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# Reconsideration of the cause of dry air in the southern middle latitude stratosphere

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**Abstract.** A previous comparison of data from the Halogen Occultation Experiment (HALOE) and of output from the NCAR Community Climate Model (CCM2) in austral spring overstated the effect of dehydration in the southern polar vortex on lower stratospheric water vapor in part due to shortcomings in the HALOE retrieval algorithm and in part to remnants of the initially dry stratosphere in the CCM2 run. A new HALOE retrieval and a longer CCM2 run both show more water vapor than previously, but HALOE still shows less in the southern hemisphere than in the northern in September–October 1992. A "dried-air" tracer in the CCM2 suggests that polar dehydration influences middle latitudes only below about 100 hPa, and seasonal variations of HALOE $H_2O$ imply no influence north of 50°S.

## Introduction

In the southern polar stratosphere from May to September, very low temperatures permit the formation of polar stratospheric clouds, which promote photochemical destruction of ozone. When these cloud particles fall out, they leave behind dehydrated and denitrified air which may be identified at lower latitudes [*Kelly et al.* 1989]. Aircraft measurements indicate that the middle latitude lower stratosphere appears to be drier in the south than the north [*Kelly et al.* 1990]. Early results for the period September 21–October 15, 1992, from the Halogen Occultation Experiment (HALOE) aboard the Upper Atmosphere Research Satellite (UARS) indicated that polar dehydration had a substantial impact on middle latitude stratospheric water vapor [*Tuck et al.*, 1993]. Similar results had also been obtained using the National Center for Atmospheric Research Community Climate Model (CCM2) [*Mote et al.*, 1993, hereafter MHRB]. Re-analysis of HALOE data and CCM2 output indicates that the presence of very dry air in southern middle latitudes in both was partly spurious. This note explains why both HALOE and CCM2 underestimated water vapor mixing ratios in southern middle latitudes, considers seasonal variations, and provides a modified interpretation of the observations.

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## HALOE Data: Update

HALOE [*Russell et al.* 1993] is a solar occultation instrument which, because of the inclination of the UARS orbit, samples the atmosphere at two different latitudes (one at sunrise, one at sunset) approximately 15 times each per day. The mean latitude of observation changes with time as the UARS orbit precesses, so that zonal averages as shown below represent a sweep from 60°N on Sept. 21, 1992 to 80°S on Oct. 15, 1992. HALOE is self-calibrating since the signal being processed to retrieve constituent mixing ratio is a ratio of solar radiance transmitted through the atmosphere to the solar radiance measured above the atmosphere. Any long term changes in instrument characteristics (e.g. by optical degradation or change in gain) are of no consequence (J.M. Russell III, personal communication, 1994).

MHRB used version 8 (V8) HALOE data, *Pierce et al.* [1994] used V9 and V16 data, and *Bithell et al.* [1994] used V16 data, but V17 is now available and I use it in this paper. V17 incorporates several improvements to the retrieval algorithm which will be discussed fully elsewhere ("A Summary of HALOE Water Vapor Observations", J. M. Russell III et al., destined for JGR). The largest changes in $H_2O$ are about 20% at the 100 hPa level and diminish to <5% at 10 hPa and above; changes in $CH_4$ were similar in nature but smaller (10–15% at 100 hPa) (J.M. Russell III, personal communication, 1994). Planned further algorithm improvements are unlikely to make a significant further impact on retrieved mixing ratios.

### Longer integration of CCM2

The CCM2 [*Hack et al.*, 1993] is a global, spectral model to which trace constituents and chemistry can be added; here, methane is transported and is converted to water vapor in the stratosphere as described by *Mote* [1995]. The resolution is approximately 2.8° (latitude) × 5.6° (longitude) × 1.5 km. As with many GCMs, parameterized gravity wave drag is too weak in the southern hemisphere winter high latitudes [*Garcia and Boville*, 1995], leading to a cold bias and excessive dehydration. This problem is crudely remedied here by increasing upper stratospheric Rayleigh friction.

MHRB showed results from the beginning of the fifth year of a CCM2 integration. Later analysis showed a positive trend of water vapor in the lower stratosphere (especially in middle latitudes) owing to the dry initial state and the long transit time of parcels through the methane oxidation region in the upper stratosphere and back to the lower stratosphere. After a further five years the trend has diminished, leaving $H_2O$ about 1–1.5 ppmv higher in middle latitudes in both hemispheres (changes in lower stratospheric methane were insignificant). Temporal sampling of CCM2 output for figures 1b and 2b is similar to the way HALOE samples the atmosphere, but shifted five days: daily zonal means of CCM2 output ($H_2O$ and $CH_4$) were interpolated to the latitude at which HALOE sampled five days later (e.g. 76° S on October 14 for HALOE, October 9 for CCM2). The shift was necessary because in the CCM2 run the vortex weakened rapidly after October 10 and middle latitude air was mixed in, producing conditions very different from those observed by HALOE on the same dates.

The run presented here branched from the multi-year run on June 1 of its final year and includes enhanced Rayleigh friction and a "dried-air" tracer Q; $H_2O$+Q is approximately conserved in the absence of methane oxidation and tropospheric moist physics. The source of Q is polar stratospheric condensation and is limited to the domain poleward of 45° S and above a latitudinally varying envelope somewhat above the tropopause: $p(\phi) = 210 - 160 * cos^2(\phi)$, that is, p=210 hPa at the pole and 130 hPa at 45°.

## Results

Figure 1 compares $H_2O$ from HALOE (V17) and the new CCM2 integration. As before, $H_2O$ in both HALOE and CCM2 increases with height and latitude due to methane oxidation. But compared to MHRB, V17 indicates more $H_2O$ in the lower stratosphere. The CCM2 generally shows more $H_2O$ than both HALOE and the earlier results due partly to a slight moist bias (which in turn is apparently caused by misrepresentation of small scales) of the CCM2's tropical tropopause [*Mote et al.*, 1994]; because of this bias, the CCM2 color scale has been shifted by 1 ppmv in figures 1b and 2b. *Bithell et al.* [1994] pointed out that because the vortex during this period was displaced from the pole and tilted with height, zonal means of HALOE data can produce a misleading picture. We note therefore that the vortex in the CCM2 is much more zonally symmetric than it was in October 1992 when HALOE observed southern high latitudes.

Figure 2 shows the approximately conserved quantity $2\times[CH_4]+[H_2O]$ which accounts for the effect on $H_2O$ of methane oxidation [*Jones et al.*, 1986]. Departures from typical stratospheric values are caused by a source or sink other than methane oxidation. HALOE $2\times[CH_4]+[H_2O]$ (Figure 2a) is nearly constant in most of the stratosphere. Higher values in the northern subtropics may represent tropospheric air, while lower values in southern high latitudes indicate dehydration. Earlier versions of HALOE showed similar dehydration but the difference in $2\times[CH_4]+[H_2O]$ between high and middle latitudes was smaller in the southern hemisphere. CCM2 $2\times[CH_4]+[H_2O]$ (Figure 2b) resembles HALOE in some respects, particularly the extent of polar dehydration, but is more symmetric about the equator and shows higher values almost everywhere, especially below 70 hPa north of 60°S. The cause of the vertical variations in CCM2 $2\times[CH_4]+[H_2O]$ is not clear but may be due to the continuing small increase in $H_2O$ ($CH_4$ is fixed in the troposphere).

Dry air in the CCM2 does not reach as far equatorward as in HALOE observations. Comparing values at the hygropause (the driest point in a vertical profile), CCM2 $H_2O$ has a nearly uniform increase from 3.5 at 77°S (values below 2.5 occur south of the latitudes shown) to 4.9 ppmv at 60° S, and then nearly constant values to 60°N. HALOE $H_2O$ increases from 2.4 at 77°S to 2.9 at 67° S, then to 3.4 at 30° S, then decreases again toward the equator.

How common is this equatorward increase in $H_2O$? Using all good HALOE profiles for the years 1992-1994, I constructed monthly mean curves of hygropause mixing ratio versus latitude by binning each profile's minimum value by latitude (in 4° increments) for different periods (Figure 3). Standard deviations in the bins are typically 0.2–0.7 ppmv. Throughout southern winter and spring, values north of 50°S are nearly constant in time and decrease toward the equator. From 50°–60°S hygropause mixing ratio decreases from June–July to October–November, but from 45°–20°S hygropause mixing ratio increases slightly (these changes are not statistically significant). If the interhemispheric difference seen in Figure 1 were due to polar dehydration, one would expect air in middle latitudes to be progressively drier from June to November, but this is not observed equatorward of 50°S. The dry band in southern middle latitudes observed in September–October 1992 was apparently unusual and its cause may lie elsewhere than in the polar vortex. The influence of the tropical tropopause is considerable: in February–March, $H_2O$ decreases toward the equator with the same slope in both hemispheres and the lower stratosphere is drier because the tropical tropopause is colder. Lag-correlation analysis (not shown) of HALOE and SAGE II data indicates that the tropical annual cycle dominates lower stratospheric water vapor between about 60°N and at least 45°S with lags increasing poleward.

Air dried in the southern vortex in the CCM2 is sharply confined in latitude and height (Figure 4). Q has a sharp gradient which slopes down toward the equator; very little of the dried air actually reaches 30°S above about 100 hPa. After the vortex breaks down in mid-October, the gradient of Q diminishes (4c) and by this time some Q tracer has re-entered the stratosphere in the tropics. The global integral of Q at the end of the run, $2.6 \times 10^{12}$ kg, represents the total amount of water removed by dehydration; *Douglass and Stanford* [1982] calculated the amount of water vapor that could

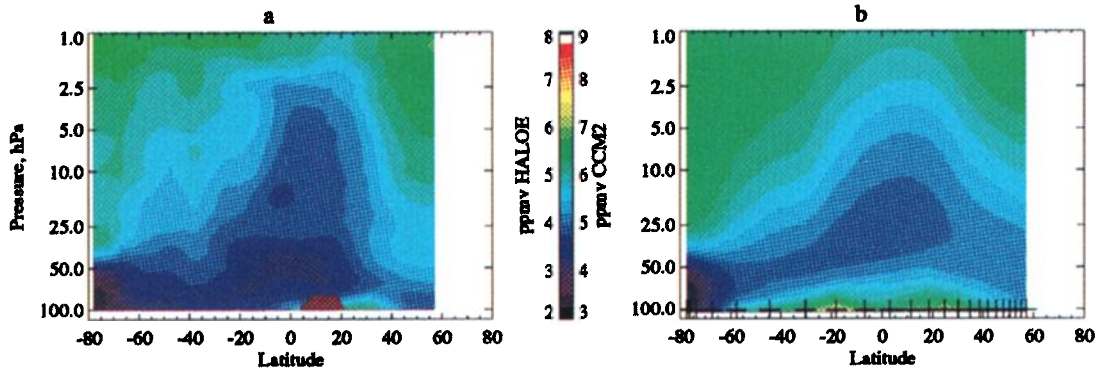


**Figure 1.** Zonal mean water vapor mixing ratio (a) observed by HALOE, September 21–October 15, 1992, (b) simulated by the CCM2, September 16–October 10. Temporal sampling of CCM2 results is similar to that for HALOE, as indicated by '+' marks on the abscissa (see text for details). Note different color scales.

be removed by condensation in the southern polar vortex and found an upper limit of about $2.7 \times 10^{10}$ kg, assuming some re-evaporation. The large discrepancy between the present results and theirs could be due to the lack of a sink for Q. Almost all of the mass of Q is in the troposphere: its global integral above 200 hPa is $3.6 \times 10^{11}$ kg and above 100 hPa only $6.5 \times 10^{10}$ kg.

## Discussion and conclusions

As the HALOE processing algorithm has matured, the interpretation of HALOE water vapor and methane has changed. *Pierce et al.* [1994] used both V9 and V16 HALOE data and ran trajectories from HALOE observations during the time period considered here. With V9, $2\times[CH_4]+[H_2O]$ outside the vortex had a bimodal distribution, implying that significant quantities of vortex air low in $2\times[CH_4]+[H_2O]$ had traveled equatorward while retaining its identity. With V16 data, however, they found that total hydrogen outside the vortex had a unimodal distribution almost at typical stratospheric values. The present results with V17 data concur with V16 (zonal means and Pierce's results) that during September–October 1992 southern middle latitudes were drier than northern middle latitudes, but V17 data show more water vapor throughout the lower stratosphere and a slightly greater difference between air inside and outside the vortex. In the mean of three years of HALOE observations, there appears to be no seasonal decrease in water vapor north of 50°S from June to November, which implies that the influence of polar dehydration is confined to high latitudes. Further analysis of HALOE data is needed to explain the dryness in spring 1992.

The sharp gradient of Q and the fact that it has no sink prevent a quantitative statement about the impact of polar drying at a given height or latitude, but its influence appears to be quite small above 100 hPa (the driest air in the CCM2 occurs about 60 hPa; see Fig 1b). Its mass above 100 hPa is about 4% of the mass of water above 100 hPa, but is mostly found at high latitudes even at the end of November. Studies with water vapor in the CCM2 [*Mote,* 1995] showed that dry air remained contained within the vortex until vortex breakup in November or December (the run shown here had a weaker vortex which broke up earlier due to enhanced Rayleigh friction), then had noticeable impact (0.5 ppmv) on middle latitude mixing ratios. Similar results were obtained by *Mahlman et al.* [1994] with ozone in the GFDL 'SKY-HI' GCM. These GCM runs

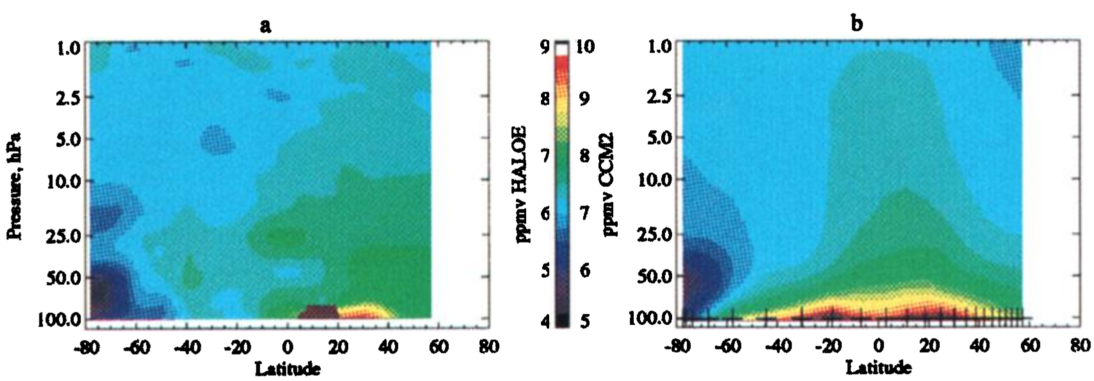


**Figure 2.** As in Figure 1 but the quantity plotted is $2\times[CH_4]+[H_2O]$.

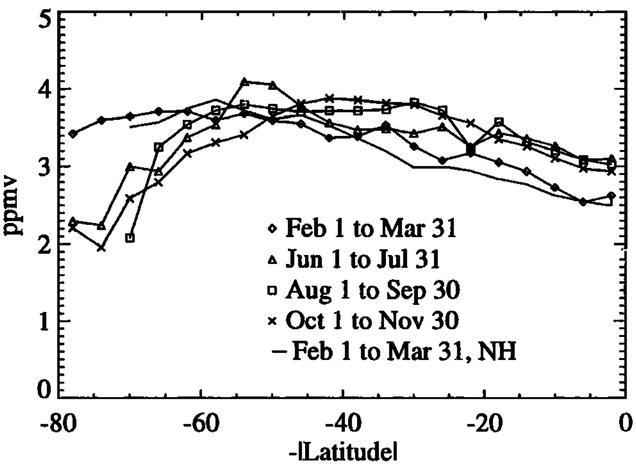


**Figure 3.** HALOE 1992-1994 lower stratospheric hygropause binned by latitude for the periods indicated. The abscissa is latitude for southern hemisphere, -latitude for northern hemisphere.

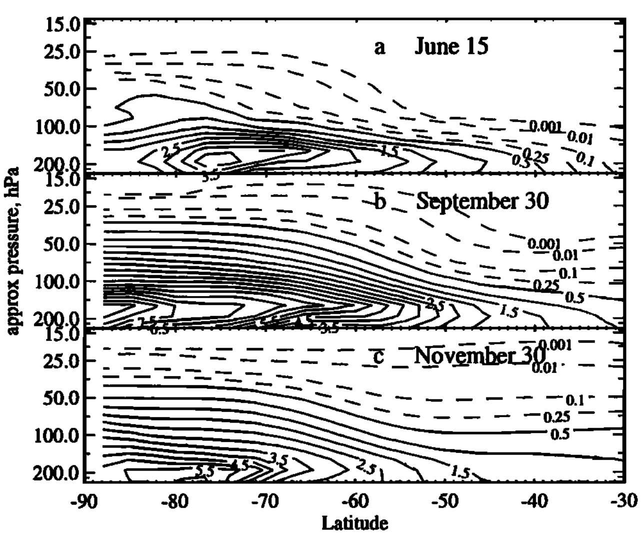


**Figure 4.** Zonal means of the Q tracer, which indicates air dehydrated in the southern polar region (see text for details), on the dates indicated. Contour interval 0.5 ppmv, and contours 0.001, 0.01, 0.1 and 0.25 are also shown (dashed).

appear to have a more robust polar vortex which persists longer into spring and which is more isolated than the observed vortex, but in the CCM2 run with enhanced Rayleigh friction, the Q tracer is still strongly confined to high latitudes above 100 hPa, and is confined below 100 hPa elsewhere.

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