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A study of the leakage of the Antarctic polar vortex in late austral winter and spring using isentropic and 3-D trajectories

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The permeability of the Antarctic polar vortex is investigated in late austral winter and spring by comparing isentropic and three-dimensional (3-D) trajectories. Trajectory computations were performed with the help of the Royal Dutch Meteorological Institute (KNMI) trajectory model, using data from the European Centre for Medium-Range Weather Forecasts (ECMWF) from August to November 1998. Large numbers of air parcels were initially released inside and outside the polar vortex on the 350, 450, and 550 K isentropic surfaces. They were integrated 4 months forward in time in an isentropic mode, as well as in a 3-D mode that uses all three wind components from the ECMWF and takes into account diabatic heating and cooling effects. For the isentropic trajectory calculations, very little transport (0.37%/week) was found for August and September, while October and November gave somewhat higher transport rates (1.95%/week). The 3-D trajectory calculations for October gave much more exchange between the vortex and midlatitudes than the isentropic ones owing to a significant number of parcels that descended inside the vortex. Descent rates were calculated for 350 K (October), 450 K (August–October) and 550 K (October). Overall, the results show that 3-D trajectories will provide more accurate leakage rates than the isentropic ones. Also, despite the large scale mixing in the polar vortex or in midlatitudes, little ozone-depleted air leaks from the ozone hole into the midlatitude stratosphere.

INDEX TERMS: 0341 Atmospheric Composition and Structure: Middle atmosphere—constituent transport and chemistry (3334); 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3349 Meteorology and Atmospheric Dynamics: Polar meteorology; 3346 Meteorology and Atmospheric Dynamics: Planetary meteorology (5445, 5739); 3399 Meteorology and Atmospheric Dynamics: General or miscellaneous; KEYWORDS: polar vortex, stratospheric mixing and transport, planetary waves, ozone hole


1. Introduction

Each austral winter and spring, the ozone hole develops in the Antarctic stratosphere. The Antarctic polar vortex creates the unique dynamical environment for the ozone hole to develop and persist over August to November [e.g., Waugh et al., 1999; Zhou et al., 2000]. The destruction of ozone within the polar vortex is the result of heterogeneous chemistry [e.g., Solomon, 1986, 1999]. Owing to the isolation of the polar vortex, air within the vortex interior cools and temperatures can drop as low as 185 K, cold enough for the formation of polar stratospheric clouds (PSCs). Although PSCs have not yet revealed all of their mysteries concerning their composition and chemistry, a key point is that they provide a reactive surface for catalytic chemical reactions that destroy ozone [e.g., Tolbert and Toon, 2001].

The persistence of the ozone hole and the cold temperatures in the interior over several months indicate that there is little exchange of air between midlatitudes and the vortex interior. The amount of exchange is an important issue for the following reasons. On the one hand, transport of warm and ozone-rich midlatitude air into the vortex would weaken it and slow down the heterogeneous processing of ozone. On the other hand, transport of very cold...
ozone-depleted air into midlatitudes might contribute to the observed downward trend in midlatitude ozone [e.g., Harris et al., 1997].

[4] Nowadays the degree of isolation and thus the amount of transport and mixing between midlatitude and vortex air across the vortex edge is still under debate. The central question in this discussion is whether the air in the polar vortex is captured on a seasonal timescale. Some previous studies [Hartmann et al., 1989a, 1989b; Schoeberl et al., 1992] have shown that there is only little exchange of air between midlatitudes and the vortex interior owing to strong gradients in potential vorticity (PV) in the horizontal and small cooling rates in the vertical ("containment vessel" hypothesis). Others [Proffitt et al., 1989; Tuck, 1989] have argued that there is a substantial downward flow of air through the vortex interior and then outwards into the lower polar and midlatitude stratosphere ("flowing processor" hypothesis).

[5] In order to find a possible way out of this controversy, various theoretical and numerical studies have been performed over the years. Juckes and McIntyre [1987] and McIntyre [1989] argue that on the basis of Ertel's potential vorticity the polar vortex should behave like an isolated material entity. Erosion of the polar vortex edge due to breaking planetary waves steepens its strong latitudinal gradient in PV.

[6] Isentropic trajectory calculations [Bowman, 1993a, 1993b, 1996; Dalhberg and Bowman, 1994; Bowman and Chen, 1994] as well as experiments using the high-resolution contour advection with surgery (CAS) technique on isentropic surfaces [Waugh and Plumb, 1994; Chen et al., 1994; Chen, 1994] show that the polar vortex is nearly impermeable for isentropic motions above the 425-K isentropic surface. Below this level the polar vortex is less isolated. Below the 400-K isentropic surface a region indicated as the "subvortex" region [McIntyre, 1995] can be identified, where substantial isentropic mixing of vortex air with lower stratospheric midlatitude air takes place.

[7] Although no substantial cross-edge transport of air is observed in these studies, air from the outer vortex can get torn off from the main vortex by breaking planetary waves and can become organized into thin filaments. Mixing between the air in the filaments and surrounding midlatitude air occurs when the spatial scale of the filaments becomes small enough for diffusive mixing to become important. The inner vortex does not show these features and resists intrusions of air from midlatitudes [Polvani and Plumb, 1992]. A drawback of the above studies is that they mostly only consider adiabatic (isentropic) motions. Also, they perform model calculations over periods of weeks to months without questioning whether these motions can still be regarded as being isentropic over such long time spans.

[8] The STRATEOLE project [Vial et al., 1994] was initiated to gain a better understanding of the dynamics and chemistry of the Antarctic polar vortex. In the near future, isopycnic balloons will be launched inside and at the edge of the vortex in late winter and spring. Trounson et al. [1995] performed three-dimensional (3-D) trajectory computations using winds from a rather coarse-gridded ($5^\circ \times 5^\circ$) 3-D stratosphere-mesosphere model. For a 10-week period they recorded the number of crossings of air parcels and isopycnic balloons across the vortex edge which were initially released in a zone between 50° and 75°S. They demonstrated the resemblance between the horizontal mixing of air parcels and balloons.

[9] Wauben et al. [1997a] performed exchange calculations using a 3-D Eulerian tracer transport model driven by the European Centre for Medium-Range Weather Forecasts (ECMWF) winds. For tracers initially released at 72.5 hPa inside the polar vortex they calculated exchange rates averaged over the 4-year period 1990–1993. They arrived at a quasi-horizontal cross-edge transport of 0.24%/day, while 0.83%/day of the vortex mass descended into the troposphere. They stated that 65% of the total tracer mass is flushed out during August–October. A shortcoming of their model is that the coarse resolution ($5.0^\circ \times 3.75^\circ$) may lead to additional numerical leakage out of the vortex.

[10] In this study a comparison is made between isentropic and 3-D trajectory computations in the polar vortex region, which has not been presented before. Also, new quantitative estimates of transport across the polar vortex edge will be obtained from high-resolution ($1^\circ \times 2^\circ$) trajectory calculations. Such a resolution is much higher than what was used in the studies of, for example, Trounson et al. [1995] and Wauben et al. [1997a]. The validity of the isentropic approximation in exchange studies of the Antarctic polar vortex will be discussed. Also, average descent rates will be determined from the 3-D trajectory computations. These values will be compared with average descent rates of tracer isopleths and values reported in the literature.

2. Trajectory Model

[11] Trajectories were calculated with the Royal Dutch Meteorological Institute (KNMI) trajectory model [Scheele et al., 1996]. The model computes the three-dimensional displacement of air parcels with the iterative scheme of Petterssen [1940] and a time step of $dt = 10$ min. The trajectory model uses ECMWF 6-hour forecasts (first-guess fields) of the three-dimensional wind and temperature. First-guess data are preferred to analysis data because they show better physical balance of the wind and mass density fields. Analyzed quantities are slightly out of balance owing to the recent addition of new observations in the analysis step. The input data are interpolated linearly in the horizontal and with log($p$) in the vertical to the instantaneous locations of the trajectories. The ECMWF data were available on a horizontal $1^\circ \times 1^\circ$ grid at 31 hybrid pressure-sigma model levels, of which 10 are in the Antarctic stratosphere. The highest model level in the stratosphere is 10 hPa. In this study we use these data for the period of 1 August 1998 at 1200 UT to 30 November 1998 at 1200 UT in order to allow comparison with Wauben et al. [1997a].

[12] The accuracy of the trajectory calculations is influenced by errors in the numerical trajectory integration scheme and errors in the wind fields. The errors due to the numerical scheme are of the order of 1% or less [Stohl et al., 2001]. However, the study of Stohl et al. [2001] focuses on 3-D trajectories in the troposphere. In this study we also deal with isentropic as well as with 3-D trajectories in the stratosphere. The relative error in the final position of air parcels for these types of trajectories in the stratosphere due to errors in the wind field was determined as follows.
[13] An air parcel was integrated forward in time from its initial position. From its final position it was then integrated backward in time. It is expected that an air parcel that is integrated backward in time from its final position will not exactly return to its initial position. It turned out that the positioning error relative to the traveled distance error was 5% or less for isentropic trajectories and 2% or less for 3-D trajectories (R. Scheele, personal communication, 2001). Errors in the trajectories will therefore be determined mainly by errors in the wind field, as was already suggested by Bowman [1993a].

### 3. Experimental Setup

[14] Air parcel trajectories were calculated both in the isentropic mode and in the 3-D mode. The isentropic mode conserves potential temperature ($\theta$) along the trajectories. Air parcels that are initially on an isentropic surface are tied to that surface explicitly by the model. The 3-D mode takes into account vertical air motions caused by diabatic heating and cooling effects. These effects become especially important in early Southern Hemisphere spring (October–December), when the sun rises and the Antarctic atmosphere starts to warm. The air parcels were started on the 350, 450, and 550 K isentropic surfaces because these levels represent the lower, middle, and upper vortex ($\sim$13–25 km) levels, respectively. This region also covers the altitudes at which ozone is destructed in early winter and spring (respectively. This region also covers the altitudes at which the Vortex isentropic surfaces. PV is given in potential vorticity units (PVU) (1 PVU = $10^6$ Km$^2$ kg$^{-1}$ s$^{-1}$).

### 3.1. Initial Position of Air Parcels Inside/Outside the Vortex

[15] The initial position of the air parcels inside or outside the vortex was determined with the help of PV maps on isentropic surfaces. PV is given in potential vorticity units (PVU) (1 PVU = $10^6$ Km$^2$ kg$^{-1}$ s$^{-1}$). The initial position of air parcels starting inside/outside the critical PVin/PVout contour corresponding to the inner/outside the vortex edge. For air parcels that initially started inside the polar vortex the PVout contour will be denoted as the critical PV contour. Similarly, for air parcels that initially started outside the polar vortex the PVin contour will be denoted as the critical PV contour.

### 3.2. Exchange Diagnostics

[16] An air parcel is assumed to have left or entered the polar vortex if the air parcel crosses the critical PV contour and does not cross this contour again for the next 120 hours. The time span of 120 will be denoted as the threshold residence time.

[17] The threshold residence time was introduced to eliminate positioning errors and was determined by preliminary analyses of the trajectory runs. At regular time intervals, area (isentropic runs) and mass-weighted fluxes (3-D runs) were determined for air parcels that crossed a given critical PV contour. Following Dalhberg and Bowman [1994] and Seo and Bowman [2001], area and mass exchange rates were calculated by determining the initial area and volume (mass) of air parcels and the area and mass of parcels that left or entered the vortex. For several different threshold residence times, exchange rates could be determined for intruding or extruding air parcels. In general, we expected that the area and mass exchange rates represented by parcels leaving or entering the vortex should increase with time. However, for threshold times <96 hours we regularly observed a decrease in the exchange rates represented by parcels that left the vortex. Further inspection showed that this was due to frequent reversible parcel displacements; that is, air parcels left or entered the vortex for a couple of hours but then returned. In this context it is worth mentioning that the computation of PV along the trajectories may not be very accurate owing to the dependency of PV on first-order wind and temperature derivatives. There is also an uncertainty in the PV value of the critical PV contour due to the vertical interpolation of wind, temperature, and pressure in the trajectory model. By increasing the threshold to 120, exchange rates could be determined for intruding or extruding air parcels. In general, we expected that the area and mass exchange rates represented by parcels leaving or entering the vortex should increase with time.

### Table 1. Critical Potential Vorticity (PV) Contours for Different Starting Dates and Isentropic Surfaces in the Isentropic Interior Runs

<table>
<thead>
<tr>
<th>Date</th>
<th>PV Contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 K</td>
<td>450 K</td>
</tr>
<tr>
<td>98080112</td>
<td>-6.0</td>
</tr>
<tr>
<td>98083012</td>
<td>-6.0</td>
</tr>
<tr>
<td>98093012</td>
<td>-6.5</td>
</tr>
<tr>
<td>98103012</td>
<td>-6.5</td>
</tr>
</tbody>
</table>

*The critical PV contours were determined with help of PV maps on isentropic surfaces. PV is given in potential vorticity units (PVU) (1 PVU = $10^6$ Km$^2$ kg$^{-1}$ s$^{-1}$).

### Table 2. Numbers of Air Parcels Starting at Different Dates and Isentropic Surfaces in the Isentropic Interior Runs

<table>
<thead>
<tr>
<th>Date</th>
<th>350 K</th>
<th>450 K</th>
<th>550 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>98080112</td>
<td>2014</td>
<td>4698</td>
<td>4128</td>
</tr>
<tr>
<td>98083012</td>
<td>2862</td>
<td>4630</td>
<td>4468</td>
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<tr>
<td>98093012</td>
<td>2261</td>
<td>4098</td>
<td>4080</td>
</tr>
<tr>
<td>98103012</td>
<td>2575</td>
<td>4366</td>
<td>3834</td>
</tr>
</tbody>
</table>

*Example: On 98083012, 4360 parcels start on the 450-K isentropic surface.

### Table 3. Exchange Rates for the Isentropic Interior Runs Computed for August–November 1998

<table>
<thead>
<tr>
<th>Date</th>
<th>350 K</th>
<th>450 K</th>
<th>550 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>98080112</td>
<td>0.00</td>
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</tr>
<tr>
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<td>0.06</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>98093012</td>
<td>0.33</td>
<td>1.34</td>
<td>1.95</td>
</tr>
<tr>
<td>98103012</td>
<td>0.40</td>
<td>0.08</td>
<td>1.16</td>
</tr>
</tbody>
</table>

*Errors in the trajectories will therefore be determined mainly by errors in the wind field, as was already suggested by Bowman [1993a].

Table 3. Exchange Rates for the Isentropic Interior Runs Computed for August–November 1998

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<tr>
<td>98080112</td>
<td>0.00</td>
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<td>0.37</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.40</td>
<td>0.08</td>
<td>1.16</td>
</tr>
</tbody>
</table>

*Errors in the trajectories will therefore be determined mainly by errors in the wind field, as was already suggested by Bowman [1993a].
Figure 1. Potential vorticity (PV) (0.1 PVU) at (a) 350 K on 98080112 and (b) 350 K on 98083012 and at (c) 450 K on 98080112 and (d) 450 K on 98083012 and at (e) 550 K on 98080112 and (f) 550 K on 98083012, based on European Centre for Medium-Range Weather Forecasts fields. The shaded contours mark the vortex edge.
mass-exchange rates and exchange across PV contour) and Troun¬day et al. [1995] (determination of the vortex edge and threshold time).

3.3. Isentropic Mode

In the isentropic mode, 12 model runs were performed in which trajectories were started separately on the 350, 450, and 550 K isentropic surfaces on 1 August 1998 at 1200 UT, 30 August 1998 at 1200 UT, 30 September 1998 at 1200 UT, and 30 October 1998 at 1200 UT. Different initial times were used in order to get unambiguous information about the time evolution of the exchange across the vortex edge. The month of August is typically the period of vortex buildup and development of the ozone hole. In September the polar vortex is at its strongest, with decreasing ozone values, and it reaches minimum values in October. The onset of vortex breakdown is usually in November. Henceforth these runs will be denoted as the isentropic “interior” runs.

In order to study the permeability of the polar vortex edge to intruding midlatitude air, two additional isentropic runs were started in which air parcels were initially outside the polar vortex on the 450 K isentropic surface on 1 August 1998 at 1200 UT, and 30 September 1998 at 1200 UT. Different initial times were used in order to get unambiguous information about the time evolution of the exchange across the vortex edge. The month of August is typically the period of vortex buildup and development of the ozone hole. In September the polar vortex is at its strongest, with decreasing ozone values, and it reaches minimum values in October. The onset of vortex breakdown is usually in November. Henceforth these runs will be denoted as the isentropic “interior” runs.

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In order to study the permeability of the polar vortex edge to intruding midlatitude air, two additional isentropic runs were started in which air parcels were initially outside the polar vortex on the 450 K isentropic surface on 1 August 1998 at 1200 UT, and 30 September 1998 at 1200 UT, respectively. On the 350 and 550 K isentropic surfaces the polar vortex was less well defined and therefore less favorable to perform the calculations on. The choice to represent a late winter (August) and spring (October) situation was motivated by the observation that these periods showed respectively few and large intrusions of air from the polar vortex to midlatitudes (section 4.1). Henceforth these runs will be denoted as the isentropic “interior” runs.

The critical PV contours for different starting dates and different isentropic surfaces used in the isentropic interior runs are listed in Table 1. For the two isentropic exterior runs starting on 98080112 and 98093012 the critical PV contour was at −37 PVU at 450 K. (Henceforth dates are denoted as a year/month/day/hour combination. For example, 98080112 corresponds to 1 August 1998, 1200 UT.)

Trajectories were calculated for several thousands of parcels. In Table 2 the number of parcels that started in the isentropic interior runs for four subsequent starting dates, and isentropic surfaces are summarized. Note that in each run a different number of parcels started. This is because the shape and area of the polar vortex changes in time as well as with height. For the isentropic exterior run, 4978 parcels started on 98080112 and 5546 air parcels started on 98093012 at 450 K.

3.4. 3-D Mode

From the results of the isentropic interior runs it turned out that the highest leakage rates were found in October. In order to see if leakage is still larger in the 3-D mode it was decided to start a run first on 98093012. Again, air parcel trajectories were started inside the vortex on the 350, 450, and 550 K isentropic surfaces.

Additional 3-D runs were performed for trajectories that started on 93080112, 93083012, 93093012, and also for 98080112 and 98083012 at 450 K for comparison with previous results published in the literature. From these runs, descent rates could be determined.

For the 3-D run that started on 98093012 the critical PV contours on the 350, 450, and 550 K level were at −6.5, −20, and −50 PVU, respectively. Additionally, the critical PV contours were determined at 340, 400, 500, 600, 650, 700, 750, 800, and 850 K for 98093012, 98101012, 98102012, and 98103012. At intermediate levels and times a linear interpolation scheme was applied.

For the 3-D trajectory calculation that started on 98093012 the same air parcels were started on the 350, 450, and 550 K isentropic surface on 98093012 as in the isentropic case (Table 1). Initially, 3603, 4253, and 4481 air parcels, were started inside the vortex at 450 K for the additional runs that started on 93080112, 93083012, and...
93093012, respectively. Also, 4680 and 4661 air parcels were initially started inside the vortex at 450 K for the trajectory runs that started on 98080112 and 98083012, respectively.

4. Isentropic Trajectory Results

4.1. Isentropic Interior Runs

[26] For each date and level and at regular time intervals the number of air parcels that crossed the critical PV contour and obeyed the critical residence time was calculated. From this, average transport rates expressed in percent per week could be determined. The results are summarized in Table 3.

[27] It can be seen that there is no or only very little transport out of the polar vortex in August and September on all three isentropic surfaces, indicating a nearly impermeable polar vortex edge. This is confirmed by the strong PV gradients marking the edge of the polar vortex throughout August and September (Figure 1). The strongest PV gradients are found at 450 K. At 550 K a clear vortex edge can be identified, although features of weak filamentation are also present. This may explain the somewhat higher exchange rate in August at 550 K.

[28] It is remarkable that virtually no air parcels have crossed the critical PV contour in August and September at 350 K. Almost all air parcels released at 350 K on 98080112 and 98083012 stayed within the region marked by the critical PV contour, as can be seen from Figure 2. The parcels are well mixed inside the area confined by the critical PV contour. Note, however, from Figure 1 that at 350 K on 98080112 and 98083012 the vortex edge is not so well defined. There is more than one closed contour for the critical PV, and the air parcels confined by it may well reach into midlatitudes.

[29] These results mostly confirm those of previous studies [Bowman, 1993a; Chen, 1994; Chen et al., 1994]

Figure 3. Location of air parcels that left the polar vortex after 240 hours since the start on 98093012 at 550 K.
using isentropic trajectories calculations and contour advection techniques. In those studies, nearly complete isolation of the polar vortex is found above ~425 K. Chen [1994] concluded from his contour advection calculations at 350 and 375 K that the air inside the vortex is very well mixed on 31 August 1993 after 40 days of integration. Most of this air is still confined within the “line of separation” separating the inner and outer vortex. If we tentatively identify Chen’s “line of separation” with our critical PV contour, then our findings are in qualitative correspondence with those of Chen at 350 K. He suggested that the low exchange rates at 350 K are related to the strong PV gradients marking the tropopause obstructing air parcels to intrude into the troposphere.

[30] Slightly larger leakage rates were found for October and November, especially at 550 K. As noted in earlier in this section, during August and September and also in October and November there was an increased intensity of filamentation at 550 K. Several filaments were wrapped around the vortex. Subsequent mixing with midlatitude air may transfer vortex air into midlatitudes. The filaments developed at locations where the PV gradient was weak. This facilitates the exchange of air between the polar vortex and midlatitudes. Figure 3 gives an example of a situation where air parcels were organized in a filament. It shows the distribution of air parcels that have left the polar vortex after 240 hours since the start on 98093012 on the 550-K isentropic surface. The corresponding PV distribution on 98101012 at 550 K is shown in Figure 4. From Figure 4, two filaments wrapped around the main vortex can clearly be identified. The locations of a major part of the air parcels shown in Figure 3 coincides with the filament in Figure 4, located between ~60°E and 120°E and 40°S and 50°S. This filament developed soon after the start on 98093012 near a location with relatively weak PV gradients, and most air parcels shown in Figure 3 leave the vortex here. The filament persisted for most of the time between the start and 98101012. The other filament, located between ~90°W and 180°W and 30°S and 40°S, developed at a later time, making it less likely for air parcels to have left the vortex through this filament on 98101012. Note that the PV gradients near the location where the filaments develop are weaker than elsewhere near the vortex edge. The large filaments observed in October at 550 K were less pronounced in November at 550 K and in October and November at 450 K. On the 350-K isentropic surface the polar vortex is not so well defined from August to November, and therefore it is hard to distinguish any filaments.

4.2. Isentropic Exterior Runs
[31] To investigate possible intrusions of air parcels from midlatitudes into the polar vortex, two trajectory runs were
performed in which the air parcels were initially located outside the polar vortex on the 450-K isentropic surface (see section 3.3). For the run starting on 98080112 we did not find a single air parcel that entered the polar vortex, which would correspond to a perfectly impermeable vortex edge for exterior air parcels. In section 4.1 it was noted that in August at 450 K there was no air parcel that crossed the vortex edge starting from the interior. This indicates that in August at 450 K the polar vortex edge acts as a perfect barrier to quasi-horizontal mixing. For the trajectory run starting on 98093012 at 450 K an exchange rate of 0.20% per week was found. Figure 5 shows the locations of air parcels that crossed the vortex edge after 3 weeks (504 hours), as well as those that stayed outside the vortex. Parcels that have entered the vortex were initially quite close to the outer edge of the vortex. Obviously, these parcels would have the highest probability of entering the vortex core. Parcels that started well outside the polar vortex are well mixed at midlatitudes. Note that the exchange rates in October at 450 K for parcels entering the polar vortex from midlatitudes are even lower than for parcels moving from the vortex core to midlatitudes (Table 3). This could be a confirmation of previous suggestions made by Juckes and McIntyre [1987] and Polvani and Plumb [1992] concerning the “one-sidedness” of air mass intrusions. They stated that the outer vortex edge is more robust to exchange of air from midlatitudes into the vortex core than the inner vortex edge is to exchange of air from the vortex core into midlatitudes. They attribute this to the absence of breaking planetary waves near the inner vortex. At this point it is interesting to note that our results suggest that although there is very little cross-edge mass exchange in August and September on the 350-, 450-, and 550-K levels, mixing inside the vortex core itself is significant. A clear example of this is shown in Figure 2 for 350 K and Figure 6 for 450 and 550 K. A region of strong mixing inside the vortex core and at midlatitudes, separated by a zone of weak mixing and little mass exchange corresponding to the vortex edge was also found in a recent study by Lee et al. [2001].

5. 3-D Trajectory Results

In section 4 the largest exchange rates were found for isentropic trajectories starting inside the vortex on 98093012 at 350, 450, and 550 K (Table 3). In order to investigate if diabatic effects change the leakage, 3-D trajectories were calculated starting from the same locations on 98093012 at 350, 450, and 550 K. In this 3-D mode the air parcels can traverse isentropic surfaces owing to vertical movements related to diabatic cooling or heating processes. As a result, we can not only quantify quasi-horizontal cross-edge transport (as in the isentropic case) but also vertical exchange...
through the vortex “bottom” and “top.” The top of the vortex in our model runs was restricted by the upper level of the ECMWF model corresponding to the 10-hPa isobaric level ($q_{25}/C25$ 850 K). No air parcels can leave the vortex through the top level. The bottom of the vortex was determined using PV maps on isentropic surfaces. We searched for an isentropic surface where there was still a PV gradient present that marked the edge of the vortex. It turned out that below the 340-K isentropic surface no clear vortex edge structure was visible anymore. Therefore the bottom of the vortex was taken to be at the 340-K isentropic surface. Air parcels descending below 340 K might eventually enter the troposphere. The troposphere can be assumed to start below the $/C0$ 3.5 PVU contour ($/C24$ 307 K). This altitude was derived from ECMWF PV/$q$ cross sections for October 1998.

The quasi-horizontal and vertical exchange rates are summarized in Table 4. One should be cautious in directly comparing the quasi-horizontal transport of the 3-D trajectories and the isentropic trajectories (Table 3). The leakage rates in Table 4 are mass leakage rates, whereas the leakage rates in Table 3 correspond to area leakage rates (see also section 3.4). Tentatively, we might state that cross-edge leakage rates of the 3-D trajectories are somewhat larger compared with the purely isentropic mode, except at 450 K where the leakage rate in the 3-D mode (1.27%/week) is slightly smaller than for the isentropic mode (1.34%/week).

[33] The greater exchange in the 3-D mode is not unreasonable, since air parcels are not restricted to conserve potential temperature and PV. Parcels may now descend to a height where there is an increased chance of crossing the critical PV contour and may move to midlatitudes. At higher $\theta$ levels (450 and 550 K) the polar vortex still acts as an almost impermeable barrier to quasi-horizontal cross-edge transport.

[34] Vertical exchange rates are largest for the trajectories starting at 350 K and are very low for 450 and 550 K. For all three levels there were no air parcels that entered the troposphere. It is interesting to note that although on average air parcels descend within the vortex, a significant amount of parcels moves to higher $\theta$ levels than where they started, as is shown in Figure 7. Rising air parcels are mainly found near the edge of the polar vortex. A possible explanation for this is that in spring (October), air parcels near the edge are likely to be subjected to heating.

6. Validity of the Isentropic Approximation

[35] The results in section 5 showed that the 3-D trajectory computations gave rise to additional transport across the vortex edge, in comparison with isentropic exchange rates (section 4). In other studies of the polar vortex using isentropic trajectories [e.g., Bowman, 1993a; Bowman and Chen, 1994] and the CAS technique [e.g., Chen et al., 1994; Chen, 1994], mixing and mass transport is determined on isentropic surfaces after several weeks to months of model

**Table 4.** Exchange Rates for the Three-Dimensional Run Starting on 98093012 on the 350-, 450-, and 550-K Isentropic Surfacesa

<table>
<thead>
<tr>
<th>Level</th>
<th>Cross-edge transport</th>
<th>Descending below 340 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>350 K</td>
<td>0.62</td>
<td>4.11</td>
</tr>
<tr>
<td>450 K</td>
<td>1.27</td>
<td>0.02</td>
</tr>
<tr>
<td>550 K</td>
<td>2.42</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>4.31</td>
<td>4.13</td>
</tr>
</tbody>
</table>

aExchange rates were calculated after a 4-week integration. Rates are given in percent per week.

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**Figure 7.** Distribution of air parcels after 4 weeks since the start on 98093012 at 350, 450, and 550 K.
integration. In these studies it is not questioned whether motions can still be regarded as being adiabatic after such long periods. In order to test the validity of the isentropic approximation after long periods of integration, a number of 3-D trajectories were selected that were initially located well inside the vortex at $-90^\circ W$ and $88^\circ S$, $84^\circ S$, $80^\circ S$, $78^\circ S$, $72^\circ S$, $68^\circ S$, and $64^\circ S$ at 350, 450, and 550 K. The trajectories were integrated 4 weeks forward in time, starting on 98093012. The change in potential temperature $\theta$ along the trajectories as a function of time is shown in Figure 8.

**Figure 8.** Potential temperature $\theta$ as a function of time since the start ($t = 0$). Trajectories started on 98093012 at 350, 450, and 550 K.
On all three isentropic surfaces, trajectories start to deviate significantly (5–10 K) from their initial isentropes <48 hours after the start. Qualitatively, the same behavior was found for August, September, and November. Note that the deviation from the initial isentropes is largest for air parcels that start on the 450- and 550-K isentropic levels. Also, in most cases the air parcels move to lower isentropic levels, but as time increases, their rate of descent decreases. A possible explanation for this is that the descent rates within the polar vortex are not the same on different isentropic levels. 

Manney et al. [1994] showed that vertical cooling rates within the polar vortex were larger at higher isentropic levels (larger potential temperature). Motivated by their results, average cooling rates were determined on the 350-, 450-, and 550-K isentropic levels for air parcel trajectories that started on 9809312 (see section 5). The largest descent rate was found for air parcels that started at 550 K (2.2 K/day), and smaller rates were found for those that started at 450 K (0.6 K/day) and 350 K (0.3 K/day). Therefore air parcels that start initially at 550 K will experience the largest descent, but this will gradually decrease as they move to lower isentropic levels where the descent rates are smaller. This effect becomes less pronounced for air parcels that start at 450 and 350 K. It is interesting to note from Figure 8 that for individual air parcels, descent rates in θ can be of the order of 5 K/day or less. Obviously, diabatic processes do play an important role in the polar vortex even on short timescales.

**7. Comparison With Eulerian Exchange Estimates**

Our results form an interesting contrast with the findings of Wauben et al. [1997a]. They performed calculations with a global tracer transport model using the same ECMWF data as in the present study but for August–October of the years 1990–1993. Tracers were released on 1 August 1990–1993 on the 72.5-hPa isobaric level (θ ≈ 420 K), inside as well as outside the polar vortex. Exchange rates were then calculated for the second half of the integration period, i.e., from the second half of September to the end of October. Wauben et al. [1997a] calculated quasi-horizontal exchange using a fictitious vortex boundary at 61°S. (The vortex boundary was incorrectly stated to have been at 51°S by Wauben et al. [1997a] [Tuck and Proffitt, 1997; Wauben et al., 1997b].) They determined vertical exchange rates for tracers that entered the atmosphere below the 275-hPa isobaric level, which they designated as the “troposphere.”

The quasi-horizontal and vertical exchange rates of Wauben et al. [1997a] (their Table 1) can be compared with our results at 450 K. To allow such a comparison, additional 3-D trajectories were calculated for August–October 1993 and for August and September 1998 for air parcels that were initially located inside the vortex.

The results obtained for August–October 1993 at 450 K allow a direct comparison with the results of Wauben et al. [1997a]. In our case, very little cross-edge transport was observed for August (0.03%/week) and September (0.03%/week), and slightly more was observed for October (0.44%/week). The total contribution to cross-edge transport for the period August–October 1993 (0.50%/week) is much smaller than what was found by Wauben et al. [1997a] (1.19%/week) for the same period and year. In our case there were no air parcels that descended below 340 K for August–October, compared with 5.18%/week given by Wauben et al. [1997a] for tracers descending below 275 hPa (≈300 K).

For the months of August and September 1998 at 450 K, we found no quasi-horizontal transport across the vortex edge at all. Hence, in our case, the only contribution to cross-edge transport at 450 K stems from October 1998. Since there is no direct comparison possible with Wauben et al. [1997a], our results will be compared with their mean exchange rates. The mean quasi-horizontal exchange rate of Wauben et al. [1997a] (1.68%/week) is only slightly larger than ours (1.27%/week) at 450 K in October. In our runs for August–October 1998, very few parcels that started at 450 K descended below 340 K in August (0.00%/week), September (0.01%/week), and October (0.02%/week). Wauben et al. [1997a] found a mean rate of 0.81%/week for tracers descending below 275 hPa (≈300 K).

Wauben et al. [1997a] find an average radiative cooling rate for August–October 1993 of ~0.3 K/day in θ and state that their values are in good agreement with cooling rates calculated by detailed radiative transfer models [Hartmann et al., 1989b; Rosenfield et al., 1994]. Our calculations at 450 K show average cooling rates of 0.48 K/day in θ for August–October 1993 and 0.67 K/day for August–October 1998, which is in closer agreement with the values found by Manney et al. [1994] and recently Hicke et al. [1998]. Kawamoto and Shiotani [2000] calculated vertical descent rates in the Antarctic polar vortex from long-lived trace gas data provided by the Halogen Occultation Experiment and come to values of 1.1–1.9 km/month, which is in correspondence with our results (0.48 and 0.67 K/day and ≈1.2 and 1.3 km/month, respectively).

Much larger descent rates (1.75 K/day) were found by Proffitt et al. [1989], derived from aircraft measurements which are necessarily only available for limited domains in space and time. In this context it is interesting to note that in section 6 we also found large descent rates of 5 K/day or less for individual air parcels. Wauben et al. [1997a] may have underestimated vertical motions owing to their use of a relatively coarse horizontal resolution.

From the above context it is also interesting to note that despite the overestimation of the cross-edge transport by Wauben et al. [1997a], they found a clear year-to-year variability in the quasi-horizontal exchange rates, with larger exchange in so-called even years (1990 and 1992) and smaller rates in odd years (1991 and 1993). Wauben et al. [1997a] attributed this to fluctuations in planetary wave activity. Shindell et al. [1997] showed that the interannual variations in the severity of the Antarctic ozone hole in winter are driven by variations in tropospheric wave activity. In our case, smaller cross-edge exchange rates were also found for the odd year 1993 and larger rates for the even year 1998. Also, our results showed that the average cooling rate for 1993 was smaller than that for 1998, which is in agreement with recent observations of Kawamoto and Shiotani [2000], who identified an interannual oscillation in the vertical descent rates with smaller rates in the odd years (1993, 1995, and 1997) and larger rates in the even years (1992, 1994, and 1996). They gave dynamical evidence for the role of planetary waves in the interannual
variability of vertical descent rates and show that planetary wave activity is more severe in even years than in odd years.

8. Conclusions

[45] In this paper the permeability of the Antarctic polar vortex edge in late austral winter and spring has been investigated in a quantitative sense. We have provided new quantitative estimates on the amount of transport across the Antarctic polar vortex edge. Also, isentropic and 3-D trajectory results were compared with each other. The validity of the isentropic approximation for trajectories in the Antarctic vortex region has been investigated.

[46] The results can be summarized as follows:

1. For isentropic trajectories, very little quasi-horizontal exchange across the vortex edge was observed in August and September 1998 (<0.3%/week). The months October and November 1998 gave somewhat higher leakage rates, with a maximum value in October at 550 K of 1.95%/week. The latter was due to the more frequent occurrence of filamentation in this month. Two isentropic runs for August and October 1998 at 450 K showed no or only little transport (0.2%/week), respectively, of midlatitude air across the vortex edge into the vortex core.

2. The 3-D trajectory results for October 1998 showed maximum quasi-horizontal mass leakage rates at 550 K of 2.42%/week. Somewhat lower rates were found at 350 K (0.62%/week) and 450 K (1.27%/week).

3. Both isentropic and 3-D trajectory results showed little quasi-horizontal exchange. However, the 3-D trajectory results showed that diabatic effects are already important on a timescale of a couple of days. Therefore 3-D trajectory calculations will provide more accurate exchange rates than the isentropic ones.

4. A comparison was made between our 3-D trajectory results and the Eulerian model results of Wauben et al. [1997a]. The quasi-horizontal leakage rate of Wauben et al. [1997a] for August–October 1993 (1.19%/week) is significantly larger than our mass leakage rate (0.50%/week) at 450 K for the same period and year. The mean quasi-horizontal leakage rate of Wauben et al. [1997a] (1.68%/week) was only slightly larger than our value at 450 K (1.27%/week) for August–October 1998. We found average diabatic cooling rates of 0.48 and 0.67 K/day in θ for August–October 1993 and 1998, respectively, which are in good agreement with recently reported values in the literature. The average value of 0.3 K/day of Wauben et al. [1997a] for the same months is probably too low as a consequence of their coarse model resolution.

5. Larger quasi-horizontal exchange rates and diabatic cooling rates were found for the even year 1998 than for the odd year 1993. These results support observations in recent literature concerning the interannual variability of the permeability of the polar vortex.

[47] Overall, our results confirm that the Antarctic polar vortex edge is highly impermeable in late austral winter and spring. This is also the season when major depletion of ozone occurs within the polar vortex. The modeled and observed ozone chemical loss rates in the Antarctic ozone hole reported by other authors [e.g. MacKenzie et al., 1996; Ricaud et al., 1998; Solomon, 1999] are on average of the order of 1.0–2.0%/day, which is much higher than the exchange rates in our study. Hence our results support the “containment vessel hypothesis” in contrast to the “flowing processor” hypothesis, which assumes that dynamical and chemical timescales are approximately of the same order of magnitude.

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