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Ozone and aerosol observed by Lidar in the Canadian Arctic during the winter of 1995/96

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Abstract. Lidar observations of stratospheric ozone made at Eureka (80.0°N,86.42°W) during the 95/96 winter show substantial declines in ozone mixing ratios. Reductions in ozone levels of up to 40 % between the 410 K and 580 K isentropic levels were observed between mid-January and mid-March. The correlation of the ozone data with potential vorticity and concurrent lidar observations of stratospheric aerosol is consistent with the claim that significant chemical depletion did occur.

Introduction

Although not as marked as the decline in lower stratospheric ozone mixing ratios associated with the formation of the Antarctic "ozone-hole" substantial reductions in Arctic lower stratospheric ozone have been observed [*Manney et al.* 1995, *Browell, et al.* 1993]. The degree of ozone depletion is linked to the prevalence of polar stratospheric cloud (PSC) formation which in turn is linked to the occurrence of low stratospheric temperatures. PSC particles provide surfaces on which heterogeneous chemical conversion of chlorine species from inactive to active forms will occur. In the presence of sunlight these chlorine compounds will engage in catalytic destruction of ozone [*Rodriguez*, 1993].

Compared to the southern hemisphere polar vortex, the northern hemisphere (NH) polar vortex is usually much more dynamically perturbed by planetary wave activity. As a result, the low temperatures required for PSC formation are generally not as long lived nor widespread leading to less ozone destruction [*Schoeberl and Hartmann*, 1991]. However, the year-to-year variation of temperatures within the northern polar vortex is also generally much more pronounced leading to large yearly variations in the degree of northern polar ozone depletion. During the 95/96 winter, temperatures within the northern lower stratosphere were at their lowest levels compared to the past 17 years [*NOAA*, 1996]. Temperatures below those required for PSC formation (about 189 K) were present at latitudes above 60°N from early December to early March. Based on the current understanding of polar ozone depletion these low temperatures may be expected to lead to significant decreases in NH polar ozone.

From late-November to mid-March lidar observations of stratospheric ozone and aerosol were carried out at a facility operated by the Canadian Atmospheric Environment Service (AES) located at Eureka (80.0°N, 86.4°W). Figure 1 shows the isentropic potential vorticity (PV) of the 475 K level for four representative times during the 95/96 winter. Except for a brief period in early March the lower stratosphere above Eureka was within the confines of the polar vortex. In this paper, lidar measurements showing large declines in lower stratospheric ozone within the polar vortex during the 95/96 winter are presented. Comparison of the the ozone observations with potential vorticity and lidar aerosol data shows that the observed declines are consistent with the occurrence of chemical depletion.

Measurement Technique

The AES/ISTS ozone lidar transmits light at 308 and 353 nm and receives the elastic aerosol/molecular backscatter at the transmitter wavelengths as well as the inelastic vibrational Raman N_2 backscatter at 332 and 385 nm. The system is described in more detail elsewhere [*Donovan et al.* 1995]. Ozone profiles were deduced using the DIAL method with both the 308/353 nm and 332/385 nm wavelength pairs.

Measurements of the aerosol backscatter ratio, R, (the total molecular and aerosol backscatter coefficient divided by the molecular backscatter coefficient alone) were made by ratioing the 353 return by the 385 nm Raman N_2 signal. This method removes much of the uncertainty associated with accounting for the aerosol extinction. Molecular extinction effects in both the ozone and aerosol measurements were accounted for us-

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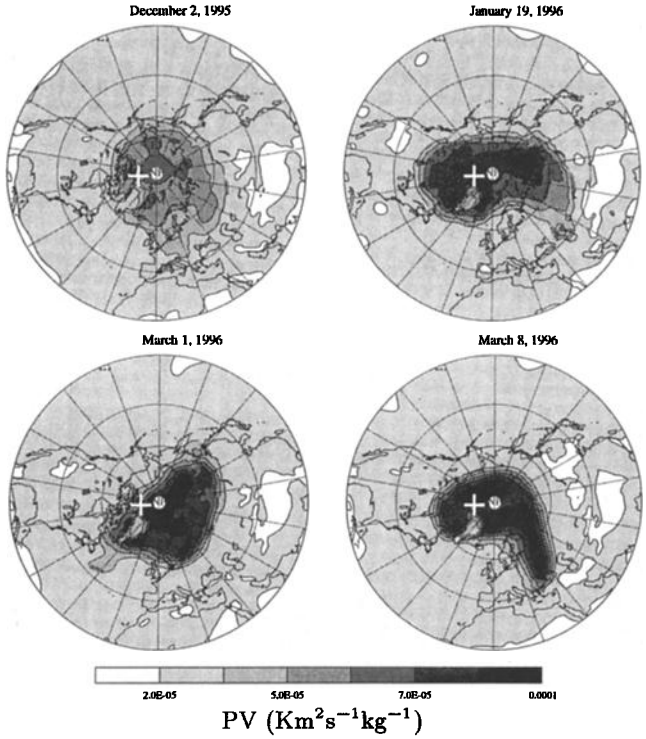

Figure 1. Northern hemisphere isentropic potential vorticity at 475 K calculated from the Canadian Meteorological Center (CMC) objective analysis throughout the observation period. The measurement site is denoted by the white +.

ing density profiles deduced from meteorological sondes launched every 12 hrs from the Eureka weather station.

The DIAL measurements of ozone using the inelastic Raman backscatter allow the accurate retrieval of ozone profiles regardless of the presence of substantial amounts of aerosol [*McGee et al.* 1993]. Under the stratospheric aerosol levels usually present during the measurement period the aerosol amounts were not sufficient to adversely affect the accuracy of the ozone retrievals using the 353/308 nm wavelength pair. However, the presence of PSCs and high cirrus clouds can significantly interfere with the elastic DIAL retrieval of ozone in the stratosphere and upper troposphere. An example of this is shown in Figure 2. Here the scattering ratio shows strong peaks corresponding to PSCs at 19 and 21 km and a smaller peak at 7 km corresponding to a thin cirrus layer. The ozone profile derived using the Rayleigh/Mie backscatter wavelengths shows large spurious fluctuations associated with the presence of the clouds while the ozone profile given by the inelastic Raman N_2 backscatter wavelengths is significantly less perturbed by the clouds.

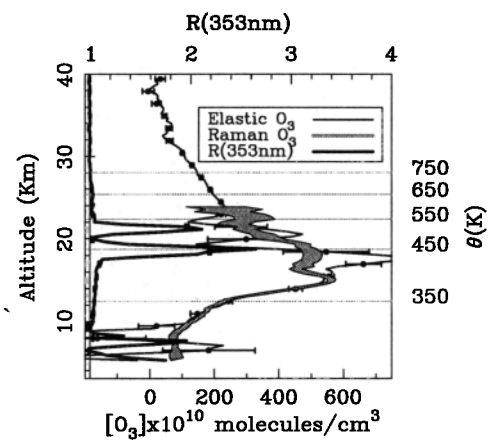

Figure 2. Sample ozone profiles and aerosol scattering ratio profile showing a cirrus cloud layer and two strong PSC layers. The ozone profile labeled 'Elastic' was derived from the elastic wavelength pair while the other was derived using the Raman backscatter wavelengths. The shading and error bars denote the statistical uncertainty.

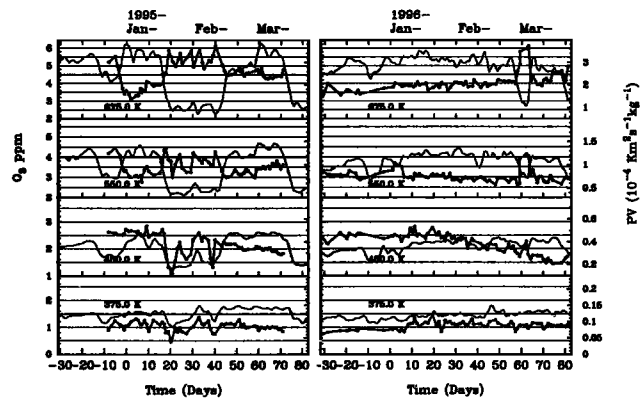

Figure 3. Ozone mixing ratio (dark line) and potential vorticity for different potential temperature levels. The values shown are averages over ± 25 K about the levels shown.

Because of the small backscatter cross section for Raman scattering, (as compared to Rayleigh scattering) Raman ozone measurements are limited up to about 23-25 km altitude while the elastic wavelength returns are used above. Based on the agreement between the Raman and Rayleigh/Mie derived ozone profiles (in the absence of aerosol) and comparison with ECC ozone sonde profiles, the accuracy and precision of the ozone measurements is judged to be within a few percent throughout the upper troposphere and lower stratosphere [*Donovan et al.*, 1995].

Observations

With respect to the position of the polar vortex above Eureka the 95/96 measurement season was markedly different from the 94/95 winter. During the course of the 94/95 season the lower stratosphere above Eureka spent significant periods of time both inside and outside of the vortex boundaries, while in 95/96 the lower stratosphere above Eureka was mainly inside the vortex except for a brief period in early March. To correlate the observed changes in ozone mixing ratios with the dynamics of the polar vortex, the ozone data were compared with PV and lidar aerosol observations.

The distribution of ozone in the lower stratosphere (in the absence of strong chemical depletion) is largely controlled by dynamics. As a result, one expects the

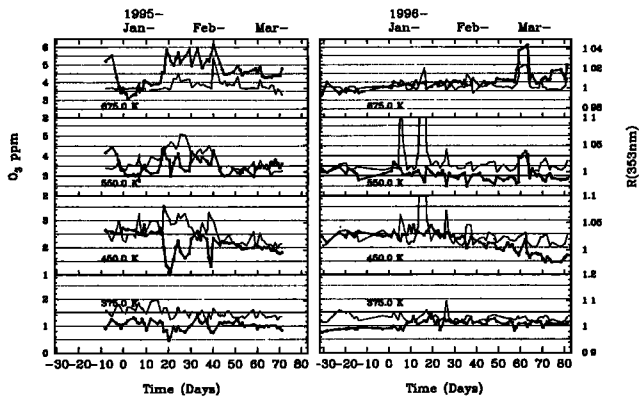

Figure 4. As Figure 3., but showing ozone mixing ratio (dark line) and aerosol scattering ratio (R).

ozone mixing ratio to be correlated with other quantities that can be considered pseudo-tracers such as PV and the background aerosol scattering ratio [*Plumb and Ko*, 1992]. Figure 3 shows the ozone mixing ratios along with the isentropic potential vorticity (PV) at different potential temperature levels for both the 94/95 and 95/96 winters. The correlation between the observed ozone mixing ratios and PV [*Vaughan and Price*, 1991] is particularly evident in the 94/95 data showing the large variation between the distribution of ozone inside (high PV) and outside (low PV) the polar vortex. The correlation between PV and ozone mixing ratio can be seen to be positive at lower altitudes and changes sign on moving to higher levels within the vortex.

The observed aerosol scattering ratios and the ozone mixing ratios for the same levels as in Figure 3 are shown in Figure 4. In general, aerosol scattering ratios are quite small above about 450 K inside of the polar vortex. The large 'spikes' (uncorrelated with any changes in PV or ozone) present throughout the January 1996 R data are due to the presence of strong PSCs above Eureka. Radiosonde soundings indicated that the temperatures at these altitudes did fall below PSC temperatures during these events.

The background aerosol scattering ratios above about 400 K are negatively correlated with PV, thus the correlation between aerosol scattering ratios is opposite that between ozone and PV (i.e. negative at lower levels changing to positive at higher levels). A similar correlation has been noted previously [*di Sarra et al.*, 1992]. Here the aerosol observations are used mainly to help distinguish between periods inside and outside of the vortex. The background intra-vortex aerosol scattering ratios are so low above 450 K that little quantitative information can be by gained by comparing the intra-vortex ozone mixing ratios and aerosol scattering ratios.

During the course of a given winter strong altitude dependent diabatic descent generally occurs within the confines of the polar vortex [*Rosenfield et al.*, 1994]. This descent will tend to increase stratospheric ozone mixing ratios throughout the season as ozone rich air is transported downwards across isentropic surfaces. Consistent with the occurrence of diabatic descent, for both seasons intra-vortex ozone mixing ratios above about 580 K show general increases throughout the winter. Below 580 K a similar increase would be expected, however substantial decreases are seen to occur. This is particularly evident in the 450 K ozone data shown in Figures 3 and 4 where a distinct downwards trend in intra-vortex ozone (as identified by the low aerosol scattering ratios and high PV) can be clearly seen for both seasons. Such decreases are consistent with the occurrence of strong chemical depletion.

Figure 5 shows the average intra-vortex ozone mixing ratio profiles for several periods during the 94/95 and 95/96 winters. Only measurements which were considered to be inside the confines of the vortex (i.e. low background aerosol scattering ratios above 450 K and PV within about 85 % of the vortex maximum at all levels) were included in the averages. For 95/96 averages for four approximately monthly intervals are shown while for 94/95 three shorter time periods are displayed. For both winters at higher altitudes (above about 550 K) ozone mixing ratios increased. Below this level ozone mixing ratios declined with the 95/96 data showing the largest reduction of about 40 % at the 450 K level between mid-January and mid-March. This estimate of ozone reduction does not take into account the expected increase due to diabatic descent which would increase ozone mixing ratios at these levels. Assuming a typical value for the descent expected around the 450-500 K levels of about 25 K [*Rosenfield et al.*,1994] and applying this to our observations gives an estimated increase on the order of 15 %. This leads to an estimated overall average ozone loss of about 50-55 % or 1.1-1.3 % per day between mid-January and mid-March in 1996 at the 450 K level.

The observations presented here are limited in the sense that they were conducted at a single location. However, due to the relatively flat quasi-horizontal gradients present within the confines of the polar vortex, the length of time spent inside the vortex and the number and consistency of the observations, the average intra-vortex profiles presented are likely a good representation of the vortex as a whole and comparisons at the approximate level made are valid.

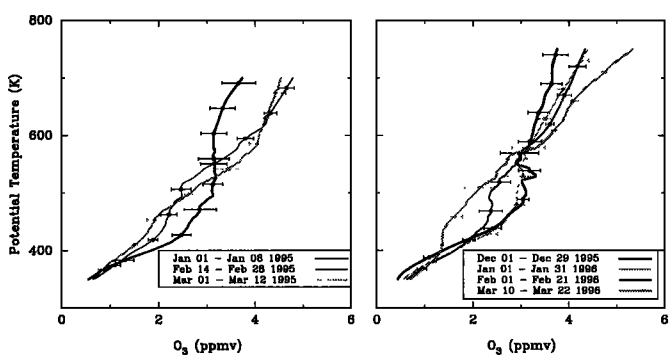

Figure 5. Average intra-vortex ozone mixing ratio profiles throughout the 94/95 (left) and 95/96 (right) measurement periods. The error bars show the standard deviation of the mean profiles.

The observed ozone trends are consistent with Microwave Limb Scanner (MLS) measurements of intra-vortex ozone made in December, February and early March (*Manney et al.* submitted to Geophys. Res. Lett., 1996). The lidar observations indicate that the region of ozone loss extended to the base of the vortex (about 400 K). This is below the minimum altitude covered by the MLS instrument. The lidar observations also suggest that ozone loss continued until mid-March, about a week after the last occurrence of PSC temperatures. Compared to the 94/95 season, intra-vortex ozone losses for the 95/96 season were larger in magnitude. This is consistent with the generally lower vortex temperatures. The occurrence of significant chemical depletion is also consistent with observations of elevated ClO levels made by the MLS instrument on the UARS satellite (*Santee et al.* submitted to Geophys. Res. Lett., 1996).

The fact that ozone loss occurred strongly near the vortex base is significant because transport to midlatitudes is most likely to occur at these altitudes. Transport of chemically activated intra-vortex air to lower latitudes (though perhaps not the dominant factor) possibly significantly contributes to declines in midlatitude ozone [*Norton and Chipperfield.*, 1995].

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