On the ratio of the components of the atmospheric vertical
electric current density in fair weather

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Abstract. This work presents the results of ground-based and tethered balloon observations of altitude profiles of the components of the atmospheric vertical electric current density. The magnitude of the conduction current density was observed in the range 0.2 - 2 pAm⁻². The ratio of the negative to positive component of the conduction current density averaged 1.6 outside the layer, where their dependence on the height was noticeable. In the framework of developed numerical model with reasonable values of the parameters it is found that the ratio of the convection current density to the density of the total vertical atmospheric electric current in the atmospheric boundary layer mainly falls in the range 0.2 - 0.6 and tends to increase under strong convection and low electrical conductivity. An exponential parameterization of the dependence of the electromotive force on the ground-level electrical conductivity is proposed.

1. Introduction
The Earth’s atmosphere is a weak conductor through fair weather [1, 2] regions of which a downward electric current with a density of the order of 10⁻¹⁵ A/m² continually flows. This air-earth conduction current is driven by ubiquitous atmospheric electric field, which is due to a variety of worldwide electromagnetic phenomena. Among these are global thunderstorm activity, mesoscale convective systems, electrified clouds, charged precipitation, magnetospheric dynamo, etc. [3 - 9]. In addition to global and large-scale generators, local space charge on aerosols and/or microdroplets can produce significant disturbances in the electric field, thereby affecting the ratio of the components of the atmospheric electric current density [10, 11]. Above the planetary boundary layer, the net vertical electric current density is the sum of the polar conduction current densities due to oppositely directed drift of positive and negative air ions in the electric field and diffusion currents acting against the ion concentration gradients [12]. The balance of the components of the atmospheric vertical electric current within the boundary layer is significantly complicated by the turbulent mixing of space charge arising from the electrode effect at the earth’s surface and conductivity inhomogeneities caused by the attachment of ions to aerosol particles of various origins, which are abundant in the lower atmosphere [13 - 16]. Time-dependent and patchy distribution of the rate of exhalation of radioactive radon gas is another reason for the generation of large fluctuations in the ion production rate and eventually in the conductivity, which can enhance charge separation processes in a following way. Small ions, created in a continuous process of air ionization and then advected by a velocity field are involved into a turbulent cascade extending from a scales comparable to the mixed-layer height up to the smallest scales determined by the Schmidt number. This cascade along with inhomogeneous distribution of...
radioactive nuclei results in a wide range of spatiotemporal scales of fluctuations in polar electrical conductivities. The ratio of polar conductivities considered as a local imbalance of positive and negative components of the conduction current determines a change of charge density in time in a certain volume due to an electric field. Under these circumstances, the convection (otherwise turbulent) current associated with the vertical mixing of space charge by a turbulent flow can comprise a significant fraction of the net electric current density, thereby giving rise an electromotive force (EMF). This issue has attracted attention and first theoretical and modeling estimates indicated that the values of this variable in very unstable boundary layer can reach several tens of percent of the ionospheric potential [17]. Subsequent attempts to assess this EMF acting in fair weather regions of the lower atmosphere over land and sea gave a value of a few tens kilovolts distributed in the first several hundred meters above the earth’s surface [18]. Recently performed calculations using contemporary methods for modeling turbulent transport processes in the convective boundary layer gave a smaller range of values not exceeding 20 kV. The results of this simulation made it possible to put forward an assumption about the possibility of the formation of electrical stratification with several series-connected sections, in which the generators can operate in the opposite direction, partially compensating each other [19, 20]. Estimates of the electromotive force based on the data collected during systematic ascents and descents of a tethered balloon with a measuring platform fall in the range of 5 - 55 kV, which is consistent with those obtained earlier, but the localization of the charge separation region did not allow to assume that the generator was associated with convective mixing of space charge [21].

This work aims to estimate variability of the components of the atmospheric vertical electric current density in the atmospheric boundary layer (ABL) above land based on results of balloon-borne observations and a model of turbulent electrodynamics consisted of a large-eddy simulation to reproduce of atmospheric turbulent flow dynamics and the Poisson equation for calculation of electric potential and electric field created by a distribution of air ions and charged aerosol particles.

2. Site and instrumentation

Ground-based and tethered balloon observations of atmospheric electricity was conducted at the mid-latitude Borok Geophysical Observatory site [58°04’ N; 38°14’ E] located in an environment with a natural electromagnetic, radioactive and aerosol background. The results of observations presented in this work were obtained in the summer-autumn season 2019. A winch-driven helium-filled balloon made of polyester fiber material was used for measuring aloft. The following devices were mounted on the original measuring platform: two electrostatic field mills, two Gerdien chamber type sensors of air polar conductivities, sensor of radon activity Radon Scout PMT, aerosol particle counter AEROTRAK 9306v2, barometric altimeter, GPS receiver, meteorological and telemetric sensors, autonomous controlling and data collection systems, and power supply [21]. The elevation of platform varied from 2 to 500 m depending on wind speed and research program.

Instrumentation for ground-based observations consisted of three electrostatic field mills, one of which was placed on a metal sheet flush with the ground and two others were mounted at a height of 1 m above the earth’s surface. Three Gerdien chamber type sensor of polar conductivities were installed on a mast on a heights of 0.35 m, 1.3 m, and 2.1 m. Temperature profiles were measured with a meteorological temperature profiler MTP-5HE.

3. Governing equations and numerical methods

The building blocks of the numerical model for simulation of turbulent electrical processes in the atmosphere are the conservation equations for the momentum, mass, energy, and electric charge, Poisson equation for the electric potential, and Ohm’s law in the differential form. Simulations of large-scale turbulent flow field in the ABL are performed with the Parallelized Large-Eddy Simulation Model (PALM) version 6.0 code with adjustable parameters for connecting subgrid turbulent flows of momentum and scalar quantities [22]. The model solves the following system of filtered Navier-
Stokes equations under anelastic approximation with the advection-diffusion equation for the filtered potential temperature

\[
\frac{Du}{Dt} + 2\Omega \times u = -\nabla \left( \frac{\delta \rho}{\rho_0} \right) + g \frac{\delta \theta}{\theta_0} k + \frac{F}{\rho_0},
\]

(1)

\[
\nabla \cdot (\rho_0 u) = 0,
\]

(2)

\[
\frac{D}{Dt} \left( \frac{\delta \theta}{\theta_0} \right) + \frac{w}{\theta_0} \frac{d\theta_0}{dz} = \frac{Q}{\rho_0 c_p T_0},
\]

(3)

\[
\frac{\delta \theta}{\theta_0} = -\frac{\delta \rho}{\rho_0} \frac{1}{\rho_0} \frac{dp_0}{dz} - \frac{\delta \rho}{\rho_0},
\]

(4)

\[
\frac{\delta \rho}{\rho_0} = \frac{\delta \rho}{\rho_0} + \frac{\delta T}{T_0},
\]

(5)

taking into account the Coriolis force and damping internal waves in the overlying weakly stable free atmosphere. The instantaneous resolved flow field \( u \), is found as a solution on a Cartesian rectangular grid, the cell size of which is determined by the filtration procedure. The anelastic approximation assumes small deviations of density \( \delta \rho \), pressure \( \delta \rho \) and temperature \( \delta T \) from their reference vertical profiles \( (\rho_0, p_0, T_0) \) [23]. A dynamic eddy viscosity is used as a structural subgrid-scale model to determine the contribution of unresolved scales to the stress tensor [24].

The contribution of the velocity fluctuations at the subgrid scales to the evolution of scalar fields is modeled by an isotropic divergence-free field of random Fourier modes

\[
u'(r, t) = \sum_{n=1}^{N} \left[ a_n \cos(k_n r + \omega_n t) + b_n \sin(k_n r + \omega_n t) \right].
\]

(6)

with a geometric distribution of the lengths of random isotropic wave vectors \( k_n \) in the range from the geometric mean width of the LES filter \( k_t \) to the inverse Kolmogorov scale \( k_m \), taking into account the spectral flux of the turbulent kinetic energy (TKE) in the inertial range [20, 25, 26]

\[
E_{SGS} = \int_{k_m}^{k_t} C_k \varepsilon^{2/3} k^{-5/3} dk.
\]

(7)

This allows its conjugation with the rate of dissipation of the TKE in the explicitly resolved LES scales

\[
\varepsilon = k_c \left( \frac{2E_{SGS}}{3C_k} \right)^{3/2}.
\]

(8)

A significant advantage of this approach is the high accuracy of the reproduction of the scaling of the scalar relative dispersion [26].

In the vicinity of the atmosphere-earth boundary an anisotropy and inhomogeneity of statistical parameters of turbulence is pronounced. Moreover, near-wall turbulence statistics is intermittent and strongly non-Gaussian. In order to generate subgrid-scale near-wall turbulent flow field \( u' \), a second-order Lagrangian stochastic model is involved which takes into account leptokurtic statistics of random accelerations and variations in the instantaneous dissipation rate of the TKE along Lagrangian trajectories [27]. In a weakly stable free atmosphere, a first-order Lagrangian stochastic model is used, which is coupled to LES in terms of turbulence statistics and the subgrid TKE dissipation rate [20].
The balance equations for the concentration of small ions are

\[
\frac{Dn^\pm}{Dt} = q - \alpha n^\pm n^\pm - n^\pm \sum_j \beta_j^\pm (D_a) f_j^\pm (D_a) dD_a \pm \nabla(\mu^\pm n^\pm \nabla \phi) + \nabla(D_m^\pm \nabla n^\pm),
\]

where \( q \) is the ion pair production rate, \( \alpha \) is the recombination rate, \( \beta_j^\pm \) are the size dependent ion-aerosol flux coefficients accounting for the attachment rate of small ions to aerosol particles with the effective diameter \( D_a \) and carrying \( j \) elementary charges (\( j \) can be equal to zero), \( f_j^\pm \) are the aerosol particles size distribution functions, \( \mu^\pm \) the mean mobilities of small ions, \( \phi \) is the electric potential, and \( D_m^\pm \) is the molecular diffusivity of small ions. Polydisperse atmospheric aerosol is described by a three-mode particle size distribution function, which depends on the sources of particles and their evolution.

The ion pair production rate \( q \) is calculated as the amount of ion production rates from cosmic rays (\( q_c \)), soil radiation (\( q_s \)) and the contribution of alpha- and beta-particles emitted in the sequence of decays of radon and thoron, releasing from the soil into the atmosphere and their short-lived daughter products

\[
q = q_c + q_s + \sum_j \frac{\lambda_j R_j E_j^{(\alpha, \beta)}}{E_j^{(\alpha, \beta)}},
\]

where \( E_j^{(\alpha)} \) and \( E_j^{(\beta)} \) are the energies spent by alpha- and beta-particles respectively on a single ionization act, \( R_j \) are the concentration of radionuclides in the decay chain of radon isotopes, and \( \lambda_j \) are their decay constants [28].

The evolution of the atmospheric distribution of radioactive inert gases radon and thoron, as well as their daughter products, is calculated based on the exhalation rate and the numerical model of turbulent dispersion. The balance equations for the concentration of charged aerosol particles (large ions) are [29]

\[
\frac{DN_j^\pm}{Dt} = n^+ \beta_{j-1}^+ N_{j-1}^\pm - n^+ \beta_j^+ N_j^\pm + n^- \beta_{j+1}^- N_{j+1}^\pm - n^- \beta_j^- N_j^\pm,
\]

with the ion-aerosol flux coefficients derived in [14]. The number of balance equations for charged aerosol particles is determined by the product of the number of considered charge states of particles by the number of size fractions obtained as a result of discretizing the particle size distribution function.

The numerical solution of the Poisson equation

\[
\Delta \phi = - \frac{e}{\varepsilon_0} \left\{ n^+ - n^- + \sum_j jN_j \right\}
\]

obtained by the conjugate gradient method solving a system of discrete Poisson equations defines the distribution of the electric potential in the computational domain using the time-evolving space charge density distributions interpolated on the grid. At domain’s side walls periodic boundary conditions are set. The earth’s surface is considered to be an ideally conducting plane; therefore, the equipotentiality boundary condition is set on the earth’s surface. The potential at the upper boundary of the computational domain is determined by the density of the total vertical electric current \( J \) and the electrical resistance of the atmospheric column \( R_e \) above the domain

\[
V_t = V_i - JR_e.
\]

The connection between the values of the total current density \( J \) and the EMF of a generator operating in this column is specified out through Ohm’s law for the section of the circuit containing the generator [19].
where $V_i$ is the potential drop between the lower ionosphere (at an altitude of about 60 km) and the earth’s surface (ionospheric potential), $R$ is the total electrical resistance of the considered atmospheric column.

Polar components of the conduction current density are found from
\[
j^\pm_e = e \mu^\pm n^\pm \nabla \phi.
\]

The continuity equation relates the time variation of the space charge density with the local change in space of the components of the total current density
\[
e \frac{\partial}{\partial t} \left( n^+ - n^- + \sum_j j^\pm N^j \right) + \nabla \cdot \left( j^+ + j^- + e D^+ \nabla n^+ - e D^- \nabla n^- \right) = 0,
\]
\[
(16)
\]
where $j^\prime_j$ is the density of turbulent electric current defined as
\[
j^\prime_j = e \left( n^+ - n^- + \sum_j j^\pm N^j \right) (u^\prime + u).
\]

Effects associated with molecular diffusion becomes noticeable only at significant gradients of ion concentrations that can be achieved very close to the earth’s surface. Simple estimates show that at distances from the surface comparable to the Kolmogorov scale the density of diffusion electric current becomes comparable to the value of the conduction current density and requires taking into account. The turbulent and molecular fluxes of ions to the earth’s surface in this neighborhood are treated in the same way as in [19].

In this study we have simulated 12 cases with different surface vertical turbulent sensible and latent heat fluxes, aerosol particle concentration, and radon exhalation rate. Specific values of input parameters are presented in table 1.

**Table 1.** Simulation parameters. $z_i$ is the mixed-layer height, $L$ is the Monin-Obukhov length. The reference value of aerosol particle concentration taken as a relative unit corresponds to $9.17 \times 10^9$ particles per m$^3$.
4. Results and discussion

4.1. Polar components of the conduction current density
A total of 51 high-altitude profiles of the total conduction current density and its polar components were analyzed that were observed during 8 days of fair weather from August 16 to September 12, 2019. Figure 1 shows an example of temporal changes in vertical profiles of the atmospheric vertical conduction current density with the polar components observed in the afternoon of August 20, 2019 along with the time base of temperature vertical distribution over the period of balloon-borne observations. The magnitude of the conduction current density for the entire time of observations fell into the range 0.2 - 2 pAm⁻². In most cases the positive conduction current density measured near the earth’s surface was greater or equal than the negative one. However, an episode was registered when the negative component exceeded more than twice the positive one near the earth’s surface. The ratio of the negative component to positive one averaged 1.6 outside the layer where their noticeable change with height was observed. A possible reason for such a difference in the polar components of the conduction current density is that during measurements polar conductivities by the Gerdien's chamber, small ions with a mobility less than the threshold are not detected by the sensor, but can still contribute to the conductivity. Since the core of the distribution function of negative small ions by mobility is located in the region of larger values of the argument than of positive ones, this leads to a greater underestimation of the positive conductivity and, hence, the positive component of the conduction current density. In quasi-static conditions, the change in the conduction current density with height indicates the operation of the generator, which either moves positive charges against the electric field or negative charges along it. Traditionally, the nature of this generator, which we look at in the next section, is associated with convective transport of a positive space charge from the electrode layer upwards [17]. Similar altitude profiles in which the magnitude of the conduction current density starting from the surface decreases with height to a certain level, and then remains constant, were also observed over the ocean [18]. However, we also observed another type of altitude profiles with the maximum value of the conduction current density not near the earth’s surface, but at a certain height located from about 50 to 120 m. In these cases, the value of the current density at the maximum could exceed 2 times the values at the surface and at higher altitudes, which were approximately equal.

Numerical simulation results show for all considered cases approximate equality of the polar components and the presence of a maximum of the conduction current density located in the range of heights from 20 to 40 m. The maximum value of the conduction current density among simulations made belongs to case with maximal sensible heat flux S12 and its ratio to the total vertical current density is 1.6, while the minimum value of the peak is realized in case with maximal radon exhalation rate S9 and its ratio to the total vertical current density is 1.35. The main difference between the simulation results and the measured profiles is the thickness of the atmospheric layer, in which there is a nonzero gradient of the polar components and the total conduction current density. In this sense, the model better reproduces the cases of strong convection with an insignificant wind shear, which were observed in [18]. Factors increasing electrical conductivity contribute to a decrease in both the conduction current density and its gradient in the upper part of the boundary layer. An increase in the total surface turbulent heat flux as well as in the Bowen ratio results in a more vigorous updraughts causing a decrease in the total vertical current density in line with the mechanism described in [19, 20].

4.2. Turbulent electric current density and EMF
Neglecting the diffusion current density, the absolute value of quasi-static conduction current density in a layer of thickness h where the convective turbulent generator acts is equal to
The second term represents the magnitude of the density of the total atmospheric vertical electric current and is always positive. As can be seen from equation (18), the change in the local conduction current density with respect to the total downward fair-weather current density is determined by the contribution of the convection current density and the EMF generated by this current divided by the total atmospheric columnar electrical resistance $R$, wherein both the EMF and $R$ are the function of the conductivity.

$$j_c = j_i + \frac{\int_0^h \sigma^{-1} j_i \, dz}{R}.$$  \hspace{1cm} (18)

Figure 1. Evolution of average vertical profiles of (a) temperature according to MTP-5HE data, (b) total conduction current density (black) and its polar components (blue and red) on August 20, 2019
Figure 2a shows the vertical dependence of the ratio of the convection current density to the total electric current density in the ABL calculated in the numerical model. With a reasonable choice of parameters this quantity mainly falls in the range 0.2 - 0.6 and tends to increase under strong convection and low electrical conductivity. This effect is understandable, since an increase in vertical turbulent fluxes and/or a decrease in conductivity leads to an increase in the distance overcome by the space charge until it dissipates. Figure 2b shows calculated EMF with respect to ground-level conductivity. Simulations S2, S4-S9 differing in aerosol particle concentration or radon exhalation rate can be approximated by the exponential law

\[ \text{EMF} = E_0 \exp\left(-\frac{\sigma}{\sigma_0}\right), \]  

(19)

Figure 2. Simulation results: a) average vertical profiles of the ratio of the convection current density to the total electric current density in the atmospheric boundary layer, b) scatterplot of EMF vs. air electrical conductivity near ground surface.

where \( E_0 = 33 \) kV and \( \sigma_0 = 23.5 \) fSm\(^{-1}\). Moderate convection cases S1 and S10 give lower EMF values, while strong convection cases S11 and S12 show higher EMF. All the calculated EMF are within the range 5.5 - 24 kV, which corresponds the range from 2.75% to 12% of the ionospheric potential \( V_i \) taken equal 200 kV. Thus, taking into account the total area of the globe occupied by convection, the contribution of the fair-weather convective generator to maintenance of the ionospheric potential can be expected at the level of several percent of its value.

5. Conclusions

This work presents the results of ground-based and tethered balloon observations of altitude profiles of the components of the atmospheric vertical electric current density. The magnitude of the conduction current density was observed in the range 0.2 - 2 pAm\(^{-2}\). The ratio of the negative component of the conduction current density to positive one was 1.6 on average outside the layer where their noticeable
dependence on the height was observed. In the framework of developed numerical model with reasonable values of the parameters it is found that the ratio of the convection current density to the total atmospheric electric current density in the boundary layer mainly falls in the range 0.2 - 0.6 and tends to increase under strong convection and low electrical conductivity. A numerical model for electrodynamics of the ABL is presented that based on the LES model PALM to reproduce of atmospheric turbulent flow dynamics combined with the kinematic simulation of subgrid-scale scalar transport and the Poisson equation for calculation of electric potential and electric field distribution created by air ions and charged aerosol particles. The model is capable of evaluating the polar components of the conduction current density as well as the convection current density for various regimes of turbulence, aerosol loading, and radon exhalation rates. Results of numerical simulation indicate approximate equality of the polar conduction current density components and the presence of a maximum of the conduction current density located in the range of heights from 20 to 40 m. It is found that factors increasing electrical conductivity contribute to a decrease in both the conduction current density and its vertical gradient in the upper part of the boundary layer. An increase in the total surface turbulent heat flux as well as in the Bowen ratio results in an increase in the EMF and a decrease in the total vertical current density. The EMF of fair-weather convective generator with respect to the ground-level conductivity is approximated by the exponential law. Based on estimates obtained it is suggested that the contribution of the fair-weather convective generator to maintenance of the ionospheric potential can be expected at the level of several percent of its value.

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