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A volcanism dependent model for the extinction profile of stratospheric aerosols in the UV-visible range

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Abstract. We present a climatological model of the extinction coefficient of stratospheric aerosols in the UV-visible range based on SAGE II data. The model is a function of wavelength, latitude, relative altitude with respect to the tropopause and depends on the volcanism level. The vertical structure describes the tropopause region, the Junge layer and the high altitude domain. The model is shown to predict realistic extinction profiles with an reasonable accuracy.

1. Introduction

Volcanism may be considered as the major source of the high variability of stratospheric aerosols and the Pinatubo eruption in June 1991 enhanced the stratospheric optical thickness by two orders of magnitude. Moreover, due to the microphysical evolution after an eruption [*Russell et al.*, 1993], aerosol is the most changing stratospheric constituent over decadal periods. Therefore, it clearly influences the Earth's radiative budget and the heterogeneous chemistry processes involved in global ozone depletion.

From the data collected by the SAGE II experiment [*Chu et al.*, 1989], several climatologies have been built [*Hitchman et al.*, 1993] [*Thomason et al.*, 1997] for describing background and volcanic aerosols [*McCormick et al.*, 1996]. They result in a better knowledge of the spatial and geographic distribution of aerosol [*Trepte et al.*, 1994] and its role in heterogeneous processes [*Thomason et al.*, 1997].

Most of the above-mentioned works have used the infrared SAGE II channel at $\lambda = 1.02\ \mu m$ as representative of the aerosol loading although [*Thomason et al.*, 1997] derived surface area density information by using principal component analysis over the 4 standard aerosol channels of SAGE II at wavelengths of 0.385, 0.453, 0.525 and 1.02 μm.

Beside its evident impact on the modelization of the stratosphere, aerosol affects the accuracy of remote sensing retrievals, especially in the UV-visible range. Indeed, the spectral dependence on wavelength may interfere with all absorbers or scatterers characterized by a continuum. Furthermore, large eruptions can give rise to excessive slant path optical thicknesses for limb occultation instruments.

Our model named ECSTRA (=Extinction Coefficient for STRatospheric Aerosol) has been developed as part of the GOMOS experiment [*Bertaux et al.*, 1991] in the future ENVISAT mission. The development of inversion algorithms required an aerosol model for simulating the whole processing chain. This model must be realistic, robust, depending on both wavelength and altitude variables. It should be able to simulate a very clean or a highly volcanic stratosphere. Although not capable of describing fine spatio-temporal structures, the model may turn out to be a useful and easy-to-handle tool for others, not only in the field of remote sensing but also for radiative transfer calculations or modelling.

2. Data Processing and Parameter Definition

We based the ECSTRA model on the SAGE II data measured from Oct 84 until Dec 95. Standard averaging techniques [*Hitchman et al.*, 1993] have been applied to reject outliers and led to a more significant description of the extinction dependence in the altitude z, latitude φ and wavelength λ. This procedure produced an array of 135 temporal bins (monthly averaged) times 16 latitudinal bins ($\Delta\varphi = 10$ degrees) times 50 vertical bins ($\Delta z = 1\ km$) times the nominal 4 wavelength bins.

As usually, the total optical thickness at 1.02 μm can be defined from the extinction profile β as:

$$\delta = \int_{z_t+2\ km}^{\infty} \beta(z, 1.02)\ dz \tag{1}$$

where the lower bound is located 2 km above the bin mean tropopause z_t in order to limit contamination by clouds. One can also compute a global mean optical thickness $\bar{\delta}$ by

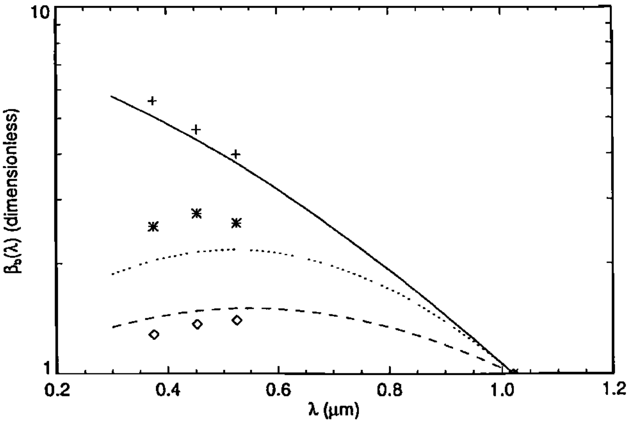

Figure 1. SAGE II spectral extinction β_b at $z = 20.5\ km$ (symbols) and related profiles computed by ECSTRA (lines) on April 15th, 1989 (+, *solid*), June 15th, 1993 ($*$, *dotted*) and June 15th, 1992 ($\diamond$, *dashed*). Volcanism values are respectively $V = 3.1$, $V = 5.2$, $V = 6.7$.

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Table 1. Spectral coefficients (See eq. (7))

	k=0			k=1			k=2		
	j=0	j=1	j=2	j=0	j=1	j=2	j=0	j=1	j=2
α_{1jkl} :									
l=0	−12.3	−9.13	−.393	4.07	3.76	.0794	−.355	−.405	.0431
l=1	4.54	.793	.301	−2.18	−.282	−.168	.228	.0303	.00337
l=2	−.499	.0877	−.0422	.239	−.0407	.0224	−.0257	.00429	−.00115
l=3	.0151	−.00646	.00139	−.00717	.00295	−.000692	.000773	−.000312	.000044
α_{2jkl} :									
l=0	−4.96	−15.4	−.486	1.57	6.58	−.115	−.157	−.698	.0889
l=1	4.24	.641	.0691	−2.15	−.131	−.0958	.222	.00569	−.00795
l=2	−.522	.258	−.0816	.273	−.128	.0452	−.0289	.0147	−.00348
l=3	.0173	−.0156	.00481	−.00899	.00760	−.00242	.000959	−.000851	.000234

taking the meridional average of δ. The bell-shaped latitudinal dependence and weak zonal variation [*Trepte et al.*, 1994] of δ suggested to use λ , φ and z' as basic parameters, where

$$z' = z - (z_t + 2\ km) \tag{2}$$

Since the volcanic aerosol loading influences the spectral and vertical properties of the extinction coefficient, we defined a global volcanism parameter V as

$$V = \ln(1 + \frac{\overline{\delta}}{\delta_0})\ \ with\ \delta_0 = 10^{-4} \tag{3}$$

where the logarithm facilitates smooth interpolations of the extinction profile properties. δ_0 is just an arbitrary scaling quantity, not a possible background optical thickness. It is clear that V only does make sense when the global geographical spreading of a volcanic cloud is complete and ECSTRA is not expected to be accurate in transient regimes (3-12 months) after eruptions. Seasonal variations are also smoothed out in the definition of V and can only be described through the evolution of the tropopause. Nevertheless, this simple definition of V allows simple temporal simulations when new eruptions of amplitude A_i at time t_i superimpose on relaxing aerosol from previous events as

$$\overline{\delta}(t) = \sum_i A_i \exp(-(t - t_i)/\tau_i)\ \ [t \geq t_i] \tag{4}$$

Typical decay times τ_i have been reported to be about 9-12 months and V was found to range from 2 to 7 for real data between October 84 and December 1995. Future or past eruptions could be described by fitting $\overline{\delta}$ to measured or assumed values.

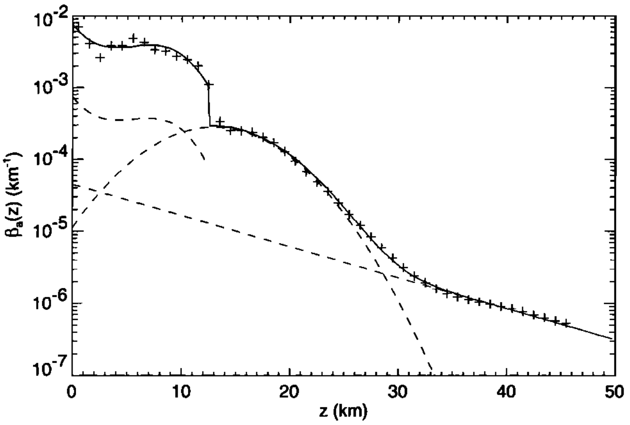

Figure 2. Mean SAGE II vertical extinction β_a (+) for May 1991 at $\varphi = 55\ S$ and corresponding profile computed by the Levenberg-Marquardt minimization scheme (solid line). $V = 2.7$, $z_t \simeq 10.5$. The contribution of clouds (9) and of both aerosol terms (10) are indicated by the dashed lines. The cloud contribution has been divided by 10 for the sake of clarity.

3. Analytical Formulation

Considering β as a macroscopic quantity[*Fussen et al.*, 1998], we express it as:

$$\beta\left(z', \lambda\right) = \beta_a\left(z'\right) \cdot \beta_b\left(\lambda\right) \tag{5}$$

where $\beta_a\left(z'\right)$ is the vertical profile at 1.02 μm (in km^{-1}) while $\beta_b\left(\lambda\right)$ is the dimensionless spectral dependence. This formal separation reflects the presence of a steep vertical structure (through the aerosol layer) and a smoother spectral dependence. In fact, we have been led to also introduce a vertical variation of the aerosol optical properties as shown below, keeping in mind that, for coherency, this variation should remain smaller than the variation described by $\beta_a\left(z'\right)$.

3.1. Spectral Dependence

We have expressed the wavelength dependence as:

$$\beta_b\left(\lambda\right) = e^{\left(a_1 \Delta\lambda + a_2 \Delta\lambda^2\right)}\ \ with\ \ \Delta\lambda = \lambda - 1.02 \tag{6}$$

This exponential dependence was suggested by [*Yue*, 1986] and has the advantage of being positive everywhere. We used a quadratic argument as the minimal form capable of describing the extremum observed during periods of high volcanism [*Russell et al.*, 1993]. Both a_i are function of the basic parameters $\theta = \frac{\pi}{2} - \varphi$, z' and V according to the following expansion:

$$a_i = \sum_{j=0}^{2} \sum_{k=0}^{2} \sum_{l=0}^{3} \alpha_{ijkl} \cdot P_{2j}(\theta) \cdot V^k \cdot z'^l \tag{7}$$

where the $P_{2j}(\theta)$ are Legendre polynomials symmetric with respect to the equator. The α_{ijkl} (see table 1) were computed by solving the associated linear least-squares problem for the binned SAGE II data.

Table 2a. Vertical fit coefficients (See eq. 11- 14)

term in:	u_1	u_2	u_{45}	v_{45}	w_{45}	u_5	v_5
P_0	.130E+1	.938E+1	.804E+0	−.229E+0	.440E−1	.149E+0	.222E−2
P_2	−.610E−1	−.134E+1	.229E+0	−.675E−1	.123E−1	−.856E−2	−.129E−3
P_4	.103E+0	.220E+1	−.353E+0	.868E−2	.298E−2	−.248E−1	.182E−2

Table 2b. Vertical fit coefficients (*ctd*)

term in:	x_6	x_7	x_8	x_9
P_0	−.120E+2	−.256E+1	−.330E+0	−.995E−2
P_2	.469E+1	.220E+1	.192E+0	.702E−2
P_4	.196E+1	−.763E+0	−.214E+0	−.115E−1

Typical spectral dependences of β are shown in figure 1. This confirms that the spectral dependence is affected by high volcanism [*Brogniez et al.*, 1996] implying the presence of larger particles.

3.2. Vertical Dependence

The main structure of the stratospheric aerosol profile is the well-known Junge layer located a few km above the tropopause. However, the transition at this level is not always clear, depending on volcanism. At higher altitudes, a systematic slope change in the aerosol extinction profile can be detected in the experimental results, indicating that the aerosol particles become very small [*Weisenstein et al.*, 1997]. We discovered that the following expressions produce a good fit over the whole altitude range:

$$\begin{aligned} \beta_a(z') &= \beta_{aero}(z') + \beta_{cloud}(z') \qquad z' < 0 \\ &= \beta_{aero}(z') \qquad z' \geq 0 \qquad (8) \end{aligned}$$

where

$$\beta_{cloud}(z') = \left[e^{x_6 + x_7 z' + x_8 z'^2 + x_9 z'^3} \right] km^{-1} \qquad (9)$$

and

$$\beta_{aero}(z') = \left[e^{x_1 + x_2 z'} + e^{x_3 - \left[(z' - x_4)/x_5 \right]^2} \right] km^{-1} \qquad (10)$$

The vertical profile is non-linear with respect to the parameters $x_i, i = 1..9$ which have been optimized by using a standard Levenberg-Marquardt minimization scheme running over the whole altitude range. In (8), we have included a tropospheric cloud contribution which allows the true stratospheric aerosol contribution to be freely determined (i.e. not influenced by the cloud component when matching the tropopause). This cloud contribution is ex-

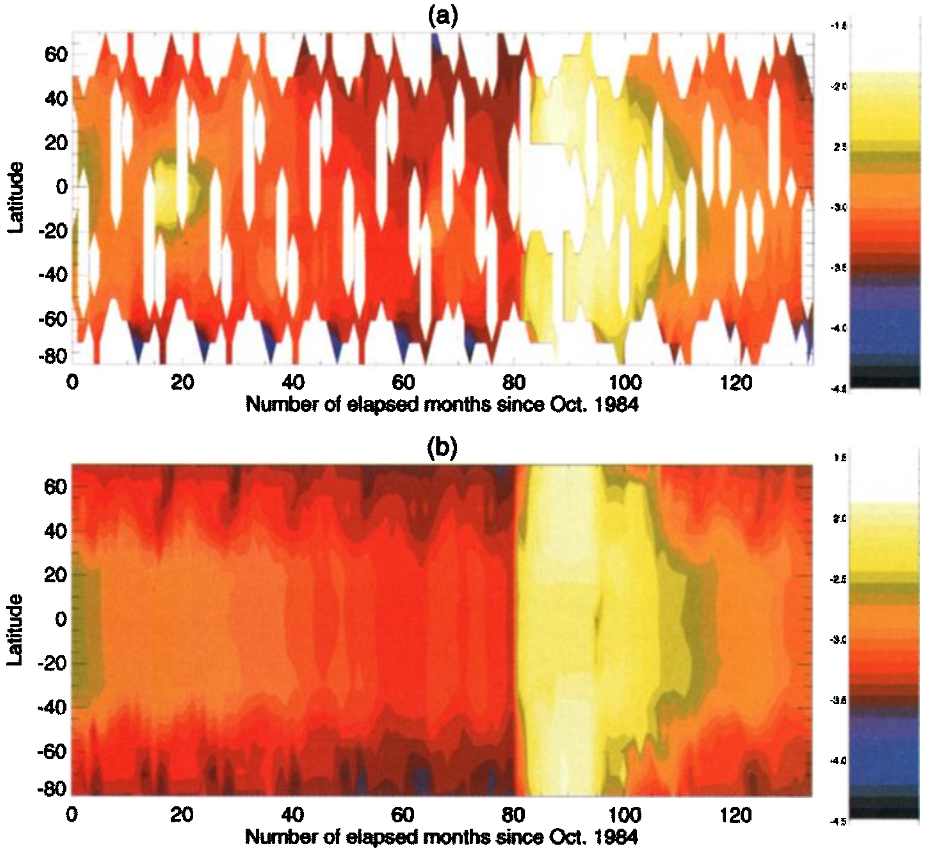

Figure 3. $\log(\beta(20.5\ km, 0.525\ \mu m))$ as a function of time and latitude. (*a*) SAGE II data; (*b*) ECSTRA results.

pected to vanish abruptly above the tropopause. The first term in (10) is related to the slope change at higher altitudes. The latter one describes a peak centered at x_4 with an amplitude $\exp(x_3)\ km^{-1}$ and a width x_5 corresponding to the Junge layer. Both contributions are naturally constrained to be positive during the optimization procedure. A typical vertical profile at 1.020μm is shown in figure 2.

The dependence of the x_i on latitude and volcanism has been modelized by:

$$V_{\min} = \ln\left(1 - \frac{e^{x_1}}{\delta_0 \cdot x_2}\right) = u_1 \quad (11)$$

$$-\frac{1}{x_2} = u_2 \quad (12)$$

$$\frac{x_4}{x_5} = u_{45} + v_{45}\left(V - V_{\min}\right)^2 + w_{45}\left(V - V_{\min}\right)^3 \quad (13)$$

$$\frac{1}{x_5} = u_5 + v_5\left(V - V_{\min}\right)^2 \quad (14)$$

while x_3 is derived from the δ value related to (10):

$$\delta = -\frac{e^{x_1}}{x_2} + e^{x_3}\frac{\sqrt{\pi}}{2}x_5\left(1 + erf\left(\frac{x_4}{x_5}\right)\right) \quad (15)$$

and V_{min} is the value of V in the absence of a Junge layer (i.e. the second term of (15) vanishes). It must be noticed that the system of equations [(3), (11)-(15)] is not fully coherent, because V has been defined from $\overline{\delta}$ and not δ. Nevertheless, a close investigation of (15) showed that the error on x_3 induced by just replacing δ by $\overline{\delta}$ does not exceed a few percents. The parameters x_6, x_7, x_8, x_9 were found to be insensitive to the volcanism. All u_k, v_k, w_k, x_6, ..., x_9 have been given a symetric latitudinal dependence by expanding them over the $\{P_0(\theta), P_2(\theta), P_4(\theta)\}$ basis. (see tables 2a-2b)

4. Performances

In order to compare data computed by ECSTRA with SAGE II input data, we define the relative error on the decimal logarithm of the extinction coefficient as:

$$E_R = \frac{\log(\beta_{SAGE}) - \log(\beta_{ECSTRA})}{\log(\beta_{SAGE})} \quad (16)$$

Out of the transient periods following volcanic eruptions, E_R has been found to be about 5% in the 0-15 km range above the tropopause and for all wavelengths. For higher altitudes, E_R lies below 10% except for latitudes comprised between 30°S and 30°N, where E_R belongs to the range $10 - 20\%$ above 0.6μm and to the range $15 - 25\%$ below it.

As an illustration of the performances of the ECSTRA model, figure 3 shows the time and latitude dependences of the total extinction profile at $z = 20.5km$ and 0.525 μm. Notice that the zones of perceptible discrepancy between SAGE II and ECSTRA are related with the transients of the eruptions of Monte Ruiz in November 1985 and Pinatubo in June 1991.

5. Conclusions

The ECSTRA model is a robust tool to investigate the role of aerosols in the attenuation of light through the atmosphere. By comparison with the SAGE II data, its error range is found to be satisfactory, especially in the lower and middle stratosphere. Assuming a light scattering model, it can also be used to derive microphysical properties of aerosols. A free copy of the Fortran 77 code can be obtained by sending an electronic mail request to the authors.

In the future, we are planning to extend the spectral range of the ECSTRA model toward the infrared domain, which is not a trivial task. Indeed, important absorption structures may superimpose on scattering contributions and will complicate the description of the spectral dependence. Therefore, we will extend our data set by adding data selected from by different space borne experiments (HALOE, MLS, ISAMS, POAM,..).

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