Assessment of the lightning discharge energy depending on the height of the territory above sea level for Western Siberia

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Abstract. The work presents the data analysis of the energy of lightning discharges recorded by WWLLN on the territory of Western Siberia. A comparison of the discharge energy distributions in four altitude zones has been performed. Altitude zones are divided into the following conditional categories: lowlands (up to 300 m above sea level), low mountains (from 300 to 1000 m above sea level), middle mountains (from 1000 to 2000 m above sea level) and high mountains (more than 2000 m above sea level). Territories with an altitude of less than 2000 m above sea level are characterized by the presence of thunderstorm foci with an increased density of discharges. At altitudes over 2000 m above sea level, the discharge density is minimal. The energy of 90% of the discharges for lowlands and low mountains does not exceed 10 kJ. A greater number of discharges with energies above 10 kJ are noted in the middle and high mountains. The greatest increase in the energy of lightning discharges is observed for heights over 2000 m above sea level.

1. Introduction

Despite the long-term study of thunderstorm activity, issues related to the peculiarities of the occurrence and spatial distribution of thunderstorms and lightning discharges are still important. For the present, a number of factors have been identified that affect the territorial differentiation of lightning discharge formation.

Differences in lightning activity over continents and oceans, within continents over plains and mountains may be due to different regimes of cloud electrization and conductivity of the water or land surface [1]. Land has the highest density of lightning discharges [2], while the discharge energy is statistically higher over the oceans [3]. The conditions conducive to the formation of more powerful lightning discharges over the oceans are poorly studied. This may be facilitated by the better conductivity of salt water compared to moist soil [4].

Within the continents, thunderstorm and lightning activity has significant spatial heterogeneity. One of the reasons for the formation of such heterogeneity is relief. For mountainous areas, in comparison with low lands, the share of ground discharges increases [5-12], and also larger values of current strength are recorded [12]. In mountainous areas, there is an increase in vertical air exchange, which is especially well traced on the slopes of mountain ranges facing moisture-laden airstreams [13-15].

The aim of this work is to study the dependence of the energy of lightning discharges on the height of the territory above sea level. The data on the localization and energy values of lightning discharges are provided by the World Wide Lightning Location Network (WWLLN). The study region is Western Siberia.
2. Materials and methods
The description of the equipment of receiving stations and the method of registration of lightning discharges by the World Wide Lightning Location Network (WWLLN) is given in publications [16, 17]. The WWLLN network operation is based on the analysis of the difference in the group time of the arrival of the lightning signal (atmospheric) at the points of registration of the network in the frequency range from 3 to 30 kHz. A lightning discharge is detected by the system if its signal is detected by five or more stations. For each lightning discharge, the date, time, geographical coordinates (latitude and longitude), the number of stations where the electromagnetic pulse was registered are recorded. Lightning strike energy (J) is also calculated for a spherical wave in the frequency range from 6 to 18 kHz in 1.33ms. The method for processing WWLLN data in order to determine the energy of a lightning strike is described in detail in [18]. In assessing the energy of a lightning discharge, we used data from the stations that registered the discharge and located at a distance of 1000 to 8000 km from the discharge location. The average power value is written to the data file.

Based on WWLLN data, we have collected statistical characteristics of the energy of lightning discharges recorded in Western Siberia from June to August in 2016-2019. Based on this information, a comparison of the discharge energy distributions in four altitude zones has been performed. Altitude zones are divided into the following conditional categories: lowlands (up to 300 m above sea level), low mountains (from 300 to 1000 m above sea level), middle mountains (from 1000 to 2000 m above sea level) and high mountains (more than 2000 m above sea level). Altitude information was generated from SRTMGL3 digital elevation model [19]. Free geoinformation software QGIS and GRASS were used as a tool for processing spatial data and collecting cartometric statistics.

Comparison of the energy distributions of lightning discharges for the considered altitude zones was carried out using the linear regression method proposed in [3].

3. Results and discussion
The main part of Western Siberia is occupied by the West Siberian Plain, to the south of it are the Altai Mountains, the maximum height of which reaches 4506 m above sea level (mount Belukha).

The highest density of lightning discharges is typical for areas with an altitude of up to 1000 m above sea level. In the area of the West Siberian Plain, areas with an increased density of lightning discharges are dispersed in space and confined to areas favorable for the formation and development of convective clouds in areas with high humidity and heights of 100, 600 m and 2000 m above sea level [20, 21]. Swampy and heavily watered lowlands between the Ob and Irtysh rivers (55-61 degrees N, 60-75 degrees E) stand out as a thunderstorm focus. The foothills of the Altai-Sayan region, located between the Ob and Yenisei rivers (52-55 degrees N, 82-90 degrees E), have a similar intensity of lightning activity. In this region, the formation of more intense lightning activity can be facilitated by the intensification of forced convection on the windward slopes of the Salair Ridge and Kuznetsk Alatau with heights, respectively, up to 590 m and 1900m above sea level [20-22]. The density of lightning discharges is minimal at altitudes over 2000m above sea level in the desertified parts of Altai [22].

The energy of lightning discharges has a lognormal distribution (figure 1). With an increase in altitude, an increase in the energy of lightning discharges is noted. This tendency is well reflected by the decile and median values of the discharge energy recorded in different altitude zones of Western Siberia (table 1). The median values of the energy of discharges for the lowlands are 2-3 times less than the median values of the energy of discharges arising at altitudes above 1000 m above sea level. For 90% decile values, this difference becomes more significant - 3-5 times. Despite these differences, lightning flashes with maximum energy values (several tens of MJ) were recorded not in high mountains, but on flat terrain with heights of less than 300 m. For areas of the territory elevated to a height of more than 1000m and located in the south of western Siberia, the maximum discharge energy does not exceed 1 MJ.
Figure 1. Energy distribution of lightning discharges for different altitude zones.

Table 1. Characteristics of the energy of lightning discharges according to WWLLN data for 2016-2019 for different altitude zones.

| Parameters       | Lowlands (less than 300 m above sea level) | Low mountains (300-1000 m above sea level) | Middle mountains (1000-2000 m above sea level) | Highlands (more than 2000 m above sea level) |
|------------------|--------------------------------------------|--------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Minimum (J)      | 3                                          | 1                                          | 16                                           | 4                                             |
| 10% decile (kJ)  | 0,2                                         | 0,3                                        | 0,4                                          | 0,5                                           |
| Median (kJ)      | 0,8                                         | 1,4                                        | 1,7                                          | 2,4                                           |
| 90% decile (kJ)  | 5                                           | 7                                          | 13                                           | 26                                            |
| Maximum (MJ)     | 32                                          | 1,3                                        | 0,7                                          | 0,7                                           |
| Linear Regression|                                             |                                             |                                               |                                               |
| Slope ($\frac{\partial \log_{10}E}{\partial i}$) | 0,19                                       | 0,19                                       | 0,21                                         | 0,23                                          |

The slope of the linear regression for the decimal logarithms of the average energy of the discharges and the decile numbers to which they belong allows us to estimate by what percentage (logarithmically) the energy of a lightning flash increases with a transition by 1 decile. The calculated regression equations for different altitude zones have a coefficient of determination of more than 0.9. For areas of Western Siberia with heights of less than 1000m above sea level, the energy of lightning discharges increases on average by $10^{0.19} = 55\%$ per decile, for areas with heights from 1000 to 2000m - by $10^{0.21} = 62\%$ per decile, above 2000m - by $10^{0.23} = 70\%$ per decile (table 1) The obtained values of the slope of the linear regression for Western Siberia are consistent with the results presented in [3] for the WWLLN data for 2009-2012.

Additionally, the ranking of lightning discharges by energy intervals was performed, which made it possible to calculate the density of discharges within such intervals for each altitude zone. Hereafter, we compared these densities in order to determine how the indicators of highlands differ from those of other high-altitude zones. Figure 2 shows the result of the work done. The greatest difference in the ratio of the discharge densities is observed for the highlands and lowlands, the smallest difference for the highlands and middle mountains. A sharp discrepancy between the indicators of highlands and lowlands begins from discharges with energies above 1 kJ. A characteristic feature of high-
mountainous areas in the south of Western Siberia is a high density of lightning flashes with energies above 10 kJ.

Figure 2. The ratio of the density of lightning discharges in high mountains to the density in other high-altitude zones for different energy levels.

The occurrence of lightning discharges of greater power in the highlands as compared to the lowlands and low mountains is characteristic of all continents. This is clearly seen on the map of the spatial distribution of the slope of the linear regression performed for the whole world according to WWLLN data for 2009-2012 and presented in [3]. The maximum values of the slope of the regression are confined to mountains with heights of 3000-6000m above sea level. The largest territory is occupied by areas of the Western Cordillera (South America). Smaller and significantly «local points» are observed in the region of the Tibesti mountain plateau in central Sahara (Africa) and in the mountains of the Altai-Sayan region (Northern Asia). Thus, in the high-mountainous regions with an arid climate, there are special conditions for the formation of the most powerful lightning discharges. The answer to the question «What is the reason for this feature?» has yet to be found and substantiated.

At the moment, from the entire possible set of factors, one should not exclude the influence of deep faults, which are most often traced by gravity field anomalies and can be seismically active. In the zones of structural and geological inhomogeneities of the earth's crust, there is an intense gas exchange, aerosol exchange, heat and moisture exchange, which can cause a change in baric fields and provoke ascending currents. This is confirmed by the formation of so-called tectonic clouds along active geological faults or in places of tectonic centers [23]. Due to the intense energy and mass transfer in geoactive zones, the presence of which is common to the mountains in the south of Western Siberia, conditions for the formation of the most powerful lightning discharges can be developed [24].

4. Conclusion
Modern global and regional studies, carried out on the basis of instrumental measurements of lightning activity, have found places of positioning of thunderstorm foci with the maximum density of lightning discharges. It turned out that lightning discharges with low energies predominantly occur in thunderstorm foci. There are areas where a small number of lightning discharges with higher energies are observed. On a global scale, these are oceans; on a regional scale, within continents, these are highlands. The tendency to localize the most powerful discharges at altitudes above 2000m above sea level can be traced on all continents, especially in mountainous regions with an arid climate. A global assessment of the distribution of areas with high lightning discharges energy was performed in [3], but
a regional assessment for individual inland areas was not carried out. For the territory of Western Siberia, such studies were performed for the first time.

In this work, the spatial distribution of the lightning discharge energy, depending on the height above sea level in the territory of Western Siberia, was studied in detail. Within this region thunderstorms with an increased density of lightning discharges are localized in areas with heights of no more than 2000m above sea level. Based on WWLLN data, it is shown that with a small number of lightning discharges occurring at altitudes above 2000m above the sea level, the intensity (power) of 50% of the discharges exceeds 2 kJ, for 10% of lightning discharges it exceeds 26 kJ (90% decile). While for areas with lower altitudes, the median values of the energy of lightning discharges vary in the range from 0.8 to 1.7 kJ, the values of 90% decile range from 4.8 to 13 kJ. There is a sharp increase in the number of lightning discharges in the highlands, starting from 10 kJ. The greatest increase in the energy of lightning discharges is observed for heights over 2000m above sea level.

A detailed analysis of the reasons for such a distribution of the energy of lightning discharges is the subject of future research.

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