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AN OBSERVATIONAL STUDY OF THE 'OZONE DILUTION EFFECT': OZONE TRANSPORT IN THE AUSTRAL SPRING STRATOSPHERE

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ABSTRACT

In a previous observational analysis, Atkinson *et al* (1989) ascribed a sudden decrease in southern hemisphere mid-latitude total ozone during December 1987 to an 'ozone dilution effect' brought about by the breakup of the polar stratospheric vortex at that time. A question alluded to but unanswered by that study was the degree to which the observed total ozone decrease might have been caused by the quasi-horizontal equatorward transport of 'ozone hole' air from within the vortex, and to what degree by the vertical advection from lower levels of air naturally low in ozone, a dynamical adjustment process which must accompany the equatorward outbreak of a discrete high-latitude airmass.

In the present study, analyses of Ertel potential vorticity, TOMS total ozone and SAGE and ozone sonde vertical profile data are employed using a novel technique to examine the 1987 event in greater detail, to answer this question. Recent progress is then reported in refining the technique and extending the investigation to examine the dynamical evolution of the austral spring stratosphere during other recent years, to shed more light on the precise nature, frequency and severity of such 'ozone dilution' events, and the effect that this process may have on long term ozone behaviour in the southern hemisphere.

1. INTRODUCTION

Atkinson and Easson (1988) first noted a sudden and persistent decrease in total ozone between 11 and 13 December 1987 at Melbourne, Australia, which led to a record low monthly mean. Figure 1 shows Melbourne ozone sonde profiles obtained on 08 and 22 December, respectively just before and some time after the event (when total ozone remained low). The two profiles show that the decrease occurred throughout the 200-30 hPa layer, with little change above or below. Atkinson *et al* (1989) examined the event using TOMS and NMC data, demonstrating the large horizontal scale of the event. Daily maps of 500K Ertel potential vorticity (EPV) evolution over the period suggested that as the polar vortex was squeezed by anticyclones in the south Pacific and Indian Oceans, a tongue of vortex air was eroded and advected over New Zealand and southeastern Australia. They argued that the close correlation between the areal distributions of TOMS total ozone decrease and 500K EPV decrease, supported to some degree by isentropic back-trajectory analyses, provided strong evidence for an Antarctic ozone hole 'dilution effect' - the quasi-horizontal transport into mid-latitudes of ozone-poor air from within the ozone hole, produced by the dynamical breakup of the polar vortex during December 1987. The Atkinson *et al* analysis, however, stopped short of quantifying the relative contributions to the observed ozone decrease of horizontal and vertical transport. While the former, via the well-established connection between the occurrence of the ozone hole and the injection into the atmosphere of CFCs and halons, might be viewed as an anthropogenic 'ozone dilution' effect, the latter can be regarded as a quite natural process resulting from the adjustment which must accompany the meridional transport of differential potential vorticity in order for the atmosphere to maintain dynamical balance. Also, Atkinson *et al* considered just the one noteworthy event.

In view of the possible biospheric impacts both of repeated 'ozone dilution' events, and their potential long-term contribution to a secular decrease in mid-latitude ozone, an investigation is currently underway of the morphology of these events over the last decade, in order to provide an assessment of their potential frequency and severity in future years, and their implications for mid-latitude ozone. The first objective of the investigation is to examine the dynamical structure of the 1987 event in closer detail, quantifying the relative roles of horizontal and vertical advection. The technique employed to achieve this first objective and the results obtained to date are described below.

2. DATA

The meteorological data employed are the NMC Climate Analysis Center daily (12Z) southern hemisphere stratospheric analyses of geopotential height and temperature at 18 levels from 1000 to 0.4 hPa, which have been interpolated prior to use from their original 65 by 65 equal area grid to a 5 degree latitude by 5 degree longitude grid. The period covered is from August 01 to January 31 each year from 1979/80 to 1989/90.

The two primary ozone data sources used are the TOMS Version 6 gridded total ozone (TO) data set (1978 - 1990) and the SAGE and SAGE II ozone volumetric mixing ratio (OMR) profile data set (1979 - 1981 and 1984 - 1989). Use is also being made of ozone sonde data from several southern hemisphere locations.

3. THE 1987 EVENT

Ideally, a detailed re-examination of the December 1987 mid-latitude ozone decrease might involve direct observation of ozone vertical profiles across the region before,

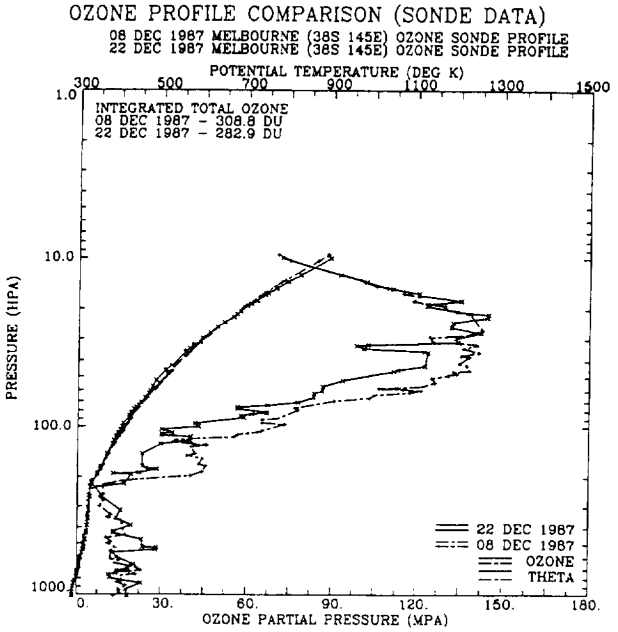

Figure 1. Ozone sonde vertical profiles at Melbourne, showing pressure (hPa) vs ozone partial pressure (mPa) and potential temperature (K), for 08 and 22 December 1987.

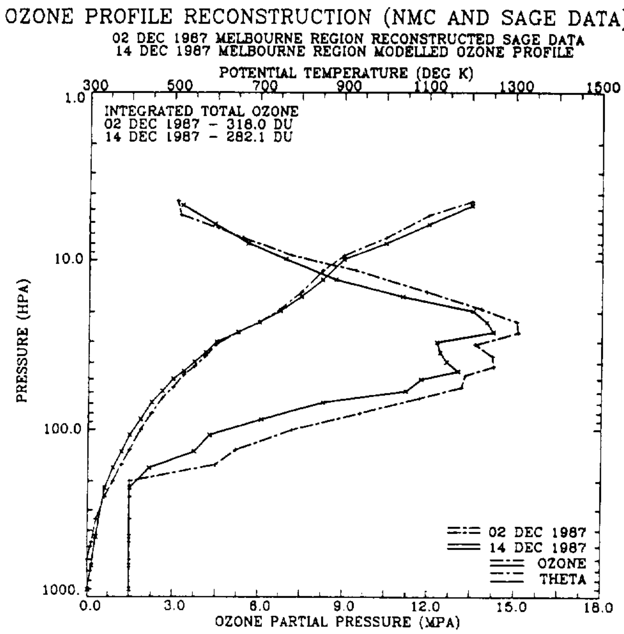

Figure 2. SAGE ozone profile reconstruction at 40S 145E, showing pressure (hPa) vs ozone partial pressure (mPa) and potential temperature (K), for 02 and 14 December 1987.

during and immediately after the event, examination of back-trajectories to determine accurately air mass origins, and direct ozone profile observation at these origins. Then with a knowledge of the vertical displacement of the isentropic surfaces during the period, and assuming negligible diabatic and photochemical effects, the problem could be solved simply.

For several reasons this is not possible. The only available ozone sonde data in the region of the decrease are the two ozone sonde profiles from Melbourne, and another two from Lauder, New Zealand after the event (a third just prior to the decrease provides data only up to 65hPa). The SAGE II instrument typically provides about 15 profiles per day, evenly spread around a latitude circle, as the satellite observation location moves gradually south from the equator to sub-polar latitudes and back again in a period of about 40 days. In this manner it provides a complete (except for high latitudes) hemispheric 'sweep' in a period of about 20 days. Unfortunately, there are no data available for the period from 04 to 17 December. Also, it seems unlikely that the coarse resolution of the NMC stratospheric data is adequate to derive sufficiently accurate individual back-trajectories. In view of these limitations a novel technique was devised in an attempt to reconstruct the ozone evolution over the region.

All of the available SAGE profiles south of 10S during the period from 01 August to 31 December 1987 were first used to obtain interpolated values of OMR at 32 'standard' isentropic levels from 300 to 1200K, which were then binned according to sweep. Since OMR and EPV are expected to be reasonably well conserved and intercorrelated over short periods, at least in the lower stratosphere, the daily EPV analyses at each level were interpolated in space and time to produce EPV estimates coincident with the SAGE data. Scatter plots of OMR vs EPV were then constructed to depict the 'polar vortex relative' meridional distribution of OMR, a coordinate transformation technique first described by Schoeberl and Lait (1991). While at each level the plots for each sweep were similar prior to the final warming in December, the correlations deteriorated markedly in the post warming period. Closer examination revealed that even after significant wave amplification events the scatter plots tended to shift. This is presumably due to lateral mixing during breaking events, both within the vortex and within vortex fragments, as significant features in the EPV/OMR fields cascade to scales below the resolution of the NMC satellite data, but still discernible by the SAGE instrument. The isentropic OMR/EPV correlations were found to be improved by first normalising EPV by the temporally interpolated map minimum, each normalised EPV value then representing the fraction of the EPV at the dynamical centre of the vortex at the time. More importantly, by applying a running mean filter through each set of isentropic data, and interpolating values from the resulting curves, 'meridional' cross-sections were then easily constructed for each sweep, showing the hemispheric evolution of OMR through the season, from within a dynamical reference frame.

The isentropic OMR/EPV running mean curves from the SAGE sweep of 10 November to 04 December were adopted to provide an empirical conversion from EPV to OMR for the period from 02 to 14 December. The observed EPV fields at each isentropic level on 02 December were then used via the conversion relationships, as surrogate ozone data. As a trial run, an attempt was made to model the ozone profiles at 40S 145E, just south of Melbourne, on 02 and 14 December. The EPV values there on 02 December were picked off each of the 24 EPV analyses and corresponding values of OMR interpolated from the correlation curves. The NMC isentropic pressure analyses were then used to pick off corresponding pressure values at each surface. Inspection of the 'initial' profile thus obtained revealed erroneously high tropospheric OMRs, so, since SAGE data quality deteriorates substantially below tropopause level, and since the two December ozone profiles from Melbourne suggested a roughly constant ozone partial pressure of about 1.5 mPa throughout the troposphere at the time, the surrogate profile was then integrated, replacing all derived OMRs below the 200 hPa level with a crude

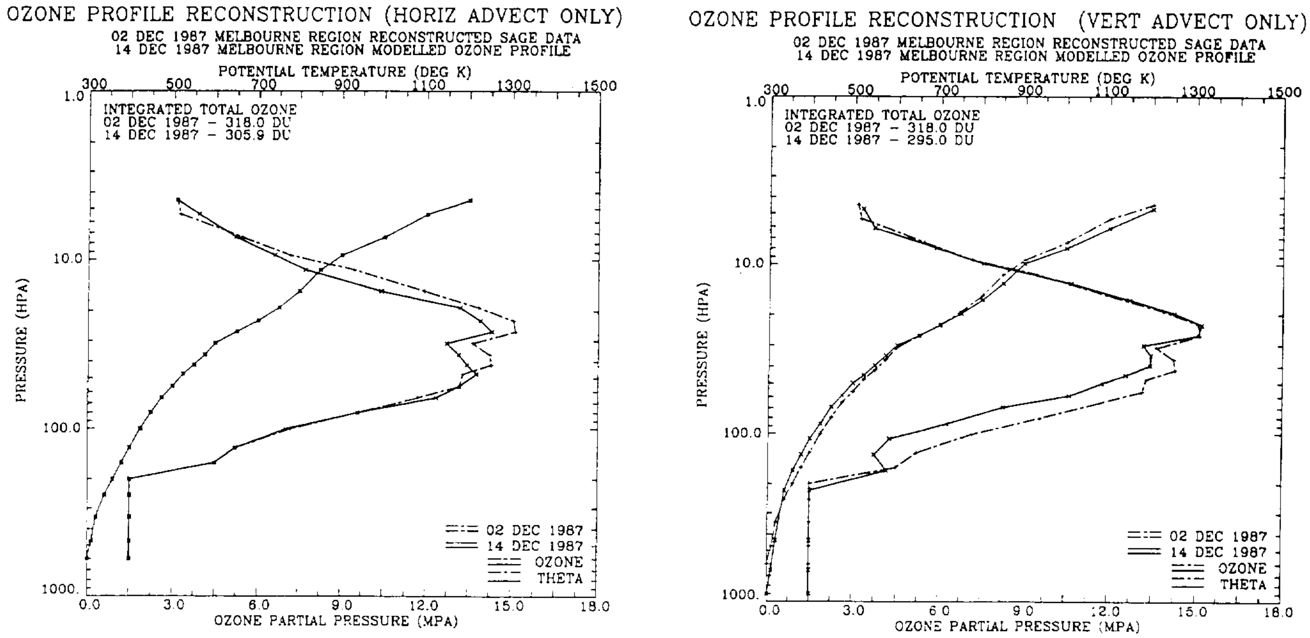

Figure 3. Contribution to the modelled SAGE ozone column change at 40S 145E between 02 and 14 December from (a) horizontal advection, and (b) vertical advection.

residual corresponding to a constant 1.5 mPa column and adding an upper residual based on the assumption that OMR decreased linearly with pressure to zero at infinity above the 1200K level (Figure 2). The resulting modelled SAGE TO value obtained was 318 DU, somewhat higher than the TOMS value for the day of 304 DU, but equal to the TOMS three day mean.

Calculation of a corresponding profile for 14 December was not so straightforward. Because the date falls after that of the polar vortex collapse, when the OMR/EPV correlations have deteriorated significantly, two options appeared available. The first was to use the post-warming 'normalised EPV'/OMR correlation curves and the EPV values interpolated from the analyses of 14 December. This proved unsuccessful. A second technique was adopted for the trial run, which it was thought might enable the superior EPV/OMR correlations from before the vortex collapse to be used with some validity. At each of the 24 isentropic levels, a 'contour advection with surgery' (CAS) scheme (Waugh and Plumb, manuscript in preparation) was employed, by which the EPV contours of 02 December were advected as passive material contours, using balanced winds derived from the NMC data over the period from 02 to 14 December. While wind fields derived from the NMC data might be expected to suffer resolution problems similar to the EPV fields, Waugh and Plumb have found that wind resolution is not a critical factor when using CAS. If the problems with the EPV analyses are due to horizontal mixing, then while individual trajectories might suffer substantially, bulk contour advection might be expected to present a more reliable picture of the EPV evolution than the EPV maps themselves.

The resulting contour advection maps for 14 December were then used to interpolate visually EPV values at 40S 145E, and the November EPV/OMR correlation curves were used to assign OMR values at each level. The NMC temperature analyses were again used to pick off appropriate isentropic pressure values and the same vertical integration of the resulting profile performed as for 02 December. TO for the resulting 'SAGE' profile (Figure 2) was found to be 282 DU, comparing well with the TOMS value of 280 DU (3 day mean 277 DU). Comparison of the two profiles with the two Melbourne sonde profiles (Figure 1) suggests the results to be not unreasonable, taking into consideration the time differences.

If the modelled profiles represent a reasonably accurate depiction of the 1987 event near Melbourne, then the result is particularly interesting. By allowing the changes in isentropic OMRs from 02 to 14 December, while holding the pressure at each surface constant, it is possible to obtain simply a first order estimate of the effect of horizontal advection alone. Conversely, by holding the OMRs constant and allowing the pressure to change, the contribution from vertical motion of the isentropes can be assessed. This was done for the two trial profiles (Figure 3) and suggests that only about 40% of the observed TO decrease between the two dates was due to equatorward advection of low OMR air, and this occurred almost exclusively above the 50 hPa level. The 60% due to vertical motion occurred below the 30 hPa level, where an 'ozone hole dilution effect', if any, would be expected to occur.

The overall picture, then, is of a polar EPV outbreak extending from about 450K to the 1000 K surface with poleward flow in a developing ridge below the 400 K surface. While the flow above 450 K was equatorward, it was only above about 600 K where low OMR polar air from within the vortex (but above the 'ozone hole') reached Melbourne. At lower levels the air reaching Melbourne originated at the vortex edge, not inside the ozone hole, hence there was little change in OMR from horizontal advection. Instead it was the vertical motion fields produced by the EPV advection pattern which produced most of the ozone change. With strongest poleward advection near 350 K and strongest equatorward advection near 700 K, a marked 'residual circulation' ascent region spanned the intervening layer, with descent regions above and below. Subsequent examination of the contour advection maps suggests that much of the horizontal advection of lower OMRs above 50 hPa would already have occurred by 08 December, the date of the first Melbourne sonde flight, so the lack of

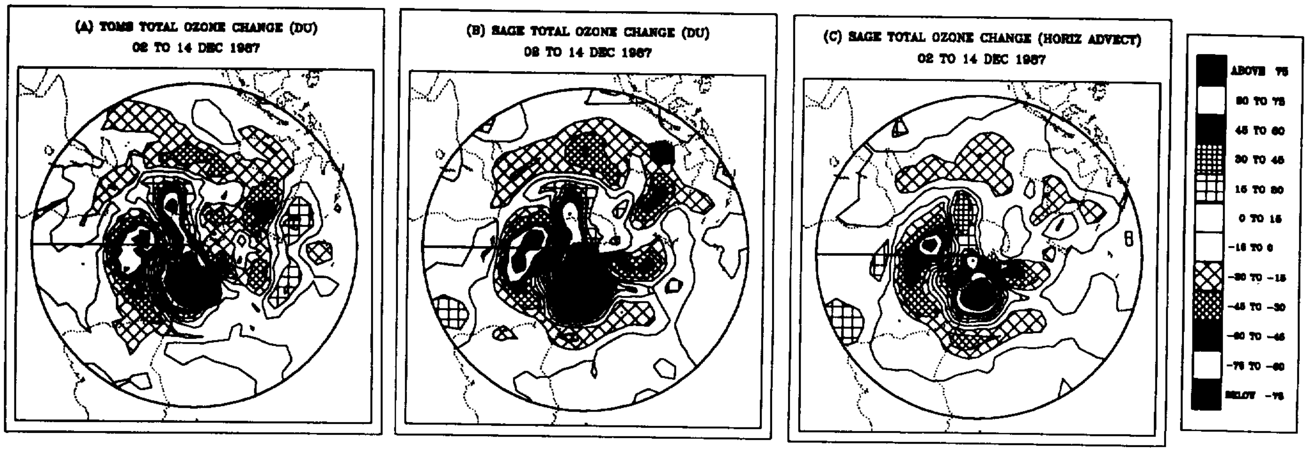

Figure 4. Change in total ozone (DU) between 02 and 14 December 1987, from (a) TOMS, (b) SAGE reconstruction, and (c) SAGE reconstruction for horizontal advection only.

change above 30hPa in the sonde profiles between 08 and 22 December is consistent with the modelled picture. (Considerable caution must be taken, however, in interpreting too closely the results for these upper levels, since the assumptions of material conservation of OMR and EPV, upon which the technique is based, become less valid with increasing height.) If this is the case, then the trial run suggests that the change in TO at Melbourne between 08 and 14 December was due almost exclusively to vertical motion, with virtually no 'ozone dilution effect' being felt there.

4. FURTHER WORK AND CONCLUDING REMARKS

While the above results might be viewed as negating the conclusions of the Atkinson *et al* analysis, this is not the case. Very recently, the technique described above has been refined and extended to enable reconstruction of the three dimensional ozone evolution over the hemisphere during the 1987 event. This was accomplished after inverting the 24 EPV advected contour plots to produce gridded EPV fields, replacing the 200 hPa SAGE OMR cutoff level with the level of the local dynamical tropopause (where EPV = -1.5 PVU), and replacing the 1.5 mPa ozone partial pressure tropospheric column with an empirically determined algorithm which allows for a meridional gradient of tropospheric ozone. The resulting hemispheric maps of SAGE reconstructed TO compare well to those of TOMS TO on both 02 and 14 December, as do the corresponding maps of total ozone change during the period (Figure 4a,b). Separation of the TO change into components due to horizontal and vertical advection shows that the TO decrease over SE Australia was indeed due largely to vertical motion, while over the SW Pacific, the Indian Ocean and over the Atlantic and South American regions most of the change was due to a marked 'ozone dilution effect' (see Figure 4c).

The final step in the analysis of the 1987 event, curently underway, is the use of the NMC data, after spherical harmonic decomposition, in an inversion of the quasi-geostrophic omega equation, to obtain a closer insight into the dynamical forcing and its three dimensional structure, which produced the observed pattern of vertical motion.

At the completion of the examination of the 1987 event, the technique described above is to be used to analyse a number of other potential 'dilution' events which have been identified from the analyses of the last decade. This work will be reported elsewhere.

The preliminary results reported above suggest that the novel technique described is an effective means of enabling a useful reconstruction of the instantaneous three dimensional hemispheric distribution of stratospheric ozone, in the absence of sufficient direct ozone observations for the purpose. The detailed analysis of the 1987 ozone dilution event using this technique also leaves little doubt now that the mid-latitude TO decrease was primarily due to the equatorward advection of ozone-depleted air from within the decaying Antarctic ozone hole.

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