ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2009, Vol. 45, No. 5, pp. 663–673. © Pleiades Publishing, Ltd., 2009.
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# Russian Studies in the Field of Atmospheric Electricity in 2003–2007

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Received May 25, 2009

**Abstarct**—This paper presents the results of Russian studies in the field of atmospheric electricity for the National Report on Meteorology and Atmospheric Sciences to the XXIV General Assembly of the International Union of Geodesy and Geophysics (the city of Perugia, July 2–13, 2007).[1]

**DOI:** 10.1134/S0001433809050132

## INTRODUCTION

This publication gives a review of Russian studies in the field of atmospheric electricity in 2003–2006 (and part of 2007) prepared by the Commission on Atmospheric Electricity of the National Geophysical Committee (NGC) (see http://ngc.gcras.ru/) for the National report on meteorology and atmospheric sciences to the XXIV General Assembly of the International Union of Geodesy and Geophysics (IUGG) (see http://www.iugg.org/) that took place in the city of Perugia, Italy, on July 2–13, 2007 (Russian National Report, 2007).

Atmospheric electricity is a fundamental problem of atmospheric physics that has been attracting much attention for many years. Many aspects of the physics of thunderstorm electricity and fair-weather electricity, the formation of the electrical structure of thunderclouds, the initiation of breakdown and propagation of lightning, and the role of lightning generators in the global electric circuit have recently gained essential development thanks to the wide application of new technical instruments and modern computational methods [1–8]. New tendencies are discovered in evaluating the mechanisms and energetics of atmospheric electricity in connection with the appearance of new data obtained with the help of balloon cloud sounding, measurements from airplanes, ground-based and satellite observations, experiments on triggering lightning, and laboratory modeling of the processes of cloud particle electrization. The role played by the fine structure of the distribution of thundercloud field and charge, the electro-gas-dynamic turbulence, and the high-energy processes that lead, in particular, to X-ray and gamma ray bursts during a thunderstorm, was revealed. A new geophysical phenomenon, i.e., discharges in the middle atmosphere, has attracted great attention in recent years. A theoretical analysis of all this new information, which is necessary to understand the physical processes of the formation of the global electric circuit, electric structure of thunderclouds, and initiation of breakdown and propagation of lightning, required new approaches based on modern methods of geophysical electrodynamics [1–7]. Meanwhile, interest is growing in problems of the operative monitoring of thunderstorm phenomena and the active impact on thunderstorm processes [8]; therefore, a special (forth) section of this article is devoted to reviewing works in this field.

## 1. IONS AND AEROSOLS. FAIR–WEATHER ELECTRICITY

The study of ions and charged aerosols is a classical section of atmospheric electricity studies that has been attracting increased attention in recent years due to investigations into the role that charged particles play in forming fine-dispersed aerosols that affect the optical atmospheric properties and also can serve as nuclei of water condensation and ice nucleation. In particular, the phenomenon of the intense emission of super-small (nanometer) aerosols (ENA) in the troposphere—known in foreign literature as a "nucleation

[1] The Russian national report on meteorology and atmospheric sciences for the period of 2003–2006 presented to the International Commission on Meteorology and Atmospheric Sciences during the XXIV General Assembly of the International Union of Geodesy and Geophysics, Perugia, Italy, July 2–13, 2007, Mokhov, I.I., Krivolutskii, A.A., Eds., Moscow: MAX Press, 2007, p. 180. See also: Mokhov I.I., *Rossiiskie issledovaniya v oblasti meteorologii i atmosfernykh nauk v 2003–2006* (Russian Studies in the Field of Meteorology and Atmospheric Sciences in 2003–2006), *Izv. RAN. Fizika atmosfery i okeana*, 2009, vol. 45, nos. 2, 4.

burst"—is of great interest. The facts of the flash emission of aerosol particles from a nanometer size interval (diameter $D$ = 3–100 nm) have been fixed in all continents and in the entire tropospheric layer. A review of the results of the experimental and theoretical research on this poorly known phenomenon is given in [9]. Intense and long ENA in Northern Europe have been studied in more or less detail; moreover, 60–70% of observations were made in forest areas in the presence of snow cover and 10–20% of observations were performed in seacoasts. ENA most often take place in spring and autumn; in 95% of cases it takes place in the daytime and under conditions of clear and calm weather typical for anticyclones. ENA are characterized by a rapid initial increase in the concentration of nanoparticles up to the values of $10^3$–$10^5$ cm$^3$. The so-called nuclear fraction with the diameter size $D$ = 3–15 nm is formed upon the expiry of 1–2 hours. The appearance of the Aitken fraction $D$ = 20–80 nm and enlargement of aerosol particles inside the cumulative fraction $D$ = 80–200 nm are possible within the next 4–6 hours. As a result, the cycle of birth and transformation of atmospheric aerosol particles with sizes varying from one to hundreds of nanometers is reproduced within 6–8 hours. The formation and condensation rates of nuclei with a diameter of 100 nm increase by a factor of 10–100 in the periods of ENA. The "aerosol" and "electrical" states of the atmosphere are important factors of ENA genesis. More intense ENA become apparent when there was a small content of background aerosols in the presence of atmospheric ions of medium mobility with $D$ = 2–3 nm.

The statistically grounded fact that the emissions of medium atmospheric ions (MIs) with a mobility of 0.8–0.25 cm$^2$/(V s) forestall each appearance of nanoparticles was revealed for the first time in the course of the international experiment ESUP (Spring 2000, Finland). It should be noted that the physical nature and role of MIs in atmospheric processes have not yet been ascertained. They occupy the intermediate position in the mobility scale between light (a mobility of 1–3 cm$^2$/(V s) and heavy (a mobility of $4 \times 10^{-2}$ cm$^2$/(V s)) atmospheric ions. In the absence of high supersaturations, ions are a product of non-elastic collisions with precedents, i.e., neutral microparticles with sizes on the order of D = 1–2 nm that, in their turn, appear thanks to the association (recombination) of heteropolar light ions. It was revealed in [11] that the growth in concentration of MI from the background values on the order of 10–100 cm$^{-3}$ to $10^3$ cm$^{-3}$ takes place when a specific square of atmospheric aerosol particles does not exceed $S$ = 1–3 μm$^2$/cm$^3$. The intense formation of MIs generally forestalls the generation of the nanometer-range aerosol particles with sizes of $D$ = 3–10 nm. If $S > 100$ μm$^2$/cm$^3$, medium ions and nanoparticles are not formed.

Generalizing experimental data made it possible to formulate the following requirements for the characteristics of emissions stimulating the "gas-aerosol" conversion in the near-surface atmosphere [12–15]:

(1) The energy of quanta (particles) must exceed the energy of ionization for the main air components (approximately 15 eV) independently of the type of emission (UV, alpha, beta, gamma, or neutron).

(2) The formation of aerosol in ionized gas requires the presence of light ions of both polarities, i.e., both negative and positive ions, so that the operating emission and content of gases must stimulate the bipolar ionization of air.

(3) The condition as regards the age of light ions must also be fulfilled: in the first place, initial ions with a lifetime on the order of 1–10 ms and less do not have time to form a hydrate shell around a molecular ion; in the second place, fresh molecular ions have a structure such as $O_2^-$, $N_2^+$, etc., which is not suitable for the formation of a stable cluster.

The results of modeling the gas-aerosol conversion in different meteorological conditions under the action of UV emission and bipolar ionization also point to the significance and expediency of taking into consideration electrical interactions during the formation and evolution of stratospheric aerosol, in the first place, during the formation of primordial condensation nuclei in the layers of stratospheric aerosol.

Investigations into the dynamics of air ionization are tightly connected with studying the dynamics of the electric field and current in the atmosphere, particularly under fair-weather and foggy conditions. A number of principal results in studying the so-called short-period pulsations of the electric field (in a frequency band of $10^{-3}$–1 Hz) and aeroelectric structures were obtained in recent years [16–20]. These results can be briefly formulated as follows:

(1) The short-period pulsations of the electric field in the near-surface atmosphere have power-law spectra in a frequency band of $10^{-2}$–$10^{-1}$ Hz both under conditions of fair weather and under conditions of fog. The measured indices of spectrum power vary from –1.23 to –3.36, depending on the meteorological and geophysical conditions of the experiment. A spectrum has a "hard" slope for long time intervals (of approximately several hours).

(2) The distribution obtained for structured spectra is bimodal: it has two peaks (in the range of –2.75…–3.0 and in the range of –2.25…–2.5). The distribution of non-structured spectra (i.e., spectra of pulsations observed in the absence of aeroelectric structures) is asymmetric with the strongly pronounced peak value related to the interval of slope indices from –2.5 to –3.

(3) The intensity of electric field pulsations increases more than by one order of magnitude under conditions of fog. This being the case, the indices of the spectrum do

not radically differ from the corresponding indices under conditions of fair weather [19, 20].

(4) Based on the theoretical model taking into consideration the contribution of turbulent mixture of charged particles and the presence of aeroelectric structures in the boundary atmospheric layer, it was shown that the spectrum of field fluctuations $S_E(\omega) \sim \omega^{-11/3}$ in the inertial interval for homogenous turbulence with a charge density as a passive scalar. The slope indices close to –11/3 are observed for both structured and non-structured spectra. Although the case of homogenous turbulence in the atmosphere is rare, it serves as a good approximation for the pulsations generated by near-surface structures. This approximation works well when estimating the indices of spectrum slopes for large time realizations. This speaks for the fact that the main energy of short-period electric field pulsations is focused in near-surface aeroelectric structures. The spectrum generated by the turbulence of a remote structure turns out to be proportional to $\omega^{-5/3}$. A comparison with the results of experiments shows that remote structures do not make an essential contribution to the energetics of the process and become apparent in few non-structured spectra when an observation is made from the ground surface; however, these structures determine the dispersion of indices for the slope of pulsation spectra [16–18].

Along with a study on the electrodynamics of fog, works on the development of methods for exerting an active electric influence on fog were also continued. Thus, changes in the characteristics of fog under the impact of corona discharge on it were considered in [21]. The experimental data obtained during tests carried out under in situ conditions are presented. The obtained characteristics of fog are compared with the characteristics of its development under in situ conditions according to the data of a 4-yr observation period. The influence of a corona discharge on the characteristics of fog is so essential that the authors recommend that it be used to carry out practical works on improving the meteorological conditions in fog.

The significant correlations between the value of the aeroelectric field density and air temperature in the surface atmospheric layer were discovered based on the synchronous observations of the aeroelectric field and air temperature that were made in August–October 2002 and June–September 2003 in the instrumentation test site of the Borok middle-latitude observatory [22]. A positive correlation between the variations in the temperature and density of the aeroelectric field under the conditions of unstable stratification (late morning–day) and a negative correlation under the conditions of stable stratification (late evening–night) were revealed. The simultaneous increase in the amplitude of pulsations of field density and temperature most frequently takes place in the local noon time. The intense variations in electric field density are consistent with the near-scale changes of the temperature field. The positive time shift of variation $E$ with respect to $T$ that reached 40 minutes was discovered during a temperature activity higher than usual. The simultaneous aeroelectric and temperature coherent structures accompanied by short-period pulsations of field density and air temperature in the lowest layer were found. Possible interaction, mechanisms of the aeroelectric field density and temperature of atmospheric air that explain their positive correlation under conditions of stable stratification (late morning–day) and negative correlation in the late evening and at night are discussed. The increase in electrical activity caused by the growth in intensity of turbulent convection and formation of aeroelectric structures is presented as the most important process.

A number of works study the interrelation between the electric field in the atmosphere and meteorological factors, electrode effect, as well as the properties of particle charging and charge transfer in the boundary atmospheric layer [23–27]. Thus, the results of analyzing the joint measurements of electric atmospheric parameters (the electric field density and the positive and negative electric conductivity) and variations of atmospheric pressure caused by different changes of meteorological conditions (rain, fog, snowstorms, and thunderstorms) are presented in [24]. The measurements were performed at the High-Latitude Automated Complex installed in the Kola Peninsula (the Apatity) and including three spaced (the base of the order of 300 m) microbarographs for measurements in a band from $10^{-4}$ to 1 Hz. How the seasonal and daily changes of the vertical component of the atmospheric electric field in the surface atmospheric layer depended on the variations of components of the interplanet magnetic field (IMF) and galactic cosmic rays, as well as the level of magnetic disturbance, were also investigated. A similarity was found between the daily dependences of the southern $B_z$–component of the IMF and vertical component of the atmosphere electric field for two seasons: autumn and spring.

Quantitative measurements of saltation flows in a wind-sand flow were carried out [26]. The works on revealing the correlation of the variations in the electrical field and VLF emissions with seismic activity were continued [28].

## 2. THE GLOBAL ELECTRIC CIRCUIT

A number of new results have recently been obtained which have led to a deeper understanding of physical processes in the global electric circuit. A new description of the global atmospheric electric circuit that relies upon the results of analyzing the energy of the quasi-stationary field of thunderstorm and fair weather areas has been suggested and substantiated. The electric energy generated by thunderclouds and Nimbo-Status shower clouds was ascertained to average $3 \times 10^{13}$–$10^{14}$ J, which is two to three orders of magnitude higher than the energy concentrated in the Earth-ionosphere global spherical condenser. The average rate of electrical energy dissipation by conduction currents in the environs of thunderclouds and lightning flashes is equal to $3 \times 10^{11}$–$3 \times 10^{12}$ W. These estimates characterize the global circuit as being the most dynamic of the existing geophysical systems with a sufficiently high energy supply [29, 30].

Analytical expressions have been obtained for the cloud energy and its average dissipation rate in the atmosphere with the exponential conductivity profile. They give reasonable values for the energy and its dissipation rate at values of current density supporting the distribution of charges in a cloud on the order of 1–10 nA/m$^2$. These expressions also give a visual explanation to the fact that the lifetime of electric energy in the atmosphere turns out to be less than the local lifetime of a charge and (energy) near the Earth surface [31]. The subsequent development of studies on the energy of the global circuit must be connected with a more detailed consideration of sources and with the development of the gas-dynamic lightning models that will enable a more adequate description of lightning energy. It is natural that the estimates of the global contribution of some factors are also impossible without the exact knowledge of statistics of thunderstorm and lightning activity.

A number of new models (mostly numerical) permitting one to describe non-stationary and electromagnetic processes in the global electric circuit [32–35] in both flat and spherical geometry, as well as models of stationary global current systems, were developed [36, 37].

The dynamics of transient currents flowing after lightning flashes (the transient stage can last from several tens to several hundreds of seconds and leads to the transfer of a charge in the ionosphere and partial neutralization of a charge transferred onto the ground) and the contribution of these currents to the global electric circuit were investigated [38, 39]. Cloud-to-ground flashes and intra-cloud flashes, along with quick transients, were ascertained to generate long transient currents of large magnitude. "Normal-polarity" cloud-to-ground flashes charge the global circuit, while "normal-polarity" cloud flashes lead to its relaxation. The efficiency of flashes such as cloud-to-ground flashes (i.e., the ratio of summary charges transferred into the ionosphere and onto the ground) significantly depends on the height of the charge location in the conductive atmosphere and varies within the limits of 15–90% in the height interval of 1–14 km above the ground (in the model with exponential conductivity). The efficiency of cloud flashes is, on the average, significantly smaller that that of cloud-to-ground flashes; however, their average contribution to the current circuit can be comparable, because the quantity of cloud flashes considerably exceeds that of cloud-to-ground flashes. Estimates of the global balance of transient currents were made which show that, in the period of intense lightning activity, the contribution of transient currents determined by lightning flashes can be of order of the quasi-stationary current. However, the contribution of transient currents to the global current balance most likely does not exceed 20%.

A model of the non-stationary electric circuit in the atmosphere was developed which is based on the Maxwell equations written in an electrostatic approximation. An equation for the potential of the electric field in the atmosphere with the exponentially growing electric conductivity of the atmosphere was solved that describes the establishment of a stationary electric field in the atmosphere when the lightning generators are switched on at the initial moment. Based on analyzing the solution, it was shown that three stages exist in the process. Estimates of the influence of cloud discharges and cloud-to-ground discharges on the value of the ionosphere potential were given [40, 41].

Based on the numerical generation model of the global circuit field under the action of lightning generators, it was found that the sign and value of the Earth's charge significantly depended on the latitude distribution of atmospheric conductivity [37]. The Earth's charge turns out to be positive for the real latitude distribution of atmospheric conductivity. The dependence that the complete charge has on the degree of latitude heterogeneity of conductivity with consideration for the surface orography and anisotropy of conductivity in the upper atmospheric layers was numerically investigated.

The variability effects of the global circuit were studied in a number of works with the help of the ground-based observations of the electric field and current [6, 42]. Thus, the value of the potential gradient (for the vertical component of the electric field in the near-surface atmosphere) has been continuously registered since 1998 at the Vostok station in Antarctica within the framework of a joint Russian-Australian project. The data of continuous observations during the 10-day period of April 2008 that satisfy the conditions of fair weather were analyzed in [42]. The field behavior at the Vostok station was compared with the number of lightning discharges obtained according to the data of the land-based network for electromagnetic observations. A negative correlation was found between the hourly average field values and the number of intense lightning discharges.

## 3. THE PHYSICS OF THUNDERSTORM ELECTRICITY

The problems of lightning climatology, as well as role of large-scale and mesoscale atmospheric circulation, convection, and generation of aerosols in the genesis of thunderstorm cells, are a subject of active discussion due to the appearance of new data on lightning and thunderstorm statistics [3–7, 43]. This being the case, the study on the regional properties of lightning statistics and the subsequent development of land-based and satellite instruments for thunderstorm mapping is of great importance, the more so because the thunderstorm cells of middle latitudes can make an essential contribution to the global thunderstorm activity [5, 43]. A lot of attention has recently been paid to the so-called mesoscale convective systems (with the horizontal scales varying from tens to hundreds of kilometers) that are an important source of thunderstorm activity, including discharges in the middle atmosphere (sprites, jets, and elves) in a number of regions (in particular, in the Great Plains of the United States and in South America). The results of recent investigations speak for the fact that the multilayer structure of a spatial charge is present in similar systems [5, 33]. This being the case, the presence of a lengthy stratified area with an integrated electrical structure and horizontal scale on the order of several hundreds of kilometers is a characteristic property of mesoscale systems. The indicated observations showed the need for developing new approaches to describing sources of atmospheric electricity, permitting one to take into consideration both the considerable horizontal scales of a source and its complex multi-layer structure. A new method for modeling the distributed quasi-stationary tropospheric sources of electricity was suggested in [32, 33]. The constructed model permitted electric fields and currents in the environs of mesoscale systems to be calculated and enabled a complete current flowing to the ionosphere from a given convective system to be estimated. The results of calculations showed that the contribution of such systems to the global electric circuit must considerably exceed the contribution of ordinary thunderstorms.

The question about the dynamics of accumulation and dissipation of electric energy in a thundercloud was discussed in few works until recently. The following values of energy were obtained in [44] based on the results of in situ measurements of the electric field: $5 \times 10^{11}$ J and $2 \times 10^{12}$ J for two mesoscale convective systems and $2 \times 10^{11}$ J for a severe thundercloud with an anvil. It is sufficient to generate several hundreds or thousands of usual (negative-polarity) lightning flashes, but only 10–100 positive cloud-to-ground flashes. The above-given estimates are confirmed by model calculations in [33]; the three-dimensional model of field and current distribution in the environs of mesoscale convective systems that is presented here gives a value on the order of $10^{11}$ J for the summary energy accumulated in a system with a scale of 200 km.

The question about the possible influence of the inhomogeneous (fine) structure of thundercloud electric field on the process of lightning initiation has recently been attracting a lot of attention [2–6]. The dynamics of the accumulation of electric energy and its distribution over the spectrum of spatial scales varying from global scales to micro-scales (connected with the separation of charges on hydrometeors), as well as the spatial and time characteristics of the processes of electric energy dissipation in the atmosphere, are also one of the most urgent tasks of investigating the global electric circuit. The presence of the fine structure of a thundercloud electric field was demonstrated for the first time and its characteristics were researched in [45] based on systematic balloon measurements. Analyzing the results of measurements showed that the spectra of the electric field in a thundercloud had a power-law character for a rather wide interval of scales from tens of meters to kilometers. The spectrum index turned out to be close to –2 in the series of experiments.

Essential help in studying the fine electric structure of a cloud and stage of discharge initiation can be rendered by perfecting the systems for receiving high-frequency emission of thunderclouds and by working out the theory describing the development of discharge and formation of radio-emission within the framework of the fractal-dynamic approach [46]. It is necessary to point out that the question about the fine structure of a field and charge in a multi-phase system as complex as a thundercloud is an important fundamental problem; approaches to solving it are only being traced in both the theoretical and experimental respect. The system of parametric expressions describing microphysical processes taking place in a convective cloud was presented in [47]: the phase transitions of moisture and coagulation of cloud particles and (or) precipitation particles, as well as the charging of the indicated particles and exchange of electric charge between them. The obtained system of parametric expressions represents a universal block that can be attached to the different models of convective clouds with different dimensions and a spatial-time structure that satisfy certain requirements. This block describes the sources and sinks of moisture and an electric charge in a cloud. The indicated block was tested by the example of a separate model, and the obtained results were shown to correspond to the data of full-scale observations.

Studying the role of energetic particles—cosmic rays and runaway electrons in discharge initiation and the generation of high-frequency electromagnetic pulses registered in a whole series of experiments—is one of the most important aspects of thunderstorm electrodynamics [4–6, 49]. In particular, the change in intensity of a flux of secondary cosmic rays in the depth of the atmosphere during thunderstorms was observed in several experiments, but it was most completely studied in the experiment at the Baksansk Neutrino Observatory of the Institute of Nuclear Research, Russian Academy of Sciences (INR RAS) [50, 51]. A distribution of the deviation of the counting rate of cosmic-ray soft components (electrons, positrons, and gamma-quanta) in the energy range of 10–30 MeV from the average daily counting rate that was built after thoroughly selecting data on 52 thunderstorm episodes for three observation seasons was measured as a function of the density of the near-surface electric field. To explain the information obtained, a number of works involve a phenomenon that is new for atmospheric electrodynamics: the avalanche-like multiplication of high-energy electrons (runaway breakdown) [4, 52–61]. According to estimates made by the authors of [4, 52–54], the critical field strength is 100–150 kV/m in the thunderstorm atmosphere at heights of 4–6 km, which is significantly lower than the critical field of usual discharge in dry air. When an electric field reaches values higher than the breakdown threshold, each secondary electron of cosmic rays initiates micro-breakdown, which can lead to the considerable ionization of air and essential change of its conductivity. Extensive air showers of cosmic rays are accompanied with a strong local multiplication of secondary particles; this leads to current pulse generation under the conditions of fast breakdown, which is of interest both to understand the mechanism of lightning generation and to study superhigh-energy cosmic rays [53]. However, the electric current generated in the process of runaway breakdown is mainly determined by slow (thermal) electrons. The detailed kinetic theory taking into account low-energy electron ionization (1–100 eV), recombination, and emission processes was developed in [52]. The exact theory was shown to predict the considerable multiplication of thermal electrons and the increase of the electric current better than the previous estimate of the electron number.

The explanation was given for super-power short radio-emission pulses observed during thunderstorms [54]. According to the observation data, the source of pulses is at heights of 10–20 km. A model was developed which is based on the interaction between an extensive air shower (EASh) and runaway breakdown in a thunderstorm electric field. The main property of this interaction for high-altitude discharge is that an EASh gains a developed character when a primary cosmic ray particle moves almost perpendicularly to a thunderstorm electric field. This case has not been considered earlier. The essential increase of runway breakdown was shown to take place in this case, which leads to the formation of narrow bipolar radio-emission pulses with a great peak power of up to 100 GW. The nonlinear effect of discharge current saturation was shown to have a place for primary high-energy cosmic rays. The kinetics of particles with a wide energy spectrum was also studied in [55] as applied to atmospheric conditions.

The presence of a small-scale electric field in a thunderstorm cell whose amplitude exceeds the threshold value for electron escape turns out to be significant enough for the process of electron acceleration up to relativistic energies. Such acceleration is considered in [56] with consideration for the final spatial dimensions of a cloud. Along with the acceleration, stochastically oriented electric cells in presence of collisions with air molecules lead to an abrupt increase in the lifetime of relativistic electrons in a cloud thanks to the diffusive character of their trajectories and permit one to explain the considerable duration of X-ray and gamma bursts and the actual absence of any correlation with lightning flashes.

In [60] a scheme is described for calculating the modulation of a flux of cosmic muons by the electric field of a stratified cloud, and the results of calculating the muon spectrum and intensity of muon decay and ionization at heights of up to 5 km are presented. It was noted that beam disturbances and a decay rate could reach 10–25%. The amplitude of changes in these characteristics is sufficient enough that they can be measured.

A new impetus to the development of ideas about the electromagnetic environment of the Earth was given by observations of optical phenomena in the upper atmosphere correlating with thunderstorm activity: sprites, elves, and jets [5]. The study on high-altitude discharges in the atmosphere has turned into an extensive and intensely developing field of geophysical electrodynamics. As the experimental data characterizing the morphology of the phenomenon have recently been accumulated, it has become possible to study in detail the properties of the structure and dynamics of high-altitude discharges and to question the role of these discharges in the functioning of the global electric circuit and balance of small atmosphere constituents [6, 7]. The experimental and theoretical calculations show that a high-altitude discharge must be considered part of the dynamic process, including the formation of the field and charge structure in a cloud and a lightning discharge on the ground. Different approaches are discussed to model the structure and dynamics of sprites, inclusively, with the involvement of runaway electrons [4, 59]. In particular, a quasi-electrostatic model of electric-field generation in the atmosphere was developed that takes into account the properties of charge distribution and charge dynamics in the mesoscale convective systems that serve as one of the main sources of positive discharges on the ground and the unipolar and bipolar models of a lightning discharge were comparatively analyzed within its framework [62].

The angle and energy distribution of high-energy electrons that resulted from the numerical modeling of relativistic runaway breakdown by the Monte-Carlo method was used to calculate the gamma-emission of high-altitude atmospheric discharges in a geomagnetic field [59]. The obtained results are consistent with the characteristics of gamma-ray bursts above clouds (according to the satellite data), which demonstrates the applicability of the high-altitude discharge model with consideration for the breakdown mechanism of relativistic runaway electrons.

A lot of attention is still paid to the classical problems of lightning discharge physics [2]. The theory of the formation of a cloud-to-ground lightning leader near surface objects with consideration for a corona discharge was developed in [63]. The potential of a descending leader and, consequently, a return stroke current were shown to depend on the position of the source inside the cloud where the bi-leader discharge starts to form and also on the trajectory form of the descending leader.

## 4. THE METHODOLOGY OF STUDYING THUNDERSTORM ELECTRICITY FOR THE GOAL OF HYDROMETEOROLOGICAL SERVICE

Over the last 10–15 years, increasingly greater attention has been focused on the practical problems of thunderstorm electricity in the field of operative hydrometeorological service: warning about dangerous weather phenomena connected with strong convective clouds (thunderstorms, tornadoes, hail, squall, and service precipitations); preventing airplanes from getting struck by lightning; protecting electric facility from a lightning strike; specifying the quantity of falling precipitations when observing areas of thunderstorm activity from AES (artificial earth satellites); warning about the possibility of forest fires; forecasting the evolution of tropical cyclones, etc. [8]. This was promoted by developing instrumental methods for monitoring thunderstorms systems and sensors such as ALDF, LDAR, SAFIR, OLS, LIS, etc., and putting them into immediate practice. This gave start to the accumulation of factual data about the properties of electric activity of service convective clouds that provide information about the significant microphysical restructuring of clouds and possible dangerous phenomena by virtue of some cause-and-effect relations ahead of time, i.e., it becomes possible to reveal informative signs (predictors) of dangerous phenomena on their basis. The abrupt multiplication of cloud lightning (60 discharges per minute and more) 10–15 min before the appearance of tornado or 5–10 min before the formation of squalls (microbursts) that are dangerous for aviation can be ranked among such predictors. The reversal of lightning polarity from predominately negative to positive polarity with the inverse reversal after the end of hail often takes place in hail clouds during hail generation and hail fall. It is obvious that the research on the physical mechanisms, time parameters, and stability of such relations under different synoptic and physical-geographical conditions fosters an increase in the quality of diagnosing and forecasting the degree of danger of clouds and atmospheric processes as a whole.

The so-called “electrically-active” zones (EAZ), i.e., the areas where electric charges are sufficient enough to initiate lightning formation, are an important object when studying the electric characteristics of clouds [65, 66]. The microphysical, dynamical, and electric properties of such zones are of primary importance both in estimating the energy balance of a cloud as a whole and to develop capabilities to regulate its thunderstorm activity by the methods of active impacts. A direct correlation was noted between the intensity of a thunderstorm and the velocity of ascending flows in a separate convective cell [66]. Strong ascending flows are thought to transfer a greater quantity of cloud particles that take part in the process of discharge formation and separation into the upper part of a cloud, and the limit of the high-reflectivity zone of a cloud is the area of charge separation. It is here that the electrically-active zones of a cloud are likely to be.

The different mechanisms of cloud electrization are currently under consideration; however, many specialists recognize the fact that charge transfer during collisions of ice crystals with graupels (polycrystalline particles) can lead to the accumulation of a charge of approximately 10 Coulombs within 10–15 min. The temperature conditions, growth rate of ice particles, and presence of liquid droplets determine the electric charge sign. The studies on the location of areas of mixed phase composition and electric charges showed that the distribution of electric fields necessary to produce lightning depends on the structure of air motions in convective clouds. The observations made by a number of authors fixed the positive correlation between the density of charges on the ground and the radiolocation reflectivity of clouds. The intensity of a thunderstorm (the number of discharges per time unit) was noted to be proportional to the velocity of ascending flows in a separate convective cell. Strong flows transfer the great quantity of particles taking part in the process of electric charge generation and separation into the middle and upper parts of a cloud. This being the case, the periphery of the high-reflectivity zone is supposed to be an area of efficient charge separation: large polycrystalline particles get a negative sign when colliding with smaller ice particles and descend into the middle and lower parts of a cloud; meanwhile, positive charged particles are carried to the upper part of a cloud. Consequently, an EAZ is understood to be part of a convective cloud where there are simultaneously crystalline and polycrystalline ice and water particles, the proportional concentration of which ensures the effective process of charge formation by contact electrization. The lifetime of an EAZ is connected with the duration of ascending flows, and its size and exact location can be fixed during radar observations of ionized lightning channels that actually illustrate the charge structure of a cloud [65].

The restoration of the sources of radar reflections in a thundercloud is principally important to physically interpret the data of radars used for these purposes. The multi-wave active-passive method for sounding thunderclouds while receiving the electromagnetic emission of lightning discharges in the middle-wave and ultra long-wave radio-wave bands in order to "decipher" radar reflections from ionized lightning channels at wavelengths of 11, 35, and 200 cm was developed for this purpose [8, 66]. The multichannel registration of radars and radio-receivers data with an accuracy of 1 km and 1 ms made it possible to investigate the spatial and time structure of lightning flashes with a duration of 0.6–0.8 s and higher.

The quantity of echo peaks ($R_{\text{m peak}}$) in the very high-frequency band (RLS P-12) that follow each other with an interval of 80–90 ms is known to coincide with the number of return strokes fixed on a frequency of 7 kHz. The number of $R_{\text{m peak}}$ in the decimetric wave band (RLS P-10) turned out to be 2–3 times smaller. The time interval between echo peaks at $\lambda$ = 11 cm amounted to ~30 ms. The quantity and time of the appearance of $R_{\text{m peak}}$ at this wavelength coincided with the succession of A-type pulses noted in time intervals between repeated lightning flash discharges [8]. The following physical interpretation of obtained data can be given with the help of the multi-wave active-passive method: a radio-location set working in the decimetric wave band is able to detect weak-current discharges connecting new charge areas to the channel on the ground in the intervals between return strokes in the upper part of a cloud. The time succession of echo peaks and electromagnetic pulses illustrates the process of the development of lightning channels inside a cloud (between the local zones of electric charges) that is interrupted by return strokes. Analogous results were obtained with the help of the radio-interferometer system SAFIR. This system fixed small-scale cloud discharges with a duration of 10–30 ms in the intervals between return strokes. The location of EAZs in a cloud can also be ascertained using the radars of the decimetric wave band.

The earlier obtained data on the interrelation between the intensity of a thunderstorm and the velocity of ascending flows make it possible to believe that the location of EAZs is determined by the spatial and time scale of ascending flows and that their microphysical properties are determined by the inhomogeneities of the phase composition of cloud particles. These areas are of the greatest interest for the subsequent investigation with the help of Doppler and polarimetric (radar and SHF-radiometric) methods for the sake of estimating both the energy balance of a cloud as a whole and the active impacts. In particular, the capabilities of the radar search of electrically-active zones in a cloud that are involved in a thunderstorm discharge were considered in [65]. The methods that permit one to identify the sources of radar reflection formation were presented to compare the radar observations of lightning at wavelengths of 10 and 200 cm while recording the electromagnetic emission of these discharges at frequencies of 7 and 500 kHz. It was demonstrated that the MRL-5 radar was able to fix the location, sizes, and time of existence of electrically-active zones; an investigation of the microphysical properties of them will promote an increase in the efficiency of impacting the thunderstorm-hail processes.

The laboratory modeling of the spectra of electro-gas-dynamic (EGD) turbulence of a convective cloud in a weakly ionized aerosol medium was achieved for the first time in [67, 68]. The spectra of fluctuations in a potential were ascertained to be close to the power-law spectra with an index varying from –2 to –3 in the absence of an external electric field. The methods for measuring the spectra of EGD turbulence were suggested to be used to diagnose the compact areas of a strong field (50 V/cm and more) in thunderclouds, which is necessary to research the problem of lightning initiation and to search for electrically-active zones in thunderclouds.

The problems of regional thunderstorm activity were studied in [69–71]. Thus, the 29.5 days' variations in the level of VLF noises of a thunderstorm nature on a frequency of 8.7 kHz that were registered at the Yakutsk station in 1979–1994 were considered in [69] by the epoch superposition method. The activity of the African thunderstorm center is reflected by VLF noises at night in winter, and local thunderstorms in the eastern Siberia are reflected by them in the daytime in summer. Observations of changes in the electromagnetic emission of lightning discharges during the development of a thunderstorm cell in localities near Moscow and the evolution of a deep cyclone with the final coordinates of the center near the coast of the Kola Peninsula were given in [71]. The methods for processing and statistically estimating the obtained results for the characteristics of atmospherics flows in the form of the difference and ratio between the numbers of signals with different polarities were suggested. A correspondence was revealed between the anomalous changes of these characteristics in the case of vortex phenomena and the generation of atmospherics with a predominately negative polarity. The possibility of using the range-difference system to determine the place of lightning discharges for the passive radiolocation of dangerous meteorological phenomena was shown.

The methodical problems of distant thundercloud sounding were considered in [72–77] as applied to solving the tasks of operative hydrometeorological service, including active impacts on hydrometeorological processes. Due to new thunderstorm registration technologies being introduced and thanks to versatile data on the thunderstorm activity of clouds being accumulated, the goal of studying the microphysical, dynamic, and electric properties of electrically-active zones and their interrelation with dangerous phenomena arising in such clouds was formulated. It is of great practical significance to substantiate the predictors of dangerous phenomena connected with strong convection when they happen in the national lightning direction-finding network. Consequently, introducing new thunderstorm registration technologies and comparing the data obtained while doing so with the data of the existing active-passive complexes makes it possible to study the microphysical, dynamic, and electric properties of electrically-active zones and their interrelation with dangerous phenomena in the cloudy atmosphere. Accumulating data and substantiating the predictors of phenomena that are connected with strong convection and that have an electrical nature is gaining great practical significance toward being achieved in the national thunderstorm registration network.

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