Climatology of large-scale isentropic mixing in the Arctic winter stratosphere from analyzed winds

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Abstract. Dynamic isolation of the winter Arctic circumpolar vortex is studied using analyzed winds derived from geopotential height fields. Isentropic trajectories are calculated for ensembles of particles initialized on uniform latitude-longitude grids. Transport across isolines of Ertel potential vorticity (PV) is used to characterize the mixing processes of ejection of vortex air and entrainment of midlatitude air into the vortex. During January and February a barrier to mixing, where exchange of air is inhibited, typically forms near the vortex boundary. At 450 K, transport across the barrier is predominantly in the form of thin filaments of particles ejected from the vortex. These filaments tend to wrap around the vortex, creating a layered structure of vortex and midlatitude air at the vortex edge. Near or total splits of the vortex into two or more distinct vortices are quite common based on these trajectory calculations. Significant entrainment deep into the vortex is rare and results from only a limited number of the splitting events. During December and March the mixing barrier is less evident due to nonconservative factors during the spin-up and breakdown of the vortex, respectively. In December both ejection and entrainment are only weakly inhibited by the mixing barrier. Exchange in March is dominated by ejection of air from the vortex.

Introduction

The basic mechanisms responsible for the formation of the Antarctic ozone hole are now fairly well understood. Heterogeneous chemical reactions occurring on polar stratospheric clouds (PSCs) cause rapid ozone loss in the stratosphere over Antarctica. The essential ingredients for the ozone loss are cold temperatures, which produce the PSCs, and sunlight, which drives the photochemical reactions. These conditions are satisfied within the Antarctic polar vortex during austral spring because the cold polar vortex persists beyond the end of the polar night. Isolation of the polar vortex is also important, since replenishment of depleted ozone by transport would mitigate the ozone loss.

The degree of isolation of the Antarctic polar vortex has been controversial. Based on Airborne Antarctic Ozone Expedition (AAOE) data, Tuck [1989] and Proffitt et al. [1989] have argued that the vortex is not isolated, but acts as a “flowing processor,” entraining high-ozone extratropical air in response to radiative cooling and subsidence within the vortex. A contrasting picture developed from theoretical arguments and modeling experiments by Jackes and McIntyre [1987], views the polar vortex as an isolated “containment vessel” [McIntyre, 1989]. Alternative analyses of AAOE data by Hartmann et al. [1989] and Schoeberl et al. [1989, 1992] indicate the Antarctic vortex is well isolated. Radiative transfer calculations by Rosenfield [1992] also suggest that radiative cooling rates within the vortex are small, so subsidence and entrainment are weak.

Recent Lagrangian and semi-Lagrangian transport calculations by Bowman [1993] and Chen et al. [1994] using analyzed winds give further support for an isolated Antarctic polar vortex, at least at higher levels. In fact, as originally suggested by McKenna et al. [1989] and Podolske et al. [1989], the degree of isolation appears to be altitude dependent. Bowman found that exchange at or above the 450 K isentropic surface was rare during the period of peak ozone destruction. The exchange that was observed consisted almost entirely of a few well-defined events in which filaments were ejected by the vortex to midlatitudes. This behavior can be observed in the total ozone as well [Bowman and Mangus, 1993]. No evidence for significant entrainment into the Antarctic vortex was observed. At lower levels (below 425 K), however, there is significantly more exchange of air between the interior and exterior of the Antarctic polar vortex.

The current absence of a well-defined ozone hole in the Arctic stratosphere is a distinct contrast to the Antarctic. The fact that the Arctic vortex warms much earlier than the Antarctic undoubtedly plays a major role in creating the differences between the hemispheres: by the time the polar night ends in the Arctic, the vortex is too warm to support PSCs. Nevertheless, evidence of perturbed ozone chemistry (CIO in particular) is found in the Arctic polar vortex [Pahey et al., 1990; Brune et al., 1990]. Tuck et al. [1992] and Proffitt et al. [1990] have analyzed data from the Airborne Arctic Stratospheric Experiment (AASE) and claim that the Arctic vortex also behaves like a “flowing processor.” In fact, Proffitt et al. [1990] suggest that a large influx of ozone into the Arctic polar vortex prevents the formation of an Arctic ozone hole. Schoeberl et al. [1992], on the other hand, have also analyzed the AASE data and have concluded that the vortex is relatively well isolated.

Trajectory calculations have been carried out to examine the isolation issue in the Arctic. Plumb et al. [1994] analyzed the 1991-1992 Arctic winter season using the technique of contour advection with surgery (CAS) to produce very high-resolution estimates of advection processes. They found evidence for three possible events of intrusion of midlatitude air into the vortex on the 450 K isentropic surface during that time period. These
events are associated with major disturbances leading to extreme
eridng or a splitting of the vortex. Their qualified estimate of
the amount of air involved in these intrusions is of the order of a
few percent. This is in agreement with high-resolution
barotropic simulations by Polvani and Plumb [1992]. However,
Plumb et al. [1994] questioned the validity of comparing the
model study to the highly disturbed vortex conditions observed
in their CAS experiments.

There is general agreement that air is drawn out of the Arctic
vortex in the form of filaments; however, the fate of these
filaments is still the subject of active research. Waugh et al.
[1994] and Waugh and Plumb [1994] have used the CAS
technique to demonstrate the formation of filaments by
wavebreaking events during the winter of 1991-1992. They
found that at 450 K, wave breaking produces thin filaments
which tend to wrap around the vortex edge forming a narrow
band of interleaved layers of vortex and midlatitude air.
Furthermore, these filaments did not "roll up" into blobs of
vorticity. This led Waugh et al. [1994] to question the claim by
Tuck et al. [1992] that evidence for such blobs of recent vortex
air exists in the European Centre for Medium-Range Weather
Forecasts (ECMWF) analyses.

To date, research on Arctic stratospheric mixing has
emphasized detailed analysis of specific events, primarily from
the AASE period. It is important to determine whether these
events are representative of the Arctic vortex or are anomalous.
To that end, a climatology of mixing would be useful. In this
study, mixing is examined by using 14 winter seasons of
analyzed winds to compute isentropic tracer trajectories.
Diagnostics such as transport across isopleths of Ertel potential
vorticity (PV) and observation of the evolution of the trajectories
themselves are used to characterize the mixing processes of
ejection of vortex air and entrainment of midlatitude air into the
vortex. The importance of these two exchange processes to the
dynamics of the Arctic polar vortex is determined for the years
studied. A related question addressed here is whether a barrier to
mixing exists in the Arctic as is found at the vortex edge in the
Antarctic [Bowman, 1993]. The period of interest is the winter
months from December through March. In early December the
jet is accelerating to winter velocities, and vorticity values are
still relatively low. By the end of March the jet has decelerated
again to the point where the vortex breaks down. Thus, the
period under investigation covers the life cycle of the winter
vortex.

Data

The data set for this study, developed by Randel [1987], is a
compilation of daily (1200 UT), global, geopotential heights from
the Climate Analysis Center stratospheric analysis (70-0.4 mbar)
and the National Meteorological Center (NMC)
troposphere/lower stratospheric analysis (1000-100 mbar)
transformed the gridded NMC analyses to zonal Fourier
components, through wavenumber 12, on a 40-point Gaussian
grid. Bad or missing data have been replaced by interpolated
values. More detailed information on the data set can be found in
Randel [1987] and Trenberth and Olson [1987].

Methods

Temperatures and Winds

Temperatures and winds are computed as in Randel [1987].
The procedure will be briefly outlined here. Temperatures are
determined by assuming hydrostatic balance. Winds are derived
from geopotential heights using the gradient wind equation to
determine zonal-mean winds and the linear balanced wind
equations for waves 1-12. Geostrophic winds are used if the
linear balance equation becomes singular. Winds are
transformed to a global Gaussian grid with 5° longitudinal
resolution and ~4.5° meridional resolution. The interpolation to
isentropic surfaces is linear in log θ.

Ertel potential vorticity on isentropic surfaces is calculated
from the McIntyre and Palmer [1983] approximation:

\[ Q = -\varphi \frac{\partial \theta}{\partial \varphi} (\zeta + f) \tag{1} \]

where

\[ \zeta = \frac{1}{a \cos \phi} \left( \frac{\partial v}{\partial \lambda} - \frac{\partial (\cos \phi \cdot u)}{\partial \phi} \right) \tag{2} \]

The differentiated terms are computed using techniques
similar to those discussed above. Only zonal wavenumbers 0
through 6 are included in the PV calculations to reduce the noise
introduced by the multiple finite differencing. All values of PV
are given in units of 10^{-5} K m^2 s^{-1} kg^{-1}. PV values at particle
locations are calculated by linear interpolation in space and time.
It is important to note that many small-scale features of the
vorticity field are not present in this analysis, leading to
significant uncertainty in the PV values for individual particles.
Unfortunately, this issue cannot be addressed in the context of
the current study.

Trajectories

Isentropic Lagrangian trajectories are computed using a
fourth order Runge-Kutta scheme [Bowman 1993]. The daily,

![Figure 1. Area fluxes across isopleths of Ertel potential vorticity (PV) on the 450 K isentropic surface for December 1990. Fluxes indicate the percent of the initial vortex area transported across each PV contour between December 1 and 31. Solid curves represent the total area flux. Dashed curves indicate the component of the flux toward higher values of PV, while the dotted curves give the flux toward lower PV. Vertical line at 2.4 PV units indicates the mixing barrier Qp. PV values are in units of 10^{-5} K m^2 s^{-1} kg^{-1}.](image-url)
Figure 2. Exchange fluxes across PV isopleths on the 450 K isentropic surface for December 1978-1991. Dashed curves indicate the flux of entrained air (air which crosses $Q_e$ toward higher values of PV). Dotted curves give the flux of ejected air (air which crosses $Q_e$ toward lower values of PV). Vertical line at 2.4 PV units indicates the mixing barrier $Q_e$. PV values are in units of $10^{-5}$ K m$^2$ s$^{-1}$ kg$^{-1}$.
gridded velocity components are interpolated linearly in space and time to the particle locations. Near the pole, velocities are transformed to a local Cartesian coordinate system to prevent difficulties due to the singularity at the pole.

Trajectories are computed on the 450 K isentropic surfaces in the lower stratosphere. Particles are initialized on both 64 x 64 and 128 x 128 uniform longitude-latitude grids. Calculations initialized with an equal-area grid (particle density proportional to cosine of latitude) are examined to further test the sensitivity of the integrations to particle resolution. The initial latitude range for all grids is from 13° N to 88° N. The particle trajectories are integrated for 30 days beginning on December 1, January 1, February 1, and March 1. For January 1981 it was necessary to begin the integration on December 30, 1980, to avoid initializing with a highly distorted vortex. Integrating through the distorted event indicated a much lower degree of mixing than initializing during the event. This initialization problem is rather common in the northern hemisphere and will be discussed further in following sections. The January 1986 calculation was initialized on the third day of the month and integrated for only 28 days to avoid apparent errors in the analyzed velocity fields during the first 2 days of the month.

The precision of the numerical integration scheme has been evaluated by Bowman [1993]. He suggested that numerical errors in the trajectory calculations are at least an order of magnitude less than the uncertainties in the derived winds. He concluded that errors in the trajectories are dominated by errors in the winds, not truncation error due to the numerical scheme.

**Diagnostic Quantities**

Bowman [1993] found that in the Antarctic it is possible to define the boundary between the interior and exterior of the vortex using total column ozone maps from the Total Ozone Mapping Spectrometer (TOMS). Defining a vortex boundary in the northern hemisphere is more difficult for several reasons. TOMS data are less useful, since much of the interesting vortex dynamics occur within the polar night, where ozone measurements are not available. The Arctic vortex is also typically much more distorted than the Antarctic, which suggests that there might be considerably more mixing occurring. Therefore, the approach taken here is to define mixing in terms of the transport of air parcels to higher or lower values of potential vorticity. The transport statistics are then examined for the presence or absence of a barrier to mixing. Specifically, we ask, Is there an isopleth of potential vorticity on an isentropic surface across which there is little or no exchange of air? Thus, mixing is defined based on the Lagrangian transport itself, rather than in relation to a necessarily arbitrary vortex boundary.

The transport statistics are presented as area-weighted fluxes of particles across PV contours during a month. The transport across PV contours must be a result of nonconservative effects, that is, mixing or diabatic processes. Only the initial and final PV values are used in this comparison to minimize the effects of frequent reversible displacements experienced by the particles. The robustness of this approach was confirmed by using 3-day averages for the initial and final PV values. No qualitative or significant quantitative differences were found between these two approaches. The amount of air represented by the particle flux across PV contours is referred to as the total area flux. The total flux can be divided into two component fluxes: the area flux represented by particles which cross each PV contour moving to higher values of PV and the flux of air towards lower PV. A mixing barrier exists if there is a distinct minimum in the total area flux for some PV value. When there is no barrier indicated by the total particle flux, a minimum may still exist individually in either the flux to lower or higher PV. That is, particles may be ejected from the vortex in a particular month but not entrained, or vice versa. In these cases, only one component exhibits a barrier to mixing. Occasionally in December and March none of the flux curves exhibit a clear mixing barrier. In such cases one is chosen.
Figure 4. Area flux curves, as in Figure 1, for February 1984 on the 450 K isentropic surface. Fluxes represent changes in particle PV between February 1 and March 2. The mixing barrier is located at 2.9 PV units.

somewhat arbitrarily by examining scatter plots of initial PV versus final PV. Once the mixing barrier has been selected, the PV at that point is given the symbol $Q_b$.

Applying the above definitions typically indicates a barrier to mixing on the equatorward edge of the region of maximum PV gradient. This is near the location of the conventional definition of the vortex edge. Because of this consistency and for ease of discussion, the mixing barrier is treated as if it were the vortex boundary. It is important to remember, however, that the mixing barrier is defined in terms of 30-day trajectory calculations and will not necessarily coincide with the vortex edge on any given day.

The mixing processes of most interest are those of entrainment of midlatitude air into the vortex and ejection of vortex air. Entrained air is comprised of those particles that move to higher PV and cross the mixing barrier at $Q_b$, while ejected air is the particles which move to lower PV and cross $Q_b$. All fluxes are normalized by the initial area of the vortex to provide a rough gauge of the mixing timescale for the vortex interior. (The inverse of the normalized flux at the vortex boundary is the mixing timescale in months.) How far the exchanged particles penetrate into their new domains can be ascertained by direct observation of the particle trajectories and through the entrainment and ejection flux curves.

Results

Thirty-day isentropic trajectory calculations are computed for the winter months of December 1978 through March of 1992 on the 430 K isentropic surface. This region of the lower stratosphere is where previous research dealing with ozone transport has been concentrated. Only results from experiments using the uniform 128 x 128 particle grid will be discussed. There are no discernible differences between these calculations and equal-area calculations with a similar total number of particles. The lower-resolution experiments also give essentially identical results.

Early Winter Cases

December of 1990 is, in a sense, an average example of the mixing observed during the early winter at 450 K in terms of the amount of air exchanged across the mixing barrier during the integration. The total and component fluxes for this month are plotted in Figure 1. Figure 2 shows the entrained and ejected fluxes during December for all years in the sample. The width of the entrainment and ejection curves provides a good measure of the dispersion of air parcels in the vicinity of the vortex boundary. The vertical line in this and all subsequent plot fluxes indicates the location of $Q_b$. There is a local minimum in the total flux (solid) curve at ~2.4 PV units. The amount of air losing PV (dotted curve) is relatively low at this point, and the amount of air gaining PV (dashed curve) reaches a local minimum. These curves suggest a change in the mixing properties in the region of the mixing barrier, although exchange is still high. Entrainment of air into the vortex, represented by the magnitude of the dashed curve at 2.4 PV units in Figure 1 or Figure 2, is approximately 47% of the initial vortex area, while ejected air, indicated by the dotted curve, amounts to 17% of the initial vortex sample.

How far the air parcels disperse when exchanged across the mixing barrier is also an important indicator of mixing. For example, it can be argued that exchanged air located near the vortex edge may not have irreversibly crossed $Q_b$ as compared to air that is more deeply mixed. The exchange flux curves in Figure 2 show the amount of air crossing $Q_b$ as well as the depth of penetration of that air. In the case of December of 1990 the ejection flux (dotted curve) drops off quickly in PV coordinates, while the entrainment flux (dashed curve) indicates mixing well into the vortex. It is important to remember that the vortex interior is a region of sharp PV gradients, so entrainment extending 1 PV unit into the vortex, for example, is entirely different in physical coordinates than ejection 1 PV unit into mid-latitudes. However, it is still apparent that significant mixing into the vortex has occurred.

Further evidence for the degree of mixing can be seen in the initial and final locations of the exchanged particles for the integration. In Figure 3 the locations of three sets of particles are overlaid on the PV analysis for December 1 and 31. 1990. Small dots represent vortex particles that start inside the vortex on December 1 and remain inside the vortex on December 31. These are included to show the basic structure of the vortex. The ejected particles are indicated by crosses and the entrained particles by triangles. These are the particles that have crossed the mixing barrier (heavy contour at 2.4 PV units) when comparing the first and last days of the integration. The ejected particles are primarily located near the mixing barrier on December 1. Many of the entrained particles are also concentrated at the vortex edge. In particular, there is a large concentration in the region of a ridge located at the Greenwich meridian near the pole. This is an important feature of entrainment events that will be discussed later. On December 31 the ejected particles have formed a filament which is in the process of wrapping around the vortex. The entrained particles are predominantly found in a thick band at the vortex edge, but some have penetrated quite deeply into the vortex core.

Midwinter Ejection Cases

Some air is ejected from the edge of the vortex during even the most isolated months. February 1984 is an example of extensive ejection and erosion of the vortex with little entrainment (compare the various fluxes across the mixing barrier located at ~2.9 PV units in Figure 4 and Figure 5). The structure of the ejection events during this example is typical of the 450 K level. Note in Figure 6 the near total lack of entrained particles
Figure 5. Exchange flux curves, as in Figure 2, for February 1979-1992 on the 450 K isentropic surface. Fluxes represent changes in particle PV between February 1 and March 3 (March 2 for leap years).
Figure 6. Locations of vortex and exchange particles plotted with the PV analysis, as in Figure 3, on February 1, 1984, February 11, 1984, February 16, 1984, February 21, 1984, February 26, 1984, and March 2, 1984. The heavy line is the mixing barrier at 2.9 PV units. Trajectories are calculated on the 450 K isentropic surface.
(triangles) and the large number of ejected particles (crosses) located throughout the vortex on February 1 (5% and 43% of the initial vortex air, respectively). Early in the calculation most of the ejected particles are found in a small vortex fragment that partially splits from the main vortex for several days (February 11 and 16). As this blob is drawn back into the vortex, it shears out into two long, thin filaments that are wrapped and folded around much of the vortex, creating the layered structure seen on February 26 and 31.

**Midwinter Entrainment Cases**

Clear cases of significant entrainment during the midwinter months of January and February are less common. Some months appear to show large entrainment, but it is actually due to limitations of the low resolution PV analyses on the first or last days of the integration period, which are used to classify the particles. When the vortex is highly distorted on the first day of the integration, particles that are actually inside the vortex can be erroneously classified as outside. These “outside” particles are usually quickly entrained into the vortex, suggesting that they may have been incorrectly labeled as extravortex air. This can be tested by lengthening the trajectory calculations by beginning a day or two earlier (not later, which would simply avoid the “entrainment” event). When the integration is initialized earlier, typically under less disturbed conditions, these particles are usually diagnosed as inside the vortex. The particles are temporarily expelled from the vortex in a coherent blob, then reabsorbed into the vortex within a few days. Similar considerations apply at the end of the month. The reversibility of entrainment can be tested by extending the integrations several more days to see whether entrained particles remain in the vortex and mix with the vortex air or are expelled back into the sur

remain near the vortex edge until the last day of the integration when a large tongue of entrained air can be seen penetrating deep into one portion of the vortex (Figure 11). There is some indication that diabatic changes in the vortex may be important in this calculation. Future work is planned to clarify this question further.

**Vortex Breakdown**

The breakdown occurs during the period from late February through early April. March 1983 is a typical breakdown event for 450 K. The exchange flux curves for March are shown in Figure 12. The entrainment curve goes rapidly to 0 by 2.5 PV units, but there is no barrier indicated by the ejection curve. On March 1, 1983, the vortex is still well-developed (Figure 13). In this case, over 77% of the vortex air in this figure is ejected by the end of the calculation. The entrained group is small, representing 15% of the initial vortex air. By March 31 the vortex has weakened significantly, and the vortex particles are scattered over much of the hemisphere. Entrained particles have also been mixed throughout much of the vortex. This vortex breakdown sequence in the Arctic is similar to the Antarctic example shown in Figure 11 of Bowman [1993].

**Discussion**

It is now possible to discuss the climatology of mixing in the Arctic winter vortex based on all 14 years of trajectory calculations.

**January and February**

The Arctic vortex is most isolated during the midwinter months of January and February. A summary of exchange across the mixing barriers is given in Figure 14. Black bars give the amount of air entrained across Q, while the white bars indicate ejection. On average, the entrainment is less than the ejection, especially in February. In half of the midwinter calculations,
Figure 8. Locations of vortex and exchange particles plotted with the PV analysis, as in Figure 3, on February 1, 1989, February 11, 1989, February 21, 1989, and March 3, 1989. The heavy line is the mixing barrier at 2.0 PV units. Trajectories are calculated on the 450 K isentropic surface.

entrainment is less than 20% of the initial vortex sample. A weaker barrier (20% to 30% entrainment) is found in seven additional examples (25% of the months). During the remaining years, large numbers of particles cross the mixing barrier, but predominantly remain at the vortex edge, as in January of 1988. With the exceptions of February 1989 and January 1979, cases of deep entrainment seen in the exchange curves in Figures 5 and 10 (e.g., January 1984 and January 1991) are the result of diagnostic errors.

The weakness or lack of a barrier to total mixing in January and February is primarily due to a lack of barriers to ejection. A strong barrier to ejection (ejection of less than 20% of the vortex air) occurs in only one quarter of the cases. Otherwise, the barrier to ejection is weak (5 cases as defined above) or nonexistent. Finally, it should be noted that even in the most isolated case (February 1989), there is still a total transport across the barrier of the order of 30%.

March and December

Mixing in December and March is strongly influenced by nonconservative processes involved with the spin-up and
Figure 10. Exchange flux curves, as in Figure 2, for January 1979-1992 on the 450 K isentropic surface. Fluxes represent changes in particle PV between January 1 and 31 except for 1981 (December 30, 1980, and January 31) and 1986 (January 3 and 31).
breakdown of the vortex. Because of this, mixing barriers are weaker and somewhat ambiguous during these periods. The summary of transport across the mixing barriers for December and March is also shown in Figure 14.

As the jet accelerates in the northern hemisphere in December, some particles near the vortex edge appear to be entrained across the mixing barrier. Much of this entrainment may be due to nonconservative changes in the PV. In other cases the vortex is not well organized at the beginning of December, and actual entrainment occurs as the vortex develops. The result is that entrainment is less than 30% in only three cases. There are five cases of weak ejection barriers. Exchange remains large during the other December calculations.

In March the situation is essentially the reverse of December. There is evidence for a weak ejection barrier (ejection less than 30%) only during 1982 and 1992 in Figure 14. In the other cases, mixing is completely dominated by ejection to midlatitudes. During most years, entrainment is less than 15%. In only one case does entrainment surpass the weak barrier criteria. Lack of entrainment is predominantly due to weakening of the vortex during this period. That is, particles are not transported to higher PV values because the high PV values are disappearing.

Determining the reality and significance of exchange events is often difficult and involves a degree of subjectivity. In particular, the degree of entrainment is difficult to ascertain because of the sensitivity of this process to errors in the PV analyses. There are three primary factors which can lead to the misdiagnosis of exchange. The first two, errors in the PV analysis and reversible exchange events, have already been discussed and are likely responsible for a portion of the mixing in each calculation. The third process is large-scale diabatic changes in the PV field with timescales less than a month, typically in December and March. In such situations, PV contours are not good approximations of material lines, and transport across these contours does not necessarily represent material exchange. Because of these factors, the mixing indicated by these calculations should be considered as an upper bound to large-scale isentropic mixing. Unresolved scales in the observed wind fields undoubtedly increase mixing, but a quantitative discussion of this issue awaits improvements in data resolution.

Summary

The climatological average entrainment and ejection across the mixing barrier for each month are given in Table 1. The trend over the winter season is apparent. Entrainment is large (49%) during the vortex spin-up period in December then rapidly decreases to 15% by the end of the season. Ejection, on the other hand, is initially moderate at 29% and increases only slowly until the vortex breakdown in March, when it becomes very large. The results suggest mixing times for the vortex in midwinter of the order of 2 to 3 months.

Conclusions

Results from isentropic trajectory calculations using analyzed winds indicate the presence of a barrier to entrainment and/or ejection during the midwinter months of January and February for the winter seasons of 1978-1979 through 1991-1992. This barrier typically forms on the equatorward edge of the region of maximum PV gradient in close proximity to the vortex edge. Entrainment is more consistently inhibited by the barrier than ejection during this portion of the winter cycle. Weaker barriers are found during the months of December and March, when rapid large-scale diabatic changes in the PV field combine with mixing processes to influence changes in particle PV, making it difficult to quantify mixing. As a general rule, entrainment dominates as the vortex strengthens in early winter, while in the spring the weakening vortex ejects large numbers of particles that are rapidly mixed throughout the hemisphere.

These results correspond to the preponderance of evidence for the Antarctic vortex [Hartmann et al., 1989; Schoebri et al., 1989, 1992; Bowman, 1993; Chen et al., 1994]. It is difficult to
Figure 12. Exchange flux curves, as in Figure 2, for March 1979-1992 on the 450 K isentropic surface. Fluxes represent changes in particle PV between March 1 and 31.
Figure 13. Locations of vortex and exchange particles plotted with the PV analysis, as in Figure 3, on March 1, 1983 and March 31, 1983. The heavy line is the mixing barrier at 2.5 PV units. Trajectories are calculated on the 450 K isentropic surface.

make a detailed comparison between the hemispheres here because of the poor horizontal resolution of the PV analyses compared to the TOMS data and the sensitivity of mixing to initial conditions in the Arctic. However, filamenting of the vortex edge by breaking waves appears to be a common and robust characteristic of both hemispheres [Bowman and Mangus, 1993; Waugh et al., 1994]. The mixing time for the Arctic vortex is of the order of the length of the winter season or somewhat longer at these levels. Near total isolation of the vortex does occur in the Antarctic region [Bowman 1993], but not the Arctic.

Figure 14. Summary of the exchange across the mixing barrier for all months in the study. Black bars indicate entrainment as a percentage of the initial vortex air. White bars show ejection.
Table 1. Monthly Climatological Transport Across the Mixing Barriers

<table>
<thead>
<tr>
<th>Month</th>
<th>Entrainment*, %</th>
<th>Ejection*, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>49</td>
<td>29</td>
</tr>
<tr>
<td>January</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>February</td>
<td>19</td>
<td>40</td>
</tr>
<tr>
<td>March</td>
<td>15</td>
<td>65</td>
</tr>
</tbody>
</table>

* Values of entrainment and ejection are average values of the respective time series presented in Figure 14 for each month.

Entrainment appears to be more common in the Arctic, but is predominantly limited to the vortex edge. Since ejection well into midlatitudes is observed, the lack of deep entrainment cannot be attributed solely to problems with the wind data. Rather, it must be considered a real feature of the Arctic vortex.

Waugh et al. [1994] found that CAS experiments performed at 450 K produced thin filaments of ejected vortex air rather than thick tongues. Thicker filaments are characteristic of earlier observational studies of the middle stratosphere by McIntyre and Palmer [1983, 1984] among others. Differences in the character of the flow in the lower and middle stratosphere were cited by Waugh et al. [1994] as an explanation for differences in filament structure. The results of this study are in close agreement with those of Waugh and his colleagues. Vortex air is also found to be ejected in the form of thin filaments which either wrap around the vortex, creating a layered structure of vortex and midlatitude air at the vortex edge, or separate from the vortex to mix well into the midlatitudes.

Entrainment events have been linked to either splitting of the vortex during sudden warmings or extreme ridging of the vortex edge due to underlying blocking in the troposphere [Plumb et al., 1994]. As postulated by Plumb in the same paper, the splitting events are common in the Arctic. Near or total splits of the vortex, as seen in the PV analysis and particle trajectories (not necessarily in geopotential height), occur routinely in January and February. The winter season of 1985 was particularly disturbed. The vortex was split into as many as three major fragments for nearly the entire period from December through February, yet little entrainment is observed after December. Entrainment appears to be limited to only a portion of the vortex splitting events, suggesting that such events are necessary but not sufficient conditions for the occurrence of deep entrainment. There are still many unanswered questions as to the dynamical factors influencing both entrainment and ejection. The approach taken in this study is fundamentally kinematic and cannot address these. Work on the dynamics of mixing is planned to try to resolve these issues. It is important to note that the 1991-1992 winter season that has been so extensively studied [e.g., Plumb et al., 1994; Waugh et al., 1994] is a rather normal year in terms of mixing and the degree of perturbation experienced by the vortex.

The question of chemical processes in the Arctic vortex is not specifically addressed in this study. It is possible, though, to postulate some reasons for the presence of the perturbed chemistry in the Arctic observed by Brune et al. [1990] and Fahey et al. [1990]. As stated in the introduction, ozone chemistry depends on the simultaneous presence of cold temperatures (for PSC formation) and sunlight for photodissociation. These criteria are not met at the end of the polar night due to warm temperatures. During the peak of winter, when PSCs are present, the vortex is distorted and displaced from the pole sufficiently that portions frequently occupy sunlit regions. This is particularly true in February when the polar night region is small. In addition, ejected filaments can be large and remain coherent for tens of days as they circulate around the midlatitudes. Both situations would create the opportunity for ozone destruction to occur in these midlatitude regions (where northern hemisphere ozone loss is observed).

Acknowledgments. Our thanks to W. Randel for allowing us to use his compilation of the NMC stratospheric analyses and his codes for the balanced wind calculations. Thanks to Darryn Waugh, Donal O’Sullivan, and an anonymous reviewer for helpful suggestions. One author (S.P.D.) was partially supported in this work by a NASA Graduate Student Researcher Program (GSRP) Fellowship through the Goddard Space Flight Center. This work was funded by NASA grant NAGW-3446 to the Texas A&M University.

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(Received December 28, 1993; revised July 25, 1994; accepted July 25, 1994.)