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Electricity of mid-latitude atmospheric boundary layer above land: results of observations and numerical modeling

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Abstract. Complex tethered balloon observations aimed to investigate mid-latitude atmospheric boundary layer (ABL) electricity including simultaneous measurement of spectral distribution of aerosol particles, radon activity, polar electrical conductivities and atmospheric electric field were conducted in the summer-autumn seasons 2016 and 2017. It is found that vertical profiles of polar electrical conductivities are largely determined by temperature stratification and stability of the ABL. Balloon observations on fixed altitude allowed registering a clear diurnal variation in aerosol concentration, radon activity, polar and total electrical conductivities related to diurnal variation of the ABL stability. Variability ranges for polar electrical conductivities ratio, space charge and atmospheric conduction current densities have been estimated. Results of numerical modeling of diurnal variation of radon activity, polar electrical conductivities and conduction current are presented and compared with the observed ones.

1. Introduction

Atmospheric electricity is a complicated geophysics section uniting atmospheric thermodynamics, high-energy particle physics, chemistry of atmospheric gases and suspended matter with electrodynamics of multicomponent turbulent environment. In a broad sense, the urgent object of research is global electric circuit (GEC) and its interaction with the space environment and planetary climatic system. It is generally accepted that the global potential difference between the Earth’s surface and lower ionosphere is maintained by the GEC generators which are global thunderstorm activity, electrified shower clouds, mesoscale convective systems, ionospheric and magnitospheric dynamo [1, 2]. Ionization of atmosphere and global potential difference that falls predominantly into the range 200–400 kV allow for conduction current to pass through the atmosphere with the density about $10^{12}$ A/m$^2$ which is not dependent on height in undisturbed regions [3-5]. Electricity of atmosphere undisturbed by thunderstorms, any precipitation or electrified clouds results from totality of GEC generators acting in turbulent media with inhomogeneous and time-varying electrical conductivity [6-8]. The study of the impact of meteorological processes and turbulence on electricity in the lowest atmospheric portion which is distinguished as atmospheric boundary layer (ABL) is necessary primarily to determine local sources contributing to measured electric field and to estimate the components of the balance of atmospheric electric currents connecting the atmosphere and the Earth’s into unified current loop.
The electrical conductivity of the atmosphere is formed in a continuous process of ionization of molecules by cosmic rays along with decay products of radioactive nuclei. Molecular ions newly created in this process are immediately involved in a chain of mutual recombination, physical-chemical transformations and attachment to aerosol particles which can be thought as a main sink for small ions in the ABL above land. Extremely low conductivity in the lower atmosphere \( \sigma \approx 10^{-14} \text{ S m}^{-1} \) results in that the characteristic lifetime of electric charge \( \tau_e = \varepsilon_0 / \sigma \) (where \( \varepsilon_0 \) is electrical constant 8.85 \( \times \) 10\(^{-12}\) \( \text{F m}^{-1} \)) is about several minutes. This implies that space charges involved in the atmospheric flow can be transported to the distances comparable with the outer scale of turbulence in the ABL [9, 10]. The dynamics and spatial distribution of electrical conductivity and space charge in the ABL are highly influenced by regional transport of air masses and atmospheric stability. The latter strongly affects the turbulent transport efficiency with respect to scalar fields of electrically charged atmospheric constituents along with their precursors as well as to vector fields including gradients of scalar fields, which determine turbulent fluxes of scalars, electric field and current density. For the development of numerical models of the ABL electrodynamics which are based on results of mostly ground-based observations the necessity arises for observational test of theoretical estimates and acquisition of new results, establishing the dependencies between the vertical distribution of aerosol particles, radon activity and electrical stratification of the atmosphere [10-14].

In this work, we will focus on the connection between turbulent activity and vertical profiles of electrical variables in the undisturbed by thunderstorms, electrified clouds or any precipitation ABL, the influence of near surface electrode layer on the diurnal variation of polar electrical conductivities, the ratio of polar electrical conductivities depending on radon activity and aerosol concentration. The results of numerical modeling will be compared with observations carried out during field ground-based remote sensing campaigns in 2016 and 2017.

2. Instrumentation and methods of observation

Complex field observations of electric state of mid-latitude lower atmosphere including simultaneous measurement of spectral distribution of aerosol particles, volumetric radon activity, specific polar electrical conductivities of air and atmospheric electric field intensity were conducted with tethered balloon and maintained by synchronous work of ground-based information-measuring facilities of mid-latitude geophysical observatory «Borok» in the summer-autumn seasons 2016 and 2017. The measurement site of the observatory [58°04’ N; 38°14’ E] is located in an environment with a natural electromagnetic, radioactive and aerosol background.

Especially for balloon observation the original measuring platform had developed with the following equipment: two electrostatic fluxmeters field-mill type, two sensors of air polar conductivities, sensor of radon activity Radon Scout PMT, aerosol particle counter AEROTRAK 9306v2, meteorological and telemetric sensors, data collection system and power supply [15]. Totally 28 balloon ascents were carried out in 2016, including 11 ascents on the program of studies of vertical profiles, 17 ascents on the program of studies of diurnal variation at certain altitudes. The total duration of the balloon observations in the field campaign in 2017 was 224 hours among which 48 hours were according to the program of studies of vertical profiles and 176 hours were according to the program of studies of diurnal variation at altitude 90 ± 10 m. The elevation of platform varied from 50 to 400 m depending on the scientific program.

Instrumentation for ground-based observations included an isolated long wired antenna measuring the air-earth current, five electrostatic fluxmeters, one inverted fluxmeter, one Gerdien chamber type sensor of polar conductivities all mounted at a height of 1 m above ground-level, one fluxmeter placed on a metal sheet flush with the ground. Vertical profiles of wind speed and direction were measured with a 3-component acoustic Doppler locator (SODAR) VOLNA-3 in the range 60–800 m above ground level with 5-m resolution and at 5-min intervals. Temperature profiles were measured with a meteorological temperature profiler MTP-5HE. The measurements of radon and thoron activities in air were made with sensors AlphaGUARD PQ2000, Radon Scout PMT, and seismic radon station SRS-
05. Measurements of turbulent variables were conducted using two digital ultrasonic meteorological units METEO-2H placed at 2 m and 10 m above the ground.

3. Results and discussion

3.1. Diurnal variation
Temperature vertical distribution data demonstrating typical variability of the temperature field associated with the ABL evolution are shown in figure 1. Figure 1a shows registered changes in 5-min averaged temperature vertical profile during the day, while figure 1b shows six 30-min averaged profiles of potential virtual temperature, the use of which, along with the analysis of the surface turbulent heat flux, makes identification of the ABL stability regime accessible [11, 12]. Diurnal variations of radon activity and electrical conductivity observed near the earth’s surface at heights of 0.2 m and 1 m respectively, and at a heights of 90 ± 10 m are shown in figure 2. It also shows such important turbulent parameters as turbulent kinetic energy (TKE) and friction velocity at a height of 2 m above surface. One can see that the maximum values of both polar and total conductivities are reached later than at the surface. The enhancement of TKE production associated with the development of convection and increased buoyancy contribution to the TKE budget lead to increased variance of vertical velocity and more intensive vertical mixing of radon isotopes along with their progenies. Convective mixing supplies the radioactive elements upward until their concentration become well mixed, therefore, radon activity and electrical conductivity aloft increase while at the surface their decrease is observed. In contrast, night radiative cooling of the earth’s surface leads to an increase in conductivity due to enhanced ionization of air by radon isotopes with their progenies accumulated in the stable ABL with suppressed vertical turbulent transport. Such an increase can be partially smoothed by both the condensational growth of aerosol particles and subsidence of coarse-mode particles to the earth’s surface that intensifies attachment of small ions and its depletion. This is indicated by the observations of variation of aerosol particles size distribution shown in figure 3. As can be seen, there is a noticeable increase in the concen-
concentration of most measured fractions of particles during nighttime near the ground. While holding the measuring platform at a fixed elevation more than 24 hours a distinct diurnal variation in aerosol concentration was identified with maximum value at night from 00 to 05 hours (local time) and minimum value in the afternoon from 14 to 18 hours. It is found that the polar conductivities have a different amplitude of diurnal variation at different heights.

3.2. Vertical profiles
Observations of vertical profiles in the morning and afternoon convective ABL showed that aerosol concentration was nearly constant with height except for a coarse fraction of particles with diameters exceeding 5 µm whose concentration tended to decrease with altitude. Radon concentration had also approximately uniform profile with an amplitude of fluctuations, as a rule, not exceeding 40% of the mean value throughout lowest 200 m. The polar electrical conductivities in the daytime convective ABL was nearly equal, the total conductivity was nearly constant with height except for the lowermost layer 50 – 100 m thick, in which the conductivity was observed to decrease with altitude (figure 4). At night, vertical profiles are typical with increasing to the surface conductivity and decreasing to the surface electric field intensity that accompanied by the increase near the earth’s surface of radon, thoron and their daughter products. When the ABL transforms from convective to stable the average concentration of aerosol particles in the surface layer tends to increase. Herewith, the larger the particle size, the earlier the concentration increases, and the closer to the surface, the more pronounced the effect.

Continuous simultaneous measurements of several related variables provided an opportunity to estimate the effect of aerosol contamination on atmospheric electrical conductivity, electric field and conduction current. In particular, it was registered the result of increasing concentration of particles in the range of 0.3-1 µm by an order of magnitude was a decrease in total conductivity down to the

![Figure 1. Diurnal course of average vertical profiles of (a) temperature, (b) potential virtual temperature according to MTP data on August 20, 2017](image-url)
values of 2-3 fS m\(^{-1}\). At that time the electric field intensity increased up to 500 V m\(^{-1}\), however, the conduction current had not exceed 1.3 pA m\(^{-2}\), that is approximately 2 times less than the typical values.

It was observed that the spatial inhomogeneities in the vertical profile of atmospheric electric field might be characterized as alternating charge layers of opposite polarity with the electric charge concentrated predominantly on heavy ions and aerosol particles. The values of space charge densities obtained for the entire time of balloon observations were in the range from –625 to 420 pC m\(^{-3}\), and the density of the vertical conduction current varied from 0.4 to 16 pA m\(^{-2}\).

3.3. Conductivity ratio
The contribution of polar electrical conductivities to the total one and the range of variability of their ratio are of particular interest since these parameters, on the one hand, indicate presence of unipolar space charges in the atmosphere. On the other hand, they have impacts on the atmospheric conduction current and turbulent electric current associated with the space charge transfer by atmospheric motions. Observations showed that the contribution of each of the polar components to the total electrical conductivity varies with height and in time.

Figure 5 shows conductivity ratio depending on the total conductivity obtained as a result of continuous balloon observations at heights of 95 ± 10 m for 24 hours on September 24, 2017. Minute mean values of the polar conductivities were selected for analysis, day and night values were separated from each other. It seems that with increasing of the total conductivity the ratio of positive to negative component tends to the corresponding ratio of values of small ion’s average mobilities, which means the tendency to equality of small ion concentrations. In the case of small total conductivity, which mainly observed aloft in the night in contrast to the ground-level measurements, one can see a considerable scatter in the conductivity ratio. Low values of electrical conductivity are a consequence of high aerosol loading, low ionization rate or both. But only high aerosol concentration can lead to noticeable deviation of conductivity ratio from unity because of symmetric nature of air ionization. Thus, a significant predominance of one polar conductivity over another could be an evidence of presence of unipolar
Figure 2. Diurnal variations of hourly averaged (a), (b) polar electrical conductivities, (b) radon activity, (d) turbulent kinetic energy, and (e) friction velocity. In total 12 days in August-September 2017.
Figure 3. Daily course of concentrations of aerosol particles in six diameters ranges at a height of 1 m above the ground. According to hourly averaged 1-min datasets for August 18-30 2017.

charge concentrated on aerosol particles and contributing to the vertical profile of atmospheric electric field. Robust statistical confirmation of the overwhelming contribution of negative conductivity to the total one at heights of 95±10 m has been received as can be observed from figure 5. Note that formation of a layer of negative space charge at a certain height can be a consequence of a decrease in conductivity with altitude in accordance with the expression:

\[ \frac{\partial}{\partial z} (\rho \sigma) - \frac{\partial}{\partial z} \left( \rho' w' \right) \], (1)

where \( \rho \) is the average space charge density, \( \phi \) is the atmospheric electric potential relative to the ground, \( \rho' \) and \( w' \) are the turbulent fluctuations of space charge density and vertical velocity respectively. Equation (1) suggests quasi-stationary current flow with charge density vertical profile unchanged in time or changing slowly enough. In the case when the second term in brackets is positive, or negative but in absolute value is less than the first term, the charge density is negative. It is obvious that the second term will be small if the conduction current varies slightly with height and the charge density remains unchanged in time.

Further, we can estimate the part of the space charge concentrated on small ions using the following expression:

\[ \rho_i = \frac{\sigma_+}{\mu_+} - \frac{\sigma_-}{\mu_-}, \] (2)
where $\sigma^+$ and $\sigma^-$ are the positive and negative electrical conductivities, $\mu^+$ and $\mu^-$ are the average mobilities of small positive and negative ions respectively. Such an estimation gives the variability range of the small ions’ space charge density $\rho_i$ approximately from $-33$ to $21$ pC m$^{-3}$ that is substantially narrower than the variability range of the total charge density mentioned above. Therefore, it can be concluded that in the lower atmosphere electric charge is mainly concentrated on heavy ions and aerosol particles.

**Figure 4.** Vertical profiles of (a), (d) polar electrical conductivities; (b), (e) radon activity; (c), (f) temperature observed on August 22, 2017 – upper row, on September 12, 2017 – lower row. Local time (UTC+3 hours) is indicated during the descent and ascent of balloon with the measuring platform.

### 3.4. Numerical modeling

In order to account for the effect of turbulence on electricity in the ABL, a transported probability density function (PDF) method is applied as an advanced modeling approach, which is a suitable mathematical tool for turbulent flows with reacting scalars. This method provides computationally efficient solution algorithm for a set of transport and reaction equations [16, 17]. Compared to previous studies invoking RANS with first- or second-order closures for turbulent moments, we appeal to the stochastic PDF approach because the former can fail when describing the counter-gradient transport by large-scale turbulent motions and, at the same time, can noticeably exaggerate a concentration in the far field away from a source. The choice of a computational scheme for atmospheric turbulent electrical processes is particularly critical since the lifetimes of radon daughter...
products and the ion-aerosol attachment rates are of the same order as the turbulent time scales. In addition, PDF technique can be successfully applied

![Figure 5](image)

**Figure 5.** Ratio of positive to negative conductivity as a result of balloon-based observations on September 1, 2017.

to turbulence with non-stationary statistics which is inevitable if the time evolution of the ABL is considered. Therefore, this approach provides an opportunity to describe the surface electrode layer coupled with the overlying boundary layer via turbulent transport under a wide range of stability conditions in a self-consistent manner. This ability is especially important in the case of unstable ABL when large-scale convective eddies provide an essential contribution to vertical transport of heat, moisture and other substances.

Thorough description of the electrodynamic model of the ABL, calculation results and their comparative analysis with observations can be found in [10-13, 18]. An idealized daily cycle of the ABL underlies the parameterization of turbulent statistics. It is used for numerical integration of stochastic equations for random velocity increments of Lagrangian tracers, with the help of which the vertical profiles are determined. Here we give only a short presentation of the modeling results concerning the diurnal variations of radon activity, polar electrical conductivities and conduction current at the ground-level and at a height of 90 m for the sake of comparison with the results of simultaneous ground-based and tethered balloon observations. Figure 6 displays an example of the modeling results.

4. Summary and conclusions

This study presents preliminary results of extensive ground-based and balloon-based measurements held on mid-latitude geophysical observatory «Borok» in the summer-autumn seasons 2016 and 2017. The data obtained in the field campaign are used to investigate fair-weather electrical processes in the undisturbed ABL with an emphasis on behavior and variability range of atmospheric electric parameters in the first few hundred meters above land surface.
We found that the variations in vertical profiles of radon activity, aerosol concentration, polar and total electrical conductivities are related to daily evolution of the ABL. The profiles of atmospheric electric field point out the processes of charge separation and electrical stratification of the ABL taking shape of alternating charge layers of opposite polarity the lifetime of which may exceed $\tau_e$. We presented the quantitative estimations of variability ranges of space charge accumulated in these layers, space charge related to small ions and variability range of the atmospheric conduction current density. It is shown that electric charge is mainly concentrated on heavy ions and aerosol particles in the lower atmosphere. This is supported by the fact that electrically charged layers in the ABL are formed due to conductivity vertical gradient under conditions of slightly varying with high conduction current density and slowly varying in time charge density.

**Figure 6.** Diurnal variations of hourly averaged (a), (b) polar electrical conductivities, (c) conduction current density, and (d) radon activity by modeling.
A considerable scatter (up to two order of magnitude) of polar conductivity ratio is observed in the case when the conductivity is less than 7 fS m$^{-1}$. It was registered that increase in concentration of aerosol particles in the range of 0.3-1 µm by an order of magnitude led to a decrease in total conductivity down to the values of 2-3 fS m$^{-1}$ and conduction current density less than 1.3 pA m$^{-2}$. Based on balloon measurements it can be concluded that above the electrode layer small ion concentrations tend to be equal with increasing of electrical conductivity.

Presented here results of stochastic simulation based on transported PDF method are in reasonable agreement with the data obtained by the simultaneous measurements of radon activity at different heights, but their accordance with observed variations of polar electrical conductivities is worse. An obvious reason for this is that while there is insufficient data to reproduce aerosol dynamics in the ABL in detail. Thus, we infer that although the main processes responsible for the evolution of electrical conductivity in the ABL are taken into account correctly in the model, but their finer details require additional studies.

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