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Large loss of total ozone during the Arctic winter of 1999/2000

B.-M. Sinnhuber,[1] M. P. Chipperfield,[1] S. Davies,[1] J. P. Burrows,[2]
K.-U. Eichmann,[2] M. Weber,[2] P. von der Gathen,[3] M. Guirlet,[4,5]
G. A. Cahill,[5] A. M. Lee,[5] and J. A. Pyle[4,5]

Abstract. Three-dimensional model calculations are used together with total ozone observations from the Global Ozone Monitoring Experiment (GOME) and ozone sonde measurements at Ny-Ålesund, Spitsbergen to quantify the chemical ozone loss inside the Arctic polar vortex in winter 1999/2000. GOME shows March 2000 mean Arctic total ozone values of 365 DU, about 100 DU less than the 1980–1989 mean from TOMS data, well reproduced by the model calculations. A comparison of the modeled ozone with a passive ozone tracer and ozone sonde observations at Ny-Ålesund shows that by the end of March 2000 about 2.5 ppmv of ozone are chemically depleted in the lower stratosphere, corresponding to more than 70% ozone loss. At the same time, the inferred loss in total ozone inside or at the edge of the polar vortex is between 90 and 140 DU. The large ongoing loss during March 2000 is likely to be due to widespread denitrification, which maintains high chlorine activation during this period.

Introduction

During the recent cold winters of the 1990s, significant ozone loss has been observed over the Arctic, resulting from chlorine activation on polar stratospheric clouds (PSC) at low temperatures and subsequent catalytic photochemical ozone destruction (see WMO [1999] and references therein). Although the stratospheric chlorine loading has reached its maximum or is already declining there is growing concern that a possible decrease of Arctic stratospheric temperatures due to the emission of greenhouse gases could lead to enhanced stratospheric ozone depletion for the next decades [Shindell et al., 1998].

The high degree of variability in the Arctic polar vortex compared to its Antarctic counterpart makes a quantification of chemical ozone depletion difficult from total ozone observations alone. Chipperfield and Jones [1999] used three-dimensional model calculations to identify the relative contributions of transport and chemistry to the observed total ozone values over the Arctic. Here we use a similar approach to quantify the amount of chemical ozone loss in the Arctic winter of 1999/2000. We compare the model to total ozone observations of the Global Ozone Monitoring Experiment (GOME) on board the ERS-2 satellite [Burrows et al., 1999] and measurements of the lower stratospheric ozone mixing ratio from ozone sonde observations at Ny-Ålesund, Spitsbergen (79°N, 12°E). The joint European and U.S. THESEO 2000/SOLVE campaign, which took place between November 1999 and March 2000, offers a unique opportunity to study in greater detail the processes involved in Arctic ozone depletion.

After the two relatively warm Arctic winters of 1997/98 and 1998/99 the winter of 1999/2000 was characterized by very low temperatures from late November/early December 1999 until March 2000 and a record long period of temperatures below possible PSC type I formation temperature. Figure 1 shows the minimum temperatures north of 45°N at the 46 hPa level from UKMO analyses [Swinbank and O'Neill, 1994]. The area of the possible PSC existence covered most of the polar vortex during late December and January, in agreement with numerous observations of PSCs during that period. In early March the temperatures inside the Arctic polar vortex finally increased above the possible PSC existence temperature.

Data analysis and Results

We have used the SLIMCAT three-dimensional chemical transport model (CTM) [Chipperfield, 1999]. The model is forced by temperatures and horizontal wind fields from UKMO analyses. It was initialized in October 1991 from a 2D model and run until November 1, 1999 at a relatively coarse resolution of $5^\circ \times 7.5^\circ$, when the higher resolution integration with $2.5^\circ \times 3.75^\circ$ was started. In addition, we continued the low resolution model integration throughout winter 1999/2000. The model has 24 isentropic levels between 330 K and 3000 K, resulting in a vertical resolution of approximately 1 km in the lower stratosphere. Chemical ozone loss is diagnosed by comparison with a modeled passive ozone tracer, which was initialized with the modeled ozone field on December 1, 1999. As a result of the low stratospheric temperatures, the model shows high levels of chlorine activation and subsequent ozone loss during the Arctic winter of 1999/2000. Triggered by temperatures below the ice point in December and January, the model (at both high and low resolution) produced widespread, significant denitrification unlike any other modeled winter since the integration began in 1991.

Ozone sonde observations at Ny-Ålesund between November 1999 and the end of April 2000 are shown in Figure 2 for the 450 K isentropic level, approximately at 18 km al-

[1]School of the Environment, University of Leeds, Leeds, UK
[2]Institute of Environmental Physics, University of Bremen, Germany
[3]Alfred Wegener Institute for Polar and Marine Research, Potsdam, Germany
[4]European Ozone Research Coordinating Unit, Cambridge, UK
[5]University of Cambridge, Cambridge, UK

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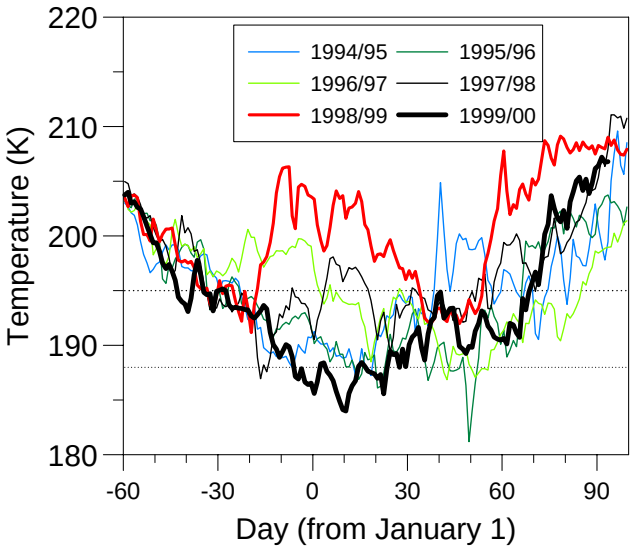

Figure 1. Minimum temperatures at the 46 hPa level from UKMO analyses for the last 6 winters. The winter of 1999/2000 was characterized by very low temperatures during December and January and a long period of temperatures below the possible PSC formation temperature.

titude. Ny-Ålesund was well inside the Arctic vortex over practically the whole period until early April, except for a short period during late March. The modeled passive ozone tracer is in reasonable agreement with the observations during December, with the model slightly overestimating the observations. The model shows an increase of ozone between November and mid-January due to the diabatic descent of higher ozone mixing ratios from above, in good agreement with the observations. Starting then in mid-January, a rapid decline of both the observed and modeled ozone volume mixing ratio can be seen, reaching values below 1 ppm at the end of March, or more than a 70% reduction of the initial

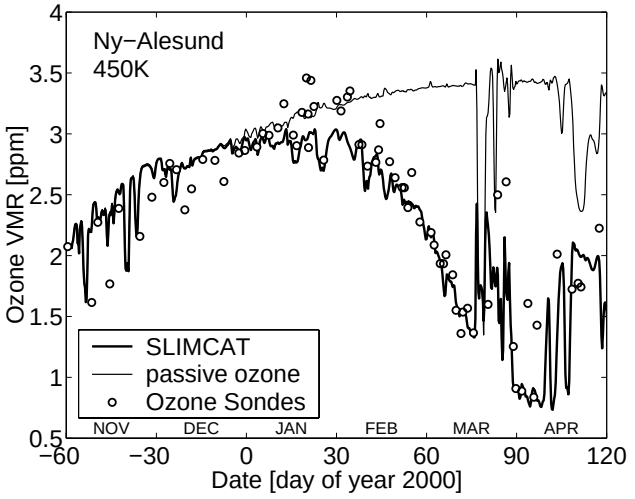

Figure 2. Ozone sonde measurements at Ny-Ålesund, 79° N, compared to the SLIMCAT three-dimensional transport model output for Ny-Ålesund at the 450 K isentropic level. The comparison with the modeled passive ozone tracer shows that by the end of March 2000 more than 2.5 ppm or 70% of the ozone at this level has been chemically depleted.

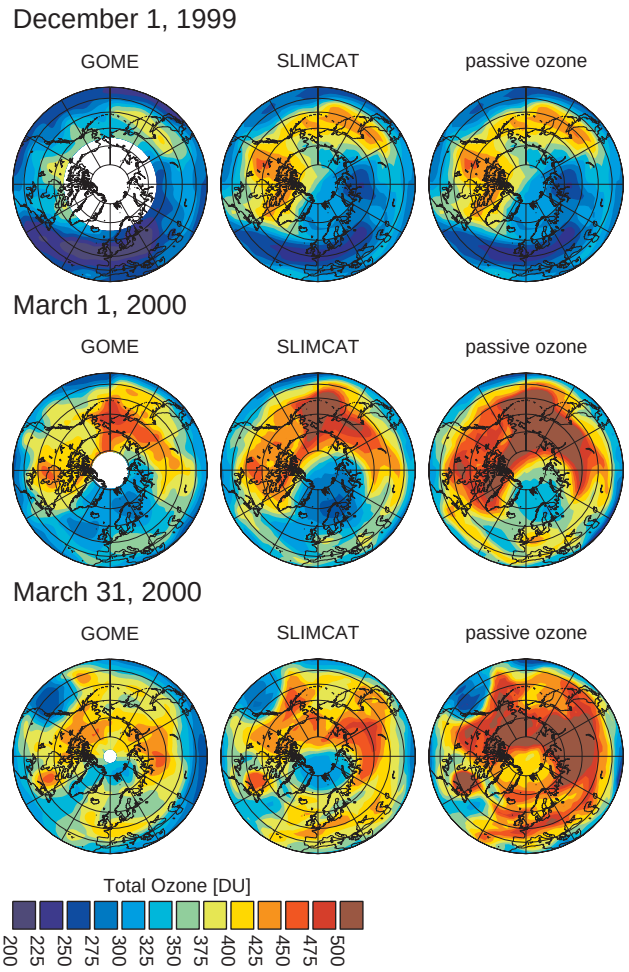

Figure 3. Total ozone observations from the GOME instrument (left column) compared to the SLIMCAT model (middle column) for December 1, 1999, March 1 and March 31, 2000. The model reproduces well the observed evolution of total ozone throughout the winter. Comparison with the modeled passive ozone tracer (right column) shows that by the end of March 2000 between 90 and 140 DU, or about 30%, of the Arctic total ozone has been chemically depleted.

values in January. These losses are comparable, or even larger than, the losses during the cold winters of 1995/96 and 1996/97 [Manney et al., 1996, 1997, Knudsen et al., 1998, Sinnhuber et al., 1998]. Above 500 K there is only little ozone depletion this winter. The modeled ozone for 1999/2000 is in excellent agreement with the observations, indicating that the model correctly reproduces the chemical ozone depletion during this winter. This appears to be in contrast to the results for previous cold winters, where the model tends to underestimate the ozone loss [Guirlet et al., 2000].

In order to quantify the overall extent of the chemical ozone loss for the winter of 1999/2000, we have compared the modeled passive ozone tracer to GOME total ozone observations. A constant offset of 30 DU has been added to the model's ozone column, to account for the column below 330K. Figure 3 shows that the model is in good agreement with GOME's total ozone observation on December 1, 1999, when the passive ozone tracer was initialized. The model only slightly overestimates the ozone column, consis-

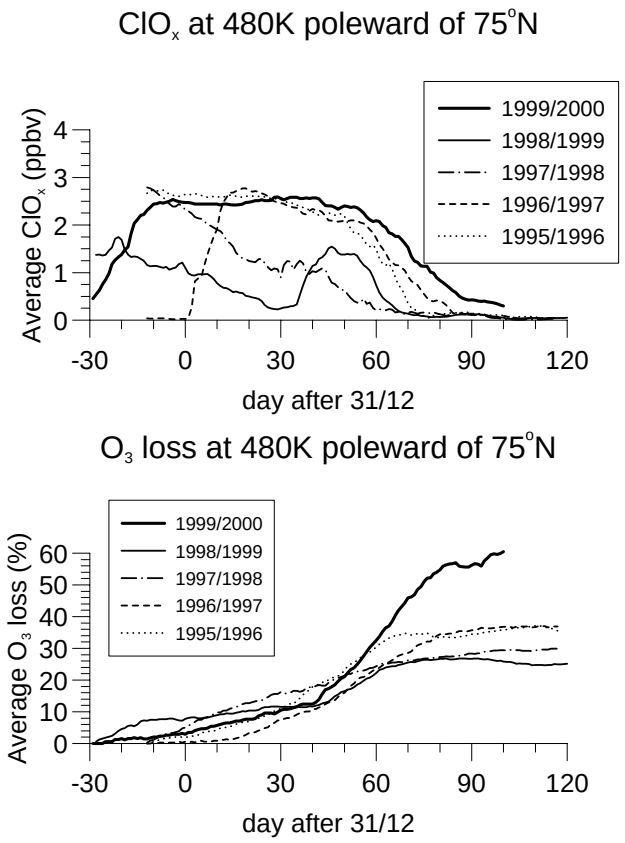

Figure 4. Modeled vortex average chlorine activation (ClO_x = $ClO + 2 \times Cl_2O_2$) and ozone loss at the 480 K isentropic level, compared to previous years. Figure updated from Guirlet et al. [2000].

tent with the lower stratospheric ozone being slightly too large in early winter, as seen in Figure 2. The total ozone on December 1, 1999 is itself interesting: Very low values of total ozone below 200 DU have been observed over western and northern Europe. However, the comparison with the model shows that these very low total ozone values are not due to chemical ozone loss but rather due to transport of low ozone from low latitudes and the uplifting of the lower stratospheric isentropic surfaces over Europe and the European Arctic.

Figure 3 shows that the SLIMCAT model reproduces well the observed evolution of total ozone throughout the winter. Both GOME observations and the model show total ozone of less than 300 DU over the Arctic during early March. Comparison with the passive ozone tracer shows that by March 1, 2000 between 50 and 80 DU of the ozone column has been chemically depleted. However, part of these low total ozone values inside the polar vortex are due to transport. By March 31, 2000 the diagnosed chemical total ozone loss reaches between 90 and 140 DU over the Arctic, corresponding to about 30% of the total column.

Discussion and Conclusion

Arctic total ozone during March 2000 was much lower than the longterm mean. GOME shows monthly mean total ozone north of 63°N during March 2000 of 365 DU, in contrast to the pre-1990 TOMS March mean of 450 DU [Newman et al., 1997]. The March 2000 value is comparable to March 1996 (370 DU) and March 1997 (360 DU), as observed by GOME, which agrees with TOMS mean values to within 10 DU. The SLIMCAT model shows that the chemical ozone depletion accounts for a mean loss of 72 DU north of 63°N during March 2000, and is thus largely responsible for the anomalously low ozone.

At the end of March 2000, the modeled lower stratospheric ozone loss of about 70% inside the Arctic vortex corresponds to an integrated column loss of between 120 and 140 DU, about 30% of the total column. The modeled ozone loss for the winter 1999/2000 is thus almost 50% larger than our model results for previous winters [Chipperfield and Jones, 1999]. However, there is evidence that the model underestimates the loss for the previous cold winters of 1995/96 and 1996/97 [Guirlet et al., 2000]. Müller et al. [1997a, b] derived a total ozone loss of 50–70 DU for March 1997 and even 120–160 DU for March 1996 inside the Arctic vortex.

Figure 4 compares the modeled active chlorine and ozone loss with previous winters. To allow a direct comparison of the model results for these different winters, we have also used the same model configuration as described by Guirlet et al. [2000] for winter 1999/2000. Although this is a different model configuration to the one used in Figures 2 and 3, the results shown for winter 1999/2000 are essentially identical for the two model runs. While the temperature evolution of the winter 1999/2000 resembles the winter of 1995/96 from mid-January on (Figure 1), the accumulated loss in our model is much higher for the current winter than for the winter of 1995/96 or any other previous winter. Before early March the accumulated ozone loss is comparable for the winters of 1995/96 and 1999/2000. However, while the ozone loss levels off in early March 1996, ozone loss continues during March 2000. This is very likely to be due to the large denitrification present in the model for the current winter, but not for the previous winters, as only in this winter did the UKMO analyses show large areas of temperatures below the ice frost point which triggered the denitrification in the model. However, as there are indications for denitrification for previous cold Arctic winters [e.g. Hintsa et al., 1998, Waibel et al., 1999, Kondo et al., 2000] this suggests a possible explanation for the underestimation of ozone loss in previous years by the SLIMCAT model and will be investigated in more detail. It has already been demonstrated that denitrification can lead to a significant increase of Arctic ozone loss [Rex et al., 1997, Chipperfield and Pyle, 1998, Waibel et al., 1999], a situation which apparently was realized during the current winter 1999/2000. The ozone loss during this winter thus demonstrates the potential for additional severe Arctic ozone depletion if there is a trend towards colder stratospheric temperatures in the Arctic.

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M. P. Chipperfield, S. Davies, and B.-M. Sinnhuber, School of the Environment, University of Leeds, Leeds, LS2 9JT, UK. (bms@env.leeds.ac.uk)

J. P. Burrows, K.-U. Eichmann, and M. Weber, Institute of Environmental Physics, University of Bremen, P.O. Box 330440, 28334 Bremen, Germany.

P. von der Gathen, Alfred Wegener Institute for Polar and Marine Research, P.O. Box 600149, 14401 Potsdam, Germany.

G. A. Cahill, M. Guirlet, A. M. Lee, and J. A. Pyle, Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge, CB2 1EW, UK.

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