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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Print Version
Interactive Discussion
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A 2003 stratospheric aerosol extinction and PSC climatology from GOMOS measurements on Envisat

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Abstract

Stratospheric aerosols play an important role in a number of atmospheric issues such as midlatitude ozone depletion, atmospheric dynamics and the Earth radiative budget. Polar stratospheric clouds on the other hand are a crucial factor in the yearly Arctic and Antarctic ozone depletion. It is therefore important to quantify the stratospheric aerosol/PSC abundance. In orbit since March 2002, the GOMOS instrument onboard the European Envisat satellite has provided a vast aerosol extinction data set. In this paper we present an aerosol/PSC climatology that was constructed from this data set, together with a discussion of the results.

1. Introduction

Since its discovery (Junge et al., 1961), the stratospheric aerosol layer has gained increasing attention because of its role in a number of atmospheric phenomena. The role of these aerosols at midlatitudes in heterogeneous ozone chemistry was discovered only recently (Solomon et al., 1996). Due to their optical scattering and absorption properties, aerosols have a significant impact on the Earth radiative budget (Dutton and Christy, 1992), and hence on the global climate. Stratospheric aerosols primarily consist of droplets of a sulfuric acid solution, of which the source gas SO_2 is injected in the stratosphere by strong volcanic eruptions. Events like these can increase the stratospheric aerosol loading by several orders of magnitude. The last volcanic eruption of this strength, Mount Pinatubo in the Philippines, dates already from 1991. It has provided an excellent opportunity to study the impact of aerosols on ozone chemistry, climate and atmospheric dynamics (for a general review on volcanism and the atmosphere, see Robock, 2000). Since 1991, due to slow sedimentation, the aerosol abundance has gradually decreased to the present day level, the lowest since decades. Nevertheless, the absorption/scattering efficiency of aerosols is such that they still show their imprint in a wide range of optical measurements.

Polar Stratospheric Clouds (PSCs) are usually discussed separately from sulfuric acid aerosols because the particles of which they consist have a different state, morphology and composition and because they only form at extremely low temperatures in the polar stratosphere. PSCs receive a lot of attention because Arctic and Antarctic ozone depletion is mainly induced by heterogeneous reactions on the surface of PSC particles (Solomon et al., 1986; Molina, 1991).

In this paper we present a stratospheric aerosol/PSC climatology for the year 2003 that was derived from measurements carried out by the GOMOS instrument onboard the European Envisat satellite. Such a climatology serves many purposes. In a qualitative way, a global picture of aerosols and PSCs gives insight into the reasons for the variability of these species. Furthermore, a climatology can be used in other studies that need a quantitative characterization of aerosols and PSCs, such as stratospheric chemistry modelling, optical calculations and measurement corrections. We present results for the entire year, as well as for 3-month periods to show the interseasonal variability.

2. The GOMOS instrument

The Envisat satellite was launched on 1 March 2002, and is at present fully operational. On board, it carries a range of instruments designed to measure data with specific application in a wide diversity of Earth science studies. One of these instruments, GOMOS (Global Ozone Monitoring by Occultation of Stars; see e.g. Bertaux et al., 1991, 2000; Kyrölä et al., 2004; ESA, 2001) is a UV/Visible/near-IR spectrometer that works in occultation mode: while orbiting the Earth, the instrument measures the transmission of light from stars that are setting behind the Earth's horizon. Since the starlight has to pass through the Earth's atmosphere, it is partly scattered or absorbed by atmospheric gasses and particles. The measurements therefore can be used to retrieve gas concentration and aerosol extinction profiles. Using a scanning mirror and a star tracker, GOMOS continuously observes selected stars; during one orbit, several different occultations are measured. In this way, several hundreds of occultations with good global coverage can be measured per day. Measurements are taken both on the dark and Sun-illuminated side of the Earth, although in the latter case scattered sunlight represents an extra source of error for retrievals. Given the fact that during one orbit about 30 to 50 ocultations can be measured, the entire data set for the year 2003 contains more than 100 000 occultations.

The spectrum of the starlight is measured by four spectrometers operating in a wavelength range from 250 to 950 nm. Additionally, GOMOS is equipped with two fast photometers of which the signals are used to correct for star scintillation and to retrieve high-resolution temperature profiles. While GOMOS originally was conceived as an instrument designed to measure highly accurate ozone profiles, a few other species can also be derived. Typically, the UV/Vis wavelength range combined with the sensitivity of the GOMOS spectrometers allows the retrieval of ozone, NO_2, air, NO_3, O_2 and aerosol extinction profiles. While ozone can be retrieved up to 100 km of altitude, the other species are usually only detectable from the upper troposphere to about 50 km.

3. GOMOS retrievals

The current GOMOS algorithm works in two steps (for more details, see Kyrölä et al., 1993; ESA, 2001). First, all measured transmittance spectra are inverted to slant path integrated density (for gasses) and optical thickness (for aerosols). This spectral inversion step is performed for all tangent altitudes separately, using a nonlinear least-squares algorithm. Second, using the matrix of weighting functions, these data are spatially inverted to local gas concentration and aerosol extinction profiles. Since the measurements are contaminated with residual star scintillation due to the imperfect demodulation by the fast photometers, this spatial inversion is performed with a Tikhonov regularization method, where the regularization parameter is chosen such that some predetermined target resolution is achieved.

Unlike the case for gasses, where the extinction cross sections are known from laboratory measurements, the aerosol extinction spectrum is a priori unknown. Typically, some parametrized function of wavelength is used (such as a polynomial, see e.g. Fussen et al., 2001; Berthet et al., 2002), with sufficient degrees of freedom to capture the aerosol extinction behaviour. However, the random error variance of the other constituent retrievals increases with the number of aerosol parameters. This is the case for ozone, still the main target constituent of the GOMOS mission. It is certainly the case for air retrievals, since the air and aerosol extinction spectra are both very smooth functions of wavelength. To avoid this problem, it was decided to describe the aerosol extinction with one parameter:

$$\beta_a(\lambda) = N\frac{\sigma_0}{\lambda} \tag{1}$$

with the scaling factor σ_0=3.10^{-7} cm^2 nm and N (unit: cm^{-3}) the parameter to be retrieved.

The reason for this analytical form is twofold. First, it is a decreasing function of wavelength, roughly corresponding to the extinction spectrum of moderately small particles, such as the ones that populate the 2003 stratospheric aerosol layer. And second, the decrease is less steep than the $1/\lambda^4$ Rayleigh limit, thus reducing the interdependence of aerosol and air retrievals.

Some criticism is appropriate here. While a $1/\lambda$ model may be able to describe typical background aerosol spectra, it will fail to represent large aerosol particles in volcanic periods, for which is known that they exhibit flatter spectra or show maxima in the visible wavelength range. On the other size range, for extremely small particles, the physical aerosol spectrum is by definition indistinguishable from the $1/\lambda^4$ air spectrum. In between these extreme cases, we find an entire gamut of possible spectra, some of which will look very different from our model. For all these cases, the retrievals with our model will probably be biased with respect to the actual situation. Furthermore, we should mention that Eq. (1) represents an aerosol model of which the form of the extinction spectrum is constant in altitude, a rather limited description of reality.

4. Data processing

As mentioned before, GOMOS is able to take measurements at the Sun-illuminated as well as the dark side of the Earth. For day side observations, the measurements are corrected by subtracting the bright limb component, that is measured with the upper and lower bands of the CCD detector. Nevertheless, after subtraction, the residual noise is large enough to significantly decrease the retrieval accuracy. We therefore decided to use only nighttime measurements. After this data selection, about 50 000 occultations were left to use.

The spatial grid for the climatology consists of 18 latitude bins with a width of 10°, with bin centers ranging from 85° S to 85° N. The altitude grid consists of bins having a width of 1 km, and centers ranging from 0 to 60 km. The climatology is zonal, meaning that no variations along longitude are considered. We furthermore use monthly bins, from January until December 2003.

Every bin contains a number of data points, of which the statistical distribution is a priori unknown. From visual inspection, we found that many distributions were asymmetric, with occasional strong outliers. In such cases, the statistical mean is a poor way to describe the central tendency of the distribution, and therefore the use of the median (or 0.5 percentile) was our preferred estimator. In addition, the 0.1, 0.2, 0.3, 0.4, 0.6, 0.7, 0.8 and 0.9 percentiles were calculated to describe the variance of the distributions. Typically, there are a few hundred data points in each bin.

5. Results

Figure 1 shows four plots of the logarithm of aerosol extinction at 500 nm, calculated for 3-month periods: January to March, April to June, July to September and October to December. Clearly visible is the umbrella-shaped aerosol layer, having the largest altitude above the equator and gradually sloping downwards when moving to the poles. An interesting feature is the isolated maximum in the tropics at an altitude of 15 to

17 km, that gradually moves towards the North, and then heads back southwards at the end of the year. The maximum has been observed by other instruments as well and is caused by the presence of high subvisual cirrus clouds in the tropics, while the movement is in phase with the seasonal shift of the Intertropical Convergence Zone (ITCZ) (see Wang et al., 1996). Also interesting are the elevated levels in the Antarctic region in the period July to September, most certainly caused by the occurence of PSCs in the Antarctic vortex during winter. However, no elevated extinction levels are observed in the Arctic region from January to March. This is explained by the much lower occurence of PSCs, due to the weaker polar vortex.

The median 500 nm aerosol extinction climatology for the entire year 2003 is presented in Fig. 2. The first plot again shows the logarithm of the 500 nm aerosol extinction, while the second plot shows a representation of the yearly variance, calculated with percentiles:

$$V = \frac{p_{0.8} - p_{0.2}}{2} \qquad (2)$$

This plot shows most clearly where the strongest variations in aerosol extinction are present: the already mentioned maximum in the tropics, and the Antarctic appearing and disappearing of PSCs (giving rise to strong variations up to altitudes as high as 28 km).

In Fig. 3, the PSC phenomenon is presented with more detail. Shown are climatological values for the months June, July, August and September, for latitude bins 85° S and 75° S, roughly corresponding to locations respectively inside and outside the polar vortex. While the profiles outside the vortex maintain a more or less constant shape during the entire period, one can observe a strong enhancement in the lower stratosphere inside the vortex. Furthermore, the peak gradually descends to lower altitudes as time passes by, an observation that is likely caused by the combination of downward transport, sedimentation and changing temperature.

6. Conclusions

The presented climatology was constructed from the nighttime subset of the entire 2003 GOMOS data set. Although recent aerosol values are extremely low, GOMOS has been able to provide quality aerosol extinction profiles, that exhibit all the features that ought to be expected. The typical shape of the aerosol layer, and the occurence of PSCs within the Antarctic winter vortex are only the two most prominent features that are observed in the climatology. In the near future, when the quality of the bright limb retrievals will be much better, much more profiles will be available to improve the climatology. Furthermore, an additional study will be performed to find a more adequate model for the spectral extinction behaviour of aerosols and PSCs. The general conclusion from the results presented here is that GOMOS will be able to provide a quality long-term aerosol climatology that can be used in a wide field of studies.

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Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
|◀ | ▶|
◀ | ▶
Back | Close
Full Screen / Esc
Print Version
Interactive Discussion

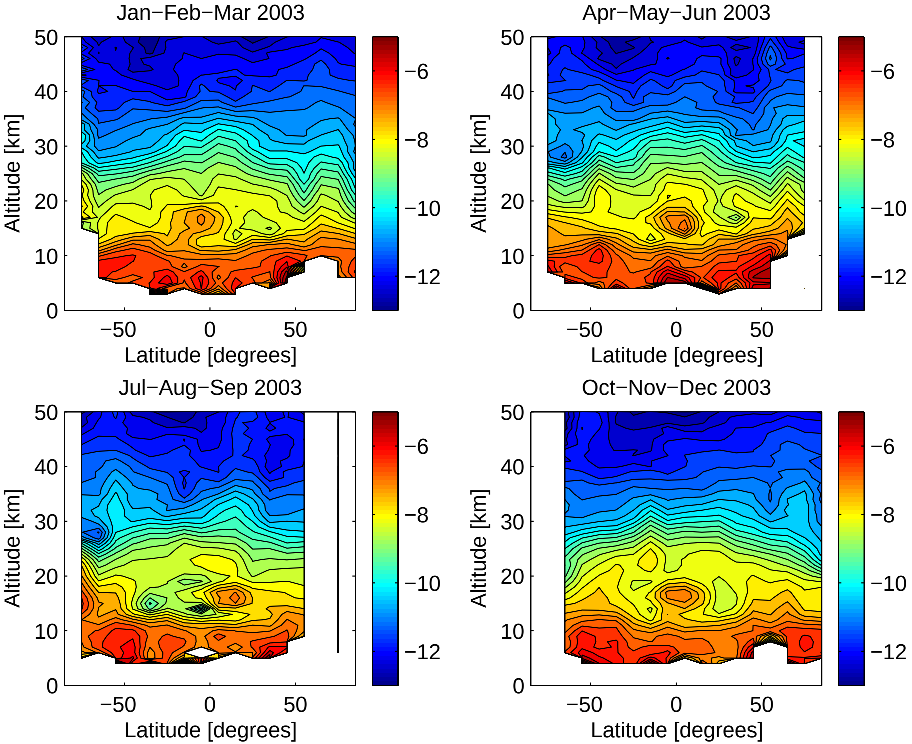

Fig. 1. The natural logarithm of the 500 nm aerosol extinction median values for 4 different periods of the year 2003. From top left to bottom right: Jan./Feb./Mar., Apr./May/June, July/Aug./Sept., Oct./Nov./Dec. 2003. Notice the movement of the maximum in the tropics, and the appearance of Polar Stratospheric Clouds in the Antarctic lower stratosphere during July/Aug./Sept.

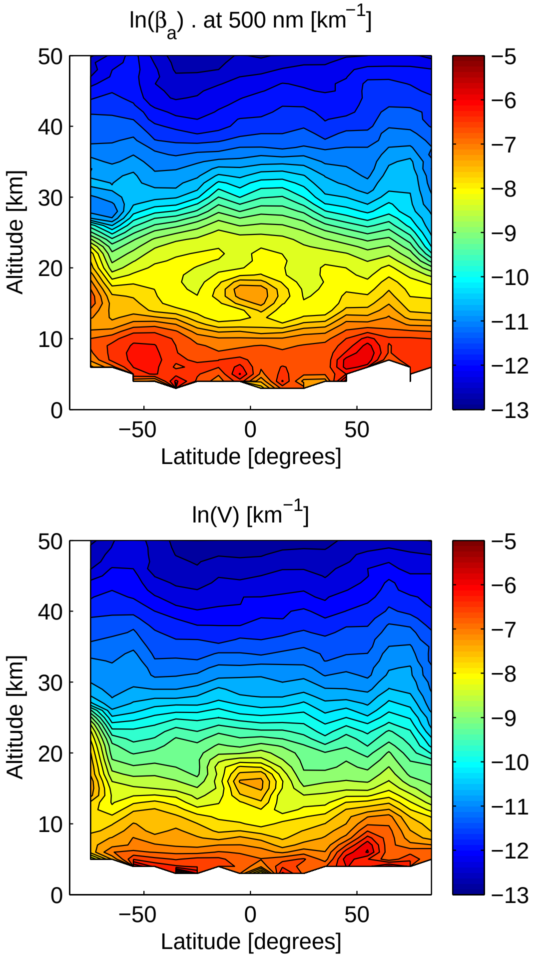

Fig. 2. Top: the natural logarithm of the 500 nm aerosol extinction median values for the year 2003. Bottom: the 500 nm aerosol extinction variability as defined in Eq. (2).

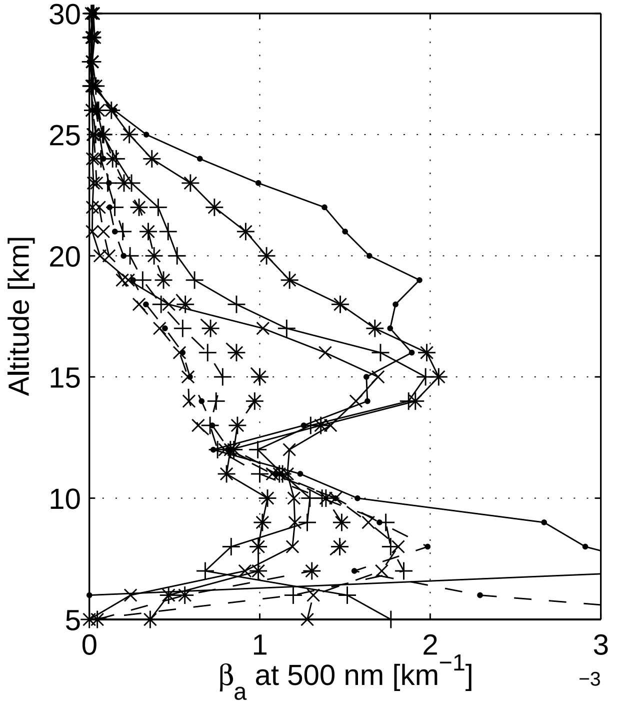

Fig. 3. The 500 nm aerosol extinction median values for June (dots), July (asterisks), August (+) and September (x) 2003, inside (75° S; solid lines) and outside (65° S; dashed lines) the South polar vortex. Data for the 85° S bin where not available for these months. The PSC signature is clearly present in the lower stratosphere above 12 km.

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
I◀
▶I
◀
▶
Back
Close
Full Screen / Esc
Print Version
Interactive Discussion
EGU