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WVSS-II on FAAM
Aircraft

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Performance of WVSS-II hygrometers on the FAAM Research Aircraft

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Abstract

We compare the performance of five hygrometers fitted to the Facility for Airborne Atmospheric Measurement's (FAAM) BAe 146-301 research aircraft using data from approximately one hundred flights executed over the course of two years under a wide range of conditions. Bulk comparison of cloud free data show good agreement between chilled mirror hygrometers and a WVSS-II fed from a modified Rosemount inlet but that a WVSS-II fed from the standard flush inlet appears to over read compared to the other instruments, except at higher humidities.

Statistical assessment of hygrometer performance in cloudy conditions is problematic due to the variable nature of clouds, so a number of case studies are used instead to investigate the performance of the hygrometers in sub optimal conditions. It is found that the flush inlet is not susceptible to either liquid or solid water but that the Rosemount inlet has a significant susceptibility to liquid water; it is not susceptible to ice. In all conditions the WVSS-II respond much more rapidly than the chilled mirror devices, with the flush inlet-fed WVSS-II being more rapid than that connected to the Rosemount.

1 Introduction

Water vapour is well established as the most important greenhouse gas and, hence, is crucially important in determining the radiation budget of the atmosphere. Its vertical distribution has a significant impact on local radiative heating and cooling, and on the net fluxes at the surface and at top of atmosphere. Its three dimensional distribution has a large impact on the dynamics and thermodynamics of the atmosphere as well as controlling the distribution of clouds. A thorough understanding of the distribution of water vapour is, therefore, critically important to our understanding and monitoring of climate change, to improve forecasts from operational numerical weather prediction (NWP) and to better interpret data from current and future satellite instruments.

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Meteorological observations from commercial aircraft have been an important part of the global observing system for some time, making a demonstrable positive impact on the output of both NWP models and human forecasters (Moninger et al., 2006; Petersen et al., 2010) as well as to the aviation industry (Baker et al., 2011). Aircraft routinely provide air temperature and derived wind speed and direction data via the World Meteorological Organisation's (WMO) Aircraft Meteorological Data Relay (AMDAR) programme (WMO, 2014a). AMDAR allows for the inclusion of humidity data, and such observations have been included for well over a decade, but only around one hundred aircraft currently report humidity operationally, mostly in the USA. A contributing factor in this may be that the only sensor to meet the requirements of AMDAR, currently, is the Water Vapour Sensing System version two (WVSS-II) (WMO, 2014a).

No peer reviewed literature exists assessing the performance of the WVSS-II and, although numerous unpublished items reporting intercomparison results may be found (e.g., Mamrosh et al., 2006; Baker et al., 2011; Bedka et al., 2006; Hoff, 2010), these are of limited use for the purposes of atmospheric research. In the main, the WVSS-II has been compared to radiosondes launched at, or close to, an airfield attended by commercial aircraft fitted with a WVSS-II, and the emphasis is on the boundary layer and lower free troposphere. This is a valuable exercise in assessing the utility of such routine AMDAR measurements as an adjunct to, or as a replacement for, radiosonde observations for NWP purposes, and positive impacts on forecasts have been reported (Moninger et al., 2006; WMO, 2014b) but these studies have two serious limitations: (1) a radiosonde and an aircraft cannot be guaranteed to sample the same air mass throughout their ascents, which increases the uncertainty, and (2) the WVSS-II measurements in question are compromised by the restrictions imposed by the manner in which they are encoded for transmission (Bedka et al., 2006). These shortcomings are avoided in this study as all humidity data were recorded simultaneously on the same aircraft and all WVSS-II data were recorded at higher resolution via the WVSS-II's diagnostic/research output.

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In 2010 Deutscher Wetterdienst (DWD) provided the Met Office with two WVSS-II units to be trialled on the FAAM aircraft as part of the EUMETNET AMDAR (E-AMDAR) programme. These have been operated semi-routinely alongside the existing two chilled mirror hygrometers.

Here we present data collected on an opportunistic basis during approximately one hundred flights of the FAAM aircraft which took place between 22 February 2011 and 23 September 2013. The flights were mainly conducted around the UK but data are included from various experiments at locations ranging from the western Sahara to the Svalbard Islands, as well as the southern United States and south eastern Canada, encountering a wide range of conditions. Data have been recorded at altitudes up to 11 km with absolute humidities ranging down from around 13 g m⁻³; the lowest value is not known for reasons that shall be discussed below.

The following section briefly describes the instruments compared in this paper with the treatment of offsets between them described in Sect. 3. Section 4 describes the relative performance of the four hygrometers in cloud free conditions while Sect. 5 presents a number of case studies illustrating the performance of the WVSS-II in cloudy conditions and in rapidly changing conditions.

2 Instruments and installation

2.1 Buck CR-2 (Buck)

The Buck measures atmospheric dewpoint using the chilled mirror technique. Air is extractively pumped through an aft facing inlet, located 1.8 m aft of the nose and outside the 99 % free-stream boundary layer, through a heated pipe into a sample chamber and over a mirror-like metal surface. The mirror temperature is regulated using a Stirling-cycle cooler until condensation begins to form on the mirror, this being the dew or frost point. The condensation layer is monitored optically, and the mirror temperature is measured using an embedded platinum resistance thermometer. The Buck

is calibrated annually at the National Physical Laboratory in Teddington, and the dew-point measurement is directly traceable to ITS-90 (FAAM, 2014a). Data from the 2013 calibration show the Buck to be accurate to better than ± 0.7 K, for frost points down to 203 K (approximately 0.002 g m^{-3} at an altitude of 10 km).

2.2 General Eastern 1011B (GE)

The GE is another thermoelectric chilled mirror dew point/frost point hygrometer, originally fitted to the Met Office C-130 and transferred to the FAAM aircraft in 2004. Its inlet is unheated, located 6 m aft of the nose and 4 cm from the skin, leaving it within the boundary layer. The accuracy of the FAAM instrument is given by the manufacturer as ± 0.2 K above 273 K, decreasing to ± 1 K between 233 and 198 K (General Eastern Instruments, 1987) with a resolution of 0.03 K. The actual performance of the instrument is strongly dependent on the ambient temperature, and data may be subject to an increasing positive bias below around 250 K (FAAM, 2014b).

2.3 Total Water Counter (TWC)

The TWC is a Lyman- α absorption instrument developed by the Met Office for use on its C-130 aircraft and transferred to the FAAM aircraft in 2004. The operating range, accuracy and resolution are quoted as 0 to 20 g kg^{-1} , $\pm 0.15 \text{ g kg}^{-1}$ and $\pm 0.005 \text{ g kg}^{-1}$, respectively (Nicholls et al., 1990) but, in practice, this can be improved upon as the accuracy is primarily determined by the manner in which it is calibrated, and the instrument which it is calibrated against (e.g., Abel et al., 2014; Brown and Francis, 1995). Note that although this instrument will measure the combined amount of water in all phases, it may be regarded as a hygrometer in cloud free air. As the TWC uses magnesium fluoride windows and a Lyman- α source, both of which degrade over time, the instrument must be calibrated on a flight-by-flight basis using one of the chilled mirror instruments (usually the GE) and, therefore, does not provide an independent measurement. For this reason, and because it is not operated on all flights, it has been

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seen to report absolute humidities down to 0.6 mg m^{-3} when connected to the AIDA cloud chamber (then containing 0.1 mg m^{-3}) but unpublished, preliminary data from intercomparison with the Physikalisch-Technische Bundesanstalt's (PTB) humidity standard (Thunder 3900) as part of AquaVIT₂ suggest a lower limit of around 15 mg m^{-3} (D. Smorgon, personal communication, 2013). It is suspected that the discrepancy is caused by desorption of water from the walls of the plumbing used to connect wvssF to the humidity standard as this had been open to atmospheric conditions whereas the plumbing between the instruments and the AIDA chamber had been maintained at a low pressure and low humidity for several days. Previous laboratory work has, however, suggested a lower detection limit of 3.6 mg m^{-3} (Hoff, 2009) but it should, perhaps, be noted that substantial differences in the performance of some WVSS-II units have been seen in the past (Petersen et al., 2010), and lower limits seen in laboratory studies are very unlikely to be matched in the field.

As previously noted, the WVSS-II has two data outputs: one uses the ARINC 429 protocol and is used on conventional AMDAR installations, the other (used on the FAAM aircraft) uses RS232. The RS232 output has significantly better resolution than the ARINC 429 (the limitations of which are discussed in Petersen et al., 2008 and Bedka et al., 2006), and also includes "housekeeping" data.

3 Offsets

The offset between pairs of hygrometers during the test period has been calculated in the following way, using only data indicated to be cloud free (liquid water content less than 0.01 g m^{-3}) according to the cloud droplet probe (CDP) (Lance, 2010). Where the humidities differ by more than a factor of two, the data are rejected as this generally indicates an instrument malfunction. Data are then selected from periods where the instruments appear to be stable. The criterion used to determine this was that the difference in the absolute rates of change of the two humidities was required to be below a certain threshold value. This criterion does not require the two instruments to be

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reporting the same values but it does require that they be tracking changes in the atmosphere in the same way, thereby filtering out periods where instrument lag dominates, or where either instrument is not stable. The situation may exist (although it is very rarely seen) where both chilled mirrors are unstable and their mirrors briefly oscillate in phase; to guard against the inclusion of data from such periods the differential rate of change was smoothed using a Gaussian filter with a thirty second full width at half maximum. The aforementioned limit was then set so as to reject 90 % of the available data. This value, to some extent arbitrary, is a compromise arrived at by inspection, between retaining sufficient data for meaningful comparison and maximising the rejection of poor data. From the remaining data, a median, percentage difference was calculated. This single figure takes no account of calibration drift which might have occurred during the period over which the data were collected. Although the possibility of drift occurring should be considered, the nature of the flying makes this difficult for a number of reasons. Firstly, simply by the nature of fieldwork, none of the measurements are precisely reproducible. Secondly, most flights occurred as part of specific experiments sometimes lasting several weeks at a time which targeted particular areas and conditions. It is therefore likely that any “drift” calculated would include some element due the differing climatologies, the significance of which cannot readily be quantified but is believed to be substantial. Where data exist, figures are shown for the new wvssF after the old (Table 1). It should be noted, however, that annual laboratory calibrations of the Buck indicate minimal drift.

Comparison to the PTB’s Thunder 3900 during AquaVIT₂ suggest that wvssF may under read by around 3 % which, although significant with respect to the comparisons presented here, is well within SpectraSensors’ specifications.

4 Cloud free comparisons

Data were selected in the same manner as for the offset assessment except that in all cases the differential rate of change used was that relating to the two chilled mirror

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devices (chosen as they are the slowest responding, and least stable, instruments); this ensures that in all cases the data under consideration come from measurements of the same air. As we are interested, here, in comparing the relative performance of the hygrometers rather than the quality of their absolute calibration, in each case, the single-figure offset (Table 1) has been used to adjust the data; this also permits the inclusion of data from the new wvssF alongside the old. Figures 2–4 show comparisons of the four hygrometers plotted as [instrument 1]-minus-[instrument 2] as a percentage of [instrument 2], vs. [instrument 2]. This percentage measure was chosen to facilitate the graphical representation of differences otherwise spanning several decades. In each, boxes are overlaid indicating the median and upper and lower quartiles, with whiskers denoting the 2nd and 98th percentiles, of the difference between the instruments (calculated in bins, plotted at bin medians).

It is immediately clear that the criteria used to select data, although strict, do still permit the inclusion of some “bad” data; in the interests of preserving objectivity, however, no attempt to remove these has been made. It is also clear that comparison below 0.02 g m^{-3} is hampered by a lack of good data and that all four hygrometers agree in more humid conditions.

The Buck and wvssR show excellent agreement (within the interquartile range (IQR)) throughout the range of observed humidities, with the median being within $\pm 3\%$ for most of this range (Fig. 2). Unpublished, preliminary data from AquaVIT₂ suggest that the wvssR may under read by about 3% for humidities greater than 0.01 g m^{-3} and over read substantially below this value; there may be some support of this in the data presented here. Although Buck CR2 should be able to measure substantially lower humidities than the WVSS-II, in the past the FAAM Buck has struggled to produce mirror temperatures below -70°C (behaviour also noted at AquaVIT₂), which may contribute to the agreement seen here in drier conditions, possibly masking some over reading of the wvssR.

Although the GE and Buck agree to within the IQR throughout most of their range (Fig. 3), the GE exhibits an increasing tendency to over read below 0.1 g m^{-3} , which

approximates to a mirror temperature of around 230 K; this is typical of the frost points encountered when the ambient temperature is around 250 K, supporting FAAM's suspicions of a possible positive bias below 250 K.

The performance of the wvssF is more problematic (Fig. 4). Although above 1 g m^{-3} wvssF and wvssR agree very well, with an IQR of 1% at 2 g m^{-3} , it is clear that the wvssF reads progressively higher than wvssR as the humidity reduces, with the difference lying outside the IQR for humidities below 0.5 g m^{-3} . Since the instruments are fundamentally the same, and measuring the same air mass, the small spread of data might be expected. The substantive difference between the two is in the inlet design; over reading of the WVSS-II fed from the standard flush inlet has been noted by other groups operating a WVSS-II alongside other hygrometers (A. Hoff, S. Carlberg, personal communications, 2011). It should, however, be borne in mind that because the flush inlet samples air approximately 5 mm from the skin of the aircraft, the performance of this inlet may vary significantly from depending on the type of aircraft and location on that aircraft (A. Hoff, personal communication, 2011; B. Ford, personal communication, 2012); this has not been investigated, here.

5 Case studies

In the following case studies, the offsets calculated for the bulk comparison (Sect. 4) and described in Sect. 3, have not been applied.

5.1 Rapid changes

Figure 5 shows a time series from flight B668 on 23 January 2012, between Iceland and the Faroes. At this time the aircraft was profiling in and out of a moist, stratocumulus topped boundary layer, with much drier air above. The top panel shows the aircraft altitude, with the grey shading indicating where the aircraft was in cloud (here defined as where the CDP indicated a liquid water content greater than 0.01 g m^{-3}). The

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from the foregoing, but differing behaviours can be seen in the presence of liquid water. In the cloud penetration at 1100 s the *wvssR* appears to be reporting total water rather than vapour, agreeing well with the total water estimate. In the previous two penetrations and the initial one, however, although there is clearly some susceptibility to liquid water, *wvssR* only matches the TWC values at the smaller end of the size spectrum. It should be noted, however, that the mean volume radius at which the departure from the total water values occur varies. In all penetrations but the second one, there appear to be a gradual transition between approximately 5 and 10 μm but in the second cloud penetration there is a relatively rapid transition from about 7.5 to 10 μm , where the *wvssR* might be expected to report total water content. When the mean volume radius is larger than this, the *wvssR* reports between the total water and vapour only values, as seen elsewhere, but when the mean volume radius drops below 5 μm there appears to be an enhancement, with the *wvssR* reporting higher values than the estimated total water content. Although this would suggest that the susceptibility of this inlet to liquid increases as droplet size reduces, Vance et al. (2011) shows an example of susceptibility to liquid droplets of around 20 μm radius. It is therefore not possible to draw conclusions about the importance of droplet size, from these data but, but it is clear that the *wvssR* is likely to ingest and evaporate liquid cloud droplets whereas the *wvssF* is not. This is, perhaps, not surprising as it has been noted that Rosemount housings used for temperature measurements are also susceptible to errors due to wetting in liquid cloud (e.g., Lawson, 1990; Lenschow, 1974).

5.3 Ice clouds

Figure 7 shows a time series from flight B672 on 30 January 2012, over the Northwest Approaches and North Channel. The aircraft performed a Lagrangian descent in a “race-track” pattern throughout the depth of cirrus cloud over a period of hours; the portion of the descent presented here is also discussed by Abel et al. (2014). The upper panel shows absolute humidity from the five instruments: *wvssF* (black), *wvssR* (red), Buck (green), GE (blue) and TWC (purple) which has been calibrated against

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Unpublished, preliminary data from AquaVIT₂ suggest that although the WVSS-II may be able to measure humidities as low as 0.6 mg m⁻³ it is likely to over read substantially below 15 mg m⁻³; there may be evidence to support this from the airborne data presented but uncertainties in the other instruments leave this inconclusive. Although the Buck and GE show good agreement in more humid conditions, the GE appears to over read in drier conditions, supporting FAAM's suspicion of a positive bias when mirror temperatures are below 250 K (FAAM, 2014b).

In order to facilitate comparison of the relative performance of the hygrometers, calibration offsets between the instruments have been estimated and removed, absolute accuracies being better assessed in the laboratory than in the field. Whilst the possibility of calibration drift during the test period is acknowledged, the nature of the flying makes quantification of this problematic and so zero drift has been assumed. The results presented here, therefore, refer to relative performance only, rather than absolute.

The wvssF shows very rapid response to large changes in humidity, only slightly slower than the TWC. Although the wvssR is noticeably slower to respond than the wvssF, it is substantially faster than the two chilled mirrors and neither WVSS-II suffer from the long stabilisation periods often required by the chilled mirror instruments.

Although the wvssF appears to be immune to liquid cloud, the wvssR is not and may, under certain conditions, report a value closer to the total water content than the vapour content. It has not been possible, from these data, to define these specific conditions.

Neither WVSS-II appears to be susceptible to the presence of varying sizes and concentrations of ice particles.

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Table 1. Percentage average offsets between pairs of hygrometers. Where comparison with the new wvssF exists, the value for this is given in parentheses.

| | | $\frac{\text{test} - \text{ref.}}{\text{ref.}} \times 100$ | test hygrometer | | | |
|---------------------|-------|--|-----------------|-------|--------------|----|
| | | | wvssF | wvssR | Buck | GE |
| reference hygro. | wvssF | | -1.9 (0.33) | -4.8 | -5.2 (-0.43) | |
| | wvssR | 1.9 (-0.35) | | -0.52 | -2.2 | |
| | Buck | 4.0 | 0.16 | | -2.1 | |
| | GE | 5.2 (0.31) | 2.0 | 1.3 | | |



Figure 1. External view of WVSS-II fitted to FAAM aircraft showing the two inlets (Rosemount, left, flush right) angled down to match the local air flow in flight.

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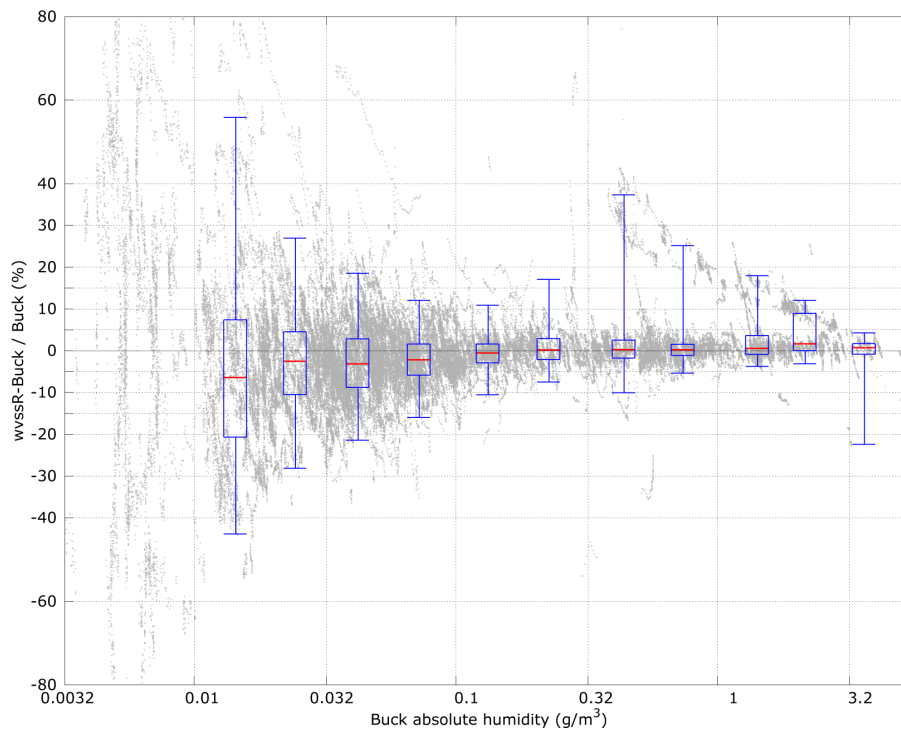


Figure 2. wvssR minus Buck in cloud free conditions. Boxes indicate binned quartiles with the whiskers at 2nd and 98th percentiles.

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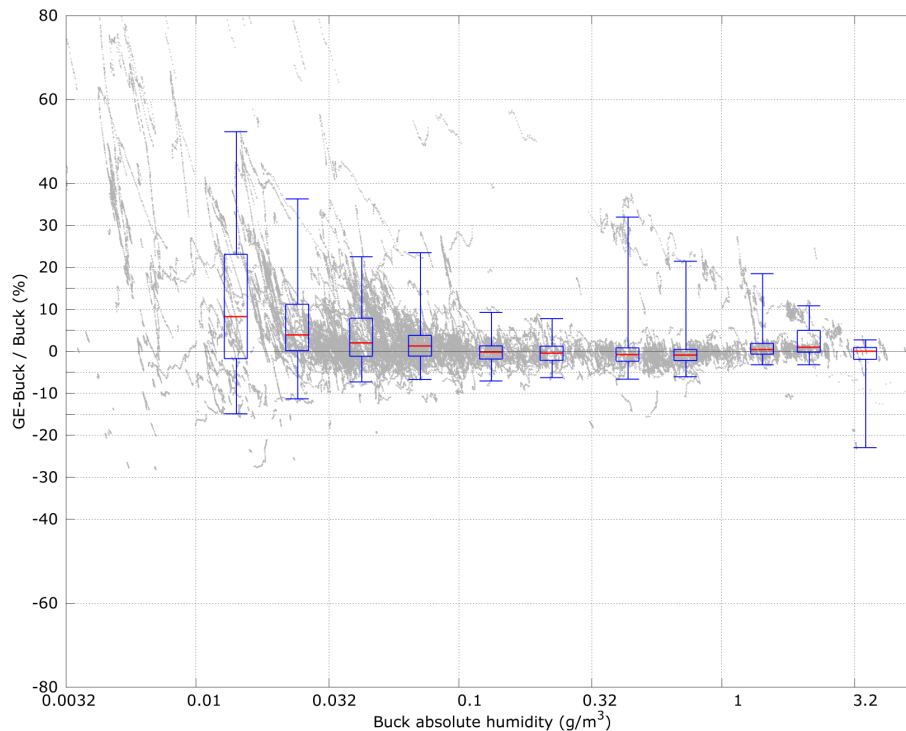


Figure 3. GE minus Buck in cloud free conditions. Boxes indicate binned quartiles with the whiskers at 2nd and 98th percentiles.

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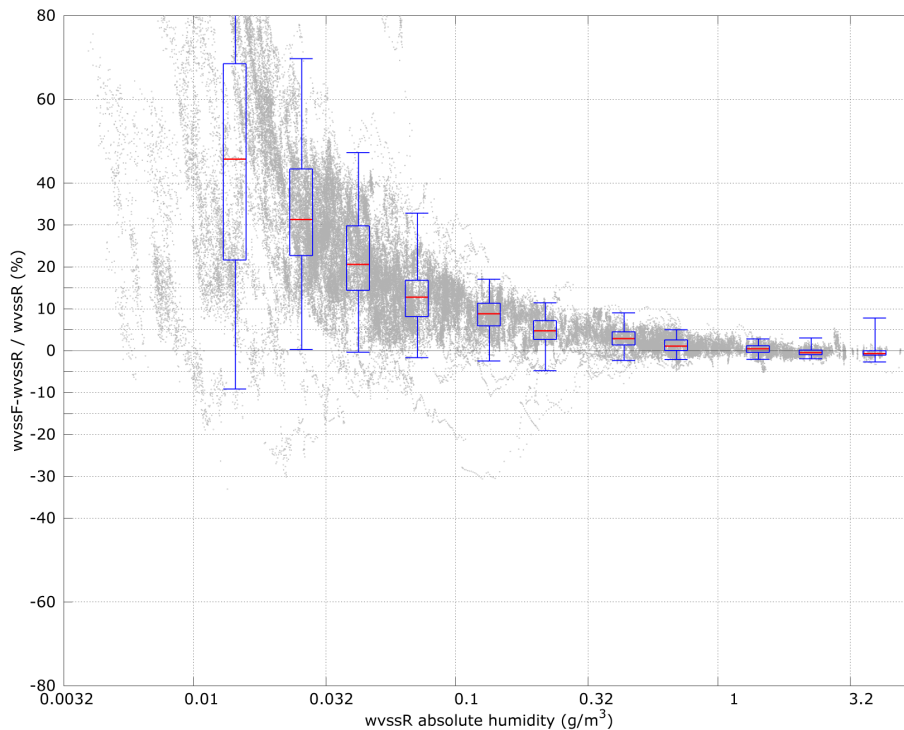


Figure 4. wvssF minus wvssR in cloud free conditions. Boxes indicate binned quartiles with the whiskers at 2nd and 98th percentiles.

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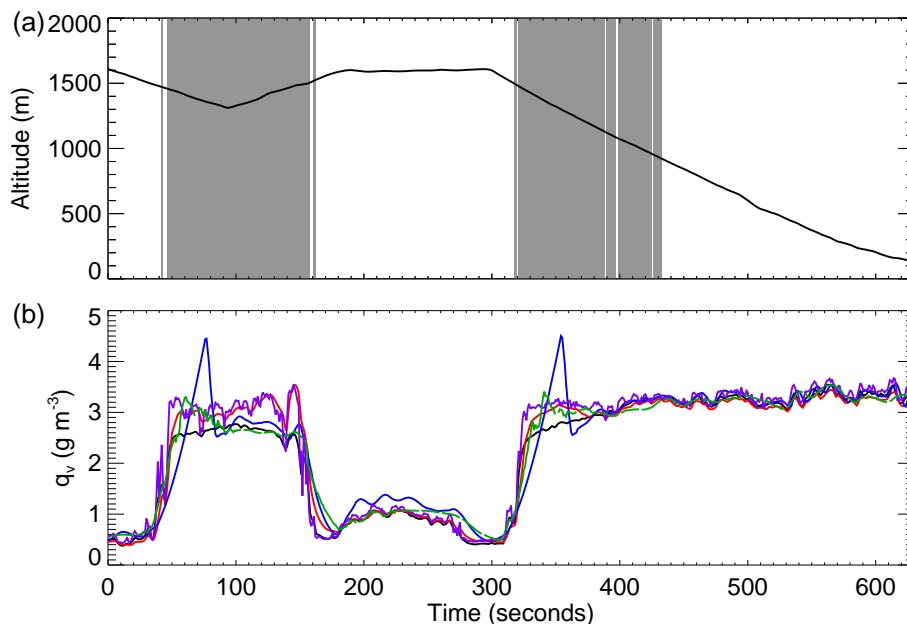


Figure 5. Time series from flight B668 when the aircraft was profiling in and out of a moist boundary layer with much drier air above. The top panel shows the aircraft altitude with periods in cloud shaded in grey. The lower panel shows absolute humidity from the Buck being (green), GE (blue), TWC (purple), wvssF (black) and wvssR (red).

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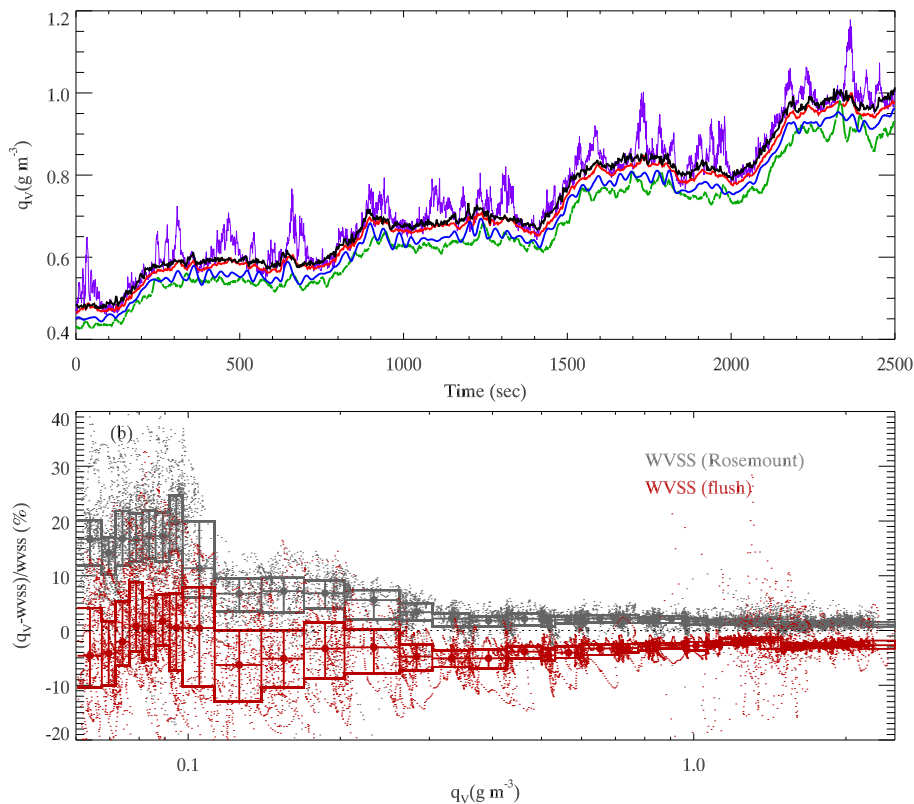


Figure 7. Time series from flight B672 showing part of a Lagrangian, “race-track” pattern descent through cirrus cloud with embedded fall streaks. Upper panel shows absolute humidity from wvssF (black), wvssR (red), Buck (green), GE (blue) and TWC (purple). Lower panel shows a comparison of wvssR (red) and wvssF (grey) to the Buck during this period in terms of absolute humidity with boxes indicating upper and lower quartiles.