SCHEME FOR RECONSTRUCTING VALUES OF THE SCATTERING COEFFICIENT IN THE LOW TROPOSPHERE

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We propose a general scheme for reconstructing vertical profiles of the scattering coefficient at the wavelength of $\lambda = 0.52$ μm *within the altitude range up to* 5 km. *The external factors (season, type of air mass, and time of a day) as well as the data of measurements (near-ground values of the scattering coefficient, optical thickness, temperature, and relative humidity of air) are used as input parameters. The scheme assumes the account for correlation between the values of scattering coefficient at different altitudes, as well as the dependence of the height of mixing layer on the heating of the lower atmospheric layers. The errors of reconstructing the vertical profiles* $\sigma_{\rm d}(H)$ *and* $\sigma_{\rm m}(H)$ *are analyzed for different ways of taking into account the external factors and input parameters. It is shown that the use of such an approach provides a decrease in the error even at this stage approximately by* 30% *for winter and by* 3 to 4 *times for summer in comparison with the rms error of this parameter in the corresponding data arrays.*

Vast experimental data obtained using airborne sounding of the atmosphere[1] and analysis of factors affecting the variability of the submicron aerosol characteristics in the lower troposphere presented in our previous papers[2–4] allows us to start the development of an empirical regional model of aerosol optical parameters in the altitude range up to 5 km.

The general scheme for reconstructing vertical profiles of the scattering coefficient at the wavelength $\lambda = 0.52$ μm has been developed at the first stage of the model development. The scheme proposed is based on the principles of the hierarchy of external factors and multivariant account for *a priori* information and input parameters measured. The general scheme of reconstruction is shown in Fig. 1.

One can divide it into three blocks. The first block makes it possible to obtain the information on the mean values and variances of the parameters we determine in the altitude range up to 5 km, only by setting the external factors. The following external factors (input parameters of this block) have been selected: season, type of air mass, and time of a day. This block contains the information on the mean values and variance of the vertical profile of the scattering coefficient $\sigma_{\rm d}(H)$ of the dry matter of aerosol particles, *in situ* scattering coefficient $\sigma_{\rm m}(H)$, temperature $T(H)$, relative humidity of air $R(H)$, specific humidity $Q(H)$, and the parameter of condensation activity $\gamma(H)$. We have not revealed any significant differences in the parameter $\gamma(H)$ in different air masses and different time of a day due to statistically poor bulk of data, so for the input parameter we used only seasons.

It is clear that knowledge of only seasonal and synoptic situations makes it possible to reconstruct the mean values with the rms error close to 100%[2] and it is hardly acceptable for more accurate estimates. At the same time, the data on mean vertical profile of aerosol characteristics can be useful for different kind of climatic calculations, because, as it was mentioned above, our results are in good agreement with the long-term average synoptic and meteorological data for the region under investigation.[1]

Before discussing the next block of the reconstruction scheme, we should like to emphasize that the experience of observations in the atmosphere and great amount of experimental data analyzed are an evidence of the fact that the accuracy of reconstruction (ratio of the rms error to the mean value) can not be better than 50–60% when using the model of aerosol optical characteristics with only seasonal, monthly and synoptic characteristics as input parameters (the interannual variability of aerosol content revealed, when analyzing the long-term data[4–6] on the vertical profile of aerosol number density $N(H)$, has cast some doubt on this estimate, which may be considered as being too optimistic). That is why the second block of the scheme proposed is connected with the parameters to be measured.

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One can conventionally select two groups, among the great amount of optical and meteorological characteristics, that can be measured (meteorological parameters can be calculated in the case of climatic modeling) and used as input parameters. These are the data that can be obtained in the near-ground atmospheric layer and the data on vertical profiles or the total optical thickness obtained with the ground based systems (they are united in the group "sounding" in Fig. 1).

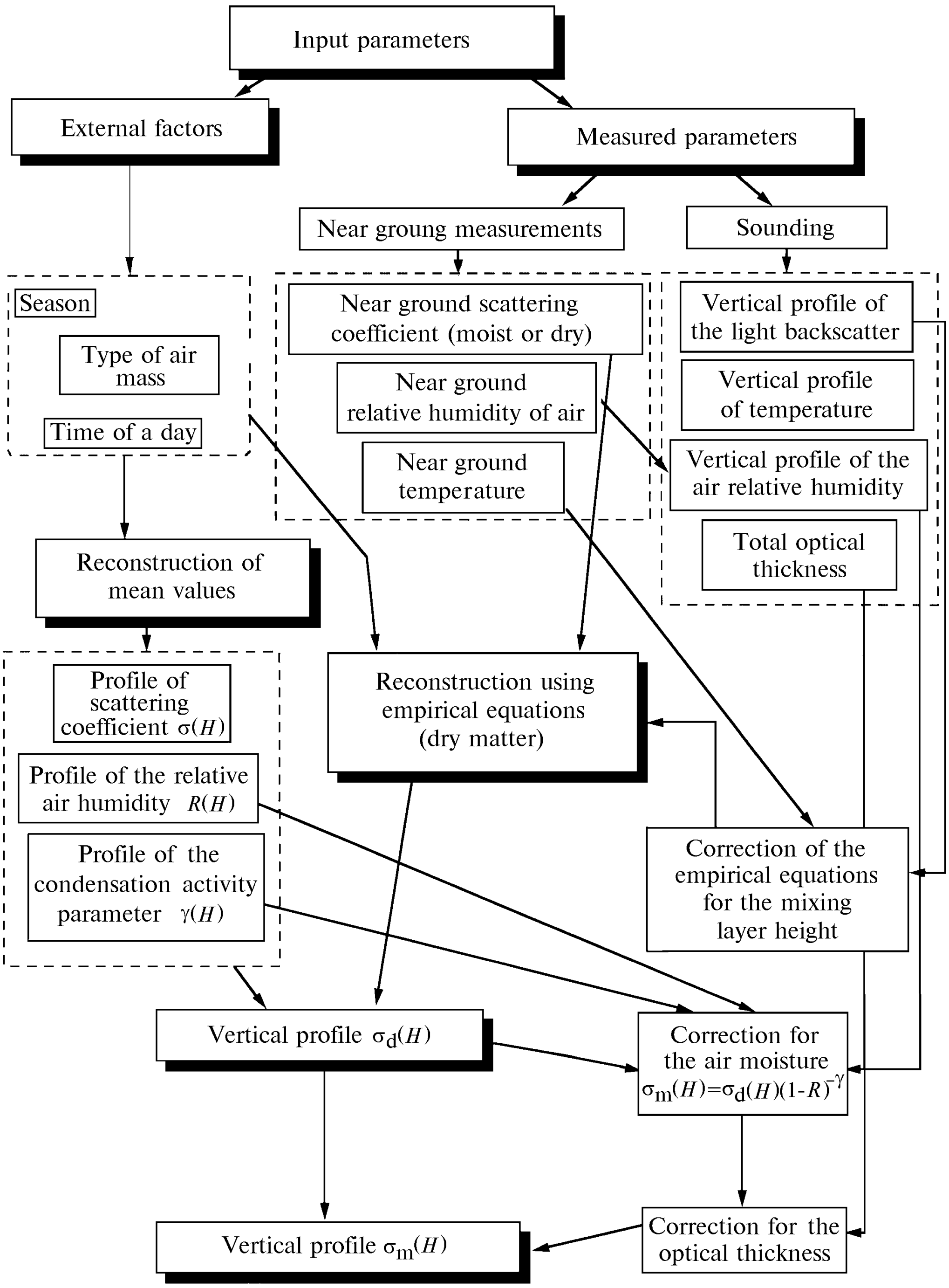

FIG. 1. Scheme of reconstructing of the vertical profile of the scattering coefficient.

At this stage of creating the reconstruction scheme we tried to include and test, as input parameters, only the characteristics that are most easy for measurements. In the group of "ground based measurements" there are the scattering coefficients ("dry" or "moist"), temperature and relative humidity of air. For further development of the model one should include measurements of the atmospheric transmission in a wide wavelength range, as well as the data on the scattering phase matrix components. In the group "sounding" we consider the possibilities of obtaining data on the vertical profiles of meteorological (aerological sounding), use of photometers for measuring the optical thickness, as well as the lidars. As the analysis of autocorrelation matrices of the scattering coefficients $\sigma_d(H)$ and $\sigma_m(H)$ show,[2] the measurement data on σ at some altitudes, for example, above and below the mixing layer, can be used for reconstruction of the entire vertical profile most effectively. But to obtain such data one should have a mobile carrier such as aircraft-laboratory, helicopter or a balloon with the instruments onboard it, i.e. the use of quite expensive tools, that limits the possibility of their routine use in practice of aerosol observations. It is clear, that to develop a model for a wide wavelength range it is necessary to include the data on the spectral optical thickness and solar aureole measurements.

Inclusion of the lidar data into the list of measured parameters, we had in our minds the following ideas. The development of lidar facilities is aimed at obtaining a complete data set on the vertical profiles of different atmospheric parameters, including the aerosol characteristics, directly from the data of sounding. At the same time, known problems in solving the lidar sounding equation determine the need for *a priori* information for interpretation of the lidar data. In this case the use of the reconstruction scheme proposed will be useful. Depending on the information available, the lidar data can be interpreted by using the scheme in different ways. For example, when using Raman lidars[8] that are capable of simultaneously obtaining the data on humidity, temperature and backscattering coefficient profiles, the scheme proposed is fully applicable. In the case of single-frequency lidars operating in a monostatic mode it is quite useful to have information on the near-ground values of optical characteristics and on the total optical thickness, and then to reconstruct the profile in the entire altitude range.

Since a detailed description of the techniques for reconstructing the profile from the data of lidar sounding is an independent problem that is out of the scope we concern with in this paper, let us limit ourselves only by the aforementioned ideas, and when testing the scheme proposed let us use the parameters that were determined in our airborne experiments.

The third, of the principal blocks of the scheme, is directly connected with the reconstruction of the vertical profile of aerosol scattering coefficients. Let us note that at the stages of testing the operation ability of the scheme the principal block "reconstruction using empirical equations" and the blocks of reconstructed meteorological parameters contain the empirical functions, the parameters of which are determined in the frameworks of linear regression equations. A more detailed analysis of the relations and selection of an optimal combination of the input parameters is the problem at the next stage of creating the model, and is not considered in this paper.

The block of reconstruction assumes the following sequence of procedures:

By setting the external factors, i.e. season, air mass and time of a day (in a necessary combination), we enter into the system of empirical equations. If no information is available, additionally only the mean values of the vertical profile of the scattering coefficient of the dry matter of aerosol particles $\sigma_d(H)$ are the outcome of this block.

If data on the near-ground values of the scattering coefficient (moist "*m*" or dry "*d*") are available, the input into this block is done through the value of the "dry" scattering coefficient $\sigma_d(0)$ (if the near-ground measurements have been carried out for σ_m, the value $\sigma_d(0)$ is first calculated using the Kasten-Hanel formula

$$\sigma_m = \sigma_d\ (1 - R)^{-\gamma}, \quad (1)$$

where R is the relative humidity of air, and γ is the parameter of the condensation activity.

Then the vertical profile $\sigma_d(H)$ is reconstructed using linear empirical equations of the form

$$\sigma_d(H) = K(H)\ \sigma_d(0) + C(H)\ , \quad (2)$$

where $K(H)$ and $C(H)$ are the empirical coefficients for corresponding (by the external factors) data arrays.

If the data on air temperature are available (either near-ground values $T(0)$ or a vertical profile $T(H)$), the empirical equations (2) are corrected for the height of the mixing layer. In the case when only the near-ground value $T(0)$ has been measured, the daily average value $\bar{T}(0)$ is determined taking into account the mean daily behavior of temperature in the corresponding array of data. If the measurements of the vertical profile of temperature $T(H)$ have been performed in some layer at the height $\tilde{H}$, the integral value $\bar{T}_{\tilde{H}}$ is calculated. Then, the height of the mixing layer H_k ("correlation" layer in our case) is determined from these data[2]:

$$H_k = 0.75\ \exp[(4.5{\cdot}10^{-3}\ \tilde{H} + 6.5{\cdot}10^{-2})\bar{T}_{\tilde{H}} + 0.2\ \tilde{H}]\ , \quad (3)$$

where $\bar{T}_{\tilde{H}}$ – is the mean temperature of the atmospheric layer of the height $\tilde{H}$.

Then, the coefficients $K(H)$ and $C(H)$ of Eq. (2) are corrected. Correction is carried out as follows. If

$H_k < \bar{H}_k$ ($\bar{H}_k$ is the seasonal mean value of the "correlation" layer height), then:

– $K(H)$ и $C(H)$ are assumed constant up to the height $H = H_k - 200$ m;

– the "upper" parts of the dependences $K(H)$ and $C(H)$ are extrapolated from the height $\bar{H}_k$ down to the height $H_k + 200$ m;

– linear interpolation between "lower" and "upper" parts of the dependencies $K(H)$ and $C(H)$ is carried out on the height interval $\Delta H = 400$ m (i.e. from $H_k - 200$ m to $H_k + 200$ m).

If $H_k > \bar{H}_k$:

– the "lower" parts of the dependences $K(H)$ and $C(H)$ are extrapolated from the height of the seasonal mean mixing layer $\bar{H}_k$ up to the height $H_k - 200$ m;

– linear interpolation is performed on the portion from $H_k - 200$ m up to $H_k + 200$ m;

– $K(H)$ and $C(H)$ are not changed on the interval from $H_k + 200$ up to 5 km.

Vertical profile $\sigma_d(H)$ is calculated after the correction of the equation coefficients.

Then the scattering coefficients are calculated taking into account the relative air humidity. Moistening of $\sigma_d(H)$ is performed by Eq. (1) using the measured near ground $R(0)$ or vertical $R(H)$ values of the relative humidity (if such data are not available, then the mean values $\bar{R}(H)$ from corresponding array of data are used). The value of the condensation activity parameter γ is either the set based on the external factors or its mean value $\bar{\gamma}$ is used (in particular, we took the value $\bar{\gamma} = 0.5$ in all examples presented below).

In the case when a researcher has gotten the data on the total optical thickness τ, the scheme provides the possibility of taking into account its value when reconstructing the profile $\sigma(H)$. In the case when only τ is known, and measurements of the parameters are impossible, the seasonal mean profile $\bar{\sigma}(H)$ is recalculated proportionally to the ratio $\bar{\tau}/\tau_{meas}$ (where $\bar{\tau}$ and τ_{meas} are the seasonal mean and measured values of the optical thickness, respectively). At the presence of other measured parameters in the subsequence of operation we have chosen the value τ_{rec} is calculated from the reconstructed profile $\sigma_m(H)$ in the height range up to 5 km.

Then the value of the optical thickness of the molecular atmosphere τ_M, seasonal mean value $\overline{\Delta\tau}_5$ of the remainder of the optical thickness of the height range above 5 km obtained from the cyclic mean model of the atmosphere[9] and the value of the optical thickness reconstructed using our scheme are subtracted from the measured value $\Delta\tau$, i.e.

$$\Delta\tau = \tau_{meas} - \tau_M - \Delta\bar{\tau}_5 - \tau_{rec} . \quad (4)$$

Vertical profile of the coefficient of correction for τ is calculated in the following form:

$$K_\tau(H) = \frac{1}{\tau_{rec}} \int\limits_{H-\Delta h}^{H+\Delta h} \sigma_{rec}(h)\, dh . \quad (5)$$

Then the vertical profile of the scattering coefficient is corrected:

$$\sigma(H) = \sigma_{rec}(H) + K_\tau(H)\, \Delta\tau \,/\, 2\Delta h . \quad (6)$$

Let us note that selection of the optimal way of using τ is a different problem to be discussed in the future papers, and its statement needs for certain experimental verification.

In order to illustrate the feasibility of the scheme proposed and to estimate its sensitivity to the input parameters, let us first consider the data of reconstruction of the vertical profile of the dry matter of aerosol particles $\sigma_d(H)$.

Figures 2 *a*, *b*, *c*, and *d* (winter, spring, summer and fall, respectively) show the relative errors $\varepsilon(H)/\bar{\sigma}(H)$ obtained at the reconstruction of $\sigma_d(H)$ at the altitudes of 0.2, 1, 2, 3, 4, and 5 km. Here $\varepsilon(H)$ is the rms. error in reconstructing calculated by the formula:

$$\varepsilon(H) = \frac{1}{N} \sum_i (\sigma_{rec,\,i}(H) - \sigma_{meas,\,i}(H))^2, \quad (7)$$

where $\sigma_{rec,i}(H)$ and $\sigma_{meas,i}(H)$ are the reconstructed and measured values of the scattering coefficient, respectively. The first column is the rms deviation of the data in the corresponding seasonal arrays. The second column characterizes the variance when using the value of the near ground scattering coefficient $\sigma_d(0)$ as input parameter for reconstructing $\sigma_d(H)$. The third column is for the case of using only the value of the total optical thickness τ, and the fourth column is for joint account for $\sigma_d(0)$ and τ. And finally, the fifth column (except for winter) shows the errors in reconstructing, when $\sigma_d(0)$ is taken into account, and the height of the mixing layer reconstructed from the temperature profile $T(H)$. The sixth column shows the errors for the case of joint account of σ_0, T and τ.

It is seen from the data shown in Fig. 2, as should be expected from the analysis of the autocorrelation coefficients of $\sigma_d(H)$, that the poorest reconstruction is observed for winter, where a decrease of the error in the case of joint account of $\sigma_d(0)$ and τ is approximately 30%. Other arrays

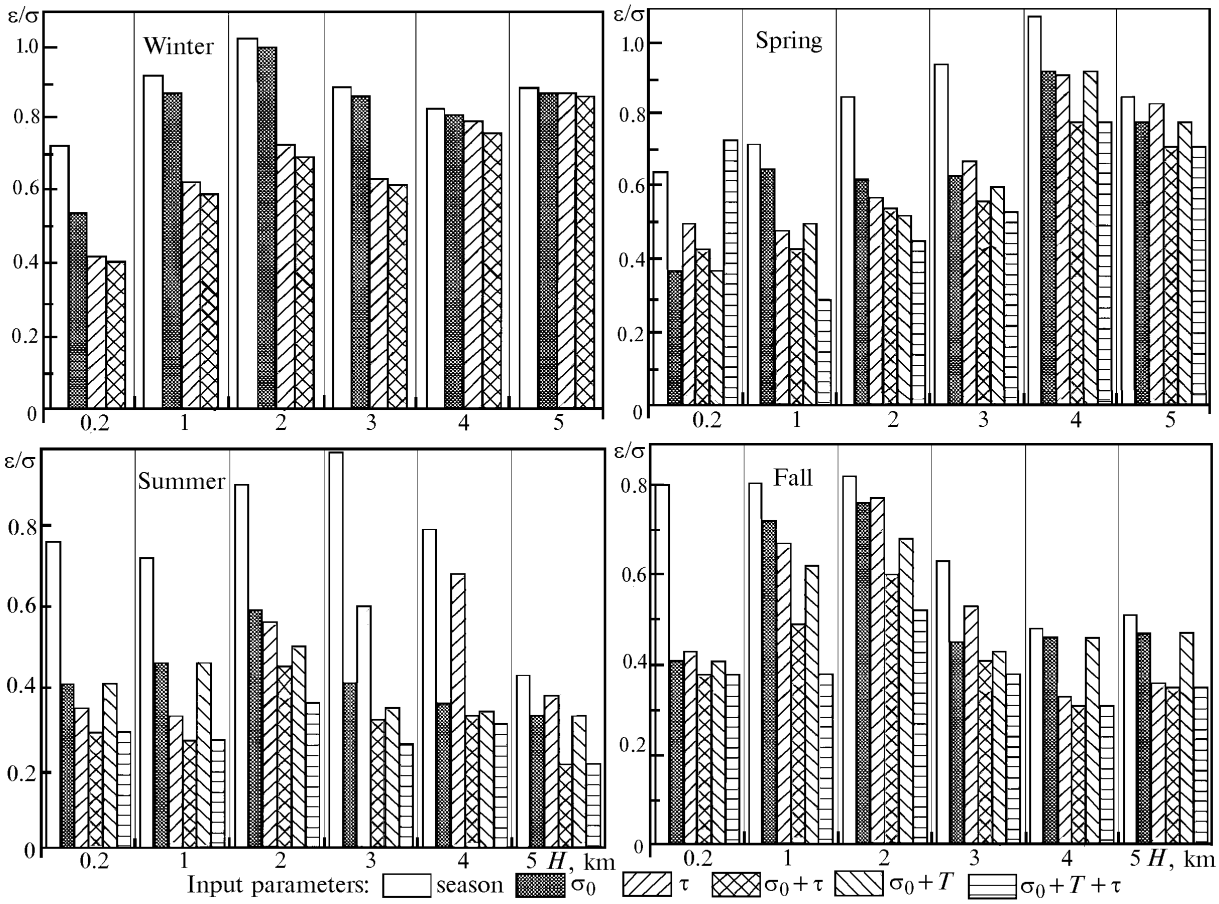

FIG. 2. Relative error in reconstructing the vertical profile of the scattering coefficient of the dry matter of aerosol particles for different seasons.

of data are reconstructed much better (Fig. 2 *b*, *c*, and *d*). Taking into account the height of the mixing layer and τ for summer data makes it possible to decrease the error in reconstructing $\sigma_d(H)$ to 30–35%, i.e. practically by 3 to 4 times.

If a concrete profile of the relative humidity $R(H)$ is unknown, the accuracy of reconstruction of the values σ_m *in situ* becomes more poor.

Corresponding reconstruction errors are shown in Fig. 3 for two cases:

1) when the mean profile $R(H)$ for corresponding season has been used for calculation of $\sigma_m(H)$;

2) when the profile $R(H)$ has been reconstructed from the measured near-ground value of the relative humidity using the correlation between $R(0)$ and $R(H)$.

It is seen, that in the second case the mean relative error of the reconstruction is a little bit less.

Omitting a more detailed analysis of the errors (because it will be expedient to do this when finally forming the model), let us note that the analysis of the factors causing the variability shows that the additional possibilities of improving the accuracy of reconstruction of $\sigma(H)$ are related to taking into account the type of air mass and diurnal behavior of the aerosol characteristics.[3,4]

It is clear that at this stage of forming the aerosol optical model using the scheme proposed we can directly reconstruct only the vertical profile of the scattering coefficient at one wavelength (λ = 0.52 μm in our case), that limits its practical significance. However, it is necessary to remind that within the frameworks of the one-parameter models of the atmosphere developed for the near-ground layer[10,11] it is just this value, which is the input parameter used for reconstruction of all optical characteristics of hazes in the visible wavelength range.

The usefulness of the analysis carried out in this paper is in the fact that we are convinced that the account for the analyzed external factors (season, type of air mass, relation of the height of the mixing layer with the atmospheric heating, etc.) in combination with the optical parameters, which can

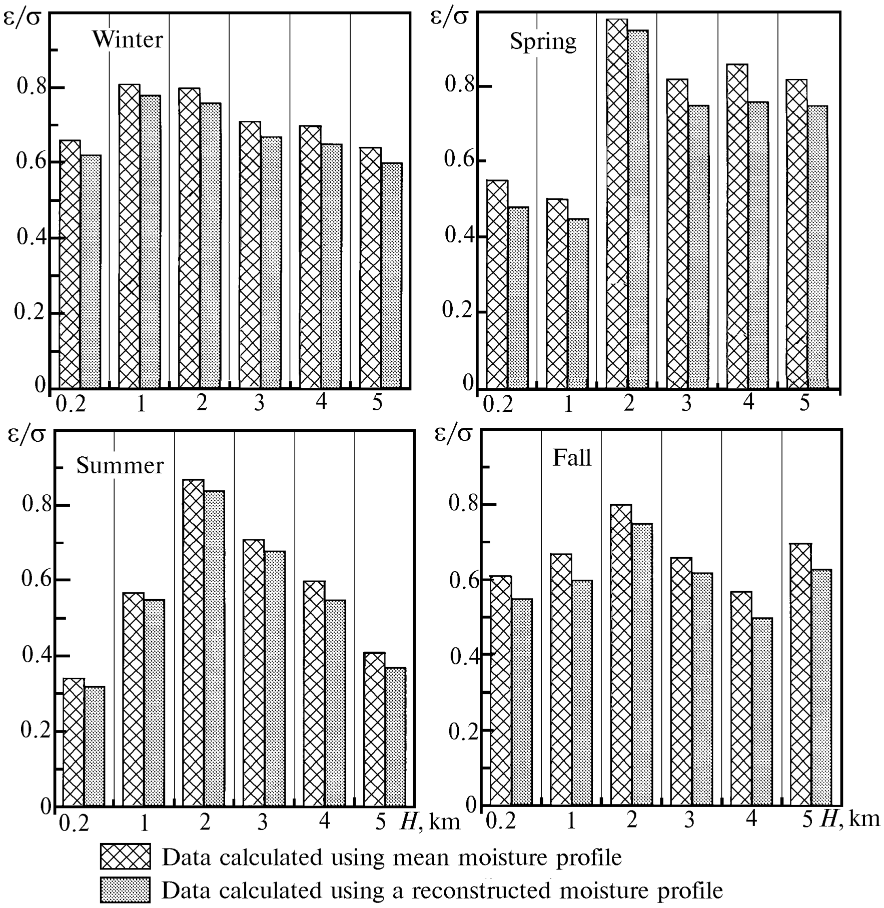

FIG. 3. Relative error in reconstructing vertical profile of the scattering coefficient for different seasons.

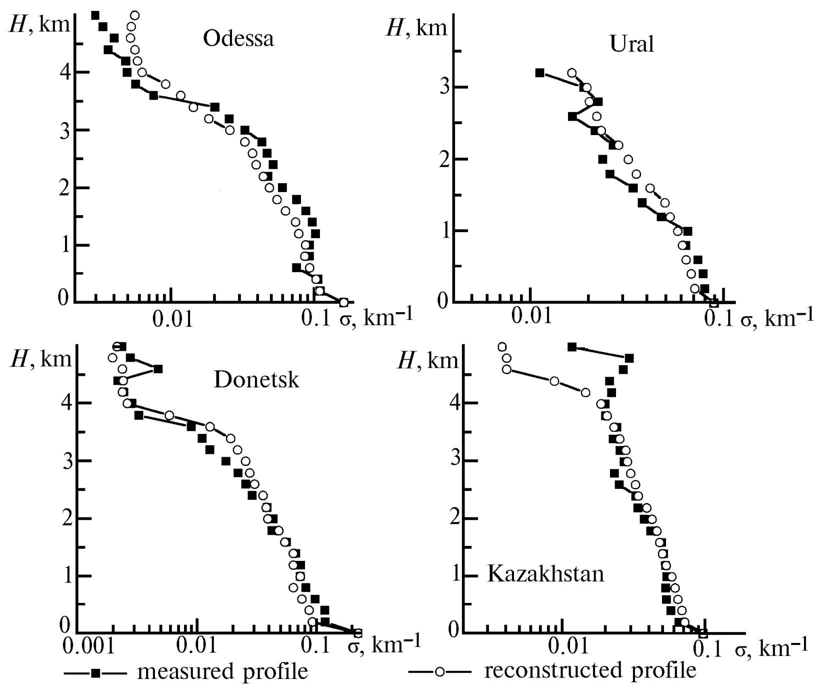

FIG. 4. Examples of reconstruction of the mean vertical profiles $\sigma_d(H)$ for different regions.

easily be measured on the ground, allows one to expect the accuracy of the reconstruction which can be hardly reached by another techniques. Moreover, if the necessary set of input parameters is available (near-ground values σ(0), optical thickness τ, vertical profile of air temperature and relative humidity), the scheme discussed allows one to estimate the vertical profile of the scattering coefficient over other geographical sites on the continents for practically all seasons. To illustrate this conclusion, Figs. 4 *a*, *b*, *c*, and *d* show the results of reconstruction of the mean profiles $\sigma_d(H)$ for different regions obtained during warm season.

As is seen, the measured profiles and those reconstructed using our scheme are in a good agreement. Another aspect, which attracts our attention when estimating the errors in the scheme analyzed, is the following. As is seen, the errors in reconstructing the aerosol optical parameters increase as the altitude increases. At the same time, for the majority of practical applications it is necessary to know the optical characteristics of the air, i.e. the sum of aerosol and molecular components. This circumstance strongly favors better accuracy of reconstruction, because the portion of the contribution coming from the molecular scattering increases as the altitude increases (the aerosol content decreases). Figure 5 shows the seasonal mean profiles of the turbidity factor

$$F = (\sigma_a + \sigma_m)/\sigma_m , \quad (8)$$

where σ_a and σ_m are the aerosol and molecular scattering coefficients, respectively.

It is seen that, starting from the altitude of 3 km, the value of the turbidity factor in these data (except for spring) is close to 2, that means that a decrease in the relative error in reconstructing the total scattering coefficient of air is about 2 times.

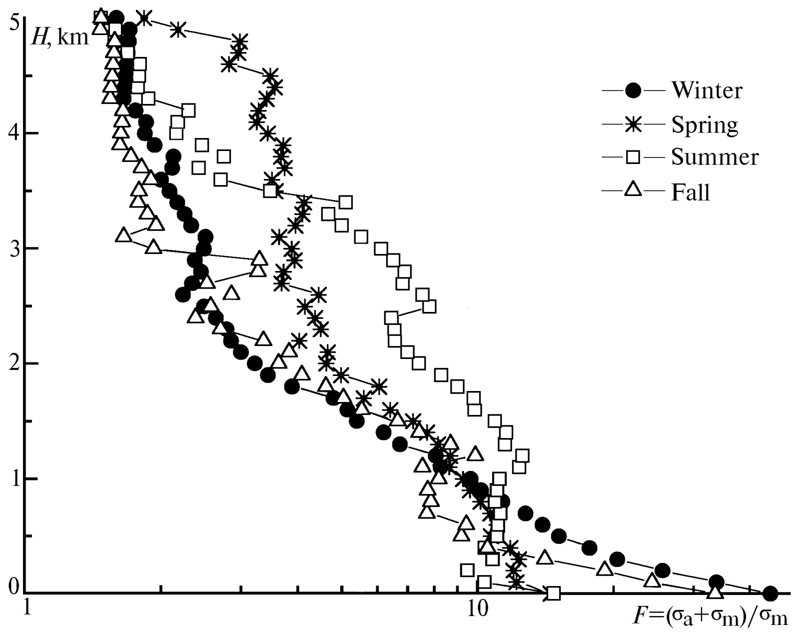

FIG. 5. Seasonal mean vertical profiles of the turbidity factor.

Final analysis of the reconstruction errors we have carried out and some examples presented here allow us to show certain optimism that good empirical basis is created for the development of the dynamic model of the optical characteristics of submicron aerosol (at least, on the regional scale) under continental conditions.

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