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Effects of multi-source topographic features on lightning activity in Inner Mongolia: a quantitative analysis based on spatio-temporal data mining and machine learning

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ABSTRACT
In order to explore the relationship between multi-source terrain features and lightning activity in Inner Mongolia, monitoring data and digital terrain elevation data of thunderstorm activity in Inner Mongolia from 2014 to 2025 were collected, and the spatio-temporal data mining method of mathematical and statistical analysis was used to analyze the distribution characteristics of lightning activity in Inner Mongolia. Based on the selected terrain feature factors, the machine learning method of multiple regression analysis is used to establish a research model of multi-source terrain features and lightning activity for quantitative analysis. The results show that the frequency of ground flashes in Inner Mongolia is mainly concentrated in May-October, accounting for more than 92% of the whole year, and the seasonal characteristics of its ground flash activities are significant, and the current intensity is mainly concentrated in the range of 20-40 kA. Correlation analysis reveals that multiple features of multi-sourced terrain are positively and negatively correlated with the frequency of lightning ground flashes and the current intensity ($p < 0.05$), and the prediction error of the constructed regression model for the ground flashes' frequency and the current intensity is 7.31%. The prediction errors of the constructed regression model on ground flash frequency and current intensity are 7.31% and 5.08%, which can provide a reference for lightning disaster prevention and mitigation in Inner Mongolia.

Keywords: spatio-temporal data mining, machine learning, regression model, correlation analysis, lightning activity in Inner Mongolia

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1. Introduction

With the continuous progress of China's social productivity, the ability to develop and utilize natural resources has greatly improved, but it is still not free from the hold of natural disasters. The frequent occurrence of natural disasters reduces the speed of social advancement and decreases the total output value of the national economy, and the challenge of how to cope with natural disasters is in front of the government and the people [1-4]. Therefore, it is important to recognize the causes of natural disasters, development and distribution patterns, pay attention to environmental protection, prevent disasters, and try to avoid natural disasters for the sustainable development of Chinese society [5-7].

Inner Mongolia is located in the northern border of China, close to Mongolia and Russia in the northwest, the whole territory is dominated by the plateau, most of which is above 1000 meters above sea level, commonly known as the Inner Mongolia Plateau, and the main mountain ranges are the Daxing'anling Mountains, Helan Mountains, Wulashan Mountains, and Daqingshan Mountains, with vast grasslands in the east and extensive deserts in the west [8-11]. There are famous lakes such as Hulun Lake and Beier Lake, and the Yellow River flows through the southwestern part of the region, and such complex topographic features also cause Inner Mongolia to become a place where lightning activities are frequent [12-14]. Since topography can have a great influence on atmospheric circulation and precipitation, especially convective systems, fronts and cyclonic systems, topography and mountain ranges can influence the direction of prevailing winds, and the slope of the topography can directly affect the updrafts that may trigger strong weather such as thunderstorms and thus cause lightning and precipitation, and there is an obvious linear correlation between them [15-18]. Lightning is a common atmospheric physical phenomenon, which often causes natural disasters and brings great losses to buildings and people's lives and properties, and frequent lightning activities have become one of the serious disasters affecting economic and social development in Inner Mongolia [19-22].

Literature [23] analyzed the characteristics of thunderstorms with extreme lightning activities (TELAs), taking regions such as Northeast China as an example, and provided a valuable reference for early warning and forecasting of strong convection. Literature [24] examined the climatological characteristics of lightning in China's land areas, revealing that this feature decreases overall from south to north and from east to west, with the average maximum occurring in the southern and eastern coastal provinces. Literature [25] analyzed the spatial and temporal distribution characteristics of lightning in China and the differences between positive and negative cloud-to-ground lightning, revealing that lightning activity is most frequent in summer, while lightning activity in high-density areas shows diversity. Literature [26] describes the three-dimensional lightning monitoring using VLF/LF in Ulanchab, Inner Mongolia, verifies that the VLF/LF lightning locator has good monitoring capability, and points out that there is a certain correlation between lightning-prone areas and surface water in Ulanchab. Literature [27], through a series of analyses, showed that the change of climate on the Mongolian Plateau has contributed to the northward movement of vegetation, which poses a challenge to future fires spreading northward, and this study provides a reference for the relationship between the northward movement of vegetation and fires globally. Literature [28] analyzed wildfires caused by lightning strikes and examined modeling studies of lightning strike-induced wildfires using lightning data recorded by satellites and different methods of statistical analysis, noting that there is a lack of understanding of lightning strike fires, and fewer experiments have been conducted to construct models of lightning strike ignition dynamics. Literature [29] proposed a research method for analyzing cloud-to-ground lightning based on clustering algorithms and applied it to the evaluation of the ground flash process on transmission lines tripped by lightning strikes, revealing that the frequency of cloud-to-ground lightning varies with the elevation of the ground lightning activity.

In this paper, the meteorological data and digital elevation data of Inner Mongolia from 2015 to 2024 are collected as research samples, and spatio-temporal data mining is conducted to explore the spatio-temporal distribution characteristics of lightning activity in Inner Mongolia from the dimensions of ground flash frequency and current intensity. Subsequently, 11 multi-source terrain feature factors were extracted, and the correlation analysis between the selected terrain factors and lightning ground flash frequency and current intensity was carried out to explore the influence of multi-source terrain features on lightning activities in Inner Mongolia. On this basis, the multiple regression analysis method is used to establish the model of annual average ground flash return frequency per unit area and the model of average current intensity based on the terrain factors, and the regression model is examined by comparing the model prediction and the results of ground flash frequency and current intensity with the actual observation results. Finally, from the perspectives of strengthening publicity, enhancing prevention and strengthening responsibility, it puts forward mine safety countermeasures in Inner Mongolia.

2. Sources and methodology

2.1. Sources

The data on thunderstorm days come from the 10-year (2015-2024) day-by-day thunderstorm observation data of Inner Mongolia meteorological observation stations. When counting the number of thunderstorm days, according to the Code for Surface Meteorological Observations, the occurrence of one or more thunderstorms on a particular day at a station is recorded as one thunderstorm day with 20:00 BST as the day boundary, and if a thunderstorm crosses over 20:00, it is counted as two thunderstorm days. The lightning location data come from the Inner Mongolia Meteorological Data Center, including the specific date, time, latitude and longitude, lightning current amplitude and other parameters of each ground flash. The digital elevation data were obtained from the geospatial data cloud platform of the Computer Network Information Center of the Chinese Academy of Sciences.

Conventional mathematical and statistical analysis methods of meteorological data were used to analyze the characteristics of lightning activities in Inner Mongolia.

2.2. Terrain feature extraction

Eleven surface factors, including longitude, latitude, altitude (H), slope (SL), aspect, profile curvature (SE), plane curvature (SU), slope variability (SOS), aspect variability (SOA), terrain undulation (RDLS), surface cutting depth (CD), surface roughness (RO), and elevation coefficient of variation (EV), were extracted from all lightning data in the same grid point.

2.3. Machine learning methods

Regression modeling is one of the machine learning methods and is the best tool to study and model the linear relationship between the parameters of interest and the independent parameters.MLR is a statistical method that attempts to model the correlation between the variables involved and the response variable based on linear equations in the observed data. The equation of MLR model for this study is:

$$Y_i = b_0 + b_1 \cdot x_{i1} + b_2 \cdot x_{i2} + \ldots + b_k \cdot x_{ik} + e_i \tag{1}$$

where Y_i is the dependent variable, b_0 is the intercept, x_{ik} is the independent variable, b_k is the vector of regression coefficients, and e_i is the residuals, i.e., the random error after removing the effect of the k independent variable on the Y used to discriminate discrete outliers. An outlier is a discrete outlier if the residuals e_i of one set of data (x_i, y_i) are much larger than the residuals of other data in the constructed regression model equation (1).

In this study, MATLAB was used to calculate the MLR model. The MLR in this study minimizes the sum of squared errors between the measured and predicted variables, and the regression coefficients are determined using the least squares technique to minimize the sum of squared errors (RSS), which is defined as follows:

$$RSS = \sum_{i=1}^{n} (y - b_0 - b_1 \cdot x_{i1} - b_2 \cdot x_{i2} - b_3 \cdot x_{i3} - \cdots - b_k \cdot x_{ik}) \tag{2}$$

After constructing the model, model validation is required. Model validation is probably the most important step in the model construction sequence. The validation process may include checking the goodness-of-fit of the regression, investigating whether the regression residuals are random, and testing whether the predictive performance of the model decreases substantially when applied to data not used for model estimation.

Goodness-of-fit is the degree to which a regression line fits the observations. The coefficient of fit R^2 is a measure of goodness of fit, i.e., the proportion (or percentage) of the explained y variance in the total variance of y that is accounted for by the regression model, and ranges from 0 to 1. The closer the value of R^2 is to 1, the better the regression line fits the observations. Conversely, the smaller the value of R^2, the worse the fit.

The fit coefficient R^2 is calculated using the following formula:

$$R^2 = 1 - (SS_{res} / SS_{tot}) \tag{3}$$

where SS_{res} represents the residual sum of squares, which is the sum of the squares of the differences between the true and predicted values, i.e. the error between the predicted and true values. SS_{tot} denotes the total sum of squares, which reflects the total error between the n observations of the dependent variable and its mean, and indicates the degree of dispersion of the values, with larger values indicating greater dispersion. SS_{res} / SS_{tot} denotes SS_{res} excluding the effect of dispersion. where the expressions for SS_{res} and SS_{tot} are given below:

$$SS_{res} = \sum_{i} (y_i - f_i)^2 \tag{4}$$

$$SS_{tot} = \sum_{i} (y_i - \overline{y})^2 \tag{5}$$

$$\overline{y} = (\sum_{i=1}^{n} y_i) / n \tag{6}$$

where, f_i denotes the true value and y_i denotes the predicted value.

In addition, the significance of the multiple regression equation is tested (F-test) by constructing the statistic F. If the p value of the F-test is less than 0.05, it means, the overall regression is significant. Then:

$$F = (SS_{reg} / k) / (SS_{res} / (n - k - 1)) \tag{7}$$

$$SS_{reg} = \sum_{i} (f_i - \overline{y})^2 \tag{8}$$

where SS_{res} denotes the residual sum of squares and SS_{reg} denotes the regression sum of squares. the larger the F the more significant the linear relationship exists. In addition, the smaller the residual variance S^2 is, the more accurately the regression equation is predicted, and the residual variance S^2 is equivalent to the error mean square error MSE, defined as:

$$MSE = SS_{res} / (n - k) \tag{9}$$

In this study, checking the goodness-of-fit of the regression was used to initially judge the accuracy of the model, and then the outliers were eliminated, and when the goodness-of-fit exceeded 90%, the regression equations were determined and the lightning activity data not used to construct the model were used for validation comparisons.

The correlation between the average annual ground flash return frequency per unit area (Y), the absolute value of the average annual current intensity (I) and the topographic factors were analyzed at intervals of 50 m. The topographic factors with good correlation (P-value < 0.05) were selected to establish the regression model, and the normal distribution test was performed for models Y and I , respectively.

3. Characteristics of the spatial and temporal distribution of lightning activity

3.1. Characterization of the frequency of ground flashes

3.1.1. Characteristics of annual changes. The annual average change in the frequency of ground flashes from 2015 to 2024 is shown in Fig. 1.The total number of ground flashes in Inner Mongolia monitored by the lightning locator from 2015 to 2024 shows a yearly increasing trend from 7136 to 12837, the trend of negative ground flashes is consistent with the total number of flashes, the number of negative flashes increases more significantly year by year, and the positive flashes show a fluctuating changes, ranging from 700 to 1600 times. The sample Inner Mongolia region is divided into east, west, south and north, and the average annual change in the frequency of ground flashes is shown in Figure 2. The number of ground flashes in western and southern Inner Mongolia is the highest, higher than that in the eastern and northern regions. The number of ground flashes in western and southern Inner Mongolia increases significantly year by year, and the frequency of ground flashes in eastern Inner Mongolia fluctuates. For the west and south of Inner Mongolia, where the frequency of ground flashes is relatively high, the awareness of lightning protection should be improved in order to reduce the occurrence of lightning disasters.

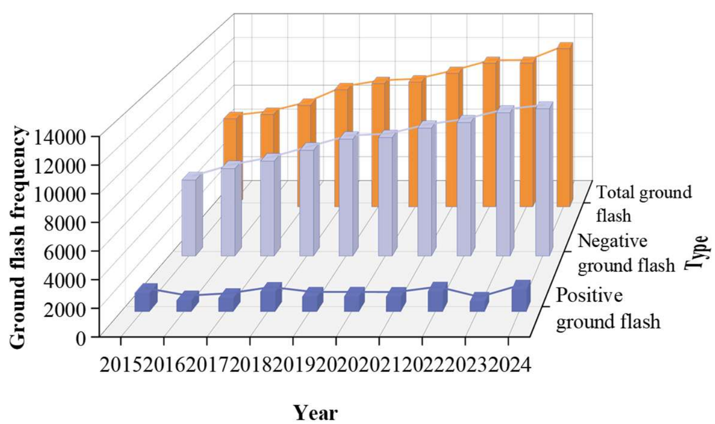


Fig. 1. The annual average change of ground flash frequency

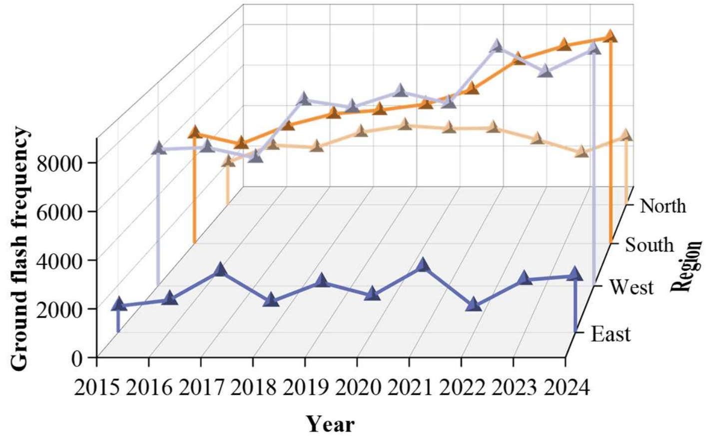


Fig. 2. The average variation of ground flash frequency in all regions

3.1.2. Characteristics of monthly changes. The monthly ground flash frequency and monthly positive flash ratio of lightning activity from 2015 to 2024 are shown in Figures 3 and 4. The monthly variation of ground flash frequency in Inner Mongolia is in a single-peak type, and the ground flash activity is mainly concentrated in May-October, with the peak occurring in September, in which the ground flash frequency in May-October accounts for more than 92% of the total ground flash in the year.In 2024, the most frequent ground flash activity was detected in September, amounting to 3,222 times. There is basically no ground flash activity from November to March each year, and there is a small amount of ground flash activity in April, May, and October.

In addition, the variation characteristics of negative ground flashes are similar to that of total ground flashes, and the probability of positive ground flashes is higher in the early spring and summer. 2015, 2021, and 2022 all have the highest percentage of positive ground flashes in the month of April, 2016 has the highest percentage of positive ground flashes in the month of September, and 2017, 2018, and 2019 have the highest percentage of positive ground flashes in the month of October. 2020 has the highest percentage of positive ground flashes in the months of July versus August. The months with the highest percentage of positive ground flashes in 2023 and 2024 are both August. On the contrary, in the winter, although the frequency of lightning is low, the average current intensity is high, and the probability of positive ground flash is relatively high. Positive ground flash intensity is large, broken ring is stronger, should strengthen preventive measures. Generally speaking, ground flashes in Inner Mongolia are characterized by a monthly single-peak distribution, and summer is the high incidence period of lightning activity.

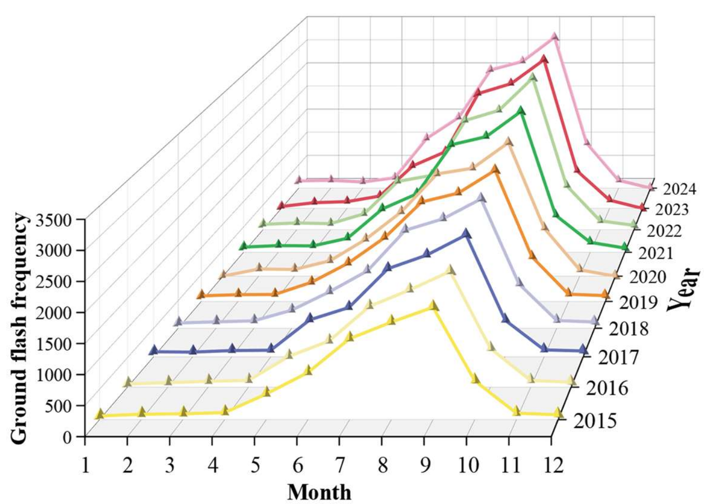


Fig. 3. The monthly change of the ground flash frequency

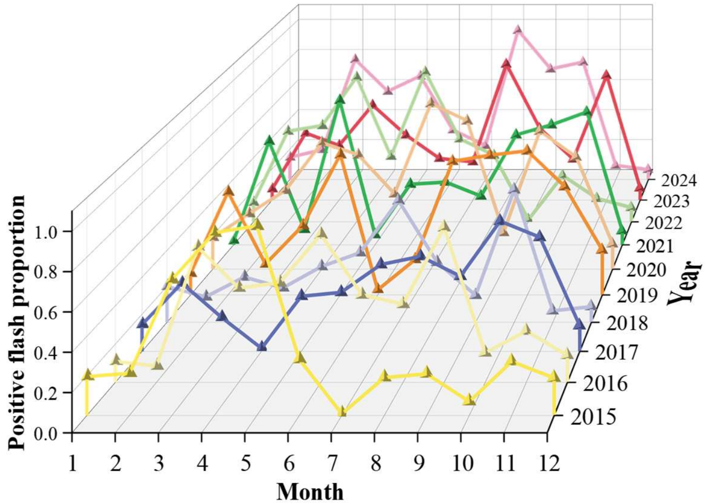


Fig. 4. The monthly change of the proportion of positive flash

3.1.3. Characterization of daily changes. The daily changes in the frequency of ground flashes from 2015 to 2024 are shown in Figure 5. The daily variation of ground flashes in Inner Mongolia is more significant, and the daily variation of ground flashes is mainly of double-peak and double-valley type.The total number of ground flashes in Inner Mongolia was monitored by lightning locator in 2015-2024 with two high values and two low values within one day, and the occurrence in each region is basically the same. Lightning activity mostly occurs in the afternoon hours, and relatively few occurrences in the morning, mainly concentrated in 13:00-18:00, accounting for 34.17% of the whole day, of which the most occurrences are in 14:00-16:00, with a cumulative total of 5,040 occurrences in 2015-2024, and the sub-peak occurs in 03:00-07:00, accounting for 28.58% of the whole day. The trough of the day is mainly in 9:00-12:00, with 11:00-12:00 occurring the least, 6669 times, and the next lowest value occurs from 21:00 to 01:00 of the next day.

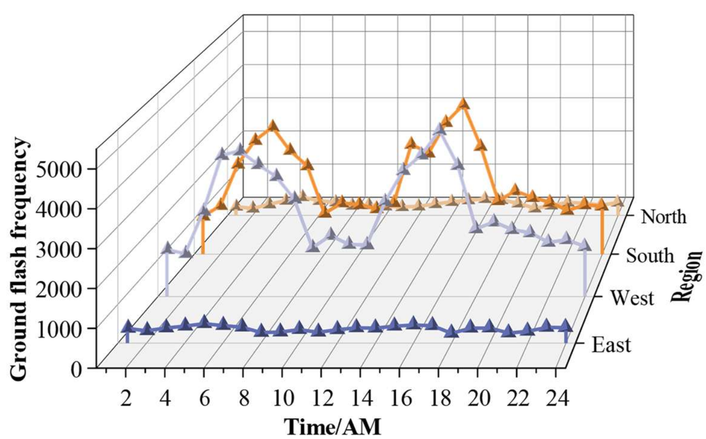


Fig. 5. The daily changes of the ground flash frequency

3.2. Current strength characteristics

3.2.1. Overall distribution of current strength. Taking the data from 119 representative observation sites in Inner Mongolia in 2024 as an example, the overall distribution of current intensity at different observation sites is shown in Fig. 6. The Latitude and Longitude of the locations where the thunderstorm activities occurred range from 37 to 50 and 100 to 124. The total ground flash current intensity is 50012.95 kA, except for the observation point (Latitude, Longitude) = (37.883, 105.4), where the total ground flash current intensity is centered at 20-40 kA.

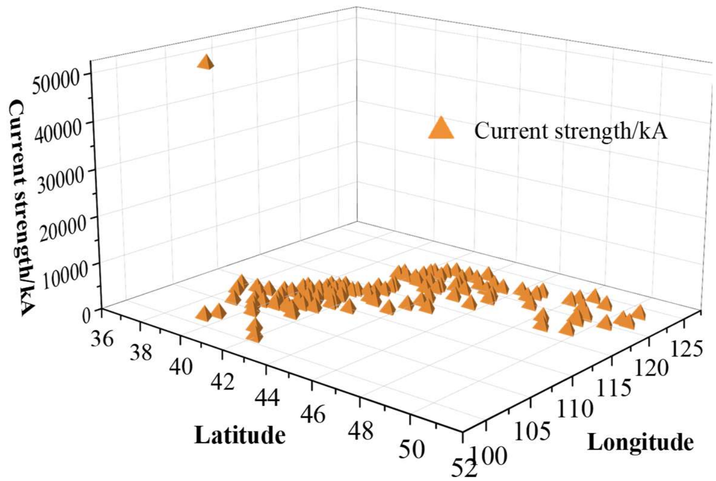


Fig. 6. The current intensity distribution of different observation points

3.2.2. Current Intensity Probability Intersectionalization. The frequency and cumulative percentage changes of ground flashes occurring in different ground flash current intensity intervals were analyzed by dividing the lightning current intensity intervals according to every 20 kA.The frequency and cumulative percentage changes of ground flashes occurring in different ground flash current intensity intervals from 2015 to 2024 are shown in Figure 7. The percentage of positive and negative ground flashes in Inner Mongolia are all in a single-peak type, and both peak at 20-40 kA, accounting for 29.42% and 50.23%, respectively. Positive earth flash frequency in 40-60kA reached the second peak, in 20-60kA, the percentage of positive earth flash as high as 53.71%. Negative earth flash frequency 40-60kA reached the second peak, 20-60kA negative earth flash percentage as high as 64.77%. 88.45% of the negative earth flash current intensity less than 120kA, 86.87% of the positive earth flash current intensity less than 140kA. When the intensity of ground flash current is more than 140kA, the proportion of positive ground flash and negative ground flash in each interval segment is less than 5% and 3%.

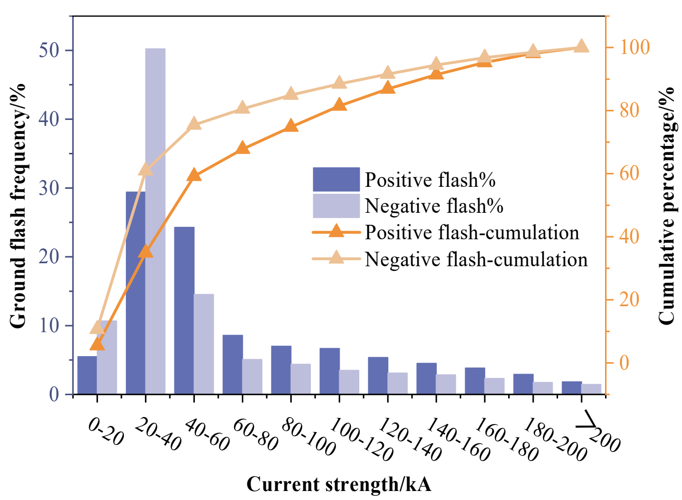


Fig. 7. The frequency and cumulative percentage of different current intensity intervals

3.2.3. Monthly changes in current strength. The monthly change of current intensity of positive ground flash, negative ground flash and total ground flash in Inner Mongolia is shown in Fig. 8. October is the maximum intensity month, September is the second month, the change of ground flash current intensity from January to September is small, and the minimum value of positive ground flash current intensity is 52.48kA in March. The minimum values of negative ground flash and total ground flash current intensity were observed in August with 27.37kA and 25.341kA, respectively. The monthly average values of positive ground flash, negative ground flash and total ground flash current intensity were 68.47kA, 34.57kA and 33.91kA, respectively, and the intensity was less than the average value in the rest of the months, except for September-November. Although the frequency of positive earth flash is less than the frequency of negative earth flash, the average value of positive earth flash current intensity is 1.98 times of the average value of negative earth flash current intensity, and the intensity of positive earth flash current is significantly higher than that of negative earth flash current intensity, a negative earth flash discharge process can usually release dozens to hundreds of coulombs of negative charge within the cloud on the earth, while the positive earth flash can release hundreds to thousands of coulombs of kilometers of electric charge moments, which can result in a more serious lightning strike disaster.

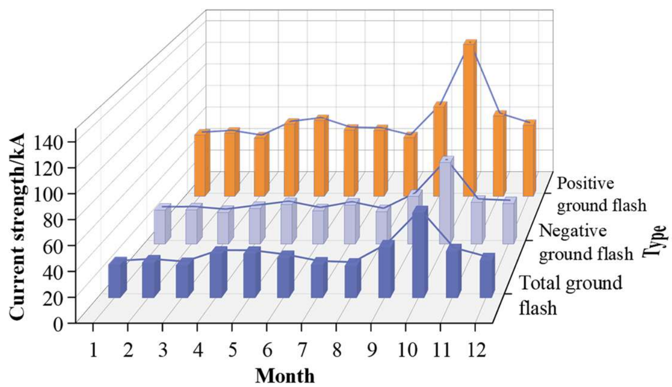


Fig. 8. Monthly variation characteristics of current intensity

3.2.4. Daily variation of current strength. The daily variation of ground flash current intensity in Inner Mongolia is shown in Fig. 9, in all time periods, the positive ground flash current intensity is greater than the negative ground flash current intensity, the positive ground flash current intensity peaks at 4:00 and 16:00, and the ground flash current intensity is 74.46 kA and 67.91 kA, respectively, and the rest of the time period the ground flash current intensity is less than 60 kA. The minimum value of positive ground flash current intensity occurs at 01:00 and is 54.04kA. The negative ground-flash current intensity peaked at 03-08 and 14-16, and the rest of the time the ground-flash current intensity was less than 30kA, the minimum value of the negative ground-flash current intensity appeared at 17:00, which was 20.43kA.The variation of the total ground-flash current intensity was similar to that of the negative ground-flash current intensity, and the daily average value of the positive ground-flash current intensity was 58.59kA, which was 2.35 times of that of the negative ground-flash current intensity. The occurrence of positive ground flashes indicates that the intensity of thunderstorms is stronger and more severe disasters will occur, so the study of positive ground flashes can provide a certain theoretical basis and technical support for disaster prevention and mitigation.

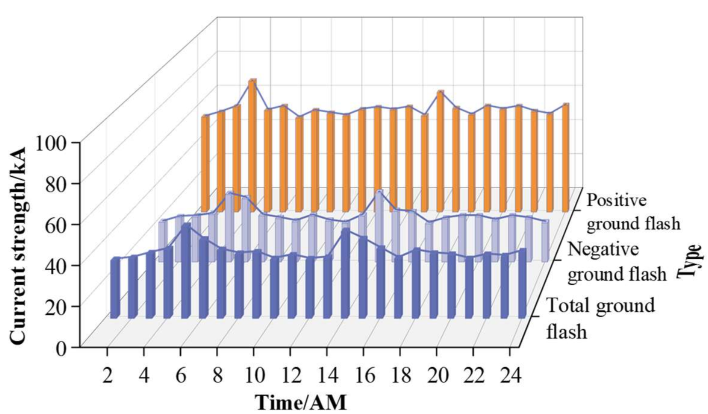


Fig. 9. Daily variation characteristics of current intensity

4. Impact of terrain features on lightning activity

4.1. Correlation analysis

In order to investigate the relationship between each surface characterization factor and lightning activity, correlation analysis was performed using SPSS software, and the results were tested for significance at 95% confidence level, which indicated significant differences when the significance level of the factor was P-value < 0.05, and no significant differences when P-value ⩾ 0.05.

4.1.1. Frequency of ground flashes and topographic features. According to the statistics of every 50 m above sea altitude, SPSS software was used to calculate the Pearson correlation coefficient between the average annual ground flash frequency per unit area and 11 topographic factors in Inner Mongolia from 2015 to 2024, and the significance test of the correlation coefficient was carried out, the correlation results between the ground flash frequency and the terrain factors are shown in Table 1, "*" is the significance test with a confidence of 95%, "-" is a negative correlation, and P-value is the significance level of the factors with a confidence of 95%. The correlation coefficients of lightning ground flash frequency with elevation variation coefficient (EV) and profile curvature (SE) were 0.524 and 0.424, respectively, which were positively correlated, and negatively correlated with height above sea level (H), planar curvature (SU), surface roughness (RO), depth of cut (CD), and degree of topographic relief (RDLS), all of which passed the significance test of confidence level of 95%.

Table 1. The correlation results of ground flash frequency and topographic factor

Topographic factor	Correlation coefficient	P-value
H	-0.728*	0.002
EV	0.524*	0.006
AS	-0.166	0.376
SOS	0.267	0.071
SU	-0.362*	0.016
RO	-0.421*	0.011
SOA	0.134	0.493
SE	0.424*	0.015
CD	-0.475*	0.008
SL	0.053	0.161
RDLS	-0.416*	0.003

4.1.2. Current strength and topographic features. According to the annual average current intensity of ground flash return data in Inner Mongolia from 2015 to 2024 per 50m altitude, the Pearson correlation coefficient between the annual average ground flash return current intensity and the terrain factor is shown in Table 2. There is a positive correlation between the intensity of the lightning flow and the five topographic factors, namely altitude (H), aspect(AS), surface roughness (RO), surface cutting depth (CD) and terrain relief (RDLS), all of which passed the significance test of 0.05 and negatively correlated with the coefficient of variation (EV) and slope variability (SOS), P of 0.003 and 0.008, respectively, indicating that the influence of these two factors on the intensity of lightning lightning flow is also statistically significant.

Table 2. The correlation results of current strength and topographic factor

Topographic factor	Correlation coefficient	P-value

H	0.845*	0.007
EV	-0.457*	0.003
AS	0.351*	0.037
SOS	-0.554*	0.008
SU	0.146	0.312
RO	0.561*	0.004
SOA	0.174	0.338
SE	-0.185	0.293
CD	0.606*	0.009
SL	0.233	0.548
RDLS	0.605*	0.005

4.2. *Modeling and Testing*

4.2.1. Modeling. Combining the above analyses, a multiple linear regression model for the average annual ground flashback frequency and average annual current intensity per unit area was established based on the topographic factors with significant correlation:

Y =2.525-0.003*H-43.547*EV+7.63*10^{-11}*SU+7.93*10^{-5}*RO+6.57*10^{-11}*SE+0.105*CD-0.169* RDLS

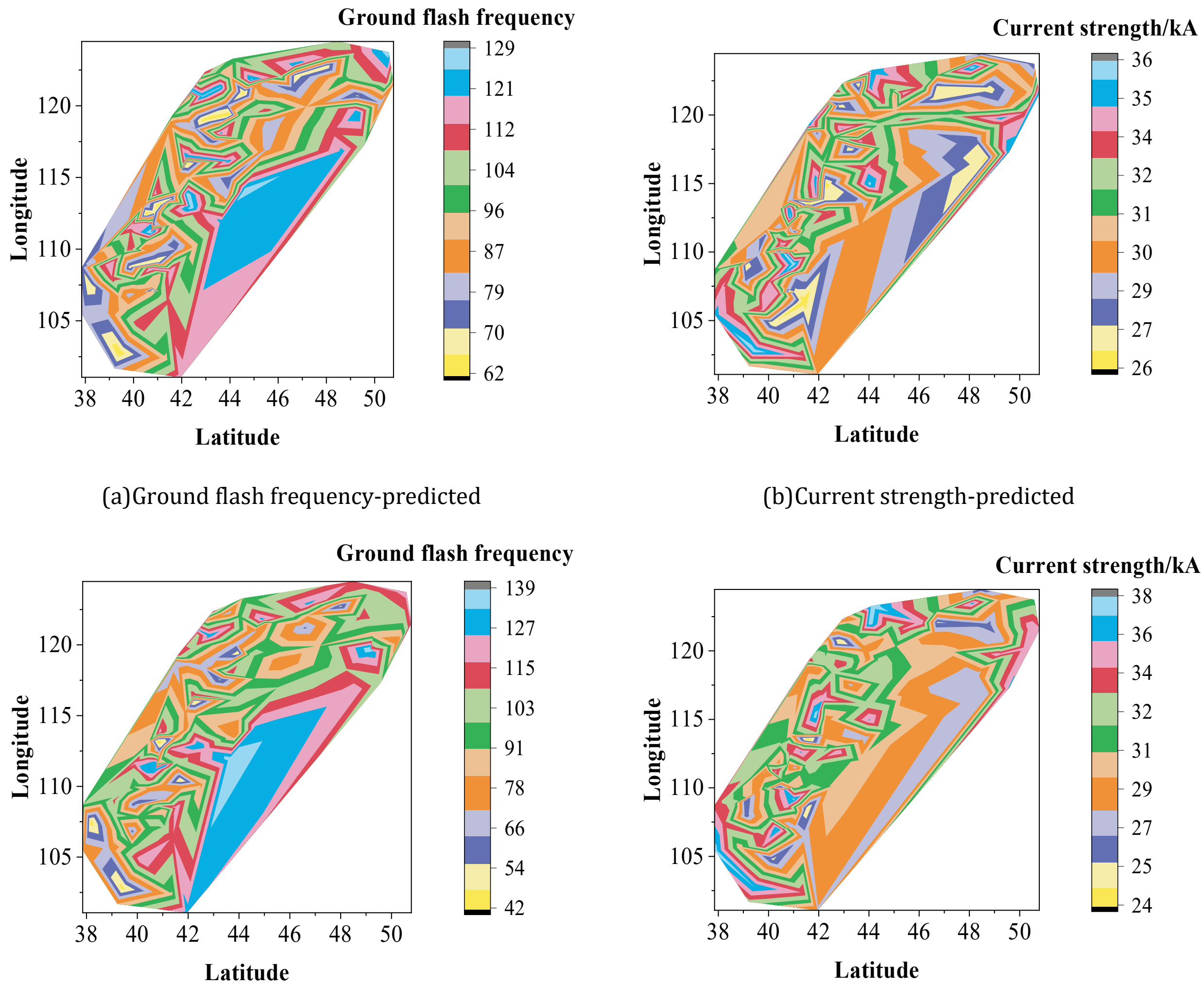
I =26.754+0.023*H+368.372*EV+0.188*AS-0.447*SOS-0.001*RO-2.278*CD+3.295* RDLS

The compound correlation coefficients of the two regression models were .938 and .927, respectively, both of which passed the test of significance with a confidence level of 0.05 for a highly positive correlation.

4.2.2. Model testing. The lightning activity data of Inner Mongolia in 2024 were brought into the model for examination, and the distributions of the annual average ground flash return frequency and average current strength per unit area were plotted according to a 3km×3km grid, and compared with the real data, respectively. The spatial distribution of the model calculation results and observation results are shown in Fig. 10, where (a) and (c) are the calculation results and observation results of the annual average ground flashback frequency, and (b) and (d) are the calculation results and observation results of the average current intensity. The model calculations of the average annual ground flashback frequency per unit area are greater than the observed values, and the difference between the calculated maximum value and the observed maximum value is 7.75%.

According to the error rate = (predicted value - actual value)/actual value, the error between the calculated value and the observed value of each grid is calculated, and the error rate of all grids is averaged to obtain the mean value of error between the predicted value and the observed value of the average annual ground flashback frequency per unit area is 7.31%.

Comparison of Fig. (b) and Fig. (d) shows that the distribution of the average current intensity calculation results and observation results are more similar, and the values show that the calculation results are biased higher than the observation results. The difference between the calculated and observed current values of the model within each grid has a mean value of about 5.08%.



(a)Ground flash frequency-predicted (b)Current strength-predicted

(c)Ground flash frequency-actual (d)Current strength- actual

Fig. 10. The spatial distribution of the results and observations of the model

5. Mine safety countermeasures in Inner Mongolia

Inner Mongolia Autonomous Region is located in the northern border of China, due to the geographical location and topography, the formation of temperate continental monsoon climate mainly complex and diverse climate, as well as unreasonable human activities and other impacts, the region's frequent occurrence of lightning disasters, to put forward the countermeasures for the defense of Inner Mongolia region against lightning disasters.

5.1. Strengthening mine risk reduction awareness

As the basis for the development of disaster prevention and mitigation work, the importance and necessity of publicity work plays a particularly significant role, and the role of enhancing public participation in mine disaster awareness is even more prominent. The development of this work mainly includes three basic levels: (1) lightning disaster prevention and mitigation work can not be separated from the systematic and standardized publicity plan. (2) Actively carry out comprehensive and systematic publicity work, and extend the publicity work to the rural areas, communities, schools, factories and mines at all levels. (3) Reasonable design of mine risk reduction publicity content, the effectiveness of the publicity work is truly reflected, and increase the general knowledge of lightning protection publicity.

5.2. Upgrading mine disaster prevention

1) Constructing a perfect lightning monitoring and early warning system, delineating key areas and key scopes through the installation of lightning locators and other technical means, and constructing a perfect lightning localization system.

2) Relying on computer system science, summarize the law of lightning activity, reasonably assess the probability, intensity and subsequent loss of lightning disasters in different units and regions, and construct a perfect social benefit assessment system for lightning disaster defense.

3) Continuously increase the cultivation and construction of talents, on the one hand, encourage active participation in various types of training and on-the-job education of the staff, on the other hand, we should optimize the structure of the existing talent team, and actively introduce professionals with strong ability and wide knowledge.

4) Build an efficient lightning disaster information collection system with the help of a new information technology platform, and set up lightning safety officers in key areas to promptly and accurately recover and report lightning disaster information, as well as to further strengthen the safety supervision work.

5.3. Enhanced management accountability

1) Ensure that the work of technical and managerial personnel is carried out within the scope of the legal and regulatory system and in accordance with local planning and management mechanisms. Improve the engineering quality supervision of lightning protection facilities in new, renovation and expansion projects, and do a good job of technical evaluation of the design of lightning protection devices. In the daily work, to be able to do a good job in the daily inspection work, the unqualified device, the management department must be required to rectify and pursue the relevant responsibility.

2) fully implement the principle of who is in charge of who is responsible, according to the law, lightning protection work into the various departments of the safety production supervision system, to ensure the depth of the implementation of relevant laws and regulations.

6. Conclusion

The study analyzes the ground flash frequency characteristics and current intensity characteristics of lightning activity in Inner Mongolia based on the collected data of lightning activity from 2015-2024 using spatio-temporal data mining methods, and uses machine learning methods to construct a multiple regression model of multi-source terrain features and lightning activity and test the model.

1) The frequency of ground flashes in Inner Mongolia from 2015 to 2024 shows an increasing trend year by year, and the number of ground flashes is higher in the west and south. The seasonal characteristics of lightning activity in Inner Mongolia are obvious, with summer and early fall being the peak periods of lightning activity, and the frequency of ground flashes from May to October accounts for more than 92% of the year, especially in September.

2) The current intensity of ground flashes is increasing, and the frequency percentages of positive and negative ground flashes in Inner Mongolia are in a single-peak type, and all of them peak at 20-40 kA. 86.87% of positive ground flashes and 88.45% of negative ground flashes have current intensities of less than 140 kA and 120 kA, and the average value of the positive ground flash current intensity is 2.35 times that of the average value of the negative ground flash current intensity, and the current intensity of positive ground flashes is greater than that of negative ground flashes at all times of the day. The average value of positive ground flash current intensity is 2.35 times the average value of

negative ground flash current intensity, and the positive ground flash current intensity is greater than the negative ground flash current intensity in all hours of the day.

3) The coefficient of variation of elevation and profile curvature of multi-source terrain features are positively correlated with the lightning ground flash frequency, while elevation, plane curvature, surface roughness, depth of surface cutting and terrain undulation are negatively correlated with the lightning ground flash frequency. Elevation, slope direction, surface roughness, surface cutting depth and topographic relief were positively correlated with the intensity of ground flash current, and the coefficient of variation of elevation and slope variability were negatively correlated with the intensity of ground flash current. The test results of the regression model show that the errors between the model prediction and the actual value of the ground flash frequency and current intensity are 7.31% and 5.08%, respectively.

4) In summary, the proposed countermeasures for mine safety in Inner Mongolia include strengthening the publicity of lightning disaster prevention and mitigation, enhancing the level of operational work carried out for lightning disaster prevention, and strengthening the management responsibility system in three dimensions, which provide objective scientific basis for preventing lightning disasters as well as enhancing the management of lightning disaster prevention and mitigation.

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