UNIVERSAL SPECTRA OF ELECTRIC FIELD PULSATIONS IN THE ATMOSPHERE

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ABSTRACT

Short-term ($f \cong 0.001$–1 Hz) electric field pulsations in the surface atmospheric layer have been measured during 1999 under the fair-weather and fog conditions. It is shown that at frequencies 0.01–0.1 Hz these pulsations have a power-law spectrum with the spectral index varying in the range from –1.23 to –3.36. The distribution obtained for the structured spectra is bimodal. The intensity of the electric-field pulsations under fog conditions increases by about an order of magnitude compared to the case of fair-weather conditions.

INTRODUCTION

The electric field of the atmosphere is a highly variable parameter [1]. While average values of this field near the ground are about 100–150 V/m, the vertical component of the aero-electric field intensity amounts to several kilovolts per meter during precipitations, snowdrift, thunderclouds, and fogs. Under the fair-weather conditions, variations in the electric field relative to the average value can amount to 1 to 50 % depending on the frequency. For example, diurnal variation in the electric field, observed on a global scale, is usually accompanied by a 20 % increase in the DC component of the electric-field intensity occurred at about 20:00 UT. A significant part of the experimental results described below corresponds to the fair-weather conditions, and the data for the subsequent statistical analysis were selected according to the stringent constraint $V < 2$ m/s on the wind velocity.

One of the key problems in studies of aero-electric pulsations is the analysis of their spectral characteristics [2-4]. The experimental studies of short-term pulsations of electric field, charge density, and current had revealed for their relation to the turbulent mixing of charged particles and space-charge drift in the near-surface layer. On the other hand, it was established experimentally that, in certain cases, the current fluctuations result from the displacement current, i.e., there is a one-to-one relation between the field and current spectra in the region of sufficiently large scales (or lower frequencies). This stipulates for seeking universal laws of behavior of the fluctuation spectra of the field, current, and charge density, which are analogous to the Kolmogorov spectra of temperature and wind-velocity fluctuations in a turbulent atmosphere.

EXPERIMENTAL TECHNIQUE AND RESULTS

Atmospheric electric observations were performed at the Borok Geophysical Observatory [58.03 N, 38.97 E] under conditions characterized by the absence of industrial pollution and a low level of electromagnetic interference. Our experiment was performed in May-September of 1999. During the experiment, the aero-electric field was measured synchronously at five equidistant points located along the north-south axis at a distance of 15 m from each other. During the second stage of the experiment, 9 sensors were mounted along a line of length 450 m. The sensors were mounted at a height of 1.5 m above the ground in all the experiment. The sensors of potential gradient were electrostatic flux meters of the “field mill” type, which were specially designed to perform long-term precision in-situ measurements under natural-experiment conditions. The experimental technique allowed us to perform regular testing of the measurement channel and obtain digital amplitude time realizations calibrated by the measured parameter. The threshold sensitivity of the sensor was equal to 0.1 V/m. Both the DC component of the atmospheric electric field and

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its short-term pulsations were registered in our experiment. The bandwidth of the measured frequencies covered the range f = 0–5 Hz. Each measurement channel was equipped with a low-pass filter with identical amplitude and phase characteristics. The sampling rate of the digital recording was equal to 10 Hz.

Processing of the experimental results included calculation of the spectra of electric-field pulsations using temporal realizations lasting from tens of minutes to 24 hours. The spectral density in the frequency range 10^{-2}–10^{-1} Hz can be fit with a high accuracy by a power law (Fig. 1.). The spectrum at frequencies 10^{-4}–10^{-2} Hz is characterized by the presence of low-frequency variations, which lead to variations in the power-law index, deviations from the power-law shape, and saturation of the spectrum in different realizations.

One of the goals of our experiment was the study of the relation between the spectral characteristics and the formation of aero-electrical structures. To reach this goal, we obtained a sequence of the structural functions $D(r)$, where r is the distance along the line of sensors, calculated for every 5-min interval during each 24-hour realization, i.e., the method of structural-temporal analysis proposed in was applied. In total, during the first stage of the processing we analyzed about four months of amplitude-time realizations of the electric-field pulsations from July till September of 1999. The processing technique included selection of temporal intervals of the pulsations, whose duration was determined by the time of existence of aero-electrical structures and amounted to 15–20 min (Fig. 1.).

Analysis of the behavior of the structural-temporal profiles shows that the existence of aero-electrical structures is followed by time periods of nonstructured pulsations whose amplitudes and, therefore, energies are comparatively small. We will call (somehow tentatively) the spectra of such pulsations the nonstructured spectra. To clarify the features of the statistical behavior of the structured and nonstructured spectral indexes, we analyzed more than 60 realizations. The spectral indexes for aero-electrical structures fall in the range from –3.36 to –2.03. The range of spectral indexes for nonstructured spectra is from –2.89 to –1.23.

The obtained results make it possible to construct statistically significant distributions of the number of realizations over spectral indexes for structured and nonstructured pulsations. The statistical distributions are obtained using 33 structured and 25 nonstructured realizations. The resulting distribution for the structured spectra is bimodal, i.e. it has two maxima in the index ranges from –3.0 to –2.75 and from –2.5 to –2.25. The distribution of the nonstructured spectra is asymmetric and has a pronounced maximum corresponding to the interval of hard spectra with indexes from –3.0 to –2.5 (Fig. 2).

Analysis of the mean indexes of the structured and nonstructured spectra shows that these values do not differ for the confidence level $p < 0.1$. However, the variability of the nonstructured spectral index is higher compared to the structured one. The spread of amplitude (the magnitude of the difference between the maximum and minimum values) of the nonstructured spectral index (1.66) is somehow greater than the same value for the structured spectra (1.33). This relation is more significant for the relative indexes of variability. The indexes of variation of the spectral indexes in structures and in nonstructured fragments are reliably different for the confidence level $p < 0.05$.

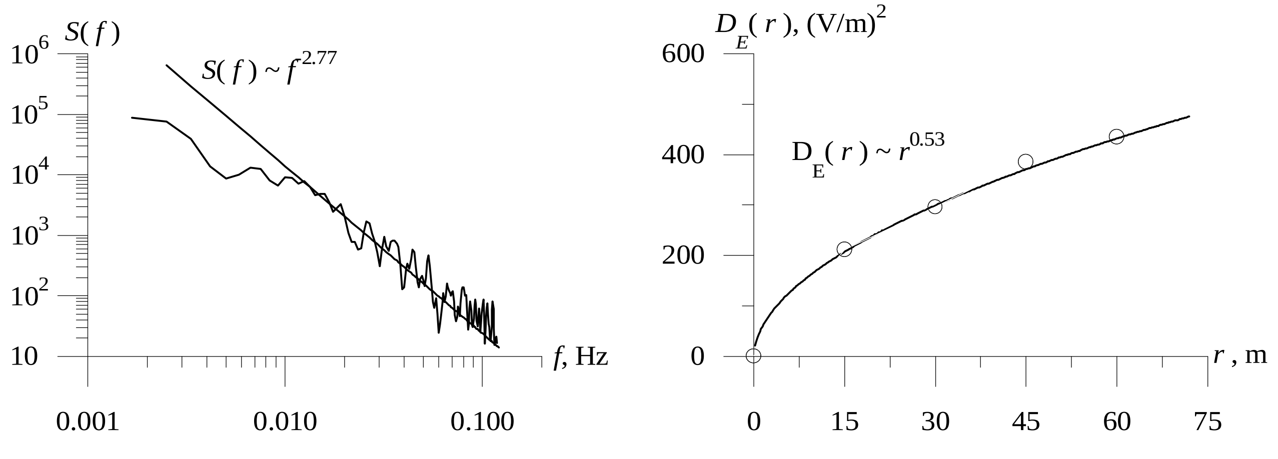

Fig. 1. Spectrum $S(f)$ and structural function $D_E(r)$ of the structured electric-field pulsations of the near-surface atmosphere by the data obtained at the Borok Geophysical Observatory on July 21, 1999 from 14:27 to 14:47 LT.

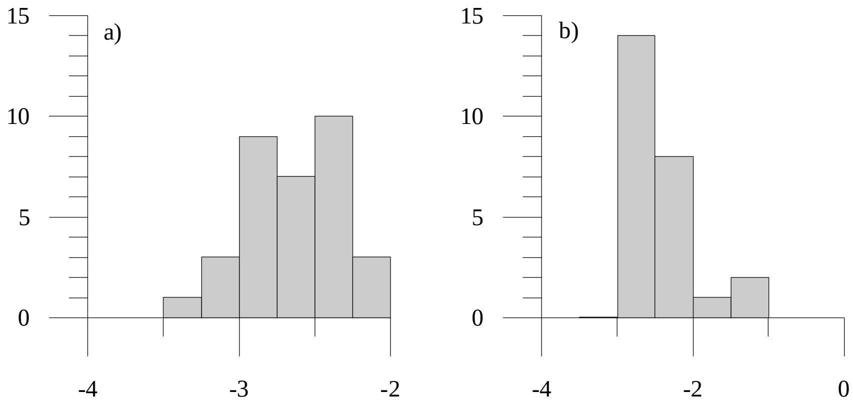

Fig. 2. Spectral-index distributions of the structured (a) and nonstructured (b) electric-field pulsations of the near-surface atmosphere.

The experimental results given above correspond to the fair-weather conditions i.e., were obtained in the absence of precipitations, lower cloudiness, and fog. It is known that the mean values of the electric parameters of the lower atmosphere change drastically under the conditions of «disturbed» weather. It is interesting to study the dynamics of the aero-electric state in the presence of such variations. Fog is a wonderful natural laboratory for such studies. The structural-temporal profile of the electric-field dynamics under fog conditions was studied. All such profiles were obtained as a temporal sequence of structural functions calculated by averaging over 5-min intervals. The calculations were made using the results of synchronous observations of the electric field at nine points spaced by distances from 15 to 450 m. It is seen that the energy of aero-electric pulsations under fog conditions is about an order of magnitude greater than the energy of electric-field pulsations under the fair-weather conditions (Fig. 3).

DISCUSSION OF THE RESULTS

Generalizing the results of recent experimental studies and theoretical models developed on their basis, we can characterize the dynamics of the surface atmospheric layer in the absence of anthropogenic pollution in the following way. The electric state of the near-surface layer is formed by ions of different signs created due to atmospheric ionization by cosmic rays and the natural terrestrial radioactivity. Note that the surface layer is a thin boundary region of the atmosphere where both the vertical electric field and the global-circuit current exist. To date, the occurrence of aero-electrical structures, whose origin is closely related to the atmospheric turbulence, was mentioned several times. It was established that the life time of such structures exceeds the response time of the free near-surface atmosphere. Aero-electrical structures consisting of turbulent vortex sets with captured electric charges have horizontal sizes from a few hundred meters to kilometers (Fig. 4).

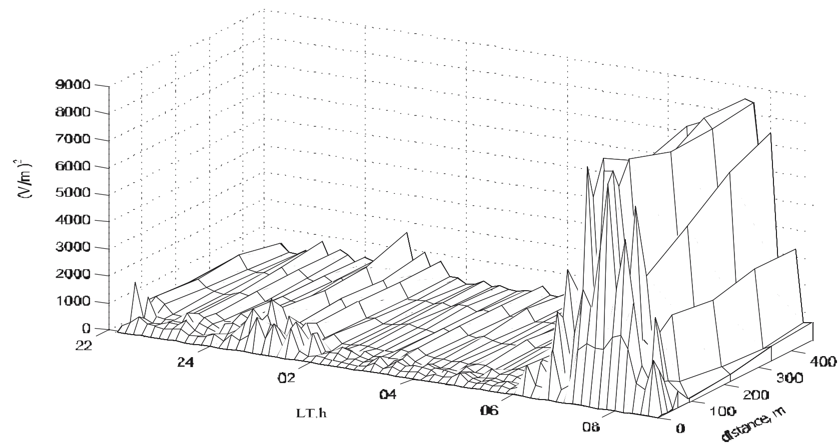

Fig. 3. Aero-electric structures detected at the Borok Observatory during the fog on September, 15-16, 1999.

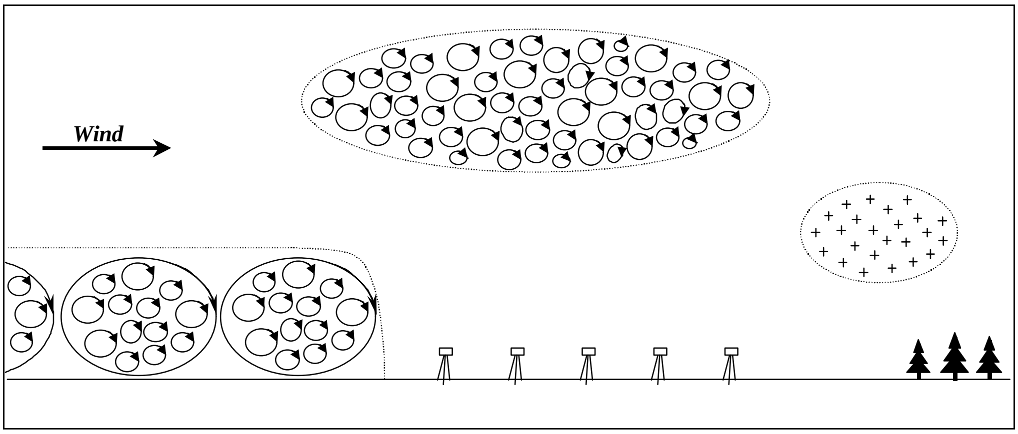

Fig. 4. Turbulence and aero-electric structures in the near-surface atmosphere.

The vertical size of such structures is usually determined by the height of the surface layer and the time scales of the electrodynamical parameters. The aero-electrical structures formed initially due to capture of positive and negative ions and aerosols by the small-scale mechanical turbulence travel along the ground under the action of wind. The appearance of vertical convective flows lead to a vertical displacement and carrying an aero-electrical structure out of the near-surface electric layer. Since the lifetime of an aero-electrical structure carried to some height is large, this aero-electrical structure is a source of electric-field pulsations observed on the ground. In addition to near-surface structures and structures remote in height with respect to the observation point (Fig. 4), positive and negative space charges also forms the corresponding response of the electric-field fluctuations detected by a ground-based device. Hence, the results obtained in the previous section show that the electric-field pulsations in the surface atmospheric layer have Kolmogorov power-law spectra.

CONCLUSION

Summarizing the obtained experimental results, we can draw the following main conclusions:

1. The electric-field pulsations of the near-surface atmosphere in the frequency range 10^{-2}–10^{-1} Hz have power-law spectra under both fair-weather and fog conditions. The power-law index varies from –3.36 to –1.23 depending on the conditions. However, the most probable values of the index occupy the range from –3.0 to –2.25.
2. The distribution obtained for the structured spectra is bimodal. It has two maxima in the index range from –3.0 to –2.75 and in the region from –2.5 to –2.25. The distribution of the nonstructured spectra is asymmetric with a pronounced maximum corresponding to the range of hard spectra with indexes from –3.0 to –2.5.
3. The intensity of the electric-field pulsations under fog conditions increases by more than an order of magnitude. At the same time, the spectral indexes of the majority of the observed events do not differ significantly from the corresponding indexes under the fair-weather conditions.

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