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Simple measures of ozone depletion in the polar stratosphere

R. Müller¹, J.-U. Groß¹, C. Lemmen^{1,*}, D. Heinze¹, M. Dameris², and G. Bodeker³

¹ICG-1, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

²DLR, IPA, Oberpfaffenhofen, Germany

³NIWA, Private Bag 50061, Omakau Central Otago, New Zealand

* now at: Copernicus Instituut voor Duurzame Ontwikkeling en Innovatie, Universiteit Utrecht,
3584CS Utrecht, The Netherlands and Institut für Küstenforschung,
GKSS-Forschungszentrum Geesthacht GmbH, 21502 Geesthacht, Germany

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Correspondence to: R. Müller (ro.mueller@fz-juelich.de)

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Abstract

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We investigate the extent to which commonly considered quantities, based on total column ozone observations and simulations, are applicable as measures of ozone loss in the polar vortices. Such quantities have been used frequently in ozone assessments by the World Meteorological Organization (WMO) and to assess the performance of chemistry-climate models. The most commonly considered quantity is monthly mean column ozone poleward of a latitude of 63° in spring. For the Arctic, these monthly means were found to be insensitive to the exact choice of the latitude threshold, unlike the Antarctic where greater sensitivity was found. Choosing a threshold based on the location of the transport barrier at the vortex boundary instead of geometric latitude led to a roughly similar year-to-year variability of the monthly means, but in particular years deviations of several tens of Dobson units occurred. Moreover, the minimum of daily total ozone minima poleward of a particular latitude, another popular measure, is debatable, insofar as it relies on one single measurement or model grid point. For Arctic conditions, this minimum value occurred often in air *outside* the polar vortex, both in the observations and in a chemistry-climate model. As a result, we recommend that the minimum of daily minima no longer be used when comparing polar ozone loss in observations and models. As a possible alternative, we suggest considering the minimum of daily average total ozone poleward of a particular equivalent latitude (or in the vortex) in spring. This definition both obviates relying on one single data point and reduces the impact of year-to-year variability in the Arctic vortex breakup on ozone loss measures. However, compact relations of such simple measures with meteorological quantities that describe the potential for polar heterogeneous chlorine activation and thus ozone loss were not found. Therefore, we argue that where possible, more sophisticated measures of chemical polar ozone loss that include additional information to disentangle the impact of transport and chemistry on ozone, should be employed.

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1 Introduction

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Since the early eighties, substantial chemical ozone loss has occurred over winter and spring each year in the Antarctic; (e.g., [Jones and Shanklin, 1995](#); [Tilmes et al., 2006](#); [Huck et al., 2007](#); [WMO, 2007](#)) substantial chemical loss of ozone has likewise been reported for recent cold Arctic winters (e.g., [Manney et al., 2003](#); [Tilmes et al., 2004](#); [WMO, 2007](#)). In the very cold Arctic winter of 2004/05, the chemical loss of ozone came closer to Antarctic values ([Manney et al., 2006](#); [Rex et al., 2006](#); [Tilmes et al., 2006](#); [von Hobe et al., 2006](#); [Jin et al., 2006](#)). Sophisticated methods have been developed to separate dynamically induced changes of polar ozone from chemical ozone depletion (e.g., [Proffitt et al., 1990](#); [Manney et al., 1994](#); [Müller et al., 1996](#); [Rex et al., 2002](#); [Harris et al., 2002](#); [Christensen et al., 2005](#); [Goutail et al., 2005](#); [Tilmes et al., 2004](#), and references therein). Furthermore, the deduced chemical ozone loss has been shown to be closely related to the potential for the formation of polar stratospheric clouds (PSC, [Rex et al., 2004](#); [Tilmes et al., 2004, 2006](#)).

However, these methods rely on rather comprehensive data sets that are not available for all winters of interest, particularly those before the 1990s. Similarly, the necessary information for applying such sophisticated methods to simulations conducted with chemistry-climate models (CCM) is often not available for the archived model output (e.g., [Austin et al., 2003](#); [Eyring et al., 2006](#); [Lemmen et al., 2006b](#)).

Therefore, measures of chemical polar ozone depletion are commonly employed that rely solely on total column ozone data (e.g., [Newman et al., 2004](#); [Bodeker et al., 2005](#); [Huck et al., 2007](#)). Such simple measures include the average total column ozone in spring (March, NH and October, SH) poleward of 63° , or the minimum of daily total column ozone minima over the polar cap (e.g., [Newman et al., 1997](#); [Müller, 2003](#); [Austin et al., 2003](#); [WMO, 2003](#); [Eyring et al., 2006](#); [WMO, 2007](#)). In particular, the average March total column ozone poleward of 63° N ([Newman et al., 1997](#)) has been used frequently for assessments of the World Meteorological Organization (WMO) and of the Intergovernmental Panel on Climate Change (IPCC, e.g., [WMO, 1999, 2003](#);

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IPCC/TEAP, 2005; WMO, 2007). The value of 63° N was chosen by Newman et al. (1997), because “...the area poleward of 63° N is [...] large enough to contain the polar vortex, yet small enough to not be dominated by mid-latitude air masses in the lower stratosphere”. Obviously, this condition will be better fulfilled in some Arctic winters than in others depending on the varying size and shape of the polar vortex (Waugh and Randel, 1999; Karpetchko et al., 2005).

Moreover, the minimum of daily total ozone minima poleward of a particular latitude has been used as a standard to assess the performance of CCMs (e.g., Austin et al., 2003; WMO, 2003; Eyring et al., 2006; WMO, 2007). This measure is problematic, insofar as it relies on one single measurement or model grid point. Knudsen (2002) has criticised the use of this parameter and pointed out that the minimum ozone in the Arctic is frequently caused by high pressure systems rather than by chemical ozone destruction. He therefore argued that e.g., the March 63° N–90° N mean total column ozone should be a more suitable measure for the development of polar ozone.

Here, we scrutinise the information that can be deduced from simple (total column ozone based) measures of chemical ozone loss and investigate circumstances where mis- and over-interpretations might occur. Our study uses a combined data set of satellite-based total column ozone measurements (Bodeker et al., 2005) from 1978 to 2007 (Sect. 2). Monthly mean column ozone poleward of 63° in spring (Newman et al., 1997; WMO, 2007) shows similar year-to-year variability as vortex mean ozone, but neither of these quantities shows a close relation with meteorological quantities that describe the potential for polar heterogeneous chlorine activation and thus ozone loss (Sect. 3). Furthermore, we argue here that the minimum of daily total ozone minima poleward of a particular latitude should no longer be used when comparing polar ozone loss between observations and CCMs because this minimum value often occurs in air *outside* of the polar vortex (Sect. 3). We discuss alternatives for such simple measures, both measures based on total ozone observations alone and measures based on more sophisticated techniques.

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2 The total column ozone data set

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The data set used here is version 2.6 of the NIWA combined ozone data base which provides daily total column ozone fields from November 1978 to March 2007. It is based on version 8 TOMS (Total Ozone Mapping Spectrometer) retrievals from four different satellites (Nimbus 7, Meteor 3, ADEOS, and Earth Probe), total column ozone retrievals from application of the TOMS version 8 retrieval algorithm to OMI (Ozone Monitoring Instrument) measurements, version 3.1 GOME (Global Ozone Monitoring Experiment) ozone retrievals, GOME total column ozone fields from the KNMI TO-GOMI algorithm, and version 8 SBUV (Solar Backscatter Ultra-Violet) retrievals from four different satellites (Nimbus 7, NOAA 9, NOAA 11, and NOAA16). It updates the data set described in [Bodeker et al. \(2005\)](#), extending it to the end of March 2007, and implementing a number of improvements including:

- Data from both the Dobson spectrophotometer and Brewer spectrometer global networks are now used to remove offsets and drifts between the various satellite-based total column ozone data sets used to construct the data base.
- Data from the Ozone Monitoring Instrument (OMI) flown onboard NASA's Aura satellite since September 2004 are now used. Differences between OMI overpass measurements and ground-based measurements are small (-2.8 ± 5 DU) and the OMI grid data are corrected before they are combined with the other data sources which are also corrected as in [Bodeker et al. \(2005\)](#).
- A better correction function for the Earth Probe TOMS ozone measurements has been derived to account for non-linearities in the drift between the Earth Probe TOMS measurements and ground-based measurements in recent years. Since September 2004 these data are only used when OMI data are unavailable.
- Better screening of anomalous ozone measurements from the DLR GOME retrieval at high solar zenith angles has been implemented.

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- 5 – In previous versions of the combined database, data from only one satellite-based instrument were used on any given day. In this version of the database, data from all satellite-based instruments are considered sequentially to fill each 1.25° longitude by 1.0° latitude grid cell with a priority of Nimbus 7 TOMS, Meteor 3 TOMS, OMI, Earth Probe TOMS, ADEOS TOMS, the KNMI and then DLR GOME ozone retrievals, and then the 4 SBUV data sets. For example, if most, but not all, of the globe is covered by Nimbus 7 TOMS and Meteor 3 TOMS data are available to fill the gap, then these data are used for this. Both data sets, as before, are first corrected for offsets and drifts against the ground-based measurements. In previous versions of the data base however, only the Nimbus 7 data would have been used for that day and the gap in the data would remain.
- 10

3 Results

3.1 Mean total column ozone over the poles in early spring

To test the sensitivity of the calculated Arctic mean ozone to the selected latitude limit, 15 the March mean Arctic total column ozone for a latitude boundary at 63° N, as originally chosen by [Newman et al. \(1997\)](#), is compared with the mean for boundaries at 60° N, 65° N, and 70° N in Fig. 1 (top panel). Clearly, the monthly spatial means are not very sensitive on the exact choice of the threshold latitude. A very similar picture is found for the average total ozone column in April (see electronic supplement). During 20 the eighties, and in the warmer winters during the nineties, choosing a more poleward threshold latitude yields greater average ozone columns. The opposite (a smaller ozone column for a more poleward threshold latitude) is observed for the cold Arctic winters 1994/1995, 1995/1996, and 1999/2000 where substantial chemical ozone loss was observed (e.g., [Manney et al., 2003](#); [Tilmes et al., 2004](#)). The strongest effect from 25 changing the threshold latitude is found for the winter 1996/1997, a winter where the March mean column ozone showed an unusually strong meridional gradient ([Newman](#)

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Using equivalent latitude (Φ_e) rather than geographic latitude as an estimate of the boundary of the vortex (e.g., Butchart and Remsberg, 1986; Lary et al., 1995), should lead to a better demarcation between polar and mid-latitude air. Therefore, in Fig. 1 (bottom panel), the total column ozone average for March in the Arctic is shown using both the latitude and the equivalent latitude poleward of 63° N as the threshold. Here and throughout the paper equivalent latitude and other diagnostics of the vortex edge are evaluated on the 475 K potential temperature level, except where stated otherwise. Overall the two averages show a similar inter-annual pattern. When equivalent latitude is used as the threshold, Arctic winters with a polar centric vortex (e.g., 1996/1997) show little change, while winters in the nineties with substantial chemical ozone loss within a perturbed vortex show lower averages. This result is not surprising because, when using equivalent latitude as the threshold, the average ozone is less likely to be influenced by air from outside the vortex where, in winters with substantial ozone loss, ozone is higher.

An estimate of the location of the vortex boundary, i.e. the location of the strongest barrier to meridional transport in the polar region, and which is based on fluid-dynamical theory, is the maximum gradient in potential vorticity in equivalent latitude constrained by the horizontal wind velocity (Nash et al., 1996). The edge of the vortex defined in this way agrees reasonably well with observed strong tracer gradients at the vortex boundary (e.g., Greenblatt et al., 2002; Müller and Günther, 2003). Because the area of the polar vortex varies substantially from year to year in the Arctic (e.g., Karpetchko et al., 2005; Tilmes et al., 2006), a constant equivalent latitude cannot provide an accurate estimate of the vortex area. Thus, because chemical ozone loss is confined to within the vortex boundary, one expects that the average total column ozone poleward of the vortex edge as defined by Nash et al. (1996) should show lower values than an average based on geometric or constant equivalent latitude. This is indeed borne out by the analysis, with the exception of the warm winters of 1978/1979, 1984/1985, 1987/1988, and 1998/1999 (Fig. 1, bottom panel). All four of these Arctic

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winters show a very low PSC formation potential and thus a very small potential for chemical ozone destruction (Rex et al., 2004; Tilmes et al., 2006). For all other winters, the polar average total column ozone using a potential vorticity gradient based threshold is lower than using any other threshold and the difference is particularly pronounced for winters showing strong ozone depletion. The sole exception is the winter of 1996/1997 that showed an unusually inhomogeneous ozone distribution within the Arctic vortex with a particularly low ozone column in the vortex core (e.g., Newman et al., 1997; Manney et al., 1997; McKenna et al., 2002).

The Arctic vortex, typically, is strongly eroded in April and is therefore smaller than the area encompassed by the 63° N equivalent latitude contour (e.g., Waugh and Randel, 1999). Consequently, column ozone in April averaged over the vortex area as deduced using the Nash et al. (1996) criterion is expected to be lower than the average column ozone poleward of 63° N equivalent latitude, as is the case here (see electr. suppl., <http://www.atmos-chem-phys-discuss.net/7/9829/2007/acpd-7-9829-2007-supplement.zip>). Because the Arctic vortex in April is unlikely to be polar centred, computing a polar average column ozone using geometric latitude rather than equivalent latitude as the threshold, should lead to even more ozone-rich mid-latitude air masses being included in the average, and thus should lead to even greater averages as it is indeed the case (see electr. suppl., <http://www.atmos-chem-phys-discuss.net/7/9829/2007/acpd-7-9829-2007-supplement.zip>).

Although originally designed for the Arctic, the concept of the average total ozone column poleward of a threshold latitude of 63° has been extended to the Antarctic, where October mean values are commonly considered (e.g., WMO, 1999; IPCC/TEAP, 2005; WMO, 2007). In the Antarctic, the choice of the threshold latitude has a much stronger impact on the October average polar column ozone compared to the Arctic; the difference between a threshold of 60° S and 70° S is noticeable in every Antarctic winter analysed here and can be as large as ~50 DU (Fig. 2, top panel). The pattern of inter-annual change in the October mean ozone column, however, is not strongly affected by the choice of the threshold latitude. These statements are likewise valid for

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the average total ozone column in September (see electronic supplement). As for the Arctic, the sensitivity of Antarctic average total column ozone to the latitude poleward of which the average is calculated depends on the steepness of the meridional gradients in ozone across the vortex edge. For the latitude range considered in Fig. 2, the ozone gradients are steeper in the Antarctic than the Arctic (see e.g. Fig. 5 of Brunner et al. 2006) and so Antarctic mean total column ozone is expected to be more sensitive to the spatial limiting latitude.

In the Antarctic, the 63° S equivalent latitude contour is often located within the polar vortex in early spring (e.g., Bodeker et al., 2001, 2002). As a result, the difference between the average column ozone poleward of the Nash defined vortex edge and the average poleward of 63° S equivalent latitude (Fig. 2, bottom panel) is smaller than in the Arctic. Using the Nash vortex edge as the limiting contour for the averaging includes air masses towards the vortex edge that are not included if a threshold of 63° S equivalent latitude is used. Because total column ozone in the Antarctic vortex increases towards the vortex boundary (Bodeker et al., 2002), using the Nash criterion will generally lead to greater polar total ozone averages (Fig. 2, bottom panel). The only obvious exception to this observation in the October time series analysed here is the winter of 2002. In this winter, at the end of September, a sudden stratospheric warming occurred in the Antarctic vortex, leading to a much smaller and weaker vortex than usual, reminiscent of Arctic conditions (e.g., Krüger et al., 2005; Newman and Nash, 2006).

3.2 Minimum column ozone in the polar region

3.2.1 Minimum polar total column ozone in observations

The minimum of daily total column ozone between 60° and the pole for the period March/April in the Arctic and September–November in the Antarctic has been employed as measure of polar ozone loss for the validation of CCMs (Austin et al., 2003; WMO, 2003; Eyring et al., 2006; WMO, 2007). The minimum of daily total column ozone used

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in this study is defined as the minimum value of the daily minima over the respective periods, i.e. one single measurement or one single model grid point within a two month period.

In Fig. 3 it is shown that for winters with little chemical ozone destruction a substantial fraction of the daily minimum ozone columns occur *outside* the polar vortex. For half of the winters considered here about 50% of the daily minima occur outside of the vortex. And for only four winters is the fraction of minima occurring outside below 25%.

If the minimum value of daily total ozone minima poleward of 60°N (as used, e.g., in WMO, 2003, 2007) is computed, it provides information from within the polar vortex in 10 only 12 out of the 29 winters considered here (Fig. 4). The deviation between the vortex minimum total ozone and the poleward of 60°N minimum total ozone is significant, with a maximum deviation of ~50 DU in the winter of 1984/1985.

In the Antarctic, because of the stronger reduction in column ozone due to chemical ozone destruction, the situation is different. For the period considered here, the 15 minimum of daily column ozone between 60° S and the pole for the period September–November (not shown) is always located within the vortex.

3.2.2 Minimum column polar ozone in model results

Differences between different simple measures of ozone loss and between simple and more sophisticated analyses also occur when analysing results from model simulations, as will be shown below. Since the prediction of the recovery of polar ozone 20 is based on simulations with CCMs (e.g. Austin et al., 2003; WMO, 2003, 2007), the identification of a recovery period may depend on the analysis methodology chosen for ozone loss. In the last two ozone assessments (WMO, 2003, 2007) the spatial minimum of the daily spring ozone minimum poleward of 60° served as a quantifier for the state of the polar ozone layer for comparison with simulations from different CCMs.

For simulated ozone columns, here, we use as an example two time slice experiments from the chemistry-climate model ECHAM4.DLR(L39)/CHEM (hereafter abbreviated as E39/C Hein et al., 2001; Schnadt et al., 2002). Each ensemble experiment

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consists of 20 recurrent simulations with constant boundary conditions (sea surface temperature, greenhouse gases), one for the 1990s and one for the near-future. The near-future conditions originally aimed at the year 2015, but in the interim it has been found that the sea surface temperatures used are too high. Therefore, results from the future simulation should not be considered as a reliable projection of a specific period but rather as being indicative of possible future conditions. The 1990 time slice results, in contrast, are in agreement with the results derived from the most recent transient ensemble run for 1960 to 1999 (Dameris et al., 2005; Eyring et al., 2006). A detailed description of both time slice experiments and the simulation of ozone therewith is given elsewhere (Schnadt, 2001; Lemmen, 2005).

Figure 5 compares ensemble statistics of both time slices analysed separately for the polar cap and the dynamically defined vortex, all data reported for April 1. For example, in the 1990 simulation poleward of 60° N (dark blue colour), the spatial mean ozone column (ordinate) was 387 DU and the range was 310–439 DU. In half of the years, the spatial mean column was larger than 403 DU. For the same analysis, the mean and range of the spatial minimum column (abscissa) are 291 DU and 218–369 DU. Column values for ‘future’ (cyan, dark yellow) are consistently higher than for ‘1990’ (blue, red) due to a lower chlorine loading and more dynamical heating leading to a stronger downward transport (Schnadt et al., 2002; Eyring et al., 2006).

For both time slices, the spatial mean total column ozone is higher over the polar cap than over the vortex, and the spatial minimum column is lower over the polar cap than over the vortex; this difference in spatial analysis is more pronounced in the future experiment (with less chemical ozone destruction). For the 1990 experiment, 50% of the years have a minimum column less than 310 DU analysed within the vortex, but 75% of these winters have a minimum column less than 310 DU analysed within the polar cap. Evidently, for many years the spatial minimum is located outside the vortex in spite of the on average lower ozone column within the vortex.

The erroneous association of the spatial minimum column ozone with high chemical ozone loss becomes clear in a comparison with analysed chemical ozone loss. Chemi-

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cal ozone loss based on a methane-ozone tracer correlation with reference established on 1 January each simulated year and compared to the 1 April methane-ozone relation was first presented by Lemmen (2005) for this data set. Here, the loss values are recalculated based on an improved method to determine the vortex edge. The 5 vortex edge was determined by fitting a third-order polynomial to the potential vorticity (PV) distribution as a function of Φ_e for each potential temperature level between 340–640 K, defining the vortex edge by the steepest PV gradient constrained by the wind maximum on each level, converting the PV value at the vortex boundary to modified PV (Lait, 1994), and then using the median of these modified PV values as the criterion for 10 distinguishing between vortex and out-of-vortex air masses in the model. The ozone column and vortex data for individual years of both time slice experiments are given in the online supplement (timeslice_column.tsv).

For both time slices, Fig. 6 relates the location (in equivalent latitude) of the minimum ozone column and the maximum chemical ozone column loss to the location of the 15 vortex edge as defined by Nash et al. (1996). For all winters of both time slice experiments, the maximum chemical column ozone loss is located within (or, in two cases, on) the polar vortex edge, i.e., in the shaded region in Fig. 6. For only three winters in each time slice experiment is the polar cap ozone minimum located within the vortex. On the ensemble average (determined separately for each time slice, uncertainty given as one standard deviation), the vortex edge is located at $\Phi_e \approx 74^\circ \pm 8^\circ$ in 20 1990 ($78^\circ \pm 6^\circ$ for “future”), and the location of the polar cap minimum around $62^\circ \pm 15^\circ$ ($57^\circ \pm 13^\circ$), i.e., clearly outside of the vortex.

Arguably, the simulated vortex area, $\Phi_e > 74^\circ$ on 1 April for many of the analysed 25 winters, is smaller than observed climatological Arctic vortex areas (e.g., Karpetchko et al., 2005, report $\Phi_e \approx 69^\circ$ for the climatological Arctic vortex edge). The remaining vortex possibly does not encompass all chemically depleted air masses at this time anymore. Still, even when a generous vortex boundary definition such as $\Phi_e = 63^\circ$ is considered, for more than half of all winters the polar cap minimum ozone is located outside this rather generously defined vortex.

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5 Lemmen et al. (2006b) recommended that a more sophisticated measure should be applied to CCM simulations to isolate chemical (halogen-induced) ozone loss from total ozone change; they suggested using tracer-tracer correlations (TRAC) (e.g., Proffitt et al., 1990; Tilmes et al., 2004; Müller et al., 2005). They demonstrated their applicability to output from a model simulation (Lemmen et al., 2006b) and employed TRAC on a recent 40-year transient CCM simulation (Lemmen et al., 2006a).

The fact that the size of the Arctic vortex in E39/C is smaller than in reality is highlighted in Fig. 7 where the strength of the barrier to meridional transport ($\kappa = \nabla P V \cdot v$, where v is the absolute value of the horizontal wind velocity, Bodeker et al., 2001) is compared with the same quantity calculated using output from the transient run with E39/C (Dameris et al., 2005) as a function of equivalent latitude on the 550 K surface. Observed potential vorticity and wind fields on the 550 K surface were obtained every 10 6 hours from the NCEP/NCAR reanalysis data base for these calculations. We focus on the first ten days of April to avoid too much sampling of vortex break downs which 15 are more likely to occur towards the end of April and on the years 1990–1999 to focus on the period when ozone depletion over the Arctic maximises. Clearly the dynamical vortex in E39/C is weaker and broader than in reality and leans poleward. As a result, moving poleward in E39/C, ozone decreases more slowly than in reality. Furthermore, the dynamical vortex in the Arctic, as inferred from the maximum in κ would be smaller 20 in area in E39/C (at $\Phi_e \approx 73^\circ$) than in reality (at $\Phi_e \approx 69^\circ$, Karpetchko et al., 2005).

A similar result is reported by Tilmes et al. (2007a)¹ for the WACCM3 model, where the maximum of κ in the Arctic is smaller in magnitude and located further poleward with a much wider peak compared to observations.

¹Tilmes, S., Kinnison, D., Müller, R., Sassi, F., Marsh, D., Boville, B., and Garcia, R.: Evaluation of heterogeneous processes in the polar lower stratosphere in WACCM3, J. Geophys. Res., submitted, 2007.

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3.2.3 Minimum of the daily average column ozone

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As an alternative measure for the maximum chemical impact on column ozone over the polar region, we suggest that the daily mean area weighted ozone over the polar region should be considered and then that the minimum value reached in March in the Arctic and in October in the Antarctic should be selected. This value should approximately reflect the maximum impact of chemical loss on the ozone column before the vortex breaks down or before substantial mixing into the vortex occurs. The time series of this quantity for March in the Arctic (Fig. 8) shows substantial year-to-year variation, with values below 350 DU reached in several years. Generally, the lowest values are reached if ozone is averaged over the polar vortex (with the edge determined from the gradient in PV (Nash et al., 1996) on the 475 K potential temperature level) and the greatest values if the average is taken poleward of 63° N. Averages taken poleward of an equivalent latitude of 63° N range between the two extremes. This indicates that throughout the period considered, column ozone is generally lower within the boundary of the Arctic vortex than outside.

The minimum daily average polar ozone in October in the Antarctic (Fig. 9) shows less year-to-year variability and clearly lower ozone values than in the Arctic. All values after 1980 are lower than 300 DU and a decline of the values between ~1980 and 1995 is noticeable. Compared to the Arctic, there is less variation in this quantity depending on whether latitude/equivalent latitude of 63°S or the vortex boundary is chosen as the limit of the region over which averages are calculated. This observation is consistent with the Antarctic vortex being approximately polar concentric and with a vortex boundary close to 63° S (e.g., Bodeker et al., 2002; Karpetchko et al., 2005).

3.3 Relation between the mean polar ozone column and meteorological conditions

In the Arctic, chemical ozone loss is closely related to the particular meteorological conditions in each year. Rex et al. (2004) reported that Arctic chemical loss is linearly related to a measure of the likelihood of polar stratospheric cloud occurrence referred

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to as V_{PSC} . V_{PSC} is defined as the volume of stratospheric air below the threshold temperature for the existence of nitric acid trihydrate, averaged over a certain period and altitude range (Rex et al., 2004). Tilmes et al. (2006) have extended this analysis to Antarctic conditions, introducing the PSC Formation Potential of the polar vortex (PFP).

5 PFP² is a similar measure as V_{PSC} , but takes into account the size of the vortex. Here we investigate whether the simple measures of polar ozone loss discussed above show any relation to the measures of chlorine activation in the vortex such as V_{PSC} and PFP.

Figure 10 shows a scatterplot of V_{PSC} against the average column ozone poleward of geometric or equivalent latitude 63°N and within the vortex. Obviously, in contrast to 10 the compact relation between V_{PSC} and chemical ozone loss (Rex et al., 2004; Tilmes et al., 2004), there is no close relation between V_{PSC} and March average ozone. This holds irrespective of the horizontal boundary specified as the limit for the averaging. Apparently, the March average ozone is a measure that does not adequately differentiate 15 between chemical loss and dynamical resupply of ozone that both change substantially from year to year. Furthermore, the March average ozone poleward of geometric latitude of 63°N is particularly sensitive to the strong year-to-year variability in the lifetime and shape of the Arctic vortex (Waugh and Randel, 1999; Karpetchko et al., 2005).

We argued above that the minimum of March daily average polar column ozone 20 should be a quantity more closely related to chemical ozone loss than those shown in Fig. 10. Thus one might expect that the minimum of March average ozone shows a more compact relation with V_{PSC} . The minimum of daily average ozone when plotted against V_{PSC} (Fig. 11) indeed shows a certain structure, especially, when vortex averages or averages poleward of 63°N equivalent latitude are considered. However, there 25 is no clearly compact and especially no linear relation of this quantity with V_{PSC} .

²PFP is calculated in the following way. For all days when a vortex exists and for a defined altitude range, V_{PSC} is divided by the volume of the polar vortex, and these values are then integrated over a defined time period. Finally this value is divided by the total number of days in the period (Tilmes et al., 2006).

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Some outliers, e.g. the years 1999, 2001, and 2006 can be understood. For these years, the final warming was very early such that no vortex existed during March, with the consequence of a larger ozone column caused by the influx of mid-latitude ozone-rich air. Concentrating on data for the years when the polar vortex in March was intact, we find a tighter relation between V_{PSC} and the minimum of daily average ozone column poleward of $\Phi_e=63^\circ$ that is indicated by the dotted line in Fig. 11. From the three different quantities shown, the polynomial fit with this quantity has the lowest deviation ($1\sigma=5.5 \text{ DU}$) from the observations and shows (nearly) monotonic decrease with increasing V_{PSC} .

When PSC occurrence or the potential for chlorine activation is compared for the Arctic and Antarctic, V_{PSC} is no longer a suitable measure, because the polar vortex is much larger in the Antarctic than in the Arctic; for such a comparison, the PFP should be used instead of V_{PSC} (Tilmes et al., 2006). In Fig. 12, PFP is plotted against the minimum of March daily average polar column ozone, where only data points for averages poleward of 63° equivalent latitude are shown. The well known fact that PFP is larger in the Antarctic than in the Arctic (Tilmes et al., 2006) and that polar column ozone is greater in the Arctic than in the Antarctic (Dobson, 1968; WMO, 2007) are reflected in this plot. However, for this combination of meteorological and ozone measures, again no clearly compact relation emerges.

20 4 Discussion

Among the quantities describing stratospheric ozone, total column ozone is the one most easily measured. Indeed, the longest atmospheric time series exist for total ozone (e.g., Staehelin et al., 1998; Brönnimann et al., 2003) and the Antarctic ozone hole was discovered, and the discovery corroborated, through measurements of total column ozone (Chubachi, 1984; Farman et al., 1985; Stolarski et al., 1986). However, variations in total ozone are caused by both chemical change and by transport, and the different impact of these processes is often difficult to disentangle.

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Transport contributions to polar ozone variability are closely controlled by the strength of the middle atmospheric (Brewer-Dobson) circulation that is driven by tropospheric wave forcing. For both the Arctic and Antarctic, a stronger-than-average planetary wave forcing in winter leads to more transport of ozone to high latitudes because of a stronger circulation and a higher-than-average polar lower stratospheric temperature and a weaker vortex in early spring, whereas a weaker wave forcing leads to less transport, lower polar temperatures in spring and to a stronger vortex (Fusco and Salby, 1999; Newman et al., 2001; Weber et al., 2003). The variability in polar ozone due to the variability in wave forcing is much larger in the Arctic than in the Antarctic, while chemical loss is more persistent in Antarctica.

Here we argue that measures of chemical ozone loss based on monthly averages of total column ozone over the polar cap, although they contain information about chemical ozone loss, must be interpreted with caution. The particular value of such measures will depend on the selected definition of the equatorward boundary of the region over which averages are calculated. In the Arctic, the year-to-year variability of the size of the polar vortex has a particularly strong impact. Averages over the polar cap do not show compact relationships with meteorological measures of the extent of chlorine activation (and thus the potential for ozone destruction) in the polar vortices such as V_{PSC} and PFP.

Although frequently employed, the minimum value of daily total column ozone minima over the polar region is a particularly problematic measure, insofar as it relies on a single measurement or on a single model grid point. We have shown here that for the Arctic, both in a CCM and in observations, that a significant fraction of the minimum values of daily total ozone minima occur *outside* the polar vortex. Clearly, if the minimum ozone value on a particular day occurs outside the vortex, it does not provide information on halogen driven chemical ozone loss initiated by heterogeneous chlorine activation. Because of the strong chemical ozone loss in the Antarctic, this problem is much less pronounced there. It should, however, become increasingly relevant for simulations of future ozone loss, when much less chemical ozone loss is expected. Based

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on this analysis we must question the applicability of a simple measure such as a minimum polar cap ozone value for both the E39/C model and observations, and strongly caution against application of this simple measure to results from other CCM simulations. It is remarkable that there is substantial variation in the magnitude of minimum total column ozone in current model simulations ranging roughly from 220 to 320 DU whereas the observations lie in the range of 290 DU to below 200 DU ([WMO, 2007](#), Fig. 6–13).

Clearly, employing sophisticated measures of polar chemical ozone loss that show a compact correlation with meteorological measures of chlorine activation ([Rex et al., 2004](#); [Tilmes et al., 2006](#)) is the best method to assess the temporal evolution of polar ozone loss in both models and observations. However, when only total column ozone data are available, we propose that the minimum of March average total ozone in the vortex (where the vortex boundary could be determined by the maximum gradient in PV or by an equivalent latitude criterion) should be considered. This quantity is not strongly influenced by low column ozone outside the vortex and does not rely on a single measurement or model grid point. Further, in contrast to monthly averages, its year-to-year variability is not substantially affected by varying dates of vortex breakdown in the Arctic.

5 Conclusions

Quantities deduced from measurements of total column ozone are frequently used as measures of polar ozone loss. One of the common measures is monthly mean column ozone poleward of 63° for March and October in the Arctic and Antarctic, respectively. For the Arctic, a latitude of 63° is a reasonable boundary for polar air, whereas for the Antarctic the values of the October means (but not their year-to-year variability) are sensitive to the exact choice of 63° . A better definition of the polar vortex boundary can be obtained using the gradient in PV ([Nash et al., 1996](#)) or equivalent latitude, however, under no circumstances can a close relation of such simple measures be obtained with

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meteorological quantities that describe the potential for polar heterogeneous chlorine activation (and thus ozone loss).

The minimum of daily total ozone minima poleward of a particular latitude is a problematic measure, insofar as it relies on one single measurement or on one single model grid point; for Arctic conditions, it is not unlikely that this minimum value occurs in air outside the polar vortex. We suggest that this concept should no longer be used when comparing polar ozone loss in observations and models.

Considering the minimum of daily average total ozone poleward of a particular equivalent latitude (or in the vortex) in spring, avoids the problem of relying on one single data point and reduces the impact of year-to-year variability in the Arctic vortex breakup on ozone loss measures. We propose this measure as a candidate for a useful simple measure of polar ozone loss. In any event, it is preferable to employ more sophisticated measures of chemical polar ozone loss (e.g., Harris et al., 2002; Rex et al., 2004; Tilmes et al., 2006; Lemmen et al., 2006b; WMO, 2007) that bring in additional information to disentangle the transport and the chemical impact on ozone.

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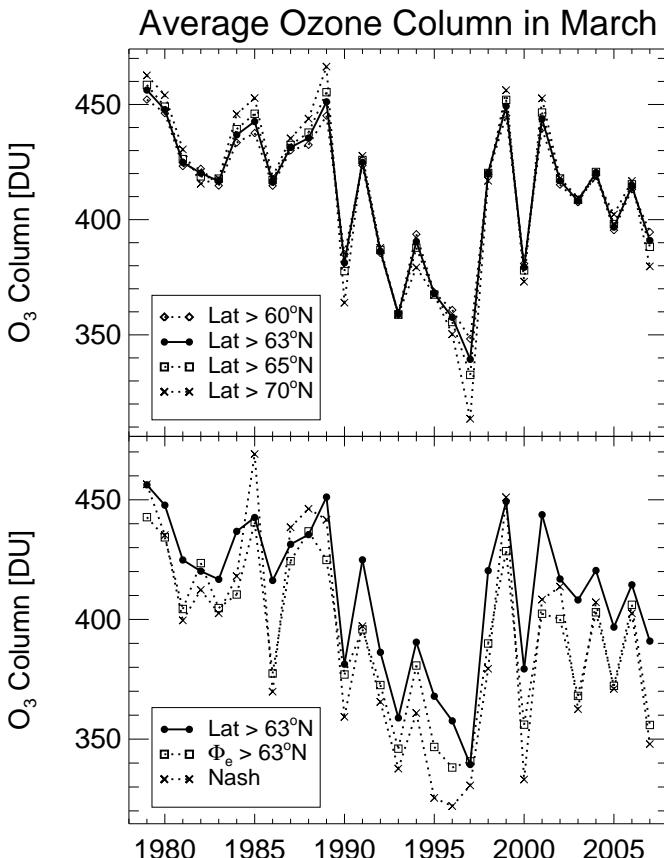


Fig. 1. Top panel: March mean Arctic total column ozone averaged poleward of 60° N, 63° N, 65° N, and 70° N. Bottom panel: March mean Arctic total column ozone averaged poleward of 63° N compared with calculations using the equivalent latitude of $\Phi_e=63^{\circ}\text{N}$ and the Nash-criterion (applied on the 475 K potential temperature surface) as vortex edge definitions. All averages are area weighted averages.

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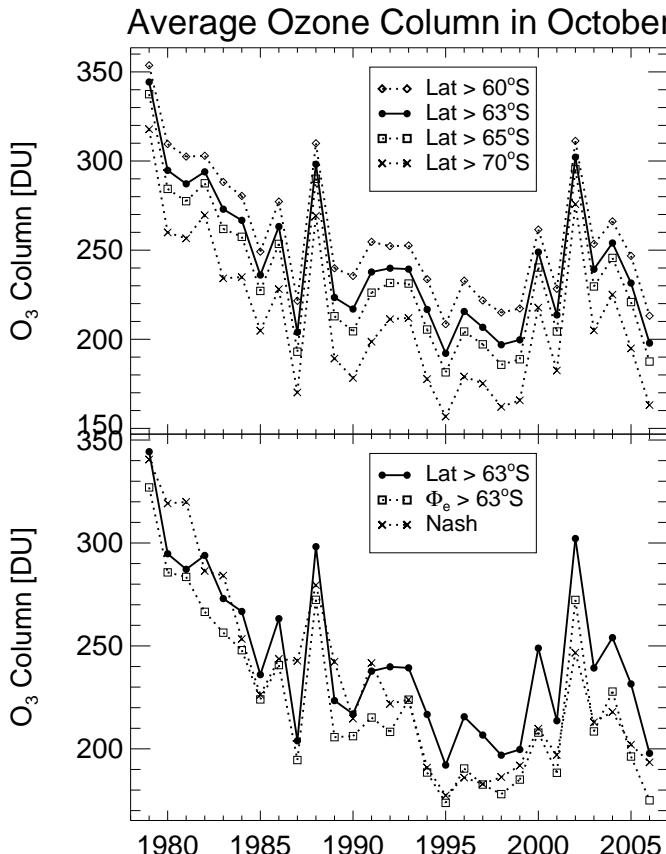


Fig. 2. Top panel: October mean Antarctic total column ozone averaged poleward of 60° S, 63° S, 65° S, and 70° S. Bottom panel: October mean Antarctic total column ozone averaged poleward of 63° S compared with calculations using the equivalent latitude $\Phi_e=63^\circ$ S and the Nash-criterion (applied on the 475 K potential temperature surface) as vortex edge definitions.

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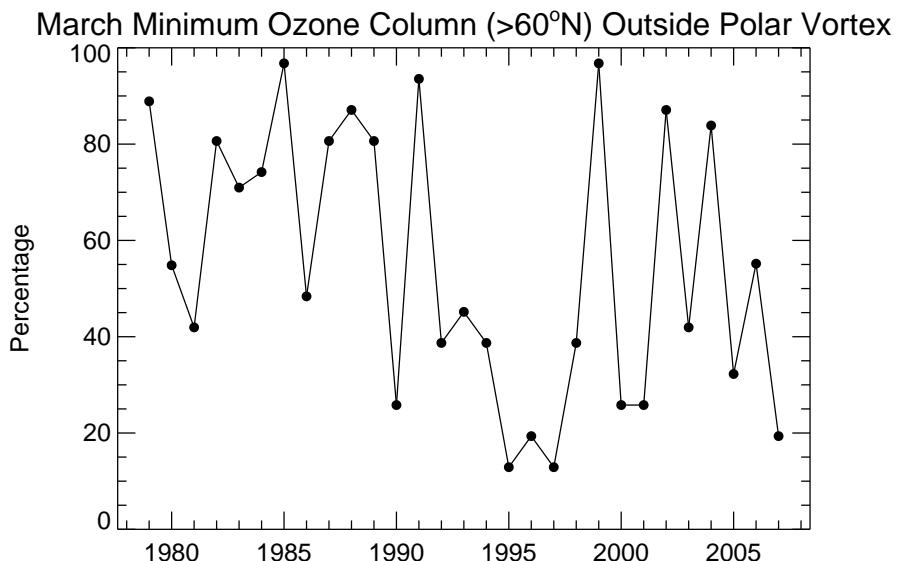


Fig. 3. The fraction (in percent) of the daily total column ozone minima in the region 60° N–90° N occurring outside of the polar vortex in March. The polar vortex is defined here by the maximum gradient in potential vorticity (Nash et al., 1996).

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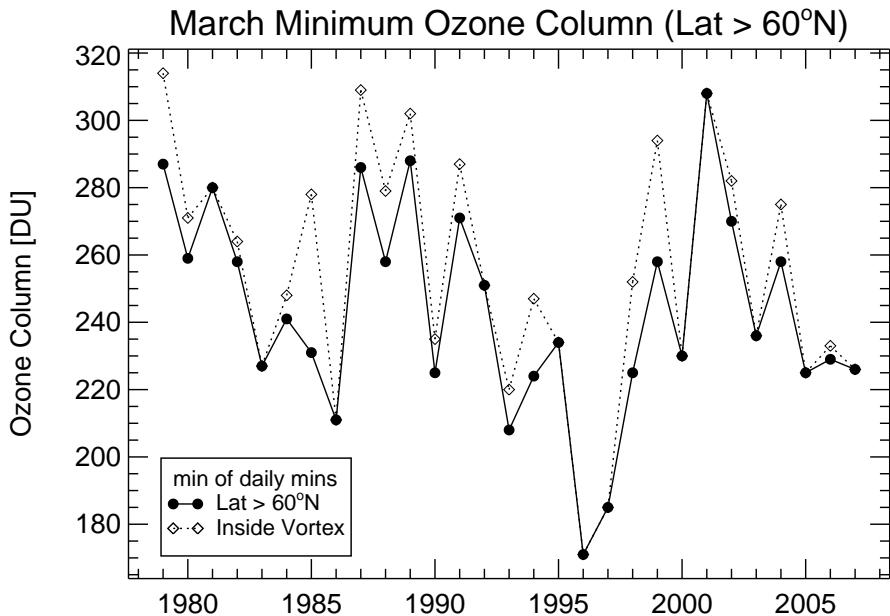


Fig. 4. The minimum total column ozone in the Arctic poleward of 60° N in March (solid line) computed as the minimum of daily minima. The dashed line shows the same calculation but excluding any minima occurring outside of the polar vortex. The polar vortex is defined here by the maximum gradient in potential vorticity ([Nash et al., 1996](#)).

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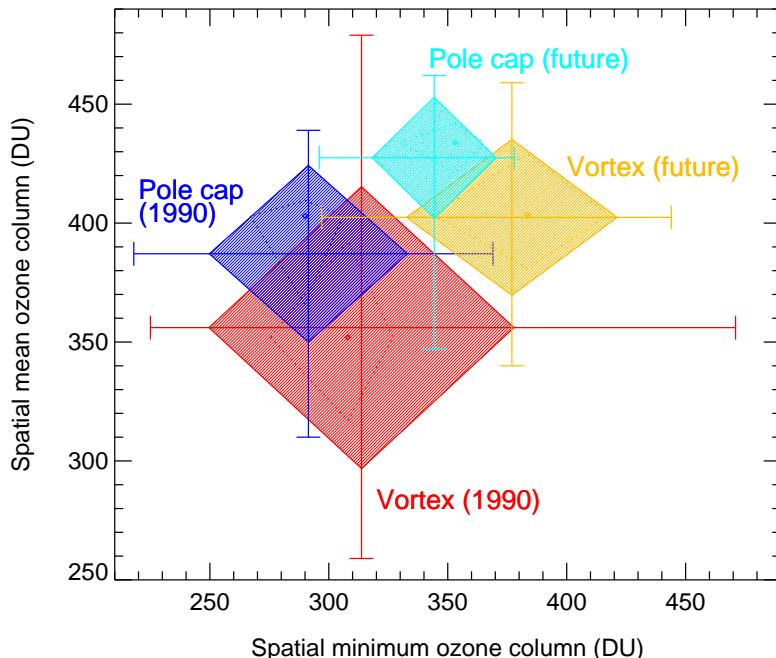


Fig. 5. Simulated 1 April total ozone column from two CCM 20-year ensemble (time slice) experiments with 1990 and near-future boundary conditions for greenhouse gases and sea surface temperatures. For each time slice and for each analysis region (polar cap north of 60° N, or vortex according to the maximum gradient in potential vorticity, Nash et al. 1996) the ensemble statistics of spatial mean ozone column are contrasted to those of the spatial minimum ozone column. Each box-whisker diagram indicates range, mean, and one standard deviation, quartiles are indicated as dotted lines centred around the median shown as open diamonds.

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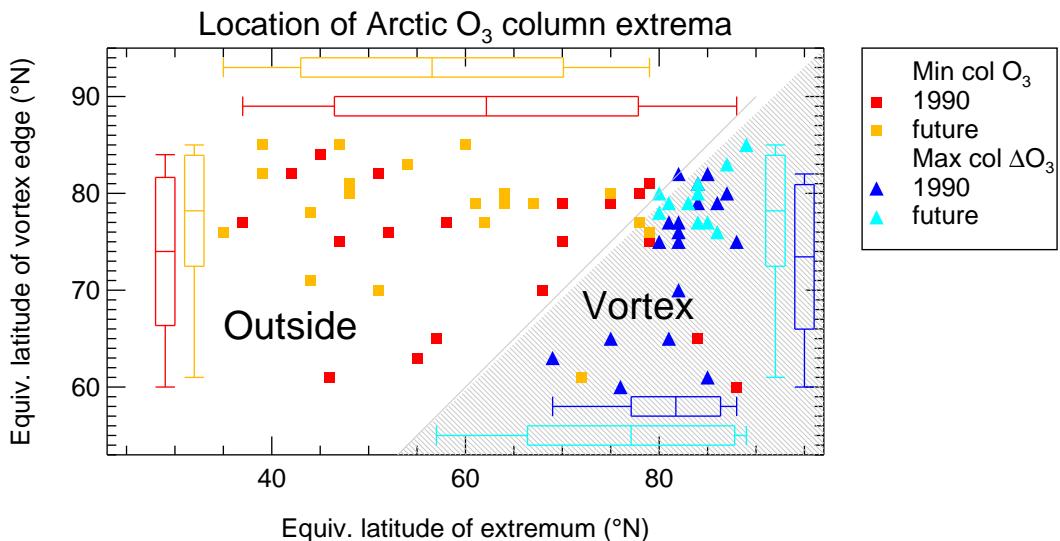


Fig. 6. Simulated 1 April location of the minimum ozone column and the maximum chemical loss column from two CCM 20-year ensemble (time slice) experiments with 1990 (blue, red) and near-future (dark yellow, cyan) boundary conditions for greenhouse gases and sea surface temperatures. For each time slice and for each analysis method (spatial minimum ozone column within the polar cap and spatial maximum of tracer-tracer correlation derived maximum chemical ozone loss). Box-whisker diagrams indicate the respective mean, standard deviation, and range of locations. The shaded area denotes the polar vortex.

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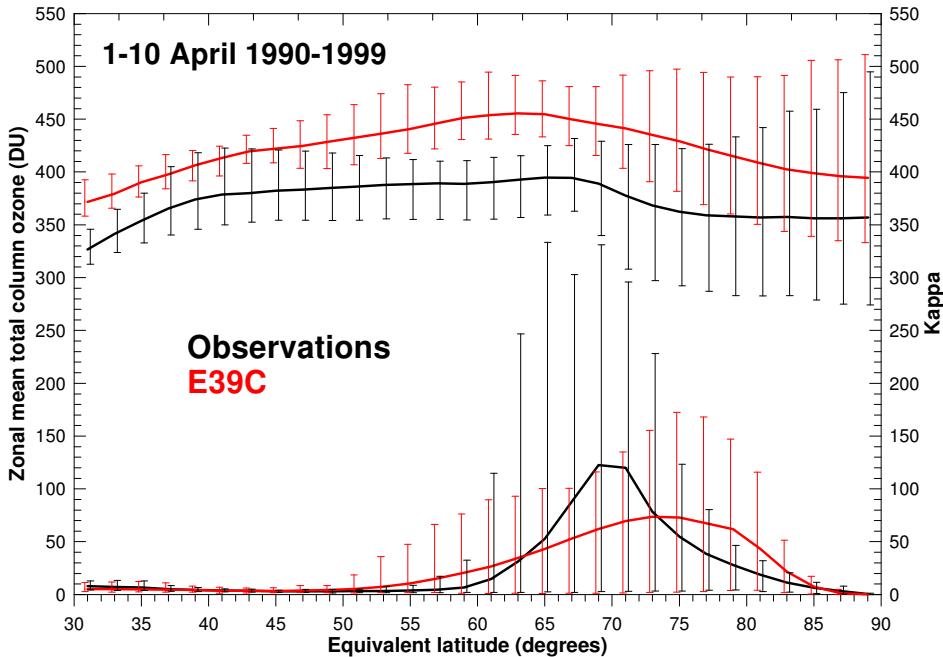


Fig. 7. Equivalent latitude (on the 550 K surface) zonal mean total column ozone (top two curves plotted against the left ordinate), and the strength of the barrier to meridional transport κ , (bottom two curves plotted against the right ordinate) for the northern hemisphere averaged over the years 1990–1999 and 1–10 April. Observations are shown in black and model results (from the transient run of E39/C, Dameris et al., 2005) in red. The vertical bars show the extremes (maximum and minimum values over the period).

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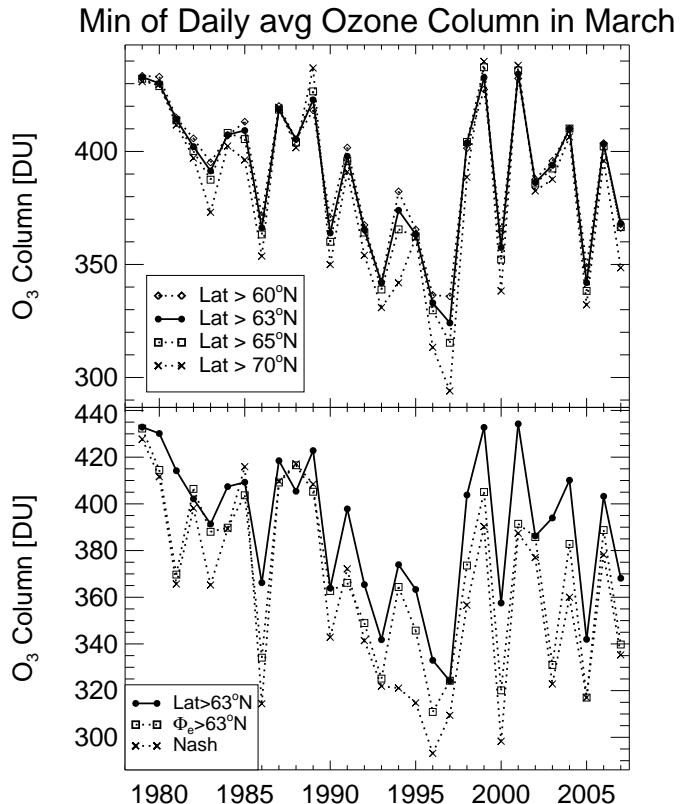


Fig. 8. The minimum of the daily average ozone for March poleward of 63° N (open squares), poleward of 63° N equivalent latitude (solid circles), and poleward of the vortex edge according to the Nash-criterion applied on the 475 K potential temperature surface (crosses).

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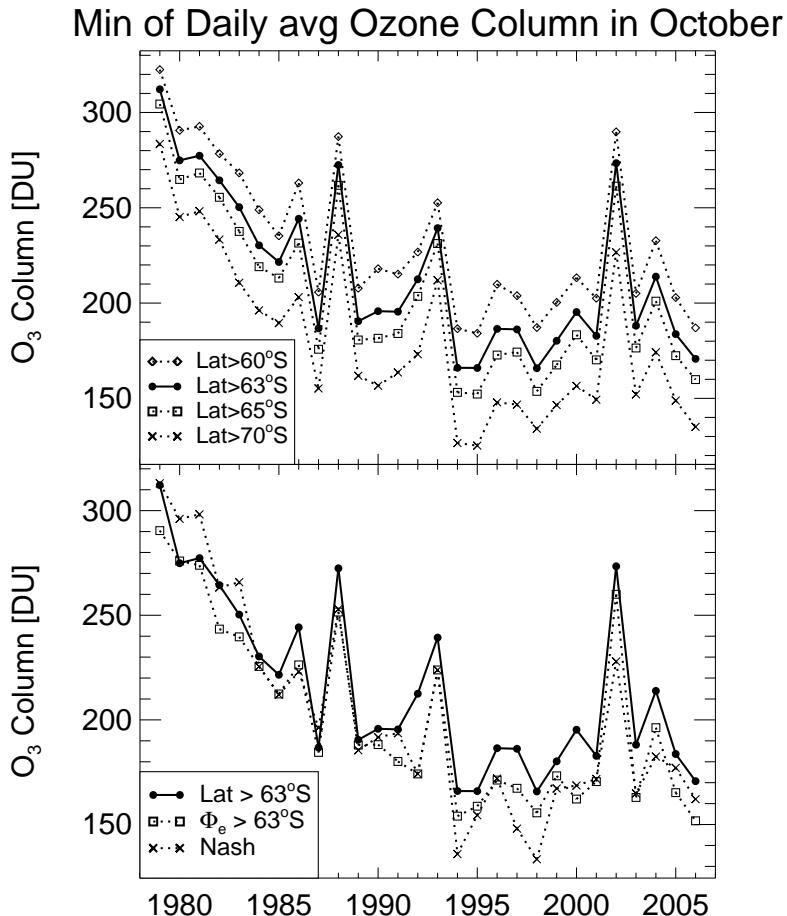


Fig. 9. As in Fig. 8, but for the Southern hemisphere polar vortex in October.

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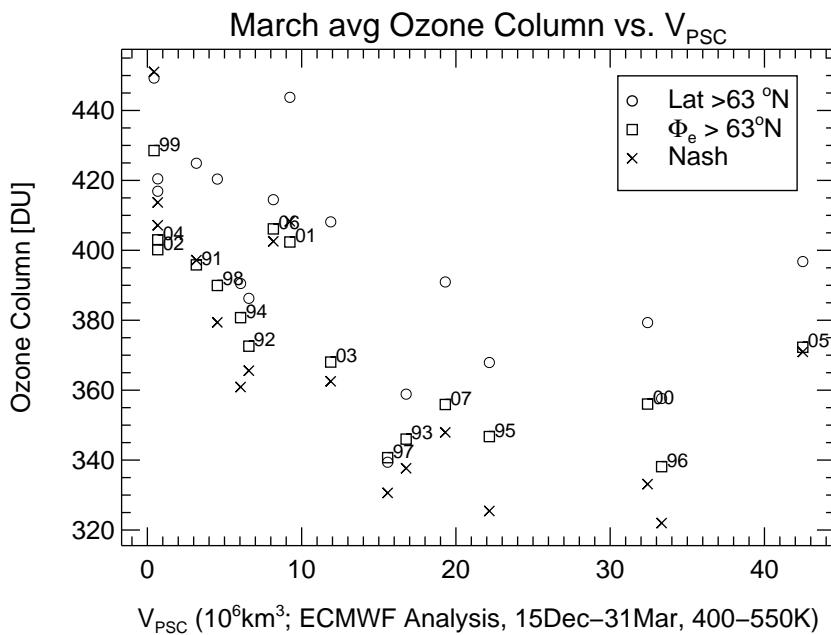


Fig. 10. The relation between V_{PSC} and the total column ozone in March averaged over the Arctic polar region. Circles show averages poleward of 63° N, squares averages poleward of 63° N equivalent latitude, and crosses averages poleward of the vortex edge defined by the maximum gradient in potential vorticity.

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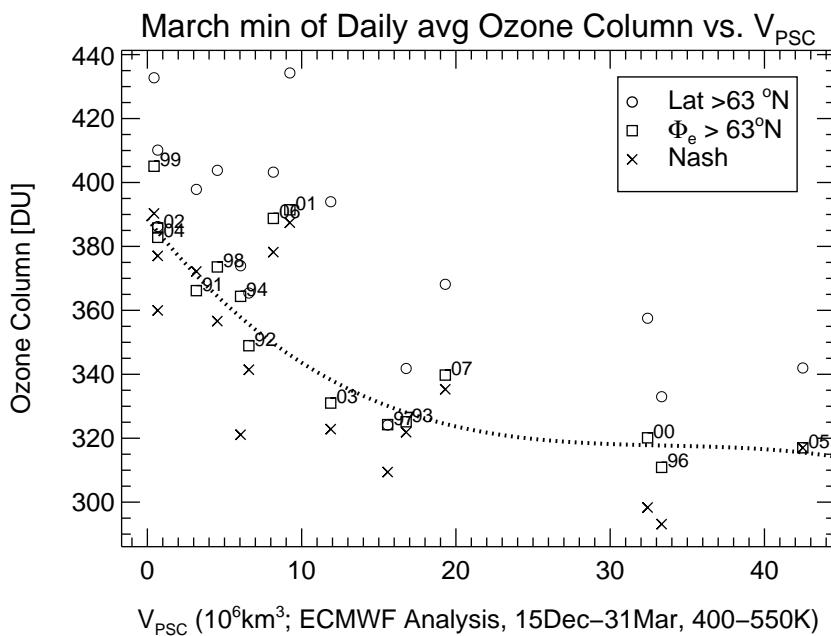


Fig. 11. The relation between V_{PSC} and the minimum of March daily average polar column ozone (symbols as in Fig. 10). The dotted line shows an empirical fit through the minimum ozone values for averages poleward of an equivalent latitude of 63° N with the exception of the years 1999, 2001, and 2006 for which the final warming occurred before March. Not shown (and excluded from the fit) is the year 1995 because of poor data quality; only 3% of the data points poleward of 63° equivalent latitude are valid. The polynomial describing the fit is given by $M = 388.6 - 6 \cdot 10 \cdot V + 0.178 \cdot V^2 - 0.00176 \cdot V^3$, where V is V_{PSC} in 10^6 km^3 and M is the minimum of March daily average polar column ozone in Dobson units (this relation being valid for $V_{\text{PSC}} < 42.5$).

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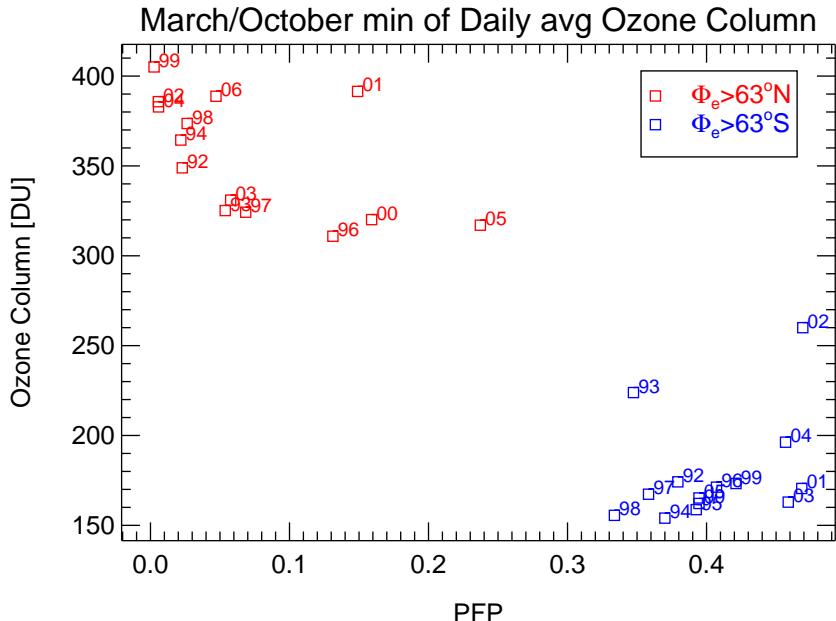


Fig. 12. The relation between PFP and the minimum of March daily average polar column ozone for both the Arctic (red symbols) and the Antarctic (blue symbols). Only data points for averages poleward of 63° equivalent latitude are shown. PFP values are calculated based on the MetO analysis (Swinbank and O'Neill, 1994), averaged over the altitude region 400–550 K for the period 15 December to 31 March and 15 June to 30 September for the Arctic and Antarctic, respectively. Note that the PFP values shown here are slightly improved compared to those reported by Tilmes et al. (2006), see also electr. supplement (<http://www.atmos-chem-phys-discuss.net/7/9829/2007/acpd-7-9829-2007-supplement.zip>).

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