

15. "Scientific assessment of ozone depletion: 1991" [Global Ozone Research and Monitoring Project Rep. 25 (World Meteorological Organization, Geneva, Switzerland, 1992)].
16. The H_2O trend is estimated by calculating the difference between the average H_2O with the H_2O residual estimated in K. Kelly *et al.* [Geophys. Res. Lett. 17, 465 (1989)], and scaling with the CH_4 trend. The H_2O difference is a result of CH_4 oxidation in the stratosphere.
17. The HNO_3 trend is estimated by assuming that the NO_y trend is the same as the N_2O trend (0.2%) and using the scaling of NO_y (10).
18. Projected injections of NO_y and H_2O are taken

from scenario F in M. Prather *et al.* [NASA Ref. Publ. 1272 (1992)]. In this report, NO_y is estimated to increase 4 ppbv and H_2O will increase by about 1 ppmv, for an emission index of 15 and a Mach number 3.2.

19. T. Peter *et al.* [Geophys. Res. Lett. 18, 1465 (1991)] calculated a doubling of the PSC probability for future fleets of stratospheric aircraft (a 1.7 K increase in the 50-hPa NAT saturation temperature using a two-dimensional chemistry model).
20. We thank all the participants in the AASE II mission.

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Chemical Loss of Ozone in the Arctic Polar Vortex in the Winter of 1991–1992

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In situ measurements of chlorine monoxide, bromine monoxide, and ozone are extrapolated globally, with the use of meteorological tracers, to infer the loss rates for ozone in the Arctic lower stratosphere during the Airborne Arctic Stratospheric Expedition II (AASE II) in the winter of 1991–1992. The analysis indicates removal of 15 to 20 percent of ambient ozone because of elevated concentrations of chlorine monoxide and bromine monoxide. Observations during AASE II define rates of removal of chlorine monoxide attributable to reaction with nitrogen dioxide (produced by photolysis of nitric acid) and to production of hydrochloric acid. Ozone loss ceased in March as concentrations of chlorine monoxide declined. Ozone losses could approach 50 percent if regeneration of nitrogen dioxide were inhibited by irreversible removal of nitrogen oxides (denitrification), as presently observed in the Antarctic, or without denitrification if inorganic chlorine concentrations were to double.

Loss rates for O_3 were estimated for the lower stratosphere during AASE II in 1991–1992. We computed distributions of reactive chlorine ($\text{Cl}^* \equiv [\text{ClO}] + 2 \times [(\text{ClO})_2]$) and bromine ($\text{Br}^* \equiv [\text{BrO}] + [\text{BrCl}]$) (where brackets denote concentration) along the flight track of the ER-2 airplane by assimilating in situ observations of ClO and BrO with a simple

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model. Relations between potential vorticity (PV) and potential temperature (Θ), meteorological tracers (1, 2), and Cl^* and Br^* were developed to compute O_3 loss rates for the north polar region, accounting for the influence of insolation, temperature, and pressure as air circulates around the polar vortex (3, 4). Seasonal changes observed for ClO (5), NO (6), HCl (7), and O_3 (8) were investigated with the use of a photochemical model constrained by meteorological observations (9) and measured surface areas for sulfate aerosol (10); factors regulating chemical removal of O_3 in the Arctic were examined with this model.

Reactions on the surfaces of polar stratospheric clouds (PSCs) (11), which are composed of condensed phases of H_2O and HNO_3 (12), catalyze the rapid conversion of HCl and ClNO_2 to labile species of inorganic chlorine in the polar vortex during winter (13, 14). Three catalytic cycles involving halogens account for ~95% of photochemical loss of O_3 in the vortex.

1) The self-reaction of ClO forming its dimer, $(\text{ClO})_2$, followed by photolysis

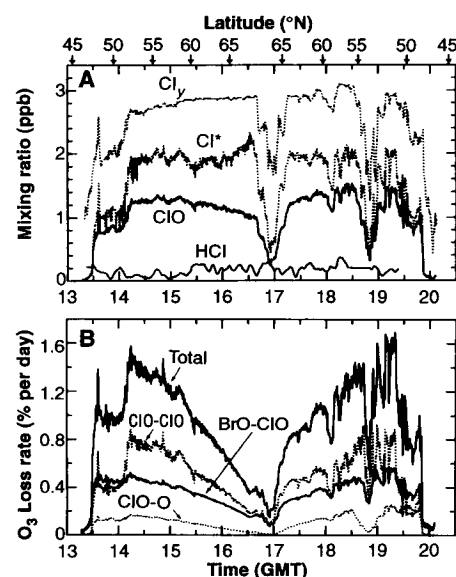
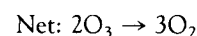
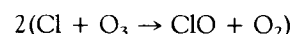
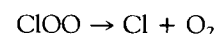
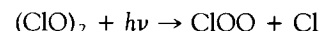
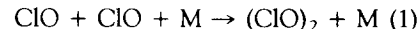
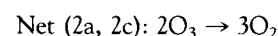
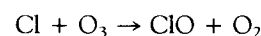
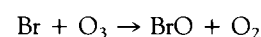
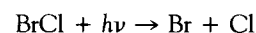
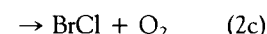


Fig. 1. Observations and reconstructions for 20 January 1992. (A) Observed mixing ratios of ClO and HCl, inferred mixing ratios for Cl^* and Cl_2 , and (B) the 24-hour mean loss rates for ozone, computed using Eq. 4 and Cl^* shown in (A). The total recombination rate and contributions from the ClO-ClO, BrO-ClO, and ClO-O catalytic cycles (reactions 1, 2, and 3) are shown. All measurements taken along the ER-2 flight track, plotted against universal time (GMT). Corresponding latitudes are indicated at the top of the figure.



catalyzes the recombination of two O_3 molecules with the use of one photon (with energy $h\nu$) (15). Thermal decomposition of $(\text{ClO})_2$ short-circuits this cycle, regenerating ClO without producing Cl atoms or recombining O_3 .

2) The reaction of BrO and ClO and the photolysis of BrCl



also catalyzes recombination of O_3 (13). Photolysis of OClO produces O atoms; therefore, reaction 2b does not destroy O_3 (16).

3) The reaction sequence

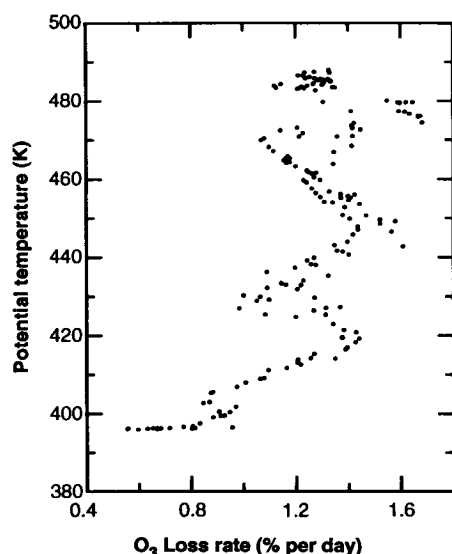
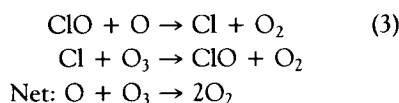


Fig. 2. The 24-hour mean loss rates for O_3 plotted against potential temperature Θ , for observations taken on 20 January 1992 during the descent and ascent in sunlight (solar zenith angle $< 80^\circ$) at $52^\circ N$. The altitudes 20, 16, and 15 km correspond approximately to $\Theta = 500$, 420, and 400 K, respectively.



represents a minor loss of O_3 , with rates accelerating in spring when the concentration of O atoms increases.

Hydrolysis of N_2O_5 on sulfate aerosols efficiently converts NO_x ($NO + NO_2$) to HNO_3 , which is very stable at low sun angles (6, 17). Catalytic cycles involving NO_x , normally important at mid-latitudes, are negligible in the winter polar stratosphere (18). The catalytic cycle involving reaction of ClO with HO_2 represents less than 5% of the total loss of O_3 [on the basis of calculated values for HO_2 , corroborated by column measurements of $HOCl$ (19)] and is therefore not considered here.

The photochemical loss rate of ozone is

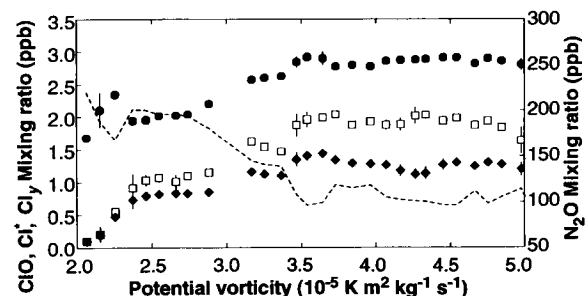
$$\begin{aligned} \frac{d[O_3]}{dt} = & -2\{k_{ClO+ClO}R[M][ClO]^2 \\ & + (k_{ClO+BrO(a)} + k_{ClO+BrO(c)})[BrO][ClO] \\ & + k_{O+ClO}[O][ClO]\} \end{aligned} \quad (4)$$

where k is the rate coefficient for the specified reaction, M denotes an air molecule, and R is

$$\frac{J_{(ClO)_2}[(ClO)_2]}{J_{(ClO)_2}[(ClO)_2] + k_{(ClO)_2+M}[M][(ClO)_2]}$$

the fraction of $(ClO)_2$ that photolyzes, where J is the photolysis frequency for the specified reaction. Removal rates attributable to reaction 1 decline at temperatures above 220 K, where $R \rightarrow 0$ (20). Loss of O_3 requires sunlight to photolyze $(ClO)_2$, $BrCl$ (the

Fig. 3. Observed mixing ratios for ClO (◆) and N_2O (dashed line) and inferred mixing ratios for Cl^* (□) and Cl_y (●) on the isentropic surface defined by $\Theta = 470 \pm 10$ K, plotted against potential vorticity (PV). Data were averaged in intervals of PV equal to $5 \times 10^{-7} K m^2 kg^{-1} s^{-1}$. The edge of the polar vortex was located at $PV \approx 2.1 \times 10^{-5}$ with a transition region between 2.3×10^{-5} and $3 \times 10^{-5} K m^2 kg^{-1} s^{-1}$. The interior of the vortex had uniform concentrations of $Cl_y \approx 2.8$ ppbv and $Cl^*/Cl_y \approx 0.75$. Vertical bars denote standard deviation (smaller than the symbol in many bins).



nighttime reservoir for BrO), and O_3 (to generate O atoms).

Equation 4 allows us to compute instantaneous rates for O_3 loss along a flight track directly from measured radicals (5, 21), apart from R and $[O]$, which are calculated with Eqs. 5 and 7 below. To determine global loss rates of O_3 , we must infer radical concentrations throughout the polar vortex from observations along the flight track, and the loss rate must be integrated over 24 hours (3).

The diurnal variations of ClO, BrO , and O are governed by

$$\begin{aligned} \frac{d[ClO]}{dt} = & 2J_{(ClO)_2} + k_{(ClO)_2+M}[M][(ClO)_2] \\ & - 2k_{ClO+ClO+M}[M][ClO]^2 \end{aligned} \quad (5)$$

$$\begin{aligned} \frac{d[BrO]}{dt} = & J_{BrCl}[BrCl] \\ & - k_{ClO+BrO(c)}[BrO][ClO] \end{aligned} \quad (6)$$

$$\frac{d[O]}{dt} = J_{O_3}[O_3] - k_{O+O_2+M}[O][O_2][M] \quad (7)$$

Equation 5 balances production and loss of $(ClO)_2$, Eq. 6 balances production and photolysis of $BrCl$, and Eq. 7 balances photolysis of O_3 with recombination of O and O_2 ; each process has a relaxation time shorter than 1000 s. We determined the concentration of reactive chlorine corresponding to each measurement of ClO by matching observations to diurnal calculations with Eq. 5. Concentrations of BrO were about twice as high inside the vortex than outside, with little change during the winter; hence, a fixed relation was adopted between Br^* and Θ (22).

Concentrations of ClO began to increase dramatically in late December after temperatures over Asia had cooled to the threshold for PSCs (5, 9). Concentrations of ClO peaked in late January and then declined slowly in February and March. On 20 January 1992, the ER-2 aircraft departed Bangor, Maine ($44^\circ 47' N$, $68^\circ 47' W$), at 1300 GMT, flew north at ~ 18 -km altitude ($\Theta = 460$ K), and turned south to return at ~ 19 km ($\Theta = 490$ K), with brief descents to 15 km at 65° and $52^\circ N$. Figure 1A shows

data for ClO and HCl and inferred values of Cl^* and total inorganic chlorine, Cl_y [computed from observations of N_2O and organochlorine gases (23)]. A steep decline in N_2O and an increase in ClO were observed just north of Bangor (Fig. 1A) at the edge of the polar vortex ($PV \approx 2.1 \times 10^{-5} K m^2 kg^{-1} s^{-1}$). Mixing ratios for ClO rose to 0.8 parts per billion by volume (ppbv) ($1 \text{ ppbv} = 10^{-9} \text{ mole fraction in air}$) near the vortex edge, increasing to 1.2 to 1.4 ppbv further inside; less than 15% of Cl_y was converted to Cl^* outside the vortex, 60% near the edge, and 75 to 85% in the interior (24). Figure 1B shows loss rates of ozone along the flight track, computed by integrating Eq. 4 over 24 hours. Removal rates exceeded 1.4% per day: 50% attributed to reaction 1, 35% to 2, and 15% to 3.

Ozone loss rates in the polar vortex (Fig. 2) were uniform for $420 < \Theta < 500$ K (16 to 20 km), declining at lower Θ . The mixing ratios of ClO, Cl^* , Cl_y , and N_2O versus PV for $\Theta = 470 \pm 10$ K are shown in Fig. 3. Monotonic increases of the Cl^* value on an isentropic (constant Θ) surface were derived for 8 of the 10 flights in the vortex; similar values for Cl^* were observed for a given PV on flights a few days apart. These results imply a homogeneous distribution for Cl^* in the polar vortex, extending over more than 4 km in the vertical and as far north as $70^\circ N$. Values of Cl^* versus PV were similar in 1989 and 1992 (3).

We computed distributions of Cl^* and daily loss rates for O_3 throughout the vortex using global meteorological fields for PV and the observed relation between Cl^* and PV (Fig. 4). Regions with elevated Cl^* were exposed to sunlight in lobes of the vortex that extended to $45^\circ N$, one of which was sampled by the ER-2. The mean ozone loss rate for the vortex region ($PV > 2.1 \times 10^{-5} K m^2 kg^{-1} s^{-1}$) was 0.4% per day, notably lower than rates along the flight track (Fig. 1B). This difference illustrates the importance of assimilating aircraft observations in a tracer model to account for distortion of the polar vortex from axial symmetry (2, 3). Ozone loss rates found here are similar to those inferred from

measurements of ClO in the Arctic lower stratosphere made between 1 and 13 January 1992 by the Microwave Limb Sounder on the Upper Atmosphere Research Satellite (25).

After 1 February, minimum temperatures in the vortex exceeded the threshold for PSCs (5, 9), ending PSC processing. Little or no denitrification was observed (26), and Cl* and rates for ozone destruction began to decline (Fig. 5). The influence of illumination is evident in Fig. 5B: Loss rates were larger for given Cl* at lower latitudes (lower PV). However, elevated Cl* persisted longer at high latitudes, and O₃ losses integrated over the winter were similar for a wide range of latitudes. About 0.7 part per million by volume (ppmv) (1 ppmv = 10⁻⁶ mole fraction in air) of O₃

(~15 to 20%) was removed by reactions 1 through 3 at $\Theta = 470 \pm 10$ K in the Arctic polar vortex in 1991–1992, similar to losses for 1988–1989 (3, 27).

The ozone loss rates in Fig. 5B represent snapshots of an isentropic surface on which air parcels move adiabatically (28). Non-adiabatic processes, such as radiative cooling, can significantly modify PV and Θ over time scales of a month, with changes in Θ of about -70 K over the winter (29). The seasonal integral at $\Theta = 470$ K nevertheless may approximate net ozone removal at ~18 km because O₃ loss rates are uniform in both vertical (420 < Θ < 500 K) (Fig. 2) and horizontal (Fig. 5B) dimensions. Transport of O₃ to $\Theta = 470$ K during the winter makes it difficult to detect net chemical removal of 0.7 ppmv (8). Analysis of temporal variations of N₂O and O₃ suggest reduction of 15 to 20% of O₃ at 17 km (8) and 10 to 15% between 10 and 12 km (30), consistent with chemical loss rates computed here.

Season-long observations during AASE II provide a unique opportunity to test ideas about the photochemical processes regulating radical concentrations in the polar vortex. We calculated production and loss of O₃ and the evolution of ClO, HCl, NO, and BrO from 15 December 1991 to 30 March 1992 for a hypothetical air parcel at $\Theta = 470$ K, 65°N (PV $\approx 2.8 \times 10^{-5}$ K m² kg⁻¹ s⁻¹), assumed to circulate around the vortex every 8 days, by solving time-dependent equations (31) with a comprehensive set of chemical reactants, reaction rates, and photolysis cross sections (20). Data from the ER-2 in December were adopted to define initial concentrations of total nitrogen oxides

(NO_y) (6), HCl (7), O₃ (8), H₂O, CH₄, temperature (9), and the surface area of sulfate aerosols (10) on 15 December. Values of Cl_y were inferred from measured N₂O (23, 26). The reaction efficiency for hydrolysis of N₂O₅ on surfaces of sulfate aerosols was assumed to be 0.10 (32).

Mean temperatures within the vortex (~210 K in January, ~230 K in March) were adopted from meteorological analyses for 1991–1992 (9). Temperatures below the PSC threshold were assumed to occur 1 day out of 8, from 9 to 25 January (9). Production of Cl* by reaction of HCl and ClNO₂ on PSC surfaces was assumed to be rapid and stoichiometric (5, 7). Complete return of HNO₃ to the gas phase was assumed upon PSC evaporation, consistent with observations for 1991–92 (26).

Calculated changes of ClO, HCl and NO (Table 1, case A) correspond closely to observations (Fig. 6), indicating accurate simulation of rates for key processes regulating ClO after the cessation of PSCs: photochemical decomposition of HNO₃, which regenerates ClNO₂, and reaction of Cl with CH₄, which regenerates HCl. A study that included detailed air parcel trajectories to examine recovery from PSC processing reached similar conclusions (33). The integrated removal of O₃ was ~19%, similar to empirical values from the ER-2 data discussed above.

What conditions would allow high concentrations of Cl* to persist into spring, as observed in the Antarctic (34)? If PSC processing persisted for another month, O₃ losses would increase modestly (Table 1, case B): Photolysis of HNO₃ accelerates rapidly as the season progresses, limiting

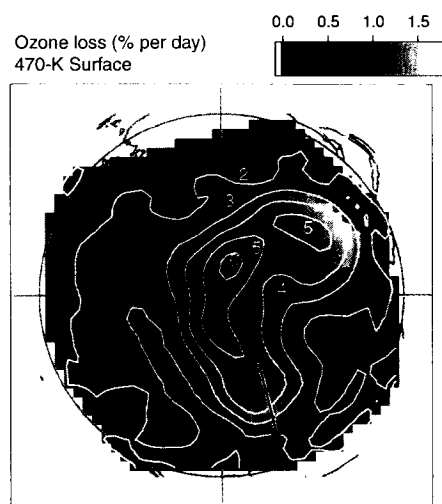


Fig. 4. Distribution of the 24-hour mean loss rate for O₃ (percent per day) in the north polar vortex for the 470 ± 10 K isentrope, derived with global fields of PV and the relation between Cl* and PV shown in Fig. 3, as described in the text. Contours of PV (in units of 10^{-5} K m² kg⁻¹ s⁻¹) and the flight track of the ER-2 (black line, with circle denoting Bangor, Maine) are shown. Latitude circles 60° and 30°N and a map of the continents are denoted by green lines.

Table 1. Photochemical model results for ozone loss at 18 km.

Case	Model conditions	O ₃ removal* (%)
A	PSCs every 8 days until 25 January	19
B	PSCs every 8 days until 26 February	26
C	Case A plus 90% denitrification at first PSC event	44
D	Case A plus twice the present Cl _y	48

*Stated relative to a model without PSCs (see Fig. 6).

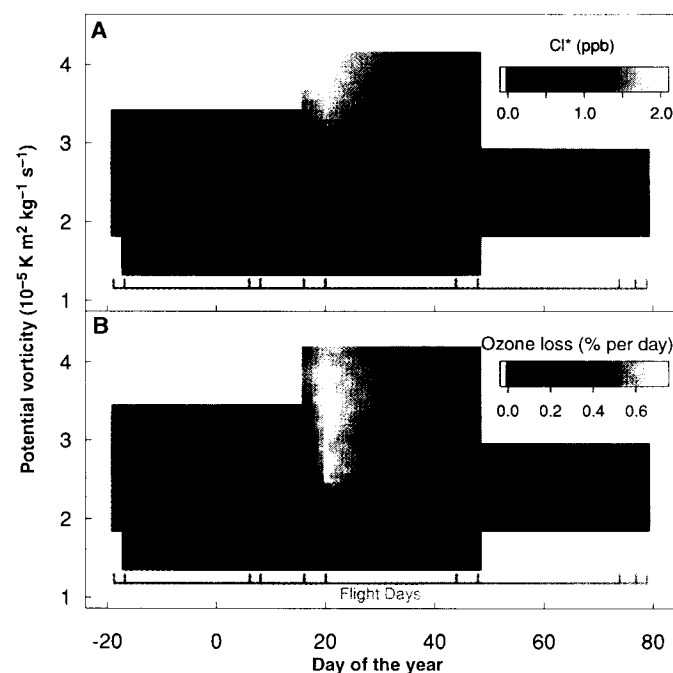


Fig. 5. (A) Calculated mixing ratio of Cl* (41) and (B) 24-hour mean loss rate for ozone on the $\Theta = 470 \pm 10$ K isentropic surface, plotted as a function of PV and day of the year for the Arctic polar vortex in 1991–1992. Day 1 is 1 January 1992, and negative numbers refer to 1991.

loss of O_3 after each PSC encounter. Extremely cold temperatures throughout the vortex (<195 K) in March could produce larger losses of O_3 if HNO_3 were sequestered in an aerosol phase. If HNO_3 were irreversibly removed by the sedimentation of PSCs (denitrification), Cl^* would remain elevated until equinox, and O_3 losses would increase significantly (31, 35) (Fig. 6 and Table 1, case C). Much of the Antarctic polar vortex is denitrified because of pervasively cold temperatures (36), but only sporadic denitrification has been observed in the Arctic (26, 36). Large-scale denitrification could occur in the Arctic if there were an anomalously cold winter or if ice cloud formation were enhanced by increased concentrations of stratospheric H_2O . Cooling of the polar vortex could occur as a result of increasing CO_2 (37) or

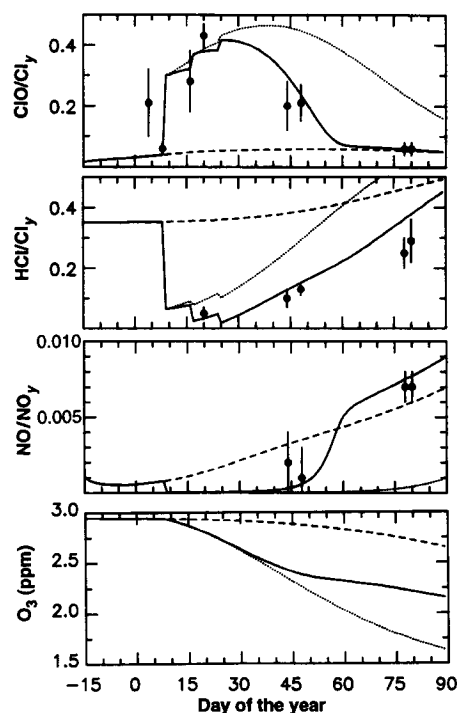


Fig. 6. Calculated seasonal evolution (day 1 corresponds to 1 January) of ClO , HCl , NO , and O_3 at noon for a hypothetical air parcel circulating at 18 km altitude, $65^\circ N$ latitude, processed periodically by PSCs as described in the text. Model results for case A in Table 1 (no denitrification), case C (90% denitrification following the first PSC event), and a parcel with no PSC processing are shown by the solid, dotted, and dashed lines, respectively. Reductions in O_3 during March in the absence of PSC processing occurs because of reactions involving NO_x . Data points represent mean and standard deviation of observations for $\Theta = 470 \pm 30$ K and $PV > 2.8 \times 10^{-5} K m^2 kg^{-1} s^{-1}$. Data for ClO and NO were restricted to daytime measurements (solar zenith angle $< 86^\circ$). Concentrations of ClO , HCl , and NO have been normalized to either Cl_y or NO_y to remove the influence of small-scale atmospheric gradients.

declining concentrations of O_3 (38). Large ozone reductions would also be expected in the Arctic without denitrification if concentrations of inorganic chlorine were to double beyond present-day values (Table 1, case D). This scenario appears unlikely if present revisions (39) to the Montreal Protocol of 1987 (40) are effective in reducing inputs of chlorocarbons and bromocarbons to the atmosphere.

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- Concentrations of BrO versus Θ from 1989 (21) were increased by $\sim 10\%$ to reflect preliminary data from 1991–1992. The relationship between Br^* and Θ was developed with use of Eq. 6 and profiles of Cl^* , O_3 , and temperature inside the vortex for 20 January 1992. A value of $Br^* = 12$ parts per trillion by volume (pptv) ($1 \text{ pptv} = 10^{-12}$ mole fraction in air) was used for $\Theta = 470$ K, yielding $BrO = 8.75$ pptv for solar zenith angle $= 86^\circ$ on 20 January.
- Total inorganic chlorine (Cl_y) was calculated with the relations between N_2O and the source gases CCl_3F , $C_2Cl_2F_3$, CCl_2F_2 , CH_2Cl , CH_3CCl_3 , and CCl_4 [J. W. Elkins *et al.*, *Eos* **73**, 106 (1992)], as described by S. R. Kawa *et al.* [*J. Geophys. Res.* **97**, 7905 (1992)].
- We adopted cross sections from J. B. Burkholder, J. J. Orlando, and C. J. Howard [*J. Phys. Chem.* **94**, 687 (1990)], which gave $Cl^*/Cl_y \approx 0.75$ deep inside the vortex. The use of cross sections from (20) (including absorption at longer wavelengths reported by W. B. DeMore and E. Tschuikow-Roux [*ibid.*, p. 5856]) gives $Cl^*/Cl_y \approx 1$ inside the vortex. Uncertainties in Cl^* have little effect on computed loss rates of O_3 because recombination depends mainly on observed daytime concentrations of ClO (Eq. 4).
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- The apparently detached parcel with high Cl^* in early January ($2.1 \times 10^{-5} < PV < 2.7 \times 10^{-5} K m^2 kg^{-1} s^{-1}$) is an artifact; small-scale features with high ClO and low N_2O , characteristic of air with high PV from deep inside the vortex, alternated with low- ClO , high- N_2O air over 10- to 100-km scales. Meteorological fields of potential vorticity are typically unable to resolve features on this scale (2).
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