4D-VAR ASSIMILATION OF STRATOSPHERIC AEROSOL PROPERTIES USING AEROSOL EXTINCTION SATELLITE DATA

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ABSTRACT

A 4D Variational assimilation system of stratospheric aerosols has been developed. The aerosol assimilation system is applied to the 1.02 μm optical extinction data as measured by SAGE–II (Stratospheric Aerosol and Gas Experiment). A very simple model, a minimal standard aerosol model, was used for either the evolution of aerosols and for the observational operator to map observations into model values. Since this assimilation was set up to provide aerosol analyses for isolated cases, the implementation of a straightforward choice of the first-guess field and corresponding background error covariances is discussed. The results of the aerosol analysis for the period January 1989 are discussed focussing on the added value of aerosol data asssimilation. With a minimal aerosol model, the results show that the assimilation analyses offer the possibility to obtain direct global dynamically consistent information of the 1.02 μm aerosol extinction and aerosol surface area densities. The aerosol analyses can also be used to study dynamical features in greater detail.

INTRODUCTION

In the late eighties, it became clear that heterogeneous processes on polar stratospheric clouds (PSC) play a major role in polar winter/spring ozone destruction. After the eruption of Mt Pinatubo, a large ozone decrease was found which was due to the enhanced aerosol load. An overview of phenomena can be found in the Ozone Assessment Report (WMO, 1994). This discovery has lead to the inclusion of heterogeneous processes on stratospheric aerosols in the general chemical schemes of the stratospheric composition. These heterogeneous processes are commonly implemented in numerical models by simple parameterisations and climatological aerosol density fields. However, these heterogeneous processes depend with varying degrees of importance on the detailed composition and size distribution of the aerosol particles. With recent advances in stratospheric chemical modelling and in the knowledge of these heterogeneous processes, more consistent aerosol fields become necessary in these models. In general, there is growing need for availability of consistently analysed fields of stratospheric remote sensing data, either for a better understanding of processes involved in chemical composition. Chemical assimilation using the 4D–VAR technique as already shown to be very promising (Fisher and Lary, 1995). In this study, we will show first results of 4D–VAR assimilation of stratospheric aerosols. Several space-borne instruments measure optical quantities at different wavelengths related to aerosol properties. Some physical aerosol properties (number density, size distribution, and composition) are retrievable from spectral inversiondepending on the wavelength range of respective instruments. The SAGE–II sensor (Stratospheric Aerosol and Gas Experiment) was launched into a 57° inclination orbit onboard the Earth Radiation Budget Satellite (ERBS) in October 1984. During each sunrise and sunset observed by the orbiting spacecraft, the instrument uses the solar occultation technique to measure attenuated solar radiation through the Earth's limb. The 1.02 μm channel of SAGE–II is dedicated to stratospheric aerosols.

MODEL DESCRIPTION

The 4D–VAR assimilation tries to minimise the misfit or cost function between model values and observations with respect to the initial model conditions (Talagrand and Courtier, 1987). The thus obtained initial conditions Using the notation proposed by Ide *et al.* (1997), the cost function is given by:

$$J[\mathbf{x}(t_0)] = \frac{1}{2}[\mathbf{x}(t_0) - \mathbf{x}^b(t_0)]^T \mathbf{B}_0^{-1}[\mathbf{x}(t_0) - \mathbf{x}^b(t_0)] + \frac{1}{2}\sum_{j=0}^{n}(H_j[\mathbf{x}(t_j)] - \mathbf{y}_j)^T \mathbf{R}_j^{-1}(H_j[\mathbf{x}(t_j)] - \mathbf{y}_j) \qquad (1)$$

The 3-D model field is represented by $\mathbf{x}$. The first guess or background values $\mathbf{x}^b(t_0)$ are defined at $t = t_0$, and $\mathbf{B}_0$ is the estimated background error covariance matrix. The observations are denoted $\mathbf{y}_j$ and $\mathbf{R}_j$ is the error covariance matrix, the suffix j represents the model time–step. The observational operator, H_j, maps the model values into the observational space. The solution of the minimisation process are model initial conditions such that the model solution reproduces the observations to some degree determined by the ratio $\mathbf{R}_j/\mathbf{B}_0$ for the assimilation time period given by n in equation 1. The model describing the aerosols consists of two major parts: the transport model and the aerosol model. The transport model has varying horizontal resolution equivalent to a T21 , T42 or a T63 resolution, with 5 vertical stratospheric levels. The 3–D grid uses the same coordinates as the low–resolution version of the European Centre for Medium–Range Weather Forecasts (ECMWF) weather prediction model. The advection is implemented using the semi–lagrangian scheme of Smolarkiewicz and Rash (1991). The driving dynamical fields are from ECMWF analyses. In this study, the model was run in a T21 resolution with 6-hour time-step. Although aerosols are characterised by their size distribution and composition, this aerosol information is not completely available in the SAGE–II data due to the limited spectral range of the measurements. Thomason *et al.* (1997) derived an aerosol surface climatology from the aerosol extinctions and proposed a simple relationship to derive surface area densities from the 1.02 μm extinction. This straightforward concept forms the basis of our minimal aerosol model and observational operator. Neglecting variations in aerosol size distribution, and relying on the existance of this simple relationship bewteen optical extinction and surface density, a unique mapping of optical extinction at 1.02 μm to number density forms a simple observational operator. This implies that in the model surface aerosol variations can only originate from number density variations. This simplification is enforced by the utilisation of the optical extinction at only 1 wavelength. Since satellite aerosol data have successfully been used to deduce stratospheric circulation (Trepte and Hitchmann, 1992), the sulphate aerosols are considered as inert tracers. Finally, with this minimal aerosol model, events as thin cirrus clouds and polar stratospheric clouds are thus not taken into account in this minimal aerosol model. For the SAGE–II data, the retrieved profiles of the 1.02 μm extinction and the associated error estimates (Chu *et al.*, 1989) have been used directly in the assimilation process. The data are mapped on the nearest horizontal model grid point, and interpolated on the vertical model levels. In the assimilation system, data within the time interval [t+Δt/2,t-Δt/2] are considered instantaneous at model time t, with Δt the model time–step. In this implementation, the observation errors were assumed to be spatially uncorrelated, the covariance matrices were therefore diagonal. The observations errors as estimated by SAGE–II were used without further additional model resolution dependent representativeness error estimates. The minimisation process requires the explicit knowledge of the gradient vector of the cost function with respect to the model initial state. This gradient vector is determined by integrating backward the adjoint model. The adjoint model is constructed with the aid of an automatic differentiation tool,TAMC (Giering, 1997). The quasi-Newton algorithm M1QN3 from INRIA (Gilbert and Lemaréchal, 1989) has been used in the minimisation of the cost function. Since it is envisaged to perform assimilation of aerosol properties on isolated cases, the background term and its error covariance are prepared starting from the SAGE–II optical extinction data. The data are interpolated (and extrapolated) on to the model grid using the technique described in Franssens *et al.* (1998) for the month covering the assimilation period. This interpolated field is then used as background. The background error covariance matrix is the temporal covariance in the interpolated aerosol fields for a 3–month period, in this case Dec–Jan–Feb, for 2 successive years. Thus the background error covariance takes into account the temporal variability of the aerosols properties as present in the SAGE–II data.

RESULTS

An arbitrary period was selected to test the implementation of the aerosol model and the behaviour of the assimilation process. The assimilation properties were determined for period with a low aerosol load starting on January 10, 1989. In this study, a 20–day assimilation time window was taken to maximise the data information content. Different experiments were set up: (i) $\mathbf{B}_0$ (see equation 1) as described above, (ii) B_0 increased by a factor of 30, (iii) same as (ii) but with every second observation for each hemisphere not taken into account, and, (iv) same as (ii) but with a 10–day assimilation time window. The first two experiments were used to study the influence of $\mathbf{B}_0$ on the final result. It was found that the temporal variability of the background term, deduced from the SAGE–II data and represented by $\mathbf{B}_0$, was not large enough. This is easily explained by the relatively poor data coverage. The third experiment allowed an assessement of the analysis by comparing aerosol profiles between the analysis and observations at locations where the observations were not taken into account in the assimilation process. An example of analysed aerosol profiles, for experiments (ii) and (iii) is shown in Figure 1. In this example, the observation was not taken into account in the assimilation in experiment (iii) and is reproduced by the analysis to the same degree as for experiment (ii). In general, the assimilation analysis constraint by only half of the observations, is able to reproduce the observed properties. However larger deviations between the model and observations are found in the tropical regions at lower altitudes. As already mentioned, the SAGE–II data can be contaminated by thin cirrus clouds in the tropical regions. The aerosol model is not able to take into account these events when occurring and therefore several observations in the tropics are found difficult to reproduce, mainly at the two lowest model levels (70 and 100 hPa). Using the statistical model of Kent *et al.* (1993), we found that these observation were not pure aerosols. This can be considered as an advantage, as to aid in the detection of non-aerosol events when the statistically derived models are not valid. An important disadvantage is the possible uncontrolled intrusion of these cirrus cloud events in the assimilation process, for example in experiment (iii). Figure 2. shows the assimilated aerosol extinction at 30 hPa for January 15, 0 UT, for experiment (ii). Compared to the background (Franssens *et al.*, 1998), which represents up to some extent a climatological picture, the aerosol fields exhibit a greater dynamical variability with high optical extinction values in the tropics decreasing towards high latitudes. The analysis shows in greater detail the dynamical features. In Figure 2 a streamer is observed east of Japan showing transport of tropical into mid–latitudes. The lifetime of this streamer as deduced from the analyses is approximately 3–4 days, which is consistent with other studies (Riese *et al.*, 1999). The main features of this streamer are also present in the other experiments.

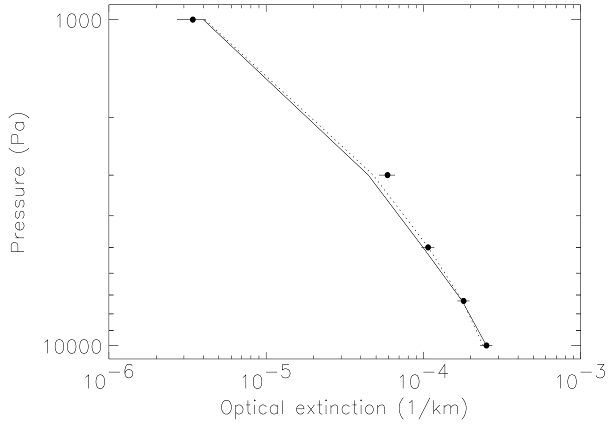

Fig. 1. Model calculated optical extinction (experiment (ii), full line, experiment (iii), dotted line) and observations as function of altitude for January 25 0 UT at 47° N and 84° W. SAGE II data are represented by the symbols with the error estimates. See text for destails.

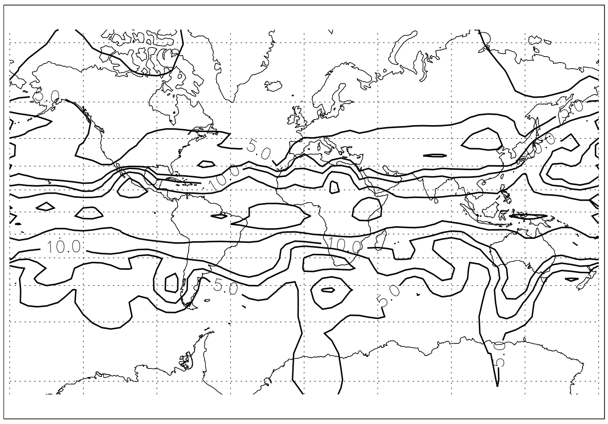

Fig. 2. Assimilated aerosol optical extinction (10^{-5} km^{-1}) for January 15, 0 UT at the model 30 hPa model level.

CONCLUSION

4D–Var assimilation has proven to be a valuable tool to address local spatial and temporal information of stratospheric aerosols, based on nearby remote sensing data. The results show that the assimilation analysis is capable of reproducing to a high degree the observed aerosol extinction data at 1.02 μm . The analysis can easily be extended to provide global aerosol surface area density fields using the formulation of Thomason *et al.* (1997). The aerosol observations themselves already contain information on dynamical features of the stratosphere (for example Trepte and Hitchmann, 1992). The aerosol assimilation analysis extends this information to spatial and temporal scales definded by the model resolution. In addition, preliminary results show that non–aerosol events can be detected by this assimilation technique. The presented assimilation framework has the great advantage of flexible and easy extension of the model to include a multi–wavelength approach with a micro–physical description of the aerosols, and to include assimilation of chemical species. This technique offers great possibilities as an aid in validating space-borne instruments for ongoing and upcoming missions and can subsequently add substantial value to the pure data.

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