Swiss H_2O Hub observations of post Hunga Tonga UTLS water vapor with chilled mirror hygrometers

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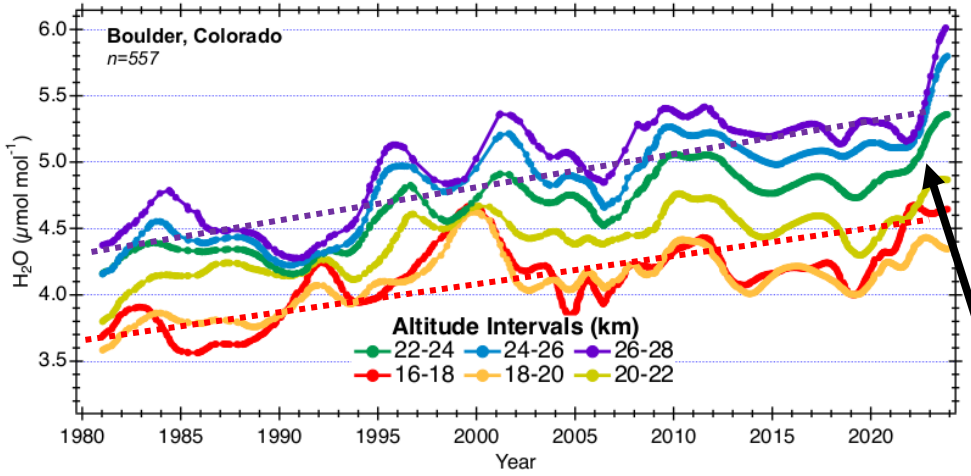
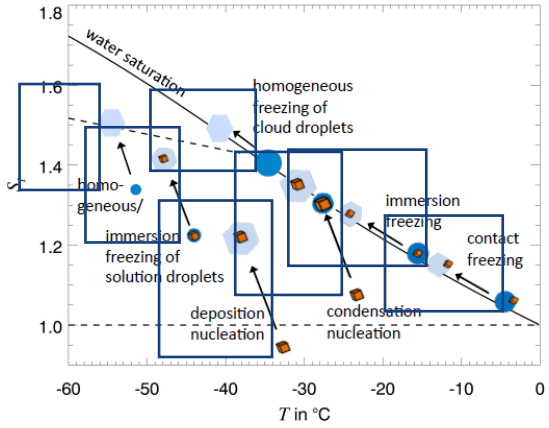
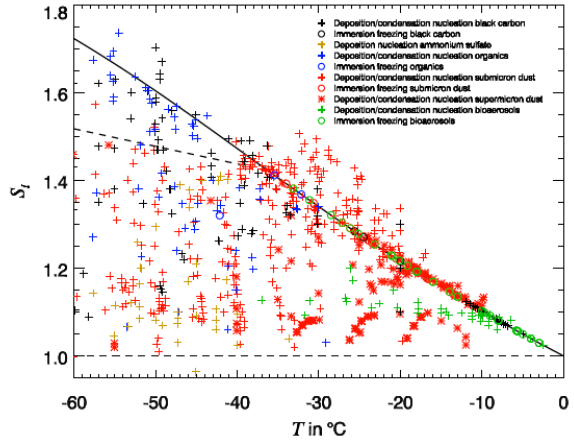
Motivation

Need for high quality measurements of UTLS H_2O



NOAA FPH data (https://gml.noaa.gov/ozwv/wvap, Dale Hurst)

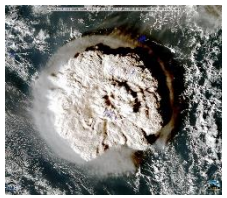




Hoose and Möhler, 2012

Monitoring the climate

Small trends in stratospheric water vapour (few hundreds of ppbv/decade) can have a significant impact on the rate of global warming, ozone layer and the large-scale circulation (e.g., Solomon et al., 2010; Charlesworth et al., 2023).



Hunga Tunga plume (Himawari-8)

Studying microphysical and chemical processes in the UTLS

Understanding of ice nucleation mechanisms and cloud microphysical processes requires an accuracy often better than 10% (e.g., Hoose and Möhler, 2012).

Cirrus and contrails (Schumann et al., 2017)

Assessing drifts and biases

in satellite instruments and current climate models (e.g. Livesey et al., 2021; Charlesworth et al., 2023).

Swiss H_2O Hub Consortium

1. Uni Bern: **CRYOWARA**
   Microwave radiometer, *remote sensing*

2. MeteoSwiss: **RALMO**
   Raman lidar, *remote sensing*

3. Empa: **ALBATROSS**
   Mid-IR absorption spectroscopy, *in-situ*

4. ETH Zürich: **PCFH**
   Peltier-cooled frost point hygrometer, *in-situ*

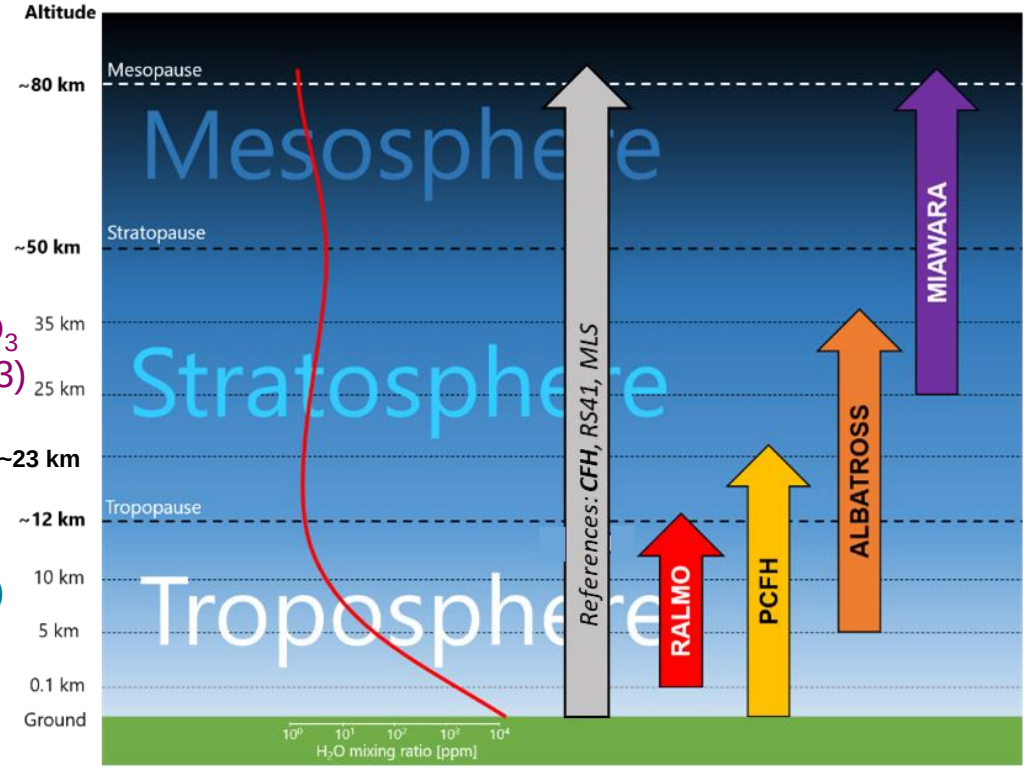
5. Reference: **CFH**, MIAWARA
   Auxiliary references: RS41, Aura/MLS, SCISAT-1/ACE-FTS

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)



also funded by the Federal Office for the Environment and the Oeschger Centre for Climate Research

Chilled Mirror Hygrometers (CMH)

Working principle:

i) a mirror is cooled until a dew or frost layer forms onto the mirror.
ii) a feedback controller manipulates the temperature of the mirror such that the condensate *neither grows nor shrinks*.
iii) the (averaged) mirror temperature gives an estimate of the dew/frost point

Cooling technique:

Cryogenic (R23, liquid N_2, ethanol+dry ice), Electric (Peltier device).

Condensate growth feedback technique:

Specular mirror reflectivity, or condensate scattering.
PID control of mirror heater / of Peltier current.

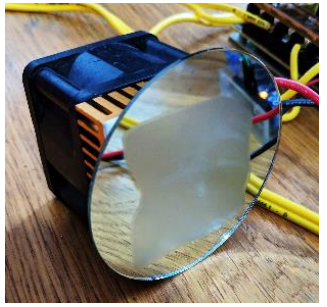
Metrological water vapor standard:

Rely solely on measuring temperature (SI-traceable).
Used as transfer standard for humidity.

'Golden Points'

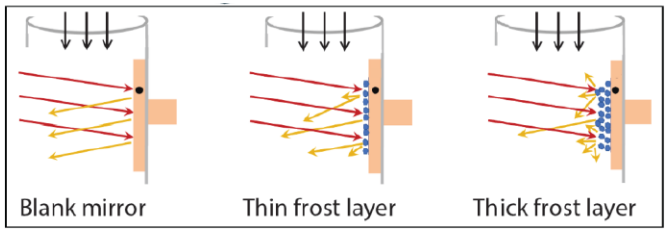
Equilibrium between frost layer and surrounding air
→ minima and maxima of the mirror reflectivity
→ better than 0.2 K in FP or 3-4 % in H_2O mixing ratio
→ automatic retrieval

dew on mirror



Arduino Chilled Mirror Hygrometer © MIT

specular reflected light feedback



The specular "bulk reflectivity" U_m decreases as mirror coverage increases and vice-versa

Eq. of chilled mirror hygrometry

$$p_{H_2O}(t) = p_{H_2O,sat}(\boldsymbol{T_m}) - \frac{\beta(t)}{\alpha} \cdot \frac{d\boldsymbol{U_m}}{dt}$$

with sensitivity constant α in $\frac{\mathrm{mV}}{\mu\mathrm{gcm}^{-2}}$

Balloon-borne CMH

- **high accuracy and vertical resolution**
- **easily measure in the tropopause region and in the lower stratosphere**

Instruments: new developments

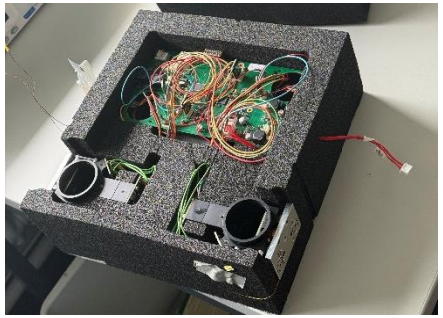
PCFH (ETHZ / mylab GmbH)

Goals

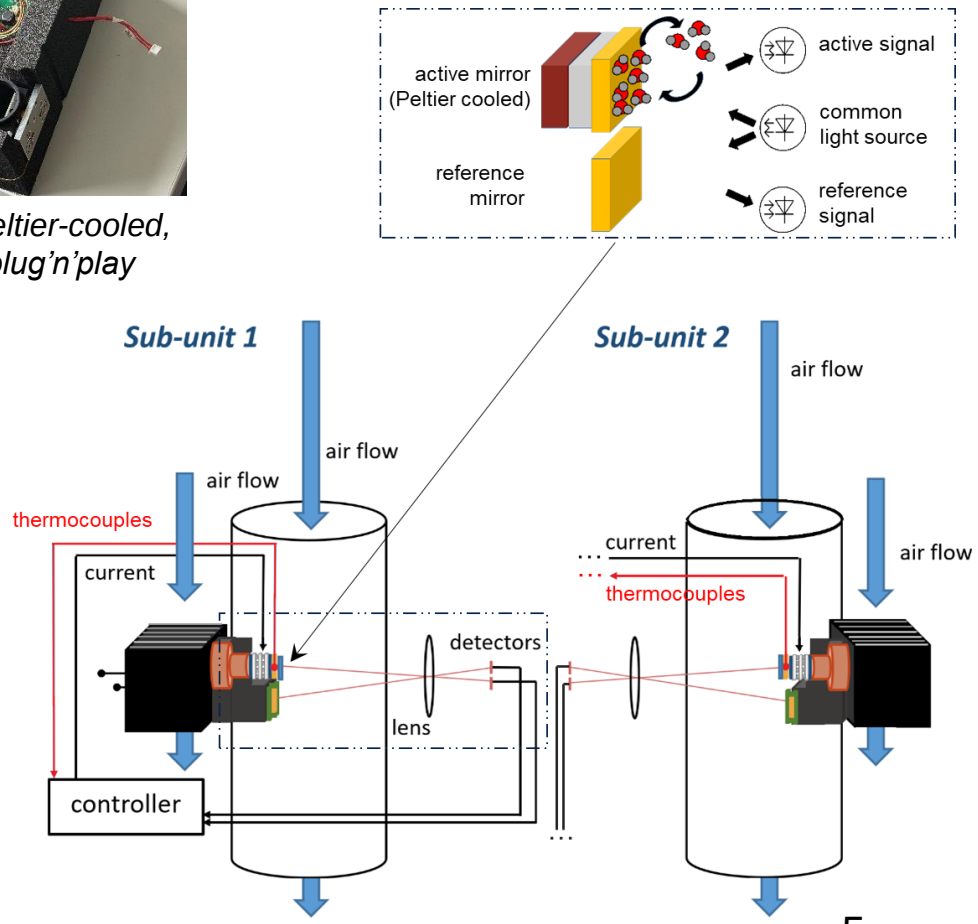
- replace coolant liquids with **Peltier elements**
- **reduced logistic and preparation efforts**
- eventually be **on par with CFH** at least up to 23 km

Realization

- cooling double-stage Peltier
- **two fully independent sub-units**
- easy handling



PCFH v2025: Peltier-cooled, double inlet, plug'n'play



Instruments: new developments

CFH-DIA (ETHZ / UniBe, En-Sci)

CFH (EN-SCI, USA)

Goals

- **low-GWP** coolant liquid
- same accuracy as CFH-R23
- **non-intrusive** modification and **similar weight** as CFH-R23

Realization

- CFH (En-Sci) with slush of **dry ice & alcohol (DIA)**
- not plug'n play (dry ice, cold liquids, glueing of tubes)
- usual precautions (liquid clouds & balloon contamination, daytime noise)

DIA: Al-plate fitted below cold finger

DIA: slush of dry ice and ethanol (~ 94 % 'Brennsprit')

Note: DIA is not new (e.g. Thornwaite & Owen, 1940; GRUAN LC/NOAA/FZ Jülich, ICM-12, 2020).

Instruments: new developments

Dual Telemetry + High Resolution Datalogs

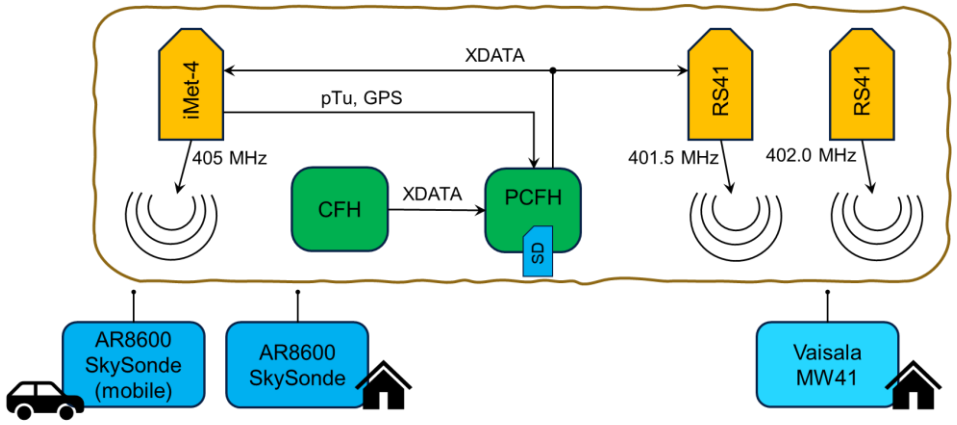
- Dual XDATA telemetry: iMet-4 & RS41
- PCFH Log: PCFH logs its internal data along with XDATA from CFH and iMet-4 on SD card (**high resolution**, **no telemetry gaps**)

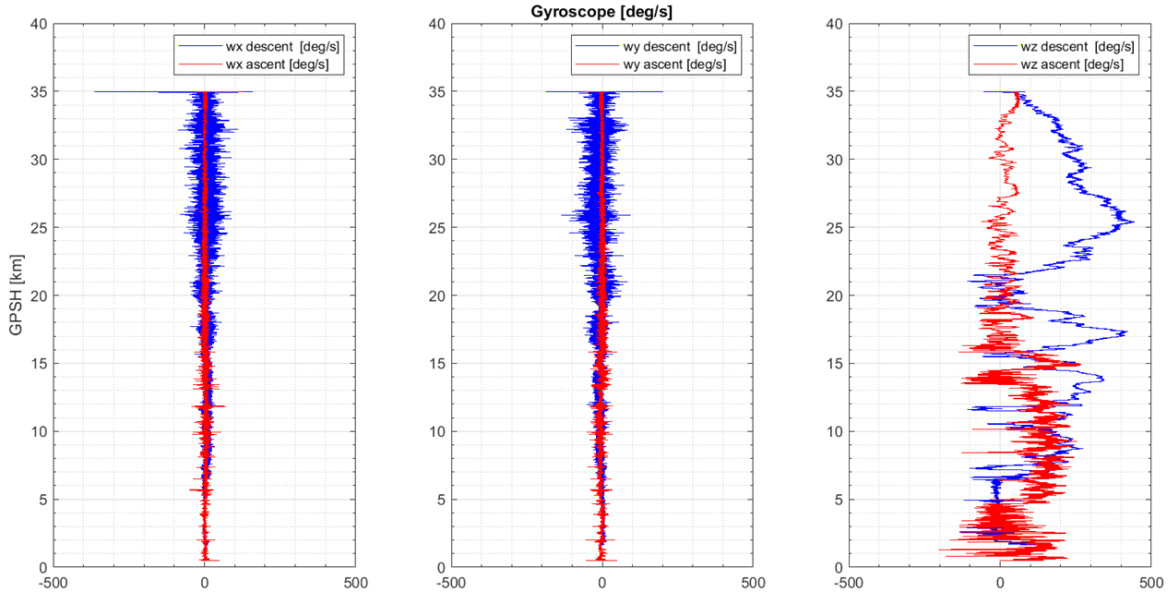
Also:

- Cryogen investigations: RS41-Tcryo (MW41 ‘degraded’ sounding)
- Inlet Tube investigations: Heating Pad
- Ballooning investigations: Action Camera, Accelerometer, Line Cutter, Live GPS-Tracking

04.09.2023 over PAY

Tcryo with RS41





Accelerometer data: ‘Twirling’ (right panel), confirmed by action cam

Methods: new frost point retrieval protocol

Golden Points and nonequilibrium correction

At the frost point, dU_m/dt=0, i.e. the mirror reflex signal assumes a **minima** or **maxima**.

→ "**Golden Points**" of chilled mirror hygrometers

→ better than 0.2 K in FP or 3-4% in H_2O mixing ratio.

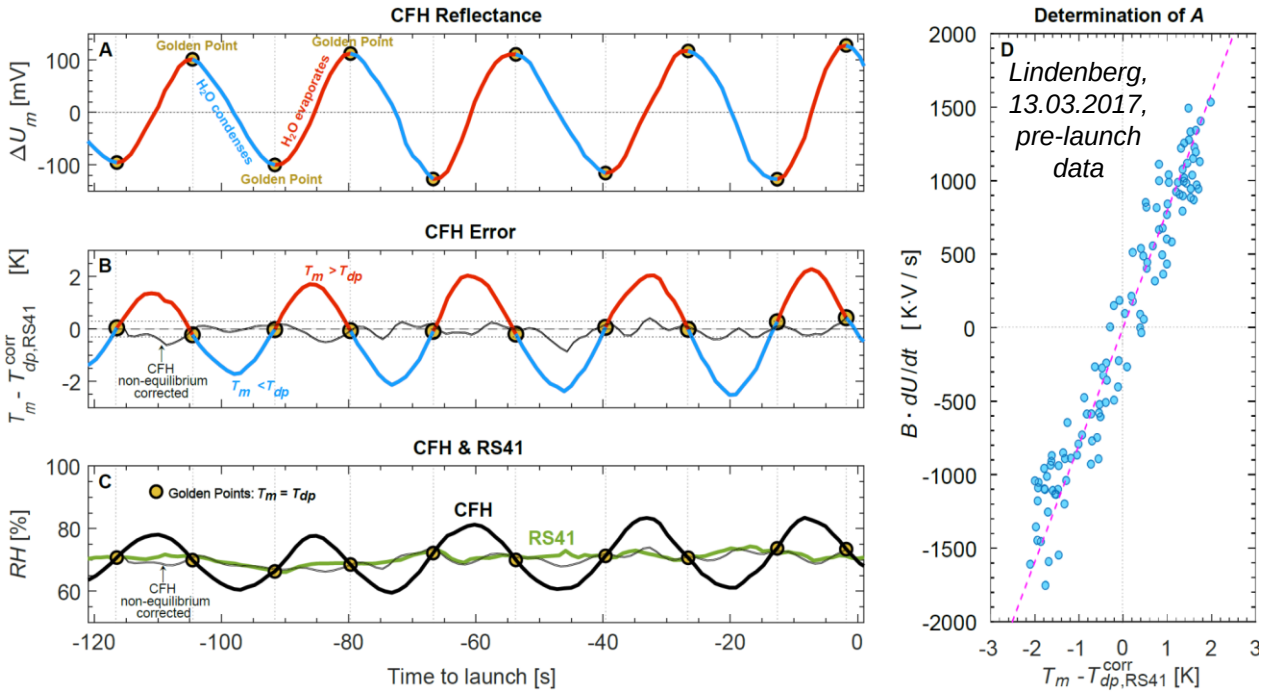
see also Dobson, Brewer and Cwilong (1946)

The oscillations, or nonequilibrium errors, **can be corrected with the sensitivity constant *α*** of the mirror condensate, allowing high-resolution, high-accuracy H_2O retrievals in the UTLS.

→ For CFH, we use the RS41 (that we recalibrate trough the CFH Golden Points), to retrieve *α*.

→ For PCFH, we can **auto-retrieve** *α* using a cascaded PID controller

Golden Points and nonequilibrium 'textbook' correction example



$$p_{H_2O}(t) = p_{H_2O,sat}(\boldsymbol{T_m}) - \frac{\beta(t)}{\alpha} \cdot \frac{d\boldsymbol{U_m}}{dt}$$

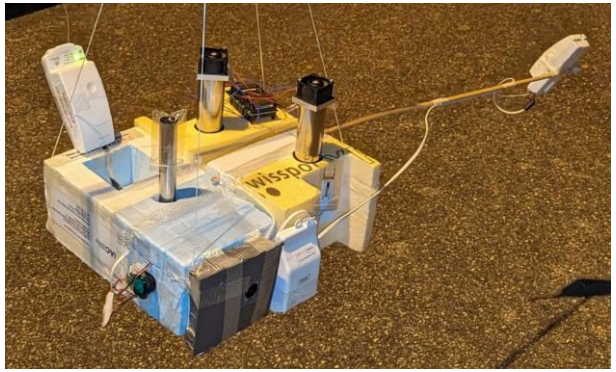
with sensitivity constant α in $\frac{\mathrm{mV}}{\mu\mathrm{g cm}^{-2}}$

Poltera et al., in review (egusphere-2025-2003)

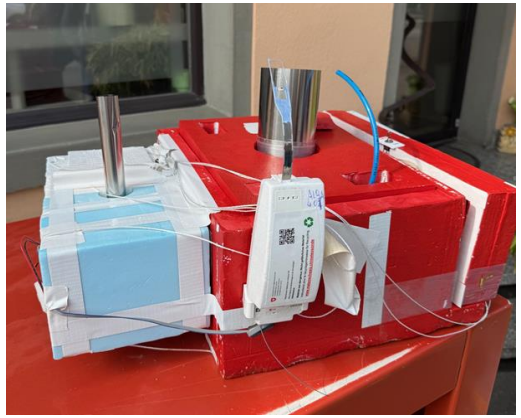
Swiss H_2O Hub Deployments

Seasonal deployments

PCFH and CFH-DIA are currently being deployed within the GAW/GCOS-CH project
"***Swiss H_2O Hub**: High-quality water vapor measurements from ground to space*".



PCFH-CFH-RS41-imet4
06.09.2023



ALBATROSS-CFH-RS41
27.03.2025

Launch in Payerne
17.08.2023

~50 % landing
on land

~50 % landing
on trees

33 flights, **100% instruments recovery!**

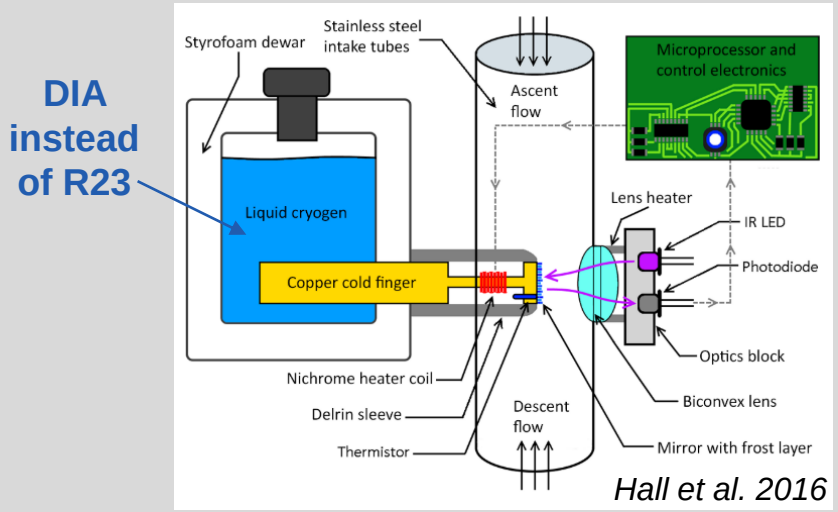
20 x valid CFH stratospheric data **-> 60 % success** (tests/engineering flights, clouds)
100 % success when flown with ALBATROSS

First Results: CFH-DIA

CFH-DIA nonequilibrium correction

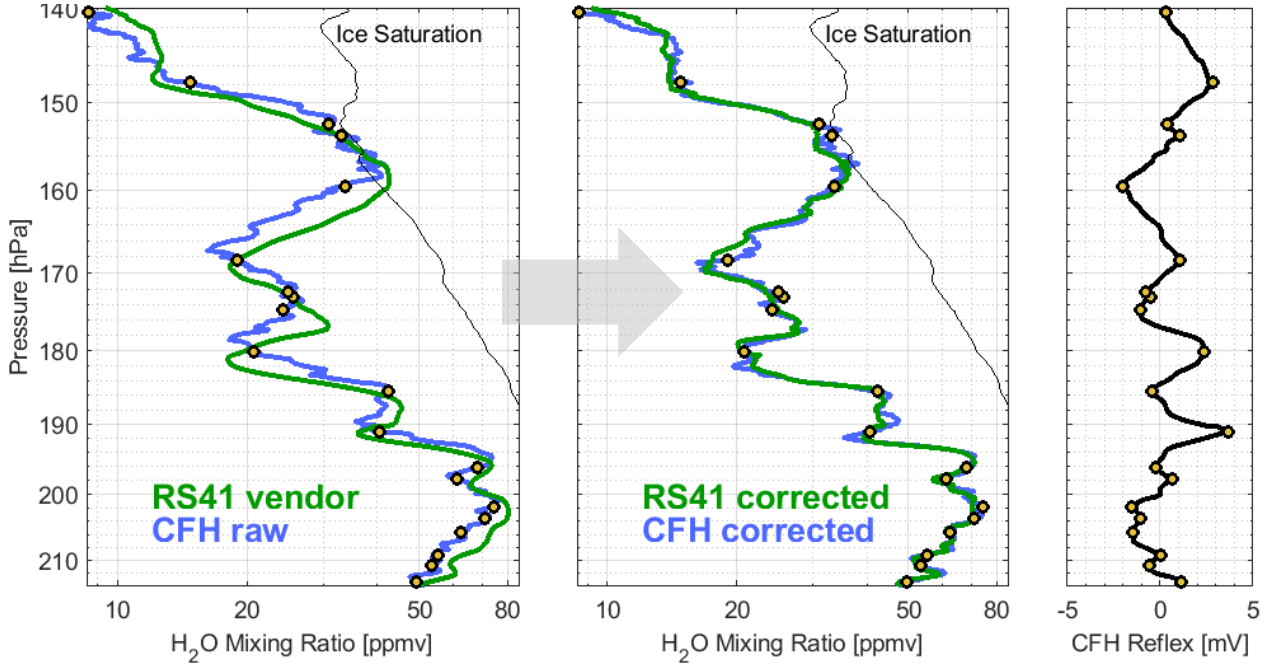
CFH-DIA mirror temperature accuracy and noise of reflex signal equivalent to CFH-R23.

→ nonequilibrium correction with CFH-DIA **equivalent** as with CFH-R23, can be used to construct **reference humidity retrievals** for validating other instruments in Swiss H_2O Hub.



Hall et al. 2016

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

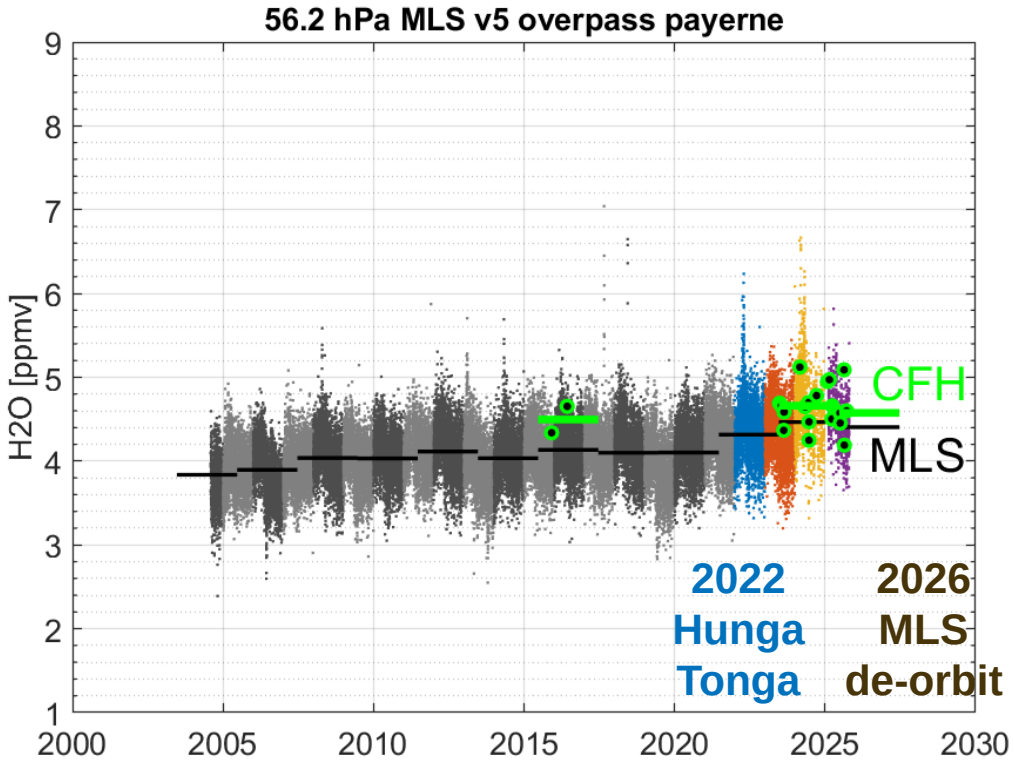


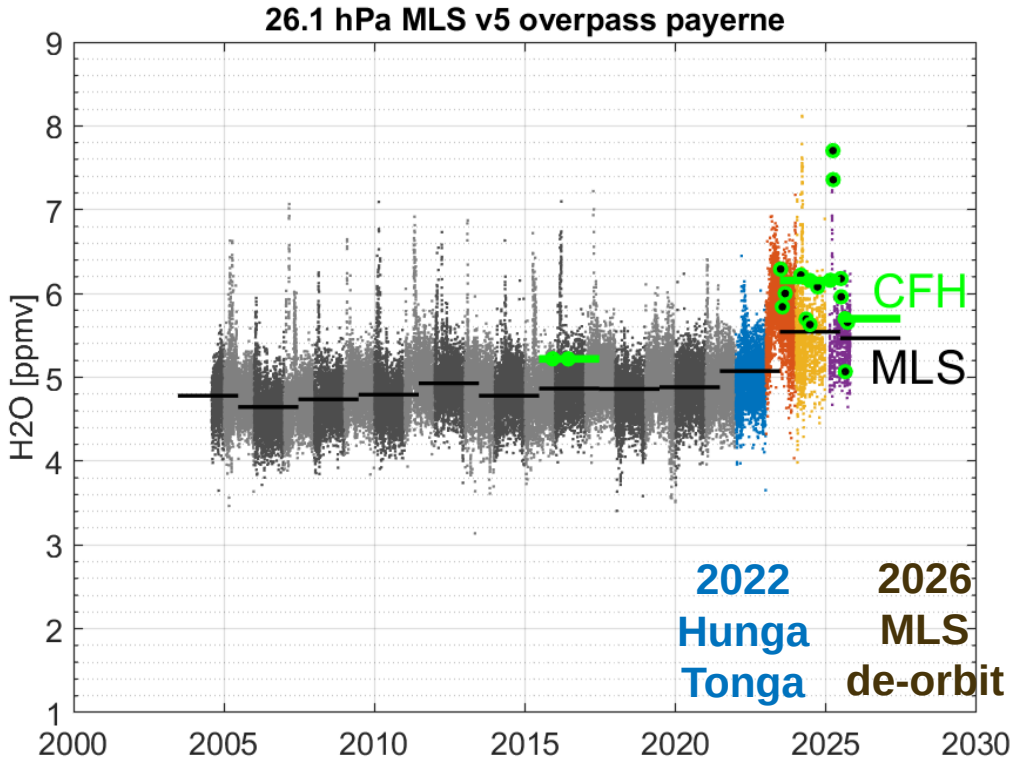
Nonequilibrium correction **reveals fine structures** in the cirrus layer. High-quality RS41 suffers from residual time-lag and bias errors and needs to be corrected.

Poltera, Wienhold et al., in prep.

First Results: comparison with Aura/MLS

Pre- and Post Hunga Tonga



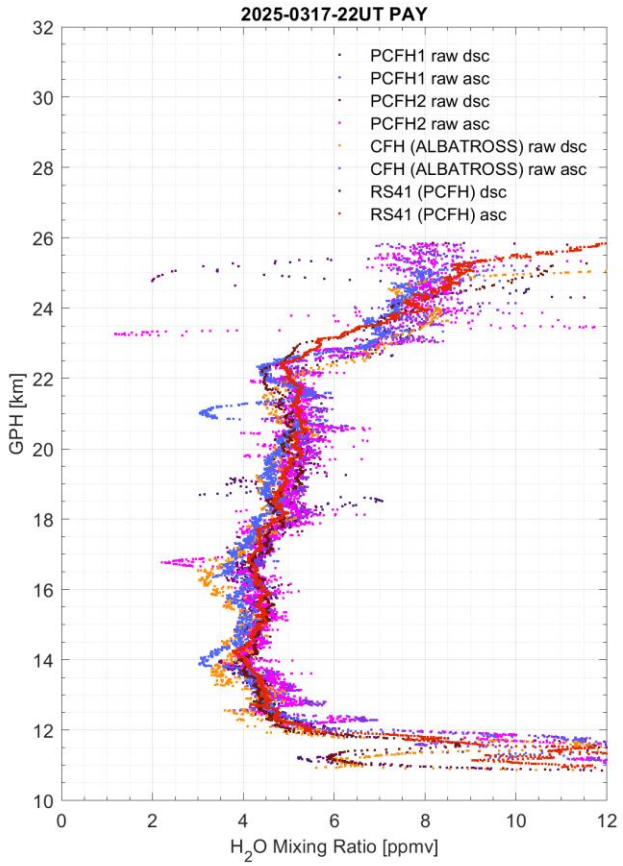


- **Hunga Tonga** contribution (≈< 1 ppmv) after ~ 1 year in lower stratosphere over Switzerland
  - **High WVMR episodes** over midlatitudes in early Spring (polar vortex breakoff)
- **Dry Bias** of MLS v5 (see also Livesey et al., 2021), duty-cycle since 2024, de-orbit in 2026
- **SwissH_2OHub:** valuable dataset with seasonal **post Hunga-Tonga** SWV measurements

Poltera, Wienhold et al., in prep.

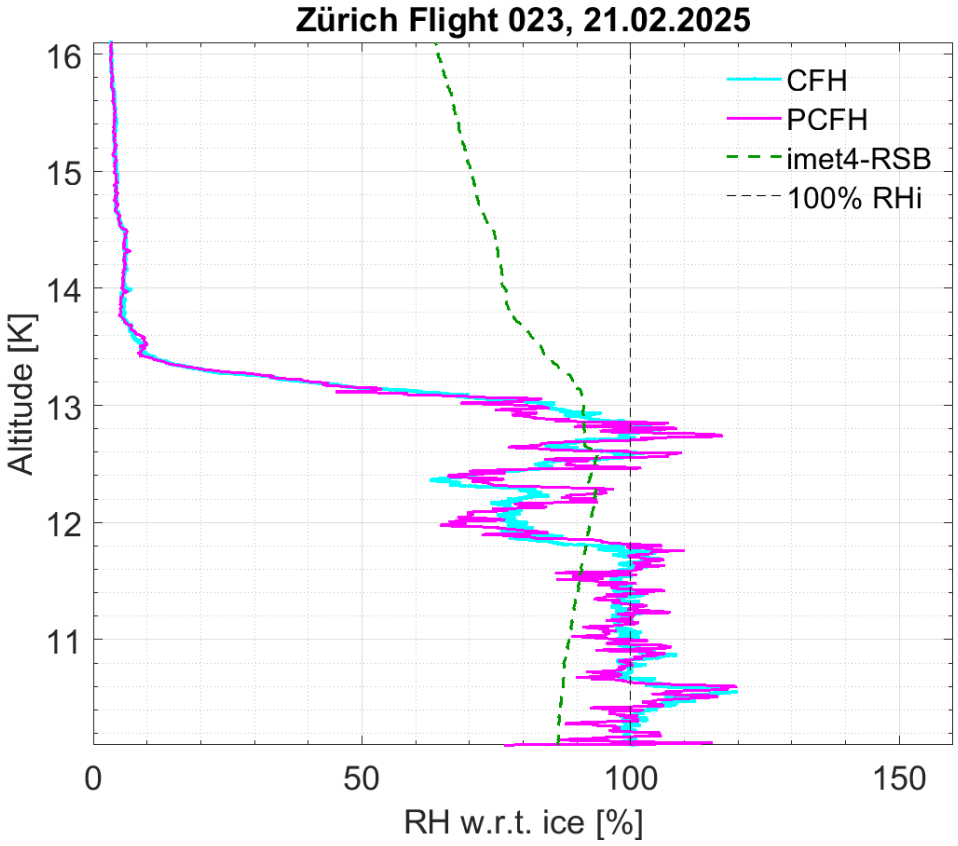
First Results: PCFH 2025 re-design

First flights in 2025



2025-0327_22UT PAY Flight
In the stratosphere, PCFH agrees with CFH within 0.5 K and with RS41 Tair within 0.2 K

Successful first flights, with PCFH **on par** with CFH in the UT/LS, using **no cooling liquids** and **<1 h preparation time**!



PCFH RHi in UTLS on par with CFH near the tropopause. Lesser quality radiosondes are less accurate in UTLS.

Poltera, Wienhold et al., in prep.

Take Home Messages

H2O Hub, PCFH & CFH-DIA hygrometers

- Frost point hygrometers are reference SI-traceable sensors for measuring water vapor. Highest accuracy (< 4% error) and vertical/temporal resolution is achieved with the Golden Points and nonequilibrium correction technique.

- CFH-DIA can be used as an alternative to CFH-R23 for Swiss H_2O Hub.

- The **newly developed PCFH** with a cascaded PID controller is an instrument of equal performance as CFH-DIA, but with a modular design, no cold liquids involved and significantly less preparation effort.

- **Swiss H_2O Hub**: first seasonal in-situ measurements of upper tropospheric and lower stratospheric H2O over the Alpine region, including observations of post Hunga-Tonga UTLS water vapor with low-GWP frost point hygrometers, with ~ 20 valid stratospheric measurements so far (analysis in progress).

Thank you! Questions?