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Influence of Cosmic Ray Invasions and Aerosol Plasma on Powerful Atmospheric Vortices

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ABSTRACT

The Earth's atmosphere is affected by various ionizing sources. The maximum ionization of atmospheric particles by cosmic rays corresponds to the altitude of formation of tropospheric clouds. In the high-latitude troposphere for the region of the geomagnetic polar cap, in the winter period, the excitation of local cyclonic structures are observed which are accompanied with ice storms, with invasions into middle and subtropical latitudes. The time of excitation of such cyclones is about a day that is comparable with the time of excitation of tornadoes, which are generated at low latitudes. Localization of polar cyclones is not accidental. The region of the polar cap is connected with geomagnetic field lines extended into the tail of the Earth's magnetosphere. This area is open for the penetration of cosmic rays. The ionization of aerosols in the stratosphere and the upper troposphere by precipitating particles of cosmic rays enhances the vortex activity of the atmosphere. The important role of the aerosol impurity is manifested in the generation of plasma vortices and in the accumulation of energy and mass in the atmosphere by vortices during condensation of moisture. Due to the cascade character of the ionization process, the influence of cosmic radiation turns out to be non-linear and increases with increasing pollution of the atmosphere. Aperiodic electrostatic perturbations, which play a remarkable role in the genesis of vortices, are stochastically excited in plasma inhomogeneities. During the interaction of plasma vortices and Rossby vortices, a large-scale vortex structure is formed and grows.

Keywords: aerosol plasma, geomagnetic field, cosmic rays, atmospheric vortex activity, polar winter cyclones, aperiodic disturbances

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1. INTRODUCTION

The atmosphere of the Earth is constantly affected by various heat and ionizing sources. Particles of the atmosphere are ionized by photons, protons, ions, electrons and other particles generated by cosmic rays when nuclei are destroyed [1,2]. The average power of the solar wind injected into the magnetosphere, and, consequently, into the atmosphere, is about 10^{23} units of CGSE per day. Galactic cosmic rays are a stream of charged particles,

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mainly protons, in the energy range of 100 MeV – 100 GeV, penetrating the solar system from interstellar space. The interaction of high-energy cosmic particles with the nuclei of the components of the atmosphere leads to the formation of radionuclides. In cosmic streams, protons dominate (~85%), but there are also helium nuclei (~10%), electrons (~1%) and atomic nuclei with a nuclear charge up to $z \sim 30$ are observed. The process of ionization of atmospheric components by energetic particles of cosmic rays is the cascade one. An energetic particle of cosmic rays produces about a million or more acts of ionization in the atmosphere. The maximum ionization of atmospheric particles by cosmic rays corresponds to the altitude of formation of tropospheric clouds. Cloudiness and precipitation decrease during the decrease in the intensity of galactic cosmic rays, and the amount of cloudiness and precipitation increase after the arrival of solar cosmic rays from a flare on Earth. These changes are about 10%. After the invasion of large fluxes of accelerated particles into the polar regions of the Earth, a change in temperature is observed in the upper atmosphere. Cosmic rays are actively involved in the formation of thunderstorm electricity.

Solar-terrestrial relations in the formation of atmospheric clouds and climate are nonlinear [3-7]. Periods of high solar activity are usually accompanied by droughts and elevated temperatures [8]. Periods of low activity in middle and northern latitudes are characterized by a decrease in temperature and long snowy winters. Mechanisms of effects of the ionizing flux from energetic particles of solar and galactic origin on the lower atmosphere, weather and climate are presented in [9-15]. Variations in solar activity over an 11-year cycle change the mean value of the solar constant (solar radiant energy flux of 1368 W/m^2) by no more than 0.2%, and this change occurs in phase with the relative number of sunspots (the Wolf number). Solar flares of 3 points and above are usually accompanied by the generation of solar cosmic rays. There are observed synchronous changes in the density of clouds after intense solar flares from solar and global meteorological data. Changes in the transparency of the atmosphere under the influence of cosmic rays were detected. A noticeable increase in the regeneration of cyclones off the southeastern coast of Greenland was found after the onset of solar proton events [12]. The cause of changes in the temperature field may be the effect of radiation effects on variations in upper clouds. The relationship between solar activity and variations in the geomagnetic field is statistically traced. Fluctuations in atmospheric pressure increase with periods of tens of minutes and hours during magnetic storms, the intensity of the electric field of the atmosphere changes. In particular, it is shown that when the Earth enters the enhanced flow of the solar wind, the pattern of distribution of surface pressure changes noticeably, the instability of the troposphere increases, the intensity of circulation changes, and the combination of properties of these phenomena indicates the trigger mechanism of their origin. Regional studies also confirm the important role of solar activity in meteorological processes [16, 17]. So, it is shown in [16] that the time course of solar activity is synchronous with the distribution of dangerous meteorological phenomena (in the average monthly distribution, the correlation coefficient is 0.77, in the average annual distribution, the correlation coefficient is 0.82); years with a maximum of dangerous meteorological phenomena are characterized by the maximum manifestations of solar activity (and the drops are also synchronous). It was revealed in [17] that the wave process of attenuation and increase of thunderstorm activity in the Altai Mountains is subordinated to solar activity and is a link in solar-terrestrial interconnections: thunderstorm minima and maxima "fall" on corresponding solar activity extremums. Ionization of the atmosphere by external sources is a necessary condition for the excitation of plasma vortices.

Polar mesoscale cyclones are an unique natural phenomenon in the atmosphere of the Arctic [18, 19, 20]. They were discovered and described in the mid-twentieth century due to the development of satellite sensing of the atmosphere. The applied interest in polar cyclones is primarily associated with the need to predict the possible occurrence of

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dangerous weather phenomena and their impact on the objects of economic infrastructure and ships. Such structures often appear in the Arctic and have a radius not exceeding 1500 km. Polar winter cyclones are accompanied by ice storms. The rise time of such cyclones and their lifetime is 15–25 hours, which is comparable with the time of the initiation of tornadoes at low latitudes. Tornadoes are associated with hurricanes, destruction and floods. Wind speed in polar winter cyclones increases up to a storm value of 15–20 m/s. Invasions of polar cyclones into mid-latitudes are also observed, with abundant precipitation and a sharp cooling, even to subtropics. Cyclone amplification is associated with phase transitions of water. Aerosols have a marked influence on the global and regional climate [21]. An important source of aerosol is volcanic eruption. Volcanic lightning is observed, therefore, plasma is emitted into the atmosphere. The ionization mechanism is thermal in this case, similar to friction. The kinetic energy of the movement of particles is converted into ionization energy. Cosmic rays ionize particles directly in the atmosphere. Climate relations are multi-parameter ones. The increasing influence of deserts on the climate is monitored. This is illustrated by the example of Europe. Droughts are frequent and intensified. It affects not only the Sahara desert, but also anthropogenic desert, the destruction of forests and vegetation. We consider the influence of cosmic rays on the ionization of aerosol as climatic. Aerosol particles play an important role in the generation of atmospheric vortices [22]. It was found that aerosol particles up to 50 nanometers in diameter significantly accelerate convection and precipitation [23]. At phase transitions during condensation and crystallization of moisture on the aerosol particles, latent heat is released; structures of a cyclonic type accumulate energy. With the mosaic cellular distribution of ionized aerosols in the geomagnetic field, plasma vortices are excited on pressure gradients orthogonal to the geomagnetic field [4, 6, 24, 25]. At the rotor genetic level, plasma vortices interact with atmospheric vortices like particle velocity vortices.

The main goal of the paper is to demonstrate the role of cosmic ray invasions and aerosol plasma in the generation of powerful atmospheric vortices. In particular, the aim of the work is to show that the excitation of polar cyclones in the winter period is not accidental. Such cyclones are localized in the region of the polar cap of the geomagnetic field. Under the pressure of the plasma of the solar wind, the magnetic force lines of the polar cap are extended into the tail of the magnetosphere. This zone is open to the penetration of solar and galactic cosmic rays into the geomagnetic field and precipitation into the atmosphere. When the magnetic field lines reconnect, plasma particles in the magnetotail are accelerated by the betatron mechanism. The precipitation of cosmic particles into the stratosphere and upper troposphere, the ionization of aerosols, and the phase transitions of atmospheric moisture cause nucleation of cells of a cyclonic type with an inhomogeneous mosaic distribution of aerosol admixture in the atmosphere. Heating and ionization of particles at low latitudes in a tornado are associated with solar photon flux and cosmic ray intrusions. An important role in the genesis of vortices is played by aperiodic electrostatic perturbations of an inhomogeneous plasma with an increase in the electric field inside the plasma cell.

2. INFLUENCE OF FLUXES OF CHARGED PARTICLES AND ATMOSPHERIC POLLUTION ON THE STRENGTHENING OF ATMOSPHERIC VORTICES IN LOW AND HIGH LATITUDES

Polar winter cyclones are called "explosive". The wind speed increases to a storm speed, about 15–20 m/s, in a time of about a few hours. Ice storm in high latitudes lasts about a day. With precipitation, cyclones lose energy. Powerful polar cyclones pass into middle latitudes, amplify at phase transitions of moisture, carry cooling and precipitation to subtropics.

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Changing the transparency of the atmosphere depends on the accumulation of smog of natural and anthropogenic origin. Atmospheric pollution is carried by air masses at a distance of thousands of kilometers. In one-dimensional geometry, the force acting on the aerosol particle in the air stream is given below [26].

$$F_s = j_n S_a p_n = N_n(\mathrm{v}_n - \mathrm{v}_a) S_a m_n (\mathrm{v}_n - \mathrm{v}_a) ,$$

where j_n - is the stream of air particles, atoms and molecules, relative to an aerosol particle, S_a - is the aerosol particle frontal section, p_n - is the impulse transmitted to an aerosol particle from one particle of air, m_n - is the average mass of air particles. From the equation of motion of an aerosol particle $m_a(d\mathrm{v}_a / dt) = F_s$, an estimate of the time τ of the acceleration of the particle in the air flow to the speed **v**:

$$-(\mathrm{v}_n - \mathrm{v}_a)^{-1} |_0^{\mathrm{v}} = \tau N_n S_a m_n / m_a .$$

For $\mathrm{v} \sim 0.5\mathrm{v}_n$ we have $\tau = m_a / (m_n \mathrm{v}_n N_n S_a)$. In estimating the time of capture of a particle with a mass m_a and a frontal section S_a by an air stream, flow swirls when flowing around the particle are not taken into account. The dynamic pressure of the flow on the particle decreases with increasing particle velocity, the rise occurs with a change in acceleration. Under the action of vertical pressure gradients, for example, in the vicinity of a cloudy shade, aerosol impurity is pumped to cloud heights of the order of several kilometers and into the stratosphere. If the lifting force and acceleration when a stream leaks onto a particle exceeds the force of gravity and the acceleration of gravity, the particle rises and is carried by the stream. If the particle shape is lamellar, a lifting force arises when a horizontal air flow flows around the particle. The orthogonal projection of the force F_s to the frontal surface is $F_1 = F_s \sin\alpha$, the lifting force is $F = F_1 \cos\alpha = F_s \sin(2\alpha)/2$. At the angles of attack $\alpha \sim 0,\ \pi/2$, the lifting force of the horizontal flow tends to zero, but aerosol particles can rise in the atmosphere at vertical pressure gradients by vertical air flows. The lifting force is maximum for the angle of attack $\alpha \sim \pi/4$. Flight properties of aerosols depend on their mass, size and shape. An example of well-flying aerosols can be pollen and fine dust generated by friction of transport with the road surface. For $\alpha > \pi/2$, the particle falls. Dust is blown away unevenly by the wind. The process depends on the topography of the underlying surface. Moisture condensation by non-charged aerosols depends on their chemical composition and surface structure. Particles can be hydrophilic and hydrophobic. Ionized particles can be classified as hydrophilic, since the attraction of water molecules is related to their polarization by the electric field (here, Van der Waals forces manifest themselves through the phenomenon of dielectrophoresis [27]).

It is known that precipitations of charged particles into the atmosphere are observed mainly in high latitudes of both hemispheres in auroral ovals - zones-belts surrounding the magnetic poles of the Earth [28]. During the quiet Sun, on the day side, the zone boundary is ~16° from the magnetic pole, on the night side — ~23°. During solar activity, the auroral oval expands. Given the shift of the magnetic poles of the Earth from the geographic poles, the boundary of the zone can reach latitude of 42°. Thus, this zone almost completely covers the areas of predominantly occurring polar cyclones [18] (although complete coincidence is not required, because this is not necessarily a deterministic connection, but only one of the possible trigger mechanisms).

The formation of powerful polar winter cyclones can be associated with the eruption of cosmic rays into the atmosphere in the polar cap of the geomagnetic field. Cosmic ray ionization of an aerosol enhances condensation and crystallization of moisture on an aerosol. The heat generated by moisture phase transitions leads to an increase in pressure gradients in the cellular structure of the aerosol impurity. Plasma vortices are excited. The

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mosaic cellular distribution of the aerosol impurity at high latitudes is formed by the amplification of acoustic-gravity wave packets at wind speed gradients. During the interaction of plasma vortices and Rossby vortices, an increasing cyclonic structure is formed. In the genesis of vortices, aperiodic electrostatic disturbances of an inhomogeneous plasma can play an important role (see below for details). In plasma flows orthogonal to the geomagnetic field, an MHD electric field generator is excited, and the electric field in plasma inhomogeneities is amplified.

The uneven mosaic distribution of smog contributes to the uneven heating of the daytime atmosphere and to the excitation of atmospheric vortexes on the pressure gradients. Uneven heating, ionization and condensation of moisture in aerosol cells over the ocean at low latitudes provoke excitation of the tornado vortex structure. The growth of pressure gradients in the cells of the uneven distribution of aerosols is also associated with condensation and crystallization of moisture. This mechanism plays an important role in the excitation of polar winter cyclones.

Aerosol impurity affects the heating of the atmosphere, is ionized by external sources, condenses moisture, plays an important role in the formation of vortex structures in a gyrotropic medium. Atmospheric gyrotropy is associated with the influence of the Coriolis force on particles and, for charged particles in the geomagnetic field, the influence of the Lorentz force.

As the cyclone approaching the anticyclone from the Atlantic approaches, the jet flow in the area between the cyclone and the anticyclone directed northward increases. Such currents carry aerosols and moisture into high latitudes. The lifetime of Aitken particles in the stratosphere is years – tens of years. Their ionization by cosmic rays enhances the phase transitions of atmospheric moisture on aerosols. At the same time aerosols become heavier. The deposition of aerosol into the troposphere accelerates the processes of excitation of plasma vortices at altitudes of cloud formation.

Oscillations and vortices in the atmosphere are associated with a local excess of kinetic energy and free potential energy in the atmospheric layer. In atmospheric cloudiness, strong electric fields and associated plasma vortices are observed, which affect the genesis of atmospheric vortex structures [29-31]. Winter thunderstorms are recorded in middle and high latitudes.

The most powerful and closest to the Earth external source of heat and ionizing radiation is the Sun [32]. Particles of the atmosphere are ionized by streams of solar photons, as well as photons, protons, ions, electrons and other particles, which are formed with the destruction of the nuclei of atmospheric particles by cosmic rays. The process of ionization of atmospheric components by energetic particles of cosmic rays is cascade, the number of ionizing particles increases many times with the destruction of the atomic nucleus. For the background flux of cosmic rays outside the atmosphere $j_1 \sim 0.1$ cm^{-2} sterad.$^{-1}$ s^{-1}, the flux of secondary particles generated by the destruction of the nuclei of atmospheric particles by cosmic rays, increases by ~10^6 times – they are Auger cascade showers. The rate of ionization of aerosols by cosmic ray particles is $s \sim j_2 \sigma_a N_a \sim 10^{-3} - 10^{-2}$ cm^{-3} s^{-1} at altitudes of cloudiness for particles of Aitken, $\sigma_a \sim 10^{-10}$ см^2, $N_a \sim 10^2$ см$^{-3}$ – are the cross-section and concentration of particles. The ionization rate increases sharply with an increase in the concentration of aerosol particles in the atmosphere, with an increase in ionizing fluxes during solar flares and galactic fluxes. The fluxes of galactic rays are not stationary; they depend on processes in stellar matter and electromagnetic fields. The ionization rate of

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aerosol cloud changes as parameters N_a, σ_a change by several orders of magnitude. The cross section of the aerosol particle is several orders of magnitude greater than the cross section of atoms and molecules and increases with moisture condensation. Estimates show that cosmic rays are an important source of ionization of particles in the atmosphere, even at the background level of the cosmic ray flux and the concentration of Aitken particles. Cosmic ray fluxes depend on the time of day, latitude and longitude, the geomagnetic field affects charged particles [33,34].

The capture of cosmic rays by a magnetic field depends on the "rigidity" s_p, the ratio of the particle momentum to the charge. "Rigidity" is associated with the Larmor radius of a particle $r_B = s_p c / B$, where *B* is the magnetic field strength. The penetration of a particle into a magnetic field depends on the field strength. It is probable that particles enter the atmosphere of the Earth through the polar cap, on geomagnetic field lines stretched into the tail of the magnetosphere when solar plasma fluxes flow into the geomagnetic field. Atmospheric vortex activity at high latitudes during the winter period and such rare phenomena as winter thunderstorms at middle and high latitudes can be associated with a sharp local increase in the rate of ionization of atmospheric pollution by cosmic rays [25].

Intrusion of cosmic rays into the atmosphere is manifested by weak effects of ionization. Ionization increases 4 times relative to ionization at sea level at an altitude of 4800 km, and it increases 10 times at an altitude of 8400 km. The geomagnetic field affects the transfer of plasma cosmic particles in near-Earth space. There is an association of the excitation of atmospheric plasma vortices and their influence on the formation of atmospheric vortex structures of cyclones and anticyclones at high latitudes (including in the polar night conditions) with the excitation of energetic charged particles in the auroral zone and the polar cap [35]. The transfer of humid and warm air masses to high latitudes on pressure gradients with uneven heating of the atmosphere and ocean, mainly by solar photon flux, and the invasion of ionizing cosmic particles into the atmosphere lead to the excitation of plasma vortices [7].

The contribution of cosmic rays to heating is small; the energy fluxes of cosmic rays are several orders of magnitude lower in comparison with the energy fluxes of solar photons. The ionization of aerosol clouds by cosmic ray particles accelerates the processes of moisture condensation. In phase transitions (steam, individual water molecules – water droplets – ice, snow), latent heat is released, infrared radiation when the electronic shells of interacting particles change during the formation of condensates. The impact of cosmic rays (an ionizer of particles) on phase transitions in the atmosphere with a non-uniform spatial distribution of aerosols (aerosol clouds) during the condensation of moisture by aerosols enhances the vortex activity of ionized aerosol impurities [25].

The generation and stability of plasma vortices is influenced by electromagnetic radiation and other factors, for example, acoustic-gravity waves [36-39], the electric and magnetic fields of various sources, including man-made, associated with human activity. With the accumulation of mass by a moving plasma vortex, a state of weakly stable holding by the vortex of the cloud mass in the field of gravity can be achieved. In such a state, even weak external influences on the structure of the plasma vortex can stimulate precipitation and the extinction of the vortex, or vice versa, the strengthening of the vortex [40].

When ionized aerosols move in fields of pressure gradients orthogonal to the geomagnetic field, electric fields and plasma vortex structures are excited in cellular fields of aerosols. There is a transfer of thermal energy of non-uniform heating into a plasma vortex motion in

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crossed fields, an electric field of a vortex and a geomagnetic field. Ions of different mass may be involved in this movement. The equation does not depend on the mass of the ions.

3. Theoretical Analysis of the spatio-temporal evolution of cyclones, anticyclones, Rossby vortices

Theoretical studies of the spatio-temporal evolution of coherent structures (such as cyclones, anticyclones, Rossby vortices, etc.) received a new impetus after the discovery of the analogy between the Hasegawa-Mima equation [41,42] and the barotropic vorticity equation, which is used to describe large-scale vortex flows in the atmosphere and ocean.

In our case, deriving the conservation equation for the plasma vortex in the presence of a frontal temperature jump $(\partial \ln T / \partial y >> \partial \ln T / \partial x)$, we can obtain an equation of the type of the generalized Hasegawa – Mima equation [43]:

$$\frac{\partial}{\partial x}[-\mathrm{v}_{dw} \ln(\Delta\Phi) + \frac{e}{T}\mathrm{v}_{dw}\Phi + \frac{e}{M\Omega_{0i}}\frac{e}{T}\frac{\partial \ln T}{\partial y}\frac{\Phi^2}{2}] + \frac{e}{M\Omega_{0i}}J(\Phi, \ln(\Delta\Phi)) = 0 \,, \qquad (1)$$

where $J(\Phi, \ln(\Delta\Phi)) = \Phi_x(\ln(\Delta\Phi))_y - \Phi_y(\ln(\Delta\Phi))_x$, v_{dw} - is the vortex drift velocity, *M* - is the ion mass, Ω_{0i} - is the ion cyclotron frequency, the axis *Z* is directed along the external magnetic field, Φ - is the electric field potential. The components of the drift velocity along the *X* and *Y* axes are determined by the formulas, respectively: $u = -e\Phi_y / (M\Omega_{0i})$, $\mathrm{v} = e\Phi_x / (M\Omega_{0i})$, where $\Omega' = \mathrm{v}_x - u_y = e(\Phi_{xx} + \Phi_{yy}) / (M\Omega_{0i})$ - is the drift rotor. From equation (1) it follows

$$\frac{\partial}{\partial x}[-\mathrm{v}_D \ln(\Delta\Phi) + \frac{e}{T}\mathrm{v}_D\Phi + \frac{ce}{BT}\frac{\partial \ln T}{\partial y}\frac{\Phi^2}{2}] + \frac{c}{B}J(\Phi, \ln(\Delta\Phi)) = 0 \,. \qquad (2)$$

Changes in the geomagnetic field can lead to disturbances and the breakdown of the plasma vortex. The electric field of the plasma vortex:

$$\mathbf{E} = \ln(N / N_0)(\nabla T) / e + (T / e)\nabla \ln N \,,$$

the rotational velocity of plasma particles in crossed fields:

$$\mathbf{V}_d = [c / (eB^2)]\{\ln(N / N_0)[\nabla T \times \mathbf{B}] + T[\nabla \ln N \times \mathbf{B}]\} \,,$$

the particle concentration, the temperature of the electronic component *T*, and the potential of the electric field are related by the Boltzmann distribution [43]. The energy density of the electric field of the vortex W_1 is $W_1 = (8\pi e^2)^{-1}\{\ln(N / N_0)\nabla T + T\nabla \ln N\}^2$, where the concentration distribution of particles in the plasma vortex structure is given in the form $N = N_0 \exp(e\Phi / T(y))$, *T* - is the electronic component temperature, N_0 - is the particle concentration for $\Phi = 0$.

Plasma instabilities of inhomogeneous plasma provoke the development of nonlinear processes. Different types of instabilities can be observed in inhomogeneous plasma of ionized smog [44]. So, electrostatic oscillations can be excited, for example, on drift gradient plasma instabilities. If the density gradient of particles is directed against gravity $\nabla N \uparrow\downarrow \mathbf{g}$, the cloud of smog is unstable, where *N* is the concentration of particles, **g** is the acceleration of the gravitational field. For this type of instability, the main role is played by heavy particles (ions), the contribution of the light electronic component is small. In ionized cloudiness, impurity instability can be excited if the density gradient of an impurity of heavy cold ions is directed against the density gradient of "hot" background plasma. In layers with a plasma density gradient directed against gravity, it is possible the development of hydrodynamic

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instability with the growth increment of the order $\gamma \sim \sqrt{g \partial \ln(N)/\partial y}$, where $\partial \ln(N)/\partial y$ is the vertical relative gradient of plasma density. Drift instabilities affect polar cyclones as they propagate to low latitudes. In non-uniform magnetized plasma, gravitational-dissipative instability can develop. The development of instability is most likely in low and middle latitudes. Frequency and growth increment of free oscillations are respectively detailed in the equation given below [44]:

$$\omega = \omega_{ni} + g\kappa / \omega_{ni}, \quad \gamma = (\gamma_0 / \omega_{ni})^2 z_i \nu \ ,$$

where *N* – is the concentration of plasma, $\omega_{ni} = k_y \kappa c T_i / e_i B$, $\gamma_0 = \sqrt{g\kappa}$, $\kappa = \partial \ln N / \partial x$, *c* – is the speed of light, $z_i = k_\perp^2 T_i / (m_i \Omega_i^2)$; $(T_i, e_i, m_i, \Omega_i)$ – are accordingly the temperature, charge, mass and ion cyclotron frequency, $(k_\perp, k_y)$ - are the components of the wave vector of perturbations perpendicular to the geomagnetic field and along the axis **y**, $\mathbf{x} \uparrow\downarrow \mathbf{g}$. An orthogonal coordinate system with a **z** axis parallel to an external magnetic field is selected, $\mathbf{z} \| \mathbf{B}$. For the region of the geomagnetic equator, it is assumed that $\mathbf{g} \perp \mathbf{B}$. Below the maximum of the ionospheric layer *F*, where $\nabla N \uparrow\downarrow \mathbf{g}$, the development of the gradient instability of a magnetized ionospheric plasma in a gravitational field leads to the appearance of plasma inhomogeneities and scattering of radio waves. Gravitational-dissipative instability at low and middle latitudes may contribute to the separation of aerosol plasma in atmospheric cloudiness and the excitation of plasma vortices in the inhomogeneous plasma structure.

Using [45], we obtain an analytical solution for the dielectric constant of a nonstationary inhomogeneous plasma. From the Vlasov equation for the electron distribution function

$$\left\{ \frac{\partial}{\partial t} + \mathbf{v}\nabla + \left(\frac{e\mathbf{E}}{m} + [\mathbf{v}\Omega] \right) \nabla_{\mathrm{v}} \right\} f = 0$$

for the case of one-dimensional distribution of particles in velocity, without magnetic field $\Omega = 0$, in linear approximation $f \to f_0 + f$ for electric field disturbances, we have:

$$f = -\int_0^\infty \exp(-\mathrm{v}\tau\nabla)(\frac{e\mathbf{E}}{m}\nabla_{\mathrm{v}} f_0(t-\tau))d\tau \ ,$$

where the retarded potential $\exp(-\mathbf{v}\tau\nabla)$ for cold plasma $f_0(\mathrm{v}) = \delta(\mathrm{v})$ leads only to convergent integrals. We assume that electrostatic perturbations are potential $\mathbf{E} = \nabla\phi$ and proceed to the spectrum in the one-dimensional case $\phi \sim \int \phi_{k,\omega} \exp(ikz - i\omega t) dk d\omega$. Then the dispersion equation of a cold inhomogeneous plasma follows from the Poisson equation $\mathrm{div}\mathbf{E} = 4\pi e \int f d\mathrm{v}$. Let us assign the distribution function of particles nonstationary and non-uniform along the ***z*** axis in the form $f_0 = N_0 \exp(ct) \exp(-z^2/b^2) \delta(\mathrm{v})$ and for *c*<0 we obtain the dispersion equation of electrostatic disturbances of the electronic component of the plasma inhomogeneity in operator form

$$-\int_{-\infty}^{\infty} k^2 e^{ikz - i\omega t} \phi(k,\omega) dk d\omega = -\frac{4\pi e^2}{m} N_0 e^{ct} \int_{-\infty}^{\infty} d\mathrm{v} \int_0^\infty d\tau e^{-c\tau} \exp(-\mathrm{v}\tau\nabla) \int_{-\infty}^{\infty} ik \exp[ikz - i\omega(t-\tau)] \times$$

$$\phi(k,\omega) dk d\omega \int_{-\infty}^{\infty} dk' e^{ik'z} N_0(k') \frac{\partial \delta(\mathrm{v})}{\partial \mathrm{v}} . \qquad (3)$$

For small v we have $\exp(-\mathrm{v}\tau\nabla) \sim 1 - \mathrm{v}\tau\nabla$ and, using the delta function representation as $\delta(x,\alpha) = \frac{\alpha}{\pi^{1/2}} \exp(-x^2\alpha^2)$, $\lim_{\alpha\to\infty} \delta(x,\alpha) = 0, \ x \neq 0$, taking into account the orthogonality of the

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spectral components, we obtain the dispersion equation of electrostatic perturbations from expression (3):

$$\varepsilon = 1 + \omega_p^2 \exp\left(ct - \frac{z^2}{b^2} \right)\left[1 + \frac{2zi}{kb^2} \right] \frac{(c^2 - \omega^2 + 2i\omega c)}{(c^2 + \omega^2)^2} = 0 \, . \qquad (4)$$

Aperiodically increasing electrostatic disturbances manifest themselves in a simple approximation for a cold plasma that is non-uniform along the ***z***-axis with a particle distribution function

$$f_0(z, \mathrm{v}_z) = N_0 \exp(-z^2/b^2)\delta(\mathrm{v}_z) \ ,$$

$$k = \frac{(2zi\omega_p^2/b^2\omega^2)\exp(-z^2/b^2)}{1 - (\omega_p^2/\omega^2)\exp(-z^2/b^2)} \, , \qquad (5)$$

where *k* – is magnitude of the spatial vector of electrostatic disturbances, $\omega_p^2 = 4\pi N_0 e^2/m$ - is the square of the plasma frequency of electrons for the center of inhomogeneity. Provided $1 - (\omega_p^2/\omega^2)\exp(-z^2/b^2) < 0$ at frequencies less than the local plasma frequency, the electric fields increase.

Aperiodic electric fields are excited in plasma inhomogeneities. An electric field component appears, parallel to the power lines of the geomagnetic field, which is important for the formation of lightning channels. The formation of the cellular structure of inhomogeneous plasma is stochastically deterministic. Plasma vortices are excited in plasma with a magnetic field in the cells. The formation of the cellular structure is associated with the electrostatic instability of inhomogeneous plasma, an aperiodic increase of the electric field in the plasma inhomogeneity. In extremums at $\partial k/\partial z = 0$, the growth of aperiodic electric fields is not monotonous. Aperiodic electric fields along geomagnetic field lines enhance the interaction of plasma vortices in a geomagnetic field tube. This leads to an acceleration of the growth of the atmospheric vortex structure during the interaction of plasma vortices with Rossby vortices at the rotor level as the particle velocity vortices. The geomagnetic field affects the localization, excitation and interaction of plasma vortices. In the polar zone, where the inclination of the geomagnetic field lines relative to the horizontal approaches $\pi/2$, a local explosive cyclone is excited. Part of the energy of atmospheric vortex structures is generated by plasma vortices, while the excitation and interaction of plasma vortices depends on the mechanisms of generation of electric fields. A cellular MHD generator and associated plasma vortices are excited on pressure gradients orthogonal to the geomagnetic field. In inhomogeneous plasma along the geomagnetic field, aperiodic electric fields are excited, accelerating the interaction of plasma vortices. Atmospheric vortex structure in aerosol plasma increases. Electromagnetic plasma processes play an important role in the mechanisms of localization, excitation and amplification of atmospheric vortex structures - cyclones, anticyclones, and tornadoes in a double gyrotropy medium. In a polar atmosphere, the cyclone structure acquires an explosive character like a tornado at low latitudes. This is facilitated by the generation of electric fields in geomagnetic power tubes with aerosol plasma.

The formation of mosaic cellular distributions of aerosol impurities at high latitudes is associated with the propagation and amplification of acoustic-gravity wave packets at wind speed gradients. We consider the effect of wind shifts on wave propagation. Let the horizontal directional velocity depend only on the vertical coordinate *z*. In the coordinate system moving with the constant wind speed $U_0(z)$ along the *x* axis, the system of linearized hydrodynamic equations of motion for a material point can be written as

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$$\frac{\partial u}{\partial t} + w\frac{\partial U_0}{\partial z} = -\frac{1}{\rho_0}\frac{\partial p}{\partial x}, \quad \frac{\partial w}{\partial t} = -\frac{1}{\rho_0}\frac{\partial p}{\partial z} - g\frac{\rho}{\rho_0},$$

where u, w - are small perturbations of horizontal and vertical speed, p, ρ - are pressure and density disturbances, ρ_0 - is density, *g* - is acceleration of gravity. The transition to a fixed laboratory coordinate system from a moving system is associated with the Doppler frequency shift $\pm kU_0$ (the sign depends on the directions U_0 and *k*). In the linear approximation, the continuity equation for an incompressible medium when moving in a plane x, z is represented as $\frac{\partial \rho}{\partial t} + w\frac{\partial \rho_0}{\partial z} = 0$. Differentiating with respect to *t* the equation for *w* and the equation of incompressibility $\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0$ and substituting $(w, p) \sim (w(z), p(z))\exp(ikx - i\sigma t)$, $w = W\exp(-c_1 z)$, $c_1 = (\frac{\partial \ln \rho_0}{\partial z} + \frac{k}{\sigma}\frac{\partial U_0}{\partial z})/2$ for the case $\frac{\partial U_0}{\partial z} = const$, we obtain

$$\frac{\partial^2 W}{\partial z^2} + \left\{ -\frac{1}{4}\left(\frac{\partial \ln \rho_0}{\partial z} + \frac{k}{\sigma}\frac{\partial U_0}{\partial z}\right)^2 + \right.$$

$$\left. + \frac{k^2}{\sigma^2}(N^2 - \sigma^2) + \frac{k}{\sigma}\frac{\partial \ln \rho_0}{\partial z}\frac{\partial U_0}{\partial z} \right\} W = 0, \qquad (6)$$

where the sign of the expression in braces $\{\ldots\} = s_1$ determines the type of equation. If $s_1 > 0$, equation (6) is the equation of oscillations, and when $s_1 < 0$ - the equation of damped or increasing perturbations:

$$\partial^2 W / \partial z^2 - a^2 W = 0, \; W = c_2 \exp(\pm az);$$

$$\partial^2 W / \partial z^2 + a^2 W = 0, \; W = c_2 \exp(\pm iaz),$$

where the arbitrary constant c_2 can be determined, for example, from boundary conditions at $z = 0$. The transition to the laboratory coordinate system is made by replacing $\sigma \to \sigma \pm kU_0$. From these equations it can be seen that the wind shear significantly affects the wave disturbance. The relationship of vertical and horizontal movements is determined by the complex ratio of environmental parameters. In the vertical plane, the wave number for the equation of oscillations turns out to depend on the parameters of the inhomogeneous medium, as does the amplitude of oscillations. For $s_1 < 0$ the buoyancy wave fade out, leaving the channel where the horizontal wind speed is constant. Depending on the ratio c_1, s_1, an increase in disturbances at the wind discontinuity is possible. With a decrease in the density of the atmosphere $\partial \rho_0 / \partial z < 0$, the amplitude of the waves can also increase. On the gradients of wind speed, acoustic-gravity wave packets are amplified. The effect of mosaic cellular distributions of atmospheric pollution on the enhancement of vortex structures, jet flows and turbulence is theoretically tracked. In the approximation of a compressible medium, the square of the Brenta-Väisäl frequency is [46]:

$N^2 = -g\left[\frac{\partial \ln \rho_0}{\partial z} + \frac{g}{c_s^2}\right]$, where c_s - is the speed of sound.

The pressure gradients in the cyclonic vortex cell are directed from the center of the cell to the periphery. This is connected with the condensation of moisture, the growth of the optical thickness of the cell (the cloud) and with increasing pressure gradients in the vicinity of the

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cloudy shade. When a moist air mass moves from the periphery of the aerosol cell to its center, water molecules pass into condensate, and latent heat is released. The concentration of water molecules in the formation of condensate gradually decreases, and therefore the rate of formation of condensate decreases from the periphery of the aerosol cell to the center. The effect of aerosol plasma on cell formation of a cyclonic type is clearly manifested in the structure of a tornado. In anticyclonic cells, pressure gradients are directed toward the center. As a consequence, the above considered movement of humid air and the formation of condensate in cells of anticyclonic type does not occur, in contrast to cells of cyclonic type. In the large-scale vortex structure of the anticyclone, local formation of cells of a cyclonic type is possible.

The formation of polar winter cyclones is associated with a mosaic cellular distribution of aerosols. Such spatial distributions of the aerosol impurity can occur when acoustic-gravity waves are amplified at the wind velocity gradients in the jet streams. Jet streams directed to high latitudes are formed at the boundary of the anticyclone and the cyclone approaching it. Anticyclone accumulates pollution. The influence of anthropogenic pollution on the cyclogenesis of the atmosphere is increasing. The influence of cosmic rays on atmospheric processes in the polar cap is intensified, since this region of the geomagnetic field is open for cosmic rays.

Global jet streams circulate around the Earth: two polar, two subtropical and one equatorial [47,48]. The width of the flows horizontally is hundreds of kilometers, vertically - less than 5 km, height - about 11 km. Under the influence of atmospheric vortex structures, jet streams become sinuous. The jet flow directed northward forms in the region of the approach of the Atlantic cyclone and anticyclone. The jet flow transfers pollution and moist cyclonic air into high latitudes, and under its pressure the polar flow acquires a bend. A polar cyclone is likely to be excited in this region. In winter, the excitation of plasma vortices is associated with the invasion of cosmic rays into the polar atmosphere. Whirlwinds are “explosive”, growing rapidly, like tornadoes, but their average life time is about a day. Polar winter cyclones are intensified during phase transitions of moisture. In the polar latitudes of the Russian northern seas, moist air is transferred from the warm Atlantic and in the east from the Pacific Ocean. Seasonal differences were found in the effect of solar activity on individual types of atmospheric circulation (including reliable correlations) [49].

Tornadoes are excited and amplified over the ocean in low latitudes. The moisture from the surface of the ocean evaporates under the influence of the solar photon flux, on pressure gradients it is pumped and condensed on aerosol particles in a tornado. In [50], the effect of cosmic rays on tornado amplification was considered.

Aerosol plasma vortices interact with Rossby waves and vortices. The excitation of Rossby waves and vortices in hydrodynamic flows is associated with large-scale pressure gradients in inhomogeneous heating of the atmosphere (and the ocean) and with the dependence of the Coriolis force on the latitude. The effect of Coriolis force associated with the Earth's rotation on atmospheric movements is estimated by the ratio of inertial force to Coriolis force. The Arctic region of the atmosphere is characterized by maximum Coriolis force due to the Earth's rotation, and the Rossby number for winter polar cyclones is of order Ro ≤ 10 [18,51].

For the vortex structures of the neutral atmosphere, the Obukhov-Charney equation used the approximation of shallow water rotating at a constant speed, with a free surface in the gravitational field and a given bottom relief. In the coordinate system with the *z* axis directed along the local vertical, *x* - to the east, *y* - to the north, the equation describes the preservation of the vortex [51]

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$$\frac{\partial}{\partial t}(\Delta\Psi - L_0^{-2}\Psi) + \{\Psi, \Delta\Psi\} + \beta\frac{\partial\Psi}{\partial x} - \gamma\frac{\partial\Psi}{\partial y} = 0 , \qquad (7)$$

here {…} – Poisson brackets, $\Delta = \partial^2/\partial x^2 + \partial^2/\partial y^2$, $u = -\partial\Psi/\partial y$, $\mathrm{v} = \partial\Psi/\partial x$, $\Psi = gh/f_0$, $\beta = (f_0/H_0)(\partial h_1/\partial y)$, $\gamma = (f_0/H_0)(\partial h_1/\partial x)$, $f = f_0(1 + h_1/H_0)$, $f_1 = 2\Omega_0\sin(\phi)$ - is Coriolis parameter, Ω_0 - is the Earth rotation speed, ϕ - is latitude, $f_0 = f_1(45^\circ)$, $L_0 = \sqrt{gH_0}/f_0$. The function $h_1(x, y, t)$ is set to the relief, the unevenness of the bottom. The parameters β, γ are responsible for the dispersion of large-scale wave processes. The effect of a non-ionized aerosol impurity during condensation of moisture on vortices and Rossby waves could be inscribed in the equation like the effect of bottom relief. The gyrotropy of an aerosol ionized impurity in the geomagnetic field, the excitation of plasma vortices increase atmospheric vortex activity. In equation (7) the effect of the MHD generator is not marked. The interaction of Rossby vortices and plasma vortices occurs at the rotor level as the interaction of particle velocity vortices.

3. CONCLUSION

Under the influence of atmospheric vortex structures, jet streams become sinuous. The jet flow directed northward forms in the region of the approach of the Atlantic cyclone and anticyclone. Anticyclone accumulates pollution. The jet flow transfers pollution and moist cyclonic air into high latitudes, and under its pressure the polar flow acquires a bend. A polar cyclone is likely to be excited in this area.

In winter, the excitation of plasma vortices is associated with the invasion of cosmic rays into the polar atmosphere. The ionization of an aerosol impurity by particles of cosmic rays accelerates the processes of condensation and crystallization of atmospheric moisture. An increase in the concentration of aerosols and cosmic ray fluxes of solar and galactic origin causes a nonlinear in power response of atmospheric processes, increasing the excitation of plasma vortices. Nonlinearity is associated with the cascade nature of the ionization process, with the effect of condensation of moisture and latent heat upon excitation and enhancement of aerosol plasma vortices in the atmosphere.

At low latitudes, powerful atmospheric votrices, tornadoes, are excited over the ocean. In the high-latitude troposphere in the region of the geomagnetic polar cap in the winter period, local cyclonic structures with ice storms, invasions into middle and even subtropical latitudes are excited. The vortices are explosive in nature, growing rapidly. The time of excitation of such cyclones is 15–25 hours, which is comparable with the time of initiation of a tornado. The nature of the vortex is electromagnetohydrodynamic. The accumulation of energy of cyclonic structures is associated with moisture condensation in mosaic cellular distributions of aerosol impurities. When aerosols are ionized by solar photons and cosmic rays, plasma vortices are generated in the cells in the geomagnetic field. During the interaction of plasma vortices and Rossby vortices, a large-scale vortex structure is formed and grows.

The formation of a mosaic cellular distribution of aerosols is associated with the amplification of acoustic-gravity wave packets at wind speed gradients. At low latitudes, excitation of drift instabilities in an aerosol plasma is likely. The formation of the cellular structure is associated with the electrostatic instability of an inhomogeneous plasma, an aperiodic increase of the electric field in the plasma inhomogeneity. In plasma flows orthogonal to the geomagnetic field, an MHD electric field generator is excited, and the electric field in plasma inhomogeneities is amplified. Pollution, aerosol impurities contribute to the excitation and strengthening of atmospheric vortices. The influence of anthropogenic pollution on atmospheric processes is increasing. With the intensification of the vortex structures, the climate contrast, floods, droughts, hurricanes, and the invasion of cold in low latitudes increase.

During attenuation of acoustic-gravity waves on the wind speed gradients, a mosaic cellular structure of the distribution of the aerosol impurity is formed. The excitation of plasma vortices in cells and their electromagnetic interaction accelerates the growth of a large-scale vortex. Plasma vortices at the rotor level interact with Rossby vortices. In the genesis of vortices, aperiodic electrostatic disturbances of an inhomogeneous plasma play an important role.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

AUTHORS' CONTRIBUTIONS

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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