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Modeling of ionization–recombination processes in the atmospheric surface layer

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ABSTRACT

The electrical structure of non-stationary horizontally-homogenous surface layer with multi-charged aerosol particles was mathematically modeled in the approximation of turbulent electrode effect. The profiles of positive and negative small ions and nuclei, electric field, polar air conductivity, current density and space charge density were computed in different time periods and various physical conditions. The mathematical model of non-stationary horizontally homogenous surface layer with aerosol particles was made regarding turbulent mixing and convective transport. The space-time distributions of positive and negative small ions and nuclei, electric field, electrical conductivity, current density and space charge density for various physical conditions (aerosol concentrations, turbulent mixing, convective transport, air ionization rate, electric field strength near surface, aerosol particles size) were received. Experimental data of electrical and meteorological parameters were measured and analyzed. It was received that theoretical results are in a good agreement with experimental data.

1. Introduction

The surface layer processes research is an important scientific task. It is known that the surface layer state determines the condition of the whole atmosphere. Besides, the human activity mostly occurs in this layer. The atmospheric surface layer characterized by various physical factors, such as: turbulent exchange processes, surface ionization sources and aerosol particles. Hydrodynamic flows in the atmosphere, arisen as a result of wind and underlying surface interaction, are turbulent and described by large Reynolds' numbers. The convective current is generated as the result of earth surface heating. All these factors exercise the significant influence on the electrical processes near the surface [13]. The electrode effect is a character feature of the layer near the Earth's surface [18,20]. In fair weather conditions the electrode layer thickness varies from a few tens of centimeters to tens of meters.

All electrical processes on the Earth are combined in the global electric circuit which is well known from numerous works [30,33]. The imposition of local-origin electric field disturbances to the global variation of the electric field is one of the most difficult problem of analysis and generalization of the surface layer experimental data. Thereby this problem requires the development of theoretical concepts and appropriate mathematical models of electrodynamic processes occurring near the Earth's surface.

The surface layer equations with term, describing the volume charges turbulence diffusion, were examined by Ref. [32] for the first time. The atmospheric total current was represented as the sum of conductivity current and turbulent current. The problem of turbulent electrode effect modeling was discussed in monographs of Refs. [8,14,22]. The importance of turbulent mixing for electrode effect models was accentuated in these works. The stationary surface layer electrodynamic model with aerosol particles was developed by Schweidler [28] and Scholz [27]. They obtained the solution analytically in the approximation that heavy ions are exceeds the number of light ions. However the authors had to use some physical assumptions. To overcome the assumptions that simplify the mathematical model, Hoppel W.A. was the first who use the numerical method for solving the equations describing the stationary electrode effect [12]. But the stationary models do not solve the problem of the characteristic time of stationary state establishment and its dependence on the process parameters. The model of non-stationary turbulent electrode effect with basic balance equations of light ions concentration and Poisson equation was developed by Latham and Poor [21].

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Non-stationary electrodynamic structure of the convective-turbulent surface layer under uncontaminated atmosphere was modeled by Kupovykh, Redin, Boldyreff [4–6]. It was stated that stationary regime establishing period is about 12 min and does not depend on turbulent and convection rate. However the vertical convection component profile was specified as constant or as exponent. Such profiles are correct only in case of small convection transfer values.

The experimental measurements of atmospheric electrical parameters have engaged the interest of many research centers. The long-term atmospheric electricity measurements of the surface electric potential gradient have been carried out since 1962 in Sweden, Marsta station [15], at Lerwick Observatory in the Shetland Isles during most of the 20th century [10], at Eskdalemuir, Scotland [11]. Fair-weather atmospheric electric field was also recorded at the Portela meteorological station, Lisbon [29]. Simultaneous measurements of radioactive gases concentrations and electrical conductivity have been made at Mysore, India [24,25]. A joint dataset of fair-weather atmospheric electricity has been made by Tammet [31]. In Russian Federation a large amount of data have been collected by Voeikov Main Geophysical Observatory (MGO) in St. Petersburg. The synchronous measurements of atmospheric electric field were also made at Kola Peninsula [7] and many other stations.

Though it is obvious that high-mountains measurements, where anthropogenic pollution are negligible, along with the ocean and high-latitude observations are very useful to highlight the effects of global atmospheric electricity [17]. But character features of atmospheric electricity parameters at alpine regions are not fully understood. Many research results have suggested that the observations at the alpine stations near Elbrus (The Republic of Kabardino-Balkaria, Russia) may be representative for the monitoring of the atmospheric electric field on a global background level [18,20].

First experimental researches of atmospheric electrical parameters near Elbrus Mountain were undertaken on the Peak Terskol, Priut-11 and Azau valley by Gerasimova [9], Pudovkina [26] and Krasnogorskaya [17]. Measurements of potential gradient (V') of the electrical field were held on three stations near Elbrus: Lower Arhyz (2000 m), Shadzhatmaz (2100 m) and Peak Cheget (3040 m). The steadiest feature of diurnal variations on high-level stations located above 2000 m was morning minimum (*01-04 UT*) and evening maximum (*16-22 UT*). This feature of electric field diurnal variation is absent in the case of station height decreasing. The similarity of electric field diurnal variations in the alpine conditions to Carnegie curve allowed to assume that steady regularity of electric field diurnal variations is caused by the global unitary variation of an ionosphere potential.

Table 1
Electrodynamic characteristics of the surface layer with aerosol particles.

Coefficients	Parameters	Aerosol concentration values (N, m^{-3})			
		10^8	10^9	10^{10}	10^{11}
$\upsilon_0 = 0$ m s^{-1},	t_{ust}, s	700	800	1000	1300
$D_1 = 0.1$ m s^{-1}	L, m	96.30	88.90	88.50	79.70
	E_0/E_∞	2.05	2.02	1.57	1.07
$\upsilon_0 = -0.1$ m s^{-1},	t_{ust}, s	800	800	1000	1900
$D_1 = 0.1$ m s^{-1}	L, m	96.30	86.20	79.90	68.20
	E_0/E_∞	1.87	1.85	1.56	1.09
$\upsilon_0 = 0.1$ m s^{-1},	t_{ust}, s	700	700	900	1400
$D_1 = 0.1$ m s^{-1}	L, m	97.20	91.30	89.50	84.10
	E_0/E_∞	2.25	2.18	1.55	1.06

2. Theory

According to the latest researches, the light ions mainly determine the lower atmosphere electric conductivity, which is formed by the influence of Earth's layer radioactivity emission, air radioactivity additives and cosmic radiation. The electric conductivity rises with altitude and it could be found from the following equation [19]:

$$\lambda = \lambda_0 \exp\alpha(r - r_0), \tag{1}$$

where r_0 – Earth radius, $a^{-1} = 6.4$ km.

The results show that the exponential character of electric conductivity is perturbed in the boundary layer up to the altitude of 2 km. In this case, the hydrodynamic turbulence processes, which depend on the meteorological and geographical conditions, play the significant role in this layer.

The combined equations describing the non-stationary electrodynamic state of the horizontally-homogenous convective-turbulent atmospheric surface layer with single-charged aerosol particles are [20,23]:

$$\begin{cases} \dfrac{\partial n_{1,2}}{\partial t} \pm \dfrac{\partial}{\partial z}(b_{1,2}En_{1,2}) - \dfrac{\partial}{\partial z}\left(D_T(z)\cdot\dfrac{\partial n_{1,2}}{\partial z}\right) + \dfrac{\partial}{\partial z}(\upsilon(z)\cdot|n_{1,2}) = q - \alpha\, n_1 n_2 - n_{1,2}\eta_2 N_0 - n_{1,2}\eta_1 N_{2,1}, \\ \dfrac{\partial N_{1,2}}{\partial t} - \dfrac{\partial}{\partial z}\left(\chi(z)\cdot\dfrac{\partial N_{1,2}}{\partial z}\right) + \dfrac{\partial}{\partial z}(\upsilon(z)\cdot N_{1,2}) = n_{1,2}\eta_2 N_0 - n_{2,1}\eta_1 N_{1,2}, \\ N_1 + N_2 + N_0 = N = \text{const}, \\ \dfrac{\partial E}{\partial z} = \dfrac{e}{\varepsilon_0}\cdot(n_1 - n_2 + N_1 - N_2), \end{cases} \tag{2}$$

where $n_{1,2}$ is the polar ions density (positive n_1 and negative n_2), E is the electric field value, $b_{1,2}$ is the ions mobility, α is the recombination coefficient, $q(z,t)$ is the ionization rate, E_0 is the electric field on the surface, N_1, N_2 are the space ions concentrations, N_0 is the neutral nuclei concentration, N is the aerosol concentration, ε_0 – electric constant.

The coefficient of turbulent diffusion was expressed by:

$$D_T(z) = \chi(z) = D_1 z,$$

where D_1 – multiplier in turbulent diffusion coefficient.

The following physically correct profile was used to describe the convective transfer:

$$\upsilon(z) = \upsilon_0\cdot\frac{z}{L}\cdot\left(1 - \frac{z}{L}\right), \tag{3}$$

where $\upsilon_0 = \pm 0.2$ m s^{-1}, $L = 100$ m is the character surface layer thickness.

The expression $n_1|_{z=l} = n_2|_{z=l} = n_\infty = n$ was used to derive the boundary conditions [20]. Then the following equations was received from (1):