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Polar vortex conditions during the 1995-96 Arctic winter: Meteorology and MLS ozone

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Abstract. The 1995-96 northern hemisphere (NH) winter stratosphere was colder than in any of the previous 17 winters, with lower stratospheric temperatures continuously below the type 1 (primarily HNO_3) polar stratospheric cloud (PSC) threshold for over 2 1/2 months. Upper tropospheric ridges in late Feb and early Mar 1996 led to the lowest observed NH lower stratospheric temperatures, and the latest observed NH temperatures below the type 2 (water ice) PSC threshold. Consistent with the unusual cold and chemical processing on PSCs, UARS MLS observed a greater decrease in lower stratospheric ozone (O_3) in 1995-96 than in any of the previous 4 NH winters. O_3 decreased throughout the vortex over an altitude range nearly as large as that typical of the southern hemisphere (SH). The decrease between late Dec 1995 and early Mar 1996 was ~2/3 of that over the equivalent SH period. As in other NH winters, temperatures in 1996 rose above the PSC threshold before the spring equinox, ending chemical processing in the NH vortex much earlier than is usual in the SH. A downward trend in column O_3 above 100 hPa during Jan and Feb 1996 appears to be related to the lower stratospheric O_3 depletion.

Meteorology

The 1995-96 NH winter stratosphere was the coldest in the 18 year record of US National Meteorological Center (NMC) data. Fig. 1 compares 1995-96 Arctic minimum NMC temperatures at 465 K potential temperature (~50 hPa) with those in the NH and SH since the Upper Atmosphere Research Satellite (UARS) launch, and in the 13 NH winters before the UARS launch. After 1 Dec 1995, temperatures were below 195 K (the approximate type 1 PSC threshold) on 89 days, compared to a previous NH maximum of 82 days in 1994-95 [*Zurek et al.*, 1996], and below 188 K (the approximate type 2 PSC threshold) on 27 days, as opposed to a previous NH maximum of 18 days in 1983-84.

Upper tropospheric blocking is common in the NH late winter, especially over the north Atlantic [e.g., *O'Neill et al.*, 1994, and references therein]. Fig. 2 shows calculated high-resolution UK Meteorological Office (UKMO) potential vorticity (PV) (using the me-

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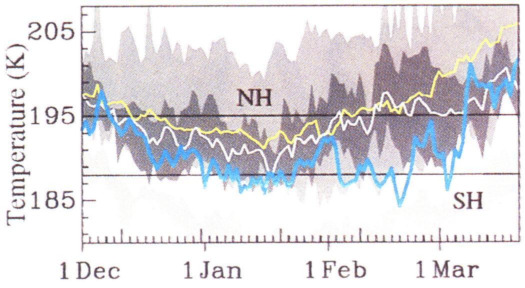

Figure 1. Minimum 465 K NMC vortex temperatures during the 1995-96 NH winter (cyan line), compared with the envelope and average for the 1991-92 through 1994-95 NH winters (dark shading, white line) and the 1978-79 through 1990-91 NH winters (medium shading, yellow line), and the envelope for 1992 through 1995 SH winters (light shading, SH curves begin 1 Jun).

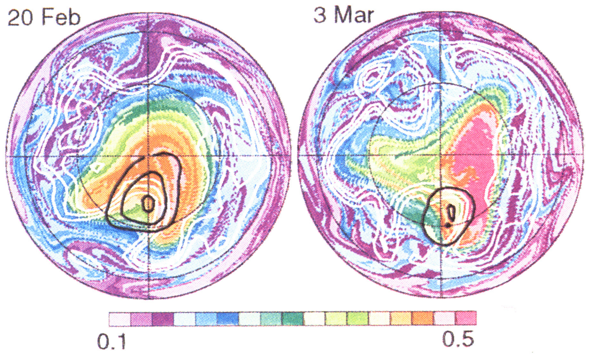

Figure 2. High-resolution UKMO 465 K PV (colors), 465 K 185, 190 and 195 K temperatures (black, concentric, with 195 K enclosing the largest area) and 315 K PV (white) on 20 Feb and 3 Mar 1996. The projection is orthographic, with 0° at the bottom and 90°E to the right; dashed lines are 30° and 60°N.

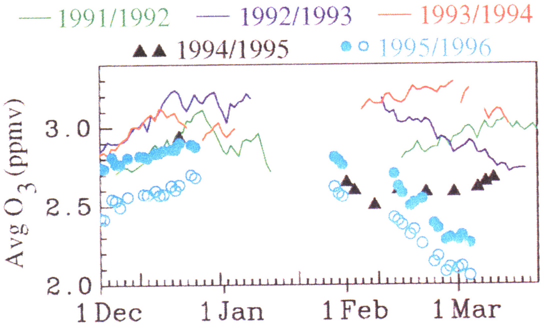

Figure 3. Vortex-averaged Version 3 MLS O_3 (lines, solid symbols, ppmv) for 1 Dec through 20 Mar. Open cyan circles show 1995-96 Version 4 MLS data. Large gaps in Jan are when MLS observed SH high latitudes.

thod of *Sutton et al.* [1994]) at 465 K on 20 Feb and 3 Mar 1996, during 2 blocking events; superimposed are 465 K UKMO temperature and 315 K (tropospheric, ~300 hPa) PV. During blocking events, the upper troposphere ridge (which can be seen in the "omega" shaped excursion of the 315 K PV contours near 0° longitude in Fig. 2) leads to a cold, high tropopause under an unusually cold region in the lower stratosphere [e.g., *Petzoldt et al.*, 1994; *O'Neill et al.*, 1994]. As discussed in detail by *O'Neill et al.* [1994], upper tropospheric blocking causes a northward excursion of the jet stream extending into the lower stratosphere (so the coldest

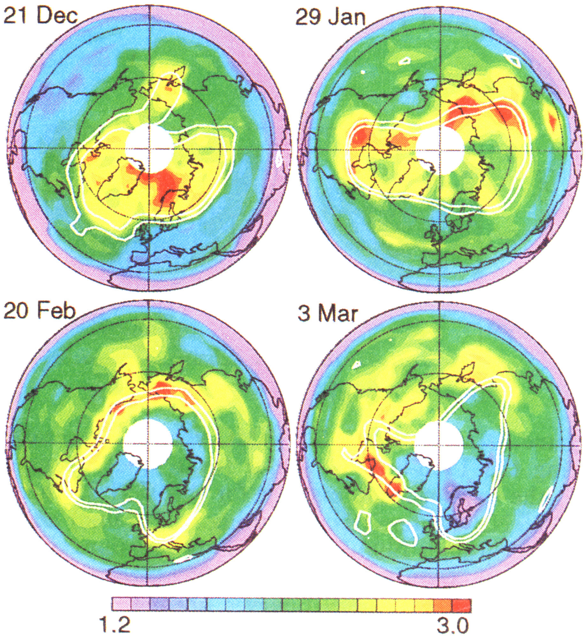

Figure 4. 465 K MLS O_3 on 21 Dec 1995, 29 Jan, 20 Feb and 3 Mar 1996. Layout is as in Fig. 2; 0.25 and 0.30×10^{-4} K m^2 kg^{-1} s^{-1} PV contours are overlaid.

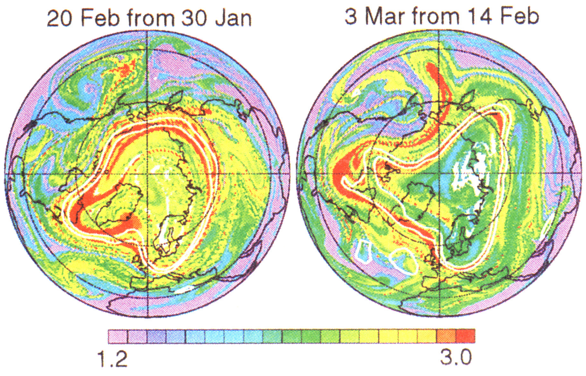

Figure 5. High-resolution 465 K O_3 (ppmv) from transport calculations on 20 Feb and 3 Mar 1996. Layout is as in Fig. 4.

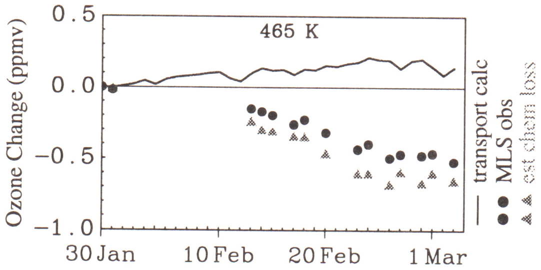

Figure 6. Observed (black circles) and calculated (line) O_3 change from 30 Jan through 3 Mar 1996, and chemical O_3 loss estimated from these (grey triangles).

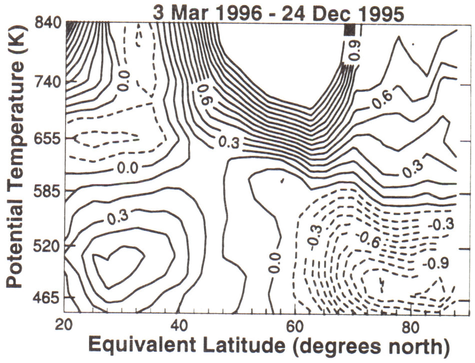

Figure 7. Observed O_3 change (ppmv) between 24 Dec 1995 and 3 Mar 1996, in equivalent latitude/θ-space (see text). Dashed contours indicate that O_3 decreased.

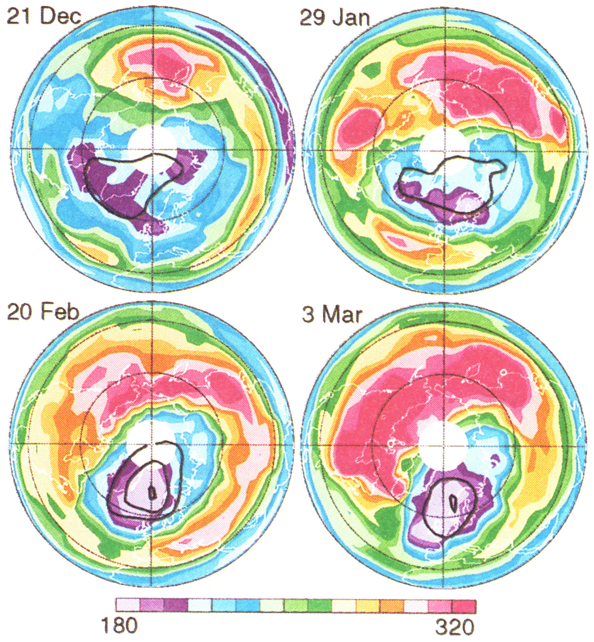

Figure 8. As in Fig. 4, but for MLS column O_3 above 100 hPa. 46 hPa UKMO temperature contours of 185, 190 and 195 K are overlaid.

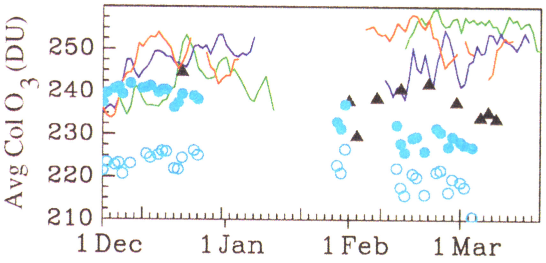

Figure 9. Average MLS column O_3 poleward of 40°N for column $O_3 \leq 260$ DU (≤ 250 DU for Version 4, to account for the bias between versions). Symbols and line styles are as in Fig. 3.

area is along the vortex edge, as seen in Fig. 2 in the 465 K PV field), and may lead to entrainment of midlatitude air into the vortex by advection on isentropic surfaces (such intrusion occurred after 20 Feb 1996 at and below 465 K). With the strongest winds blowing through the coldest region, large amounts of air can quickly experience PSC processing. Coupled with already unusually low minimum temperatures in 1996, the events shown in Fig. 2 led to the latest observation of 465 K temperatures below 188 K in the NH and the lowest NH temperatures in the NMC record (Fig. 1).

While each NH winter since the UARS launch included periods of unusual cold [*Zurek et al.*, 1996], the 1995-96 winter was the most persistently cold, with temperatures below 195 K on 80 consecutive days. Temperatures were below 195 K in a larger geographical region and up to higher altitudes than during any of the previous 17 NH winters. 1995-96 was also the only NH winter since the UARS launch to be unusually cold throughout Feb (Fig. 1). Consistent with heterogeneous chemistry on PSCs arising from the unusual cold, the UARS Microwave Limb Sounder (MLS) observed enhanced ClO in the NH vortex in mid- to late-Dec 1995, with vortex-averaged values higher than previously observed at this time [*Santee et al.*, 1996]. During Feb 1996, Arctic lower stratospheric ClO was as high as previously observed by MLS, and high values persisted into early Mar 1996 [*Santee et al.*, 1996]. As expected given this chlorine activation, MLS O_3 observations presented here show greater chemical O_3 destruction in the 1995-96 winter than previously observed in the NH.

Data and Analysis

The MLS Version 3 O_3 data are described by *Froidevaux et al.* [1996]. Version 4 data are being produced and will be shown except when comparing directly to previous years for which Version 4 data are not yet available. Version 4 changes include retrieval of HNO_3 in the same band as the O_3 data used here [*Santee et al.*, 1996] and refinements in tangent pressure retrievals, field-of-view pointing and estimated errors. Version 4 O_3 at 465 K in the Arctic is on average ~0.2-0.25 ppmv lower than Version 3 O_3 (see Fig. 3). For both versions, precisions of individual O_3 measurements are ~0.2 ppmv, with absolute accuracies of 15-20% in the lower stratosphere. Full vertical scanning measurements were taken on about 2 days out of every 3 during the north-looking periods in Nov/Dec 1995 and Feb/Mar 1996 (MLS observed SH high latitudes during Jan 1996). A problem with the UARS spacecraft caused MLS to be turned off on 2-12 Feb 1996.

MLS data are gridded by binning and interpolating 24 h of data, and interpolated to isentropic (potential temperature, θ) surfaces using UKMO [*Swinbank and O'Neill*, 1994] temperatures. PV and high resolution PV [*Sutton et al.*, 1994] are calculated from the UKMO analyses. Three-dimensional O_3 transport calculations use UKMO horizontal winds, computed diabatic descent rates, and a reverse trajectory procedure like that of *Sutton et al.* [1994], but including diabatic effects. These are run on both a 4° by 5° latitude-longitude grid [*Manney et al.*, 1995a, b, 1996a] (for examination of many levels and time periods), and a high-resolution (0.8° equatorial spacing) equal-area grid (for detailed examination of individual cases). UKMO temperatures and PV are also used in the analysis of MLS O_3 for consistency. UKMO NH lower stratospheric temperatures are typically 1-3 K higher than NMC temperatures [*Manney et al.*, 1996b]; an exception is during the blocking event about 20 Feb 1996, when UKMO temperatures were ~3 K lower than those from NMC.

Ozone

Fig. 3 shows 465 K NH vortex-averaged MLS O_3 during 1995-96 and the previous 4 winters. Vortex-averaged O_3 in early Dec 1995 was similar to previous years, but the increase during Dec was smaller. This is probably mainly due to interannual differences in polar vortex development; comparison with transport calculations provides no evidence of chemical loss at this time.

465 K MLS O_3 maps during the 1995-96 winter are shown in Fig. 4. Between 25 Dec 1995 and 29 Jan 1996 (when MLS observed SH high latitudes), 465 K vortex O_3 decreased slightly (Figs. 3 and 4). Small decreases (~5%) were observed up to 585 K over this period. Diabatic descent is expected to increase lower stratospheric O_3 at this time, and transport calculations on the 4° by 5° grid show increases of 10-15%. Combined with observed decreases, this suggests chemical losses of ~10% and ~20% at 465 K and 585 K, respectively, over the period; sensitivity tests using different initialization days and/or the high resolution calculations show very similar results.

465 K vortex-averaged O_3 decreased rapidly in Feb 1996, with largest decreases well within the vortex. By Feb, high O_3 was concentrated along the vortex edge (Fig. 4); this pattern results both from greater increases via diabatic descent along the vortex edge and from chemical loss in the vortex interior. Between 29 Jan and 3 Mar 1996, vortex-averaged O_3 (Fig. 3) decreased by ~0.017 ppmv/d or ~0.7%/d. For comparison, the decrease over the period shown in Feb/Mar 1993 is ~0.012 ppmv/d or ~0.4%/d. High-resolution transport calculations without chemistry for periods of ~3 weeks (Fig. 5) show calculated O_3 in the vortex interior considerably higher than that observed on both 20 Feb and 3 Mar (calculated O_3 is lower on 3 Mar than on 20 Feb because MLS O_3 had decreased between the initialization days for the 2 calculations). On 20 Feb 1996, since highest O_3 is along the vortex edge, the distortion of the flow during the blocking event leads to horizontal (isentropic) transport of air with higher O_3 from the vortex edge into its interior. A slight increase in observed vortex-averaged O_3 (Fig. 3) was also seen at this time. Filaments of high O_3 pulled off the vortex edge over the Pacific (Fig. 5) appear to correspond to higher O_3 regions in the MLS observations (Fig. 4).

A vortex-averaged O_3 increase of ~0.005 ppmv/d at 465 K is expected due solely to transport processes during Feb 1996 (Fig. 6), leading to an estimated chemical loss rate of ~0.022 ppmv/d or ~0.8%/d. Chemical depletion is masked less by transport than in previous winters, when transport calculations imply O_3 increases of ~0.007 ppmv/d (1994-95, *Manney et al.* [1996a]), ~0.009 ppmv/d (1992-93 and 1993-94, *Man-*

ney et al. [1995a, b]) and ~0.01 ppmv/d (1991-92). Less downward O_3 transport in 1995-96 may be related to the unusual cold, since temperatures closer to radiative equilibrium lead to less diabatic descent; interannual differences in vertical O_3 gradients may also contribute. Even with a smaller increase by transport, the greater observed decrease rate results in a faster estimated chemical O_3 loss rate in 1995-96 than in previous NH winters observed by MLS.

Fig. 7 summarizes the observed O_3 loss over the 1995-96 NH winter, showing O_3 changes from 24 Dec 1995 to 3 Mar 1996 as a function of equivalent latitude (PV expressed as the latitude enclosing the same area as the PV contour, e.g., *Buchart and Remsberg* [1986]) and θ. O_3 decreased throughout the vortex (equivalent latitude greater than ~60°) below ~550 K. This is in contrast to previous years: in 1992-93 and 1994-95, large O_3 decreases (calculated over the same length of time, including the time when most O_3 destruction was expected) were confined near the vortex center and below ~520 K; in 1991-92 and 1993-94, which had shorter cold periods, little decrease was seen. The pattern of decrease in 1995-96 is qualitatively similar to that in recent SH winters, and the magnitude of the decrease is ~2/3 that over the equivalent SH period. In contrast to the SH, however, the 1996 NH final warming began in early Mar (as is typical in the NH, Fig. 1), so little additional chemical O_3 loss was expected; in the SH, temperatures below 195 K are typically present for 1-2 months longer, and O_3 continues to decrease for ~1 month after the spring equinox.

MLS column O_3 above 100 hPa, with 46 hPa temperatures overlaid, is shown in Fig. 8. Column O_3 tends to be correlated with lower stratospheric temperature and has been observed to be extremely low during upper tropospheric blocking events when temperatures are also low and the tropopause is high [e.g., *Petzoldt et al.*, 1994, and references therein]. Column O_3 would be correlated with the lower stratospheric vortex only if PV and temperature fields were correlated (i.e., symmetric and concentric), or if the column O_3 morphology was dominated by chemical loss confined to the vortex (one or both of these conditions usually occurs in the SH winter). Since this is not the case in the NH winter (cf. Figs. 2 and 8), a vortex average is not appropriate for column O_3. Thus, Fig. 9 shows time trends by averaging in the region north of 40°N where column O_3 is less than 260 DU. In this average, column O_3 above 100 hPa in late Dec is lower than in previous years, probably due to interannual differences in dynamics or chemical effects other than those associated with processing on PSCs, since significant chlorine catalyzed depletion is neither expected nor observed at this time.

Comparison of Fig. 9 with Fig. 1 shows column O_3 variations on time scales of days to be correlated with lower stratospheric temperature changes. On longer time scales, column O_3 is expected to increase in the absence of chemical effects, due to diabatic descent and other dynamical processes. A small overall downward trend in average column O_3 appearing in a linear regression for late Dec 1995 through early Mar 1996 may thus result from chemical O_3 depletion in the lower stratosphere. This decreasing trend was about twice that found for the same period in 1992-93 and 1994-95; in 1991-92 and 1993-94, the fitted trends were increasing. Although some Arctic chemical O_3 loss was observed in each winter since the UARS launch, the 1995-96 winter was unique in that lower stratospheric O_3 decreased throughout the entire period from late Dec through early Mar. Lower and more sustained low temperatures and greater ClO enhancement [*Santee et al.*, 1996] led to O_3 losses large enough to noticeably affect column O_3. NH ozone depletion comparable to that in the SH would require both persistence of low temperatures into spring, and late winter temperatures even lower than those observed in 1995-96.

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