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Scenario-based hazard analysis of extreme high-temperatures experienced between 1959 and 2014 in Hulunbuir, China

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Abstract

Purpose – Extreme high temperatures are a significant feature of global climate change and have become more frequent and intense in recent years. These pose a significant threat to both human health and economic activity, and thus are receiving increasing research attention. Understanding the hazards posed by extreme high temperatures are important for selecting intervention measures targeted at reducing socioeconomic and environmental damage.

Design/methodology/approach – In this study, detrended fluctuation analysis is used to identify extreme high-temperature events, based on homogenized daily minimum and maximum temperatures from nine meteorological stations in a major grassland region, Hulunbuir, China, over the past 56 years.

Findings – Compared with the commonly used functions, Weibull distribution has been selected to simulate extreme high-temperature scenarios. It has been found that there was an increasing trend of extreme high temperature, and in addition, the probability of its indices increased significantly, with regional differences. The extreme high temperatures in four return periods exhibited an extreme low hazard in the central region of Hulunbuir, and increased from the center to the periphery. With the increased length of the return period, the area of high hazard and extreme high hazard increased. Topography and anomalous atmospheric circulation patterns may be the main factors influencing the occurrence of extreme high temperatures.

Originality/value – These results may contribute to a better insight in the hazard of extreme high temperatures, and facilitate the development of appropriate adaptation and mitigation strategies to cope with the adverse effects.

Keywords Hazard, Detrended fluctuation analysis (DFA), Extreme high temperature, Hulunbuir, Weibull

Paper type Research paper

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1. Introduction

The environmental and socioeconomic impacts of climate change are of fundamental importance for future planning and management, and these are likely to result specifically from increasing climate variability, especially in terms of the frequency and/or intensity of extreme weather events (Easterling *et al.*, 2000; Xu *et al.*, 2006). Temperature and precipitation are perhaps the most widely used indicators to describe climate and weather, and small variations in mean temperature can also be associated with large changes in the frequency, intensity and magnitude of extreme events (Katz and Brown, 1992; Feng *et al.*, 2013). For many impact applications and decision support systems, the evidence of extreme events is much more important than the mean climate state (Kunkel *et al.*, 1999). Thus, there is a consensus within the climate change community that the frequency or intensity of extreme climate events will have more serious impacts on ecosystems, agriculture and human society (e.g. through floods, droughts, hurricanes, storms, extreme heat and cold) than changes in the mean values (New *et al.*, 2006). In arid and semiarid areas, the spatial and temporal distribution of water resources is directly impacted by temperature conditions (Zhang *et al.*, 2009), and these areas are much more vulnerable to climate change. Thus, exploring the changing characteristics of extreme temperature events in arid and semiarid areas is a prerequisite for assessing the impact of climate change on the regional ecological environment and agricultural development. As noted by the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2012), the vulnerability of an area to extreme weather events depends not only on the number of people affected but also on the area's response capacity to extreme weather. These factors are related to the latitude, altitude, habitat suitability, climate zone, topography, other natural conditions, the level of economic development, traffic accessibility, irrigation, water conservation facilities and other socioeconomic conditions (Chong *et al.*, 2015).

Northeastern China is sensitive to climatic warming and has experienced dramatic changes in the past several decades (Piao *et al.*, 2006); for example, the annual temperature has increased by more than 1°C over the past 20 years (Sha *et al.*, 2002). Hulunbuir is a city within the territory of Inner Mongolia, which is one of the world's four major natural grassland regions and is sensitive to global warming. Detailed climatic knowledge of this region is currently lacking and climate data are too sporadic and incomplete for informed decision-making. Previous studies of the region have mainly addressed the issues of vegetation protection and desertification, and the studies of extreme temperature events are sparse. Few studies of climate change in Inner Mongolia have mainly focused on the temporal and spatial variations of low temperature in winter and high temperature in summer (Chen *et al.*, 2012a), and precipitation change (You *et al.*, 2010; Su *et al.*, 2010). Alternatively, they have selected simple indicators to analyze extreme events (Bai *et al.*, 2009, 2014; Yan *et al.*, 2014; Guo *et al.*, 2015; Song *et al.*, 2015; Jiang *et al.*, 2016) that have mainly concerned the entire province, and ignored regional differences. Inner Mongolia is particularly vulnerable to temperature extremes as it is a wide provincial region in China, and is strongly influenced by the East Asian monsoon (Song, 2005), which may undermine development efforts and lead to incoherent responses to climate change.

Extreme low temperature is prone to occur in Inner Mongolia and has been paid much attention to by researchers, from both long-term and short-term perspectives. For example, An (2015) analyzed the circulation characteristics of abnormal low temperature types during 1961-2012, Chen *et al.* (2012b) analyzed the characteristics and causes of extreme low temperature in Inner Mongolia in the winter of 2009 and 2010 and Yang *et al.* (2011) investigated the effects of extreme low temperature. However, the analysis of extreme high temperature in a normally cold area is important as there is a focus on adaptation and mitigation strategies for extreme events. Moreover, for extreme high temperatures, there is no effective measure available to prevent or minimize the impacts. Detailed information relating, for example, to variations in the frequency of extreme high temperatures and their effects on human activities is lacking in most conventional studies using hazard-scenario analysis. Thus, it is necessary to systematically address the occurrence of extreme temperature events in hazard-scenario analysis of Hulunbuir. The objectives of this study of Hulunbuir are:

- to identify extreme high-temperature events during the past 56 years;
- to model the hazard of extreme high temperatures and then to produce a hazard-scenario design for further analysis; and
- to consider the possible impact factors of extreme high temperatures.

2. Material and methods

2.1 Study area

Hulunbuir is located in between 47′05’-53°20′N and 115°31′-126°04’E. It is governed as a prefecture-level city in northeastern Inner Mongolia of the People’s Republic of China. The region is occupied by the grassland, the Hulun and Buir Lakes (the latter partially in Mongolia) and the Khingan mountain range (Figure 1). It is bordered by Russia to the north and west, Mongolia to the south and west, Heilongjiang Province to the east and Hinggan League to the south. The topography becomes gradually flatter from east to west, with decreasing elevation. The city of Hulunbuir has a humid continental climate (Köppen Dwb) bordering on subarctic (Köppen Dwc), although the northern part of the city is subarctic. Winters are long, very dry and severe, due to the semi-permanent Siberian High; whereas summers are short, very warm and rather wet, due to the influence of the East Asian monsoon. The weather tends to be sunny throughout the year with at least a 55 per cent probability of sunshine in all the months and an annual total greater than 2,700 h. Approximately, 70 per cent of the annual rainfall occurs during the three summer months. The annual mean air temperature and precipitation are approximately −3 to 0°C and 250-400 mm,

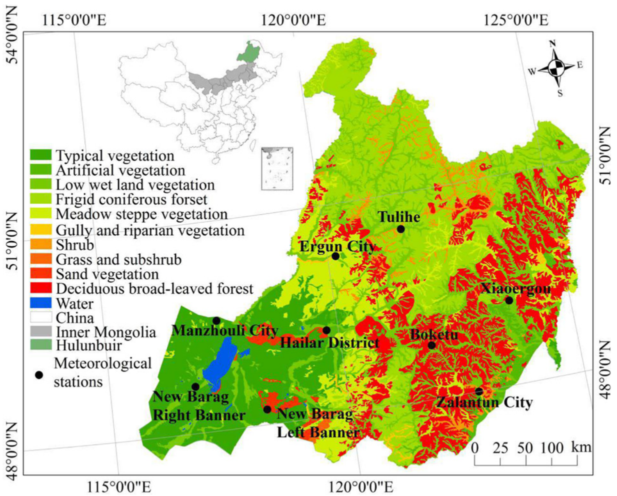

Figure 1.
Distribution of meteorological stations and vegetation types in Hulunbuir

respectively, representing a temperate continental climate. Meadow grassland and steppe are regularly distributed throughout the grassland area (Yang *et al.*, 1994).

2.2 Data and methods

2.2.1 Data acquisition and preparation. To ensure consistency and to obtain the longest continuous set of observations possible, data from nine ground-based meteorological stations (Table I) in Hulunbuir were collected from the China Meteorological Data Sharing Service System (http://data.cma.cn/). The data sets are time series of the daily maximum and minimum temperature and annual extreme high temperatures recorded from 1959 to 2014 in Hulunbuir. Data records from 1959 to 2014 were used as the data prior to 1959 contains many missing values. If a station had more than 1 per cent missing data, and the missing data at one station exceeded three consecutive months, then the station was excluded. Finally, after the application of strict quality control procedures, nine available stations from Hulunbuir, providing data from 1959 to 2014, were selected for study. Even though the meteorological stations are not evenly distributed throughout Hulunbuir, they represent each topographical area and therefore the results can be regarded as representative of the entire region.

2.2.2 Data analysis. To understand the dynamics of extreme high-temperature events in Hulunbuir, an integrated approach was used, including GIS analysis, detrended fluctuation analysis (DFA), probability density functions and hazard-scenario analysis. The methodology is briefly described below.

2.2.2.1 Detrended fluctuation analysis. The detrended fluctuation analysis (Peng *et al.*, 1994, 1995) has proven useful for revealing the extent of long-range correlations in time series. The relative values of all terms in a time series ($x_1, x_2, \ldots, x_n$) and the analytical steps are described as follows:

- Step 1: An integrated time series should be analyzed (with N observations).
- Step 2: The integrated time series is divided into boxes of equal length n. In each box of length n, a least square line is fitted to the data (representing the trend within that box). The y coordinate of the straight-line segments is denoted by $y_n(k)$.
- Step 3: In each box, the integrated time series, $y_n(k)$, is detrended by subtracting the local trend, $y_n(k)$. The root-mean-square variation of this integrated and detrended time series is calculated by:

Stations	Longitude/°E	Latitude/°N	Elevation/m
Ergun City (EC)	120.18	50.25	581.4
Tulihe (TH)	121.68	50.48	732.6
Manzhouli City (MC)	117.43	49.57	661.7
Hailar District (HD)	119.75	49.22	610.2
Xiaoergou (XG)	123.72	49.20	286.1
New Barag Right Banner (NR)	116.82	48.67	554.2
New Barag Left Banner (NL)	118.27	48.22	642
Boketu (BT)	121.92	48.77	739.7
Zalantun City (ZC)	122.73	48.00	306.5

Table I. Meteorological stations of Hulunbuir

$$F(n) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left[y(k) - y_n(k)\right]^2} \tag{1}$$

This is repeated over all time scales (box sizes) to characterize the relationship between $F(n)$, the average fluctuation and the box size n. Typically, $F(n)$ will increase with box size. A linear relationship on a log-log plot indicates the presence of power law (fractal) scaling. Under these conditions, the fluctuations can be characterized by a scaling exponent, the slope of the line relating log $F(n)$ to log(n).

DFA was used to determine the threshold of the extreme high temperatures for each station and then to identify the extreme high-temperature events. Generally, if the local temperature was higher than the threshold, it was considered that an extreme high-temperature event had occurred.

2.2.2.2 Probability density function of the Gumbel, Weibull and P-III distributions. In the probability theory and statistics, various asymptotic distributions are the most commonly used methods to address extreme value problems (Papoulis and Pillai, 2002). For the analysis of long time series (more than 30 years), Gumbel, Weibull and P-III distributions are widely used. For the analysis of time series of intermediate length (about 15-20 years), the Poisson–Gumbel compound distribution is used extensively, whereas a two-logarithmic normal distribution is used to analyze short time series (approximately 1 year) (Tu, 1984; Duan, 2004). Extreme high temperatures over the past 56 years were analyzed in this study, and therefore the Gumbel, Weibull and P-III distribution were used. The formula for the distribution is defined as follows:

$$F(x) = \begin{cases} \exp\{-[1 - k(x-\zeta)/a]^{1/k}\}, k < 0, x > \zeta + a/k \\ \exp\{-\exp[-(x-\zeta)]\}, k = 0 \\ \exp\{-[1 - k(x-\zeta)/a]^{1/k}\}, k > 0, x > \zeta + a/k \end{cases} \tag{2}$$

where ξ, α and k are constants known as the location, scale and shape parameters, respectively. The k value determines the type of the distribution function: when $k = 0$, the Gumbel distribution is used, when $k > 0$, the Weibull distribution is used and when $k < 0$, the Fréchet distribution is used.

Reference to Table II shows that the k values of the nine stations are all greater than 1 and that the Dn values are all greater than 0.05; thus, the model passes the Kolmogorov–Smirnov test. Following this analysis, the Weibull distribution was selected as an appropriate method for analyzing the return period of extreme high temperatures in this paper.

Table II. Parameters for the distribution of extreme high temperatures for the selected meteorological stations during 1959 and 2014

Parameters	NC	TH	MC	HD	XG	NR	NL	BT	ZC
ξ	0.59	0.94	0.67	1.02	1.49	1.1	1.08	1.33	1.44
k	1.39	1.8	2.02	1.51	1.61	1.84	1.65	1.85	1.43
α	1.59	1.33	2.02	1.45	1.56	2.21	1.9	1.46	1.89
Kolmogorov–Smirnov test (Dn)	0.09	0.07	0.11	0.09	0.06	0.08	0.14	0.09	0.07
Residual sum of squares (R)	0.15	0.09	0.21	0.17	0.05	0.17	0.26	0.17	0.08

The Weibull distribution is named after Waloddi Weibull, who described it in 1951, although it was first defined by Fréchet (1927), and first applied by Rosin and Rammlerto to describe a particle size distribution. From a survey of the literature, it was found that the Weibull distribution is also noted for providing flexible, adaptable and accurate results for the analysis of extreme values (Wang, 2013; Gao, 2014). The Weibull distribution is a continuous probability distribution derived from theory, and its parameters are determined by the actual data. Therefore, the results calculated from the Weibull distribution (combining theory and experience) are in accord with real world situations.

In term of materials science, the parameter k, the distribution of weights, is known as the Weibull modulus. In this study, the Weibull modulus (Figure 2) was selected to simulate extreme high-temperature scenarios for four different return periods (10, 30, 50 and 100 years).

2.2.2.3 Probability and intensity analysis. UNESCO (1991) defined a natural hazard as a potentially damaging phenomenon with a certain occurrence probability for a given area within a specific period. Analysis of probability and intensity of extreme high temperatures are the basis of the analysis of extreme high-temperature hazards. Extreme high-temperature events can be described in terms of various parameters, such as maximum temperature, number of high temperature days and annual average temperature (Yin, 2013). In the present study, the parameters used include annual extreme high temperature and the number of warm days and warm nights (Albert *et al.*, 2009); its probability was equal to the proportion of warm days and warm nights during a year (detailed in Table III). The annual number of extreme high temperatures can be regarded as a measure of the intensity of extreme high-temperature events. As these data are the most relevant indicators of extreme high temperature, other types of magnitude metrics (e.g. average temperature) were not considered.

2.2.2.4 Extreme high-temperature events hazard index. A hazard curve, combined with the probability and intensity of extreme high-temperature events in Hulunbuir over the past 56 years, was constructed to estimate the sensitivity of Hulunbuir to potentially hazardous extreme high temperatures. An extreme high-temperature hazard formula was defined, as follows:

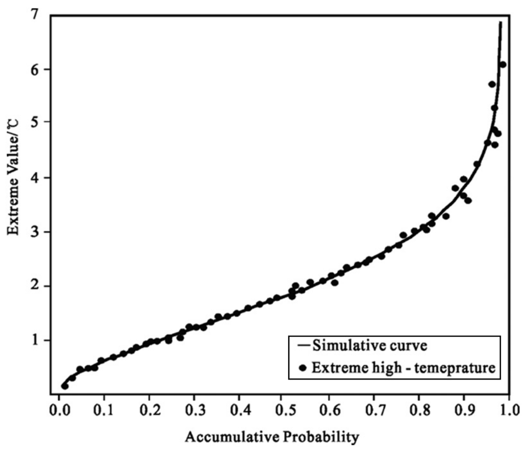

Figure 2.
Simulation curve meteorological stations of extreme high temperatures

$$H = P * I \tag{3}$$

where, H, one of the risk factors, is the hazard of extreme high temperatures, and P and I are the probability and intensity of the extreme high-temperatures, respectively. Thus, H depends on the values of P and I: as P or I increases, the hazard of extreme high-temperature increases. To make the results easily comprehensible and comparable, the H values were divided into five levels using the natural break-point method in GIS: extreme low hazard, low hazard, moderate hazard, high hazard and extreme high hazard.

3. Results

3.1 Risk identification of extreme high-temperature events

The bar chart showing the number of days with extreme high-temperature events (Figure 3) reveals that Hulunbuir experienced many extreme high-temperature events during the past 56 years, although there are spatial differences. Specifically, the annual number of days with high-temperature events varied from 20 to 90 days. The area with the lowest frequency of high temperature event was NR, whereas NL had the highest frequency. This is likely attributable to the presence of Hulun Lake, which has a large surface area. The pattern of changes of extreme high-temperatures is complex: in certain areas and at certain times of the year, there were few extreme high-temperature events, whereas in other years, many high-

Table III. Definition of indices of extreme temperature

Category	Index	Descriptive name	Definition
Relative indices	TN90	Warm nights	The number of days with daily minimum temperature above the 90th percentile of daily minimum temperatures Days when TN > 90th percentile of 1959-2014
	TX90	Warm days	The number of days with daily maximum temperature above the 90th percentile of daily maximum temperatures Days when TX > 90th percentile of 1959-2014

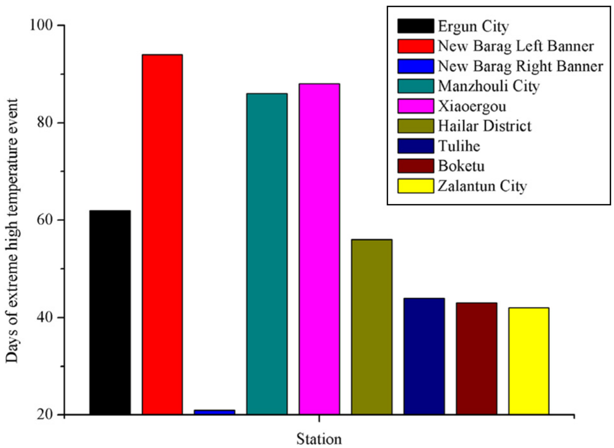

Figure 3. Number of days with extreme high-temperature events for the nine meteorological stations of Hulunbuir

temperature events occurred. Further work is needed to determine the occurrence characteristics and the variation of the degree of hazard of extreme high-temperature events.

3.2 The hazard of extreme high-temperature events

3.2.1 Analysis of the variation of extreme high temperatures. The occurrence of extreme high temperature increased from 1959 to 2014 throughout almost the whole of the Hulunbuir area, with values fluctuating between 12°C and 20°C (Figure 4). However, extreme high temperatures were not uniformly distributed and regional disparities are evident. On a regional basis, the highest rate of increase (0.35°C-0.44°C per decade), occurred in EC and TH, in the central area of Hulunbuir. A moderate rate of increase (0.24°C-0.29°C/decade) occurred over the large area of NR in the southwestern part of Hulunbuir, whereas the lowest rate of increase (0.13°C-0.19°C/decade) was in ZC in the southeastern part of Hulunbuir (Figure 5).

3.2.2 Analysis of the probability of occurrence of warm nights and warm days. To determine the probability of the occurrence of warm nights (TN90) and warm days (TX90),

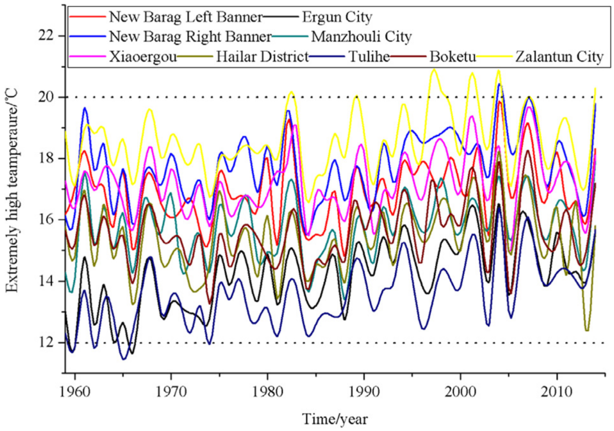

Figure 4. Time series of extreme high temperatures for the nine meteorological stations in Hulunbuir

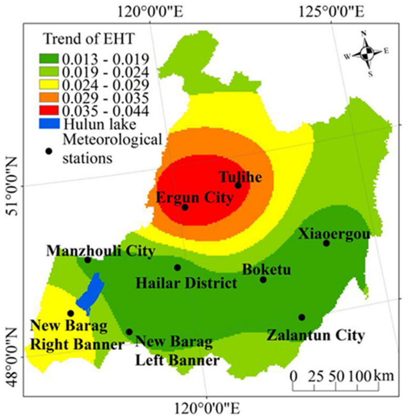

Figure 5. Spatial distribution of extreme high temperatures in Hulunbuir

the threshold value of extreme high temperatures was calculated using the definition given in Table III and these are listed in Table IV. There are distinct regional differences in the threshold of extreme temperature indices: the threshold in TH was the lowest in both TN90 and TX90, whereas NR was the highest in both TN90 and TX90.

The spatial distributions of threshold values for extreme high-temperature indices are generally very similar (Figure 6), with the only difference being the magnitude of change. Spatially, the extreme high-temperature threshold values in Hulunbuir increased from north to south and from the center to the periphery. The threshold values of extreme high temperatures are significantly related to topography, with high-altitude stations exhibiting low values, and vice versa. These findings contrast with those of previous studies, which reported that high threshold values were more prominent at higher elevations than at lower elevations (Li, 2014).

Low extreme high-temperature threshold values occur across cool-temperate coniferous forest and deciduous broad-leaved forest, while whereas high value areas are distributed across typical steppe and modified vegetation (Figure 1). The very high values of TX90 in NR and NL are in accord with the typical sparse steppe vegetation in this sand area, which results in a rapid heating rate compared to other areas. Surprisingly, the value for TN90 was very high. After detailed analysis, it was determined that Hulun Lake, with a very large surface area, caused the temperature to decrease slowly at night, in contrast to other land areas. Thus, topography, the type of vegetation cover, and proximity to major bodies, may be the main factors controlling the threshold value of extreme high-temperature indices in Hulunbuir.

In general, the regional average probabilities of TN90 and TX90 increased from 1959 to 2014 across almost the whole of Hulunbuir (Figure 7). There are two well-defined intervals: low amplitude fluctuations from 1959 to 1983 and high amplitude fluctuations from 1984 to

Table IV.
The threshold values of extreme temperature indices

Index	NC	TH	MC	HD	XG	NR	NL	BT	ZC
TN90	14	10.5	14.4	15	14.5	15.8	15.7	12	16.5
TX90	26.7	25.2	27.1	26.9	27.6	28.5	28.3	25.4	27.9

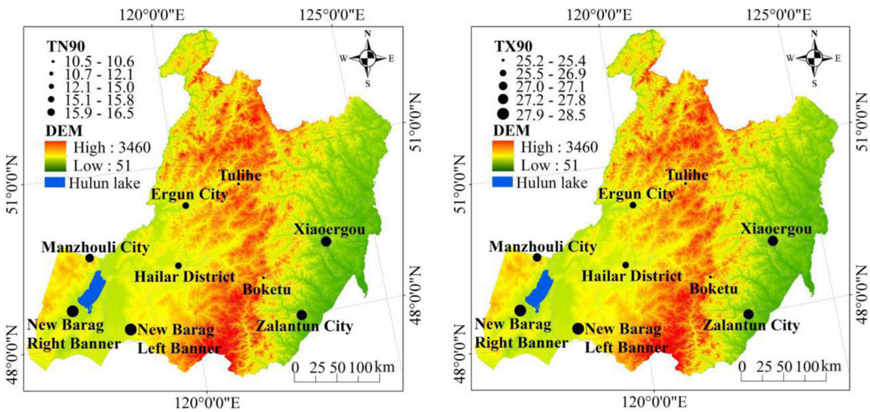

Figure 6.
Spatial distribution of the threshold value of extreme high-temperature indices (TN90 and TX90)

2014. Thus, the probability for the TN90 and TX90 series can be divided into two sub-series based on these two distinct patterns of variation.

3.2.3 Hazard index analysis. Based on decomposition and construction of hazard indices using the above EHTEHI analysis, it was found that both the variation and probability of extreme high-temperature hazards were essentially the same (Figure 8). Thus, there were both spatial and temporal differences in nonlinear trend processes in Hulunbuir, which implies that the strategies for the prevention or mitigation in the pre-disaster stage should be different. Generally, the hazard of extreme high temperatures remained at a relatively constant level from 1959 to 1983, followed by a pattern of significant fluctuations from 1983 to 2014. This finding can be mainly attributed to recent global warming that has resulted in the increased intensity of extreme high-temperature events, which is combined with Hulunbuir being influenced by the presence of cold continental high-pressure air in winter.

3.2.4 Hazard scenario design for Hulunbuir. The Weibull distribution was used to simulate the hazard of extreme high-temperature events at nine meteorological stations in Hulunbuir and subsequently to calculate the hazard values under different scenarios.

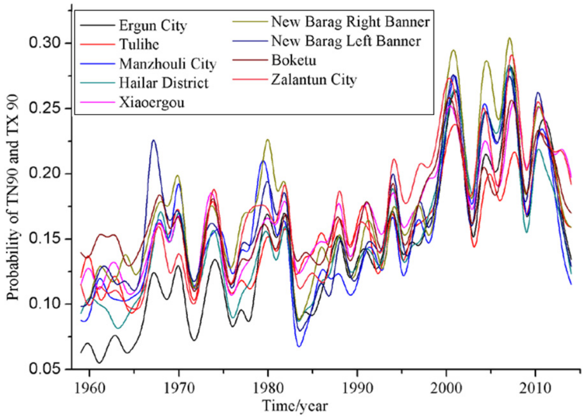

Figure 7.
Time series of the probability of TN90 and TX90 for the nine meteorological stations in Hulunbuir

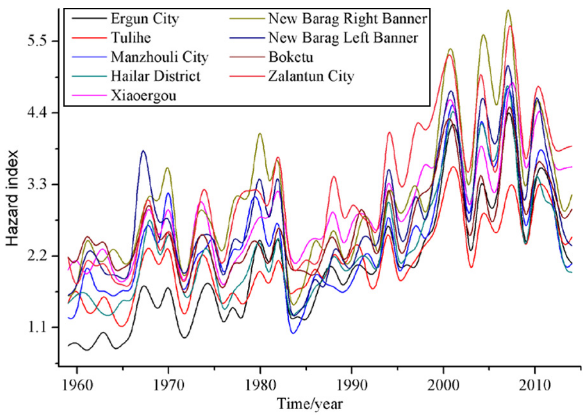

Figure 8.
Times series of extreme high-temperature hazard for the nine meteorological stations in Hulunbuir

Conventional Kriging, a GIS point interpolation method, which is commonly used in meteorology, was performed to determine the spatial distribution of hazard values of extreme high temperatures for different return periods. The results for each return period are described. The spatial distributions of the observed hazard values across Hulunbuir for different return periods are illustrated in Figure 9 and listed in Table V.

There is a good level of consistency between the various scenarios. Scenarios for the 10-year, 30-year, 50-year and 100-year return periods are illustrated in Figure 9. In the scenario for the 10-year return period, the distribution is circular with the hazard level increasing from the center to the periphery, especially in the southeast and southwest parts of Hulunbuir. Thus, the center exhibits an extreme low hazard and the periphery an extreme high hazard risk, especially in the southeast and southwest areas. A large area of NR and ZC exhibits an extreme high hazard, whereas TH, EC and HD are in the extreme low hazard area. The areas of extreme low hazard, low hazard, moderate hazard, high hazard and

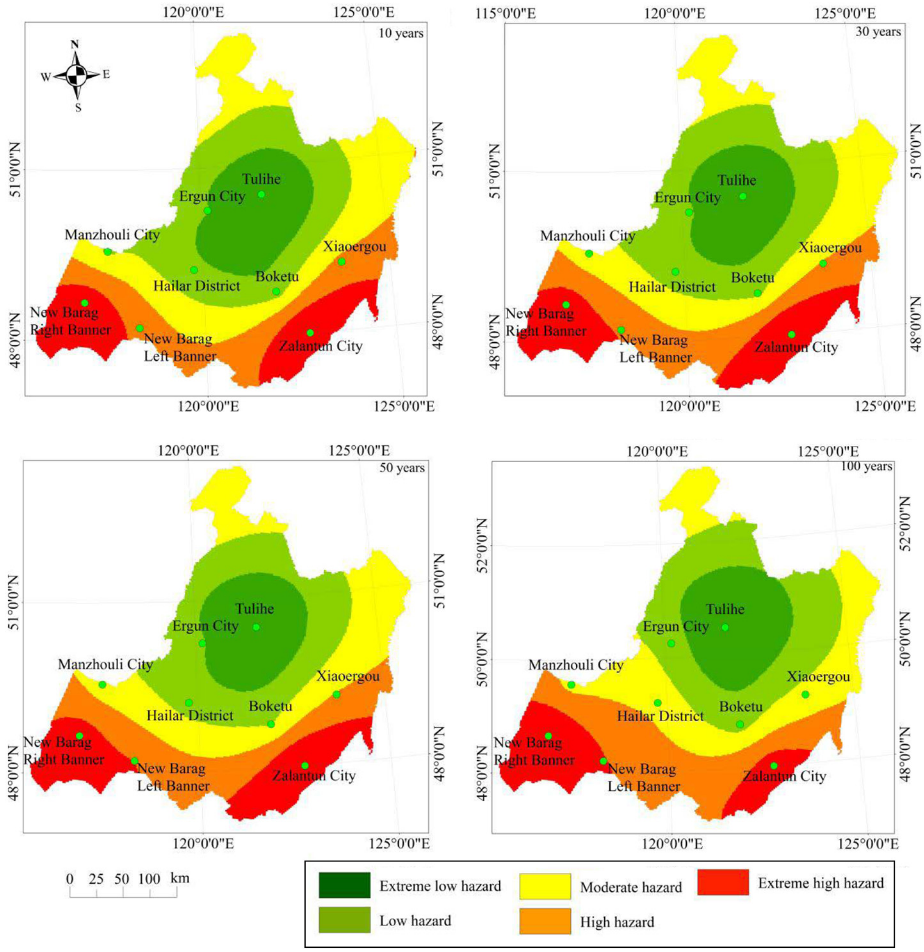

Figure 9.
Scenarios of the spatial distribution of the degree of hazard for four return periods

extreme high hazard are 41,398.90 km^2, 64,539.15 km^2, 68,544.90 km^2, 41,929.96 km^2 and 36,536.17 km^2, respectively.

In the scenarios for the 30-year, 50-year and 100-year return periods, the hazard of extreme high temperature exhibits the same trend, but the center moves northeastwards (Figure 9). As the return period increases, the areas of high hazard and extreme high hazard both increase (see Table V). From a field survey, it was determined that typical steppe covers the southwestern area of the Hulunbuir high plain, modified vegetation is distributed in the southeastern valley plain and cool-temperate coniferous forest covers the Greater Xing'an Mountains in the central area of Hulunbuir. Thus, to some extent, the distribution of vegetation types reflects the hazard of extreme high temperatures given that vegetation can reduce the hazard level by reducing high temperatures.

4. Discussion

On the basis of historical observation data and extreme temperature indices, the spatiotemporal variability of extreme temperature events in Hulunbuir over the past 56 years has been analyzed. The occurrence of extreme high-temperature events exhibits an increasing trend across both the whole region and regionally. The threshold value of extreme high-temperature indices increased with decreasing latitude and altitude, and was also related to topography, vegetation type and the distribution of major water bodies. The trends within a given sub-region were not always the same and in fact were sometimes the opposite. Possible reasons for these observations are discussed below.

4.1 Role of topography in providing conditions for extreme high temperatures

Hulunbuir is occupied by the Da Hinggan, Hulunbuir high plain and valley plains, which leads to different atmospheric depths that in turn may provide conditions for extreme weather conditions. That is, the differences in the terrain in Hulunbuir plays an important role in determining variations in the distribution of the frequency and intensity of extreme high temperatures. Topography plays a key role in affecting hydrothermal conditions by blocking or shifting the position of cold air and therefore it has a significant effect on the distribution of extreme high temperatures. The Da Hinggan Mountains, which extend from the northeast to the southwest in the central part of the study area, are directly affected by cold air from Siberia. Spatial and frequency differences in hazard in the study are obvious and these may be caused by cold air surges passing through the western foot of the Da Hinggan Mountains following cold air outbreaks. The effect of the mountains is to impede the flow of cold air and increase cold air retention in the region, which increases the frequency of cold surges (Liu *et al.*, 2015); in addition, high temperatures may dominate the two adjacent areas for long periods of time. Topography also has a large impact on the threshold value of extreme high-temperature indices. The distinctive characteristics of the terrain in Hulunbuir (previously characterized as "easy in and difficult out" – Huang, 1986; Lv, 1956) resulted in the threshold value of extreme high temperatures in the center being lower than in the two adjacent areas. Thus, the

Hazard level	10 years	30 years	50 years	100 years
Extreme low hazard	41,398.96	38,101.2	37,989.42	40,290.39
Low hazard	64,539.15	66,309.14	64,604.36	64,231.74
Moderate hazard	68,544.9	65,563.88	64,641.63	61,995.97
High hazard	41,929.96	44,025.99	45,171.82	53,155.37
Extreme high hazard	36,536.17	38,948.93	40,541.92	33,275.67

Table V. Areas of different hazard levels in four return periods (unit: km^2)

distribution of extreme high temperatures exhibits a distinct altitudinal trend. However, the location of the meteorological stations may be another factor, which can influence the occurrence of extreme high temperatures, as the altitude of the meteorological stations would inevitably impact the results.

4.2 Relationship between abnormal atmospheric circulation and extreme high temperature

In general, the atmospheric circulation in the Northern Hemisphere troposphere enhances the development of anticyclonic circulation across the Eurasian continent, centered in Mongolia. The Arctic Oscillation (AO), for example, has a significant effect on atmospheric circulation and hence the climate of the Northern Hemisphere (Yao *et al.*, 2014). Specifically, the AO affects the cold air in polar regions by strengthening the polar vortex and Liu *et al.* (2015) found that during 1960 to 2012, the AO exhibited an increasing trend, which contributed to the gradual weakening of polar high pressure and the strengthening of low pressure at mid-latitude areas, which led to extreme high temperatures. Therefore, a decrease in the intensity of the Siberian High and the Asian winter monsoon can lead to an increase in the frequency of extreme high-temperature events.

You (2014) studied the influence of anomalous atmospheric circulation on extreme weather events during the past 50 years in Inner Mongolia. They found that anomalous atmospheric circulation mainly occurred in the area between 60°E-80°E latitude and 20°2N-40°N longitude because the Ural Mountains and the Okhotsk Sea blocked the high-pressure zone, which resulted in the Asian Polar Vortex contracting to the Ural Mountains and its northern region from north to west. This resulted in Mongolia and Inner Mongolia being controlled by the high-pressure ridge. Pressure in Siberia then became abnormally high, which led to the widespread occurrence of abnormally high temperatures in Inner Mongolia.

Warm days, warm nights, long day length with a high number of sunshine hours and a clear and cloudless sky enable insolation to reach the ground surface; in addition, a dry sandy terrain, already warmed by the preceding hot days, can also lead to the occurrence of extreme high temperatures, especially in areas far from major water bodies.

5. Conclusions

In the context of ongoing global warming, the systematic study of the spatiotemporal occurrence of extreme weather events may enable proactive management of the associated risks of extreme events, thus reducing the impacts and minimizing potential human and economic losses. In the current study, statistical testing and RS/GIS analysis were combined to conduct the first analysis of the hazard of extreme high temperatures experienced across Hulunbuir from 1959 to 2014, including hazard identification, scenario design and analysis of the factors promoting extreme high temperatures. Records from nine meteorological observation stations were used to characterize the occurrence of extreme high temperatures in terms of their annual occurrence and the numbers of warm days and warm nights. The main conclusions are as follows:

- The results of DFA show that Hulunbuir has experienced extreme high-temperature events in the past 56 years, with some regional differences; locations NR and NL had the lowest and highest frequencies, respectively.
- The threshold value of the extreme high-temperature indices in Hulunbuir increased from north to south and from the center to the two margins. This was the result of differences in topography, vegetation cover and the distribution of water bodies.
- There is a high level of consistency between the scenarios for Hulunbuir: the center has an extreme low hazard, whereas the hazard degree increased from the center to the periphery; in addition, NR and ZC experienced an extreme hazard in all four

return period scenarios (10, 30, 50 and 100 years). With the increasing length of return period, the areas of high hazard and extreme high hazard increased.

- From 1959 to 2014, the incidence of extreme high-temperatures increased across almost the whole of the Hulunbuir region; the fluctuations ranged from 12°C to 20°C. A distinct altitudinal trend is evident, which may be a result of the altitude of the meteorological stations. Topography and abnormal atmospheric circulation conditions may be other important factors. The vegetation coverage may also act to reduce the hazard by reducing temperatures.

These results may provide a better insight to the hazard of extreme high-temperatures, and facilitate the development of appropriate adaptation and mitigation strategies to cope with the adverse effects of extreme high temperatures. For example, attention should be paid to the vegetation coverage in the high hazard and extreme high hazard areas, given the possibility of the implementation of poorly planned vegetation modification strategies.

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