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Research Article

Assessment of Disaster Loss Index and Characteristics of Gale Disaster in Typical Arid and Semiarid Lands

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This study aims to illustrate the various characteristics of gale disaster loss in typical arid and semiarid areas and to divide the classification of disaster loss. Based on 1399 gale disasters in 48 counties (or cities) of Southern Xinjiang, the typical arid and semiarid lands, during 1980–2019, the disaster loss index, which comprehensively expresses six disaster factors, is constructed through mathematical statistics. The percentile method is used to divide the disaster loss index into four levels: mild (level I), moderate (level II), severe (level III), and very severe (level IV). The geographical distribution, annual variation, and interannual variation characteristics of the frequency and intensity of gale disasters in Southern Xinjiang were analyzed from the overall and different levels. The results show that the most frequent and hardest-hit areas in Southern Xinjiang are concentrated in Turpan and Aksu. The gale disasters have their peak occurrence in April with the most vigorous intensity. The frequency of gale disasters in Southern Xinjiang has increased yearly, but the intensity did not show a fluctuation trend. The frequency and intensity of level I to III gale disasters increased yearly, but the frequency and intensity of level IV gale disasters did not fluctuate. Identifying high-risk areas and periods of gale disaster loss is conducive to the policy formulation and hierarchical management of disaster prevention and control in arid and semiarid lands.

1. Introduction

Gale disaster is a common natural disaster that severely impacts industrial and agricultural production, transportation, and daily life [1, 2]. Gale disasters are caused by strong wind (wind force ≥8) and sandstorms [3]. It has become the main meteorological disaster in Southern Xinjiang, typical arid and semiarid lands. Xinjiang Gales are characterized by high frequency, strong wind, and long duration, which is harmful to crop growth in various seasons, mainly affects crop sowing in spring, and destroys tall plants and mature crops in summer. In addition, it also causes soil wind erosion and desertification and destroys the ecological environment [4–7]. Meanwhile, a large amount of ground dust and sand rises with the gale, resulting in reduced visibility, lost roads, collisions, falling water, and other casualties. When the fallen sand dust covers the cropland, it is difficult for the leaves to photosynthesize, or it will cause damage to mature crops such as shearing [8–13]. With the rapid development of the global economy and the frequent occurrence of extreme weather events caused by climate change, it is of great significance to study the spatiotemporal variation characteristics of gale disasters in Southern Xinjiang for disaster prevention and mitigation.

The temporal distribution characteristics of the world's gales with dust and sandstorms disaster have been widely reported, but initially, they were limited to descriptive and qualitative research. Jauregui [14] analyzed seasonal and annual variation of wind-dust storms in Mexico from 1981 to 1987. Brazel and Nickling [15] observed the occurrence variation patterns of different types of wind-dust storms in Arizona from 1965 to 1980.

With the development of geographic information technology, the research on the temporal and spatial distribution characteristics of gale and sandstorm disasters has become a hot topic. Gou et al. [16] confirmed that strong winds, rain temperature, and sand storms cause disasters together. And the study also described the spatial and temporal distribution of this kind of disaster in the Xilin Gol area. Indoitu et al. [17] monitor and assess the spatial and temporal distribution of strong wind-dust storms over the Central Asian region during the last seven decades. Then the research focuses on the hazard assessment and the exploration of disaster-causing factors. In the fuzzy comprehensive evaluation method [18, 19], the key disaster-causing factors, such as sediment transport potential, days of strong wind, average wind speed, and maximum wind speed, are usually selected to calculate the weight, and the intensity of gale disasters is graded by constructing a quantitative evaluation model of gale disasters. Some studies calculate the estimated risk value of different levels of gale days and use GIS technology to classify the level of gale disaster [20, 21], while others classify the highway gale disaster level using the comprehensive risk index calculated by the natural disaster risk index method [22, 23]. Disaster factors can reflect the harmful degree of different causes of gale disasters from many aspects. Given the different emphasis of the study, the selection of disaster factors and the classification method of the disaster loss index have not formed a unified standard. So far, the research on the spatial-temporal distribution and long-term variation characteristics of gale disasters at different levels in Southern Xinjiang has not been carried out.

The primary objectives of this work are

(1) To construct the disaster loss index, which was graded by six disaster factors in each gale disaster event, using the mathematical statistics method

(2) To analyze the spatial distribution, annual change, and long-term trend of different levels of gale disasters in Southern Xinjiang

(3) To the policy formulation and hierarchical management of gale disaster prevention and control in arid and semiarid lands by identifying high-risk areas and periods

2. Study Area and Materials and Methods

2.1. Study Region. Southern Xinjiang, as the typical arid and semiarid lands, is located in the hinterland of Eurasia, which refers to the area under the jurisdiction of the south of Tianshan Mountains in Xinjiang, including Hami City, Turpan City, Mongolia Bayinguoleng Autonomous Prefecture (Bazhou), Aksu Prefecture, Kizilsu Kirghiz Autonomous Prefecture (Kezhou), Kashgar Prefecture, and Hotan Prefecture. These seven areas (prefecture-level cities) are under the jurisdiction of 48 counties and cities, accounting for $131.895 \times 10^4\,\text{km}^2$, accounting for about 82.4% of the total area of Xinjiang (Figure 1). High mountains surrounding Southern Xinjiang are the Tianshan Mountains in the north, the Kunlun Mountains and the Altun Mountains in the south, the Pamir Plateau in the west, and Gansu in the east. The Tarim Basin is located in the middle of the south, with the famous Taklimakan Desert in the basin [24, 25]. The whole region is composed of mountains, plains, and deserts. Light and heat are sufficient, and evaporation is much larger than precipitation in an arid continental climate. The terrain structure and geographical position make the Southern Xinjiang vegetation coverage rate low, and the ecosystem is fragile. Once the gale weather occurs, the environment to its containment gets poorer, the environment deteriorates further, and the sandstorm caused by strong wind often causes severe losses to the fruit, cotton, and grain in Southern Xinjiang.

2.2. Literature Review. The literature review mainly highlights the time period, method, study region, research purpose, and significant findings of the study most related to wind loss analysis, as listed in Table 1, including studies [26–38] as follows.

2.3. Data. According to the gale disaster information recorded by the Civil Affairs Department of Xinjiang Uygur Autonomous Region, this paper sorts out 1399 gale disaster events in 48 counties in Southern Xinjiang from 1980 to 2019, including occurrence time (year and month), occurrence area (county and city), and six disaster factors. The six disaster elements of gale disaster events are the death toll (persons), the number of collapsed houses (rooms), the number of collapsed sheds (seats), the number of damaged sheds (seats), the number of dead livestock (heads), and the area of affected cropland (hm^2). If a gale disaster occurs once in a county, the number of gale disasters is recorded as 1.

2.4. Construction Method of Loss Index of Gale Disaster Events. When the six disaster factors describe a certain gale disaster event, they cannot be added directly due to their different units, so they cannot be used to compare the intensity of different gale hazard events directly. In order to compare the strength of each gale disaster event, it is necessary to construct a disaster loss index that can comprehensively express six disaster factors (Z_i). The authors use the dimensionless linear summation method to construct Z_i and consider the weight of six disaster factors in the construction.

Take each disaster element to contain N samples so that the data set composed of six disaster elements can be represented by the matrix $X_{N\times 6}$. Then the calculation formula of each gale disaster event (Z_i) is

$$A_j = \frac{\sum_{i=1}^{N}\left(X_{ij}/X_{j\text{Max}}\right)}{\sum_{i=1}^{N}\sum_{j-1}^{6}\left(X_{ij}/X_{j\text{Max}}\right)},$$
$$Z_i = \sum_{j=1}^{6} A_j \frac{X_{ij}}{\overline{X}_j}. \quad (1)$$

The above formula $i = 1, 2, \ldots, N$, N represents the total storm events ($N = 1399$). $j = 1, 2, \ldots, 6$, A_j represents the weight coefficient of the j-th disaster element, $\overline{X}_j$ and X_{iMax}, respectively, represent the average and maximum value of the j-th disaster element. $(X_{ij}/\overline{X}_i)$ and (X_{ij}/X_{iMax}) indicate that two schemes are used for the dimensionless processing of the data. When determining A_j and Z_i, the maximum and average dimensionless schemes are both used to ensure

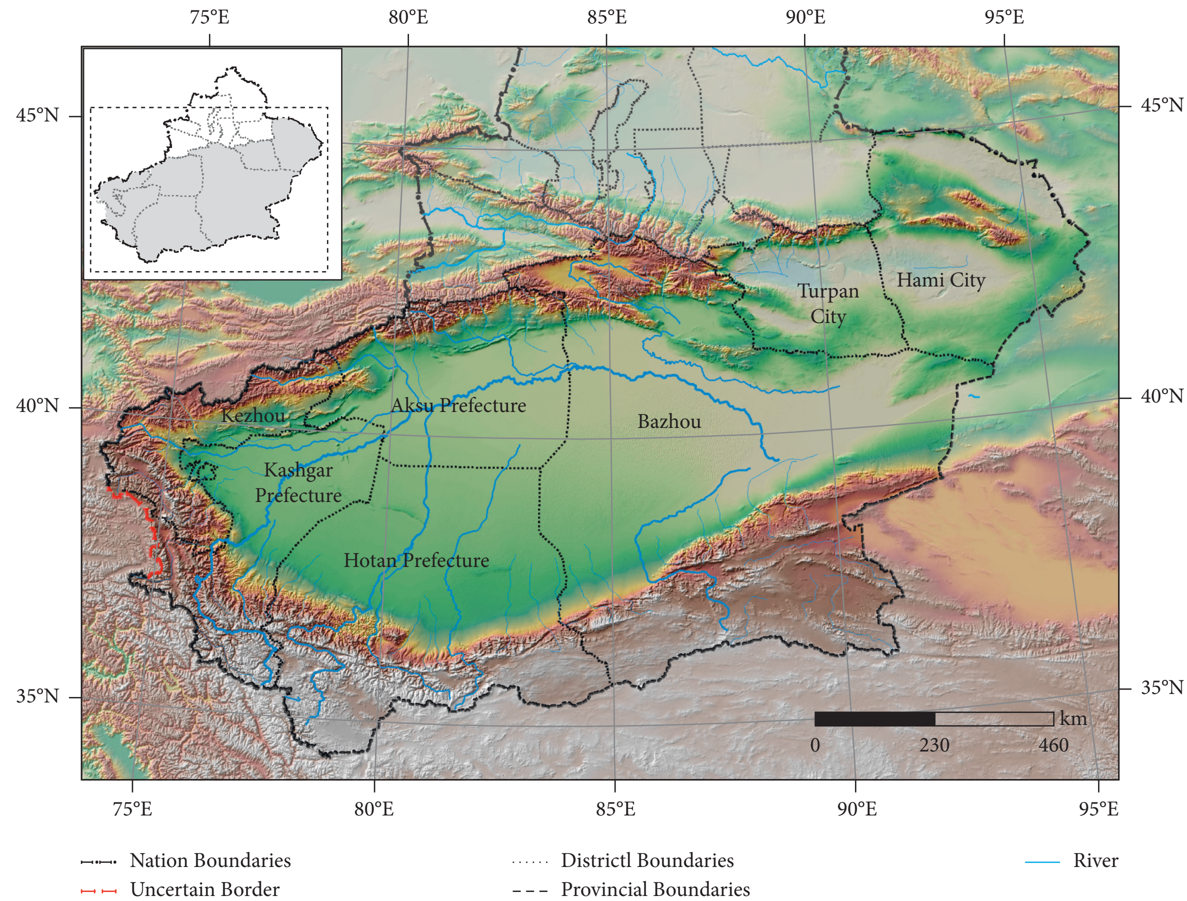


Figure 1: Topography and administrative division of the study region.

Table 1: Overview of the most related to gale/wind loss analysis.

Authors	Time period	Method	Study region	Purpose/aim	Major findings
Baredo [26]	1970–2008	Normalization is used to account for changes in the socioeconomic factors	Across 29 European countries	To put windstorm kyrill into a historical context by examining large historical windstorm event losses	No trend in the normalized windstorm losses Increasing disaster losses are driven by societal factors and increasing exposure
Xiao et al. [27]	1949–2009	Developed a Tropical Cyclone Potential Impact Index (TCPI)	China	To assess the regional impact of TCs, analyzed the spatial pattern, trends, and interannual variation of the TCPI	A weak decreasing TCPI trend over the period; quoted the air mass trajectories, disaster information, intensity, duration, and frequency of tropical cyclones and constituted the TCPI
Pinto et al. [28]	1960–2000	Both rank statistics and return periods (RP) are estimated by fitting an extreme value distribution using the peak over threshold method to potential storm losses	"Core Europe," which comprises countries of Western Europe	Quantify possible changes of the associated event-based storm losses	An increased risk of occurrence of windstorm-associated losses, which can be attributed mainly to changes in the meteorological severity of the events

Table 1: Continued.

Authors	Time period	Method	Study region	Purpose/aim	Major findings
Lou et al. [29]	1970–2008	The principal component as the input of a BP neural network model	Zhejiang Province, China	To establish an assessment model and process disaster-inducing assessment factors, disaster-formative environments and disaster-affected bodies	Loss assessment values of tropical cyclones were higher than the actual losses, but the gap was smaller in severe storms
Li and Fang [30]	1990–2009	Correlation analysis; develop a loss index for rapidly assessing tropical cyclone (TC) disaster loss	China	Effective for rapid damage assessment	Developed a loss index to assess TC disasters rapidly
Cusack [31]	Flushing from 1910 to 1914 and 1995 to 2010 for de Bilt	Storm damage using a model measuring loss impacts upon society	Netherlands	To have a wind speed time series solely reflecting changes in storm strength	A 101-year time-series of storm losses is developed from the near-surface wind speed records at five Dutch stations
Kruger et al. [32]	2004–2014	Application of extreme value distribution, estimation of four factors using the peak-over-threshold method, relative categorization of overall wind hazard	South Africa	To develop strong wind statistics, disaster models for the built environment and estimations of tornado risk, and a general analysis of the strong wind hazard	Identified high hazard areas with strong winds
Chen et al. [33]	2006–2015	Gamma hurdle model (GHM)	Taiwan, China	To assess typhoon damages： return period analysis and loss prediction	Accounted for the combined effect of rainfall and wind by a loss prediction model
Chen et al. [33]	1983–2015	A hazard footprint-based normalization method	China	To improve the spatial resolution of affected areas and the associated exposures to influential tropical cyclones	Contributed to a more realistic estimation of the population and wealth affected by the influential tropical cyclones for the original year and the present scenario
Chen et al. [34]	1993–2009	Comprehensive evaluation by model combination method	Guangdong, China	To predict tropical cyclone (TC) disaster loss	Constructed a more accurate and stable individual model to predict TC disaster loss
Guo and Li [35]	1985–2014	Confirmatory factor analysis	Guangdong, China	Accurately estimate the economic losses inflicted by typhoon storm surge	Impact indicators from various risk factors at different time periods have not changed significantly, while their degree of relevance has varied with each risk factor
Chen et al. [36]	1949–2018	Kernel Density Estimation (KDE) index as the hazard index	Six typical provinces of China	To describe the occurrence probability of hazards; evaluation mapping and result analysis	Master the characteristics and pattern of typhoon activity for typhoon warning and disaster prevention and mitigation
Wang et al. [37]	2009–2020	Inverse distance weighted interpolation technique	Guangdong–Hong Kong–Macau greater bay area (GBA)	To provide scientific support for typhoon disaster prevention and mitigation in the GBA	Constructed the hazard index, vulnerability index, and comprehensive risk index better reflecting the actual losses, verified the spatial correlation between typhoon disaster risk indexes and actual losses

Table 2: The weight, average, and maximum value of disaster elements.

	Death toll (persons)	Collapsed house (room)	Collapsed shed (seat)	Damaged greenhouse (seat)	Livestock deaths (head)	Damaged area of cropland (hm^2)
Weight coefficient	0.14	0.12	0.12	0.13	0.24	0.26
Mean value	0.08	13.14	9.41	87.72	299.43	2919.45
Maximum value	11	2245	1582	14204	25580	230825.5

the rationality of the weights and the discreteness of the disaster loss index of gale disaster events. The average, maximum, and weight coefficients of the six disaster elements calculated from 1399 gale disaster events are listed in Table 2. Among the six disaster factors, the weight coefficient of the livestock deaths and the affected cropland area is larger, and their contributions are more. The other four disaster factors have smaller weight coefficients and relatively small contributions.

2.5. Classification Method of Gale Disaster Events. The percentile method is used to classify the loss index Z_i of gale disaster events. Percentile is a position indicator [39], and P_r represents a percentile to divide all the observed values into two parts. In theory, the observed value of r% is smaller than it, and the observed value of (100-r)% is huger than it. The one-dimensional matrix X is obtained by arranging the sample data from small to large; then the formula of the r-th percentile P_r is as follows:

$$P_r = X_{[d]} + \left(X_{[d+1]}\right)(d - [d]), d = 1 + (N - 1)r\%. \quad (2)$$

In the formula, d represents the bit of percentile P_r, $[d]$ denotes the integer part of d, and $X_{[d]}$ and $X_{[d+1]}$ represent the data on $[d]$ and $[d+1]$, respectively. The thresholds corresponding to the four levels of Z_i are obtained by taking 10%, 25%, and 50% of 100-r (Table 3). According to the threshold range of Z_i. Each gale disaster event can be divided into corresponding levels.

Table 3: Classification standard of gale disaster events.

Percentile r (%)	Loss index (Z_i)	Level of Z_i
$r \leq 50.0$	$Z_i \leq 0.21552$	Mild (level I)
$50.1 \leq r \leq 75.0$	$0.21553 \leq Z_i \leq 0.69402$	Moderate (level II)
$75.1 \leq r \leq 90.0$	$0.69403 \leq \leq 2.05797$	Severe (level III)
$r \geq 90.1$	$Z_i \geq 2.05798$	Very severe (level IV)

3. Results and Analysis

3.1. Spatial Distribution of Gale Disaster. By dividing the cumulative disaster occurrence times of counties and cities in a certain region by the number of years and counties and cities, the average annual occurrence times in the region are obtained. Similarly, the average annual disaster loss index of a region is obtained by dividing the cumulative disaster loss index by the number of years and the number of counties and cities. The average annual occurrence times of Hami, Turpan, Bazhou, Aksu, Kashgar, Kezhou, and Hotan were 0.6, 1.5, 0.6, 0.9, 0.7, 0.3, and 0.6, respectively. The average annual occurrence times of Turpan were the highest, followed by Aksu (Figure 2(a)). The average annual disaster loss indexes of the seven regions were 0.35, 1.72, 0.52, 1.26, 0.40, 0.53, and 0.73, respectively. The average annual disaster loss index of Turpan was the largest, followed by that of Aksu (Figure 2(b)). It can be seen that the frequent and severe disaster areas are concentrated in Turpan and Aksu. The counties and cities with the largest and most frequent occurrences of gale disasters in Southern Xinjiang are Tokson County and Aksu City, respectively, and the average annual occurrences are 2.1 and 1.7 times, respectively. Gaochang District (3.28) and Shaya County (2.14) have the largest and second-largest average annual disaster loss index, respectively. The top two average single gale disaster intensities were Wushi County and Wuqia County, and the average single gale disaster indexes were 6.61 and 4.63, respectively.

3.2. Annual Changes in Gale Disasters. The gale disaster in Southern Xinjiang occurred most in spring (March–May), accounting for 80.1% of the annual occurrence. Summer (June–August) occurred more frequently, accounting for 15.3% of the annual occurrences. In autumn (September–November) and winter (December–February of the following year), the occurrences were relatively small, accounting for 2.4% and 2.1% of the annual occurrences, respectively. The number of occurrences of levels I to IV gale disasters showed a single peak distribution during the year, with the highest in April and the second in May (Figure 3(a)). The percentages of the total number of occurrences in April and May of the level I to IV gale disasters in the total number of occurrences in the year are 70%, 76%, 81%, and 83%, respectively. It can be seen that the levels I to IV gale disasters are concentrated in April and May in spring. Similarly, the average disaster index also showed a single peak distribution, the largest in April, followed by May (Figure 3(b)). The intensity of monthly gale disasters in the year is determined by level IV. Overall, gale disasters in Southern Xinjiang occur frequently from April to May in spring, and the disaster is severe. The level IV gale disasters determine the intensity of gale disasters.

3.3. Interannual Changes in Gale Disasters. The number of gale disasters in a certain year in Southern Xinjiang is the total number of gale disasters in 48 counties and cities in that year, and the annual disaster loss index is the total value of the annual disaster loss index of 48 counties and cities.

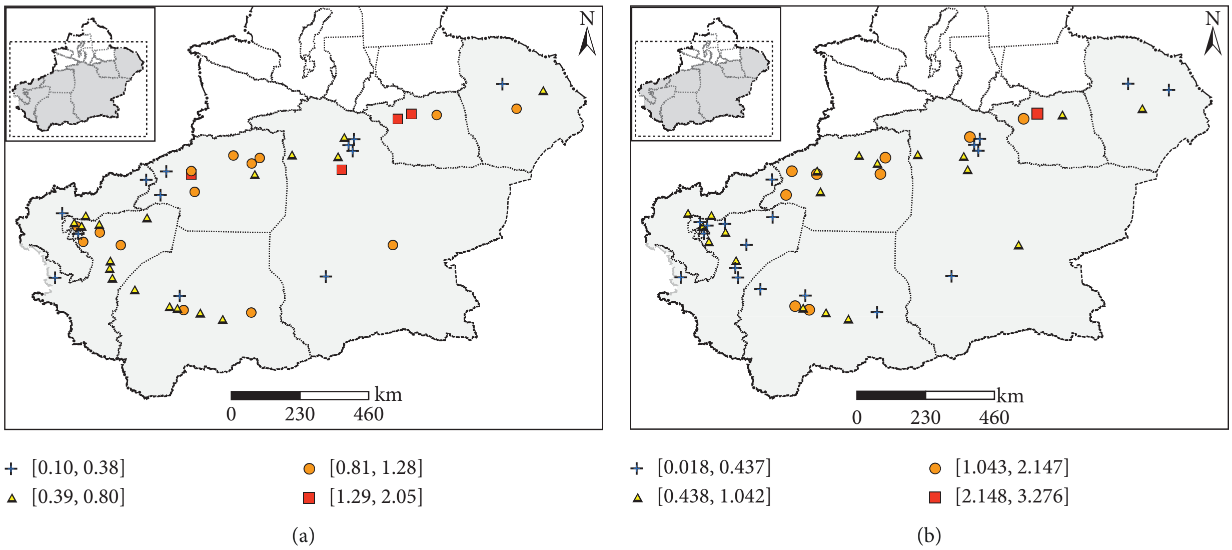


FIGURE 2: Spatial distribution of the average annual occurrence frequency and average annual disaster loss index of gale disasters in Southern Xinjiang. (a) Average annual occurrence times and (b) average annual disaster loss index.

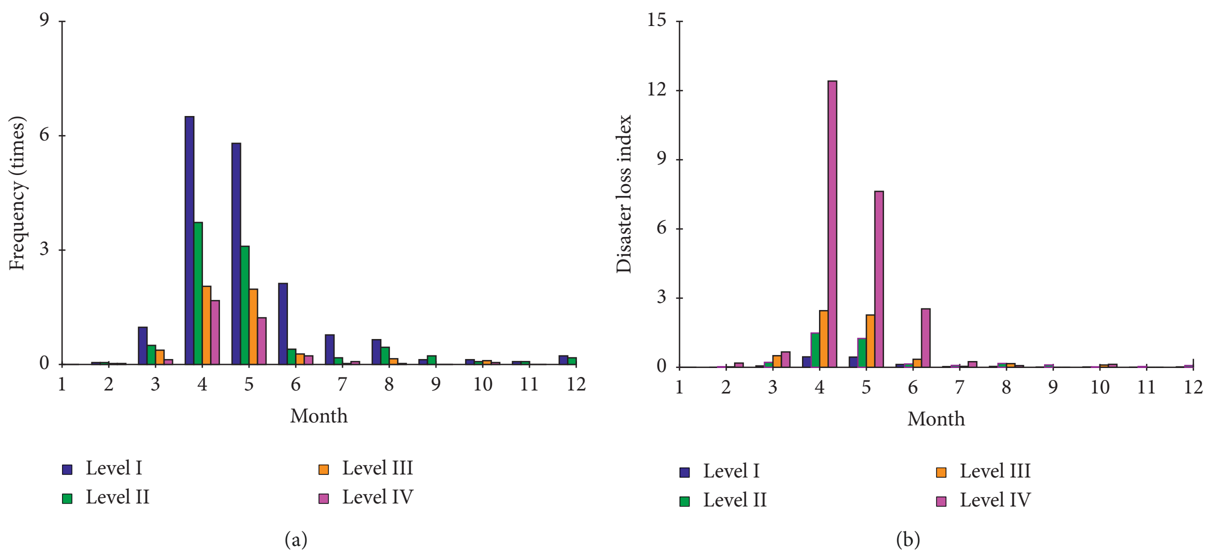


FIGURE 3: Annual variation of the average occurrence times and the average loss index of the level I to IV gale disasters in Southern Xinjiang. (a) Average occurrence times and (b) average loss index.

During the 40 years from 1980 to 2019, the number of gale disasters in Southern Xinjiang showed a significant linear growth trend, increasing by 11.9 times every ten years, and the reliability level exceeded 0.001 (Figure 4(a)). However, the annual disaster loss index (Z_y) fluctuates around the climate average of 35.0. In the strongest disaster year in 1986, the annual disaster loss index reached 283.3. In 1999, the annual disaster loss index reached 161.9 (Figure 4(b)). Therefore, the frequency of gale disasters in Southern Xinjiang increased year by year, but the intensity of gale disasters did not change.

3.4. Individual Characteristics of Levels I to IV Gale Disasters. Figures 5(a), 5(d), 5(g), and 5(j) show the average annual occurrences of gale disasters of levels I to IV. The top two regions in the average annual number of occurrences are Turpan and Aksu (level I), Kashgar and Aksu (level II), Turpan and Hotan (level III), and Turpan and Aksu (level IV). The top two counties and cities in the average annual number of occurrences are Toxon County and Yuli County (level I), Aksu City and Yuepu Lake County (level II), Gaochang District and Yingjisha County (level III), and Gaochang District and Luopu County (level IV).

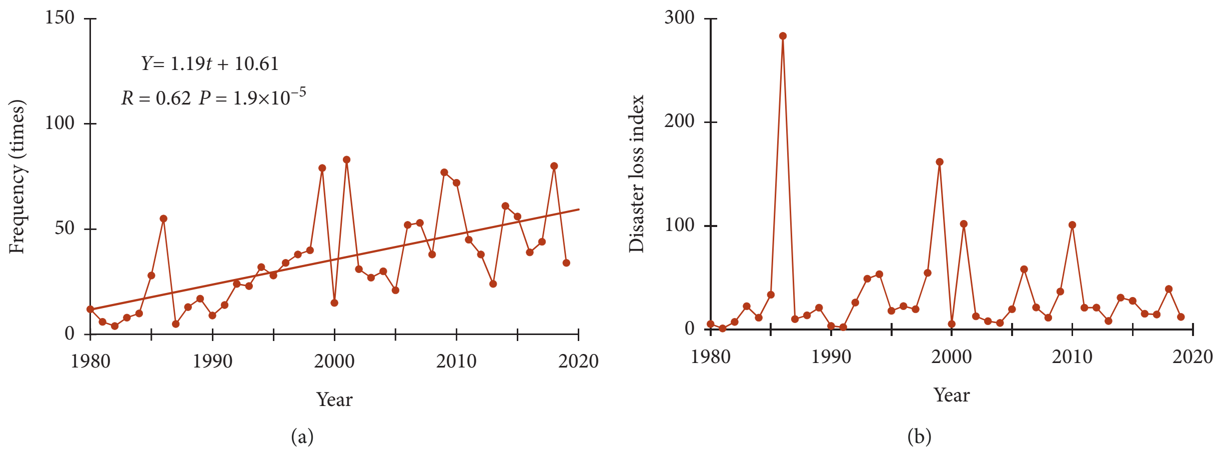
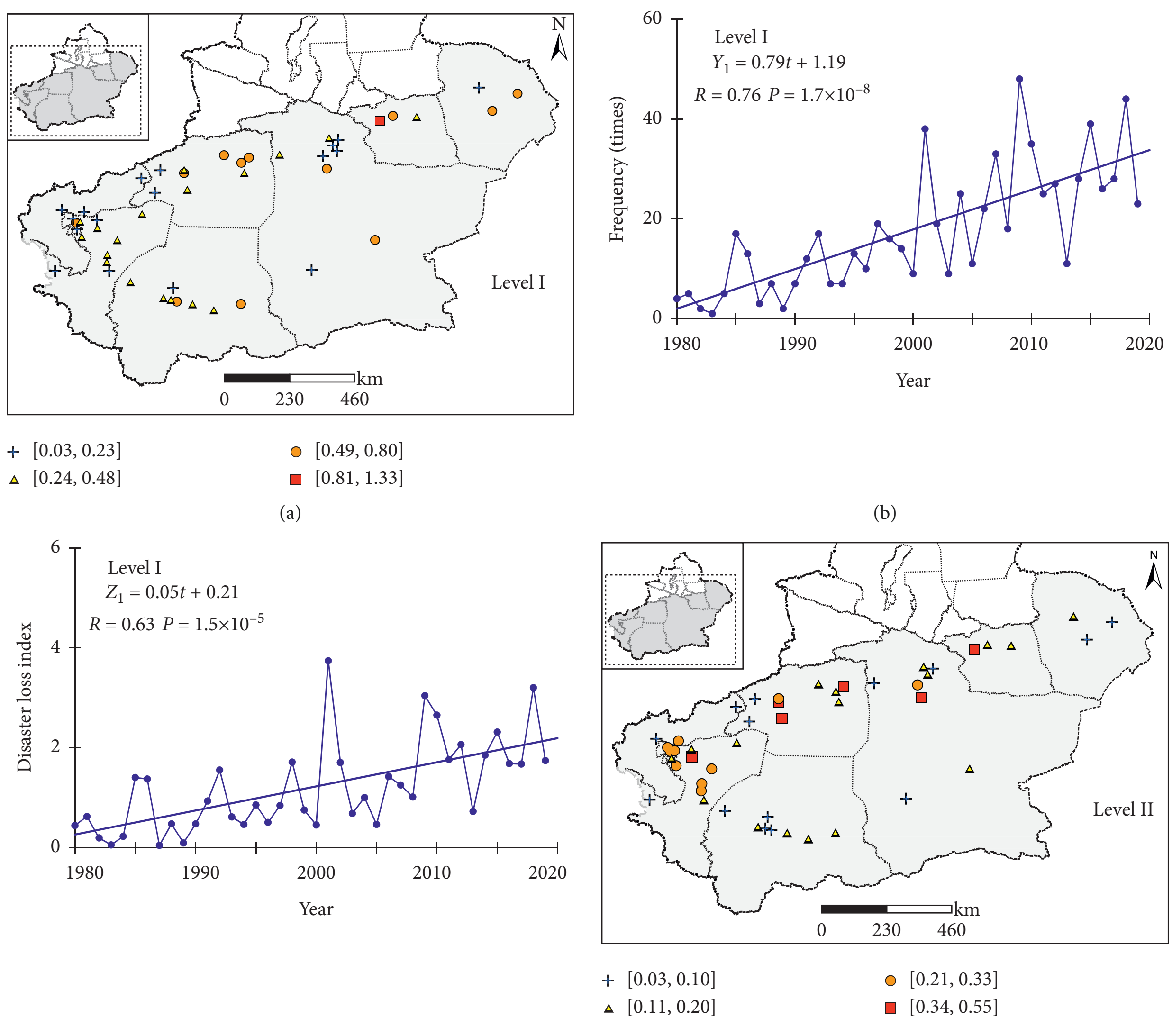


Figure 4: Interannual changes in the annual occurrence times of gale disasters and the annual loss index in Southern Xinjiang. (a) Annual occurrence times and (b) annual disaster loss index. Note: R indicates the correlation coefficient, P Indicates the level of reliability, and the straight line indicates a linear trend.



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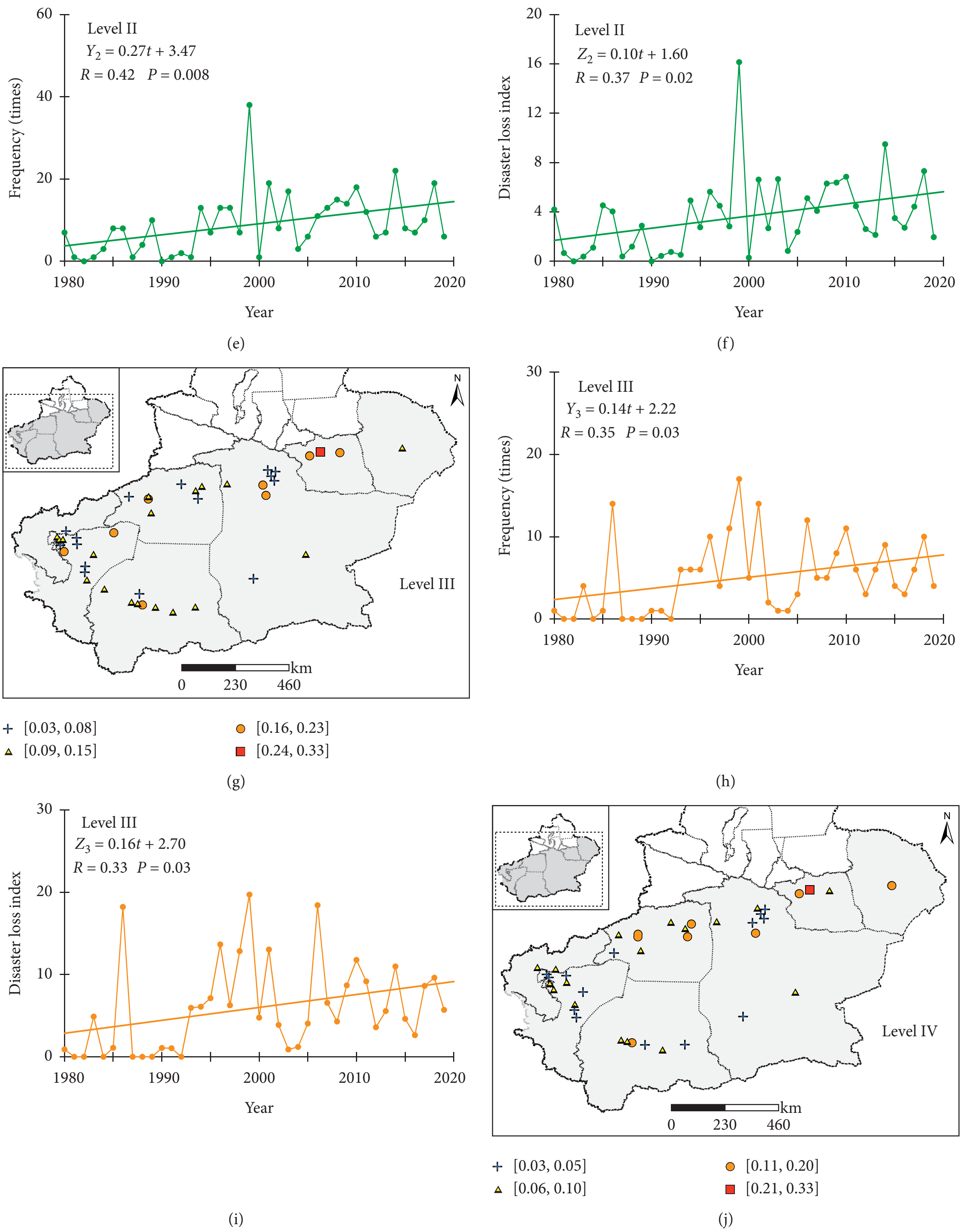

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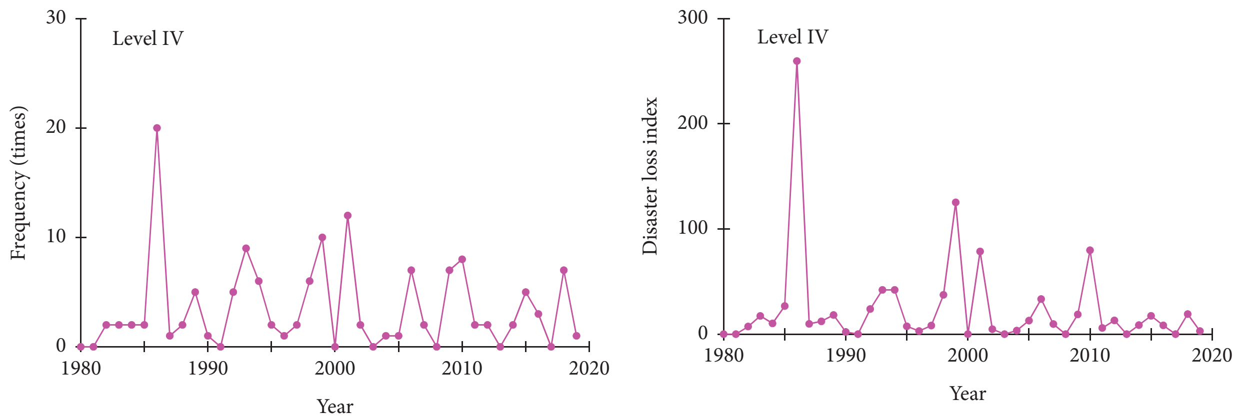

(k) (l)

Figure 5: Spatial-temporal distribution of level I to IV gale disasters (a, d, g, j) spatial distribution of the annual average number of occurrences of level I–IV gale disasters, respectively; (b, e, h, k) interannual variation of occurrence times of level I to IV gale disasters, respectively; (c, f, i, l) interannual changes in the annual disaster loss index of level I to IV gale disasters, respectively.

Figures 5(b), 5(e), 5(h), and 5(k) show the interannual variation of occurrence times of the level I to IV gale disasters in Southern Xinjiang. It can be seen from the figure that the occurrence times of level I to III storm years showed a significant linear growth trend, and its significant level exceeded the reliability level of 0.05. The occurrence times of level I to III gale disasters increased 7.9, 2.7 and 1.4 times per 10 years, respectively. However, the occurrence times of level IV disaster years fluctuate around the climate average of 3.5 times.

Assuming that the 40-year average of the occurrence times Y_i of the level I to IV gale disasters is $\overline{Y}_i$ (i take 1 to 4, respectively, representing the level I to IV gale disasters), let $\overline{Y} = \sum_{i=1}^{4} \overline{Y}_i$, then the contribution rate of the occurrence times (Y) of the level I to IV gale disasters to the occurrence times (Y) of the Southern Xinjiang gale disasters is defined as ($G_i = 100\overline{Y}_i/\overline{Y}$). In the following, the calculation method of the contribution rate of the annual disaster loss index of the level I to IV to the annual disaster loss index of Southern Xinjiang is similar. According to the calculation, the contribution rates of the occurrence times of the level I to IV gale disasters to the occurrence times of gale disasters in Southern Xinjiang are 50%, 25.7%, 14.3%, and 10%; it can be seen that the total contribution rate of level I to III gale disasters reaches 90%. Therefore, with the linear increase of the number of gale disasters of levels I to III, the number of gale disasters in Southern Xinjiang increased yearly.

Figures 5(c), 5(f), 5(i), and 5(l) show the interannual variation of the annual loss index of gale disasters with levels I to IV. It can be seen from the figure that the annual disaster loss indexes of levels I to III show a significant linear increase trend, and their significant level exceeds the reliability level of 0.05. The annual disaster loss index of levels I to III increases by 0.5, 1.0, and 1.6 per 10 years, respectively, but the annual disaster loss index of level IV fluctuates around the average climate of 24.2. Similar to the above calculation, the contribution rates of the annual disaster loss index of level I to IV to the annual disaster loss index of Southern Xinjiang are 3.4%, 10.3%, 16.9%, and 69.3%, respectively, which shows that the contribution rate of level IV is the main component. Therefore, the annual disaster loss index of levels I to III increases yearly, and the climate fluctuation of level IV determines that the annual disaster loss index of gale disasters in Southern Xinjiang also shows climate fluctuation.

Based on the above analysis, it is found that the occurrence times of gale disasters in Southern Xinjiang increase year by year. Among them, the occurrence times of general to severe (level I to III) gale disasters increase year by year, but the occurrence times of great gale disasters (level IV) fluctuate around the average climate. The intensity of gale disaster events in Southern Xinjiang fluctuates yearly around the average climate. Among them, the intensity of general to severe (level I to III) gale disaster events increases yearly, while the intensity of special gale disaster events (level IV) fluctuates around the average climate year by year.

4. Conclusions

In geographical distribution, the region with the largest number of gale disasters and the largest average annual loss index is Turpan, followed by Aksu, indicating that the most frequent and hardest-hit areas of gale disasters in Southern Xinjiang are concentrated in Turpan and Aksu. The most frequent average annual occurrences of gale disasters region lay in Tokson County, followed by Aksu City. And the top two average annual loss indexes were Gaochang District and Shaya County, respectively.

Regarding seasonal distribution, the occurrence of gale disasters in spring (March-May) in Southern Xinjiang is the most, accounting for 80% of the annual occurrence, and it is concentrated in April and May. The average occurrence frequency and average disaster loss index of gale disasters levels I to IV show unimodal distribution. In April, it not only occurs most but also has the most vigorous intensity.

In the long-term trend, the number of gale disasters in Southern Xinjiang showed a significant linear growth trend, increasing 11.9 times every ten years. Among them, the occurrence times of level I to level III storm years showed a significant linear growth trend, increasing 7.9, 2.7, and 1.4 times per 10 years, respectively. The occurrence times of level IV storm years did not show a rising and falling trend. The annual disaster loss index of gale disasters in Southern Xinjiang did not show a rising and falling trend. Among them, the annual disaster loss index of level I to level III showed a linear growth trend, increasing by 0.5, 1.0, and 1.6 per 10 years, respectively, but the annual disaster loss index of level IV did not show a rising and falling trend.

In this paper, we have constructed a disaster loss index in the long-term database from 1980 to 2019 and obtained the spatiotemporal distribution characteristic of the different levels of gale disaster. Ranking the high-risk and most frequently occurring areas is conducive to policy formulation and hierarchical management of gale disaster prevention and control. Further work, including causes of disasters and effectiveness of disaster management, is required.

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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