Analysis of Spatial Patterns and Interannual Variation Characteristics of Snow Disasters in Xinjiang (Postprint)

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Date: 2021-01-26T00:00:00+00:00

Abstract

Utilizing data from seven disaster elements of snow disaster events in Xinjiang from 1961 to 2018 (occurrence frequency, number of deaths, number of collapsed houses, number of collapsed sheds, number of collapsed greenhouses, number of livestock deaths, and affected area), a snow disaster loss index was constructed using the ratio weighting method and dimensionless linear summation method. The snow disaster loss index is significantly correlated with the seven disaster elements, and its magnitude can represent the severity of snow disaster losses. Based on the Gamma distribution of the loss index, the hazard level of snow disasters is divided into four grades: general, relatively severe, severe, and extremely severe. The results indicate that snow disasters in Xinjiang occur more frequently in Northern Xinjiang than in Southern Xinjiang, are mainly distributed in agricultural and pastoral areas, and primarily occur from November to April of the following year. Extremely severe snow disasters appeared in the Ili River Valley, Altay City, Toli County, Artux City, Bayinbuluke, and Barkol County. The interannual variability of snow disasters in Xinjiang has intensified, and the annual disaster loss index (snow disaster intensity) exhibits a linear increasing trend; extremely severe snow disasters occurred in 1985, 1990, 2001, 2006, 2008, and 2010. Among the five climatic elements of wind speed, temperature, water vapor pressure, snowfall, and snow depth, the main climatic influencing factors for the interannual variation of snow disasters in Xinjiang during the concentrated period from November to April of the following year are snowfall and average snow depth. Overall, snow disasters in Xinjiang show obvious spatial heterogeneity, with interannual variations demonstrating an intensifying trend.

Full Text

Preamble

Arid Zone Research, ChinaXiv Partner Journal, Vol. 37 No. 6, Nov. 2020

Spatial Pattern and Interannual Variation Characteristics of Snow Disasters in Xinjiang

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Abstract: Based on seven disaster elements from snow disaster events in Xinjiang from 1961 to 2018—frequency, deaths, collapsed houses, collapsed sheds, collapsed greenhouses, livestock deaths, and affected area—this study constructed a snow disaster damage index using the ratio weighting method and dimensionless linear summation. The damage index showed significant correlation with all seven disaster elements, and its magnitude could represent the severity of snow disaster damage. According to the gamma distribution of the damage index, snow disaster severity was classified into four grades: mild, moderate, severe, and extra severe. The results indicate that snow disasters in Xinjiang occur more frequently in northern Xinjiang than in southern Xinjiang, are mainly distributed in agricultural and pastoral areas, and primarily occur from November to April of the following year. Extra severe snow disasters appear in the Ili River Valley, Altay City, Toli County, Artux City, Bayinbuluk, and Barkol County. The interannual variability of snow disasters in Xinjiang has intensified, with the annual damage index (snow disaster intensity) showing a linear increasing trend. Extra severe snow disasters occurred in 1985, 1990, 2001, 2006, 2008, and 2010. Among the five climatic factors—wind speed, temperature, vapor pressure, snowfall, and snow depth—the main climatic factors affecting the interannual variation of snow disasters during the concentrated period from November to April are snowfall and average snow depth. Overall, snow disasters in Xinjiang show obvious spatial differences and an intensifying interannual trend.

Keywords: snow disaster; disaster loss index; spatial pattern; interannual variation; climate factor; Xinjiang

Snow disaster is a major natural disaster caused by concentrated snowfall in winter and spring that forms large-area persistent snow cover, severely impacting transportation, power supply, communications, and agriculture and animal husbandry. Xinjiang, Inner Mongolia, Qinghai, and Tibet are regions in China with severe snow disasters, which cause serious harm to local economic and social development. For example, when snow depth exceeds 30 cm in plains and 50 cm in mountainous areas of the Xinjiang Tacheng region, heavy snow blocks transportation and causes forage shortages, leading to livestock starvation, freezing, and burial, with mortality rates reaching as high as 8.0×10^{-3}.

In recent decades, under a background of warming and humidification, all seasonal precipitation in Xinjiang has increased, particularly winter snowfall in northern Xinjiang. Consequently, snow disaster events have increased, and snow disaster analysis and assessment have become research priorities. Snow disaster severity is closely related to snow cover area, snow depth, snowfall days, and intensity. Domestic researchers have conducted relevant studies: Hu Liequn et al. studied the spatiotemporal distribution characteristics of Xinjiang meteorological snow disasters from 1960-2014 using snow depth data from 105 stations; Dong Wenjie et al. analyzed the climatic characteristics of snow disasters in the eastern Qinghai-Tibet Plateau pastoral areas using snow cover area, snow depth, snow days, and affected area; Han Shaoshuai et al. constructed a comprehensive snow disaster risk evaluation model for Northeast China using multi-source data including meteorology, topography, socioeconomics, and historical snow disasters; Meng Wanzhong et al. analyzed the grade, spatiotemporal variation characteristics, periodic patterns of snow disasters in Inner Mongolia from 1912-2016 and their relationship with ENSO events; Guo Xiaoning et al. studied the spatiotemporal distribution and variation characteristics of snow disasters on the Qinghai Plateau from 1961-2008 using county-level snow disaster records and meteorological statistics; Xu Jianhui et al. examined the spatiotemporal autocorrelation of snow disasters in Xinjiang from 2000-2010; Li Yabin et al. classified snow disaster intensity in Heilongjiang Province and established a pre-assessment method; Han Xiujun et al. calculated meteorological disaster loss values for cities and counties in Liaoning Province based on economic losses, frequency, and average disaster intensity for zoning; Ma Xiaofang et al. conducted comprehensive risk assessment of snow disasters in Qinghai Province using socioeconomic, natural, and meteorological factors; Sui Qi et al. proposed a traffic risk assessment method combining multi-source information.

These research achievements represent accumulated experience from different sectors including meteorology, agriculture, animal husbandry, civil affairs, and transportation, with varying analysis content, methods, and focuses. Currently, there is no complete unified quantitative analysis and evaluation standard in China. The seven disaster elements—snow disaster frequency, deaths, collapsed houses, collapsed sheds, collapsed greenhouses, livestock deaths, and affected area—are all documented in detail in snow disaster reports, describing disaster impact from different perspectives, yet few studies have used these seven elements quantitatively to assess snow disaster severity.

This study first selected these seven disaster elements and used ratio weighting and dimensionless calculation methods to construct a comprehensive damage index expressing the severity of all seven elements. By calculating correlations between the damage index and each disaster element, the rationality of the index construction was verified. Second, through statistical testing of the damage index distribution function, objective quantitative severity grading was performed based on probability, allowing discussion of spatial patterns and interannual variation trends of snow disasters in Xinjiang. Finally, temperature, vapor pressure, wind speed, snowfall, and snow depth were selected to explore climatic factors influencing interannual snow disaster variation.

1.1 Study Area Overview

Xinjiang' s topography features a "three mountains surrounding two basins" pattern. The Altai Mountains stand in the north, the Kunlun Mountains in the south, and the Tianshan Mountains traverse the center, dividing Xinjiang into northern and southern parts—the Junggar Basin in the north and the Tarim Basin in the south. The area south of the Tianshan Mountains is southern Xinjiang, while north of the Tianshan is northern Xinjiang. Xinjiang has a typical temperate continental arid climate, with an average annual temperature of 10.4°C and average annual precipitation of 188 mm. In winter (December-February), the average temperature is -5.0°C, with long, cold winters. The Altai region, Tacheng region, and areas along the Tianshan Mountains in northern Xinjiang have relatively low average temperatures. Average snowfall is 32.6 mm, with greater snowfall in the Altai region, Tacheng region, and Ili River Valley. Average snow depth is 5.0 cm, with thicker snow in the Altai region, Tacheng region, and Ili River Valley. Alpine areas have both heavy snowfall and thick snow accumulation. The interaction between eastward-moving weather systems and this special topography makes Xinjiang one of China' s most snow disaster-prone regions.

1.2 Data Sources

Based on snow disaster records from the "China Meteorological Disaster Canon: Xinjiang Volume" and snow disaster information documented by the Xinjiang Uygur Autonomous Region Civil Affairs Department from 1961-2018, we compiled data for 89 counties (cities) in Xinjiang, including occurrence time (year/month/day), affected area (county/city), deaths (persons), collapsed houses (rooms), collapsed sheds (units), collapsed greenhouses (units), livestock deaths (heads), and affected area (hm^2). If a snow disaster occurred in a county (city) region on a given day, it was counted as one snow disaster event. For analysis of climate factors affecting interannual snow disaster variation, we selected 105 representative meteorological stations with complete data in Xinjiang from 1961-2018. For each station, we analyzed the concentrated snow disaster period from November to April, including average temperature (T, °C), average wind speed (V, $m \cdot s^{-1}$), average vapor pressure (e, hPa), cumulative snowfall (RR, mm), and average snow depth (h, cm) to explore climatic influences on interannual variation.

1.3 Research Methods

Since seven disaster elements express snow disaster severity, to facilitate comparison of snow disaster intensity across counties and years, we constructed a comprehensive snow disaster damage index (Zi) using ratio weighting and dimensionless linear summation. First, weights for each disaster element were determined by the ratio method, then dimensionless linear summation was applied to obtain Zi. For the seven disaster elements, each consisting of n samples, the data could be represented by matrix X. The calculation method for Zi is given by formula (1):

$$Z_i = \sum_{j=1}^{7} a_j \frac{X_{ij}}{\bar{X}_j}$$

where i represents the sample length, j represents the disaster element. aj and X̄j represent the weight and average value of the j-th disaster element, respectively. The weight aj is calculated by formula (2):

$$a_j = \frac{X_{ja}}{\sum_{j=1}^{7} X_{ja}}$$

where Xja is the maximum value of the j-th disaster element, and Σj Xja represents the sum of dimensionless values for all seven disaster elements.

To analyze spatial distribution characteristics and interannual variation of snow disasters, formula (1) was used to calculate county-level and annual disaster damage indices. When calculating the county index, n = 89, representing the 89 counties in Xinjiang that experienced snow disasters, with X being the cumulative values of each disaster element for each county. When calculating the annual index, n = 58 (years), with X being the cumulative values of each disaster element for each year.

1.4 Determination of Damage Index and Grade Thresholds

Using cumulative values of each disaster element for all 89 counties from 1961-2018 and annual cumulative values, formula (2) calculated weights for the seven disaster elements, and formula (1) yielded county-level damage indices (Zs) and annual damage indices (Zk). Correlation coefficients between Zs and the seven disaster elements ranged from 0.71 to 0.98, and between Zk and the elements from 0.74 to 0.95, with confidence levels $\alpha < 0.001$ for all coefficients. This indicates that Zs and Zk are significantly correlated with all seven disaster elements, demonstrating that the damage index can comprehensively reflect snow disaster intensity and its variation.

To classify snow disaster severity grades for counties and years, we first determined the probability density function of the damage index using histogram and hypothesis testing methods, then established thresholds for different grades based on probability density. Using sample sequences of county and annual damage indices, we applied the graphical method for probability density distribution with group numbers determined by small-sample grouping rules. The histograms (Fig. 1) showed the damage index approximately follows a gamma distribution. Calculated mean = 0.99 and variance $\sigma^2 = 0.73$ for county indices, and = 1.37 and $\sigma^2 = 0.73$ for annual indices.

Using the relationship between gamma distribution parameters, we calculated shape parameter $\alpha = 1.37$ and scale parameter $\beta = 0.73$ for counties, and $\alpha = 1.89$ and $\beta = 0.73$ for years. Following the testing method in reference [25], we calculated test statistic V = 4.64 for counties and V = 4.64 for years. At significance level $\alpha = 0.05$, the critical value from the ^{2} distribution table is $\lambda = 14.07$. Since V $< \lambda$ for both, the damage index probability distribution is confirmed as gamma distribution, expressed as:

$$f(Z) = \frac{1}{\beta^\alpha \Gamma(\alpha)} Z^{\alpha-1} e^{-Z/\beta}$$

where Z represents the damage index (Zs for counties, Zk for years), α is the shape parameter, β is the scale parameter, and $\Gamma(\alpha)$ is the gamma function: $\Gamma(\alpha) =$ $_0$^∞ t^{α-1} e^{-t} dt.

From the gamma distribution function, we calculated quantile thresholds Zp for county and annual damage indices. Based on different Zp values, samples were divided into four severity grades: mild, moderate, severe, and extra severe (Table 2). This distribution-based grading method overcomes subjectivity in manual classification, making the grading objective and reasonable. The key to grading is determining the distribution function, and the probability values selected in grading conform to statistical principles [26].

2.1 Spatial Distribution Characteristics of Snow Disasters in Xinjiang

The spatial distribution of county damage indices shows obvious spatial differences in Xinjiang snow disasters (Fig. 2), with more disasters in northern than southern Xinjiang and more in western than eastern regions. High-value areas are concentrated in northern and northwestern Xinjiang and western southern Xinjiang pastoral areas, while low-value areas are mainly in oasis plains: Bortala-Mongolia Autonomous Prefecture-Shihezi City-Changji Hui Autonomous Prefecture, Aksu Prefecture-Bayin' gholin Mongol Autonomous Prefecture, and the Turpan Basin.

According to the classification standards, there are 37 counties with mild grade, 28 with moderate, 18 with severe, and 6 with extra severe snow disasters, accounting for 41.6%, 31.5%, 20.2%, and 6.7% respectively. Extra severe snow disasters are distributed in Nilka County, Xinyuan County, Yining County, Huocheng County, Altay City, Toli County, Bayinbuluk, Artux City, and Barkol

County (Fig. 2). Notably, the four counties with extra severe snow disasters in the Ili River Valley (Nilka, Xinyuan, Yining, and Huocheng) form a contiguous area, as do the three counties/cities with severe or higher grades in Altay Prefecture (Altay City, Fuyun County, and Qinghe County). Similarly, the four counties/prefectures with severe or higher grades in Kizilsu Kirgiz Autonomous Prefecture (Artux City, Akqi County, Wuqia County, and Akto County) also form a contiguous area. Areas with moderate or higher grades correspond to regions with relatively heavy snowfall and thick snow depth [14].

The average damage index for the 89 counties is 0.77, with significant differences among prefectures. The top five prefectures/cities by average damage index are: Kizilsu Kirgiz Autonomous Prefecture (1.38), Ili Prefecture (1.27), Altay Prefecture (1.16), Tacheng Prefecture (0.96), Urumqi City (0.91), and Hami City (0.77).

2.2.1 Seasonal Distribution of Snow Disasters

Snow disasters in Xinjiang occur in all four seasons, most frequently in winter (46.5%), followed by spring (39.5%), less in autumn (10.8%), and rarely in summer (3.2%). Snow disasters mainly occur from November to April, accounting for 89% of annual events. The peak period is February-March (38% of annual events), which is late winter to early spring, differing significantly from the peak in March-April on the eastern Qinghai-Tibet Plateau [7]. This seasonal distribution is closely related to large cumulative snow amounts and thick snow depth in late winter to early spring, as well as livestock transition, lambing and nursing, poor body condition, and forage difficulties in pastoral areas. Therefore, forecasting and early warning for late winter and early spring snowfall processes should be strengthened to prepare for disaster prevention and mitigation.

2.2.2 Interannual Variation and Climatic Causes

The magnitude of the annual damage index (Zk) indicates snow disaster severity in a given year. From 1961-2018, the annual damage index shows a significant linear increasing trend, rising by 0.25 per decade, indicating intensifying snow disasters in Xinjiang. In terms of frequency, there are 18 years with moderate or higher grade snow disasters, showing that over the past 58 years, years with moderate or higher severity have gradually increased. Extra severe snow disasters occurred in 1985, 1990, 2001, 2006, 2008, and 2010, demonstrating significantly increased frequency of extra severe events in the 21st century. Both the linear trend and grade frequency indicate an increasing trend in Xinjiang snow disasters.

Previous studies show snow disasters depend mainly on snowfall, temperature, and snow depth, and are somewhat related to wind speed, while snowfall is also related to atmospheric water content (vapor pressure) [27]. Therefore, this study selected average temperature (T), average vapor pressure (e), average wind speed (V), cumulative snowfall (RR), and average snow depth (h) from

November to April for 105 meteorological stations across Xinjiang from 1961-2018. These were averaged to obtain annual sample sequences of the five climatic elements for analysis with the annual damage index.

As shown in Fig. 4, average wind speed first decreased then increased, with a sudden change in 1997. This pattern is inconsistent with the linear increasing trend of the annual damage index. Average temperature shows a linear increasing trend (Fig. 4b), which is not a factor for snow disaster intensification. Although rising temperatures increase atmospheric water content, causing vapor pressure to increase linearly (Fig. 4c), the temperature increase remains within -0.5°C, not causing stable winter snow to melt but rather increasing vapor pressure, which further facilitates increased snowfall. Both cumulative snowfall and average snow depth show linear increasing trends (Fig. 4d, 4e), corresponding well with the linear increase in the annual damage index.

Correlation analysis between climatic elements and the annual damage index quantifies climatic influences. Correlation coefficients between cumulative snowfall (RR), average snow depth (h), average temperature (T), average vapor pressure (e) and the annual damage index (Zk) are 0.74, 0.75, 0.21, and 0.55 respectively (significance level $\alpha = 0.001$). Zk is significantly correlated with RR and h, but not with T and e. The best correlations are between T and e, and e and RR, further demonstrating their sequential relationship. The linear regression equation quantitatively expresses the relationship:

$$Z_k = 0.018 + 0.428 \cdot RR + 0.021 \cdot h$$

The regression equation is highly significant, with positive coefficients for both RR and h, meaning the annual damage index increases with snowfall and snow depth. Therefore, winter snowfall and snow depth are the main climatic factors affecting interannual variation of snow disasters in Xinjiang.

3 Conclusions

1) Based on seven disaster elements from Xinjiang snow disaster events—frequency, deaths, collapsed houses, collapsed sheds, collapsed greenhouses, livestock deaths, and affected area—county-level (Zs) and annual (Zk) snow disaster damage indices were constructed using ratio weighting and dimensionless linear summation. Correlation coefficients between Zs/Zk and the seven elements range from 0.71-0.98 and 0.74-0.95 respectively, with confidence levels $\alpha < 0.001$, indicating the damage indices can comprehensively express snow disaster intensity. Statistical tests show both Zs and Zk follow gamma distributions, based on which four severity grades (mild, moderate, severe, extra severe) were established. The damage indices and their grades were used to analyze spatiotemporal distribution of snow disasters in Xinjiang.

2) Snow disasters in Xinjiang show obvious spatial differences. The top five prefectures/cities by damage index are: Kizilsu Kirgiz Autonomous Prefecture, Ili Prefecture, Altay Prefecture, Tacheng Prefecture, Urumqi City, and Hami City. High-value areas concentrate in northern and northwestern Xinjiang and western southern Xinjiang pastoral areas, while low-value areas are in oasis plains. Extra severe snow disasters occur in Nilka County, Xinyuan County, Yining County, Huocheng County, Altay City, Toli County, Bayinbuluk, Artux City, and Barkol County—these are difficult and key areas for disaster prevention and relief.

3) Snow disaster frequencies in winter, spring, autumn, and summer are 46.5%, 39.5%, 10.8%, and 3.2% respectively. Snow disasters mainly occur from November to April (89% of annual events), related to heavy snowfall and thick snow depth during this period. From 1961-2018, the annual damage index shows a significant increasing trend of 0.25 per decade. Since the 21st century, years with moderate or higher severity have increased significantly, indicating a worsening trend. Among the five climatic factors, the linear trend of average temperature from November to April is inconsistent with the annual damage index trend, while cumulative snowfall and average snow depth are not only closely correlated with but also show consistent trends with the annual damage index. Therefore, snowfall and snow depth are the main climatic factors affecting interannual variation of snow disasters in Xinjiang.

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Note: Figure translations are in progress. See original paper for figures.