Ozone Loss Inside the Northern Polar Vortex During the 1991-1992 Winter


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ABSTRACT

Measurements made in the outer ring of the northern polar vortex from October 1991 through March 1992 reveal an altitude dependent change in ozone, with decrease at the bottom of the vortex and substantial increase at the highest altitudes accessible. The increase is the result of ozone rich air entering the vortex, and the decrease reflects ozone loss accumulated after descent through high concentrations of reactive chlorine. The depleted air that is released out of the bottom of the vortex is sufficient to significantly reduce column ozone at mid-latitudes.

During the Antarctic late winter and early spring, the decrease in ozone (O₃) due to anthropogenic chemical loss is sufficient to overwhelm the naturally occurring increase due to transport of O₃ rich air from lower latitudes (1). The dearth of O₃ is obvious in column measurements and has been called an O₃ hole. The seasonal onset of the chemical O₃ loss is not as easily observed since it is masked by increases due to transport (2, 3). In the Northern Hemisphere vortex, the period of significant loss is relatively short, due to the warmer, less stable Arctic vortex dissipating by late winter. In this case, a weaker loss is overwhelmed by a stronger seasonal increase due to transport (4, 5). Although an O₃ hole does not form, the Arctic vortex contains less O₃ than normal.

Concern over O₃ loss recently intensified with reports of significant column O₃ decrease over the heavily populated mid-latitudes in all seasons and both hemispheres (6). These mid-latitude changes are not completely understood (7), but
it appears that the decreases are due to chemistry occurring at mid-latitudes (8) and transport of \( O_3 \), poor air from polar to mid-latitudes (2, 4, 9, 10).

In 1991-1992 the second NASA-NOAA Airborne Arctic Stratospheric Expedition (AASE II) was undertaken to investigate the cause of the mid-latitude \( O_3 \) decreases and to assess the possibility of an ozone hole occurring in the Northern Hemisphere during this century. Daytime measurements of atmospheric chemical and dynamical components were made simultaneously at high latitudes from October through March. Three flights out of Fairbanks, Alaska (65° N) from 6-12 October flew to or near the pole, followed by 17 flights out of Bangor, Maine (45° N), from 12 December through 20 March, of which 8 penetrated the polar vortex.

In this report we use AASE II measurements from instruments (11) aboard the NASA ER-2 high altitude aircraft to evaluate offsetting effects of chemical \( O_3 \) destruction and transport by analyzing the evolution of chemical species in the outer ring of the winter vortex (12). We focus on the vertical distribution of change in \( O_3 \), the causes of the observed change, and whether loss of \( O_3 \) in the polar vortex can account for the winter mid-latitude \( O_3 \) decrease.

\( O_3 \) is naturally produced and destroyed through photochemistry that occurs in the stratosphere. Before about 1980, the minimum of sunlight that occurs during polar winter was insufficient to trigger substantial \( O_3 \) production or destruction (13), but with our present elevated concentrations of stratospheric chlorine, rapid losses can occur.

To distinguish change in \( O_3 \) (mixing ratio by volume) due to transport from loss due to chemistry, we adopt a method using an empirically derived functional relation between a conserved tracer, nitrous oxide (\( N_2O \)) (14), and \( O_3 \) (4, 15, 16). The function is used as a reference for \( O_3 \) and represents simultaneous measurements of \( O_3 \) and \( N_2O \) before wintertime loss has occurred. Because \( N_2O \) has a lifetime of years, changes from the reference reflect recent changes in \( O_3 \). The difference between a measured value of \( O_3 \) and a reference value calculated from the simultaneously measured \( N_2O \) represents the wintertime loss (17).

Daily meteorological and chemical data show that the vortex perimeter wobbled considerably during AASE II, so identifying its location along each flight leg is critical to our analysis of the vortex interior. The boundary of the polar vortex has been previously defined in a variety of ways, including (i) the region of very high chlorine monoxide (\( C_1O \)) (18) (ii) the peak in the wind speed (4) (iii) threshold values in potential vorticity (PV) (10, 19) or its maximum gradient (20) and (iv) gradients in \( N_2O \) and water vapor (21). Elevated concentrations of reactive chlorine were usually found in the polar vortex (22) and indicated significant \( O_3 \) destruction was underway. Concentrations of the reactive chlorine species \( C_1O \) were very high on every flight that penetrated the polar jet from December through March (23), so we defined the vortex boundary to exclude all data with \( C_1O < 150 \text{ pptv} \) from the vortex interior and to exclude data clearly outside the dynamical boundary (Table 1). Our boundaries are conservative in the sense that some parcels experiencing loss (high \( C_1O \)) lie slightly outside the boundary, and no air from outside the dynamical vortex is included within the boundary.

For a vertical coordinate, we used potential temperature (a measure of
entropy and denoted by $\Theta$, which increases with altitude and is calculated from measured temperature and pressure (24). In the absence of wave induced mixing and diabatic cooling, air parcels will stay on constant $\Theta$ (isentropic) surfaces. Although altitude is more intuitive as a vertical coordinate, it is less useful at high latitudes during the winter months, particularly when an understanding of transport is required. In our coordinate system, diabatic cooling is equivalent to descent. We define $\Theta = 410 \pm 10$ K as the bottom of the vortex (4), suggesting relatively free exchange of air with lower latitudes at and below that level (25).

$O_3$ increased inside the vortex from October through March by about 1000 ppbv (part per billion by volume) at all values of $\Theta$ (Fig. 1A). However, the steady (isentropic temporal) increase was interrupted by a small decrease in $O_3$ of about 250 ppbv from December into January below 460 K. From late January through March the $O_3$ mixing ratios were nearly constant below 460 K, but continued to increase above that level. These increases are due to $O_3$-rich air that has been transported to high latitudes. The result is a 50% increase in the column $O_3$ between 15 and 20 km from October through mid February.

Over the same period and above 460 K, $O_3$ also increased substantially relative to $N_2O$, but $O_3$ significantly decreased below that level (Fig. 1B). These changes in $O_3$ for a constant $N_2O$ are evident comparing the raw data of October with February data (Fig. 2A). The greatest $O_3$ decrease was found below the bottom of the vortex during the months of January and February (Fig. 2B).

A quadratic fit (26) to the October $O_3-N_2O$ data is given by

$$O_3^{OCT}(ppbv) = 1682 + 18.62X N_2O(ppbv) - 0.0798X (N_2O(ppbv))^2$$

with $N_2O > 130$ ppbv and $\sigma = 172$ ppbv

and we use this function as the October reference (27). We denote measured mixing ratios of $O_3$ by $O_3^M$, thus, change in $O_3$ since the October reference period can be simply viewed as statistical change in the quantity $O_3^M - O_3^{OCT}$. There are three types of air parcels we distinguish by comparison with the October reference:

(i) type I: $O_3^M - O_3^{OCT} > 2\sigma$ (increased $O_3$)

(ii) type D: $O_3^M - O_3^{OCT} < -2\sigma$ (decreased $O_3$)

(iii) type 0: $-2\sigma < (O_3^M - O_3^{OCT}) < 2\sigma$ (unchanged $O_3$).

Whether a parcel is of type I, 0, or D depends upon its $O_3$ content relative to $N_2O$ in October (the parcel’s initial 0,- $N_2O$ relation) and the photochemical production and loss of $O_3$ in that parcel since October.

Parcels of type I have increased $O_3$ that must be attributed to photochemical production or to an initial 0,- $N_2O$ relation that differs from the October data, i.e. air that was not sampled in October. $O_3$ production is not responsible for the increase observed, because average production rates during the winter are apparently much less than the measured rate of increase (28). However, if during October, parcels of type I are above ER-2 altitudes, then descent (decreasing $\Theta$) in
the vortex during the following months might contribute to the increase. N\textsubscript{2}O generally decreases with increasing $\Theta$, and N\textsubscript{2}O > 130 ppbv would not be expected to persist above ER-2 altitudes. As N\textsubscript{2}O decreases, O\textsubscript{3} is expected to increase at these $\Theta$'s. Simultaneous measurements of N\textsubscript{2}O and O\textsubscript{3} at higher $\Theta$'s have never been made at high latitudes in October, so no direct verification is available. In lieu of these measurements, we used sonde data for October 1991 at five $\Theta$ levels from 530 K to 610 K for each of two high latitude stations, Resolute (75° N) and Alert (82° N) verifying the increase of O\textsubscript{3} with increasing $\Theta$. This sonde data along with ER-2 data allowed us to extend the O\textsubscript{3} - OCT reference to N\textsubscript{2}O mixing ratios of 50 ppbv and $\Theta = 610$ K (29) (Fig. 2C). This extended reference implies that neither descent in the vortex, nor mixing of higher altitude air (N\textsubscript{2}O < 130 ppbv) with air of type O can produce the increased O\textsubscript{3} in parcels of type I found in later months. An influx of air from outside the vortex is apparently the only source available for the increase.

To verify this we have compared the O\textsubscript{3} - N\textsubscript{2}O relation for parcels of type I with a linear fit to the December through March data from outside the vortex (30). The fit is given by

$$O_3^{\text{EXT}} (\text{ppbv}) = 7172 - 23.06 \times N_2O (\text{ppbv})$$

with N\textsubscript{2}O > 150 ppbv and $\sigma = 240$ ppbv

and agrees very well with the O\textsubscript{3} - N\textsubscript{2}O relation for parcels of type I (Fig. 2C). This suggests that the increase in O\textsubscript{3} is due to air that penetrated the vortex.

A confirmation of this result is provided by the January and February O\textsubscript{3} - N\textsubscript{2}O data. If the interior of the vortex were isolated from its exterior at some $\Theta$ level, two disjoint O\textsubscript{3} - N\textsubscript{2}O relations would develop as O\textsubscript{3} increased outside the vortex due to transport, and was chemically destroyed preferentially inside. However, we found that for $\Theta$'s accessible to the ER-2, the O\textsubscript{3} - N\textsubscript{2}O relations were practically indistinguishable over their common range of N\textsubscript{2}O (Fig. 2D). At the bottom of the vortex, with $\Theta < 420$K, air parcels are of type D, both inside and outside the boundary and appear as a single line. This is consistent with relatively free exchange of O\textsubscript{3} poor air latitudinally at and below the bottom of the vortex. At the highest flight levels, with $\Theta > 500$K, the parcels are practically all of type I. Although the two data sets still have identical overlap, they appear as two nearly intersecting lines. This is not consistent with free exchange across the boundary, but does indicate that lower latitude parcels have penetrated the vortex. Apparently, parcels with N\textsubscript{2}O of about 150 ppbv have recently entered at this level and still have their exterior character, while other parcels have apparently mixed with vortex air of lower N\textsubscript{2}O content. This has produced the line of vortex data characteristic of mixing (Fig. 2D). Although not shown in our figures, allisentropic levels above the bottom of the vortex were similar to the $\Theta > 500$K level, showing distinct somewhat linear data sets with common overlap. This indicates that air penetrated the vortex at all flight altitudes.

We found virtually no air parcels with N\textsubscript{2}O < 140 ppbv outside the vortex boundary (31), indicating that air deep inside the vortex with N\textsubscript{2}O < 140 ppbv did not escape the vortex and retain its identity in the process. This does not exclude
vortex peel-off (10) as a contributor of vortex edge material at mid-latitudes.

Parcels of type D contain less $O_3$ which must be attributed to photochemical loss or to an initial $O_3 \cdot N_2O$ relation below the $O_3$ reference. Diabatic cooling (descent) rather than diabatic heating dominated throughout the period, and descent inside the vortex without $O_3$ loss will increase rather than decrease $O_3$ relative to $N_2O$ (Fig. 1B). Air outside the vortex is rich in $O_3$ and cannot directly account for the decrease. We conclude that the dominant cause of the decrease in $O_3$ must be photochemical loss that has occurred during winter.

Why was $O_3$ constant at 460 K? Diabatic cooling was taking place, so air with enhanced $O_3$ must have descended through the 460 K isentrope. This should have increased $O_3$ relative to $N_2O$, so lack of change represents a close balance between the increase due to transport (including descent) and photochemical loss. Transport similarly masks $O_3$ at all levels throughout the outer vortex.

To quantify the offsetting effects of transport and photochemical loss, we calculated average daily loss rates, flight-by-flight, from December through March for air parcels of types 1, O, and D (Table 2). We assumed conservatively only 6 hours of daily solar exposure and restricted $N_2O$ to mixing ratios common to all three parcel types (Fig. 2C). A relatively weak $O_3$ loss began by mid-December (Fig. 3A). In early January, the rate of $O_3$ destruction increased substantially and was greatest in parcels of type L. By mid-January, the destruction rate was greatest for parcels of type O and D, although the mixing ratios of $ClO$ were comparable (32) (see Table 2). By mid-February, the $O_3$ destruction in type 1 parcels had decreased significantly, but remained relatively high for types O and D. This is because i) air parcels initially of type 1 lost $O_3$ and became parcel types O and D, and ii) relatively unprocessed air of type 1 (i.e. containing lower levels of reactive chlorine) had been transported into the vortex, and hence had a lower $O_3$ destruction rate.

Comparison of the calculated $O_3$ loss rates with the measured rates of $O_3$ change (Table 2) show the measured rates underestimate loss in all parcel types (Fig. 3A, B). Transport induced increases even dominated the significant loss rates calculated at the highest levels.

Although much is understood about high latitude $O_3$ photochemistry, our understanding of polar vortex dynamics is far from complete and the topic is somewhat controversial. The dispute began for the Antarctic and extended to the Arctic, concentrating on whether the vortex is an isolated air mass (33) or not (2, 4, 21, 34). Advocates of isolation argue that both polar vortices define a region of highly isolated air (35), and that polar loss has virtually no affect on mid-latitude $O_3$ before the vortex breaks up. They also argue there is one-way transport from the vortex edge to mid-latitudes as the vortex erodes. The opposing view contends the vortex is a flowing processor, with $O_3$ rich air entering and depleted or processed air (i.e. air high in reactive chlorine) leaving the vortex region. Supporters of the flowing processor claim that replenishment of vortex $O_3$ descending flow through the vortex, and peeling off of processed edge material must be accounted for to accurately evaluate the mass of $O_3$ destroyed due to polar processes and its subsequent dilution of $O_3$ at lower latitudes (2). The flowing processor has been
criticized with dynamical arguments claiming that poleward fluxes into the vortex are not significant (35, 36).

The \( \text{O}_3 \) change over the winter months can be conservatively estimated inside and outside the vortex at various \( \Theta \)'s directly from the \( \text{O}_3 \) \text{OCT} reference (Fig. 4A). This reference ignores poleward transport as required for an isolated vortex. If instead, we assume there was sufficient poleward flow of air into the outer ring of the vortex to replace the October air with exterior air, then \( \text{O}_3 \) loss accumulated over the period would be better estimated using \( \text{O}_3 \) \text{EXT} (Fig. 4B). This approach is considered as an upper limit for the loss accumulated, particularly for December when parcels remaining from October might still be descending through the vortex. The \( \text{O}_3 \) \text{OCT} analysis indicates only small isentropic gradients in \( \text{O}_3 \) change when crossing into the vortex, while the \( \text{O}_3 \) \text{EXT} analysis reveals the abrupt increase in loss expected in the region of highly elevated reactive chlorine. Although no loss was found above 460 K using \( \text{O}_3 \) \text{OCT}, the loss calculated with \( \text{O}_3 \) \text{EXT} (Fig. 4B) compares well with the 25% at 18 km obtained from AASE lidar measurements (25) and with the 20% at \( \Theta \approx 470 \) K calculated with a photochemical model that utilized AASE measurements and meteorological tracer data (37). However, the larger decrease we found at lower \( \Theta \)'s (using both references) and the mixture of depleted and enhanced \( \text{O}_3 \) we found at and below the bottom of the vortex outside its boundary (Fig. 4B), has not been reported by others. The altitude distribution of \( \text{O}_3 \) decrease outside is consistent with the altitude distribution of the long term decrease reported from sonde and from satellite measurements (38). Fig. 4B portrays a vortex that is not an impenetrable container, nor is it unconstrained with no sides and no bottom. For each \( \Theta \) level outside the boundary, the vortex can be pictured as a leaky bucket: fluid enters the bucket over the lip (air enters the vortex at a \( \Theta \) level), the walls of the bucket restrict the fluid as it descends and mixes with fluid already in the bucket (air descends and mixes inside the vortex), until it exits through the leaky bottom (until it reaches the vortex bottom where it is released).

We define the \( \text{O}_3 \) mass deficit, \( \Theta \), of a portion of the atmosphere as the mass of \( \text{O}_3 \) lost relative to a reference \( \text{O}_3 \) content, and is calculated as

\[
\Theta = k \int [w \times A \times (\text{O}_3^M - \text{O}_3^{REF}) \times \rho] \, dt \tag{3}
\]

where \( \rho \) is the air density, \( \text{O}_3^{REF} \) is either \( \text{O}_3 \) \text{OCT} or \( \text{O}_3 \) \text{EXT}, \( w \) is the rate of parcel descent at the bottom of the vortex, \( A \) is the area of descent, and \( k \) is a constant (mass/\( \text{O}_3 \) molecule). We calculated vertical velocities from -70 meters/day in early winter to -55 meters/day in late winter, and the outer ring of the vortex was assumed as the area of descent (39). When \( \text{O}_3 \) loss is thus integrated from 12. December, 1991 through 20 March, 1992, we obtained \( \Theta = 9 \) megatons (MT) for the case using the October reference and \( \Theta = 18 \) MT using the exterior reference (Fig. 3C). These deficits correspond to 1.3% and 2.6% respectively of the total mass of \( \text{O}_3 \) from 30° to 60° N (700 MT), a significant part of the 4% average wintertime mid-latitude column \( \text{O}_3 \) decrease observed over the past decade (6). Descending air that is deeper inside the vortex, air that is spun-off from the side of the vortex, and the release of depleted air at the time of the vortex demise will also contribute to the \( \text{O}_3 \) mass lost at high latitudes.
Table 1. Vortex boundaries and $\Theta$'s at boundary for flights in the data in analysis (40). Boundaries are such that ClO > 150 pptv at all latitudes poleward of its location (except during dives) and it was coincident or poleward of steep meridional gradients in N$_2$O and PV.

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Table 2. Averages of ten second $O_3$, $N_2O$ and ClO data for parcels of type I, 0 and D (Fig. 2c). All data are inside the vortex and $130 \text{ ppbv}<N_2O<180 \text{ ppbv}$. $O_3@155$ is the average $O_3$ normalized to $N_2O = 155 \text{ ppbv}$ by using the measured value for $dO_3/dN_2O$. Loss rates ($dO_3/dt$) are calculated from averaged ten second measurements of $[\text{ClO}]^2$ and by assuming six hours of daily solar exposure and altitude dependent bromine monoxide concentrations that are consistent with 1989 AASE data (41). The loss rates represent the forward rate of ClO dimer formation along with the reactions of ClO with BrO. Temperature dependent rate constants are from the 1992 JPL compilation (42).

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FIGURE CAPTIONS

Fig. 1. Evolution of O$_3$ inside vortex (43). (A) Vertical distribution of O$_3$ mixing ratio inside vortex over period of mission. (B) Change in O$_3$ mixing ratio with respect to N$_2$O (14) using the O$_3$ OCT reference. Flights used and vortex boundaries are listed in Table 1. The three October flights are considered as a unit to represent the October O$_3$ and N$_2$O data. Data from the other flights in Table 1 are entered into the analyses individually.

Fig. 2. Plots of O$_3$ against N$_2$O during AASEII mission. (A) The three October flights to the pole (small closed circles) are compared with the February data inside the vortex (larger open circles). The heavy line is the O$_3$ OCT reference. (B) The outlines of the full range in monthly O$_3$ - N$_2$O observations inside the vortex are overlaid in monthly sequence, with data below 420 K indicated for the months of January and February. The O$_3$ OCT reference is also shown. (C) The outline of Fig. 2B data is divided into the parcel types I, O, and D defined in text. Average $\Theta$'s from 415 K to 510 K for October aircraft data are indicated as vertical bars. The extension of the October O$_3$ - N$_2$O data to 50 ppbv < N$_2$O < 130 ppbv is from O$_3$ sonde and extrapolated aircraft data (29). (D) Aircraft data from inside and outside the vortex boundary during January and February, 1992 are plotted for $\Theta$ > 500 K (squares and +'s) and $\Theta$ < 420 K (circles and +-'s).

Fig. 3. (A) Calculated daily O$_3$ loss rates (Table 2). (B) O$_3$ @155 (Table 2) from 4 January through 17 February, with linear fits to the data from parcel types I, O, and D. Slopes of lines represent measured daily O$_3$ loss rates. (C) O$_3$ mass deficit (see text) in the air released from the bottom of the vortex.

Fig. 4. Cross section through vortex boundary of %O$_3$ change referenced through (A) O$_3$ OCT and (B) O$_3$ EXT. Data with N$_2$O > 130 ppbv from the four flights of 16 January through 17 February are taken as a unit then averaged to produce the contour (43). The horizontal coordinate was averaged over 1° of latitude.
REFERENCES AND NOTES

12. The vortex interior has two different aspects: an outer ring generally within or near the polar night jet and characterized by high wind speeds and intermittent sunlight, and an inner vortex usually at the highest latitudes (nearer the pole) with much lower wind speeds and much less sunlight. Most of the flights during AASE 11 did not penetrate the inner vortex, therefore the data are considered as representative of the outer vortex.
14. N2O data were not available for 20 March so another conserved tracer CFC-11 was used in its place.
17. O3 loss occurs naturally during the summer at high latitudes (see J. C. Farman et al., Quart.J.R.Met.Soc., 111, 1013 (1985)) and must be considered when evaluating wintertime loss. If this 03 poor air becomes trapped at high latitudes during vortex formation in early November and remain as an isolated pool through January and February, the reference function must represent the fall 03-N2O relation.
24. $\Theta = l'(K) (1000/ P(mbar))^{0.286}$.
26. The fit was obtained from 6,8,12 October, 1991 ten second data. The $\text{O}_3$ and $\text{N}_2\text{O}$ measurements were averaged into 8 equal $\Theta$ ranges from 360 to 520 K and a quadratic fit to these averages was calculated, thus weighting the data equally by $\Theta$. An unweighed fit was compared and found to be almost identical except at the highest values of $\text{N}_2\text{O}$, where the $\text{O}_3$ was about 10% higher in the unweighed fit.
27. Air with $\text{N}_2\text{O} < 130 \text{ ppbv}$ was not accessible to the ER-2 early in the mission, but diabatic cooling brought much lower values within aircraft altitudes during January and February. Accordingly, parcels with $\text{N}_2\text{O} < 130 \text{ ppbv}$ are excluded from all comparisons with the October reference.
29. Monthly averages of $\text{O}_3$ sonde data for October 1991 are calculated at five $\Theta$ levels from 530 K to 610 K for each of the two high latitude stations, Resolute (75° N) and Alert (82° N), thus providing some station to station variability. $\text{N}_2\text{O}$ is estimated for the same five $\Theta$ levels by extrapolating a quadratic fit to the October $\text{N}_2\text{O}$ -0 aircraft data. $\Theta$ has been limited to 610 K, since the extrapolation implies that the average $\text{N}_2\text{O}$ mixing ratio at 610 K is 50 ppbv, therefore is an extreme limit for finding air with $\text{N}_0 > 130 \text{ ppbv}$.
30. This exterior reference is calculated from 10 second data that are more than 2° of latitude outside the boundary of the vortex and with $\Theta > 420$ K. Data within 2° were excluded to avoid contamination of the exterior data with vortex data that fall outside our conservative choice for a vortex boundary, and $\Theta > 420$ K to exclude air parcels coming out of the bottom of the vortex. Equation 2 is practically identical to the fit to the 1989 AASE exterior data.
31. On only one occasion did we find air parcels with $\text{N}_2\text{O} < 140 \text{ ppbv}$ outside the vortex boundary, that being $< 1^\circ$ outside on 17 February. These parcels had the character of vortex air.
32. This is primarily due to the loss rate being nearly proportional to the square of the air density, therefore producing an enhanced loss at the higher pressures in type D and O parcels. (see D. M. Murphy, J.Geophys.Res., 96,5045 (1991)).
39. The rate of descent at the bottom of the vortex (w) can be estimated, by assuming diabatic cooling rates of 1 K/day, multiplied times the measured vertical gradients in Θ. Since most of the data are in the outer ring, the area of descent (A) has been limited to 1.2 x 10^13 m^2, an area equivalent to that from 65°N to 72°N, or approximately half the area of the vortex. N_2O > 150 ppbv at the bottom of the vortex so within the range for the functions O_3^{OCT} and O_3^{EXT}. Our calculations result in a conservative estimate of total O_3 mass destroyed.
40. A flight on 6 January, 1992 also penetrated the polar vortex but data were not available from all of the instruments.
42. Jet Propulsion Laboratory, Publ. 92-20, Pasadena, CA (1990).
43. Contour plots are produced using DeltaGraph® Professional v. 2.0.2 software to produce XYZ contour line plots. The contoured data are averaged into 7 equal theta ranges from 380 K to 560 K. All data are plotted without smoothing and usually appear as sharp corners. The data are equally weighted with linear interpolations on triangular grids between data points to span the gaps.
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FIGURE 1A
INSIDE VORTEX

$$O_3$$ (ppbv)

FIGURE 1B
INSIDE VORTEX

$$O_3$$ change (ppbv) using $$O_3$$ reference

DAY NUMBER

APPROXIMATE PRESSURE ALTITUDE (km)
**FIGURE 3A**

N2O = 130 TO 180 ppbv

**FIGURE 313**

N2O = 130 TO 180 ppbv

**FIGURE 3C**

O3 MASS DEFICIT (MT)

From O3^{EXT}

From O3^{OCT}
FIGURE 4A

[Graph showing potential temperature and latitude relative to boundary.]

FIGURE 4B

[Graph showing potential temperature and latitude relative to boundary.]