Description of the submicron aerosol vertical profile in the lower troposphere by the three-layer representation

M.V. Panchenko and S.A. Terpugova

Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

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It is proposed to use the notion of a three-layer aerosol vertical profile as a first approximation in the lower troposphere: the interval from 0 to H_1 is the ground layer, the interval from H_1 to H_2 is the mixing layer, and above that is the free atmosphere. The ground layer is parametrized relative to baric formations. The height of the mixing layer was calculated on the basis of data on the total degree of heating of the lower layers. The slope of the profile in the mixing layer was estimated from its statistical correlation with the ground-level value of the scattering coefficient and the average temperature of the mixing layer.

The present paper, based on airborne nephelometer data[1,2] in the lower troposphere above Western Siberia, discusses the possibility of a simple parametrization of the vertical profile of the submicron particle content in the lower troposphere. As a parameter associated with the particle concentration we consider the scattering coefficient for zero relative humidity $\sigma_d(H)$.[2]

Earlier studies have shown that the main seasonal trends of the variability of $\sigma_d(H)$ profiles are represented fairly adequately by a three-layer height distribution of the aerosol content.[2,3] Such a representation is depicted schematically in Fig. 1. The following altitude ranges are distinguished: 1) the ground layer with height H_1, in which significant diurnal variations of the aerosol and meteorological parameters are observed; 2) the boundary layer, or mixing layer (according to the definition of K.Ya. Kondrat'ev[4,5] – the zone of active turbulent exchange), in which the height H_2 varies from season to season and the aerosol concentration and aerosol optical characteristics are generally assumed to be constant with height; 3) the layer of free atmosphere. Between the mixing layer and the free atmosphere, as a rule, lies a transitional zone of thickness ~200–400 m.

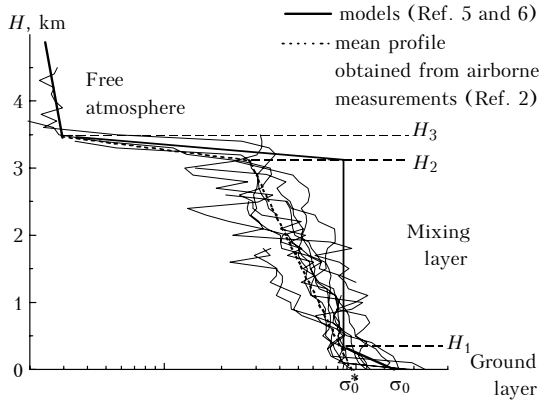

Fig. 1. Representation of the vertical profile of the scattering coefficient as three layers.

We consider the applicability of such an approach to discrete realizations of the aerosol profile for a specific region. All of the available measured profiles were analyzed as to the possibility of representing them as three layers.[7] The points H_1, H_2, and H_3 were determined from a graph of the corresponding profile as the heights at which the rate of falloff of the scattering coefficient of dry aerosol with increasing height undergoes an abrupt change. In each of the layers the profile was approximated by the formula

$$\sigma_d(H) = \sigma_d(H_{0,i}) \exp[-\alpha_i(H - H_{0,i})], \qquad (1)$$

where H is the height, α_i is a parameter defining the slope of the profile in the corresponding layer; and $H_{0,i}$ is the lower boundary of the layer in question.

Table 1 lists the corresponding mean-seasonal values of the heights and the profile slope parameters α_i [see formula (1)].

Table 1. Mean-seasonal values of the parameters of the three-layer approximation of the scattering coefficient profile

	H_1, km	H_2, km	H_3, km	α_1	α_2	α_3	α_4
Winter	0.03	0.28	0.38	0.35	7.5	2.6	0.71
Spring	0.04	1.26	1.58	4.0	0.29	3.0	0.4
Summer	0.06	1.94	2.2	1.9	0.19	5.2	0.44
Autumn	0.08	1.25	1.55	3.1	0.34	4.5	0.34

Figure 2 shows pie charts which show what percent of the realizations of a given data set is satisfactorily described by the three-layer representation. It can be seen from the figure that representing the vertical profile as three layers is most valid in summer; in winter it is applicable only for a limited number of situations. In spring and autumn this representation is realized mainly under stable weather conditions in nearly stagnant air masses, i.e., the three-layer model affords a good description of the aerosol vertical profile for situations in which the process of formation of the profile is sufficiently extended. Under other conditions the profile has a more complicated multilayer structure.

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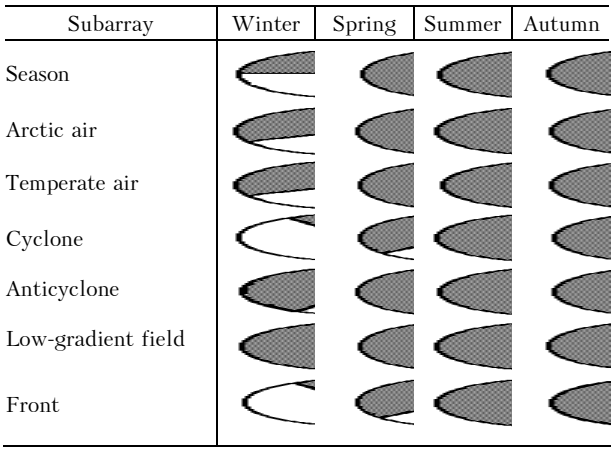

Fig. 2. Applicability of the three-layer model to description of vertical profiles of the scattering coefficient in different synoptic situations.

Let us now consider the parametrization of the aerosol profile in each layer in more detail.

The ground layer of the atmosphere at a height of 100 m is the most variable. The largest variations of both the meteorological parameters and the aerosol particle concentration are seen in it, and the influence of the underlying surface, season, time of day, wind speed and direction, etc. is greatest in it. In existing models[4–6] for the ground layer the aerosol concentration decreases abruptly with height. However, the measurement data show that this is not always the case. The presence of a temperature inversion may serve as a quite reliable criterion of the existence of a ground layer in the vertical aerosol profile, but these data are not always available; therefore, we made an attempt to estimate the parameters of the aerosol profile in the ground layer from synoptic indicators.

Table 2 presents data for different seasons on the percentage of realizations in different air masses and baric formations in which the presence of an aerosol ground layer is observed. A pronounced aerosol ground layer is almost always observed in summer and autumn in arctic air masses while in temperate air masses only in regions of increased pressure. In temperate air masses in autumn and spring the parametrization cannot be realized due to poor statistics of the data.

No significant dependence of the existence of the ground layer on the time of day was observed in our data.

In the mixing layer the aerosol content is often assumed to be constant with height.[5,6] But, as an analysis of a large body of experimental data shows (these data are depicted in Fig. 1 by thin lines) this representation is valid only as a first approximation since under conditions, in which the main aerosol sources are located at ground level, a flat aerosol profile with height would require practically instantaneous mixing.

Different approaches to estimation of the mixing layer height can be found in literature.[5,9–11] However, estimating this height through the activity of turbulent exchange (which from the point of view of the main mechanism is absolutely valid), a number of problems arise since processes of turbulent exchange along the vertical are strongly influenced by the temperature profile and the state of the underlying surface, and also gradual day-to-day heating (or cooling) of the entire lower troposphere. Aerosol processes have much more inertia, and the height H_2 is due to comparatively prolonged mixing of particles along the vertical,[11] taking place over the lifetime of the given air mass.

Table 2. The portion of profiles (%) modeling of which requires to take into account the ground aerosol layer

Spring							
Arctic air – 44				Temperate air – 26			
Cyclone	–	day	37	Cyclone	33	day	14
Anticyclone	25	evening	72	Anticyclone	66	evening	67
Low-gradient field	–	night	33	Low-gradient field	0	night	40
Ridge	50	morning	–	Ridge	–	morning	–
Low-pressure trough	–			Low-pressure trough	–		
Summer							
Arctic air – 75				Temperate air – 50			
Cyclone	85	day	67	Cyclone	25	day	46
Anticyclone	75	evening	50	Anticyclone	100	evening	50
Low-gradient field	100	night	92	Low-gradient field	100	night	52
Ridge	100	morning	100	Ridge	67	morning	–
Low-pressure trough	–			Low-pressure trough	33		
Autumn							
Arctic air – 63				Temperate air – 57			
Cyclone	60	day	57	Cyclone	40	day	50
Anticyclone	63	evening	50	Anticyclone	67	evening	52
Low-gradient field	50	night	77	Low-gradient field	–	night	67
Ridge	–	morning	–	Ridge	80	morning	–
Low-pressure trough	34			Low-pressure trough	–		

For a definite height of the mixing layer for each profile we calculated the mean temperature $\overline{T}_i$ of layers of different height. Figure 3 shows two scatter plots of the height of the mixing layer and the mean temperature of the layer from 0 to 3 km. It is evident from the figure that the relation between H_2 and $\overline{T}_3$ is nonlinear, and when the data are replotted on a logarithmic scale in height it becomes linear. Table 3 lists the correlation coefficients between the mixing layer height and the mean temperature of layers of different height.

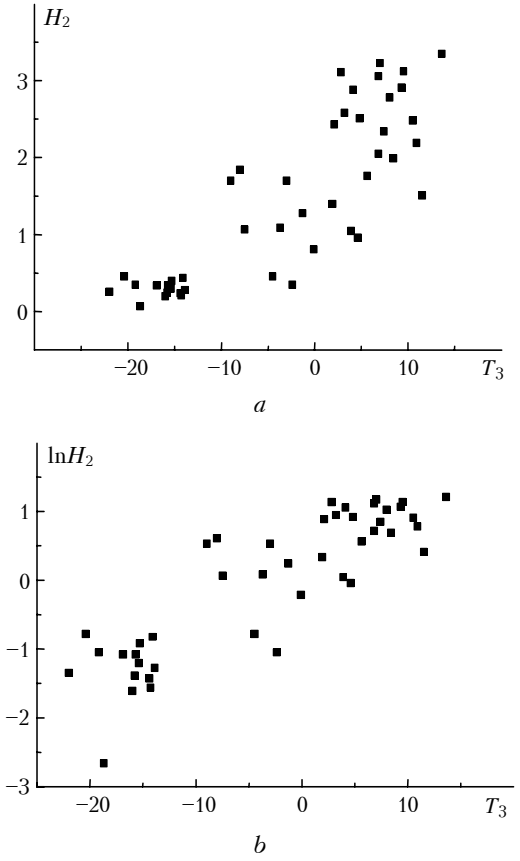

Fig. 3. Scatter plots of the height of the mixing layer and the mean temperature of the 0–3 km layer: (*a*) linear scale in height; (*b*) logarithmic scale.

From this we conclude that the relation between the height of the mixing layer H_2 and the temperature $\overline{T}_i$ is adequately expressed in the form

$$\ln(H_2) = A_i\,\overline{T}_i + B_i. \qquad (2)$$

Figure 4 plots the dependence of the coefficients A and B on the height of the layer, over which the temperature has been averaged.

We see that the dependences are nearly linear, which gives a basis to estimate these coefficients from the following regression equations:

$$A = -\,0.514 + 0.173\,H; \qquad (3)$$

$$B = 0.042 + 0.0094\,H.$$

Table 3. Correlation coefficients between the mixing layer height and mean temperature of the atmospheric layers of different height

H, km	$\rho_{H_2,\overline{T}_i}$	$\rho_{\ln H_2,\overline{T}_i}$
0.5	0.56	0.76
1	0.61	0.80
1.5	0.65	0.80
2	0.67	0.81
2.5	0.70	0.82
3	0.72	0.82
3.5	0.73	0.83
4	0.5	0.87
4.5	0.74	0.84
5	0.73	0.84

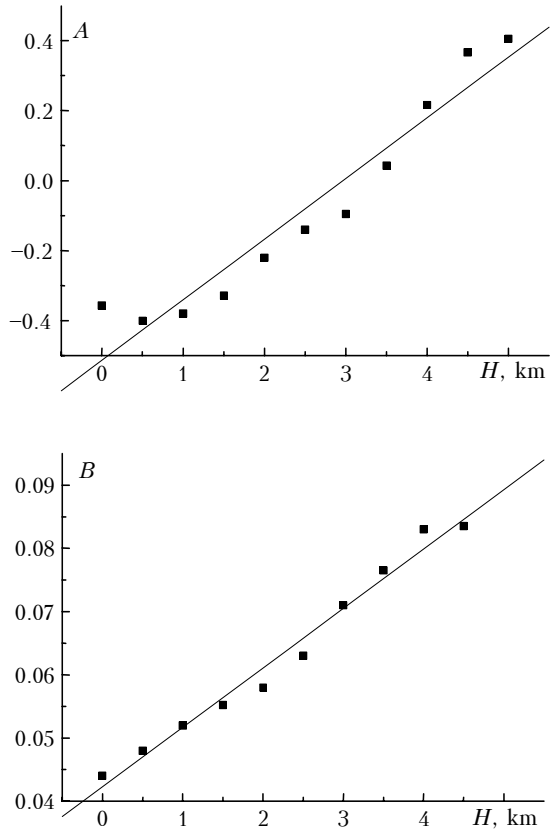

Fig. 4. Coefficients of the regression formula to reconstruct the height of the mixing layer.

Consequently, to estimate the height H_2, we can use the following combined dependence:

$$H_2 = 0.6 \exp\left[(0.04 + 0.01\,\tilde{H})\,T_{\tilde{H}} + 0.2\,\tilde{H}\right], \qquad (4)$$

where $T_{\tilde{H}}$ is the mean temperature of the layer, °C, lying at the height $\tilde{H}$, km.

The main factors determining the slope of the profile in the mixing layer can be the following:

1) the intensity of the ground-level aerosol sources;

2) the rate of aerosol transport in the vertical direction.

As a parameter characterizing the intensity of the ground-level aerosol sources, we may consider the ground-level value of the scattering coefficient σ_0. (In our earlier estimate of the parameters of the mixing layer[8] we did not consider it. In the case where it shows up distinctly in the experimental data, to retrieve $\sigma(H)$ we used the value σ_0^*, defined by extrapolating the profile in the mixing layer down to ground level).

It is well known that the velocities of ordered vertical movements in the atmosphere are determined by the temperature gradient.[12,13] And of course, in the first phase of our work, we attempted to relate the profile slope parameter in the mixing layer α_2 to the mean temperature gradient in this layer. The corresponding scatter plot is shown in Fig. 5 where the value of the correlation coefficient is also indicated. No direct relationship between the parameters is seen. This is completely understandable since the process of aerosol mixing along the vertical has a much longer delay time than variations in temperature stratification. Therefore, it is much more logical to link the slope of the profile with the mean degree of heating of the lower layers of the atmosphere than with the temperature gradient (by degree of heating we mean the mean temperature of the layer extending from the underlying surface to some height H).

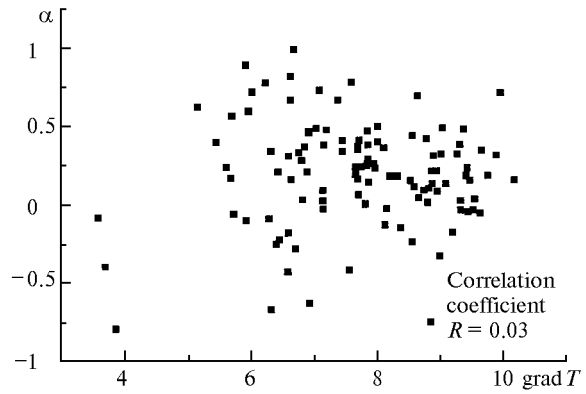

Fig. 5. Correlation diagram between the coefficient of the profile slope in the mixing layer and mean temperature gradient.

To retrieve the profile, we used the ground-level value of the scattering coefficient and the mean temperature of the 0–3 km layer $\overline{T}_3$. Table 4 lists total and partial correlation coefficients between the indicated parameters for different seasons and the entire data set.

Two ways of estimating the profile slope are now possible:

1) from the single parameter σ_0. In this case we constructed the following regression formula:

$$\alpha_2 = 0.89 + 0.24 \ln\sigma_0; \qquad (5)$$

2) from the two parameters σ_0 and $\overline{T}_3$ (here we constructed a two-parameter linear regression):

$$\alpha_2 = 0.26 + 0.1 \ln\sigma_0 + 0.02 \overline{T}_3, \qquad (6)$$

where σ_0 is in km^{-1} and temperature is in °C.

Table 4. Total and partial correlation coefficients of the slope of the profile in the mixing layer with the logarithm of the ground-level value of the scattering coefficient and the mean temperature of the 0–3 km layer

Correlation coefficient	Spring	Summer	Autumn	All seasons
$\rho_{\alpha,\ln\sigma_0}$	0.37	0.55	0.51	0.50
$\rho_{\alpha,\overline{T}}$	0.32	0.45	0.38	0.41
$\rho_{\alpha,\ln\sigma_0\mid\overline{T}}$	0.52	0.65	0.55	0.57
$\rho_{\alpha,\overline{T}\mid\ln\sigma_0}$	0.15	0.20	0.16	0.18

Table 5. Standard deviation of the profile slope parameter in the mixing layer, determined using regression formulas (5) and (6)

Standard deviation	Spring	Summer	Autumn
Initial data set	0.37	0.34	0.37
Determined from σ_0	0.25	0.18	0.24
Determined from σ_0 and $\overline{T}$	0.20	0.14	0.20

Table 5 lists the standard deviation of the parameter α_2 determined using regression formulas (5) and (6).

For the free atmosphere we took the mean-seasonal values of the profile parameters since it is clear that in this layer the aerosol content is already much less correlated with the ground-level sources at the observation point and has a regional character. Consequently, retrieval of the profile using only σ_0 is not expedient.

Figure 6 plots the rms error $\varepsilon(H) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}[\sigma_{retr}(H) - \sigma_{meas,i}(H)]^2}$ of retrieval of the "dry" aerosol scattering coefficient profile in the mixing layer for different seasons taking into account one σ_0 or both (σ_0 and $\overline{T}_3$) parameters.

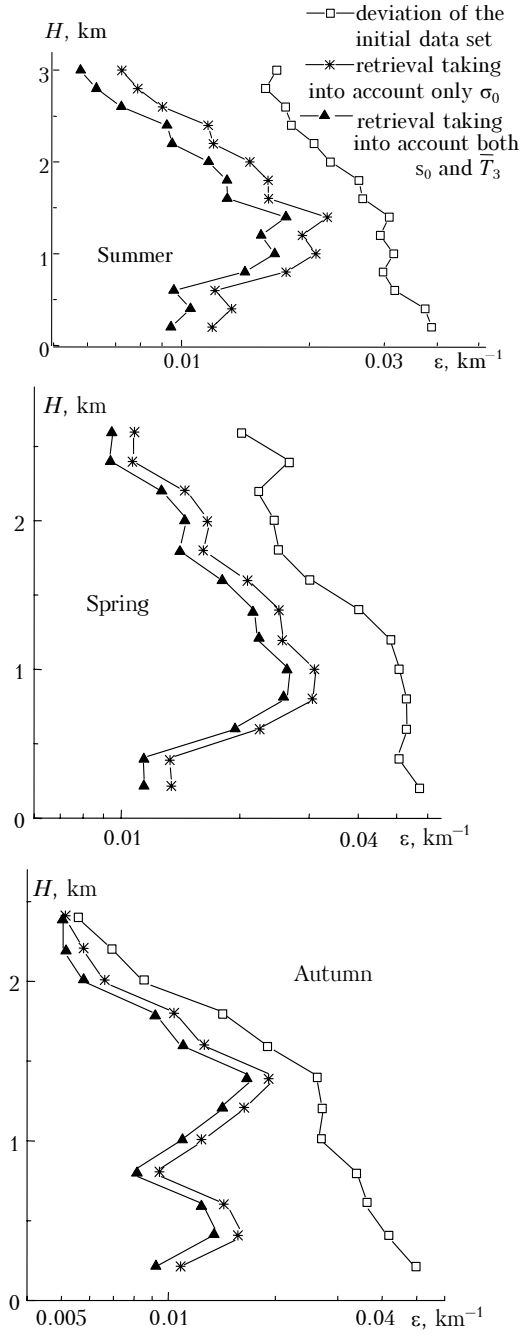

Fig. 6. RMS error of retrieval of the aerosol scattering coefficient profile in the mixing layer for different seasons.

From Fig. 6 it can be seen that taking the ground-level value of the scattering coefficient and the mean temperature of the lower layers into account makes it possible to decrease the rms error of retrieval of the vertical aerosol profile in the mixing layer by more than a factor of two in comparison with the standard deviation of the initial data set for seasons of the year when the main aerosol sources are located at ground level.

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