Antarctic stratospheric ozone from the assimilation of occultation data

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Ozone data from the solar occultation Polar Ozone and Aerosol Measurement (POAM) III instrument are included in the ozone assimilation system at NASA's Global Modeling and Assimilation Office, which uses Solar Backscatter UltraViolet/2 (SBUV/2) instrument data. Even though POAM data are available at only one latitude in the southern hemisphere on each day, their assimilation leads to more realistic ozone distribution throughout the Antarctic region, especially inside the polar vortex. Impacts of POAM data were evaluated by comparisons of assimilated ozone profiles with independent ozone sondes. Major improvements in ozone representation are seen in the Antarctic lower stratosphere during austral winter and spring in 1998. Limitations of assimilation of sparse occultation data are illustrated by an example.

1. Introduction

Antarctic ozone loss is largely confined to a distinct lower stratospheric layer within a polar vortex because of the unique meteorology of this region (e.g. World Meteorological Organization 2003; Solomon 1999 and references therein). Polar processes influence the ozone distribution outside the polar regions. After the breakup of the polar vortex, ozone-poor polar air dilutes ozone-richer air in mid-latitudes causing seasonal changes in mid-latitudes. Transport of vortex-processed air, which contains active chlorine radicals, also contributes to ozone loss at mid-latitudes. The amount and interannual variability of mid-latitudinal ozone loss is affected by polar processing and in particular by the strength and stability of the polar vortex (e.g. Millard et al. 2002; Hadjinicolaou et al., 1997).

Nadir viewing satellite instruments measuring ultraviolet or infrared radiation have provided multi-decadal records of global ozone data that have been available in near-real time. Thus, many assimilation systems use ozone data from nadir instruments for real time estimation and forecasting or in multi-year analyses of historical data (e.g. Stajner et al. 2004). However, the usability of data from nadir instruments for quantifying the vertical distribution of the polar ozone loss is limited by their coarse vertical resolution and, for solar backscatter ultraviolet instruments, by their inability to make measurements in the polar night.

Limb viewing satellite instruments provide ozone profiles with a better vertical resolution. Measurements of microwave or infrared radiances provide daytime and nighttime coverage, typically over a wide range of latitudes. Consequently they have a potential to improve the quality of assimilated stratospheric ozone globally, and especially in the polar regions (e.g. Levelt et al. 1998; Struthers et al. 2002).

Solar occultation satellite instruments provide sparse atmospheric profile measurements with even better vertical resolution. The Polar Ozone and Aerosol Measurement (POAM) III instrument provides polar ozone profiles from solar occultation measurements (Lucke et al., 1999). The assimilation of occultation data is hampered by their sparseness. This was illustrated in the assimilation of Halogen Occultation Experiment (HALOE) data. Ménard et al. (2000) assimilated HALOE methane data into a two-dimensional transport model on a single isentropic surface in the stratosphere. Using a Kalman-filtering approach, they found that oversimplified error covariance models led to unreliable results. Chipperfield et al. (2002) assimilated HALOE data for four species with long photochemical lifetimes into a three-dimensional chemistry and transport model (CTM), also including a scheme to conserve tracer-tracer correlations. The assimilation had an impact on the global distribution of constituents. However, the largest reduction in the analysis errors, and the improved in the agreement with independent data were seen close to the locations of HALOE measurements.

A question arises: Can assimilation of the sparse POAM III data capture the three-dimensional stratospheric ozone evolution over the entire Antarctic? In this study we assimilate POAM III ozone data and evaluate their impact on the Antarctic ozone.

2. Assimilation system

The ozone assimilation system used in this study is based on that of Stajner et al. (2004). Satellite ozone data are assimilated into a CTM with a parameterization of the gas phase stratospheric chemistry. Data from the NOAA 14 Solar Backscatter UltraViolet/2 (SBUV/2) instrument constrain ozone in the sunlit stratosphere. Assimilated ozone agrees within 10% with HALOE data (Stajner et al. 2001). The resolution and accuracy of SBUV/2 data degrades in the lower stratosphere. At high solar zenith angles, near the polar night region, the SBUV/2 data are often not assimilated because the

retrieval algorithm flags them as lower quality data. Comparisons with sonde profiles (below) show that the representation of lower stratospheric ozone profiles at high latitudes is inadequate in the SBUV-only assimilation during winter and spring. We investigate if additional constraint from POAM data provides assimilated ozone fields that are adequate for studies of polar ozone processes.

3. POAM III data

The POAM II and POAM III instruments have provided ozone data from solar occultation measurements for several years (1993-1996 and from 1998 to present). This feasibility study focuses on the austral winter and spring in 1998. From a sun-synchronous satellite orbit, POAM III makes measurements of 14-15 sunsets and sunrises 25.4° longitude apart, on two latitude circles (Lucke *et al.*, 1999). The northern circle changes from 54°N to 71°N, and the southern from 63°S to 88°S during the course of the year. Routine measurements are made down to the mid-troposphere in cloud free conditions. The vertical resolution of version-3 ozone data is about 1.1 km and they have random errors smaller than 5% above 15 km (Lumpe *et al.*, 2002). Comparison of POAM III with other satellite and ozone sonde data showed an agreement to within 5% from 13 to 60 km (Randall *et al.*, 2003). POAM and other occultation data were used successfully to construct polar ozone maps on isentropic surfaces (Allen and Nakamura 2003). Thus the POAM data provide high quality information about polar ozone distribution.

We assimilated version 3 of POAM ozone data between 14 and 60 km. This altitude range was motivated by the ease of implementation of the observation operator for our model, which has hybrid levels between surface and 161 hPa, and pressure levels above. All the chosen POAM levels lie in the pressure level part of our model grid. The errors in POAM ozone were modeled as uncorrelated, using standard deviations provided in the data files. The lowest error standard deviations of ~3% are found near 30 km. The error standard deviations at altitudes below 20 km can exceed 20%, especially in the presence of PSCs and low ozone values. In the assimilation experiments no change was made to the treatment of the SBUV data (Stajner *et al.* 2004).

4. Evolution of the lower stratospheric ozone over Antarctica

The evolution of ozone in the polar vortex is illustrated by instantaneous maps from the POAM and SBUV assimilation at 70 hPa (Fig. 1 a, c, and e). In wintertime, before the heterogeneous ozone loss begins, the slow descent leads to an accumulation of ozone in the lower stratosphere within the polar vortex. Higher ozone values are seen over Antarctica than in the middle latitudes (Fig. 1a). In springtime the sun starts to illuminate the air mass within the polar vortex. Activated chlorine and bromine compounds serve as catalysts for a rapid ozone loss, which begins near the polar vortex edge (Fig. 1c). A distinction between the weakly mixed ring of air near the Antarctic vortex edge and the well-mixed vortex core was pointed out by Lee *et al.* (2001). Distortions of the vortex push parts of the vortex to lower latitudes where sunlight is stronger. As sunlight advances towards the pole almost complete ozone depletion is seen throughout the vortex (Fig. 1e).

The ozone fields from SBUV-only assimilation fail to capture the main aspects of the ozone evolution over Antarctica: wintertime accumulation within the vortex (Fig. 1b), early springtime progression of the loss from the vortex edge towards the inner core (Fig. 1d), and the severity of the depletion later in the spring (Fig. 1f). Figure 1 shows that there is a substantial impact of POAM data throughout the vortex, not just near the measurement locations. Note that no heterogeneous chemical processes are included in the CTM, so the success of the assimilation depends on using high-quality data.

In Fig. 2 assimilated ozone is compared with the independent Neumayer ozone sonde (near 70°S, 8°W). Assimilation of NOAA-14 SBUV/2 data does not capture the ozone accumulation in the lower stratosphere. When POAM data are assimilated the profile shape is changed: ozone amounts at pressures higher than 40 hPa increase, and the ozone amounts for pressures lower than 40 hPa decrease. Including POAM data leads to ozone profile in substantially better agreement with the Neumayer sonde, especially in the lower and middle stratosphere.

A partial ozone reduction in early spring is seen in the independent South Pole ozone sonde profile on September 28, 1998 (Fig. 3a). Two well-captured maxima of ozone partial pressure at 20 and 150 hPa bracket the region in which a varying degree of loss is seen. There are three ozone minima at 30, 45, and 80 hPa, and two smaller ozone maxima at 35 and 50 hPa. The POAM assimilation reproduces this stratospheric profile shape, with the exception of a higher ozone layer around 35 hPa. However, the vertical extent of this layer is finer than the resolution of our model, in which two neighboring model levels are centered near 30 and 40 hPa. The SBUV assimilation gives a profile with improperly placed ozone maximum at 30 hPa, and strongly underestimates the other maximum at 150 hPa.

Nearly complete ozone destruction is seen in the South Pole ozone sonde profile in the layer between 40 and 100 hPa on October 20, 1998 (Figs. 3b, and 1e,f). The assimilation with POAM data captures this depleted layer and very sharp ozone gradients from the edges of this layer towards well-captured maxima at 30 and 150 hPa. In contrast, the SBUV assimilation underestimates the extent of the ozone loss at pressures

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less than 100 hPa and the magnitude of the ozone maximum in the lowermost stratosphere.

A limitation of the POAM assimilation is illustrated in ozone profiles at Neumayer on September 23, 1998 (Fig. 4). The sonde profile exhibits a shallow laminar feature near 40 hPa, not captured by either assimilation, embedded in a deep layer of depleted ozone between 20 and 100 hPa. Using contour advection with surgery, Moustaoui *et al.* (2003) showed that this lamina is a part of a filament of ozone-rich air transported poleward from the inner edge of the polar vortex. The ability of the dynamics to capture such narrow and shallow filaments is often limited (Manney *et al.*, 2004). In this case the satellite ozone data that were assimilated did not capture this filament. The SBUV data lack vertical resolution needed to capture such shallow features. POAM was measuring near 88°S at this time, in a different air mass unaffected by the filament.

5. Conclusions

In this letter we present results from the first assimilation of POAM III ozone data. We used POAM III data to provide additional constraints on polar ozone within a global system that already assimilates NOAA 14 SBUV/2 data. Assimilation of POAM data significantly improved the representation of ozone profiles over Antarctica in wintertime and springtime of the year 1998. Wintertime accumulation of ozone in the lower stratosphere within the polar vortex was captured. Springtime ozone depletion was represented in a properly confined lower stratospheric layer. Ozone profiles from assimilations with and without POAM data were evaluated by comparison to independent ozone sonde profiles at Neumayer and the South Pole.

We found that assimilation of just 14 to 15 solar occultation profiles provided daily by POAM in one hemisphere significantly improves the representation of lower stratospheric ozone within the polar vortex, which is not adequately observed by SBUV data. This study shows that a successful assimilation of solar occultation data provided a sufficient constraint to capture a geophysical phenomenon on a regional scale. A case that illustrates a limitation of the dynamical model that was not overcome through POAM assimilation was presented. An ozone filament that originated at the vortex edge was missed while POAM was sampling the innermost vortex core.

Assimilation of sparse POAM data constrains polar ozone profiles. A multi-year assimilation of POAM II and POAM III data could provide insight into interannual variability of the polar ozone distribution in early spring and potentially in qualifying the impacts of mixing into middle latitudes. Moreover, assimilation of POAM data, if they were available in real time, could significantly improve operational polar ozone analyses and forecasts.

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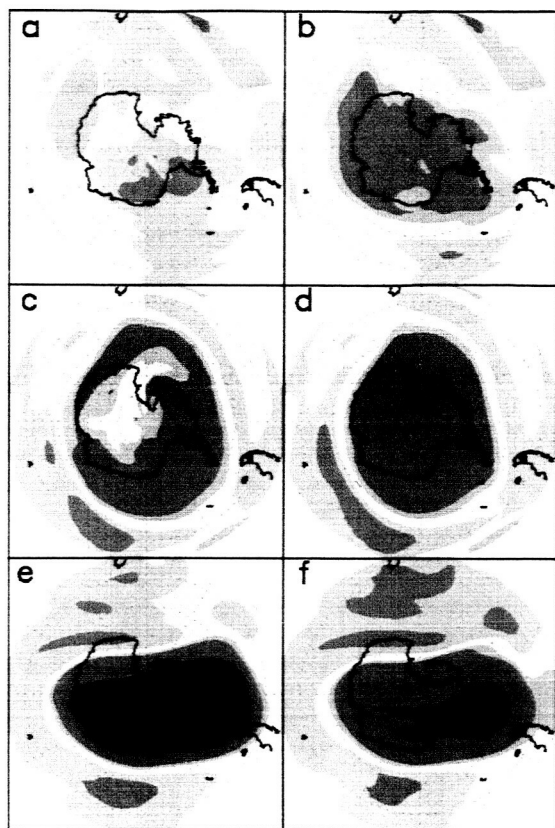
Figure 1. Ozone mixing ratio (in ppmv) at 70 hPa is shown in southern polar stereographic projection up to 45°S on three days in year 1998: August 1 (a and b), September 1 (c and d), and October 20 (e and f). The ozone is from POAM and SBUV assimilation (a, c, and e) or from SBUV-only assimilation (b, d, and f). Note the nonlinear scale.
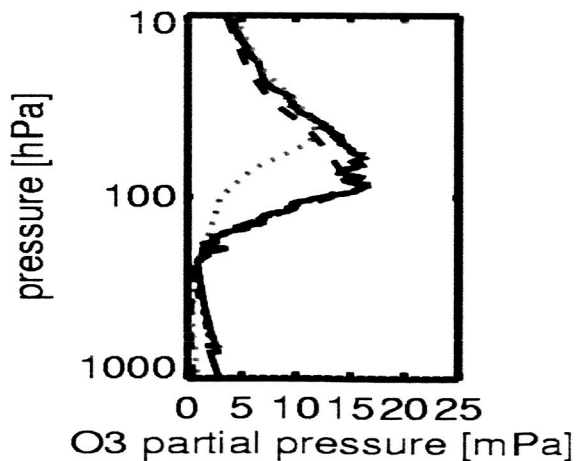

Figure 2. Ozone profiles at Neumayer (near 70°S and 8°W) from ozone sonde (black) and from assimilation systems that used only SBUV data (green) or SBUV and POAM data (red) are shown on July 8, 1998.
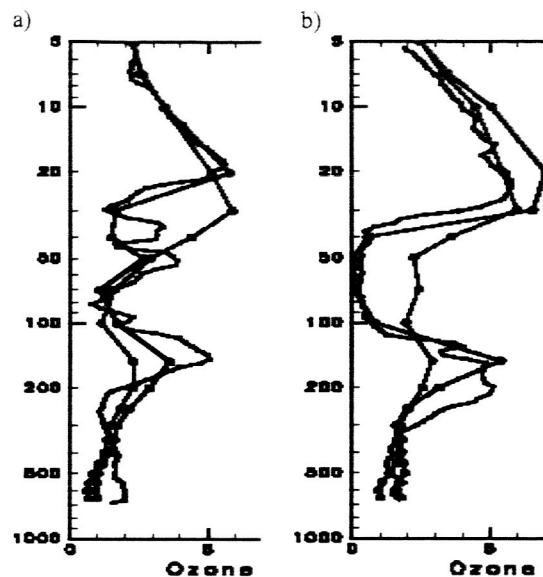

Figure 3. Ozone partial pressure profiles (in mPa versus atmospheric pressure in hPa) from the sonde at South Pole (black) and from assimilation systems that used only SBUV data (red) or SBUV and POAM data (blue) are shown for September 28 (left) and October 20, 1998 (right).
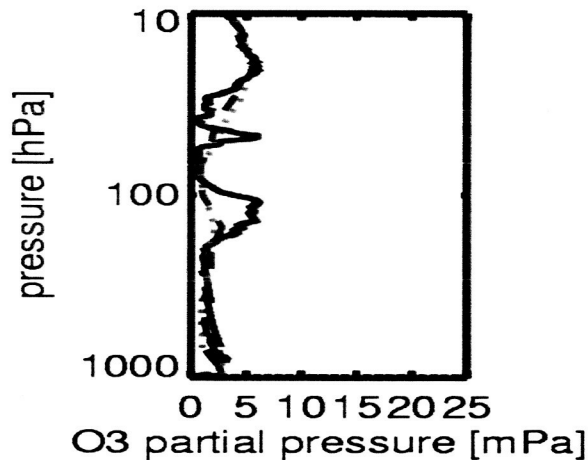

Figure 4. Comparison of ozone sonde profile at Neumayer (black) and ozone from assimilation system that used only SBUV data (green) or SBUV and POAM data (red) is shown for September 23, 1998.

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Summary

The impact of man-made chemicals on atmospheric ozone is the strongest in very cold polar regions. Almost all ozone over Antarctica is destroyed during spring in a layer between about 14 and 22 km altitude. The ozone-poor air from this layer later dilutes the air away from poles during late spring and summer. Within the next 50 years the amounts of man-made ozone-depleting chemicals in the atmosphere are expected to decline due to international protocols limiting their production and release. Consequently, the ozone layer is expected to recover. At the present time the ozone layer is still in a fragile state and the precise timing of the start of the ozone recovery is questionable due to year-to-year variability in natural processes that influence ozone amounts. Thus, scientific efforts to understand processes that control ozone distribution and monitor ozone evolution continue. Satellite instruments provide daily maps of the total ozone columns and the evolution of the Antarctic "ozone hole". However, detailed measurements of finely resolved vertical ozone distribution in the polar regions are much more limited. The Polar Ozone and Aerosol Measurement (POAM) III instrument provides about 15 measurements of ozone profiles each day near Antarctica. We combined POAM and other satellite instrument measurements with a global model that captures atmospheric motion of ozone and a simplified chemistry, using an advanced statistical analysis technique that is known as data assimilation. Our method provides three-dimensional ozone distributions that are consistent with both POAM measurements and with the global ozone model. We found that when POAM data are used the representation of Antarctic ozone distribution in our model improves substantially. The vertical extent of the layer in which the ozone is destroyed is well captured. The evolution of the ozone depletion is realistic. The depletion starts in sunlit regions in the early spring and later advances towards the pole, resulting in almost complete ozone destruction in a several kilometers thick layer. When sunlight warms up the region and meteorological conditions change in the late spring or early summer, ozone gradually recovers. We found that even though only about 15 POAM measurements are available each day over Antarctica at about constant geographical latitude, they can provide a good constraint on the ozone field throughout the Antarctic region. Our study focused on the evolution of the "ozone hole" in the year 1998. Its success indicates that POAM data provide enough information to reconstruct many features of the evolution of ozone over Antarctica. Furthermore, we suggest that the POAM data could be used to constrain real-time ozone estimates and ozone forecasts.