Estimation of submicron aerosols influence on the electrical conductivity of the atmosphere surface layer

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Abstract. The analysis of the results of complex expeditionary measurements in the surface atmosphere, some of which has recently been published, is continued. Measurements of the Geophysical research laboratory of Southern Federal University, Faculty of Physics during the joint expeditions with Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (IAP RAS) at scientific stations IAP RAS: in 2017- on the territory of the Tsimlyansk Scientific Station in the steppe zone, and in 2018 and 2019 – on the Kislovodsk High-Mountain Scientific Station, located on the alpine plateau Shadzhatmaz, 2100 m above the sea level. Quantitative relationships between the polar conductivities of the surface atmosphere and the concentration of submicron aerosols for various physical and geographical conditions are obtained. The observed decrease in polar conductivities reversely proportional to aerosol concentration is due to a decrease in the concentration of small atmospheric ions caused by their adsorption by aerosol particles. The empirical regression series are approximated by a logarithmic function with a high accuracy of the approximation. The presence of a causal relationship between the investigated values is confirmed by the dispersion analysis. The observed differences in the regression equations parameters are explained by different conditions during periods of observation.

1. Introduction
A lower atmosphere feature is the significant variability of electrical characteristics [1-4]. The underlying surface considerably affects the adjacent atmospheric layer, being a source of its impurities, determining its temperature regime and, therefore, stability and vertical mixing. The impurities that are of great importance for the processes of electrical conductivity near the earth’s surface include the natural isotope radon-222 stemming from the radioactive family of uranium-238. Radon-222 is α-radioactive, which makes it highly ionizing. The aerosols and natural radionuclides in the atmosphere surface layer determine its electrical condition. The electrical conductivity of the atmosphere is almost completely determined by the so-called small ions, the most mobile of all atmospheric ions. For positive and negative small ions, the mobility $b_s$ is within the range $(1±2)·10^{-4}$ m$^2$/V·s. The change in the concentration of positive and negative small ions over time is due to the intensity of ion formation $q$ and the small ions disappearance processes: the reunification
of positive and negative small ions, the attachment of small ions to charged $N_{\pm}$ and neutral $N_0$ ions of lower mobility (condensation nuclei and aerosols): $\frac{dn_{\pm}}{dt} = q - \alpha n_+ n_- - \beta_{\pm} n_{\pm} N_{\pm} - \gamma_{\pm} n_{\pm} N_0$. Here, $\alpha$ is the coefficient of small ions recombination, and $\beta_{\pm}$ and $\gamma_{\pm}$ are small ions to aerosol particles attachment coefficients. Under stationary conditions, when $dn_{\pm}/dt = 0$, the concentration of small ions is proportional to the ionization processes intensity, and reversely proportional to the amount of aerosols in the atmosphere. Obviously, the specific electrical conductivity $\lambda_\pm = n_\pm e b_\pm$ also depends on these factors: $\lambda_\pm = \frac{q e b_\pm}{\alpha n_\pm + \beta_{\pm} n_{\pm} N_{\pm} + \gamma_{\pm} N_0}$. The interaction of aerosols and small ions is important not only for conduction processes, but also for the formation of electric field local variations caused by space charges. The formation of a space charge is facilitated by the movement of small atmospheric ions of different polarities during the conduction current near the electrode surface of the earth, as well as under conditions of ionization intensity decreasing with height due to soil radioactivity and its emanation. This causes the air electrical conductivity decrease with height, and is the reason for its negative gradient near the ground. Thus, due to the conduction current in the surface atmosphere, space charge layers of small ions of different polarities are formed.

The presence of aerosols in the atmosphere contributes to the fact that the charge of small ions, having relocated to aerosol particles due to small ions adsorption by aerosols, can stay in the surface atmosphere for a long time: the lifetime of large ions is hours, unlike several minutes for small ions. What this charge will amount to in terms of sign and density will be determined by the polar concentrations of small ions and their aerosols attachment coefficients [5].

Thus, studies show that the physicochemical properties of aerosol particles affect their magnitude as well as polarity and, as a consequence, the electrical condition of the surface layer. The significant role of water vapor in these processes should be noted. Smirnov [6], proceeding from the results of experiments in an adiabatic chamber, notes that an increase in humidity leads to the accumulation of charges on the particles. Besides, “while media with insoluble nuclei (porous silicas, etc.) are predominantly negatively charged, media with soluble nuclei (sodium chloride, etc.) are characterized by positive charges.”

The aim of the study is to obtain quantitative relationships between the polar conductivities of the surface atmosphere and the concentration of submicron aerosols for various physical and geographical conditions.

2. Methods

A feature of experimental studies in the natural environment is no possibility to arbitrarily vary the parameters of the medium, just as it is done in laboratory experiments. Therefore, to provide for the possibility of parameterization of atmospheric processes models, a series of complex observations are carried out in different physical and geographical conditions, which is achieved by periodically changing the observation point. In this case, it becomes possible to accumulate experimental data for various combinations of natural factors that determine the parameters of atmospheric processes. A joint analysis of data accumulated over many years in a number of districts of the Rostov Region, with measurement results in other regions, makes it possible to detect the features of the formation of the electrical structure of the surface layer under different conditions.

This study continues to analyse the results of complex expeditionary measurements in the surface atmosphere, some of which are presented in a recent work [7]. Measurements of the Geophysical research laboratory of Southern Federal University, Faculty of Physics during the joint expeditions with Obukhov Institute of Atmospheric Physics of the Russian Academy of Sciences (IAP RAS) in the period from 2014 to 2019 were carried out at scientific stations of IAP RAS: in 2014-2017 on the territory of the Tsimlyansk Scientific Station in the steppe zone, and in 2018 and 2019 – on the
Kislovodsk High-Mountain Scientific Station, located on the alpine plateau Shadzhatmaz, 2100 m above the sea level. The scientific stations differ significantly in their thermodynamic conditions. Tsimlyansk in August is characterized by dry, hot and windy weather. Kislovodsk station in the summer is much cooler, with high humidity, frequent fogs, and cloud masses passage through the observation site. The observation platforms at both stations are located on vast flat areas with low-cut grass stand.

During the expedition period, at both stations, measurements of the atmosphere polar electrical conductivities were carried out using A.I. Voeikov Main Geophysical Observatory (MGO) system sensor. The concentration of aerosols was registered by the laser aerosol spectrometer LAS-P of the Karpov Institute of Physical Chemistry system in the ranges: 0.1-0.2; 0.2-0.3; 0.3-0.4; 0.4-0.5; 0.5-0.7; >0.7 μm. Also, the volumetric activity of radon-222 in the atmosphere was determined using the AlphaGUARD PQ2000 PRO radon monitor. Measurements were carried out at a height of 1 meter. In addition, vertical profiles of the atmospheric polar electrical conductivity and radon-222 content in the air were measured in Tsimlyansk in 2017 and on Shadzhatmaz plateau in 2019. Values were recorded at the levels of 0.05; 0.3; 0.6; 1.0; 2.0; 3.0 m by sequentially placing the sensors at the indicated heights, with measurement cycles performed for 10 minutes at each height. Each profile measurement lasted one hour. The main meteorological parameters of the surface layer were recorded. L.R. Orlenko method was used to calculate the turbulence coefficient based on data on air temperature and wind speed at heights of 0.5 and 2 meters. Measurements went on around the clock for about 10 days. For the analysis, the hourly averaged values were used mainly. A detailed description of the whole complex of measurements can be seen in [7].

3. Observation results and discussion

On the basis of the results obtained during the expeditions of 2017-2019, there were determined empirical regression series of polar electrical conductivities $\lambda$, by the aerosol concentration $N$ (particle diameter greater than 0.1 μm). For this, hourly average conductivity values were grouped for intervals of aerosol concentration values.

The observed decrease in polar conductivities reversely proportional to aerosol concentration is due to a decrease in the concentration of small atmospheric ions caused by their adsorption by aerosol particles. The regression lines in Figure 1 are logarithmic function graphs of the type $\lambda = C - k \ln N$. The bars show the standard error values. If the aerosols concentration $N$ in the equation is given in $10^6 \text{ m}^{-3}$, then the coefficient $C$ and, accordingly, the electrical conductivity will have the dimension $\text{fSm/m}$.

Table 1 shows the regression equations parameters for three measurement periods in accordance with Figure 1. Here, $R^2$ is the reliability value of the grouped data approximation.

|                          | for $\lambda_+$ | for $\lambda_-$ |
|--------------------------|-----------------|-----------------|
|                          | $C$, fSm/m      | $k$, fSm/m      | $R^2$ | $C$, fSm/m      | $k$, fSm/m      | $R^2$ |
| Tsimlyansk, August 2017  | 55              | 7.2             | 0.90  | 43              | 5.1             | 0.95  |
| Shajatmaz, August 2018   | 108             | 15.0            | 0.98  | 115             | 16.0            | 0.97  |
| Shajatmaz, August 2019   | 56              | 6.3             | 0.89  | 68              | 8.6             | 0.82  |

Similar empirical dependences were obtained by the authors of [8], but with the following difference: the particle size interval during measurements was shifted, in relation to ours, in the direction of small particles predominance (0.003-0.200 μm), as a result of which the observed counted particle concentrations were an order of magnitude higher.
Figure 1. The dependence of the positive (red circles) and negative (blue triangles) electrical conductivities of the atmosphere on the concentration of aerosol particles with a diameter of more than 0.1 μm according to the results of summer expeditions at the IAP RAS scientific stations: a) Tsimlyansk Scientific Station, 2017, 296 hours; b) Kislovodsk High-Mountain Scientific Station, 2018, 96 hours; c) Kislovodsk High-Mountain Scientific Station, 2019, 230 hours.
The observed differences in the regression equations parameters (Table 1) are explained by different conditions in the steppe and high-altitude observation points, as well as by different conditions in different periods of observation in the same point. The important factors are thermodynamics, humidity, the ion formation intensity (primarily, radon-222) and, of course, the physicochemical properties of aerosols, which affect the attachment coefficients of small ions of different polarities to aerosol particles. In Tsimlyansk, in the summer drought conditions, at very high air and soil temperatures [7], the dispersive aerosol properties differ from those of predominantly condensation or moist aerosol under conditions of low temperature and high humidity observed during the summer expeditions to the Shadzhatmaz plateau.

According to the results of 2017, the correlation coefficients of the electrical conductivity and the concentration of aerosols for a pair of the LAS-P aerosol spectrometer and the Gerdien sensor, Voeikov MGO system turned out to be negative, which indicates a feedback between the parameters. For particles with a diameter ranging 0.1-0.2; 0.2-0.3; 0.3-0.4; 0.4-0.5 μm, the values of the correlation coefficient were -0.40; -0.35; -0.29; -0.14 for positive electrical conductivity and -0.39; -0.32; -0.28; -0.19 for the negative respectively. As is seen, polar conductivities with the concentration of the smallest particles of the submicron size demonstrate a particularly close relationship.

The correlation coefficients between the electrical conductivity of the atmosphere and the concentration of aerosols are negative for the high plateau but, they turned out to be higher than those for Tsimlyansk: for aerosols of different sizes, the correlation coefficients range from 0.5 to 0.7. According to the results of 2018 on the Shadzhatmaz plateau for particles with a diameter in the range of 0.1-0.2; 0.2-0.3; 0.3-0.4; 0.4-0.5; 0.5-0.7; 0.7-1.0; more than 1.0 μm, the values of the correlation coefficient respectively amounted to -0.60; -0.71; -0.64; -0.60; -0.56; -0.57; -0.57 for positive electrical conductivity and -0.53; -0.72; -0.73; -0.73; -0.72; -0.72; -0.63 for the negative one.

The presence of a causal relationship between the investigated values is confirmed by the dispersion analysis. As is shown in Table 2, the actual values of the F-test \( F \) calculated from the experimental data exceeded the standard \( F_{st} \) values for the corresponding sample volume for all the investigated size ranges, but especially for small particles. The strength of the effect on the electrical conductivity of the atmosphere, \( h^x \), calculated by the Snedekor method, was significantly higher for particles with a diameter <0.3 μm than for larger particles.

| Particle size \( d \) [μm] | \( \lambda_+ \) [fSm/m] | \( \lambda_\) [fSm/m] | \( F_f \) | \( F_{st} \) | \( h^x \) | \( F_f \) | \( F_{st} \) | \( h^x \) |
|--------------------------|---------------------|---------------------|--------|--------|--------|--------|--------|--------|
| >0.1                     | 25,6                | 3,0                 | 22%    | 25,4   | 3,0    | 22%    |
| 0.1-0.2                  | 21,1                | 2,6                 | 23%    | 18,4   | 2,6    | 20%    |
| 0.2-0.3                  | 22,8                | 3,0                 | 21%    | 18,6   | 3,0    | 18%    |
| >0.3                     | 4,4                 | 3,0                 | 4%     | 4,6    | 3,0    | 4%     |

Aerosol emission into the atmosphere during summer measurements in Tsimlyansk was often associated with smoke caused by steppe fires. Aerosol concentration at such times increases by several times and even by an order of magnitude in comparison with undisturbed conditions. It was interesting to analyze how a significant change in the content of aerosols in the surface air affects the vertical profiles of polar conductivities.

In order to study this effect, the entire array of data obtained by the LAS-P spectrometer in August 2017 was divided into four groups of measurements with different contents of aerosols with a diameter > 0.1 mm. For each group, the vertical conductivity profiles shown in Figure 2 were obtained.
by averaging. The graphs show the transformation of vertical profiles of the polar electrical conductivities of the atmosphere in a layer up to 3 meters, depending on the concentration of aerosols. With an increase in the content of aerosol particles (from state 1 to 4), as can be seen in the figure, the electrical conductivity across the entire layer is reduced, which causes the profile to shift to the left. Estimates show that when the concentration of aerosols varies from 100 to 500 particles per cubic centimeter of air, the electrical conductivity for different heights is reduced by a factor of 3-5.

![Figure 2](image)

**Figure 2.** Vertical profiles of negative (blue triangles) and positive (red circles) electrical conductivities of the atmosphere with different aerosol content (Tsimlyansk, August 2017, height 1 meter, d>0.1 μm, the bars show the standard error values):
1 – less than $100 \cdot 10^6$ m$^{-3}$; 2 – $(200\div400) \cdot 10^6$ m$^{-3}$; 3 – $(400\div600) \cdot 10^6$ m$^{-3}$; 4 – more than $600 \cdot 10^6$ m$^{-3}$; “+” - for positive conductivity, “−” - for negative conductivity.

The general view of the atmospheric conductivity profiles near the earth seems typical of summer conditions in Tsimlyansk. Windy weather prevents the accumulation of radon-222 and ionization increase in the lower atmosphere, but promotes active adsorption of small ions by the earth’s surface. Because of this, the polar conductivity near the underlying surface is reduced, and their profiles are tilted to the right in the layer up to two meters from the ground. The type of vertical conductivity profiles depending on the conditions was analyzed in [2,7].

4. Summary
The effect of the aerosol component of the surface atmosphere on its electrical state is undeniable. In particular, the electrical conductivity of the atmosphere exhibits a pronounced decrease with aerosols concentration growth. The obtained empirical relations between the studied values are important for the models developed in atmospheric electricity. It is necessary to clarify the factors that determine the parameters of the regression equations. Further research should be aimed at finding out how aerosols of different physicochemical nature and different size ranges interact with ions. It is necessary to clarify the role of water vapor and its phase transitions in these processes.

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**Acknowledgments**

The paper is performed with support of Russian Foundation for Basic Research Grants № 16-05-00930 A, № 17-05-41121 RGS_a and № 19-05-50110 - Microworld.