Atmospheric electrical profiles in the surface layer depending upon significant factors

G Petrova 1*, I Panchishkina 1, A Petrov 1, O Chkhetiani 2

1Southern Federal University Physics Faculty, 5, Sorge st., Rostov-on-Don, 344000, Russia
2A.M. Obukhov Institute of Atmospheric Physics Russian Academy of Sciences
3 Pyzhevsky trans., Moscow, 119017, Russia

E-mail: georgpu@rambler.ru

Abstract. Processes of electric characteristics vertical profiles formation in atmospheric surface layer are analyzed on the basis of measurements results of summer expeditions performed both in the recent years (2012 - 2017) and during earlier periods, mainly at the territory of the Don steppes. The most important among approaches, on which the performed research is based, is the complex character of measurements. The most significant parameters for electric processes in the atmospheric surface layer are monitored alongside with the atmospheric electrical characteristics. The paper discusses formation mechanisms of the observed types of atmospheric electrical conductivity profiles with consideration of radon-222 volumetric activity and mixing processes in the surface layer.

Introduction
The result of many-year comprehensive research allows to typify the observed atmospheric electric profiles with consideration of surface layer stratification, radon-222 content in the air and in the soil gas [1, 2].

At present, the influence of surface layer thermodynamics on its electrical state can be considered a generally accepted idea [3-5]. As is known, the temperature stability of the surface atmosphere determines the intensity of vertical mixing processes. With unstable stratification, conditions for moving impurities along the vertical axis and, correspondingly, reducing their vertical gradients are created. With stable stratification, the vertical exchange is weakened, which contributes to the accumulation of impurities near the earth’s surface and the occurrence of significant vertical gradients of their concentrations. Such impurities, which are of great importance for electrical conductivity processes near the earth's surface, include the natural radon-222 isotope from the radioactive family of uranium-238.

Uranium presence in the subsoil differs significantly in different parts of the globe. Clays, limestones, sandstones, coal seams, characterized by a local increased content of uranium, belong to radon-generating geological objects, which are numerous in the Rostov region. The $^{222}Rn$ (radon-222) isotope half-life – 3.8 days – is long enough to allow it to move along the pores and cracks in the soil and enter the atmosphere. Radon-222 is α-radioactive, which provides for its high ionizing ability: according to Bricard [6], every α-decay of radon generates 200,000 ion pairs in the surface...
atmosphere. Along with cosmic rays, radon-222 is the main ionizer of the surface atmosphere, determining its electrical conductivity variations. Therefore, understanding the features of the atmosphere vertical conductivity profile under different turbulent mixing is impossible without taking into account the activity of this radionuclide.

**Methods**

The results of summer expeditions of the scientific laboratory of geophysical research of the Southern Federal University Physics Faculty, carried out for decades mainly in the Rostov region steppe zone of the south of Russia, are analyzed. Since 2014, the expeditions have been conducted jointly with the A.M. Obukhov Institute of Atmospheric Physics (IAP) of Russian Academy of Sciences at the IAP Science Station near Tsimlyansk.

Specific polar electrical conductivities of air are measured by means of Gerdien instruments: sensors of the Voeikov Main Geophysical Observatory (Voeikov MGO) system and the Litvinov system sensor. The intensity of the electric field of the atmosphere at the ground level is recorded by the fluxmeter (Voeikov MGO). For computer registration of the signal of these sensors, the L761 ATSP board from L-Card company was used. The potential of the atmosphere is determined by the known method of the radioactive collector (isotope of thorium, ionium $^{230}$Th). Based on the measured values of the electrical potential, the potential gradients for a number of layers are calculated to a 4-meter layer. Based on the Poisson equation, the density of the total space charge at different levels is estimated. The density of the space charge of small ions is determined from the results of measurement of polar ion concentrations. For calculations, the average values of the mobility of small ions are taken equal to $1.36 \times 10^{-4}$ and $1.56 \times 10^{-4}$ m$^2$/V∙s for positive and negative ions, respectively.

Along with the registration of atmospheric-electrical characteristics, the content of radon-222 in atmospheric air and soil gas is monitored by the radon monitor “AlphaGUARD PQ2000 PRO” from Genitron Instruments GmbH. The radon monitor works by the ionization chamber method. A special filter of the device allows the radioactive isotope $^{222}$Rn to enter the chamber, restraining other isotopes, as well as moisture and dust. To measure the volume activity of radon-222 in soil gas to a depth of 1 meter, the external devices included in the AlphaGUARD kit were used: the soil gas sensor AlphaGUARD Soil GasUnit and the gas electronic pump AlphaPUMP.

Simultaneous measurement of the polar conductivities vertical profiles and of radon volume activity during the experiment is carried out by sequentially placing the instruments at six different levels of a wooden mast (0.05, 0.3, 0.6, 1.0, 2.0, 3.0 m). To synchronize polar conductivity and radon volume activity measurements, "AlphaGUARD" is adjusted so that time-averaging of Rn-222 volumetric activity is carried out by a radonimeter for 10-minute intervals. Thus, within one hour one profile of each value is determined. Before measuring the activity of radon at the next altitude, a forced pumping of the chamber is carried out for quick sampling from the required atmosphere level. Radon-222 then diffuses through the filter into the ionization chamber, which allows measuring its volumetric activity continuously.

The concentration of aerosols was registered by the aerosol counter AZ-10 (2012-2016) in six dimensional ranges (μm): 0.3-0.4; 0.4-0.5; 0.5-1.0; 1.0-2.0; 2.0-5.0; > 5.0, - and a 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 (2017).

Continuous recording of the main meteorological parameters is performed by a digital meteostation M-49m. Along with this, hourly gradient measurements of air temperature and humidity are carried out by Assman aspiration psychrometers and wind speed by cup and vane anemometers. Measurements of the thermodynamic parameters make it possible to calculate the turbulence coefficient by the method of L.R. Orlenko; its values are necessarily taken into account when grouping and analyzing the experimental data.

During the expeditions, measurements were made around the clock for 7-10 days, on a site with grass cut, amid a broad flat field with steppe vegetation.
Observation results and discussion
The empirical regression range constructed from the data obtained in the period from August 6 to 13, 2016 at the IAP RAS Tsimlyansk scientific station, shows that the electrical conductivity, both positive and negative, increases with radon concentration increase (Figure 1). The empirical dependences obtained are approximated by a linear function with a confidence of approximation of 0.99: \( \lambda_+ = 16 + 0.2 \cdot A_{Rn} \) for positive electrical conductivity and \( \lambda_- = 15 + 0.2 \cdot A_{Rn} \) for negative conductivity (electrical conductivity is given in fSm/m, radon activity \( A_{Rn} \) in Bq/m\(^3\)). In total, 657 10-minute series of synchronous round-the-clock measurements of polar electrical conductivities and volumetric radon activity at a height of 1 meter were used to construct the regression range data.

The bars on the graphs show the standard error values used to estimate the representativeness of the data:

\[
S_x = \frac{\sigma_x}{\sqrt{n}}
\]  
(1)

Here \( n \) is the sample size, \( \sigma_x \) is the selective standard deviation of some value \( x \):

\[
\sigma_x = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}}
\]  
(2)

The results of radon activity measurements in soil gas show that radon content in the soil of the sites in the Kashar district and in Tsimlyansk is similar and does not differ significantly from other sites in the Rostov region. Figure 2 is a graph showing the volumetric activity of radon-222 in the soil gas of the upper 10-cm soil layer. As research shows, it agrees in the best way with radon soil-to-atmosphere flow.

**Figure 1.** Synchronous measurements of the atmosphere electrical conductivity and the volume activity of radon-222 at the Tsimlyansk scientific station of A.M. Obukhov Institute of Atmospheric Physics of Russian Academy of Sciences (August 2016).

**Figure 2.** Volumetric activity of radon-222 in the upper 10-cm layer of soil in the sites of the Rostov region of Tsimlyansky, Kashar and Orlovskij regions in the summer months (July-August) during the expeditions of 1995-2017.
Observations show that radon content in the atmosphere depends substantially on the mixing conditions. So, according to summer measurements in Rostov region sites, the volumetric activity of radon at an elevation of 0.05 m above the ground changes linearly with a wind increase from 0 to 1.5 m/s, dropping by 3-4 times on this wind speed interval (Fig. 3). For these wind speeds, the following linear regression equations for the volumetric activity of radon $A_{Rn}$ (Bq/m$^3$) at an altitude of 0.05 m were obtained from the wind speed $V$ (m/s) at an altitude of 2 m: Mikhailovka $A_{Rn} = 55 - 27 \cdot V$; Talloverov $A_{Rn} = 91 - 44 \cdot V$; Platov $A_{Rn} = 126 - 58 \cdot V$; Orlovskij $A_{Rn} = 130 - 62 \cdot V$. For each of the three Kashar district sites, the reliability of the approximation is $R^2 = 0.99$, for the Orlovskij district it is $R^2 = 0.98$. With further wind speed increase, the content of radon-222 near the earth’s surface varies but little: it decreases slowly and nonlinearly from 1.5 to 3 m/s, and then remains practically unchanged at the level of 10-20 Bq/m$^3$.

Daily changes in the mixing conditions during the summer in the steppe zone of the south of Russia determine the distinct daily rhythm of radon content observed in the Rostov region in the summer with a minimum in daytime and a maximum at night. Violations of this rhythm, found on the chart, are associated with windy nights. Radon-222 ultimate permissible concentration (UPC) for enclosed premises is 100 Bq/m$^3$. In the Rostov region sites, UPC is confidently overcome during quiet summer nights in the open atmosphere. In the Kashar district sites, this occurs in 15% of round-the-clock measurements hours.
Figure 4. Vertical profiles of the negative (blue) and positive (red) specific electrical conductivities of the atmosphere (a) and the volumetric activity of radon-222 in the atmosphere (b) for unstable (1, 2, 5, dotted lines) and stable (3, 4, 6, solid line) temperature stratification of the surface layer: I – Talloverov 2009; II - Fedorovka 2012; III – Tsimlyansk 2014; IV – Tsimlyansk 2015; V – Tsimlyansk 2017.

Significant differences in radon activity in the atmosphere, observed from the measurements results at different observation sites, seem to result from both local features of the soil emanation and the atmosphere dynamics features. This affects the features of the vertical conductivity profiles.

Graphs of Figure 4 show measurement results at two sites in the Kashar district: Talloverov (I) and Fedorovka (II), and in three expeditions in Tsimlyansk (III-V). Green shows the vertical profiles of radon volumetric activity (b), red and blue, respectively, show positive and negative electrical conductivity of the atmosphere (a). Solid lines show values averaged for stable temperature stratification and low wind speed, when turbulent mixing in the surface layer is weakened (see Table 1). As a rule, in the summer in the Don steppes, this is typical for night hours without wind. The
dashed lines give the profiles of values for a considerable turbulence, averaged for hours with high wind speed and unstable stratification, which characterizes day periods. The bars on the graphs show standard error values.

When considering the graphs it is obvious that in the case of weak turbulent exchange both the radon content and the electrical conductivity in the atmosphere are large in comparison with those for intensive mixing conditions. In addition, with a weak exchange, significant vertical gradients of quantities are observed, which cannot be said of the developed turbulence situation, when the characteristics depend little on altitude.

In the Kashar region, the Talloverov site is characterized by higher values of radon activity and its gradient in the atmosphere than for Fedorovka, which determines both the higher electric conductivity of the air and its more significant gradient. According to the results of three summer expeditions, radon activity in Tsimlyansk atmosphere turned out to be lower than in other sites under study in the Rostov region. However, radon flow from the soil to the atmosphere for Tsimlyansk, as already shown (Fig. 2) seems typical of the region.

As the surface atmosphere thermodynamic parameters analysis has shown, Tsimlyansk scientific station is characterized by higher wind speed than in the points of the Kashar district (Table 1). This includes stable temperature stratification conditions of the surface layer, when there is no convection. As a result, due to the peculiarities of the wind regime, turbulent mixing appears to be noticeable even at night, preventing radon from accumulating near the earth’s surface and facilitating its transfer to higher layers of the atmosphere. Because of this, its concentration near the ground is low, which determines the features of the vertical profiles of electrical conductivity.

**Table 1.** Values of surface layer parameters averaged for unstable and stable stratification

| Site        | Unstable temperature stratification                         | Stable temperature stratification                        |
|-------------|-------------------------------------------------------------|---------------------------------------------------------|
|             | \( t_2, \) \[°C\] | grad \( t \), \[°C/m\] | \( V_2 \), \[m/s\] | \( K_t \), \[m²/s\] | \( Rn_{0.05} \), \[Bq/m³\] | \( t_2, \) \[°C\] | grad \( t \), \[°C/m\] | \( V_2 \), \[m/s\] | \( K_t \), \[m²/s\] | \( Rn_{0.05} \), \[Bq/m³\] |
| Talloverov  | 50 hours                                                   | 118 hours                                               |
| 2008        | Mean            | 30.3     | -0.3    | 1.7 | 0.08 | 28 | 17.0 | 0.7 | 0.3 | 0.00 | 84 |
|             | St.deviation    | 4.2      | 0.7     | 0.02|      |    | 4.6  | 0.1 | 0.00|      | 36 |
| Fedorovka   | 19 hours                                                 | 41 hours                                               |
| 2012        | Mean            | 26.2     | -0.5    | 2.2 | 0.10 | 15 | 17.1 | 0.6 | 0.5 | 0.01 | 40 |
|             | St.deviation    | 2.2      | 1.1     | 0.05|      |    | 3.2  | 0.3 | 0.01|      | 29 |
| Tsimlyansk  | 59 hours                                                 | 17 hours                                               |
| 2014        | Mean            | 29.3     | -0.2    | 3.3 | 0.10 | 13 | 22.8 | 1.1 | 0.8 | 0.02 | 34 |
|             | St.deviation    | 5.8      | 0.6     | 0.04|      |    | 4.9  | 0.4 | 0.02|      | 12 |
| Tsimlyansk  | 59 hours                                                 | 14 hours                                               |
| 2015        | Mean            | 30.1     | -0.3    | 4.1 | 0.12 | 11 | 21.5 | 0.7 | 1.2 | 0.03 | 24 |
|             | St.deviation    | 4.4      | 1.0     | 0.04|      |    | 3.7  | 0.4 | 0.05|      | 13 |
| Tsimlyansk  | 21 hours                                                 | 19 hours                                               |
| 2017        | Mean            | 32.1     | -0.5    | 4.5 | 0.17 | 12 | 23.8 | 0.6 | 2.0 | 0.07 | 20 |
|             | St.deviation    | 4.7      | 1.8     | 0.04|      |    | 2.7  | 0.3 | 0.04|      | 16 |
Tsimlyansk profiles transformation analysis from 2014 to 2017 presents an interesting case. As seen in the graphs III-V in Fig. 4, radon content in the atmosphere varies from season to season. This is especially noticeable for night periods with stable stratification. For these periods, from year to year, there is also a corresponding trend in the conductivity profile. If in the year 2014 (Figures 4, III) the values of the electrical conductivity as a whole increase markedly as they approach the ground in connection with the enhancement of ionization, then in 2015 this decrease is less pronounced (Figures 4, IV), and in 2017 a decrease in the electrical conductivity along the direction to the earth’s surface (Figures 4, V).

This situation is realized in the ionized gas near the solid body surface, i.e. the earth’s surface, because of its adsorption of ions. Usually this is observed only for the lowest part of the electrical conductivity profile up to half a meter in thickness. In the case of 2017, obviously, due to the weak effect of the ionizer due to the low content of radon-222 in the surface layer, the adsorption prevailed to a height of 2 meters.

Summary
Long-term expeditionary studies results show that the vertical distribution of the lower atmosphere electrical parameters depends on the combined effect of factors determining the formation of ions, their loss and “aging”, and the thermodynamic factors affecting the redistribution of impurities in the atmosphere to turbulent diffusion. The spatial-temporal variability of the soil emanation determines the differences in such a powerful atmospheric air ionizer as radon-222. Its accumulation near the earth’s surface with a weakened turbulent exchange causes considerable gradients of electrical conductivity passage through the surface layer with a changing electrical conductivity of the conduction current promotes the formation of layers of a positive and negative volumetric charge of small ions [7]. Adsorption of this charge by aerosols contributes to the fact that charged layers exist in the lower atmosphere for many hours because of the long lifetime of large ions, determining the structure of the electric field and its magnitude near the earth. The air temperature and humidity, influencing the formation of aerosol and its properties, indirectly determine the electrical structure of the surface layer, as evidenced by recent experimental data.

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Acknowledgments
The paper is performed with support of Russian Foundation for Fundamental Research Grants № 16-05-00930 A, № 17-05-41121 RGS_a.