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## Abstract

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# ON THE DETERMINATION OF THE COEFFICIENTS OF VERTICAL MIXING OF PARTICLES IN THE FREE ATMOSPHERE

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By the present time a large body of material has been accumulated on the vertical distribution of the concentration of Aitken condensation nuclei (with radius $r < 0.1\ \mu$) and of large particles ($0.1\ \mu < r < 1\ \mu$). Most of the data ([1]) indicate an exponential decrease with height in the concentration of aerosol particles in the free atmosphere in the layer up to 4 km. A theoretical consideration based on Fick' s equation of turbulent diffusion also leads to the exponential law (1) for the decrease of the concentration of aerosol particles with height under a stationary state of the atmosphere, $dN/dt = 0$,

$$N_z = N_0 e^{-wz/k}, \tag{1}$$

where $N_z$ is the concentration of particles having mean Stokes settling velocity $w$ at the level $z$, and $k$ is the coefficient of turbulent mixing in the atmosphere. From formula (1) it follows that the concentrations of particles with a greater velocity $w_2$ must decrease with height more rapidly than the concentration of particles having the smaller $w_1$. Measurements carried out by I. I. Gaivoronskii ([2]) and others showed that the concentration of Aitken condensation nuclei in the atmosphere decreases in the same way as the concentration of particles of the order of 1 $\mu$ in size. These results are in contradiction with the conclusions drawn on the basis of formula (1).

To clarify this question, measurements were made from an Il-14 aircraft of the concentration of large particles (whose effective optical radius was $r_{\text{eff}} = 0.1\ \mu$) and giant particles ($10\ \mu > r > 3\ \mu$) by the methods described in works ([3,4]). Measurements were carried out at heights of 100; 200; 300; 500; 750; 1000 m and then every 500 m up to 3000 m.

Characteristic data on the decrease with height of the concentrations of three particle fractions, obtained in summer over land, are given in Fig. 1. On the basis of the data presented in Fig. 1, by formula (1) the values were found: $k_1 = 8 \cdot 10^2$ cm$^2$/sec, calculated from the decrease with height in the layer from 200 to 1000 m of the concentration of large particles ($r_{\text{eff}} \simeq 0.1\ \mu$), and

$k_2 = 3.2 \cdot 10^5$ cm$^2$/sec from the change in the concentration of particles of size $r \simeq 5$ $\mu$ in the same layer. If the value $k_2$ agrees in order of magnitude with the coefficients of turbulent mixing $k_{\mathrm{tv}}$, calculated from temperature-wind soundings of the atmosphere by the formulas of D. L. Laikhtman ($^{5,6}$), then the value $k_1$, calculated by formula (1), proves to be 3 orders of magnitude smaller than $k_2$, which contradicts the physical meaning of this quantity. It follows from this that formula (1) is unsuitable for describing the height distribution of large particles and, still more, of Aitken condensation nuclei. Formula (1) is derived from the assumption that the principal mechanism of the lowering of particles in the atmosphere is their settling under the action of gravity. This assertion is apparently true for giant particles, but is not valid with respect to large particles and Aitken nuclei.

It may be assumed that one of the possible reasons for the rapid decrease with height of the concentration of large particles in clear anticyclonic weather (under which conditions most of our measurements were carried out) is the descending motion of air masses in the anticyclone with velocity $c$. Under this assumption, the change with height in the concentration of particles of a definite size can be written in the form

$$N_z = N_0 e^{-\left(\frac{w+c}{k_a}\right)z}, \tag{2}$$

where $k_a$ is the new coefficient of turbulent mixing of aerosol particles in the free atmosphere.

Knowing the simultaneously obtained height distributions of the concentrations of two fractions of particles of different sizes, one can, on the basis of formula (2), find $c$, eliminating $k_a$, whose value does not depend on particle size, at least in the range 0.1—10 $\mu$. The mean value of $c$, calculated from a large number of measurements of the decrease with height in the concentration of both large and giant particles, proved to be $1.0 \pm 0.6$ cm/sec. Having the value of $c$, the coefficients of turbulent mixing of particles $k_a$ can be determined from formula (2) from the measured change with height in the concentration of only one particle fraction. The coefficients $k_a$ found by this method from the data presented in papers (1, 2) agree in order of magnitude with the data $k$ (5, 6) obtained by the method of D. L. Laikhtman. The coefficient $k_a$ can be determined independently of the parameter $c$ introduced by us; for this it is necessary to know the height distribution of the concentrations of two particle fractions $(N_1, N_2)$, then

$$k_a = \frac{0.43\,(w_2 - w_1)\,z}{\log \frac{N_{(1)z}}{N_{(1)0}} - \log \frac{N_{(2)z}}{N_{(2)0}}}. \tag{3}$$

**Fig. 1.** Change in the concentration of aerosol particles of different size with height in summer, over land, in the daytime. Sounding: Krasnoyarsk, 3 VII 1958, 14 hr. 30 min.—17 hr. 20 min.
1—$N_{r>0.1\mu}$; 2—$N_{r>5\mu}$; 3—$N_{r>8\mu}$.

Figure 1. Change in the concentration of aerosol particles of different size with height in summer, over land, in the daytime. Zondazh: Krasnoyarsk, 3 VII 1958, 14 hr. 30 min.–17 hr. 20 min. 1–$N_{r>0.1\mu}$; 2–$N_{r>5\mu}$; 3–$N_{r>8\mu}$.

Figure 1: Figure 1. Change in the concentration of aerosol particles of different size with height in summer, over land, in the daytime. Zondazh: Krasnoyarsk, 3 VII 1958, 14 hr. 30 min.–17 hr. 20 min. 1–$N_{r>0.1\mu}$; 2–$N_{r>5\mu}$; 3–$N_{r>8\mu}$.

Fig. 2

Figure 2: Fig. 2

From simultaneously measured decreases with height in the concentrations of three particle fractions $N_1, N_2, N_3$, six values of $k_a$ were found in each layer $\Delta z$: three by formula (2), taking $c = 1.0$ cm/sec into account, and three by formula (3). All six values differ from one another by no more than ±60%, i.e., they coincide in magnitude within the accuracy of the errors of their determination.

On the basis of the fact that the values of the parameter $c$, found from the decrease in concentration of both large and giant particles, proved to be the same, and that the values of $k_a$ found by formulas (2) and (3) coincide in magnitude with the coefficients $k$ found by the formulas of D. L. Laikhtman, it may be considered that formula (2) correctly describes the height distribution of the concentration of both large and giant particles in the free atmosphere.

Formula (2) passes into formula (1) for particles whose Stokes settling velocity $w \gg c$. For particles with $w \ll c$, formula (2) gives a change of concentration with height that does not depend on particle size.

To obtain the dependence of $k_a$ on $z$, in each layer $\Delta z$ taken between the heights at which the aerosol-particle concentrations were measured, mean values of $k_a$ were determined from the six values calculated by formulas (2) and (3).

The variation of $k_a$ with height in clear anticyclonic weather during the daytime in summer is shown in Fig. 2A over land and over the sea in Fig. 2B. During the daytime in summer over land, in the layer from 100 m to 1-2 km, intensive mixing of particles is observed, caused by strongly developed convection; in this case the value of $k_a$ reaches maximum values equal to $(5\text{-}20) \cdot 10^5$ cm$^2$/s. Above this layer the value of the coefficient $k_a$ sharply

**Fig. 2.** Dependence of the coefficient of turbulent mixing of particles on height.
**A** –in summer, during the daytime over land; sounding at Barabinsk, 23 VII 1958, 10:00–14:00.
**B** –in summer, during the daytime over the sea; sounding east of Sakhalin Island, 16 VII 1958, 12:10–15:00, sea (50 km from the shore)

decreases to $(1\text{-}2) \cdot 10^5$ cm$^2$/s. Over the sea during the daytime in summer, convection usually does not arise, and therefore a smooth increase in the value of

$k_a$ is observed in the layer from 100 to 3000 m. Above 2000–3000 m the values of $k_a$ over the sea and over land, as a rule, coincide, amounting to (1–5)$\cdot 10^5$ cm$^2$/s.

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*Note: Figure translations are in progress. See original paper for figures.*