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SPRINGTIME STRATOSPHERIC WATER VAPOUR IN THE SOUTHERN HEMISPHERE AS MEASURED BY MLS

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Abstract. The effects of the break-up of the antarctic vortex on the water vapour distribution are studied using MLS measurements of water vapour made during September 1991 and November 1991. In early November at 22 hPa a moist area is found within the polar vortex, consistent with an observed descent of order 10 km and strong radiative cooling. As the vortex erodes (beginning of November 1991), parcels of moist air become detached from the edge of the vortex and mix rapidly (within 2-3 days) with drier mid-latitude air. When the vortex breaks up (mid-November), larger parcels of moist air from both the edge and the inner vortex migrate to mid-latitudes. These parcels have a longer lifetime than those produced by vortex erosion, probably because they are correlated with higher potential vorticity gradients. The break-up of the vortex is accompanied by a mean adiabatic equatorward transport resulting in a significant increase in mid-stratospheric water vapour values at mid-latitudes in late spring.

Introduction

The Microwave Limb Sounder (MLS) carried by the Upper Atmosphere Research Satellite (UARS) launched on 12 September 1991 measures concentrations of several species of importance in the middle atmosphere, principally ClO, O_3 and H_2O (Waters, 1989). The satellite yaws around at intervals of approximately one month. This leads to a period in which the region sampled by MLS is from $\sim 80°$S to $\sim 34°$N followed by one in which it is from $\sim 34°$S to $\sim 80°$N.

In this paper we concentrate on measurements from the MLS H_2O channel at 183 GHz. The MLS measurements of water vapour have a horizontal and vertical resolution of ~ 400 km and ~ 4 km respectively. With the present version of the retrieval software (V0003), the precision and accuracy for individual profiles at 46 hPa are 0.5 ppmv and 15% respectively, while at 4.6 hPa they are 0.3 ppmv and 15%. The data for each 24 hour period centred on 1200 UT have been linearly interpolated onto a fixed latitude-longitude grid. Ascending and descending portions of the orbit were treated separately and then averaged.

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Although H_2O in the antarctic vortex has been studied previously from a variety of observing systems, MLS allows the evolution of broad-scale features of the H_2O distribution to be observed daily over an unprecedented areal and vertical extent. Here we make use of the southward-looking observations in conjunction with potential vorticity (PV) based on wind and temperature analyses from the UK Meteorological Office (Swinbank and O'Neill, 1992) to discuss some aspects of the circulation during the break-up of the antarctic vortex in spring, showing evidence of descent in the vortex, erosion at the vortex edge and transport of vortex air to low latitudes.

The vertical descent

In the antarctic vortex in the lower stratosphere in winter, a process of dehydration and denitrification is believed to take place as a result of the formation of polar stratospheric clouds. This allows active chlorine to be released which results in the "ozone hole". By early November 1991, however, when MLS began an extended period of looking south, the main area of the vortex was found to be moist at 22 hPa (the highest pressures at which the profiles have significant information in the current retrieval software). Figure 1 shows H_2O at 22 hPa on 8th November 1991 (hereafter dates shown as e.g. 911108). The moist area is found to be well correlated with the highest values of -PV as discussed further below. The high mixing ratios in the vortex are presumably a result of descent bringing moist air from above. Several studies of zonal mean circulation and heating rates have found cooling and descent in polar regions in spring (e.g. Gille and Lyjak, 1986). It is also well known (e.g. Schoeberl et al., 1992), that vertical descent (downward across isentropes) at ~ 50 hPa occurs at the edge of the polar vortex in winter and early spring. Since in November 1991 the vortex is shifted from the pole by at least 10°, evidence that vertical descent has taken place is clearly visible in a longitude vs η cross-section ($\eta = ln(\theta)$, θ = potential temperature) as in figure 2*a* in which MLS H_2O values for 911108 have been linearly interpolated in the vertical onto isentropes and averaged within a 70°S-60°S latitude bin. Also shown are estimates of the Ertel PV (figure 2*b*) and the net diabatic heating rates (figure 2*c*) averaged within the same latitude bin.

The heating rates are calculated by the method of Haigh (1984) using MLS retrievals of H_2O, O_3 and temperature as input. As a check on the sensitivity the input fields were perturbed by typical MLS uncertainties. The perturbation to the heating rate was $\leq 10\%$ in the stratosphere.

On a given isentrope through most of the stratosphere in figure 2, there is a region of high H_2O correlated with

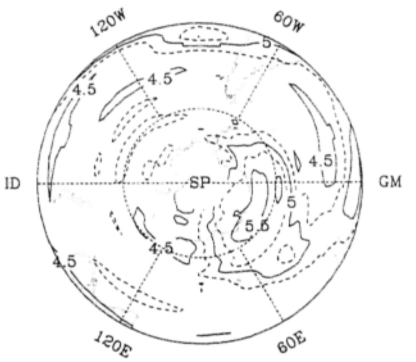

Fig. 1. Polar stereographic map of H_2O (ppmv) at 22 hPa on 911104. The map extends to 30°S.

high -PV. It is seen that the radiative cooling (negative net heating rate) above $\eta = 6.6$ is greater within the vortex (rate of change of temperature $\sim$ 3 K.day^{-1} at $\eta = 6.8$) than outside it ($\sim$ 1.5 K.day^{-1} at $\eta = 6.8$) and that it increases with η. The inferred vertical displacement of the water isopleths is large, being from $\eta = 6.9$ to 6.5, which corresponds to $\sim$ 10 km. In comparison Schoeberl et al. (1992) found a value of 2-3 km at $\eta \sim 6$, consistent with our calculation of a smaller net heating rate at that height.

Movement of the moist area

To understand better the movement of the moist area and the polar vortex we have interpolated the MLS H_2O measurements at a series of days in November 1991 and superimposed them on PV maps calculated from the UKMO assimilated data set (see figure 3). We obtain essentially similar PV distributions based on NMC data. Note that whereas the PV is based on analyses for 1200 UT, the H_2O fields are effectively a 24 hour average. The 'edge'

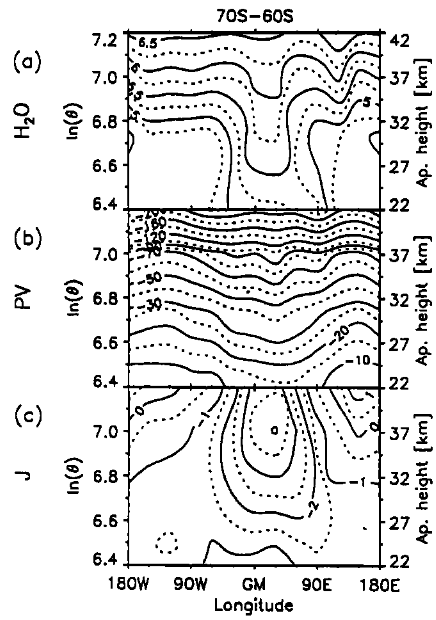

Fig. 2. Longitude vs ln(θ) cross-sections for the latitude bin 70°S-60°S for 911108 of *a*) H_2O mixing ratio (ppmv), *b*) PV/(10^{-5} K.m^2.kg^{-1}.s^{-1}) and *c*) net heating rate, J/(K.day^{-1}).

or 'wall' of the vortex can be defined by the value of its steepest gradient and labeled (Tuck et al., 1992) as 'conservative' (any parcel of air inside a given PV contour is within the vortex) or 'liberal' (any parcel of air outside a given PV contour is outside the vortex). In figure 3, lightly shaded areas represent the 'wall' of the vortex between the 'liberal' contour value of -10×10^{-5}Km^{-2}kg^{-1}s^{-1} and the 'conservative' contour value of -12.5×10^{-5}Km^{-2}kg^{-1}s^{-1}. The heavily shaded areas represent the moist region where H_2O values exceed 5.1 ppmv.

The spatial and temporal correlation between the moist area and the polar vortex can be clearly seen from figure 3. Initially the vortex is coherent and offset somewhat from the pole. As time proceeds, it elongates, splits into two and finally fragments into several pieces. Outside the main vortex, there are some moist air parcels which are correlated with PV areas having the signature of the interior or 'wall' of the vortex. On 911104 one such ex-vortex moist air parcel is located in the region 30–35°S and 10–90°W (over South America). The movement of this feature westward along the 35°S latitude circle to southern Australia is consistent with the observed winds. Despite a reduction in the size of the vortex and the difficulty in establishing the lifetime of such features (Tuck et al., 1992), its lifetime is estimated to be much greater than two weeks. In view of these correlations, we use the measured H_2O fields in an attempt to quantify the impact of vortex erosion and break-up at mid-latitudes.

Erosion and break-up of the vortex

It is widely believed that strong gradients of PV at the edge of the polar vortices inhibit transfer into the vortex (McIntyre, 1989). However, the small-scale horizontal mixing occuring at the vortex edge is strong enough to peel out filaments of the vortex to the surrounding air. This effect has been modeled by Juckes and McIntyre (1987) and reported by Kelly et al. (1989) for the southern vortex and by Tuck et al. (1992) for the northern vortex.

During the period 911104 to 911108 a filament of moist air is extruded ($\sim$ 40°S and $\sim$ 20°E) from the main wet region. The PV analysis strongly suggests that this is a piece of the vortex edge which is being pulled off. Thereafter, trace of this moist filament is lost. This could be due to a lack of resolution and/or rapid horizontal mixing which dilutes any wet areas outside the vortex into the surrounding drier air. The lifetime of these southern hemisphere spring features is estimated to be 2-3 days in contrast to a lifetime of 2 weeks for the air parcel moving along the 35°S latitude mentioned above. This is consistent with PV gradients at the vortex 'wall' being weaker in late spring than in early spring.

Murphy et al. (1989) show that erosion of the vortex by 3–4° in latitude represents a surface area loss of $\sim$ 50 %. In order to quantify the effect of the erosion and break-up processes on the vortex during the period 911104-911125, we have calculated from 90°S to the equator the surface area loss associated with the moist region where H_2O is greater than 5.1 ppmv, and the surface area losses associated with the 'liberal' and 'conservative' definitions of the vortex.

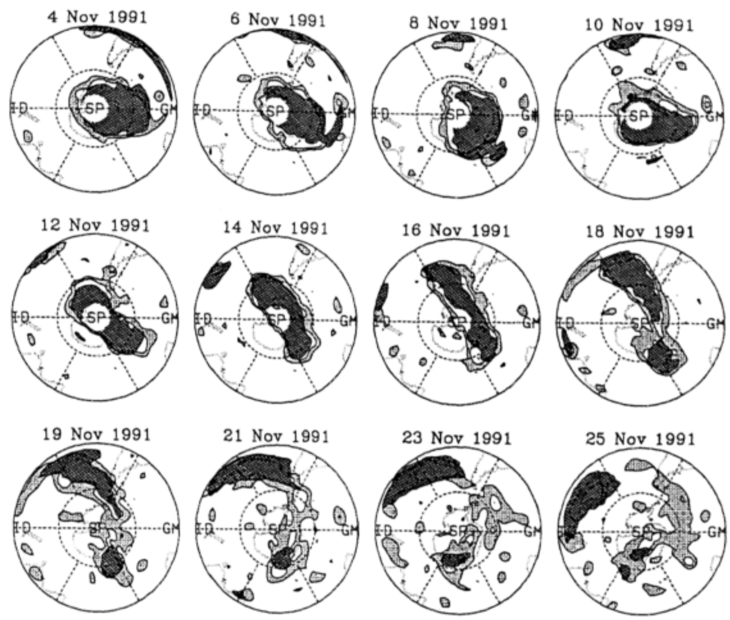

Fig. 3. Time sequence of PV (UKMO-derived) and H_2O at 650 K for November 1991. The maps are on a polar stereographic projection from 30°S to 90°S. The lightly shaded area provides a representation of the 'edge' of the vortex by marking regions where PV/(10^{-5} K.m^2.kg^{-1}.s^{-1}) lies between -12.5 and -10. The heavily shaded area marks regions where H_2O exceeds 5.1 ppmv.

From 911104 to 911108 we find a decrease in surface area of 4.1 × 10^6 km^2 (~ 10 %) for the 'liberal' vortex, 2.1 × 10^6 km^2 (~ 10 %) for the 'conservative' vortex and 4.5 × 10^6 km^2 (~ 20 %) for the moist region. The intermediate region encompassing mixing ratios 4.8 to 5.1 ppmv expands by 9.4 × 10^6 km^2 (~ 70 %). The loss-rate for the period 911118-911125 (post break-up) in the area of the moist region almost doubles, decreasing the area by 5.7 × 10^6 km^2 (~ 35 %), whereas the intermediate region expands by 4.9 × 10^6 km^2 (~ 15 %). Thus the total area is conserved to within 15 % in the later period; however, this is not the case in the earlier period. This suggests that horizontal mixing is dominant during vortex break-up but that diabatic effects are of more significance earlier. The discrepancy between the PV and moist area changes may be attributable to the different observing techniques and/or the different conservation properties of tracers and PV (Haynes and McIntyre, 1987). Furthermore, the change in areas could indicate that the motion is divergent (Butchart and Remsberg, 1986). It is not possible to extend estimates for area-loss based on the previous PV values into the later period as they no longer define the vortex edges. A consideration of whether the dramatic rise in the rate of loss of moist area is due to an accelerated mixing to unresolved scales, convergence or movement off this isentrope is beyond the scope of this letter.

Effect on zonal mean fields

The movement of wet air from polar to middle latitudes caused by the equatorward transport induced by the vortex break-up produces detectable changes in the zonal means, to which we now turn.

Figure 4 shows the meridional cross-sections of H_2O mixing ratio zonally averaged along isentropes for 910923, 911104 and 911125. The distributions are broadly consistent with the concept that air is dried as it enters the stratosphere at the tropical tropopause because of the low temperatures, and that it progressively moistens through methane oxidation (e.g. Jones et al., 1986) as it is carried round in the diabatic circulation and subjected to lateral mixing by planetary-scale waves.

The strong gradients around 60°S in the zonally-averaged H_2O fields on 910923, which correspond to the 'edge' of the zonally-averaged vortex (see figure 4*a*), from η =

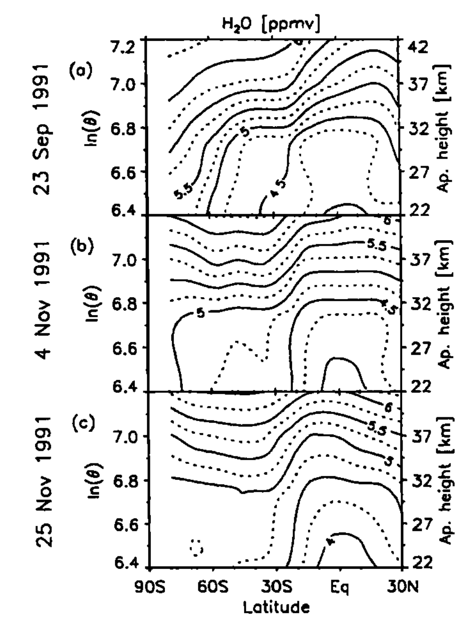

Fig. 4. Latitude vs ln(θ) cross-sections of zonal-mean H_2O mixing ratio (ppmv) for *a*) 910923, *b*) 911104 and *c*) 911125.

6.5 to $\eta = 6.8$ may provide evidence of strong descent at the vortex edge and limited mixing across it.

The cross-section for 911104 corresponds to the first map in the sequence in figure 3 and thus shows the situation prior to the transport of vortex air to lower latitudes. The mid-latitude dry air (≤ 4.75 ppmv) at $\eta = 6.5$ is in stark contrast to the moist high latitude air (≥ 5 ppmv). By 911125 (figure 4c), after the break-up of the vortex, there is no longer an H_2O gradient poleward from 30°S and the previously dry mid-latitude region at $\eta = 6.5$ has been filled by wet high latitude air to reach values ≥ 4.75 ppmv. This rapid equatorward transport induced by the break-up of the vortex is thus in the opposite direction to the prevailing mean diabatic circulation.

Conclusions

MLS measurements of H_2O in spring 1991 in the southern hemisphere, interpolated onto isentropes have shown that *i*) significant descent occurs at the centre and edge of the southern vortex which moistened its interior between 650 and 900 K, *ii*) the temporal and spatial evolutions of the moist areas detected at 650 K in November 1991 correlate well with different phases of the vortex erosion and break-up and *iii*) the break-up of the vortex at 650 K generated a mean equatorward transport in the opposite direction to the prevailing mean diabatic circulation. This moistens the mid-latitudes in the zonal mean. Moist air parcels detected outside the vortex correlate with air parcels having the signature of the 'edge' and interior of the vortex. Some ex-vortex air parcels generated by the erosion of the vortex in November 1991 dilute very rapidly (2-3 days) with the surrounding drier air and any impact on the mid-latitude zonal-mean H_2O distribution is difficult to detect. Others, however, measured around 35°S, have a much longer lifetime (≥ 10 days). These can be attributed to an erosion of the vortex occurring in early spring where the PV gradient at the vortex edge is greater than in late spring, thus horizontal mixing may be expected to be less efficient. A further effect of the erosion and break-up of the vortex as detected by MLS is a movement of air at $\theta = 650$ K which is both H_2O-rich and O_3-poor (not shown here), over inhabited areas: over South America in early November 1991 and over South Australia in late November 1991.

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