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 was colder than any of the previous 17 NH winters, with temperatures continuously below the type 1 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 winter lower stratospheric temperatures, and the latest observation of NH temperatures below the type 2 PSC threshold. Consistent with the unusual cold and past evidence of chemical processing on PSCs, the lower stratospheric ozone (O_3) decrease observed by UARS MLS in 1995-96 was greater than in any of the previous 4 NH winters. O_3 decreased throughout the vortex over an altitude range approaching that typically seen in the southern hemisphere (SH). The decrease between late Dec and early Mar was ~2/3 of that over the equivalent SH period. However, as in other NH winters, temperatures in 1996 rose above PSC thresholds before the spring equinox, so conditions comparable to the SH ozone hole did not arise. Column O_3 above 100 hPa showed a small downward trend from late Dec 1995 through early Mar 1996, apparently due to the lower stratospheric O_3 depletion.

Meteorology

The 1995-96 NH winter was colder overall than any of the previous 17 NH Winters. Fig. 1 compares high latitude minimum U.S. National Meteorological Center (NMC) temperatures in 1995-96 at 465 K potential temperature ($\sim$50 hPa) with those in the NH and SH in other years 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 formation threshold near 50 hPa) on 89 days, compared with a previous NH maximum of 82 days in 1994-95 [*Zurek et al.,* 1996]. Temperatures were below 188 K (the approximate type 2 PSC threshold) on 27 days during the 1995-96 winter, as opposed to a previous maximum of 18 days in 1983-84.

Two upper tropospheric blocking ridges had a profound effect on the lower stratospheric flow. Fig. 2 shows 465 K maps from calculations of high-resolution UK Meteorological Office (UKMO) potential vorticity (PV) (using the method of *Sutton et al.* [1994]) on 20 Feb and 3 Mar 1996; superimposed on these are 465 K UKMO temperature contours and 315 K ($\sim$300 hPa) PV contours. As noted by *O'Neill et al.* [1994] (and references therein), upper tropospheric blocking events (as evidenced by the buckling of the 315 K PV contours) are associated with a pattern of low temperatures and distortion of the vortex in the lower stratosphere, such that the coldest region is along the vortex edge. Thus, very low temperatures were located near the region of strongest winds, so that large amounts of air could quickly experience PSC processing. High-resolution PV fields indicate intrusion of extra-vortex air into the vortex in the days following 20 Feb, at 465 K and levels below. These 2 events in 1996 led to the latest observation of 465 K temperatures below 188 K in the NH (Fig. 1) and, during the first of these events, the lowest NH temperatures in the NMC record (these briefly approached values typical of the SH at the equivalent time of year).

While each NH winter since the UARS launch has included periods of unusual cold [*Zurek et al.,* 1996], the 1995-96 winter was the most persistently cold, with temperatures remaining continuously below 19L K for 80 days. It was also the only year since the UARS launch to be unusually cold throughout February (Fig. 1). Consistent with the unusual cold and past evidence of heterogeneous chemistry on PSCs, the UARS Microwave Limb Sounder (MLS) observed enhanced ClO in the NH vortex in mid- to late-Dec 1995, with most of the sunlit portion of the vortex filled with high ClO, and vortex-averaged values higher than previously observed at this time [*Santee et al.,* 1996]. During Feb 1996, lower stratospheric ClO was as high as previously observed by MLS, and high values persisted into early Mar 1996 [*Santee et a /.,* 1 996]. The unusual and persistent cold and the chlorine activation observed by M 1,S indicate the likelihood of greater chemical O_3 destruction in the 1995-96 winter than previously observed in the NH. We present here MLS O_3 observations which confirm this expectation.

Data and Analysis

The MLS Version 303 data and validation are described by *Froidevaux et al. [1996].* Version 4 data are now being produced and will be shown except when comparing directly to observations in 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 205 GHz O_3 data presented here (see *Santee et al.* [199[i]) and refinements in tangent pressure retrievals, fidd-of-view pointing and estimated errors. Version 4 O_3 data at 465 K are on average ~0.2-0.25 ppmv lower than Version 3 data in the polar regions discussed here. For both versions, precisions of individual O_3 measurements are typically ~0.2 ppmv, with absolute accuracies of 15-20% in the lower stratosphere. To conserve the lifetime of the MLS scan mechanism, full vertical scanning measurements were taken on only about 2 days out of every 3 during the north-looking periods in Nov/Dec 1995 and Feb/Mar 1996. In addition, a problem with the UARS spacecraft caused h41, S to be turned off’ on 4-12 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 fields [*Sutton et* al., 1994] are calculated from the UKMO analyses. Three-dimensional O_3 transport calculations are done using 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-arm grid (for detailed examination of individual days and levels). UKMO meteorological data are used in the analysis of MLS O_3 to be consistent with these calculations. UKMO NH lower stratospheric temperatures are usually 1-3 K higher than NMC temperatures [*Manney et al.,* 1996b]; an exception is during the ridging event around 20 Feb, 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. As noted above, the Version 4 averages are ~0.23 ppmv lower than those for Version 3 (which can be directly compared with previous years). Fig. 4 shows 465 K MLS O_3 maps during the 1995-96 NH winter. Vortex-averaged O_3 in early Dec 1995 was similar to previous years, but the increase during Dec was slightly smaller. This difference is thought to be primarily due to interannual differences in the development of the polar vortex and associated transport; comparison with transport calculations suggests no evidence of chemical loss at this time.

Between 25 Dec 1995 and 29 Jan 1996, 465 K vortex O_3 decreased slightly (Figs. 3 and 4). Small decreases (~5%) were observed up through 585 K over the same period. In general, transport processes are expected to increase lower stratospheric O_3 at this time, through replenishment by diabatic descent. Transport calculations on the 4° by 5° grid show increases of 10-15%, which, combined with observed decreases, gives estimated 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.

During Feb 1996, 465 K vortex-averaged O_3 decreased rapidly, with largest decreases well within the vortex. By early February, high O_3 is concentrated along the vortex edge (Fig. 4). 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. On 20 Feb 1996, since highest O_3 is along the vortex edge, the distortion of the flow by the upper tropospheric ridge leads to the intrusion of *higher* O_3 into the vortex in the transport calculation. A slight increase in observed vortex-averaged O_3 (Fig. 3) was also seen at this time. Filaments of higher O_3 pulled off the vortex 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 ~0.02 ppmv/d or ~0.8%/d. Chemical depletion is masked by transport to a lesser degree 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, *Manney et al.* [1995a, b]) and ~0.01 ppmv/d (1991-92). Even with a smaller increase due to transport, the greater observed rate of decrease 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 O_3 loss observed by MLS over the 1995-96 NH winter, showing changes in lower stratospheric O_3 between 24 Dec 1995 and 3 Mar 1996 as a function of equivalent latitude (PV expressed as the latitude that would encompass the same area as the PV contour, see, 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-$5, large O_3 decreases (calculated over the same length of time, for a period encompassing the time when most 03 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 199596 is qualitatively similar to that in recent SH winters, and the magnitude of the decrease is ~2/3 that over the equivalent S11 period. In contrast to the SH, however, the NH final warming in 1996 began in early March (as is typical in the NH, Fig. 1), so little additional chemical O_3 loss was expected; in the S11, temperatures below 195 K are typically present for 1-2 months longer, and 03 continues to decrease for ~1 month after the spring equinox.

Maps of h41,S column O_3 above IO() hPa, with 46 hPa UKMO temperature contours overlaid, are 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 [e.g., *Petzoldt et 01.*, 1994, and references therein]. Since column O_3 is not, in general, expected to be correlated with the vortex (cf. Figs. 2 and 8), Fig. 9 indicates the time trends by showing the average column O_3 in the region that is both north of 40° N and where column O_3 is less than 260 DU (less than 250 DU for Version 4, due to the bias between versions). In this average, column O_3 above 100 hPa in late Dec is lower than in previous years. This difference is likely due mainly to interannual variability in dynamical processes or in chemical effects other than those associated with heterogeneous chemistry on }'S(1s, since significant chemical depletion by this mechanism is neither expected nor observed at this time.

During Feb 1996, column O_3 varied on a time scale of a few days; comparison of Fig. 9 with Fig. 1 shows these variations to be correlated with changes in lower stratospheric temperature. While column O_3 values fluctuated from day to day, between late Dec 1995 and early Mar 1996 there was a small overall decrease (~1 O DU) that may reflect the observed chemical O_3 depletion in the lower stratosphere. This decrease was at least twice that in any of the previous 4 NH winters over a similar period; in 1991-92 and 1993-94, increases of about this magnitude were seen. Although chemical O_3 loss in the NH vortex was observed at some time in each of the 5 winters 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. More sustained low temperatures and greater ClO enhancement [*Santee et al.*, 1996] during this winter led to O_3 losses sufficiently large that the effect on column O_3 was noticeable. NH ozone depletion comparable to that in the SH would require both persistence of temperatures below PSC thresholds after the spring equinox, and temperatures during late winter and early spring even lower than those observed in 1995-96.

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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), the envelope and average for 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 June).

Figure 2. High-resolution UKMO 465 K PV (colors), 465 K 185, 190 and 195 K UKMO temperature contours (black) and 315 K PV contours (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 O_3 (ppmv) for 1 Dec through 20 Mar. Open cyan circles show Version 4 MLS data in 1995-96.

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 x 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 column O_3 above 100 hPa. 46 hPa temperature contours of 185, 190 and 195 K are overlaid.

Figure 9. Average column O_3 poleward of 40°N for column $O_3 \leq 260$ DU (≤ 250 DU for version 4) from MLS during 5 NH winters. Symbols and line styles are as in Fig. 3.

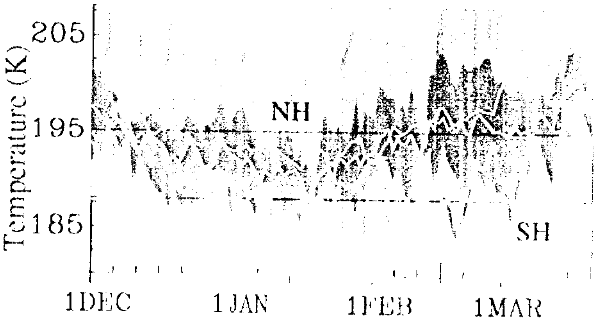


Fig. 1

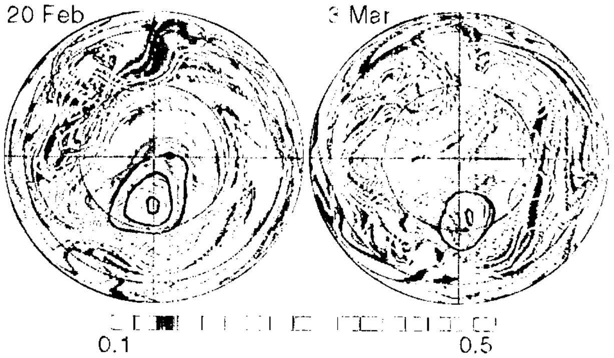


Fig. 2

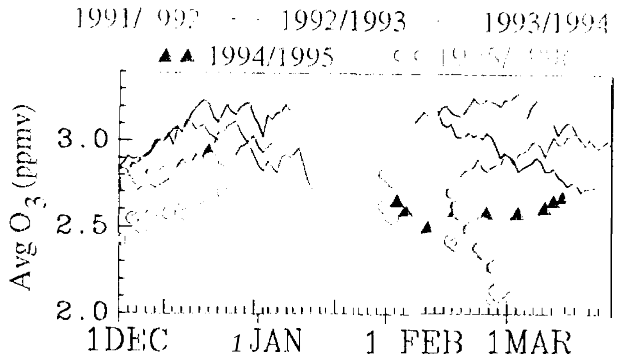

1991/1992
1992/1993
1993/1994
▲▲ 1994/1995
1995/1996
Avg O_3 (ppmv)
3.0
2.5
2.0
1DEC
1JAN
1 FEB
1MAR

Fig. 3

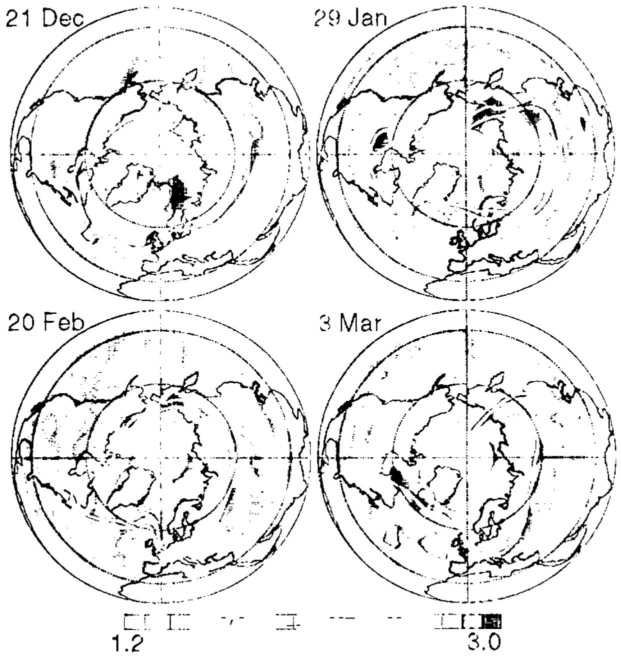
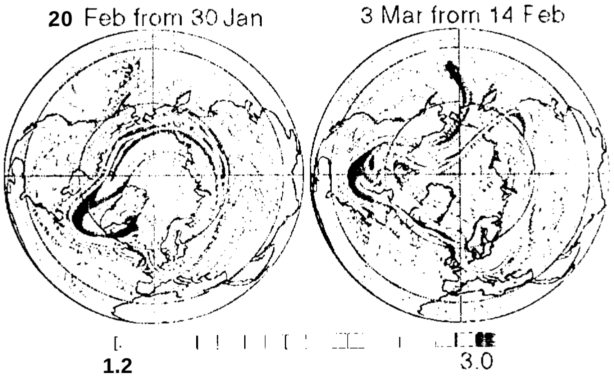
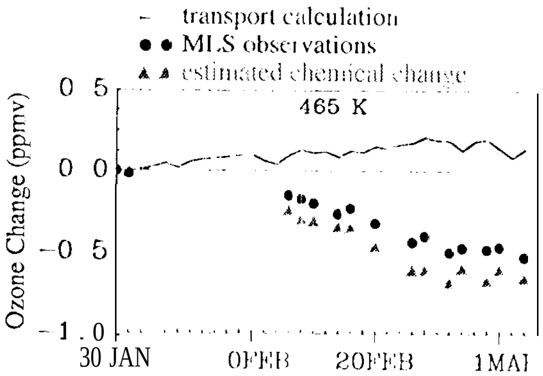


Fig. 4


20 Feb from 30 Jan

3 Mar from 14 Feb

Fig. 5


transport calculation
MLS observations
estimated chemical change
465 K
Ozone Change (ppmv)
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0.0
−0.5
−1.0
30 JAN
0FEB
20FEB
1MAR

Fig 6

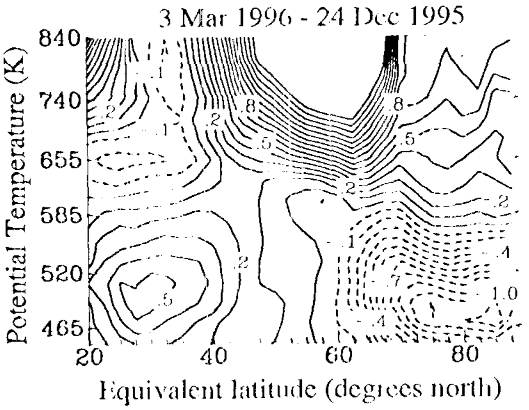
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Fig. 7

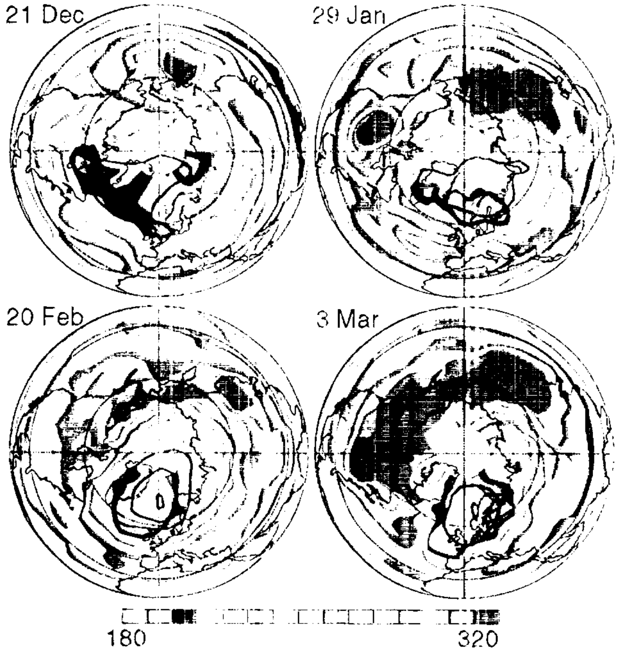

Fig. 8

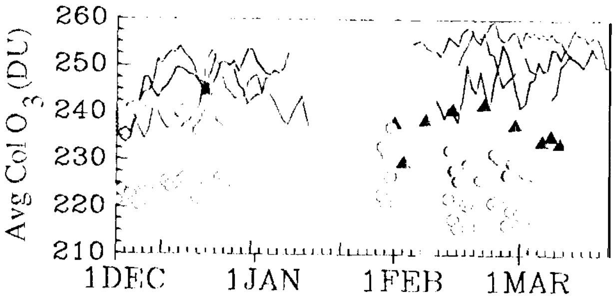

Fig. 9