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CONTENTS

SOLITONS AND SELF-ORGANIZATION

FLUID DYNAMICS

PARAMETRIC ACOUSTICS

OPTICAL SPECTROSCOPY

REMOTE SENSING OF THE ATMOSPHERE

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IMPACT OF RADIOACTIVE CONTAMINATION ON ELECTRIC CHARACTERISTICS OF THE ATMOSPHERE. NEW REMOTE MONITORING TECHNIQUE

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A new method is considered for remote sensing of radioactive contamination in the atmosphere. The method is based on an anomalous response of ionospheric characteristics on the significant variations in an electric field near the Earth's surface, caused by the atmosphere ionization. The feasibility to use satellites for global monitoring of radioactive contamination is shown.

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1. Introduction

Nuclear power industry should become a main energy source of the 21st century, although this did not happen in the 20th one due to a number of reasons, first of all due to a sufficient amount of cheap petroleum and gas at the world market, emergencies at atomic power plants that gave rise to social distrust, and a lack of convincing safety concepts. Therefore, as the part of atomic plants increases in the power production, the development of new efficient methods for detecting and monitoring radioactive contamination of the environment becomes increasingly urgent.

At normal operation, atomic plants virtually do not exhaust products that cause significant radioactive precipitation. However, serious exceptions are the emergencies at nuclear reactors and plants, for example in Windscale (Great Britain) in 1957, Three-Mile-Island (USA) in 1979, and the world greatest emergency at Chernobyl in 1986 (the former Soviet Union) [1].

The basic impact of radioactive fission products on the environment is its ionization [2] changing electric properties of air [3,4]. Hence, the problem of remote detection and identification of radioactive contamination by disturbed atmosphere electric characteristics seems to be of interest.

2. Model of an exhaust radioactive cloud

In the case of emergency at a nuclear plant, a great amount of radioactive particles, vapors, and ashes can be exhausted to the height of 1–2 km. For instance, the most powerful outflow of radioactive products from the Chernobyl plant unit was within the first two or three days after the emergency in the North-Western direction. According to aircraft data, the jet height exceeded 1200 m on April 27, 1986. The maximum radiation level in the plant vicinity was at the height of 600 m. Later on the jet height did not exceed 200–400 m [1].

In such a cloud, under the impact of ionizing radiation as well as due to ion friction and adsorption onto atmospheric aerosols, many particles become positively or negatively charged. Small ions have a higher mobility than large ones, but very fast adhere to aerosol particles and form large ions or ionic clusters, which less subject to drift in an electric field. These heavy aerosol particles, for example, water drops in the cloud, are strongly subject to the Earth's gravity. Via convective processes, the ionization source in the cloud can significantly separate the space charge due to the transport of opposite-sign ions by water drops. Such separation is impossible with only the light ion drift under the action of the Earth's electric field [3].

Fundamentals of the theory of charge separation in the cloud by water drops were developed by Wilson [5]. After him, the falling drop (or an ice crystal) gains an induced dipole moment in the Earth's electric field. Hence, when falling, the drop attracting negative and repulsing positive ions collects and transports a negative charge to the cloud bottom. In other words, the falling drop polarization changes the attachment of small ions of any polarity, that in turn gives rise to charge separation and generates a strong electric field in the atmosphere.

The cloud contains ascending and descending convective fluxes of water drops and ice crystals, therefore one can also assume the small drops entrained by the ascending flux to carry the positive charge upward in a similar way.

Below we propose a two-scale model of atmospheric aerosol kinetics in the radioactive exhaust cloud.

First, "large" neutral aerosols (drops) are assumed to exist initially in the atmosphere. At the time $t = 0$ and height H a source of small ions of both signs appears in the layer of thickness z. Water vapor condenses in this layer, that is there exists a source of large neutral aerosols. Second, when calculating we take into account the following processes: diffusion of all particles; large and small charged particle drift in the local electric field; fall of large drops (particles) at a constant velocity under the gravity action; and transport of small particle upward at a constant velocity by ascending air flows. Third, we consider the particle interaction in the following way: small charged particles are assumed to recombine at a certain constant rate α similar to elementary ions, however, when a large neutral or a charged particle and a small charged particle collide, they can adhere. Kinetic coefficients β_{ij} of this process are different for various pairs of interacting particles, besides β_{ij} depend on the local electric field E. For weak fields, $E\mu/V \ll 1$, the dependence of the attachment

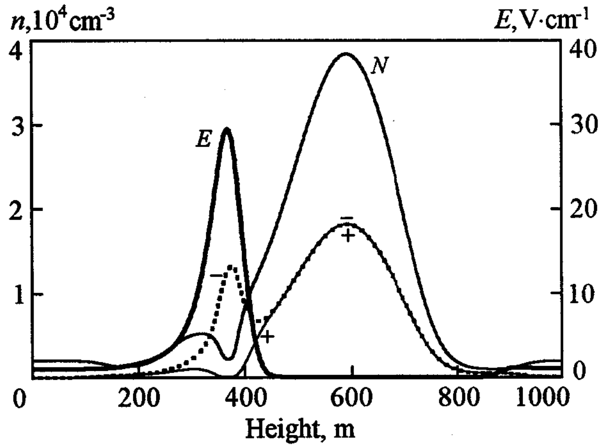

Figure 1. Calculated height distribution of the concentration N of neutral aerosols, the positive (+) and the negative (−) space charge induced by the drop transport, and the electric field E in the exhaust cloud (at $t = 864$ s after the process start) for the following parameters: $V = 20\,\mathrm{cm\cdot s^{-1}}$, $\nu = 7\,\mathrm{cm\cdot s^{-1}}$, $\mu_- = 0.19\,\mathrm{cm^2\cdot V^{-1}\cdot s^{-1}}$, $\mu_+ = 0.12\,\mathrm{cm^2\cdot V^{-1}\cdot s^{-1}}$, $M_\pm = 10^{-3}\,\mathrm{cm^2\cdot V^{-1}\cdot s^{-1}}$, $d_+ = 0.28\ \mathrm{cm^2\cdot s^{-1}}$, $d_- = 0.43\ \mathrm{cm^2\cdot s^{-1}}$, $D_+ = 3\cdot 10^{-3}\ \mathrm{cm^2\cdot s^{-1}}$, $D_- = 4\cdot 10^{-3}\ \mathrm{cm^2\cdot s^{-1}}$, $\alpha \simeq 10^{-6}\,\mathrm{cm^3\cdot s^{-1}}$, $\beta^0(N + n_\mp) = 2\cdot 10^{-6}\,\mathrm{cm^3\cdot s^{-1}}$, $\beta^0(n_\pm + N_\mp) = 4\cdot 10^{-6}\,\mathrm{cm^3\cdot s^{-1}}$, $\beta^0(N_\pm + N_\mp) = 3\cdot 10^{-6}\ \mathrm{cm^3\cdot s^{-1}}$, $N(t=0) = 2\cdot 10^3\ \mathrm{cm^{-3}}$, and $q = 10^5\,\mathrm{cm^{-3}\cdot s^{-1}}$.

coefficient on the field can be considered as linear [6]

$$\beta_{ij} = \beta_{ij}^{0}\left(1 \pm 4\,\frac{E\mu}{V}\right), \tag{1}$$

where β_{ij}^{0} is the ion attachment coefficient in the absence of field [7]; the sign in parenthesis is defined by the adhering ion polarity: minus for negative and plus for positive ions (if the field E directed up is positive), μ is the mobility of a small particle, and V is the velocity of the falling large aerosols.

The set of equations describing kinetics of these processes is written as

$$\begin{aligned}
\frac{\partial n_1}{\partial t} &= d_1\,\frac{\partial^2 n_1}{\partial z^2} - \mu_1\frac{\partial}{\partial z}(En_1) + q - \alpha n_1 n_2 - \beta_{10}Nn_1 - \beta_{11}N_2 n_1 - \nu\frac{\partial n_1}{\partial z}\,,\\
\frac{\partial n_2}{\partial t} &= d_2\,\frac{\partial^2 n_2}{\partial z^2} + \mu_2\frac{\partial}{\partial z}(En_2) + q - \alpha n_1 n_2 - \beta_{10}Nn_2 - \beta_{11}N_1 n_2 - \nu\frac{\partial n_2}{\partial z}\,,\\
\frac{\partial N_1}{\partial t} &= D_1\,\frac{\partial^2 N_1}{\partial z^2} - M_1\frac{\partial}{\partial z}(EN_1) + V\frac{\partial N_1}{\partial z} - \beta_{00}N_1N_2 + \beta_{10}Nn_1 - \beta_{11}N_1 n_2,\\
\frac{\partial N_2}{\partial t} &= D_2\,\frac{\partial^2 N_2}{\partial z^2} + M_2\frac{\partial}{\partial z}(EN_2) + V\frac{\partial N_2}{\partial z} - \beta_{00}N_1N_2 + \beta_{10}Nn_2 - \beta_{11}N_2 n_1,\\
\frac{\partial N}{\partial t} &= \beta_{11}n_2N_1 + \beta_{11}n_1N_2 - \beta_{10}Nn_2 - \beta_{10}Nn_1 + \beta_{00}N_1N_2 + Q - \nu\frac{\partial N}{\partial z}\,,\\
\frac{\partial E}{\partial z} &= 4\pi e\Big(n_1 - n_2 + N_1 - N_2\Big),
\end{aligned} \tag{2}$$

where n_1 and n_2 are the concentrations of positive and negative ions, ν is the velocity of light ions, q is the ionization rate, d_i and μ_i are the diffusivity and mobility of elementary ions, α is the recombination coefficient of elementary ions, N_1 and N_2 are the concentrations of positively and negatively charged aerosol particles, β_{ij} is the attachment coefficient for a small ion of ith polarity to a large aerosol particle of jth polarity, N is the concentration of neutral aerosol particles, D_i and M_i is the diffusivity and mobility of large ions, Q is the source of neutral aerosols (drop production rate at condensation).

According to this model, the drops eventually transport their negative charge to the Earth's surface. The time of charge expansion over the surface is assumed to exceed all the characteristic times of other processes, thus the charge transferred by the fallen drops onto the surface is conserved there.

Figure 1 shows the calculated concentration distribution for positively and negatively charged drops, as well as the distribution of electric field and neutral drops in the case of a radioactive cloud exhaust to the height $H = 600$ m with a constant volume ionization source q of Gaussian profile in the layer 200 m thick [1]. The basic mechanism of charge separation is the negative charge transport by drops falling down and the positive charge transport upward due to convective jets in the cloud. This process can substantially increase the electric field up to a few kV $\cdot$ m^{-1} at great areas covered by the cloud. One sees the charge separation in the cloud top to be negligible at heights about 600 m and lines (+) and (−) virtually coincide, however, at a height of 370 m the charges are separated with a sharp field gradient. Figure 2 displays the time dependencies of positive and negative drops concentrations, as well as of the electric field at the maximum gradient in the cloud layer at a height of 370 m.

Thus, the proposed model of an ionized cloud shows the possible formation of an anomalous

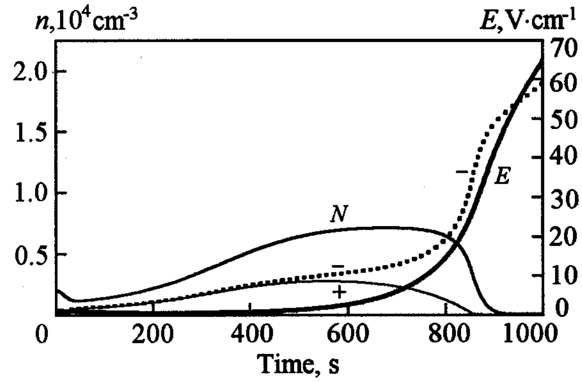

Figure 2. Time dependencies of the neutral and charged particle concentrations and the electric field at a height of 370 m.

electric field in the lower troposphere at radioactive contamination. The variations in atmospheric conductance, including the lower ionosphere, were detected above the Chernobyl plant during the emergency of 1986 and above the Leningrad plant during a negligible exhaust on March 24, 1992 [8].

The proposed model of electric field generation in the radioactive cloud is to an extent similar to processes in thunderclouds, the difference consists in a constant ionizing source existing inside the cloud. Therefore, ordinary clouds ionized by radioactive products can transit into thunderclouds due to a faster intracloud charge separation. This assumption is confirmed by the experimental fact of an elevated after-Chernobyl thunderstorm activity in Scandinavia having received radioactive aerosol clouds [9].

3. Ionospheric response to tropospheric processes

The Earth's atmosphere is very sensitive to external factors, therefore its characteristics are subject to some regular and irregular variations. Usually, the ionosphere state is considered as related merely to solar and cosmic influences. However, some studies show short-term anomalous variations appearing in the ionosphere even at constant external factors [10]. The ionosphere variability is usually understood as short-term (shorter than 4 h) variations in electron density and other atmospheric parameters, existing with no apparent external causes under quiet conditions, in the absence of geomagnetic perturbations. It is quite natural to look for the cause of these variations in the troposphere or at the Earth's surface. Volcanic activity, cyclones, thunderstorms, explosions, various contaminations in the troposphere, all these have a response from the ionosphere [10–12].

Above we have considered the possibilities to form an anomalous electric field in the atmosphere above great areas. A significant electric field in the lower troposphere affects the ionospheric electron density, ion composition, and temperature. Here we propose one of the possible mechanisms of this impact, that is the electrodynamic one [12], according to which significant variations in the vertical electric field at the Earth's surface induce the horizontal field in the ionosphere. Just the latter field causes anomalous variations there.

The problem of electric field penetration into the ionosphere from the sources localized in the ground atmosphere (0–20 km) was first considered in [13] and in more recent work [14]. This work suggests that the field is not totally shielded and penetrated into the ionosphere where it is of order $1\,\mathrm{mV\cdot m^{-1}}$. Thus the latter value is eight orders of magnitude weaker as compared to that in the troposphere caused, for example, by a giant thundercloud. As for atmospheric electricity, the field of $1\,\mathrm{mV\cdot m^{-1}}$ is virtually zero, while in the ionosphere this value cannot be neglected.

The atmospheric conductance tensor $\hat{\sigma}$ depends on the height, more correctly, on the behavior of charged particles at various heights, in a complex way. In the lower atmosphere the conduction is isotropic due to collisions between charged particles and excessive neutrals, but this isotropy disappears as the height increases. In a more rarefied atmosphere, especially ionosphere, the number of charged particles increases compared to the neutral components. The Earth's magnetic field orders the ion and electron drift around a spiral along lines of force. However, up to a certain height the neutral components' concentration is still significant, and those do not strongly affect the ion drift. Apart from the conventional conduction, the so-called Pedersen conduction and the Hall conduction arise there [13]. As a result, the conductance $\sigma_{\parallel}$ along the geomagnetic lines of force in the ionosphere is much higher than the transverse conductance $\sigma_{\perp}$, hence the electric field is perpendicular to the lines of force there. When considering various field effects in the ionosphere E-region, the declination of geomagnetic lines of force (at middle and high latitudes) is usually neglected and the approximation of vertical lines of force is used. Then one allows for only the horizontal component of electric field. At heights greater than 90 km, for example in the F-region, the declination of magnetic lines of force should be taken into account.

Thus, by virtue of the anisotropic conduction related to the geomagnetic field, the local nonuniformities of electric field in the troposphere, in particular the vertical component variations related to the thundercloud fields [13,14], as well as those caused by radioactive contamination [12], can cause the field component perpendicular to the geomagnetic lines of force in the ionosphere. This component is of the order at least of few mV $\cdot$ m^{-1}; such fields are substantial for the ionosphere, but are insignificant for the troposphere.

To illustrate the effect in the ionosphere, induced by an electric field created by the radioactive cloud near the Earth's surface, we will use the model of a local electric field of the seismic nature [14,15]. In this case the field at a height $z \geqslant z_2 = 90$ km is determined by expression

$$E_r = -\frac{\partial}{\partial r}\phi\Big|_{z=z_2} = \int\limits_0^{\infty} J_1(kr)\Big\{A_2(k)\, I_\nu(kf|_{z=z_2}) + B_2(k)\, K_\nu(kf|_{z=z_2})\Big\} f^{\nu}\Big|_{z=z_2} k\,dk, \qquad (3)$$

where ϕ is the electric potential, J_1 is the Bessel function of the first kind, I_ν and K_ν are the modified Bessel functions of first and second kind, respectively,

$$f = \frac{2h_1h_0}{h_1 - h_0}\exp\left\{-\frac{h_1 - h_0}{2h_1h_0}(z - z_1)\right\},$$

where $\nu = h_1/(h_1 - h_0)$, h_0 and h_1 are the characteristic scales of inhomogeneities, $z_1 \simeq 65$ km [15]. The factors A_2 and B_2 are defined from the boundary conditions of the problem

$$-\frac{\partial}{\partial r}\phi\Big|_{z=0} = E_0\exp\left\{-d\left(\frac{r}{a}\right)^2\right\}, \qquad (4)$$

while the solution for ϕ is found from the equation of continuity for a stationary current $\mathbf{j}$

$$\operatorname{div}\mathbf{j} = 0, \qquad \mathbf{j} = -\hat{\sigma}\cdot\nabla\phi. \qquad (5)$$

It is noteworthy that at the ionospheric level $z_2 = 90$ km the electric field is radial and axisymmetrical about z.

Figure 3 shows the electron concentration N_e isolines at the height $z = 500$ km in 2 h after beginning of the field action. The filled circle indicates a vertical projection of the cloud center, that is the tropospheric electric field source, onto the corresponding ionospheric level. One sees that the field makes the horizontal distribution of ionospheric plasma substantially nonuniform in the F2-region above the field localization in the basic plane. A characteristic size of the perturbed region exceeds 400 km. The maximum change in plasma concentration relative to its unperturbed value is about 20%. The horizontal distribution of ionospheric plasma is characterized by two pronounced foci of positive and negative perturbations in N_e. Note that this numerical simulation of the impact of the radioactive contamination cloud on the ionosphere, based on the model [13,14], is valid for high and middle latitudes. As to the lower latitudes and equator zone, special studies are required.

Figure 4 displays a distribution of deviation δf_0 for the critical frequency f_0 from its average for the ionospheric layer F2. This distribution is measured in a few hours after the emergency at Three-Mile-Island nuclear power plant in 1979 by the Interkosmos-19 satellite. The average value of the critical frequency is calculated for an undisturbed ionosphere. The bipolar structure of the electronic concentration proportional

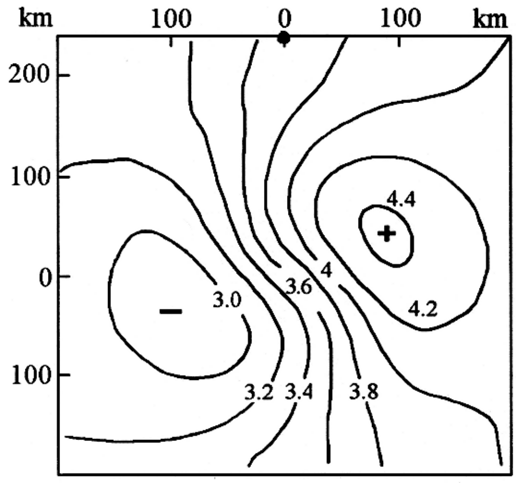

Figure 3. Calculated isolines of electron concentration N_e (in $10^4\,\mathrm{cm}^{-3}$) at the horizontal plane $z = 500$ km in 2 h after "enabling" the field. The values of concentration are marked by figures at lines. The filled circle indicates the center of a tropospheric perturbation in the electric field.

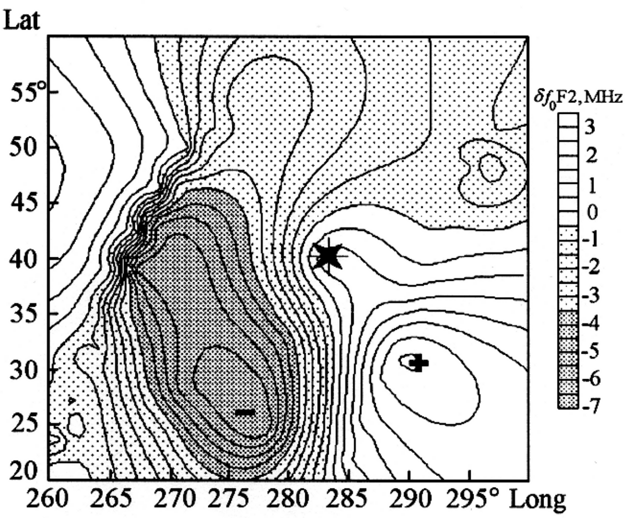

Figure 4. Distribution of the critical frequency deviation from the average in the layer F2 above Three-Mile-Island nuclear plant after the emergency according the data of the Interkosmos-19 satellite. The asterisk indicates the plant. (One degree of geographical coordinates at the layer F2 is 116.5 km.)

to f_0^2 above the place of emergency marked by an asterisk is well observed on the figure. The area of ionospheric perturbations much exceeds that calculated in Fig. 3. It is likely that the real horizontal sizes of radioactive pollution in the near-ground atmosphere were substantially greater than the size of the local electric field accepted by us for calculation by the model [15].

The presented experimental data confirm the theoretical calculations and allows us to conclude the atmospheric electric field to be a very important source of ionosphere variability.

4. Conclusion

In the present work the impact of radioactive contamination of the atmosphere on air electric characteristics is considered. The drop model of a radioactive cloud is proposed, for possible formation of significant electric fields from local sources in the troposphere at radioactive contamination. These electric field perturbations in the lower atmosphere near the Earth's surface are shown to cause the corresponding variability in the ionosphere.

The efficiency of electric field penetration into the ionosphere is very low (equal or below 10^{-6}), however if fields of order $1\,\mathrm{kV \cdot m^{-1}}$ exist near the Earth's surface, the field of a few millivolts penetrate into the ionosphere, that is sufficient for the observed variations in the ionospheric plasma density. This results in a transformation of the vertical field near the Earth's surface into the horizontal field in the ionosphere due to the following reasons.

(i) The tropospheric air conductance is isotropic and is much less than the Earth's conductance, therefore only the vertical electric field exists in the lower troposphere under conventional conditions.

(ii) On the contrary, in the ionosphere the conductance along the geomagnetic field lines of force much exceeds that across the field, therefore the ionospheric electric field perpendicular to the magnetic field lines of force exceeds the corresponding longitudinal component.

The electric field penetration into the ionosphere depends on the conductance tensor, whose anisotropy just furnishes the field of order $1\,\mathrm{mV \cdot m^{-1}}$ at the corresponding heights.

Remote measuring of the ionosphere response to variations in the tropospheric electric field can be used as a technique for monitoring of radioactive contamination in the troposphere. It may be done by remote sensing of ionosphere from outer space or using a network of Earth-based ionosphere sondes [12].

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