Two-parameter model of radiation extinction by aerosol in atmospheric hazes

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We propose an empirical model which allows one to calculate the radiation extinction by aerosol in the near-ground hazes in the wavelength range from 0.4 to 12 μm from the measured values of the extinction coefficient at two wavelengths in the visible spectral range. It is shown that the model satisfactorily describes empirical and calculated models of aerosol extinction for different climatic zones and the majority of types of optical weather (haze, fog haze, haze with drizzle, haze with steady rain, haze with snow or graupel, and ice fog).

1. Introduction

Aerosol, water vapor, and greenhouse gases play determining role in the formation of the optical state of the atmosphere. Calculations of the variability of weather and climate are usually performed by use of tens of versions of radiation blocks to the general circulation models, but only six of them take into account the aerosol optical properties. Modern models need a significant improvement of the accuracy of numerical description of the characteristics of practically all optically significant components of the atmosphere and their spatiotemporal variability. Moreover, practically all optical models that are being used in radiation calculations provide for only poor account for the dynamics. In the best case, aerosol blocks contain only rough division into seasons and geographical zones. At present, the main attention should be paid to creation and development of the dynamic models of the global scale suitable for use under any conditions.

The development of empirical aerosol models is one of the most important tasks of atmospheric optics. The most interesting are the models of atmospheric hazes which are typical aerosol formations in the boundary layer of the atmosphere that occur during 90% of time in the majority of geographical regions.[1] Single-parameter models are usually used in calculating the aerosol extinction coefficients in the IR wavelength range from their values measured in the visible range. The input parameter of such models often serves the aerosol extinction coefficient at 0.55 μm, that is connected with the simplicity of its calculating by the Koshmieder formula $\alpha(0.55) = 3.91/S_m - \sigma_R(0.55)$, where S_m is the meteorological visibility range, and $\sigma_R(0.55)$ is the molecular (Rayleigh) scattering coefficient. One can not construct a single-parameter model by selecting the types of optical weather on the basis of one optical parameter in the visible range. This is caused by the fact that the extinction of radiation in the IR range is basically determined by coarse aerosol fraction, while in the visible it is determined by the fine and coarse fractions of aerosol particles. So one should additionally use seasonal, geographical, synoptic, and meteorological characteristics. The use of such characteristics is based on the fact that the relationship between the contributions of fine and coarse aerosol fractions to the optical characteristics in the visible range is significantly different for different geographic regions, seasons, and types of the optical weather. In this connection, the single-parameter models constructed for a specific region are inapplicable to other regions without proper experimental verification.

An example of using a geographical characteristic in modeling the radiation extinction by aerosols is the empirical model constructed for the coastal zone of Black Sea.[2] Geographical and seasonal characteristics have also been used in constructing a single-parameter model for an arid zone,[3] where the seasonal peculiarities of the spectral behavior of the aerosol extinction coefficients were revealed. Synoptic and meteorological characteristics were also used in the Filippov–Makarov–Ivanov model,[4] which has the form

$$\alpha(\lambda) = 3.91\ (n_0 + n_1 \lambda^{-n_2})/S_m\ , \qquad (1)$$

where $\alpha(\lambda)$ is the aerosol extinction coefficient at the wavelength λ, S_m is the meteorological visibility range, n_0, n_1, and n_2 are the adjustment parameters. This model includes 12 types of atmospheric turbidity: 5 types of haze, 3 types of fog haze, haze with drizzle, haze with steady rain, haze with snow or graupel, and ice fog. Each type of the model is characterized by the ranges of S_m, temperature and relative humidity of air, as well as has its own set of the adjustment parameters. In the model (1) S_m changes from 1 to 50 km, temperature changes from −35 to +25°C, relative humidity – from 30 to 100%, n_0 – from 0.004 to 0.56, n_1 – from 0.35 to 0.79, and n_2 – from 0.39 to 2.

The use of this model for calculating the aerosol extinction in the IR showed that the model underestimates the values $\alpha(\lambda)$ for some atmospheric turbidity. Besides, this model does not work at the meteorological visibility range greater than 50 km and

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air temperature greater than +25°C that is characteristic, for example, of arid zones. These facts lead to the development of single-parameter seasonal models of the aerosol extinction.[3]

The main disadvantage of single-parameter models is the difficulty of determining the applicability conditions for use of one or another model in the transitional seasons (change of spring to summer, summer to fall, etc.) that leads to increased errors in reconstructing the aerosol extinction coefficient. Another disadvantage of such models is that those don't take into account the variations of the number density of submicron aerosol particles during a selected season, which determines the variations of the extinction coefficients in the visible range to a greater extent than in the IR range. The attempts to exclude the variations of $\alpha(\lambda)$ in the visible range caused by variations of the submicron aerosol number density lead to the construction of a two-parameter model of the aerosol extinction.

2. Physical grounds of the model

Physical grounds for constructing the model were presented for the first time at IX All-Union Symposium on the laser radiation propagation in the atmosphere[5] in 1987, and then stated in a more detail in Ref. 6. The grounds are in the fact that the difference between the values of two aerosol extinction coefficients in the visible range only weakly depend on the size distribution of coarse aerosol particles, and is mainly determined by the size distribution of fine aerosol particles.

Let us suppose that there are two wavelengths in the visible spectral range, λ_1 and λ_2 ($\lambda_1 < \lambda_2$), the extinction at which is determined by the fine and coarse aerosol particles. One need to calculate the aerosol extinction at the third wavelength in the IR range ($\lambda_1 < \lambda_2 < \lambda_3$), the extinction at which is determined only by coarse aerosol particles. To do this in the best way, it is necessary to exclude the extinction by submicron particles at λ_1 and λ_2. It turns out that one can do it using the difference between two aerosol extinction coefficients at the wavelengths λ_1 and λ_2. To explain such a possibility, let us analyze data presented in Fig. 1.

Let the extinction coefficients of coarse aerosol particles at the wavelengths λ_1, λ_2, and λ_3 have neutral spectral behavior and are equal to α_3, and the extinction coefficients of submicron particles at λ_1 and λ_2 are equal to α_1 and α_2, respectively. Then the aerosol extinction coefficients at the wavelengths λ_1 and λ_2 are equal to $\alpha_1 + \alpha_3$ and $\alpha_2 + \alpha_3$, and the difference between them is $\alpha_1 - \alpha_2$. When changing the number density of submicron particles by N times, and coarse particles by M times, the aerosol extinction coefficients at the wavelengths λ_1 and λ_2 are equal to $\alpha_1 N + \alpha_3 M$ and $\alpha_2 N + \alpha_3 M$ and the difference between them is $N(\alpha_1 - \alpha_2)$.

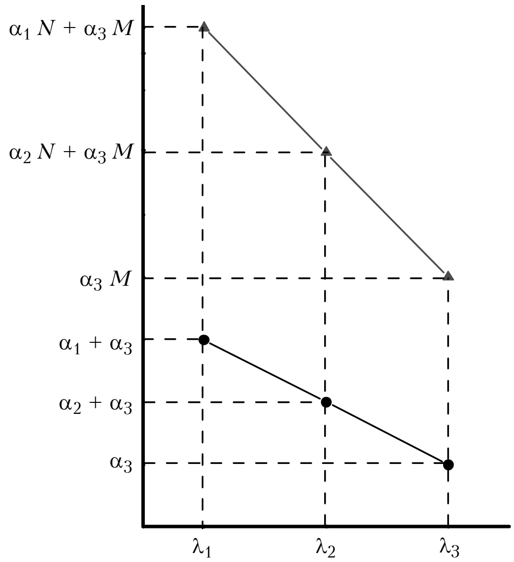

Fig. 1. To the physical grounds for a two-parameter model of the aerosol extinction.

Thus, the difference between two aerosol extinction coefficients in the visible range is proportional to the number density of submicron aerosol and does not depend on the coarse aerosol number density. Actually, this difference depends on both the shape of normalized size-distribution function of submicron and coarse aerosol particles and their number density. So in such a way one can compensate only for variations of the extinction coefficients caused by variations of the shape of normalized particle size-distribution function.

3. Two-parameter model of the aerosol extinction

In practice, the technique for excluding the extinction by submicron particles is based on the use of the values $\alpha(\lambda)$ at two wavelengths in the visible spectral range. The first two-parameter model for calculating $\alpha(\lambda)$ at the wavelength 10.6 μm was presented in Ref. 7. The formula proposed in Ref. 8 for calculating the aerosol extinction coefficients in the wavelength range from 0.4 to 12 μm is as follows

$$\alpha(\lambda) = \alpha_s(0.69)\left(\frac{\lambda}{0.69}\right)^{-n} + \alpha_c(0.69)\,\frac{K(\lambda)}{K(0.69)}, \qquad (2)$$

where $\alpha_s(0.69) = 0.67\alpha(0.48) - 0.26\alpha(0.69) - 0.023$; and $\alpha_c(0.69) = 1.26\alpha(0.69) - 0.67\alpha(0.48) + 0.023$ are the extinction coefficients of submicron and coarse aerosol fractions at the wavelength 0.69 μm, respectively; $\alpha(0.48)$ and $\alpha(0.69)$ are the extinction coefficients at the wavelengths 0.48 and 0.69 μm, $K(\lambda)$ and $K(0.69)$ are the coefficients characterizing the relative spectral behavior of the extinction coefficient of the coarse fraction, and $n = -\ln\{[\alpha(0.48) - K(0.48)/K(0.69)\alpha_c(0.69)]/[\alpha(0.69) - \alpha_c(0.69)]\}/\ln(0.48/0.69)$.

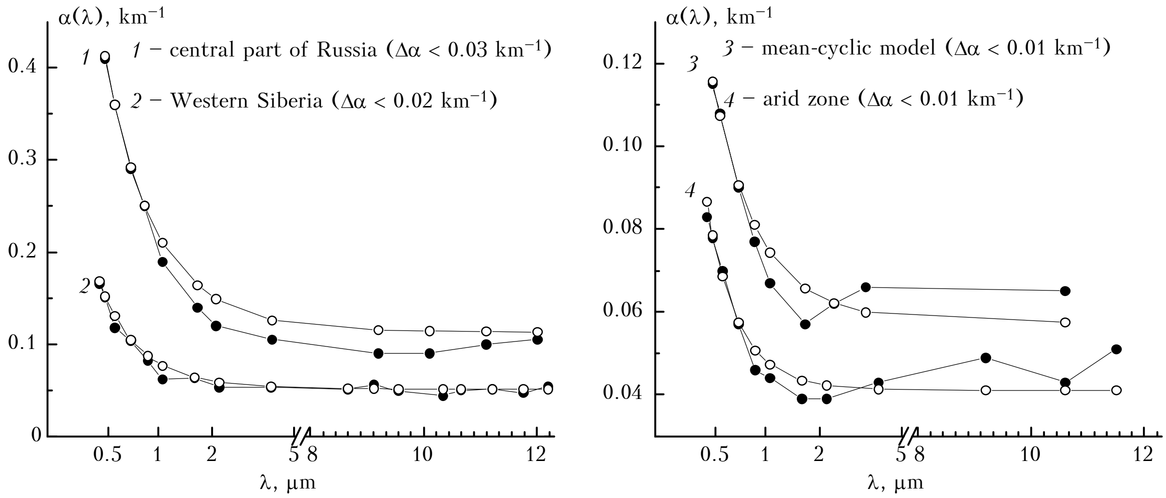

Fig. 2. Comparison of the experimental and calculated (solid circles) aerosol extinction coefficients in the wavelength range from 0.44 to 12 μm using a two-parameter model (2) (open circles).

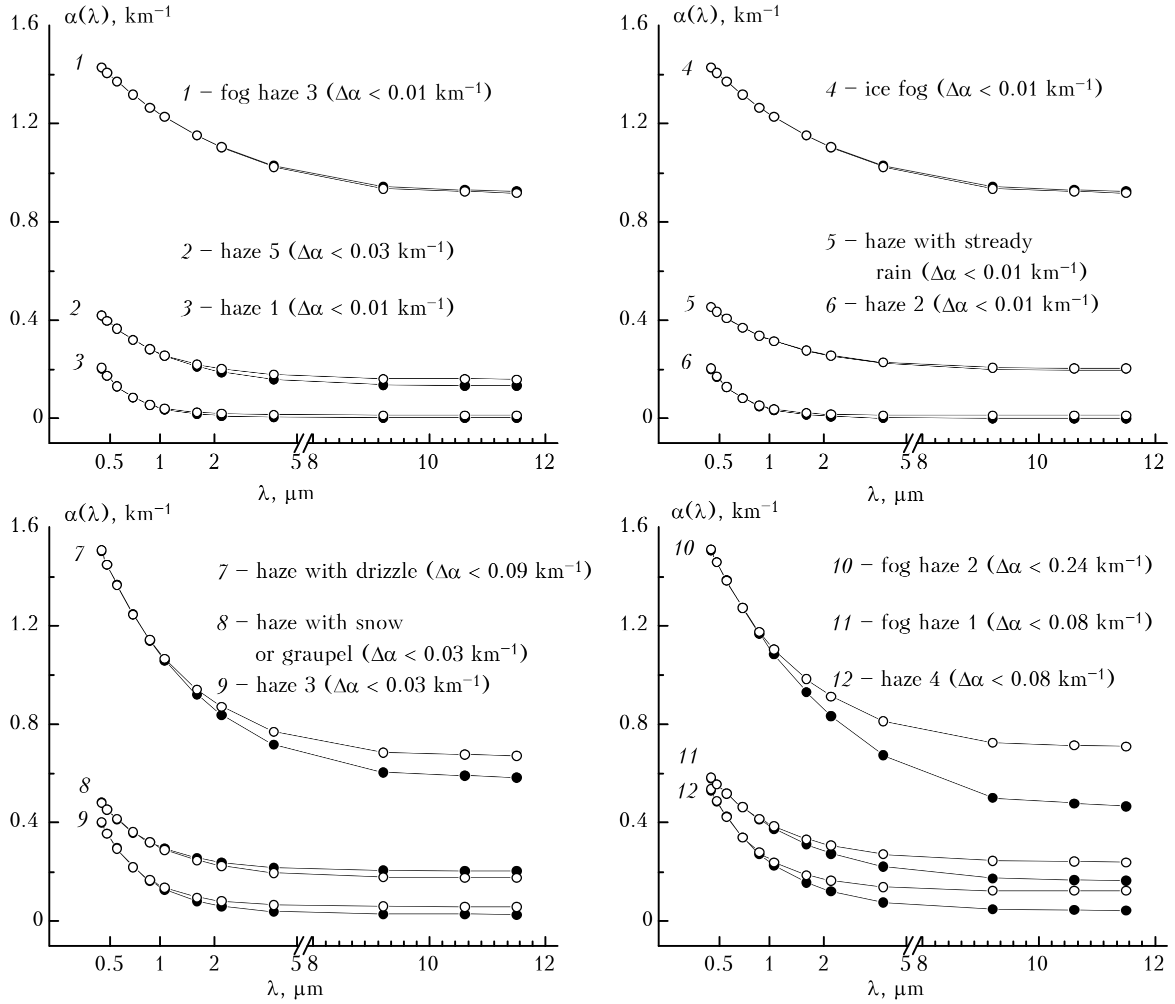

Fig. 3. Comparison of aerosol extinction coefficients in the wavelength range from 0.44 to 12 μm calculated using 12 single-parameter models (1) (solid circles) and a two-parameter model (2) (open circles).

The first term in Eq. (2) describes the spectral behavior of the extinction coefficient of submicron aerosol fraction by the Angström formula with the index n. The second term in Eq. (2) describes the spectral behavior of the extinction coefficient of the coarse aerosol fraction. To calculate it, one can accept the value $K(\lambda) = 1$ or to use the data from Ref. 9 obtained for the wavelength range from 0.3 to 15 μm and relative humidity 10 to 90%.

The two-parameter model for atmospheric hazes satisfactorily describes the experimental data in different climatic zones and numerical models of aerosol extinction in the wavelength range from 0.4 to 12 μm. Figure 2 shows the comparison of the model (2) with the experimental data obtained in Central Russia,[10] Western Siberia,[11] arid zone of Kazakhstan,[12] and the numerical data of the mean-cyclic model[13] constructed based on the statistically significant data on the microphysical parameters of atmospheric aerosols. It is seen from the figure, that the difference ($\Delta\alpha$) between the experimental (numerical) data and calculated results on the extinction coefficients by the two-parameter model does not exceed 0.01–0.03 km^{-1}.

Figure 3 shows the results of comparison of the aerosol extinction coefficients in the wavelength range from 0.4 to 12 μm calculated by the two-parameter model and 12 single-parameter models (1) at the mean values of the meteorological visibility range. The difference between the calculated aerosol extinction coefficients does not exceed 0.01–0.03 km^{-1} for eight models (haze 1, haze 2, haze 3, haze 5, fog haze 3, haze with steady rain, haze with snow and graupel, and ice fog). The difference is 0.08–0.09 km^{-1} (67, 31, and 15%) for three models (haze 4, fog haze, and haze with drizzle). The difference is maximum for fog haze 2, 0.24 km^{-1} (34%). The values of aerosol extinction coefficient calculated by the model (2) and 12 models (1) in the wavelength range from 0.4 to 1.06 μm differ by no more than 0.02 km^{-1}.

4. Conclusion

Thus, the two-parameter model for atmospheric hazes satisfactorily describes the experimental and numerical models of aerosol extinction for different climatic zones and the majority of the types of optical weather (haze, fog haze, haze with drizzle, haze with steady rain, haze with snow or graupel, and ice fog). In our further studies we suppose to develop a model for any pair of extinction coefficients at different wavelengths and any set of input parameters in the visible wavelength range.

It is also planned to use a few values of optical parameters in the visible wavelength range for constructing the aerosol models for vertical atmospheric paths. The necessity of constructing such models is caused by the fact that the spectral transmission in the range from 0.344 to 0.627 μm is measured at the ozone measurement stations of Russia. Using such models one can complete the sets of experimental data with data of model calculations of the aerosol optical thickness of the atmosphere in the wavelength range from 0.7 to 12 μm.

Acknowledgments

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