Atmospheric Research 135–136 (2014) 244–254

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Space charge and aeroelectric flows in the exchange layer: An experimental and numerical study

S.V. Anisimov *, S.V. Galichenko, N.M. Shikhova

Borok Geophysical Observatory of Schmidt Institute of Physics of the Earth, Russian Academy of Sciences Borok, Yaroslavl, 152742, RF, Russia

ARTICLE INFO

Article history:
Received 14 March 2012
Received in revised form 26 January 2013
Accepted 27 January 2013

Keywords:
Atmospheric electricity
Electroaerodynamics
Electrical layer
Space charge transport
Short-period pulsation
Aeroelectric structure
Turbulence

ABSTRACT

Experimental research on the turbulent transport of aeroelectrical field inhomogeneities and modeling of the formation of the dynamic electrical layer in the PBL has been carried out. The transport of aeroelectric inhomogeneities was detected on the basis of field observations during electrodynamics campaigns in the seasons of 2006–2011. Investigations of a dynamic component of the boundary layer electric field are carried out in terms of numerical modeling of spatially heterogeneous turbulent transport of space charge. The modeling of aeroelectric field dynamics is executed by means of a method of probe structures. The response of the aeroelectric field to the transport of aeroelectrical turbulence is investigated. Observations of the aeroelectric field intensity, the vertical profiles of wind speed and direction and the heights of a layer with a temperature inversion are used as input model parameters. Basic model parameters of space charge distributions are analyzed. It is shown that the evolution of an aeroelectrical vertical electric field profile is defined by the formation of dynamic electrical layers in the lower atmosphere. Estimations of the interrelation of aeroelectric field dynamics and trends of meteorological parameters are adduced for boundary layer conditions. It is shown that the velocity of transfer of aeroelectric field heterogeneities is defined by the velocities of space charge transport in electrical layers of the boundary layer. The influence of the large-scale wind velocity structure to the space charge spatial distributions is investigated. It is shown that the space–time aeroelectric field dynamics are due to the integrated contribution of the transfer of electric space charge. From the results of electric field observations the numerical estimation of space charge transport in the exchange layer is performed.

1. Introduction

The electrical characteristics of the undisturbed Planetary Boundary Layer (PBL) are most affected by the surface properties, ionization processes and space charge transport (Hoppel et al., 1986; Anisimov and Mareev, 2008). The electrodynamic state of the PBL is characterized by intensive spatial–temporal variations, one of the sources of which is transport of electric space charge by atmospheric flows.

It was found (Israel, 1958) that in general the atmospheric agitation is a direct result of the atmospheric exchange processes, provided by turbulent cells. Turbulent eddies mix ions, charged aerosols and radioactive particles, and generate the perturbations in aeroelectric field, charge and current (Hoppel et al., 1986). Several studies were devoted to the spatial variability and were organized by means of observations of electric field and electric current density at separate points. Whitlock and Chalmers (1956) made such measurements with the help of two field mills (placed 100 m apart) to obtain information about the charges responsible for the variations in the potential gradient over time periods of minutes. It was concluded that the changes in the potential gradient must be associated with the movement of space charges. Brasefield (1959) made simultaneous observations of the atmospheric potential at 33 m, 21 m, and 8 m above ground level, using radioactive probes. It was shown that clouds of charged ions frequently passed at altitudes of 10 m and less. The origin of the

---

* Corresponding author. Tel.: +7 485 472 4663; fax: +7 485 472 4024.
E-mail address: anisimov@borok.yar.ru (S.V. Anisimov).

0169-8095/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.atmosres.2013.01.012

ion clouds is uncertain but it appears that some of them were produced by motor vehicles, particularly diesel-powered vehicles. Bent and Hutchinson (1966) showed that usually at a height of 19 m above the ground the space charge density was considerably greater than that at 1 m. They explained these phenomena in terms of the electrode effect and revealed space charge heterogeneities during passing convection cells. Kamra (1969) studied the short term variations of the electrical potential gradient in fair and disturbed weather and also in windy and windless days. He founded that the magnitude and occurrence of the electric field pulsations depend on the mean value of the potential gradient. Besides, it was revealed that the pulsation is attributed to changes in the space charge density caused by the electrode effect in fair weather and the aerosol content in disturbed weather. Yerg and Johnson (1974) investigated the fair-weather atmospheric potential gradient variations in the frequency range between 0.004 and 0.06 Hz with cooper screen passive antennas at a height of 1 m above the ground. Three antennas were located in a line, so the second antenna was moved off from the first by 152.4 m and the third antenna was at 76.2 m away from the second. The results indicated that the pulsations in the electric field were associated with drifting space charge clouds of 135–425 m diameter. Kamra (1982) researched the fair-weather space charge distribution in the surface layer (the lowest 2 m) for different meteorological conditions.

The space charge dynamics of the PBL determines the generation of short-period (frequency band $\Delta f = 0.001$–1 Hz) aeroelectric field pulsations. The observations of the atmospheric electric field confirm that the dynamics of the electrical state of a surface atmosphere on a regional-scale is defined by the turbulent conditions in the PBL (Anisimov et al., 2002). It is necessary to emphasize that the intensity of the electric field is not a local physical value, and the spectrum of aeroelectric field variations is formed by the cumulative action of space charge heterogeneities in the vicinity of the point of observation (Anisimov et al., 2003; Shatalina et al., 2005). Recent observations show that, even at the initial stage, convective energy transfer from a heated underlying surface in the atmosphere and a part of this energy is converted to electric energy, which brings to the formation of the aeroelectrical structures at different spatial scales. The remote observations of the aeroelectric field enabled the identification of the presence of the aeroelectric structures of typical horizontal scale ~10^2–10^3 m in the PBL (Anisimov et al., 1994, 1999, 2005). A possible mechanism for the formation of the aeroelectrical structures can consist of the development of specific instabilities of a weakly ionized multi-component medium with the subsequent formation of dissipative structures. The model of the aeroelectrical structures generation is based on the collective interaction between charged aerosols and light atmospheric ions, and takes into account the interaction of kinetic coefficients and the electric field (Anisimov et al., 1999; Anisimov and Mareev, 2008).

It is known that after the sunrise the convective instability of the bottom of the PBL is developed as a result of heating of the underlying surface (Wyngaard, 2010). The intensification of vertical fluxes causes displacement of the temperature inversion boundary and essential growing of the convective boundary layer that (as shown by observations) is accompanied by a positive trend of the aeroelectric field and the generation of short-period aeroelectric field pulsations. It has been shown experimentally that low-lying surface layer space charge is upwardly mixed to the heights of the upper boundary of the atmospheric exchange layer (Marshall et al., 1999; Matthews, 2012).

The aim of this work is concluded in experimental research of turbulent transport of aeroelectrical field inhomogeneities and the modeling of formation of the electrical layers in the PBL.

2. Experimental technique

Atmospheric electric observations were performed in a remote testing area of the middle-latitude Borok Geophysical Observatory (58° 04′ N and 38° 14′ E) under some conditions characterized by the absence of industrial pollution and a low level of electromagnetic interference. The times of observations included the summer–autumn seasons of 2006–2011. For example, the measuring complex (Fig. 1) for the 2006 season consisted of eight sensors of the atmospheric electric field intensity, five high-sensitivity sensors of air temperature, a three-component SODAR, with the axes of the acoustic pattern orientated upright and along the north–south and the west–east directions with zenith corners at 30°. The digital meteorological station registered a full set of meteorological parameters in a continuous mode with a 10 Hz sampling rate. Aerophysical digital data were recorded with the sampling rate of 10 Hz. The aeroelectric field was observed synchronously at eight locations located along the north–south direction. In the 2006 season five of them were placed at equal distances of 10 m, and the other sensors were placed at distances of 102, 192 and 282 m from the first sensor in the line. The total length of the line was about 282 m. The sensors were installed at a height of 1.5 m. As the sensor of the aeroelectric field intensity we used electrostatic fluxmeters of the “field mill” type, which had been specially designed to perform long-term precision measurements. The threshold sensitivity of the sensor was about 0.1 V/m. The dynamic range of the measurements has not been less than 80 dB (Anisimov et al., 1994). Values of the electric field were reduced to the surface value by a reduction coefficient which was equal to 0.3 and based on the ratio of hourly average values of the intensity of the electric field at the height of 1.5 and at the ground level. Hourly-averaged means and variances differ from each other by not more than 5% for the eight field mills. The accuracy of the registering channels was controlled by means of regular calibrations. Fig. 2 shows the typical record of eight point aeroelectric field variations by synchronous remote sensing.

Measurements of average high-altitude profiles of a component of wind speed in the PBL were carried out with the help of an acoustic locator (SODAR). The technique for such measurements is well established (Soler et al., 2003; Kallistratova and Coulter, 2004; Tamura et al., 2007) and enables the documentation of average (over 10–60 min) profiles of wind speed and its direction with an accuracy consistent with meteorological standards. SODARs LATAN-2 and Volna-3 (Gladkikh et al., 1999; Kouznetsov, 2007) were used during these experiments. LATAN-2 key parameters of the acoustic locators were: working frequency — 3700 Hz, a high-altitude range of 20–600 m, the height resolution — 5–10 m, and the period of a cycle of one sounding — 10 s. Fig. 3 shows a typical example of high-altitude profiles of horizontal u and vertical w wind speeds. This is the result from the acoustic sounding of June 3, 2006. Observations of the high-altitude profiles of wind