Dynamical control of NH and SH winter/spring total ozone from GOME observations in 1995–2002

M. Weber, S. Dhomse, F. Wittrock, A. Richter, B.-M. Sinnhuber, and J. P. Burrows

Institute of Environmental Physics, University of Bremen, Bremen, Germany

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[1] The abnormal high wave activity in austral spring 2002 led to the first observation of a major stratospheric warming in the southern hemisphere resulting in a net winter increase of mid- to high latitude total ozone until September 2002. In previous years chemical ozone depletion inside the Antarctic vortex was sufficiently high to reduce mean total ozone south of 50° in September to values slightly below that of March (fall) as observed by GOME during the period 1995–2001. This unusual event permits us to examine the interannual variability in total ozone and OClO (the latter being an indicator of the level of chlorine activation inside the polar vortex) as measured by GOME combining data from the southern and northern hemisphere. It is shown that the absolute winter eddy heat flux between 43° and 70° latitudes at 100 hPa correlates extremely well ($r = 0.97$) with spring-to-fall ratio of total ozone polewards of 50° and anti-correlates with the winter integrated maximum OClO column amounts ($r = -0.94$) using this combined data set. The unusual ozone ratio for austral winter/spring 2002 lies almost midway between typical values for Antarctica and those for recent cold Arctic winter/spring seasons. *INDEX TERMS:* 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 3319 Meteorology and Atmospheric Dynamics: General circulation; 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3362 Meteorology and Atmospheric Dynamics: Stratosphere/troposphere interactions. **Citation:** Weber, M., S. Dhomse, F. Wittrock, A. Richter, B.-M. Sinnhuber, and J. P. Burrows, Dynamical control of NH and SH winter/spring total ozone from GOME observations in 1995–2002, *Geophys. Res. Lett.*, *30*(11), 1583, doi:10.1029/2002GL016799, 2003.

1. Introduction

[2] Interannual variations of winter/spring total ozone have been linked to planetary-scale wave activity as approximated by the extratropical lower stratospheric eddy heat flux [*Fusco and Salby*, 1999; *Randel et al.*, 2002]. The slow meridional residual circulation also known as the Brewer-Dobson circulation governs the diabatic ascent in the tropics and descent of stratospheric airmasses (and trace gases) in the polar regions [*Haynes et al.*, 1991]. This circulation is driven by planetary-scale Rossby and gravity waves, that propagate from the troposphere and break in the stratophere and higher levels [*Haynes et al.*, 1991; *Rosenlof and Holton*, 1993]. This process is most efficient during hemispheric winters [*Rosenlof*, 1995]. The diabatic descent in the polar region is responsible for the steady increase of lower stratospheric ozone over winter particularly in the Arctic region [e.g. *Chipperfield and Jones*, 1999]. The polar stratospheric temperatures are also controlled by planetary-scale wave forcing. Low midwinter wave activity leads to weaker downward diabatic descent in mid- to high latitudes, stronger cooling of the lower polar stratosphere (closer to the radiative equilibrium temperature), and to a strengthening of the polar vortex [*Newman et al.*, 2001; *Waugh et al.*, 1999]. In addition to changes in transport, chemical depletion due to heterogeneous processes plays an increasing role at lower temperatures [e.g. *Solomon*, 1999].

[3] Temperatures in the SH polar stratosphere are persistently colder than in the NH resulting in large chemical ozone depletion observed for more than a decade during austral spring [e.g. *Farman et al.*, 1985]. It is also known that planetary-scale wave activity plays a more minor role in the SH leading to rather minor perturbations of the Antarctic polar vortex. As a consequence the accumulated mid- to high latitude ozone mass is lower during austral spring than in the corresponding NH season. Figure 1 shows the annual cycle of GOME mean total ozone in the 50°–90° latitude band in the southern hemisphere since 1995. While an increase in total ozone from late summer to spring is clearly detectable in the northern hemisphere (see Figure 2 in *Eichmann et al.* [2002]), an ozone reduction is observed in the SH by September. The increase in extratropical ozone in austral winter/spring 2002 is clearly an exception to the general behaviour in previous years and is a consequence of the abnormal midwinter wave activity in 2002 [*Sinnhuber et al.*, 2003].

[4] As the high interannual variability of winter/spring ozone and temperature in the NH has been subject of many recent investigations [e.g. *Pawson and Naujokat*, 1999; *Harris et al.*, 2002; *Eichmann et al.*, 2002; *Weber et al.*, 2002], this year's warming event in the SH motivated a closer look at the connection between planetary-scale wave activity and winter/spring ozone in both hemispheres using meteorological analysis from UKMO [*Swinbank and O'Neill*, 1994] and multi-annual trace gas observations from the Global Ozone Monitoring Experiment GOME from the period 1995–2002 [*Burrows et al.*, 1999]. The links between OClO (chlorine activation), ozone, winter volume of polar stratospheric clouds, which foster heterogenous reactions and the build-up of active chlorine from reservoir species, and winter eddy heat flux are investigated.

2. GOME Trace Gas Data

[5] From the UV/visible GOME nadir radiances vertical columns of several trace gases, for instance, O_3, NO_2, BrO,

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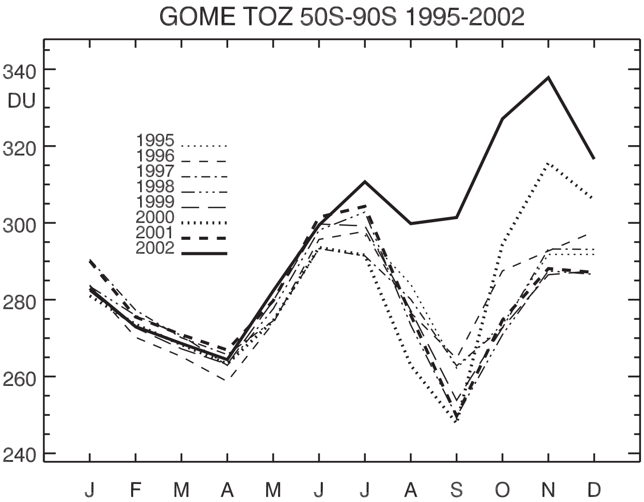

Figure 1. Area-weighted GOME total ozone between 50°S and 90°S excluding polar night region.

and OClO [*Burrows et al.*, 1999; *Richter et al.*, 1998; *Wagner et al.*, 2001] are retrieved using the differential optical absorption technique (DOAS). Total ozone used here are the GOME Data Processor (GDP) Version 2.7 data [*Bramstedt et al.*, 2002]. Zonal mean total ozone values were derived from area-weighted and gridded daily total ozone values as shown in Figure 1.

[6] As OClO is photolysed rapidly, it only achieves significant daytime concentrations under twilight condition near the terminator line. Slant columns have been converted to vertical columns using air mass factors (AMF) computed with a multiple scattering radiative transfer model GOME-TRAN [*Rozanov et al.*, 1997] for standard profiles for OClO. The absolute errors of OClO vertical columns under twilight condition are, therefore, conservatively estimated at 50% [*Weber et al.*, 2002]. In order to evaluate the interannual variability of chlorine activation for both hemispheres a proxy for the cumulative winter chlorine activation has been defined by summing up the daily maximum OClO vertical column amount at 90° solar zenith angle between May and September (November and March in NH) and by dividing that number by 365.

3. Meteorological Analysis

[7] Meteorological quantities are derived from the UKMO assimilation data system *Swinbank and O'Neill*, 1994]. The eddy heat flux $\overline{v'T'}$, which is proportional to the vertical component of the Eliassen-Palm flux and a measure of the strength of planetary wave activity, is calculated in a similar manner as described by *Randel et al.* [2002]. It was determined at the 100 hPa level and an area-weighted average was calculated from 43° to 70°, the latitude range where it reaches maximum in both hemispheres. Monthly mean heat flux values are calculated from the daily means.

[8] Figure 2 shows the range of the monthly mean and transient heat flux observed during the last decade in the SH. The transient heat flux is here defined as the square root of the sum of the squared differences between daily values and the monthly mean and can be interpreted as the variability within a given month. In winter/spring 2002 the SH transient heat flux was above the usual decadal range (1992–2001) starting in July 2002 and this anomaly peaked in September 2002, almost at twice the maximum value observed within the last ten years. This is in line with the observation that the hemispheric total ozone started to deviate from the typical range seen in previous years (1995–2001) in July 2002 and reached a maximum enhancement of 35–50 DU in September 2002 as shown in Figure 1.

4. Dynamical Control of Spring Ozone

[9] Before looking at the connection between winter heat flux and early spring ozone, the relationship between PSC volume, which can be regarded as a proxy for the chemical ozone depletion inside the polar vortex, and winter heat flux is investigated. Figure 3 depicts the correlation between winter heat flux and PSC volume inside the polar vortex for the period 1992–2002. The mean winter eddy heat flux was derived from Gaussian integration of monthly heat fluxes between March and September (between September and March in NH) and by dividing that number by the sum of weights. The average PSC volume, V_{PSC}, was obtained by integrating daily derived volumes of the extratropical region with temperatures below PSC existence threshold temperatures of 195 K between May and October (November and March in NH) and dividing that value by 365 (units km^3).

[10] The clustering of data points can be divided into three regimes, 1) the unperturbed cold Antarctic winter with high PSC volume (>100 $\times$ 10^6 km^2) and low absolute winter heat flux, 2) cold Arctic winters (92/93, 94/95–96/97, 1999/00) with moderate PSC volumes and moderate winter heat fluxes, and 3) warm Arctic winters with low or negligible PSC volumes and high winter heat flux (1993/94, 97/98, 98/99, and 2000/01, 2001/02). The austral winter/spring season 2002 can be regarded as a new class with elevated winter heat flux and a winter PSC volume, smaller than normal but still considerably higher than observed during cold winters. Fitting linear curves for each hemisphere (correlation coefficient r of -0.70 and -0.62 in SH and NH, respectively) show that the relationship between heat flux and PSC volume is not as simple as stated earlier.

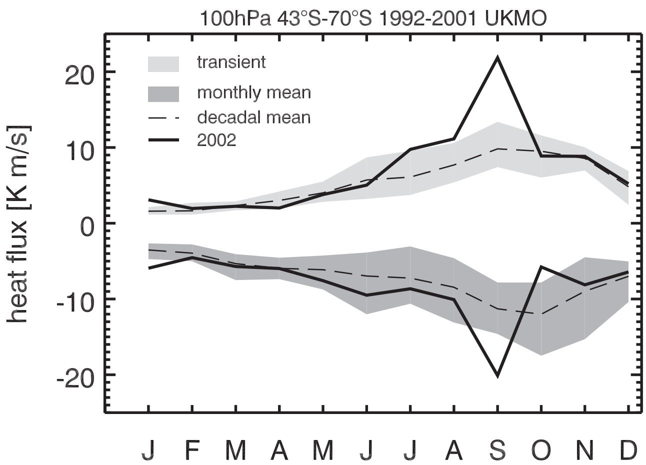

Figure 2. UKMO monthly mean total and transient eddy heat flux 1992–2002. The shadings indicate the range observed during the last decade with negative values being monthly means and positive values being transient.

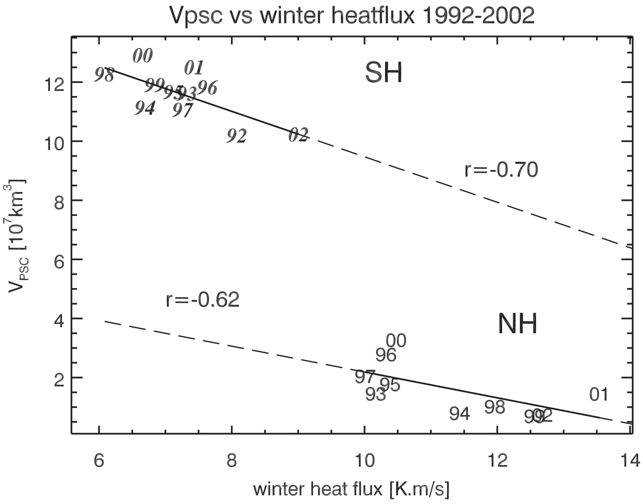

Figure 3. Scatter plot of winter integrated PSC volume and absolute winter heat flux at 100 hPa. Years for northern hemispheric winters are given for March (non-italics), e.g. 99 means boreal winter/spring season 1998/99.

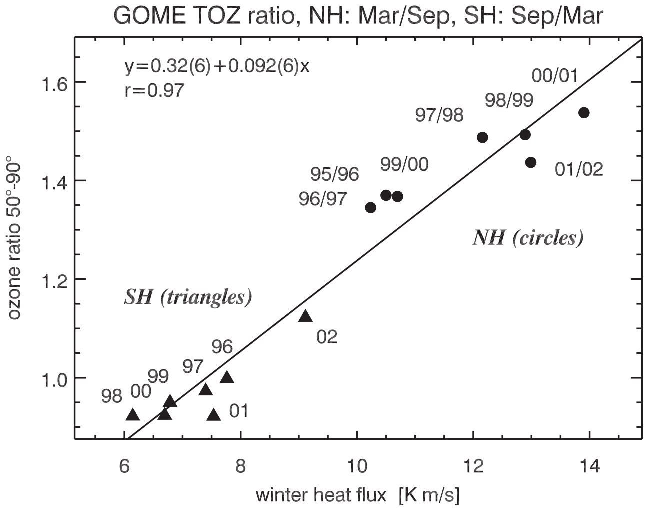

Figure 5. Correlation between winter total ozone ratio (SH: Sep/Mar ratio, NH: Mar/Sep ratio) and mean winter heat flux. Note that the SH mean winter heat flux is negative but is plotted with a positive sign.

Particular care has to be taken by extrapolating the results from one hemisphere to the other.

[11] In Figure 4 the relation between the winter mean of maximum OClO column amounts observed at 90°SZA in both hemispheres and the winter heat flux is shown. Both quantities show a correlation coefficient of $r = -0.94$. This plot together with Figure 3 proves the strong linkage between chlorine activation (and as a consequence chemical depletion of ozone) in the polar region, stratospheric temperatures (as indicated by PSC volume), and the mid- to high latitude winter wave activity. The linear relationship as shown in Figure 4 is nevertheless in contrast to the non-linear relationship in PSC volume between hemispheres as shown in Figure 3. This may be explained by the fact that assuming complete chlorine activation (like in cold Arctic winters and regularly above Antarctica) the main difference in observed maximum hemispheric OClO columns results most likely from activated air masses extending over a larger altitude range in austral winter/spring [*Wagner et al.*, 2001].

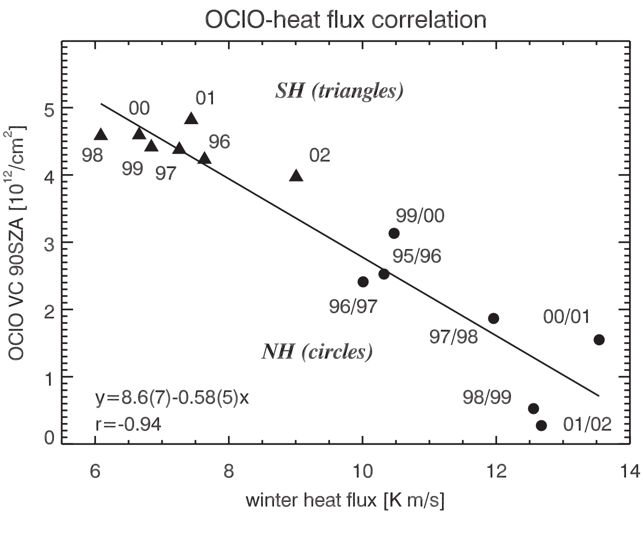

Figure 4. Relationship between mean winter OClO vertical column amount and winter heat flux. Note that the SH mean winter heat flux is negative but is plotted with a positive sign.

[12] In Figure 5 the spring-to-fall total ozone ratio poleward of 50° (March over September in NH and September over March in SH) is shown as a function of the average winter heat flux. By combining data from both hemispheres a remarkably compact relationship between both parameters and hemispheres is found. The spring/fall total ozone ratio is generally below one in the SH indicating that the chemical ozone depletion inside the Antarctic vortex more than outweighs the gain resulting from the accumulated diabatic descent during winter (see also Figure 1), except for the 2002 austral spring where the ratio reached 1.15. During cold Arctic winters the GOME spring-to-fall ratio is slightly below 1.4 and well above that value during the so-called warm Arctic winters. The relationship between the winter heat flux and the hemispheric ozone gain shows a correlation of $r = 0.97$ at a 95% confidence level. The same correlation is achieved, if the analysis is based on ozone zonal mean, poleward of 60°. *Andersen and Knudsen* [2002] have shown that 75% of the decrease in March total ozone north of 63°N in the mid nineties can be attributed to polar vortex chemical depletion. As shown in Figure 4 of their paper and in this study, two depletion mechanisms are closely coupled. Low winter wave activity reduces the winter supply of ozone through diabatic descent and the low polar stratospheric temperatures associated with it lead to additional chemical depletion due to enhanced PSC formation and chlorine activation in such cold stratospheric winters.

5. Discussion and Conclusion

[13] We have shown that the interannual variability of the mid latitude winter eddy heat flux at 100 mbar correlates extremely well with the variable hemispheric ozone spring/fall ratio when combining data from both hemispheres. This ozone ratio is largely determined by the cumulative effect of the residual circulation driven by the planetary-scale wave

activity throughout the winter in conjunction with different levels of chemical depletion. The unusual September 2002 ozone gain lies almost midways between the values for typical cold Arctic winters and all other Antarctic winters observed by GOME. As planetary scale wave activity has an impact on polar stratospheric temperatures [*Newman et al.*, 2001] and PSC formation, the polar vortex ozone depletion becomes closely linked to the planetary-scale wave activity driving the slow meridional circulation. A surprising result was that the abnormal wave activity in austral winter/spring 2002 only lead to a minor reduction in winter OClO in line with the notion of almost no changes in chemical ozone loss compared to earlier Antarctic winters [*Sinnhuber et al.*, 2003].

[14] Several model studies have demonstrated that the decadal decline in mid- to high latitude ozone in combination with increases in greenhouse gases induce a negative stratospheric temperature trend, which in turn may reduce the strength of the residual circulation [*Shindell et al.*, 1998, 2001; *Schnadt et al.*, 2002]. This feedback mechanism may potentially delay future ozone recovery despite anticipated falling stratospheric chlorine levels [*Shindell et al.*, 2001], although there are some indications for a possible intensification of planetary wave activity in the NH [*Schnadt et al.*, 2002]. The observed longterm trends in polar stratospheric temperatures and total ozone in both hemispheres support the notion of a positive feedback mechanism [*Randel and Wu*, 1999].

[15] The effect of the planetary-scale activity on ozone and polar stratospheric temperature occur on short timescales ranging from a month [*Fusco and Salby*, 1999; *Randel et al.*, 2002; *Newman et al.*, 2001] up to an entire season (this study). This close interaction of meteorology and chemistry on short time scales complicate the identification of the cause-effect relationship on decadal time scales. Identification of longterm changes in the residual circulation beyond the natural variability may, nevertheless, provide an important clue to the connection between climate change and stratospheric ozone. The unusal major stratospheric warming event in the SH may provide a hint that apart from expected changes in halogen loading two competing forcing mechanism may gain importance in influencing future ozone trend: first, stratospheric cooling due to changes in radiative forcing as a consequence of increased greenhouse gases and, secondly, enhanced interannual variability of winter heat flux as a result of a warming trend in the coupled ocean-troposphere system.

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M. Weber, S. Dhomse, F. Wittrock, A. Richter, B.-M. Sinnhuber, and J. P. Burrows, Institute of Environmental Physics, University of Bremen FB1, PO Box 330 440, D-28334 Bremen, Germany. (mark.weber@uni-bremen.de)