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Match observations in the Arctic winter 1996/97: High stratospheric ozone loss rates correlate with low temperatures deep inside the polar vortex

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Abstract. With the Match technique, which is based on the coordinated release of ozonesondes, chemical ozone loss rates in the Arctic stratospheric vortex in early 1997 have been quantified in a vertical region between 400 K and 550 K. Ozone destruction was observed from mid February to mid March in most of these levels, with maximum loss rates between 25 and 45 ppbv/day. The vortex averaged loss rates and the accumulated vertically integrated ozone loss have been smaller than in the previous two winters, indicating that the record low ozone columns observed in spring 1997 were partly caused by dynamical effects. The observed ozone loss is inhomogeneous through the vortex with the highest loss rates located in the vortex centre, coinciding with the lowest temperatures. Here the loss rates per sunlit hour reached 6 ppbv/h, while the corresponding vortex averaged rates did not exceed 3.9 ppbv/h.

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Introduction

In the 1996/97 winter very low ozone columns were observed above the Arctic [*Newman et al.*, 1997]. These were partly caused by dynamical effects [*Lefèvre et al.*, 1998]. The winter was characterized by a strong, symmetric polar vortex that developed unusually late in winter and remained stable until the beginning of May. Through January the vortex was inside the polar night. Temperatures dropped in the beginning of February and stayed below PSC coexistence temperatures until the end of March at 50 hPa [*Naujokat et al.*, 1999]. Here we use the Match technique [*von der Gathen et al.*, 1995; *Rex et al.*, 1997; 1998; 1999] to quantify the chemical ozone inside the vortex in early 1997.

Measurement strategy and Analysis

A coordinated Match campaign as described in *Rex et al.* [1999] was carried out between January 7 and April 11, 1997, both inside and outside the polar vortex. During this time forward trajectories were calculated from European Centre for Medium-Range Weather Forecasts (ECMWF) analyses and forecasts, using locations of ozonesonde measurements as starting points, in order to track the probed air parcels. In cases when a parcel was predicted to pass over one of the 36 ozone sounding stations participating in the campaign (Fig. 1), a launch request was made. A total of 746 sondes was successfully launched from these stations.

For the post campaign analysis a second set of trajectories was calculated from analysed ECMWF data, using cooling rates from the SLIMCAT model [*Chipperfield et al.*, 1999]. The criteria for accepting a match were chosen as in winter 1994/95, with the exception of the matchradius that was reduced to 400 km (250 km) to improve the statistical error between 450 K and 500 K by about 5 %. A match was assigned to the vortex when the mean normalized potential Vorticity (PV) along the trajectory was higher than $36\,s^{-1}$. Normalized PV is defined as scaled PV [*Dunkerton et al.*, 1986] multiplied by a constant factor of $2.65 \cdot 10^5$ so that it has the same numerical values as Ertel's PV on the 475 K isentropic surface. In the final analysis the data of 285 sondes is used. The chosen matches sampled the vortex homogeneously in terms of PV values most of the time. Calculated loss rates can thus be interpreted as vortex

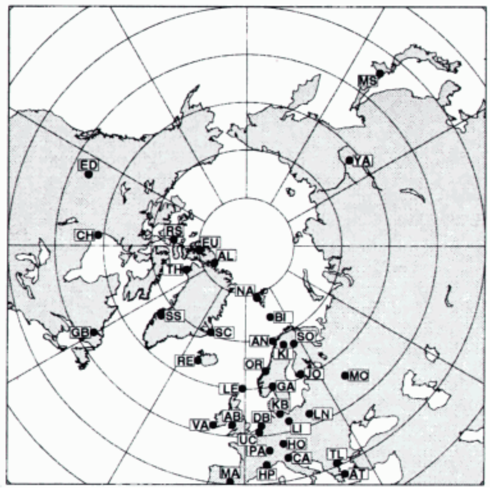

Figure 1. Map of all participating ozonesonde stations in the 1996/97 Match campaign.

averages, with some caveats discussed below. Ozone loss rates per sunlit hour were determined by calculating linear regressions of the change of the ozone mixing ratio versus sunlit time. For these regressions matches of a 14 day period and a 20 K vertical region were used. Finally these rates were multiplied with the mean sunlit time per day inside the vortex to obtain loss rates per day. The given error bars are 1 σ uncertainties of the regression coefficients and do not include possible systematic effects, such as possible systematic errors in the used cooling rates.

Results and discussion

Fig. 2 shows the ozone loss per day as a function of time and potential temperature. Results are obtained between the end of January and the end of March, covering potential temperature levels between 400 K and 520 K to 550 K. Above 425 K the depletion started in early February and continued into March. Maximum loss rates between 25 and 45 ppbv/day were reached. This period coincides with the findings of *Goutail et al.* [1998] who report the highest chemical loss in column ozone between February 1 and March 10. The integrated ozone loss during the period and vertical region shown in Fig. 2 is 43±9 DU. Since the results cover most of the time and vertical region where extensive PSC conditions (see below) existed it is likely that the integrated loss reflects a large fraction of the total accumulated column loss in 1996/97. This is compatible with the results of *Müller et al.* [1997], who calculated 50-70 DU for the 1996/97 column ozone loss. The derived value is much smaller than column losses in 1994/95 and 1995/96 with 120-160 DU [*Rex et al.*, 1999; *Goutail et al.*, 1999; *Müller et al.*, 1997], supporting the model based finding of *Lefèvre et al.*, [1998] that the extreme low ozone columns measured in 1997 [*Newman et al.*, 1997] were partly caused by dynamical effects.

Fig. 3A shows the temporal evolution of the ozone loss rate at 475 ± 10 K. The shaded curve represents the area of the northern hemisphere where temperatures (derived from ECMWF analyses) might allow PSC existence, assuming a constant H_2O mixing ratio of 4.6 ppmv and the LIMS January 1979 HNO_3 profile and following the analysis of NAT formation by *Hanson et al.* [1988]. While there were not enough soundings to obtain results for the first cold period in January, the loss rates start increasing some days after the beginning of February, shortly after temperatures drop below the PSC threshold in substantial parts of the northern hemisphere. The ozone loss rates increase further until the first third of March, when they drop considerably, although temperatures inside the vortex still allow the existence of PSCs. Fig. 3B shows the average of the minimum temperatures in a 10 day history for the air parcels involved in the corresponding data points in panel A. For each air parcel the minimum temperature is the lowest temperature on the trajectory that links the matching pair of sondes or on a 10 day backward trajectory starting from the first sounding. A clear relation can be seen between the loss rates and the minimum temperatures in the air parcel histories. To our knowledge this is the most direct observation of the dependence of ozone loss on low temperatures so far.

Comparing this temperature analysis to the shaded curve in panel A suggests that the smaller ozone loss rates in the second half of March are determined by a sample of matches that does not reflect the mean vortex conditions. Further, during that period Fig. 3C shows only few matches in the vortex core, which is where any PSCs would be expected (Fig. 4, bottom panel). An underestimation of the vortex averaged loss rates in the second half of March is therefore possible.

Fig. 4 shows the mean ozone loss per sunlit hour between February 10 and March 10, averaged from 450 K to 500 K with respect to the relative location inside

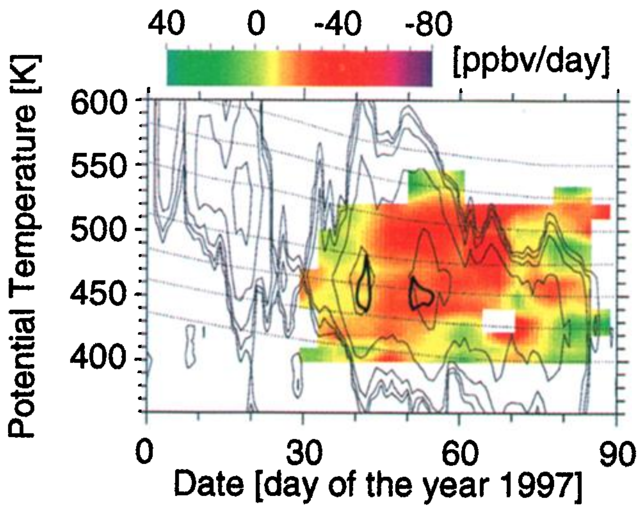

Figure 2. Ozone loss rates per day as a function of time and potential temperature. The fine lines indicate the 0.3, 0.7, 1.5, 4.0 and 8.0 · 10^6 km^2 isolines for the area of possible PSC type I existence, the bold line is the 0.3 · 10^6 km^2 isoline for the area of possible PSC type II existence as derived from ECMWF analysis. The dashed lines describe the diabatic descent (vortex average) of the air masses during the winter as determined by the SLIMCAT model.

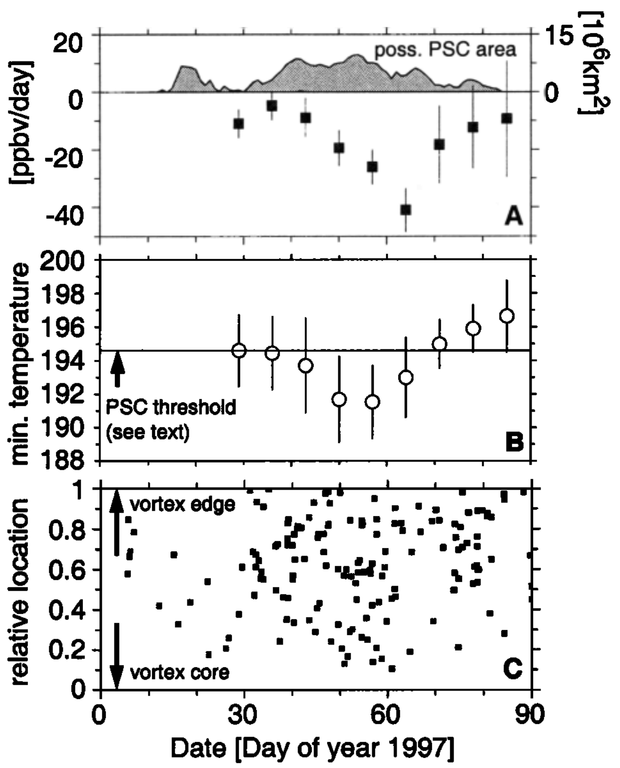

Figure 3. Panel A: ozone depletion rates per day at 475 ± 10 K with 1 σ error bars as a function of time. Each data point represents a linear regression between ozone change and sunlit time of matches in a 14 day period around the given date. The shaded curve is the area at 475 K with temperatures allowing PSC existence (see text). Panel B: minimum temperatures along a 10 day backward trajectory and the trajectory between the two soundings for the corresponding matches. Panel C: relative position of the individual match events inside the polar vortex. The scale is chosen in a way that 0 refers to the vortex center (highest PV value) while 1 represents the vortex edge. On a given day equal intervals on the scale correspond to equal area fractions of the vortex, while decreasing numbers represent increasing PV.

the vortex. The depletion rates vary from low values at the vortex edge to about 6 ppbv/h at the vortex core. This is in qualitative agreement with the results of *Müller et al.*, [1997] who report larger observed ozone losses towards the vortex interior. During the same period the vortex averaged loss rate did not exceed 3.9 ± 0.8 ppbv/h. This is considerably lower than maximum vortex averaged loss rates per sunlit hour observed in previous years, that are 10 ± 1 ppbv/h in 1991/92 and 1994/95 and 10 ± 3 ppbv/h in 1995/96 [*Rex et al.*, 1997; 1998; 1999]. Corresponding to the inhomogeneous ozone loss, the minimum temperatures experienced by the air parcels in a 10 day history (Fig. 4, open circles) are more than 5 K higher at the vortex edge than in the vortex centre. The largest areas with temperatures below the PSC threshold are situated towards the vortex centre between the first third of February and mid March (Fig. 4, bottom panel). Thus only a part of the vortex was affected by major ozone depletion, which kept the overall ozone loss low.

Manney et al. [1997] give calculated ozone loss based on MLS data for the end of February 1997. For the 465 K potential temperature level they calculate a loss rate of 1.3 %/day between Feb 20 and Feb 26. For a comparable height and time region (465 ± 10 K and Feb 16 to Mar 2) we determine a lower loss rate of 25 ± 6 ppbv/day, which corresponds to 0.9 ± 0.2 %/day assuming an initial mixing ratio of 2.7 ppmv. However, the results agree within 2 σ, and differences may also be introduced by the different periods used for the two analyses, so the results are not contradictory.

Knudsen et al. [1998] calculated vortex averaged ozone depletion for different isentropic levels using ozonesonde data. The integrated ozone loss in 450 K (475 K) is 1.1 ppmv (1.2 ppmv) compared to 0.9 ± 0.2 ppmv(0.9 ± 0.2 ppmv) as determined in this work. The slight difference between these results can be assigned to the application of different cooling rates, since values determined by them decrease to 0.9 ppmv (1.0 ppmv) when they use

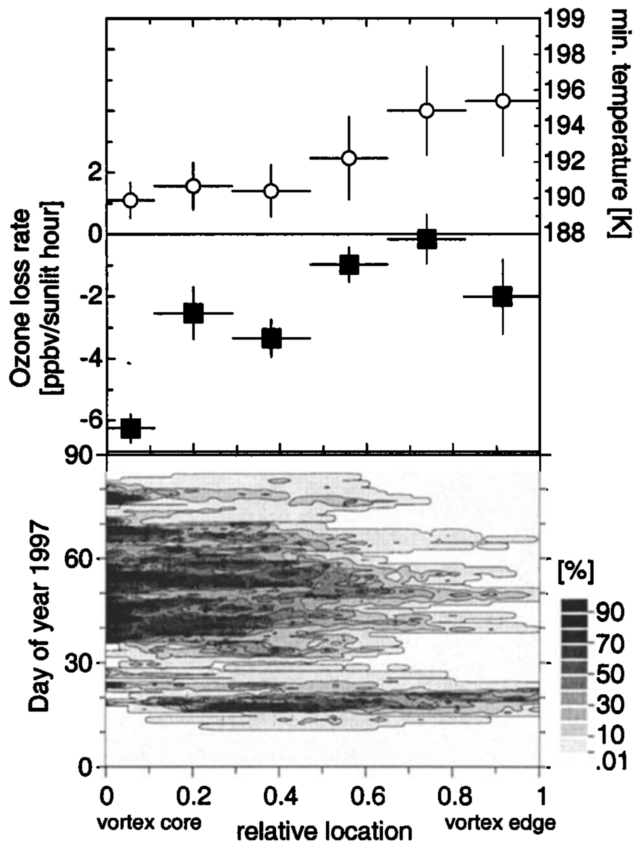

Figure 4. Top Panel: ozone loss rates per sunlit hour as a function of relative location (see Fig. 3) inside the vortex. The squares symbolize linear regressions of matches between Feb 10 and March 10 and between 450 K and 500 K. The horizontal bars indicate the limits for the contributing matches. The open circles represent the corresponding minimum temperatures in a 10 day history (as in Fig. 3B). Bottom panel: derived from ECMWF analysis, the greyscale indicates the percentage of area with temperatures allowing PSC existence (see text) in the 475 K level as a function of relative location and date.

the same cooling rates as in this study (B. M. Knudsen, private communication). The cooling rates calculated by *Knudsen et al.* [1998] use observed ozone profiles that are mapped into a PV/theta space and are up to 80% higher than the rates used in this study, which are based on climatological ozone profiles and apply a global flux correction [*Chipperfield et al.*, 1999]. This leads to the conclusion that, depending on which of the cooling rates are more precise, the ozone loss reported in this study might be underestimated by 1 σ.

Conclusion

Significant ozone loss in the Arctic stratosphere was observed between mid February and mid March 1997, but the vortex averaged ozone loss rates determined in 1996/97 are lower than in 1992, 1995 and 1996. This supports the picture that the extreme low ozone values observed in 1997 can be attributed at least partly to dynamical effects. The ozone loss was mainly concentrated in the vortex core, coinciding with the lowest temperatures. A direct correlation between the determined ozone loss and the temperature history of the air parcels was observed.

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