ISSN 0001-4338, Izvestiya, Atmospheric and Oceanic Physics, 2019, Vol. 55, No. 6, pp. 562–572. © Pleiades Publishing, Ltd., 2019.
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Russian Studies of Atmospheric Electricity in 2015–2018

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Received July 12, 2019; revised July 28, 2019; accepted August 7, 2019

Abstract—The most significant results of Russian studies in the field of atmospheric electricity in 2015–2018 are reviewed. The review is a part of the Russian National Report on Meteorology and Atmospheric Sciences to the International Association of Meteorology and Atmospheric Sciences (IAMAS). It was presented and approved at the 27th General Assembly of the International Union of Geodesy and Geophysics (IUGG)[1]. The review is followed by a list of the main Russian works on atmospheric electricity published in 2015–2018.

Keywords: atmospheric electricity, physics of lightning, atmospheric discharges, global electric circuit, lightning direction finding, forecast

DOI: 10.1134/S0001433819060112

INTRODUCTION

This paper reviews the results of Russian studies in the field of atmospheric electricity over 2015–2018. Atmospheric electricity has been and remains one of the fundamental problems of atmospheric physics. The physics of atmospheric electricity is developed in many directions in recent years, e.g., fair-weather electricity, processes of cloud electrization and formation of their electrical structure, and relationships of thunderstorm activity with other dangerous weather phenomena. Experimental studies of atmospheric electricity in Russian research centers significantly contribute to the improvement of theoretical and numerical models of different electrical processes in the atmosphere, as well as of global electrical circuit models. New data were received in lightning physics, including new results on the structure of leader and streamer discharges. Much attention was paid to the study of high-energy processes such X-ray and gamma radiation flashes during thunderstorms. The study of lightning activity from space continued with the help of special microsatellites. Laboratory studies of different atmospheric discharge types should be especially noted. The main results for each field of the study are given in the corresponding sections of the work in detail.

[1] Russian National Report, Meteorology and Atmospheric Scienses, 2015–2018. Eds: I.I. Mokhov, A.A. Krivolytsky. National Geophysical Committee RAS. Moscow: MAX Press, 2019, 332 p.

1. ELECTRICITY IN FAIR WEATHER CONDITIONS

Fair-weather atmospheric electricity was actively studied in Russia in 2015–2018. The interest in the processes running in the convective atmospheric boundary layer increases due to a need for fundamental studies of cloud formation and electrical effects associated with industrial and natural aerosols. Long-term observations of the atmospheric electric field make it possible to reveal the main features of its daily and seasonal variations [1], study the convection effect on the electrical conductivity in the surface air layer [2], assess the effect of aerosol and radioactive air pollution [3], and experimentally study the variability of vertical atmospheric electric currents in the surface air layer [4].

An analysis of long-term observations of the atmospheric electric field in Yakutsk allowed one to reveal two maxima in spring, summer, and autumn months and one maximum and one minimum in winter months in the daily variations. The seasonal variation in the monthly mean field strength has maxima in spring and autumn and minima in summer and winter. The variations in the monthly mean electric field strength over a 5-year period show a trend toward a decrease in the amplitude of seasonal variations in the field strength, as well as in the total field strength [1].

Based on the data of monitoring electrical parameters of the surface air layer carried out in Tomsk in 2006–2017, their slow variations caused by the passage of cumulonimbus clouds and associated atmospheric phenomena in the warm and cold seasons were studied. Slow variations in the electric field potential gradient were statistical analyzed. The distribution of the total duration of the slow variations in the potential gradient was shown to be described by the power law. The resulted distribution is approximated by two sections in the warm season and one section in the cold season [5].

Regularities in the diurnal dynamics of the scaling and energy characteristics of the aeroelectric field under different states of the surface air are revealed in [6] based on field observations. It is shown that short-period aeroelectric pulsations in the frequency range $\Delta f = 0.001–1$ Hz are self-similar and have the fractal dimension $D = 1.1–1.8$. Regions with intermittency have been found in the time intervals characterized by a change in the stratification of the atmospheric boundary layer. It is shown that the intermittency of the aeroelectric field is characterized by multifractality with the spectrum width far zero, a non-Gaussian distribution of field increments, and a change in the spectral density from ~2.3 to ~4 for $\Delta f = 0.01–1$ Hz.

The solar activity effect on the electric-field variations in the surface air layer was studied. The manifestation of the Forbush effect in them was ascertained from atmospheric–electric observations in the high mountain Elbrus region. The relationship between the electric field and solar and geomagnetic activity was analyzed [7].

Much attention was paid to the development of theoretical and numerical models of formation of an electrode layer in the surface air, in particular, to the effect of aerosols and convection on the surface air conductivity. In [8], based on an analysis of field observations and numerical simulation results, a decrease in the electrical conductivity near the surface due to the development of convection in the atmospheric boundary layer is ascertained. It is shown that intensification of turbulence generation due to convection, accompanied by an increase in the turbulent kinetic energy and dispersion of vertical velocity fluctuations, promotes more intense vertical mixing of radon and radioactive daughter products. The variations in the electrical conductivity and strength of the aeroelectric field, determined by the radon emission, air ionization, separation of charges at electrical conductivity irregularities, and turbulent transport of radioactive elements and volumetric electric charges, are estimated [2].

An electrodynamic model of a horizontally homogeneous aerosol-free surface air layer is considered in [9–11]. The model consists of balance equations for positive and negative light ions (aeroions) and a Poisson equation. Analytical expressions are derived for stationary distributions of concentrations of aeroions, electric field, and electric charge density in the approximations of classical and turbulent electrode effects [9]. The height of the classical electrode layer in an aerosol-free atmosphere is estimated to be ~10 m; its structure is mainly determined by the electric field. The strengthening of the electric field increases electrode layer height and, hence, the scale of the distribution of electric parameters. When changing to the turbulent conditions in the surface air layer, the electrode-layer height increases to several tens of meters [10]. The turbulent electrode layer height is determined by both the electric field and the degree of turbulent mixing. An increase in the external electric field weakens the turbulence effect. The distributions of the electrical parameters of the surface air layer are derived versus the aerosol concentration in the atmosphere and the degree of turbulent mixing [11].

2. GLOBAL ELECTRIC CIRCUIT

The concept of the global atmospheric electrical circuit (GEC) plays a fundamental role in the study of atmospheric electricity, since it unifies all electrical processes running in the atmosphere. The interest in the study of GEC has been gradually increasing in recent years. Great attention is currently paid to the numerical simulation of GEC. Input parameters of GEC models usually include the distributions of the conductivity and source current density (which represent the separation of charges inside a thunderstorm and electrified storm clouds); therefore, parameterization of these variables is the most important part of each GEC model. A new parameterization was suggested in [12] for conductivity during different stages of a solar cycle, which was used for estimating changes in the GEC parameters produced by large-scale changes in the conductivity due to the solar activity. The problem of parameterization of the current of a source representing different electrified cloud types is considered in [13]. An attempt to introduce additional source currents of seismic nature was made in [14]. The problem of agreement of theoretical predictions of the GEC parameters with observations is discussed in [15].

Much more general problems which concern the equations of GEC, where ionospheric generators and anisotropic conductivity are used, have been analyzed in [16] from a mathematical point of view. The authors show the correctness and convenience for numerical simulation of both quasistationary and stationary problems, which describe SCE with different boundary conditions. The different boundary conditions at the top of the atmosphere are analyzed in [17], along with estimation of the disturbances caused by thunderstorms at the magnetoconjugate points. The implementation of thunderstorm stresses in numerical models of GEC is considered in [18], which is especially important for the theoretical explanation of changes in GEC on the scale of 11-year solar cycles [12]. The role of the Earth's orography in the analysis of GEC is discussed in [19].

Another important field of research is the interaction of the GEC with ionospheric and lithospheric processes. The penetration of unsteady ionospheric electric fields into the lower atmosphere is analyzed in [20]. The related problem of simulation of penetration of an electric field from the ground into the ionosphere is considered in [21, 22]. Electric fields at ionospheric altitudes produced by thunderstorm generators are estimated in [23]. The interaction between the lithosphere and ionosphere, especially in the context of earthquakes, is analyzed and discussed in [24, 25].

3. ELECTRICAL PROCESSES IN CLOUDS

Describing, simulating, and observing electrical processes in clouds are an important component of atmospheric electricity researches. The study of electrical processes in clouds includes a great number of tasks, in particular, theoretical and experimental studies of the emergence and evolution of convective systems, simulation and forecast of thundercloud development, and the search for correlations between meteorological data and lightning activity.

The forecast of thunderstorm events with the use of numerical mesoscale models is one of the most important practical applications of the simulation of electrical processes in clouds. Statistical estimates of 26 atmospheric instability indices, commonly used in the global practice of thunderstorm activity forecasting, are given in [26]; a new index of thunderstorm forecast is suggested accounting the vertical wind speed component. Modern techniques for forecasting thunderstorms with the use of numerical models are also considered in [27]. The analysis of a possibility of using the lightning activity index LPI for forecasting lightning flashes in [27] shows a number of disadvantages which result in the deterioration of forecast reliability when using indirect indices. In view of this, a new algorithm has been suggested for forecasting lightning activity on the basis of direct calculation of the electric field. Characteristic values of the electrical parameters calculated with the use of the parameterization developed showed a good correlation with field-measurement data of the electric field and the potentials in thunderclouds. The results of the study of a powerful thunderstorm event on the territory of Nizhny Novgorod region on June 1–2, 2015, with the WRF numerical model and the parameterization of electric processes developed in [27] are presented in [28]. A good agreement between the radar reflectivity simulation results and weather radar data is shown, as is the correspondence of the electrical parameters calculated to the data of spaced electric field reception and detection. A model of electrization of cumulonimbus clouds is suggested in [29]; it uses the results of WRF-ARW mesoscale numerical model forecast as input data and allows predicting atmospheric electric-field parameters and comparing the forecast results with the thunderstorm foci.

The effect of thunderstorms in the Black Sea basin on the chemical composition of the atmosphere is studied in [30] in numerical simulation. It is ascertained that changes in the temperature field associated with thunderstorm activity are higher in the continental part of the region than above the water surface. The results of a simulation of the effect of aerosol pollution of air on a thick convective cloud, its electrical structure, and precipitation are given in [31]. The authors show the effect of aerosol impurities on the dynamic, microphysical, and electrical characteristics of the cloud; a sharp increase in the total number of ice crystals and hailstones (by about 5 and 2 times, respectively); and a 1.4-fold increase in the rainfall intensity maximum and a 1.8-fold increase in the amount of precipitation. An increase in the concentration of natural aerosol with ice-forming properties changes the spatial distribution of charges over the cloud and creates an inverse electrical structure.

Experimental and theoretical studies of the processes of cloud electrization in high dust, sand, or snow flows, including the effects connected with turbulent mixing of particles, are of particular interest. A hardware complex was created for experimental measurements of fluctuations of the electric current of saltation and saltating grain concentration, as well as turbulent pulsations of the wind speed. The complex provided synchronous measurements of these parameters on a desert territory in Kalmykia [32]. Those measurements made it possible to estimate the distribution of the specific charge of saltating sand grains for the first time; it varied from 10 to 150 μC/kg at a mean of 48.5 μC/kg. The regularities in transformation of statistical characteristics of variations in such parameters as wind speed, concentration of sand grains, and electric current density of saltation due to nonlinear processes in the wind-sand flow were also ascertained. High-speed video recording of the wind-sand flow [33] revealed quasi-horizontal trajectories of sand grains in the lower millimeter layer of saltation. A wind profile model was suggested for stationary saltation conditions on the basis of the results [33].

Much attention was also paid to the study of the turbulence effect on the electrization of particles in the atmosphere in 2017–2018. The contribution of turbulence into the electrization of thunderclouds and snow and dust storms was theoretically studied in [34]; a model was suggested of large-scale electric field generation in a weakly conducting medium, which contains two particle types charged by collisions. A significant difference was found between the turbulence effect in the cases of induction and noninduction charge separation. However, in both cases, turbulence induced an additional growth of the large-scale electric field in systems under study, which has a significant effect, especially in the case where the electric field strength was close to the breakdown value. Works [35, 36] are devoted to the detailed study of the turbulence effect on the thundercloud electrization. The analytical estimates performed in these works for the disturbances of electrical parameters of a thundercloud under the turbulence effects at different turbulence and hydrometeor parameters were used for improving the parameterization of electrical processes and numerical simulation of thunderstorm events. The detailed comparison of the results of numerical simulation of thunderstorm events without and with accounting for turbulence effects made it possible to reveal a number of characteristic features in changes in the distributions of electrical parameters of a thundercloud.

4. LIGHTNING PHYSICS

Active experimental and theoretical researches in lightning physics have been carried out in Russia in recent years. Thus, experiments on the initiation of ascending and descending leaders during the development of a long spark with a high-voltage pulse voltage generator and with the help of an artificial charged water aerosol cloud were continued on the experimental site of Complex High-Voltage Test Bench of VNIITF High-voltage Research Center (Istra) [37]. Streamer flashes from steps of positive and negative leaders of a long spark were imaged in detail for the first time with high-voltage equipment (a 6-MV pulsed voltage generator) and a high-speed camera with an exposure of 0.2 ns [38]. The shape and structure of streamer flashes of leaders of both polarities are similar, in contrast to the idea about their difference which has been existed so far. The similarity of the shapes of the step channel of a positive leader and the channels of long streamers was found, which allowed the authors to suggest the hypothesis about the formation of a positive leader step in the streamer channel, in contrast to the formation of a negative leader step during the spatial leader rise [39]. In addition, detailed optical and IR images of the contact area between positive and negative leaders and the through phase were obtained for the first time on the basis of model experiments with a negative charged cloud. It was ascertained that the velocities of positive and negative leaders within the common streamer zone coincided and increased with the current strength. The results are important for the solution of fundamental problems of the dynamics during the main lightning stage [40]. A possibility of initiating electric discharges with a crossbow bolt (projectile) moving in the electric field of a cloud of negatively charged water droplets was first shown in [41].

The results of experimental studies of the formation of ascending leaders of models of lightning rods and protected objects under the action of an artificial thundercloud of negative polarity are presented in [42–45]. Two ways an ascending leader can develop are revealed: continuous and with a stop in the gap. It is found that the average current of an ascending leader in the case of continuous leader development in the gap is 1.4 times larger than in the case with a stop. It is ascertained that a counter descending leader from an artificial thundercloud generally deviates from the vertical more strongly than an ascending leader from the model of a lightning rod or object [42]. The significant effect of the shape and size of models of lightning rods and objects on the probability of their strike by a discharge from a cloud is shown. The optimal sizes of rod and cable lightning rods are estimated which ensure the earlier start of ascending leaders from them in comparison with the formation of ascending leaders from objects protected.

The analysis of some experimental data has shown the appearance of high frequencies (up to several hundred MHz) in the spectrum of signals recorded by antennas in the cases where a high-power streamer corona is formed from a part of the main discharge channel near the boundaries of the charged one and their correspondence to the cloud stage of the discharge formation [43]. It has been experimentally shown that groups of large hydrometeors of different shapes significantly increase the probability of initiating a channel discharge between an artificial thunderstorm cell and the ground, especially under the positive polarity of the cloud [44, 45]. The results can be used for the development of a technique for direct artificial initiation of lightning between a thundercloud and the earth.

The fundamental problems of lightning physics and the latest achievements of instrumental (primarily satellite) recording of discharge phenomena in the atmosphere are also actively discussed [46]. The generation of plasma formations in a thundercloud with the parameters required for the initiation and development of a lightning discharge is considered a nonequilibrium phase transition induced by electrostatic noise [47]. The dominant effect of the positively charged lower layer on the typology and dynamics of a lightning discharge in a thundercloud has been shown for the first time with the use of a new 3D model of lightning development, which includes bidirectional discharge propagation and its dynamic probabilistic branching and the possibility of a simultaneous rise and/or decay of peripheral branches; it also takes into account the evolution of conductivity, longitudinal electric field, and the discharge channel current [48].

A consistent theoretical model has been suggested for the first time; it can explain the near-lognormal distribution of peak currents in cloud-to-ground lightning discharges observed in measurements of currents of natural and trigger lightning discharges [49]. According to the model, the distribution of peak currents of the first and subsequent components of lightning flashes is not strictly lognormal, but close to lognormal in a certain range of values. In the region of extremely high peak currents (on the order of and higher than 100 kA), the distribution can differ significantly from lognormal, which is important to consider when solving lightning protection tasks.

Particular attention was paid to the study of a relatively recently discovered phenomenon: compact intracloud lightning in a thundercloud. A hypothesis has been developed in [50] according to which compact intracloud lightning is a consequence of the development of avalanches of high-energy relativistic runaway electrons initiated by a wide atmospheric shower and runaway breakdown. Numerical simulation of the development of a positive streamer around charged water droplets at atmospheric pressure, typical of the thundercloud altitude and at different background fields, droplet sizes, and charges, was performed in [51].

A new fractal model of a compact intracloud lightning is suggested in [52, 53]. In this model, intracloud lightning is considered a result of an interaction of two (or more) bipolar streamer structures formed in a strong large-scale electric field of a thundercloud. It is shown that a single bipolar streamer structure accumulates significant electric charges of different signs near its ends while developing. The features of the electromagnetic radiation of a compact intracloud lightning are studied within the model suggested. It is shown that high-frequency radiation is negligible during the preliminary stage of compact lightning when compared to the main stage. A good correlation between a high-frequency radiation burst and the maximum of a low-frequency electric field pulse during the preliminary lightning stage is found; the high-frequency radiation spectrum has a power-law form with an exponent from −2 to −1.

The scheme of wild fires in the climate model of the Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (CM IPA RAS), is expanded by taking into account the effect of lightning activity and population density on the frequency of fires and suppression of fires [54]. Using CM IPA RAS, numerical experiments were carried out in accordance with the conditions of the CMIP5 climate model comparison project (CoupledModelsIntercomparisonProject, phase 5). The frequency of lightning flashes was specified in accordance with the LIS/OTD satellite data. The calculations have shown the dominant role of the anthropogenic factor in the occurrence of wildfires, except for subpolar regions and, to a lesser extent, tropical and subtropical regions. Considering the relationship between the number of fires and lightning activity and population density in the model enhances the effect of wildfire parameters on the climate change in the tropics and subtropics when compared to the CM IPA RAS version, where the effect of fire sources on large-scale characteristics of wildfires is ignored.

5. HIGH-ALTITUDE DISCHARGES

The study of high-altitude discharges has been quite actively continued by Russian scientists. Satellite observations and laboratory and numerical simulations have been carried out. The work [55] is devoted to questions of the initiation of sprites. A spherical plasma inhomogeneity located at mesospheric altitudes in the quasi-electrostatic field of a thundercloud is considered a possible reason for sprite formation. Assuming the control of plasma formation conductivity by the processes of collisional ionization and electron attachment to neutral molecules, a simple semi-analytical model of ionization instability in a quasi-electrostatic field is developed. A numerical radial symmetric self-consistent model of sprites at altitudes from 60 to 90 km is suggested in [56]. The disturbances of the ion, electron, and neutral particle concentrations and of the photon emission intensity at mesospheric altitudes are analyzed for a sprite at night. The toroidal structure of an electric field and sprite radiation are observed in the upper part of the diffuse region of the sprite due to the rapid displacement of the electric field. At altitudes of 83–87 km, a decrease in the electron concentration is associated with the enhancement of the effect of dissociative attachment to molecular oxygen, which significantly reduces the conductivity at these altitudes. The effect of thunderstorm activity on plasma-chemical processes in air at altitudes of 95–100 km is considered in [57]. It is shown that the electric fields of clouds, unipolarly charged after lightning discharges, increase the electron concentration at these altitudes, which should noticeably increase positioning errors in the global satellite system.

A series of papers are devoted to the orbit of the Chibis-M microsatellite: a universal transport and launching device for launching microsatellites with a mass of 40–50 kg has been designed. A procedure increasing the *Progress* cargo ship orbit altitude for orbiting microsatellites after it completes the main task of delivering cargo to the ISS was attempted for the first time; it ensured a significant economic effect. A fully functional MS complex was designed; the cycles of its tests and the spacecraft flight control circuits were worked out [58–60]. The prospects of a satellite study of low-frequency electromagnetic fields generated by both ordinary lightning in the troposphere and stratospheric and mesospheric electric discharges of sprite and blue jet types are analyzed in [61]. The sensitivity of devices required for recording different discharge effects on the atmosphere are estimated. The Vernov satellite observation results are analyzed in [62] in comparison with the Universitetsky-Tatyana-1,2 satellite data.

A laboratory simulation of high-altitude discharges is carried out by two Russian groups. At the Institute of Applied Physics, Russian Academy of Sciences, a setup has been created for the experimental study of high-voltage discharges in gas with the pressure gradient [63]; the possibility of simulating sprites and jets in the pressure gradient in a large plasma setup in a pulsed mode has been shown. The application of the so-called apokampic discharge to the simulation of high-altitude discharges is discussed in a number of works [64, 65].

6. HIGH-ENERGY PHENOMENA IN THE ATMOSPHERE

The study of high-energy phenomena in the Earth's atmosphere is a new direction in atmospheric physics, closely related to the study of high-altitude discharges. The phenomena of generation of energetic elementary particle fluxes in thunderstorm clouds are divided into two classes: terrestrial gamma-ray flashes (TGFs) and thunderstorm ground enhancements (TGE). The relationship and correlation between these two classes remain subjects of discussion.

The RELEC instrumentation complex operating onboard the Vernov satellite was used for the acquisition of additional data on TGFs at Budker Institute of Nuclear Physics, Russian Academy of Sciences (INP RAS), and the Russian Space Research Institute, Russian Academy of Sciences. The Vernov data were processed and served as a basis for the catalogue of TGFs [66]. TGFs in the catalogue are of ~400 μs in length; 10–40 gamma quanta are recorded for this time. Each TGF is accompanied by temporal profiles, spectral parameters, a geographical point, and the results of a comparison with data from other Vernov instruments. The flash recorded in the subpolar region over the Antarctica is considered a candidate to TGFs.

The development of processing techniques for high-energy events in the Earth's atmosphere is described in [67]; the results of the complex study of archive observation data of SPI gamma spectrometer accumulated for 7 years of the INTEGRAL observatory work are presented. The problems of in situ data processing are discussed, including a search algorithm and technique for the automatic classification of events detected (both terrestrial and cosmic gamma-ray flashes) on the basis of a set of criteria.

The location of the geographical regions of TGF excess/deficiency is compared with the location of regions of a high concentration of tropospheric impurities [68]. The (KNMI/NASA) OMI data on NO_2 content in the troposphere are used as a measure of tropospheric pollution. It is shown that the NO_2 content in the TGF "deficiency zones" is two-times higher than in the "excess zones." The additional analysis of the NO_2 concentration distribution around TGF sites on the basis of high-resolution WWLLN (WorldWideLightningLocationNetwork) radio data shows the absence of peculiarities in the NO_2 distribution on a scale of tens of kilometers, characteristic of urban agglomerations.

The status of world scientific research of fluxes of energetic particles originating in thunderstorm clouds and detected by ground-based detectors (TGEs) is determined by works at the Aragats cosmic station. A bulk of observation data on high-energy atmospheric phenomena is analyzed in [69–72]. The brief results are as follows. A TGE always interrupts after a lightning flash occurred in the same thundercloud. The analysis of the TGE spectra has shown the high-energy part of TGE to disappear immediately after a flash. A decrease in the density of a flux of energetic particles from a thunderstorm is concurrent with a lightning flash on the millisecond scale [71].

The key issue of atmospheric physics, i.e., the problem of initiating a lightning discharge, is fed by new TGE observations. The time resolution of the equipment used made it possible to relate the dynamics of an energetic particle flux to the redistribution of charges inside a thundercloud. Based on the model of avalanches of relativistic runaway electrons, the authors of work [70] state that the development of a TGE event in a thundercloud favors the initiation of a negative cloud-to-ground lightning discharge. The theoretical aspects of the physics of fluxes of energetic particles from thunderclouds are considered in [72]; the author declares the model of relativistic runaway electron avalanches to be sufficient for explaining observation data without the mechanism of relativistic feedback suggested by Dwyer.

The long-term cycle of experimental studies of variations in the cosmic-ray secondary particles during thunderstorms carried out at the Carpet array of Baksan Neutrino Observatory INP RAS provided grounds to assume the possibility of runaway breakdown in the atmosphere in the near-threshold mode [73, 74]. The breakdown is characterized by the presence of an electric field in the stratosphere with a potential difference of ~100 MV [74]; in the field, runaway electrons, which generate gamma rays with energies up to 30 MeV, avalanche multiply. A non-self-sustaining glow discharge is a wider known analogue to the discharge assumed. The transition of a discharge to an independent state by the "cyclic generation" of bremsstrahlung photons is considered in [73]. The region of the breakdown type under study, which is more likely to form in the stratosphere between the top charge of a thundercloud and the ionosphere, should be accompanied by glow and disturb the electric and magnetic fields with a characteristic time of several minutes. This underlies the principle of discharge detection from measurement data. A correlation between long-term continuous thundercloud glow and the anomalous disturbance of the cosmic-ray secondary particles detected at the ground level is ascertained. The case of interruption of global micropulsations of the geomagnetic field due to slow runaway breakdown in the stratosphere in the threshold mode is described in [73]. The interaction of a thunderstorm front with the precipitation of protons into the atmosphere from the Earth's radiation belt due to seismic activity has been detected; the effect of seismic activity on the night glow is discussed in [74].

The measurements of the surface flows of energetic particles at the Tien-Shan cosmic ray station provided new data on extensive air showers and high-energy radiation of lightning discharges [75–77]. The energy spectrum of particles of a wide air shower in the range

10^{14}–10^{17} eV is studied. High-energy lightning discharge radiation was observed within 10 s after a flash; gamma radiation, energetic electrons, and neutrons were simultaneously detected [76]. The time series of the neutron flux generated by atmospheric discharges were detected with the use of ground-based and underground detectors [75, 77]. A significant part of neutrons is emitted in a short period of time immediately after a discharge (200–400 μs). This time gap allows an assumption about neutron generation mainly in a dense medium (presumably in the soil).

Observations at the high-altitude Tien-Shan station made it possible to simultaneously detect radiation in the RF (0.1–30 MHz), IR (610–800 nm), UV (240–380 nm), and soft X-ray (0.1–4 MeV) ranges [77]. The next step in the study of thunderstorm processes at the Tien-Shan station was the detection of optical, radio, and gamma radiation during the bright stage of a lightning discharge. In 2016, several hundred bursts of optical radiation due to nighttime lightning of ~30 thunderstorm events were recorded at a distance of 3–10 km from the source. The importance of observations of lightning discharges in a wide energy range for checking and comparing the consequences of different theoretical models of atmospheric discharges is shown. Among them, the so-called "dark discharge" ("dark lightning") is of special interest. The assumption about the existence of this discharge is based on the model of relativistic runaway electron avalanche. The detailed analysis of the relationship between energetic particle fluxes and lightning discharges, as well as possible conditions for the development of a dark discharge, is the direction of future research based on the ensemble of data on high-energy events, which continues to be replenished by data of observations at the high-altitude Aragats and Tien-Shan stations.

The data ensemble on high-energy events in the atmosphere is also enriched by observations of thundercloud electric field amplified neutron fluxes, which are among the main components of secondary cosmic rays. Preliminary results were obtained using a complex of devices created at Shafer Institute of Cosmophysical Research and Aeronomy, Siberian Branch, Russian Academy of Sciences, for the synchronous detection of variations in the neutron flux, electric-field strength, and electromagnetic radiation during lightning discharges [78]. The neutron flux intensity was measured with SNM-15 counters (resolution of 10 μs; in and without lead shell) during nearby lightning discharges around Yakutsk. Variations in the electric field and neutrons during snowstorms in polar Tiksi, with powerful snow charges and strong winds of up to 60 m/s, were analyzed. It was shown that the electric-field strength can reverse and reach 90 kV/m during the events under study, which is not accompanied by electric discharges and bursts of neutrons.

The data on amplifications of the neutron flux during a thunderstorm have also been successfully used to study thunderstorm nuclear reactions [79]. The assumption has been verified about photonuclear reactions due to gamma quanta of the bremsstrahlung radiation of high-energy runaway electron avalanches, capable of developing in a thunderstorm electric field, as a cause of enhancement of the neutron flux. The importance of distinguishing between the response of detectors to neutrons, electrons, and gamma rays is discussed. The contribution of thunderstorms to variations in the content of atmospheric radiocarbon ^{14}C, widely used for dating archaeological artifacts and works of art [80], is estimated. It is shown that the thunderstorm neutron flux per lightning discharge measured in thunderstorm active regions provides a local rate of radiocarbon production comparable to that by cosmic radiation. A previously unknown natural source of not only ^{14}C radiocarbon, but also other isotopes in the atmosphere (^{13}N, ^{15}N, ^{15}O, ^{17}O, ^{13}C), has been discovered.

7. INTEGRATED TECHNIQUES FOR STUDYING THUNDERSTORMS

The study of regional peculiarities of the atmospheric electric field under the formation of thick convective (thunderstorm) clouds is of great importance, since variations in the field strength characterize the processes of electrization of weather phenomena developed in a region and provide information on the regional GEC parameters. Actual data on the effects of dangerous weather events (showers, thunderstorms, etc.), large-scale atmospheric circulations, and solar–terrestrial relationship on daily and seasonal variations in the atmospheric electric field in regions are still not enough to organize reliable disaster warning.

Joint research into the formation and electrization of thunderclouds through field observations and numerical simulation is important. Works [81, 82] are devoted to the joint analysis of instrumental observations of the LS8000 lightning recorder, meteorological radars, electric-field strength sensors, and results of numerical simulation of electric parameters of thick convective clouds with the use of a 3D model developed at the High Mountain Geophysical Institute. The analysis made it possible to identify the peculiarities of the effects of electric processes on the formation of microstructural characteristics of convective clouds and precipitation. A 3D nonstationary numerical model of thick convective cloud development was used with a detailed description of the hydrothermodynamic, microphysical, and electrical processes in an unstable atmosphere accounting the vertical profile of wind speed and direction. The model determined the volumetric charges of clouds, the electrostatic potential of a cloud created by these charges, and the horizontal and vertical components of the cloud electric field. In parallel with that, the model calculated the radar reflectivity of clouds at wavelengths of 3.2 and 10 cm for comparison with actual radar data. The model calculation results showed nonlinear character of interaction of processes in thick convective clouds and their important role in the formation of the cloud microstructure.

To identify the correlations between electric discharge and cumulonimbus cloud parameters during cloud development, simultaneous radar, radiometric (Meteosat/SEVIRI radiometer), and radio receiver measurements in the North Caucasus were analyzed [83]. A correlation was found between the scale of inhomogeneity of the cloud radiation temperature field and the frequency of electric discharges, as well as an increase in the electric discharge frequency with precipitation intensity: the electric discharge frequency attained its maximum at a precipitation rate of about 70 mm/h.

The analysis of MPL-5 radar and LS8000 lightning direction finder data on the development of a thick thundercloud in [84] showed a correlation between the total LF lightning current and the LF and VHF lightning frequency. According to the measurements, the total charge transferred by negative lightning discharges from a cloud to the ground is 387 C; the average charge per lightning is 0.44 C. To study a thick thunderstorm cloud above Pyatigorsk on May 29, 2012, accompanied by a strong hail, a 3D nonstationary model of a convective cloud was used [85]. The cloud parameters that were calculated made it possible to analyze the evolution of the precipitation field and charge structure during cloud development.

Studies of radio emission from close thunderstorms carried out in the Nizhny Novgorod region have shown that radio emission is concentrated in time intervals of fractions of microsecond in length, with an interpulse gap of several microseconds, and it does not show a smooth increase [86]. Radio emission is recorded not only during lightning discharges, but also in the gaps between them. A significant dependence of thunderstorm activity on the underlying surface type was shown and confirmed in [87, 88]. Thus, the intensity of thunderstorms over a megalopolis is 46% higher than over underpopulated territories on average. At the same time, the intensity of thunderstorms over dense forests is about 2.4 times higher than over farmland.

The results of 5-year study of thunderstorm activity in different North Asian regions are presented in [89]. Data on such parameters as the density of ground discharges and the corresponding currents are required for more effective lightning protection. The lack of regular satellite and ground-based observations in this region caused the use of WWLLN global network data. The average efficiency of lightning detection by this system was about 15% for cloud-to-ground discharges and more than 30% for lightning with a peak current higher than 100 kA in 2012. According to this work, the average density of lightning discharges showed a gradual increase over that period, and the number of intracloud discharges prevailed over the cloud-to-ground discharges. It should be noted that the probability of detection of intracloud discharges by the WWLLN network is quite small. In Central Yakutia, the share of cloud-to-ground lightning was 40–60% in the summer. When averaging the thunderstorm points over a grid of $0.25° \times 0.25°$, local maxima of the thunderstorm frequency were found, which were caused by the relief.

CONCLUSIONS

Studies of atmospheric electricity in the Russian Federation received a new impetus for the development in 2015–2018. A wide range of experimental and theoretical studies of fair-weather electricity and the effect of atmospheric ions and aerosols on it were performed. Experimental and theoretical studies of the global electric circuit were carried out, including with the use of climate and chemistry-climate models. A complex of experiments were carried out in the field of physics of lightning and lightning protection, including with the use of unique laboratory test benches and the Complex High-Voltage Test Bench of VNIITF High-Voltage Research Center (Istra). Studies of climatology of atmospheric electrical phenomena and regional meteorological features of thunderstorms were successfully continued in several Russian regions; thunderstorm simulation and forecasting techniques were improved. Numerous laboratory experiments were carried out with the aim of studying the features of development of lightning discharges, both cloud-to-ground and earth–ionosphere. The Chibis-M microsatellite was orbiting; its main task is to study discharge phenomena in the upper atmosphere. The Vernov satellite observation results are analyzed. Measurements of the surface fluxes of energetic particles made at the Tien-Shan station provided new data on extensive air showers and high-energy radiation of lightning discharges.

The following conferences on atmospheric electricity have been successfully held in the past three years: V and VI International Lightning Protection Conferences (St. Petersburg, 2016 and 2018) and the Second and Third "Global Electric Circuit" all-Russian conferences (Borok, Yaroslavl Region, 2015 and 2017). Russian scientists (12 people, including 11 representatives from RAS institutions) took an active part in the 16th International Conference on Atmospheric Electricity (ICAE2018, Nara, Japan, June 2018), which is held every four years and is the main international forum on atmospheric electricity.

FUNDING

This work was performed within the State Assignment for Institute of Applied Physics, Russian Academy of Sciences (project no. 0035-2019-0010).

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Translated by O. Ponomareva