Mixing and Chemical Ozone Loss during and after the Antarctic Polar Vortex Major Warming in September 2002

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ABSTRACT

The 3D version of the Chemical Lagrangian Model of the Stratosphere (CLAMS) is used to study the transport of CH₄ and O₃ in the Antarctic stratosphere between 1 September and 30 November 2002, that is, over the time period when unprecedented major stratospheric warming in late September split the polar vortex into two parts. The isentropic and cross-isentropic velocities in CLAMS are derived from ECMWF winds and heating/cooling rates calculated with a radiation module. The irreversible part of transport, that is, mixing, is driven by the local horizontal strain and vertical shear rates with mixing parameters deduced from in situ observations.

The CH₄ distribution after the vortex split shows a completely different behavior above and below 600 K. Above this potential temperature level, until the beginning of November, a significant part of vortex air is transported into the midlatitudes up to 40°S. The lifetime of the vortex remnants formed after the vortex split decreases with the altitude with values of about 3 and 6 weeks at 900 and 700 K, respectively.

Despite this enormous dynamical disturbance of the vortex, the intact part between 400 and 600 K that “survived” the major warming was strongly isolated from the extravortex air until the end of November. According to CLAMS simulations, the air masses within this part of the vortex did not experience any significant dilution with the midlatitude air.

By transporting ozone in CLAMS as a passive tracer, the chemical ozone loss was estimated from the difference between the observed [Polar Ozone and Aerosol Measurement III (POAM III) and Halogen Occultation Experiment (HALOE)] and simulated ozone profiles. Starting from 1 September, up to 2.0 ppmv O₃ around 480 K and about 70 Dobson units between 450 and 550 K were destroyed until the vortex was split. After the major warming, no additional ozone loss can be derived, but in the intact vortex part between 450 and 550 K, the accumulated ozone loss was “frozen in” until the end of November.

1. Introduction

In September 2002, the Antarctic polar vortex was split into two parts due to a major stratospheric warming. A major warming had not hitherto been observed since data records have been available for the Antarctic and it occurred 6 weeks earlier than any final warming observed so far (Charlton et al. 2005; Manney et al. 2005; Newman and Nash 2005). This unprecedentedly early vortex split created many filaments and vortex remnants containing ozone-depleted air that were rapidly transported into the midlatitudes (Allen et al. 2003; Orsolini et al. 2005). Transport across the Antarctic vortex edge has been a subject of many previous studies published in the last 15 years (see, e.g., Choi et al. 2002 and references therein).

To study the spatial distribution and the lifetime of the vortex remnants during and after the vortex split in September 2002, high-resolution transport studies of CH₄ and passive ozone (O₃) were carried out with the 3D version of the Chemical Lagrangian Model of the Stratosphere (CLAMS; Konopka et al. 2004). CLAMS is a chemical transport model based on a Lagrangian
formulation of tracer transport with mixing intensity being driven by the local horizontal strain and vertical shear rates (McKenna et al. 2002; Konopka et al. 2004).

The parameters controlling the deformation-induced mixing are the critical Lyapunov exponent $\lambda_t$ (i.e., only flow deformations stronger than a certain threshold value, i.e., with the Lyapunov exponents $\lambda_t$ larger than a critical value $\lambda_t^*$, are mixing relevant), grid adaptation frequency $1/\Delta t$, and the spatial resolution of the model, that is, the mean horizontal $r_0$ and vertical separation $\Delta z$ between the air parcels (APs). The choice and validation of these parameters is described in detail in (Konopka et al. 2004). Starting from a reliable initialization of the model, CLAMS tracer distributions can be used to quantify the transport of vortex air into the midlatitudes and, if ozone observations are available, to quantify the chemical ozone loss by comparing the passive ozone transported in the model with the observations (see, e.g., Goutail et al. 1999).

In the next section, we use CH$_4$ initialized from Halogen Occultation Experiment (HALOE) observations both to validate the CLAMS transport and to discuss the spatial distribution of the vortex air over the time period covering the split event, that is, between 1 September and 30 November 2002. We quantify in section 3 how rapidly one part of the vortex was irreversibly mixed into midlatitude air and how strongly isolated was the other part of the vortex that “survived” the major warming. Furthermore, initializing the model calculations using ozone measurements from both the Polar Ozone and Aerosol Measurement III [POAM III (version 3) (Lucke et al. 1999; Lumpe et al. 2002)] and HALOE (Russell et al. 1993) instruments, we compare in section 4 the distribution of passively transported ozone with the measurements of those two satellites that are available until the end of November. In this way, we study the impact of the major warming on the evolution of the ozone hole. Section 5 discusses the results.

2. Tracer transport with CLAMS

a. Configuration and initialization of the model

CLAMS transport studies were carried out with Lagrangian APs covering the Southern Hemisphere in the vertical range between $\theta = 350$ and 1400 K, where $\theta$ denotes the potential temperature. The isentropic transport is driven by European Centre for Medium Range Forecasts (ECMWF) winds, and the cross-isentropic velocities are calculated with a radiation module (Morcrette 1991; Zhong and Haigh 1995) and by taking into account profiles of ozone and water vapor derived from a 10-yr HALOE climatology.

The mean horizontal separation between the APs, $r_v$, is given by 100 and 200 km poleward and equatorward of 30$^\circ$S, respectively. The mean vertical separation between the APs results from a prescribed constant aspect ratio $\alpha = 250$ that defines the ratio between the horizontal and vertical scales resolved in the model. Thus, the mean vertical separation between the APs is given by 0.4 and 0.8 km in the high- and low-resolution regime, respectively. The critical Lyapunov exponent $\lambda_t$ is set to 1.5 day$^{-1}$. The grid adaptation frequency is given by $1/\Delta t$ with the length of the pure advection steps $\Delta t$ set to 24 h. Konopka et al. (2004) discuss the optimization of these grid and mixing parameters by finding a best agreement between the CLAMS tracer studies and high resolved in situ observations collected during the Stratospheric Aerosol and Gas Experiment III (SAGE III) Ozone Loss and Validation Experiment/Third European Stratospheric Experiment on Ozone (SOLVE/THOSEO 2000) campaign.

The initial distribution of CH$_4$ and ozone on 1 September is obtained from results of the Mainz 2D model (Grooß 1996) combined with HALOE observations between 11 August and 10 September, which are used to correct the distributions from the Mainz 2D model in the midlatitudes and in the vortex. The details of the isentropic version of the initialization are described by Grooß et al. (2005; see Fig. 1). Here, we generalize this procedure to 15 isentropic levels uniformly covering the vertical domain of the model and interpolate between these levels to initialize the Lagrangian APs with vertical positions in between. The initial distribution of ozone in the vortex is further adjusted employing POAM III observations by maximizing the correlation coefficient between the observed and transported ozone values during the first 6 days of simulation.

To quantify the dilution of the vortex air due to intrusions of the midlatitude air into the vortex, an artificial tracer is transported in CLAMS that marks, at the beginning of the simulation on 1 September, the APs within and outside of the vortex by 100% and 0%, respectively, with the vortex edge defined by the maximum potential vorticity (PV) gradient (Nash et al. 1996). This vortex tracer describes the percentage of the pure vortex air in each AP over the course of the model run. The boundary conditions at the top and bottom layers are applied after each time step $\Delta t$ and are derived from the PV/CH$_4$ and CH$_4$/O$_3$ correlations valid in these layers at the initialization time. The boundary conditions for the artificial vortex tracer are defined, as at the initialization time, by use of the Nash criterion.

b. CLAMS CH$_4$ distributions during the split event

The model results for the CLAMS CH$_4$ distribution for 21 September (i.e., before the vortex split), 26 September (i.e., during the vortex split), and 20 October (i.e., after the vortex split) are shown in the first, second, and third columns of Fig. 1, respectively. In particular, the isentropic distribution of CH$_4$ at $\theta = 500$ and 800 K can be seen in the first two rows of Fig. 1 (the white solid lines denote the vortex edge). The third row shows the vertical cross section along the 55$^\circ$E
FIG. 1. CLAMS distribution of CH₄ on (left column) 21 and (middle column) 26 Sep and (right column) 20 Oct. In the first two rows the isentropic cross sections at θ = 500 and 800 K are plotted (colors within the circles denote the HALOE observations). The third row shows the vertical cross sections along the 55°E (−125°W) meridian that corresponds to the white dashed lines in the first two rows. The last two rows show contours of the vortex edge colored with its potential temperature and derived from the strongest gradients of (fourth row) ECMWF PV or (last row) CH₄ with respect to the equivalent latitude, that is, according to the procedure described by Nash et al. (1996).
During the following days, the combined impact of the planetary waves 1 and 2 resulted in the first in the practically unmixed core of the vortex. This boomerang-like shape of the vortex can also be recognized in the contour plots of the vortex edge derived from the CH₄ and PV fields (Fig. 1, rows 4 and 5). Here, in addition to the vortex edge derived from the analyzed PV, some filaments and vortex remnants are present in the contours derived from the CH₄ distribution.

In the subsequent 5 days (not shown), the vortex arm above South America became smaller, zonally stretched and vertically sheared and, consequently, broke up in many fragments that were transported equatorward. The vortex arm near southern Africa returned back to the pole and became reestablished, together with the only slightly disturbed vortex part between 400 and 650 K, a circumpolar vortex. This remerged vortex, however, is characterized by much smaller zonal winds and a much smaller area than before the split event.

The spatial distribution of CH₄ about three weeks later, on 20 October, can be seen both in the right column in Fig. 1 and in Fig. 2 where zonally averaged (i.e., in the equivalent latitude space) values of CH₄ are shown. The colors within the circles on the isentropic cross section in Fig. 1 (rows 1 and 2) denote the HALOE measurements (mapped to 1200 UTC), which agree fairly well with the CLAMS calculations. A clear signature of the diabatic descent in the vortex during the vortex split can be seen on 20 October at θ = 500 K by comparing the CH₄ distribution on this day with the corresponding distribution on 26 September. The strongest descent rates are simulated near the vortex edge with the total descent near the edge exceeding the subsidence of the vortex core by about 15 K (see also Fig. 2).

The vertical cross section of the CH₄ distribution on 20 October (see Fig. 1, row 3) shows clear signatures of vortex remnants in the altitude region between 600 and 1000 K. In particular, the vortex edge contours derived from CH₄ fields have more small-scale structures if compared with the vortex edge derived from analyzed ECMWF PV. This indicates that the stratospheric dynamics, triggered by the vortex split, creates tracer fields with much higher spatial variability than the analyzed PV fields can resolve.

Furthermore, the zonally averaged CH₄ distribution shown in Fig. 2 together with the contour lines (black lines) of the zonally averaged vortex tracer indicate that, despite the strong distortion of the Antarctic stratosphere caused by the split event, the lower part of the vortex below about 600 K remained well isolated from the influence of midlatitude air masses. The white dots denoting the equivalent latitude of the vortex edge agree fairly well with the 75% contour line of the vortex tracer. Thus, the region between the 75% and 98% contour lines can be interpreted as the mixing zone inside the vortex in the vicinity of the vortex edge. The air masses with a percentage of 98% and greater constitute the practically unmixed core of the vortex.
c. CLAMS \( \text{CH}_4 \) versus HALOE observations

Before discussing the spatial distribution and the lifetime of the vortex remnants, we investigate in Fig. 3 the quality of CLAMS transport by studying the correlation between HALOE observations of \( \text{CH}_4 \) from 1 September to 30 November poleward of 30 °S and the corresponding CLAMS simulations. The colors denote the percentage of pure vortex air within the simulated air masses. In Fig. 3 (top), the nearest CLAMS APs relative to the HALOE observation (tangent point) are used. By applying this method, a good correlation between CLAMS simulation and HALOE observation could be achieved before the vortex split (filled circles), whereas after the split (open triangles) some deviations are present for air masses containing vortex air (gray dashed area). Such air masses with a large percentage of pure vortex air were sampled near the vortex edge and can be assigned, within the model, to some small-scale vortex remnants formed after the split event. Many of these features are below the spatial resolution of the HALOE instrument where the horizontal and vertical scales of the sampled volume are of the order of 500 km and 4 km, respectively (Russell et al. 1993).

In Fig. 3 (bottom), a weighted interpolation is used that mimics the HALOE observation geometry. In particular, we represent the sampled HALOE volume (cylinder) by three collinear points separated by 250 km, map these points to the synoptic time, and determine the nearest CLAMS AP to each of these points. The mean value over these three CLAMS APs now represents one HALOE measurement with the consequence that the correlation coefficients increases from 0.85 for the nearest-neighbor approximation (Fig. 3, top) to 0.92 for the weighted interpolation (Fig. 3, bottom). The remaining deviations are probably caused by the errors of the simulated absolute position of the vortex remnants.

3. Spatial distribution and lifetime of vortex remnants

The diagnostic of the \( \text{CH}_4 \) distributions as discussed in the previous section has shown that, after the split event, the lower stratospheric vortex remained intact while the large part of the middle stratospheric vortex was rapidly redistributed over the Southern Hemisphere. By analyzing the (artificial) vortex tracer we now study the impact of the major warming on the dilution of the air masses in the vortex and on the meridional redistribution of the air masses originating from the vortex. Furthermore, we investigate the influence of the stratospheric mixing on the lifetime of vortex remnants formed during the major warming when a significant part of the vortex above 600 K decayed into many small fragments.

The zonally averaged meridional distribution of the vortex air calculated as a function of time and equivalent latitude at two isentropic levels \( \theta = 500 \) and \( 800 \) K is shown in Fig. 4. In this figure, a high percentage of vortex air (note logarithmic color scale) means that
only a small fraction of the APs in a bin around the considered equivalent latitude originates from the extravortex region defined at the initialization time. The white contours denote the zonally averaged (i.e., averaged in the equivalent latitude space) wind speed (in m s\(^{-1}\)), and the gray line is the equivalent latitude of the vortex edge derived from the Nash et al. (1996) criterion.
By comparing the top and bottom panels in Fig. 4, clear differences in the meridional distributions of the vortex air at \( \theta = 800 \) K and \( \theta = 500 \) K can be seen. Whereas at \( \theta = 800 \) K, after 26 September, a rapid erosion of the vortex coupled with a fast redistribution of the vortex air masses over the midlatitudes can be observed (up to \( 40^\circ \) S), the impact of the major warming on the distribution of vortex air at \( \theta = 500 \) K is more moderate. At both 500-K and 800-K levels, the vortex edge shrinks in early October to equivalent latitude values of about \( 78^\circ \) and \( 68^\circ \) S, respectively, and correlates fairly well with high wind velocities at the poleward flanks of the jet stream. The vortex at 500 K prevails until the end of November with a high percentage of the vortex air in the equivalent latitude range between \( 80^\circ \) and \( 90^\circ \) S. At 800 K, although the Nash criterion indicates a recovery of the vortex at the 800-K level after the final warming around 25 October, the stratospheric winds are not strong enough to justify this conclusion. This statement is further corroborated by a strong dilution of the vortex tracer after this date. The fact that the vortex edge defined by the Nash criterion does not, under certain circumstances, constitute a strong transport barrier has recently been reported for the Arctic vortex by Steinhorst et al. (2004, manuscript submitted to J. Geophys. Res.).
It should be emphasized that mixing, that is, the irreversible part of transport, has a negligible influence on the discussed meridional distribution of the vortex air. Even for CLAMS simulations without mixing (pure trajectory calculations; not shown), the zonal averaging of the (unmixed) air parcels leads to a similar meridional distribution of the vortex air as for a simulation where mixing would be exaggerated [for a detailed study of this effect see Konopka et al. (2003)]. Thus, the large-scale meridional transport of vortex air into the midlatitudes is controlled by the chaotic advection induced by planetary waves rather than by mixing.

However, mixing may significantly influence the lifetime of vortex remnants, that is, the time necessary to mix vortex air homogeneously with ambient air (Konopka et al. 2003). To quantify this effect, we define an AP as only weakly mixed or clearly distinguished from the extravortex air if the percentage of pure vortex air in such air masses is greater than 75%. By analyzing CLAMS simulations with optimized mixing parameters, we calculate in each isentropic layer the relative contribution of such "unmixed" APs to all APs in the layer poleward of 30°S. The results of this procedure are shown in Fig. 5. It should be emphasized that, in contrast to the meridional distribution of the vortex air discussed in Fig. 4, this kind of diagnostics is strongly sensitive to the intensity of mixing in the model.

To quantify the lifetime of the vortex remnants, we define the vortex air in the remnants as homogeneously mixed with the midlatitude air if the relative contribution of the weakly mixed APs in the considered isentropic level poleward of 30°S is less than 1% (gray dashed line in Fig. 5). About three weeks after the split, a strong homogenization of vortex remnants occurs in the altitude region 850–1000 K. The lifetime of the remnants increases with decreasing altitude up to about six weeks around 700 K. In the altitude range between 400 and 600 K, an intact vortex explains the large relative contribution of strongly isolated vortex air masses. The inferred lifetime of the vortex remnants increases (decreases) by about 10% if the threshold value defining the weakly mixed vortex air is changed from 75% to 65% (85%).

4. Ozone loss

Using profiles of ozone measured by the POAM III satellite instrument, Hoppel et al. (2003) showed that, although the 2002 Antarctic ozone loss was similar to previous years up to the time of the major warming, the intensity of the ozone loss was strongly diminished after the major warming, resulting in up to 20% less chemical ozone loss in the total column within the vortex than in previous winters. Furthermore, based on the very low...
ozone mixing ratios within the vortex core at 500 K observed by POAM III in October and November, they suggested that the smaller vortex that reestablished after the split event was largely isolated. Using the 2D version of CLAMS with full chemistry, Grooß et al. (2005) have shown that the increase of the polar temperatures during the late-September major warming was strong enough to lead to the disappearance of polar stratospheric clouds (PSCs), resulting in a very rapid deactivation of active chlorine under these conditions and, thus, to a stop of the chemical ozone loss within the vortex.

By comparing the CLAMS passive ozone with the POAM III and HALOE ozone observations, we now investigate the chemical ozone loss in the vortex since 1 September and, subsequently, in the part that survived the split event around 26 September. The calculated mean ozone loss in the vortex is shown in Fig. 6. Here the mean difference between POAM III ozone observations and the corresponding CLAMS results for the passive ozone tracer is calculated for a given potential temperature level and averaged over a 5-day period around the considered day (running mean). Only days when more than five POAM III ozone profiles are available were considered. The gray line in Fig. 6 (top) is the 8% contour of the distribution shown in Fig. 5 defining the region with pure, well-isolated vortex air. The white region above 500 K and around the split date are due to the noncircumpolar position of the vortex so that vortex air was not sampled by the POAM instrument. In Fig. 6 (bottom), the column ozone loss integrated between 425 and 575 K is shown (dashed gray lines in Fig. 6, top). A similar analysis based on HALOE ozone observation was carried out for two periods around 20 October and 10 November when HALOE sampled the interior of the vortex. The results (green points in Fig. 6, bottom) confirm rather well the ozone loss derived from POAM measurements.

According to this analysis, a strong ozone loss up to 2 ppmv locally and 70 Dobson units (DU; 1 DU = $2.89 \times 10^{16}$ molecules cm$^{-2}$) between 425 and 575 K occurred in the two weeks before the vortex split. A strong increase of the column ozone loss shortly before the split, then a decrease in early October, and finally a slow increase up to the end of November anticorrelate with the fluctuations in the pressure range in which the column ozone loss was calculated (this pressure range corresponds to the 425–575-K potential temperature range shown in Fig. 5).
range; see gray stripe in Fig. 6, bottom). The variations of this range are triggered by the temperature fluctuations caused by the split, that is, by strong warming and cooling before and after the split date (black line) and subsequent slow warming until the end of November. Thus, these diabatic effects rather than chemical processes are responsible for the calculated fluctuations of the column ozone loss after the vortex split. This indicates that from the end of September until the end of November the ozone loss is “frozen in” in the well-isolated part of the vortex below 550 K after the warming ended.

A slightly different way to present these results is shown in Fig. 7. Here the CH$_4$/$O_3$ correlations based on POAM III ozone observations in the vortex within the altitude range 400–600 K (crosses) (CH$_4$ values are derived from the CLAMS simulations) are compared with the corresponding CLAMS simulations of passive ozone (circles) for three time periods after the vortex split: 5–11 October, 15–21 October, and 20–30 November. The colors denote the potential temperature (left column) and the percentage of pure vortex air (right column).

Similar to the tracer–tracer correlation (TRAC) method for deducing chemical ozone loss (see, e.g., Müller et al. 1996; Tilmes et al. 2003), the CH$_4$ correlation with passive ozone can be considered as a reference, compared to which the chemical ozone loss becomes obvious as a deviation of the observed CH$_4$/$O_3$ correlation from this reference. Thus, the strong devia-

![Figure 7](http://journals.ametsoc.org/jas/article-pdf/62/3/848/3480664/jas-3329_1.pdf)
tion between the passive ozone reference and the CH$_4$/
O$_3$ relation based on POAM III ozone measurements
(maxed by the gray region) is a measure of chemical
ozone loss. The compactness of the CH$_4$/O$_3$ correla-
tions did not significantly change in the time between
the split in late September and the end of October,
indicating a strong isolation of the considered air
masses. Some signatures of mixing can be seen after 20
November (Fig. 7, bottom) although the compactness
of the CH$_4$/O$_3$ correlations is still well defined. In par-
ticular, some air masses characterized by a low fraction
of vortex air (Fig. 7, bottom right) show a clear devia-
tion (toward higher ozone values) from the compact
CH$_4$/O$_3$ correlation. Note that the increase of the high-
est ozone values during that time period (top to bottom
in Fig. 7) is due to continuing diabatic descent in the
vortex.

Thus, we conclude that the chemical loss did not
change significantly after the split, which means that
neither further chemical loss occurred nor the signature
of the chemical loss was destroyed by mixing. The in-
ferred ozone loss is mainly found in well-isolated vortex
air masses (see red symbols in Fig. 7, right column),
with the highest values of up to 2 ppmv loss in the
altitude range 450–550 K occurring between 1 Septem-
ber (initialization) and the end of October.

5. Discussion

During the fall of 2002, the Antarctic polar vortex
experienced at the end of September a unusually
strong disturbance because of a major stratospheric
warming that resulted in a split of the vortex into two
parts. By carrying out high-resolution, 3D simulations
with the Chemical Lagrangian Model of the Strato-
sphere (CLAMS), both the split process itself and the
subsequent redistribution of the vortex air were consid-
ered.

In the previous studies considering the details of the
transport of the vortex air into the midlatitudes, Hess
(1991) found in the Limb Infrared Monitor of the
Stratosphere (LIMS) data and GCM simulations that
long-lived anomalies of tracers were still observed two
months after the breakup of the polar vortex in spring
1979. Using the probability density function (PDF)
technique for 3D simulations of N$_2$O, Orsolini (2001)
identified some long-lived westward-propagating tracer
patterns in the 1998 boreal summer polar stratosphere
above 20 km that resulted from the slow advection of
partly mixed vortex remnants. By analyzing isentropic
CLAMS 2D tracer distributions over the entire North-
ern Hemisphere during late spring and early summer
1997, Konopka et al. (2003) have shown that significant
differences exist in the distribution and in the lifetime
of the vortex remnants formed after the Arctic vortex
breakup in May 1997 above and below 20 km. Above
20 km vortex remnants effectively propagate southward
(to 40°N) and are “frozen” in the summer circulation
without significant mixing. Below 20 km their lifetime is
shorter by a factor of 2 owing to significant stirring
below this altitude.

The analysis of the mixing processes after the split
event in September 2002 together with studies of the
breakup of the Arctic vortex in spring 2000 (Konopka et
al. 2003), allows us to develop the following picture of
transport processes governing the lifetime of the vortex
remnants: a long lifetime of the remnants correlates
with high absolute PV values within such air masses,
indicating that strong rotation or high angular momentum
prevents dispersion of the APs within the remnants
(McWilliams 1984) and, consequently, mixing between
such air masses and midlatitude air, at least in CLAMS,
is limited [In CLAMS, if the relative distances of the
APs to their neighbors does not significantly change
during the transport, the grid of the neighboring APs is
not deformed so that, owing to the mixing algorithm,
such APs do not mix (Konopka et al. 2004)]. After the
potential vorticity of the remnants has dissipated due
to diabatic processes or due to friction, mixing of the APs
belonging to such air masses is no longer constrained by
a PV barrier and, dependent on the deformations in the
“ambient” flow, can disperse and finally be mixed. Of
course, this subsequent transport process depends on
the intensity of the horizontal (strain) and vertical
(shear) deformations in the flow. For example, the solid
body rotation in the summer stratosphere above 20 km
mixes much weakly than does the strong or moderate
activity of planetary waves, usually present in the
stratosphere after a breakup of the polar vortices
(Konopka et al. 2003).

By comparing the CLAMS and POAM III/HALOE
CH$_4$/O$_3$ correlations between 1 September and the end
of November, a clear signature of ozone loss can be
seen in the part of the vortex that “survived” the major
warming in September 2002, that is, between 400 and
600 K. Despite this strong dynamical disturbance of the
stratosphere, these air masses consisted of almost pure
vortex air, indicating negligible dilution with air coming
from midlatitudes. In these well-isolated air masses up
to 2.0 ppmv of ozone were depleted during the consid-
ered period with highest absolute values around 480 K.
Starting from 1 September, about 70 DU of ozone was
destroyed up to the vortex split around 25 September.
After this date the accumulated ozone loss was frozen
in the vortex core and transported until the end of No-
vember without either further chemical loss or any sig-
ificant dilution by transport across the vortex edge.
According to the sensitivity studies with backward tra-
jectories, these results are not influenced by the bound-
ary condition used in CLAMS simulations. Furth-
more, isentropic studies with full chemistry (Groß
2005) and 3D investigations with linearized ozone
chemistry (Sinnhuber et al. 2003) support our conclu-
sion that the vortex split stopped the chemical ozone
loss.
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