large fluctuation as a whole. Rainstorm and flood disasters mainly occurred in the period from June to September in Sichuan. In the past 28 years, the ratios of direct economic losses, areas of crops covered and affected by the rainstorm and flood disasters and area of total crop failure in these four months to the corresponding annual averages were 95.8, 86.6, 85.4 and 90.6, respectively. These values were especially higher in July, accounting for 42.8%, 38%, 40.5% and 43.6% of the annual total, respectively.

(2) The average direct economic loss due to rainstorm and flood disasters in 21 cities and prefectures from 1985 to 2012, it was higher in Dazhou, Mianyang and Nanchong City, which are located in the north-eastern Sichuan Basin. Regions with the lowest average direct economic loss were Ya’an, Aba Prefecture and Neijiang City.

(3) Though the annual average precipitation in Sichuan showed a mild decreasing trend over the years, the annual average rainstorm volume, annual average contribution rate of rainstorms, annual average rainstorm frequency and annual average rainstorm intensity increased at 42 weather stations from 1973 to 2012, but insignificantly. The annual average rainstorm volume and annual average rainstorm frequency in Sichuan shared similar spatial distribution patterns in the past 40 years. Both were higher in the east region than in the west region. The lowest was observed in the plateau of north-western Sichuan, followed by the mountainous region of south-western Sichuan; the highest was found in Sichuan Basin in the east. The months from June to September were the major season of rainstorms, and local rainstorms were more frequent from July to August.

(4) Among rainstorm rainfall processes lasting for different days, except for large difference in maximum precipitation between rainstorm processes lasting for 1 day and for more than 10 days, the maximum precipitation of other rainstorm processes was mostly about 400mm.The overall frequency and the frequency of rainstorm processes of five intensity grades decreased from east to west of Sichuan Province. The frequencies were much higher in the basin of eastern Sichuan than in the mountainous south-western region and in the north-western plateau. The smallest frequency was found in the plateau of north-western Sichuan. Within the basin, the frequency of rainstorm intensity in the west was higher than that in the east.

However, due to the lack of data, the analysis of rainstorm and flood disaster losses is only 28 years, and the time scale is relatively short. There are many causes in inducing rainstorm and flood disaster in Sichuan, including natural and human factors. Therefore, the analysis on spatial-temporal distribution characteristics of rainstorm have to be expand. In the future, the improvement of data will strengthen the analysis of longer time scale to identify more disaster causing factors.

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