GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO. 22, PAGES 2697-2700, NOVEMBER 15, 1997

MLS observations of Arctic ozone loss in 1996-97

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Abstract. The Microwave Limb Sounder (MLS) observed ozone (O_3) loss in the Arctic vortex beginning in January 1997 at 585 K (~25 hPa) and in February 1997 at 465 K (~50 hPa). Minimum vortex-averaged O_3 mixing ratios observed in 1997 were higher than those in 1996, which were the lowest ever recorded by MLS. The vertical extent of O_3 loss and maximum local O_3 decreases were larger, but the decrease filled the vortex less completely, in 1997 than in 1996. Unusually low high-latitude column O_3 above 100 hPa in April 1997 resulted mainly from dynamical effects of the unusually persistent lower stratospheric vortex and winter-like temperature patterns. Column O_3 above 100 hPa averaged in comparable regions of the vortex showed a stronger decreasing trend in 1996-97 than in 1995-96, consistent with the larger vertical extent and maximum local values of lower stratospheric O_3 loss. Chemical O_3 loss resulted in an ~10% observed decrease in column O_3 between late January and early April 1997.

Introduction

The unprecedented persistence of temperatures below typical polar stratospheric cloud (PSC) thresholds into late Mar 1997 [*Coy et al.,* 1997, hereafter *C*97; *Santee et al.,* 1997, hereafter *S*97] raises the possibility of Arctic chemical ozone (O_3) loss occurring later than previously observed. As shown by *Manney et al.* [1994], the northern hemisphere (NH) lower stratospheric vortex (defined by the presence of strong potential vorticity (PV) gradients enclosing a significant area) typically breaks up by late March or early April. The 1997 vortex was intact and relatively strong into May [e.g., *C*97]. In 1996-97, the Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) observed the Arctic on selected days in December, late January, February and April. Because of the unusual persistence of the lower stratosphere vortex into May, MLS observed chemically processed air in April that remained confined within the vortex. These MLS observations of Arctic O_3 during 1996-97 are compared to those from earlier years, especially 1995-96, when temperatures were colder overall [*Manney et al.,* 1996, hereafter *M*96; *C*97] and chlorine activation greater than in 1996-97 [*S*97].

Data and Analysis

MLS Version 3 O_3 data and validation are described by *Froidevaux et al.* [1996]. Version 4 data are used here; *M*96 show some Version 3/4 differences in Arctic O_3. Precisions of individual O_3 measurements are ~0.2 ppmv, with absolute accuracies of 15-20% in the lower stratosphere. The precision of individual values of column O_3 above 100 hPa ($ColO_3$) calculated from MLS data is better than ~10 DU. The averages discussed below typically include over 200 observations, and thus have uncertainties of less than ~0.01 ppmv (0.5 DU) in O_3 mixing ratio ($ColO_3$). Daily MLS data are gridded by binning and averaging, and interpolated to potential temperature (θ) surfaces using United Kingdom Meteorological Office (UKMO) temperatures.

PV is calculated from the UKMO analyses. Transport calculations use UKMO horizontal winds, diabatic descent rates computed from UKMO temperatures, and a reverse trajectory procedure [*Manney et al.,* 1995a, b; *M*96; and references therein]. Uncertainties are discussed extensively by *Manney et al.* [1995a, b]; for vortex-averaged results, the calculated O_3 *change* typically has an uncertainty of ~20%.

Results

Fig. 1 shows MLS maps of 465 K O_3 and $ColO_3$ in late Jan, late Feb, and early and late Apr 1997. Fig. 2 shows 585 K and 465 K NH vortex-averaged MLS O_3 (area-weighted averages within a PV contour representing the vortex edge [*M*96 and references therein]), as well as $ColO_3$ averaged in the region north of 40°N with $ColO_3 \leq 250$ DU (see *M*96 and discussion below), during 1996-97 and 1995-96, with previous observations in the background; earlier winters are discussed by *M*96. Prior to 1997, the Arctic polar vortex had fragmented to such an extent in April that vortex averaging was no longer sensible [*Manney et al.,* 1994]. Thus for years before 1997, Fig. 2 shows averages in April over small vortex remnants, which have larger uncertainties than and are not fully comparable with the Apr 1997 values.

Between late December and late January, vortex-averaged O_3 at 585 K decreased in both 1995-96 and 1996-97. Replenishment by diabatic descent is expected to increase O_3 in the lower stratospheric vortex. *M*96 showed that the O_3 decrease at 585 K in 1995-96 must have resulted from chemical loss; the decrease in 1996-97 suggests that chemical depletion began in Jan 1997 near 585 K. This is consistent with chlorine activation, since 585 K temperatures remained below the typical PSC threshold in January and MLS observed enhanced ClO at 585 K in late Jan 1997 [*S*97]. 465 K vortex-averaged O_3 increased between late Dec 1996 and late Jan 1997, consistent with the behavior expected due to transport and the absence of temperatures low enough to form PSCs during most of this period [*C*97; *S*97]. A year earlier, significant O_3 loss at 465 K had already occurred by late Jan 1996. Since O_3 continued to increase in Jan 1997 due to transport, 465 K O_3 in late Jan 1997 was higher than in late Jan 1996.

465 K vortex-averaged O_3 decreased rapidly in Feb 1997, at a rate slightly faster than in Feb 1996. Most of this decrease occurred toward the vortex center (Fig. 1). Transport calculations show less masking of chemical loss by replenishment via diabatic descent at 465 K in Feb 1997 than in Feb 1996, with $\lesssim$10% of the loss masked in 1997, ~15% in 1996, and ~20–50% in previous NH winters [*M*96]. At

Paper number 97GL52827.
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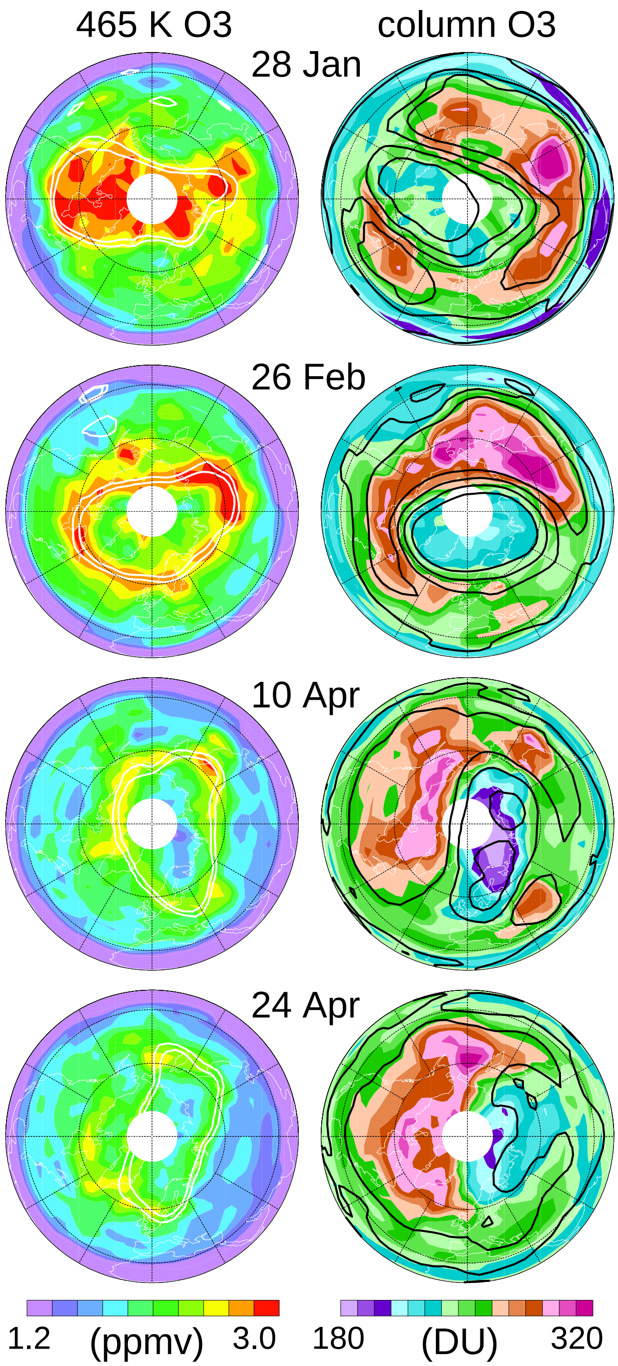

Figure 1. 465 K MLS O_3, and MLS column O_3 above 100 hPa, on 28 Jan, 26 Feb, 10 Apr and 24 Apr 1997. Two PV contours in the region of strong gradients along the vortex edge are shown on the 465 K maps. 46 hPa temperature contours of 200, 205, 210 and 215 K are overlaid on the column O_3 maps. The projection is orthographic, with 0° at the bottom and 90°E to the right; dashed lines are 30° and 60°N.

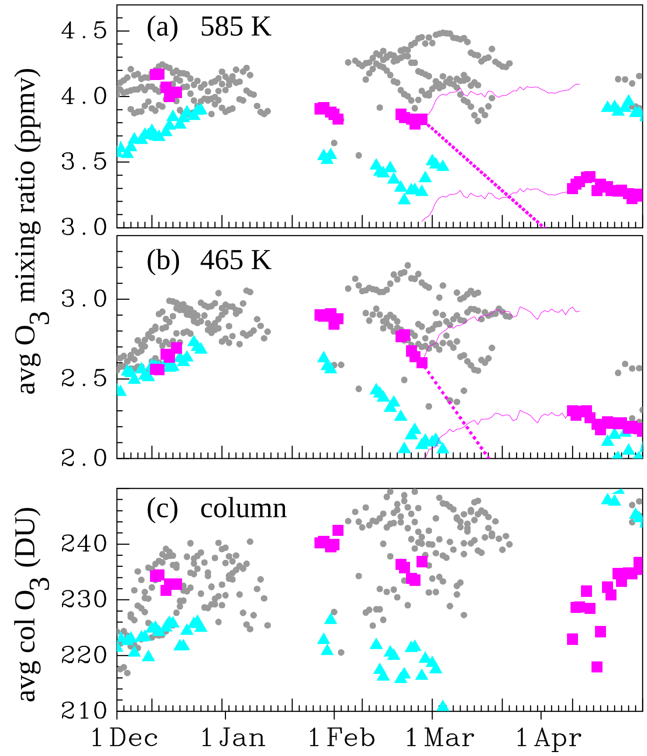

Figure 2. (a) 585 K and (b) 465 K vortex-averaged O_3 (ppmv, averaged within the outermost of the two PV contours shown in Fig. 1), and (c) column O_3 above 100 hPa (DU, averaged poleward of 40°N for column $O_3 \leq 250$ DU), for 1 December to 30 April. Cyan triangles show 1995-96, magenta squares 1996-97, and grey dots all previous UARS winters. Thin magenta lines and small magenta dots show results of transport calculations and an estimate of minimum O_3 (see text).

585 K, however, transport calculations suggest that ~75% of the chemical loss in Feb 1997 was masked by transport, an amount similar to other years [*M*96].

465 K temperatures remained low until late Mar 1997 [*C*97; *S*97], so additional O_3 loss was expected. Ground-based observations show vortex O_3 decreasing during Mar 1997 at levels between ~400 and ~520 K [*Donovan et al.*, 1997]. We used transport calculations to estimate the minimum value that MLS vortex-averaged O_3 may have reached during Mar 1997. The thin line in Figs. 2a and 2b starting from the data point on 26 Feb 1997 shows the expected behavior of O_3 due to transport alone, calculated from 26 Feb to 12 Apr 1997. While such calculations become more uncertain after ~20–25 days [*Manney et al.*, 1995a, b], tests using shorter calculations confirm that most of the O_3 change due to transport occurred before mid-March. The line ending at the 10 Apr 1997 data point shows how dynamical processes would have led to that vortex-averaged O_3 value, based on the above calculation. The dots extending from the 26 Feb MLS observation are an extrapolation of the estimated slope of chemical O_3 loss for 20-26 Feb 1997 (calculated by combining the observed change with the increase due to transport over the late January–late February period, as described by *M*96). The calculated slopes are ~0.6%/d and ~1.3%/d at 585 K and 465 K, respectively. These are slightly larger than the largest O_3 loss rates found by *MacKenzie et al.* [1996] from chemical calculations using MLS ClO in Feb–Mar 1993. That they found values near ours for comparable ClO enhancement suggests that such values might reasonably be expected from chemical loss; unfortunately, similar calculations

cannot be done for Mar 1997, since ClO observations are not available. Our calculated slopes, however, approximate the most rapid decrease likely to have occurred. The intersection of this extrapolated line with the curve back from the 10 April MLS observation then gives an approximate lower bound on the minimum vortex-averaged O_3 in 1997. At 585 K, minimum vortex-averaged O_3 mixing ratios in 1997 are estimated to be comparable to those in 1996, and at 465 K, minimum mixing ratios were probably slightly larger in 1997 than in 1996. Vortex-averaged O_3 stayed nearly constant in Apr 1997 (Fig. 2a, b), with the low O_3 mixing ratios resulting from chemical loss remaining confined within the vortex (Fig. 1).

Fig. 3 compares the spatial extent of O_3 loss observed by MLS during the 1996-97 and 1995-96 NH winters, showing O_3 changes over 69 days (chosen to include the period of most rapid observed O_3 loss in each year) as a function of equivalent latitude (PV expressed as the latitude enclosing the same area as the PV contour) and θ [e.g., *M*96]. The maximum decline in 1997 was ~1.5 ppmv, compared to ~1.1 ppmv in 1995-96. Although substantial O_3 decreases in the vortex extended somewhat higher in 1996-97 than in 1995-96, O_3 in 1995-96 decreased up to ~650 K near the vortex edge over a shorter period ending on 20 Feb 1996. The difference field in Fig. 3b thus indicates that some replenishment had already occurred by 3 Mar 1996. Large O_3 reductions in 1995-96 more completely filled the vortex at a given level than in 1997. The O_3 decrease in 1997 extends as high (~650 K) as is typical in the southern hemisphere (SH) and the change was over 2/3 that typical in the SH for a similar period. However, Fig. 3 represents nearly all of the lower stratospheric O_3 loss during these NH winters, whereas in the SH O_3 loss may continue for a month after the spring equinox. In 1997, extra-vortex O_3 also decreased in the lower stratosphere (see also Fig. 1). Such behavior has not been seen in any previous winter observed by MLS.

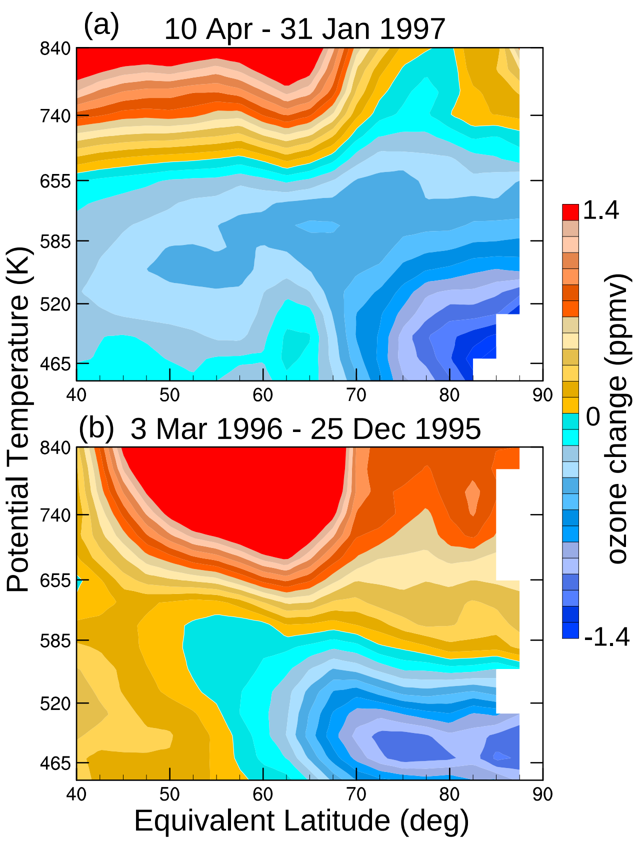

Figure 3. MLS O_3 change (ppmv) over 69 days, between (a) 31 Jan and 10 Apr 1997, and (b) 25 Dec 1995 and 3 Mar 1996, in equivalent latitude/θ-space. Except for the highest equivalent latitudes shown, values of the fields differenced were averages of ~10–20 observations; thus, uncertainties in the difference plot are typically less than ~0.1 ppmv.

Fig. 2c shows time variations of $ColO_3$ in the Arctic low-$ColO_3$ region, as detailed above. Averages within the 210 K temperature contour at 46 hPa show nearly identical trends, due to the strong spatial correlation between $ColO_3$ and temperature (e.g., Fig. 1). It is difficult to define a useful average for comparing $ColO_3$ under different meteorological conditions. Averages within a lower stratospheric PV contour, for example, would not be comparable between Feb 1996 and Feb 1997, since in Feb 1996 low temperatures positioned along the vortex edge resulted in some of the highest $ColO_3$ values being inside the vortex (at longitudes opposite the low temperature region) [*M*96], while in 1997 lowest temperatures were near the vortex center and most of the high $ColO_3$ values were outside the vortex (Fig. 1). By averaging in the low $ColO_3$ (or low temperature) region, we confine ourselves to the lower stratospheric vortex region, and to an area with most nearly comparable meteorological conditions. Furthermore, we wish only to compare trends; lower $ColO_3$ in 1995-96 in Fig. 2c was likely due to the meteorological situation [*M*96], with low temperatures along the vortex edge, and upper tropospheric blocking events, dynamical conditions that frequently lead to unusually low column O_3 [e.g., *Petzoldt et al.,* 1994]. In contrast to other years, $ColO_3$ decreased in Jan–Mar 1996 and Feb–Apr 1997, when dynamical effects were expected to increase $ColO_3$. In Fig. 1, for example, the decrease between 26 Feb and 10 Apr 1997 would not have been expected in absence of chemical O_3 loss given the considerable temperature increase. The downward trend in 1997 was ~1.25 times that in 1996, as expected from the greater vertical range and slightly larger magnitude of the lower stratospheric O_3 decrease (Fig. 3). While a decrease of at least ~10% (the observed decrease) in $ColO_3$ can be attributed to chemical O_3 loss, $ColO_3$ is so strongly influenced by meteorological conditions that determining how much $ColO_3$ would have increased over the period in absence of chemical loss (and thus quantifying the effect of lower stratospheric O_3 loss on $ColO_3$) will require a comprehensive modelling effort.

Fig. 4 shows MLS zonal-mean high-latitude (60–80°N) $ColO_3$ for 1991–1997. Interannual variability in zonal-mean MLS $ColO_3$ is generally consistent with what we see in similar zonal means (not shown) of TOMS total O_3, based on 1991-93 Nimbus-7, 1993-96 Meteor-3 and 1996-97 ADEOS TOMS data. Variations in NH column O_3 are greatest in winter, with changes in zonal means also reflecting differences in the position and size of the high-latitude region of low column O_3. $ColO_3$ was similar in all years in summer and early fall (June through October). $ColO_3$ in early Apr 1997 was lower than other springtime MLS observations. A well-defined region of low temperatures at high latitudes persisted until about 20 Apr 1997 (vestiges of this can be seen on 24 Apr 1997, Fig. 1); since low temperatures are asso-

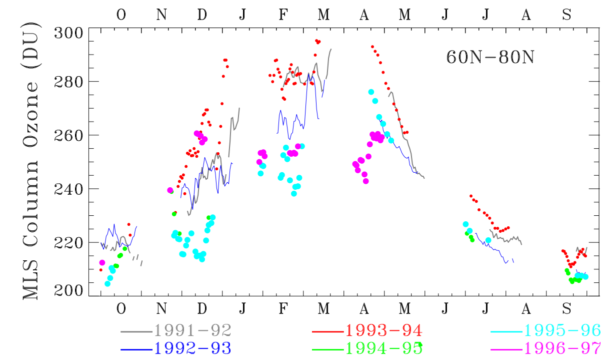

Figure 4. Zonal mean high-latitude (60°–80°N) MLS column O_3 above 100 hPa, for 1991 through 1997.

ciated with low column O_3 [e.g., *Petzoldt et al.,* 1994], this unusual dynamical situation favored lower $ColO_3$. Chemical loss also affected $ColO_3$; because the lower stratospheric vortex was intact through April 1997 (Fig. 1), O_3-depleted air remained confined in high latitudes, also contributing to unusually low zonal-mean $ColO_3$. MLS high-latitude $ColO_3$ increased rapidly in late April (see also Fig. 2c), concurrent with a rapid temperature increase and the breakdown of winter-like temperature patterns (Fig. 1). Nearly all of the interannual and temporal differences in high-latitude $ColO_3$ result from differences in the layer between 100 and 22 hPa (not shown). Since lower stratospheric O_3 mixing ratios were not increasing significantly at this time and the O_3-depleted air remained confined in the vortex (Figs. 1, 2a, 2b), much of the increase in $ColO_3$ must be due to dynamical effects associated with the increasing temperatures and belated transition to summer-like temperature patterns.

Summary

MLS observed O_3 loss in the Arctic vortex beginning in Jan 1997 at 585 K and in Feb 1997 at 465 K. Compared to the low O_3 mixing ratios observed in 1995-96 [*M*96], vortex-averaged lower stratospheric O_3 was higher in Feb 1997, due to a later onset of chemical processing [*S*97]. The decrease in 1996-97 filled the vortex less completely than in 1995-96 at a given level, but the vertical extent of O_3 loss and maximum local decreases were larger in 1996-97. Transport calculations indicate that minimum lower stratospheric O_3 mixing ratios during the 1996-97 winter were never as low as those in 1995-96. Although O_3 loss continued later in 1996-97, it also began later, resulting in more O_3 at the beginning of the period of depletion. MLS column O_3 above 100 hPa in a comparable region of the vortex showed a stronger decreasing trend in 1996-97 than in 1995-96, consistent with the larger vertical extent and magnitude of the lower stratospheric O_3 decrease. Unusually small values of high-latitude MLS column O_3 above 100 hPa in Apr 1997 were closely related to dynamical effects of the unusual persistence of winter-like temperature patterns. A ~10% observed decrease in column O_3 above 100 hPa between late Jan and early Apr 1997 resulted from chemical depletion.

Acknowledgments. We thank the MLS team for the MLS data, the UKMO for meteorological data, the TOMS data processing teams at the NASA/Goddard Space Flight Center for the TOMS data and B. P. Ridenoure for graphics and data analysis. Work at the Jet Propulsion Laboratory, California Institute of Technology, was done under contract with the National Aeronautics and Space Administration.

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(Received May 7, 1997; revised July 18, 1997; accepted September 8, 1997.)