

Spatial Grid-Based Lightning Hazard Assessment of Grasslands and Forests in the Sanjiangyuan Region (Postprint)

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Abstract

Based on lightning location data from 2021–2022 and lightning disaster data from 1984–2022 in the Sanjiangyuan region, ground flash density, ground flash intensity, and lightning disaster density were calculated. The Analytic Hierarchy Process (AHP) and ArcGIS spatial grid analysis techniques were employed to assess the risk of lightning disasters in the Sanjiangyuan region. Combined with the distribution of grasslands and forests in the Sanjiangyuan region, the lightning risk distribution for grasslands and forests was calculated separately. The results indicate: (1) Lightning disasters in the Sanjiangyuan region caused the most severe casualties in June, mostly concentrated between 12:00–20:00, with the highest number of affected individuals at 16:00 and the highest number of lightning fatalities at 17:00. Nangqên County, Zadoi County, and Yushu City in Yushu Prefecture, and Gadê County in Golog Prefecture accounted for a high proportion of casualties. (2) High values of ground flash density in the Sanjiangyuan region were concentrated in Golog Prefecture and southern Yushu Prefecture; high values of ground flash intensity were concentrated in eastern and southern Golog Prefecture and southern Yushu Prefecture; high values of lightning disaster density were concentrated in central-eastern Golog and south-central Yushu; high-risk areas for lightning disasters were distributed in Zhoxiao Township, Maozhuang Township, Dongba Township, Nyilha Township, and Jinisai Township in Nangqên County, and Xiarixia Town in Yushu City of Yushu Prefecture, as well as Baima County, Jigzhi County, Wa'eryi Township, and Lajia Town in Maqên County of Golog Prefecture. (3) High-risk areas for grassland lightning were mainly concentrated in western and southern Yushu Prefecture, and southern and central-eastern Golog Prefecture. High-risk areas for forests were concentrated in southeastern Yushu Prefecture, and southern and north-eastern Golog Prefecture. (4) In the Sanjiangyuan region, grassland and forest lightning disasters in Yushu Prefecture and Golog Prefecture showed a negative

correlation with altitude and a positive correlation with topographic relief and slope. Through the analysis and assessment of lightning disaster risk for grasslands and forests in Yushu Prefecture and Golog Prefecture of the Sanjiangyuan region, this study provides a favorable basis for lightning disaster prevention.

Full Text

Assessment of Lightning Hazard in Grasslands and Forests in the “Three River Source” Region Based on Spatial Grids

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Abstract

Lightning disasters in the “Three River Source” region of Qinghai Province resulted in the most severe casualties in June, primarily occurring between 12:00 and 20:00. The highest number of casualties was recorded around 16:00, with the most fatalities due to lightning strikes occurring around 17:00. Areas with disproportionately high casualty rates included Nangqen County, Zadoi County, and Yushu City in Yushu Prefecture, as well as Gade County in Golog Prefecture. The highest ground flash densities were concentrated in the southern parts of Yushu and Golog prefectures, while the highest ground flash intensities were observed in the eastern and southern regions of Golog Prefecture and the southern part of Yushu Prefecture. Lightning disaster density peaked in the central-eastern areas of Golog Prefecture and the central-southern parts of Yushu Prefecture. High-risk zones for lightning disasters were distributed across Zhaoxiao Township, Maozhuang Township, Dongba Township, Niangla Township, and Jinisai Township in Nangqen County, as well as Xialaxiu Town in Yushu City, Yushu Prefecture, and in Baima County, Jigzhi County, Wa'erji Township, and Laga Town in Maqen County, Golog Prefecture. High-risk areas for grassland lightning hazards were mainly located in the western and southern parts of Yushu Prefecture and the southern and central-eastern parts of Golog Prefecture. Forest lightning risks were concentrated in the southeastern part of Yushu Prefecture and the southern and northeastern parts of Golog Prefecture. The analysis revealed a negative correlation between lightning disasters and altitude, while terrain undulation and slope showed positive correlations with lightning activity. This assessment of lightning disaster risks in the grasslands and forests of Yushu and Golog prefectures within the “Three River Source” region provides a scientific basis for effective lightning disaster prevention.

Keywords: “Three River Source” region; Yushu Prefecture and Golog Prefecture; grassland and forest; thunder and lightning; hazard

Introduction

Lightning is a severe convective phenomenon that develops in specific atmospheric environments and represents one of nature's most destructive instantaneous discharge processes. It can cause forest and grassland fires, damage or disrupt power supply and communication systems, and threaten computer networks and sensitive high-tech equipment. The United Nations and the International Electrotechnical Commission have respectively listed lightning as "one of the ten most serious public hazards" and "the primary natural disaster in the electronic age." Although the frequency of lightning disasters is relatively low, a considerable proportion of lightning-related casualties result from severe thunderstorm weather. Strong potential instability and strong vertical wind shear are among the most important meteorological environmental characteristics of such weather events. As one of the ten major natural disasters, lightning ranks just behind meteorological geological disasters and rainstorm-flood disasters in terms of hazard severity, making research on its spatial and temporal distribution particularly important.

In recent years, domestic scholars have conducted extensive research on the spatiotemporal distribution characteristics of lightning disasters. Liu et al. [?] analyzed lightning disasters in Xinjiang using lightning location data; Wang et al. [?] evaluated lightning hazard levels in Xining, Qinghai using fuzzy membership methods; Gao et al. [?] performed vulnerability risk zoning for lightning disasters in Hainan Island using cluster analysis; Xu et al. [?] analyzed lightning activity patterns and hazards in the Yangtze River Valley of Luzhou, Sichuan using mathematical statistics and ArcGIS spatial analysis; Li et al. [?] established a quantitative relationship between lightning disaster evaluation indicators and risk assessment using the analytic hierarchy process (AHP) with lightning location data, geographic information, and socio-economic data from Shaoxing City; Long et al. [?] conducted risk zoning research on lightning disasters in rural Hebei using matrix methods with lightning location network data, disaster data, and rural electricity consumption data; Chen et al. [?] proposed statistical methods for lightning parameters applicable to lightning location data; Zhang et al. [?] developed a gridded lightning disaster risk assessment model based on geographic information technology; Chen et al. [?] conducted risk zoning of lightning disasters in Hebei using lightning location data, geographic information data, and socio-economic data; Tian et al. [?] performed statistical analysis of lightning disaster accidents nationwide; Liu et al. [?] analyzed lightning activity and disasters in Inner Mongolia; Deng et al. [?] analyzed the climatic characteristics and mechanisms of lightning activity in typical provinces including Sichuan, Shandong, and Heilongjiang.

Current research on lightning disaster characteristics in the Qinghai-Tibet Plateau has primarily focused on Tibet. For instance, Zhou [?] and Xu et al. [?] used surface observation data, while Duoqi et al. [?] utilized actual lightning disaster distributions and characteristics, demonstrating that plateau thunderstorm days mainly occur from May to September, exhibiting a unimodal

distribution with high frequency, wide coverage, and long duration. Casualties of people or livestock and damage to household appliances and buildings from lightning strikes were concentrated in agricultural and pastoral areas, with relatively fewer incidents in urban areas. However, Zhao et al. [?] found that the ground flash frequency in the Naqu area of the Qinghai-Tibet Plateau was significantly lower than the national average. These studies indicate significant regional differences in ground flash frequency across the Qinghai-Tibet Plateau, likely because the frequency of lightning disasters does not entirely depend on lightning activity distribution but is also influenced by population density and economic development. Currently, the characteristics of lightning disasters in Qinghai Province, particularly in the “Three River Source” region located in the hinterland of the Qinghai-Tibet Plateau, remain unclear. Therefore, it is necessary to conduct research on the spatiotemporal distribution and disaster characteristics of lightning disasters in Qinghai, especially in the “Three River Source” region. Against the backdrop of global warming and the “warming and humidification” climate change in the Qinghai-Tibet Plateau, extreme climate events have become more frequent, resulting in increasingly severe economic losses. This study analyzes the spatiotemporal distribution characteristics of lightning disasters in the forest and grassland areas of Yushu and Golog prefectures in the “Three River Source” region based on lightning location data and lightning disaster records from Qinghai Province. By calculating ground flash density and intensity distribution characteristics and employing spatial grid methods and the analytic hierarchy process, we assess the risk of lightning disasters in grassland and forest areas of the “Three River Source” region, providing a reference basis for lightning disaster prevention in high-altitude agricultural and pastoral production.

1. Study Area Overview

The “Three River Source” region is located in the southwestern part of the Qinghai-Tibet Plateau and features a continental plateau climate with pronounced plateau monsoon characteristics. Most areas receive scarce precipitation and are classified as arid or semi-arid regions. During winter, under the control of the Mongolian cold high pressure, the plateau monsoon is weak. From May to June, as the southern branch monsoon lifts northward, the plateau monsoon begins to develop and strengthen, reaching its peak in July. Due to intense heating of the plateau in summer, air converges and rises toward the plateau, creating atmospheric instability that provides conditions for the development of mesoscale and small-scale thermal convection. Combined with the highly undulating surface of the plateau, this facilitates the formation of local climates. Research indicates that when the upper troposphere is affected by the Qinghai-Tibet Plateau high, shear lines and low vortex weather systems prevail over the plateau, making the Qinghai-Tibet Plateau one of the most convectively active regions in China, frequently experiencing hazardous weather such as convective precipitation, lightning, and hail.

Yushu Tibetan Autonomous Prefecture is located in the southwestern part of Qinghai Province, between 89°27 -97°39 E and 31°45 -36°10 N, with an average elevation of 4,696 m. Golog Tibetan Autonomous Prefecture is located in the southeastern part of Qinghai Province, between 97°54 -101°50 E and 32°31 -35°40 N, with elevations above 4,200 m. Both Yushu and Golog prefectures fall within the “Three River Source” Nature Reserve and hold crucial ecological significance. Both prefectures rely on animal husbandry as their pillar industry and constitute the main region of the “Yak Capital” [Figure 1: see original paper].

2. Data and Methods

2.1 Data Sources

Lightning location data for Yushu and Golog prefectures in the “Three River Source” region from 2009 to 2021 and lightning disaster data from 1998 to 2021 were obtained from the Qinghai Provincial Meteorological Information Center. Grassland distribution data and forest distribution data for the “Three River Source” region were provided by the Qinghai Provincial Meteorological Research Institute. Based on the lightning data, ground flash density, ground flash intensity, and disaster density were calculated. According to the scale of mesoscale and small-scale weather systems, the region was divided into 25 km × 25 km grids for display using spatial grid analysis [Figure 2: see original paper]. The model flowchart is shown in [Figure 2: see original paper].

Ground flash density refers to the average number of ground flashes per unit grid area per unit time, calculated by dividing the annual average number of ground flashes in a regional spatial range by the corresponding grid area [Figure 2: see original paper]. Ground flash density effectively reflects the lightning strike probability in a grid area, with high-value areas corresponding to high-incidence lightning activity. Ground flash intensity is calculated by dividing the lightning current amplitude into different levels using the percentile method (Table 1) and then performing weighted averaging (Equation 1). This intensity value indicates the probability of a region suffering lightning disasters [cite{chen2007}].

2.2 Assessment Model

2.2.1 Model Framework Ground flash density, ground flash intensity, and disaster density were selected as indicators for lightning disaster risk assessment. Each indicator was normalized to eliminate dimensional differences, and a weighted comprehensive evaluation method was used to calculate the lightning disaster risk index H [cite{li2021}], as follows:

$$H = \sum_{j=1}^3 W_j \times H_j(x)$$

where H is the lightning disaster risk index obtained through weighted summation of the risk indicators; W_j is the weight coefficient corresponding to each risk indicator; and $H_j(x)$ represents the lightning disaster risk indicators, namely ground flash density, ground flash intensity, and disaster density.

2.2.2 Data Normalization Through spatial correlation analysis of each indicator layer, the forward range method was selected for standardization to eliminate dimensional effects [cite{zhang2016}], calculated as follows:

$$Y_{ij} = \frac{X_{ij} - \min(X_i)}{\max(X_i) - \min(X_i)}$$

where Y_{ij} is the normalized value of the i -th indicator at grid point j ; X_{ij} is the original value of the i -th indicator at grid point j ; and $\min(X_i)$ and $\max(X_i)$ are the minimum and maximum values of the i -th indicator, respectively.

2.3 Determination of Indicator Weights

The analytic hierarchy process (AHP) was used to determine the weights of risk indicators (Table 2). The process involves establishing a hierarchical structure, constructing a judgment matrix using the 1-9 scale method, determining indicator weights [cite{gao2013}], and performing consistency tests.

A hierarchical structure for lightning disaster risk assessment was established [Figure 2: see original paper], using lightning data, disaster data, and forest/grassland data to construct impact factor indicators and determine the lightning disaster risk assessment index system. The 1-9 scale method was employed to quantify the relative importance of pairwise elements at each level, constructing a comparison judgment matrix A . The weight calculation involves solving the eigenvalue problem $AW = \lambda \{max W\}$ for the comparison judgment matrix A , with the normalized solution providing the importance weight values for corresponding factors at the same hierarchical level. The consistency test uses the consistency index $CI = (\lambda \{max\} - n) / (n - 1)$. When the consistency ratio $CR = CI/RI < 0.1$, the judgment matrix A is considered to have reasonable consistency; if $CR \geq 0.1$, the judgment matrix is unreasonable and requires reconstruction.

The spatial correlations and weights of various indicators in the “Three River Source” region are shown in Table 3.

3. Results and Analysis

3.1 Temporal and Regional Distribution Characteristics of Lightning Disasters

Statistical analysis of lightning disaster data from 1998 to 2021 in the “Three River Source” region reveals that casualties were most severe in June, primarily concentrated between 12:00 and 20:00. The highest number of casualties occurred around 16:00, with the most fatalities due to lightning strikes occurring around 17:00. Nangqen County, Zadoi County, and Yushu City in Yushu Prefecture, as well as Gade County in Golog Prefecture, accounted for high proportions of casualties, with casualty rates exceeding 50% in these areas and fatality rates in Nangqen County, Zadoi County, and Yushu City exceeding 60% [Figure 3: see original paper].

Lightning disasters in Yushu Prefecture showed a bimodal temporal distribution, with peaks in June and August, accounting for over 60% of all disasters. The corresponding affected population was also concentrated in these months, with June being the most severe month for casualties, accounting for 35% of total deaths, followed by August with 28%. Lightning disasters in Golog Prefecture exhibited a bimodal pattern in June and July, accounting for over 70% of all disasters, with the disaster-affected population also concentrated in these months. The timing of lightning disasters was primarily concentrated in the afternoon and evening, with over 60% of events occurring between 12:00 and 20:00. Specifically, disaster occurrence peaked between 16:00-17:00 in Yushu Prefecture (accounting for over 30%) and between 16:00-19:00 in Golog Prefecture (accounting for over 40%) [Figure 4: see original paper].

3.2 Spatial Distribution of Lightning Disaster Timing and Casualties

The “Three River Source” region is rich in grassland and forest resources with widespread distribution, and animal husbandry constitutes the leading industry. Statistical analysis of lightning disaster data from 1998 to 2021 shows a significant increase in lightning disasters after 2005 [Figure 3: see original paper], with both the disaster-affected population and fatalities increasing substantially. In 2021 alone, lightning strikes caused 42 casualties, with fatalities accounting for half of this number.

The spatial distribution of lightning disaster timing shows that disasters in Yushu Prefecture were concentrated in its southeastern region, primarily occurring in June and August (accounting for over 60%). In Golog Prefecture, disasters were concentrated in the central-eastern region, mainly in June and July (accounting for over 70%). The spatial distribution of ground flash density shows high-value areas concentrated in most parts of Golog Prefecture and southern Yushu Prefecture. Specifically, the annual ground flash density exceeded 8 flashes per grid in Dangkar Township, Makehe Township, Zhigin Township, Ya’ertang Township, Sailaitang Township, Jika Township, and Laga Town in Maqen County, Golog Prefecture, with Laga Town reaching 13.7 flashes per grid.

In Yushu Prefecture, annual ground flash density exceeded 8 flashes per grid in Jinisai Township, Zhaoxiao Township, Dongba Township, and Maozhuang Township in Nangqen County, as well as in Aduo Township and Moyun Township in Zadoi County, and in Daka Township in Baima County, Jianshe Township, Jimai Town, Xiahongke Township, Manzhang Township, Wosai Township, and Tehetu Township in Dari County, Wa'erji Township, Suohurima Township, Zhiqingsongduo Town, and Wasai Township in Jigzhi County, and Dongqinggou Township in Maqen County [Figure 5: see original paper].

3.3 Spatial Distribution of Lightning Disasters

3.3.1 Ground Flash Density Ground flash density, defined as the annual average number of ground flashes per grid, reflects the frequency of lightning discharges. In areas with low lightning protection levels, high-frequency lightning activity corresponds to increased casualties [cite{liu2020}]. The distribution of ground flash density in the “Three River Source” region [Figure 5: see original paper] shows high-value areas concentrated in most parts of Golog Prefecture and southern Yushu Prefecture. In Golog Prefecture, the annual ground flash density exceeded 8 flashes per grid in Dengta Township, Makehe Township, Zhigin Township, Ya'ertang Township, Sailaitang Township, Jika Township in Baima County, and Laga Town in Maqen County, with Laga Town recording 13.7 flashes per grid. In Yushu Prefecture, high-density areas included Jinisai Township, Zhaoxiao Township, Dongba Township, and Maozhuang Township in Nangqen County, Aduo Township and Moyun Township in Zadoi County, and various townships in Dari, Jigzhi, and Maqen counties, with densities exceeding 8 flashes per grid [Figure 5: see original paper].

3.3.2 Ground Flash Intensity Ground flash intensity reflects the current strength of lightning and indicates the probability of a region suffering lightning disasters, representing an important factor in lightning disaster risk assessment [cite{chen2007}]. Using the percentile method to classify lightning current amplitude (Table 1), normalized values of ground flash frequency for different intensity levels were obtained and then weighted averaged (Equation 1) to derive intensity values. The distribution of ground flash intensity in Yushu and Golog prefectures shows high-value areas concentrated in the eastern and southern parts of Golog Prefecture and southern Yushu Prefecture. Specifically, the average ground flash intensity exceeded 45 kA in Makehe Township, Jika Township, Sailaitang Township, Zhigin Township, Ya'ertang Township, and Dengta Township in Baima County, and Laga Town in Maqen County, Golog Prefecture, with Makehe Township and Laga Town reaching 50 kA. In Yushu Prefecture, areas with intensity exceeding 45 kA included Jinisai Township, Zhaoxiao Township, Dongba Township, and Maozhuang Township in Nangqen County, and Aduo Township and Moyun Township in Zadoi County [Figure 5: see original paper].

3.3.4 Lightning Disaster Risk Lightning disaster risk assessment follows the principle that higher index values indicate greater risk. The classification

of lightning disaster risk index levels is shown in Table 4. The spatial distribution of lightning disaster risk in the “Three River Source” region [Figure 5: see original paper] shows that high-risk areas are concentrated in Makehe Township, Sailaitang Township, Zhigin Township, Dengta Township, Jika Township, Ya’ertang Township, Duogongma Township, and Jiangritang Township in Baima County; Xiagongma Township and Jiangqian Township in Gade County; Wa’erji Township in Jigzhi County; and Laga Town in Maqen County, Golog Prefecture; as well as Zhaoxiao Township, Maozhuang Township, Dongba Township, Niangla Township, and Jinisai Township in Nangqen County, and Xialaxiu Town in Yushu City, Yushu Prefecture. The risk index in these areas exceeded 0.22, with Makehe Township, Sailaitang Township, and Zhigin Township in Baima County, and Laga Town in Maqen County reaching 0.30-0.36, and Laga Town recording the highest value of 0.66 [Figure 5: see original paper].

3.3.5 Grassland and Forest Lightning Hazard Distribution Based on the distribution of grasslands and forests in the “Three River Source” region, separate calculations were performed for grassland lightning hazard distribution and forest lightning hazard distribution [Figure 6: see original paper]. The grassland lightning hazard distribution in the “Three River Source” region shows that high-risk areas are concentrated in the western and southern parts of Yushu Prefecture and the southern and central-eastern parts of Golog Prefecture. The maximum grassland lightning hazard index in Yushu Prefecture was found in Suojia Township, Zhidoi County (0.38), followed by Zhaoxiao Township, Dongba Township, and Jinisai Township in Nangqen County, with maximum values exceeding 0.36. In Golog Prefecture, high-value areas were concentrated in Baima, Dari, and Maqen counties, with the maximum value in Laga Town, Maqen County (0.66), followed by Zhigin Township, Dengta Township, Sailaitang Township, Makehe Township, and Duogongma Township in Baima County, all ranging between 0.37 and 0.38 [Figure 6: see original paper].

The forest lightning hazard distribution shows that high-risk areas align closely with forest distribution, particularly corresponding to major forest farms such as the Baizha Forest Farm in Nangqen County, Yushu City, the Jiangxi Forest Farm in Yushu City, the Makehe Forest Farm in Baima County, and the Yangyu Forest Farm in Maqen County, Golog Prefecture. The maximum forest lightning hazard index in Yushu Prefecture was 0.38 in Zhaoxiao Township, Nangqen County, followed by Dongba Township and Jinisai Township, both exceeding 0.36. In Golog Prefecture, the maximum value was 0.66 in Laga Town, Maqen County, followed by Dengta Township, Sailaitang Township, Jika Township, Makehe Township, and Duogongma Township in Baima County, all ranging between 0.37 and 0.38 [Figure 6: see original paper].

Zonal statistics of mean forest lightning hazard index values show that areas with mean values exceeding 0.30 in Yushu Prefecture were concentrated in Niangla Township, Maozhuang Township, Dongba Township, Zhaoxiao Township in Nangqen County, Xialaxiu Town in Yushu City, and Yuegai Township in

Qumarlêb County, with values between 0.30 and 0.36. In Golog Prefecture, areas with mean values exceeding 0.30 were concentrated in Baima County, De'ang Township in Dari County, Xiagongma Township, Ganglong Township, and Jiangqian Township in Gade County, Wa'erji Township in Jigzhi County, and Laga Town in Maqen County, with the highest mean value in Laga Town (0.66), followed by Zhigin Township, Dengta Township, and Makehe Township in Baima County, all exceeding 0.30 [Figure 6: see original paper].

3.4 Relationship Between Lightning Disaster Risk and Geographic Location

Lightning disasters in the “Three River Source” region are concentrated in the southern areas. To understand the relationship between lightning occurrence and topography, correlation analysis was performed between historical disaster density, ground flash density, ground flash intensity, lightning risk, and grassland/forest lightning risk with local geographic factors including altitude, terrain undulation, and slope (Table 5). The results show negative correlations between lightning disaster density, ground flash density, ground flash intensity, lightning risk, and grassland/forest lightning risk with altitude, and positive correlations with terrain undulation and slope. Except for the correlation between forest lightning risk and geographic factors, which was not significant, and the correlation between historical disaster density and altitude, which was not significant, ground flash density, ground flash intensity, lightning risk, and grassland lightning risk showed significant or highly significant correlations with topographic factors.

The correlation between grassland lightning risk and altitude in the “Three River Source” region was -0.32 (significant at the 0.01 level), with terrain undulation was 0.45 (significant at the 0.01 level), and with slope was 0.38 (significant at the 0.01 level), indicating that high-risk areas for grassland lightning correspond to regions with high terrain undulation and slope.

Discussion and Conclusions

This study employed spatial grid technology to analyze the spatial patterns of ground flash density, ground flash intensity, and lightning disaster density in Yushu and Golog prefectures of the “Three River Source” region, constructed a lightning disaster risk model, and evaluated lightning disaster risks in grassland and forest areas. The main conclusions are as follows:

1. Lightning disasters in the “Three River Source” region caused the most casualties in June, primarily between 12:00 and 20:00, with the highest casualty numbers around 16:00 and the most fatalities around 17:00. Nangqen County, Zadoi County, and Yushu City in Yushu Prefecture, and Gade County in Golog Prefecture accounted for high proportions of casualties.
2. Southern Yushu Prefecture exhibited high ground flash density and intensity, with lightning disasters concentrated in the central-southern areas.

Golog Prefecture showed high overall ground flash density, with greater intensity in the eastern and southern regions, and lightning disasters concentrated in the central-eastern part. High-risk areas were distributed in Zhaoxiao Township, Maozhuang Township, Dongba Township, Niangla Township, and Jinisai Township in Nangqen County, and Xialaxiu Town in Yushu City, Yushu Prefecture; and in Makehe Township, Sailaitang Township, Zhigin Township, Dengta Township, Jika Township, Ya'ertang Township, Duogongma Township, and Jiangritang Township in Baima County, Xiagongma Township and Jiangqian Township in Gade County, Wa'erji Township in Jigzhi County, and Laga Town in Maqen County, Golog Prefecture.

3. High-risk areas for grassland lightning hazards were concentrated in the western and southern parts of Yushu Prefecture and the southern and central-eastern parts of Golog Prefecture. High-risk areas for forest lightning hazards were concentrated in the southeastern part of Yushu Prefecture and the southern and northeastern parts of Golog Prefecture.
4. Lightning disaster density, ground flash density, ground flash intensity, and grassland/forest lightning risk in Yushu and Golog prefectures were negatively correlated with altitude and positively correlated with terrain undulation and slope. Except for forest lightning risk, which was not significantly correlated with geographic factors, grassland lightning risk showed significant or highly significant correlations with topographic factors.

In national lightning disaster risk research, Yuan et al. [?] found that Qinghai had a very low life vulnerability modulus for lightning disasters, at only 0.03×10^{-2} , calculated by dividing the number of people affected by lightning disasters by the administrative area of each region. Although Yushu and Golog prefectures in the “Three River Source” region are sparsely populated, lightning disasters increased significantly after 2005, with 225 people affected and 113 fatalities between 1998 and 2021, resulting in an average annual death rate of 4.7 people. This is because Zhidui County, Nangqen County in Yushu Prefecture and Maqen County, Dari County, and Gade County in Golog Prefecture are suitable growth areas for *Cordyceps sinensis* in the “Three River Source” region [cite{liang2022}]. Each year, many migrant workers come to these grasslands to collect *Cordyceps*, moving unpredictably and creating uncertainty in life vulnerability. *Cordyceps* collectors accounted for over 60% of total lightning disaster casualties. Therefore, this study could not consider the influence of local population density and GDP density as in other provincial studies [cite{chen2019}].

In research on temporal variations of lightning activity disasters, Gong et al. [?] found that disaster-causing lightning in Qinghai was mainly distributed in the southern pastoral areas and eastern agricultural areas, consistent with this study. However, their conclusion that disaster-causing lightning showed an overall decreasing trend differs from Tao et al. [?], who found that cloud-to-ground lightning on the Qinghai Plateau showed a 逐年增加 trend from 2008 to

2016. This study found that lightning disasters, affected population, and fatalities in Yushu and Golog prefectures showed a significant increase from 2009 to 2021, aligning with Tao et al.'s research. Cai et al. [?] concluded that lightning disasters in Qinghai showed an east-west decreasing and south-north decreasing pattern, with a steady upward trend, which aligns well with the above studies and this research.

In spatial distribution studies of lightning disasters, Li et al. [?] classified Yushu and Golog prefectures in the “Three River Source” region as medium-risk areas for lightning disasters, with high-risk areas mainly located in the Kunlun, Qilian, Tanggula, Bayan Har, and A’nyêmaqên mountains and local southern Qinghai areas. This study, incorporating topographic conditions, found that lightning disasters were negatively correlated with altitude but positively correlated with terrain undulation and slope. Therefore, the southern “Three River Source” region with significant terrain undulation constitutes a high-risk area for lightning disasters, consistent with Wang et al. [?], who identified high hazard factors in Nangqen County, Yushu Prefecture. This study confirms that Zhaoxiao Township, Maozhuang Township, Dongba Township, Niangla Township, Jinisai Township in Nangqen County, and Xialaxiu Town in Yushu City are high-risk areas for lightning disasters. Additionally, Makehe Township, Sailaitang Township, Zhigin Township, Dengta Township, Jika Township, Ya’ertang Township, Duo-gongma Township, and Jiangritang Township in Baima County, Wa’erji Township in Jigzhi County, Laga Town in Maqen County, and Xiagongma Township and Jiangqian Township in Gade County are also high-risk areas.

In studies on the relationship between lightning disasters and topography, Hu et al. [?] found that ground flash density first increased then decreased with altitude, and decreased with increasing slope, while ground flash intensity first decreased then increased with altitude and was positively correlated with slope. These findings differ from this study, likely because their research covered the entire province, whereas this study focuses specifically on Yushu and Golog prefectures in the “Three River Source” region, where topographic environmental parameters differ significantly from other regions. Cheng et al. [?] analyzed the relationship between lightning distribution and altitude in Liaoning, finding that lightning density decreased with increasing altitude, consistent with this study. The “Three River Source” region shows highly significant negative correlations between ground flash density, ground flash intensity, lightning disaster risk, and altitude, as Yushu and Golog prefectures have average elevations around 4,000 m, where increasing altitude only suppresses convective development.

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