Hindawi
Advances in Meteorology
Volume 2019, Article ID 7069195, 10 pages
https://doi.org/10.1155/2019/7069195

Research Article

Study on the Change Characteristics of and Population Exposure to Heatwave Events on the North China Plain

Long-Fei Zhan,[1] Yanjun Wang,[2] Hemin Sun,[3] Jianqing Zhai,[2,3] and Mingjin Zhan[1,2]

[1]*Jiangxi Provincial Climate Centre, Nanchang 330046, China*
[2]*Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Institute for Disaster Risk Management (IDRM), School of Geographical Science, Nanjing University of Information Science & Technology, Nanjing 210044, China*
[3]*National Climate Center, China Meteorological Administration, Beijing 100081, China*

Correspondence should be addressed to Mingjin Zhan; hellorm@126.com

Received 11 April 2019; Revised 3 July 2019; Accepted 24 July 2019; Published 18 August 2019

Academic Editor: Alastair Williams

In accordance with the China Meteorological Administration definition, this study considered a weather process with a maximum surface temperature of ≥35°C for more than three consecutive days as a heatwave event. Based on a dataset of daily maximum temperatures from meteorological stations on the North China Plain, including ordinary and national basic/reference surface stations, the intensity-area-duration method was used to analyze the spatiotemporal distribution characteristics of heatwave events on the North China Plain (1961–2017). Moreover, based on demographic data from the Statistical Yearbook and Greenhouse Gas Initiative (GGI) Population Scenario Database of the Austrian Institute for International Applied Systems Analysis (IIASA), population exposure to heatwave events was also studied. The results showed that the frequency, intensity, and area of impact of heatwave events on the North China Plain initially decreased (becoming weaker and less extensive) and then increased (becoming stronger and more extensive). Similarly, the trend of population exposure to heatwave events initially decreased and then increased, and the central position of exposure initially moved southward and then returned northward. Population exposure in the eastern Taihang Mountains was found significantly higher than in the western Taihang Mountains. In relation to the change of population exposure to heatwave events on the North China Plain, the influence of climatic factors was found dominant with an absolute contribution rate of >75%. Except for 2011–2017, increase in population also increased the exposure to heatwaves, particularly in the first half of the study period. Interaction between climatic and population factors generally had less impact on population exposure than either climatic factors or population factors alone. This study demonstrated a method for assessing the impact of heatwave events on population exposure, which could form a scientific basis for the development of government policy regarding adaption to climate change.

1. Introduction

Climate change includes not only changes in mean climate but also variation in weather extremes [1]. Over the past century, because of the combined effects of human activities and natural factors, Earth's climate has undergone significant change in terms of the primary features of warming and this change has shown an increasing trend in recent years [2, 3]. The trend has led to a wide range of climate anomalies, especially an increased frequency of occurrence of regional extreme high-temperature events [4]. The Fifth Assessment Report issued by the United Nations Intergovernmental Panel on Climate Change in 2014 showed that the global surface temperature increased by 0.85°C from 1880 to 2012 [5]. In different regions of the world, the annual and daily maximum temperatures have both shown a significant upward trend since the latter part of the 20th century [6, 7]. For most of China, the trend of increase in air temperature has accelerated since the 1980s [8]. From a regional perspective, the characteristics of high temperatures are complex. Overall, significant positive trends in the frequency of occurrence of extreme maximum temperature events have

been observed in most of China, and the North China Plain is one area that has experienced the most significant warming.

Increased temperature will lead to an increase in the risk of heat-related diseases and death in humans [9]. The risk of morbidity and accidental death among urban vulnerable populations and among urban and rural outdoor workers during a period of heat stress has been identified as one of the key risks of climate change in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [5]. Changes in heatwaves are an important aspect of climate change, and their impact on both natural ecosystems and human society might be more severe than the effects of the rise in average temperature [10–13]. The latest Hadley Centre Global Historical Climatology Network Daily observations show that the intensity, frequency, and duration of global heatwave events are increasing [14]. In recent years, heatwaves have surpassed other natural disasters such as hurricanes, lightning, tornadoes, floods, and earthquakes to become the primary cause of fatalities in America related to natural disasters [15–17]. Moreover, heatwaves have killed more people in Australia than any other natural hazard since 1900 [18]. It is estimated that around 40,000 people in central and western parts of continental Europe died during a record heatwave that occurred in the summer of 2003 [19, 20]. In 2013, heatwaves occurred frequently in most parts of China. For example, Changsha, Chongqing, and Hangzhou recorded 57, 49, and 47 hot days (daily maximum temperature ≥35°C), respectively, during which the highest recorded temperatures reached 38.2, 40.9, and 40.5°C, respectively. These heatwave incidents led to a direct economic loss of 83.56 billion RMB [21]. Research on high-temperature disasters has attracted widespread attention from government departments and the scientific community, and it has become the focus of climate research under the background context of global warming.

In recent years, studies on population exposure to natural disasters have achieved many results [22–27]. Research on extreme climate events has developed from value analysis at a single site [28–30] to related investigations of intensity, area of impact, and duration [26, 31]. Based on the intensity-area-duration (IAD) method, Zhai et al. [31] developed an approach for identification of a regional extreme event and analysis of its spatial coverage and duration. Extreme heatwave events can be more serious than a single high-temperature event [10]. However, few studies have considered regional persistent extreme heatwave events and the variation of associated population exposure.

The population of the North China Plain accounts for approximately 30% of the total population of China. Furthermore, the North China Plain represents the center of China's political, economic, cultural, transportation, education, and tourism activities. Therefore, it is of great scientific and practical importance to study the evolution of heatwave events and associated population exposure on the North China Plain. This study was based on daily maximum temperature data (1961–2017) from national meteorological stations on the North China Plain, in combination with demographic data and Greenhouse Gas Initiative (GGI) Population Scenario Database of the Austrian Institute for International Applied Systems Analysis (IIASA) [32, 33]. First, the frequency, intensity, area of impact, and spatial variation characteristics of heatwave events in North China are analyzed by grid unit scale. Second, the temporal and spatial evolution characteristics of population exposure to heatwave events are studied. Finally, attribution analysis is performed on the factors affecting population exposure. The main objectives of this study were to reveal the contributions of various factors to population exposure to past heatwave events on the North China Plain and to provide a scientific basis for the development of strategies effective in helping humans cope with the adverse effects of such heatwave events.

2. Data and Methods

2.1. Study Area. The area of the North China Plain considered in this study comprised the region bounded by 33°–42°N, 110°–120°E, which includes Beijing, Tianjin, Inner Mongolia, Hebei, Henan, Shanxi, Shandong, Jiangsu, Anhui, and Shaanxi (Figure 1). This region covers an area of approximately $9.0 \times 10^5\,\mathrm{km}^2$ and it contains approximately 30% of the total population of China. The North China Plain has a warm temperate semiarid monsoon climate, which has the characteristics of cold and snow in winter, a dry and windy spring, hot rainy summer, and cool dry autumn.

2.2. Data Description. The climate dataset used in this study was derived from daily maximum temperature data (1961–2017) recorded at national meteorological stations on the North China Plain, which were integrated by the National Meteorological Information Center of the Chinese Meteorological Administration. Following quality control, the daily maximum temperature data were interpolated to a $0.5^\circ \times 0.5^\circ$ grid using the inverse distance weighting method.

The North China Plain population data were obtained from the Chinese Demographic Yearbook. Using the GGI Population Scenario Database of the IIASA (which has spatial resolution of $0.5^\circ \times 0.5^\circ$ and temporal resolution of 10a) as the background of population distribution, the population data of the North China Plain provinces from the Chinese Statistical Yearbook were interpolated to a $0.5^\circ \times 0.5^\circ$ grid using the grid weight calculation method.

2.3. Method

2.3.1. Heatwave Event Identification. In accordance with the definition of heatwaves by the China Meteorological Administration, this study considered a weather process with a maximum temperature ≥35°C for more than three consecutive days as a heatwave event. This definition focuses on the hazard of persistently high air temperature. When a grid met this definition, it was assumed that there was a heatwave at that grid. Thus, we analyzed the frequency of heatwave events (i.e., number of heatwave events), intensity of heatwave events (i.e., maximum daily maximum temperature of a heatwave event), and areas

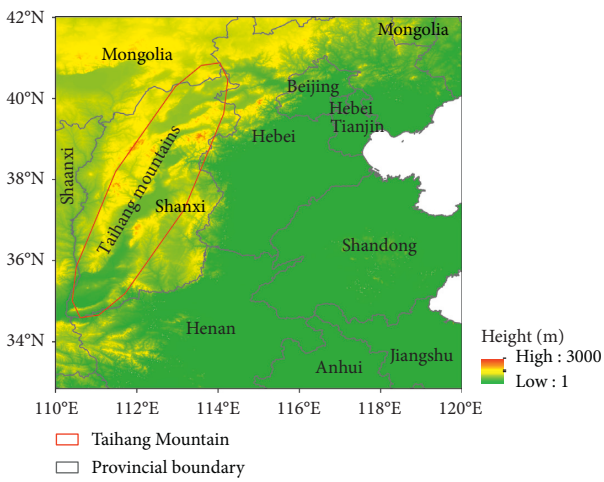

Figure 1: Map of the study area.

affected by heatwave events (i.e., maximum area covered by the heatwave).

2.3.2. Intensity-Area-Duration (IAD) Method. This study adopted the IAD method, which links the three most important features of extreme events [26, 31, 34, 35]. This method has been applied successfully in analyses of drought and extreme precipitation events in China [26, 31, 34]. The principle of the IAD method is to identify grids that neighbor the daily maximum temperature ≥35°C over a given timescale and to select continuous areas as an extreme heatwave event. The area of impact is determined by the summation of all grids, while the intensity is determined by the maximum temperature of all grids included in one event. The IAD method can be used to study the simultaneous changes in intensity and area of impact over a given duration. The steps required in the process are as follows.

First, for a given timescale (here, ≥3 d), calculate the intensities for the different periods for all grids. The grid point with the highest intensity is regarded as the "center with highest intensity" of a regional extreme daily maximum temperature event. Second, among the surrounding eight grids, find the one with the second highest intensity to establish the "center with second highest intensity." Third, among the grids surrounding the "center with second highest intensity," find the one with the third highest intensity. Determine all those grids with daily maximum temperature greater than the threshold and combine them all as a regional extreme daily maximum temperature event. Fourth, determine another "center with highest intensity" and repeat the above steps, deducing all the regional extreme daily maximum temperature events over a given timescale.

2.3.3. Spatialization of Population. Population is an imperative factor in exposure assessment in relation to heatwave disasters. The spatial distribution of the population was established using the IIASA GGI Population Scenario Database (resolution: 0.5° × 0.5°, time: 1990, 2000, and 2010) based on the total number of provinces in the Chinese Statistical Yearbook. In this process, the weight coefficient is interpolated to each grid point and calculated as follows:

$$\mathrm{POP}_{i,j} = \sum_{j=1}^{m}\sum_{i=1}^{n}\frac{P_{i,j}}{P_j}X_j, \tag{1}$$

where $\mathrm{POP}_{i,j}$ denotes the population at grid i in province j, $P_{i,j}$ is the population of the GGI Population Scenario Database at grid i in province j, P_j is the total population of the GGI Population Scenario Database in province j, X_j is the total population of province j, m is the total number of provinces, and n is the total number of grids in province j.

In this study, the population distribution of the North China Plain during 1961–1990, 1991–2000, and 2001–2017 was based on the GGI Population Scenario Database in 1990, 2000, and 2010, respectively.

2.3.4. Definition of Population Exposure and Analysis of Contribution Rate. The number of people exposed to a heatwave event was defined as the population exposure [36]. Population exposure to heatwave events is affected by the frequency of heatwaves and the number of people. Consequently, population exposure is affected by the combined effects of climatic factors (change in frequency of heatwave events and constant population size), population factors (constant frequency of heatwave events and change in population size), and climatic-population factors (changes in both frequency of heatwaves events and population size). Changes in population exposure to heatwaves can be expressed as [37]

$$(F+\Delta F)\times(P+\Delta P)-F\times P = F\times\Delta P + P\times\Delta F + \Delta F\times\Delta P. \tag{2}$$

For ease of comprehension, it is assumed that the contribution rate of increased population exposure is positive and that the contribution rate of different influencing factors in the change of population exposure to heatwaves is as follows:

Rate of contribution of climatic factors:

$$\frac{P\times\Delta F}{|(F+\Delta F)\times(P+\Delta P)-F\times P|}\times 100\%. \tag{3}$$

Rate of contribution of population factors:

$$\frac{F\times\Delta P}{|(F+\Delta F)\times(P+\Delta P)-F\times P|}\times 100\%. \tag{4}$$

Rate of contribution of combined climatic-population factors:

$$\frac{\Delta F\times\Delta P}{|(F+\Delta F)\times(P+\Delta P)-F\times P|}\times 100\%, \tag{5}$$

where F and P are the frequency of heatwave events and population size, respectively, $F\times\Delta P$ is the influence of population factors, $P\times\Delta F$ is the influence of climate factors, and $\Delta F\times\Delta P$ is the combined influence of climatic-population factors.

3. Results

3.1. Frequency, Intensity, Area of Impact, and Spatial Changes of Heatwave Events. The frequency of heatwaves reflects the number of local heatwave events, where a higher frequency usually means greater impact. Figure 2 shows the frequency of heatwave events on the North China Plain during 1961–2017. It can be seen that the decadal mean frequency of heatwave events on the North China Plain shows a significant initial trend of decrease followed by an increase. During the period with a significant downward trend (1961–1990), the decadal mean frequency of heatwave events during 1961–1970, 1971–1980, and 1981–1990 decreased from 30.0 to 17.6 and 10.7 events, respectively. During the period with an upward trend (1990–2017), the decadal mean frequency of heatwave events during 1991–2000, 2001–2010, and 2011–2017 increased to 19.4, 23.1, and 38.1 events, respectively. The highest decadal mean frequencies of 60, 59, and 58 events occurred in 2017, 2013, and 2014, respectively. Based on the daily maximum temperature data, we found that changes in air temperature caused these changes in the frequency of occurrence of heatwave events.

Heatwave intensity reflects the strength of heatwave events. Figure 3 shows the intensity of heatwave events on the North China Plain. It can be seen that the most and least intense heatwave events on the North China Plain occurred during 1961–1970 and 1971–1980, respectively. Since the 1970s, there has been a trend of increase in heatwave intensity. The average intensity of heatwaves during 1971–1980 was approximately 36.8°C; during 1981–2000, the average intensity of heatwave events remained around 36.9°C, and the mean intensity during 2001–2010 and 2011–2017 reached 37.1 and 37.3°C, respectively. During 1961–2017, the average intensity of heatwaves on the North China Plain always remained >36°C, and there were four years with intensity >38°C.

The area of impact of heatwave events on the North China Plain during 1961–2017 is shown in Figure 4. The chronological trend of the mean area of impact of heatwave events shows a decrease during 1961–1990, i.e., it decreased from $0.65 \times 10^6\,\mathrm{km}^2$ in 1961–1970 to $0.19 \times 10^6\,\mathrm{km}^2$ in 1981–1990. During 1961–1990, the area of impact of heatwave events on the North China Plain decreased by an annual average of $2.2 \times 10^4\,\mathrm{km}^2$. During 1981–2017, the area of impact of heatwave events increased significantly. For example, the average annual area of impact in 2011–2017 was 4.5 times that during 1981–1990. During 1991–2017, the area of impact of heatwave events on the North China Plain increased by an annual average of approximately $2.9 \times 10^4\,\mathrm{km}^2$. The maximum area of impact of $>1.6 \times 10^6\,\mathrm{km}^2$ appeared in 2014.

The spatial distribution of the annual average frequency of heatwaves on the North China Plain shows that the frequency of heatwaves decreased during 1961–1990 and that the area of impact gradually diminished (Figures 5(a)–5(c)). The center of high frequency gradually narrowed from southeast Hebei, central and eastern Henan, western Shandong and northwest Anhui to small areas of southern Hebei, central Henan, and northern Anhui. Conversely, the frequency and area of impact of heatwave events on the North China Plain increased significantly during 1981–2017 (Figures 5(c)–5(f)). The center of high frequency gradually expanded from southeastern Hebei and central Henan to southern Hebei, southern Shandong, and northern-central Henan. According to the spatial distribution of the annual average frequency during 1961–2017 (Figure 5(g)), heatwave events have occurred in most parts on the North China Plain, and the center of high frequency (frequency: >20 times) has been located mainly in southeastern Hebei, eastern Henan, and northern Anhui. It is evident that topography determines the spatial distribution of the frequency of heatwaves, i.e., to the east of the Taihang Mountains, low terrain means high frequency, and to the west of the Taihang Mountains, high terrain means low frequency.

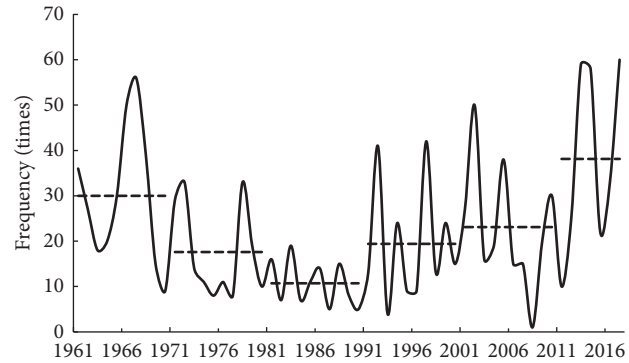

Figure 2: Frequency of heatwave events on the North China Plain.

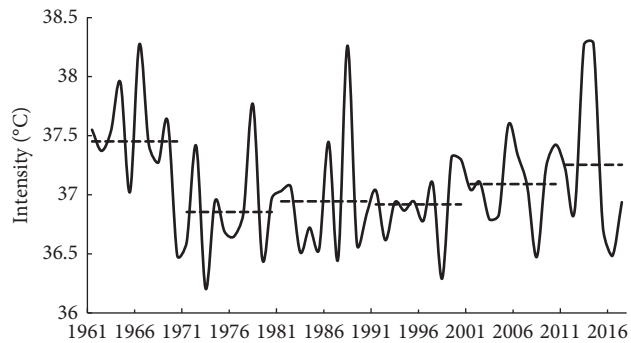

Figure 3: Intensity of heatwave events on the North China Plain.

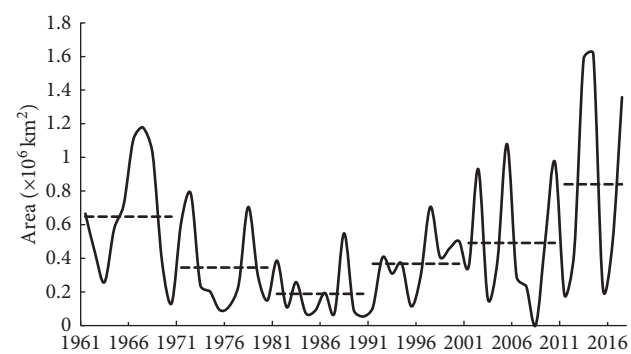

Figure 4: Area affected by heatwave events on the North China Plain.

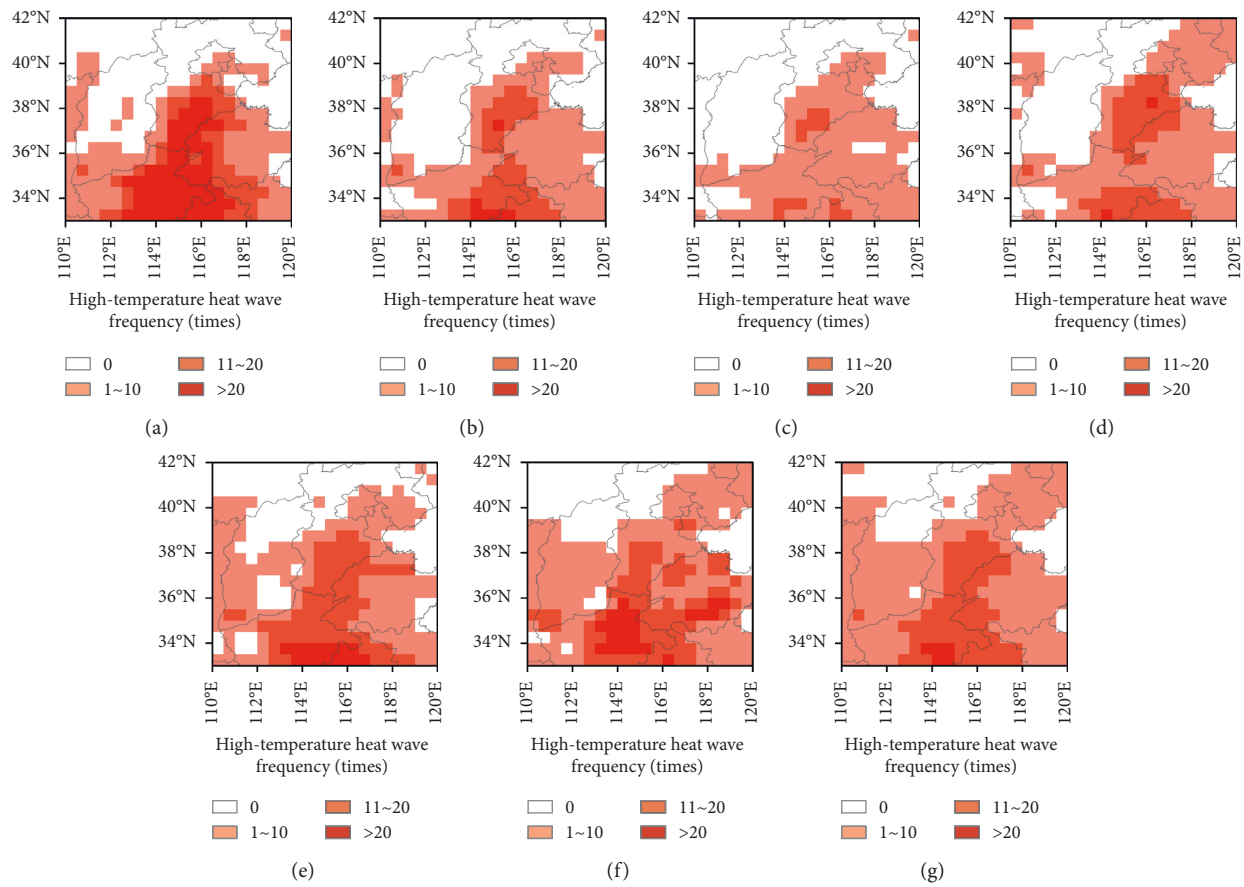

Figure 5: Spatial distribution of the annual average frequency of heatwaves on the North China Plain. (a) 1961–1970, (b) 1971–1980, (c) 1981–1990, (d) 1991–2000, (e) 2001–2010, (f) 2011–2017, and (g) 1961–2017.

The spatial distribution of the frequency of heatwaves is related to population exposure. For a population of a certain size, more frequent heatwave events will mean greater population exposure. This means that if the current size of the population is maintained, an increase in the frequency of future heatwave events will lead to an increase in population exposure.

3.2. Population Exposure to Heatwave Events. The severity of the impact of a heatwave event depends not only on the event itself but also on the levels of exposure and vulnerability of the population. The level of exposure is the extent to which the adverse effects of heatwave events affect the population, economy, and other factors [39, 40]. Population exposure is defined as the size of the population within an area affected by a heatwave. The variation in population exposure to heatwave events on the North China Plain shows a downward trend during 1961–1990 and a significant upward trend during 1981–2017 (Figure 6). During 1981–1990, population exposure decreased by approximately 58.9% (in comparison with 1961–1970) at an annual average rate of 6.8 million. During 2011–2017, population exposure increased by approximately 331.6% (in comparison with 1981–1990) at an average annual rate of around 12 million. According to current trends, population exposure on the North China Plain will exceed 1 billion in the next decade.

The spatial distribution of population exposure to heatwaves on the North China Plain is shown in Figure 7. Comparison with Figure 5 reveals that the spatial distribution of population exposure is related to the spatio-temporal distribution of heatwave events. During 1961–2017, population exposure to heatwaves occurred in Shandong, northern Jiangsu, northeast and southern Hebei, Beijing, Tianjin, Henan, southern Shanxi, and other areas. The most densely populated area affected by heatwave events was southeastern Henan (Figure 7). Population exposure to heatwaves on the North China Plain decreased during 1961–1990 (Figures 7(a)–7(c)) and the extent of the area of high values gradually retreated from north to south. The population affected by heatwave events showed an increasing trend during 1981–2017 (Figures 7(c)–7(f)) and the extent of the area of high values gradually expanded from south to north. The largest period of population exposure occurred in 2011–2017 (Figure 7(f)). Grid values with population exposure of >40 million occurred in >20% of regions. Figure 7(g) shows the spatial distribution of population exposure on the North China Plain during 1961–2017. It can be seen that population exposure to heatwaves decreased from south to north and that the center of the highest values was located in southeastern

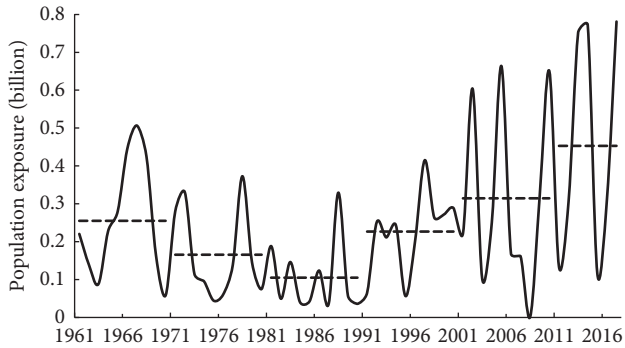

Figure 6: Population exposure to heatwave events on the North China Plain.

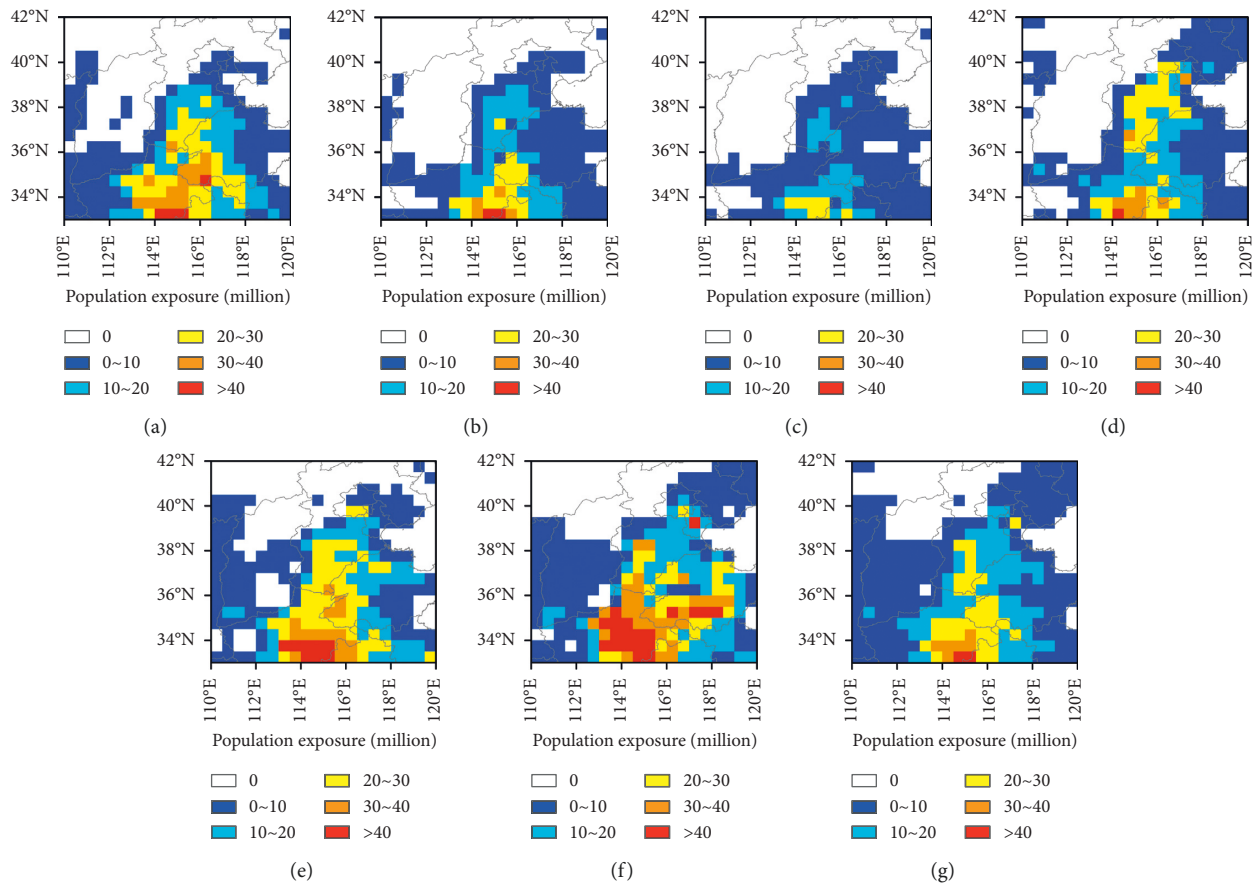

Figure 7: Spatial distribution of population exposure to heatwaves on the North China Plain. (a) 1961–1970, (b) 1971–1980, (c) 1981–1990, (d) 1991–2000, (e) 2001–2010, (f) 2011–2017, and (g) 1961–2017.

Henan. Population exposure is greatly affected by elevation, i.e., to the east of the Taihang Mountains, population exposure is large, and to the west of the Taihang Mountain, population exposure is small. Although Beijing and Tianjin have high population density, population exposure is low in these regions because of the occurrence of fewer heatwave events.

3.3. Analysis of Factors Influencing Population Exposure to Heatwaves. As can be seen from Figure 8, the population of the North China Plain is gradually increasing. The population east of the Taihang Mountains is significantly larger than to the west. The high-density population areas are Beijing, Tianjin, and southeastern parts of the North China Plain.

Changes in population exposure to heatwave events depend on changes in the spatial distributions of climate and population. Table 1 shows the rate of contribution of each factor that influences population exposure, where a negative contribution indicates that the contribution is opposite to the trend of population exposure and where the absolute value indicates the rate of that contribution. The change of population exposure to heatwave events on the North China

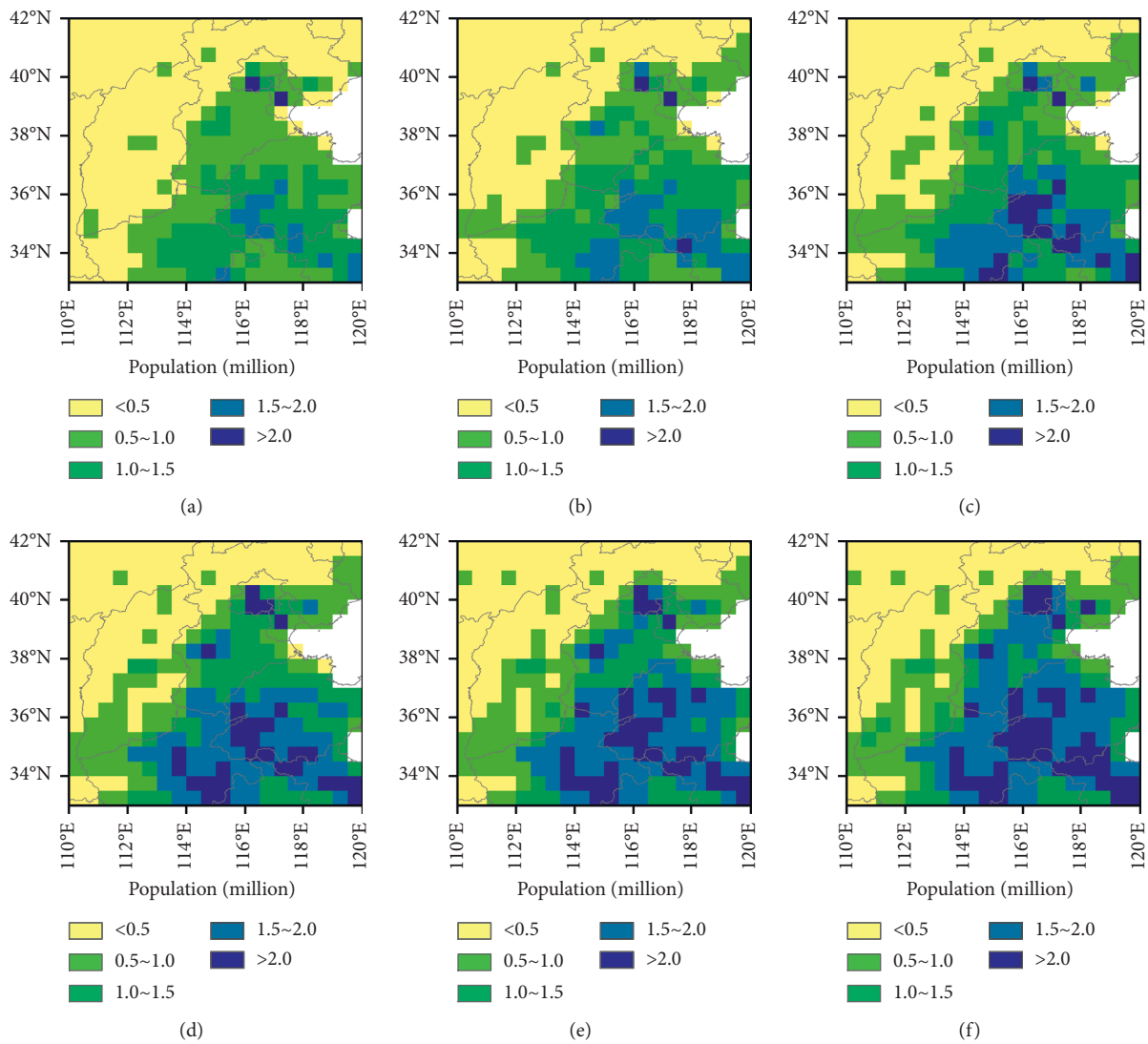

Figure 8: Spatial distribution of population on the North China Plain. (a) 1961–1970, (b) 1971–1980, (c) 1981–1990, (d) 1991–2000, (e) 2001–2010, and (f) 2011–2017.

Table 1: Analysis of factors influencing population exposure change to heatwave events on the North China Plain.

Exposure changes	Climatic factors (billion)	Population factors (billion)	Interaction of climate and population factors (billion)	Population exposure to heatwave events (billion)
1971–1980 compared to 1961–1970	−1.18 (−132.3%)	0.54 (60.7%)	−0.25 (−28.4%)	−0.89
1981–1990 compared to 1971–1980	−0.74 (−121.0%)	0.23 (38.5%)	−0.11 (−17.4%)	−0.61
1991–2000 compared to 1981–1990	0.96 (79.0%)	0.13 (10.6%)	0.13 (10.3%)	1.22
2001–2010 compared to 1991–2000	0.69 (78.0%)	0.15 (16.6%)	0.05 (5.4%)	0.88
2011–2017 compared to 2001–2010	0.03 (180.0%)	−0.005 (−24.4%)	−0.01 (−55.6%)	0.02

Plain has been dominated by climatic factors, although the rate of contribution decreased gradually and changed from a negative contribution to a positive contribution during 1961–2010. During 2011–2017, in comparison with 2001–2010, the population influenced by climatic factors increased by up to 0.02 billion (180%) because of the sharp increase in the frequency of occurrence of heatwaves. The most influential period of population factors was during 1971–1980

when the population influenced increased by 0.54 billion (60.7%) in comparison with 1961–1970. Subsequently, the population influenced by population factors gradually decreased as the contribution of population factors changed from positive to negative. In general, interaction between climatic and population factors had less impact on population exposure than either climatic factors or population factors alone.

Climatic factors have had the greatest impact on population exposure, whereas the effect of population factors has had a decreasing trend, which has resulted ultimately in a negative rate of contribution. This is because of the significant increase in heatwaves, while some provinces have experienced slow or even no population growth in recent years.

4. Conclusions and Discussion

Since the 1990s, global warming has had a significant effect on heatwaves in China and this is expected to continue. Using the IAD method based on gridded data, which combines the three most important elements (intensity, area of impact, and duration) of heatwave events, this study investigated the spatiotemporal characteristics of regional heatwaves on the North China Plain. This approach, which differs from previous analyses based solely on individual stations, allows greater understanding of heatwave events. In addition, gridded temperature data can be more reasonably combined with population data, which is helpful in assessment of the impact of heatwave events on a population.

Based on daily maximum temperature data and spatiotemporal data of population distribution on the North China Plain during 1961–2017, we calculated and analyzed the spatiotemporal evolution characteristics, population exposure change, and factors influencing heatwave events on the North China Plain over the past 57 years. The main conclusions are as follows:

(1) Heatwave events on the North China Plain exhibited obvious spatiotemporal change. From the perspective of the decadal mean, the frequency and area of impact of heatwave events both declined initially and then increased, with the lowest values during 1981–1990. The intensity of heatwave events showed an initial downward trend, remained reasonably stable during 1981–2000, and then increased during 2001–2017. From the perspective of spatial change, the area of impact and frequency of heatwave events both decreased at first and then increased, and the center of heatwave events receded southward and then extended northward. From the spatial distribution of heatwave events during 1961–2017, it was found that areas with high incidence of heatwave events were located mainly in southeastern Henan and southern Hebei. The frequency of occurrence of heatwaves was found to be affected by elevation, i.e., heatwaves occurred more frequently to the east of the Taihang Mountains in comparison with areas to the west. Thus, the findings of this study in relation to the characteristics of heatwaves on the North China Plain are similar to other earlier studies [14, 41, 42].

(2) Under the background of global warming and the given spatial distribution of population, it was found that the trend of population exposure on the North China Plain showed significant decrease during 1961–1990 followed by an increase during 1991–2017. Spatially, during 1961–1990, the area of population exposure gradually narrowed and the center of high values moved southward. Conversely, during 1991–2017, the center of high values moved northward and the number of people affected by heatwaves increased. During 1961–2017, the region with the highest population exposure was located in southeastern parts of Henan.

(3) Population exposure on the North China Plain was found to be influenced by climatic factors, population factors, and combined climatic-population factors. In the change of population exposure to heatwave events, climatic factors played the leading role, population factors increased the population exposure to heatwaves in all decades except for a marginal decrease from 2001 to 2010 to 2011–2017, but there was a decreasing trend in the magnitude of this contribution. During 1961–2010, there was a decreasing trend in the interaction between climatic factors and population factors. The population exposure to climatic factors first decreased and then increased, consistent with the change of frequency of occurrence of heatwave events. The increase in the population in heatwave event areas has led to an increase in the number of people exposed to heatwave events. According to the climatic and demographic trends, it was established that climatic factors will continue to contribute positively and will remain the most important driver in the future, whereas population factors will contribute at a low or even negative rate, consistent with the conclusions of Huang et al. [37].

The effect of a heatwave event on population exposure is not only related to its strength, area of impact, and duration but also to the spatiotemporal distribution of the population. Limited by the temporal resolution of the IIASA GGI Population Scenario Database, the population distribution data used in this study were the background fields of the spatial distribution of population in 1990, 2000, and 2010. Thus, we did not consider population distributions with higher temporal resolution. This will be a focus of future research.

The mechanism maintaining high temperatures on the North China Plain has not yet been fully elucidated. Xie et al. [43] suggested that the continental subtropical high is the

main synoptic system responsible for high temperatures on the North China Plain. Conversely, Wei et al. [43] proposed that the occurrence of summer temperature anomalies on the North China Plain is determined primarily by east-west anomalies of the western Pacific subtropical high. However, the question of how the western Pacific subtropical high and continental high pressure might interact to produce high temperatures on the North China Plain will require further in-depth research.

In addition to population exposure, the disaster risk associated with heatwaves is related to factors such as high temperature adaptability of different populations and to the regional level of defense against the effects of heatwaves. Age, gender, occupation, disease status, medical resources, and economic level all affect the response of a population to the effects of heatwaves. Therefore, it will be necessary to undertake further study on the spatiotemporal evolution of heatwave disaster vulnerability under future scenarios, based on the findings of this study, to improve the level of risk management in relation to heatwave events.

Our results provide valuable evidence of the suitability of the proposed method for assessing the impact of heatwave events on population exposure, and they could provide a scientific basis for the development of government policy regarding adaption to climate change.

Data Availability

The daily maximum temperature data (1961–2017) used to support the findings of this study were supplied by http://data.cma.cn/under account and so cannot be made freely available. The North China Plain population data used to support the findings of this study have been deposited in the Chinese Demographic Yearbook (http://www.stats.gov.cn/tjsj/ndsj/). GGI Population Scenario Database of the IIASA used to support the findings of this study were supplied by http://www.iiasa.ac.at/web-apps/ggi/GgiDb/dsd?Action=spatial under account and can be freely available. All other data are available from the authors upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This study was supported by the CDM Fund "Jiangxi Climate Change Adaptation Program" (2014102) and bilateral cooperation project between the Natural Science Foundation of China and the Pakistan Science Foundation (41661144027). The CMA Climate Change Science Fund (CCSF (201722, 201810)) provides a policy-oriented training course for PhD students. The authors are thankful for the support of the High-level Talent Recruitment Program of the Nanjing University of Information Science and Technology (NUIST).

References

[1] E. M. Fischer and R. Knutti, "Anthropogenic contribution to global occurrence of heavy-precipitation and high-temperature extremes," *Nature Climate Change*, vol. 5, no. 6, pp. 560–564, 2015.

[2] C. W. Team, R. K. Pachauri, and L. A. Meyer, "IPCC climate change 2014: synthesis report summary for policymakers," in *Contribution of Working Groups I, II, and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, 2014.

[3] S. Sodoudi, P. Shahmohamadi, K. Vollack, U. Cubasch, and A. I. Che-Ani, "Mitigating the urban heat island effect in megacity Tehran," *Advances in Meteorology*, vol. 2014, Article ID 547974, 19 pages, 2014.

[4] Y. Ma, X.-M Zeng, Y. Zhang et al., "Impact of the choice of land surface scheme on a simulated heatwave event: the case of Sichuan-Chongqing area, China," *Advances in Meteorology*, vol. 2017, Article ID 9545896, 17 pages, 2017.

[5] R. K. Pachauri, M. R. Allen, V. R. Barros et al., "Climate change 2014: synthesis report," in *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 151, Cambridge University Press, Cambridge, UK, 2014.

[6] M. R. Kousari, H. Ahani, and R. Hendi-Zadeh, "Temporal and spatial trend detection of maximum air temperature in Iran during 1960–2005," *Global and Planetary Change*, vol. 111, pp. 97–110, 2013.

[7] A. C. Kruger and S. S. Sekele, "Trends in extreme temperature indices in South Africa: 1962–2009," *International Journal Of Climatology*, vol. 33, no. 3, pp. 661–676, 2013.

[8] Y. Shi, Y. Shen, E. Kang et al., "Recent and future climate change in Northwest China," *Climatic Change*, vol. 80, no. 3-4, pp. 379–393, 2007.

[9] L. Bai, G. Ding, S. Gu et al., "The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011–2013," *Environmental Research*, vol. 132, pp. 212–219, 2014.

[10] C. R. Upperman, J. Parker, C. Jiang, X. He, R. Murtugudde, and A. Sapkota, "Frequency of extreme heat event as a surrogate exposure metric for examining the human health effects of climate change," *PLoS One*, vol. 10, no. 12, Article ID e144202, 2015.

[11] H. Shen, H. Ma, J. Wang, L. Wang, and J. Li, "Variation characteristics of extreme air temperature events in Qinghai Province," *Journal of Glaciology and Geocryology*, vol. 34, pp. 1371–1382, 2012.

[12] T. Fischer, M. Gemmer, L. Liu, and B. Su, "Change-points in climate extremes in the Zhujiang River Basin, South China, 1961–2007," *Climatic Change*, vol. 110, no. 3-4, pp. 783–799, 2012.

[13] T. Fischer, B. Su, Y. Luo, and T. Scholten, "Probability distribution of precipitation extremes for weather index-based insurance in the Zhujiang river basin, South China," *Journal of Hydrometeorology*, vol. 13, no. 3, pp. 1023–1037, 2012.

[14] S. E. Perkins, L. V. Alexander, and J. R. Nairn, "Increasing frequency, intensity and duration of observed global heatwaves and warm spells," *Geophysical Research Letters*, vol. 39, no. 20, p. 20714, 2012.

[15] National Center for Health Statistics: National Vital Statistics System: Mortality Data, 2007.

[16] National Weather Service: Weather Fatalities, 2018.
[17] S. Greene, L. S. Kalkstein, D. M. Mills, and J. Samenow, "An examination of climate change on extreme heat events and climate-mortality relationships in large U.S. Cities," *Weather, Climate, and Society*, vol. 3, no. 4, pp. 281–292, 2011.
[18] L. Coates, K. Haynes, J. O'Brien, J. McAneney, and F. D. de Oliveira, "Exploring 167 years of vulnerability: an examination of extreme heat events in Australia 1844–2010," *Environmental Science & Policy*, vol. 42, pp. 33–44, 2014.
[19] A.-J. Valleron and A. Boumendil, "Épidémiologie et canicules: analyses de la vague de chaleur 2003 en France," *Comptes Rendus Biologies*, vol. 327, no. 12, pp. 1125–1141, 2004.
[20] P. A. Stott, D. A. Stone, and M. R. Allen, "Human contribution to the European heatwave of 2003," *Nature*, vol. 432, no. 7017, pp. 610–614, 2004.
[21] China Meteorological Administration, *The Top Ten Weather and Climate Extreme Events in China in 2013*, China Meteorological Administration, Beijing, China, 2013.
[22] C. L. Gray and V. Mueller, "Natural disasters and population mobility in Bangladesh," *Proceedings of the National Academy of Sciences*, vol. 109, no. 16, pp. 6000–6005, 2012.
[23] S. Re, *Mind the Risk: A Global Ranking of Cities under Threat from Natural Disasters*, 2013.
[24] Y. Hirabayashi, R. Mahendran, S. Koirala et al., "Global flood risk under climate change," *Nature Climate Change*, vol. 3, no. 9, pp. 816–821, 2013.
[25] B. Jongman, P. J. Ward, and J. C. J. H. Aerts, "Global exposure to river and coastal flooding: long term trends and changes," *Global Environmental Change*, vol. 22, no. 4, pp. 823–835, 2012.
[26] C. Jing, T. Jiang, Y. J. Wang et al., "A study on regional extreme precipitation events and the exposure of population and economy in China," *Acta Meteorologica Sinica*, vol. 74, no. 4, pp. 572–582, 2016.
[27] M. Zhan, X. Li, H. Sun, J. Zhai, T. Jiang, and Y. Wang, "Changes in extreme maximum temperature events and population exposure in China under global warming scenarios of 1.5 and 2.0°C: analysis using the regional climate model COSMO-CLM," *Journal of Meteorological Research*, vol. 32, no. 1, pp. 99–112, 2018.
[28] P. X. Wang and J. H. Yang, "Extreme high temperature events and response to regional warming in recent 45 years in Northwest China," *Journal of Desert Research*, vol. 27, no. 4, pp. 649–654, 2007.
[29] F. Zhang, H. Gao, and X. Cui, "Frequency of extreme high temperature days in China, 1961–2003," *Weather*, vol. 63, no. 2, pp. 46–49, 2008.
[30] B. Su, M. Zhan, J. Zhai, Y. Wang, and T. Fischer, "Spatio-temporal variation of haze days and atmospheric circulation pattern in China (19612013)," *Quaternary International*, vol. 380-381, pp. 14–21, 2015.
[31] J. Zhai, J. Huang, B. Su et al., "Intensity–area–duration analysis of droughts in China 1960–2013," *Climate Dynamics*, vol. 48, no. 1-2, pp. 151–168, 2017.
[32] S. Rao, K. Riahi, E. Stehfest et al., *IMAGE and MESSAGE Scenarios Limiting GHG Concentration to Low Levels*, IIASA, Laxenburg, Austria, 2008.
[33] International Institute for Applied System Analysis (IIASA), *GGI Scenario Database Ver 2.0*, International Institute for Applied System Analysis (IIASA), Laxenburg, Austria, 2009.
[34] J. Huang, J. Zhai, T. Jiang et al., "Analysis of future drought characteristics in China using the regional climate model CCLM," *Climate Dynamics*, vol. 50, no. 1-2, pp. 507–525, 2018.
[35] H. Sun, Y. Wang, J. Chen et al., "Exposure of population to droughts in the Haihe River Basin under global warming of 1.5 and 2.0°C scenarios," *Quaternary International*, vol. 453, pp. 74–84, 2017.
[36] A. Fouillet, G. Rey, F. Laurent et al., "Excess mortality related to the August 2003 heat wave in France," *International Archives of Occupational and Environmental Health*, vol. 80, no. 1, pp. 16–24, 2006.
[37] D. Huang, L. Zhang, and G. Gao, "Changes in population exposure to high temperature under a future scenario in China and its influencing factors," *Journal of Geographical Sciences*, vol. 10, no. 2, 2018.
[38] C. B. Field, V. Barros, T. F. Stocker et al., "IPCC, 2012: managing the risks of extreme events and disasters to advance climate change adaptation," *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, Cambridge University Press, vol. 30, no. 11, pp. 7575–7613, Cambridge, UK, 2012.
[39] C. W. Team, R. K. Pachauri, and L. A. Meyer, "IPCC, 2014: climate change 2014: synthesis report," *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the intergovernmental panel on Climate Change*, Vol. 151, IPCC, Geneva, Switzerland, 2014.
[40] G. A. Meehl and C. Tebaldi, "More intense, more frequent, and longer lasting heat waves in the 21st century," *Science*, vol. 305, no. 5686, pp. 994–997, 2004.
[41] H. Shi, "Climatic characteristics and the spatio-temporal variation of high temperature days in North China in 1960–2009," *Scientia Geographica Sinica*, vol. 32, no. 7, pp. 866–871, 2012.
[42] Z. Xie, J. Cui, H. Liu et al., "A study on the severe hot weather in Beijing and North China part I-statistics and synoptic case study," *Climatic & Environmental Research*, vol. 4, 1999.
[43] J. Wei, H. Yang, and S. Q. Sun, "Relationship between the anomaly longitudinal position of subtropical high in the Western Pacific and severe hot weather in North China in summer," *Acta Meteorologica Sinica*, vol. 62, 2004.