Two-parameter model of aerosol extinction in 0.4–12 μm wavelength range for horizontal and slant paths

N.N. Shchelkanov

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

Received October 5, 2002

A two-parameter model is proposed for calculation of atmospheric aerosol optical depths in 0.4 to 12 μm wavelength range along a zenith path and 1-km long horizontal path. The input parameters of the model are the values of aerosol optical depth at the wavelengths of 0.48 and 0.69 μm. The model can be used for separation of the atmospheric aerosol optical depth into two parts each being caused by the corresponding extinction by submicron and coarse aerosol fractions.

Introduction

The solar radiation incident on the Earth's surface strongly depends on the amount of aerosol, water vapor, greenhouse gases, and clouds, i.e., main atmospheric factors that significantly influence the climate and weather on the Earth. Understanding the observed climate change and improvement of weather predictions have been impossible without regular monitoring of aerosol content throughout atmospheric depth.

Presently, over 100 observation sites of Aerosol Robotic NETwork (AERONET), organized by the U.S. National Aeronautics and Space Administration (NASA), operate on all continents. These sites perform observations of aerosol optical depth (AOD) in 0.34 to 1.02 μm wavelength region. The global system of radiation measurements under the auspices of World Meteorological Organization (WMO) includes over 900 stations,[1,2] measuring atmospheric AOD. The Russian ozonometric stations[3] have accumulated long time series of data on AOD in 0.344 to 0.627 μm wavelength range. In a wider wavelength range, from 0.35 to 4 μm, only episodic measurements of the atmospheric AOD are being performed.[4,5]

Meanwhile, for most applications of atmospheric optics, the data on the spectral behavior of AOD in both visible and infrared (IR) spectral regions, including atmospheric transmission window 8–12 μm, are needed. In this regard, of great interest are the models allowing one to calculate AOD values in the IR from measurements in the visible range. Using such models one could complement the missing spectral data with the model values of the AOD.

Reference 6 presents first version of a two-parameter model of the extinction of optical radiation by aerosol for horizontal paths. This model satisfactorily describes the experimental and calculated data, but has some limitations and drawbacks. For instance, it is applicable only if the input values of aerosol extinction coefficient at the wavelengths of 0.48 and 0.69 μm are related as $\alpha(0.48) > 0.39\alpha(0.69) + 0.034$; otherwise, calculation of the extinction by the submicron aerosol component gives negative results. When input values of aerosol extinction coefficient are assumed to be equal at wavelengths 0.48 and 0.69 μm, the extinction coefficient of the submicron aerosol fraction is predicted by the model to be $0.41\alpha(0.69)-0.023\ \text{km}^{-1}$. On the other hand, it is clear that the extinction by submicron aerosol must be close to zero in this case, because the quasi-neutral behavior of aerosol extinction is typical only for the coarse aerosol fraction. Therefore, this model version[6] cannot be used for separation of aerosol extinction by submicron aerosol from that by the coarse aerosol fraction. To circumvent these disadvantages, another one model version has been developed.

1. Second version of the two-parameter model of aerosol extinction

A refined formula for calculation of atmospheric aerosol optical depths has the following form:

$$\tau(\lambda) = (\tau_1 - \tau_2)\, k_1\, (1 + k_2\, \tau_2)\, (\lambda/\lambda_2)^{-n} + \\ + [\tau_2 - (\tau_1 - \tau_2)\, k_1\, (1 + k_2\, \tau_2)]\, K(\lambda)/K(\lambda_2), \quad (1)$$

where τ_1 and τ_2 are the atmospheric aerosol optical depths at the wavelengths λ_1 and λ_2 ($\lambda_1 < \lambda_2$) in the shortwave spectral range; k_1 and k_2 are the fit parameters; $K(\lambda)$ and $K(\lambda_2)$ are the coefficients representing the spectral behavior of optical depths of the coarse fraction of atmospheric aerosol;

$$n = -\ln \{[\tau_1 - (\tau_2 - (\tau_1 - \tau_2)\, k_1\, (1 + k_2\tau_2))\, K(\lambda_1)/ \\ /K(\lambda_2)]/[(\tau_1 - \tau_2)\, k_1\, (1 + k_2\tau_2)]\}/\ln(\lambda_1/\lambda_2).$$

Model (1) is presented as a sum of two terms. The first term describes the spectral behavior of extinction by submicron fraction of aerosol according to Angström formula. The second term describes the spectral behavior of extinction by the coarse aerosol fraction. The spectral behavior of the extinction by coarse aerosol particles can be specified by either setting $K(\lambda)$ to 1 or using data from Ref. 7, presented for the wavelength range 0.3 to 15 μm.

The expressions $(\tau_1 - \tau_2)\, k_1\, (1 + k_2\tau_2)$ and $\tau_2 - (\tau_1 - \tau_2) \times k_1\, (1 + k_2\tau_2)$ in formula (1) present atmospheric aerosol optical depths at the wavelength λ_2 due to submicron and coarse fractions of aerosol, respectively. These expressions, as well as the values of their empirical constants, are obtained by fitting them to experimental data.

In contrast to the earlier formula of the two-parameter model,[6] equation (1) includes an extra multiplier $(1 + k_2\tau_2)$; and in this formula, the expression $(\tau_1 - \tau_2)k_1$ has no free term, while the empirical coefficient k_1 of τ_1 is equal to the coefficient of τ_2, removed from the parenthesis.

Formula (1) can be used to calculate atmospheric aerosol optical depths along the zenith direction and on a horizontal path 1 km in length. Note that the atmospheric AOD along a 1-km long horizontal path gives the aerosol extinction coefficient. For the pair of wavelengths $\lambda_1 = 0.48$ μm and $\lambda_2 = 0.69$ μm, the fit parameters are determined to be $k_1 = 0.7$ and $k_2 = 5$.

2. Comparison of the model and experimental data

In Fig. 1, model (1) is compared with the experimental data, obtained on horizontal paths in the wavelength range 0.4 to 12 μm for the Central Russia,[8] North-Western Russia,[9] Western Siberia,[10] and arid region of Kazakhstan.[11] From the figures it is seen that the discrepancies (δα) between experimental data and calculations of aerosol extinction coefficients, based on two-parameter model, do not exceed 0.01–0.03 km^{-1}. Thus we can conclude that the results satisfactorily agree since the obtained discrepancies are within the uncertainty of the experimental data available.

Figure 2 compares model (1) and the experimental data obtained along slant paths for three regions of South Atlantic[5] (Dark Sea, Canary Islands, and open ocean) in the wavelength range 0.37–4 μm and one region of North Atlantic[4] (Norwegian Sea) in the wavelength range 0.35–2.2 μm. Because the amount of experimental data for the North Atlantic is small (78 spectra), Figure 2 presents one spectrum averaged over 1982–1983 data.

Figure 3 compares model (1) and experimental data obtained along the slant paths in the wavelength range 0.35–2.2 μm for Eurasian part of Arctic[4] (Barents Sea and Wrangel Island) and South-Eastern Kara Kum desert[4] (Repetek sand-arid reserve) for two seasons.

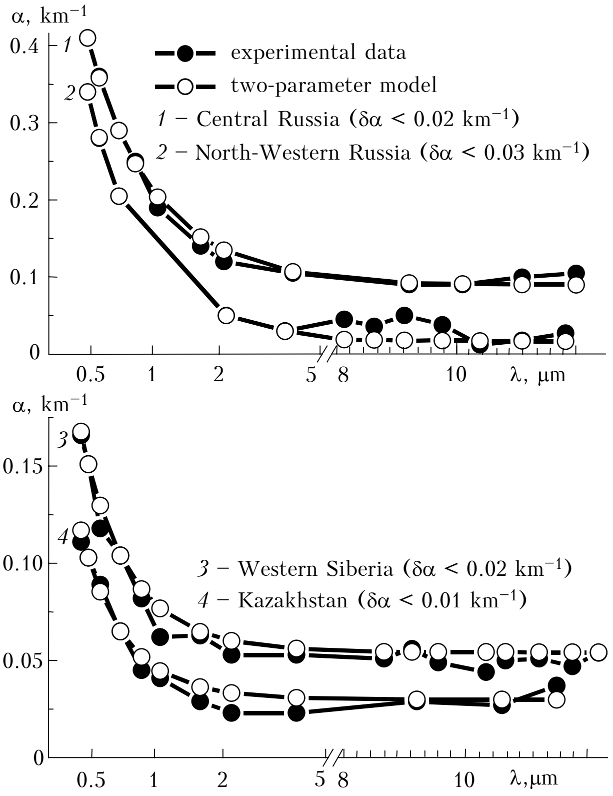

Fig. 1. Comparison of two-parameter model (1) with the experimental data obtained along horizontal paths for different regions of Russia and Kazakhstan.

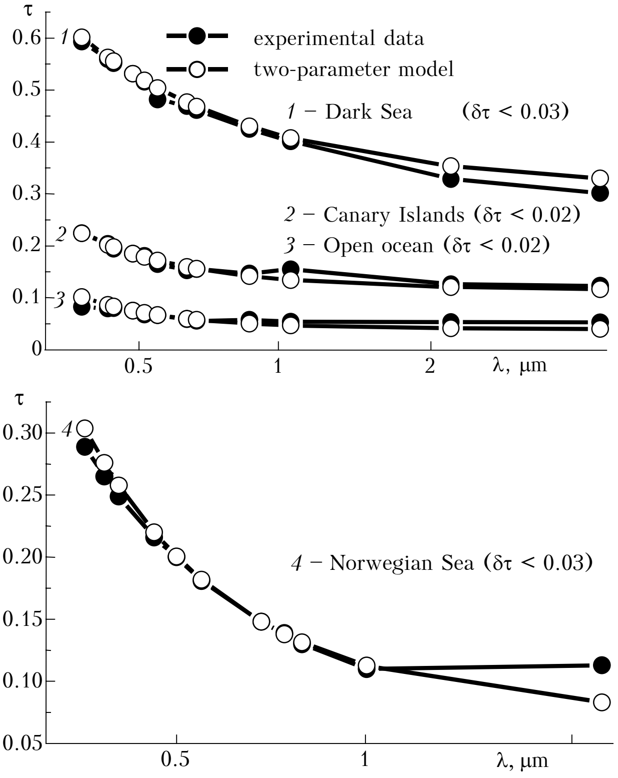

Fig. 2. Comparison of two-parameter model (1) with experimental data obtained along the slant paths over different regions of the Atlantic Ocean.

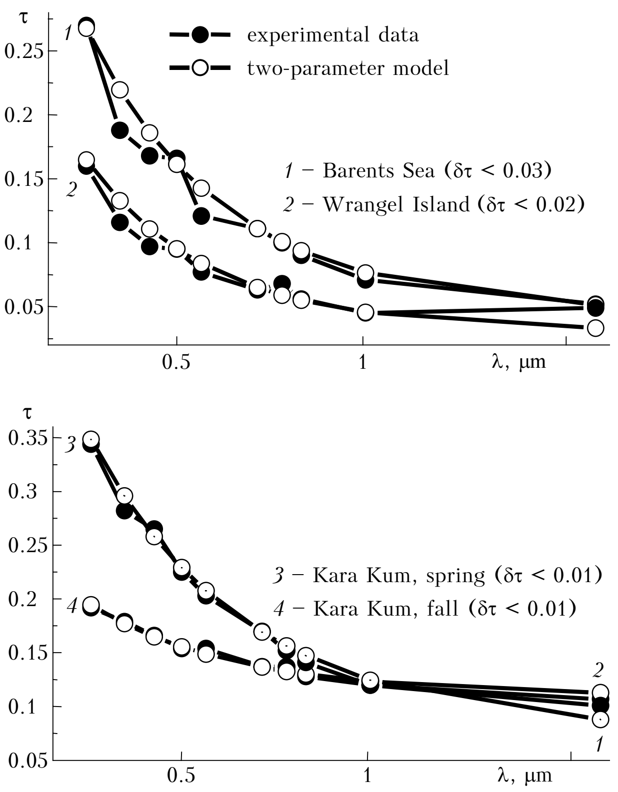

Fig. 3. Comparison of two-parameter model (1) with the experimental data, obtained along slant paths for Eurasian part of Arctic and South-Eastern part of Kara Kum desert.

From the figures it is seen that the differences ($\delta\tau$) between the atmospheric AOD calculated from two-parameter model and inferred from the experimental data does not exceed 0.01–0.03, i.e., well within the experimental errors.

Figure 4 compares aerosol extinction coefficients in the wavelength range from 0.4 to 12 μm, calculated from two-parameter model (1) and 12 one-parameter models of the State Institute of Applied Optics[12] for intermediate values of meteorological visibility range (S_m). For four models with high values of the visibility range S_m = 20–50 km (Haze 1, Haze 2, Haze 3, and Haze 4) and one model with intermediate values of S_m = 5–15 km (Haze with snow or graupel), the differences between calculated aerosol extinction coefficients do not exceed 0.01–0.03 km^{-1}. For three models with the intermediate values of the visibility range S_m = 5–15 km (Haze 5, Haze with continuous rain, Fog Haze 1), the difference is 0.05, 0.04, and 0.09 km^{-1} (38, 16, and 55%). For the four models with low values of the visibility range S_m = 1–5 km (Fog Haze 3, Ice Fog, Haze with drizzle, Fog Haze 2), the difference is 0.04, 0.04, 0.11, and 0.09 km^{-1} (4, 4, 19, and 19%). Thus, within the absolute error of less than 0.03 km^{-1}, or within the relative error less than 20%, the two-parameter model describes 10 out of the 12 one-parameter models of the State Institute of Applied Optics.

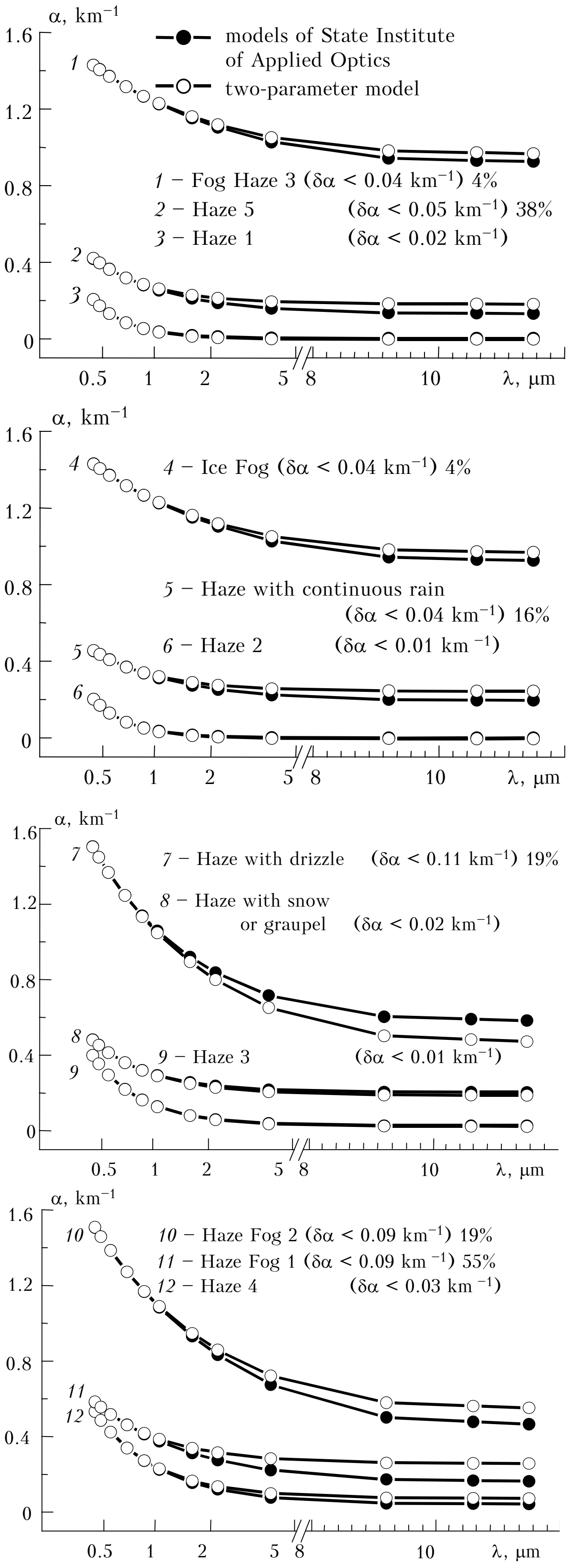

Fig. 4. Comparison of aerosol extinction coefficients in the wavelength range from 0.4 to 12 μm, calculated from 12 one-parameter models and two-parameter model (1).

Conclusion

The two-parameter model discussed well fits the experimental data on spectral behavior of atmospheric aerosol optical depth, obtained for different climatic regions along the horizontal and slant paths, as well as calculated results of one-parameter models of the State Institute of Applied Optics.

The differences between experimental data and calculations using two-parameter model are within 0.03 km^{-1} in the wavelength range 0.4–12 μm for the horizontal paths, and within 0.03 km^{-1} in the wavelength range 0.35–4 μm for the slant paths.

The performed analysis of the model results in the wavelength range 0.4–2.2 μm has not revealed that they systematically overestimate or underestimate the experimental data for horizontal or slant paths. This suggests that the two-parameter model is equally successful at simulating the spectral behavior of aerosol extinction along the horizontal and slant paths. Because of this as well as of the fact that the two-parameter model well fits the experimental data for a horizontal path in the wavelength range from 0.4 to 12 μm, it can also be recommended for calculation of aerosol extinction along the slant paths in the wavelength range from 0.4 to 12 μm.

This version of the two-parameter model is applicable at $\tau(0.48) \geq \tau(0.69)$ and, in this case, it can be used for separation of atmospheric aerosol optical depth into two components that are caused by the extinction by submicron and coarse aerosol fractions, respectively.

References

1. N.N. Shevchenko, Trudy VNIIGMI – MTsD, Issue 85, 43–59 (1983).
2. V.A. Smerkalov, *Applied Atmospheric Optics* (Gidrometeoizdat, St. Petersburg, 1997), 334 pp.
3. G.P. Gushchin, *Methods, Instrumentation, and Results of Measurement of Spectral Atmospheric Transparency* (Gidrometeoizdat, Leningrad, 1988), 200 pp.
4. O.D Barteneva, N.I. Nikitinskaya, G.G. Sakunov, and L.K. Veselova, *Transparency of Atmospheric Depth in the Visible and IR Spectral Range* (Gidrometeoizdat, Leningrad, 1991), 224 pp.
5. D.M. Kabanov and S.M. Sakerin, Atmos. Oceanic Opt. **13**, No. 8, 657–663 (2000).
6. N.N. Shchelkanov and Yu.A. Pkhalagov, Atmos. Oceanic Opt. **12**, No. 12, 1037–1040 (1999).
7. S.D. Andreev, “Optical properties of atmospheric aerosols in infrared spectral range,” Dissert. Doct. Phys.-Math. Sci., St. Petersburg (1995), 338 pp.
8. V.L. Filippov, A.S. Makarov, and V.P. Ivanov, Izv. Akad. Nauk SSSR, Ser. Fiz. Atmos. Okeana 15, No. 3, 257–265 (1979).
9. N.N. Paramonova, A.M. Brounshtein, K.V. Kazakova, and O.A. Nemets, Trudy Gl. Geofiz. Obs., Issue 496, 94–99 (1985).
10. Yu.A. Pkhalagov, V.N. Uzhegov, and N.N. Shchelkanov, Atmos. Oceanic Opt. **9**, No. 6, 455–458 (1996).
11. Yu.A. Pkhalagov, V.N. Uzhegov, and N.N. Shchelkanov, Atmos. Oceanic Opt. **7**, No. 10, 714–720 (1994).
12. V.L. Filippov, A.S. Makarov, and V.P. Ivanov, Dokl. Akad. Nauk SSSR **265**, No. 6, 1353–1356 (1982).