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Evidence for Arctic ozone depletion in late February and early March 1994

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Abstract. Significant chemical ozone (O_3) loss in the 1993-94 Arctic winter occurred mainly during an unusually late cold spell of ~10 days in late Feb/early Mar. Over the 30 d period studied (including the cold spell), observed vortex-averaged O_3 at 465 K (~40 hPa) decreased by ~10%. New three-dimensional, diabatic trajectory calculations show that this observed decrease represents only about half of the net chemical loss (~20%) during the 30 day period. The resupply of lower stratospheric O_3 by transport in Feb 1994 was considerably greater than in 1993, when transport masked only about a quarter of the chemical loss in Feb/Mar. The net estimated chemical loss over 30 days in 1994 was comparable to that over the same 30 days in 1993, but mainly occurred at a faster rate during the brief cold spell. These results highlight the impact of Arctic interannual variability on the relative roles of chemistry and dynamics in O_3 evolution during recent Arctic winters.

Introduction

Because the Arctic polar vortex is more variable than the Antarctic, conditions in the Arctic are favorable for polar stratospheric cloud (PSC) formation and resultant chlorine activation and ozone (O_3) depletion for a shorter time than in the southern hemisphere, and dynamical processes play a more important role in the O_3 evolution. Arctic O_3 depletion has been detected when temperatures were below PSC formation thresholds, in Jan/Feb 1989 [e.g., *Salawitch et al.*, 1990; *Schoeberl et al.*, 1990], Jan/Feb 1992 [e.g., *Salawitch et al.*, 1993], and through most of the 1992-93 winter [e.g., *Larsen et al.*, 1994; *Manney et al.*, 1994a]. Arctic O_3 depletion varies markedly due to interannual variability in the timing and duration of temperatures low enough for PSC formation [e.g., *Zurek et al.*, submitted to *Geophys. Res. Lett.*]. Transport processes such as diabatic descent may also vary significantly, changing the interplay between chemistry and transport.

Diabatic descent is expected to mask some chemical O_3 loss [e.g., *Schoeberl et al.*, 1990]. *Schoeberl et al.* [1990], *Larsen et al.* [1994], and *Manney et al.* [1994a] used passive tracer measurements to diagnose changes due to transport, and thus distinguish chemical from dynamical effects. *Manney et al.* [1995, hereafter *M95*] used a trajectory technique including diabatic effects to examine three-dimensional (3d) O_3 transport during Feb and Mar 1993, contrasting observed with purely advected O_3 distributions to separate chemical and dynamical effects, and showed that transport masked up to ~25% of lower stratospheric chemical O_3 depletion.

The lower stratospheric vortex was relatively warm compared to other recent winters through most of the 1993-94 northern hemisphere (NH) winter, until a period of sudden cooling in late Feb (Fig. 1a); this was the latest occurrence of temperatures below a PSC formation threshold in any of the previous 16 Arctic winters [*Zurek et al.*, submitted to *Geophys. Res. Lett.*]. Minimum temperatures (from the United Kingdom Meteorological Office (UKMO)) were slightly below the type I PSC threshold (~195 K) after early Jan 1994, warming to slightly above it in early Feb [*Waters et al.*, 1995]. The Microwave Limb Sounder (MLS) on the Upper Atmosphere Research Satellite (UARS) observed some enhanced chlorine monoxide (ClO, the dominant form of reactive chlorine that destroys O_3) in early Feb, with a subsequent decrease until the late Feb drop in temperatures; ClO then increased [*Waters et al.*, 1995]. Fig. 1b shows that "vortex-averaged" (described below) MLS O_3 on isentropic surfaces in the lower stratosphere decreased below ~450 K in late Feb 1994; a larger decrease throughout the lower stratosphere occurred (during a gap in observations) in early Mar. The net observed decrease over the 30 d period is ~10% at 465 K, and ~5% at 520 and 585 K. We use an updated trajectory method to show that much of the chemical O_3 loss was masked by transport.

Data and Analysis

The MLS O_3 data are described by *Froidevaux et al.* [1995]. Precisions (rms) of individual O_3 measurements are ~0.2-0.3 ppmv, with absolute accuracies of 10-30% in the lower stratosphere. The O_3 data are gridded using a Fourier transform technique [*Elson and Froidevaux*, 1993], providing synoptic fields on a 4° latitude by 5° longitude grid. Gridded synoptic data are useful for comparison with meteorological analyses and for computing area-weighted averages. The value of this gridding method has been previously demonstrated [*Elson and Froidevaux*, 1993; *Manney et al.*, 1994a; *M95*; references therein]. Consistent results are obtained using raw data or other gridding methods. The data gap between 27 Feb and 8 Mar was caused by problems with

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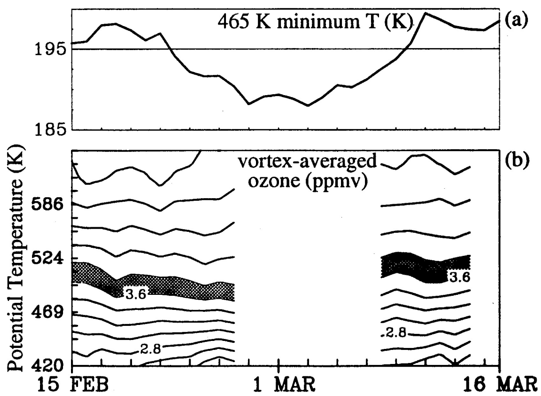

Figure 1. (a) Minimum 465 K temperatures (K) and (b) vortex-averaged (described in text) MLS O_3 (ppmv) from 420 to 655 K, for 15 Feb to 16 Mar 1994.

the MLS antenna scan mechanism; this did not degrade measurements at other times.

The trajectory code [*Manney et al.,* 1994b] is run using UKMO [*Swinbank and O'Neill,* 1994] horizontal winds and diabatic descent rates from an independent radiation code. The O_3 mixing ratio of each parcel on the initialization day is taken from MLS observations. The subsequent motion of tagged parcels represents the expected behavior of O_3 due solely to transport, and can be compared with observed O_3. Such calculations, done mainly using forward trajectory runs and subsequent gridding of the nonuniform advected fields, reproduced the main features of passive tracer evolution during the 1992-93 NH winter, including descent rates in the Arctic lower stratospheric vortex [*M95*]. Sensitivity tests [*M95*] (including different initialization dates, initialization grids and final gridding methods) indicate vortex-averaged advected O_3 changes at levels from 465 to 585 K are uncertain by less than 20% of the magnitude of the change for the first ~20 days of the calculation, increasing to $\lesssim$40% in the worst case after 30 days; most cases show much less sensitivity. This previous success of the trajectory method gives confidence that it can reproduce large scale transport in the lower stratosphere.

We update the method here, using a reverse trajectory technique similar to that described by *Sutton et al.* [1994] (described in detail by *M95*, who used it to check sensitivity to gridding methods) to get advected O_3 directly on a grid. Parcels are initialized each day on the same grid as the MLS data. The trajectory code (including diabatic effects) is run backward to the initial day, and MLS O_3 on that day is interpolated to the calculated parcel positions. This field gives the O_3 mixing ratio that would be transported to the grid locations from the 3d MLS O_3 field for the initialization day.

In the analysis, we show "vortex-averages" that are area-weighted, covering the area south of 80°N latitude (where mapped MLS data are available) where potential vorticity (PV) is higher than a value representing the vortex edge. PV is calculated from UKMO analyses and is scaled in "vorticity units" (sPV) [*Manney et al.,* 1994b] to give a similar range of values at all levels. Gridded MLS data at the highest latitudes may be suspect [*Elson and Froidevaux,* 1993], but tests using lower latitude cutoffs give nearly identical results. For the advected fields shown in Figs. 2 and 4, mapped MLS data were interpolated across the pole to eliminate gaps. However, the vortex-averages, both from observations and calculations, are constrained to include only the area where the advected O_3 field was obtained from parcels with latitudes $\leq$80°N on 15 Feb, the initialization day.

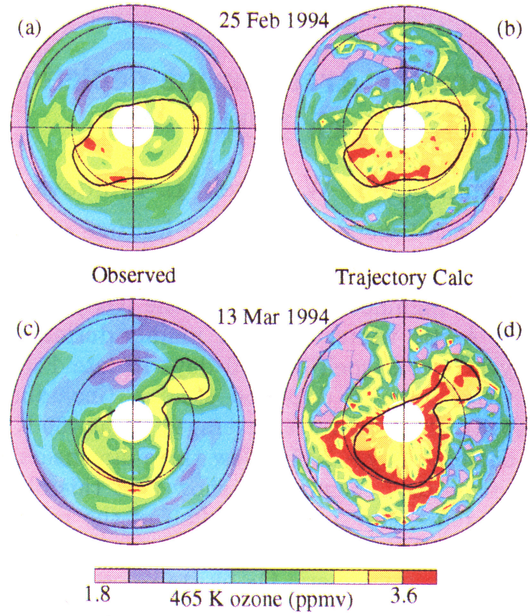

Figure 2. 465 K O_3 (ppmv) from observations and the trajectory method on 25 Feb and 13 Mar 1994. The projection is orthographic, with 0° longitude at the bottom and 90°E to the right; dashed lines are at 30° and 60°N. The 1.4×10^{-4} s^{-1} sPV contour is overlaid.

Results

Fig. 2 compares 465 K O_3 from MLS observations with that from the reverse trajectory procedure, on 25 Feb and 13 Mar 1994. High values of advected O_3 in the vortex increase slightly over observed values by 25 Feb 1994. Differences between observed and advected fields are much larger on 13 Mar, when advected O_3 has increased substantially in the vortex, but observed vortex O_3 has decreased. Vortex-averaged advected O_3 (Fig. 3) increases throughout the period, as expected

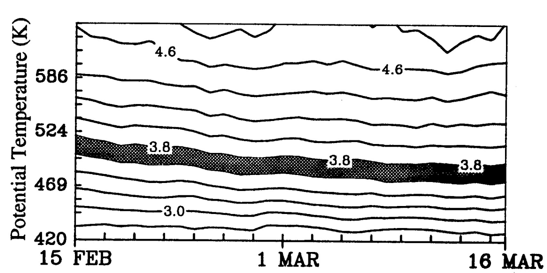

Figure 3. As in Fig. 1b, but for advected O_3 .

during periods of diabatic descent. Comparing observed (Fig. 1b) with advected vortex-averaged O_3 (Fig. 3) indicates that most of the differences in behavior are between ~25 Feb and 9 Mar (the end of the data gap). The differences between observed and advected 465 K O_3 fields (Fig. 2) and between the observed (Fig. 1b) and advected vortex-averaged (Fig. 3) O_3 show that the observed O_3 behavior is inconsistent with the effects of transport alone.

During the first ~10 d shown in Fig. 1b and Fig. 3, observed and advected O_3 evolve similarly. This, and the similarity between observed and advected O_3 morphology seen in Fig. 2, particularly in the location of the highest values, is a further indication that the calculated transport is reasonable. The highest O_3 values are along the vortex edge, and reflect a pattern of strongest diabatic descent near the vortex edge in the lower stratosphere which is common in the NH late winter [e.g., *Schoeberl et al.,* 1992; *Manney et al.,* 1994a,b].

Fig. 4 shows the spatial distribution of changes in observed and advected O_3, comparing observed and calculated lower stratospheric O_3 changes in PV/θ space [e.g., *Schoeberl et al.,* 1989; *Schoeberl et al.,* 1992; *Manney et al.,* 1994a] between 15 Feb and 13 Mar 1994. While observed O_3 decreases throughout the lower stratospheric vortex (sPV $\gtrsim 1.2 \times 10^{-4}$ s^{-1}) at levels up to ~650 K, advected O_3 decreases only in small regions outside the vortex near 520 K, and at the vortex center near 650 K. At the lowest levels, both observed and advected extra-vortex O_3 increase slightly (but more than the ~0.05 ppmv precision of MLS data

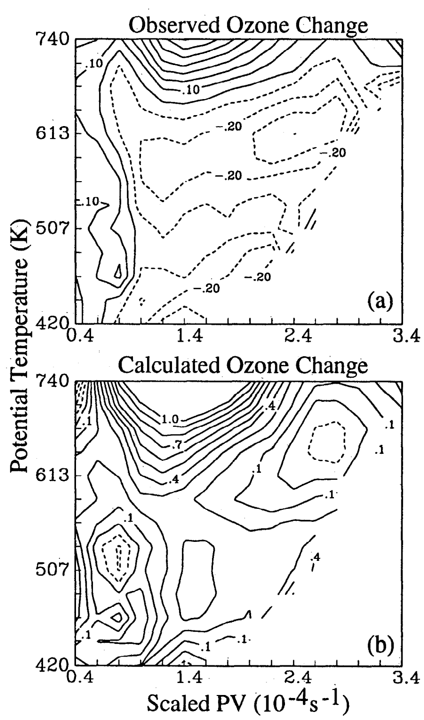

Figure 4. Differences (ppmv) in (a) observed and (b) advected O_3 in the lower stratosphere (420 - 740 K) between 15 Feb and 13 Mar 1994, as a function of sPV and θ; dashed lines indicate a decrease.

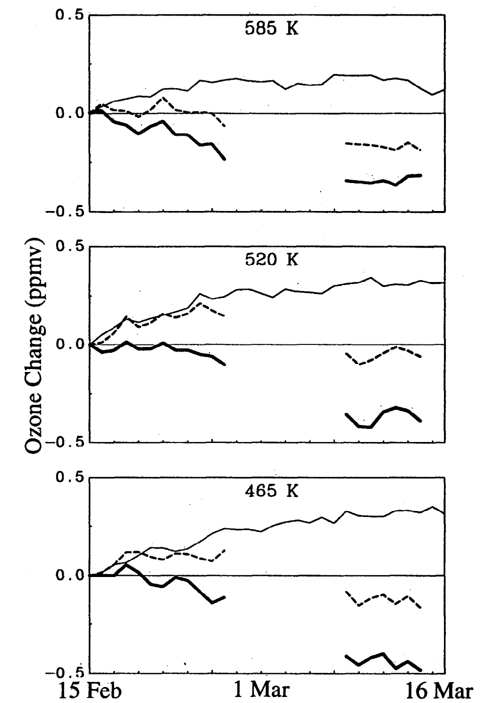

Figure 5. Observed (dashed line) and advected (thin solid line) vortex-averaged O_3 change (ppmv) at 585, 520, and 465 K, and estimated chemical change (thick solid line) for 15 Feb to 14 Mar 1994.

averaged in this way), due to transport of higher O_3 from within the vortex (as is also apparent in Fig. 2).

Assuming that advected vortex-averaged O_3 variations represent all O_3 changes due to dynamical processes, the difference between observed and advected variations, shown in Fig. 5, indicates the change in O_3 due to non-dynamical (chemical) processes. The observed lack of O_3 increase at 585 K (Fig. 5a) during the first ~12 days of the period suggests that downwelling masks some chemical depletion there. As noted earlier, the agreement between observed and advected O_3 in the first ~8 days at 520 K (Fig. 5b) and 465 K (Fig. 5c) indicates that little O_3 destruction is occurring, and supports the reliability of the transport calculation. Between the beginning ~25 Feb and the end of the data gap, there must be significant O_3 destruction by chemical processes at each level shown, some of which is masked by transport.

Based on Fig. 5, we estimate a net chemical O_3 loss over the 30 d period from mid-Feb to mid-Mar 1994 of ~20% at 465 K, and ~8-15% at the higher levels. This is only slightly less than the net loss for the corresponding 30 d in 1993 [*M95,* Fig. 12]. The 1992-93 winter was generally very cold, but temperatures increased above the PSC threshold, and ClO decreased, in early Mar [*Waters et al.,* 1995]. Chemical O_3 loss was detected through most of the 1992-93 winter [*Larsen et al.,* 1994] and decreasing O_3 was seen throughout the Feb/Mar 1993 period observed by MLS [*M95*]. In contrast, chemical O_3 depletion in 1993-94 occurred primarily during the brief cold spell in late Feb/early Mar

1994, comprising about a third of the 30 d period studied.

In 1993 maximum ClO was observed in mid-Feb, and was considerably higher than the maximum observed in 1994, but the 1994 maximum did not occur until early Mar [*Waters et al.,* 1995]. The faster rate of O_3 decrease (but over a shorter period) in 1994 is in general accord with sunlight at higher latitudes leading to more chemical O_3 loss during the late 1994 cold period. This is also consistent with loss rates and net amounts of O_3 loss in the 1994 late winter being larger that those inferred from aircraft measurements for Jan/Feb 1989 [e.g., *Schoeberl et al.,* 1990] and Jan/Feb 1992 [e.g., *Salawitch et al.,* 1993], both during cold periods that were considerably longer (~30-40 d) than that during early Mar 1994.

Comparison of advected O_3 for Feb/Mar 1994 (thin solid lines in Fig. 5) with that calculated for Feb/Mar 1993 [*M95*, Fig. 12] indicates that transport tended to increase vortex-averaged O_3 substantially more over the 30 d period studied in 1994 than at the same time of year in 1993. From mid-Feb to mid Mar 1993, the rate of increase by transport was fairly uniform [*M95*], whereas in 1994 (Fig. 5) a more rapid increase was seen during the first half of the period studied. Faster diabatic descent is probably related to the slight warming in the lower stratosphere that preceded the early Mar 1994 cooling [*Waters et al.,* 1995], since diabatic descent is usually enhanced during warmings [e.g., *Manney et al.,* 1994b]. The net result of the differences in both transport and chemistry, and in their relative timing, is that considerably more of the chemical O_3 loss between mid-Feb and mid-Mar 1994 was masked by transport than between mid-Feb and mid-Mar 1993.

Conclusions

A diabatic trajectory method initialized with observed MLS O_3 was used to simulate 3d O_3 transport in the Arctic lower stratosphere from mid-Feb to mid-Mar 1994, and to compare with similar calculations for mid-Feb to mid-Mar 1993 [*M95*]. Comparison of advected with observed O_3 indicates that chemical O_3 depletion occurred in the Arctic lower stratospheric vortex primarily during a brief (~10 d) cold period in late Feb/early Mar 1994. This is in contrast to Feb/Mar 1993, when temperatures were persistently low and O_3 loss occurred throughout the period. Calculations for 30 d periods beginning in mid-Feb show that increases in O_3 due to transport were considerably larger in Feb 1994 than in Feb 1993. The inferred chemical O_3 loss rate during the ~10 d cold spell in 1994 was sufficiently large that the net chemical O_3 loss was comparable over the 30 d periods in the two years. Over the 30 days, transport masks ~1/3 (near 585 K) to 1/2 (near 465 K) of the chemical O_3 depletion in 1994, as opposed to ~1/10 (near 585 K) to 1/4 (near 465 K) in 1993 [*M95*]. These results demonstrate how interannual variability in transport and in the timing and duration of cold periods can significantly modify the relative impact of dynamical and chemical processes in determining observed O_3 distributions in the Arctic lower stratosphere.

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