



## Denitrification in the Arctic winter 2004/2005: Observations from ACE-FTS

J. J. Jin,<sup>1</sup> K. Semeniuk,<sup>1</sup> G. L. Manney,<sup>2,3</sup> A. I. Jonsson,<sup>1</sup> S. R. Beagley,<sup>1</sup>  
J. C. McConnell,<sup>1</sup> C. P. Rinsland,<sup>4</sup> C. D. Boone,<sup>5</sup> K. A. Walker,<sup>5</sup> and P. F. Bernath<sup>5</sup>

Received 26 July 2006; revised 28 August 2006; accepted 6 September 2006; published 12 October 2006.

[1] Arctic denitrification in the winter 2004/2005 is analyzed using measurements from the satellite instrument ACE-FTS. Two methods based on changes in the correlations of odd nitrogen ( $\text{NO}_y$ ) versus methane and versus an artificial long-lived tracer are employed. The observations show that significant denitrification occurred in the region 15 km–20 km and that it was spatially inhomogeneous within the polar vortex. Before the vortex breakup in mid-March 2005 a maximum denitrification of  $8 \pm 0.8$  ppbv, accounting for a relative reduction of over 50%, was observed at  $\sim 450$  K ( $\sim 17$  km) using both methods. When averaged over the polar vortex for the first half of March, the denitrification at this level was about 4.4 ppbv and 5.0 ppbv from the artificial tracer method and the correlation method, respectively. **Citation:** Jin, J. J., K. Semeniuk, G. L. Manney, A. I. Jonsson, S. R. Beagley, J. C. McConnell, C. P. Rinsland, C. D. Boone, K. A. Walker, and P. F. Bernath (2006), Denitrification in the Arctic winter 2004/2005: Observations from ACE-FTS, *Geophys. Res. Lett.*, 33, L19814, doi:10.1029/2006GL027687.

### 1. Introduction

[2] Denitrification refers to the permanent removal of odd nitrogen ( $\text{NO}_y$ ) from the polar lower stratosphere, and is caused by the sedimentation of polar stratospheric clouds (PSCs) that contain nitric acid ( $\text{HNO}_3$ ). Polar ozone loss in spring is caused by catalytic reactions between odd oxygen ( $\text{O} + \text{O}_3$ ) and active chlorine (Cl, ClO and HOCl) and active bromine (Br, BrO, and HOBr), which are activated through heterogeneous reactions on the surface of PSCs and are deactivated through reactions with nitrogen dioxide ( $\text{NO}_2$ ) and methane ( $\text{CH}_4$ ). Therefore denitrification can delay chlorine deactivation and consequently prolong polar ozone reduction [e.g., Santee *et al.*, 1996; Rex *et al.*, 1997; Tabazadeh *et al.*, 2000; Waibel *et al.*, 1999]. This phenomenon occurs frequently in the Antarctic [e.g., Fahey *et al.*, 1990; Santee *et al.*, 2004] because of the low winter temperatures. It occurs less frequently and denitrification is less extensive in the Arctic as a result of the often disturbed Arctic polar vortex and consequent higher temperatures. However,

significant denitrification has been observed in the Arctic for several exceptionally cold winters [Sugita *et al.*, 1998; Kondo *et al.*, 2000; Fahey *et al.*, 1990, 2001; Popp *et al.*, 2001].

[3] The Arctic winter 2004/2005 was particularly cold [Kleinböhl *et al.*, 2005; Manney *et al.*, 2006], and there was significant polar stratospheric cloud formation (A. Y. Zsetsky *et al.*, manuscript in preparation, 2006). Consequent severe ozone loss has been reported [Jin *et al.*, 2006; Manney *et al.*, 2006; von Hobe *et al.*, 2006; Singleton *et al.*, 2006], and denitrification has been seen in airborne [Kleinböhl *et al.*, 2005] and EOS MLS [Schoeberl *et al.*, 2006] observations. In addition, chlorine activation and deactivation during this winter was analyzed by Dufour *et al.* [2006]. In this study we use the version 2.2 data from the satellite instrument ACE-FTS [Bernath *et al.*, 2005] to analyze the denitrification for this winter. ACE-FTS is a Fourier Transform Spectrometer with a vertical resolution of  $\sim 3$ –4 km; details of the retrieval approach are described by Boone *et al.* [2005].

[4] A useful approach to study polar denitrification is the correlation method [e.g., Fahey *et al.*, 1990; Popp *et al.*, 2001]. In this method, the deviation from the standard correlation of  $\text{NO}_y$  versus a long-lived tracer is interpreted as denitrification. However, it has been shown that this method can overestimate the extent of denitrification [Michelsen *et al.*, 1998] since tracer correlations can also be altered by mixing processes. Rex *et al.* [1999] used a mixing-line method to analyze denitrification assuming that mixing occurs in a single mixing event. Later, Plumb *et al.* [2000] showed that the mixing-line method was unable to remove all of the mixing effects. To avoid some of these problems, Esler and Waugh [2002] composed an artificial tracer that has a linear relation with  $\text{NO}_y$ , so that mixing does not change the correlations, to get a robust estimate of denitrification.

[5] The signature of depleted  $\text{NO}_y$  must be viewed with caution as  $\text{HNO}_3$  can be temporarily sequestered in PSCs, such as supercooled ternary solutions (STS), which are sufficiently small that they sediment too slowly for  $\text{HNO}_3$  removal. A potential indirect signature of denitrification via sedimentation is the increase of  $\text{NO}_y$  mixing ratios at lower altitudes when large PSC particles such as  $\text{HNO}_3$ –containing Nitric Acid Trihydrate (NAT) “rocks” evaporate [cf. Waibel *et al.*, 1999; Kleinböhl *et al.*, 2005].

[6] In this study we estimate the denitrification from both the correlation method and the artificial tracer method. We also observe the signature of evaporated  $\text{NO}_y$  at lower altitudes.

### 2. Results and Discussion

[7] We have analyzed ACE-FTS measurements between 350 K–1000 K ( $\sim 12$  km–35 km) in the Arctic ( $50^\circ\text{N}$ –

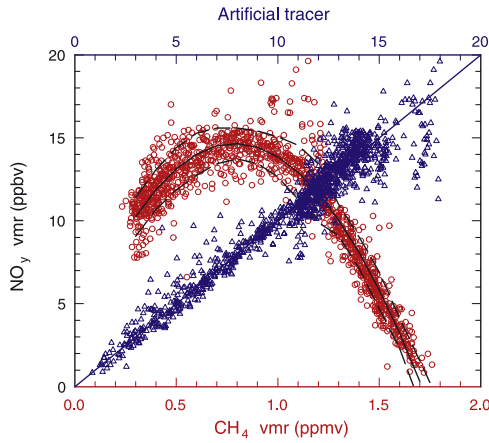
<sup>1</sup>Department of Earth and Space Science and Engineering, York University, Toronto, Ontario, Canada.

<sup>2</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA.

<sup>3</sup>Also at New Mexico Institute of Mining and Technology, Socorro, New Mexico, USA.

<sup>4</sup>NASA Langley Research Center, Hampton, Virginia, USA.

<sup>5</sup>Department of Chemistry, University of Waterloo, Waterloo, Ontario, Canada.



**Figure 1.** Correlations of  $\text{NO}_y/\text{CH}_4$  (red circles) and  $\text{NO}_y$ /artificial tracer (blue triangles) between 350 K–1000 K ( $\sim 12$  km–35 km) for 1–15 January 2005. The black solid line is a 3rd order polynomial fit for the  $\text{NO}_y/\text{CH}_4$  correlation. The black dashed lines represent the  $1\text{-}\sigma$  error range of the fit. The blue solid line represents a linear fit that has  $\text{NO}_y$  equal to the artificial tracer.

$80^\circ\text{N}$ ) for the period January–March 2005. We consider measurements north of  $50^\circ\text{N}$  with sPV (scaled potential vorticity [Manney *et al.*, 1994])  $> 1.8 \times 10^{-4} \text{ s}^{-1}$  above 500 K and sPV  $> 1.4 \times 10^{-4} \text{ s}^{-1}$  between 350 K–500 K to be inside the polar vortex. sPV is calculated from NASA’s Global Modeling and Assimilation Office Goddard Earth Observation System version 4.0.3 (GEOS-4) meteorological analyses [Bloom *et al.*, 2005].

[8] Some of the odd nitrogen species ( $\text{HNO}_3$ ,  $\text{ClONO}_2$ ,  $\text{NO}_2$ ,  $\text{N}_2\text{O}_5$ , and  $\text{NO}$ ) were not retrieved in the lower stratosphere because of low densities, thus  $\text{NO}_y$  is derived as follows

$$\text{NO}_y = \text{HNO}_3 + \text{ClONO}_2 \quad (\text{potential temperature} < 450 \text{ K}),$$

$$\text{NO}_y = \text{HNO}_3 + \text{ClONO}_2 + \text{NO}_2 + 2 \times \text{N}_2\text{O}_5 \quad (450 \text{ K} \leq \text{potential temperature} < 600 \text{ K}),$$

$$\text{NO}_y = \text{HNO}_3 + \text{ClONO}_2 + \text{NO}_2 + 2 \times \text{N}_2\text{O}_5 + \text{NO} \quad (\text{potential temperature} \geq 600 \text{ K}).$$

We estimate that errors in the  $\text{NO}_y$  estimates are less than 10%.

[9] Figure 1 shows the correlation of  $\text{NO}_y$  versus  $\text{CH}_4$  for 1–15 January 2005 and a polynomial fit to the data

$$\text{NO}_y = 0.878305 \times \text{CH}_4^3 - 20.1389 \times \text{CH}_4^2 + 30.1194 \times \text{CH}_4 + 2.99409. \quad (1)$$

where  $\text{NO}_y$  and  $\text{CH}_4$  are volume mixing ratios in ppbv and ppmv, respectively. After 15 January 2005 the deviation from this correlation is employed to derive the  $\text{NO}_y$  change in the polar vortex. However, because of the curvature of the  $\text{NO}_y/\text{CH}_4$  relationship, the correlation can change with

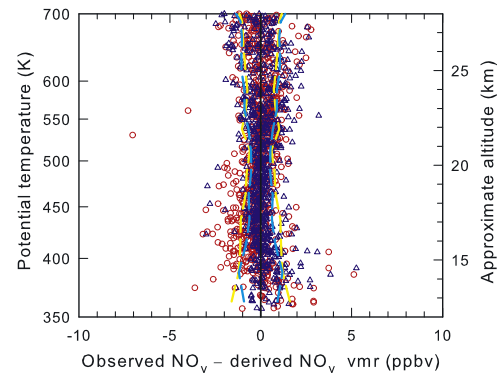
horizontal or vertical mixing. Therefore, using  $\text{NO}_y$  and  $\text{CH}_4$  observations within the  $1\text{-}\sigma$  error range of the above polynomial fit and simultaneous  $\text{N}_2\text{O}$ , CFC-11, and OCS observations between 350 K–1000 K for 1–15 January 2005, we compose an artificial tracer along the lines proposed by Esler and Waugh [2002] with the coefficients determined by a linear regression.

$$\begin{aligned} \text{Artificial tracer} = & 1.180 \times 10^{-2} \text{ CH}_4 \text{ (ppbv)} \\ & - 3.522 \times 10^{-2} \text{ N}_2\text{O} \text{ (ppbv)} \\ & - 4.778 \times 10^{-3} \text{ CFC-11 (pptv)} \\ & - 3.376 \times 10^{-2} \text{ OCS (pptv)} + 7.740 \quad (2) \end{aligned}$$

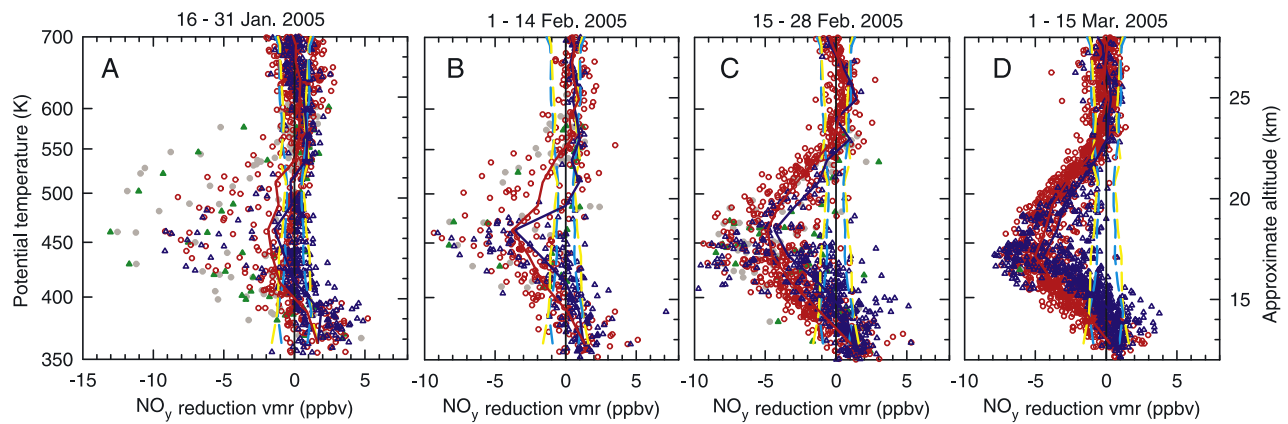
A linear correlation of  $\text{NO}_y$  with the artificial long-lived tracer for 1–15 January 2005 is obtained and shown in Figure 1. Because of the linear relationship, the correlation is insensitive to mixing processes. Here the linear fit that has  $\text{NO}_y$  equal to the artificial tracer is taken to be the representative of pre-denitrification conditions. Thus we attribute any deviation from this correlation after 15 January 2005 to denitrification or renitrification.

[10] Figure 2 shows the  $\text{NO}_y$  reductions, which are the differences between the observed  $\text{NO}_y$  and the  $\text{NO}_y$  derived from the correlation methods, for the period 1–15 January 2005. Generally, the results from the two methods are very similar and show no significant bias as expected for this period. The  $1\text{-}\sigma$  deviations from zero are almost the same above  $\sim 380$  K ( $\sim 14$  km), and are about 0.5–1.2 ppbv between 380 K–700 K.

[11]  $\text{NO}_y$  reductions inside the polar vortex between 16 January–15 March 2005 are shown in Figure 3. In order to exclude the possibility of temporary sequestration within PSC particles, observations with temperatures above and below the threshold temperature  $T_{\text{NAT}}$  for NAT formation are shown separately in this figure: we assume that no sequestration occurs above  $T_{\text{NAT}}$ .  $T_{\text{NAT}}$  is derived from simultaneous ACE-FTS water vapor and  $\text{HNO}_3$  observations using the formula of Hanson and Mauersberger [1988]. We note that there are more data points available from the correlation method than from the artificial tracer method. This is because we required all four species to be available for the artificial tracer while for some occultations



**Figure 2.**  $\text{NO}_y$  reductions for 1–15 January 2005 from the correlation method (red circles) and the artificial tracer method (blue triangles). The yellow and cyan dashed lines represent the  $1\text{-}\sigma$  deviations from zero for the two methods, respectively.



**Figure 3.**  $\text{NO}_y$  reductions inside the polar vortex for the periods 16 January 2005–15 March 2005. The open red and closed grey circles are calculations from the correlation method, and the open blue and closed green triangles are calculations from the artificial tracer method. The open and closed symbols are observations for temperatures above and below  $T_{\text{NAT}}$ , respectively. The red and blue solid lines are averages of the results with temperatures above  $T_{\text{NAT}}$  from the two methods. The yellow and cyan dashed lines are the same as in Figure 2.

not all of them were retrieved on account of low densities. Individual comparisons (not shown) indicate that differences between the results from the two methods can be seen up to 500 K, with the largest differences, over 5 ppbv for some observations, occurring between 380 K–425 K after the middle of February. This suggests that the denitrification is overestimated by the correlation method because of mixing [Michelsen *et al.*, 1998; Rex *et al.*, 1999; Plumb *et al.*, 2000]. Despite the significant differences for some of the individual denitrification estimates, the difference between their averages is less than 1 ppbv above  $\sim 425$  K ( $\sim 16$  km) and less than 2 ppbv below this level.

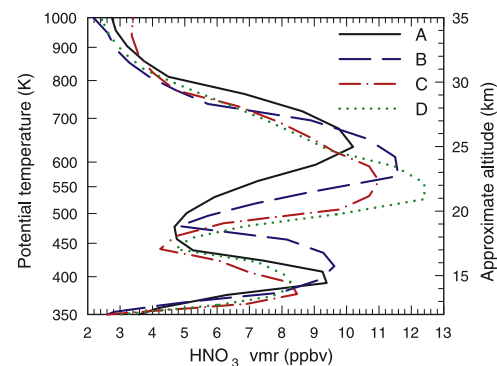
[12] The  $\text{NO}_y$  departure from the gas phase was observed as early as in the second half of January 2005 (Figure 3a). This likely reflects the presence of a pool of extremely cold air over northern Canada and Scandinavia at the end of the month [e.g., Dufour *et al.*, 2006].  $\text{NO}_y$  reductions occurred between 400 K–550 K ( $\sim 15$  km–23 km). Sequestration plus denitrification ( $T < T_{\text{NAT}}$ ) resulted in  $\text{NO}_y$  reductions as large as 12 ppbv. The largest denitrification ( $T > T_{\text{NAT}}$ ) present during this period occurred at  $\sim 450$  K ( $\sim 17$  km), and was about  $9 \pm 0.8$  ppbv from the correlation method and from the artificial tracer method, corresponding to a relative reduction of about 60%. The error is the  $1-\sigma$  deviation from zero of the  $\text{NO}_y$  reduction for 1–15 January 2005. However, the average of the vortex denitrification for this period was limited to  $< 2$  ppbv (Figure 3a), suggesting that the denitrification was not widespread.

[13] We also note an  $\text{NO}_y$  increase of  $\sim 5$  ppbv at  $\sim 400$  K ( $\sim 15$  km) and below. Since neither mixing nor horizontal transport can change the correlations to produce the  $\text{NO}_y$  enhancement, we attribute the increase to the sedimentation and evaporation of  $\text{HNO}_3$ -containing particles [cf. Waibel *et al.*, 1999]. Several typical  $\text{HNO}_3$  profiles indicating the increase at  $\sim 400$  K in January are shown in Figure 4. The increase of  $\text{HNO}_3$  at lower levels appears to be a signature of removal from upper levels, not withstanding the effect of horizontal wind shear along altitudes. Such renitrification has also been observed at potential temperatures above 340 K during the Polar Aura Validation Experiment (PAVE) flights at the end of January 2005 [Dibb *et al.*, 2006] and by

EOS MLS at  $\sim 15$  km from the end of December 2004 [see also Schoeberl *et al.*, 2006].

[14] The denitrification intensified by the end of February (Figures 3b and 3c), which is consistent with the meteorological context. The potential PSC area in which the air temperature is below  $T_{\text{NAT}}$  at 475 K remained large (over  $10 \times 10^6$  km<sup>2</sup>) until the middle of February, and did not totally disappear until the middle of March [Kleinböhl *et al.*, 2005]. We note that there were more ACE-FTS inner vortex observations available in March than in January (see equivalent latitude change in work by Dufour *et al.* [2006]) because of the poleward shifting of the orbit. It is difficult, therefore, to determine quantitatively how the denitrification intensified during this period.

[15] By the middle of March 2005, when the polar vortex broke up [Manney *et al.*, 2006], the vortex air was significantly denitrified between 400 K–500 K ( $\sim 15$  km–20 km) (Figure 3d). Both methods yield maximum denitrification estimates of about  $8 \pm 0.8$  ppbv, accounting for over 50% relative reductions locally, at  $\sim 450$  K ( $\sim 17$  km). The maximum was slightly smaller than the value at the end of February. We note that the difference in denitrification



**Figure 4.** Several typical  $\text{HNO}_3$  profiles. Line A, at ( $63^\circ\text{N}$ ,  $96^\circ\text{W}$ ) on 13 January 2005; line B, at ( $63^\circ\text{N}$ ,  $66^\circ\text{W}$ ) on 16 January 2005; line C, at ( $65^\circ\text{N}$ ,  $80^\circ\text{W}$ ) on 22 January 2005; and line D, at ( $65^\circ\text{N}$ ,  $63^\circ\text{W}$ ) on 23 January 2005.

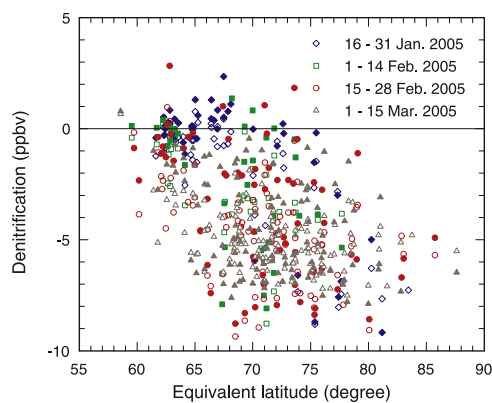
was likely because different air parcels were sampled so their denitrification histories were different as opposed to this being a signature of release of  $\text{NO}_y$  from PSC particles. The denitrification average reached a maximum by the end of February: about 5.0 ppbv and 4.4 ppbv at  $\sim 17$  km from the correlation method and the artificial tracer method, respectively. The altitude of the peak descended slightly but the maximum averages remained unchanged for 1–15 March 2005.

[16] The denitrification within the vortex was horizontally inhomogeneous in extent. Figure 5 shows the denitrification estimates plotted versus equivalent latitude (EqL, the latitude that would enclose the same area between it and the pole as a given potential vorticity contour) between 430 K–460 K where the largest  $\text{NO}_y$  reductions occurred. The broad range of denitrification estimates at high EqL suggests that the denitrification did not occur uniformly. This reflects the non-uniform distribution of temperatures below  $T_{\text{NAT}}$  inside the vortex. Meteorological analyses show that the region of the lowest temperatures during January and February was localized over Scandinavia and the north Atlantic so that vortex interior air was not processed homogeneously.

[17] Our denitrification estimates are in reasonable agreement with results from other measurements and modeling. For example, the maximum average of about 3.7 ppbv at around 450 K in early February 2005 (Figure 3b) is close to the value of  $3.1 \pm 0.8$  ppbv obtained from airborne measurements for the same period [Kleinböhl *et al.*, 2005]. However, the maximum average from the ACE-FTS data occurred  $\sim 2$ – $3$  km lower than for the aircraft data, and the largest individual  $\text{NO}_y$  reduction was about 3 ppbv larger than the largest reduction of  $\text{HNO}_3$  in the aircraft study, noting that  $\text{HNO}_3$  constitutes  $> 85\%$  of  $\text{NO}_y$  in lower polar vortex. The differences can be attributed to the coarse vertical resolution (6–10 km) of the aircraft data and the different sampling in the inhomogeneously denitrified polar vortex. The estimated maximum relative  $\text{NO}_y$  reduction in early March is slightly smaller than the 70% predicted by modeling [von Hobe *et al.*, 2006] for early March. On the other hand, the maxima of individual observations and relative reductions are comparable to analyses using balloon-borne and airborne in-situ measurements in previous cold Arctic winters such as the winter 1994/1995 [Sugita *et al.*, 1998; Waibel *et al.*, 1999] and the winter 1999/2000 [Popp *et al.*, 2001].

[18] EOS MLS data also indicate significant Arctic denitrification for this winter [Schoeberl *et al.*, 2006]. The maximum denitrification reached 18 ppbv in January and in February, and reached 14 ppbv in early March at  $\sim 450$  K. These values are  $\sim 6$ – $8$  ppbv larger than the ACE-FTS maxima. The difference can, in part, be attributed to the fact that EOS MLS  $\text{HNO}_3$  mixing ratios are up to 30% larger than those from ACE-FTS [Froidevaux *et al.*, 2006]. However, we note that comparisons of MIPAS/ENVISAT  $\text{HNO}_3$  measurements with Odin/SMR, ACE-FTS, and balloon measurements suggest good agreement with differences generally  $< 15\%$  below 30 km [Mencaraglia *et al.*, 2006; Wang *et al.*, 2006].

[19] Although the temperature in the Arctic polar vortex was particularly low in the winter 2004/2005, the air with temperature below the threshold temperature for ice formation only constituted a very small fraction of the vortex



**Figure 5.**  $\text{NO}_y$  reductions between 430 K–460 K versus equivalent latitudes. The open and closed symbols are results from the correlation method and the artificial tracer method, respectively.

volume and was not continuously present [Kleinböhl *et al.*, 2005; Jiménez *et al.*, 2006]. As a result, no noticeable dehydration was observed by ACE-FTS, and EOS MLS only observed one single dehydration event of up to 0.5 ppmv [Jiménez *et al.*, 2006]. These observations are similar to those for previous cold Arctic winters [World Meteorological Organization, 2003], and are consistent with the simulations showing that Arctic denitrification is caused by the sedimentation of large  $\text{HNO}_3$ -containing particles rather than by the sedimentation of ice particles [Carslaw *et al.*, 2002].

### 3. Summary

[20] Significant Arctic denitrification was observed by ACE-FTS in the polar vortex between 400 K–550 K ( $\sim 15$  km– $23$  km) in the winter 2004/2005 although no obvious dehydration was measured. ACE-FTS observed denitrified air from the middle of January to the middle of March. The denitrification, analyzed by a correlation method and an artificial tracer method, occurred inhomogeneously inside the vortex. Before the vortex breakup at the middle of March, both methods give a maximum local denitrification of  $8 \pm 0.8$  ppbv at  $\sim 450$  K ( $\sim 17$  km) although the correlation method produces larger denitrification estimates than the artificial tracer method for some individual observations because of episodic mixing [Manney *et al.*, 2006; Jin *et al.*, 2006; Schoeberl *et al.*, 2006]. The denitrification intensified by the end of February and the maximum average reached  $\sim 4.4$ – $5.0$  ppbv before the vortex broke up. Sedimentation and evaporation of PSC particles appear to have led to an  $\text{NO}_y$  increase below  $\sim 15$  km. The magnitude of the denitrification observed by ACE-FTS is smaller than estimates from EOS MLS observations, but is consistent with other observations and modeling results for this winter and comparable to the denitrification in previous cold winters.

[21] **Acknowledgments.** We thank Ross Salawitch for useful conversations. Funding for ACE is provided by the Canadian Space Agency and the Natural Sciences and Engineering Research Council (NSERC) of Canada. Support was also provided by the NSERC-Bomem-CSA-MSI Industrial Research Chair in Fourier Transform Spectroscopy and by the

Canadian Foundation for Climate and Atmospheric Science. Work at the Jet Propulsion Laboratory, California Institute of Technology was done under contract with the National Aeronautics and Space Administration.

## References

- Bernath, P. F., et al. (2005), Atmospheric Chemistry Experiment (ACE): Mission overview, *Geophys. Res. Lett.*, *32*, L15S01, doi:10.1029/2005GL022386.
- Bloom, S. C., et al. (2005), The Goddard Earth Observing Data Assimilation System, GEOS DAS version 4.0.3: Documentation and validation, *NASA Tech. Rep.*, 104606 V26.
- Boone, C. D., et al. (2005), Retrievals for the atmospheric chemistry experiment Fourier-transform spectrometer, *Appl. Opt.*, *44*(33), 7218–7231.
- Carlsaw, K. S., et al. (2002), A vortex-scale simulation of the growth and sedimentation of large nitric acid hydrate particles, *J. Geophys. Res.*, *107*(D20), 8300, doi:10.1029/2001JD000467.
- Dibb, J. E., et al. (2006), In situ evidence for renitrification in the Arctic lower stratosphere during the polar aura validation experiment (PAVE), *Geophys. Res. Lett.*, *33*, L12815, doi:10.1029/2006GL026243.
- 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.*, *6*, 2355–2366.
- Eslser, 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.
- Fahey, D. W., et al. (1990), Observations of denitrification and dehydration in the winter polar stratospheres, *Nature*, *344*, 321–324.
- Fahey, D. W., et al. (2001), The detection of large HNO<sub>3</sub>-containing particles in the winter Arctic stratosphere, *Science*, *291*, 1026–1031.
- 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.
- Hanson, D., and K. Mauersberger (1988), Laboratory studies of the nitric acid trihydrate: Implications for the South polar stratosphere, *Geophys. Res. Lett.*, *15*(8), 855–858.
- Jiménez, C. J., et al. (2006), Dehydration in the 2004–2005 polar winters: A first look from EOS MLS, *Geophys. Res. Lett.*, *33*, L16806, doi:10.1029/2006GL025926.
- 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.
- Kleinböhl, A., et al. (2005), Denitrification in the Arctic mid-winter 2004/2005 observed by airborne submillimeter radiometry, *Geophys. Res. Lett.*, *32*, L19811, doi:10.1029/2005GL023408.
- Kondo, Y., et al. (2000), Denitrification and nitrification in the Arctic stratosphere during the winter of 1996–1997, *Geophys. Res. Lett.*, *27*(3), 337–340.
- 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., et al. (2006), EOS MLS observations of ozone loss in the 2004–2005 Arctic winter, *Geophys. Res. Lett.*, *33*, L04802, doi:10.1029/2005GL024494.
- Mencaraglia, F., et al. (2006), Validation of MIPAS satellite measurements of HNO<sub>3</sub> using comparison of rotational and vibrational spectroscopy, *J. Geophys. Res.*, *111*, D19305, doi:10.1029/2005JD006099.
- Michelsen, H. A., et al. (1998), Correlations of stratospheric abundances of NO<sub>x</sub>, O<sub>3</sub>, N<sub>2</sub>O, and CH<sub>4</sub> derived from ATMOS measurements, *J. Geophys. Res.*, *103*(D21), 28,347–28,360.
- Plumb, R. A., et al. (2000), The effects of mixing on tracer relationships in the polar vortices, *J. Geophys. Res.*, *105*(D8), 10,047–10,062.
- Popp, P. J., et al. (2001), Severe and extensive denitrification in the 1999–2000 Arctic winter stratosphere, *Geophys. Res. Lett.*, *28*(15), 2875–2878.
- Rex, M., et al. (1997), Prolonged stratospheric ozone loss in the 1995–96 Arctic winter, *Nature*, *389*, 835–838.
- 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.
- Santee, M. L., et al. (1996), Chlorine deactivation in the lower stratospheric polar regions during late winter: Results from UARS, *J. Geophys. Res.*, *101*(D13), 18,835–18,860.
- Santee, M. L., et al. (2004), Three-dimensional structure and evolution of stratospheric HNO<sub>3</sub> based on UARS Microwave Limb Sounder measurements, *J. Geophys. Res.*, *109*, D15306, doi:10.1029/2004JD004578.
- Schoeberl, M. R., et al. (2006), Chemical observations of a polar vortex intrusion, *J. Geophys. Res.*, doi:10.1029/2006JD007134, in press.
- Singleton, C. S., et al. (2006), Quantifying Arctic ozone loss during the 2004–2005 winter using satellite observations and a chemical transport model, *J. Geophys. Res.*, doi:10.1029/2006JD007463, in press.
- Sugita, T., et al. (1998), Denitrification observed inside the Arctic vortex in February 1995, *J. Geophys. Res.*, *103*(D13), 16,221–16,234.
- Tabazadeh, A., et al. (2000), Quantifying denitrification and its effect on ozone recovery, *Science*, *288*, 1407–1411.
- von Hobe, M., et al. (2006), Severe ozone depletion in the cold Arctic winter 2004–05, *Geophys. Res. Lett.*, *33*, L17815, doi:10.1029/2006GL026945.
- Waibel, A. E., et al. (1999), Arctic ozone loss due to denitrification, *Science*, *283*, 2064–2069.
- Wang, D. Y., et al. (2006), Validation of nitric acid retrieved by the IMK-IAA processor from MIPAS/ENVISAT measurements, *Atmos. Chem. Phys. Discuss.*, in press.
- World Meteorological Organization (2003), Scientific assessment of ozone depletion: 2002, *Global Res. Monit. Project Rep.* 47, Geneva.

S. R. Beagley, J. J. Jin, A. I. Jonsson, J. C. McConnell, and K. Semeniuk, Department of Earth and Space Science and Engineering, York University, 4700 Keele Street, Toronto, Canada M3J 1L2. (beagley@nimbus.yorku.ca; jin@nimbus.yorku.ca; jonsson@yorku.ca; jack@nimbus.yorku.ca; kirill@nimbus.yorku.ca)

P. F. Bernath, D. C. Boone, and K. A. Walker, Department of Chemistry, University of Waterloo, 200 University Avenue West, Waterloo, Canada N2L 3G1. (bernath@uwaterloo.ca; cboone@sciborg.uwaterloo.ca; kawalker@acebox.uwaterloo.ca)

G. L. Manney, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA. (manney@mls.jpl.nasa.gov)

C. P. Rinsland, NASA Langley Research Center, Mail Stop 401A, Hampton, VA 23681, USA. (curtis.p.rinsland@nasa.gov)