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ORIGINAL PAPER

Meteorological disaster frequency at prefecture-level city scale and induced losses in mainland China during 2011–2019

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Abstract
Meteorological disasters (MDs), including drought, flood, hail, low temperature and frost (LTF), are causing severe damage to human life and economic development in China. Mapping the distribution of MDs and induced losses at fine spatial resolution across the whole country is helpful for disaster control. Based on the officially published records and yearbooks, the spatiotemporal variations in MD frequency at prefecture-level city scale and disaster-induced losses at provincial scale during 2011–2019 were analyzed. The result showed that there were average 1416.9 MD events every year at prefecture-level city scale. Flood and hail disasters dominated from April to September, while LTF disasters dominated from December to February. Drought disasters were mainly distributed at the second terrain step and North China Plain; frequency of flood disasters in the south part of China was higher than that in the north part of China, especially in the upper and middle reaches of Yangtze River basin; while the north part of China experienced higher frequency of hail and LTF than the south part. Cities on the second terrain step of China experienced the largest MD frequency because of the combination of disaster-causing factors and hazard-bearing body. Disaster loss analysis results showed that drought disasters had the severest effects on cropland because of the highest average covered and failed area of cropland among four MDs. Hunan, Hubei and Sichuan provinces experienced higher values of covered population and direct economic losses, while coastal provinces experienced less exposure to MDs. The results of this study can help optimal allocation of disaster mitigation and adaptive measures at both country and regional scales.

Keywords Spatial distribution · Drought · Flood · Hail · Frost · Economic losses

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1 Introduction

Meteorological disasters (MDs), including drought, flood, hail and low temperature and frost (LTF), have caused severe direct or indirect damage to human life, property and economic development. Agriculture facilities are highly vulnerable to MDs, about two-thirds losses of crops were associated with floods, and almost 90% of disaster losses in the livestock sector were attributable to drought (FAO 2018). Except for the losses related to agriculture, MDs could also induce large population affected (Guan et al. 2015; Wu et al. 2014; Ma et al. 2020a, b) and severe economic losses over the world (Liu and Yan 2011; Zhou et al. 2014; Klomp 2016; Crompton and John McAneney 2008; Tang et al. 2019). During 1970–2009, MDs caused about 1.86 million death and 1954 billion USD direct economic losses worldwide (WMO 2013). The ratio of economic losses by MDs to GDP varied greatly among countries, the largest ratios in mid-income countries were 1%, followed by 0.3% in low-income countries and 0.1% in high-income countries (IPCC 2012). During the past decades, the frequency and magnitude of extreme weather events both obviously increased because of climate change and intensive human activities (IPCC 2012; Shi et al. 2016; Sisco et al. 2017; Roxburgh et al. 2019; Tang 2020). Thus, better understandings on the characteristics of MDs are crucial to mitigate future MD risks and allocate adaptive management.

China experienced severe MDs because of its monsoon climate and dense disaster-bearing bodies (Zhang et al, 2014a, 2014b). The losses induced by MDs can take up more than 70% of total losses among all kinds of natural disasters (Qin 2007; Shi and Ying 2016). During the past decades, especially in the last two decades, research works on all aspects of MDs greatly increased in China, which contributed to better understand MDs. Wang et al. (2006) introduced the natural disaster zoning systems in China and summarized the spatial distribution and temporal dynamic processes of natural disasters. Then, many studies were conducted to identify the spatiotemporal distribution characteristics of different MDs at different scales (Fang et al. 2011; Su et al. 2011; Zhang et al. 2014a, 2014b; Guan et al. 2015; Fu et al. 2018; Lu et al. 2018; Yu et al. 2018; Wang et al. 2019; Shi et al. 2020; Shi and Cui 2020; Li et al. 2020). A lot of research works on the risk assessment (Zhang 2004; Hao et al. 2012; Liu et al. 2019; Zhou et al. 2015; Gao 2016; Wang et al. 2017; Zhang et al. 2017; Yan et al. 2017; Ye et al. 2020) and disaster impact assessments of different MDs (Liu and Yan 2011; Qiu et al. 2018; Huang et al. 2019; Guo et al. 2020) were also conducted.

The prerequisite for assessing disaster risks and formulating disaster prevention measures is to fully understand the temporal and spatial distribution characteristics of disasters. Thus, the statistical work related to the MD spatiotemporal characteristics over whole country has a long historical period. Wang et al. (1994, 1995) separated the whole country into four different regions using Hu Line (Heihe-Tengchong Line, population separation line that about 96% people live at southeastern part), Qinling-Huaihe line and edge line of Tibetan Plateau. They also pointed out the disaster characteristics in different regions. After that, many studies were conducted to analyze the provincial spatial distributions characteristics of MDs over the whole country (Fang et al. 2011; Liu and Yan 2011; Liao et al. 2013; Yao et al. 2017; Li et al. 2019; Wang et al. 2019), and there were also some studies concentrated on the specific province and regions (Wu et al. 2015; Lu et al. 2016; Wang et al. 2017; Xu et al. 2017; Huang et al. 2017; Fu et al. 2018; Liu et al. 2019; Huang et al. 2019). In recent years, research works started to use disaster census data and meteorological data at country (district) scale to analyze the spatial and temporal distribution characteristics of

MDs over large regions in China (Yu et al. 2018; Shi and Cui 2020; Shi et al. 2020; Li et al. 2020). These studies helped us to better understand the distribution characteristics of single or some MD types over a part of China and demonstrated the importance of using high-resolution MD distribution data over the whole country. However, previous studies have not analyzed all kinds of MDs at high spatial resolution such as prefecture-level city scale over whole China. The high spatial resolution data of all MDs types over whole China are essential for disaster reduction and prevention because it enables us to identify the administrative regions with the largest probabilities of experiencing all kinds of major MDs.

The main objectives of this study are therefore: (1) to explore the temporal and spatial distribution characteristics of four different kinds of MDs at prefecture-level city scale during 2011 to 2019; (2) to identify the provincial units that experienced the severest cropland losses, covered population and direct economy losses induced by MDs. The results can provide scientific bases for the mitigation of MDs risk, which are great help for early warning and reducing economic losses induced by MDs (Alca´ntara-Ayala 2002; Wei et al. 2004), and finally serving for reduction losses induced by MDs and emergency management in China.

2 Data and methodology

2.1 Research area

China has a stepped terrain that being high in the west and low in the east (Cheng et al. 2017). The terrestrial part of China can be generally divided into three terrain steps according to the elevation. The first step is the Tibetan Plateau with the average elevation more than 4000 m above sea level; the second step includes the Inner Mongolia, Loess, Yunnan-Guizhou plateaus, and the Tarim, Junggar, Sichuan basins, with the average elevation of between 1000 m and 2000 m; the third step is plains and hills with the average elevation smaller than 500 m, it begins at a line around the Greater Hinggan, Taihang, Wushan and Xuefeng mountains and extends eastward to the coast (Fig. 1). Qinling-Huaihe line has long been recognized as geographical boundary between north and south China (Liu et al. 2020). The north and south parts have differences on the aspects of climate, culture and lifestyle. There are currently 333 prefecture-level administrative regions in Mainland China, including 293 prefecture-level cities, 7 prefecture-level regions, 30 autonomous prefectures and 3 prefecture-level leagues. It should be noted that Taiwan province, Hong Kong and Macao were not included in this study due to incomplete data.

2.2 Data sources

MDs records were collected from the official Website of National Disaster Reduction Center of China (http://www.ndrcc.org.cn/zxzq/index.jhtml), the WeChat official account (Disaster Reduction in China) and the Yearbook of Meteorological of China (China Meteorological Administration 2018). In each record of MD event, the detailed information of disaster type, date, and place (prefecture-level city) was included. During 2011–2019, the changes in prefecture-level administrative regions were restricted only with several small changes. In the statistical processes, we correspondingly counted the records of MDs to current prefecture-level cities and municipalities to avoid the influence induced by the changes of administration. The yearly average frequency of four

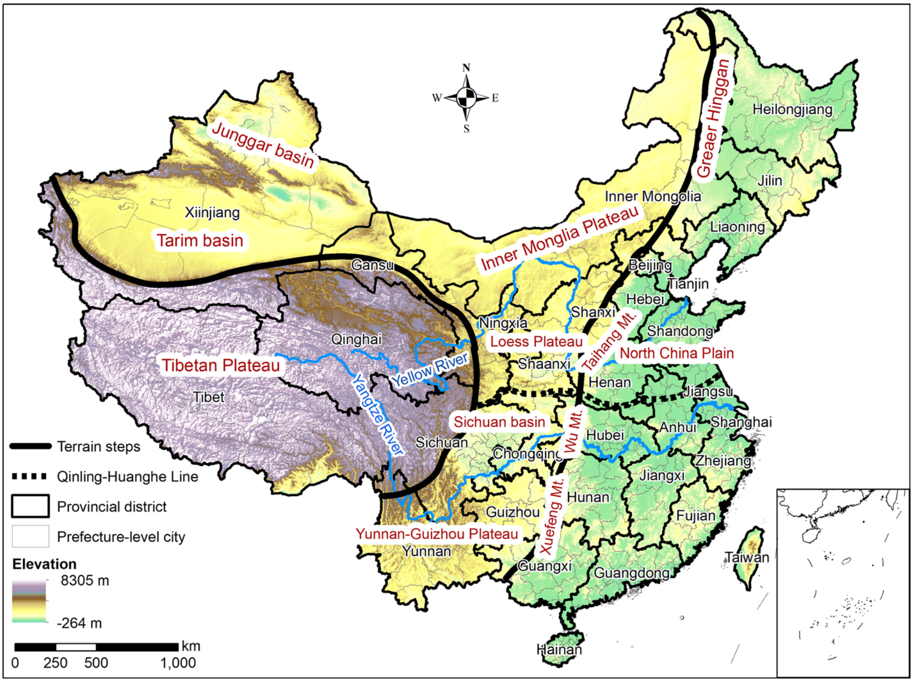

Fig. 1 Stepped terrain features and prefecture-level city distributions in China, including the schematic diagram of separation lines for three terrestrial terrain steps and Qingling-Huaihe line that dividing the north and south part of China

kinds of MDs during 2011–2019 was then displayed to show the spatial distribution of MDs, the monthly variations in frequency of MDs were used to show the temporal distribution in one year. The data of losses induced by MDs including covered area, failed area, direct economic losses, covered population, death, damaged houses and

Table 1 The indexes used and their definitions

Index	Definition
Covered area	The sown area with over 10% (including 10%) crop losses due to MDs. When the crops in the same plot suffered more than one disaster event, only the severest one was counted
Failed area	The sown area with over 80% (including 80%) crop losses due to MDs. When the crops in the same plot suffered more than one disaster event, only the severest one was counted
Direct economic losses	The total direct economic losses of agriculture, forestry, animal husbandry and fishery, industry, transportation, hydropower and other industries and water conservancy facilities due to MDs
Covered population	The population with damage losses directly induced by MDs
Death	The death population directly induced by MDs (including the missing persons)
Damaged houses	The numbers of house damaged induced by MDs
Collapsed houses	The numbers of house collapsed induced by MDs

collapsed houses (Table 1) were summarized at provincial scale because these numbers were usually published as a summary of different prefecture-level cities within one provincial unit. To comprehensively understand losses induced by MDs and find out the most severe provinces influenced by MDs, statistical data including cropland sown area, population, Gross Domestic Product (GDP) and Consumer Price Index (CPI) in each provincial unit were collected from the National Bureau of Statistics of China (http://data.stats.gov.cn).

Since all disaster records data collected on official website are manually checked and summarized item by item, and some disaster event with few losses may be neglected without publication, there are some inevitably omissions in frequency data. Because disaster records data and the yearbook data are published by different departments (Yu et al. 2018; Shi et al. 2020), there also exist differences in the disaster loss data between different datasets, which requires verification and selection processes. In this study, the frequency of MDs was mainly based on the disaster record data from official website and WeChat official account, the losses data of each province induced by MDs were mainly based on the Yearbook data and verified by the disaster record data from official website. The data used in this study are all published records, which have already experienced quality control processes conducted by the relevant government sector and statistical organization at both local and central government levels (Xu and Tang 2021), making these data convincible for analyzing the characteristics of MDs. Overall, these data are quite spatially detailed for identifying distributions of all MDs types over whole China and are helpful to reflect the historical losses in different administrative regions.

2.3 Methodology

A total of four kinds of MDs (drought, flood, hail and LTF) were included in this study. For drought disasters, one drought event can last for several months and cover many cities, which makes it hard to distinguish one event from another. Official published records on website can be continuously updated for a single event, thus, a single drought disaster event for specific city was counted only when official published records no longer updated. Frequency of other MDs was also obtained using same method. Flood disasters include the disasters induced by an increase in water volume of rivers, lakes and coastal areas, the flooding of water levels, and the outbreak of mountain torrents as a result of heavy rainfall, melting of ice and snow, ice slush, dyke breach, storm surge, etc. Typhoon disasters were counted into flood disasters because losses of disasters were mainly induced by heavy precipitation (Guan et al. 2015; China Meteorological Administration 2018). Hail disasters refer to disasters caused by strong winds, hail, tornadoes and lightning caused by a strongly convective weather. LTF disasters include low-temperature continuous rain and cold damage, frost and cold wave. Snowstorm disasters were merged into LTF disasters as they were always counted together.

To display the influences of MDs on cropland losses, the relationships between sown area and covered area, as well as failed area, were plotted. Similar relationships like provincial covered population and total population, direct economy losses and GDP were also plotted. To analyze the relationship between the direct economic losses by MDs and the GDP in various provinces, it is necessary to consider the inter-annual price changes. CPI variations were considered to uniformly convert the direct economic losses into prices of 2015 for further analysis (Wu et al. 2014; Ma et al. 2020a, b).

3 Results

3.1 Spatiotemporal variations in MD frequency during 2011–2019

During 2011–2019, the yearly average frequency of MD events in mainland China was 1416.9 times at prefecture-level city scale. For individual city, the frequency varied from 0 to 22.8 times with large spatial differences.

3.1.1 Temporal variations

The monthly and yearly variations in MD frequency are displayed in Fig. 2. Drought disasters were mainly distributed from April to August, while the frequency of drought disasters was low compared with other MDs because of its long duration and large spatial range (Zhang 2004; Hao et al. 2012; He et al. 2016). Flood disasters were mainly distributed from April to September in the rainy season affected by the East Asia monsoon. The frequency of flood was the highest in July and nearly reaching up to 150 times per year

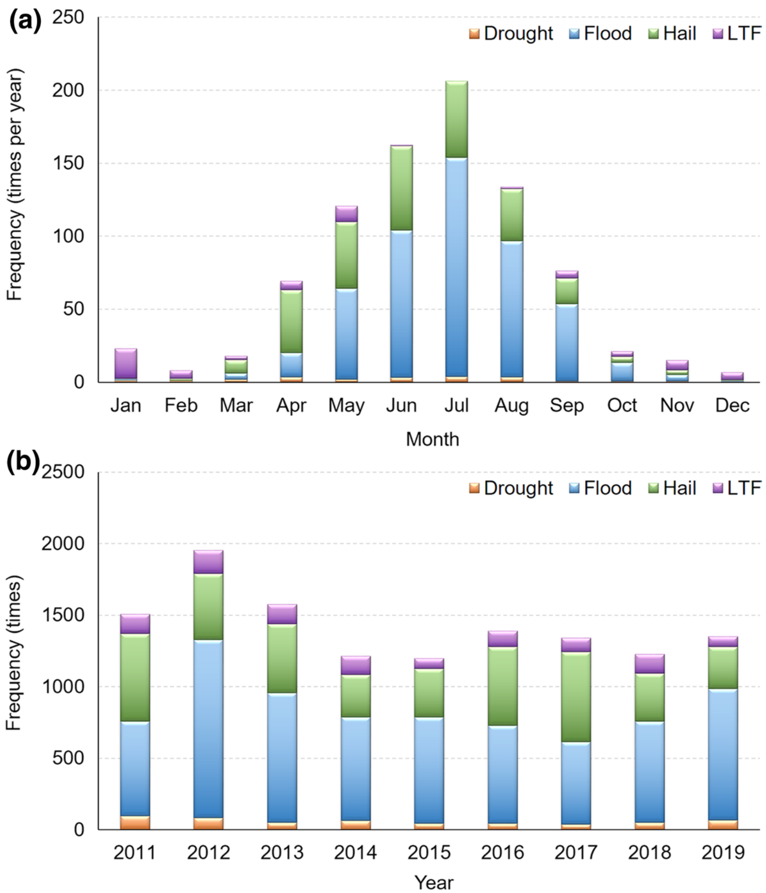

Fig. 2 Monthly variations in average MD frequency (**a**) and yearly variations in MD frequency (**b**) during 2011–2019

(Fig. 2a). Hail disasters showed similar temporal distribution characteristics with the flood disasters, mainly influenced by the regional convective weather in summer. The frequency of hail disaster ranged from 35.7 to 57.9 times during April to August, while it was smaller than 10 times in other months. LTF disasters can be found in most months except for July, because China covers a larger range of latitudes and altitudes, LTF disasters can even exist in summer in high latitude and altitude regions. From December to February at winter, the LTF disasters had the largest frequency compared with other MDs, and the frequency of other MDs ranged from 0.0 to 1.4 times. Frequency of LTF disasters in January was the highest, reaching up to 20.4 times per year (Fig. 2a).

During 2011–2019, the total frequency of all MDs varied among years from 1198 to 1954 times with relatively small changes. The total frequency was the highest in 2012, in this year, the frequency of flood exceeded 1000 times which was also largest among all years. Among four kinds of MDs, flood disasters possessed the largest part of total frequency (44%–68%), followed by hail disasters (22–47%). The frequency of drought and LTF disasters is relatively small compared with other two MDs (Fig. 2b).

3.1.2 Spatial distributions

During 2011–2019, the frequency of four kinds of MDs at prefecture-level city scale showed different spatial distribution characteristics (Fig. 3). At prefecture-level city scale, the yearly average frequency of drought disasters ranged from 0 to 1.2 times. Drought disasters mainly distributed on the second step of China (north Xinjiang, Loess Plateau,

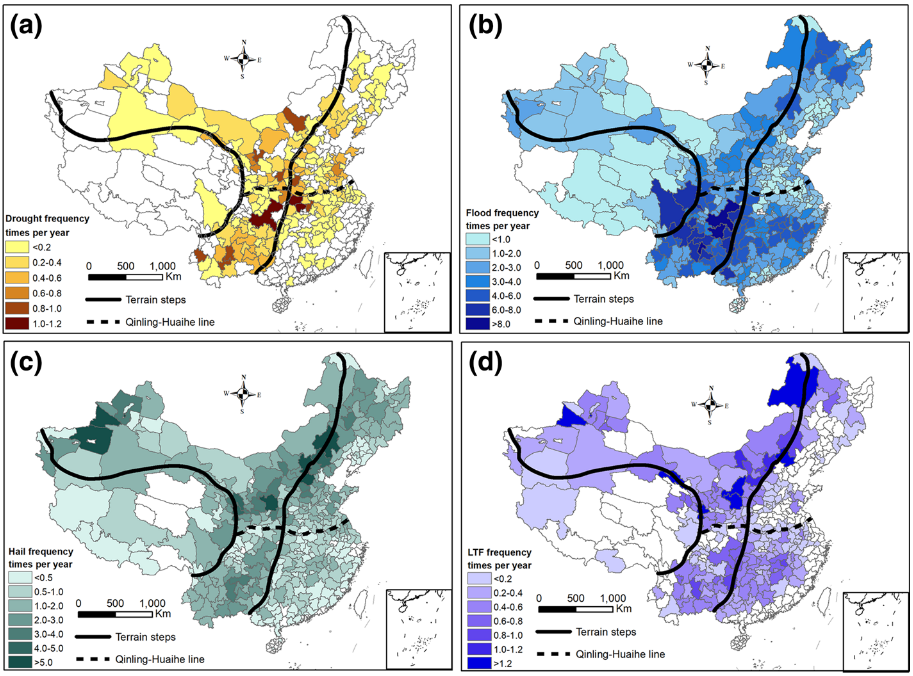

Fig. 3 Spatial distribution of yearly average frequency of drought (**a**), flood (**b**), hail (**c**) and LTF (**d**) disasters at prefecture-level city scale during 2011–2019

Yunnan-Guizhou Plateau) and North China Plain (Fig. 3a). Frequency of flood disasters was larger than other MDs (Fig. 3b), the yearly average frequency of flood disasters in different prefecture-level cities ranged from 0 to 18.8 times. Frequency of flood disasters in the south part of China was obviously higher than that in the north part of China, especially in the upper and middle reaches of Yangtze River basin. Most prefecture-level cities in this region experienced flood disasters more than 5 times per year. Frequency of hail disasters displayed great spatial variations divided by Qinling-Huaihe line. The north part of China experienced more events than the south part of China (Fig. 3c). Many prefecture-level cities in the north part of China experienced more than two hail events because of the extreme weather in summer. While in the south part of China, except for Yunnan and Guizhou provinces in the southwest part, hail disasters were not so severe as that in the north part. It should also be noted that Xinjiang experienced severe hail disasters during the past decade around the Tian Mountain. Frequency distributions of LTF disasters also showed that the north part of China experienced more LTF events than the south part of China (Fig. 3d). LTF events were mainly concentrated in two regions, one was distributed along the middle reach of Yellow River to the Mongolian Plateau, the other was in the south part of middle reach of Yangtze River basin. Frequency of LTF disasters in coastline and nearby regions was small.

The yearly average total frequency of four kinds of MDs in each prefecture-level city is displayed in Fig. 4. Natural disasters are not only determined by the disaster-causing factors like climatic condition, but also influenced by the hazard-bearing body (Zhang et al. 2017; Chou et al. 2019; Wu et al. 2019). Thus, the spatial distribution of MD frequency

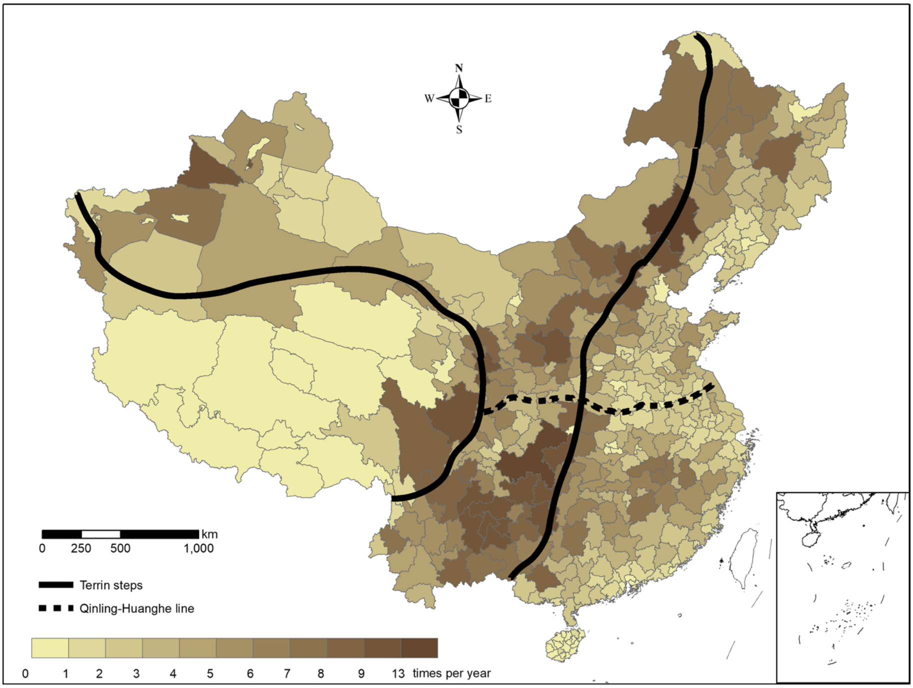

Fig. 4 Spatial distribution of yearly average total frequency of four kind of MDs at prefecture-level city scale during 2011–2019

was not only influenced by the natural climatic condition, but also coped with the density of infrastructure and regional economic development. On the first terrain step of China with average elevation larger than 4000 m, the urban economy is underdeveloped with sparsely populated. Although the natural environment in these regions is harsh, the disaster-bearing bodies such as people, houses, agriculture facilities, and infrastructure are lacking, resulting in relatively low MD frequency. On the third terrain step where average elevation is smaller than 500 m, MD frequency is also relatively low even this region has more disaster-bearing bodies, especially in the coastal and nearby regions, and this can be attributed to the better natural conditions. In addition, the emergency response and disaster prevention systems are also better constructed and maintained in this region (Shi et al. 2020). On the second terrain step with average elevation between 1000 and 2000 m, the MD frequency is higher compared with other regions. This can be attributed to the complex natural environmental conditions, large number of disaster-bearing bodies and relatively poor disaster prevention capabilities.

3.2 Spatial distribution of losses induced by MDs

Table 2 shows the losses induced by four kinds of MDs during 2011–2019. The results showed that flood disasters caused largest direct economic losses, damaged and collapsed house, covered population and death among four kinds of MDs, while drought disasters had severest effects on the cropland as the values of average covered area and failed area were the largest. Compared with the drought and flood disasters, the influences of hail and LTF disasters on the cropland, economy and population were relatively small.

3.2.1 Cropland damage

Fig. 5a and b displays the values of covered area and failed area of cropland, as well as the component parts of four different kinds of MDs. The largest value of covered area during 2011–2019 appeared in Inner Mongolia with more than 2.5 million ha every year, followed by Liaoning, Hubei, Hunan, Hebei, Shandong, Gansu, Yunnan and Henan, the covered area of above provincial units all exceeded 1 million ha. Similar patters can also be found in failed area of cropland, Inner Mongolia has largest failed area of 0.35 million ha per year, followed by Liaoning, Hunan, Heilongjiang, Guizhou and Hubei with failed area larger than 0.15 million ha per year. As for the component parts of four different kinds of MDs, drought disasters were found with largest percentages in most provincial units, especially in the north part of China. While in provincial units at the midsouth and southeast part of China, the flood disasters possessed the largest percentage and had the largest influence on the cropland among four kinds of MDs. A special exception appeared in Xinjiang that hail disasters had the largest influences on the cropland during 2011–2019.

Fig. 5c and d displays the yearly average sown area of each provincial unit and the relationship between sown area and covered area, as well as failed area during 2011–2019. The largest sown area was found in Henan province with 14.4 million ha, followed by the Heilongjiang and Shandong, both exceeding 10 million ha (Fig. 5c). The covered area and failed area of cropland showed good correlations with the sown area, and the determination coefficients were 0.55 and 0.34, respectively (Fig. 5d). Several points, namely Inner Mongolia, Liaoning, Hubei and Gansu were far above the trend line, representing that the covered area and failed area in these provincial units were on a high level which need better disaster mitigation measures. Guangdong, Jiangsu, Sichuan, Henan provinces were,

Table 2 Disaster losses induced by four kinds of MDs in China during 2011–2019

Types of MDs	Average direct economic losses (billion CNY per year)	Average covered area of cropland (thousand ha per year)	Average failed area of cropland (thousand ha per year)	Average damaged house (thousand per year)	Average collapsed house (thousand per year)	Average covered population (million per year)	Average death (person per year)
Drought	55.3	9603.0	994.3	–	–	44.9	–
Flood	163.8	7077.2	906.4	1200.2	318.1	96.9	750.1
Hail	19.0	1940.5	257.6	219.2	36.2	16.8	166.2
LTF	9.9	1484.9	126.3	9.3	–	13.3	–

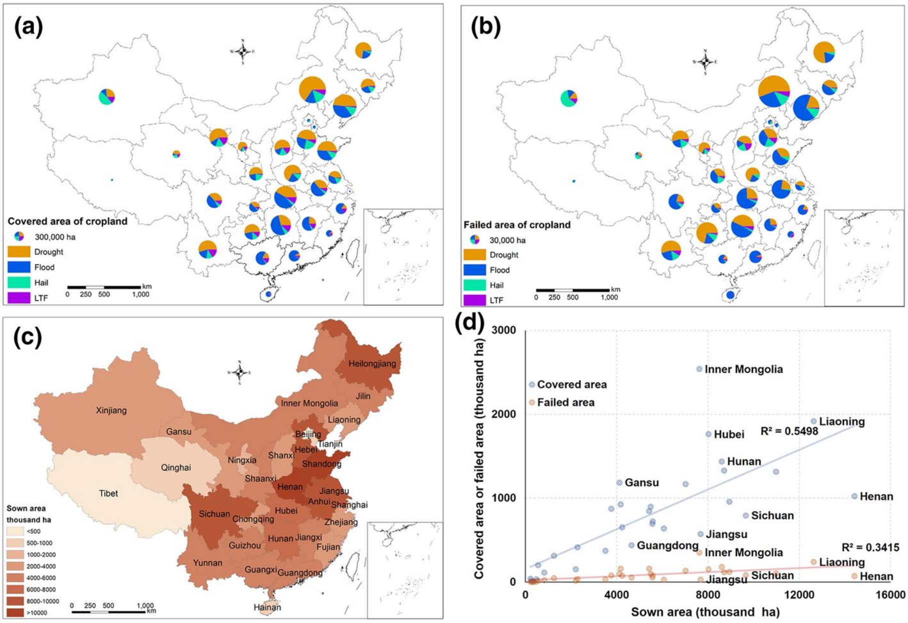

Fig. 5 Component parts of covered area (**a**) and failed area (**b**) of cropland by four kinds of MDs of each province (The size of circle represents the value of covered and failed area), yearly average sown area of each province (**c**), the relationship between the sown area and covered area, as well as failed area (**d**) during 2011 to 2019

however, below the trend line. Among these provinces, Guangdong and Jiangsu are provinces with better economic and small sown areas, Sichuan and Henan are provinces with large sown area and relatively good natural conditions under low MD risks.

3.2.2 Covered population

The largest number of covered population by MDs was found in Hunan province with 14.5 million persons per year, and followed by Sichuan, Hubei and Henan provinces. The covered population in these provinces all exceeded 10 million persons per year. These provinces are also the provinces with large population (Fig. 6a, b). For the component parts of four different kinds of MDs, in the north part of China, flood and drought disasters were two main factors that inducing covered population, hail disasters also occupied large portion of cover population on the North China plain including provinces like Henan, Shandong, Hebei. In the south part of China, flood disasters induced largest percentage of covered population except for the Yunnan province, as drought caused half of covered population in Yunnan province during 2011–2019 (Fig. 6a).

Fig. 6b shows the relationship between covered population and total population. Population in Hunan, Hubei and Sichuan provinces showed much higher exposure to MDs, as the bubbles representing these provinces were above the trend line. The population densities of three municipalities, Beijing, Tianjin and Shanghai, were higher than those of other provincial units, while the covered population by MDs was small. The covered population in coastal provinces like Jiangsu, Zhejiang, Fujian, Guangdong, Guangxi were relatively

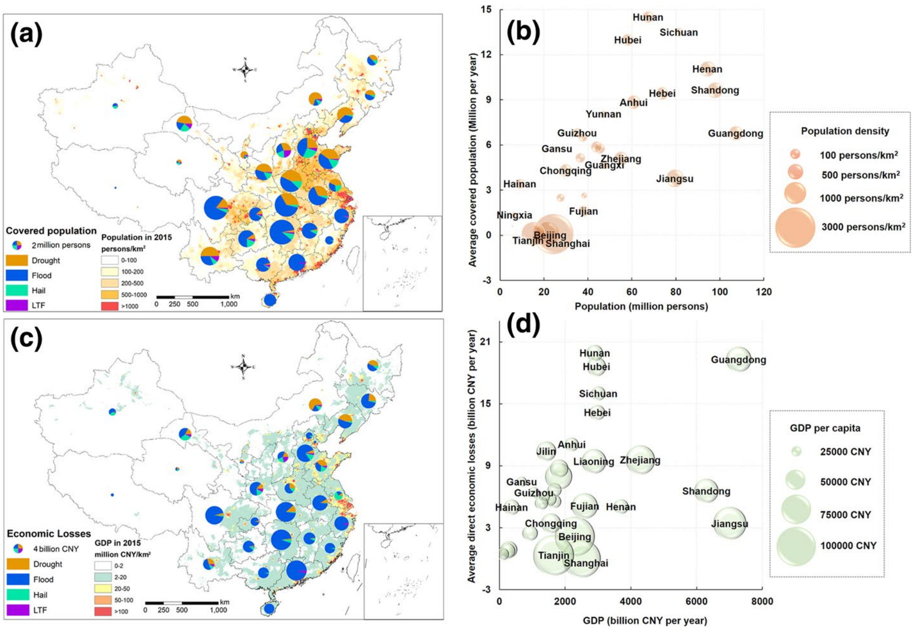

Fig. 6 The component parts of covered population (**a**) and direct economic losses (**c**) by four kinds of MDs during 2011–2019, the background shows the population density and GDP density distribution in 2015 with 1 km resolution (data from http://www.resdc.cn/), the size of circle represents the value of covered population and economic losses. The relationship between covered population and population (**b**) in which the area of bubble representing the population density. The relationship between direct economic losses and GDP (**d**) in which the diameter of bubble representing the GDP per capita

small compared with the neighboring inland provinces with similar population density (Fig. 6b). This can be attributed to the better natural living environment and disaster mitigation measures in provincial units with developed economy (Zhou et al. 2015).

3.2.3 Direct economy losses

The component parts of direct economy losses at different provincial units are displayed in Fig. 6c. The yearly average total direct economy losses in Hunan and Guangdong provinces were largest with direct economy losses of 19.9 and 19.3 billion CNY, respectively. Hubei, Sichuan, Hebei and Anhui were the followers with direct economic losses larger than 10 billion CNY (Fig. 6d). Flood disasters contributed to largest portion of direct economy losses in most provinces during 2011–2019, excepted for several provincial units like Inner Mongolia, Ningxia, Jiangsu and Shandong. Drought disasters took up largest portion (more than 70%) of direct economy losses at Inner Mongolia. Similar as population component parts, drought disasters also took a larger portion of direct economic losses in Yunnan and Liaoning provinces compared with other provincial units. Hail disasters occupied 68% of direct economic losses among four kinds of MDs in Jiangsu province. This percentage was the largest among all provincial units, while others only took up no more than 32% of total direct economic losses. LTF disasters had largest portion (22%) of direct economy losses in Shanxi province, while this portion only varied up to 14% in other provincial units.

The component analysis results can display the most important MDs that influencing the economic in each provincial unit (like drought in Yunnan, Inner Monglia and Liaoning, Hail in Jiangsu, etc.), which can be good references for the reasonable disaster mitigation investment.

Fig. 6d shows the relationship between the average direct economic losses and GDP. Similar as the covered population, the bubbles representing Hunan, Hubei, Sichuan provinces were above the average level which showed higher direct economic losses induced by MDs. Jiangsu and Shandong are two provinces with high-level GDP and large number of GDP per capita, while direct economic losses by MDs are much smaller compared with their total GDP, this can be attributed to their superior environmental conditions with less MD frequency, as well as better infrastructure construction and disaster prevention capabilities. Beijing, Tianjin and Shanghai, with largest GDP per capita, are also with small numbers of directed economic losses by MDs.

4 Discussion

China has a complex geographical feature with various climatic condition. Population distribution and socioeconomic development status also have great regional differences, these all contribute to the great differentiation in distribution and induced losses of MDs (Wang et al. 1994, 1995, 2006; Liao et al. 2013; Zhou et al. 2014; Zhou et al. 2014; Jia et al. 2016). Clarifying the distribution characteristics of MDs and induced losses can provide guidance for national and regional disaster prevention and emergency management (Guan et al. 2015; Shi and Cui 2020; Shi et al. 2020). This study mapped the spatial distributions of four different kinds of MDs at prefecture-level city scale which provided a possibility of finding the administrative regions with highest probability of exposing to these MDs.

Drought disasters were found mainly distributed at second terrain step and North China Plain and greatly influenced the cropland in this study. Similar spatial distribution results have been obtained by many previous studies (Hao et al. 2012; He et al. 2016; Yao et al. 2017; Chou et al. 2019; Wang et al. 2019), especially for agricultural drought mainly occurred in the eastern part of Northeast Plain, the central of Inner Mongolian Plateau, the Loess Plateau, north Xinjiang, the north and south of Yangtze Plain and Yunnan-Guizhou Plateau (He et al. 2013; Wang et al. 2019). Finer resolution of prefecture-level city scale gives us more opportunities for accurately find drought-prone cities. Even in the large drought-prone regions on the second terrain step, there are still many prefectures with less disasters, like Yulin, Chengdu, Mianyang, Suining, Dali, etc. Although some prefecture-level cities are in the relative safe terrain step, they are also found with high risks. For example, cities like Jingmen and Xiangyang at the third terrain step were found with relatively large number of drought disasters occurring. Thus, more research attention and future drought risk mitigation measures can be implemented in these drought-prone prefecture-level cities.

Flood has long been recognized as the most frequent and serious MDs in China (Guan et al. 2015; Yao et al. 2017; Yu et al. 2018; Wang et al. 2020), especially for the East China under the influence of East Asia monsoon (Shi and Cui 2020; Shi et al. 2020). Flood disaster-forming environmental factors analysis shows that serious flood disasters may distribute mainly in the south part of China, which has been proved by the frequency and losses distribution displayed in Figs. 3b, 5 and 6. For the aspect of spatial distribution of disaster losses, Yu et al. (2018) analyzed the variation in flood disaster caused by rainstorms during

1984–2008 based on survey data at county-level, the results were coped with this study that direct economy loss and covered population were concentrated in the south part of China. This has also been proved by other previous studies (Guan et al. 2015; He et al. 2018; Wang et al. 2020). In this study, we further evaluated the frequency of flood disasters at prefecture-level city scale and identified the cities with high risks of flood disasters mainly located in the upper and middle reaches of Yangtze River basin and Songhua River basin. This information was useful for future flood risk mitigation.

According to the statics of hail disasters on county scale among whole country during 1960–1999 (Wang et al. 1999), there were more hail disasters in the central region, less in the east and the least in the west, which is similar with the spatial distribution shown in Fig. 3c. Hail disasters researches in China were concentrated in provincial units where hail disasters were widely distributed, like Qinghai and Xinjiang (Zhang and Liu 2006; Wang and Ren 2006; Shi et al. 2015). In Qinghai province, previous result showed that northeastern part of Qinghai province had the largest hail frequency, accounting for 86.35% of the total frequency in whole province according to the statistics during 1962–2002 (Zhang and Liu 2006). Similar high frequency in the northeastern part of Qinghai Province was also observed in this study during 2011–2019, which showed that the hail disaster distribution characteristics of last decade in Qinghai province kept the same as the historical period. In Xinjiang, Shi et al. (2015) surveyed the frequency of hail disasters at county scales among whole Xinjiang during 1961–2014 and obtained similar result with Fig. 3c that hail disasters in Xinjiang were concentrated in Aksu, Bozhou and Shihezi regions.

LTF disasters have caused great losses in China in recent years, especially in 2008, a severe LTF disaster hit the south part of China, which have attracted a lot of attentions on this important disaster. A summary of spatial distributions of LTF disasters in 2012 and 2013 showed that LTF disasters were principally distributed in northeast, north and northwest China and sometimes southern China (Guan et al. 2015). This study included a longer research period and found more cities with high frequency of LTF. For example, prefectures like Yili, Zhangye, Dingli, Yulin, Yan’an, Xinzhou, Chengde, Zhangjiakou and Hulunbeier were all found with high frequency of LTF disasters. Gao (2016) assessed the snow and freezing disasters distribution in China by using the meteorological data during 1981–2010 and disaster loss data during 2004–2009, the result showed that northwestern China experienced higher frequency of snow and freezing events while southeastern part had more severe freezing disaster losses. The high loss regions induced by disasters shifted from the northwestern part to the southeastern part because of urbanization and rapid economic development in the southeastern part of China. This LTF frequency distribution during 2011–2019 in Fig. 3d also displayed that southern China experienced growing number of LTF disasters except for coastal cities, which verified that shift of high loss regions. This implies that the southeast part of China should also pay attentions to future LTF disasters and prepare mitigation measures.

5 Conclusion

This paper summarized the spatial distribution characteristics of four main kinds of MDs (drought, flood, hail and LTF) at prefecture-level city scale during 2011–2019 in mainland China. Disaster-induced losses were also summarized at provincial scale for better allocating the disaster mitigation investment. The result showed that there were average 1416.9 MD events every year at prefecture-level city scale during 2011–2019. In terms of temporal variation in frequency, flood and hail disasters were dominated in the rainy season from April to September, while LTF disasters were highest from December to February. In terms of spatial distribution, drought disasters were mainly distributed on the second terrain step and North China Plain. Frequency of flood disaster in the south part of China was higher than that in the north part of China, especially in the upper and middle reaches of Yangtze River basin. Frequency distributions of hail and LTF disasters showed that the north part of China experienced more events than the south part of China. The total frequency of four different kinds of MDs varied from 0 to 22.8 times with huge spatial differences. Prefecture-level cities on the second step with average elevation of 1000 to 2000 m experienced the largest MD frequency because of the combination of disaster-causing factors and hazard-bearing body.

Drought disasters had the most severe effects on the cropland because the values of average covered and failed area were the highest among the four kinds of MDs, followed by the flood, hail and LTF. In terms of covered population and direct economy losses, flood disasters occupied largest percentage of direct economic losses in most provinces. Hunan, Hubei and Sichuan provinces experienced higher covered population and direct economic losses during 2011–2019, while coastal provinces with developed economy experienced less exposure to MDs. The results of this study are critical and necessary for disaster risk mitigation and adaptive strategies allocation at both country and regional scales.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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