



## Severe Arctic ozone loss in the winter 2004/2005: observations from ACE-FTS

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[1] The severe Arctic ozone reduction in the winter 2004/2005 is analyzed using ACE-FTS observations and four different analysis techniques: correlations between ozone and long-lived tracers (adjusted to account for mixing), an artificial tracer correlation method, a profile-descent technique, and the empirical relationship between ozone loss and potential PSC volume. The average maximum ozone loss was about 2.1 ppmv at 475 K–500 K (~18 km–20 km). Over 60% of the ozone between 425 K–475 K (~16 km–18 km) was destroyed. The average total column ozone loss was 119 DU, ~20–30 DU larger than the largest previously observed Arctic ozone loss in the winter 1999/2000. **Citation:** Jin, J. J., et al. (2006), Severe Arctic ozone loss in the winter 2004/2005: observations from ACE-FTS, *Geophys. Res. Lett.*, 33, L15801, doi:10.1029/2006GL026752.

### 1. Introduction

[2] The Atmospheric Chemistry Experiment (ACE) is a Canadian satellite mission (SCISAT-1) whose primary science objective is to study processes related to Arctic stratospheric polar ozone (O<sub>3</sub>) loss [Bernath et al., 2005]. The primary instrument is a high spectral resolution (0.02 cm<sup>-1</sup>) Fourier Transform Spectrometer (ACE-FTS) operating from 2.3 to 13.3 μm (750–4400 cm<sup>-1</sup>) that measures temperature and many species involved in ozone-related chemistry. The retrieval approach for temperature, pressure, and volume mixing ratios (VMRs) is described by Boone et al. [2005]. Validation studies of ACE-FTS version 1.0 and 2.1 data show that stratospheric ozone is in good agreement with the observations from instruments including GOMOS [Fussen et al., 2005], HALOE [McHugh et al., 2005], POAM III, SAGE III, ozonesondes [Walker et al., 2005], Odin/OSIRIS [Petelina et al., 2005], and EOS MLS [Froidevaux et al., 2006]. In this study the new version 2.2 ACE-FTS data with updated O<sub>3</sub> retrievals, which give more consistent results in the

lower stratosphere, are employed to analyze the Arctic O<sub>3</sub> loss during the winter 2004/2005.

[3] To quantify chemical O<sub>3</sub> loss throughout the winter, and to isolate it from dynamical effects, a tracer correlation method has been used [e.g., Proffitt et al., 1990; Müller et al., 1997; Salawitch et al., 2002]. This method assumes that the correlation between O<sub>3</sub> and a long-lived tracer is preserved inside the polar vortex if there is no chemical O<sub>3</sub> reduction, and thus any change of the correlation relationship yields information on chemical O<sub>3</sub> loss. However, mixing inside the polar vortex and across the vortex edge can also change the correlations. Rex et al. [2002] and Müller et al. [2005] argued that neglecting mixing across the polar vortex edge could only result in an underestimation of the chemical O<sub>3</sub> loss. For the winter 1999/2000, when the largest ever Arctic O<sub>3</sub> loss was reported [World Meteorological Organization (WMO), 2003], mixing across the vortex edge was negligible [Ray et al., 2002; Richard et al., 2001; Salawitch et al., 2002]. Ray et al. [2002] also showed that mixing within the vortex can be responsible for most long-lived tracer correlation changes. In a study on denitrification, Rex et al. [1999] proposed a mixing-line technique to correct for the effects of mixing across the vortex edge when using the correlation method. Later, Esler and Waugh [2002] composed an artificial tracer that has a linear relation with the nitrogen family (NO<sub>y</sub>), so mixing does not change the correlations, to get a robust estimate of denitrification. Here, the correlation method with the mixing correction and the artificial tracer method are both used to quantify the O<sub>3</sub> loss. In addition, a profile-descent method [Manney et al., 2006] (hereinafter referred to as *MG2006*) is used. Finally, Rex et al. [2004] showed that there exists a quantitative empirical linear relation between the Arctic total column chemical O<sub>3</sub> loss and the potential PSC volume from mid-December to March, which offers another tool for chemical O<sub>3</sub> loss estimation.

### 2. O<sub>3</sub> Reduction Analyses from Correlations between O<sub>3</sub> and Long-Lived Tracers

[4] The SCISAT-1 orbit allowed ACE-FTS to observe the Arctic (50°N–80°N) between 1 January and 26 March 2005, and the data at potential temperatures 350 K–1700 K (~12 km–45 km) are used here. We consider measurements north of 50°N with sPV (scaled potential vorticity [Manney et al., 1994]) > 1.8 × 10<sup>-4</sup> s<sup>-1</sup> above 450 K and sPV > 1.4 × 10<sup>-4</sup> s<sup>-1</sup> between 350 K–450 K to be inside the polar vortex. Measurements with sPV < 1.0 × 10<sup>-4</sup> s<sup>-1</sup> are categorized as outside the polar vortex. We estimate the O<sub>3</sub> loss between 1–7 January 2005 and 8–15 March 2005,

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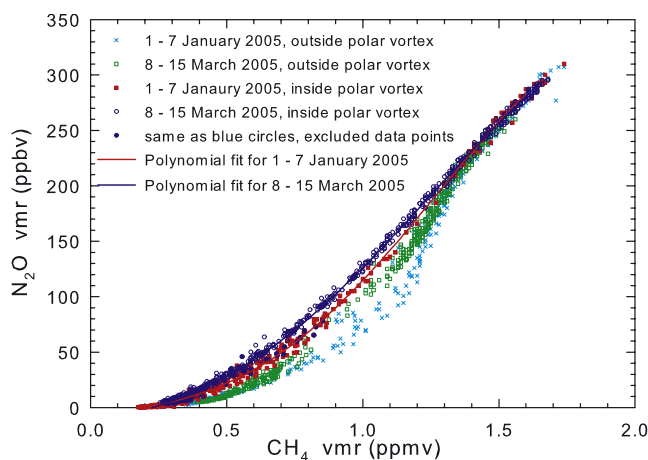
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**Figure 1.** Correlations of  $\text{N}_2\text{O}$  and  $\text{CH}_4$  between 350 K–1700 K.

after which the polar vortex broke up [MG2006]. sPV is calculated from UK Met Office analyses [Swinbank *et al.*, 2002].

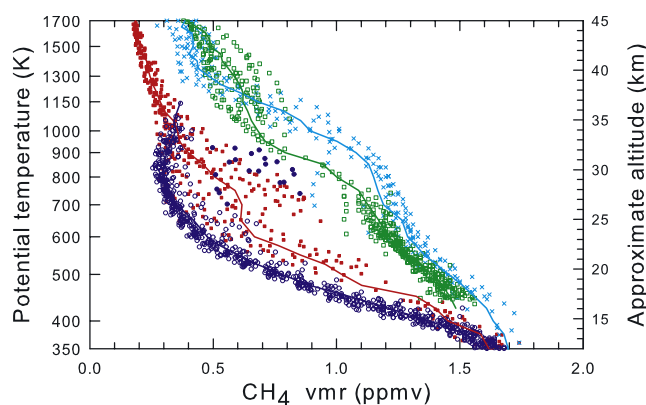
[5] Figure 1 shows correlations between nitrous oxide ( $\text{N}_2\text{O}$ ) and methane ( $\text{CH}_4$ ) for the Arctic. For  $\text{N}_2\text{O}$  values below 200 ppbv (above  $\sim 15$  km), the correlations inside the vortex are different from those outside. From early January to March 2005, the vortex correlation curve shifts to its concave side (aside from a few observations shown by the blue dots). This shift suggests that mixing within the vortex or across the vortex edge occurred. Moreover, EOS MLS observations show that the mixing occurred mainly from the inner vortex edge to the vortex core [MG2006].

[6] The blue dots (observations for 8–15 March) in Figure 1 and Figure 2 have relatively large  $\text{CH}_4$  values and indicate mixing of extra-vortex air which is not surprising as it was near the time of vortex break-up. These points are excluded in all the following  $\text{O}_3$  loss estimates to reduce the uncertainty caused by the mixing.

[7] However, when using the  $\text{O}_3/\text{CH}_4$  correlation to quantify the chemical  $\text{O}_3$  loss, the mixing effect still needs to be removed. Rex *et al.* [1999] constructed mixing lines to correct for effects on the denitrification estimates using the change in the  $\text{N}_2\text{O}/\text{CH}_4$  correlation. Using that method and the vortex  $\text{O}_3/\text{CH}_4$  and  $\text{N}_2\text{O}/\text{CH}_4$  correlations, the effect of mixing within the vortex can be roughly removed. Still, since the  $\text{O}_3/\text{CH}_4$  correlations are different inside and outside the vortex even without chemical  $\text{O}_3$  loss and both of the end members of the mixing line are set on the vortex correlations, this method cannot correct for the mixing across the vortex edge.

[8] Polynomial fits of the 1–7 January 2005  $\text{O}_3/\text{CH}_4$  correlations are shown as the black and red lines in Figure 3. The black line part is obtained using  $\text{CH}_4$  VMRs smaller than 0.30 ppmv but only retains the part below 0.22 ppmv. The red line part is obtained using the entire data set but retains only the part with  $\text{CH}_4$  VMRs larger than 0.22 ppmv. In the calculation for the mixing lines, vortex observations for 8–15 March 2005 are binned onto isentropic surfaces in 20 K intervals. For more details about this technique, see Rex *et al.* [1999].

[9] The adjusted correlation points and their polynomial representation are shown as the grey triangles and line in

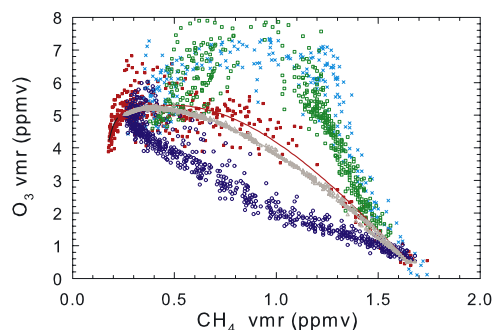


**Figure 2.** Vertical distribution of  $\text{CH}_4$ . The symbols are the same as in Figure 1 and the lines are the averages.

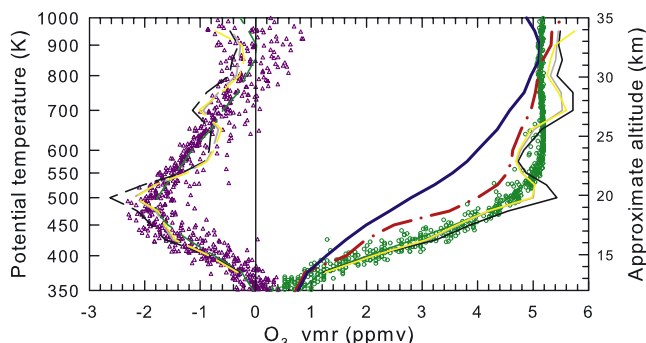
Figure 3. The modifications mainly impact the middle and lower stratospheric vortex with  $\text{CH}_4$  mixing ratios larger than 0.5 ppmv. This suggests that the impact of mixing above  $\sim 35$  km during the intervening two months was negligible for the air below.

[10] Employing the adjusted correlation function to the  $\text{CH}_4$  measurements for 8–15 March 2005, we can estimate the  $\text{O}_3$  inside the vortex, as shown in Figure 4.  $\text{O}_3$  reduction occurred between 375 K–800 K ( $\sim 14$  km–30 km) with a maximum loss of 1.8 ppmv between 475 K–500 K ( $\sim 18$  km–20 km). For individual data points,  $\text{O}_3$  loss was as large as 2.4 ppmv at these levels. The  $\text{O}_3$  loss exceeded 45% between 400 K–500 K ( $\sim 15$  km–20 km) and reached over 60% between 425 K–450 K.

[11] Using vortex averaged profiles of temperature and pressure for the periods 1–7 January and 8–15 March 2005, the total column  $\text{O}_3$  loss between 375 K and 800 K for 8–15 March 2005 is estimated to be  $\sim 114$  DU from the  $\text{O}_3/\text{CH}_4$  correlations. This value is  $\sim 25$  DU smaller than the estimate of 139 DU obtained using the correlation function without the mixing correction. Based on the adjusted  $\text{O}_3/\text{N}_2\text{O}$  and  $\text{O}_3/\text{CFC-12}$  (dichlorodifluoromethane,  $\text{CCl}_2\text{F}_2$ ) correlations, the maximum  $\text{O}_3$  loss were 2.0 ppmv and 2.1 ppmv, and the total column  $\text{O}_3$  loss estimates were 125 DU and 130 DU, respectively (Table 1). For the three tracers, the averages are 2.0 ppmv and 123 DU for maximum  $\text{O}_3$  loss and total column  $\text{O}_3$  loss, respectively.



**Figure 3.** Correlations of  $\text{O}_3$  and  $\text{CH}_4$  between 350 K–1700 K. The color symbols are the same as in Figure 1. See text for details of the lines and grey triangles.



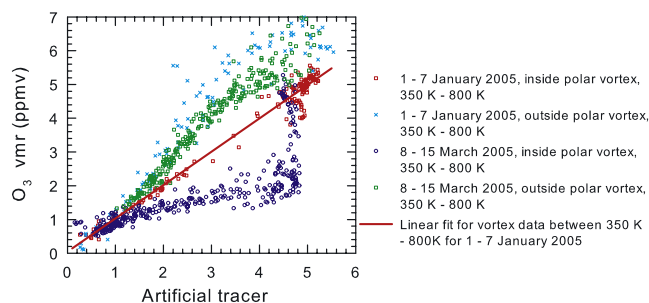
**Figure 4.** Vertical vortex  $O_3$  and  $O_3$  loss profiles. Dash-dot red line, averaged  $O_3$  observations for 1–7 January; blue line, averaged  $O_3$  observations for 8–15 March. Green circles and purple triangles are calculated  $O_3$  and  $O_3$  loss values for 8–15 March using the modified  $O_3/CH_4$  correlations (the grey line in Figure 3), while the green solid and dashed lines are their averages on isentropic surfaces. The black solid and dashed lines show the calculated  $O_3$  and  $O_3$  loss values for 8–15 March using  $CH_4$  and the profile-descent technique, while the grey solid and dashed lines, and the yellow solid and dashed lines show the same result but using  $N_2O$  and CFC-12, respectively.

### 3. $O_3$ Loss from Artificial Tracer, Profile-Descent, and Potential PSC Volume Methods

[12] Using the artificial tracer technique proposed by *Esler and Waugh* [2002] we compose an artificial tracer from simultaneous  $CH_4$ ,  $N_2O$ , CFC-11 (trichlorofluoromethane,  $CCl_3F$ ) and OCS (carbonyl sulphide) observations from 350 K to 800 K within the vortex for 1–7 January 2005 with the coefficients determined by a linear regression.

$$\begin{aligned} \text{Artificial tracer} = & 3.262 \times 10^{-3} CH_4(\text{ppbv}) \\ & -1.678 \times 10^{-2} N_2O(\text{ppbv}) \\ & +6.903 \times 10^{-3} CFC-11(\text{pptv}) \\ & -1.251 \times 10^{-2} OCS(\text{pptv}) + 3.622 \end{aligned} \quad (1)$$

[13] Using equation (1) we can obtain the artificial tracers inside and outside the vortex for 1–7 January and 8–15 March and their correlations with  $O_3$  as shown in Figure 5. The decrease of  $O_3$  with respect to this artificial long-lived tracer can be regarded as the chemical  $O_3$  loss. However, because the correlations inside and outside the vortex are different, this method cannot correct for the mixing across the vortex edge. This kind of mixing can only increase  $O_3$  for an artificial tracer value, which suggests that neglecting mixing across the edge gives a conservative  $O_3$  loss estimate for this method. However, because of the early vortex linear correlation, which cannot be changed by inner vortex mixing, this method still can reduce the uncertainty due to the mixing within in the vortex. Figure 6 shows the vertical distribution of  $O_3$  loss estimated by this method. The loss maximized at around 450 K with an average reduction of  $\sim 2.1$  ppmv, slightly larger than the estimate

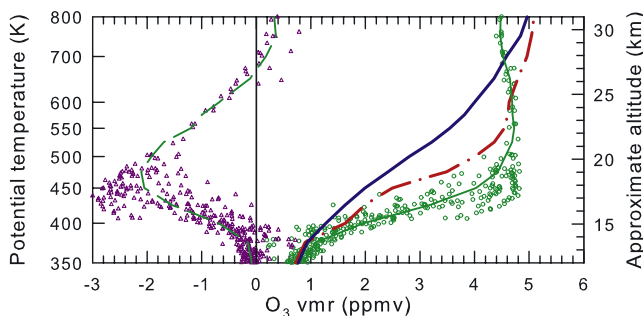


**Figure 5.** Correlations between  $O_3$  and an artificial tracer composed of  $CH_4$ ,  $N_2O$ , CFC-11, and OCS.

from the modified correlations. The reduction extended up to about 650 K ( $\sim 25$  km) and the column  $O_3$  loss between this level and 375 K was 116 DU.

[14] Next, we estimate  $O_3$  loss using the profile-descent technique [MG2006]. Using the vortex averaged long-lived tracer profiles (e.g.,  $CH_4$  in Figure 2) for 1–7 January and 8–15 March 2005, vortex descent rates can be deduced. The descent rates are then applied to the  $O_3$  profile for 1–7 January (dash-dot red line, in Figure 4 and Figure 6) to derive new  $O_3$  profiles for mid-March. The difference between the  $O_3$  measurements and the derived  $O_3$  values for 8–15 March is considered as  $O_3$  loss. Estimates based on these inferred descent rates from the profiles of  $CH_4$ ,  $N_2O$  and CFC-12 are shown in Figure 4 and Table 1. The maximum  $O_3$  loss averaged for the three species occurred at 500 K and was  $\sim 2.3$  ppmv, which is slightly larger than the estimates from the artificial tracer method and the adjusted correlations. The average total column loss using the  $CH_4$ ,  $N_2O$  and CFC-12 profiles was 128 DU, close to the results from the adjusted correlation analysis but 10% larger than the estimate from the artificial tracer method.

[15] Finally, using National Center for Environmental Prediction/National Center for Atmospheric Research Reanalysis (NCEP/NCAR) temperature data [Kistler *et al.*, 2001], and typical  $HNO_3$  and  $H_2O$  mixing ratios from ACE-FTS measurements from January to March 2005 we estimate the potential PSC volume ( $V_{PSC}$ ) to be  $41 \times 10^6 \text{ km}^3$ . According to the empirical relation of *Rex et al.* [2004], this would imply column  $O_3$  loss of  $108 \pm 15$  DU. The uncertainty range is due to uncertainties in the  $HNO_3$  and  $H_2O$  values used for the potential PSC volume calculation. This



**Figure 6.** Vertical vortex  $O_3$  and  $O_3$  loss profiles. Lines and symbols are the same as in Figure 4 except that the  $O_3$  and  $O_3$  loss values are derived from the correlations between  $O_3$  and the artificial tracer.

**Table 1.** Total column O<sub>3</sub> loss in DU and maximum VMRs loss in ppmv (in brackets)

Method	CH <sub>4</sub>	N <sub>2</sub> O	CFC-12	Average
Original correlation	139 (2.1)	131 (2.1)	131 (2.1)	134 (2.1)
Adjusted correlation	114 (1.8)	125 (2.0)	130 (2.1)	123 (2.0)
Profile-descent technique	137 (2.6)	125 (2.2)	123 (2.2)	128 (2.3)
Artificial tracer method				116 (2.1)
V <sub>PSC</sub> method				108

estimate is about 12%, 7%, and 15% smaller than the direct estimates using ACE-FTS data from the adjusted correlation analysis, the artificial tracer method and the profile-descent technique, respectively. A possible reason for relatively smallness of this estimate is that the NCEP/NCAR temperature is biased high in the lower stratosphere compared to other data sets [Manney *et al.*, 2005, and references therein].

[16] On average, ACE-FTS maximum O<sub>3</sub> loss by mixing ratio is estimated to be  $\sim 2.1$  ppmv between 475 K–500 K. This value is  $\sim 0.8$  ppmv larger than estimates from EOS MLS and POAM III using vortex-averaged descent from a radiation calculation [MG2006]. Between 450 K–500 K, the ACE-FTS estimate is  $\sim 2.0$  ppmv from the profile-descent method, which is close to the loss in the outer vortex and  $\sim 0.5$  ppmv larger than the vortex average from EOS MLS using the same method.

[17] Before the winter 2004/2005 the largest Arctic O<sub>3</sub> loss on record occurred in the winter 1999/2000 [WMO, 2003]. The above average maximum O<sub>3</sub> loss is  $\sim 0.8$  ppmv larger than the maximum loss estimated from POAM III using the profile-descent technique and modeling in the Arctic for the winter 1999/2000 [Hoppel *et al.*, 2002]. However, the loss in 2004/2005 was about 0.5 ppmv smaller than the maximum loss at 450 K at the end of March 2000 from the MATCH analysis [Rex *et al.*, 2002]. Nevertheless, since loss extended farther down where ozone VMRs are smaller, the maximum fractional loss reached 60% at between 425 K–475 K ( $\sim 16$  km–18 km), close to the estimate using various methods and data sets during SOLVE/THESEO 2000 [Newman *et al.*, 2002]. The average of the total column loss estimates from the four methods is 119 DU. This is  $\sim 20$ – $30$  DU larger than estimates at the end of March 2000 [WMO, 2003].

#### 4. Summary

[18] The Arctic winter 2004/2005 was particularly cold [MG2006] with substantial chlorine activation [Dufour *et al.*, 2006]. Table 1 shows the estimates of the maximum O<sub>3</sub> mixing ratio loss and total column O<sub>3</sub> loss from various methods. The maximum mixing ratio loss over the entire winter was  $\sim 1.8$  ppmv based on the adjusted O<sub>3</sub>/CH<sub>4</sub> correlations and  $\sim 2.0$  ppmv of average from the adjusted O<sub>3</sub>/CH<sub>4</sub>, O<sub>3</sub>/N<sub>2</sub>O and O<sub>3</sub>/CFC-12 correlations,  $\sim 2.1$  ppmv from the correlation between O<sub>3</sub> and an artificial tracer, and  $\sim 2.3$  ppmv from the profile-descent method. These estimates are  $\sim 0.5$  ppmv larger than those from EOS MLS [MG2006]. Total column O<sub>3</sub> loss was  $\sim 123$  DU based on the adjusted O<sub>3</sub>/long-lived tracer correlations and 116 DU based on the artificial tracer method. Only the effect of mixing within the vortex is corrected for in the tracer correlation methods used here. Hence, the results are likely to be conservative. However, exact mixing effects cannot be

assessed due to the unusual and complex morphology of O<sub>3</sub> in this year [MG2006]. A smaller estimate of  $\sim 108$  DU is obtained from the empirical relationship of Rex *et al.* [2004], while a larger value of  $\sim 127$  DU is obtained from the profile-descent technique. The average from the four methods is 119 DU, which is the largest Arctic column O<sub>3</sub> loss observed. Further investigation using modeling and other observations is necessary to better understand the O<sub>3</sub> depletion during this winter.

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#### References

- Bernath, P. F., et al. (2005), Atmospheric Chemistry Experiment (ACE): Mission overview, *Geophys. Res. Lett.*, **32**, L15S01, doi:10.1029/2005GL022386.
- Boone, C. D., et al. (2005), Retrievals for the atmospheric chemistry experiment Fourier-transform spectrometer, *Appl. Opt.*, **44**(33), 7218–7231.
- Dufour, G., et al. (2006), Partitioning between the inorganic chlorine reservoirs HCl and ClONO<sub>2</sub> during the Arctic winter 2005 from the ACE-FTS, *Atmos. Chem. Phys. Disc.*, **6**, 1249–1273.
- Esler, J. G., and D. W. Waugh (2002), A method for estimating the extent of denitrification of arctic polar vortex air from tracer-tracer scatter plots, *J. Geophys. Res.*, **107**(D13), 4169, doi:10.1029/2001JD001071.
- Froidevaux, L., et al. (2006), Early validation analyses of atmospheric profiles from EOS MLS on the Aura satellite, *IEEE Trans. Geosci. Remote Sens.*, **44**(5), 1106–1121.
- Fussen, D., F. Vanhellemont, J. Dodion, C. Bingen, K. A. Walker, C. D. Boone, S. D. McLeod, and P. F. Bernath (2005), Initial inter-comparison of ozone and nitrogen dioxide number density profiles retrieved by the ACE-FTS and GOMOS occultation experiments, *Geophys. Res. Lett.*, **32**, L16S02, doi:10.1029/2005GL022468.
- Hoppel, K., R. Bevilacqua, G. Nedoluha, C. Deniel, F. Lefèvre, J. Lumpe, M. Fromm, C. Randall, J. Rosenfield, and M. Rex (2002), POAM III observations of arctic ozone loss for the 1999/2000 winter, *J. Geophys. Res.*, **107**(D20), 8262, doi:10.1029/2001JD000476.
- Kistler, R., et al. (2001), The NCEP-NCAR 50-year reanalysis: Monthly means CD-ROM and documentation, *Bull. Am. Meteorol. Soc.*, **82**, 247–267.
- Manney, G. L., et al. (1994), On the motion of air through the stratospheric polar vortex, *J. Atmos. Sci.*, **51**, 2973–2994.
- Manney, G. L., K. Krüger, J. L. Sabutis, S. A. Sena, and S. Pawson (2005), The remarkable 2003–2004 winter and other recent warm winters in the Arctic stratosphere since the late 1990s, *J. Geophys. Res.*, **110**, D04107, doi:10.1029/2004JD005367.
- Manney, G. L., M. L. Santee, L. Froidevaux, K. Hoppel, N. J. Livesey, and J. W. Waters (2006), EOS MLS observations of ozone loss in the 2004–2005 Arctic winter, *Geophys. Res. Lett.*, **33**, L04802, doi:10.1029/2005GL024494.
- McHugh, M., B. Magill, K. A. Walker, C. D. Boone, P. F. Bernath, and J. M. Russell III (2005), Comparison of atmospheric retrievals from ACE and HALOE, *Geophys. Res. Lett.*, **32**, L15S10, doi:10.1029/2005GL022403.
- Müller, R., et al. (1997), Severe chemical ozone loss in the Arctic during the winter of 1995–1996, *Nature*, **389**, 709–712.
- Müller, R., et al. (2005), Impact of mixing and chemical change on ozone-tracer relations in the polar vortex, *Atmos. Chem. Phys.*, **5**, 3139–3151.
- Newman, P. A., et al. (2002), An overview of the SOLVE/THESEO 2000 campaign, *J. Geophys. Res.*, **107**(D20), 8259, doi:10.1029/2001JD001303.
- Petelina, S. V., et al. (2005), Validation of ACE-FTS stratospheric ozone profiles against Odin/OSIRIS measurements, *Geophys. Res. Lett.*, **32**, L15S06, doi:10.1029/2005GL022377.
- Proffitt, M. H., et al. (1990), Ozone loss in the Arctic polar vortex inferred from high altitude aircraft measurements, *Nature*, **347**, 31–36.
- Ray, E. A., F. L. Moore, J. W. Elkins, D. F. Hurst, P. A. Romashkin, G. S. Dutton, and D. W. Fahey (2002), Descent and mixing in the 1999–2000 northern polar vortex inferred from in situ tracer measurements, *J. Geophys. Res.*, **107**(D20), 8285, doi:10.1029/2001JD000961.

- Rex, M., et al. (1999), Subsidence, mixing, and denitrification of Arctic polar vortex air measured during POLARIS, *J. Geophys. Res.*, *104*(D21), 26,611–26,624.
- Rex, M., et al. (2002), Chemical depletion of Arctic ozone in winter 1999/2000, *J. Geophys. Res.*, *107*(D20), 8276, doi:10.1029/2001JD000533.
- Rex, M., R. J. Salawitch, P. von der Gathen, N. R. P. Harris, M. P. Chipperfield, and B. Naujokat (2004), Arctic ozone loss and climate change, *Geophys. Res. Lett.*, *31*, L04116, doi:10.1029/2003GL018844.
- Richard, E. C., et al. (2001), Severe chemical ozone loss inside the Arctic polar vortex during winter 1999–2000 inferred from in situ airborne measurements, *Geophys. Res. Lett.*, *28*(11), 2197–2200.
- Salawitch, R. J., et al. (2002), Chemical loss of ozone during the Arctic winter of 1999/2000: An analysis based on balloon-borne observations, *J. Geophys. Res.*, *107*(D20), 8269, doi:10.1029/2001JD000620.
- Swinbank, R., N. B. Ingleby, P. M. Boorman, and R. J. Renshaw (2002), A 3D variational data assimilation system for the stratosphere and troposphere, *Tech. Rep. 71*, Met Off. Numer. Weather Predict. Forecasting Res., Exeter, U.K.
- Walker, K. A., C. E. Randall, C. R. Trepte, C. D. Boone, and P. F. Bernath (2005), Initial validation comparisons for the Atmospheric Chemistry Experiment (ACE-FTS), *Geophys. Res. Lett.*, *32*, L16S04, doi:10.1029/2005GL022388.
- World Meteorological Organization (WMO) (2003), *Scientific Assessment of Ozone Depletion: 2002, Global Ozone Research and Monitoring Project—Report No. 47*, 498 pp., Geneva.
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