A GLOBAL CLIMATOLOGY OF STRATOSPHERIC AEROSOLS FROM SPECTRAL INVERSION OF SAGE II EXTINCTION MEASUREMENTS: 1985-1995

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ABSTRACT

A global climatology of stratospheric aerosols over the period 1985-1995 is presented, derived from spectral extinction measurements taken by NASA's SAGE II instrument.

A new algorithm was developed to deduce aerosol size distributions from forward extinction measurements. It is based on the Anomalous Diffraction Approximation (ADA) to Mie scattering theory and is applicable to spherical particles, either transparent or absorbing. The algorithm was especially designed for use with scarce and noisy data and does not require *a priori* information about the shape of the size distribution.

Maps of number density, surface area density, volume density and effective radius density are presented. The retrieved aerosol properties are interpreted and compared with earlier published results.

1. INTRODUCTION

A global climatology of stratospheric aerosols over the period 1985 - 1995 is presented, based on a new spectral inversion algorithm.

Aerosols have many influences on the atmosphere, such as, changes of net radiative fluxes, temperature, affection of ozone concentration and other related chemical constituents, etc. In June 1991, the Pinatubo volcano eruption provided an opportunity to test theoretical models describing aerosol-chemistry-climate interactions. A prerequisite is however that sufficiently accurate aerosol parameters can be used.

NASA's Stratospheric Aerosol and Gas Experiment (SAGE) II, launched in 1984 aboard the ERBS satellite, is a solar occultation limb scanning instrument that offered a unique opportunity to characterize the effect of extra aerosol loads on the stratosphere. It yielded aerosol extinction profiles at 0.385, 0.485, 0.525 and 1.02 µm, from 15 to 50 km altitude with 1 km vertical resolution.

The presented algorithm solves simultaneously the problem of the interpolation of the aerosol spectral extinction and the closely related problem of the retrieval of the aerosol size distribution.

Hereafter, we give a brief summary of the theoretical basis and the formulation of the algorithm. We applied the algorithm to produce a global climatology of stratospheric aerosols size parameters at a fixed altitude of 22.5 km, based on SAGE II extinction measurements.

2. THEORY

The algorithm is based on the Anomalous Diffraction Approximation (ADA) (van de Hulst, 1981). The ADA is valid for spherical particles, with radius r and complex refractive index n, when $|n-1| \ll 1 \ll kr$, $k \triangleq 2\pi/\lambda$. This approximation is sufficiently accurate for many practical purposes in atmospheric remote sensing and is mathematically more tractable than general Mie theory (van de Hulst, 1981; Kerker, 1969; Sharma, 1992).

In particular, it is applicable to SAGE II data up to about 30 km in altitude. Because stratospheric aerosols mainly consist of transparent droplets of a water and sulfuric acid mixture, we used a real refractive as in Wang et al., 1989.

For a comprehensive overview of the theoretical aspects of spectral inversion in the ADA, see Franssens et al., 2000.

3. ALGORITHM

3.1 Basis functions

Consider a sampling of the r-domain $\{r_n > 0, n \triangleq 0, N\}$. Let $\hat{A} \triangleq \{A_n(r), n = 1, N\}$ denote a set of compact support basis functions in the r-domain, with

$$A_n(r) \triangleq \frac{1}{h_n} \begin{Bmatrix} 1, & r_{n-1} < r < r_n \\ 0, & elsewhere \end{Bmatrix}, \quad (1)$$

where $h_n \triangleq r_n - r_{n-1}$, $r_n^a \triangleq (r_n + r_{n-1})/2$, $n = 1, N$.

Let $\hat{\mathrm{B}}=\{B_n(\kappa), n=1,N\}$, $\kappa(k)\triangleq 2(n-1)k$, denote a discrete set of basis functions in the κ-domain, obtained by the forward ADA transform (Franssens at al., 2000). The basis functions $\hat{\mathrm{A}}$ form an ortho-normal set by construction. As a result of the orthogonality properties of the ADA transform kernel (Franssens at al., 2000), $\hat{\mathrm{B}}$ also forms an ortho-normal set. The basis functions $\hat{\mathrm{B}}$ in the κ-domain are explicitly given by

$$B_n(\kappa) = \frac{1}{i\kappa h_n}\left(e^{-i\kappa r_n} - e^{-i\kappa r_{n-1}} + f(-i\kappa r_n) - f(-i\kappa r_{n-1})\right) \quad (2)$$

where $f(-z)\triangleq\gamma+\ln z+\mathrm{E}_1(z)$ and $\mathrm{E}_1(z)$ denotes the exponential integral.

3.2 Representation

In terms of these basis functions we approximate the perimeter density distribution $P(r)\triangleq 2\pi r N(r)$, with $N(r)$ the number density distribution, by

$$\hat{P}(r)=\sum_{n=1}^{N} c_n A_n(r) h_n \quad (3)$$

and the extinction function by

$$\hat{\tau}(k)=\sum_{n=1}^{N} c_n\left(r_n^a - \Im\left[B_n(\kappa(k))/\kappa(k)\right]\right)h_n , \quad (4)$$

with to be determined coefficients $\{c_n, n=1,N\}$. The quantity $\hat{\tau}_\infty \triangleq \sum_{n=1}^{N} c_n r_n^a h_n$ is an approximation to the geometrical limit constant $\tau_\infty = 2\int_0^{+\infty} \pi r^2 N(r)dr$, which arises explicitly in the proper theoretical formulation of the ADA (Franssens at al., 2000).

3.3 Cost function

The unknown expansion coefficients $\{c_n, n=1,N\}$ in (3) and (4) are obtained from a least squares fit of the spectral interpolant (4) through the measurement points $\{k_m=2\pi/\lambda_m, \tau_m\pm\delta\tau_m, m=1,M\}$. We minimize the cost function

$$J_1(\{c_n\})\triangleq\frac{\sum_{m=1}^{M} w_m(\tau_m-\hat{\tau}(k_m))^2}{\sum_{m=1}^{M} w_m(\tau_m)^2} \quad (5)$$

When the given extinction data is of poor quality, the least squares fit problem can become ill conditioned. In this case we need to add a regularization cost term

$$J_2(\{c_n\})\triangleq\frac{\frac{1}{2}k\sum_{n=1}^{N-1}(c_{n+1}-c_n)^2}{\frac{1}{2}k\sum_{n=1}^{N-1}c_n^2} \quad (6)$$

and then minimize

$$J(\{c_n\})\triangleq(1-\eta)J_1(\{c_n\})+\eta J_2(\{c_n\}),\ 0\le\eta<1 \quad (7)$$

where η is a Lagrange parameter. Minimizing a cost term of the form (6) reduces the 'elastic potential energy' in the retrieved size distribution shape and hence suppresses unwanted oscillations in the curve.

We used a Generalized Reduced Gradient Method (GRGM) (Lasdon et al., 1978) to minimize the cost function (7), because this algorithm allows us to specify additional constrains on the sought coefficients. We required the coefficients to be positive and the extinction interpolant (4) to pass through the error bars. For the SAGE II data, with only four spectral values, we required in addition that $N(r)$ be symmetric.

4. SAGE II AEROSOL CLIMATOLOGY

The algorithm was applied to SAGE II spectral extinction data at 22.5 km altitude, covering the period 24 October 1984 till 31 December 1995. We computed for each location the total number density $N_{tot}\triangleq\int_0^{+\infty} N(r)dr$ [cm^{-3}], the total surface area density $S_{tot}\triangleq\int_0^{+\infty} 4\pi r^2 N(r)dr$ [$\mu m^2 cm^{-3}$], the total volume density $V_{tot}\triangleq\int_0^{+\infty}\frac{4}{3}\pi r^3 N(r)dr$ [$\mu m^3 cm^{-3}$] and an (log-normal) effective radius r_m [μm].

Other parameters used were $M=4$, $N=11$ and as Lagrange parameter $\eta=0.01$.

Figs 1a,b show respectively the spectral extinction interpolation and the retrieved number density distribution for the SAGE II event of 11 November 1984, 23:36 at 22.5 km over Laramie, Wyoming, USA. This same case was studied in Wang et al., 1989 using another method. They found for the number density $N_{tot}=0.788\ cm^{-3}$, the effective radius $r_m=0.237\ \mu m$ and

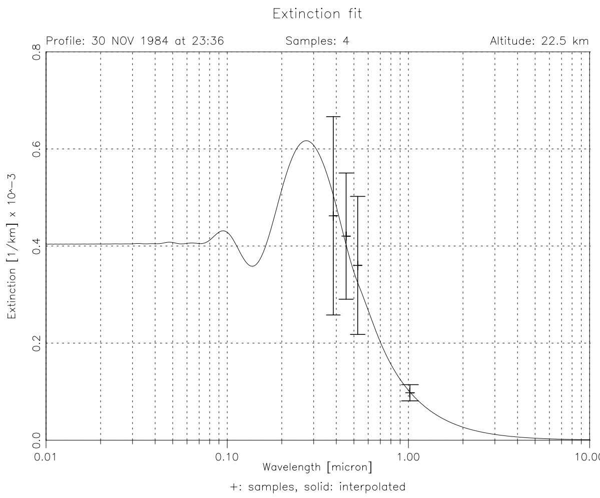

Fig. 1a. Test case spectral extinction interpolant.

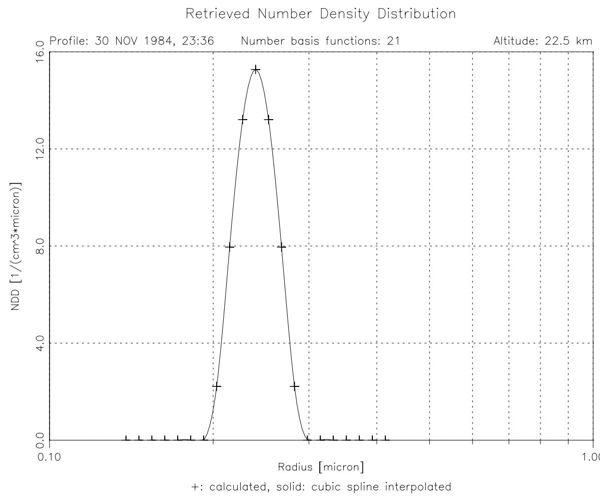

Fig. 1b. Test case retrieved number density distribution.

as variance σ=1.25. We obtained the values N_{tot}=0.818 cm^{-3}, r_m=0.241 μm and σ=1.08.

Figs. 2a,b,c,d (available from the author as color Postscript files) show the variation over longitude and latitude of N_{tot}, S_{tot}, V_{tot} and r_m on a logarithmic color coded scale, for July 1992 (about one year after the Pinatubo eruption).

Figs. 3a,b,c,d (available from the author as color Postscript files) show N_{tot}, S_{tot}, V_{tot} and r_m on a logarithmic color coded scale, versus time and latitude.

Thomason et al. deduced a global climatology for the aerosol surface area density from SAGE II data by Principal Component Analysis (PCA) (Thomason et al., 1997). Our Fig. 3b agrees very well with the general trend in their Plate 1. One clearly sees the injection of particles into the stratosphere by the (remnants of the) volcanic eruption of El Chichon (Mexico, 17.33°N, 93.20°W) on March 28, 1982, and the eruptions of Nevada del Ruiz (Columbia, 4.89°N, 75.32°W) on November 13, 1985, Kelut (Indonesia, 7.93°S, 112.31°E) on February 10, 1990 and Pinatubo (Philippines, 15.13°N, 120.35°E) on June 14, 1991. At this altitude the smaller eruption of Cerro Hudson (Chile, 45.9°S, 73.0°W) on August 15, 1991 can only be faintly distinguished from the Pinatubo injection.

In general the effects of the Pinatubo eruption as found by our method are in good agreement with earlier published values (Russell et al., 1996). Figs. 3a,b,c,d show that the relaxation time of the stratosphere after a volcanic injection is very different for surface area density, number density and effective radius. Number density has returned to almost background conditions by the end of 1993, but larger effective radii are still noticeable by the end of 1995.

Further, by comparing the four Figs. 3a,b,c,d one sees at large altitudes the simultaneous effects of cleansing of larger sized particles and re-nucleation caused by both polar vortexes. These effects are almost unnoticeable in the surface area density plot Fig. 3b.

5. CONCLUSIONS

The here presented algorithm is more powerful than most methods used before. For instance, when sufficient extinction measurements are available, it can retrieve the form of the size distribution without the need of *a priori* information. Although not used here, it can also handle extinction caused by both scattering and absorption and take the optical dispersion of the aerosol composition into account. It is numerically stable and due to the ADA also computationally fast. Being based on the ADA it cannot be used to retrieve very fine particle modes (but this would require sub UV measurements as well).

We applied the algorithm to the SAGE II data set to produce a climatology of aerosol size distribution parameters, at a fixed altitude of 22.5 km. It was found instructive to compare number density, surface area density and volume density as well as effective radius density in order to interpret aerosol evolution. Our results are in good agreement with and complement earlier published values.

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