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Global electric circuit research: achievements and prospects

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1. Introduction

The atmosphere is the most volatile and vulnerable of Earth's shells forming the human environment, and therefore the physics of atmospheric processes attracts progressively closer attention in connection with ecological problems, weather forecasting (including cosmic weather), and climate studies. At the same time, the terrestrial atmosphere is a remarkable subject of physical–mathematical research in the area of hydrodynamics and turbulence theory, the theory of dynamical systems, optics, cosmic ray physics, and atmospheric electricity [1–7]. Investigations of atmospheric electricity, being one of the fundamental areas of atmospheric physics, is attracting considerable attention recently in connection with the emergence of new experimental data obtained by ground-based and satellite-borne observations, balloon-borne probing, aircraft-borne measurements, triggering lightning experiments, and laboratory modeling [7–9].

A new impetus to the development of concepts related to thunderstorm electricity was lent by observation of optical phenomena in the upper atmosphere correlating with thunderstorm activity — sprites, elves, and jets [8]. Various physical issues of thunderstorm electricity have been discussed, in particular, in reviews published in *Physics–Uspekhi* [10, 11]. Recent experimental and theoretical work has also led to a deeper understanding of the physical processes in the classic area of atmospheric electricity research — the study of the global electric circuit (GEC). Therefore, it is quite reasonable that several new reviews in leading international and Russian journals [12–15] concerned with GEC have emerged, although none of them provide an integral picture of experimental and theoretical achievements in the area. This brief report is, in essence, a detailed plan of such a review.

2. Global electric circuit concept. Observation of the global electric circuit and its variations

The GEC is a distributed current circuit formed by high-conductivity layers of the upper ocean, Earth's crust, and the atmosphere, whose conductivity is negligible in the boundary layer, but sharply (exponentially) increases with altitude (Fig. 1).

According to Wilson's concept formulated 90 years ago [16], the main sources of electromotive force (EMF), which maintains the potential of the ionosphere, are clouds, which

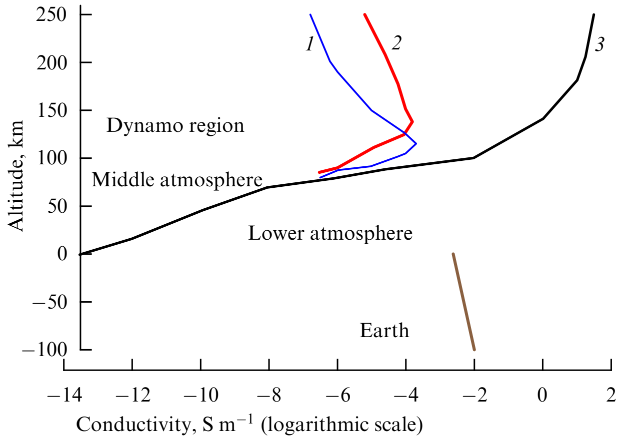

Figure 1. Typical profiles of transverse (*1* — Hall's, *2* — Pedersen's) and longitudinal (*3*) GEC conductivity [13].

have an electric structure (primarily cumulonimbus and nimbostratus clouds), while the areas of fair weather are zones of return currents (Fig. 2). As is well known, Wilson's concept was basically confirmed by experiment already in the late 1920s in a comparison of the diurnal variation of the atmospheric electric field above the oceans measured in fair weather conditions [the so-called Carnegie curve (Fig. 3)] with the diurnal variation of the number of thunderstorms on the terrestrial globe [17]. It turned out that both curves have a maximum at about 19–20 h UT and a minimum at about 4 h UT. That is why the diurnal variation of the atmospheric electric field and current has come to be known as unitary (see the well-known section "Atmospheric electricity" in *The Feynman Lectures on Physics* [18]). But numerous subsequent ground-based measurements of electric fields and currents revealed that several factors hinder extracting the unitary variation from observations near the terrestrial surface above the land: radioactivity, enhanced density of aerosol particles in the boundary layer, their charging and transfer (which perturbs the conductivity and the electric charge density), and the so-called electrode effect [14, 19, 20]. In Fig. 3, for instance, the Carnegie curve is shown together with the daily variation of the electric field plotted during 28 days of ground-based observations in fair weather in June and August of 1999 for the mid-latitude Borok geophysical observatory (GO) [14]. A morning peak caused by the development of high-intensity convection is clearly seen.

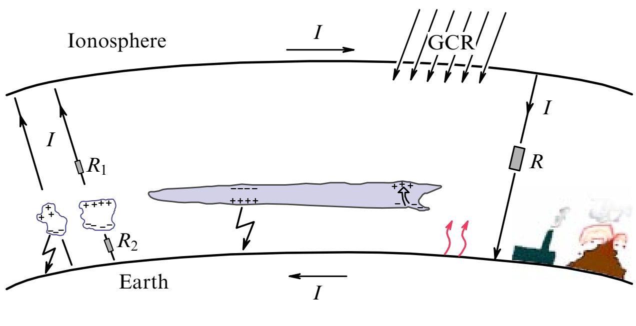

Figure 2. Schematic representation of the GEC, with the resistance $R \approx 230\ \Omega$ and the total charging current $I \approx 10^3$ A. Separately depicted are mesoscale convective systems with the horizontal scale length 150–200 km. Typical respective resistances of the above- and below-cloud regions are $R_1 \approx 10^4$ and $R_2 \approx 10^5\ \Omega$. GCR: galactic cosmic rays.

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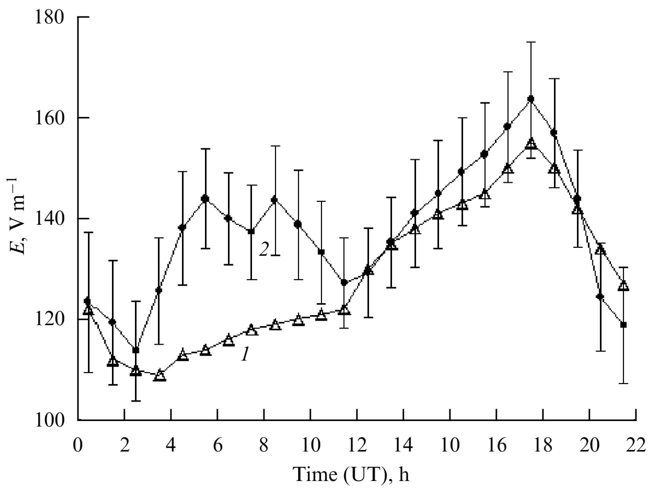

Figure 3. Unitary variation of the intensity of the atmospheric electric field (*1* — the Carnegie curve) and the average field strength according to Borok observatory observations during June and August 1999 (curve *2*). Vertical segments show the rms deviations of the hour-average field values [14].

Recent experimental data show that even at the initial stage of energy transfer from the heated underlying terrain to the atmosphere, a part of the energy is converted to electric energy in the course of convection, which manifests itself in the formation of aero–electric structures of different scales [21, 22]. Under fair weather conditions, the energy of individual structures may range from several to several hundred joules [23]. Under fog conditions, the electric energy accumulated by intense structures and their contribution to field perturbation may be substantially greater. During experiments in the Borok GO in July 2002, for instance, field perturbations with the horizontal scale length $L \approx 10$ km, height $h \approx 200$ m, and energy $W \approx 3 \times 10^4$ J were observed [24].

The theoretical analysis of the role played by convective generators in the global circuit, which takes the dynamics of convection development into account, is currently far from completion [25, 26]. We note that under the correct treatment of convective generators, the magnitude of the current that contributes to the maintenance of the ionospheric potential should depend on the magnitude of this potential, which is an inherent feature of this generator. An improved analysis of the seasonal behavior of unitary variation, according to which the peak is observed during the summer in the Northern Hemisphere, also shows the role of local effects in ground-based measurements [27, 28].

Special emphasis was recently placed on electric field measurements at high latitudes, primarily in Antarctica [29–31], where the number of cloudless days is quite large and the boundary layer is more stable due to the low temperature, although additional complications caused by geophysical effects emerge. Taking the effect of magnetospheric sources and the corresponding data averaging into account, it has been possible to reveal the diurnal variation at the South Pole and the Vostok Station [30, 31]. Therefore, despite the complexity of ground-based measurements, the exclusion of local and regional effects permits revealing the manifestations of global variations of the ionospheric potential. But the most direct way of measuring this quantity is to measure the vertical electric field strength profile in the atmosphere [12, 28, 32].

At present, the following experimental facts, along with the diurnal variation, may be considered confirmations of the existence of the global circuit:

1) the continuity of the current density with the height up to the altitudes of several dozen kilometers (see, e.g., Ref. [33], where data are outlined to show that at altitudes below 31 km, the positive j_+ and negative j_- current densities remain invariable, $j_+ \approx j_- \approx 2.5$ pA m^{-2});

2) the close values of the Earth–ionosphere potential difference measured at globally spaced points (Darwin, Australia: 220 kV; Weston, USA: 235 kV) [32].

We note that the potential difference between Earth and the upper part of the atmosphere obtained in balloon-borne measurements inside thunder clouds is also close to the values of the ionospheric potential despite the large values of the field and its variations [34] (see, e.g., Ref. 5 in Section 3).

One of the most important recent experimental achievements in the area of atmospheric electricity is the continuous (beginning in 1995) space observations of the number of lightning flashes made aboard the NASA satellites Microlab-1 (instrument: Optical Transient Detector (OTD), 1995–2000) and TRMM (Tropical Rainfall Measuring Mission) (instrument: Lightning Image Sensor (LIS), launched in 1997) [35–37]. An analysis of these observations, in particular, allowed elucidating several questions associated with the diurnal variation and, first and foremost, providing a quantitative estimate of the relative contribution from different regions of the highest thunderstorm activity to the global circuit: Africa (the Congo river basin), South America (the Amazon basin), and Southeast Asia [38, 39]. It also allowed revealing intense centers of thunderstorm activity at higher latitudes. The results of investigations confirmed that the thunderstorm activity of the African source prevailed, but its contribution to the diurnal variation was not the greatest, which is related to the governing role of quasistationary currents caused by thunder clouds and by nimbostratus clouds (including those not accompanied by a lightning storm but having a developed electric structure). The basic problem of the current balance between thunder and nimbostratus clouds and the GEC on the whole remains insufficiently studied, which invites additional ground-based and balloon- and aircraft-borne measurements [40, 41].

It is noteworthy that a significant (though episodic) contribution to the global circuit may also be due to generators arising from the charging of particles in dispersed multiphase dust and aerosol flows [42]. In this case, a significant role may be played by the difference in mobility of ions and ion clusters [43], including those related to seismic activity [44].

It is well known that a significant contribution to the GEC potential and current distributions is made by ionospheric and magnetospheric generators, along with generators located in the lower part of the atmosphere [14, 45]. In the polar cap, the morning–evening potential difference 40–100 kV (with the total current of the order of 10^6 A) is generated by the magnetospheric dynamo, which is a magnetohydrodynamic (MHD) generator that converts the kinetic energy of the solar wind to electric energy. Under low geomagnetic activity, for a horizontal source size of the order of 500 km, the contribution of the electric fields of magnetospheric convection may be responsible for about 20% of the variations of the high-latitude surface electric field [45]. Under magnetic storm conditions, the field perturbations and the latitude scale of the influence of this generator are substantially greater. The electric field variations caused by the dynamo action of tidal waves in the E-region of the ionosphere amount to 5% of the average mid-latitude field intensity (the potential difference at ionospheric altitudes is 5 – 15 kV and the total current is of the order of 10^5 A).

The authors of Refs [46–49] draw attention to the existence of another potentially important source of atmospheric electricity, a planetary electric generator, which is due to the non-solid-state character of rotation of the planetary plasma shell. The output voltage of the planetary generator, of the order of the unipolar induction EMF $U = M\omega_0/cR$ (where M is the magnetic moment of the planet, and ω_0 and R are its angular velocity and radius), is applied to the atmospheric gap as the highest-resistance part of the global electric circuit.

Two regimes of planetary generator operation are considered in the model constructed in Refs [47, 48]: 1) an 'idle' regime, which corresponds to the planet with 'fair' weather and with currents of other sources nonexistent in the atmosphere; 2) an operation regime that involves the distributed EMF of unipolar induction and thunderstorm external currents. Reasonable characteristics of GEC parameters have been obtained. An experimental investigation of the role of the planetary generator in the global circuit invites simultaneous measurements of the ionospheric potential and the atmospheric current at mid-latitudes and on the equator.

Because of the significance of the role of sources located in the upper atmosphere, the ionospheric and magnetospheric current systems are sometimes included in the GEC concept [44, 50].

We note that recent years have seen the emergence of the practice to consider, along with the classical quasistationary current circuit termed the "direct current (DC) circuit" in the English-language literature, its attendant circuit, the "alternating current (AC) circuit," which is the Earth–ionosphere resonator [15]. An analysis of the corresponding global electromagnetic resonances (the so-called Schumann resonances) yields a wealth of information about thunderstorm activity sources on the terrestrial globe [15, 51, 52].

In recent years, deeper insight has been gained into the role of cosmic rays in the global circuit and particularly in thunder clouds, although several problems remain unsolved, which are related, in particular, to lightning initiation and to the generation of high-energy particles and X- and gamma-ray photons under thunderstorm conditions [10, 52–54].

It is noteworthy that some authors' 'challenges to the GEC concept' [50, 53] are most likely associated with too narrow an understanding of the classical GEC concept, quite frequently treated, in particular, as a 'spherical capacitor' model [55]. The definition of the GEC as a distributed current circuit and a detailed accounting for different generators (electrohydrodynamic as well as magnetohydrodynamic) permit considering the GEC concept as a well-established self-consistent theory, which nevertheless calls for further development.

3. Modeling the global electric circuit. Generators and their models. Lightning discharges

The foundations of the model for describing the GEC in the framework of a steady-state approximation were formed by the mid-1980s. The most common steady-state model was proposed by Roble and Hays [45, 56]. For sources, the authors of this model considered point dipole current sources in the background of given altitudinal and latitudinal conductivity profiles.

The theoretical description of the GEC relies on the consideration of fields and currents of individual stationary sources in planar geometry [57 – 59]. This consideration is remarkable, more specifically, in that it exhibits the necessity of GEC formation "with the participation of the ionosphere." In fact, by considering a point source of the current in a medium with as exponentially increasing conductivity, it is easy to find an analytic expression for the potential (Green's function)

$$\varphi(R, z) = \frac{I}{4\pi\sigma_0} \exp\left(-\frac{z+h}{2H}\right) \frac{\exp\left[-r/(2H)\right]}{r},$$

$$r = \left[R^2 + (z-h)^2\right]^{1/2}, \qquad (1)$$

where $\sigma = \sigma_0 \exp(z/H)$, h is the coordinate of the point-like source, and z and R are the vertical and horizontal coordinates of the observation point. In the presence of a perfectly conducting boundary at $z = 0$, the total potential is found by adding expression (1) to the potential of a point current $-I \exp[-h/(2H)]$ placed at the point $z = -h$ [59]. By calculating the field $\mathbf{E} = -\nabla\varphi$ for $z > h$ and integrating $j_z = E_z$ with respect to transverse coordinates, it is easy to find the upward-flowing current (towards the upper layers of the atmosphere) as $I_0 = I[1 - \exp(-h/H)]$. This expression shows, first, that the exponential increase in the conductivity necessarily implies that a part of the current in the vicinity of a cloud flows to the ionosphere and, second, that the fraction of current flowing to the ionosphere (in comparison with the fraction that closes to Earth in the neighborhood of the cloud) increases sharply with the cloud altitude above the earth. For distributed current sources with a small transverse size, the picture is qualitatively the same (Fig. 4).

The Roble–Hays model with a 5° resolution in latitude and longitude allowed obtaining the distribution of the potential in the atmosphere under some model assumptions about the mean distribution of point-like sources in the main regions of thunderstorm activity. Subsequently elaborated were models that took transient point-like sources, distributed point-like sources of small transverse size, and conductivity perturbations into account [60 – 63], but these effects were not included in the GEC model.

As the experimental data about stationary electric sources in the atmosphere were being accumulated, an evident necessity was recognized to include several new facts into

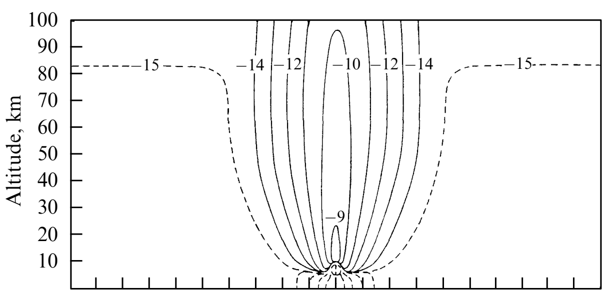

Figure 4. Isolines of the vertical current density component in the vicinity of a source above a conducting surface [59]. The numbers at the curves correspond to the values of $\log_{10}(j_z[\mathrm{A\ m^{-2}}])$. The centers of ±50 C charges are at the altitudes 5 and 10 km.

the model that were revealed during relatively recent experimental campaigns. First and foremost, balloon-borne measurements of the electric structure of developed thunder clouds demonstrated the existence of a complex multilayer electric structure (with up to eight layers); the regions with different convection rates could have different electric structures [63]. Furthermore, direct measurements of the electric structure of large-scale thunderstorm conglomerates — mesoscale convective systems (MCSs) — revealed the existence of a single quasistationary layered electric structure in stratiform regions with the transverse scale size of several hundred kilometers. The approach developed in [34] permitted both of these thunderstorm generator features to be included in simulations.

In the case of distributed steady-state electric sources, the system of Maxwell equations reduces to static current equations, which can be solved analytically under certain conditions. According to the approach outlined in Ref. [34], to model a large-scale electric cloud structure, it suffices to specify the altitudinal conductivity profile and construct the distribution of vertical external currents that provide the observed altitude profile of the electric field. To state it in different terms, it is required to solve the inverse problem of current statics and reconstruct the source from the known measured distribution of the electric field; after that, by solving the direct problem, the current density and electric field can be found both inside the cloud and in its neighborhood. In accordance with observations, the complex altitudinal electric structure of convective systems is conveniently represented as a set of horizontal layers of the vertical external current:

$$\mathbf{j}_{\mathrm{ex}}(\mathbf{r}, z) = \begin{cases} 0, & z < z_- , \quad z > z_+ ; \\ j_{\mathrm{ex}}(\mathbf{r})\,\mathbf{z}_0 , & z_- < z < z_+ , \end{cases} \tag{2}$$

where z_- and z_+ are the lower and upper layer boundaries, $j_{\mathrm{ex}}(\mathbf{r})$ is the distribution of the external current amplitude in the horizontal plane, and $\mathbf{z}_0$ is the vertical unit vector. In a simple case, the conductivity distribution has the form

$$\sigma(z) = \begin{cases} \sigma_1 , & z \leqslant 0 , \\ \sigma_0 \exp\left(\dfrac{z}{H}\right), & z > 0 , \end{cases} \tag{3}$$

where $\sigma_0 \approx 5 \times 10^{-14}$ S m^{-1} is the specific electric conductivity of the atmosphere at the terrestrial surface, $\sigma_1 \approx 10^{-3}$ S m^{-1} is the electric conductivity of Earth, and $H \approx 6 \times 10^3$ m is the reduced height of atmospheric conductivity. Profile (3) is in a reasonably good agreement with the conductivity distribution in domains of fair weather for altitudes below approximately 70 km. In accordance with the static-current approximation, the electric field is assumed to be potential, $\mathbf{E} = -\nabla\varphi$, and the conduction current density is of the form $\mathbf{j} = -\sigma\nabla\varphi$. In this case, the total current continuity condition gives the following equation for the electric potential:

$$\operatorname{div}\left[-\sigma\nabla\varphi + \mathbf{j}_{\mathrm{ex}}(\mathbf{r}, z)\right] = 0 . \tag{4}$$

The boundary conditions for Eqn (4) follow from the continuity of the potential and the vertical component of the total current density at the interfaces of the media and the layer, as well as from the unperturbed state of the potential φ at long distances from the source: $\varphi(r \to \infty, z) = 0$, $\varphi(r, z \to \infty) = 0$. It is significant that the use of a planar external current layer as an element of electric structure is justified both for thunderstorms with a moderate transverse size and for an extended stratiform region of mesoscale convective systems, whose electric structure, as shown by direct measurements, differs little at different points of the domain and at different stages of the evolution of the system.

Examples of calculations performed in accordance with the approach outlined above may be found in Refs [34, 64, 65]. Figures 5 and 6 illustrate the results of these calculations. The resultant model enabled calculating electric fields and currents in the vicinity of an MCS and estimating the total current flowing toward the ionosphere. The calculated data showed that the contribution of MCSs to the global electric circuit may greatly exceed the contribution of individual thunderstorms. An important conclusion was that despite a significant perturbation of the electric potential in the convection region (ranging up to several hundred megavolts), the leading contribution to the total vertical current and the structure of fields and currents in the vicinity of an MCS is due to the stratiform region (for the type-B MCS model considered, for instance, the total vertical current from the stratiform region is -25 A, while the contribution from

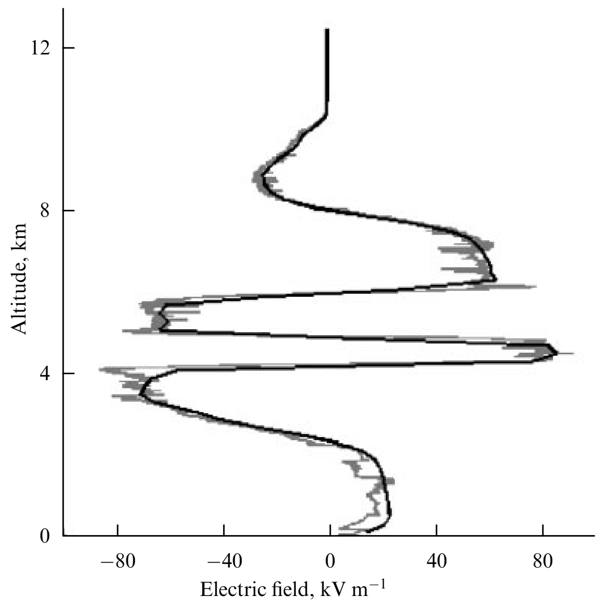

Figure 5. The altitude profile of the electric field (bright curve) obtained via balloon-borne measurements in the stratified type-A MCS stratiform region above Oklahoma on May 24, 1991 and a model electric field distribution (dark curve) [65].

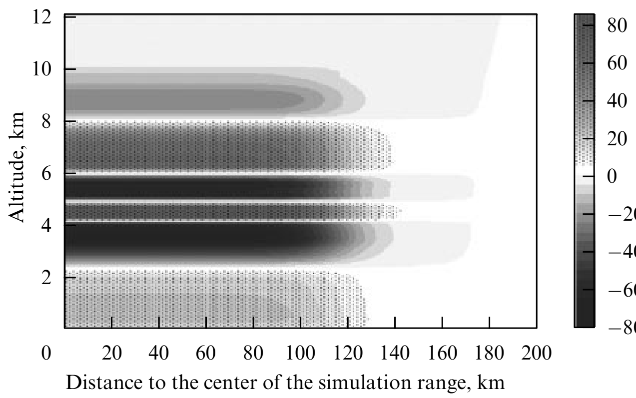

Figure 6. Distribution of the vertical component of the electric field formed by a stratiform region of mesoscale convective systems [65].

the convection region does not exceed 0.5 A). Depending on the number, transverse dimension, position, and amplitude of external current layers, the total contribution from an MCS to the global circuit may be 'positive' as well as 'negative,' when the system is a sink in the global circuit. This circumstance impels giving much consideration to the statistics and evolutionary features of MCSs in future GEC research.

The described approach to the modeling of sources also enabled deriving analytic expressions for the cloud energy and the average rate of its dissipation in the atmosphere with an exponential conductivity profile [66]. It was assumed that the external current has a smooth transverse distribution $j_{\text{ex}} = j_0 \exp(-r^2/a^2)$ and flows in the layer between the z_- and z_+ levels corresponding to the lower and upper levels of electric charge localization. Rather simple expressions are obtained when the transverse cloud size a is small or, conversely, large in comparison with the conductivity gradient scale length H. The expressions obtained in Ref. [66] permit investigating the dependence of source energy characteristics on the parameters a, H, σ_0, z_-, and z_+, comparing the contribution of different cloud regions, and estimating the role of the horizontal field component in the energy balance of the circuit. They yield reasonable values for the energy and its dissipation rate for current density values of the order of $1-10$ nA m^{-2}, which maintains the charge distribution in the cloud.

An important line in the further development of GEC simulations is the inclusion of transient processes [67–69]. In particular, the question of the contribution to the GEC from lightning and transient currents flowing after lightning flashes remains insufficiently investigated. It is commonly assumed that the electric charge transferred by a lightning flash from a cloud to ground is rapidly redistributed over the terrestrial surface and therefore makes a direct contribution to the total charge of Earth and to the effective charging current (or discharging current, depending on the flash polarity) of the GEC. It is well known, however, that this rapid process (the duration of a typical negative flash is not longer than several hundred milliseconds) is followed by a slow transient stage caused by charge redistribution in the surrounding atmosphere. The transient stage (ranging up to several dozen or hundred seconds in duration) results in a partial neutralization of the charge transferred to ground and in charge transfer to the ionosphere. The charges transferred to ground and the ionosphere after the transient stage are the total contribution from the lightning flash to the GEC.

The dynamics of transient currents were investigated in Ref. [67]. Cloud-to-ground flashes and intracloud flashes were found to generate, along with short-duration currents, transient currents of substantial magnitude. The cloud-to-ground flashes of 'normal polarity' (i.e., those that transfer a negative charge to Earth) charge the global circuit, while intracloud flashes of 'normal polarity' result in its relaxation. The efficiency of cloud-to-ground-type flashes (i.e., the ratio between the charges transferred to the ionosphere and to Earth) depends heavily on the charge location altitude in the conducting atmosphere and varies from 15% to 90% in the range from 1 km to 14 km above Earth in the model with an exponential conductivity. The efficiency of intracloud flashes is on average much lower than for cloud-to-ground flashes, but their average contributions to the GEC current may be comparable because the number of intracloud flashes is much larger than the number of cloud-to-ground flashes. The estimates of the global balance of transient currents showed that the contribution of the transient currents caused by lightning flashes during a period of high-intensity thunderstorm activity may be of the same order of magnitude as the contribution of the quasistationary current. In the global current balance, however, the contribution of transient currents is unlikely to exceed 20%.

The last decade or so has seen the introduction of GEC models that take the influence of conductivity anisotropy at high altitudes, the features of large-scale atmospheric conductivity distribution, and nonstationary effects into account [68–72]. A new impetus to the development of nonstationary models, including 'electrotechnical' ones [73], was lent by the discovery and active studies of discharges in the middle atmosphere correlating with thunderstorm activity in the troposphere.

A common avenue of GEC simulation is the development of self-consistent models capable of taking both nonstationary effects and the nonuniformity of conductivity distribution into account, including the effects related to cosmic ray flux perturbations, high-energy particle precipitation, aerosol particle ejections (for instance, in volcanic eruptions), and radioactivity. The development of the electric dynamo applied to different layers of the atmosphere, including the middle atmosphere, also appears to be important for the GEC theory [74]. In the future, it is highly desirable to elaborate combined models that self-consistently include the hydrodynamics and electrodynamics of the upper atmosphere [75] and the general circulation of the atmosphere and the ocean [76]. Such a GEC model remains to be constructed.

4. The global electric circuit as an open dissipative system

The main part of the energy flux supporting the global electric circuit comes in the form of solar radiation energy (1.37×10^3 W m^{-2}), which is the source of labile energy (which comprises internal, $\sim 8.6 \times 10^{23}$ J, and potential, $\sim 3.6 \times 10^{23}$ J, energies), the kinetic energy of the atmosphere (ranging from 6×10^{20} J to 9×10^{20} J depending on the season), and electric field energy. Of special significance to the dynamics of electric field energy accumulation and dissipation in the atmosphere are the processes of water phase transformation: just the delivery of the latent heat of water vapor condensation to the atmosphere (which amounts in magnitude to about one fourth of the solar energy flux) is responsible for the maintenance of intense ascending flows and the formation of hydrometeors, which play the key role in the electrization of clouds. The corresponding 'pyramids' of the electric energy storage and dissipation in the atmosphere are presented in Ref. [14].

To date, the authors of only a few studies have discussed the problem of the dynamics of electric energy accumulation and dissipation in a thunderstorm cloud. Based on in situ field measurements, the energy values 5×10^{11} J and 2×10^{12} J for two mesoscale convective systems, and 2×10^{11} J for a high-power thunderstorm cloud with an anvil were obtained in [77]. This is sufficient for generating several hundred/thousand ordinary lightning flashes and only $10-100$ high-energy positive cloud-to-ground flashes.

The foregoing estimates are supported by the simulation results in [34]; their three-dimensional model of field and current distributions in the neighborhood of mesoscale convective systems yields a value of the order of 10^{11} J for the total energy accumulated in a system 200 km in size, with the ohmic loss of 3×10^9 W. Therefore, the electric energy accumulated inside a thunderstorm cloud is equal to about $10^{10} - 10^{11}$ J, but may exceed 10^{12} J for severe clouds. Because the average fair-weather current is equal to 2 pA and the average vertical current of a thunder cloud, which charges the global circuit, is usually estimated at $1-2$ A, the average number of thunderstorms on the planet may be taken to be equal to 10^3. Their average accumulated energy may be estimated at 3×10^{13} J.

As suggested by the observations of sferics [15], normally up to 10 high-power sferics (the so-called Q-bursts) are detected in 1 s, whence it follows that several dozen high-power thunderstorms simultaneously boom on the globe, which yields 5×10^{13} J in total. We emphasize that the quasistationary currents of a part of severe thunderstorms and MCSs discharge the circuit [34], although they undoubtedly make a substantial contribution to the total electric energy of the atmosphere.

An additional contribution to the total electric energy is made by nimbostratus clouds. According to calculations, the average energy dissipated in the vicinity of a thunder cloud due to conduction currents is of the order of 3×10^8 W, and may range up to 3×10^9 W for intensive clouds, which yields the global total of 3×10^{11} W. A part of the energy is also dissipated by lightning flashes and sprites. For the flash energy 2×10^9 J and an average frequency of lightning flashes 50 s^{-1} [35], we obtain the global average dissipation power 10^{11} W. The average value of total electric energy dissipation per unit time is 4×10^{11} W.

For comparison, we mention that the electrostatic energy concentrated in the 'global capacitor' is estimated as $W = j_0^2 R_E^2 H/(2\sigma_0^2) \approx 4.4 \times 10^{18}$ erg $= 4.4 \times 10^{11}$ J, where R_E is the radius of Earth, $H \approx 6$ km, $\sigma_0 \approx 10^{-14}$ S m^{-1}, and the atmospheric current amplitude $j_0 \approx 2 \times 10^{-12}$ A m^{-2}. The rate of energy dissipation due to ohmic losses is $P = 4\pi\sigma_0 W \approx 5 \times 10^8$ W.

Therefore, the electric energy generated by thunderstorm clouds and by intensive nimbostratus clouds amounts to $3 \times 10^{13} - 10^{14}$ J on average, which is two to three orders of magnitude higher than the energy concentrated in the global spherical Earth–ionosphere capacitor. The average rate of the electric energy dissipation due to conduction currents and lightning flashes is equal to $3 \times 10^{11} - 3 \times 10^{12}$ W; this corresponds to the electric energy lifetime about 100 s [66]. The foregoing estimates characterize the global circuit as the most agile of the existing geophysical systems with a rather high energy storage.

5. Global electric circuit in the climat system of Earth and other planets of the Solar System

GEC climatology studies were started after Williams's work, which drew attention to the possible dependence of lightning activity (and accordingly of the state of DC and AC global circuits) on the average temperature [80]. Experimental data related to the evolution of the ionospheric potential during the 20th century are discussed in Refs [12, 15, 19]. Reliable and systematic measurement data on this quantity available to date are insufficient to judge about statistically significant variations for several decades, although a significant increase in the ionospheric potential was observed during the 1960 – 1967 period, which was obviously related to nuclear weapon tests in the atmosphere [12]. Nor is the role played by generators and dissipation regions in the GEC in the course of its evolution or the influence of 'space weather' quite clear [19].

We note that the GEC occupies a unique place among natural systems subject to climat changes. First, as noted above, due to the special character of the conductivity distribution with altitude, the global circuit naturally averages the Earth–ionosphere potential difference and thereby determines a global index — the ionospheric potential that depends on the level of global thunderstorm activity [15]. Second, thunderclouds are an extreme weather phenomenon attended with destructive rainfalls, squalls, and hail; it is natural that the study of climatic trends in extreme events arouses special interest [78, 79]. Third, there are several physical mechanisms through which electric phenomena themselves may influence the climate (see, e.g., Refs [81, 82]). It is therefore necessary to investigate both these mechanisms and the feedback relations between atmospheric electric phenomena and the variations of the climat system state.

In the last few years, high-resolution physical–mathematical models have become one of the most important instruments for studying the climate [76]. But the inclusion of atmospheric electric effects in climate models encounters several problems. The most important of them is the necessity of parameterizing the quantity and intensity of thunderclouds and lightning flashes in relation to the main physical characteristics of convective cloudiness; a step in the spatial grid in atmospheric and oceanic circulation models, even in the highest-resolution models, is large in comparison with the scale length of convection responsible for thundercloud formation [83]. The problems of the parameterization of thunderclouds as a source of nitric oxides in the atmosphere, which are responsible for the perturbations of atmosphere composition (including ozone and hydroxyl radical), and the disturbance of the radiation balance are being widely discussed at present [84]. In particular, numerical experiments were performed with the use of a high-resolution chemistry-climate model [85] and the average-climate parameterization of thunderstorm activity to study the influence of thunderstorms on the composition and radiation balance of the atmosphere and the backreaction of climate changes on the frequency and intensity of thunderstorm phenomena [86]. Further development of the physical parameterizations will allow climate models to include the feedback relations between changes in nitric oxide content and the subsequent change in the densities of ozone and other atmospheric gases, which is able to affect meteorological conditions and hence the rate of nitric oxide production in lightning discharges and the state of the GEC.

The interest in electric effects in planetary atmospheres, which is related to investigations of the possible role of atmospheric electricity in climatic processes, the formation of biospheres, and the interrelation between 'planetary' and 'space weather,' is largely stimulated by the new data obtained using interplanetary spacecraft (including Cassini, Mars Express, and Venus Express) [9]. A brief analysis of the features of the GECs for the atmospheres of other planets of the Solar System can be found in Ref. [87].

6. Summary

Several new results have recently been obtained, which have led to a deeper understanding of the physical processes in the global electric circuit.

1. A new description of the global atmospheric electric circuit has been proposed and substantiated. This description relies on the findings of an analysis of the energy characteristics of the quasistationary field in thunderstorm and fair weather regions. The resultant estimates characterize the global circuit as the most agile system among the existing geophysical systems with a rather high energy level. The further development of research into the energy characteristics of the global circuit should involve a more comprehensive study and simulations of sources, an elaboration of gasdynamic lightning models, and a monitoring of thunderstorm and lightning activities.

2. The transient currents that flow after lightning flashes and the contribution of these currents to the global electric circuit have been investigated.

3. Several (primarily numerical) new models have been developed, which permit describing nonstationary and electromagnetic processes in the global electric circuit in planar and spherical geometries. Models of stationary global current systems have also been developed. It is hoped that the nonstationary models of the global circuit will soon be brought to a level enabling the description of large-scale geophysical perturbations and the long-term evolution of the system, gaining a deeper insight into the properties of atmospheric electricity for other planets of the Solar System. Of special interest are the studies of thunderstorm and lightning climatology and simulations of the global atmospheric electric circuit in different scenarios of climate change.

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Geophysical research in Spitsbergen Archipelago: status and prospects

V V Safargaleev, E D Tereshchenko

1. Spitsbergen — a geophysical site for space weather research

The geographic position of the Spitsbergen archipelago provides a unique opportunity to solve a number of geophysical questions having important scientific and applied value. First and foremost, these are questions related to forecasting space weather.

During daytime, geomagnetic field lines connect the ionosphere over Spitsbergen with magnetospheric regions through which the energy and plasma of solar wind enter the near-Earth space. The energy collected in the magnetospheric tail is released in the course of substorms, and continuous energy influx from solar wind supports the recurrence of these most striking manifestations of space weather. The solar wind plasma that appears inside the magnetosphere mixes with the background plasma, which has essentially different properties, thus creating favorable conditions for the development of various plasma instabilities. These disturbances are also elements of space weather.

To investigate space phenomena far from Earth, the most convenient tools are 'agents' transferring information along the geomagnetic field lines, i.e., charged particles and Alfvén waves. Electrons precipitating into the ionosphere generate aurora. During the winter months, the ionosphere over Spitsbergen is not exposed to sunlight, even in daytime; this provides a unique possibility to investigate magnetopause processes by observing the daytime aurora. Disturbances generated in the process of the ion–cyclotron instability development in an anisotropic plasma are attributed, in particular, to Alfvén-type waves. The plasma anisotropy and associated wave turbulence are observed by satellites in the solar wind region directly bordering the daytime magnetopause. When the anisotropic plasma appears inside the magnetosphere on the field lines leaning on the ionosphere above Spitsbergen, the wave activity is detected by induction magnetometers as short-period geomagnetic pulsations (Pc1). The interaction of the solar wind and the interplanetary magnetic field (IMF) frozen in it with the magnetosphere also appears as a large-scale convection of magnetospheric and ionospheric plasmas. In the daytime ionosphere over Spitsbergen, the character of convection can be studied by a set of incoherent scatter EISCAT (European Incoherent Scatter Radar Systems) radars in Tromsø (TRO, Norway) and Longyearbyen (LYR, Spitsbergen), as well as by one of the auroral SuperDARN (Super Dual Auroral Radar Network) radars in Hankasalmi (HANK, Finland).

Therefore, consistent optic, magnetic, and radar observations in Spitsbergen provide a comprehensive approach to the investigation of an important formation stage of space weather, the energy and plasma influx from interplanetary space (solar wind) into the near-Earth space (magnetosphere). We note in this regard that although satellite measurements are intensively used in solving space weather problems, an analysis of ground observation data is still an effective approach, especially from the standpoint of the balance between costs and efficiency, in experimental investigations of magnetopause processes. Indeed, even if a satellite crosses the magnetopause in the 'right' place at the 'right' time (which is quite improbable), the measurements that interest us last for a few minutes only. A lasting series of ground-based observations allow following the development of a phenomenon (e.g., an abrupt change in the IMF sign or a discontinuity of the solar wind plasma pressure) for longer time intervals covering its prehistory.

The use of the ionosphere as a kind of 'screen' on which magnetospheric processes are presented also stimulates investigations of the 'screen' itself. The high variability of the Arctic-latitude ionosphere requires continuous observation. It is ineffective to obtain regular data on electron content by expensive direct rocket or satellite measurements. Cheaper, but no less informative, are the methods of remote ground-based sensing and satellite radiography. These methods allow determining the ionospheric electron density by radio waves propagating through it. Ionosonde sounding is a comparatively inexpensive method; however, it can be

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