Analysis of the Impact of Complex Geographical Parameters on Plateau Lightning Activity (Post-print)

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Abstract

Lightning activity parameters serve as crucial indicators of regional lightning activity characteristics, and the influence of terrain thereon should not be overlooked. Utilizing 2014–2018 cloud-to-ground lightning flash data from Qinghai Province, digital elevation model data, and the HWSD soil dataset, a quantitative analysis was conducted on the effects of elevation, slope gradient, aspect, and soil resistivity on the distribution characteristics of cloud-to-ground lightning flashes in Qinghai Province. The results demonstrate that: (1) Cloud-to-ground lightning flashes in Qinghai Province are primarily concentrated in regions with elevations of 3150–4850 m and slope gradients of 0–35°, with the northeast aspect exhibiting the highest flash frequency and the southeast aspect the lowest; the soil resistivity corresponding to lightning flashes is predominantly concentrated at 100 Ω · m. (2) Cloud-to-ground lightning flash density initially increases before decreasing with rising elevation, and decreases with increasing slope gradient; the average intensity of cloud-to-ground lightning flashes initially decreases before increasing with rising elevation, and increases with increasing slope gradient. (3) Within the active lightning region bounded by 92°27 00 –97°44 24 E, 31°40 48 –34°16 48 N, a correlation analysis was performed between lightning flash data and average geographic parameters within 1 km × 1 km grids; in the selected region, cloud-to-ground lightning flash density exhibits a positive correlation with average elevation and a negative correlation with average slope gradient, whereas lightning flash intensity shows a negative correlation with average elevation and a positive correlation with average slope gradient.

Full Text

Analysis of the Influence of Complex Geographic Parameters on Lightning Activity in Plateau Regions

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Abstract: Lightning activity parameters serve as crucial indicators for characterizing regional lightning regimes, with terrain exerting a significant influence that cannot be ignored. Using cloud-to-ground lightning data from 2014 to 2018 in Qinghai Province, digital elevation model data, and the Harmonized World Soil Database (HWSD), this study quantitatively analyzes the effects of altitude, slope, aspect, and soil resistivity on the distribution characteristics of cloud-to-ground lightning in Qinghai Province. The results indicate that: (1) Cloud-to-ground lightning is primarily concentrated in areas with altitudes of 3150–4850 m and slopes of 0–35°. The northeast aspect experiences the highest lightning frequency, while the southeast aspect has the lowest. The soil resistivity corresponding to lightning activity is mainly concentrated around 100 Ω • m. (2) Lightning density increases initially and then decreases with rising altitude, while decreasing with increasing slope. The average lightning intensity exhibits a decreasing-then-increasing trend with altitude, and shows a gradual increase with slope. (3) Correlation analysis was performed between lightning data and the mean values of geographic parameters within a 1 km$×$1 km grid covering the active region bounded by 92°27 00 –97°44 24 E and 31°40 48 –34°16 48 N. In the selected region, lightning density is positively correlated with mean altitude and negatively correlated with mean slope, whereas lightning intensity is negatively correlated with mean altitude and positively correlated with mean slope.

Key words: lightning activity; altitude; slope; aspect; soil resistivity; Qinghai Plateau

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Introduction

Cloud-to-ground lightning intensity and density are important parameters reflecting regional lightning activity patterns. Their distribution characteristics are not only related to climatic background and weather conditions, but also closely associated with regional topography. Terrain can directly or indirectly influence prevailing wind directions, causing frontal lifting and affecting updrafts, which enhances local instability and influences thunderstorm intensity. Therefore, investigating the variation patterns of regional lightning activity parameters with geographic parameters constitutes a significant component of lightning research.

In recent years, lightning location systems have been widely applied in lightning activity monitoring. Lightning locators can rapidly and accurately obtain cloud-to-ground lightning data, which has become the primary data source for lightning research. Additionally, with the development of remote sensing technology, the acquisition of high-resolution land surface data provides a foundation for quantitative analysis of lightning-topography relationships. Previous studies have analyzed the variation of lightning parameters with altitude, revealing certain patterns. Other researchers have examined the influence of terrain slope on lightning activity in countries such as Brazil and the United States, finding correlations between local topographic slope and lightning frequency. However, these studies have primarily focused on individual geographic parameters such as altitude or slope, without conducting comprehensive and in-depth investigations into the combined effects of multiple geographic parameters on lightning activity characteristics.

Qinghai Province is located in the eastern part of the Qinghai-Tibet Plateau, with a landscape dominated by mountains. The terrain gradually decreases from the northwestern and southeastern sides toward the central region, with extreme altitude differences reaching up to 5210 m. The province exhibits uneven spatial distribution of convective weather and complex lightning activity environmental parameters, making it one of the regions with the most vigorous convection in China. Therefore, this paper analyzes the influence of geographic parameters including altitude, slope, aspect, and soil resistivity on lightning activity patterns in Qinghai Province, providing foundational support for lightning disaster prevention and mitigation efforts in the region.

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1 Data and Methods

1.1 Data Sources 1.1.1 Lightning Location Data

This study utilizes cloud-to-ground lightning data obtained from the ADTD lightning detection network. Considering that lightning locators have poor detection capability for return strokes below 10 kA under cloud flash interference, cases with intensity less than 10 kA were excluded from the dataset, retaining only positive cloud-to-ground lightning instances.

1.1.2 Geographic Elevation Data

The digital elevation data employed in this study is the SRTM DEM product, publicly released by NASA and currently in its revised version. The data was downloaded from https://www.nasa.gov/ and processed using ArcGIS software to generate the Qinghai Province elevation map. Further data processing and extraction yielded altitude, slope, and aspect parameters for the region.

1.1.3 Soil Conductivity Data

Soil conductivity data were obtained from the Harmonized World Soil Database (HWSD) version, sourced from the National Tibetan Plateau Data Center (https://data.tpdc.ac.cn/). A Python program was developed to establish links between raster pixel values of the Qinghai Province map and soil database mapping units, enabling extraction of soil conductivity data.

1.2 Methods 1.2.1 Data Extraction

Based on the 2014-2018 cloud-to-ground lightning data, the extraction tool in ArcGIS was used to assign altitude, slope, aspect, and soil conductivity values to each lightning stroke according to its geographic location. The variation characteristics of lightning frequency, density, and intensity with different geographic parameters were then statistically analyzed.

1.2.2 Spearman Rank Correlation Coefficient

Since the lightning data extracted for different slope intervals are not equidistant or continuous, and their distribution patterns are unknown, Spearman rank correlation—a non-parametric statistical method with low sensitivity to outliers and no requirement for normal distribution—was employed to analyze the correlation between slope and lightning density. The calculation formula is:

$$r_s = 1 - \frac{6\sum d_i^2}{n(n^2-1)}$$

where r_s is the rank correlation coefficient, d_i is the rank difference for each pair of samples, and n is the sample size.

1.2.3 Pearson Correlation Analysis

According to the distribution characteristics of lightning in Qinghai Province, a lightning-intensive region was selected and gridded at 1 km$\times$1 km resolution. Lightning density and intensity were statistically analyzed for each grid cell, and the mean altitude and slope were calculated within each corresponding grid. Pearson correlation analysis was then applied to examine the relationships between lightning activity and geographic parameters in the active region.

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2 Results and Analysis

2.1 Spatial Distribution Characteristics of Lightning in Qinghai Province In 2018, a total of 40.02×10^{4} cloud-to-ground lightning strokes occurred in Qinghai Province, including 35.03×10^{4} negative strokes and 4.99×10^{4} positive strokes. Influenced by terrain distribution, the highest lightning density values appear primarily in the southern Qinghai pastoral region above 4500 m average altitude. This may be attributed to strong surface heating and complex terrain creating non-uniform thermal distribution of the underlying surface, leading to significant low-level instability and making the region more prone to severe convective weather. The second-highest lightning density occurs mainly around Qinghai Lake above 4000 m, where convective development is dominated by the Mongolian cold trough pattern. The interaction between upper-level cold troughs and low-level moisture tongues continuously transports cold, dry air into the region, creating a convectively unstable stratification favorable for severe convection.

2.2 Influence of Altitude on Lightning Spatial Distribution Lightning activity occurs within the altitude range of 1650–5450 m, with no activity above 5450 m. Analysis of lightning frequency at 100 m altitude intervals reveals that cloud-to-ground lightning is mainly concentrated between 3150–4850 m, accounting for 82.11% of total strokes. With increasing altitude, lightning frequency shows a "four peaks and three valleys" wave-like distribution, with peaks at 2450–2550 m, 3050–3150 m, 3550–3650 m, and 4350–4450 m, with the highest peak at 3550–3650 m.

Lightning density increases initially and then decreases with altitude, peaking at 3550–3650 m. Total and negative lightning density show consistent trends, while positive lightning density remains stable within 2150–4050 m and decreases above 4250 m. Regarding intensity, positive lightning average intensity is significantly greater than negative lightning across all altitude intervals, likely due to the vertical charge distribution in thunderclouds. Total and negative lightning average intensity show a decreasing-then-increasing trend with altitude, stabilizing around 3650 m. Negative lightning intensity increases gradually at higher altitudes, possibly because high-altitude lightning is primarily local convection caused by radiation, and decreasing moisture content requires higher energy for charge accumulation and channel formation.

2.3 Influence of Slope on Lightning Spatial Distribution Slope is a topographic factor describing surface inclination that promotes airflow lifting and convection formation. Statistics at 1° intervals show that 96.91% of lightning activity occurs on slopes of 0–35°, with the 0–10° interval being most active (19.12$\times10^{4}$ strokes, 47.34% of total). Lightning activity on slopes >35° is minimal (only 3.11% of total strokes).

Lightning density distribution across slope intervals shows that total and negative lightning density reach maximum values of 2.51 fl $\cdot$ km^{-2} $\cdot$ a^{-1} and 2.28 fl $\cdot$ km^{-2} $\cdot$ a^{-1}, respectively, within 0–10°, then decrease with increasing slope. Spearman rank correlation analysis reveals negative correlations between slope and both total lightning density (r = -0.78) and negative lightning density (r = -0.57).

Lightning intensity shows contrasting patterns: negative lightning average intensity increases linearly with slope, while positive lightning intensity increases slowly with a smaller slope coefficient. This difference may be because negative lightning centers located near the cloud base are more influenced by terrain than positive lightning. Strong lightning (>40 kA) analysis shows that all aspects have similar proportions of strong lightning, with the north aspect slightly higher at 11.02%, consistent with average intensity distribution patterns.

2.4 Influence of Aspect on Lightning Spatial Distribution Based on commonly used aspect classification methods at medium scales, aspect was divided into eight categories at 45° intervals. The area proportions of different aspect categories show little variation. Statistical analysis of lightning frequency across aspect intervals reveals that the northeast aspect has the most lightning strokes, while the southeast aspect has the fewest. This may be because lightning activity on the Qinghai-Tibet Plateau concentrates in summer when southwest winds dominate. Relative to the southeast aspect, the northeast-facing slopes are windward slopes where airflow lifting is more likely to trigger severe convective weather.

2.5 Influence of Soil Resistivity on Lightning Spatial Distribution Lightning activity parameters are closely related to soil resistivity, which primarily affects lightning radiation fields through the upper soil layer. Based on individual lightning data, soil conductivity data for the upper 0–30 cm layer were extracted at 0.1 $S \cdot m^{-1}$ intervals and converted to resistivity. Statistics show that lightning strokes corresponding to soil resistivity below 1 $\Omega \cdot m$ are extremely rare. Considering that most soil resistivity in Qinghai Province is around 200 $\Omega \cdot m$, lightning strokes mainly correspond to resistivity concentrated at 100 $\Omega \cdot m$, accounting for 88.06% of total strokes.

To eliminate area effects, unit-area lightning frequency was calculated. The results indicate that areas with lower resistivity generally have higher lightning frequency per unit area, suggesting that low-resistivity soils are more susceptible to lightning strikes. This may be because low-resistivity areas more easily accumulate induced charges during the lightning leader phase, enhancing electric field strength and providing favorable conditions for downward leader development. Lightning average intensity generally decreases with increasing resistivity, with negative lightning intensity showing a more pronounced decreasing trend than positive lightning, consistent with findings that smaller soil resistivity enhances negative lightning intensity more significantly.

2.6 Relationship Between Lightning Activity and Terrain in Frequent Lightning Areas Analysis reveals that lightning-intensive areas in Qinghai Province mainly appear in the southern pastoral region. Therefore, a region bounded by 92°27 00 –97°44 24 E and 31°40 48 –34°16 48 N was selected as the most active lightning area. Using 1 km$×$1 km grids, correlations between lightning activity and terrain characteristics were analyzed (Table 3).

Table 3 Correlation between cloud-to-ground lightning activity and altitude and slope in the study area

Parameter	Lightning Density	Lightning Intensity
Altitude	r = 0.54	r = -0.35
Slope	r = -0.21	r = 0.44

In the selected region, lightning density is positively correlated with mean altitude (r = 0.54), likely because higher mountains provide more significant lifting dynamics for convective clouds. Additionally, elevated surfaces raise equipotential surfaces, enhancing cloud-to-ground electric field strength and facilitating lightning initiation. Lightning density shows a weak negative correlation with mean slope (r = -0.21), consistent with previous studies finding that local mountain areas may show correlations between lightning density and slope.

Conversely, lightning intensity is negatively correlated with mean altitude (r = -0.35) but positively correlated with mean slope (r = 0.44). The negative correlation with altitude may be because at higher altitudes, the cloud base is lower, reducing the distance between thundercloud charges and the ground, making it easier to reach the critical breakdown field strength with weaker charge accumulation, resulting in lower intensity discharges. The positive correlation with slope indicates that steeper slopes are associated with stronger lightning.

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3 Conclusions

Based on lightning location data, digital terrain data, and the HWSD soil dataset, this study analyzed the influence of altitude, slope, aspect, and soil resistivity on lightning distribution characteristics in Qinghai Province. The main conclusions are:

1. Lightning strokes in Qinghai Province are mainly concentrated at altitudes of 3150–4850 m and slopes of 0–35°. With increasing altitude, both lightning frequency and density show initial increases followed by decreases. Total, positive, and negative lightning intensities exhibit decreasing-then-increasing trends with altitude.
2. Lightning activity is primarily concentrated on slopes of 0–35°, with lightning frequency and density decreasing as slope increases. Total, positive, and negative lightning intensities increase with slope.
3. The northeast aspect has the most lightning strokes, while the southeast aspect has the fewest. The north aspect shows the highest proportion of strong lightning (>40 kA).
4. Lightning strokes correspond mainly to soil resistivity concentrated at 100 Ω · m. Lightning intensity generally decreases with increasing resistivity, with negative lightning intensity showing a more pronounced decreasing trend.
5. In the southern pastoral region of Qinghai (92°27 00 –97°44 24 E, 31°40 48 –34°16 48 N), lightning density is positively correlated with altitude and negatively correlated with slope, while lightning intensity is negatively correlated with altitude and positively correlated with slope.

These findings provide a scientific basis for lightning disaster prevention and mitigation in the complex terrain of the Qinghai Plateau.

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