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Arctic ozone depletion observed by UARS MLS during the 1994-95 winter

G.L. Manney, L. Froidevaux, J.W. Waters, M.L. Santee, W.G. Read, D.A. Flower, R.F. Jarnot and R.W. Zurek

Jet Propulsion Laboratory/California Institute of Technology, Pasadena

Abstract. During the unusually cold 1994-95 Arctic winter, the Microwave Limb Sounder observed enhanced chlorine monoxide (ClO) in late Dec and throughout Feb and early Mar. Late Dec ClO was higher than during any of the previous 3 years, consistent with the colder early winter. Between late Dec 1994 and early Feb 1995, 465 K (~50 hPa) vortex-averaged ozone (O_3) decreased by ~15%, with local decreases of ~30%; additional local decreases of ~5% were seen between early Feb and early Mar. Transport calculations indicate that vortex-averaged chemical loss between late Dec and early Feb was ~20% at 465 K, with ~1/4 of that masked by downward transport of O_3. This Arctic chemical O_3 loss is not readily detectable in MLS column O_3 data.

Introduction

The northern hemisphere (NH) lower stratosphere was unusually cold in Dec 1994 and Jan 1995, and temperatures low enough for polar stratospheric cloud (PSC) formation persisted until mid-March 1995; the polar vortex was exceptionally strong throughout the winter [*Zurek et al.*, 1995]. Upper Atmosphere Research Satellite (UARS) Microwave Limb Sounder (MLS) measurements during the previous 3 NH winters showed enhanced chlorine monoxide (ClO) in the NH vortex [*Waters et al.*, 1995], and evidence for ozone (O_3) depletion in the NH lower stratosphere [*Manney et al.*, 1994; 1995a, b]. NH O_3 loss varies markedly due to interannual variability in the duration, location and extent of PSCs, and in O_3 transport [e.g., *Manney et al.*, 1995b]. MLS observations indicate significant O_3 depletion in late Dec 1994 and Feb and early Mar 1995.

Data and Analysis

The MLS data and validation are described by *Froidevaux et al.* [1995] for O_3 and by *Waters et al.* [1995] for ClO. Precisions (rms) of individual O_3 (ClO) measurements are ~0.2 ppmv (~0.5 ppbv), with absolute accuracies of 15-20% in the lower stratosphere. The MLS scan mechanism developed problems in late 1994, after which vertical scans were performed only on selected days. Full vertical scans were done on 21 Dec 1994, 1, 3, 8, 14, 21, 28 Feb, and 6, 8 and 10 Mar 1995. MLS tracked the atmospheric limb at 18±2.5 km (near 60 hPa) without vertical scanning during 22-30 Dec 1994 and 2 Feb-9 Mar 1995, excluding the scanning days. The precision of "non-scanning" ClO retrievals for 50 hPa is as good as, or better than, that of the scanning retrievals. Because enhanced ClO is localized both horizontally and vertically, with a maximum near 50 hPa, vortex-averaged ClO at 465 K (near 50 hPa inside the vortex) can be estimated from non-scanning data. An overall offset of ~0.3 ppbv in ClO, attributed to the degraded vertical resolution of the non-scanning retrievals, and obtained by comparing non-scanning and scanning retrievals on the scanning days, is added to the non-scanning ClO.

MLS data are gridded by binning and interpolating 24 h of data, and interpolated to isentropic surfaces using United Kingdom Meteorological Office (UKMO) [*Swinbank and O'Neill*, 1994] temperatures. Potential vorticity (PV) is calculated from UKMO analyses. Three-dimensional (3D, including diabatic effects) O_3 transport calculations are done using UKMO horizontal winds, computed diabatic descent rates, and a reverse trajectory procedure [*Manney et al.*, 1995a, b].

Lower Stratospheric Ozone and ClO

Fig. 1 shows 465 K UKMO minimum temperature (T_{min}) and vortex-averaged ClO and O_3 in the NH during 1994-95 and the previous 3 winters. T_{min} fell below the type I PSC formation threshold (~195 K) in early Dec 1994 and was near the type II PSC formation threshold (~188 K) from ~15 Dec 1994 through ~15 Jan 1995. Although UKMO temperatures were below the type II threshold on only a few days, comparisons with radiosonde temperatures indicate that UKMO values are 1-4 K higher than the best estimate of T_{min} during this period [*Manney et al.*, submitted to *J. Geophys. Res.*]. Late Dec 1994 temperatures were lower than in any of the previous 16 NH early winters, early Jan 1995 temperatures were more continuously low, and temperatures were below the type II PSC threshold for as many or more days as in any of the previous 16 NH winters [*Zurek et al.*, 1995].

Late Dec 1994 ClO was higher than at the same time in any of the previous 3 years. In early to mid-Jan 1995 (MLS looked south during Jan), the vortex and cold re-

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gion were offset from the pole by an amount similar to that in early Jan 1992 (when MLS observed very high ClO), placing much of the vortex in sunlight; however, the cold area was larger than that in 1992. T_{min} rose somewhat in late Jan 1995, but remained below the type I PSC threshold, and the vortex remained shifted off the pole. Meteorological conditions in Jan 1995 were thus conducive to continual ClO production and when MLS resumed NH measurements on 1 Feb, ClO was enhanced throughout the vortex. T_{min} rose above the PSC threshold on ~8 Feb 1995 (Fig. 1a) and ClO decreased rapidly; on 14 Feb only small regions of ClO>1 ppbv were observed. ClO decreased further after 14 Feb (part of this decrease may be due to MLS observing high latitudes mainly in darkness at this time), but then increased again as temperatures fell in late Feb and early Mar. By 8 Mar, vortex ClO values were enhanced to the level observed on 14 Feb.

465 K vortex-averaged O_3 in late Dec 1994 was slightly lower, and in early Feb 1995 was significantly lower, than that in any of the previous 3 NH winters (Fig. 1c). Fig. 2, which shows 465 K O_3 on several days with scanning measurements in the 1994-95 winter, reveals that the O_3 reduction occurs throughout the vortex. The O_3 decrease rate between late Dec and early Feb was similar to that in Feb and Mar 1993, with a net decrease in vortex-averaged O_3 of ~15%. The 1994-95 decrease observed by MLS is consistent with that inferred from lidar observations for the same period at Eureka (80°N, 86°W) [*Donovan, et al.*, 1995].

The expected O_3 variation due solely to 3D transport (open symbols in Fig. 1c) is calculated [*Manney et al.*, 1995a, b] to estimate how much O_3 depletion was masked by resupply via diabatic descent, and to explore the possibility that O_3 may have decreased because lower O_3 air was drawn into the vortex. 3D transport tends to increase O_3 slightly during late Dec, with more rapid increases in late Jan and early Feb. Vortex-averaged O_3 in early Feb 1995 would have been ~3.1 ppmv if only transport were important, as opposed to the ~2.6 ppmv observed. This implies that the observed decrease was caused by chemistry, and indicates that ~1/4 of the chemical destruction was masked by transport. Both the late Dec and early Feb O_3 decrease and the resupply of O_3 by transport were similar in magnitude to those in Feb/Mar 1993 [*Manney et al.*, 1995a]. However, in contrast to 1992-93, most of the O_3 destruction near 465 K in 1994-95 took place earlier in the winter when 1) less of the high latitudes were exposed to sunlight (so chemical processing was possible in a smaller area), and 2) less ozone had previously been transported to the lower stratospheric vortex by diabatic descent (so lower minimum values of 465 K O_3 were observed during the 1994-95 winter).

Intrusions of low O_3 air into the vortex in early Feb decrease computed vortex-averaged O_3 by no more than 0.15 ppmv. The observed O_3 decrease between 1 and 8 Feb may have been related to such an intrusion. Observed vortex-averaged O_3 remained nearly constant after early Feb, whereas transport would have been expected to increase vortex O_3. This suggests additional chemical loss of ~0.3-0.4 ppmv of vortex O_3. Figs. 2c, d show that highest O_3 values were near the vortex edge throughout Feb and early Mar 1995. The transport calculations also result in maximum O_3 along the vortex edge, where strongest diabatic descent occurs, but yield higher O_3 than observed in the vortex center. The observed 465 K O_3 morphology thus results from a combination of chemical and dynamical effects. The transport calculation initialized on 28 Feb implies that most of the O_3 change between then and 10 Mar can be explained by transport. Both inferred chemical O_3 loss and resupply by diabatic descent in late Feb/early Mar 1995 are smaller than during the cold spell in late Feb/early Mar 1994 [*Manney et al.*, 1995b].

Fig. 3 shows the O_3 change between 21 Dec 1994 and 3 Feb 1995 in PV/θ-space. The O_3 decrease was confined below ~520 K, and occurred throughout most of the center of the vortex at the lowest levels shown, the localized O_3 decrease was ~30%. Lidar observations [*Donovan et al.*, 1995] show that the O_3 decrease extended to lower altitudes than are reliably observed by MLS.

Column Ozone

Fig. 4 shows MLS column O_3 above 100 hPa on the same days as in Fig. 2. Fig. 5 shows column O_3 on one day during each of the previous 3 NH winters observed by MLS, and in the 1978-79 winter observed by the Limb Infrared Monitor of the Stratosphere (LIMS) (LIMS observations are included only for comparison of morphology because of possible biases between MLS and LIMS measurements). The selected days are near the time of minimum observed high latitude column O_3. The morphology is similar in each case, with lowest column O_3 in a confined region coincident with lowest temperature; the colocation of low column O_3 and low temperature has been previously noted [e.g., *Bojkov,* 1988]. The unusually low values and the morphology of column O_3 in Jan 1992 are thought to have been due primarily to dynamical effects [*Petzoldt et al.*, 1994 and references therein]. The morphology of column O_3 in 1979, when negligible chemical depletion was expected [*Manney et al.*, 1994], clearly demonstrates that the pattern of low values in a confined region coincident with low temperature does not in itself suggest chemical depletion.

Maximum column O_3 increased between 21 Dec 1994 and 3 Feb 1995 (Fig. 4a, b), as expected due to transport. Fig. 6 shows a time series of minimum column O_3 in the vortex region for the NH winters observed by MLS (uncertainties in individual column O_3 values from MLS are typically ~7 DU [*Froidevaux et al.*, 1994]). Column O_3 on 3 Feb 1995 is ~10% lower than on the previous and succeeding days observed. Rapid column O_3 variations of 10% or more are common, and in many instances are demonstrably not related to chemical depletion. A rapid decrease of ~40% in late Feb 1994 is contemporaneous with a rapid cooling (Fig. 1a). Although chemical depletion occurs at this time [*Manney et al.*, 1995b], the lower stratospheric decrease begins later than the column O_3 decrease (Fig. 1c), and is more than a factor of 3 too small to account for the decrease

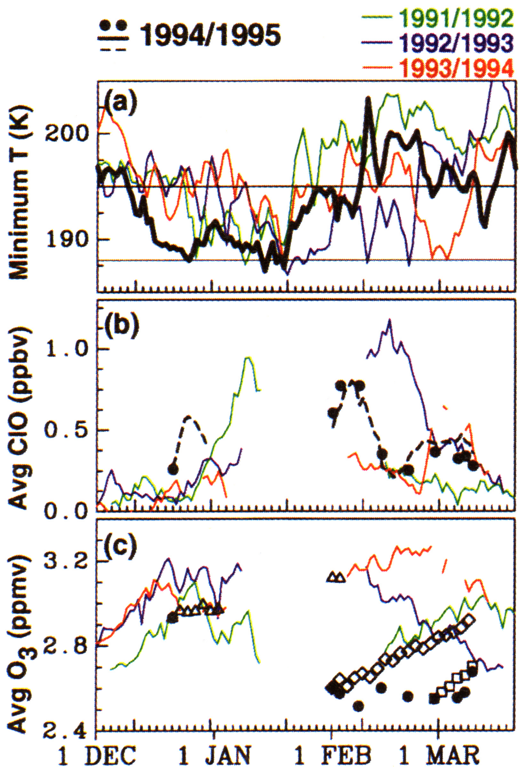

Figure 1. (a) Minimum 465 K vortex temperatures; vortex-averaged (b) ClO and (c) O_3 for 1 Dec through 20 Mar. Black dots in (b) and (c) show scanning MLS data in 1994-95; dashed line in (b) shows ClO from non-scanning data (see text). Open symbols in (c) show transport calculations initialized on 21 Dec 1994 (triangles), 1 Feb 1995 (diamonds) and 28 Feb 1995 (squares).

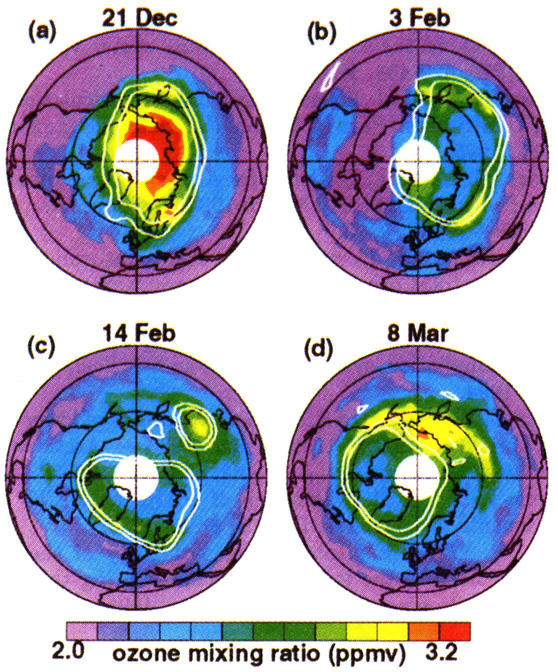

Figure 2. 465 K MLS O_3 on 21 Dec 1994, 3 and 14 Feb, and 8 Mar 1995. The projection is orthographic, with 0° longitude at the bottom and 90°E to the right; dashed lines are at 30° and 60°N. 0.25 and 0.30×10^{-4} K m^2 kg^{-1} s^{-1} PV contours are overlaid.

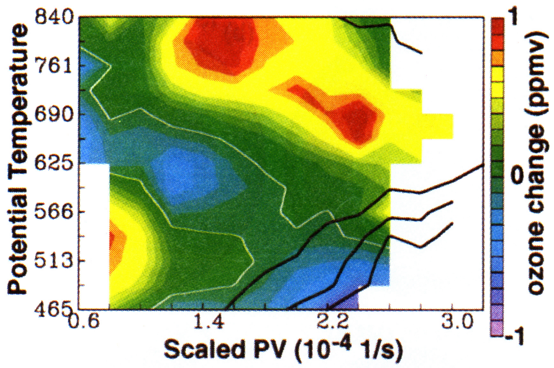

Figure 3. O_3 change between 21 Dec 1994 and 3 Feb 1995, in PV/θ-space. PV is scaled to give a similar range of values at all levels. Black contours are 0.4, 0.6 and 0.8 ppbv of ClO averaged for 1, 3, and 8 Feb 1995, with highest values at highest PV. The PV contour used for vortex averages in Fig. 1 corresponds to a scaled PV of 1.2×10^{-4} s^{-1}. White contour is zero O_3 change.

in column O_3. The very low column O_3 in Feb 1994, when lower stratospheric ozone was relatively high (Fig. 1c), also emphasizes the significance of higher altitude O_3 at NH high latitudes [e.g., *Froidevaux et al.*, 1994]. Fig. 6 suggests that column O_3 increased overall during Feb and Mar 1993, while lower stratospheric ozone decreased (Fig. 1c). A slight downward trend is suggested over the 1994-95 winter, with an ~5% decrease between 21 Dec and 10 Mar. Determining to what degree this change is inconsistent with purely dynamical effects would require accurate and detailed modeling of O_3 transport throughout the stratosphere. The variability in Fig. 6 clearly shows the difficulty of isolating chemical effects in the NH by examining column O_3.

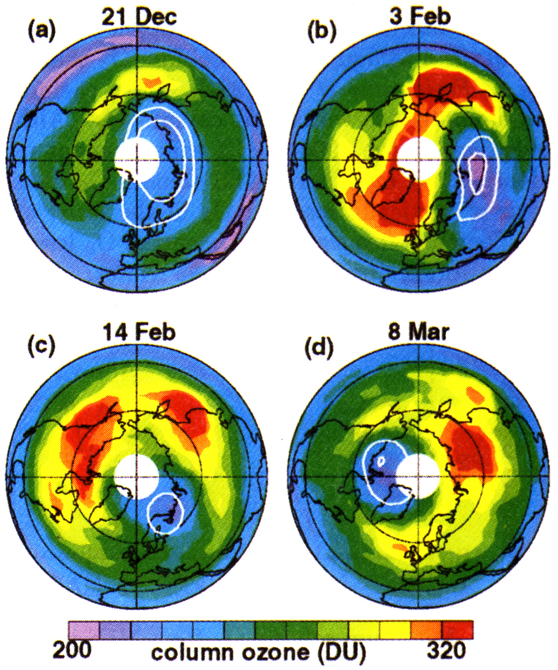

Figure 4. As in Fig. 2, but for column O_3 above 100 hPa. 46 hPa temperature contours of 195 and 200 K are overlaid.

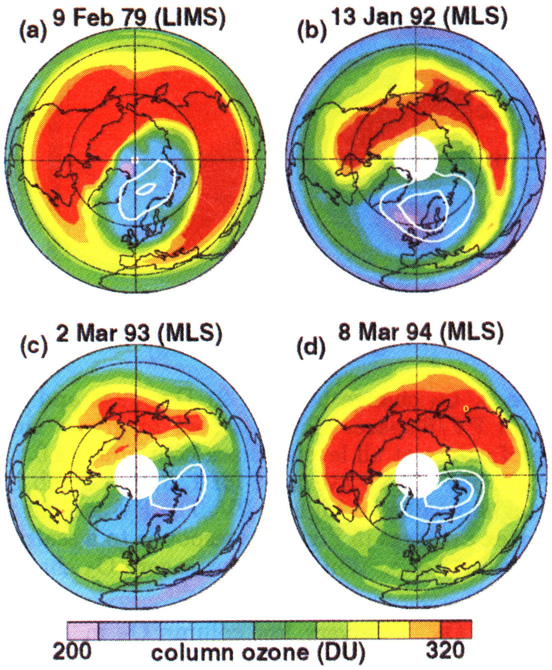

Figure 5. As in Fig. 4, but for 9 Feb 1979 (LIMS) and 13 Jan 1992, 2 Mar 1993 and 8 Mar 1994 (MLS).

For comparison with NH column O_3, Fig. 7 shows early and late winter column O_3 in the southern hemisphere (SH). In early winter (21 June 1994), SH column the vortex. ClO was enhanced over a similar region. In O_3 is very similar to that in the NH. Minimum SH column O_3 above 100 hPa on 8 Sep 1994, in late winter, was typical for that season in the SH, ~130 DU, in contrast to ~200-215 DU in each NH winter. In the SH, not only does chemical O_3 depletion dominate dynamical effects in the lower stratosphere [e.g., *Manney et al.,* 1995a], but also the SH middle and upper stratosphere contribute less to high latitude column O_3 than in the NH [e.g., *Froidevaux et al.,* 1994]. Thus, chemical effects dominate late winter SH column O_3. Although chemical loss in the 1994-95 NH winter cannot readily be identified by examining MLS column O_3 data, the analysis of vertically resolved O_3 in the lower stratosphere demonstrates significant chemical O_3 loss in the NH polar vortex during the 1994-95 winter.

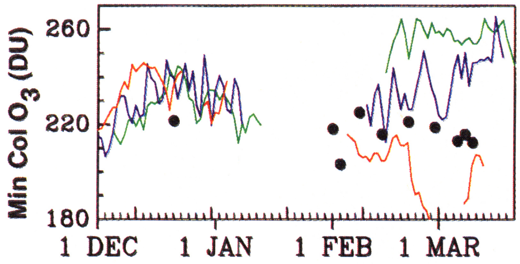

Figure 6. Minimum column O_3 from MLS in the vortex region during 4 NH winters. The area searched for minima is confined to the area with PV$\geq$0.14 $\times$ 10^{-4} K m^2 kg^{-1} s^{-1} on the 420 K isentropic surface. Symbols and line styles are as in Fig. 1.

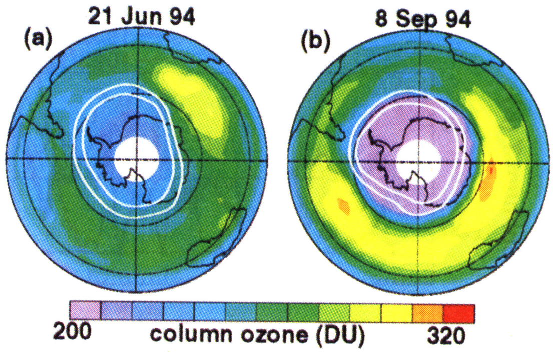

Figure 7. As in Fig. 5, but for 21 Jun and 8 Sep 1994 in the SH. 0° longitude is at the top.

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D. A. Flower, L. Froidevaux, R. F. Jarnot, G. L. Manney (manney@camel.jpl.nasa.gov), W. G. Read, M. L. Santee, J. W. Waters, R. W. Zurek, Mail Stop 183-701, Jet Propulsion Laboratory, Pasadena, CA 91109.

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