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Literature Review on Extreme Precipitation Events and Their Population and Economic Exposure in Xinjiang Uygur Autonomous Region

Yuying He

Xi'an International Studies University, Xi'an, China

ABSTRACT

In recent years, with the gradual acceleration of global warming, the water cycle has intensified, leading to frequent extreme weather events such as rainstorms and high-temperature heatwaves. Among them, the occurrence of extreme precipitation events has caused huge losses to human life, property, and socio-economic development. This paper reviews the definitions of extreme precipitation events and exposure, studies on extreme precipitation events at different regional scales at home and abroad, studies on exposure, and the research status at home and abroad on the threshold of extreme precipitation events, the selection of extreme precipitation indicators and exposure indicators. It is found that there are still deficiencies in the selection and division of spatiotemporal scale indicators for extreme precipitation events and in the comprehensive research on exposure. On this basis, the spatiotemporal distribution law of extreme precipitation events and the research prospects of exposure are prospected.

KEYWORDS

Xinjiang; Extreme precipitation events; Extreme precipitation threshold; Exposure; Population and economy

1. INTRODUCTION

Over the past century, with the continuous improvement of industrial levels, the global temperature has shown a continuous upward trend. The risks brought by climate change have gradually become a major challenge affecting global security and development [1]. The Fifth Assessment Report of the IPCC points out that the global average surface temperature increased by 0.85°C from 1880 to 2012. Due to global warming, the water cycle has intensified, leading to frequent extreme weather and climate events such as high-temperature heatwaves, severe droughts, and heavy precipitation. Precipitation-related extreme events are one of the most influential consequences of climate warming. Extreme precipitation has been reported as the main disaster related to extreme weather globally. The frequency of regional extreme precipitation has significantly increased, and the intensity has significantly enhanced, leading to the occurrence of some unprecedented extreme events, which have caused huge losses to human life, property, and socio-economic development, especially having adverse effects on agriculture, livelihoods, drainage systems, transportation services, and human deaths [2-6]. How to deal with global climate change and its adverse effects is a major challenge faced by the international community today [4]. At the global and regional scales, the frequency and intensity of extreme precipitation will further increase [5]. Therefore, studying the spatiotemporal variation characteristics of extreme precipitation is of great significance for coping with global climate change.

China has a complex terrain, and the huge land-sea difference makes the region extremely sensitive to climate change, resulting in frequent natural disasters. The *China Climate Change Blue Book (2023)* shows that from 1961 to 2022, the frequency of extreme heavy precipitation events in China showed an increasing trend [7]. Studies have shown that since the early 1950s, the area affected by floods has shown an upward trend; since 1961, extreme precipitation events in China have significantly increased, and the extreme precipitation amount and extreme precipitation days in most areas have shown an increasing trend [8]. The change characteristics of extreme precipitation in China are basically consistent with the global overall trend, but the regional characteristics are obvious. In most parts of China, the frequency and intensity of heavy precipitation and extreme heavy precipitation events can be observed to increase, and the characteristics of decreasing light rain and increasing heavy rain are shown. The overall performance of extreme precipitation in China is that the number of heavy precipitation events in Northeast and North China shows a decreasing trend, while that in the west of Northwest China, the middle and lower reaches of the Yangtze River, South China, and the Qinghai-Tibet Plateau shows an increasing trend. Especially in the Northwest, the middle and lower reaches of the Yangtze River, the southeast coast and other regions, the increasing trend of extreme precipitation frequency and precipitation intensity is more significant [3,9]. Under the background of climate change characterized by global warming, the frequent and severe occurrence of extreme climate events in China has seriously affected the sustainable development of the economy and society, especially after the superposition of extreme climate events and the socio-economic system, it is extremely easy to cause huge socio-economic risks [10]. The economic losses caused by rainstorms and floods each year account for 37.2% of the total economic losses caused by meteorological disasters, and the number of deaths accounts for 11.7% of the total number of disasters [1]. From July 21 to 22, 2012, the extreme rainstorm process in Beijing caused 79 deaths and economic losses of 11.64×10^8 yuan, and threatened more than 1.90×10^4 residents [9]. Henan, China, also encountered unprecedented historical extreme precipitation, and the resulting extreme flood disaster caused a total of 14.786 million people to be affected, 398 deaths, and direct economic losses of more than 120 billion [2].

China's Northwest Region is located in the heartland of Eurasia, north of the Qinghai-Tibet Plateau. Geographically, it has the topographic features of gobi, desert, mountains, etc. The region has a temperate continental climate, and the natural environment is characterized by drought and semi-drought. Limited by geographical conditions, it is dry and less rainy all year round. The annual precipitation in desert areas such as the southern Xinjiang Basin and western Inner Mongolia is generally less than 50 mm, forming China's extremely arid region. There are relatively rainy areas along the Tianshan Mountains, Qilian Mountains and other high mountains, and the annual precipitation in individual mountainous areas exceeds 500 mm. This unique geographical and climatic condition makes the Northwest Region have the characteristics of water shortage, severe drought, wide distribution of ecologically fragile areas, and strong dependence of the ecological environment on precipitation [11]. Xinjiang is located in the Northwest Region and is in the arid and semi-arid zones. Due to not being directly affected by the monsoon system, it has obvious climatic differences from the eastern part of China. Xinjiang's special terrain of "three mountains enclosing two basins" has many deserts and gobi. Affected by the terrain, the precipitation is extremely uneven, and the climate difference between southern and northern Xinjiang is very large, making the precipitation in Xinjiang show the characteristics of more in northern Xinjiang and less in southern Xinjiang. As a sensitive area to global climate change, Xinjiang is also the core area of the Silk Road Economic Belt in the "Belt and Road" initiative. Regional precipitation has a significant impact on its ecological environment and economic development [12]. Therefore, studying the change characteristics and future trends of extreme precipitation is of great practical significance for scientifically understanding the spatiotemporal changes of flood and drought disasters, carrying out the prediction and simulation of urban rainstorm and flood disasters, further formulating disaster mitigation strategies, and reducing disaster losses [2, 9].

2. RESEARCH PROGRESS AT HOME AND ABROAD

2.1. Extreme Precipitation Events

Scholars have given definitions of extreme precipitation events from different perspectives. Katz et al. [13] believed from the perspective of the relative sensitivity of extreme precipitation events that precipitation exceeds a certain threshold within a certain period, and this change exceeds the average sensitivity of climate change. Moreover, the more extreme the precipitation event, the greater this sensitivity. Beniston et al. [14] believed that extreme precipitation events should meet the conditions of relatively low occurrence frequency, reaching a certain intensity value, and causing serious economic losses. Hu Yichang et al. [15] studied and believed that if the average state of a precipitation event is more extreme than that of ordinary precipitation events for a long period of time, this situation can also be considered an extreme precipitation event. Liu Fengxia [16] believed that extreme precipitation events refer to events where the precipitation state seriously deviates from its average state and are not easy to occur in a statistical sense, and they have the characteristics of suddenness and strong destructiveness compared with the average precipitation. She defined regional extreme precipitation events as precipitation events that reach the threshold on a given duration scale and continuous area. Mo Jianfei [17] also regarded the precipitation at a certain observation station in a certain period exceeding the threshold of the station as an extreme precipitation event.

In recent years, many scholars have carried out studies on extreme precipitation at different spatial scales. The IPCC [18] once pointed out that with the increase of global temperature, the total amount, frequency, and intensity of extreme precipitation have significantly increased, and this conclusion has been verified in many regions around the world. Alexander [19, 20] and others analyzed the spatio-temporal distribution pattern characteristics of global extreme precipitation by using the daily precipitation data of nearly 600 stations worldwide and pointed out that although the extreme values of extreme precipitation in different regions lack spatial consistency, overall, extreme precipitation shows an increasing trend globally. Frich [21] and others analyzed and found that under the condition of global warming, the water cycle is intensified, the probability of extreme precipitation events in the mid-high latitudes of the Northern Hemisphere increases, and the range of extreme precipitation is gradually expanding. Kong Feng et al. [22] reviewed the precipitation events in the past century and found that the global average precipitation did not change significantly, but the change trend of extreme precipitation was obvious, especially in the mid-high latitudes, the extreme precipitation events significantly increased, and the areas where extreme precipitation events significantly increased were more than those where they significantly decreased, with obvious regional distribution. In two-thirds of the land areas in the Northern Hemisphere, the probability of extreme precipitation events increased, and the intensity was also gradually increasing.

Zhai et al. [23] studied 124 stations in China and found that the number of extreme precipitation days from 1951 to 2000 showed a decreasing trend, but the intensity of extreme precipitation showed an increasing trend. Yang Jinhu et al. [24] studied and showed that the periodic oscillations of annual extreme precipitation time in different regions of China are not completely consistent, and there is a good correlation between extreme precipitation events and annual extreme precipitation. Zhai Panmao et al. [25] analyzed the changes of extreme precipitation events in China under the background of climate change and pointed out that the number of precipitation days in most regions showed a decreasing trend, but the average intensity and frequency showed an increasing trend, and the range of regions affected by extreme precipitation in China is constantly expanding. Liu Xuehua et al. and ZHAI et al. [26, 27] analyzed the trends of extreme precipitation total and precipitation extreme values in China and found that the national extreme precipitation index and annual precipitation showed an overall linear increasing trend. The trend of extremely strong average precipitation intensity in the central and eastern regions was more significant, the increasing trend of extreme precipitation in the Northwest Region was obvious, but it showed a decreasing trend from the eastern part of Northeast China to most of North China.

In recent years, a large number of studies on the regional climate of Xinjiang, especially precipitation changes, under the background of global warming have been carried out. Many research results show that under the background of global warming, the climate of Xinjiang has experienced a change mainly characterized by a humidification trend and shows a trend of transformation from warm-dry to warm-wet; regional precipitation has obviously shown an increasing trend, extreme precipitation events have increased, and the annual precipitation recorded by most stations underwent a relatively obvious mutation in the mid-1980s [28]. Li Jianfeng et al. [29] studied and showed that the possibility of simultaneous occurrence of extreme strong and weak precipitation in central Xinjiang, western southern Xinjiang, eastern northern Xinjiang, and northern Xinjiang decreases. Zhao Yong et al. [30] used the daily precipitation data of 32 stations in the Tianshan area from 1961 to 2007 to study the summer extreme precipitation in the Tianshan area and found that the extreme precipitation events in the Tianshan area showed an increasing trend. Yang Lianmei [31] pointed out that the extreme precipitation amount and frequency in the northern foot of the Tianshan Mountains and the Aksu area increased significantly, and the change of extreme precipitation amount led to the change of annual precipitation amount. Shi Yafeng et al. [32] pointed out that the climate of Northwest China, mainly Xinjiang, underwent a transformation from warm-dry to warm-wet in 1987.

2.2. Population and Economic Exposure Caused by Extreme Precipitation Events

Exposure refers to various resources such as personnel, livelihoods, environmental services, infrastructure, as well as economic, social, or cultural assets, etc., which are in a position likely to be adversely affected [17, 33]. In recent years, many scholars have made certain progress in the study of population exposure and socio-economic exposure. Population exposure is usually expressed by indicators such as the number of affected people or population density in the study area [34]. Lin Wenqing [35] pointed out that population exposure refers to the product of the number of extreme events in the grid and the population. Population exposure refers to that personnel are in a position where they may be adversely affected, and it is dynamic. It refers to the average number of people affected by each extreme precipitation event, that is, the affected population in previous events, which is mainly affected by the population situation in the grid covered by the event [16, 36]. Mo Jianfei [17] pointed out that socio-economic exposure refers to the total socio-economic amount exposed to the influence range of extreme precipitation events.

The IPCC [37] Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) points out that disaster risk is a combination of extreme events, exposure, and vulnerability. It can be seen that exposure is one of the key factors of extreme event risk and its impact, and analyzing exposure is an important part of disaster risk assessment and management. At present, many scholars have made certain progress in this field, and their methods are mainly based on the collected historical disaster data and socio-economic statistical data to study the exposure of disasters [17]. Jing Cheng et al. [1] took the population and GDP exposed to the extreme precipitation events as the exposure indicators of population economy and carried out the study on the exposure of China's population economy to regional extreme precipitation events. Wang Yuyan et al. [33, 38] used the rainstorm and flood disaster investigation data and socio-economic loss data of Jiangsu Province from 1984 to 2011 to analyze the exposure evolution characteristics of rainstorm and flood events in Jiangsu Province during the observation period from the aspects of the exposure range of heavy precipitation events, the population and crops exposed to heavy precipitation events. Wang Yanjun et al. [38-40] used the disaster investigation and socio-economic loss data of China's rainstorm and flood disasters from 1984 to 2012 to analyze the exposure of rainstorm and flood disasters from the aspects of the influence range of rainstorms, the number of people exposed to rainstorm events, the economy and crops exposed to rainstorm events. Liu Lanfang et al. [41] selected 8 elements such as population density as the evaluation indicators of drought exposure and carried out the risk assessment of agricultural drought in the southern region of China in 2013. Zhai et al. [42], based on the use of the intensity-area-duration (IAD) method, studied the extreme high temperature and population exposure in China under different future warming targets.

2.3. Research Methods on Extreme Precipitation Events and Their Population and Economic Exposure

Previous studies usually used extreme precipitation thresholds and various extreme precipitation-related indices to analyze the spatio-temporal distribution characteristics of extreme precipitation events. The early selection of extreme precipitation thresholds mainly adopted the absolute threshold method. For example, Groisman [43] used 25.4 and 50.8 mm as the extreme precipitation thresholds; the China Meteorological Administration stipulates that 50-100 mm/d is a rainstorm, and not less than 100 mm/d is a heavy rainstorm, etc. However, the extreme precipitation defined in this way will have a large area of no-rainstorm areas in the upper reaches of some basins. At the same time, whether extreme precipitation events cause disaster losses depends not only on the characteristics of the events themselves but also on many other factors (such as geographical environment, facility quality, and disaster prevention awareness, etc.). In arid and semi-arid areas, a small precipitation event may trigger disasters such as floods, landslides, and debris flows [44], and the absolute threshold can no longer adapt to explaining the extreme situation of precipitation events. Therefore, some scholars have adopted the methods of extreme value sequence or percentile to determine extreme precipitation (such as the maximum precipitation sequence, 95th percentile value) to enhance the comparability of extreme precipitation change trends in rainy and less rainy areas and better analyze the characteristics of extreme precipitation events. For example, Plummer et al. [45] proposed to use the 99th percentile of daily precipitation as the threshold of heavy precipitation, Zhai Panmao et al. [46] used the multi-year average value of the 99th percentile of the precipitation sequence as the threshold of extreme precipitation events, and Pan Aoda et al. [47] used the multi-year average value of the 95th percentile of the annual wet day (daily precipitation not less than 0.1 mm) precipitation sequence as the threshold of extreme precipitation, etc. Huang Yan et al., Yuan Wende et al., He Shuqiao et al. [48-50] used the percentile threshold method to define extreme precipitation events, and used the Mann-Kendall rank correlation method, inverse distance weighted interpolation method, wavelet analysis method, etc. to carry out the spatio-temporal change analysis of extreme precipitation events in China. Li Yong et al. [11] used the daily precipitation data of 364 national meteorological information centers in the five provinces (regions) of Northwest China from 1961 to 2020, and used linear interpolation, percentile threshold, linear regression, least square method, etc. to analyze the spatio-temporal distribution characteristics and change trend characteristics of summer precipitation in Northwest China. Zhang Qiang et al. [51] defined 8 extreme precipitation indices based on the daily precipitation data of 53 rain gauge stations from 1957 to 2009, used the K-S method to determine the most appropriate probability distribution function of precipitation indices, systematically analyzed the univariate extreme values of extreme precipitation and the two-dimensional joint probability distribution characteristics of precipitation extremes, and studied the spatial evolution characteristics of the probability changes of precipitation extremes in Xinjiang. Seyoum et al. [52] analyzed the change trends of single-event or multi-event extreme precipitation indices (single-day maximum precipitation (RX1day), 5-day maximum precipitation (RX5day), and heavy rain days (R20)) in summer in North America from 1979 to 2013. Wang et al. [53] According to four extreme precipitation indices, including total extreme precipitation, total heavy precipitation, maximum 5-day precipitation, and the number of heavy rain days, studied extreme precipitation events in Siberian permafrost and non-permafrost regions.

In recent years, domestic scholars have conducted relevant research on the exposure and vulnerability of rainstorm and flood disasters. Most studies on exposure evaluate it by constructing an indicator system and determining weights using the internal relationships between different indicators. This evaluation method is simple and practical, requiring no complex calculations or simulations, and can reflect the comprehensive disaster exposure under the action of multiple influencing factors, so it is widely used [54]. In the selection of population exposure indicators, researchers mostly use population density, the number of affected people, or the product of disaster days and the corresponding population as population exposure indicators, thus giving different population exposure characteristics. The research results all show that the population exposure to extreme climate events generally shows a significant increasing trend [16]. Yin Zhan'e et al. [55] analyzed the vulnerability of rainstorm waterlogging disasters in Pudong District of Shanghai using GIS technology. Wang Ying et al. [56] evaluated the rainstorm and flood disasters in agriculture in southern China from the aspects of hazard-bearing body exposure. Mo Jianfei et al. [17] determined the extreme precipitation threshold based on many years of disaster-causing heavy precipitation processes, combined with geographic information, constructed a spatial model of extreme precipitation events in Guangxi in different periods, constructed a social and economic spatial model of Guangxi based on multi-source data such as night-time light remote sensing data, remote sensing background information, and social and economic statistics, effectively coupled the two, constructed a social and economic exposure model of flood in Guangxi basin under extreme precipitation events, and analyzed the spatio-temporal variation characteristics of social and economic exposure of flood in Guangxi basin. Wang Yuyan et al. [33] adopted a mathematical statistics method based on historical disaster data, collected and sorted out the disaster data and social and economic data of rainstorm and flood disasters in Jiangsu Province from 1984 to 2011, and analyzed the exposure and vulnerability of disasters from the perspective of time and space. Gao Chao et al. [57] constructed a sea-level rise risk exposure assessment model based on global tide and surge reanalysis data, combined with three major indicators of population, economy, and land use data, evaluated the population and economic exposure of China's coastal areas under sea-level rise risk, and showed that the population and economic exposure will be the highest in 2025 in the future.

Based on the above, this study uses the daily precipitation data of Xinjiang Uygur Autonomous Region from 1961 to 2021, and defines the precipitation events that reach the threshold on the given duration scale and continuous area as extreme precipitation events. Taking the extreme degree of precipitation events as the relative intensity, using the Intensity-Area-Duration (IAD) analysis method, the relative intensity, impact area, and strongest center of extreme precipitation events in Xinjiang Uygur Autonomous Region from 1961 to 2021 were studied, and based on the impact area of previous events, the population and GDP exposed to the extreme precipitation events were used as the exposure indicators of population economy, and the exposure of population economy in Xinjiang Uygur Autonomous Region to extreme precipitation events was preliminarily carried out.

3. RESEARCH REVIEW AND PROSPECT

3.1. Research Review

3.1.1. Based on Bibliometric Analysis

The number of publications on extreme precipitation events has decreased since 2020, but due to the frequent occurrence of extreme weather events, especially rainstorm and flood disasters in recent years, it still maintains a certain level of publication. On the contrary, the number of publications related to exposure has generally been on the rise, which indicates that the study of exposure is still a hot topic in a short period of time. In addition, from the perspective of theme distribution and keyword clustering, the themes related to extreme precipitation events are mainly linked to themselves, their spatio-temporal variation characteristics, and their attribution analysis, while the themes of exposure are mainly linked to vulnerability, risk assessment, population livelihood, etc. This indicates that scholars have less research on economic exposure, and there are relatively few literatures that combine extreme precipitation events with exposure. From the perspective of the disciplinary distribution of the literatures published by scholars, it can be clearly seen that the literatures related to extreme precipitation events and exposure are mainly distributed in meteorology, water conservancy and hydropower engineering, environmental science and resource utilization, geophysics and other disciplines, while the number of literatures purely belonging to geography is extremely small. Moreover, most of these disciplines are biased towards natural science research, and pay less attention to the impact of human factors on extreme climate and the impact of extreme climate on humans. The research of geography, compared with other disciplines, can better reflect the coupling of human-land relationship and can better emphasize the element of human in the research of natural science. Compared with meteorology, which mainly focuses on the impact of natural forcing on extreme climate, geography can better reflect the role of human forcing in extreme climate and the role of extreme climate on humans. Therefore, it can be considered to combine extreme precipitation events with population economic exposure to analyze the impact of extreme precipitation on human beings and social economy, so as to provide a scientific basis for the formulation of disaster emergency management departments and national relevant strategies.

3.1.2. Based on Literature Content Analysis

In terms of extreme precipitation event research, due to the limitation of observation data, the past research on extreme precipitation in Xinjiang was mainly concentrated on climate analysis such as decadal, annual, and monthly scales, or case analysis of single heavy precipitation weather, and there were few studies on smaller scales such as daily scale. Although there are many studies on the spatio-temporal distribution of extreme precipitation in Xinjiang, the division of many study areas is not detailed enough. This is due to the topographic restriction of "three mountains enclosing two basins" in Xinjiang, and the spatio-temporal distribution of extreme precipitation in different regions is different. Most of the existing studies are aimed at the change amount and spatio-temporal change trend of regional extreme precipitation. Due to the great regional differences in extreme precipitation events, the definition of events has not yet reached an international consensus, resulting in the lack of research on the characteristics and change laws of extreme precipitation events. The IAD method can accurately find the time and range of regional extreme events, but there may still be certain errors.

In terms of exposure research, however, due to the difficulty in collecting disaster data, socio-economic statistical data are mostly based on administrative units such as provinces, cities, and counties, which makes the exposure research lack accurate and refined evaluation. Most studies only analyze a single element such as population exposure, and few studies further combine extreme precipitation events with elements such as the economy and cultivated land in the study area, nor do they explore the vulnerability of the study area under the influence of extreme precipitation events. The size of the disaster risk of extreme precipitation events depends not only on the characteristics of the disaster-causing factors such as frequency, intensity, and duration, but also to a large extent on the exposure level of the disaster-bearing body. The current research on extreme precipitation mainly focuses on the determination of thresholds, the evolution characteristics of extreme precipitation frequency and intensity, or the analysis of extreme precipitation characteristics based on extreme indices, while the research on population and socio-economic exposure caused by extreme precipitation events is still relatively weak.

3.2. Prospect

In the future, the research on extreme precipitation events still needs to be further refined in the division of time and space scales. For example, the spatio-temporal distribution law of extreme precipitation events in a certain place can be studied by studying the daily scale extreme precipitation amount in time and dividing different regions according to the terrain in space. And the accuracy of the research results can be strengthened by comparing and verifying with the specific event records in the historical data. For the research on exposure, it is necessary to strengthen the research on exposure and vulnerability caused by extreme precipitation events, and enhance the comprehensive research on exposure, such as combining population exposure with socio-economic exposure or cultivated land exposure, so as to more comprehensively consider the impact of extreme precipitation events on all aspects of human life and production, and provide scientific reference for further carrying out disaster prevention and mitigation research and formulating national emergency management strategies.

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