The distribution of lightning discharges across the altitude of the territory in the Altai-Sayan region

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Abstract. For the territory of the Altai-Sayan region, based on the WWLLN data (Word Wide Lightning Location Network) for 2011-2019 and data from the digital elevation model SRTM, the lightning density distribution was constructed for eight altitude zones of the five-hundred-meter interval (from 0 to 4000 m). The errors of spatial registration of lightning discharges were taken into account. It was found that the density of lightning discharges decreases with increasing altitude, which is not uniform for the considered altitudinal zones. With an increase in altitude of 500 m, a decrease in the density of lightning discharges by 20-80% is noted. Therewith, for territories with altitudes of 1000-2500 m, the density of lightning discharges is almost the same. During the period under review, there is a high level of variation in the density of lightning discharges for territories with an altitude of up to 500 m and more than 3000 m above sea level. The most stable lightning activity manifests itself at altitudes of 1500-2500 m above sea level.

1. Introduction

It is known that the role of mountains in the formation of local weather conditions, including thunderstorms, is significant. In mountainous areas, there is an increase in vertical air exchange, which is especially well seen on the slopes of mountain ranges, facing towards moisture-laden air flows. [1-3]. High and steep slopes have a thermal and dynamic effect on the adjacent air layer [4]. Therefore, in the mountains, significant differences in thunderstorm activity can be observed even at tens of kilometers apart, taking into account changes in altitude up to one or two kilometers [2].

For various mountain regions, the dependence of thunderstorm and lightning activity on altitude [2, 5-10] and on the angle of inclination of the slope surface was revealed [11, 12]. For the territory of the former USSR, it was shown that the greatest gradient of thunderstorm activity is observed in the altitude interval of 20-200 m, while the maximum value of thunderstorm activity is observed in mountainous regions at an altitude of 1400-1600 m [13]. The focal nature of the increased density distribution (15-20 discharges per sq.km. a year) of lightning discharges was established. Such foci of lightning activity are observed in the band of 50-60 degrees north latitude, the most active are confined to the mountains of the Caucasus, Altai, they are fixed above the Lesser Khingan range. Modern research has detailed estimates of the density of lightning discharges obtained in the 20th century for the territory of the USSR. The focality of thunderstorm activity was confirmed and developed in further studies, including the territory of Western and Eastern Siberia [6, 7, 14].

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For the territory of North Asia (40-80 N and 60-180 E) based on WWLLN data (Word Wide Lighting Location Network) for 2009-2014, analytical expressions were obtained for the dependence of the distribution of lightning discharge density on latitude, longitude, and altitude [6, 15]. Analytical expressions for each factor take into account the location of the foci of lightning activity and the nonlinearity of the distribution of lightning discharge density with increasing altitude above sea level. It is shown that maxima of the density of lightning discharges are observed at altitudes of 100, 600 and 2000m above sea level and can correspond to river valleys, foothills, small hills and high mountains. Therewith, in areas with an altitude of 1000 to 3500m above sea level, there is a high variation in the density of lightning discharges from zero to maximum values. This leads to errors in modeling the dependence of lightning activity on the altitude.

The aim of the work is to study the nature of the distribution of lightning activity in dependence to the altitude in the Altai-Sayan region based on WWLLN data for 2011-2019. Altai-Sayan region (ASR) is located in the center of Eurasia, its area is more than a million square kilometers. This is a mountainous country with a rugged topography and it is highly elevated above sea level. Territories with altitudes from 1000m to 3500m prevail here, that is of great interest in terms of studying the influence of the terrain on the distribution of lightning discharges.

2. Materials and methods
Lightning activity in the concerned region was estimated on the basis of WWLLN data for 2011-2019. The work of WWLLN network is based on the analysis of time difference of arrival of the lightning signal atmospheric (in the frequency range from 3 to 30 kHz) to the nearest network stations [16]. A lightning discharge is detected by the system if its signal is detected by five or more stations. A detailed description of the registration of lightning discharges by this network is presented in a number of publications available on the WWLLN website [17], as well as in the work [18]. The detection efficiency of the system according to estimates for 2012 is on the average about 11–15% for all discharges, for discharges with a current higher than 40 kA - 25%, higher than 130 kA - more than 30% [19, 20]. The error in determining the coordinates of a lightning discharge on the average is 5 km.

WWLLN data on atmospherics contain the following indicators: date, time, latitude, longitude, error, and the number of stations electromagnetic pulse was recorded by. The network does not determine the type of lightning discharge. Since the maximum spectral density of atmospherics generated by ground-based lightning discharges falls on the low frequency range of 3-30 kHz, it is reasonable to assume that WWLLN detects mainly powerful impulses of ground-based lightning discharges [21].

Altitude information was generated on the basis of the digital terrain model SRTMGL3 [22]. The parameters that predetermined the use of this model are:
1) high spatial resolution (3 arcseconds),
2) data openness (the model is available for download from the site of the US Geological Survey - https://earthexplorer.usgs.gov/),
3) as well as the global scale (from 60 degrees north latitude to 56 degrees south latitude), which allowed the formation of continuous coverage of the territory of the studied region.
As a tool for processing spatial data and collecting cartometric statistics, we used free geoinformation software - QGIS and GRASS.

Error check in localization of lightning discharges was performed as follows. A circle (a buffer) was constructed around each discharge with a radius equal to the value of the error in estimating its coordinates. Then, for each lightning discharge buffer, cartometric statistics on its applicate to sea level were collected and basic statistical indicators (average values, median, minimum, maximum, median altitude deviation) were calculated. In our opinion, the most informative of these indicators are median values, since they minimize the error in determining the altitude of the “contact” (“struck by discharge”) underlying surface above sea level.

The influence of the altitude characteristics of the territory on lightning activity was studied on the basis of the distribution of the density of lightning discharges over altitude zones. The altitude interval
for constructing the distribution series was determined taking into account the error in estimating the coordinates of lightning discharges based on the analysis of the median deviation of altitudes. The maximum values of the median deviation of altitudes inside the buffer of lightning discharges for all years of observations were in the range of 657-794m above sea level. These are very high rates of altitude variation in a hypothetical range of action (of the buffer) of a lightning discharge. At the same time, for 75% of lightning discharges, the values of the median deviation of altitudes in the buffer do not exceed 150m. Therefore, the size of the interval for grouping lightning discharges by the median altitude indicator inside their buffers was chosen equal to 500m above sea level. In this case, the risk of incorrect assignment of a lightning discharge is reduced taking into account the error of its coordinates to the grouping interval, since the width of the interval (altitude zone) exceeds the triple value of the median deviation of altitudes inside the lightning discharge buffer. Thus, the studied region was divided into 8 altitudinal zones with an altitude interval of 500 meters. The area was calculated for each altitudinal zone, the number of lightning discharges was determined, whose median altitudes of the buffers belonged to this altitude zone. Based on these indicators, the density of lightning discharges was calculated for each altitudinal zone.

The authors believe that the proposed approach in the analysis of the influence of altitudinal characteristics of the terrain on the density of lightning discharges has an advantage over the “classical” approach. Usually the territory is divided into “small” sections of equal area, for which the number of lightning discharges is determined and the average altitude above sea level is calculated. In the conditions of a strongly rugged terrain, the altitude indicators, due to altitude large difference, will be overvalued for such areas. Errors may also occur in tracking the number of discharges occurring at the boundaries of “small” sections, taking into account the presence of an error in determining the coordinates of lightning discharges by the WWLLN network.

3. Results and discussion
The nature of the distribution of thunderstorms in the Altai-Sayan region is determined by the processes of general circulation, which are formed by a complex of climatic and physical-geographical factors. The local features of microclimatic conditions are significantly affected by the spatial extension of mountain ridges, which have a predominantly sublatitudinal and submeridional direction. Their relative position, altitude difference, the presence of basins determine the mosaic nature of climatic conditions. River valleys and basins have the lowest altitudes relative to other terrain. The lowest altitudes are typical for the northern part of the region, here they are about 250 meters. To the southeast, there is a general rise of the territory, here the basins are located at an altitude of up to 2200 meters. However, the maximum altitude of the territory - Mount Belukha - is located in the west of the region and reaches 4509 meters.

The total area of the region is 1 million 70 thousand square kilometers. At the same time, about 60% of the area of the considered territory falls on the altitude range from 1000 to 2500 m above sea level (Figure 1), which can be conditionally categorised as the midlands. The share of low mountains is also quite high; territories below 1000m occupy more than 30% of the area.

Analysis of the distribution of lightning activity showed that with increasing altitude, the average annual density of lightning discharges decreases (Figure 2). The highest density of lightning discharges is characteristic for the zone of transition from plains to mountainous territories. The absolute elevations of this zone do not exceed 1000m, but the terrain varies: from leveled areas to very rugged with deeply incised valleys and steep slopes of their sides. These areas are the most developed and populated, this fact identifies the greatest risks for engineering structures, business facilities and people when lightning activity enhances.
At altitudes from 1000 to 2500 m, the density of lightning discharges decreases by 30-50% in contrast to areas with altitudes of up to 1000 m (Figure 2). For territories of these altitudes, lightning discharges are confined to the western and northwestern macro slopes of the ridges, and also to the windward slopes of the ridges enclosing the intermountain basins in the Northwest, Northern, Central Altai, Tuva and Khakassia [23].

At altitudes of more than 2500 m, the density of lightning discharges with each altitude gain of 500 m decreases by 35-50% compared to the previous altitude zone, sharply decreases by 80% above 3500 m and reaches a minimum (Figure 2).

Lightning activity has significant variation in different years. The year 2011 stands out in the temporal distribution, when lightning activity was recorded at the minimum in indicators for the study period. The maximum values of lightning activity were recorded in 2014 and 2017 (Figure 3).

In the considered time period, an altitude-dependent variation in the density distribution of lightning discharges is observed. A slight burst in the density of lightning discharges for altitudes from 1500 m to 2000 m in 2011-2013 and in 2019 can be noted. It should be noted that a similar peak, but more pronounced, was found for the territory of North Asia in 2009-2014 by other researchers [6].

In order to identify the most stable altitude levels in terms of lightning activity, we evaluated the variation of the density of lightning discharges for different altitude zones (table 1).
Figure 3. Density distribution of lightning discharges in the Altai-Sayan region in 2011-2019

Table 1. The distribution of lightning discharge density over the territory at different altitudes above sea level in 2011-2017. (bold type indicates the density values of lightning discharges, large values compared with indicators for areas with a lower altitude above sea level).

| Altitude, m | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | Coefficient of variation of the number of lightning discharges, V (%) |
|-------------|------|------|------|------|------|------|------|------|------|--------------------------|
| to 500      | 0.10 | 0.16 | 0.19 | 0.34 | 0.24 | 0.36 | 0.36 | 0.26 | 0.12 | 43                       |
| 500-1000    | 0.10 | 0.14 | 0.15 | 0.27 | 0.18 | 0.27 | 0.28 | 0.20 | **0.13** | 35                       |
| 1000-1500   | 0.07 | 0.10 | 0.11 | 0.17 | 0.12 | 0.15 | 0.19 | 0.15 | 0.10 | 29                       |
| 1500-2000   | **0.08** | **0.11** | **0.12** | 0.15 | 0.12 | 0.14 | 0.18 | 0.14 | **0.12** | 21                       |
| 2000-2500   | 0.07 | **0.12** | 0.10 | 0.13 | 0.09 | 0.12 | 0.14 | 0.11 | **0.12** | 19                       |
| 2500-3000   | 0.05 | **0.12** | 0.06 | 0.10 | 0.05 | 0.06 | 0.08 | 0.06 | 0.08 | 33                       |
| 3000-3500   | 0.02 | 0.08 | 0.03 | 0.05 | 0.02 | 0.03 | 0.03 | 0.03 | 0.04 | 49                       |
| 3500 and higher | 0.00 | 0.01 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | 0.01 | 0.01 | 33                       |

The smallest level of density variation of lightning discharges relative to the average annual values (coefficient of variation 19-21%) is observed for territories with altitudes from 1500 to 2500m. The greatest variation of lightning activity is characteristic for territories with altitudes more than 3000m, where the coefficient of variation has a maximum value of 49%. The coefficient of variation of lightning discharge density is close to this value (43%) in areas where altitude is below 500m.

Let us pay attention to the fact that in 2012 the highest indicators of lightning discharge density were observed for territories with an altitude range of 2500-3000m and 3000-3500m (table 1). The manifestation of greater lightning activity at these altitudes in 2012 led to high values of the coefficient of variation in the density of lightning discharges for 2011-2019. The genesis of such an anomaly of lightning activity in the conditions of the highlands of the Altai-Sayan region in 2012 is not obvious to the authors of the work and requires a deeper analysis with the use of additional data on the nature of climatic conditions of that year.

Summarizing the results obtained in this study, taking into account the results presented in the works [6, 14, 23, 24], we can assume the following picture of the formation of lightning activity in the Altai-Sayan region.

The variation of lightning activity is determined by the development of cyclonic activity in Western Siberia [14] in different years. Mountain structures can be considered as a barrier that delays the
advancement of air masses and changes the nature of baric formations [25, 26]. Therefore, zones of transition from plains to mountains (up to 1000 m) have maximum values of lightning discharge density.

At altitudes from 1000 to 2500m, the level of lightning activity decreases almost twice as compared with low mountains. In areas from 2500m to 3500m, the density of lightning discharges is almost two times less with altitude moving higher every 500m. Above 3500m, lightning activity is minimal.

At altitudes from 1500m to 2500m, cyclonic activity has a lesser effect on the variation of lightning activity. Here, a pronounced focal character of the spatial distribution of lightning discharges takes place [6, 23]. The formation of foci of lightning activity may be due to the terrain (angle of inclination of the slope surface) [8, 11, 12] and the geological and geophysical specifics of the area [24].

4. Conclusion
In the course of the work, we made an analysis of the location of more than 1 million 400 thousand lightning discharges taking into account the error in their registration made by the global lightning direction-finding system WWLLN.

It was found that the density of lightning discharges decreases with an increase in the altitude of the area, the decrease is uneven for different altitude zones. The highest density of lightning discharges is characteristic of hilly plains up to 500m and foothills with altitudes of up to 1000m. At a level of altitudes from 1000 to 2500 m, the density of lightning discharges decreases by 30-50% compared with previous altitude zones. For altitudes greater than 2500m, the decrease in lightning activity is repeated by about 35-50% for each subsequent altitude zone (2500-3000m and 3000-3500m). Above 3500m, a more pronounced decrease (by 80%) occurs compared to the previous altitude zone and the density of lightning discharges attains a minimum.

Between 2011 and 2019, there is a high level of variation in the density of lightning discharges for territories with altitudes of up to 500m and higher than 3000m above sea level. More stable lightning activity acts in areas with an altitude of 1500-2500m.

Taking into account the specifics of detecting electromagnetic radiation from lightning flashes made by the WWLLN network, it can be assumed that the obtained distribution of lightning discharges over high-altitude zones is typical mainly for powerful pulses of ground-based lightning discharges.

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