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Revisiting the lower stratospheric water vapour trend from the 1950s to 1970s

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Abstract

Previous work showed a near-continuous increase in stratospheric water vapour between the 1950s and 1990s from a variety of instruments, without recourse to fits between instruments. We reassess the trend from the earliest, the UK frost-point hygrometer, 1954–1976. An error in previous work omitted to transform values from ppmm to ppmv. When corrected, they fit more convincingly with measurements by later frost-point hygrometers. Minor instrument changes between the 1950s and 1970s do not introduce a potential bias to the trend but do increase its error. If the full 1970s data are included, the trend becomes 2.1 ± 0.8%/year (two-sigma). Copyright © 2011 Royal Meteorological Society

Keywords: **water; stratosphere; global change; frost point**

1. Introduction

The SPARC Assessment Report of water vapour in the stratosphere (SPARC 2000) and a companion paper (Rosenlof *et al*., 2001) showed that the mixing ratio of stratospheric water vapour increased by about 1%/year from the 1950s to the 1990s.

The earliest instrument was the frost-point hygrometer in the UK's Meteorological Research Flight (MRF). This observed water vapour in the lower stratosphere above southern England in the mid-1950s and again in the mid-1970s (Cluley and Oliver, 1978). The original airborne instrument is described in detail in Meteorological Office (1961): a polished thimble is cooled from below by liquid nitrogen and is exposed to a flow of outside air. The illuminated thimble is observed by eye, the observer controlling the coolant allows frost to form on the thimble and then to evaporate. The temperatures of frost forming and evaporating are measured by a platinum resistance thermometer on the lower part of the thimble, and the mean of the two temperatures taken as the frost point.

In this article, we reassess the trend in these earliest measurements by taking account of changes in arrangement of the hygrometer and by correcting an important editorial error that had crept into previous work.

2. Scaling error in later quotes of data from the UK's MRF frost-point hygrometer

Water vapour values from the UK frost-point hygrometer in the MRF were tabulated in units of mass mixing ratio by Cluley and Oliver (1978). Unfortunately, they were plotted as volume mixing ratios in Rosenlof *et al.* (2001) and in SPARC (2000). The UK values should have been multiplied by 1.609 before plotting, this being the ratio of the molecular weight of air (28.97) to water (18).

This simple mistake occurred despite the factor 1.609 appearing in the data preparation programme for the plots. It occurred despite scrutiny by the 12 co-authors of Rosenlof *et al*. (2001), by the large number of authors who contributed to SPARC (2000), and by the large number of referees who reviewed it (of which HKR was one). In Figure 1, we redraw the important plot with the correct scaling of UK values. Fortunately, the major conclusion of Rosenlof *et al*. (2001), that the average increase over all instruments considered was about 1%/year, is unchanged by this mistake because no trends between instruments were discussed.

Because frost-point hygrometers have always been thought by the stratospheric community to be close to a primary standard, it was disturbing to students of water vapour trends (Fueglistaler and Haynes, 2005) to see the apparent difference between the UK airborne measurements and balloon-borne measurements with frost-point hygrometers. When the reversal in trend in the year 2000 became apparent (Randel *et al*., 2006), this earlier difference was yet more puzzling. We now show all the earlier frost-point values from the lower stratosphere (Figure 2), which are more harmonious than before despite instrument differences.

3. Differences between the UK's MRF frost-point hygrometer in the 1950s and the 1970s

SPARC (2000) stated that the earliest instrument, the frost-point hygrometer in the UK's MRF, was unchanged between the 1950s and 1970s. However,

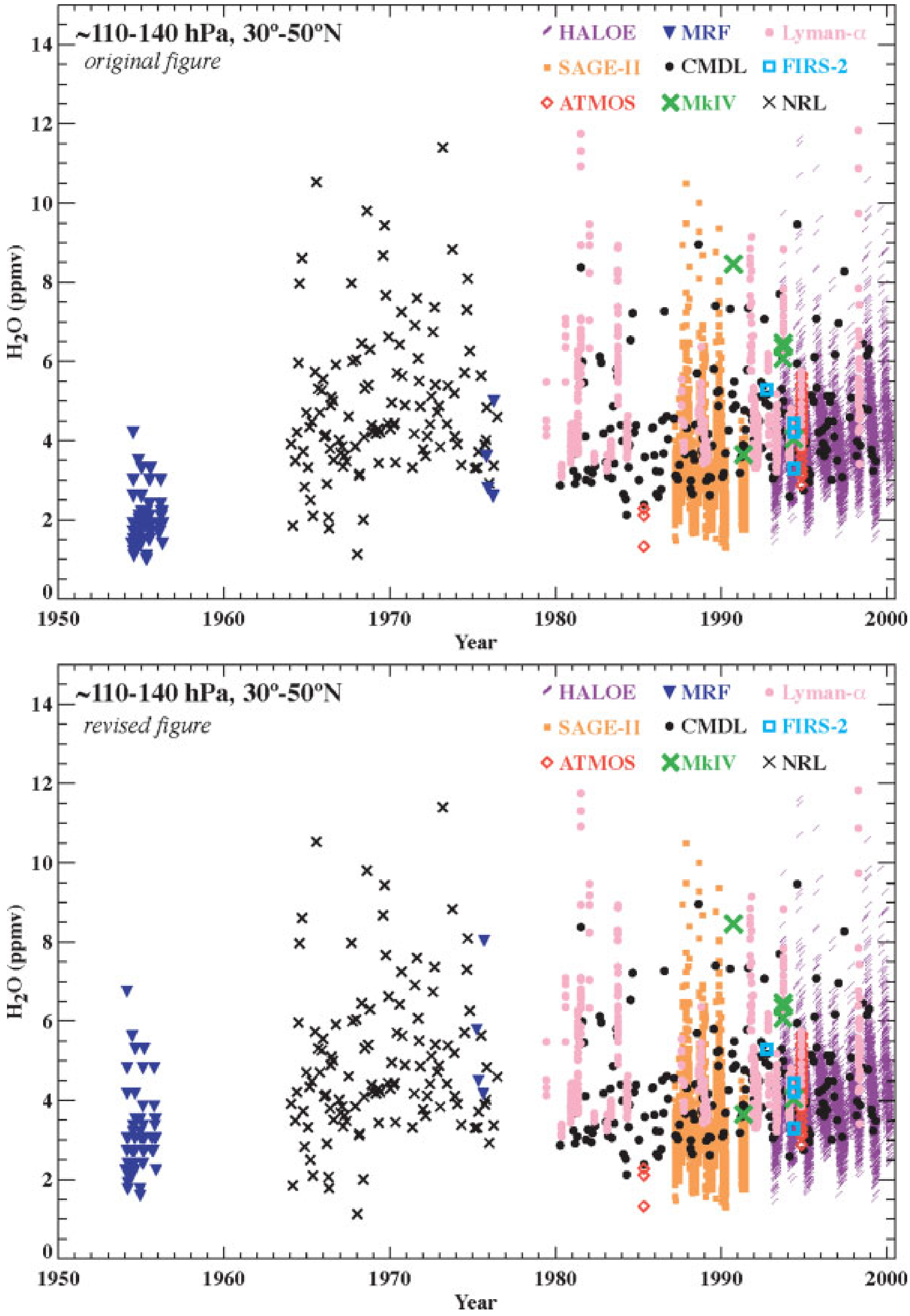

Figure 1. Time series of water vapour from a variety of sensors, in the lower stratosphere (110–140 hPa) at northern mid-latitudes (Figure 2.67 of SPARC 2000). Above, as originally drawn; below, with correct UK instrument MRF scaling.

although Cluley and Oliver (1978) state that the modification made in the 1970s had 'no effect on the performance', they list important differences which we now examine.

3.1. Hysteresis

The earlier instrument had a much larger hysteresis between frost forming and frost disappearing. Early analyses of the 1950s data used the mean frost point, so hysteresis created a bias because of the large nonlinearity of saturation vapour pressure with temperature – the mean temperature is not the mean vapour pressure. The 1950s instrument had a hysteresis of about 6 K, which is more than a factor 2 in vapour pressure, whereas the 1970s instrument had only 2–3 K hysteresis. However, all results were recomputed by Cluley and Oliver (1978) using mean vapour pressure, which removed the possibility of bias from that source. There is another possibility of bias due to frost formation and evaporation not necessarily being symmetric around the frost point, as formation is controlled by the availability of water vapour, whereas evaporation is not. Any such bias would be larger with

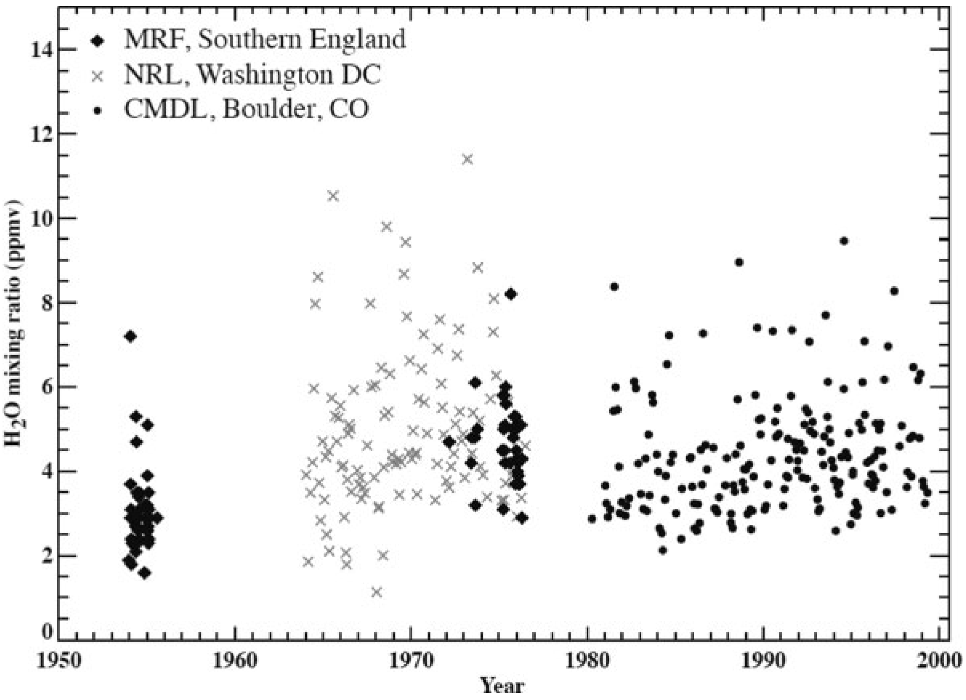

Figure 2. Time series of water vapour from frost-point hygrometers only, in the lower stratosphere (110–140 hPa) at northern mid-latitudes. This consists of the full set of UK frost-point data from the Meteorological Research Flight (MRF) as discussed in Section 5, together with the frost-point measurements of Figure 1 from NRL and CMDL.

the larger hysteresis of the 1950s instrument. Unfortunately, it is impossible to evaluate this possibility without a laboratory trial of the original apparatus.

3.2. Flow rates

The 1950s instrument had a much smaller flow rate and poorer visibility of the cooled mirror. These factors were no doubt responsible for the larger hysteresis above. But although poorer visibility should give rise to more noise, it is difficult to see how it could create a bias. The smaller flow rate should reduce the heat flow out of the thimble thereby reducing the temperature gradient within it, but this is accounted for below.

3.3. Temperature gradients

The earlier instrument had a much smaller temperature gradient between the temperature sensor and the cooled mirror. The large gradient of the 1970s instrument, 2.0 ± 0.1 K, was carefully measured by Oliver and Cluley (1978), and they estimated the gradient in the earlier instrument to be 0.6 ± 0.3 K. Cluley and Oliver (1978) recomputed the mixing ratios using the appropriate correction for each instrument, again eliminating bias. However, the additional error in trend between the 1950s and 1970s must then be equivalent to ±0.32 K. At the temperatures in question this is ±6% in mixing ratio. Assuming a random distribution and equivalence to a one-sigma error, over the 20 years between mean dates of each data subset this additional error becomes ±0.6%/year two-sigma.

4. Random errors in the observations

Grant (1963) measured the random error of the earlier version of the hygrometer, using six observers in a set of laboratory tests. His conclusion was that the random error of a frost point at −75 °C was 1.6 K. Cluley and Oliver (1978) assert that the dirt on the surface might add another ±5% to the random error budget. They also measured the inlet and outlet pressures of air flow in flight and give the error in pressure as ±6%, which translates directly to an error in mixing ratio. It is tempting to add the effect of such random errors when calculating the error budget of the trend line. However, this would be incorrect, as the scatter in the data about the trend line must already include these random errors. The only use we can make of this random error would be if we wished to ascertain the true variability in the stratospheric water vapour over UK during 1973–1974, by subtracting the square of this random error from the variance in the measurements. This is not the objective of this study.

5. The trend in water vapour from 1950s to 1970s and its error

SPARC (2000) and Rosenlof *et al.* (2001) made selections of points by pressure range in order to calculate trends. The selection was useful when assessing trends from a variety of instruments, to find if trends differed with altitude.

Unfortunately, as can be seen in the figures, such a selection leaves a much smaller density of points in the 1970s than the 1950s – there were only six

UK data points in the 1970s, as most flights then were to a lower altitude. But much humidity was minimum at altitudes below 140 hPa in the 1950s, yet were clearly stratospheric (such minima would now be regarded as normal at mid-latitudes, the so-called hygropause). The minima were used by Cluley and Oliver (1978) to derive a 'representative stratospheric humidity' for each flight. Hence it is more useful when discussing trends in the UK data to include all 39 points in the1970s accepted by Cluley and Oliver (1978), now shown in Figure 2. A least squares fit to all the data (1950–1970s) has slope 0.08 ± 0.02 ppmv/year, equal to 2.1 ± 0.54%/year (two-sigma errors). Each data set (1950s and 1970s) covered more than a year and included all seasons.

As argued in Section 4, the error in the fitted slope already includes any contribution from the random error in the measurements. Hence we need to only add the contribution from the additional error due to differences in temperature gradients (Section 3.3., ±0.6%/year) to the error in the fit above (±0.54%/year). Taking the root-sum-square of these errors, the trend then becomes 2.1 ± 0.8%/year (two-sigma), i.e. at least 1.3%/year. This is the trend in water vapour and its error, from the 1950s to 1970s, and in mixing ratio is equivalent to 0.08 ± 0.03 ppmv/year, i.e. at least 0.05 ppmv/year.

This value should be compared to that from reanalysis of frost point balloon data since 1980 (CMDL in our Figures) and its extension to 2010 (Hurst *et al.*, 2011). This showed net increases in water vapour over the entire period of 0.75%/year (1 ppmv), but made up of periods of differing trends, including a decrease from 2001 to 2005. Clearly, more work is needed to properly attribute the reasons for long-term trends in stratospheric water vapour.

References

Cluley AP, Oliver JM. 1978. Aircraft measurement of humidity in the low stratosphere over southern England 1972–1976. *Quarterly Journal of the Royal Meteorological Society* **104**: 511–526.

Fueglistaler S, Haynes PH. 2005. Control of interannual and longer-term variability of stratospheric water vapor. *Journal of Geophysical Research* **110**: D24108, DOI: 10.1029/2005JD006019.

Grant DR. 1963. Accuracy of dew and frost points measured by frost-point hygrometers. *Quarterly Journal of the Royal Meteorological Society* **89**: 546–549.

Hurst DF, Oltmans SJ, Vomel H, Rosenlof KH, Davis SM, Ray EA, Hall EG, Jordan AF. 2011. Stratospheric water vapor trends over Boulder, Colorado: analysis of the 30 year Boulder record. *Journal of Geophysical Research* **116**: D02306, DOI: 10.1029/2010JD015065.

Meteorological Office. 1961. *Handbook of Meteorological Instruments Part II, Instruments for Upper Air Observations, M.O. 577*. HMSO: London; 166–174.

Oliver JM, Cluley AP. 1978. A systematic error in the measurement of frost point using a Meterological Office Mk 3 hygrometer. *Quarterly Journal of the Royal Meteorological Society* **104**: 503–509.

Randel WJ, Wu F, Vömel H, Nedoluha GE, Forster P. 2006. Decreases in stratospheric water vapor after 2001: links to changes in the tropical tropopause and the Brewer-Dobson circulation. *Journal of Geophysical Research* **111**: D12312, DOI: 10.1029/2005JD006744.

Rosenlof KH, Oltmans SJ, Kley D, Russell JM III, Chiou E-W, Chu WP, Johnson DG, Kelly KK, Michelsen HA, Nedoluha GE, Remsberg EE, Toon GC, McCormick MP. 2001. Stratospheric water vapor increases over the past half-century. *Geophysical Research Letter* **28**: 1195–1198.

SPARC. 2000. Assessment of upper tropospheric and stratospheric water vapour. In *WMO/TD No 1043 (SPARC Report No 2)*, Kley D, Russell JM III, Phillips C (eds). SPARC: Verrieres le Buisson, France.