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UARS MLS observations of lower stratospheric ClO in the 1992–93 and 1993–94 Arctic winter vortices

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Abstract. UARS MLS measurements of lower stratospheric ClO during the 1992-93 and 1993-94 Arctic winters are presented. Enhanced ClO in the 1992-93 winter was first observed in early December, and extensively during February when temperatures were continually low enough for PSCs. Sporadic episodes of enhanced ClO were observed for most of the 1993-94 winter as minimum temperatures hovered near the PSC threshold, with largest ClO amounts occurring in early March after a sudden deep cooling in late February.

Introduction

The Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) [*Barath et al.*, 1993] has now made measurements of O_3 and ClO, the dominant form of reactive chlorine that destroys O_3, through three Arctic winters. *Waters et al.* [1993] describe MLS ClO measurements for the 1991-92 Arctic winter, with implications of lower stratospheric O_3 loss in January 1992 when ClO was greatly enhanced. Additional evidence of O_3 loss in the 1991–92 Arctic vortex has been presented [e.g., *Browell et al.*, 1993; *Proffitt et al.*, 1993; *Salawitch et al.*, 1993; *Lefèvre et al.*, 1994; *Lutman et al.*, 1994; *Manney et al.*, 1994a], and further analyses of the MLS 1991-92 Arctic winter ClO results have been performed by *Douglass et al.* [1993] and *Schoeberl et al.* [1993]. *Manney et al.* [1994a] compare MLS O_3 measurements with passive tracer observations during the 1992-93 Arctic winter, and show substantial chemical loss of lower stratospheric O_3 during Feb-Mar 1993 when ClO was enhanced. The evolution of ozone and its relation to polar vortex dynamics for the three northern and two southern winters of MLS observations are discussed by *Manney et al.* [1995].

Data and Analysis

ClO and O_3 data used here (Version 3) are from the MLS 205 GHz radiometer. Precision (rms) of individual measurements at altitudes reported here are ~0.2 ppmv for O_3 and ~0.5 ppbv for ClO, with estimated absolute accuracies of 15–20% [*Froidevaux et al.* and *Waters et al.*, submitted to *J. Geophys. Res.*].

Temperatures are from the US National Meteorological Center (NMC) analyses. Rossby-Ertel potential vorticity (PV) is calculated from NMC geopotential heights and temperatures as described by *Manney and Zurek* [1993]. NMC temperatures are used in interpolations to isentropic surfaces. Vortex-averages are calculated as described by *Manney et al.* [1993], with estimated precision of <0.05 ppmv for O_3 and <0.1 ppbv for ClO.

Results

Figure 1 shows time-series of vortex-averaged ClO and O_3, and minimum NMC temperatures in the vortex, at 465 K potential temperature (~50 hPa pres-

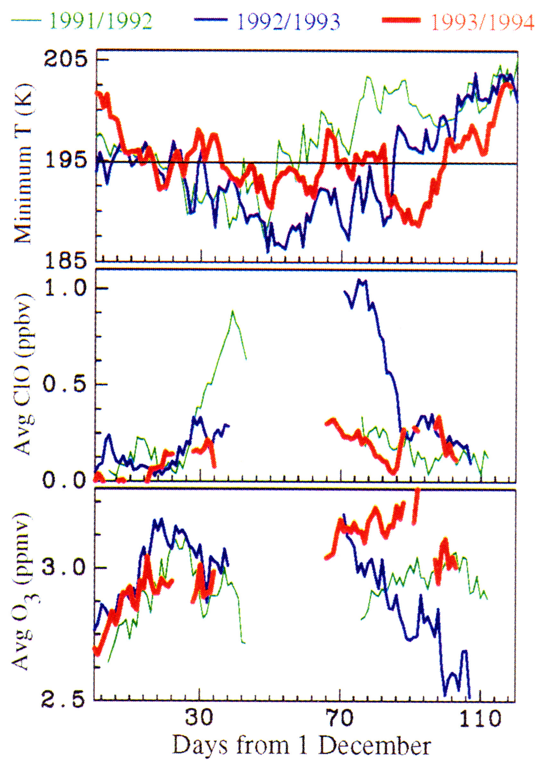

Figure 1. Vortex minimum temperature, average ClO mixing ratio (from the "day" half of the orbit, but including measurements in darkness at high latitudes) and average O_3 mixing ratio at 465 K potential temperature for 1 Dec through 30 Mar during three northern winters. The vortex boundary is defined here as the $2.5\times10^{-5}\,\mathrm{K\,m^2\,kg^{-1}\,s^{-1}}$ contour of PV. Large gaps in ClO and O_3 are when MLS looked south. It should be noted that several factors (especially dynamics) can influence the O_3 variation and must be considered before a causal relationship to ClO can be established.

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sure, ~20 km height) for the three northern winters of MLS measurements to date. (Results given here were obtained using linear interpolation between each day's measurement locations; consequently, the 1991–92 and 1992–93 curves differ slightly from those in *Waters et al.* [1993] and *Manney et al.* [1994a] which used Fourier techniques.) Temperatures in the 1991–92 and 1992–93 vortices dropped well below the threshold (~195 K) for polar stratospheric cloud (PSC) formation by mid December. A strong warming in 1991–92 [e.g., *Manney and Zurek*, 1993] raised minimum temperatures above 195 K by the end of January 1992. The 1992–93 minimum NMC temperatures remained below 195 K until a strong warming in late February [*Manney et al.*, 1994b]. The enhanced ClO in the vortex observed by MLS follows the pattern of minimum temperatures, as expected due to chlorine activation by processes on PSCs [e.g., *Solomon*, 1990]. Reactions on cold sulfate aerosols can also activate chlorine [*Solomon et al.*, 1993].

Lower stratospheric vortex minimum temperatures in mid December 1993 hovered about the PSC threshold, as they did at that time in the preceding two years. Near the end of December 1993 they rose above the threshold, but the vortex recovered after this warming and 465 K minimum temperatures again hovered around the threshold until late February. A sudden cooling occurred in late February, when the vortex strengthened and temperatures fell well below 195 K for about two weeks until start of the final warming.

Figure 2 shows maps of ClO during the 1992–93 winter for selected days from MLS north-looking periods (30 Nov – 8 Jan and 10 Feb – 18 Mar; separated by

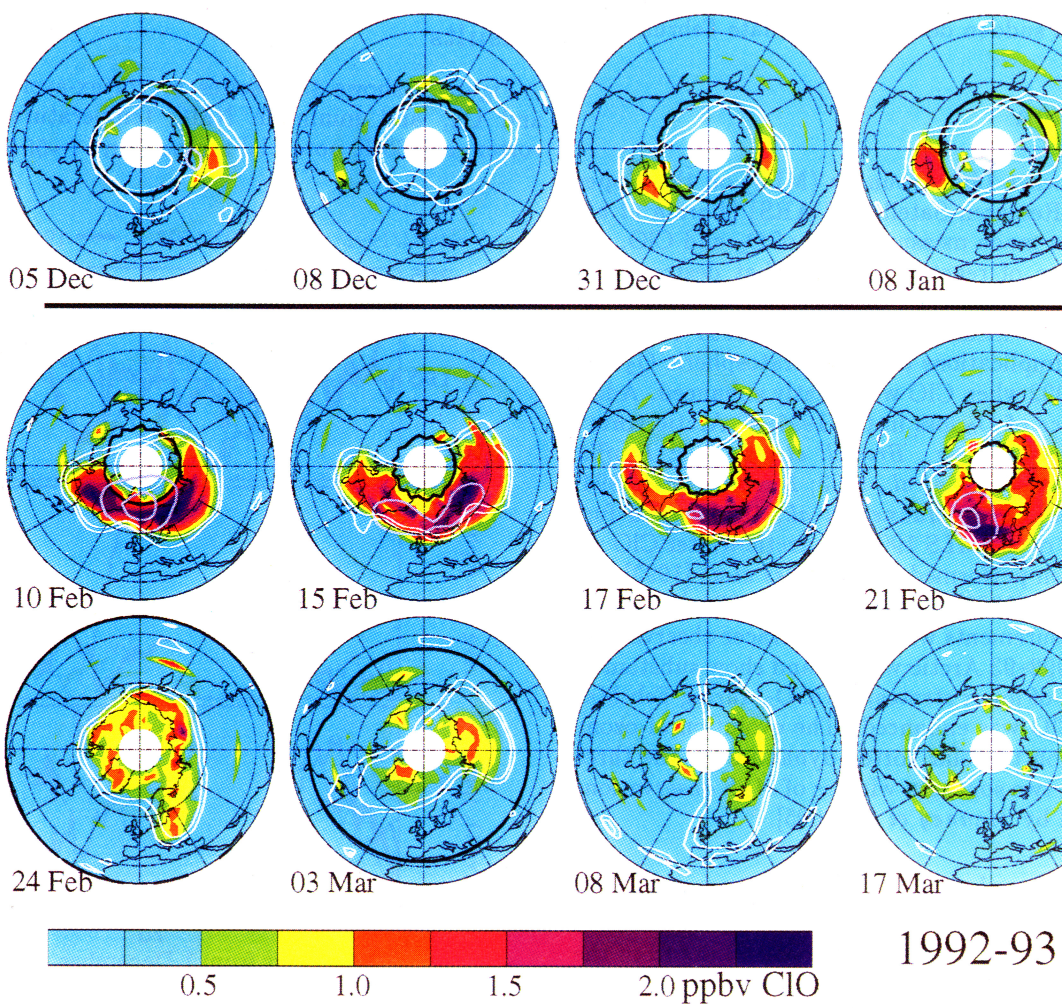

Figure 2. MLS maps of lower stratospheric ClO at 465 K potential temperature for selected days during the 1992–93 northern winter. Data are from the "day" half of the orbit. The black contour is where measurements were made at 91° solar zenith angle (sza); here sunlight becomes weak and ClO decrease towards night is expected due to reduced ClOOCl photolysis. Darkness occurs at ~94° sza, and the 'night' side of 91° sza is polewards of the black contour — except on 3 Mar when it was equatorwards (this varies due to orbit precession). Measurement local solar time and sza on a given day are nearly constant around a latitude circle. The thin white circle concentric with the pole is the edge of polar night, and measurements do not reach polewards of 80°. Irregular white contours are PV values of 2.5×10^{-5} K m^2 kg^{-1} s^{-1}(outer contour) and 3.0×10^{-5} K m^2 kg^{-1} s^{-1}(inner contour) which indicate the approximate edge of the vortex. Light violet contours indicate temperatures of 195 and 190 K, when they are present. Occasional isolated values of high ClO can be noise artifacts.

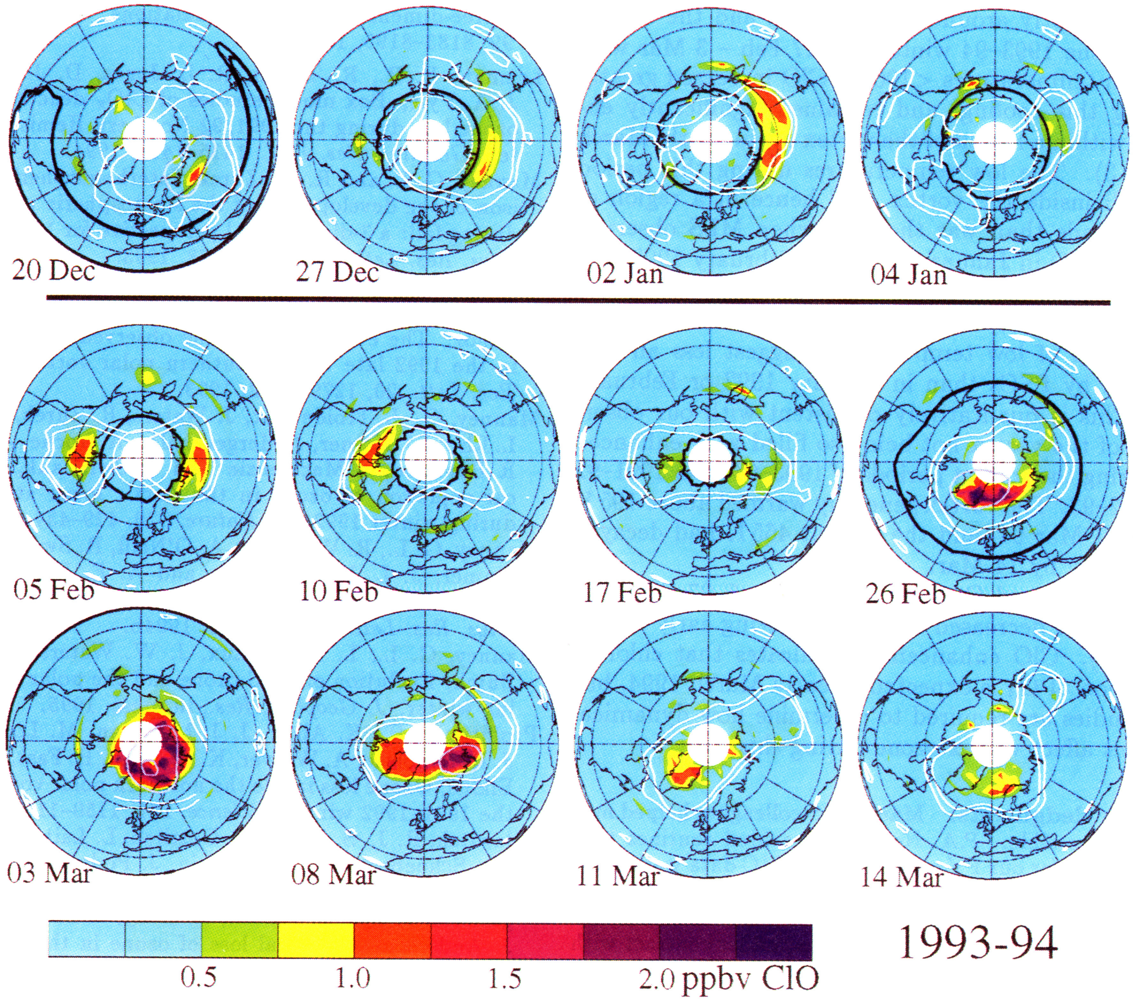

Figure 3. As in Figure 2, except for the 1993–94 winter. The 'night' side of 91° solar zenith angle (sza) of measurements was polewards of the black contour on all days, except 26 Feb when it was equatorwards. The enhanced ClO on 20 Dec over Russia was measured at ~94° sza and ~3:50 pm local solar time (just at sunset); enhanced ClO in this region was first observed by 19 Dec and persisted for several days.

horizontal line in Figure 2). Minimum temperatures were below 195 K for a few days in early December, and enhanced ClO was observed over Siberia in weak sunlight downwind from the region of lowest temperatures. Temperatures remained low enough for PSCs after about 26 Dec, but were located nearer the vortex center than in January 1992 and thus in a region of weaker winds and less sunlight. ClO abundances in early January were correspondingly less in 1993 than in 1992. When MLS north-looking resumed on 10 Feb, low temperatures were present near the vortex edge in a region of strong winds which experienced sunshine. The 10–24 Feb maps show the sunlit portion of the vortex was filled with enhanced ClO. As Arctic temperatures were continually below 195 K (Figure 1) while MLS was south-looking from 9 Jan to 9 Feb, we would also expect enhanced ClO throughout the vortex during this period. NMC temperatures generally rose above the PSC formation threshold around 24 Feb, and the enhanced ClO decayed during March.

Figure 3 shows maps of ClO during the 1993–94 winter for selected days from MLS north-looking periods (26 Nov – 4 Jan; 5 Feb – 14 Mar). Vortex temperatures were low enough for PSCs from about 18 Dec to 27 Dec (Figure 1). Most MLS high-latitude measurements in the early portion of this period occurred in darkness, but enhanced ClO was observed in weak sunlight and increased as orbit precession brought measurements into stronger sunlight. More ClO is seen on 2 Jan, although NMC 465 K temperatures were above the nominal PSC threshold by then, and the observed ClO decreased significantly by 4 Jan. Minimum temperatures at 465 K were slightly below 195 K during most of the MLS south-looking period. Significantly enhanced ClO was seen in the vortex at the beginning of north-looking measurements on 5 Feb, but at that time temperatures rose above 195 K and ClO decayed during early and mid February — with a slight increase after the brief cooling below 195 K on 8 Feb (Figure 1).

Lower stratospheric temperatures in the vortex decreased abruptly around 22 Feb 1994, and the coldest period of the 1993–94 winter was 27 Feb – 3 Mar with minimum temperatures <190 K. ClO increased greatly following this cooling, and remained significantly enhanced within a region of the vortex during early March (Figure 3). The low temperatures during this period were well inside the vortex, and hence in a region of weaker winds than was the case when MLS observed enhanced ClO in January 1992 and February 1993. Although most of the vortex received sunlight during late February and early March 1994, the weaker winds at the location of low temperatures suggest less air was processed by PSCs than in January 1992 or February 1993. This is qualitatively consistent with our observations of the vortex not being so filled with enhanced ClO during the coldest periods of 1993–94 as in 1991–92 and 1992–93. The vortex generally warmed above 195 K around 11 Mar 94, and the ClO at 465 K had decayed considerably by 14 Mar.

Vortex-averaged O_3 increased during 5–27 Feb 1994 at 465 K, but decreased noticeably during early March (Figure 1). ClO enhancement indicates that chlorine destruction of O_3 is expected in early March 1994, but more studies are required to determine how dynamical processes affect vortex ozone during this time.

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References

Barath, F. T., M. Chavez, R. Cofield, D. Flower, M. Frerking, M. Gram, W. Harris, J. Holden, R. Jarnot, W. Kloezeman, G. Klose, G. Lau, M. Loo, B. Maddison, R. Mattauch, R. McKinney, G. Peckham, H. Pickett, G. Siebes, F. Soltis, R. Suttie, J. Tarsala, J. Waters, and W. Wilson, The Upper Atmosphere Research Satellite Microwave Limb Sounder Instrument, *J. Geophys. Res.*, 98, 10,751–10,762, 1993.

Browell, E. V., C. F. Butler, M. A. Fenn, W. B. Grant, S. Ismail, M. R. Schoeberl, O. B. Toon, M. Loewenstein, and J. R. Podolske, Ozone and aerosol changes during the 1991–1992 Airborne Arctic Stratospheric Expedition, *Science*, 261, 1155–1158, 1993.

Douglass, A., R. Rood, J. Waters, L. Froidevaux, W. Read, L. Elson, M. Geller, Y. Chi, M. Cerniglia, and S. Steenrod, A 3D simulation of the early winter distribution of reactive chlorine in the north polar vortex, *Geophys. Res. Lett.*, 20, 1271–1274, 1993.

Lefèvre, F., G. P. Brasseur, I. Folkins, A. K. Smith, and P. Simon, Chemistry of the 1991–92 stratospheric winter: Three-dimensional model simulations, *J. Geophys. Res.*, 99, 8183–8195, 1994.

Lutman, E. R., R. Toumi, R. L. Jones, D. J. Lary, and J. A. Pyle, Box model studies of ClO_x deactivation and ozone loss during the 1991/92 Northern Hemisphere winter, *Geophys. Res. Lett.*, 1415–1418, 1994.

Manney, G. L. and R. W. Zurek, Interhemispheric comparison of the development of the stratospheric polar vortex during fall: a 3-dimensional perspective for 1991–92, *Geophys. Res. Lett.*, 20, 1274–1278, 1993.

Manney, G. L., L. Froidevaux, J. W. Waters, L. S. Elson, E. F. Fishbein, R. W. Zurek, R. S. Harwood, and W. A. Lahoz, The evolution of ozone observed by UARS MLS in the 1992 late winter southern polar vortex, *Geophys. Res. Lett.*, 20, 1279–1282, 1993.

Manney, G., L. Froidevaux, J. Waters, R. Zurek, W. Read, L. Elson, J. Kumer, J. Mergenthaler, A. Roche, A. O'Neill, R. Harwood, I. MacKenzie and R. Swinbank, Chemical depletion of ozone in the Arctic lower stratosphere during winter 1992–93, *Nature*, 370, 429–434, 1994a.

Manney, G. L., R. W. Zurek, A. O'Neill, R. Swinbank, J. B. Kumer, J. L. Mergenthaler, and A. E. Roche, Stratospheric warmings during February and March 1993, *Geophys. Res. Lett.*, 21, 813–816, 1994b.

Manney, G. L., L. Froidevaux, J. W. Waters, and R. W. Zurek, Evolution of MLS ozone and the polar vortex during winter, *J. Geophys. Res.*, in press, 1995.

Proffitt, M. H., K. Aikin, J. J. Margitan, M. Loewenstein, J. R. Podolske, A. Weaver, K. R. Chan, H. Fast, and J. W. Elkins, Ozone loss inside the northern polar vortex during the 1991–1992 winter, *Science*, 261, 1150–1154, 1993.

Salawitch, R. J., S. Wofsy, E. Gottlieb, L. Lait, P. Newman, M. Schoeberl, M. Loewenstein, J. Podolske, S. Strahan, M. Proffitt, C. Webster, R. May, D. Fahey, D. Baumgardner, J. Dye, J. Wilson, K. Kelly, J. Elkins, K. Chan, J. Anderson, Chemical loss of ozone in the arctic polar vortex in the winter of 1991–1992, *Science*, 261, 1146–1149, 1993.

Schoeberl, M. R., R. Stolarski, A. Douglass, P. Newman, L. Lait, J. Waters, L. Froidevaux, and W. Read, MLS ClO observations and arctic polar vortex temperatures, *Geophys. Res. Lett.*, 20, 2861–2864, 1993.

Solomon, S., Progress towards a quantitative understanding of Antarctic ozone depletion, *Nature*, 347, 347–354, 1990.

Solomon, S., R. W. Sanders, R. R. Garcia, and J. G. Keys, Increased chlorine dioxide over Antarctica caused by volcanic aerosols from Mount Pinatubo, *Nature*, 363, 245–248, 1993.

Waters, J. W., L. Froidevaux, W. G. Read, G. L. Manney, L. S. Elson, D. A. Flower, R. F. Jarnot, and R. S. Harwood, Stratospheric ClO and ozone from the Microwave Limb Sounder on the Upper Atmosphere Research Satellite, *Nature*, 362, 597–602, 1993.

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