ABSTRACT: This short report describes some recent results of global electric circuit investigations. The experimental foundation of global electric circuit conception is discussed. The main origins of global electric circuit formation are examined. The electrodynamical properties of fair-weather electricity are characterized with standpoint of universal spectra and aeroelectrical structure availability. The global electric circuit is represented as an aggregation of multi-scale electrical systems.

INTRODUCTION

Recent knowledge concerning the Earth’s electromagnetic environment has brought an essentially new approach to appreciate the aeroelectrical processes [5,15]. The global atmospheric electrical circuit, according to its classical definition, represents the current contour formed by bottom ionosphere and terrestrial surface conducting layers, with thunderstorm generators as the basic electrical sources, and the areas of a free atmosphere as zones of returnable currents. The global electrical circuit (GEC) is the integral current system, formed by an aggregate of geophysical shells and electrical sources. Consequently, the GEC has the properties determinable by physical state of the magnetosphere, ionosphere, atmosphere and lithosphere. Atmospheric electricity is an integral part of the global electrical circuit.

CONCEPTION of GEC

According to Wilson’s hypothesis the electrical potential difference between the earth’s surface and lower ionosphere \((3\times10^4\) V) is supported by the whole thunderstorms activity [6]. The general feature of GEC is the vertical electric current \((2\times10^{-12}\) A/m²), which flows downward to negatively charged earth’s surface from lower ionosphere. For stationary condition the equivalent of lower atmosphere is the resistor \(R_\Sigma \approx 300\) ohms. A lower conductivity increases with height according to exponential law and the electric field was reduced to \(\approx 10\%\) of total value at 10 ÷ 15 km altitude. The region above 50 km possesses a good conductivity comparable with the earth’s interior conductivity.

The united variations of vertical aeroelectric field and current are direct evidence for GEC action. The periodic electric field variations, measured by Carnegie expedition over ocean, are considered as display of worldwide thunderstorm activity and are the classical standard of aeroelectrical global variations. The data on near surface vertical aeroelectric field measured at the Russian Antarctic

Fig.1. Carnegie curve (f) and diurnal variation of aeroelectric field found by averaging fair weather measurements for: a) Vostok Antarctic Station [9]; b) Marsta Observatory [11]; c) Lerwick Observatory [10]; d) Eskdalemuir Observatory [10]; e) Borok Geophysical Observatory.
station Vostok are compared with the Carnegie curve. Figure 1a shows the Carnegie-like electric field variation calculated for 14 days of fair-weather condition in January 1998 [9]. Averaged over 1993-1998 years at Marsta Observatory [59°56′N, 17°35′E] (Sweden) the natural variations of vertical electric field and vertical electric current were compared with the Carnegie curve. At Marsta Observatory the diurnal variation of vertical electric field is well correlated with the Carnegie curve for winter season (Fig.1b). The correlation coefficient was 96% for the winter measurement of vertical electric field [11]. The accordance of diurnal variations to Carnegie curve was analyzed for Lerwick [60°08′N, 01°11′W], Eskdalemuir [55°19′N, 03°12′W] and Kew [51°28′, 00°19′W] observatories (Great Britain) data [10]. There is a high agreement of the diurnal potential gradient variation and Carnegie curve, with the correlation coefficient 0.97 for Lerwick (Fig.1c) and 0.96 for Eskdalemuir(Fig.1d). The diurnal cycle of Kew data is entirely different as compared to the Carnegie curve and is characterized by two daily maxima. Figure 1e shows the diurnal variation of vertical electric field measured at the Borok Geophysical Observatory [58.03°N, 38.33°E] (Russia) for the summer season. The curve was calculated for 28 days of fair-weather condition in June, August 1999. Thus the curves presented in Fig.1 are similar to the Carnegie curve for periods of minimum and maximum of diurnal variation especially.

ORIGIONS of GEC FORMATION

Traditionally the thunderstorm is accepted as the primary aeroelectrical generators driving of GEC [6]. It’s following from Wilson’s hypothesis that one of the fundamental problems of global atmospheric electric global circuit is the problem of the current budget. Thunderstorm currents and the return currents of fair-weather regions have to be in the balance. However the current balance of thunderstorm generators and fair-weather loading in the global atmospheric electrical circuit is not the fact, which is proven quantitatively [12]. The statistical examination of the Optical Transient Detector lightning data has revealed that nearly 37 lightning flashes are located around globe per second [7]. The classical estimate is 100 flashes for every second. And what is more, the modern experimental and modeling researches of mesoscale convective system, the estimates of values and direction of current output of sprites allow to make assumptions about discharges of GEC, according to these events.

Further investigations of GEC are connected with estimation of the action of a mesoscale convective system (MCS) on aeroelectrical environment. MCS is the huge electrical active region with stratiform precipitations and extending (> 150 km) horizontal layers of a charge that is much larger than typical thunderstorm parameters. From direct measurements of the electric field it follows, that extensive stratiform cloud regions play significant role in the GES formation [14]. Previous GES’s models have not estimated the contribution of MSC stratiform clouds into the current budget of GEC and the influence of MSC on the altitude profile of aeroelectric field and on the ionosphere potential. The modern model of the electrical environment of MCS has included into account the multi-layer structures and appropriate horizontal scales according to experimental results of electric field sounding [8]. The model determines the electric field and current inside and in the vicinity of MCS. It has been calculated that MCS’s can serve as an effective generator of GEC formation.

The accepted thunderstorm hypothesis of aeroelectricity generation was based on the assumption about ionosphere as an equipotential high-conductivity surface. The modern routine research of ionosphere has displayed the electrical potential difference in the lower ionosphere at all latitudes. The dawn-to-dusk potential difference (20-100 kV) onto the polar cap is generated by the magnetospheric dynamo action, including the solar wind and the Earth’s magnetic field. This process can be considered as a huge hydromagnetic generator, which transforms the solar wind kinetic energy into the electric energy. The dusk-dawn electric fields are large sources of quasi-DC field of GEC [16]. With horizontal scales = 500 km the dusk-dawn electric fields are mapped downward from ionosphere to ground and account for 20% of variations in the vertical aeroelectric field at high latitudes in geomagnetic quiet days [5]. The contribution of magnetospheric dynamo action and latitude range of its impact on GEC increases greatly during geomagnetic storm events. Figure 2 shows a fragment of amplitude–time registration of geomagnetic and aeroelectric fields at the mid-latitude observatory “Borok” [58.03°N, 38.33°E; L =2.95] for the magnetic disturbance of 26-28 April 2001 ($K_p$= 10 ÷ 50). On April 27, 2001 the cross-correlation rates $K_{H-E}$ were equal to $K_{Hx-Ez} =$
0.76 (lag = - 125 min) for the magnetic activity period with $K_p = 5_0$ and a sudden change of geomagnetic activity.

The other type of ionospheric electric fields is generated by means of the dynamo action of a tidal wind at E-layer of ionosphere. These electric fields are mapped into lower atmosphere. The aeroelectric field of the ionosphere dynamo origin equal with 0.1 value of thunderstorm-generated field at 20-30 km altitudes. At the ground the electric fields of ionosphere dynamo is about 5% of the main aeroelectric field [16].

The generator of the atmospheric electric field based on peculiarities of azimuthal flow of magnetospheric plasma can influence substantially on the distribution of aeroelectric field and currents [4]. The plasmasphere rotation generator of aeroelectricity is formed as a result of azimuthal drive of the magnetospheric plasma envelope by a diurnal rotation of the Earth. It’s known from electrodynamic of continuous media, that a quadrupole electrostatic field is developed if a good conducting planet with a dipole magnetic field rotates. The voltage between the pole and equator is defined by an angular velocity of the Earth, magnetic moment and the radius of Earth. The proposed model of the electric field generator [4] provides a potential difference between the low ionosphere and the earth surface $\sim 10^5$ V that corresponds to the ionosphere potential. The model’s estimates also give aeroelectric current density $\sim 10^{-12}$ A/m$^2$ that are close to a measured value.

FAIR WEATHER ELECTRICITY

At the beginning of this part of the review the definition of fair-weather electricity should be introduced. The atmospheric conditions are regarded as fair-weather ones if “no processes of charge separation are taking place in atmosphere” and for these atmospheric conditions “the electrical phenomena are reasonably steady, so that the principal of the quasi-static state can be used.” [6]. Short-term ($f \equiv 0.001–1$ Hz) electric field pulsations in the lower atmosphere are a significant indicator of atmospheric dynamic at fair-weather conditions. One of the key problems in studies of aeroelectric pulsations is the search for the universal Kolmogorov spectra. The short-term aeroelectrical pulsations have the universal power-law spectra under fair-weather conditions for frequencies $\Delta f \equiv 0.01–1$ Hz.
The power-law index varies from $-3.36$ to $-1.23$ depending on the conditions. However, the most probable values of the index ranges from $-3.0$ to $-2.25$ [3]. Turbulent aeroelectrical structures are an essential component of the fair-weather atmosphere electricity [2]. It follows from the structural-temporal method of analysis, that lower atmosphere consists of submesoscale aeroelectrical structures “frozen” into mean wind motion of the atmospheric airflow. The spatial horizontal dimensions of structures are $L \approx 500 \div 1000$ m, the lifetime is not less than $10 \div 20$ min. It’s interesting to note, that an electrodynamical property of fog is characterized by the presence of aeroelectrical structure also. At this the fog is shown to increase the intensity of aeroelectric field pulsations by more than an order of magnitude. The spectrum exponent of fog aeroelectrical pulsations does not differ drastically from the fair-weather spectrum exponent.

CONCLUSION
Global thunderstorm activity, MCS electrical output, magnetospheric dynamo, ionospheric dynamo and plasmasphere rotation generator form the quasi-stationary electrical state of lower atmospheric part of GEC. Thus the global electric circuit is represented as an aggregation of multi-scale electrical systems, generating and dispersing the natural electrical energy. In our point of view the further progress in understanding the atmosphere electricity formation needs the modeling of global electrical circuit similar to an open dissipative system, including electrohydrodynamics and thermodynamics processes of generation and dissipation of aeroelectrical energy [1,13]. It’s important to keep in mind while modeling, that the atmospheric electric field is governed by the universal power law of spectra and contains aeroelectrical structures. The development of network of aeroelectrictric observations and database is necessary to create the global electrical circuit model.

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