Two-Parametrical Model of Spectral Behavior of Aerosol Extinction Coefficients for Atmospheric Hazes

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Abstract

In this paper we suggest an empirical model for calculation of aerosol extinction of 0.4 μm to 12 μm radiation in the near-ground atmospheric layer from measured values of extinction coefficient at two visible wavelengths. The performance of the model under different meteorological conditions is tested. This model is shown to satisfactorily describe the experimental and calculated models of aerosol extinction for different climatic zones and most optical weather types (hazes, fog hazes, haze with drizzle, haze with incessant rain, haze with snow or snow grains, and ice fog).

Introduction

Aerosol, water vapor, greenhouse gases, and clouds play a central role in determining the optical state of the atmosphere. Earth's weather and climate changes are calculated by several tens of versions of radiation codes of atmospheric general circulation models (GCMs), but only six of them allow properly for the aerosol optical properties. Current atmospheric models require far more accurate quantitative descriptions (of characteristics) of all optically significant components of the atmosphere as well as their spatio-temporal variability. Moreover, most optical models used in radiation calculation treat weather dynamics poorly. For instance, aerosol codes at best use rather crude gradations by seasons and geographic zones. At present, major emphasis must be laid on creation and development of global-scale dynamic models usable under any weather conditions.

The most important problem of atmospheric optics has been the development of empirical models through which aerosol extinction coefficients at infrared wavelengths could be calculated from their measured visible counterparts. Of wide use here are one-parametrical models whose input typically is the aerosol extinction coefficient in the 0.55 μm wavelength region. This wavelength range is chosen because the aerosol extinction coefficient can be calculated quite easily here, simply as $\alpha(0.55) = 3.91/S_m - \sigma_{Ray}(0.55)$, where S_m is the meteorological visibility range, and $\sigma_{Ray}(0.55)$ is the coefficient of molecular (Rayleigh) scattering. The one-parametrical models are created either using regional (regional-seasonal) principle of their construction or by optical weather types. These principles are used because, in the visible range, the coarsely dispersed and submicron aerosols contribute very differently to aerosol extinction, with the difference depending on the location, season, and optical weather type; while in the infrared (IR), the extinction is dominated by coarsely-dispersed aerosol.

The regional approach is exemplified by the model for the coastal zone of the Black Sea (Kabanov et al. 1988). The regional-seasonal principle was used to construct the model for arid zone (Shchelkanov 1997), where seasonality of the spectral behavior of the aerosol extinction coefficient was detected. The constructional division by optical weather types was realized in the model of Filippov et al. (1982), defined by the formula

$$\alpha(\lambda) = \frac{3.91}{S_m}\left(n_0 + n_1\lambda^{-n_2}\right) \tag{1}$$

where $\alpha(\lambda)$ is the coefficient of aerosol extinction at a wavelength λ, S_m is the meteorological visibility range, and n_0, n_1, n_2 are fit parameters. This model includes 12 types of atmospheric turbidity: 5 types of haze, 3 types of fog haze, haze with drizzle, haze with incessant rain, haze with snow and snow grains, and ice fog. Each model type is characterized by S_m temperature, and relative air humidity ranges, as well as by a distinct set of fit parameters. In the model given by Eq. (1), S_m ranges from 1 km to 50 km, air temperature from -35 °C to +25 °C, relative air 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.

When used to calculate aerosol extinction in the IR spectral range, this model underestimates $\alpha(\lambda)$ for a number of atmospheric turbidities. In addition, this model does not work for meteorological visibility ranges in excess of 50 km and air temperatures higher than +25 °C, which are typical under conditions of arid zone. This motivated the development of one-parametrical seasonal models of aerosol extinction. The main model deficiency is the difficulty to check their validity during transitional periods of a year (e.g., during spring-to-summer or summer-to-fall change, etc.), which degrades the accuracy of retrievals of aerosol extinction coefficients. The second model drawback is the neglect of the fact that the concentration of submicron aerosol fraction may vary within a selected studied season, which translates into variations of the aerosol extinction coefficient, mostly in the visible range and to a much less degree in the IR. Attempts to remove the $\alpha(\lambda)$ variations in the visible spectral range due to variations in the concentration of submicron aerosol fraction have resulted in construction of the two-parametrical model of aerosol extinction.

Physical Grounds for Model Development

Physically, the development of the two-parametrical model (Shchelkanov and Pkhalagov 1987) relies on the fact that the difference between aerosol extinction coefficients at two visible wavelengths depends little on the size distribution of coarsely dispersed particles, and that it is mainly determined by submicron particle sizes. Suppose that there exist two visible wavelengths λ_1 and λ_2 ($\lambda_1<\lambda_2$) at which the aerosol extinction is determined both by coarsely dispersed and submicron particles, whereas we need to determine the aerosol extinction at a third, infrared wavelength λ_3 ($\lambda_1<\lambda_2<\lambda_3$), at which aerosol extinction is determined solely by coarsely dispersed particles. This can be done most optimally through removing extinction due to submicron particles in a chosen spectral interval. It is found that the difference between aerosol extinction coefficients in the visible spectral range can be used for this purpose.

Suppose that aerosol extinction coefficients of coarsely dispersed particles behave neutrally at wavelengths λ_1, λ_2, and λ_3, all being equal to α_3; whereas extinction coefficients of submicron particles are equal to α_1 and α_2 at wavelengths λ_1 and λ_2, respectively. Then, aerosol extinction coefficients at wavelengths λ_1 and λ_2 are equal to $\alpha_1+\alpha_3$ and $\alpha_2+\alpha_3$, while their difference is $\alpha_1-\alpha_2$. If the concentration of submicron particles increases by a factor of N, while that of coarsely dispersed particles increases by a factor of M, then aerosol extinction coefficients at wavelengths λ_1 and λ_2 change to $\alpha_1\cdot N+\alpha_3\cdot M$ and $\alpha_2\cdot N+\alpha_3\cdot M$, while their difference to $N\cdot(\alpha_1-\alpha_2)$. Thus, the difference between aerosol extinction coefficients at two visible wavelengths is proportional to the concentration of submicron aerosol and does not depend on the concentration of coarsely dispersed particles. In fact, though, this difference depends on both the shapes of normalized particle size distributions of submicron and coarsely dispersed particles and on their concentrations. Therefore, this method can mitigate only those extinction coefficient variations, due to changes in submicron aerosol concentration, that exceed variations caused by variability of the normalized particle size distribution function.

Two-Parametrical Model of Aerosol Extinction

Practical applications of the method of removal of submicron aerosol extinction suggest using $\alpha(\lambda)$ values at two visible wavelengths. The aerosol extinction coefficients in the wavelength region λ = 0.4 µm to 12 µm are calculated from the formula

$$\alpha(\lambda)=\alpha_{\text{s.m.}}(0.69)\left(\frac{\lambda}{0.69}\right)^{-n}+\alpha_{\text{c.d.}}(0.69)\frac{K(\lambda)}{K(0.69)}, \tag{2}$$

where $\alpha_{\text{s.m.}}(0.69) = 0.67\alpha(0.48) - 0.26\alpha(0.69) - 0.023$ and $\alpha_{\text{c.d.}}(0.69) = 1.26\alpha(0.69) - 0.67\alpha(0.48) + 0.023$ are the coefficients of extinction by submicron and coarsely dispersed aerosol fractions at wavelength 0.69 µm; $\alpha(0.48)$ and $\alpha(0.69)$ are aerosol extinction coefficients at wavelengths 0.48 µm and 0.69 µm; $K_2(\lambda)$ and $K_2(0.69)$ are the coefficients representing the relative spectral behavior of extinction coefficient of coarsely dispersed aerosol fraction; and $n = -\ln\{[\alpha(0.48)-K_2(0.48)/K_2(0.69)\ \alpha_{\text{c.d.}}(0.69)]/[\alpha(0.69)-\alpha_{\text{c.d.}}(0.69)]\}/\ln(0.48/0.69)$. The first term in Eq. (2) describes the spectral behavior of the extinction coefficient of the submicron aerosol fraction in terms of Angstrom formula with exponent n. The second term in Eq. (2) describes the spectral behavior of the extinction coefficient of coarsely dispersed aerosol fraction; it can be calculated either setting $K_2(\lambda)=1$ or using data presented by Andreev (1995) specifically for a wavelength region 0.3 µm to 15 µm and relative air humidities in the range from 10% to 99%.

Figure 1 compares calculations of the aerosol extinction coefficient in the wavelength region 0.4 µm to 12 µm, made using the two-parametrical model (2) and 12 one-parametrical models (1) for their respective mean meteorological visibility ranges. For eight models (haze 1, haze 2, haze 3, haze 5, fog haze 3, haze with incessant rain, haze with snow or snow grains, and ice fog), the difference between calculated aerosol extinction coefficients (shown in parentheses in the figures) does not exceed 0.03 km^{-1}. For three models (haze 4, fog haze 1, and haze with drizzle), the difference amounts to

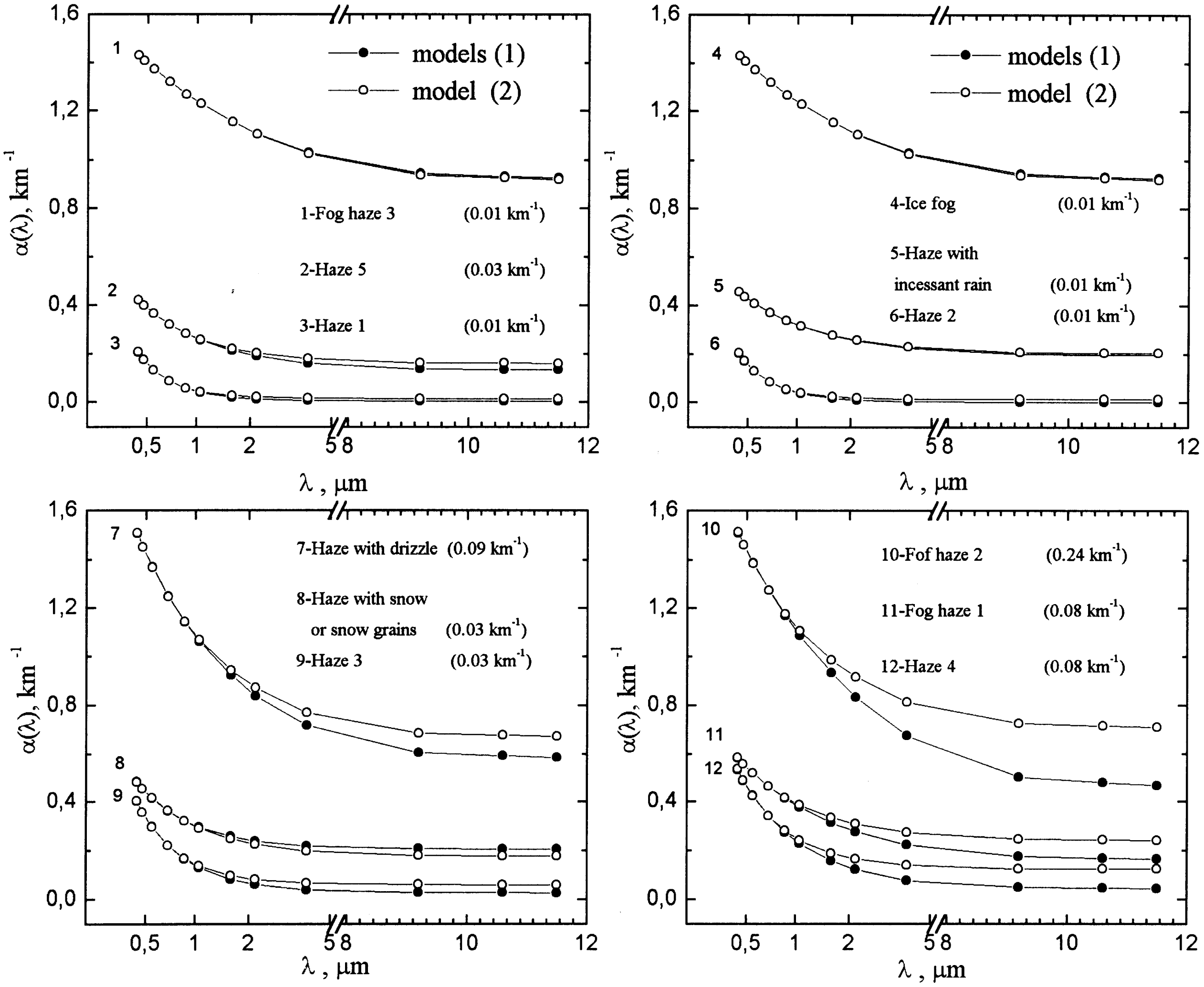

Figure 1. Comparison of aerosol extinction coefficients in the wavelength region 0.44 μm to 12 μm, calculated using 12 one-parametrical models (1) and the two-parametrical model (2).

0.08 km^{-1} to 0.09 km^{-1}. For the fog haze 2 model, the difference between calculated coefficients reaches a maximum of 0.24 km^{-1}. In the wavelength region 0.4 μm to 1.06 μm, the difference in the aerosol extinction coefficient between 12 one-parametrical models (1) and the two-parametrical model (2) does not exceed 0.02 km^{-1}.

The two-parametrical model of atmospheric hazes well fits the experimental data for different climatic zones and the calculated models of aerosol extinction in the wavelength region 0.4 μm to 12 μm. Figure 2 compares calculations, using model (2), with experimental data for the Central Russia (Filippov et al. 1979), West Siberia (Pkhalagov et al. 1996), arid zone of Kazakhstan (Pkhalagov et al. 1994), and calculated data for the mean-cyclic model (Zuev and Krekov 1986) obtained using statistically representative data on microphysical parameters of atmospheric aerosol. From the figure, it follows that the two-parametrical model fits the data to better than 0.03 km^{-1}.

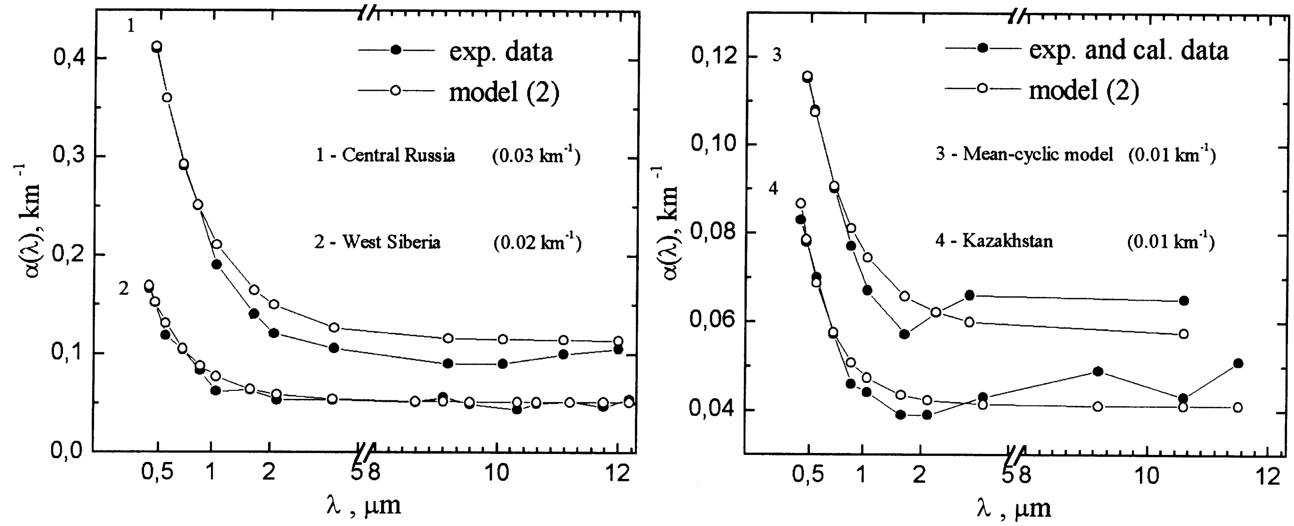

Figure 2. Comparison of experimental and calculated aerosol extinction coefficients in the wavelength region 0.44 μm to 12 μm with the two-parametrical model (2).

Conclusion

Thus, the two-parametrical model of atmospheric hazes well fits the experimental and calculated models of aerosol extinction for different climatic zones and most optical weather types (hazes, fog hazes, haze with drizzle, haze with incessant rain, haze with snow or snow grains, and ice fog). The idea of using two extinction coefficients at visible wavelengths will be employed tentatively to construct aerosol models for vertical atmospheric paths. Development of such models is motivated by the fact that the ozonometric network stations measure the spectral transparency in the visible spectral range. Use of these models will help, if necessary, complement available experimental data with model-calculated atmospheric aerosol optical depths in the 0.3 μm to 15 μm wavelength range.

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