GRAVITATIONAL SEDIMENTATION DUE TO ADVECTION OF COARSELY DISPERSED AEROSOLS IN THE ATMOSPHERE NEAR THE UNDERLYING SURFACE

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A technique is described to simulate numerically the redistribution of the coarsely dispersed aerosols over the size spectrum due to their advection by eddy flux over the uniform and nonuniform underlying surfaces. Some model estimates of the spatial modification of the aerosol size spectrum produced by gravitational sedimentation are presented.

Light scattering by atmospheric haze in the IR range of wavelengths depends essentially on both dielectric properties and relative content of the coarsely dispersed fraction as well as on the extension of the spectrum to the large particle radii. The last fact is known to be determined by the removal effeciency of aerosols from the underlying surface and by the peculiarity of their eddy mixing.

Preserving the conceptual basis of the previous model estimates[1-3] we will determine the modification in the dispersed structure of atmospheric aerosols by the reduced description of the particle size spectrum in terms of integral parameters of the lognormal distribution. In this connection, in the description of advection of coarsely dispersed aerosols over the nonuniform surface in addition to the diffusion equation for the particle number density N_i we can also apply the analogous equations for the following integral parameters: S_i and V_i. In general, this system of equations with the use of the generalized parameter vector $\hat{Q}_i$ can be represented in the form

$$U(z)\frac{\partial \hat{Q}_i(x,z)}{\partial x} = \frac{\partial}{\partial z} D(z)\frac{\partial \hat{Q}_i(x,z)}{\partial z} - W_i(R_i)\frac{\partial \hat{Q}_i(x,z)}{\partial z}, \quad (1)$$

where the parameter vector $\hat{Q}_i(x, y)$ is taken to mean either the cumulative volumes V_i or cross sections S_i or number densities N_i of the individual fractions of aerosols at some point with the coordinates x and z, W_i is the average velocity of the Stokes sedimentation of particles in the ith fraction which is estimated for each equation in terms of the modal radius of the density function of the spectral distributions of the corresponding integral parameters. The X axis is collinear to the direction of the mean wind velocity.

Vertical profiles of the horizontal velocity of the air flow $U(z)$ and the coefficient of the eddy exchange $D(z)$ in the surface layer are assumed to be linearly dependent of altitude:

$$U(z) = U_0 z \; ; \; D(z) = D_0 z \; . \quad (2)$$

The solution of Eq. (1) with the following boundary conditions:

a) the vertical profiles of the integral parameters in the inflowing eddy flux

$$\hat{Q}_i(x,z)\Big|_{x=0} = \hat{Q}_{i0}\exp(-\beta z^2)\;, \quad (3)$$

b) the horizontal distribution of the integral parameters over the underlying surface

$$\hat{Q}_i(x,z)\Big|_{z=0} = \hat{Q}_{i1}(x)\;, \qquad \text{and} \quad (4)$$

c) at high altitudes as $z \to \infty$

$$\hat{Q}_i(x,z) = 0\;, \quad (5)$$

has the form[3,4]

$$\hat{Q}_i(x,z) = \hat{Q}_{i0}\zeta^{1-p}\exp(-\beta\zeta z^2)\,\{1 - \Gamma(p, \zeta^2 z^2)\} +$$

$$+\frac{\alpha^p}{\Gamma(p)}\left(\frac{z}{2}\right)^{2p}\int\limits_0^x \frac{\hat{Q}_{i1}(\xi)}{(x-\xi)^{1+p}}\exp\left[-\frac{\alpha z^2}{4(x-\xi)}\right]d\xi\;, \quad (6)$$

where $\alpha = U_0/D_0$, $p = W_{Q_i}/2D_0$, $\zeta = \alpha/(\alpha + 4\beta x)$, and $\Gamma(p,\chi) = \frac{1}{\Gamma(p)}\int\limits_\chi^\infty \exp(-\xi)\,\xi^{1-p}\,d\xi$ is the incomplete gamma function.

If the underlying surface is divided into m uniform sections with the constant integral parameters

$$\hat{Q}_i(x,z) = \sum_{n=1}^{m}\left(\hat{Q}_{i1,\,n} - \hat{Q}_{i1,\,n-1}\right)\sigma(x - x_{n-1})\;, \quad (7)$$

where $\sigma(x - x_i)$ is the unit function given by the formula

$$\sigma(x - x_j) = \begin{cases} 1 \text{ for } x > x_{j-1}, \\ 0 \text{ for } x < x_{j-1},\; x_{1-1} = 0, \text{ and } \hat{Q}_{i1,1-1} = 0, \end{cases} \quad (8)$$

then the second integral in Eq. (1) can be represented in the form[4]

$$\frac{\alpha^p}{\Gamma(p)}\left(\frac{z}{2}\right)^{2p}\int\limits_0^x \frac{\hat{Q}_{i1}(\xi)}{(x-\xi)^{1+p}}\exp\left[-\frac{\alpha z^2}{4(x-\xi)}\right]d\xi =$$

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$$= \sum_{n=1}^{m} (\hat{Q}_{i1,\,n} - \hat{Q}_{i1,\,n-1}) \hat{\Gamma}\left[p, \frac{\hat{z}^2}{4(x - x_{n-1})}\right] \hat{}(x - x_{n-1}) \,. \quad (9)$$

Since the physicochemical composition of soil aerosols (with the specific density $\rho = 2.65$ g/cm^3) has the complicated structure we simulated simultaneously the joint development of three subfractions which then were mixed additively into one principal fraction. The initial integral parameters were chosen in such a way that the modal radii in subfractions were uniformly spaced along the R axis in the interval 1–10 μm. Thus by modifying the relative weight fraction, characteristic size and width of the spectrum of each subfraction in a numerical experiment we can simulate the processes of eddy mixing of primary aerosols the complicated dispersed composition and different specific density of substance.

In the real numerical estimates boundary conditions (3)–(5) for the size spectrum of aerosols were indirectly determined by the background values of integral parameters. In particularly, for the background content of the coarsely dispersed fraction the generalized parameter vector of the size spectrum $\hat{Q}_{bg}\{N_{\rm bg}, S_{\rm bg}, V_{\rm bg}\}$ was calculated according to the data of Ref. 5 as the additive mixture of the integral parameters $N_{i\rm bg}$, $S_{i\rm bg}$, and $V_{i\rm bg}$ of three subfractions whose sums were equal to the corresponding values given in Ref. 5: $N_{\rm bg} = 0.38$ cm^{-3}; $S_{\rm bg} = 52.0$ μm^2·cm^{-3}; $V_{\rm bg} = 49.0$ μm^3·cm^{-3}. In this case the characteristics of the ground–based source $\hat{Q}_{i1}(x)$ in terms of $\hat{Q}_{i\rm bg}(x)$ were estimated as the product

$$\hat{Q}_{i1}(x) = q_1 g(x)\, \hat{Q}_{ibg} \,. \quad (10)$$

The size spectrum of advected particles was determined in the same way

$$\hat{Q}_{i0}(x) = q_0 \hat{Q}_{ibg} \exp(-\beta\, z^2) \,. \quad (11)$$

The effect of the advective component on the formation of the spatial structure of the coarsely dispersed aerosols depends not only on the values of the parameters q_0 and β in Eq. (11), but also on the velocity of wind U_0.

According to Budyko[6] the coefficient of the eddy exchange $D(z)$ in the surface layer can be related to the mean velocity of wind

$$D(z) = D_0 \frac{z}{z_1} \sqrt{(1 - {\rm Ri})} \,, \quad (12)$$

where Ri is the Richardson number averaged over the layer; D_0 is the eddy exchange coefficient at the altitude z_1 under the equilibrium conditions

$$D_0 = \kappa^2 U_1 / {\rm Ln}(z_1/z_0) \,, \quad (13)$$

where κ is the Karman constant, U_1 is the average velocity of the air flow at the altitude z_1, and z_0 is the parameter of surface roughness.

The polydisperse character of aerosols is the fundamental point in this approach. In comparison with the monodisperse system the maxima in the distribution of the particle number density and in the distribution of particles over their volumes are noticeably spaced along the R axis for polydispersed aerosols. Therefore, in the process of diffusion in the system the additional exchange is accelerated between the cells of the aerosol field, i.e., larger and heavier particles sedimentate faster then the smaller and lighter that on large spatial scales of advection results virtually in the exchange between the structural elements of the size spectrum, i.e., subfractions. For this reason, as calculations show, the typical zones of the spatial spectral distribution of the coarse fraction can appear due to advection.

Under conditions of convective instability in the surface layer these formations as a part of large–scale eddies are carried out of the limits of the friction layer. And in the case of low hygroscopicity of particles they create premises for the formation of the anomalies of the enhanced content of coarsely dispersed aerosols at altitudes of from 1.5 km and higher, i.e., for the so–called noncondensation clouds.[7]

Figures 1–6 show the results of our numerical simulation of the horizontal variation of the parameters of the distribution of coarsely dispersed aerosols calculated starting from the integral parameters $\hat{Q}_i(x, z)$ of model (1)–(13) according to the technique described in Ref. 3.

The initial vertical distribution of the integral parameters of the dispersed structure in the inflowing eddy flux is the important factor which determines the peculiarity of the process under consideration.

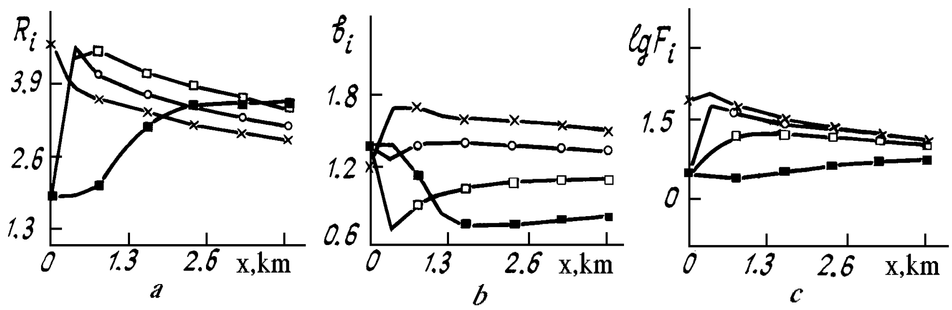

FIG. 1. Horizontal variations of the parameters of the distribution of the coarsely dispersed aerosols due to their advection over the uniform surface for $\beta = 0.1$ m^{-2}, $U_0 = 0.18$ m/s, $D_0 = 0.005$ m^2/s, *and* $W_{\rm d} = 0.0$ m/s: *a) modal radius* R_i, *b) parameter of dispersity* b_i, *and c) parameter* F_i *(see Ref. 3). Curves related to altitudes* $z = 1.0$, 4.0, 13.6, *and* 50.0 m *are marked by* ×, ○, □ *and* ■ *respectively.*

When a flux of advected aerosols becomes more uniform (β decreases from 0.1 to 0.01 m^{-2}) the number of the weighted particles (Figs. 1*c* and 2*c*) and their characteristic radii (Figs. 1*a* and 2*a*) also increase. However, the width of the particle size spectrum gets noticeably narrower at the altitudes $z < 10$ m (Figs. 1*b* and 2*b*). In the first case b_i varies within the interval 0.8–1.35, whereas in the second case it varies approximately from 1.5 to 2.4.

It can be natural to assume that eddy mixing is no less important factor that govern the size spectrum of the coarsely dispersed aerosols. When the intensity of eddy mixing D_0 increases from 0.005 to 0.06 m^2/s the particle size spectrum, first, broadens (Figs. 1*b* and 3*b*), second the maximum of the particle distribution over their volumes shifts toward the small radii (Figs. 1*a* and 3*a*), and, third, the total number of particles decreases virtually at all altitudes (Figs. 1*c* and 3*c*).

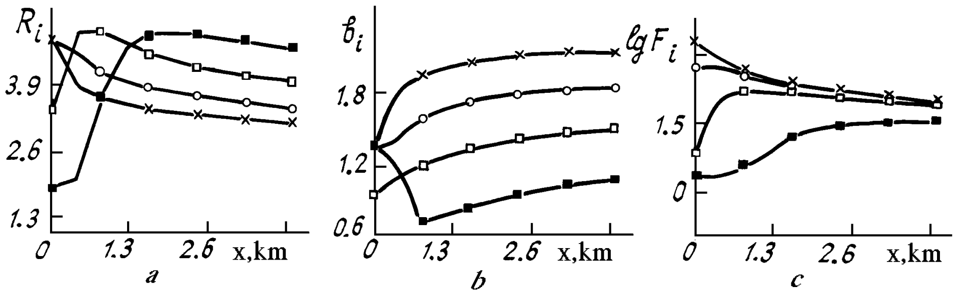

FIG. 2. The same as in Fig. 1 but for $\beta = 0.01\ m^{-2}$, $U_0 = 0.18$ m/s, $D_0 = 0.005\ m^2/s$, *and* $W_d = 0.0$ m/s. *Designations for a, b, and c are the same as in Fig. 1.*

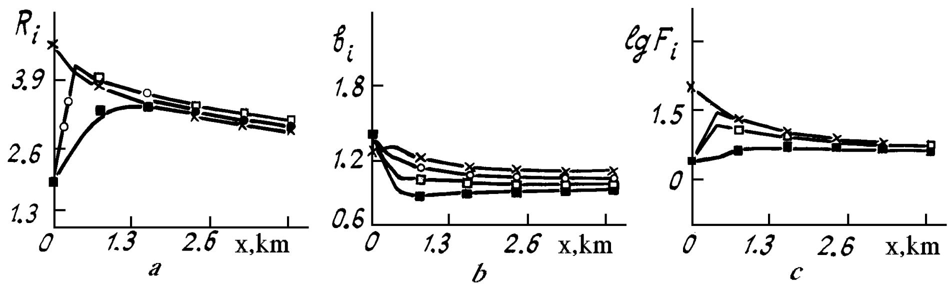

FIG. 3. The same as in Fig. 1 but for $\beta = 0.1\ m^{-2}$, $U_0 = 0.18$ m/s, $D_0 = 0.06\ m^2/s$, and $W_d = 0.0$ m/s. *Designations for a, b, and c are the same as in Fig. 1.*

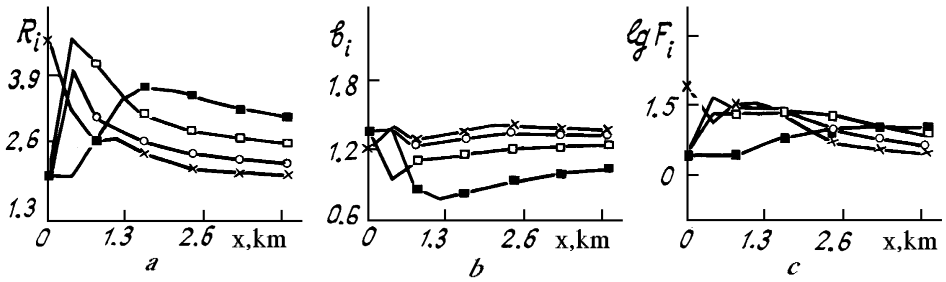

FIG. 4. The same as in Fig. 1 but for $\beta = 0.1\ m^{-2}$, $U_0 = 0.18$ m/s, $D_0 = 0.005\ m^2/s$, and $W_d = 0.045$ m/s. *Designations for a, b, and c are the same as in Fig. 1.*

In the case of low intensive eddy mixing the size spectrum of the coarsely dispersed aerosols steadily gets narrower and its maximum shifts toward the small radii as we approach a nonreflective surface.

The increase of the constant component of the particle sedimentation rate W_d from 0.0 to 4.5 cm/s (Figs. 1*a* and 4*a*), especially at distances $x \sim 1.3$ km and more results in the more sharp decrease in the particle size in the surface layer at $z < 10$ m and in the broadening of the spectrum at altitudes higher than 10 m. The constant (over size spectrum) component of the sedimentation rate is considered either as a possible increase in a hypothetical rate of particle dry sedimentation on the roughness of the underlying surface, or as a result of an air mass descent in the region of an anticyclon.

The countors of the spatial variation of the parameters of the particle size spectrum over the uniform and nonuniform underlying surfaces are shown in Figs. 5 and 6. In the first case the falling out particles are completely absorbed by the underlying surface (for instance, in the case of water surface) $\hat{Q}_i(x)|_{z=0} = 0$, and, in the second case the values of the parameter vector of size spectrum (4) obey lognormal distribution along the X axis. The calculations show that the spatial structure of the distribution of coarsely dispersed aerosols with the inhomogeneous boundary conditions is substantially modified over the region of nonuniformity (4) up to altitudes of 10–15 km.

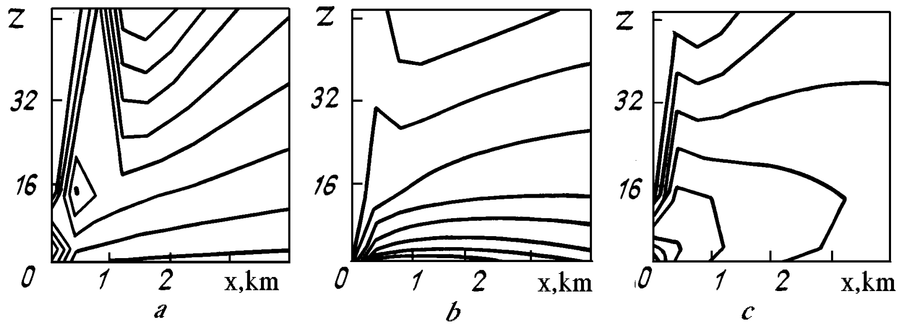

FIG. 5. Contours of the spartial variations of the parameters of the dispersed structure over the uniform underlying surface. Parameters of the process and designations for a, b, and c are the same as in Fig. 1.

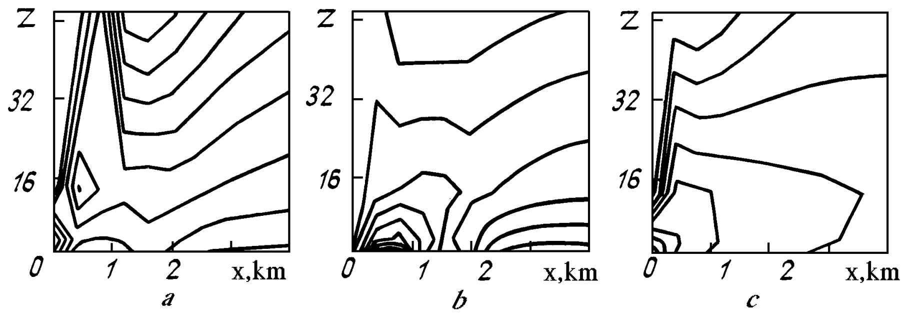

FIG. 6. Contours of the spartial variations of the parameters of the dispersed structure over the nonuniform underlying surface. Parameters of the process and designations for a, b, and c are the same as in Fig. 1.

In conclusion it should be acknowledged that some of the above–indicated regularities can be predicted, since their corresponding model estimates are intended to reveal effects of the individual variations of the input parameters of the model. It is already obvious, however, from these preliminary estimates that the spatial structure of aerosols depends substantially on both the vertical distribution of the parameters of the size spectrum of advected aerosols and the average velocity of wind and the intensity of mixing.

For the integral model concept of the process the interrelation of the parameters of the model under real geographic conditions should be taken into account.

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