Swiss H_2O Hub observations of post Hunga-Tonga UTLS water vapor with balloon-borne frost point hygrometers

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1 Introduction

Water vapor, ozone and aerosol observations are of pivotal importance for the study of dynamical, microphysical and chemical processes in the upper troposphere and lower stratosphere (UTLS)[1]. In particular, measuring water vapor is most challenging in that region, requiring high SNR and high accuracy at low air density and at water vapor mixing ratios of only a few parts per million volume (ppmv). Balloon-borne frost point hygrometers meet these requirements[2] and act as reference for research, cal/val and monitoring activities, however, with the phase down of HFCs, there is a need for future-proof instrumentation[3]. We present first results from Swiss H_2O Hub frost point hygrometer deployments in 2023-2025 over the Alpine region, using both established and newly developed instruments, as well as a new retrieval protocol for chilled mirror observations. The measurements took place in the aftermath of the 2022 Hunga Tonga volcanic eruption, whose effects on climate are predicted to last over a decade[4].

2 Balloon-borne frost point hygrometers

- ✓ **easily measure in the tropopause region and in the lower stratosphere**
- ✓ **high accuracy, dynamic range and vertical resolution**

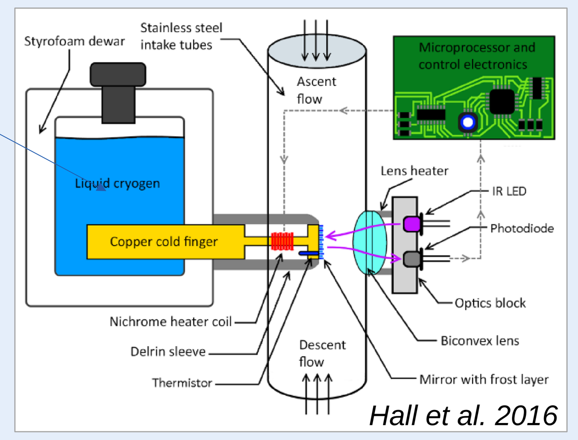
Working principle:
i) a mirror is cooled until a dew or frost layer forms onto the mirror
ii) a feedback controller adjusts the temperature of the mirror such that the condensate *neither grows nor shrinks*
iii) the mirror temperature gives an estimate of the dew / frost point

Uncertainty @ 250 m vertical resolution:
< 10 % from ground up to 28 km[5]
< 4 % under stable frost control[2,6] or at '**Golden Points**'[7] (i.e., net zero-flux)

2.1 CFH / DIA-CFH

- Reference frost point hygrometer from En-Sci, using either classical cryogen (R23), or **dry ice & alcohol (DIA)** to cool the mirror
- DIA-CFH is a **low-GWP alternative** with similar accuracy, noise, size and weight as CFH, but a residual risk of losing frost control in certain atmospheric situations
- Not plug and play (dry ice and cold liquids)

DIA instead of R23



Hall et al. 2016

2.2 PCFH

- **Fully electric** (double-stage Peltier) frost point hygrometer from mylab GmbH
- Measurements from the ground **up to at least 23 km**
- **Two** fully independent **sub-units**
- Reduced logistic and preparation efforts

DIA-CFH (left), PCFH (right), RS41 & imet4 payload, 27.03.2025

2.3 Golden Points & nonequilibrium correction

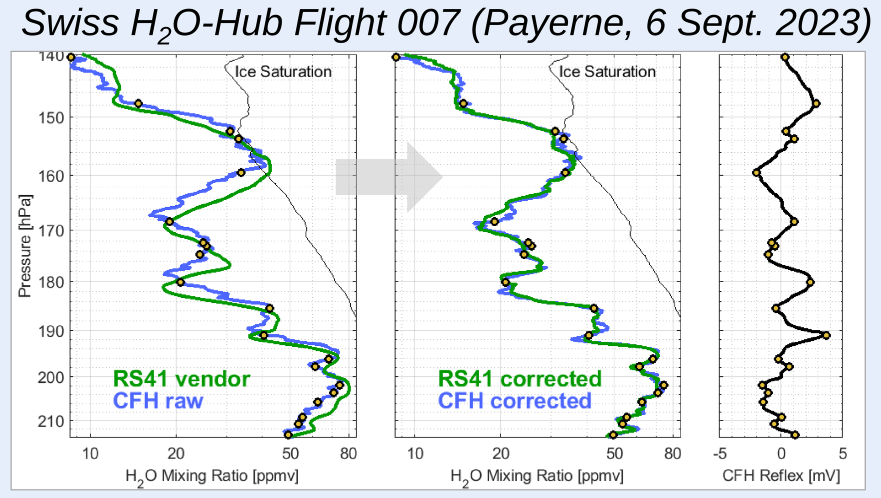
New retrieval protocol for reference humidity retrievals:

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

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

- the mirror temperature T_m is at the frost point when the mirror reflectance U_m assumes a **minimum**, **maximum**, or **plateau** ($dU_m/dt=0$) **-> 'Golden Points'**
- nonequilibrium errors ($dU_m/dt \neq 0$), can be corrected with the **knowledge of** $\boldsymbol{A}$[8]

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



The nonequilibrium correction reveals fine structures in the cirrus layer. The Vaisala RS41 radiosonde has a sensitive capacitive humidity sensor, but suffers from residual time-lag and bias errors, and needs to be corrected. RS41 also exhibits large sonde-to-sonde variability in the stratosphere.

3 Swiss H_2O Hub Deployments

GAW, GCOS, MeteoSwiss, Universität Bern, Empa, ETH zürich, mylab elektronik GmbH

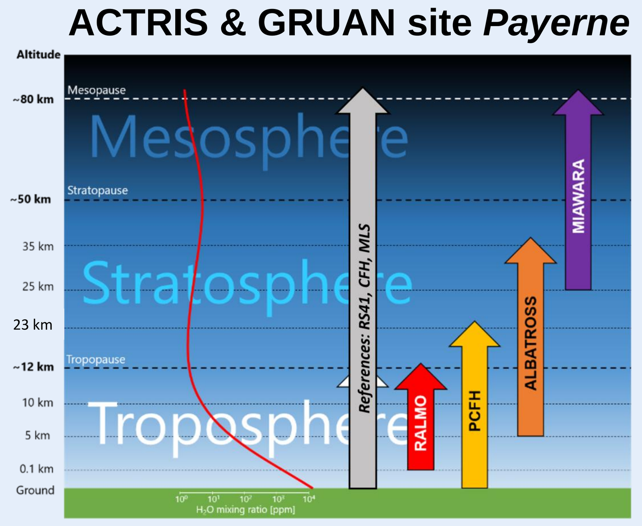
Swiss H_2O Hub:
Consortium dedicated to high-quality water vapor measurements from ground to space

Participating instruments
- **PCFH** (chilled mirror)
- ALBATROSS (absorption spectrometer)
- CRYOWARA (microwave radiometer)
- RALMO (Raman lidar)

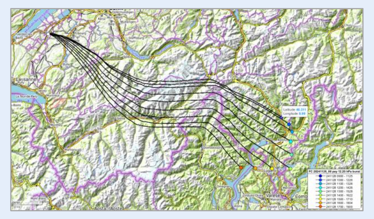
Reference instruments
- **CFH** (< 28 km)
- Aura/MLS (> 15 km)
- MIAWARA (> 35 km)

Radiosondes
- Vaisala RS41
- Imet4

ACTRIS & GRUAN site *Payerne*



Swiss H_2O Hub: 29 flights so far,
100% instruments recovery



Flight planning: IFS-LAGRANTO & GFS-Sondehub

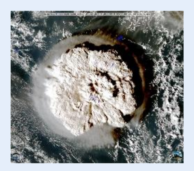
CFH (DIA) preparation 18.08.2025

Dual balloon launch in Payerne 17.08.2023

Lake Geneva from 32 km altitude 04.09.2023

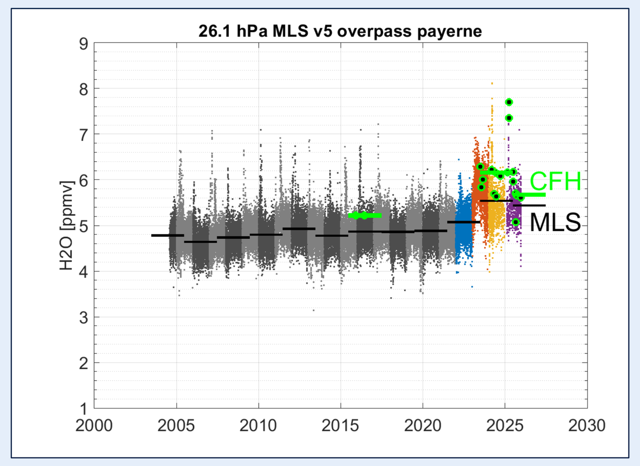
ALBATROSS, CFH & RS41 recovered 28.03.2025

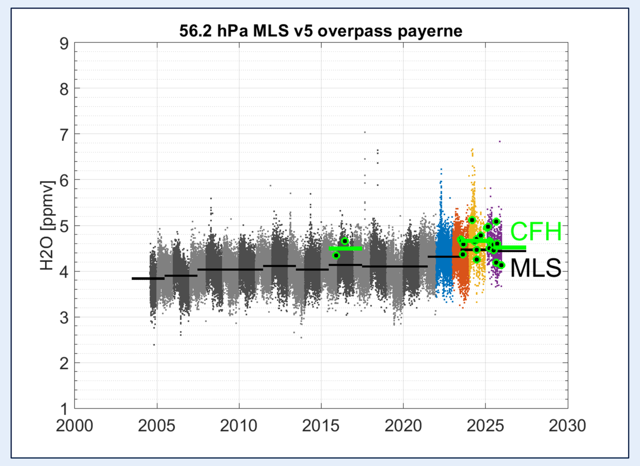
3.1 Hunga Tonga signal



Hunga Tonga plume injecting ~140 Tg H_2O or 10% global SWV increase [11] *(Himawari-8 15.01.2022)*

- Hunga Tonga contribution (≈< 1 ppmv) after ~ 1 year in lower stratosphere over Payerne.
- High WVMR episodes over midlatitudes in early Spring (possibly polar vortex breakoff) **measured in-situ within Swiss H_2O Hub** [10].
- Dry bias of MLS v5 (see also Livesey et al., 2021). MLS in duty-cycle mode since May 2024 to extend lifetime of measurements.

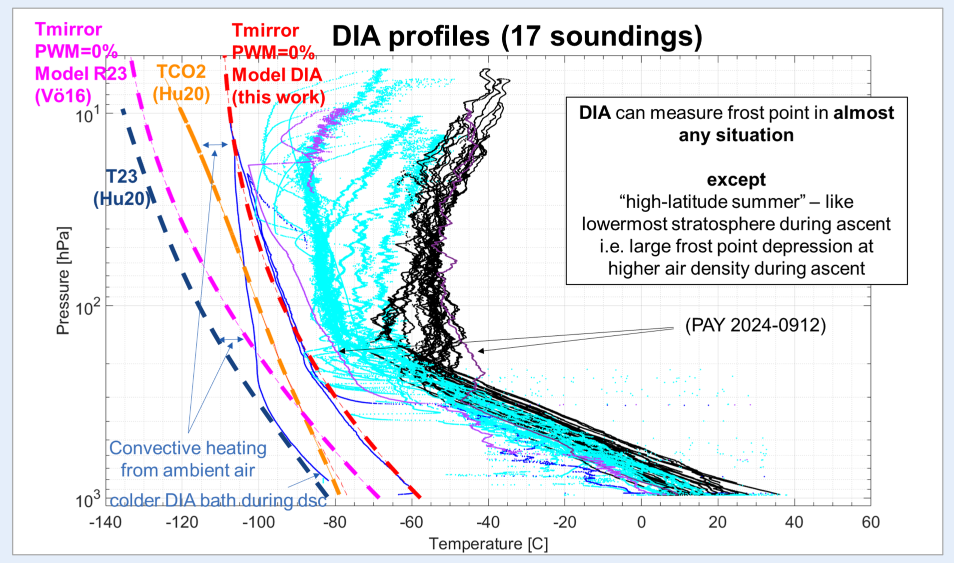




3.3 Cooling power DIA-CFH

Low-GWP DIA-CFH on par with CFH, albeit:

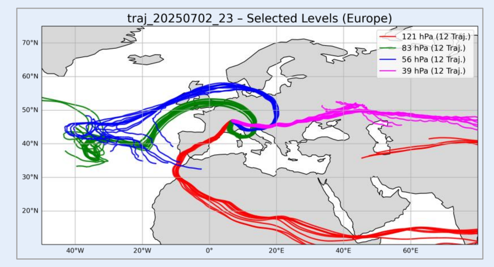
- **3 x slower** second clearing cycle with ~ 35 % slower cooling rate during ice nucleation (with standard CFH firmware 6.44), followed typically by larger nonequilibrium excursions.
- challenged when **large frost point depression** in lowermost stratosphere.



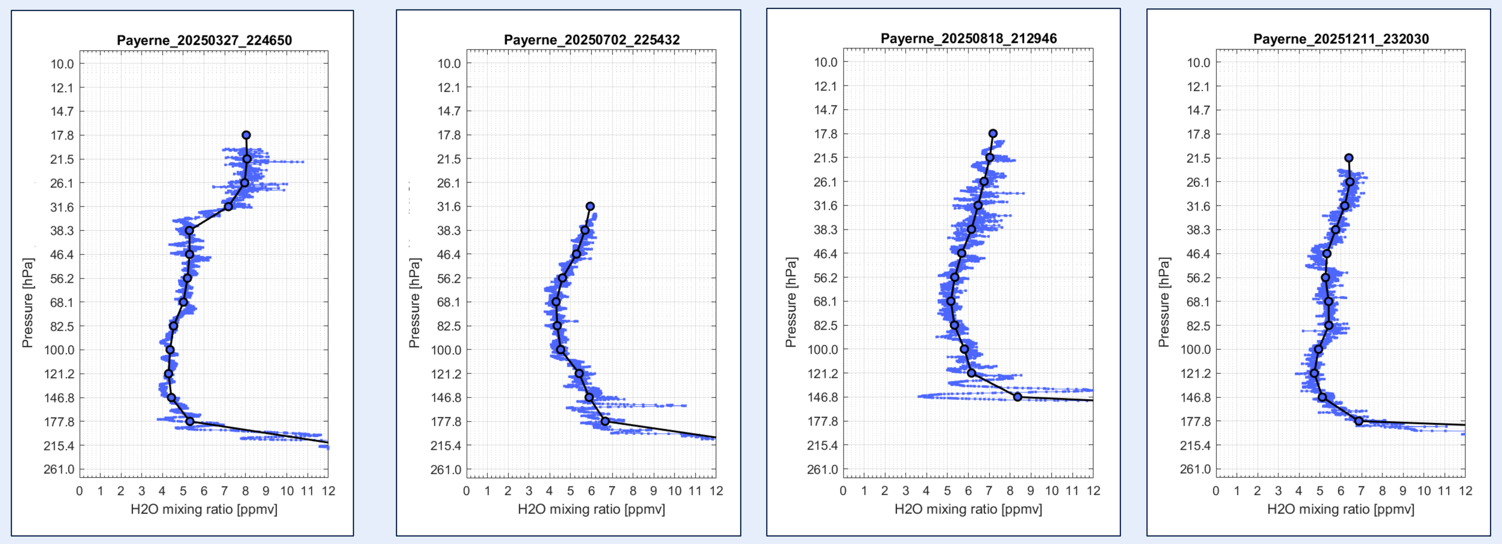
Raw CFH-DIA Tmirror (cyan) and RS41 Tair (black) profiles, revealing DIA cooling power, cold bath temperature, and several cases of contamination

3.2 Seasonal variability - 2025

Stratospheric water vapor can have different ages of air and origin regions at different altitudes[12] resulting in variability in H_2O (and thus longwave radiative flux) measurable with the most sensitive instruments.
In 2025, over Payerne, from 4 CFH & PCFH observations:
~ 2-3 ppmv variability in H_2O @ 25 km altitude
~ 1 ppmv variability in H_2O @ 18 km altitude



ERA5-LAGRANTO two weeks backtrajectories starting at different pressure levels above Payerne on 02.07.2025



Early Spring, Summer and late Fall 2025 stratospheric H_2O measurements (PCFH 1-s ascent data (Sub-Unit 1) and ± 1 pressure bins median)

3.4 Summary

- **Swiss H_2O Hub**: first seasonal in-situ measurements of UTLS H_2O over the Alpine region, including observations of post Hunga-Tonga water vapor with low-GWP hygrometers, with ~ 21 valid stratospheric measurements so far (analysis in progress). The measurement campaigns are performed in Payerne in synergy with ACTRIS & GRUAN observational activities.
- Low-GWP DIA-CFH occasionally used as reference instead of CFH.
- The fully-electric (GWP=0), 2025 re-designed PCFH achieves similar performance as the CFH reference, with a double inlet design and less preparation efforts.

References

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4. Jucker et al., JCL, 2024
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6. Vömel et al., 2016
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