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Communication

Analysis of Sprite Activity in Middle Latitudes

Andrey Evtushenko [1,2,*], Ekaterina Svechnikova [1] and Alexander Kudryavtsev [2]

1 Institute of Applied Physics, Russian Academy of Sciences, Nizhny Novgorod 603950, Russia; svechnikova@ipfran.ru
2 Department of Differential Equations, Mathematical and Numerical Analysis, Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod 603022, Russia; s22380602@itmm.unn.ru
* Correspondence: evtushenko@ipfran.ru

Abstract: Sprite activity in the middle latitudes of the Northern Hemisphere is analyzed, with the example of the territory of Russia, aiming to facilitate the planning of observational campaigns in the region. The global model previously proposed by the authors is applied, using data from the WWLLN lightning detection network for 2015–2021. It is shown that the total number of sprites per year varies widely, from 394 in 2019 to 2354 in 2015. The most intense sprite activity almost always occurs in July, but in some years, there may be a shift to June (2015) and August (2021). The highest frequency of sprite initiation is observed in the Krasnodar Territory, Altai, and the Far East. Altai shows a high intensity of sprite activity every year, which is caused by the relief and underlying surface, while Krasnodar Territory and the Far East demonstrate sprites developed by incoming convective systems, which leads to high year-to-year variability.

Keywords: sprite; high-altitude discharge; WWLLN

1. Introduction

Field observations of high-altitude discharges, alongside laboratory and numerical modeling, allow us to draw a conclusion about significant local disturbances in atmospheric parameters accompanying the development of sprites [1]. The dynamics of the main chemical components were examined in detail for sprites in night conditions using self-consistent radially symmetric modeling [2], where, in particular, it was shown that the relaxation time of the electron concentration disturbance after a single sprite varies with altitude: from a few seconds at 75 km to 1000 s by 82 km, and the radius of electron density disturbance increases from 10 km at an altitude of 75 km to 40 km at 79 km, due to differences in field dynamics, conductivity, concentration of neutral components, and rates of chemical reactions in ion conversion and recombination. Particularly powerful mesoscale convective systems (MCS) can create conditions for the initiation of a series of high-altitude discharges and thus lead to long-lived conductivity disturbances. One of the main questions for understanding the influence of high-altitude discharges in general and sprites in particular on physical and chemical processes in the mesosphere is the question of the global distribution of sprite initiation.

Reliable statistics and parameters of the global distribution of sprites based on direct observation data currently do not exist and are not expected since the creation of a global system for monitoring sprites (or any high-altitude discharges) would require the organization of constant observations in many parts of the globe, which is unattainable in the first place for financial reasons. Consequently, the development of indirect methods for assessing sprite activity, both on a global and regional scale, is an extremely urgent task.

Previously, the authors proposed a parameterization for studying the global distribution of sprites based on data from the WWLLN lightning detection system and applied it to analyzing sprite activity in 2016 [3]. In this work, a similar approach is applied to study

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sprites over the territory of Russia for the period 2015–2021. The initiation of each sprite is associated with a powerful lightning discharge, which is called the parent, which makes it possible to propose a parameterization for the distribution of sprites based on the lightning detection data. It is known that the main centers of global lightning activity are located in Southeast Asia, Africa, and the Caribbean Sea, i.e., close to the equator, where altitude discharges are recorded year-round. Along with an increase in latitude, seasonality for lightning activity becomes more and more pronounced, and the intensity and frequency of thunderstorms decrease, which leads to a significant decrease in the number of recorded high-altitude discharges, but they cannot be called very rare events [4]. There have been no large campaigns to observe high-altitude discharges directly in Russia, although few cases of recording sprites have been described. The calculations presented in this study can be used to plan observations of high-altitude discharges, in particular for choosing a place and time for observations, and, what is more, can provide an assessment of local sprite activity over the territory of Russia.

2. Methods

Parameterization for studying the global distribution of sprites according to the lightning detection system WWLLN is presented in [3]. The proposed parameterization consists of five sequential steps: (1) processing of WWLLN data, highlighting night events and skipping lightning discharges with low currents; (2) estimating peak current using lightning energy data according to the formula proposed by the developers of the WWLLN system; (3) calculating the distribution of sprite initiation over impulse charge moment change (ICMC) for positive and negative discharges, using the parameterization proposed by the authors; (4) taking into account the possibility of sprite initiation; and (5) identification of the most probable parameters, which we will further call the "basic scenario", and the sensitivity of the created model to variations in the main parameters. The basic scenario and the sensitivity of the proposed parameterizations to the selected parameters were discussed in detail in [3].

In this work, sprite activity over the territory of the Russian Federation was chosen as the object of study; data from the WWLLN lightning detection system for the 2015 to 2021 years are analyzed. The results were obtained for the base scenario.

2.1. Processing of WWLLN Data

The simulation considers only sprites in night conditions, so we leave only the lightning for which the sun has set below the horizon at an altitude of 90 km. We also cut off lightning with a peak current of less than 15 kA since they are not able to carry a sufficient charge and, consequently, cannot create conditions for sprite initiation. The results of applying the described selection are presented in Table 1. This trend generally coincides with the global dynamics of lightning activity; perhaps only in 2019 and 2020, the global decrease in lightning activity was not so great, and relative to 2015, it was 23% and 28%, respectively.

Due to the location of the Russian Federation in the mid-latitudes of the Northern Hemisphere, the seasonality of thunderstorm activity here is more pronounced than the global average. The total number of lightning discharges for the period November–March in each of the years under study is in the range of 1000–2000 discharges, i.e., no more than 0.3% of the annual number of discharges; thus, these months can be excluded from consideration. Only a few days in November–March may be of some interest, such as 30 November 2021, when 800 discharges were recorded—that is, almost half of all discharges over a period of 5 months—but such cases are very rare. In the period from 2017 to 2020, the largest number of lightning discharges was recorded in July 2015, in June 2016, and in August 2021. Considering absolute values, June 2015 is anomalous: almost half of all discharges for the year, and comparable, for example, with the number of discharges for the whole year 2019. From 17 June to 30 June 2015, the number of lightning discharges daily exceeded the characteristic values by 2–3 times, which is associated with the development of intense cyclones over the European part of Russia. Despite the significant area of the Russian Federation, lightning activity is not great and amounts to only 0.6–0.8% of the global one for the selection rules described above.

Table 1. Distribution of the number of lightning discharges by current, the total number of lightning strikes per year, and the average current per year. Statistics for Russia over the period from 2015 to 2021.

Year	Group 1 (15–100 kA)	Group 2 (100–200 kA)	Group 3 (200–300 kA)	Group 4 (300+ kA)	Total Number of Discharges	Average Current, kA
2015	78.35%	16.37%	3.05%	2.23%	753,452	80
2016	82.47%	12.91%	2.63%	1.99%	731,423	71
2017	90.28%	7.84%	1.17%	0.71%	726,637	52
2018	88.31%	9.33%	1.47%	0.89%	550,380	56
2019	93.30%	5.41%	0.82%	0.48%	354,490	42
2020	93.64%	5.19%	0.71%	0.46%	492,871	42
2021	90.47%	7.74%	1.12%	0.67%	707,237	51

An important feature of the WWLLN network is the availability of data not only on the location and exact time of each discharge starting in 2015 but also on the estimated average lightning energy, which, according to the empirical relationship proposed by the system developers, can be used for estimating the value of the peak current in the lightning channel [5]. The final results of data processing are presented in Table 1. Of great interest is the distribution of the number of discharges by current. We can distinguish four groups of discharges by current: (1)—15–100 kA, (2)—100–200 kA, (3)—200–300 kA, and (4)—over 300 kA. Naturally, group (1) will always be the largest; from 2017 to 2021, its share of the total varies from 88.3% to 93.3%, and in 2015 and 2016, the share of this group was significantly less: 78.4% and 82.5%, respectively.

As shown in [3], discharges from group (1) as well as from group (4) do not make a significant contribution to the number of initiated sprites, and groups (2) and (3) play the main role. The distribution of the number of discharges over four groups also determines the average current for the year. Maximum currents were observed in 2015–2016, with minimums in 2019 and 2020. Due to its geographical location in the mid-latitudes of the Northern Hemisphere, average currents in the Russian Federation only in the summer months are comparable to average global currents; in the spring-autumn periods, they are 20% lower.

2.2. Sprite Parameterization

The WWLLN system does not provide an estimation of the polarity of a lightning discharge, whereas this is extremely important information for sprite initiation. The development of a positive cloud-to-ground discharge is usually accompanied by a long continuous current phase of lightning discharge with significant charge transfer, which rather often leads to sprite initiation than negative lightning discharge. At the same time, the development of a negative cloud-to-ground discharge is much more likely, and according to statistics, the average ratio of positive discharges is about 10% [6–8]. To the best of the authors' knowledge, there are no statistics on the ratio of positive and negative discharges for the whole territory of Russia, while there is a study of lightning discharge statistics in the North Caucasus that does not show differences from global data [9]. Let us denote the parameter R = 10%, the relative quantity of positive discharges, and, accordingly, $1-\mathrm{R}$ = 90% for negative discharges. Therefore, in further statistical analysis, each discharge is considered to be R = 10% positive and $1-\mathrm{R}$ = 90% negative. A further transition from the peak current for positive and negative lightning to the average ICMC and its distribution, taking into account the probability of sprite initiation, is also made within the framework of the basic scenario, described in detail in [5]. Since the number of sprites initiated by negative discharges is small (as shown in further calculations), then to a first approximation, the dependence of the resulting number of sprites on the ratio of positive discharges is linear.

3. Modeling Results

The study shows that the number of sprites over Russia varies significantly from year to year: from 394 in 2019 to 2354 in 2015, see Figure 1, which could be assumed immediately from the analysis of the WWLLN data. The dynamics of the number of sprites over Russia is unexpectedly close to the global one: from 2015 to 2019, there was a gradual decline in the number of sprites, with a subsequent increase in 2020–2021. We additionally made calculations for the global number of sprites for 2015–2021, similar to the basic scenario described in our 2022 article. It can be seen that there is significant annual variability: from 2354 sprites in 2015 in Russia and 419,991 globally to 394 and 108,468, respectively, in 2019, which undoubtedly complicates the comparison of model calculations and, for example, satellite data [10]. One might expect that the change in sprite activity in mid-latitudes has a larger amplitude, but comparison with the global sprite distribution shows that the trend is quite close to the global trend. In the study carried out, both positive and negative high-altitude discharges were considered separately. The number of negative sprites is about 1%, which is in agreement with global calculations [11].

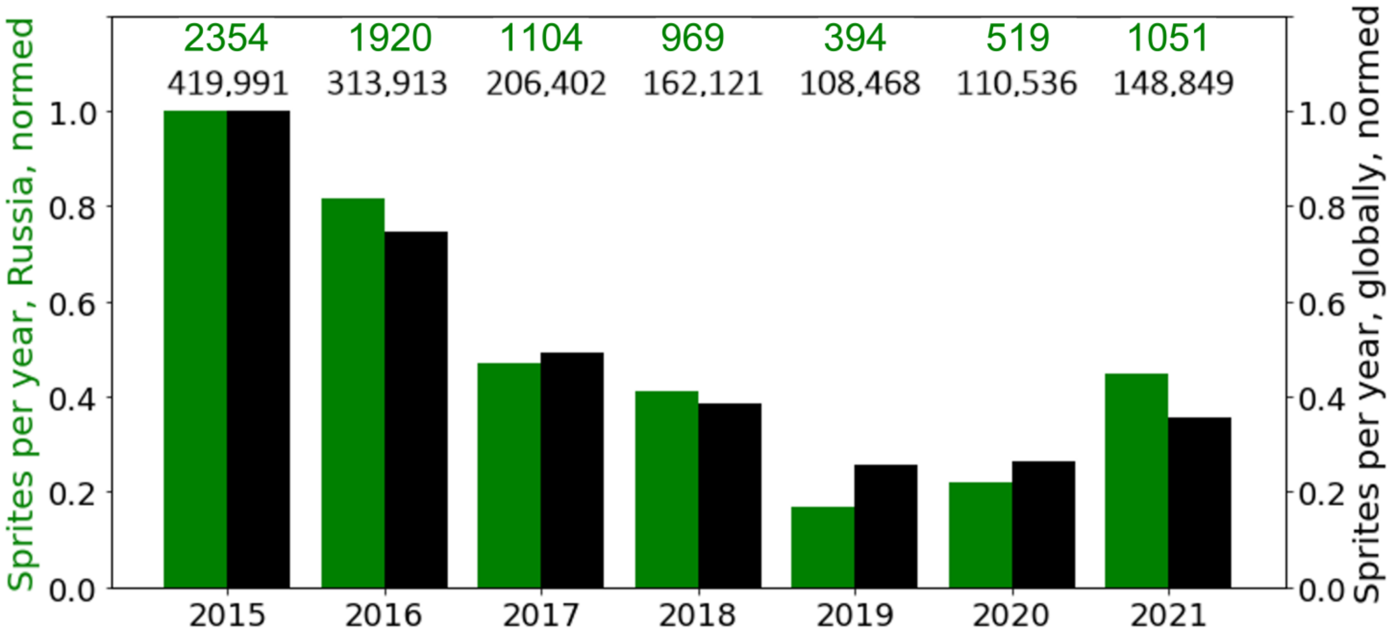

Figure 1. Number of sprites over Russia (green) and over the planet (black) in 2015–2021, relative to corresponding numbers in 2015; absolute values marked on the diagram.

Sprite activity over Russia has a pronounced seasonality (Figure 2): the largest number of high-altitude discharges occurs from June to August, while the number of sprites from November to March is negligible and amounts to less than 2% of the total. Between 2016 and 2020, the maximum number of sprites was observed in July. If August 2021 was the most active month, with a minimal excess over July, then in 2015, the number of sprites in June was almost 30% higher than in July. June 2015 was an anomalous month with over 800 sprites initiated, which is comparable to the number of sprites in 2019 and 2020 summed up, or 2018 and 2021 separately. It is particularly interesting that in 2016 and 2021, the highest number of lightning strikes was recorded in August and exceeded the number for July by 30–50%. The number of sprites in August 2021 is only slightly higher than in July, and in 2016, sprite activity peaked in July. That is, the number of lightning discharges does not always define the number of sprites; the distribution of currents is important, too.

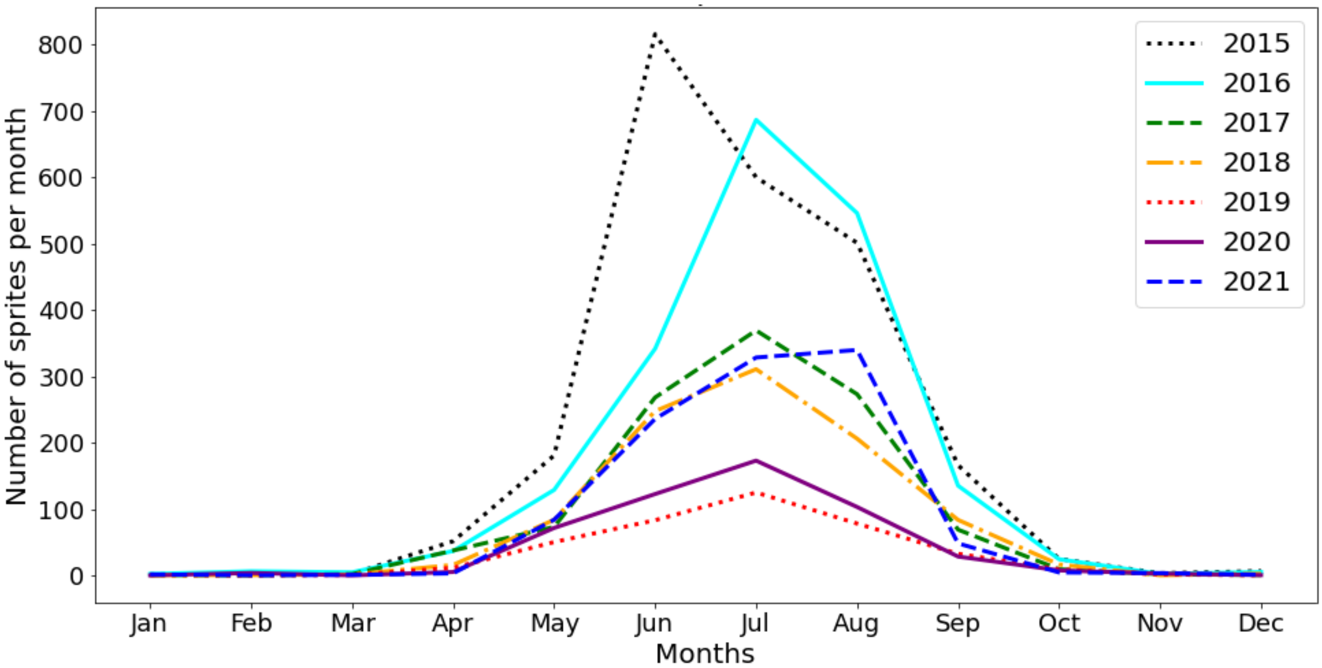

Figure 2. Seasonal dynamics of the sprite number for 2015–2021.

The map of the geographical distribution of sprites for 2015–2021 over Russia was obtained by averaging the calculated data for the entire period (Figure 3). An increase in the number of sprites with decreasing latitude is clearly visible, which is typical for atmospheric electricity phenomena in general since lower humidity and the intensity of convection at higher latitudes do not allow active separation of charges. Taking into account the calculation data for different years, we can conditionally distinguish three areas with high sprite activity: Krasnodar Territory, Altai, and the Far East. Altai is clearly visible on the final map, which is due to the constantly high number of sprites from year to year. The formation and development of MCSs in the territory from 70° to 90° east longitude and from 50° to 60° north latitude were studied in detail in [12], that is, exactly where the average sprite activity has maximum.

It is well known that MCS, due to their structure and large horizontal dimensions, are capable of accumulating large charges, which, on the one hand, contribute to high lightning activity and, on the other hand, allow the development of positive lightning discharges, characterized by high current and transferred charge. The territory considered in [12] is a forest-swamp zone with a swamp area of 40% to 90%, a forest-steppe zone with a swamp area of up to 25%, and a large number of lakes, which in the summer season increase the moisture content and convective potential of the atmosphere. Additionally, in the southeast, there are mountain systems, which also contribute to lightning activity. On average, 27 MCS are observed in this territory per year, with a characteristic area of about 9000 km^2. Sprite activity in the Far East and Krasnodar Territory, in contrast to Altai, seems to be determined by thunderstorm systems coming from outside, which determines strong variability not only year to year but also from month to month during the summer season. The average sprite activity in all three selected regions is comparable in 2015–2016; one can even say that in 2015, the all-Russian sprite statistics were determined by the European part (Figure 3), but starting from 2017, the largest number of sprites is in Altai.

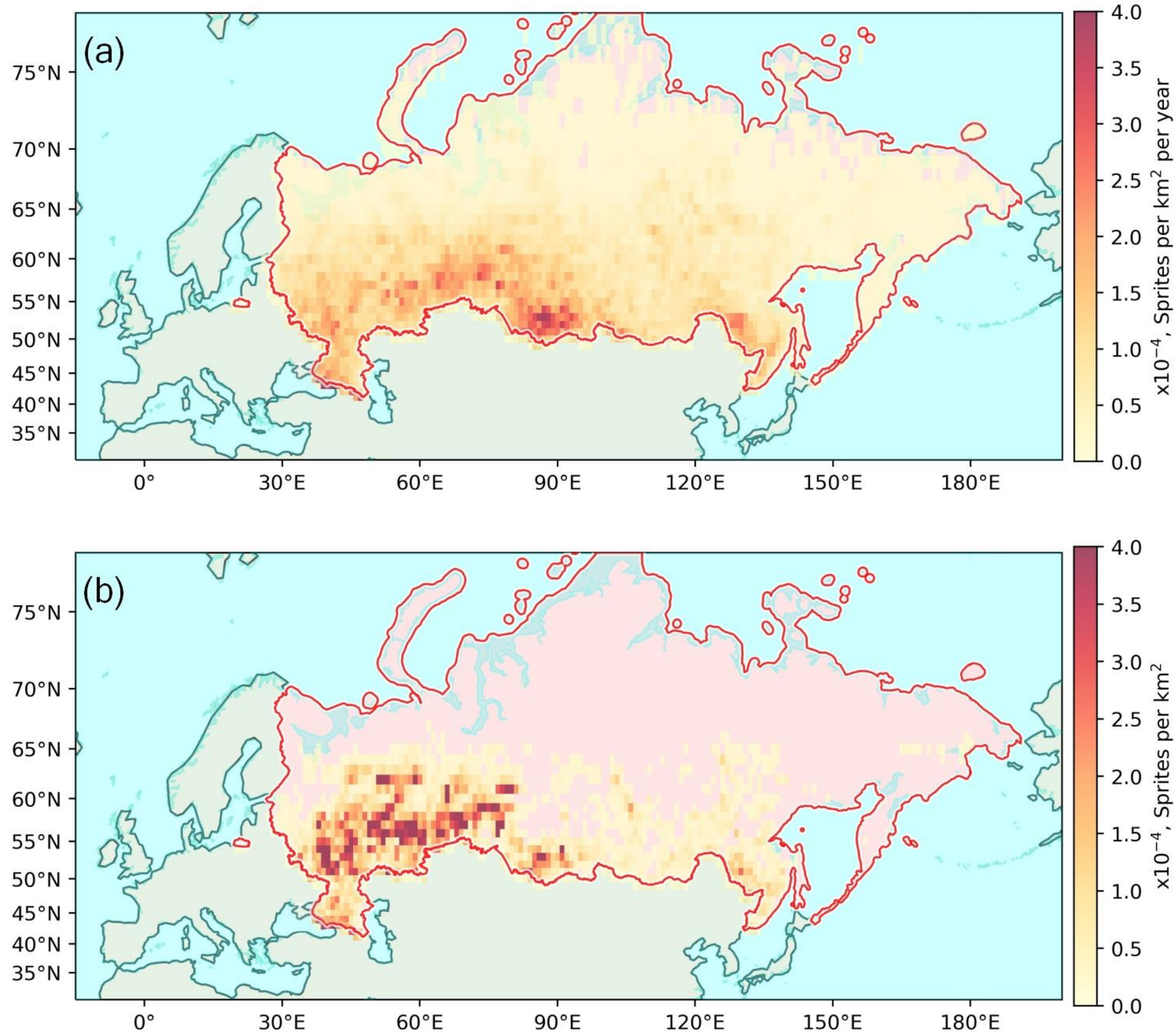

Figure 3. Average density of sprites occurrence (**a**) over the territory of Russia for 2015–2021; (**b**) sprite density over Russia in June 2015 (bottom).

4. Discussion and Conclusions

Based on data from the WWLLN lightning detection network for 2015–2021 and a set of parameterizations developed by the authors [3], the seasonal and geographic distribution of sprite initiation activity in Russia was studied. A change of almost an order of magnitude in the number of sprites year-on-year is shown as follows: from 394 in 2019 to 2354 in 2015. The annual dynamics of sprite initiation have a pronounced maximum in the warm season, and in 5 of the 7 years studied, the largest number of sprites is observed in July.

Prominent sprite activity is shown to be south of latitude 65°, with a trend for the average number of sprites to increase with lowering latitudes. Three regions with high sprite activity have been identified: Altai, Krasnodar Territory, and the Far East. It is shown that due to the characteristics of the relief and underlying surface in Altai (forest-swamp and forest-steppe zones with a high degree of swamping are complemented by a mountain system in the southeast), conditions for the formation of MCS and high sprite activity are created annually, and in the Far East and Krasnodar Territory, sprite activity is determined by incoming convective systems and has high year-to-year variability.

As with any lightning detection system, the issue of detection efficiency is very relevant for WWLLN. The influence of this factor on global distribution is discussed in detail in the article [2], where it is shown that the number of sprites can increase by several tens of percent. Since the number of receiving stations in and around Russia is quite small, one can expect that more sprites are undetected, but an accurate estimate of the effect is not possible.

Validation of the obtained model results is quite a difficult task, and solving it directly is not possible due to the lack of experimental data. In 2004, a mission for satellite observation of TLE and lightning activity was specially organized [10,13], the results ofwhich allowed, under some assumptions, to draw a conclusion about the global intensity of TLE initiation. Unfortunately, the satellite observed only a small part of the territory of Russia in the summer; however, it can be concluded that for mid-low-altitude regions, the intensity of sprite initiation should be about 10^{-2}–10^{-4} events/km^2/year [10], which is consistent with the above calculations. The qualitative and quantitative agreement of the developed global model based on WWLLN data and the results of satellite measurements is shown in [3], including analysis of the sensitivity of the model to changes in the main parameters. The proposed method for estimating sprite activity was also applied in [14], which showed good agreement with data of sprites observations carried out in Japan, which exhibits a peak during the winter thunderstorm season.

The calculations provided in this study are helpful for planning observations of high-altitude discharges, particularly estimating the possible number of sprites in a given area. Such estimations are crucial for selecting the location and timing for observations. Furthermore, the present analysis can assist in evaluating local sprite activity over the territory of Russia.

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References

1. Gordillo-Vázquez, F.; Pérez-Invernón, F. A review of the impact of transient luminous events on the atmospheric chemistry: Past, present, and future. *Atmos. Res.* **2021**, *252*, 105432. [CrossRef]
2. Evtushenko, A.A.; Kuterin, F.A. Self-consistent model of a night sprite. *Radiophys. Quantum Electron.* **2017**, *59*, 962–971. [CrossRef]
3. Evtushenko, A.; Ilin, N.; Svechnikova, E. Parameterization and global distribution of sprites based on the WWLLN data. *Atmos. Res.* **2022**, *276*, 106272. [CrossRef]
4. Yair, Y.; Price, C.; Katzenelson, D.; Rosenthal, N.; Rubanenko, L.; Ben-Ami, Y.; Arnone, E. Sprite climatology in the Eastern Mediterranean Region. *Atmos. Res.* **2015**, *157*, 108–118. [CrossRef]
5. Hutchins, M.L.; Holzworth, R.H.; Rodger, C.J.; Brundell, J.B. Far-Field Power of Lightning Strokes as Measured by the World Wide Lightning Location Network. *J. Atmos. Ocean. Technol.* **2012**, *29*, 1102–1110. [CrossRef]
6. Zajac, B.A.; Rutledge, S.A. Cloud-to-Ground Lightning Activity in the Contiguous United States from 1995 to 1999. *Mon. Weather Rev.* **2001**, *129*, 999–1019. [CrossRef]
7. Poelman, D.R.; Schulz, W.; Diendorfer, G.; Bernardi, M. The European lightning location system—Part 2: Observations. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 607–616. [CrossRef]

8. Marcos-Menéndez, J.L.; Castedo-Dorado, F.; Rodríguez-Pérez, J.R. Statistical characterization of cloud-to-ground lightning data and meteorological modelling of cloud-to-ground lightning days for the warm season in the province of León (northwest Spain). *Meteorol. Appl.* **2016**, *23*, 671–682. [CrossRef]
9. Zharashuev, M.V. A method for automated statistical analysis of cloud-to-ground discharges in the North Caucasus. *Meteorol. Hydrol.* **2022**, *4*, 111–116. [CrossRef]
10. Chen, A.B.; Kuo, C.-L.; Lee, Y.-J.; Su, H.-T.; Hsu, R.-R.; Chern, J.-L.; Frey, H.U.; Mende, S.B.; Takahashi, Y.; Fukunishi, H.; et al. Global distributions and occurrence rates of transient luminous events. *J. Geophys. Res.* **2008**, *113*, A08306. [CrossRef]
11. Williams, E.; Downes, E.; Boldi, R.; Lyons, W.; Heckman, S. Polarity asymmetry of sprite-producing lightning: A paradox? *Radio Sci.* **2007**, *42*, 1–15. [CrossRef]
12. Kuzhevskaya, I.V.; Zhukova, V.A.; Koshikova, T.S.; Pustovalov, K.N.; Nagorskiy, P.M. The spatio-temporal distribution of mesoscale convective complexes over the Southeastern Western Siberia. *Geosfernye Issled.* **2021**, 115–124. [CrossRef]
13. Chuang, C.-W.; Chen, A.B.-C. Global Distribution and Spectral Features of Intense Lightning by the ISUAL Experiment. *J. Geophys. Res. Atmos.* **2022**, *127*, e2022JD036473. [CrossRef]
14. Duan, M.; Sakamoto, T. Estimation of the Number of Sprites Observed over Japan in 5.5 Years Using Lightning Data. *Atmosphere* **2023**, *14*, 105. [CrossRef]

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