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NORTHERN HEMISPHERE MID-STRATOSPHERE VORTEX PROCESSES DIAGNOSED FROM H_2O, N_2O AND POTENTIAL VORTICITY

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Abstract. MLS H_2O, CLAES N_2O and potential vorticity calculated from UK Meteorological Office data are used to study mid-stratospheric vortex processes in the northern hemisphere winter of 1991-92. Areas of moist air (at ~ 20 hPa) and N_2O-poor air (at ~ 10 hPa) are well-correlated with high values of potential vorticity and there is little or no large scale mixing across the vortex edge. We find evidence for the descent of relatively dry mesospheric air to the 840 K (~ 10 hPa) level, as well as descent of moist air from the upper stratosphere to the 655 K (~ 20 hPa) level. A reduction in the areas of the vortex and both the moist and N_2O-poor regions is observed and there is evidence of moist and N_2O-poor air parcels being extruded from the vortex.

Introduction

The Microwave Limb Sounder (MLS) and Cryogenic Limb Array Etalon Spectrometer (CLAES) carried aboard the Upper Atmosphere Research Satellite (UARS) launched on 12 September 1991 measure concentrations of several species of importance in the middle atmosphere, including H_2O by MLS (Waters, 1993) and N_2O by CLAES (Kumer et al., 1993). UARS yaws around at periods of approximately one month, leading to an interval in which MLS and CLAES sample latitudes from ~ 80°S to ~ 34°N followed by one in which they sample ~ 34°S to ~ 80°N.

In this letter we concentrate on MLS H_2O and CLAES N_2O measurements with the aim of studying dynamical processes in the winter mid-stratospheric vortex. The period studied is 5 December 1991 to 13 January 1992 and 15 February 1992 to 3 March 1992. As MLS and CLAES were viewing south from 14 January 1992 to 14 February 1992 no northern hemisphere (NH) high latitude measurements are available in this period. The MLS H_2O and CLAES N_2O measurements have a horizontal resolution of ~ 400 km; their vertical resolutions are ~ 4 km and ~ 2.5 km respectively. With the latest MLS data files (V0003), the precision and accuracy for H_2O individual profiles at 46 hPa are ~ 0.5 - ~ 1 ppmv and ~ 15% respectively, while at 4.6 hPa they are ~ 0.3 ppmv and ~ 15% (Lahoz et al., 1993). With the latest CLAES data files (V0005) the precision and accuracy for N_2O individual profiles at 46 hPa are ~ 40 ppbv and ~ 25% respectively, while at 4.6 hPa they are ~ 10 ppbv and ~ 25 % (Kumer et al., 1993). 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.

Although H_2O, N_2O and/or potential vorticity (PV) in the arctic vortex have been studied previously from a variety of observing systems (Clough et al., 1985; Butchart and Remsberg, 1986; Loewenstein et al., 1990; Schoeberl et al., 1992), the MLS and CLAES measurements allow extensive three-dimensional and temporal coverage of the H_2O and N_2O distributions in the polar winter stratosphere as well as the opportunity for interhemispheric and interannual comparisons. As part of these studies, we make use of northward-looking observations in conjunction with PV maps based on wind and temperature analyses from the UK Meteorological Office (UKMO) to diagnose processes in the arctic vortex, showing evidence of little or no large scale mixing at the vortex edge, descent from the mesosphere and upper stratosphere into the mid-stratosphere and a reduction in vortex size.

Background

Water vapour, N_2O and PV are quasi-conserved tracers and, although there are differences in their behaviour (Haynes and McIntyre, 1987), their distributions can be used to study the couplings between radiation, chemistry and dynamics which take place in the stratosphere (Tuck, 1989; Loewenstein et al., 1990).

In order to study the distributions of H_2O, N_2O and PV we have interpolated vertically the MLS H_2O and CLAES N_2O measurements at a series of days throughout the winter of 1991-92 onto potential temperature (θ) surfaces spanning the mid-stratosphere (655 and 840 K) and superimposed them on PV maps calculated from the UKMO assimilated data set (figures 1-3). The UKMO maps have a resolution of 2.5° in latitude and 3.75° in longitude. Tests indicate that essentially similar PV distributions are obtained using National Meteorological Center (NMC) data. Note that whereas the PV is based on analyses for 1200 UT, the H_2O and N_2O fields are a 24 hour average. The 'edge' of the vortex can be defined by the value of its steepest gradient and labeled as 'conservative' (any parcel of air inside a PV contour is within the vortex) or 'liberal' (any parcel of air outside a PV contour is outside the vortex) (Tuck et al., 1992). In figures 1-3, lightly shaded areas represent the 'edge' of the vortex between the 'liberal' and the 'conservative' contour values. The heavily shaded areas represent either the moist region where H_2O values exceed a given value or the N_2O-poor region where N_2O values are below a given value. The spatial and temporal correlations described below are valid at the resolution and precision of the data.

The mid-stratosphere is where correlation between H_2O, N_2O and PV is likely, as radiative effects are relatively small and condensation and evaporation unlikely. The 655 K (~ 20 hPa) and 840 K (~ 10 hPa) isentropes are chosen as representative of this region. For 655 K we use a 'liberal' value of $10\times10^{-5}\mathrm{Km^{-2}kg^{-1}s^{-1}}$ and a 'conservative' value of $12\times10^{-5}\mathrm{Km^{-2}kg^{-1}s^{-1}}$ and denote H_2O values greater than 4.8 ppmv as moist. For 840 K we use a 'liberal' value of $40\times10^{-5}\mathrm{Km^{-2}kg^{-1}s^{-1}}$ and a 'conservative' value of $50\times10^{-5}\mathrm{Km^{-2}kg^{-1}s^{-1}}$ and denote H_2O values greater than 6 ppmv as moist and N_2O values less than 25 ppbv as N_2O-poor.

Results and discussion

The spatial and temporal correlation between the moist area and the vortex is evident at 655 K for at least 1 month

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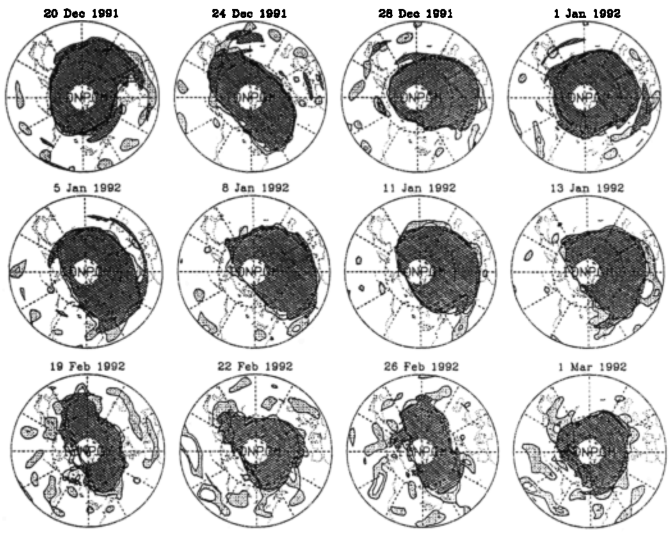

Fig. 1. Time sequence of PV and H_2O at 655 K for 1991-92 NH winter. The maps are on a polar stereographic projection from 30°N to 90°N. The lightly shaded area provides a representation of the 'edge' of the vortex by marking regions where PV/(10^{-5} K.m^2.kg^{-1}.s^{-1}) lies between 10 and 12. The heavily shaded area is where H_2O exceeds 4.8 ppmv.

and possibly as long as 3 months (figure 1). The behaviour of the N_2O-poor air is similar (figure 2). From 5 December 1991 to 13 January 1992 the vortex is fairly constant in size, changing by only ~ ± 5-10 %. During 19 February 1992 – 3 March 1992 the 'conservative' vortex decreases in area (~ 40 % at 655 K; ~ 35 % at 840 K), and, although the 'liberal' vortex decreases in area at 840 K (~ 30 %), the change in the areas at 655 K is less obvious. A similar reduction to that of the 'conservative' vortex is observed in the moist area at 655 K and the N_2O-poor area at 840 K. Such a reduction in the areas may be due to radiative effects and/or a cascade to unresolvable scales (Juckes and McIntyre, 1987), though the motion is unlikely to be non-divergent (Butchart and Remsberg, 1986). An attempt to distinguish between these two mechanisms is beyond the scope of this letter. The observed correlation between the moist areas and the vortex during 20 December 1991 – 13 January 1992 is like that found by Butchart and Remsberg (1986) who compared LIMS H_2O with PV at 850 K (~ 10 hPa).

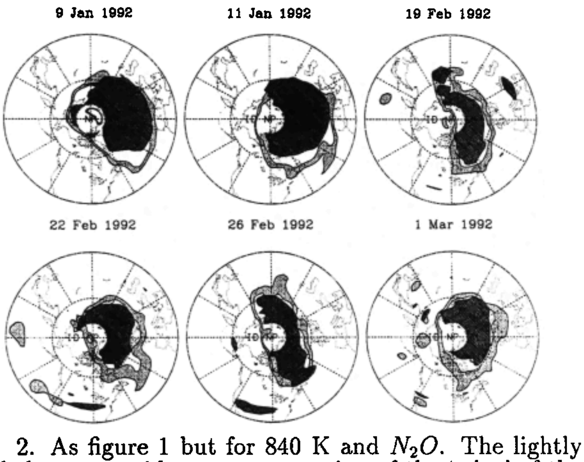

Fig. 2. As figure 1 but for 840 K and N_2O. The lightly shaded area provides a representation of the 'edge' of the vortex by marking regions where PV/(10^{-5} K.m^2.kg^{-1}.s^{-1}) lies between 40 and 50. The heavily shaded area is where N_2O is lower than 25 ppbv.

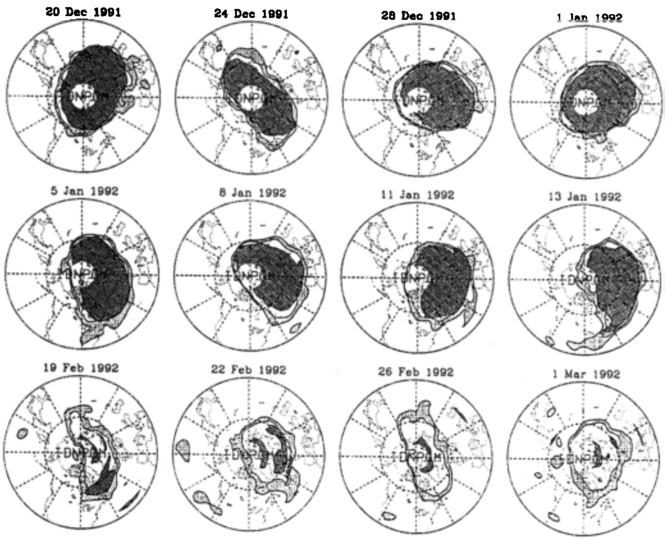

Fig. 3. As figure 2 but for H_2O. The heavily shaded area is where H_2O exceeds 6 ppmv.

At 655 K a peeling of filaments from the moist area is observed, e.g. on 20 December 1991 and 24 December 1991 (figure 1). The PV analysis suggests that these filaments are pieces of the vortex that are being extruded. One cannot always follow these filaments, possibly due to a lack of resolution and/or rapid horizontal mixing of the moist and N_2O-poor areas into the surrounding air which dilutes such parcels. During 20 December 1991 – 13 January 1992 the parcels appear to have a lifetime of at least a week, whereas during 19 February 1992 – 1 March 1992 the lifetime appears to be ~ 3 days. This is consistent with the PV gradients at the vortex edge being stronger during the earlier period (figure 1). Such peeling is expected to play an important role in the transport of moist air from the vortex to mid-latitudes in spring, when the vortex breaks up (cf. Harwood et al., 1993 for the SH). Moist and N_2O-poor parcels which have the PV signature of the vortex are observed away from the vortex (figure 2: on 26 February 1992 over USA; figure 3: on 1 March 1992 over Eastern Siberia) at 840 K. The PV suggests that these parcels originated in the vortex.

It is widely believed that strong gradients of PV at the edge of the vortex inhibit transfer into the vortex (McIntyre, 1989). However, small scale horizontal mixing at the vortex edge can peel off filaments, as has been modeled by Juckes and McIntyre (1987) and reported by Kelly et al. (1989) for the southern vortex and Tuck et al. (1992) for the northern. At 655 K during 20 December 1991 – 1 March 1992 and 840 K during 9 January 1992 – 1 March 1992 there appears to be little horizontal transport from outside to inside the vortex as evinced by the persistence of the moist and N_2O-poor areas during these periods (figures 1-2). This is inconsistent with transport of relatively dry and N_2O-rich air from mid-latitudes (see Harwood et al., 1993 and Kumer et al., 1993 for typical distributions of H_2O and N_2O) to the vortex.

The high H_2O mixing ratios in the vortex at 655 K are presumably due to moist air descending from above. Evidence of such descent can be seen in figures 4a and 4b where H_2O and N_2O values for 11 January 1992 have been linearly interpolated in the vertical onto isentropes and averaged over 60°N–70°N. Also shown are PV (figure 4c) and net diabatic heating rates (figure 4d) averaged within the same latitude bin. Figure 5 (where the latitude bin is 70°N–85°N) shows descent on 1 March 1992, although not as strong as on 11 January 1992.

The heating rates are calculated by the method of Haigh (1984) using MLS retrievals of H_2O, O_3 and temperature as input. Sensitivity tests in which the input fields were perturbed by typical MLS uncertainties suggest that these calculations are accurate to better than 10 % in the stratosphere.

Figures 4 and 5 show that H_2O and N_2O isopleths within the polar vortex are displaced downward by ~ 5 - ~ 10 km relative to the vortex exterior. This displacement is evident from η ~ 6.4 to η ~ 7 ($\eta = \ln(\theta)$) for N_2O and H_2O on 920111. On 920301 N_2O and H_2O show displacement but less clearly, especially at the higher levels and, for H_2O, at the vortex centre. These figures also show that the sharp PV gradients associated with the vortex edge tend to be co-located with similar sharp gradients in H_2O and N_2O on 11 January 1992. A similar correlation is found for 1 March 1992, although the PV gradients are less sharp.

At 840 K during 19 February 1992 – 1 March 1992 we see evidence of relatively dry air which tends to reduce the extent of the moist region inside the vortex (figure 3). A possible source of this air is the mesosphere, which for heights greater than ~ 65 km is dry (Bevilacqua et al., 1983). This is consistent with the observation that during the later part of 20 December 1991 – 13 January 1992 the trend in the maximum H_2O mixing ratio at 840 K is one of increase, indicating that moist air from the upper stratosphere has crossed the 840 K isentrope before the drier mesospheric air. As N_2O concentrations decrease with height in the stratosphere and mesosphere (Gunson et al., 1990), this descent would bring N_2O-poor air to the 840 K level in agreement with the N_2O-poor area persisting during 19 February 1992 – 1 March 1992 (figure 2). Descent of mesospheric air to ~ 10 hPa has been predicted in the SH using a global model (Fisher et al., 1993) and observed in satellite data (Russell et al., 1993). Calculations for 19 February 1992 give cooling rates of ~ 1 $K.day^{-1}$ at the centre of the vortex and ~ 2 $K.day^{-1}$ (~ 5 $km.month^{-1}$) at the vortex edge, so the descent (~ 65 to ~ 30 km, starting on 1 October 1991) could be accomplished in ~ 4-5 months (assuming descent rates of ~ 15 $km.month^{-1}$ in the mesosphere, ~ 10 $km.month^{-1}$ in the upper stratosphere (Fisher et al., 1993) and 5 $km.month^{-1}$ in the middle stratosphere), in reasonable agreement with Fisher et al. (1993). If such a descent has taken place, the flat H_2O gradients on 1 March 1992 at levels η ~ 6.9 may be due to horizontal mixing taking place after the passage of the relatively dry air.

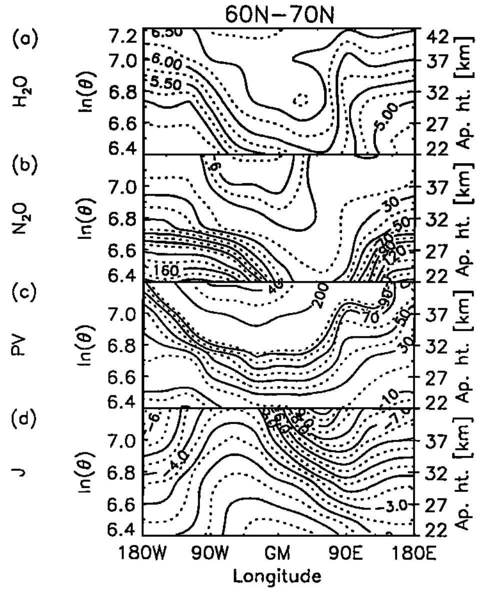

Fig. 4. Longitude vs ln(θ) cross-sections for the latitude bin 60°N-70°N for 11 January 1992 of *a*) H_2O mixing ratio (ppmv), *b*) N_2O mixing ratio (ppbv), *c*) PV/(10^{-5} $K.m^2.kg^{-1}.s^{-1}$) and *d*) net heating rate, J/($K.day^{-1}$).

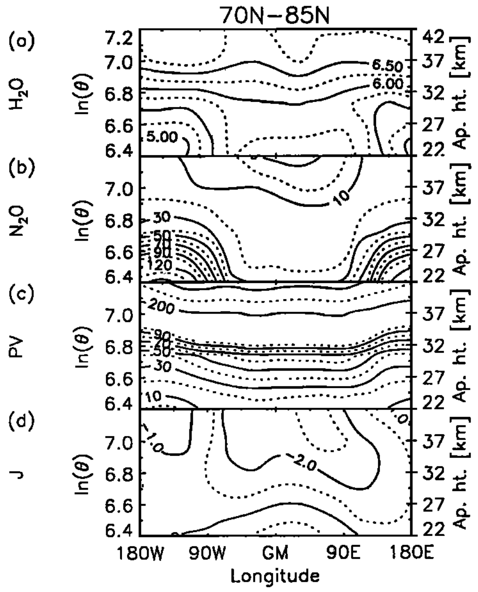

Fig. 5. As figure 4 but for 1 March 1992 and the latitude bin 70°N-85°N.

The N_2O maps at 840 K (figure 2) show little evidence of horizontal transport from outside the vortex to its interior during 19 February 1992 – 1 March 1992 and tend to rule out horizontal transport as a mechanism for drying the vortex. The sharp gradients in H_2O and N_2O at the vortex edge (figures 4 and 5) are consistent with weak horizontal transport there. More detailed discussion of the evidence for descent of mesospheric air is beyond the scope of this letter and will be the subject of a future paper.

Although the evidence for descent of mesospheric air is suggestive, there may be other mechanisms which could bring about the relative dryness observed at 840 K. Although all days considered show descent, we cannot rule out the possibility of ascent during 14 January 1992 to 14 February 1992 bringing drier air from the lower stratosphere. This appears unlikely, as such motion would bring N_2O-rich air to the 840 K level in contradiction to what is observed (figure 2). Another possibility is that after the vortex was disturbed during 14 January 1992 to 14 Februray 1992 (Naujokat et al., 1992), the PV and the H_2O and N_2O distributions behaved differently (Haynes and McIntyre, 1987).

Conclusions

MLS H_2O and CLAES N_2O measurements during winter 1991-92 in the NH provide evidence that: (a) descent of mesospheric air occurred into the vortex which dried its interior at 840 K; (b) in the mid-stratosphere, over time scales of certainly 1 month and probably 3 months, there is little or no large scale mixing across the vortex edge and the temporal and spatial evolution of the moist and N_2O-poor areas correlates well with that of the vortex; (c) descent of upper stratospheric air moistened the vortex interior at 655 K.

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