Supplementary material for:

Arctic stratospheric dehydration – Part 1: Unprecedented observation of vertical redistribution of water

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1. Selected results of balloon soundings.

The present study is based on extensive experimental material comprising various data sets. In order to avoid overloading the main part of the manuscript with numerous figures, we provide here additional information in the form of sequences of plots.

Figure S1 displays the results of selected balloon soundings carried out at FMI-ARC, Sodankylä during the first phase of the LAPBIAT-II field campaign. The plots of 17, 25 and 29 January are constructed using descent profiles with water vapour measured by FLASH-B. The remaining plots are constructed using ascent profiles with water vapour measured by CFH (see Appendix B for justification of this approach). The climatological mean water vapour profile shown in the plots is a January-mean profile from all soundings with frost point hygrometers (NOAA FPH and CFH) conducted in Sodankylä from 2002 to 2010, excluding the single historical sounding of 23 January 1996, which showed a strong dehydration signature, reported by Vömel et al. (1997). There is a remarkable match between the measured water vapour profiles and climatological profile in the unperturbed stratosphere below the dehydration and rehydration signatures. Local deviations from the mean profile are also observed below 14 km, where the water vapour vertical distribution may be affected by cross-tropopause exchange.

The vertical profiles of temperature and backscatter ratio in the plots for 17, 25, 28 and 29 January (where FLASH-B profiles are used) were measured during balloon descent. The remaining plots (where CFH profiles are used) contain the ascent profiles. The highest *BSR* value of 200 corresponding to ice PSC observation was detected on 17 January. The last indication of PSC was obtained on 25 January with *BSR* values below 10. The minimum temperature observed in each sounding was varying between 183 K (23 January) and 202 K (06 February). The minimum saturation mixing ratio of 4 ppmv was observed on 17 January.

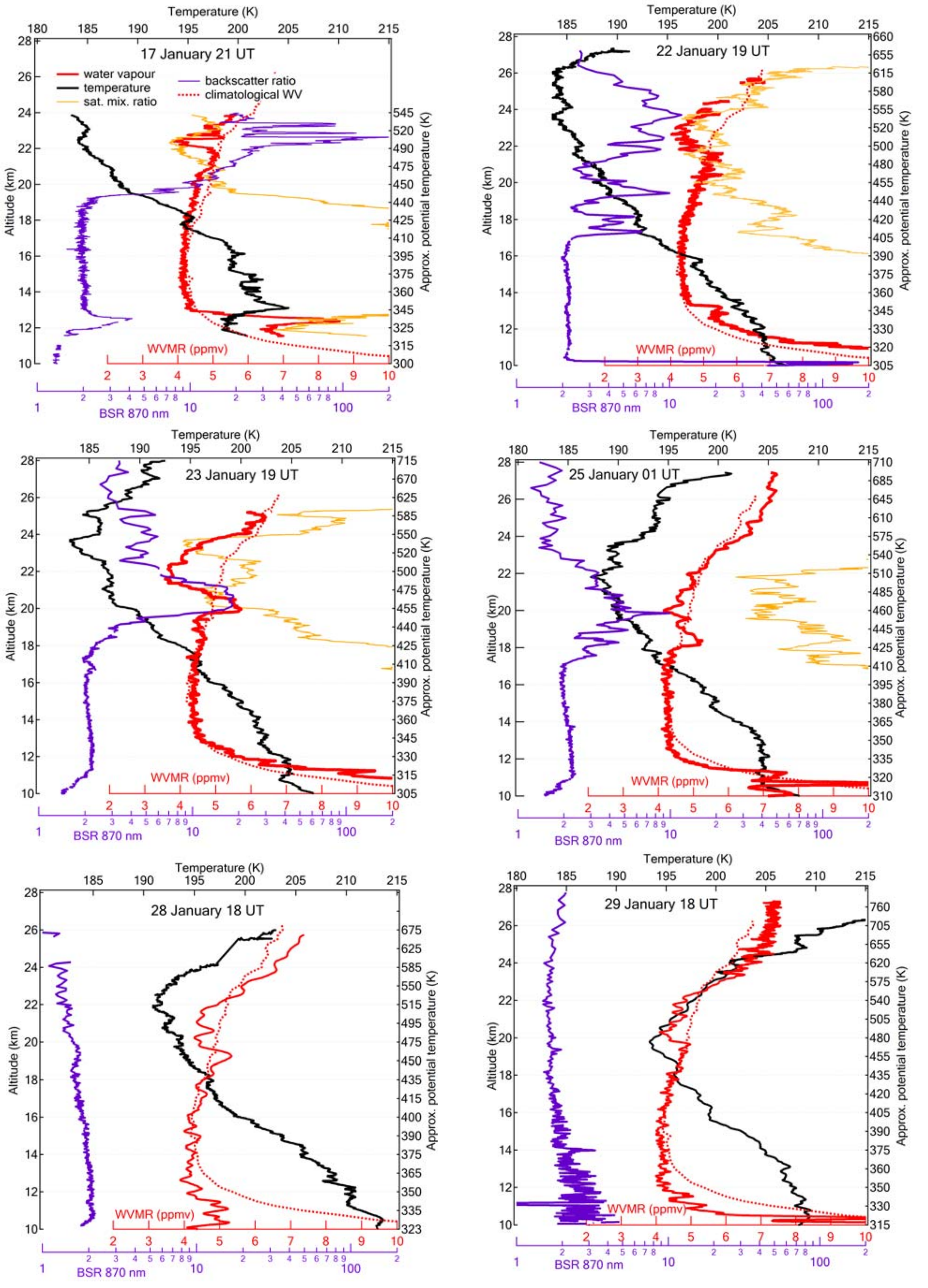

Fig. S1. *Results of selected balloon soundings carried out from Sodankylä during January 2010: water mixing ratio, climatological mean water and saturation mixing ratio (lower axis); backscatter ratio at 870 nm (lowermost axis); temperature (upper axis). The legend is given in the upper left panel. Date and UT time of the measurement are given in each panel. The time stamp refers to the time of stratospheric measurements.*

2. Intercomparison between water vapour instruments.

Since the main message of this study is delivered by the observations of water vapour by different hygrometers, it is of relevance to report the degree of agreement between these data sets. First, we compare the data from the instruments flown on the same platform (i.e. CFH - FLASH-B for balloon and FISH – FLASH-A for aircraft), then provide the results of intercomparison between all data sets.

Intercomparison of balloon hygrometers.

Among the 13 soundings with CFH conducted during the first phase of the LAPBIAT-II campaign, four of them included FLASH-B flown on the same balloon. The description of CFH and FLASH-B instruments is given in Sect. 2.1.1 and 2.1.2, respectively. As discussed therein, the performance of CFH is better during balloon ascent, although above 26-27 km the measurements may be affected by the water outgassing. Occasionally the descent measurements of CFH, whose quality strongly depends on the payload vertical velocity, can be of equal quality. In contrast, FLASH-B performs better during descent, whereas the ascent measurements above about 90 hPa are strongly affected by water outgassing due to the instrument's measurement layout. The statistical intercomparison is thus done using four pairs of CFH ascent and FLASH-B descent profiles in the 13 – 25 km altitude range. The validity of such approach is justified by the negligible temporal variability of water vapour at the stratospheric levels above 14 km. Although vertical distribution of water vapour during the sounding campaign was characterized by a noticeable variability between 18 and 24 km on a scale of tens of hours, the lag between ascent and descent sampling at 20 km altitude was always less than 30 minutes. Note also that since the balloon is following the wind motion, the ascent and descent legs would sample nearly the same air mass given a moderate wind shear in the mid stratosphere.

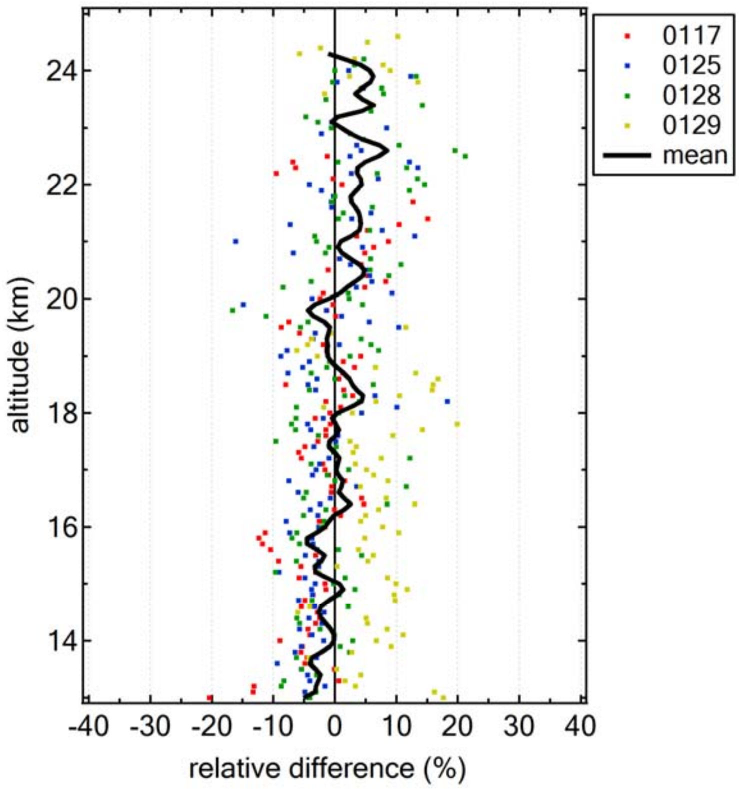

Fig. S2. *Mixing ratio relative difference between CFH ascent profiles and FLASH-B descent profiles: 100 %·$(\mu_{FLB} - \mu_{CFH})/\mu_{CFH}$.*

Figure S2 displays the results of intercomparison given as relative mixing ratio difference: $100\ \%\cdot(\mu_{FLB} - \mu_{CFH})/\mu_{CFH}$, where μ denotes water vapour mixing ratio. The mean relative difference (solid line) based on four pairs of profiles does not indicate any systematic bias or altitude dependence and remains within 10 % limits throughout the range of intercomparison and within 5 % for the major part of the range. The vertically-averaged mean difference is as small as 0.78 %, whereas the standard deviation of the difference (1-σ level) amounts to 4 %.

While the vertically-averaged difference between CFH and FLASH-B data indicates very high degree of statistical agreement, the next step is to examine the relative capabilities of the hygrometers in reproducing vertical structures in stratospheric water vapour, which are of particular importance for this study.

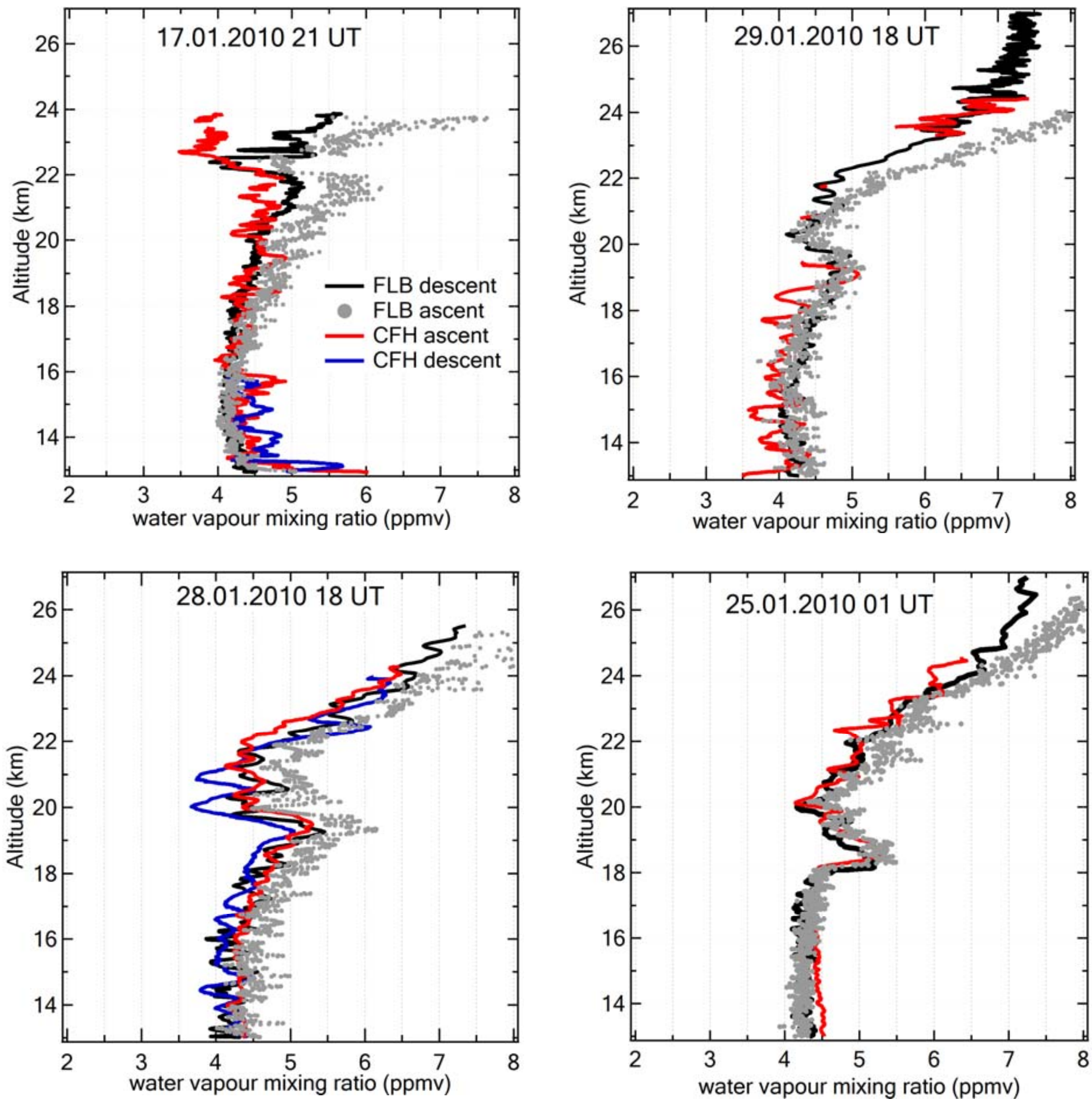

Fig. S3. *Comparison of ascent and descent profiles of water vapour mixing ratio measured by CFH and FLASH-B. The ascent CFH profiles of 25.01 and 28.01 soundings are averaged over 40 s to reduce the controller oscillations. The descent CFH profiles of 25 and 29 January, which were screened out during the initial quality check are not shown. The legend is given in the upper-left panel. The date and time of the sounding is given in each panel. The time stamps refer to stratospheric descent measurements time.*

Figure S3 displays both ascent and descent water vapour profiles of the four simultaneous CFH – FLASH-B soundings. As expected, the ascent profiles of FLASH-B are wet-biased due to the water outgassing effect and the amplitude of the bias increases with altitude. The onset of the contamination effect, defined as departure of the ascent profile from the non-contaminated descent profile, is observed at altitudes between 17 km (17 Jan) and 21 km (29 Jan) depending on the amount of moisture crossed by the payload during the tropospheric ascent leg. Note that the lower non-contaminated portion of the ascent profile is in a precise match with the descent profile, indicating a stable performance of FLASH-B.

The vertical structures in water vapour, associated with de- and rehydration and the amplitudes of the perturbations are reproduced nearly identically by FLASH-B and CFH in all soundings except the case of 17 January, which requires a special consideration. Since the sounding on 17 January sampled an active phase of ice formation and concurrent vapour uptake, rapidly alternating its vertical distribution, the ascent and descent measurements may not be directly compared. However, the reduction of water vapour above 22 km is clearly visible in CFH ascent and both FLASH-B wet-biased ascent and clean descent profiles. Due to somewhat unstable performance of the CFH feedback controller producing oscillations in the data, the uppermost part of the ascent profile and the major part of the stratospheric descent profile had to be screened out.

Overall, the measurements of water vapour by the two balloon-borne hygrometers are in excellent agreement suggesting high quality of the data and allowing FLASH-B and CFH vertical profiles to be used as coherent and interchangeable data series.

Intercomparison of aircraft hygrometers.

The intercomparison of the aircraft-borne hygrometers FISH and FLASH-A was based on the simultaneous measurements from eleven aircraft flights carried out during both phases of the RECONCILE campaign. As described in Sect. 2.2 of the article, the fundamental difference between these hygrometers, both making use of the fluorescence method, is that FISH is equipped with a forward facing inlet and therefore measures total water, while FLASH-A uses a rear-facing inlet and is thus sensitive to gas-phase water only. This difference limits the stratospheric intercomparison to the ice-free measurements, which is the case for all aircraft flights performed during RECONCILE (von Hobe et al., 2013).

Analogous to Fig. S2, Fig. S4 shows the results of intercomparison based on all data above 200 hPa and given as relative mixing ratio difference: $100\ \%\cdot(\mu_{FLA} - \mu_{FISH})/\mu_{FLA}$. While the deviation in the individual flights can exceed 15 %, the mean relative difference based on 11 flights remains below 6 % with FLASH-A showing slightly higher values compared to FISH virtually at all levels but without any altitude dependence. The vertically-averaged difference amounts to 2.7 %, which is higher than that for balloon hygrometers but is based on a far larger amount of data and is therefore of higher significance. The standard deviation of the difference (1σ level) is estimated to 3 %. Good agreement between FISH and FLASH-A in reproducing small-scale horizontal structures is demonstrated in Fig. 5 of the article. Note that since both FISH and FLASH-A were calibrated during the campaign using the same calibration facility, the small statistical discrepancies identified in this intercomparison originate from random measurements errors only.

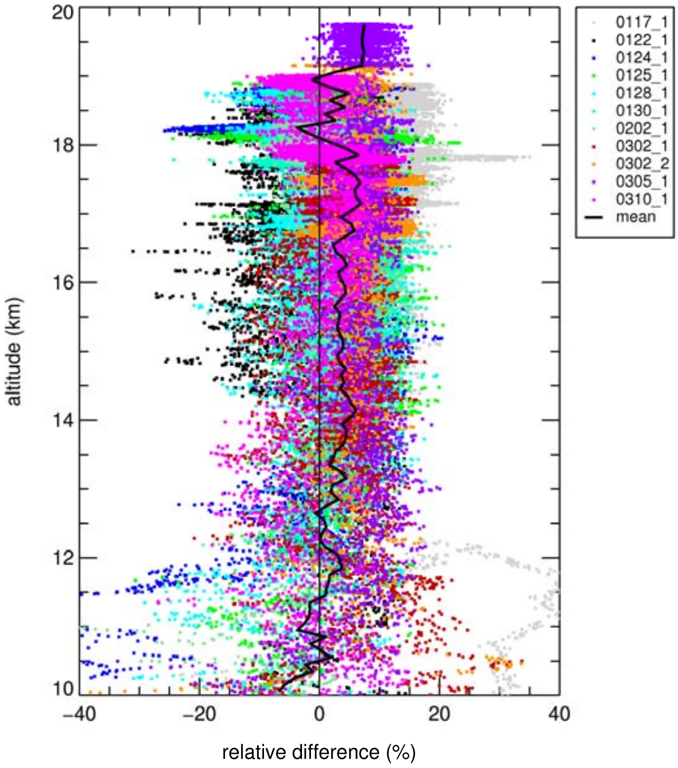

Fig. S4. *Comparison between FLASH-A and FISH based on the measurements of 11 flights, carried out during the RECONCILE campaign: relative mixing ratio difference (100%·(μ_{FLA} – μ_{FISH})/μ_{FLA}) in each flight (markers are colour coded by the flight date as shown in the legend), and mean difference (black line).*

General intercomparison

In order to estimate the agreement between the observations by aircraft and balloon hygrometers we provide in Tab. S1 mean mixing ratios measured by each of the 4 hygrometers during January at 14 - 16 km altitude range – the layer of smallest water variability inside the vortex, as shown by the balloon soundings. Also listed in the table is the standard deviation of the respective data, providing information on the precision of the measurements. The highest value of water vapour is that of CFH and the lowest is that of FISH. The maximum deviation between the data sets amounts to 11 %, which is comparable to the uncertainty limits of all hygrometers. The precision of the measurements varies between 0.09 and 0.21 ppmv.

Table S1. Mean water vapour mixing ratio measured by in-situ balloon-borne and aircraft-borne hygrometers during January at 14 - 16 km altitude range.

Hygrometer	Mean H_2O @ 14-16 km, ppmv	Standard deviation (1σ), ppmv
CFH	4.40	0.12
FLASH-B	4.20	0.09
FLASH-A	4.14	0.21
FISH	3.93	0.09