Reference Humidity Retrievals with ‘Dry Ice’ CFH during the Swiss H_2O Hub Summer 2023 campaign

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Swiss H_2O Hub Consortium

1. Uni Bern: **MIAWARA**
   microwave radiometer, *remote sensing*
2. MeteoSwiss: **RALMO**
   Raman lidar, *remote sensing*
3. Empa: **ALBATROSS**
   mid-IR laser spectroscopy, *in-situ*
4. ETH Zürich: **PCFH**
   Peltier-cooled frost point hygrometer, *in-situ*
5. References: <u>**CFH**</u>**, RS41, MLS**

UNIVERSITÄT BERN

MeteoSwiss

Empa Materials Science and Technology

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Swiss H_2O Hub

WMO GAW

GCOS GLOBAL CLIMATE OBSERVING SYSTEM

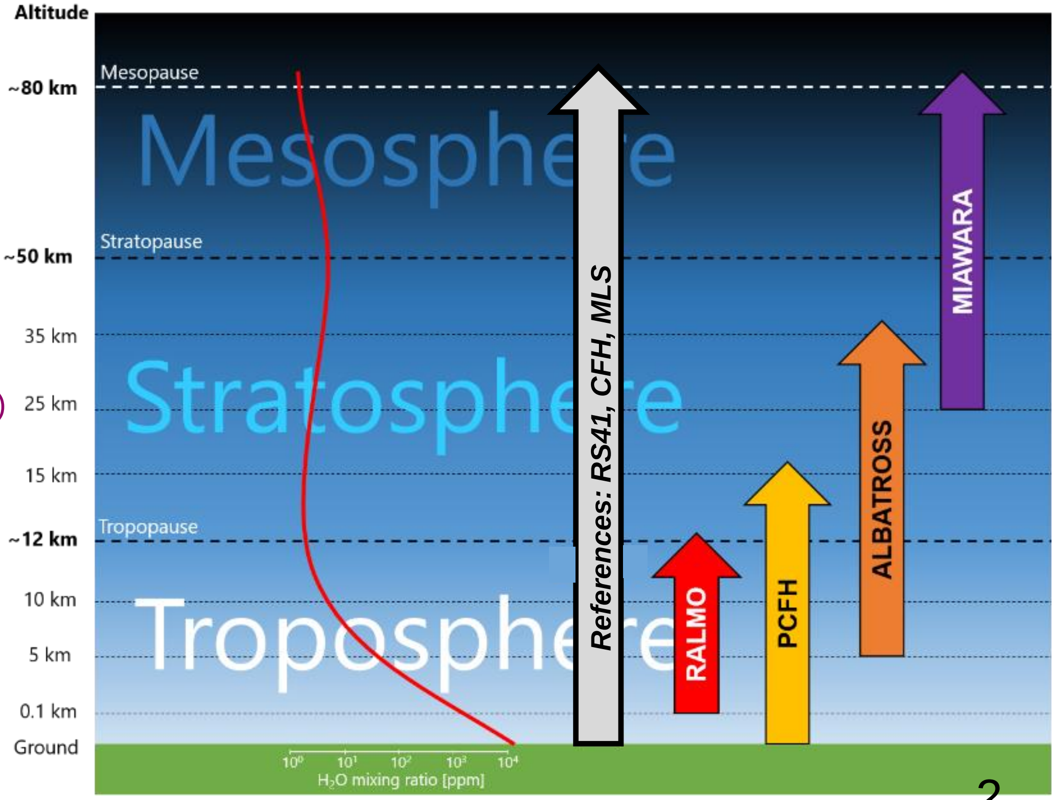
also funded by the Federal Office for the Environment

Target Objectives

- combine in-situ and remote sensing of H_2O from 0 km to 80 km
- from development/testing towards monitoring
- towards SI traceability, low drift, high accuracy

Volcanic H_2O injections: O_3 depletion (Evan et al., 2023)

UT/LS H_2O: strong radiative forcing & feedback (Solomon et al., 2010; Dessler et al., 2013)



H_2O Hub Auxiliary Reference Measurements: RS41

Quality check for CFH, 0 km to ~ tropopause

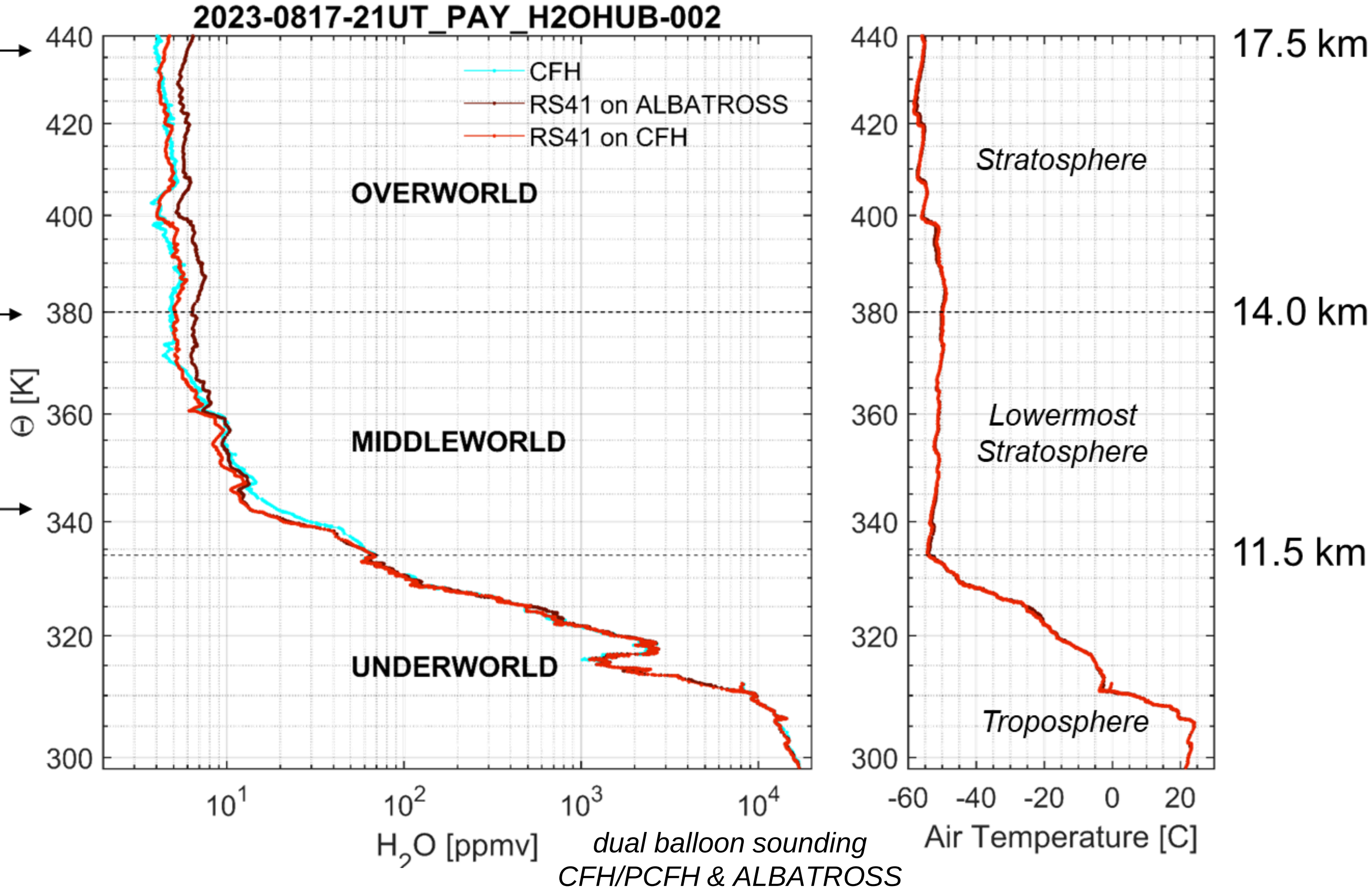
RS41 radiosonde

- Operational radiosonde
- High-performance thin-film humidity sensor
- **Plug-and-play, weather robust**…

RS41
Sensitivity loss

RS41
Sonde-to-Sonde
Variability

RS41
Systematic Errors
- time-lag overcorrection
- biases at low-RH

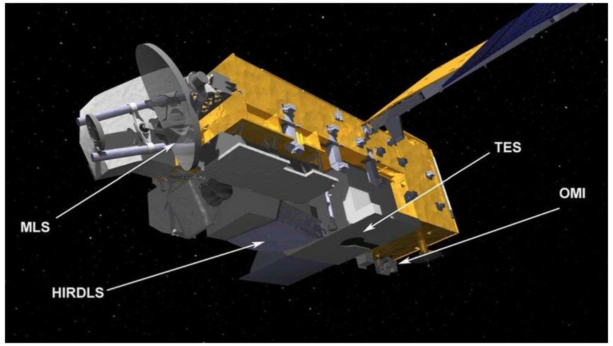


- Not SI-traceable
- Systematic errors (time-lag and sensor model errors, e.g. Poltera Diss.ETH 28342, 2022)
- Sonde-to-sonde variability deteriorates accuracy in lowermost stratosphere (e.g. Brunamonti et al., 2019)
- Not suited for dry stratosphere, **sensitivity loss at < 1.5 - 2 %RH** (e.g. Vömel et al., 2022)

H_2O Hub Auxiliary Reference Measurements: MLS

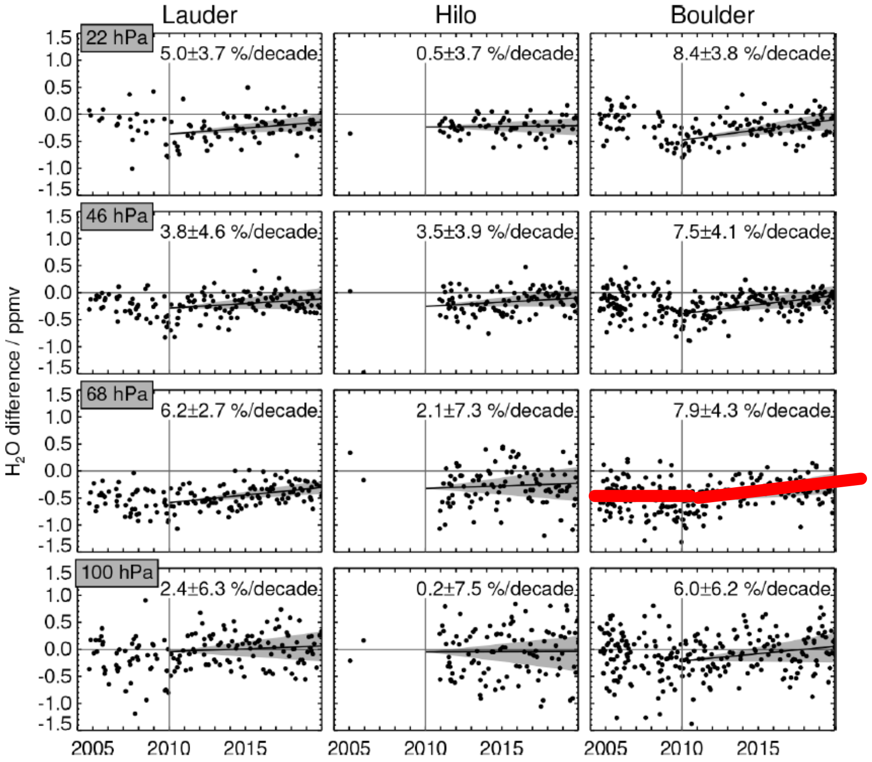
Quality check for CFH, ~ tropopause to ~ 28 km (and beyond)

Microwave Limb Sounder (MLS)



Schoeberl *et al.*, 2006

- Microwave radiometer onboard NASA's AURA satellite
- Launched in 2004
- **Global** coverage, **12-h** revisit time, from UT/LS up to mesopause



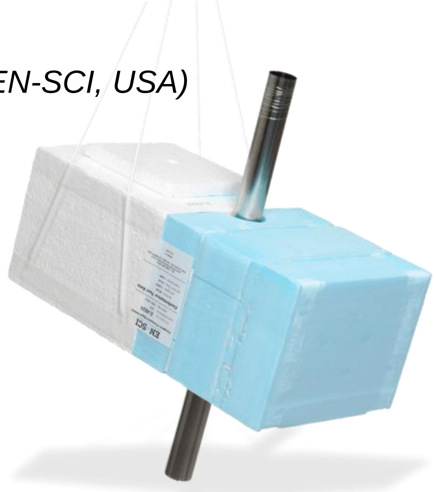
MLS v5 vs. FPH, Livesey et al., 2021

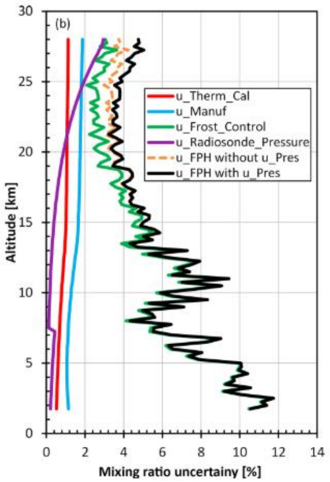
- Limited vertical resolution: ~ 1 km in the UTLS
- Collocation Uncertainty: ~ 1°
- Subject to drifts (Hurst et al., 2016; Livesey et al. 2021). MLS v5.0: **drift still remaining** (5-8 % / decade), starting around 2010 (compared to FPH).

H_2O Hub Field Reference: Cryogenic Frostpoint Hygrometer

0 km to ~ 28 km

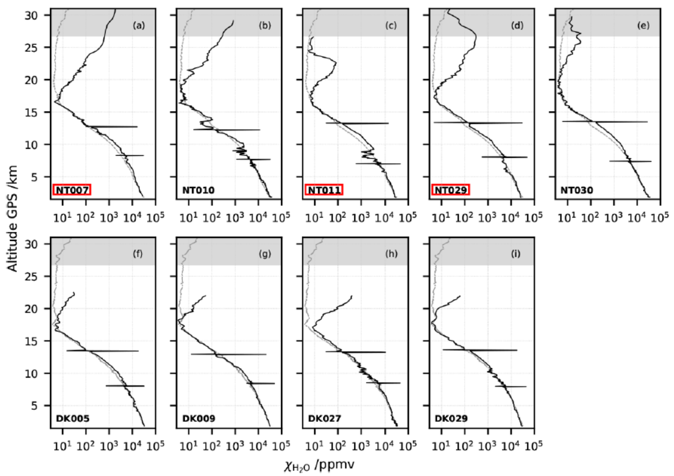
CFH (EN-SCI, USA)



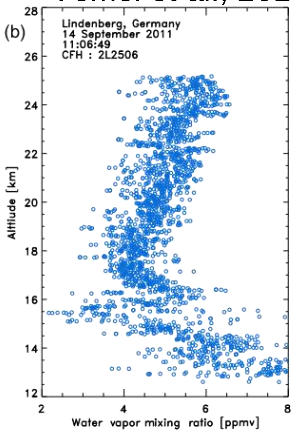


Hall et al., 2016 (NOAA FPH)

Jorge et al., 2021



Vömel et al., 2016



- Balloon-borne, **SI-traceable, high DR, low drift** chilled mirror
- **State-of-the art** detector for H_2O measurements in the UT/LS (Fahey et al., 2014)
- **Uncertainty**
  < 10 % up to 28 km (Vömel et al., 2007)
  < 4 % under stable frost control (Hall et al., 2016) or at Golden Points (Poltera et al., 2021)

- **Quality checks** needed after each flight
  contamination (Jorge et al., 2021)
  controller instabilities (Vömel et al., 2016)
- **Demanding logistics / not plug-and-play**
  cold liquids, dry ice, glue, …
- Uses HFC-23 (~ 7 t CO_2 per sounding)
  alternative coolant needed (UNEP, 2016)

R23 bottle in dry ice at ETHZ

Replacement of R23 with dry ice + alcohol (**DIA**) or **LN2 in a pressurized vessel** have given promising results (e.g. Rolf et al., ICM-12 2020; ICM-14 2022). In *Swiss H_2O-Hub*, DIA was tested on 4 out of 7 balloon flights. **Goal:** fly 'as many CFHs as we need' (specially for test / engineering flights of PCFH and/or ALBATROSS) without emptying our limited R23 reserve.

CFH DIA prototype (Rolf et al., ICM-12, 2020).

CFH LN2 prototype (Rolf et al., ICM-12, 2022).

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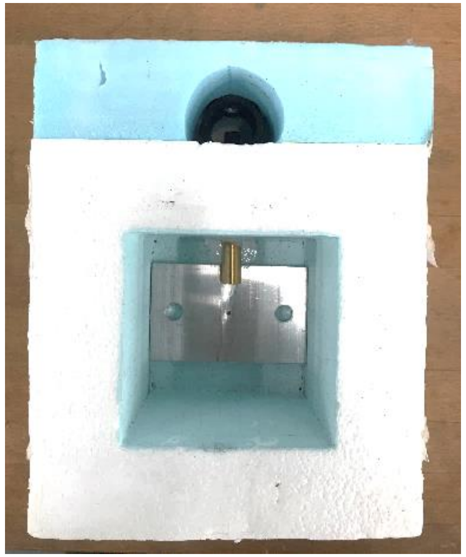
Dry Ice + Alcohol (DIA) CFH @ ETHZ

<u>Note</u>: DIA is not new (e.g. Thornwaite & Owen, 1940). Has been successfully tested on CFH/FPH before (e.g. GRUAN LC/NOAA/FZ Jülich, ICM-12, 2020).

- Fit tightly an aluminum plate below the cold finger (file if necessary)



EN-SCI CFH, FW: 6.44 with added Al plate

- Fill CFH Dewar with ~ 100 ml of pre-cooled ethanol (94% Brennsprit), until cold finger is well covered

Optional:
** T-logger (here RS41)*

- Add handful of dry ice (16 mm pellets used to pre-cool the ethanol) into the Dewar

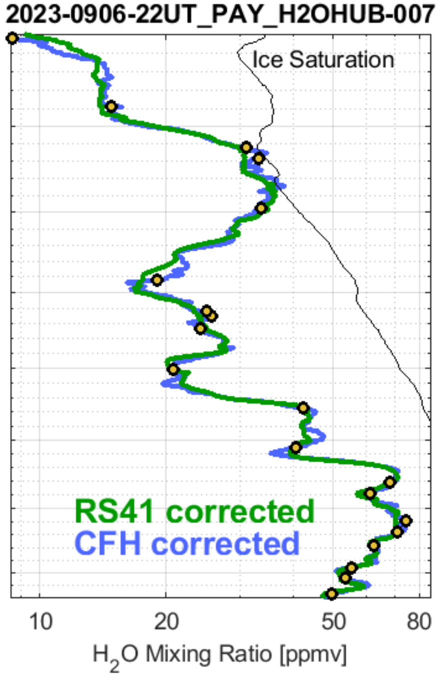
Optional:
** 'spill proof' lid mechanism*

- Fly
- & Recover

MeteoSwiss colleagues in action

mylab colleagues in action

- Perform Golden Points analysis



Poltera, 2022
Diss. ETH No. 28342
In prep. for AMT 2024

Table Overview of CFH Measurements in Switzerland

conducted by ETHZ in last 10 years

Date	S/N	Coolant	Radiosonde	Additional telemetry	Other instruments	Note
2015-1201-18UT	2L3605	**R23**	Imet-1 RSB		COBALD	
2016-0202-15UT	2L4513	**R23**	RS41-SGP		O3	
2016-0607-19UT	2L4811	**R23**	RS41-SGP		O3	
2023-0629-07UT	2L6129	**R23**	Imet4-RSB	PCFH-LOG	PCFH, HABBounder	PCFH-LOG w/o CFH
2023-0720-08UT	2L6129	**R23**	Imet4-RSB	PCFH-LOG	PCFH, HABBounder	PCFH-LOG w/o CFH
2023-0815-20UT	2L6129	**R23**	RS41-SG	Imet4-RSB	PCFH, HABBounder	PCFH-LOG failed
2023-0817-21UT	2L7314	**R23**	RS41-SG	PCFH-LOG, Imet4-RSB	PCFH, HABBounder	ALBATROSS + RS41-SG + Accelerometer + HABBounder on tandem balloon
2023-0822-20UT	2L7314	**R23**	RS41-SG	PCFH-LOG, Imet4-RSB	PCFH, HABBounder	
2023-0824-13UT	2L6129	**DIA**	RS41-SG		ActionCam	DIA w/o Alu plate
2023-0829-21UT	2L6219	**DIA**	RS41-SG	PCFH-LOG, Imet4-RSB RS41-SG Tgps	PCFH, HABBounder, ActionCam+Accelerometer	DIA w/o Alu plate
2023-0904-13UT	2L7314	**DIA + LN2**	RS41-SG	RS41-SG Tcoolant	Accelerometer+ActionCam	DIA w/o Alu plate
2023-0906-22UT	2L7314	**DIA + LN2**	RS41-SG	PCFH-LOG, Imet4-RSB RS41-SG Tcoolant	PCFH, Accelerometer+ActionCam	
2023-1219-18UT	2L7314	**DIA**	Imet4-RSB	PCFH-LOG	PCFH, HABBounder, Accelerometer+ActionCam	
2024-0223-10UT	2L7314	**DIA**	Imet4-RSB	PCFH-LOG	PCFH	
2024-0229-17UT	2L7314	**DIA**	Imet4-RSB	PCFH-LOG	PCFH	

As of March, 2024: 8 x R23 CFH, 7 x DIA CFH

R23 vs DIA Cleaning Cycle @ -53°C

Recall:

- CFH clears mirror @ Tmirror = -53°C to **form a new ice layer** with fine Ih crystals **for the stratosphere**
  - (1) ~ 7 s heat pulse
  - (2) full cooling power until ice layer formed (Umirror = 2.5 V)
- Ice layer quality **influences the sensitivity** (or 'response time') of the instrument in the UT/LS

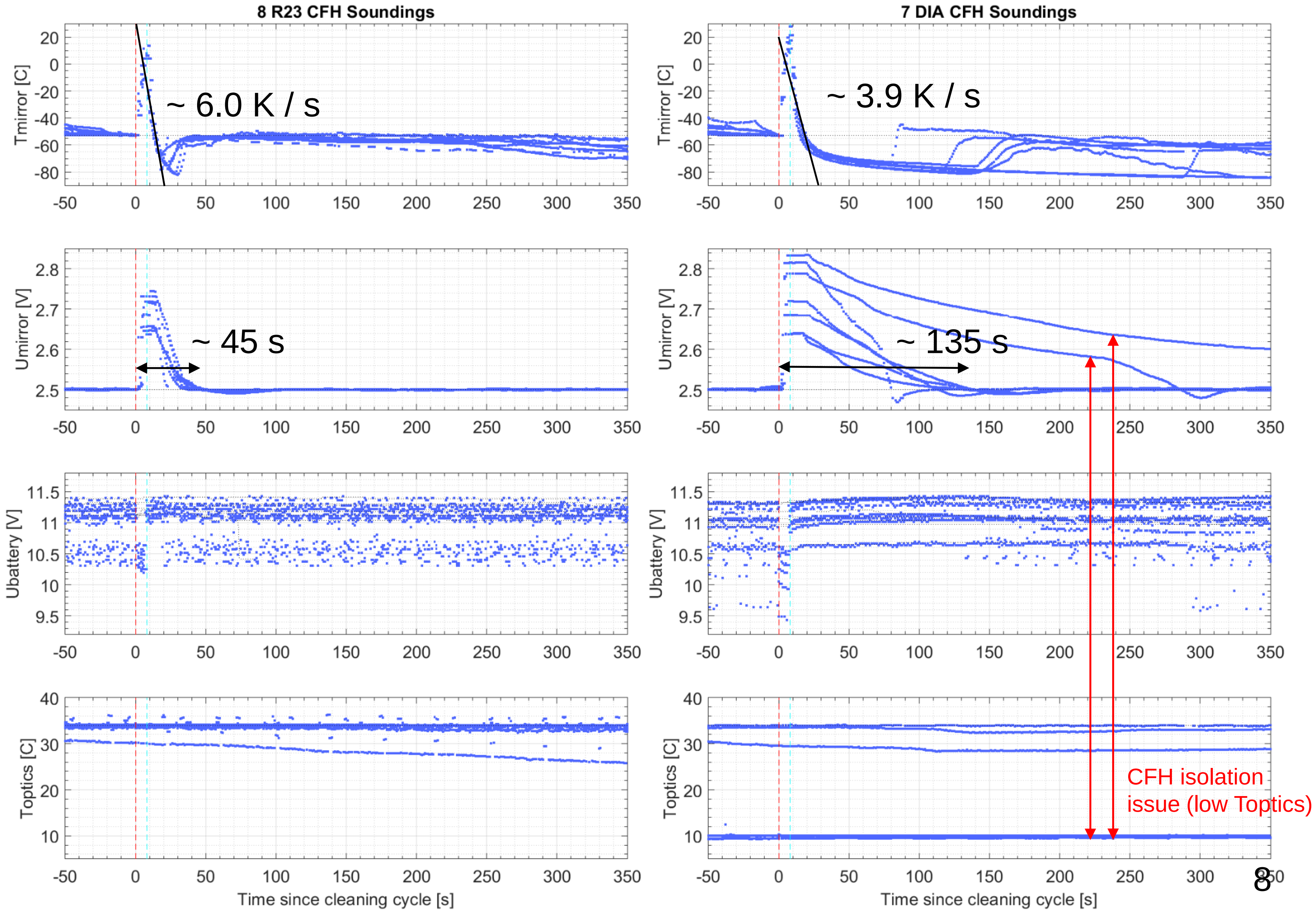
Observations:

- ice nucleation cooling rates DIA (~ 3.9 K/s) vs. R23 (~ 6.0 K/s) **= 65 % of R23 cooling power**

fits well to minimum achievable Tmirror DIA (~ - 80°C) vs. R23 (~ -95°C): (-53+80) / (-53+95) = 64%

- **~ 3 x as long to recover from cooling cycle** (with 6.44 'R23' firmware')

Observations are consistent with Dirksen et al., ICM-12, 2020 and Rolf et al., ICM-12, 2020 findings.



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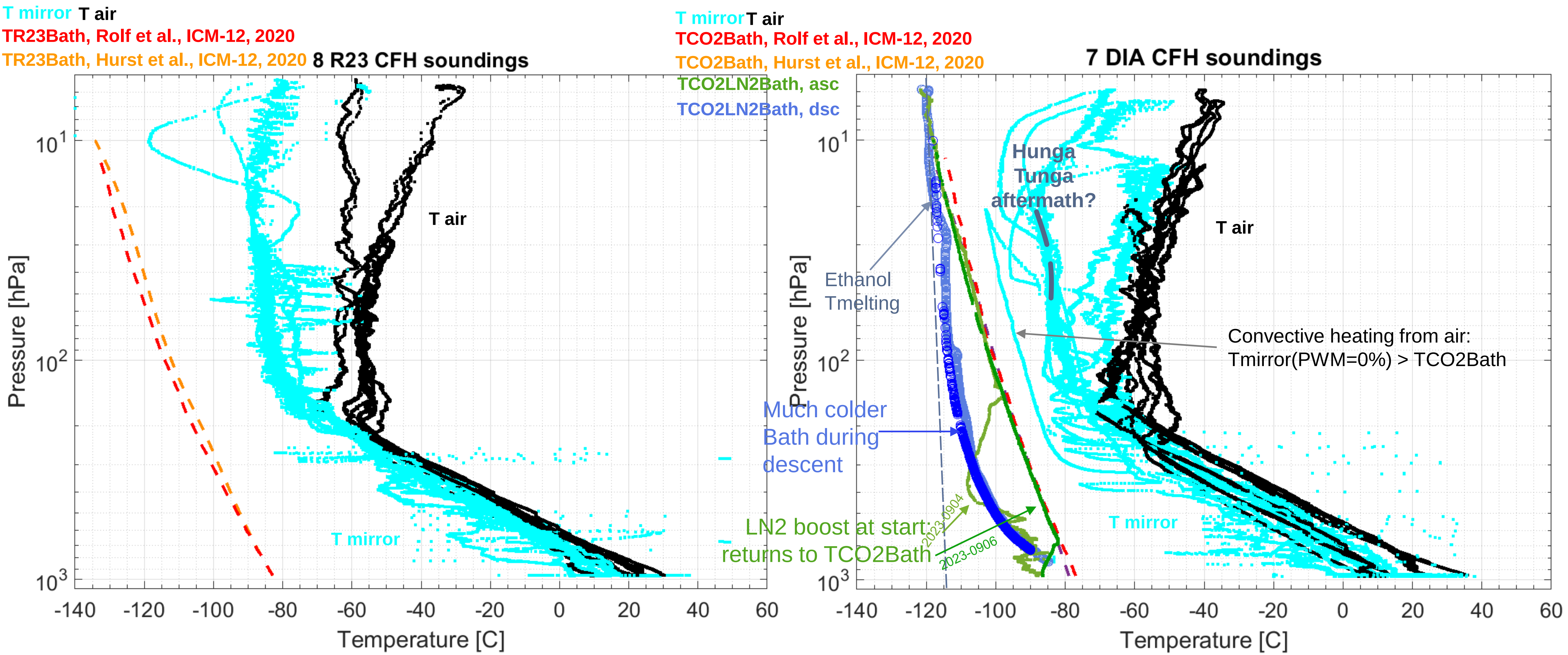
R23 vs. DIA RAW Temperature Profiles

unprocessed, raw ascent and descent, all-weather campaign data, in order to show raw mirror temperature values.
-> contamination , non-ideal descent flow, etc., that we would normally flag as bad in post-processing.



Air flow influence on minimum achievable mirror temperature

Zürich, 2024-0223-10UT PCFH+CFH sounding

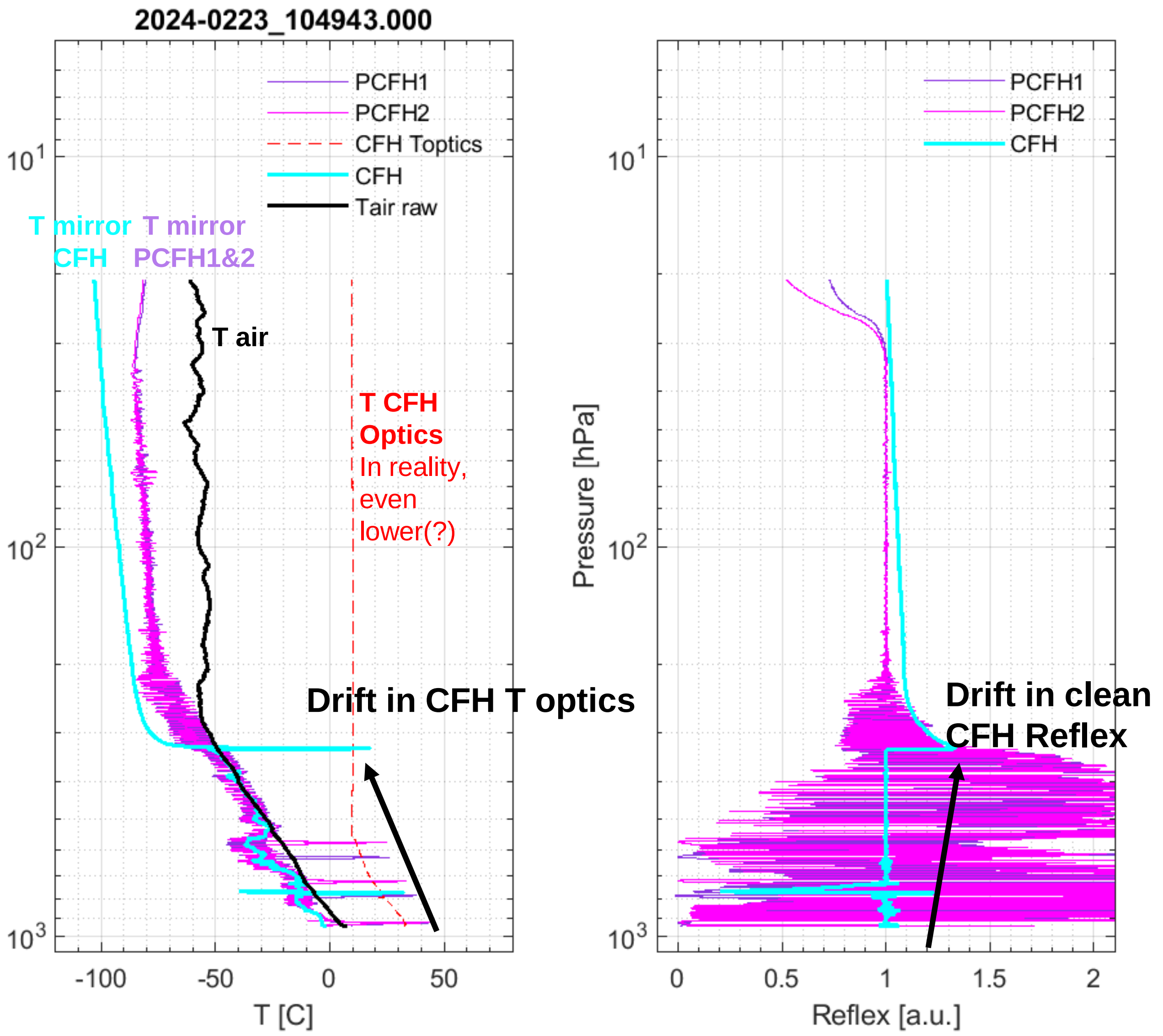
- Low CFH Toptics (out of spec.), drift in clean reflex signal (probably insulation issue during launch prep.).
- Full cooling power (PWM=0%) of 2nd cleaning cycle uninterrrupted until after balloon burst.

Tmirror << frost point, measured here accurately by **PCFH** up to 35 hPa with stratospheric PID parameters.

Tmirror(PWM=0%) ≈ TCO2Bath + 8°C because convective heating from air flow.

<u>Conclusions</u>

- Cooling power is enough for mid-latitudes (e.g. Hall and Hurst, ICM-14, 2022).
- Still enough for tropical tropopause with low frost point or high-latitude summer / SSW events with large frost point depressions in the stratosphere (?)
    - Boost DIA with liquid nitrogen in such cases(?)



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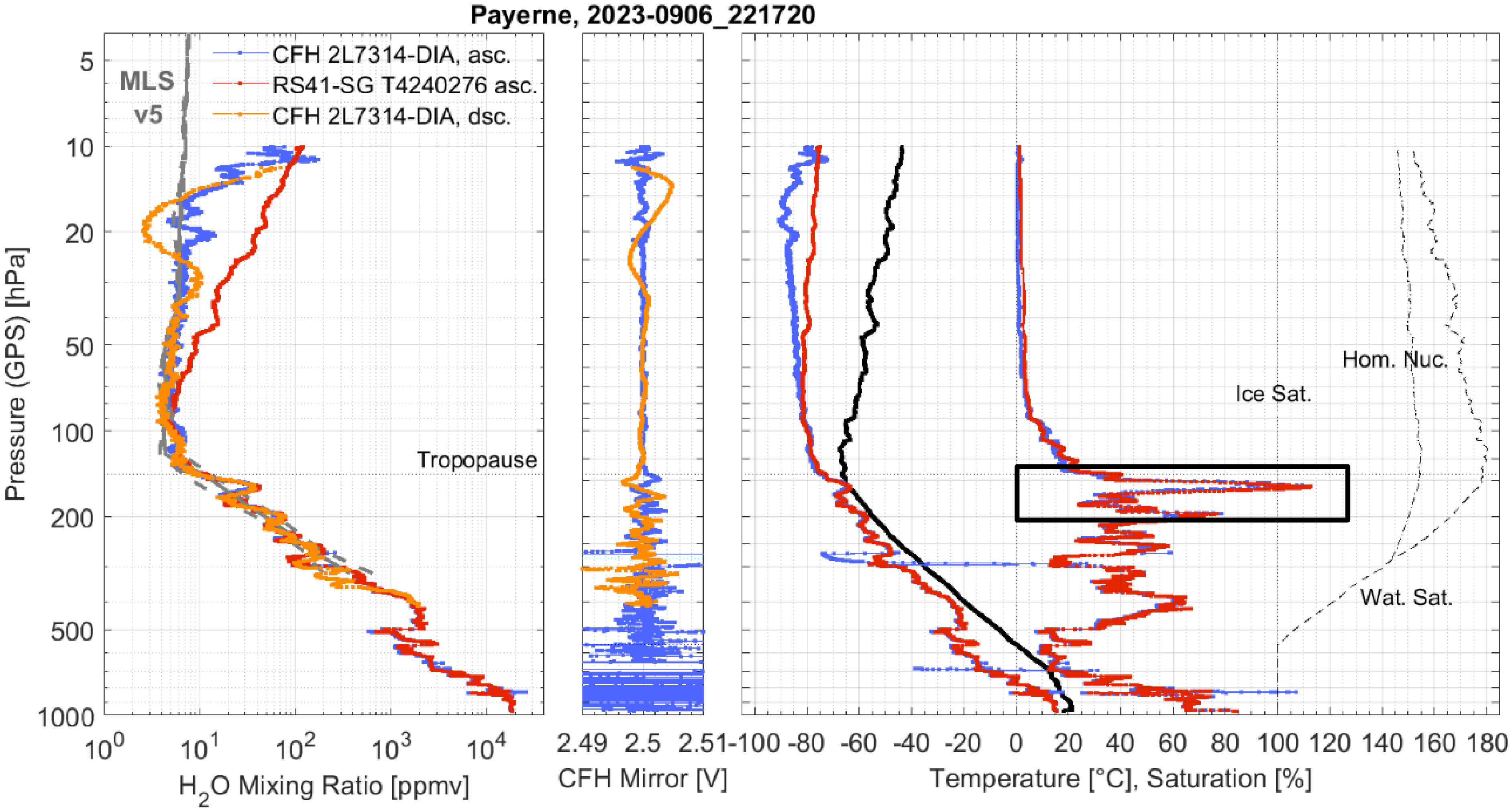
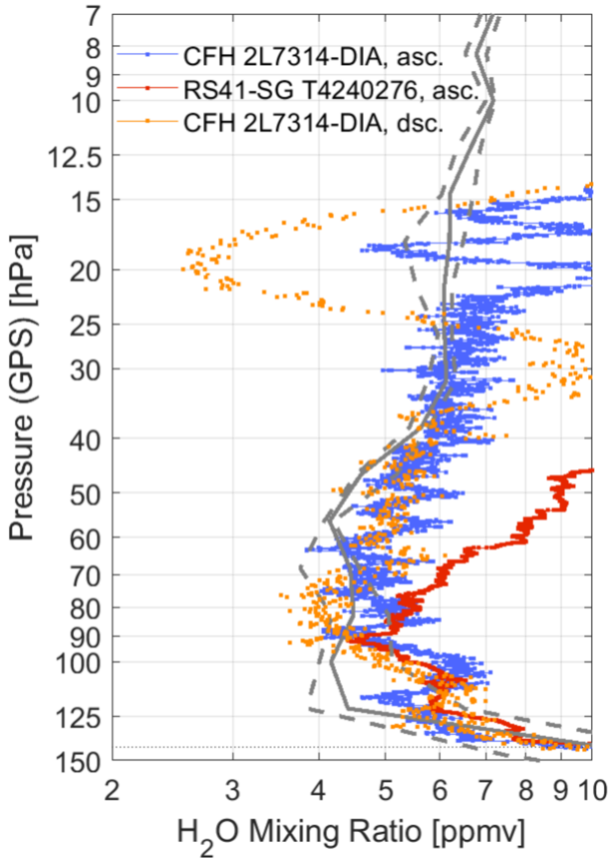
DIA CFH Validation Flight

Payerne, 2023-0906-22UT DIA CFH sounding

- Measurements up to ~ 27 km. Similar humidity features as RS41.
- In stratosphere, descent data validates the ascent data, with similar shape as MLS v5.



MLS v5
min, med, max



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DIA CFH Reference Humidity Retrievals

RS41/CFH data processing for high-resolution, low uncertainty retrievals

- Identify CFH "Golden Points" (i.e. maxima and minima in reflectivity profile)
- Apply improved time-lag (arrhenius-type) and bias correction to RS41 using CFH Golden Points
- Apply non-equilibrium error correction to CFH:

$$p_{H_2O,corr}(t) = p_{H_2O}\,(t) - \frac{B(t)}{A} \cdot \frac{dU}{dt}$$

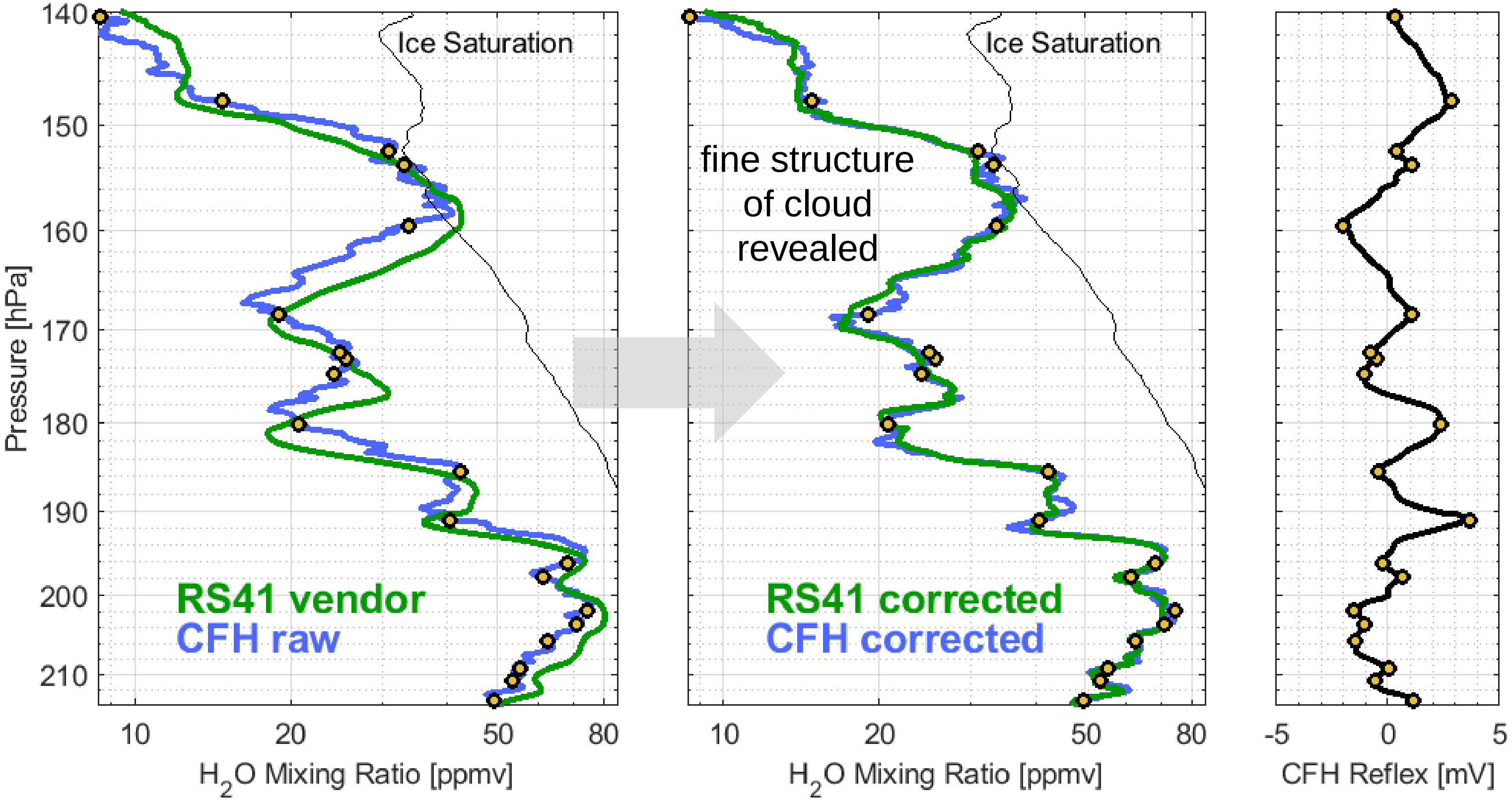
with sensitivity constant A in $\frac{\mathrm{mV}}{\mathrm{\mu g cm^{-2}}}$

estimated from corrected RS41

Poltera, Diss. ETH No. 28342, **2022**

In prep. for AMT, 2024.

Swiss H_2O-Hub Flight 007 (Payerne, 6 Sept 2023)



$$T_{f,retrieval} = 0.5 \cdot (T_{f,CFH,corr} + T_{f,RS41,corr})$$

$$\sigma_{retrieval} = \sqrt{0.11^2 + (T_{f,CFH,corr} + T_{f,RS41,corr})^2}$$

here about 10% in MR

Conclusions

- **DIA CFH implemented, tested and validated** during the H_2O Hub Summer Campaign 2023.
- Same quality of CFH reflex signal (<0.1 mV noise during night time) and same mirror temperature calibration accuracy (<0.11 K on ice films) as R23 CFH
  → **Golden Point analysis** and **reference humidity retrievals** are possible.
- **Simpler logistics** than R23, **negligible GWP**.
- **Non-intrusive** hardware modification and **similar weight** as with R23.

- Slush of ethanol and dry ice evaporates/sublimates only **slowly**.
- ~ 3 x slower second cooling cycle with ~ 35 % slower cooling rate during ice nucleation (with standard ‘R23’ firmware 6.44)
  → **non-equilibrium mirror excursions typically larger** than with R23 (flight dependent).
  Hypothesis: slightly less and slightly larger ice crystals formed during 2nd cleaning cycle compared to R23 CFH.
- General precautionary measures are still valid: risk of contamination in mixed phase clouds, increased noise in daytime measurements, not plug and play (dry ice delivery, handling with cold liquids, gluing of tubes).

GoPro camera onboard Swiss H_2O-Hub Balloon Flight 006 (4 September 2023)
View of Lake Geneva from 32 km altitude

Thank you for your attention!

Acknowlegements

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