GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO. 2, PAGES 147-150, January 15, 1998

Interhemispheric differences in stratospheric water vapour during late winter, in version 4 MLS measurements

M W Morrey, R S Harwood

Department of Meteorology, University of Edinburgh

Abstract. Observations of stratospheric water vapour, made by the Microwave Limb Sounder (MLS) during the 1992 and 1993 Arctic and 1992 Antarctic late winters have now been produced using version 4 of the retrieval software. These improved measurements are analysed as equivalent latitude zonal means. Major interhemispheric differences are revealed in the water vapour content of the vortex in the lower stratosphere. This technique emphasises mixing ratio gradients at the edges of both polar vortices, and a local maximum at the edge of the Antarctic vortex. There are some small interhemispheric differences in mixing ratios in mid-latitudes, but they are not strongly related to the dehydration of the Antarctic vortex. A mixing ratio gradient across the interior of the Antarctic vortex at 530K indicates it is not isentropically mixed. A strong local maximum in mixing ratio at the centre of the Antarctic vortex in the mid-stratosphere indicates it is not well mixed in the mid-stratosphere also. There is little evidence of significant structure inside the Arctic vortex.

Introduction

The Antarctic vortex, lasts longer, is more stable and is colder than the Arctic vortex. More Polar Stratospheric Clouds (PSC) form in the colder Antarctic, providing surfaces for inhomogeneous chemistry and leaving the vortex air dehydrated. These conditions lead to the measured interhemispheric differences in chemical species like O_3, H_2O, ClO, and NO_y in the lower stratosphere [*Santee et al.*, 1996]. The release of version 4 of the MLS water vapour measurements provides a new opportunity to study these interhemispheric differences.

Early HALOE measurements (version 8) of lower stratospheric water vapour during southern late-spring suggested mixing ratios were lower in southern mid-latitudes than in northern mid-latitudes [*Tuck et al.*, 1993]. If true, this difference could be due to mixing of dehydrated air from the Antarctic winter vortex into southern mid-latitudes. By assuming mixing across the vortex edge occurred over approximately 100 days of southern winter, Tuck *et al.* estimated a vortex flushing time scale of around thirty days. This would imply that the vortex was acting like a “flowing processor”, a suggestion discussed by Randel [1993]. However, subsequent re-analyses of the similar data indicated the descent rate was about a third of the Tuck estimate [*Schoeberl et al.*, 1995] and the influence of polar dehydration on mid-latitudes was insignificant [*Mote*, 1995]. Recent studies [*Abrams et al.*, 1996, *and references therein*] support this latter view.

Using UKMO winds and vertical velocities from a radiation calculation Manney *et al.* [1994] show that in the lower stratosphere diabatic descent over winter is concentrated in a collar around the edge of the Antarctic vortex, but more evenly distributed in the Arctic vortex. Manney *et al.* [1994] find there is little mixing inside the Antarctic vortex in the lower and mid-stratosphere. Balloon measurements of water vapour made by Vömel *et al.* [1995] in 1994, support the slower descent rate, but also indicate the Antarctic vortex is well mixed in the lower stratosphere. Earlier balloon measurements by Hoffman *et al.* [1991] indicate there is significant inhomogeneity inside the Antarctic vortex, but that the Arctic vortex is normally well mixed.

In this paper we compare the distributions of water vapour in the northern and southern hemispheres in late winter, on equivalent latitude, to resolve mixing patterns inside the polar vortices, and to determine the influence of the vortex air on mid-latitude mixing ratios.

Observations

The Microwave Limb Sounder (MLS) instrument, on the Upper Atmosphere Research Satellite (UARS), measures microwave radiances in the middle atmosphere in three frequency bands. Mixing ratios of several important species, principally ClO, O_3, and H_2O, are retrieved using these radiances. The water vapour measurements (version 4) are obtained from radiance measurements at 183 GHz [*Lahoz et al.*, 1996]. UARS orbits the earth 15 times each day, during which MLS measures an average of 1318 profiles.

The mixing ratio profiles have horizontal and vertical resolutions of approximately 400km and 5km respectively. The UARS satellite performs a 180° yaw manoevre every 30-40 days, leading to alternating periods of coverage of northern and southern high latitudes. The latitude range sampled is either from $\sim 80°$S to $\sim 34°$N or from $\sim 34°$S to $\sim 80°$N.

H_2O observations were obtained from 19th September 1991 to 25th April 1993, when the 183 GHz radiometer failed. No data were available from 2nd June 1992 - 15th July 1992 due to a UARS technical problem. The validation of version 3 of the 183 GHz water vapour retrieval by Lahoz *et al.* [1996] produced the following results. The precision and accuracy of individual measurements at 46, 22, and 10 hPa are < 0.2 ppmv and $\sim 15-20\%$ respectively, while at 4.6, 2.2 and 1hPa they are < 0.3ppmv and $\sim 15-30\%$ respectively. In a zonal mean there there are typically 15 or 30 measurements in a latitude bin, giving a corresponding increase in precision. Version 3 of the retrieval was thought

Paper number 97GL53637.
0094-8534/98/97GL-53637$05.00

to be unreliable at 46hPa in high latitudes. Version 4 of the retrieval is currently being validated, but is believed to be more accurate than version 3, especially at 46hPa [*H C Pumphrey* personal communication].

Potential vorticity (PV) is calculated from the assimilated wind fields, produced for each UARS day by the United Kingdom Meteorological Office (UKMO) [*Swinbank and O'Neill*, 1994] .

Application of Equivalent Latitude

The polar stratospheric vortices are rarely centred precisely over the poles. Their shape can also sometimes become quite distorted, especially that of the Arctic vortex. Thus analyses based on zonal means may not highlight some systematic differences or similarities of the vortices. Isentropic potential vorticity (PV) can be employed as an alternative co-ordinate to latitude for zonal mean style plots. Mixing ratios of long-lived species are normally conserved within a tube of PV and potential temperature. However, the range and distribution of absolute potential vorticity varies between different years and the two hemispheres, making interhemispheric and interannual comparisons more difficult.

The equivalent latitude of a PV contour is the latitude of a circle which encloses the same surface area about the pole as that PV contour does around the point of most extreme PV. It is a co-ordinate which utilises the PV correlated characteristics of the vortex, but conserves horizontal area [*Buchart and Remsberg*, 1986]. Interhemispheric and interannual comparisons are more straightforward using equivalent latitude.

Differences in the Lower Stratosphere

Figure 1 shows the zonal mean water vapour mixing ratio at 530K, close to 46hPa in mid-latitudes. Data was averaged over one ten day period in late winter in the southern hemisphere, and two periods from six months before and after this in the northern hemisphere. The strong dehydration at high latitudes in the southern hemisphere late winter is a result of condensation of water vapour into ice or hydrates of nitric acid to form polar stratospheric clouds, and the subsequent sedimentation of larger ice particles [*Vömel et al.*, 1995]. In contrast, the warmer Arctic vortex does not feature widespread dehydration, and its water vapour content rises during the winter season.

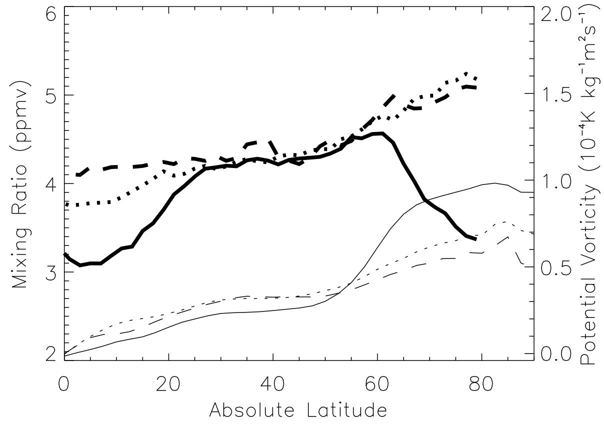

Figure 1. Zonal mean MLS water vapour mixing ratio at a potential temperature of 530 Kelvin, versus absolute latitude (bold lines & left scale) and zonal mean isentropic potential vorticity (feint lines & right scale). Southern hemisphere 15 - 24 Aug 1992 (solid line); northern hemisphere 15 - 24 Feb 1992 (dashed line) ; northern hemisphere 15 - 24 Feb 1993 (dotted line). Retrieval error on the mean mixing ratio is ~ 0.05ppmv.

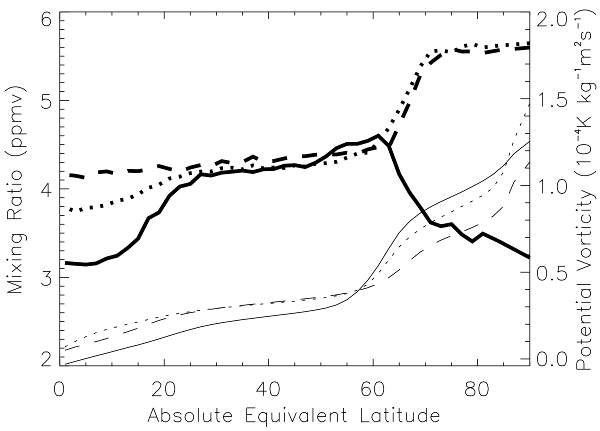

Figure 2. As figure 1 but on equivalent latitude. Beyond 80° equivalent latitude the typical retrieved error on the mean mixing ratio rises to ~ 0.25ppmv.

Figure 2 shows the same data as figure 1, but presented on equivalent latitude. Seasonal and interannual variation can be seen at the equator in both figures 1 and 2. The seasonal difference is primarily due to the signal of an annual variation in tropopause temperature being preserved in rising air in the tropical lower stratosphere [*Mote et al.*, 1995]. The interannual difference is due to a modulation of the ascent rate in the tropics by circulations associated with the QBO [*Mote et al.* 1995], which is in opposite phases in the two northern late winter periods.

Between 40° and 60° in figure 1 the mixing ratios during the 1993 northern late winter (dotted line) are consistently higher than in the 1992 southern late winter (solid line). The 1992 northern late winter (dashed line) had a more variable pattern in mid-latitudes. In figure 2 the mixing ratio between 40° and 60° is higher during the southern hemisphere period. The interhemispheric difference in figure 1 is shown to be a result of the wet Arctic vortex straying south of the polar region.

The edges of the winter vortices are more strongly resolved in figure 2 than in figure 1 because the blurring effect of a zonally non-symmetric vortex is much reduced. In mid-latitudes there is only a small difference between the 1992 southern late winter (solid) and the 1993 northern late winter (dotted) lines. This suggests that the mixing of dehydrated air across the edge of the southern vortex at 530K is small and that the northern vortex in 1993 was also well contained. The 1992 northern late winter (dashed) line is typically ~0.1ppmv higher than the 1993 northern late winter (dotted) line. If the 0.1 ppmv difference is a significant one it may be due to leakage from the northern vortex in 1992.

The PV lines in figure 2 show that the Arctic vortex in 1992 is smaller and is bounded by weaker PV gradients than in 1993. The interhemispheric differences in mid-latitudes are rather small. This is remarkable given the seasonal changes in low latitudes [*Mote et al.*, 1995] and suggests that the time required to mix significant amounts of air from the tropics to mid-latitudes is comparable to a year or longer.

In figure 2 there is a strong meridional gradient in the sub-tropics of the southern hemisphere in 1992, which suggests a sub-tropical barrier is being resolved. There is a gradient in mixing ratio across the interior of the Antarctic vortex. This indicates the interior of the vortex in not well mixed at 530K. Both Arctic vortices appear well mixed north of 70°N and there is no evidence of localised dehydration. There are two likely explanations of the lack of structure inside the northen vortex. The region of maximum descent may not be in a consistent position relative to the centre of vortex [e.g. *Schoeberl et al.*, 1992]. When the vortex is distorted in shape, or not centred on the pole, there may be significant barotropic instability, leading to enhanced mixing.

There is a rapid change in water vapour at the edge of the Antarctic vortex. There is also a clear local maximum near 60°S indicating descent is strong in this region, and also that it is fairly isolated from the colder region inside it. Manney *et al.*, [1994] show descent is concentrated in a collar inside the edge of the vortex in the lower stratosphere in the two months preceding this period. If there were significant mixing taking place at the vortex edge, a much flatter distribution would be expected. The meridional resolution of MLS is equivalent to nearly 4° in latitude, so the changes in mixing ratio across the edge of the vortices occur over virtually as small a latitude range as could be resolved. These results indicate that the Antarctic vortex at 530K is strongly isolated during this part of the season. The resolution of a similar but opposite gradient at the edge of the Arctic vortex in figure 2 is a striking result. Because the Arctic vortex is not as symmetrical about the pole as the Antarctic vortex the effect of changing to equivalent latitude is greater.

Vertical Structure in Zonal Mean

Figures 3 to 5 show the average vertical profile of water vapour on isentropic surfaces, for the northern and southern late winter yaw periods. The "equivalent pole" can only be seen by MLS when the region of highest absolute potential vorticity is more than ten degrees away from the geographic pole.

General features apparent in all three plots include: (i) the ascending pattern of low mixing ratio in the tropics associated with the upward branch of the Brewer-Dobson circulation; (ii) zones of net downward displacement of isopleths in the polar regions suggestive of strong descent; (iii) well mixed regions in mid-latitudes; (iv) a tropical hygropause which varies seasonally in height.

The upward branch of the Brewer-Dobson circulation tends to be biased towards the summer hemisphere [*Carr et al.* 1995], although this is not the case during the northern late winter of 1993, figure 5, where the region of ascent is relatively broad in the mid-stratosphere. Dunkerton and O'Sullivan [1996] attributed this interannual difference to circulations associated with the QBO. The strength of the mixing ratio gradients in the subtropics of the middle and upper stratosphere in figure 4 is due to the presence of a westerly jet in the subtropics, where planetary wave breaking is suppressed [*Dunkerton and O'Sullivan*, 1996]. Strong mixing ratio gradients are observed in the subtropics on isentropes which feature a local hygropause in the tropics. These gradients suggest the presence of a barrier to mixing in the subtropics.

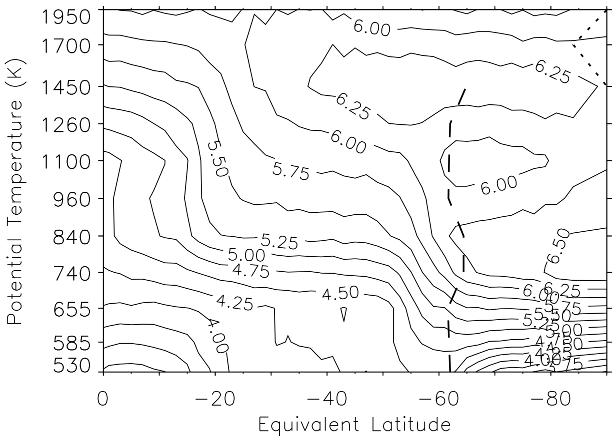

Figure 3. Zonal mean MLS water vapour (ppmv), in the southern hemisphere, 15 Aug. - 24 Aug. 1992 Typical retrieved error on the mean mixing ratio is below 0.05ppmv, rising to up to ∼ 0.25 ppmv at the vortex centre at 530K. The dashed line shows the location of the maximum PV gradient at the vortex edge, where resolvable.

The strongest interhemispheric difference is caused by the dehydration of the lower part of the Antarctic vortex. Above the dehydrated region there is a strong maximum in mixing ratio at the centre of the southern vortex at 740K. This may be the result of previous descent from the upper stratosphere and lower mesosphere, as modelled by Fisher, O'Neill and Sutton [1993] . The maintenance of this maximum at the centre of the Antarctic vortex indicates the interior of the vortex is not completely mixed in the mid-stratosphere, and it may feature significant structure. There are some indications of structure inside the Arctic vortex in the mid-

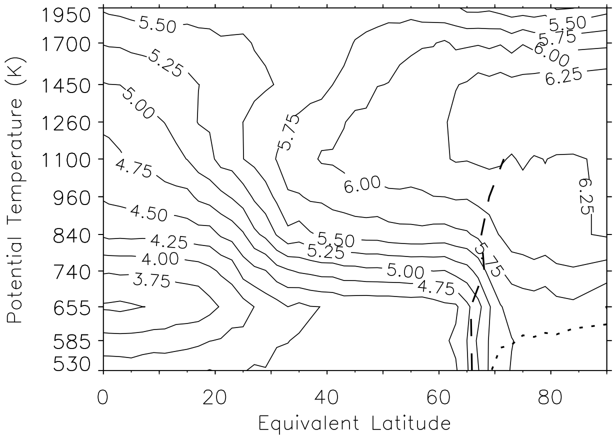

Figure 4. As figure 3, in the northern hemisphere, for the period 15 - 24 Feb. 1992. Below the dotted contour, average retrieved error on each profile exceeded 1.0ppmv.

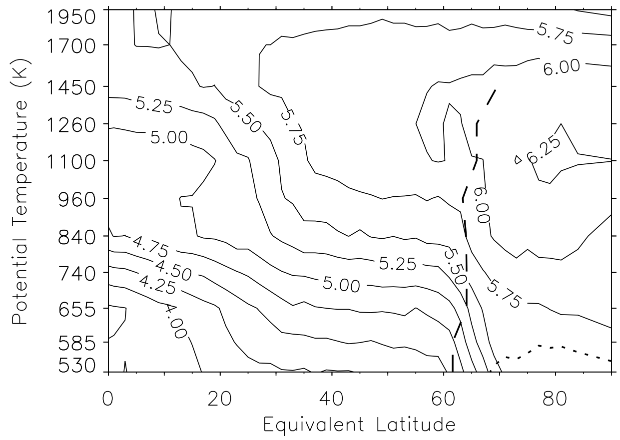

Figure 5. As figure 4, in the northern hemisphere, for the period 15 - 24 Feb. 1993.

stratosphere, but inspection of time series (not shown) show these are not persistent features.

Conclusions

Version 4 of the water vapour mixing ratios measured by MLS have been analysed on equivalent latitude zonal means for late winter periods in both hemispheres. There are marked opposite gradients in MLS water vapour inside the edges of the polar vortices in the lower stratosphere during late winter. There is a local maximum in water vapour near the edge of the Antarctic vortex at 530K. Interhemispheric differences in mid-latitude mixing ratios at 530K are surprisingly small and do not appear to be related to the dehydration of the Antarctic vortex in the lower stratosphere. These results indicate there is little mixing of vortex and mid-latitude air occurring at this level in late winter.

There is a clear gradient in water vapour mixing ratio across the Antarctic vortex in the lower stratosphere, indicating the vortex interior is not well mixed. The isentropic gradient in mid-stratospheric water vapour within the Antarctic vortex suggests the vortex interior is not well mixed, and may have internal structure. No significant mixing ratio gradients are evident in the Arctic vortex in the lower and middle stratosphere. On isentropes which feature a hygropause in the tropics there is evidence of a sub-tropical barrier in the winter hemisphere.

Acknowledgments. The assimilated winds were generated by Richard Swinbank's team at the UK Met.Office. The study of mid-latitudes at 530K was suggested by Philip Mote, who also made several helpful comments on early drafts of this paper. We also thank several past and present members of the Department of Meteorology for their advice and assistance, especially Ewan Carr and Hugh Pumphrey; the whole MLS team at the Jet Propulsion Laboratory, led by Joe Waters, especially Gloria Manney, who made several constructive comments on this paper. This work was funded by the Natural and Environmental Research Council (NERC) of the UK.

References

Abrams, M. C., et al., ATMOS/ATLAS-3 observations of long-lived tracers and descent in the Antarctic vortex in November 1994, *Geophys.Res.Lett.*, *23(17)*, 2341–2344, 1996.

Buchart, N., and E. E. Remsberg, The area of the stratospheric polar vortex as a diagnostic for tracer transport on an isentropic surface, *J.Atmos.Sci.*, *43(13)*, 1319–1339, 1986.

Carr, E. S., et al., Tropical water vapour measured by the Microwave Limb Sounder (MLS), *Geophys.Res.Lett*, *22(6)*, 691–694, 1995.

Dunkerton, T. J., and D. J. O'Sullivan, Mixing zone in the tropical stratosphere above 10mb, *Geophys.Res.Lett.*, *23(18)*, 2497–2500, 1996.

Fisher, M. A., A. O'Neill, and R. Sutton, Rapid descent on mesospheric air into the stratospheric polar vortex, *Geophys.Res.Lett*, *20(12)*, 1267–1270, 1993.

Hoffman, D. J., S. J. Oltman, and T. Deshler, Simultaneous balloon-borne measurements of stratospheric water vapour and ozone in the polar regions, *Geophys.Res.Lett.*, *18(6)*, 1011–1014, 1991.

Lahoz, W. A., et al., Validation of UARS MLS 183 GHz H_2O measurements, *J.Geophys.Res.*, *101(D6)*, 10129–10149, 1996.

Manney, G. L., R. W. Zurek, A. O'Neill, and R. Swinbank, On the motion of air through the stratospheric polar vortex, *J.Atmos.Sci.*, *51(20)*, 2973–2994, 1994b.

Mote, P. W., Reconsideration of the cause of dry air in the southern middle latitude stratosphere, *Geophys.Res.Lett.*, *22(15)*, 2025–2028, 1995.

Mote, P. W., K. H. Rosenlof, J. R. Holton, R. S. Harwood, and J. W. Waters, Seasonal variations of water vapour in the tropical lower stratosphere, *Geophys.Res.Lett.*, *22(9)*, 1093–1096, 1995.

Randel, W. J., Ideas flow on Antarctic vortex, *Nature*, *364*, 105–106, 1993.

Santee, M. L., et al., Interhemispheric differences in polar stratospheric HNO_3, H_2O, ClO, and O_3, *Science*, *267*, 849–852, 1995.

Schoeberl, M. R., L. R. Lait, P. A. Newman, and J. E. Rosenfield, The structure of the polar vortex, *J.Geophys.Res*, *97(D8)*, 7859–7882, 1992.

Schoeberl, M. R., M. Luo, and J. Rosenfield, An analysis of the Antarctic Halogen Occultation Experiment trace gas observations, *J.Geophys.Res.*, *100(D3)*, 5159–5172, 1995.

Swinbank, R., and A. O'Neill, A stratosphere-troposphere data assimilation system, *Mon.Weather.Rev*, *122*, 686–702, 1994a.

Tuck, A. F., J. M. Russell, and J. E. Harries, Stratospheric dryness, antiphased dessication over micronesia and Antarctica, *Geophys. Res. Lett.*, *20(12)*, 1227–1230, 1993.

Vömel, H., S. J. Oltmans, D. J. Hoffmann, T. Deshler, and J. M. Rosen, The evolution of dehydration in the Antarctic stratospheric vortex, *J.Geophys.Res.*, *100(D7)*, 13919–13926, 1995.

Department of Meteorology, University of Edinburgh, Kings Buildings, West Mains Road, Edinburgh EH9 3JE, UK

(Received April 28, 1997; revised December 5, 1997; accepted December 8, 1997.)