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Potential Accuracies of Retrieving the Vertical Profiles of Atmospheric Parameters (Satellite-Based Transmittance Method): 2. Spectral Coefficient of Aerosol Extinction

A. V. Polyakov and Yu. M. Timofeev

Research Institute of Physics, St. Petersburg State University, Ul'yanovskaya ul. 1, Petrodvorets, 198504 Russia
e-mail: alexandr@ldm.phys.lgu.spb.su; tim@troll.phys.spbu.ru

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Abstract—Closed-loop numerical experiments are carried out to analyze the potential accuracies of retrieving the vertical profiles of the spectral coefficient of aerosol extinction (SCAE) from slant-path atmospheric transmittance measurements with the SAGE-III spectrometer launched aboard the Meteor-3M satellite. The SCAE retrieval error depends significantly on the SCAE approximation. The minimum SCAE retrieval errors are achieved by using an aerosol extinction optimal parametrization, which lies in the expansion of variations in the aerosol extinction coefficient into the first few vectors of the quasi-empirical basis. An optimal linear parametrization with four or five parameters is the most promising to interpret remote measurements of slant-path atmospheric transmittance. The advantages of such a parametrization are especially significant when the aerosol extinction coefficients are retrieved in the short-wavelength spectral range. In this range, the errors of retrieval for optimal parametrizations can be several times smaller than those for the Lumpe parametrization. Highly accurate SCAE values retrieved by using the optimal parametrizations can simplify the solution of the subsequent inverse problem of retrieving the microphysical characteristics of stratospheric aerosol.

INTRODUCTION

Stratospheric aerosol has a profound impact on the transformation of solar radiation and the formation of polar stratospheric clouds, which influence the radiative balance and ozone destruction in the lower stratosphere. Satellite measurements contribute significantly to studies of stratospheric aerosol. On the basis of the available satellite instrumentation, such as SAM, SAGE-I, SAGE-II, POEM-II, POEM-III, and Ozon–Mir, using the same method of sounding—the slant-path atmospheric transmittance measurements—a significant amount of information on space–time variations in aerosol extinction at different wavelengths and on aerosol microphysical characteristics was obtained [1–11]. In [12], a method of optimal parametrization of the spectral coefficient of aerosol extinction (SCAE) was proposed and studied. This method is based on the A.M. Oboukhov empirical orthogonal basis [13]. In [14], an analysis of numerical experiments on estimating the ultimate accuracy of retrieving the O_3 and NO_2 vertical profiles is fulfilled on the basis of the measurements with the SAGE-III instrumentation installed aboard the Russian satellite Meteor-3M, launched on December 10, 2001. A special attention was given to the effect of the SCAE parametrization on the retrieval accuracy. It was shown that the optimal parametrization proposed in [12], as compared to the well-known parametrization of Lumpe *et al.* [15], provides a certain increase in the accuracy of ozone and nitrogen dioxide retrieval.

This work represents a continuation of the work presented in [14]. It contains data on numerical retrieval of the height and spectral behaviors of the aerosol extinction coefficient. Major features of the numerical experiments are detailed in [14]. Recall that we simultaneously solved the combined inverse problem of retrieving the ozone and nitrogen dioxide vertical profiles and the SCAE approximation parameters.

RESULTS OF NUMERICAL EXPERIMENTS

Mean Retrieval Errors

The table contains absolute (km^{-1}) and relative (%) errors of SCAE retrieval on the basis of different parametrizations. Minimum absolute errors of 0.39×10^{-5} and 0.42×10^{-5} km^{-1} are obtained for the linear

Mean absolute and relative errors of retrieval of the aerosol extinction coefficient for the height range 12–35 km

Parametrization	Rms errors; the height range 12–35 km	
	absolute, km^{-1}	relative, %
Linear optimal, 4 parameters	0.39×10^{-5}	4.7
Linear optimal, 5 parameters	0.42×10^{-5}	1.4
Logarithmic optimal, 4 parameters	0.66×10^{-5}	0.65
Lumpe	0.20×10^{-4}	8.2

parametrizations with four and five expansion terms, respectively, and a maximum absolute error of 0.20×10^{-4} km^{-1} is obtained for the Lumpe parametrization. A minimum relative error of 0.65% is obtained for the logarithmic parametrization with four parameters. The relative accuracies of the optimal parametrizations is two to ten times higher than that of the Lumpe parametrization (8.2%).

The advantages of the optimal parametrizations are based on the expansion of the aerosol extinction coefficient variations into several first eigenvectors of the empirical orthogonal basis and on the use of a greater number of approximation parameters. Recall that the Lumpe parametrization uses three parameters.

An analysis of the errors of aerosol extinction retrieval for individual realizations of the atmospheric aerosol state also demonstrates significant advantages of the optimal parametrizations (Fig. 1). The best accuracy of aerosol extinction coefficient retrieval is reached when the logarithmic optimal parametrization with four parameters is used. In this case, the error does not exceed 1% in the majority of cases. The linear optimal parametrization with five parameters also leads to a high accuracy: the error of retrieval does not exceed 2%. The Lumpe parametrization leads to a significantly higher retrieval error, which reaches 5–10% and more in most cases.

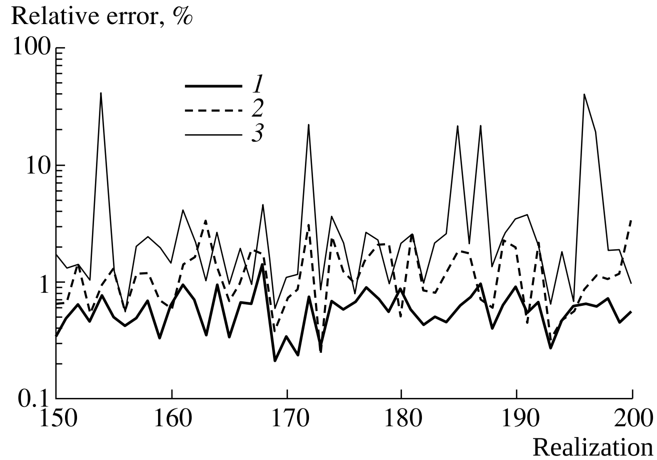

Fig. 1. Average (over the height and spectrum) relative errors in retrieving the aerosol extinction coefficient for different realizations: (*1*) logarithmic optimal parametrization with four parameters, (*2*) linear optimal parametrization with five parameters, and (*3*) Lumpe parametrization.

Vertical Profile of the Errors

Figure 2 contains the vertical profiles of the relative errors in retrieving the aerosol extinction coefficient. It is seen that the optimal parametrizations have advantages over the Lumpe parametrization. For these parametrizations, the mean errors do not exceed 4% throughout the entire height range under consideration from 12 to 35 km. The logarithmic parametrization provides errors less than 1%. For the linear approximation, the error is also less than 1% below 20 km and increases to 4% near 35 km. If the Lumpe approximation is used, the error is significantly greater and varies from 2 to 13%. For the Lumpe approximation, minimum errors (2 to 6%) relate to heights of 12 to 20 km and increase significantly at larger heights. It is seen that a maximum error of 13% is attained at a height of 28 km.

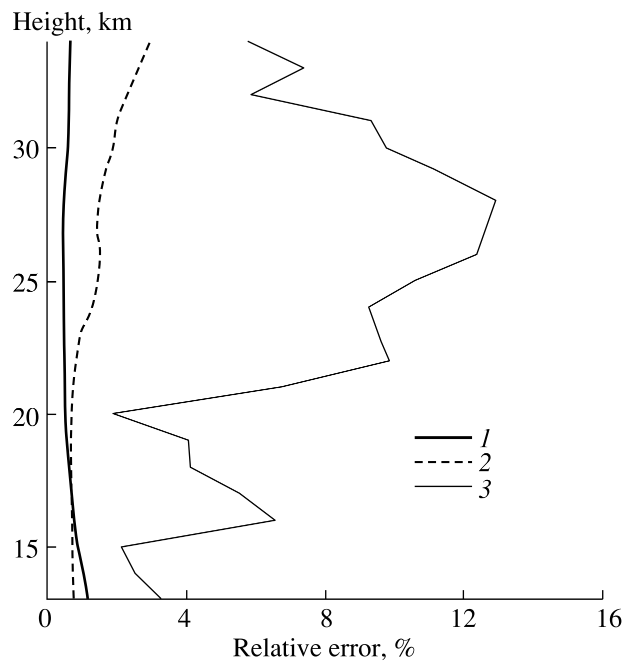

Fig. 2. Vertical profiles of the average (over the spectrum and realizations) relative errors in retrieving the aerosol extinction coefficient for different parametrizations. See Fig. 1 for the curve notation.

Retrieval of the Spectral Behavior of the Aerosol Extinction Coefficient

Let us analyze the errors in SCAE retrieval for different parametrizations. Figure 3 presents the spectral behavior of the relative retrieval error averaged over the height range from 12 to 35 km and over realizations. This figure leads to the following conclusions.

(1) The optimal parametrizations provide a significantly higher accuracy of SCAE retrieval than the Lumpe parametrization does. This is especially true for wavelengths shorter than 900 nm. The errors can differ by almost an order of magnitude. The best accuracy is reached for the linear parametrization with five parameters and the logarithmic parametrization with four parameters. On the average, the best accuracy of retrieving the absolute values of the aerosol extinction coefficient is reached for the linear parametrization with five parameters.

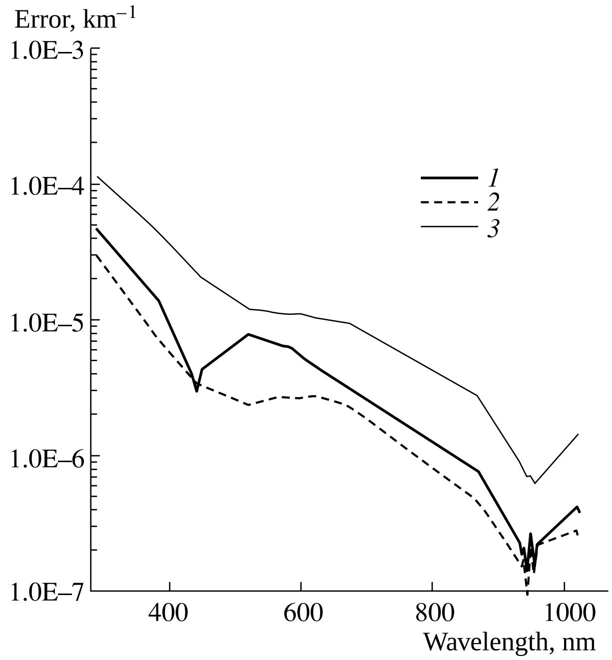

Fig. 3. Spectral behavior of the average (over the height and realizations) errors in retrieving the aerosol extinction coefficient for different parametrizations. See Fig. 1 for the curve notation.

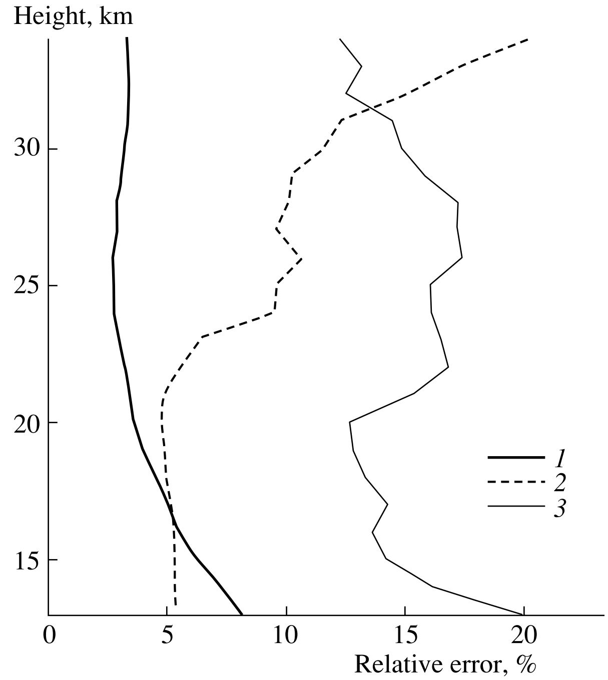

Fig. 4. Vertical profiles of the relative errors in retrieving the aerosol extinction coefficient at 290 nm for different parametrizations. See Fig. 1 for the curve notation. Numbers of the curves see in the caption to Fig. 1.

(2) The error in retrieving the spectral behavior of aerosol extinction has a general tendency to increase as the wavelength decreases. The minimum errors are observed, independently of the parametrization, for the long-wavelength spectral range of measurements with the satellite SAGE-III instrumentation. The general tendency of decreasing error with increasing wavelength is due to the fact that the relative contribution of aerosol extinction increases on the whole with wavelength and the aerosol extinction predominates over the wavelength range 1000–1550 nm. Maximum errors are characteristic of the short-wavelength measuring channel (290 nm). At this wavelength, the extinction of radiation in the atmosphere (basically through ozone absorption and molecular scattering) is so high that the atmospheric transmittance along slant paths with tangent heights of 40 km or smaller is negligible. For this wavelength and tangent heights smaller than 40 km, the aerosol characteristics is actually obtained by extrapolating the aerosol extinction values determined at longer wavelengths. Results of such extrapolations are significantly dependent on the parametrization of the aerosol extinction spectral behavior. In this spectral range, the Lumpe parametrization, which is represented rather arbitrarily as a polynomial in the wavelength logarithm, allows the retrieval of the aerosol extinction with a significant error of about 17%. The optimal parametrizations provide a higher extrapolation accuracy, which is due to the use of an optimal empirical basis compatible with the behavior of the spectral extinction of stratospheric aerosol. At 290 nm, the logarithmic optimal parametrization with four parameters and the linear optimal parametrization with five parameters provide errors of about 4 and 8%, respectively. In terms of the absolute values of errors, the advantage of the optimal parametrizations is even more significant (see Fig. 3).

We note the following. The gas absorption bands are localized within certain spectral ranges, and the aerosol extinction is a factor interfering with the retrieval of gas concentrations. Therefore, the error in retrieving the aerosol extinction coefficient in these spectral ranges significantly influences the errors of O_3 and NO_2 retrieval [14]. Analogously, the atmospheric gases interfere with the retrieval of the aerosol extinction coefficient in their absorption bands. An analysis of the numerical experiments carried out in [14] shows that, in individual realizations, high errors in retrieving the aerosol extinction coefficient at 290 nm lead to noticeable errors in retrieving the ozone concentration in the height range 40–50 km. This conclusion relates primarily to computations based on the Lumpe parametrization.

For a more detailed treatment, we will present the vertical profiles of the errors in retrieving the aerosol extinction coefficient for individual wavelengths (Figs. 4, 5). For this purpose, we choose the measuring channels at 290 and 441 nm in the ozone and nitrogen dioxide absorption bands, respectively. The former channel gives little information (see above) on the lower atmospheric layers because of a large optical thickness of atmospheric ozone and extinction by molecular scattering. Therefore, the results obtained for this channel characterize the accuracy of extrapolating the aerosol extinction coefficient to this wavelength at different heights for different parametrizations.

The advantages of the linear optimal parametrization with five parameters and logarithmic optimal parametrization with four parameters are doubtless for channels of 290 and 441 nm. For the channel 290 nm, the error associated with the Lumpe parametrization is two to four times greater than that for the optimal parametrizations (except for the linear optimal parametrization at heights above 31 km). For the channel 441 nm, the errors thus computed for some atmospheric heights differ by a factor of ten or more. In addition, we note the following. The logarithmic optimal parametrizations (and the linear optimal parametrization for the channel 441 nm) allow the retrieval of the aerosol extinction coefficient in the height range 12–40 km with a uniformly high accuracy. The Lumpe parametrization allows the retrieval of this coefficient with an acceptable error equal to 1–6% by using the channel 441 nm for the narrow height range 18–24 km, while beyond this height range, this parametrization leads to a significant increase in the error of retrieval. If we take into consideration that this spectral range is used to determine the NO_2 concentration, the results presented in the table and Fig. 4 from [14] and illustrating significant errors in NO_2 retrieval with the Lumpe parametrization become clear.

We note that the spectral range in the vicinity of 600 nm is used to obtain information on stratospheric ozone. For this spectral range, the SCAE retrieval errors for the optimal parametrizations are 1.5 to 4 times smaller than the error for the Lumpe parametrization.

For further analysis, it is necessary to take into account that radiation absorption by ozone in the channels 290 nm and near 600 nm is significantly greater than radiation absorption by nitrogen dioxide in the vicinity of 440 nm. Therefore, on the one hand, the aerosol extinction coefficient can be retrieved with lower errors for the NO_2 absorption band than for the ozone absorption band and, on the other hand, the error of the aerosol extinction influences the error of NO_2 retrieval to a greater extent than the error of ozone retrieval [14].

An analysis of the data presented in Figs. 4 and 5 together with the data of the table given in [14] confirms this assumption. First, the optimal parametrizations, namely, the linear one with five parameters and the logarithmic one with four parameters, prove to be the best from the standpoint of minimizing the errors in retrieving the gas concentrations and the aerosol extinction coefficient. Second, the effect of the parametrization type on the error of ozone retrieval is much less

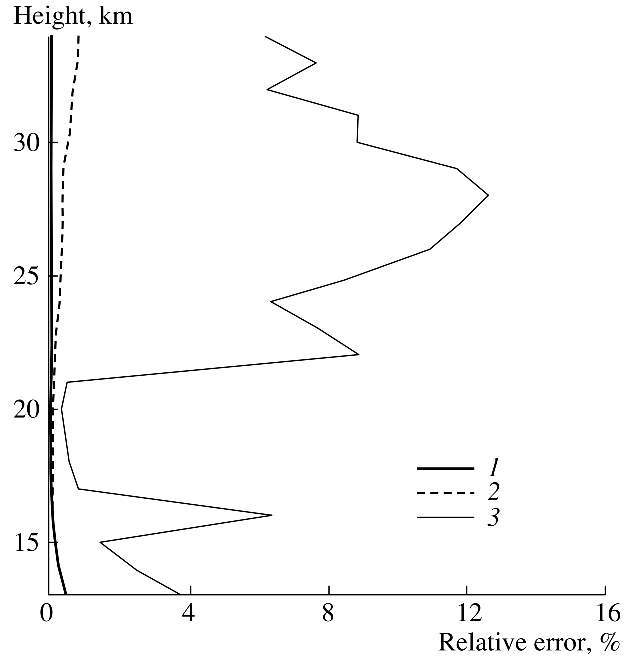

Fig. 5. Vertical profiles of the relative errors in retrieving the aerosol extinction coefficient at 441 nm for different parametrizations. See Fig. 1 for the curve notation.

than on the error of nitrogen dioxide retrieval. Actually, the best aerosol extinction coefficient retrieval in the vicinity of 440 nm is achieved for the linear optimal parametrization with five parameters; this parametrization also provides the best NO_2 retrieval.

We note that the potential accuracies of retrieving the aerosol extinction coefficient at other wavelengths is very high. The error of retrieval on the basis of the optimal parametrizations usually does not exceed 1%. The accuracy is especially high for retrieving the aerosol extinction coefficient at 1000 nm. This channel is characterized by a retrieval error of 0.01–0.1% independently of the parametrization. For this wavelength, the differences between the errors characteristic of different parametrizations are smaller than for shorter wavelengths. We have noted above that this is due to the fact that aerosol makes the main contribution to solar radiation extinction in this spectral range. Nevertheless, the logarithmic optimal parametrization with four parameters offer advantages in long-wavelength channels as well.

SCAE retrieval for different heights can be used to obtain information on aerosol microphysical characteristics, primarily, on the aerosol size distribution. For this aim, the corresponding inverse problem should be solved [8–11]. In this connection, we will consider two examples of SCAE retrieval on the basis of different parametrizations of aerosol extinction (Figs. 6, 7).

For the realization presented in Fig. 6, the minimum error in retrieving the aerosol extinction coefficient at a height of 22 km is reached on the basis of the linear

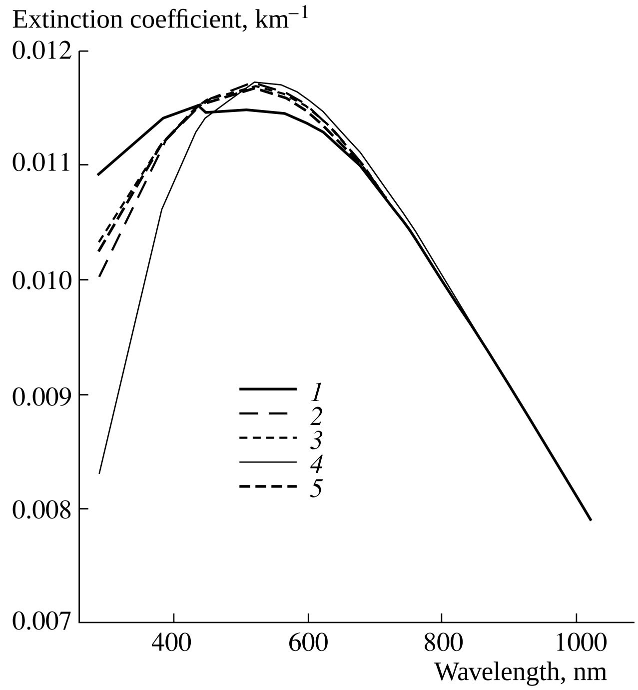

Fig. 6. Example of retrieving the spectral behavior of the aerosol extinction coefficient at a height of 22 km: (*1*) logarithmic optimal parametrization with four parameters, (*2*) linear optimal parametrization with four parameters, (*3*) linear optimal parametrization with five parameters, (*4*) Lumpe parametrization and (*5*) exact solution.

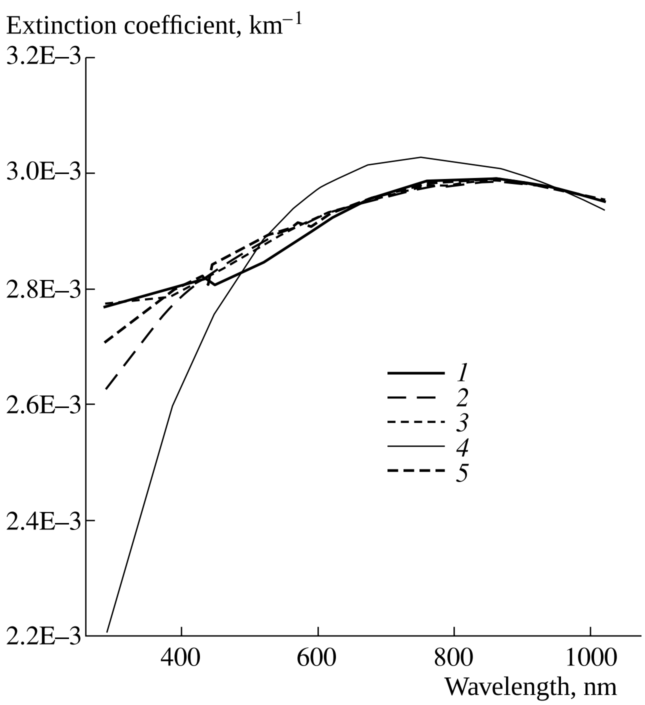

Fig. 7. Example of retrieving the spectral behavior of the aerosol extinction coefficient at 28 km. See Fig. 6 for the curve notation.

optimal parametrization with five parameters. A fairly high accuracy is also reached for the linear optimal parametrization with four parameters. Computations on the basis of the Lumpe parametrization give the maximum error of retrieval. This parametrization leads to significant errors at wavelengths shorter than 500 nm; the aerosol extinction retrieved for this spectral range is underestimated by more than 20%. For the spectral range 500–850 nm, the Lumpe parametrization leads to the overestimation of the aerosol extinction. This overestimation influences the accuracy of ozone retrieval. The application of the logarithmic parametrization to this problem also gives unsatisfactory results; namely, the retrieved aerosol extinction is overestimated for the spectral range 290–400 nm and underestimated for the spectral range 400–650 nm.

For a height of 28 km (see Fig. 7), the optimal parametrizations provide nearly the same accuracy of retrieving the aerosol extinction coefficient in the short-wavelength spectral range 290–350 nm. The Lumpe parametrization is significantly inferior to the optimal parametrizations in the retrieval accuracy for both the short-wavelength spectral range (underestimated aerosol extinction values) and the long-wavelength spectral range 500–900 nm (overestimated aerosol extinction values).

A combined analysis of the errors of SCAE retrieval for individual realizations and of the errors of ozone and nitrogen dioxide retrieval shows a clearly defined correlation between these errors: an increase in the errors of retrieving the aerosol extinction coefficient is accompanied by an increase in the errors of retrieving the gas concentration. The parametrizations providing the lowest error of SCAE retrieval in the vicinity of 600 nm simultaneously provide the lowest error of ozone retrieval (see Fig. 1 in [14]).

A similar correlation is observed between the errors in retrieving the NO_2 concentration and the aerosol extinction coefficient in the vicinity of 440 nm (see Fig. 2 in [14]).

MAIN CONCLUSIONS

The inverse problem of retrieving the spectral and height behaviors of the atmospheric aerosol extinction coefficient is simulated numerically as applied to the satellite measurements with the SAGE-III instrumentation. The simulation results lead to the following conclusions.

(1) To interpret satellite measurements of the slant-path atmospheric transmittance, the linear optimal parametrization (with four or five parameters) of the aerosol extinction spectral behavior is the most promising. On the average, such parametrizations provide minimum errors in retrieving the height and spectral behaviors of the aerosol extinction coefficient. We note that, owing to their simple linear form, these parametrizations present no difficulties in solving the complex

inverse problem of the simultaneous retrieval of the vertical profiles of ozone, nitrogen dioxide, and the SCAE.

(2) The advantages of the linear and logarithmic optimal parametrizations are especially significant in retrieving the aerosol extinction coefficient for a short-wavelength spectral range. As a result, a highly accurate extrapolation of the SCAE values from the long-wavelength range, where significant information on aerosol is contained, to the wavelength 290 nm (the last measuring channel of the SAGE-III instrumentation) is feasible. In the spectral range of this channel, the optimal parametrizations lead to retrieval errors that can be several times lower than those for the Lumpe parametrization.

(3) The linear optimal parametrizations based on an empirical orthogonal basis [12] allow a highly accurate retrieval of the aerosol extinction spectral behavior in the wide spectral range from 290 to 1500 nm. This conclusion gives promise that the inverse problem of the next stage, namely, the retrieval of the vertical profiles of the microphysical characteristics of stratospheric aerosol, will be solved with a high accuracy.

The above analysis of the ultimate accuracy of SCAE retrieval from SAGE-III measurements can be useful in designing a more sophisticated algorithm for satellite data processing.

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