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## Arctic winter 2005: Implications for stratospheric ozone loss and climate change

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[1] The Arctic polar vortex exhibited widespread regions of low temperatures during the winter of 2005, resulting in significant ozone depletion by chlorine and bromine species. We show that chemical loss of column ozone ( $\Delta O_3$ ) and the volume of Arctic vortex air cold enough to support the existence of polar stratospheric clouds ( $V_{PSC}$ ) both exceed levels found for any other Arctic winter during the past 40 years. Cold conditions and ozone loss in the lowermost Arctic stratosphere (e.g., between potential temperatures of 360 to 400 K) were particularly unusual compared to previous years. Measurements indicate  $\Delta O_3 = 121 \pm 20$  DU and that  $\Delta O_3$  versus  $V_{PSC}$  lies along an extension of the compact, near linear relation observed for previous Arctic winters. The maximum value of  $V_{PSC}$  during five to ten year intervals exhibits a steady, monotonic increase over the past four decades, indicating that the coldest Arctic winters have become significantly colder, and hence are more conducive to ozone depletion by anthropogenic halogens. **Citation:** Rex, M., et al. (2006), Arctic winter 2005: Implications for stratospheric ozone loss and climate change, *Geophys. Res. Lett.*, 33, L23808, doi:10.1029/2006GL026731.

### 1. Introduction

[2] Chemical loss of Arctic ozone for particular winters exhibits large variability, driven by variations in tempera-

ture. However, the volume of air cold enough to allow for the existence of polar stratospheric clouds (PSCs) in the Arctic vortex, averaged over winter ( $V_{PSC}$ ), exhibits a compact, near linear relation with chemical loss of column ozone ( $\Delta O_3$ ) [Rex et al., 2004; Tilmes et al., 2004].

[3] The Arctic winter of 2005 was unusually cold. The geographical extent of temperatures below the PSC formation threshold ( $A_{PSC}$ ) at particular potential temperature ( $\Theta$ ) levels was high for a broad vertical region of the polar vortex. For  $\Theta$  of 475 to 500 K, the evolution of  $A_{PSC}$  largely followed the previous record values from winter 2000 (see auxiliary material<sup>1</sup>). Below 400 K, daily values of  $A_{PSC}$  reached record levels for many weeks and the winter average was 50 to 60% larger than previously observed. For 2005,  $V_{PSC}$  (vertical integral of  $A_{PSC}$ ) reached a value 25% larger than the previous record value from winter 2000.

[4] Here, we quantify  $\Delta O_3$  using a variety of techniques. The relation between  $\Delta O_3$  and  $V_{PSC}$  is examined. Finally, a time series for  $V_{PSC}$  is shown that indicates the coldest Arctic stratosphere winters, during the past forty years, have become progressively colder.

### 2. Ozone Loss Estimates for Winter 2005

[5] Different approaches and data sets are used to characterize chemical ozone loss during the Arctic winter 2005.

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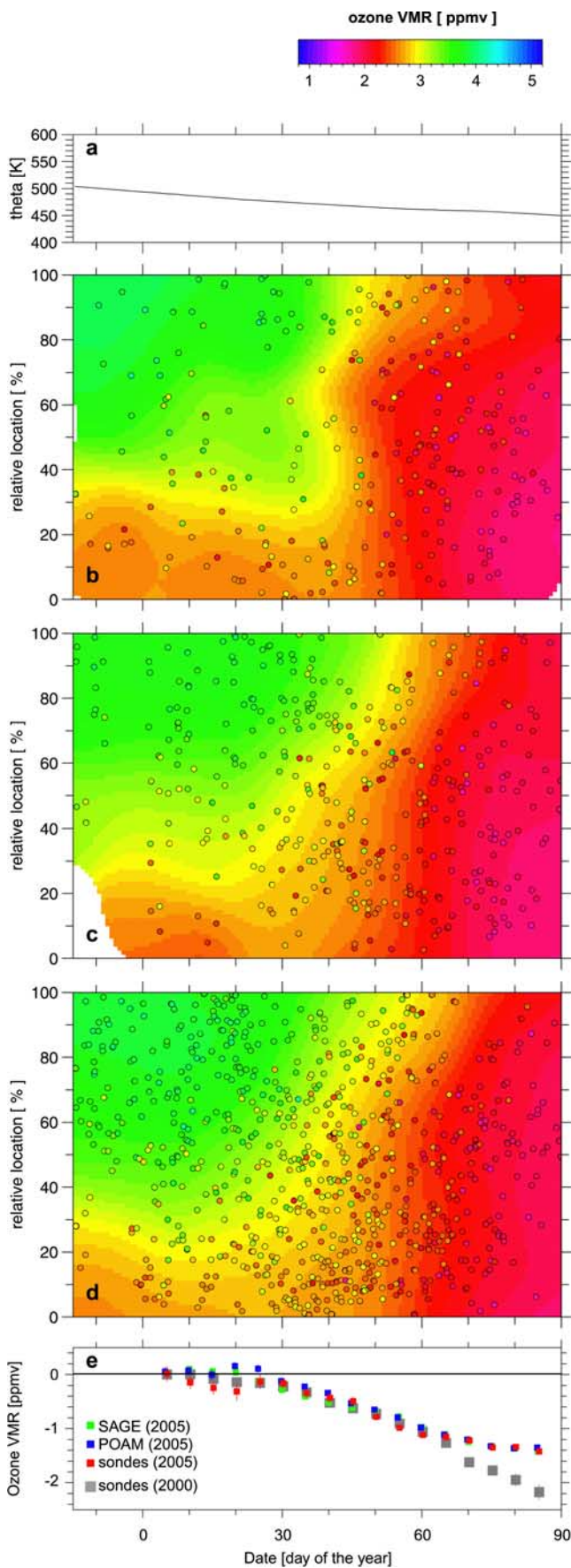
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We consider estimates based on regression analysis of data from the northern hemisphere ozone sonde station network (hereafter, ozonesondes) for air parcels sampled at different times (Match) [e.g., *Rex et al.*, 1999] and estimates based on the “vortex average descent” approach, applied to measurements by the SAGE III [*Randall et al.*, 2005] and POAM III [*Hoppel et al.*, 2002] satellite instruments. First, we describe the morphology of ozone near 450 K, which was notably different than for other cold Arctic winters.

## 2.1. Ozone Distribution and Evolution

[6] Figure 1 shows the evolution of ozone inside the Arctic polar vortex (defined by the region enclosed by the maximum gradient in potential vorticity versus equivalent latitude) on the 450 K equivalent potential temperature ( $e\Theta$ ) surface, from mid-December 2004 to March 2005, as observed by sondes, SAGE III, and POAM III. The quantity  $e\Theta$  represents the value of  $\Theta$  an air mass would achieve on 31 March using calculated, vortex average descent rates [*Rex et al.*, 2004]. The top plot shows the time evolution of  $\Theta$  for the  $e\Theta = 450$  K surface. In the absence of chemical loss and mixing,  $O_3$  should be conserved on an  $e\Theta$  surface. Figure 1e shows the evolution of vortex averaged ozone on the  $e\Theta = 450$  K surface for the winter of 2005 from sondes, SAGE III and POAM III, compared to the same quantity as observed by sondes for the winter of 2000 [from *Rex et al.*, 2002]. The data show a steady decline of ozone within the vortex between late January and early March. About 1.5 ppmv ozone was lost during the winter.

[7] The initial ozone field inside the polar vortex was characterized by relatively low ozone mixing ratios in the core of the vortex (inner 30% of the vortex area). Due to this horizontal gradient, inhomogeneities in sampling can result in uncertainties of ozone loss estimates from the vortex average [*Hoppel et al.*, 2002] or the tracer relation [*Tilmes et al.*, 2004] approaches. The sampling of the vortex by the three instruments used in this study is shown in Figures 1b–1d. Overall the sampling was quite homogenous for all instruments, with the exception of a ten day period in late January, when the sampling from the sondes was biased towards the core of the vortex (Figure 1b). A temporary dip in vortex averaged ozone from the sondes occurs at this time but has no impact on our overall ozone loss estimates. The fact that ozone loss estimates from all these instruments

**Figure 1.** (a) Time evolution of  $\Theta$  on the  $e\Theta = 450$  K surface. Measured ozone inside the Arctic vortex as a function of time and location relative to the vortex core, for the  $e\Theta = 450$  K surface, from (b) sondes, (c) SAGE III, and (d) POAM III. Circles indicate time, location and  $O_3$  of actual measurements. Location relative to the vortex core (relative location = 0%) and vortex edge (relative location = 100%) found using equivalent latitude, allowing for daily variations in vortex size [see *Rex et al.*, 1999]. Contour shading calculated by averaging over the closest measurements, gaussian weighted by distance in date/relative location space. (e) Time evolution of vortex averaged ozone mixing ratio on the  $e\Theta = 450$  K surface, from sondes, SAGE III, and POAM III (as indicated) for 2005 and from sondes for the Arctic winter of 2000.

### 380-550K partial column loss estimates:

#### winter of 2004/2005

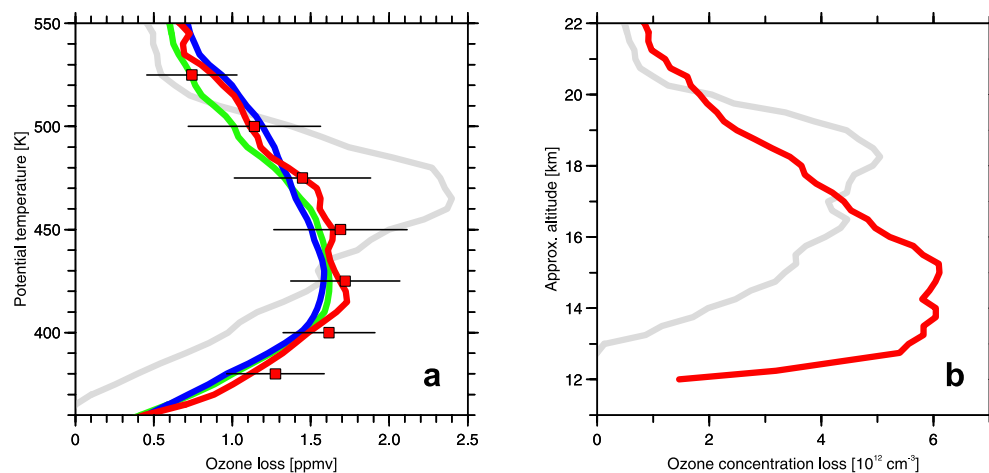
- Match: 127 +/- 21 DU
- sondes: 121 DU
- SAGE: 110 DU
- POAM: 113 DU

#### winter of 1999/2000:

- sondes: 96 DU

#### winter of 1995/1996

- sondes: 105 DU (not shown)



**Figure 2.** (a) Accumulated ozone loss mixing ratio (ppmv) between 5 Jan and 25 March, versus  $e\Theta$ , from the vortex averaged sonde method for the winters of 2005 and 2000. Also shown are ozone losses from Match and from the time evolution of vortex averaged ozone from SAGE III and POAM III. Error bars from Match represent  $1\sigma$  statistical uncertainties; additional systematic uncertainties are in the order of 20%. (b) Same as Figure 2a, except ozone loss concentration is shown from the vortex averaged sonde method for 2005 and 2000. Tabulation of chemical loss of column ozone by the various methods is also given.

agree well (Figure 1e) increases our confidence that sampling issues do not have a significant impact on our results.

## 2.2. Ozone Loss Profiles

[8] Figure 2a compares the vertical profile of ozone loss at the end of the winter derived from Match with results from the vortex average approach. We find a broad vertical range of ozone loss around 1.5 ppmv between  $\Theta$  of 400 and 450 K. Good agreement is found at all  $\Theta$  levels, further increasing our confidence that sampling or mixing issues have not influenced our results. With Match we can separate ozone changes during dark sections along the air mass trajectories from changes that occurred during sunlit portions of the trajectories [Rex *et al.*, 1999]. Figure S2 of the auxiliary material shows that changes in ozone during dark portions of the trajectories are small and if anything positive, suggesting dynamical effects did not significantly impact our estimates of ozone loss and would only lead to an underestimation of the loss rates.

[9] Figure 2a also shows the ozone loss profile for the winter of 2000 found using the vortex averaged descent approach. The maximum ozone loss for the 2005 winter, in terms of mixing ratios, was smaller than the record value reached in a narrow vertical region for the winter of 2000. This is consistent with the finding of Manney *et al.* [2006].

## 2.3. Total Column Loss

[10] The quantity most relevant for the biosphere is total ozone column. Losses of total column ozone are driven by the vertical distribution of the change in ozone concentration, shown in Figure 2b. The loss of total column ozone that occurred from 5 January to 25 March 2005, between  $e\Theta$  levels of 380 and 550 K, was 121 DU. This quantity is based on the vertical integral of the vortex averaged sonde data points in Figure 2b; the uncertainty of this estimate is  $\sim 20$  DU. Similar ozone loss is found by other instruments and from Match (Figure 2). Compared to winter 2000, the ozone loss profile in 2005 extended to lower altitudes, where ozone concentrations are large. Loss of column

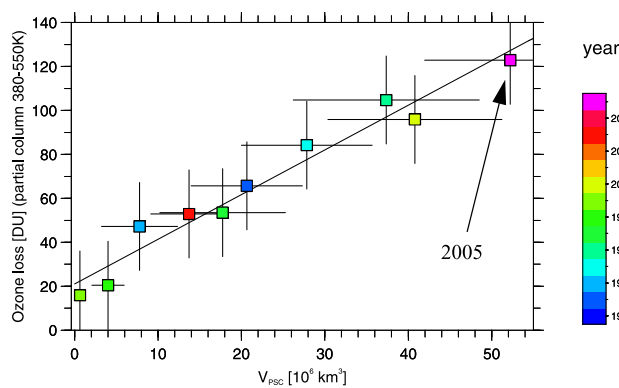
ozone for the winter of 2005 exceeds those measured during the winters of 1996 (105 DU) and 2000 (96 DU), which are the largest losses recorded previously (all values for  $e\Theta$  between 380 and 500 K). Hence, the winter of 2005 had a larger chemical loss of column ozone than any other winter during the past 40 years, although the uncertainty of the loss for this winter overlaps with the uncertainty of the loss for two previous cold winters.

[11] Quantifications of ozone losses in the vertical region below 400 K are sensitive to mixing issues (exchange of air across the edge of the polar vortex) and uncertainties in the calculated diabatic subsidence rates. The good agreement between results from Match and from the vortex average approach at 380 K (Figure 2a) suggests that mixing did not have a major impact on our ozone loss estimates at these levels. Also, we have not diagnosed substantial ozone losses in this vertical region for most previous winters (and for none of the warm winters), suggesting that the approach does not tend to produce artifacts. The larger ozone losses observed at these levels for winter 2005 are consistent with the fact that low temperatures extended to lower altitudes in this winter, compared to the previous cold winters. Note that ozone loss estimates near the bottom of the vortex are generally less reliable [e.g., Knudsen *et al.*, 1998]. Hence, the uncertainties of the loss estimates for the region below 400K are generally larger than those for the region above. But our overall conclusions still hold if the analysis is restricted to  $\Theta$  levels above 400 K (auxiliary material<sup>1</sup>).

## 3. Arctic Ozone Loss and Climate Change

[12] Based on data from the vortex average approach, Rex *et al.* [2004] reported a compact relationship between  $\Delta O_3$  and  $V_{PSC}$ . This relation was confirmed by an analysis of HALOE data using the tracer relation approach [Tilmes *et*

<sup>1</sup>Auxiliary material data sets are available at <ftp://ftp.agu.org/apend/gl/2006gl026731>. Other auxiliary material files are in the HTML.



**Figure 3.**  $\Delta O_3$  versus  $V_{PSC}$  for Arctic winters between 1993 and 2005 (no values for the warm winters of 2001, 2002, 2004 due to major mid-winter warmings and/or lack of sufficient ozone sonde measurements). Value for 2005 is indicated. Values for other winters from *Rex et al.* [2004], except all values are calculated between  $e\Theta$  levels of 380 and 550 K.  $V_{PSC}$  is found using temperatures from ECMWF,  $H_2O = 5$  ppmv, and an observed profile of  $HNO_3$  [*Rex et al.*, 2002]. The Figure is very similar if FU-Berlin data is used up to 2002 (no FU-Berlin data available after 2002). Error bars for  $\Delta O_3$  represent an upper limit of 20 DU uncertainty and for  $V_{PSC}$  uncertainty due to 1 K uncertainty in temperature. The line indicates a linear least squares fit to the points and has a slope of 15.6 DU/K cooling, based on  $7.7 \times 10^6$  km<sup>3</sup> additional  $V_{PSC}$  per Kelvin uniform cooling [*Rex et al.*, 2004]. The correlation coefficient is 0.98 with a statistical significance larger than 99.9% and an uncertainty of +0.02/−0.14 (the autocorrelation of both time series was considered for the estimation of the significance by reducing the degrees of freedom according to standard statistics; a Monte-Carlo approach was used to estimate the uncertainty: 99.9% of correlation coefficients exceed 0.84, calculated for 1000 data sets with random noise added to  $\Delta O_3$  and  $V_{PSC}$ , corresponding to the uncertainty of the individual points).

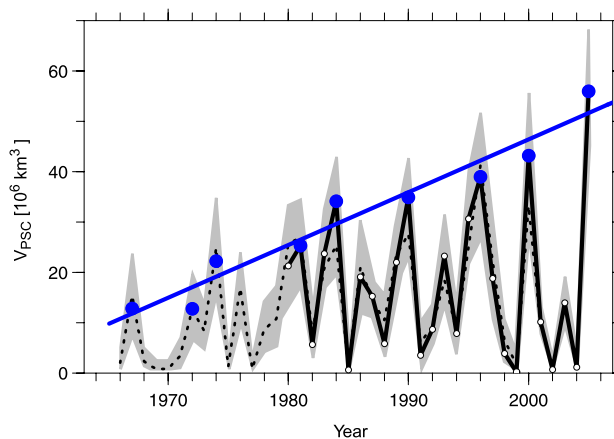
*al.*, 2004]. The observations of  $\Delta O_3$  and  $V_{PSC}$  for the winter 2005 lie along an extension of the near linear relation between these quantities observed for prior winters (Figure 3).

[13] Figure 4 shows the evolution of  $V_{PSC}$  over the past four decades. The unusually cold Arctic winter 2005 extends the long term upward trend of maximum values of  $V_{PSC}$  over the past ~forty years described by *Rex et al.* [2004]. A linear fit through the solid points in Figure 4, which represent maximum values of  $V_{PSC}$  for 5 year intervals, has a slope of  $9.9 \pm 1.1 \times 10^6$  km<sup>3</sup> per decade, similar to the slope given by *Rex et al.* [2004]. The conclusion of a large, steady rise in the maximum value of  $V_{PSC}$  does not depend on the length of the time interval or the end points chosen for the analysis (auxiliary material). The strong relation between  $\Delta O_3$  and  $V_{PSC}$  indicates  $V_{PSC}$  is the relevant parameter for relating changes in stratospheric temperature to ozone loss. Indeed, the notion of “coldest Arctic winters getting colder” can be overlooked in analyses of temperature trends [e.g., *Manney et al.*, 2005].

[14] It is unclear why the Arctic vortex has recently exhibited severely cold winters. To explore the robustness

of the observed trend, we have generated  $10^6$  random permutations of the  $V_{PSC}$  data set in a Monte-Carlo simulation, ensuring that the random data sets have the same probability density function as the original data. Table 1 gives the probabilities to observe a trend equal to or larger than the observed trend of the cold winters (prob1). A second entry, prob2, is based on the same Monte-Carlo simulations. It gives the probability of observing a trend equal to or larger than the observed trend, with the additional constraint that the uncertainty of the slope is equal to or smaller than the uncertainty of the observed trend. The trend estimates and probabilities are given for 5 and 10 year intervals for the selection of the maximum values of  $V_{PSC}$  (details for all intervals between 4 and 10 years are in the auxiliary material). The calculation is repeated assuming: (a) a 1K warm bias of the old radiosonde data (second column); (b) use of the FU-Berlin data alone up to 2002 (again assuming a 1K warm bias for the early data) and  $V_{PSC}$  from ECMWF for the remaining years reduced by the maximum difference between the FU-Berlin data and the ECMWF data during the 22-year overlap period (third column); (c) as (b) but adding random noise corresponding to an additional 1K  $2\sigma$  statistical uncertainty of the temperature data, before calculating the trend (fourth column). Table 1 shows it is very unlikely (well below 1% probability) that the observed trend toward colder winters is a purely random event or is caused by inconsistencies in the meteorological data sets.

[15] Chemistry climate models (CCMs) provide insight into processes controlling the temperature of the Arctic vortex, but results from various studies are contradictory. *Shindell et al.* [1998] suggested decreases in planetary wave activity reaching the mid-latitude stratosphere due to increased westerly winds in the subtropics would lead to stronger, colder Arctic vortices due to climate change associated with rising greenhouse gases (GHGs). *Schnadt et al.* [2002], however, showed a CCM coupled to an oceanic model resulted in a tendency for future warmer, less stable Arctic vortices, a consequence of increased



**Figure 4.**  $V_{PSC}$  over the past 40 years from ECMWF data (solid line) and FU-Berlin data (dashed line). See *Rex et al.* [2004] for a discussion of the FU-Berlin data.  $V_{PSC}$  has been calculated between 380 and 550 K for all years. The gray shading represents uncertainty of  $V_{PSC}$  due to 1 K uncertainty of the long term stability of radiosonde temperatures.

**Table 1.** Trend Estimates and Probability for Occurrence of Estimated Trend in Random Data

	Original	1K Radiosonde Trend (Assuming Warm Bias for Old Sondes <sup>a</sup> )	1K Radiosonde Trend + ECMWF Data Reduced	1K Radiosonde Trend + 1K Statistical Uncertainty + ECMWF Data Reduced
		<i>Interval 5 years</i>		
Original trend, 10 <sup>6</sup> km <sup>3</sup> /year	0.99 ± 0.11	0.80 ± 0.13	0.60 ± 0.15	0.60 ± 0.15
prob1/prob2, %	0.04/<0.0001	0.4/0.002	0.8/0.03	0.9/0.04
		<i>Interval 10 years</i>		
Original trend, 10 <sup>6</sup> km <sup>3</sup> /year	1.03 ± 0.14	0.73 ± 0.14	0.59 ± 0.21	0.59 ± 0.21
prob1/prob2, %	0.04/0.004	0.4/0.03	0.5/0.3	0.7/0.3

<sup>a</sup>See text.

planetary wave activity associated with rising sea surface temperatures, contradicting earlier CCM calculations that suggested a tendency to future colder, more stable Arctic vortices [Austin *et al.*, 1992].

[16] The increased variability of Arctic stratospheric temperature conditions during recent years [Manney *et al.*, 2005] could indicate that the mechanism described by Shindell *et al.* [1998] acts efficiently during periods of relatively weak dynamic activity, hence during stratospheric conditions that are closer to radiative equilibrium. According to this mechanism, increasing GHGs lead to a stronger meridional temperature gradient during such periods and vertically propagating waves are deflected more equatorwards, leading to further cooling at high latitudes for such situations. On the other hand, an overall increase in momentum flux from the troposphere [Schnadt *et al.*, 2002] could make these conditions less frequent. While quite speculative, this combination of behaviors could be the cause of relatively few cold winters in recent years, but an increase in the severity of the winters that are cold.

[17] We lack a fundamental understanding of the factors responsible for the rise in maximum value of Arctic V<sub>PSC</sub> shown in Figure 4. Nonetheless, the extension of this time series to a new record value for V<sub>PSC</sub> in the winter of 2005 is cause for concern. If climate forcing from increasing GHGs plays a role in rising maximum V<sub>PSC</sub>, the tendency toward colder Arctic winters will likely continue. In this case, Arctic ozone loss could continue to get worse until around the year 2020, when declining levels of anthropogenic halogens will eventually reduce chemical loss [Knudsen *et al.*, 2004]. A reliable assessment of future levels of Arctic ozone will not be possible until the observed tendency toward colder Arctic winters is understood.

[18] **Acknowledgments.** Meteorological data were provided by ECMWF and FU-Berlin. This work was supported by the BMBF (DYCHO, FKZ07ATC08) and by the EC (project SCOUT-O3). Ozone-sondes were partially funded by the EC (project QUOBI). Research at the Jet Propulsion Laboratory, California Institute of Technology, is performed under contract with the National Aeronautics and Space Administration. We thank T. Nagai and C. Trepte for providing ozone data for this study and E. Weatherhead for helpful discussions.

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