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Dusty plasma processes in Earth's polar summer mesosphere

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Abstract. A self-consistent model for the description of dusty plasma structures, such as noctilucent clouds (NLC) and polar mesosphere summer echoes (PMSE), which are frequently grouped together under the common term polar mesospheric clouds, is presented. The model takes into account the processes of condensation of water vapor, ionization, recombination, action of solar radiation, sedimentation, dust particle growth, dust particle charging, electric fields, etc. Using the model, we explain the basic data of observations on the behavior of charged component in polar summer mesosphere. Furthermore, we show the influence of initial distributions of fine particles as well as that of the processes of condensation and water molecule absorption by fine particles on the formation of NLC and PMSE. We also illustrate the possibility of the formation of layered structure and sharp boundaries of NLC.

An important feature of the summer polar ionosphere is the presence of very thin (compared to the height of the atmosphere) dust layers located at altitudes of 80 to 85 km (noctilucent clouds, or NLC) or about 90 km (polar mesosphere summer echoes, or PMSE). NLC consist of submicron particles. These can be observed by the unaided eye at sunset, whereas PMSE (which likely consist of charged nanometer-scale particles) are not observed optically but are manifested as strong radio reflections on radars operating at frequencies of 50 to 1000 MHz.

In the literature, NLC and PMSE are often united under the term of polar mesospheric clouds (PMC). An interest in the description of the dusty structure in the ionosphere increased strongly in the 2000s (Klumov et al. 2000, 2005; Dubinskii and Popel 2012) in view of, first, the development of methods for the study of dusty plasmas, and second, their possible connection to climatic changes on the Earth, in particular, global warming.

The formation of NLC and PMSE takes place in the polar atmosphere at mesospheric altitudes (80–100 km) between the end of May and the end of August. During this period, the ambient air temperature there falls below 150 K, and water vapor supersaturates. This leads to conditions favoring the growth of dust grains. The dominant nucleation mechanism appears to be the condensation of water molecules on nanometer-scale particles, which are always present at mesospheric altitudes. The characteristic grain size is of few nanometers, and their concentration is typically 10 cm^{-3} to 1000 cm^{-3}.

Here we perform further development of a theoretical model by Klumov et al. (2005) that provides a self-consistent description of NLC and PMSE. The model describes, in particular, sedimentation of dust grains in the middle atmosphere, their growth in a supersaturated water vapor, and microparticle charging processes, allowing for variations of the ion-subsystem composition in the polar mesosphere and photoelectric emission. In this paper we pay attention to condensation processes in addition to the processes taken into account by Klumov et al. (2005). The effect of charges of particles on condensation processes is also taken into account. Using the modified model we illustrate the effect of the initial distributions of dust particles, as well as the condensation and absorption of water molecules by dust particles, on the formation of NLC and PMSE. We also demonstrate the formation of a complex layered structure of NLC.

We use the following equations. A kinetic equation for the dust particle velocity distribution function $f_d(h, a, v, t)$ at an altitude h is (cf. Klumov et al. 2005)

$$\frac{\partial f_d}{\partial t} + \frac{\alpha_w m_\mathrm{w} v_\mathrm{w}^{th}\left(n_\mathrm{w} - n_\mathrm{w}^s\right)}{4\rho_d}\frac{\partial f_d}{\partial a} + v\frac{\partial f_d}{\partial h} + \left(g - \frac{\pi\rho c_s a^2 F_d(v + v_\mathrm{wind})}{m_d}\right)\frac{\partial f_d}{\partial v} = 0. \qquad (1)$$

In (1), the second and fourth terms describe, respectively, dust particle growth in the ambient supersaturated water vapor and either sedimentation or rise of dust grains subject to neutral drag. Here a is the characteristic dust particle size, m_d is the dust particle mass, m_w is the water molecule mass, α_w is the accommodation coefficient for water molecules colliding with a dust grain (normally, $\alpha_w \sim 1$), v_w^{th} is the thermal speed of water molecules, c_s is the local acoustic speed, ρ and ρ_d denote the densities of the ambient air and grain material, n_w^s and n_w are the number densities of saturated water vapor over the dust particle surface and water vapor in the mesosphere,

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v_{wind} and v are the upward components of the wind and dust particle velocity, respectively, the factor F_d (of the order of unity) reflects the effect of grain geometry, and g is the gravity of Earth.

An equation relating the pressure P_S of saturated water vapor over the dust particle with the size a and the surface charge q_d to the pressure P_0 of saturated water vapor over the planar surface is (cf. Dubinskii & Popel 2012)

$$v_d\left(P_S - \frac{N_A \mu_D q_d}{\mu_g a^2 v_d} L\left(\frac{\mu_D q_d}{T a^2}\right) - P_0\right) - \frac{N_A T}{\mu_g}$$

$$\times \ln\left\{\frac{P_S}{P_0}\right\} + \frac{2\sigma v_d}{a} + \frac{q_d^2 v_d}{8\pi a^4}\left(\frac{1}{\varepsilon} - 1 + \nu(\lambda, a)\right) = 0, \quad (2)$$

where

$$\nu(\lambda, a) = \int_a^\infty \frac{a^2(\lambda + r)^2}{r^2} \cdot \frac{2a \exp\{2(a - r)/\lambda\}}{\lambda(\lambda + a)^3} dr, \quad (3)$$

λ is the characteristic screening length of Yukawa potential characterizing the electric field of a dust particle, ε is the dielectric function of the grain material, v_d is the specific volume of the dust particle, N_A is the Avogadro number, μ_D is the dipole moment of water molecule, μ_g is the molar mass of water vapor, T is the temperature, $L(x)$ is the Langevin function, and σ is the surface tension coefficient. Solution of (2) allows us to determine the number density n_{w}^s (included in (1) by means of the relationship $n_{\mathrm{w}}^s = P_S/T$). Equation (2) has been derived (cf. Lapshin et al. 2002) using the thermodynamic potential Ω (Landau and Lifshitz 1980) of the system consisting of the charged dust particle, on the surface of which polar molecules (water) are condensed; a gaseous layer of indicated molecules; surface tension on the dust particle; and electric fields inside and outside the dust particle. The assumption has been used that the electric field outside the dust particle is characterized by the Yukawa potential. Correspondingly, the term containing the Langevin function appears in (2) because of polar character of water molecules; the last term on the left-hand side of (2) is related to the dust particle electric field, an appearance of the term $\nu(\lambda, a)$ (see (3)) being caused by the Yukawa potential characterizing the dust particle electric field.

Equation describing the dynamics of water vapor is

$$\frac{\partial n_w}{\partial t} + \frac{\partial \Gamma_w}{\partial h} = -P_w - n_w L_w - \pi \alpha_w v_w^{th} n_w \left\langle a^2 n_d \right\rangle, \quad (4)$$

where Γ_w is the vertical diffusion flux of water vapor (Murray and Plane 2005), P_w, L_w are photochemistry sources and sinks of water vapor in the mesosphere, respectively, the last term on the right-hand side of (4) describes the absorption of water molecules by dust particles. The rest of equations of the model which describe the plasma properties of the polar atmosphere at mesospheric altitudes are given in Klumov et al. (2005).

We have used two profiles shown in Fig. 6 of Amyx et al. (2008) as initial profiles of height distribution of dust particles. One of them represents the distribution of dust particles of relatively small number density at the altitudes of 90–95 km. Another corresponds to relatively thin dust layer of sufficiently high number density ($n_d = 100 - 1000\,\mathrm{cm}^{-3}$) at the altitudes of 85–87 km.

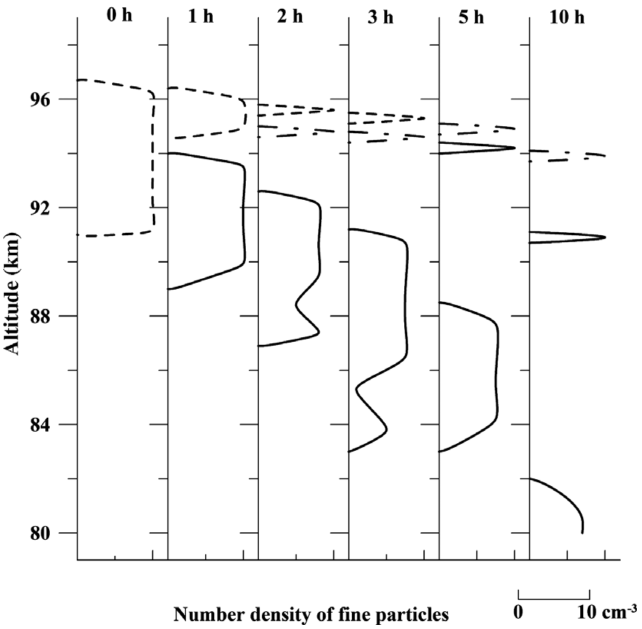

Figure 1. Evolution of the initial trapeziform profile of dust particle number density $n_d = 10\,\mathrm{cm}^{-3}$ vs. altitude for different moments of time ($t = 0, 1, 2, 3, 5, 10$ h). Dashed, dash-dot, and solid curves denote the profiles of number density for the particles with the sizes smaller than 20 nm, between 25 nm and 75 nm, and more than 80 nm, respectively.

In calculations, the first distribution is approximated by trapeziform profile so that one considers the initial number density of dust particles equal to $n_d = 10\,\mathrm{cm}^{-3}$ at the altitudes between 91 km and 96 km, and the initial radii of the particles are equal to 10 nm. Evolution of such an initial profile is given in Fig. 1. The particles being initially higher than 94 km grow rather slowly, therefore they levitate at the altitudes of 90 to 95 km for several hours. The reason for such a behavior is that the layers existing below 94 km are initially in the condensation zone, i.e. in the zone where water vapor is supersaturated. They gather (on their surfaces) the main part of water vapor and sediment downward together with the absorbed water molecules. Those particles which are initially higher than 94 km (even when reaching the condensation zone in some time) cannot grow significantly because of only small amount of residual water molecules in this zone. These small size particles exist at the altitudes of 90–93 km for hours, which explains the PMSE phenomenon.

The formation of the layered structure of NLC is illustrated (Fig. 2) by the evolution of the observed initial bell-shaped dust particle distribution of Amyx et al. (2008). The lower part of the bell-shaped distribution, which passes first through the layer of water vapor sediments, acquires some speed, and gather almost all

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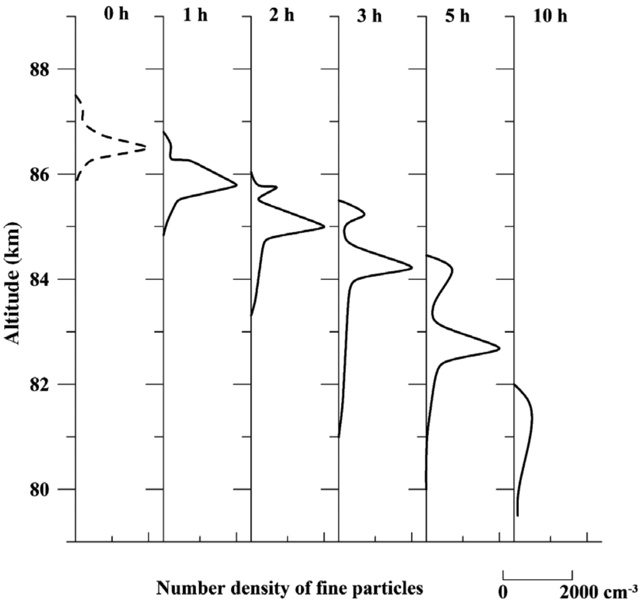

Figure 2. Evolution of the initial (Amyx et al. 2008) bell-shaped dust particle height distribution for different moments of time ($t = 0, 1, 2, 3, 5, 10$ h).

water molecules. As a result, the second (upper) part of the distribution moves slower and finally the second hump appears on the total distribution.

Thus, we have described briefly a self-consistent model of dusty plasma structures such as NLC and PMSE. Calculations based on the model illustrate the influence of initial dust distributions on the formation of NLC and PMSE, show why two types of dusty structures, namely NLC and PMSE, are formed, and justify the possibility of the formation of layered structure and sharp boundaries of NLC.

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