Total ozone during the unusual Antarctic winter of 2002

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[1] A major stratospheric warming was observed in the southern hemisphere during September 2002 for the first time. Total ozone observations from the Global Ozone Monitoring Experiment (GOME) show the ozone hole dividing into two parts in late September, followed by a reestablishment of the pole centered ozone hole (defined as the area of total ozone below 220 DU) in October. The ozone observations are well reproduced by a chemical transport model (CTM) driven by analyzed wind fields and temperatures. Antarctic total ozone was significantly higher during winter and spring 2002 than during previous years. GOME showed October averages for the area south of 63°S of 291 DU for 2002, compared to between 204 and 248 DU for the years 1995–2001. Comparison with the CTM indicates that the unusually high ozone columns are largely a result of increased transport during the winter 2002. The estimated chemical loss of total ozone of about 80 DU south of 60°S is comparable to that of previous winters. We conclude that the increased total ozone during this winter must not be considered as a sign of ozone recovery but is just a consequence of an unusual meteorological situation during the winter of 2002. *INDEX TERMS:* 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assi-milation; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3362 Meteorology and Atmospheric Dynamics: Stra-tosphere/troposphere interactions. **Citation:** Sinnhuber, B.-M., M. Weber, A. Amankwah, and J. P. Burrows, Total ozone during the unusual Antarctic winter of 2002, *Geophys. Res. Lett.*, *30*(11), 1580, doi:10.1029/2002GL016798, 2003.

1. Introduction

[2] Since the 1980s substantial depletion of stratospheric ozone has been observed first over the Antarctic and later also over the Arctic during late winter and spring as a result of increased atmospheric halogen loading due to anthropogenic emissions [*World Meteorological Organization* (*WMO*), 2003]. The relative influence of chemistry and transport on polar ozone is, however, different for the two polar regions [*Chipperfield and Jones*, 1999]. The Arctic winter stratosphere is dynamically more active than its Antarctic counterpart, resulting in an increased transport of ozone into the Arctic. At the same time, atmospheric dynamics tend to raise Arctic temperatures considerably above the radiative equilibrium temperatures [*Newman et al.*, 2001]. As a result, temperatures low enough to form polar stratospheric clouds (PSCs), a prerequisite for substantial chemical ozone loss, are reached only sporadically over the Arctic while they are common throughout Antarctic winter.

[3] Sudden stratospheric warmings [e.g., *Andrews et al.*, 1987] are an extreme case of a disruption of the stratospheric dynamics with significant impact on transport and chemistry of ozone. Major mid-winter stratospheric warmings are more or less regularly observed over the Arctic, while they were so far unknown for the southern hemisphere. Here we report on the occurrence of a major stratospheric warming during the Antarctic winter of 2002 and its impact on the Antarctic ozone hole.

[4] In a separate paper [*Weber et al.*, 2003] we present eight years of observations of total ozone during winter and spring for both hemispheres and how they are influenced by atmospheric wave activity. The unusual meteorological conditions during the austral winter of 2002 provide a scenario that, in some sense, lies between a typical Arctic and a typical Antarctic winter. *Hoppel et al.* [2003] and *Allen et al.* [2003] provide a description of ozone loss and unusual transport and mixing during the 2002 winter/spring.

[5] Here in this paper we present in more detail the evolution of ozone during the unusual winter of 2002. We use total ozone observations from GOME, together with calculations from a chemical transport model (CTM). CTMs have proved to be powerful tools to interprete total ozone observations, in particular to estimate the relative influence of chemistry and transport [*Lefèvre et al.*, 1998; *Chipperfield and Jones*, 1999; *Sinnhuber et al.*, 2000].

2. Measurements and Model

[6] The Global Ozone Monitoring Experiment (GOME) onboard the ERS-2 satellite [*Burrows et al.*, 1999] observes back-scattered radiation in nadir viewing geometry in the UV and visible wavelength ranges. In this study total ozone is used from the GOME Data Processor version 2.7 data. See *Weber et al.* [2003] for more details on the GOME data.

[7] Our CTM is forced by temperatures and wind fields from analyses of the United Kingdom Met Office (MO) [*Swinbank and O'Neill*, 1994]. The model uses isentropic levels as vertical coordinates. Transport on isentropes is calculated from MO wind fields. Vertical transport is derived from interactively calculated diabatic heating rates using the MIDRAD scheme [*Shine*, 1987; *Shine and Rickaby*, 1989]. Advection is calculated by using the second order moments scheme of *Prather* [1986]. The model runs presented in this paper use 24 isentropic levels between 330 and 3000 K (about 10 to 55 km) with a horizontal resolution of 2.5° lat. × 3.75° lon. The calculation of transport in this model is thus very similar to the SLIMCAT model [*Chipperfield*, 1999].

[8] For this study the only advected tracer in the model is ozone. Photochemical ozone changes are calculated by a

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simple linearized chemistry (Linoz), using the parameterization of *McLinden et al.* [2000]. Because the standard Linoz chemistry does not include any representation of the rapid ozone loss in the lower stratosphere as a result of chlorine activation on PSCs, we have included a simple parameterization of this polar ozone chemistry. Our parameterization destroys ozone with a constant life time of 10 days whenever the temperature is below the formation temperature for nitric acid trihydrate (NAT, assuming 5 ppmv of water and 10 ppbv of nitric acid) and the solar zenith angle is below 85°. The parameters for this simple parameterization were optimized by comparison with ozone sonde measurements at Ny-Aalesund during the Arctic winter of 1999/2000 [*Sinnhuber et al.*, 2000, Figure 2]. It should be noted, however, that this parameterization is a gross simplification of the actual ozone loss processes. It is included here to compare the morphology of the ozone hole with observations, but should not be used for quantitative comparisons.

[9] Ozone columns are calculated from the model between the bottom layer at 330 K and the top layer at 3000 K. No correction for the missing ozone contribution to the total column from levels below 330 K or above 3000 K was applied.

[10] We generated two model runs for the Antarctic winter of 2002. One with our parameterization of polar chemistry, the other without polar chemistry. The model run without polar chemistry does include the parameterized ozone changes from the Linoz scheme. However, since the lifetime of ozone in the lower stratosphere is rather long in the absence of heterogeneous chemistry, it may be considered in effect as a 'passive ozone tracer' [e.g., *Sinnhuber et al.*, 2000]. Comparisons of observed ozone with the ozone calculation without polar chemistry can thus be used to estimate the amount of polar ozone depletion. Both model runs were initialized on March 1, 2002 from an observed ozone climatology [*McPeters*, 1993], which is identical to the ozone climatology used in the Linoz scheme.

[11] In addition, for comparison with previous winters we performed a set of identical model runs for the eleven winters of 1992 to 2002. These model runs were performed without polar chemistry, allowing us to estimate the impact of interannual differences in transport on total ozone during Antarctic winter.

3. Meteorology

[12] One of the most striking events during the winter of 2002 was the occurrence of a major mid-winter warming at the end of September. Such a warming has not been observed during the previous two decades for which large scale observations are available.

[13] Meteorological analyses from the MO show a decrease of the zonal mean zonal wind at 46 hPa starting after September 17, followed by a decrease of the zonal mean zonal wind at 10 hPa a few days later. The zonal mean zonal wind at 60° S reversed at 10 hPa (from westerly to easterly) after September 24. The reversal of the zonal mean zonal wind at 10 hPa is often used—together with the observed reversal of the poleward zonal mean temperature gradient—as a criterion for a 'major warming'. A weak westerly circulation at 10 hPa was reestablished during early October.

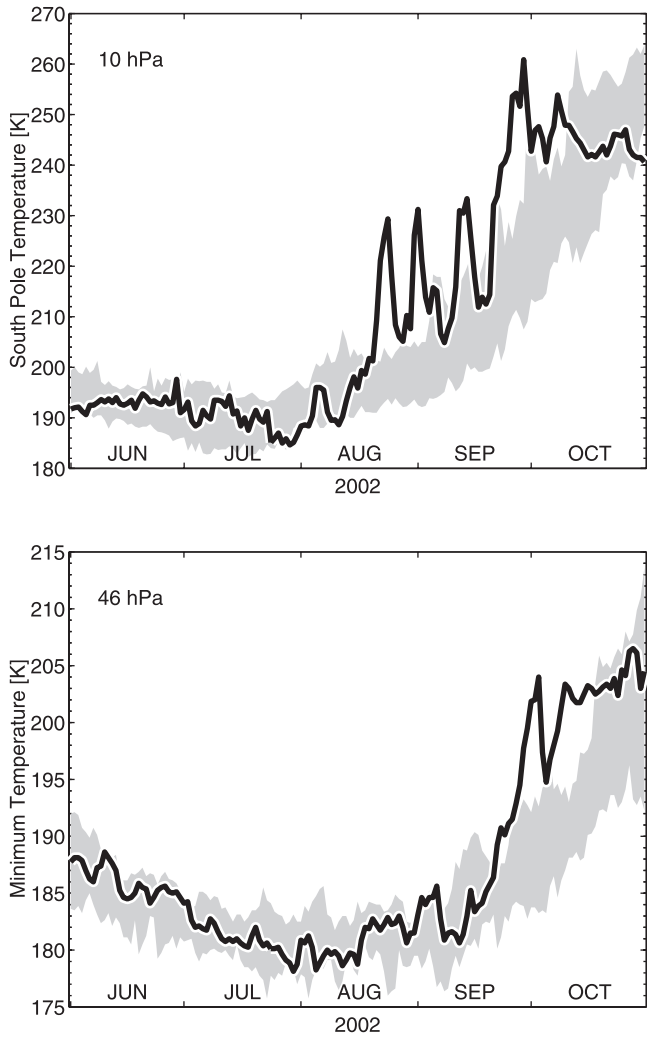

Figure 1. South pole temperature at 10 hPa and minimum temperature at 46 hPa between beginning of June and end of October 2002. The envelope of minimum and maximum values for the previous ten winters are gray shaded.

[14] Figure 1 shows South Pole temperatures at 10 hPa (upper panel) and polar minimum temperatures at 46 hPa (lower panel) from MO analyses. While the minimum temperatures at 46 hPa followed the climatology of the previous ten winters until the onset of the major warming in the second half of September, temperatures at 10 hPa already exhibited a set of warmings from mid-August on. (Similar results are obtained if one considers South Pole temperatures at 46 hPa instead of minimum temperatures.)

[15] The major stratospheric warming was accompanied by a large wave activity around 100 hPa. After September 17, 2002 the southward heat flux at 100 hPa strongly increased and reached an extreme value on September 22, much larger than any previously observed value (Figure 2). This anomalous heat flux at 100 hPa was then followed by the major warming throughout the lower and middle stratosphere a few days later. Although this large wave event at 100 hPa may have triggered the major warming at the end of September, it is, however, clear that the stratosphere was already unusually disturbed much earlier in this winter, as

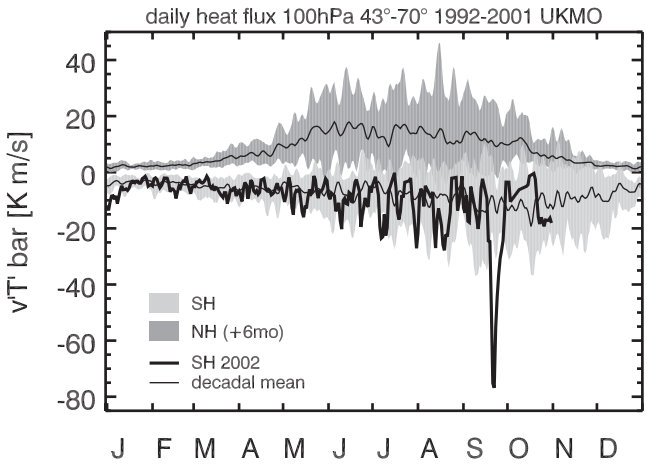

Figure 2. The daily heat flux at 100 hPa averaged between 43° and 70°S derived from MO analyses. For comparison the corresponding values for the northern hemisphere are shown, displayed shifted by six month. The extremely large southward heat flux around September 22, 2002 is evident.

seen, e.g., in the set of minor warmings at 10 hPa during August 2002.

4. Total Ozone

[16] A comparison between GOME total ozone observations and results from the CTM is shown in Figure 3 for selected days during winter 2002. The good agreement between model and observations is remarkable, given the simple nature of the parameterized ozone chemistry. However, the model does not include any tropospheric ozone. If this is taken into account the modeled total ozone column slightly overestimates the observations.

[17] Associated with the major stratospheric warming the ozone hole splits into two parts after September 25, clearly seen in the GOME observations and well reproduced by the CTM. One part of the split ozone hole moved equatorwards over the south Pacific and quickly disappeared. The other part of the split ozone hole moved polewards again where it stayed relatively undisturbed throughout October. The final break up of the ozone hole was then observed in early November 2002, about one month earlier than during previous years [*WMO*, 2003].

[18] The model run with 'passive ozone' nicely shows that even without polar chemistry a deep ozone minimum develops over the Antarctic during late winter and spring. Polar chemistry then leads to an additional reduction of Antarctic total ozone of roughly 100 DU by October. The model shows that ozone loss starts in the illuminated collar region around the edge of the polar night in early August with very little exchange with the inner vortex, in agreement with the results of *Lee et al.* [2000].

[19] Mean Antarctic total ozone was significantly higher during winter 2002, compared to previous winters. GOME total ozone averaged over the area 63°S–90°S was 291 DU during October 2002, compared to between 204 and 248 DU with a mean of 220 DU for the years 1995–2001.

[20] Figure 4 shows an estimate of the total column ozone loss, calculated as the difference between the daily GOME total ozone columns and the model run without polar

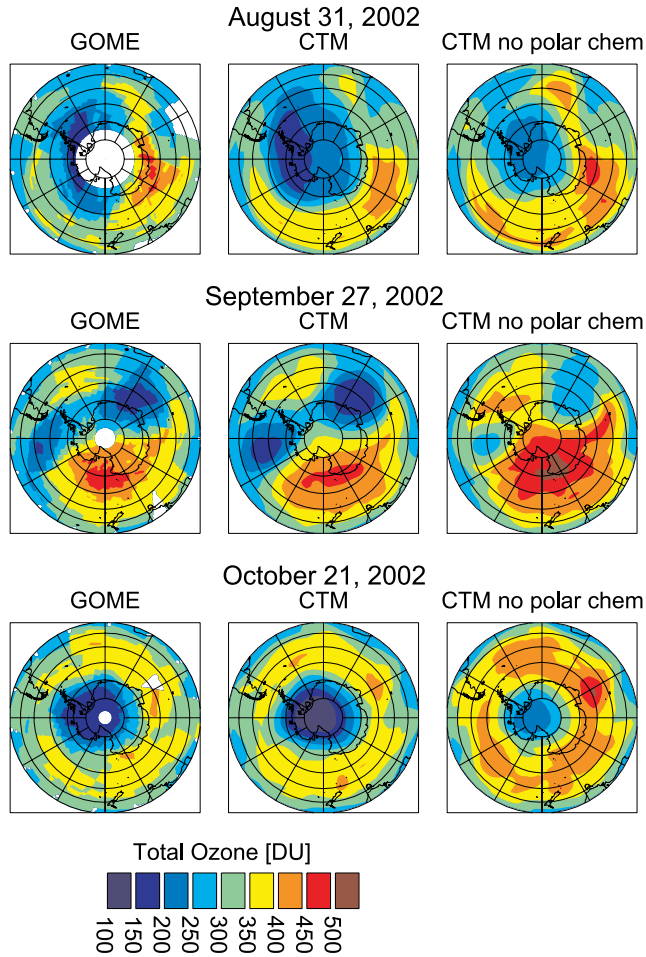

Figure 3. Total ozone from GOME and our CTM between August and October 2002 for selected days. GOME data are composed of observations over 24 hours, while the CTM results are for 12 UT.

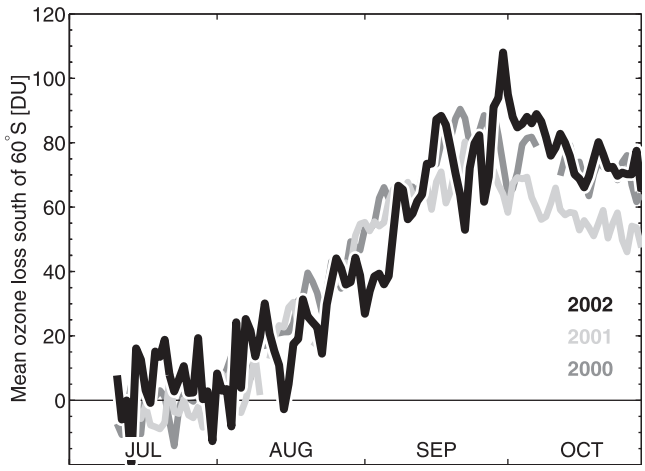

Figure 4. Estimated chemical loss of total ozone south of 60°S for the winters of 2000, 2001, and 2002, calculated as the difference between GOME total ozone and the CTM without polar chemistry.

chemistry, averaged over the area south of 60°S. For comparison, in addition to the winter 2002 the same analysis is also performed for the winters 2000 and 2001. No significant difference between observed and modeled ozone columns exists during July for all three years. Chemical ozone loss then starts in early August, indicated by the increasing difference between observations and model, and the accumulated ozone loss reaches a maximum of about 80 DU at the end of September.

[21] Perhaps somewhat surprising is the fact that the ozone loss during winter 2002 was about the same as for the previous two winters. In particular, column ozone loss stopped at about the same time at the end of September for all three years. No sign of ongoing ozone loss during October could be identified from this analysis for any of the three years investigated. The small decrease of the accumulated ozone loss during October probably reflects dilution of ozone depleted polar air by undepleted mid-latitude air masses.

5. Discussion and Conclusion

[22] The comparison of observed total ozone with our CTM calculations shows that the unusually high Antarctic total ozone during winter and spring 2002 can be explained well by the unusual meteorological conditions during this winter. The CTM calculations indicate that there was substantial chemical ozone depletion by October 2002, comparable to that during previous years. This is consistent with the cold Antarctic minimum temperatures in the lower stratosphere which followed the climatology of the previous ten years until mid of September 2002 (Figure 1) and the estimated extent of chlorine activation from GOME OClO observations [*Weber et al.*, 2003]. However, because total ozone was higher during winter 2002, the relative ozone loss (e.g., when expressed in per cent loss) was slightly smaller during winter 2002, compared with previous winters. *Hoppel et al.* [2003] found that by mid October 2002 the chemical loss between 14 and 20 km in the vortex core was about 95 DU, compared to about 120 DU in other years.

[23] The increase in total ozone during the winter of 2002 compared to previous winters is consistent with the enhanced tropospheric wave activity during this winter, seen e.g. in the heat flux at 100 hPa [*Weber et al.*, 2003]. An increase in the heat flux is expected to result in an increased poleward and downward flux of ozone [e.g., *Randel et al.*, 2002]. Calculations with our CTM for the last 11 years show that total ozone at the end of August was about 40 to 50 DU higher in 2002 than during the previous winters. As these model runs do not include a representation of polar chemistry, this demonstrates that this increase is due to anomalies in transport of ozone. Figure 2 of *Weber et al.* [2003] shows that the transient heat flux at 100 hPa was already significantly higher than in previous years during July and August 2002.

[24] Therefore we would like to emphasize that the increase of Antarctic total ozone during winter and spring 2002 compared to previous winters was a result of abnormal meteorological conditions during this winter. The situation during this winter must not be considered as evidence for a recovery of Antarctic ozone. In agreement with our current understanding of polar ozone chemistry, the Antarctic stratosphere will continue to be prone to substantial ozone depletion as long as the stratospheric halogen loading remains high.

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