In-flight validation of the ALBATROSS balloon-borne laser spectrometer for UTLS water vapor

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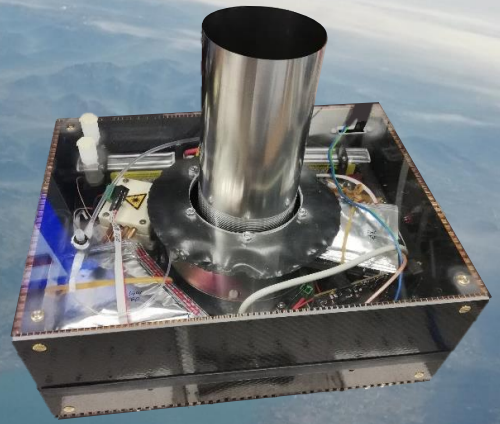
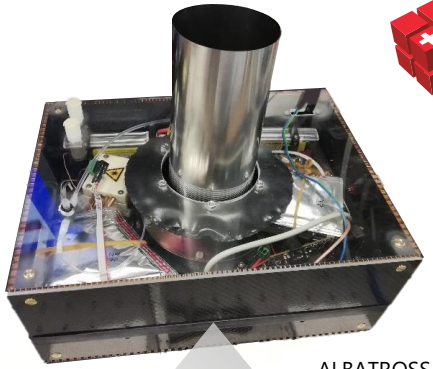


Outline

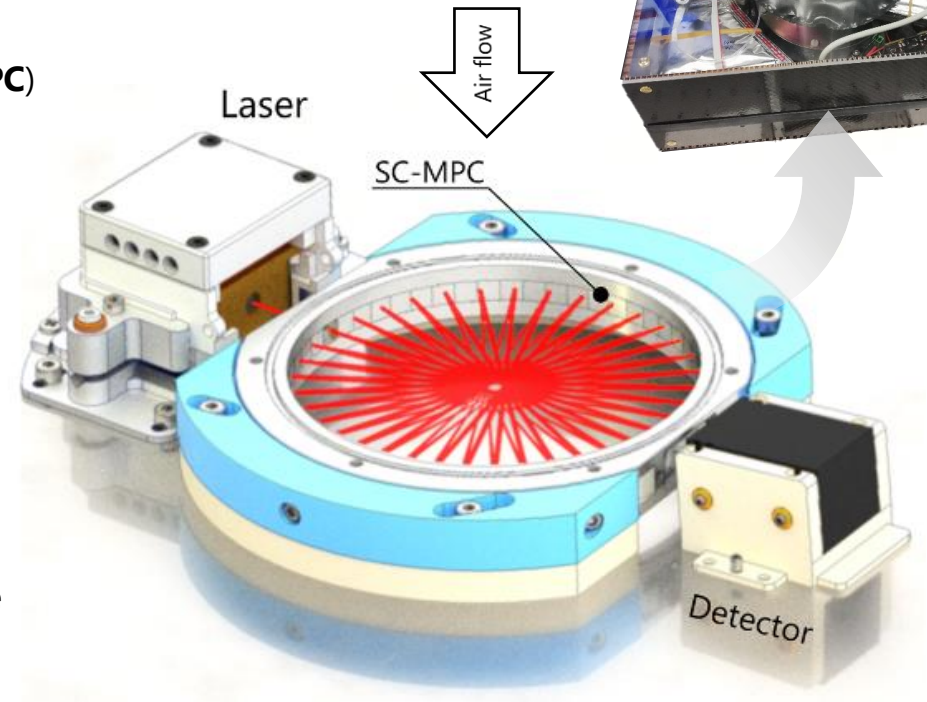
- Instrument description
- The *AquaVIT*-4 intercomparison
- In-flight validation
  - Technical challenges
  - Highlights
  - Statistical comparison
- Summary and conclusions

The ALBATROSS balloon-borne spectrometer

- **Mid-IR** laser absorption spectroscopy
- Quantum cascade laser (**QCL**) at 6.01 µm
- Segmented circular multipass cell (**SC-MPC**)
- **Compact and robust** optical design
- **Lightweight** (3.5 kg)
- Fast response (1 Hz)
- Low power consumption (15 W)
- Two configurations:
  - Closed-path (lab): Closed cell, extractive sampling
  - **Open-path (flight):** Open cell, large flow rate (>1500 SLM)



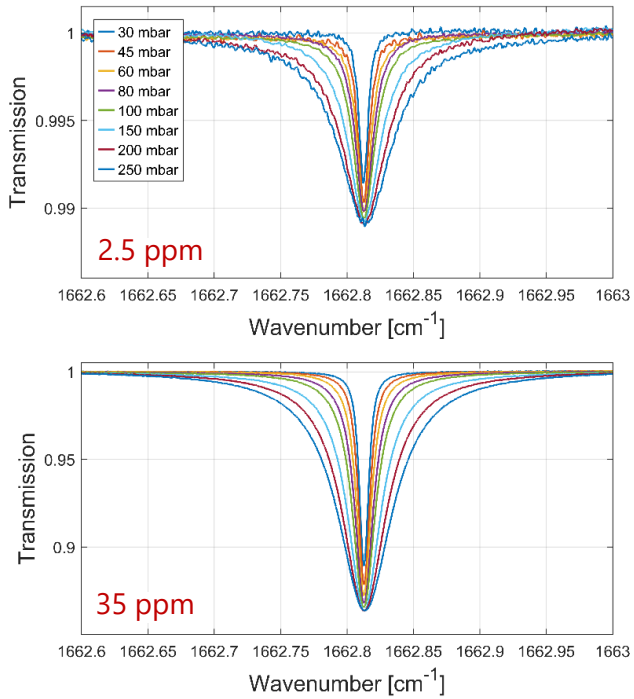
ALBATROSS in flight configuration (**2024**)
Size: 31×23×12 cm^3

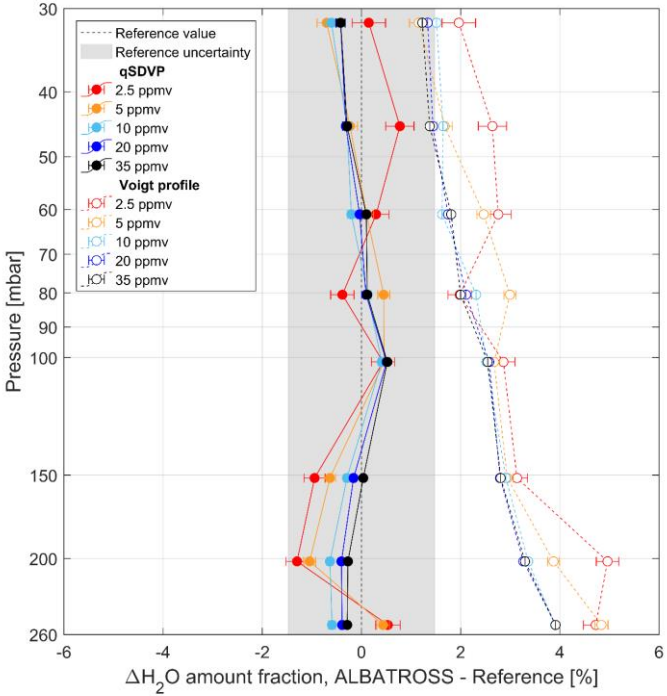


Graf et al., *Atmos. Meas. Tech.*, 14, **2021**

The ALBATROSS balloon-borne spectrometer

- **SI-traceable** reference gases generated by dynamic-gravimetric permeation method
- **UTLS-relevant** conditions (2.5–35 ppm H_2O, 30–250 hPa)
- **Accuracy< ±1.5 %** at all conditions
- **Precision < 30 ppb** (i.e., 0.1 % at 35 ppm) at 1 s resolution

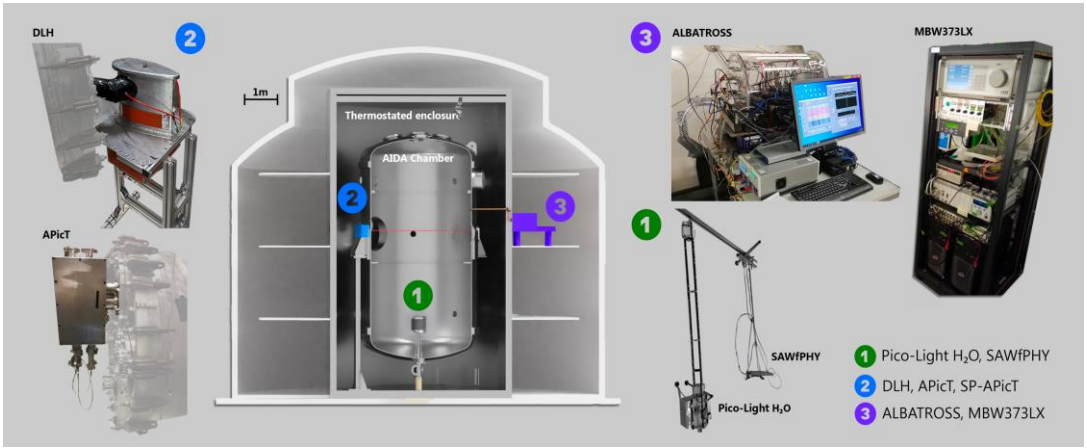




Brunamonti et al., *Atmos. Meas. Tech.*, 16, **2023**

The *AquaVIT*-4 intercomparison

- Held at AIDA climate simulation chamber (KIT, Germany) in 2022
- Four participating hygrometers deployed on stratospheric balloon or aircraft platform
- UTLS-relevant conditions (0.5–500 ppm H_2O, p = 15–500 mbar, T = 185–235 K)
- **Blind intercomparison** (independent referees)

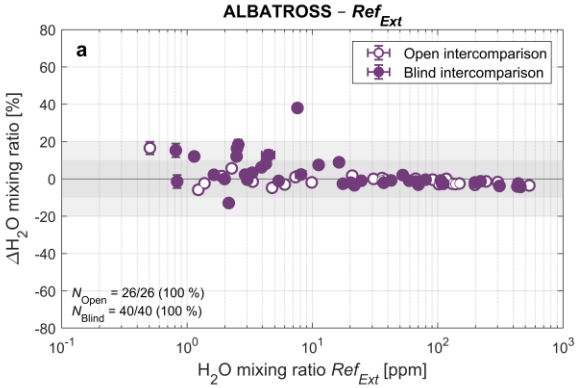


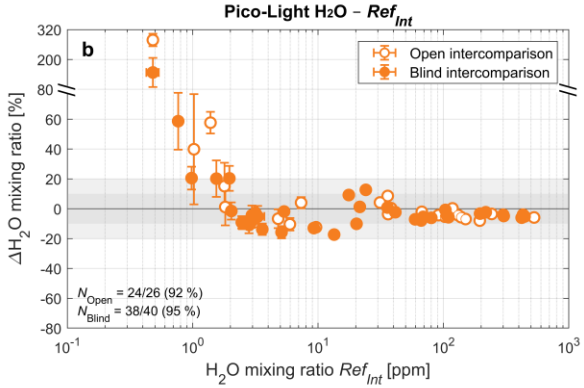
Instrument	*Institute*	*Technique*
APicT	KIT, Germany	TDLAS (1.37 µm)
SP-APicT	KIT, Germany	TDLAS (1.37 µm)
MBW373LX	KIT, Germany	Dewpoint mirror hygrometry
ALBATROSS	Empa, CH	QCLAS (6.01 µm)
DLH	NASA, USA	TDLAS (1.39 µm)
Pico-Light H_2O	CNRS, France	TDLAS (2.63 µm)
SAWfPHY	LMD, France	Frostpoint hygrometry

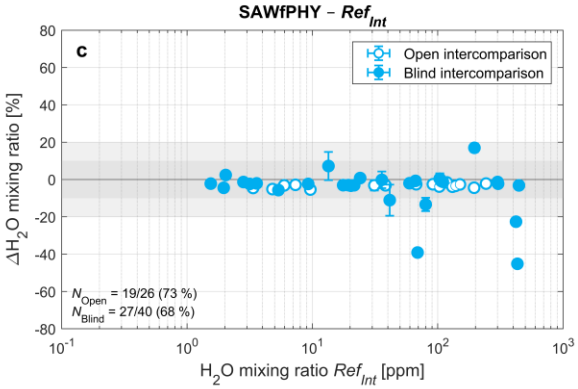
Brunamonti et al., *Atmos. Meas. Tech.*, 18, **2025**

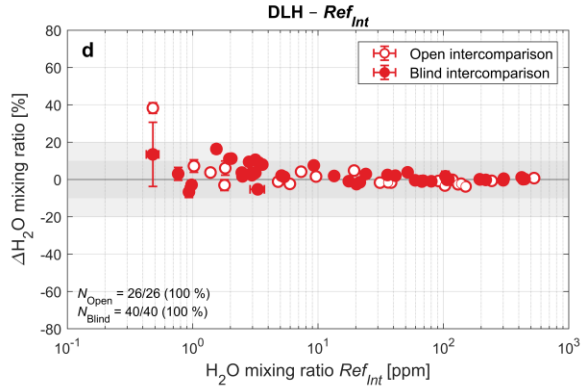
The *AquaVIT*-4 intercomparison

Results:
Accuracy





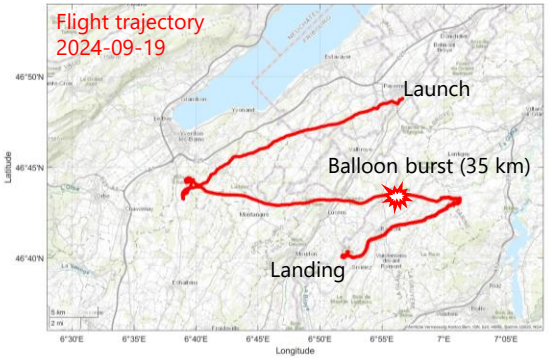


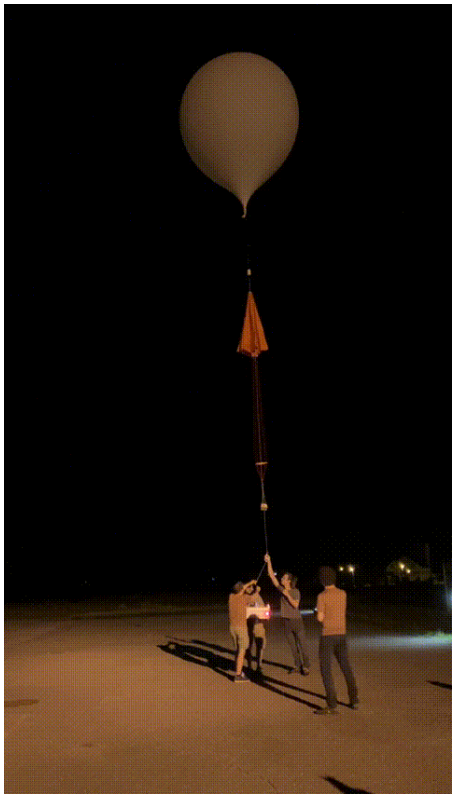


Brunamonti et al., *Atmos. Meas. Tech.*, 18, **2025**

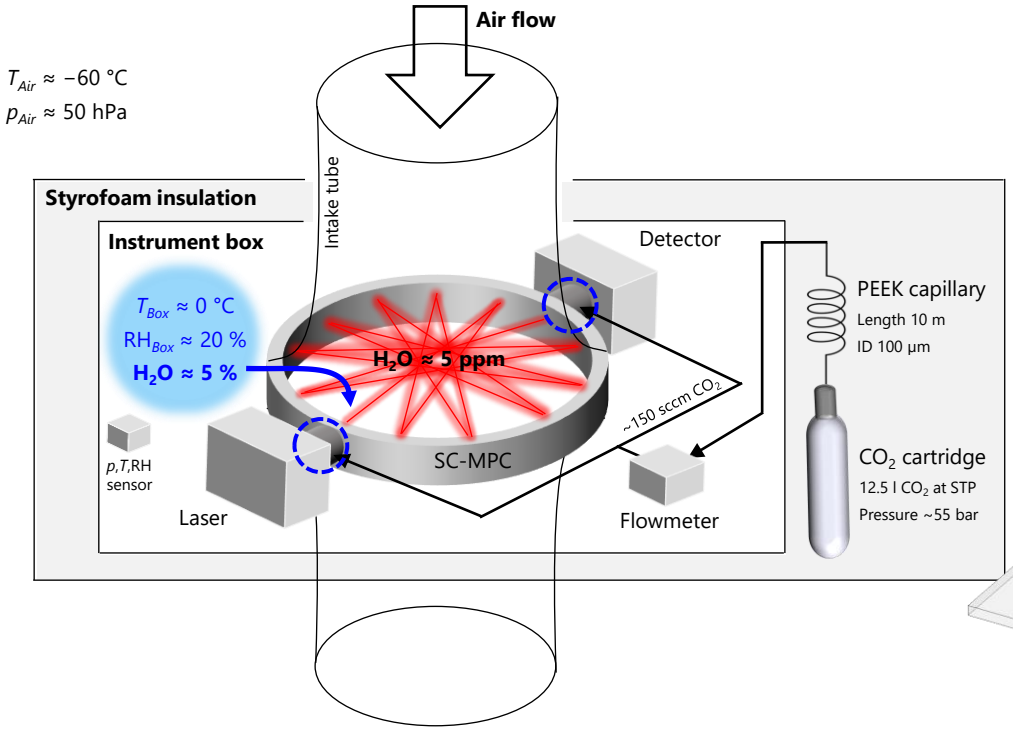
In-flight validation

- Five test flights performed from MeteoSwiss Payerne Observatory within the ***Swiss H_2O-Hub*** project in 2023-2025
- Payload: cryogenic frostpoint hygrometer (**CFH**), Vaisala RS41
- Balloon burst up to **35 km** altitude (pressure ~5 hPa)
- **ALBATROSS recovery mandatory** → Accurate flight planning and landing point prediction required!





Technical challenges: Self-contamination

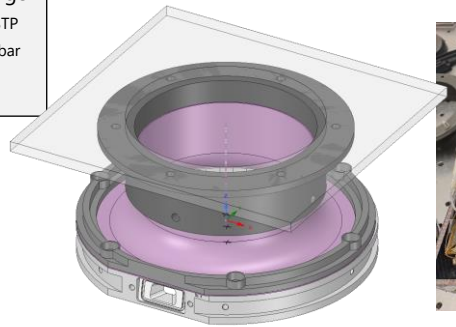


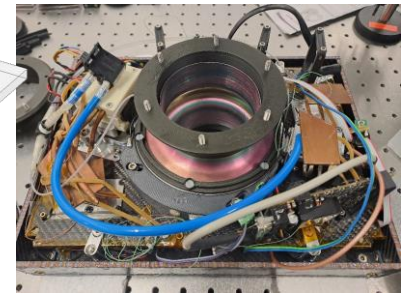
1. Outside-cell absorption

- Absorption contribution from H_2O outside the SC-MPC
- "Connectors" to shield the internal optical path from H_2O in the box
- **In-flight purging** by CO_2 cartridge (25 g) coupled to PEEK capillary

2. Box-to-cell "leakage"

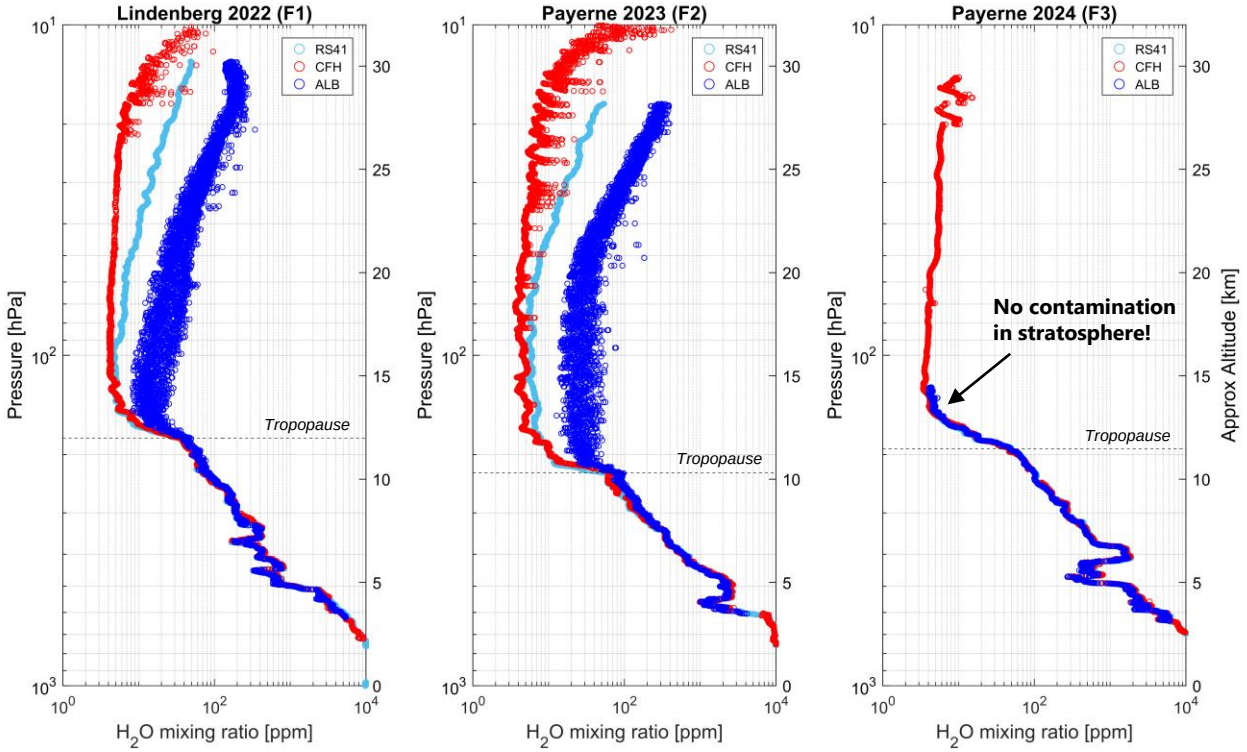
- Improved leak tightness by revised intake tube design



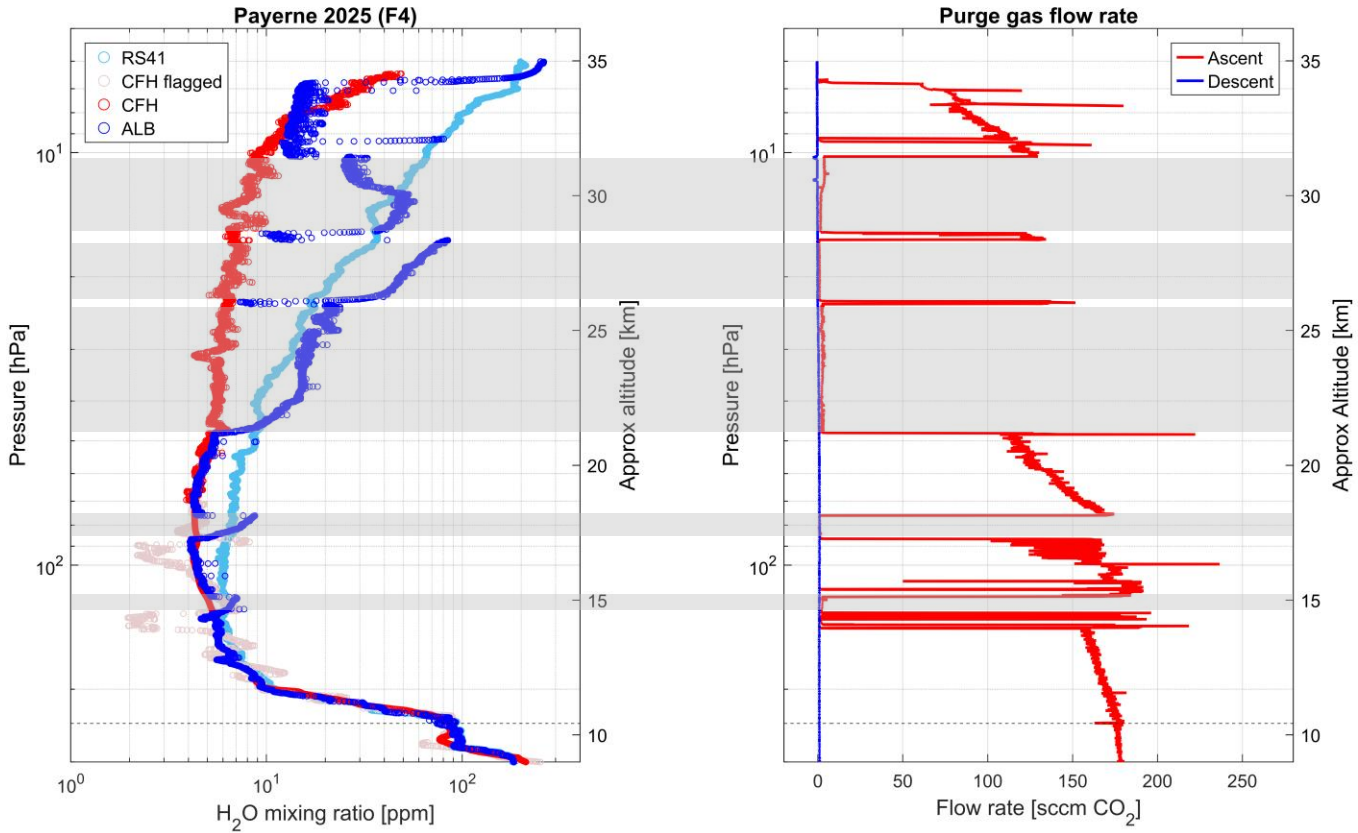


Flight 18 June 2024 (F3)

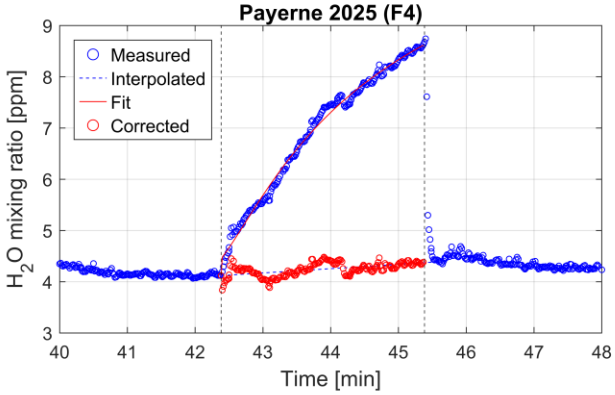
- CFH flown in parallel on separate balloon (weight restrictions)
- Payload released by cutter at **15.5 km** altitude due to geofence
- **No contamination** in the stratosphere
- **Good agreement** with CFH (±10 %)

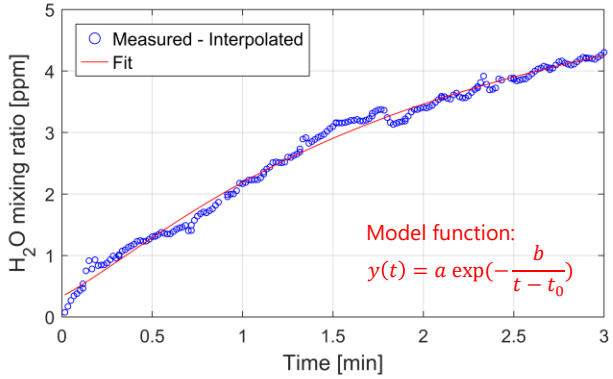


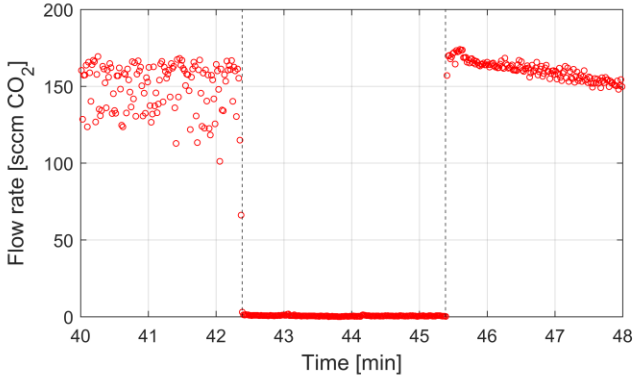
Flight 19 Sept 2024 (F4)

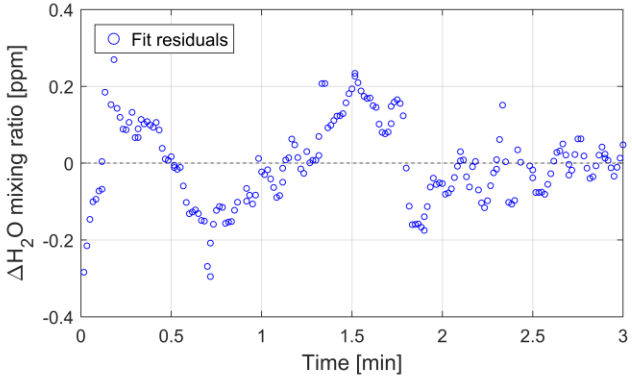


Flight 19 Sept 2024 (F4)









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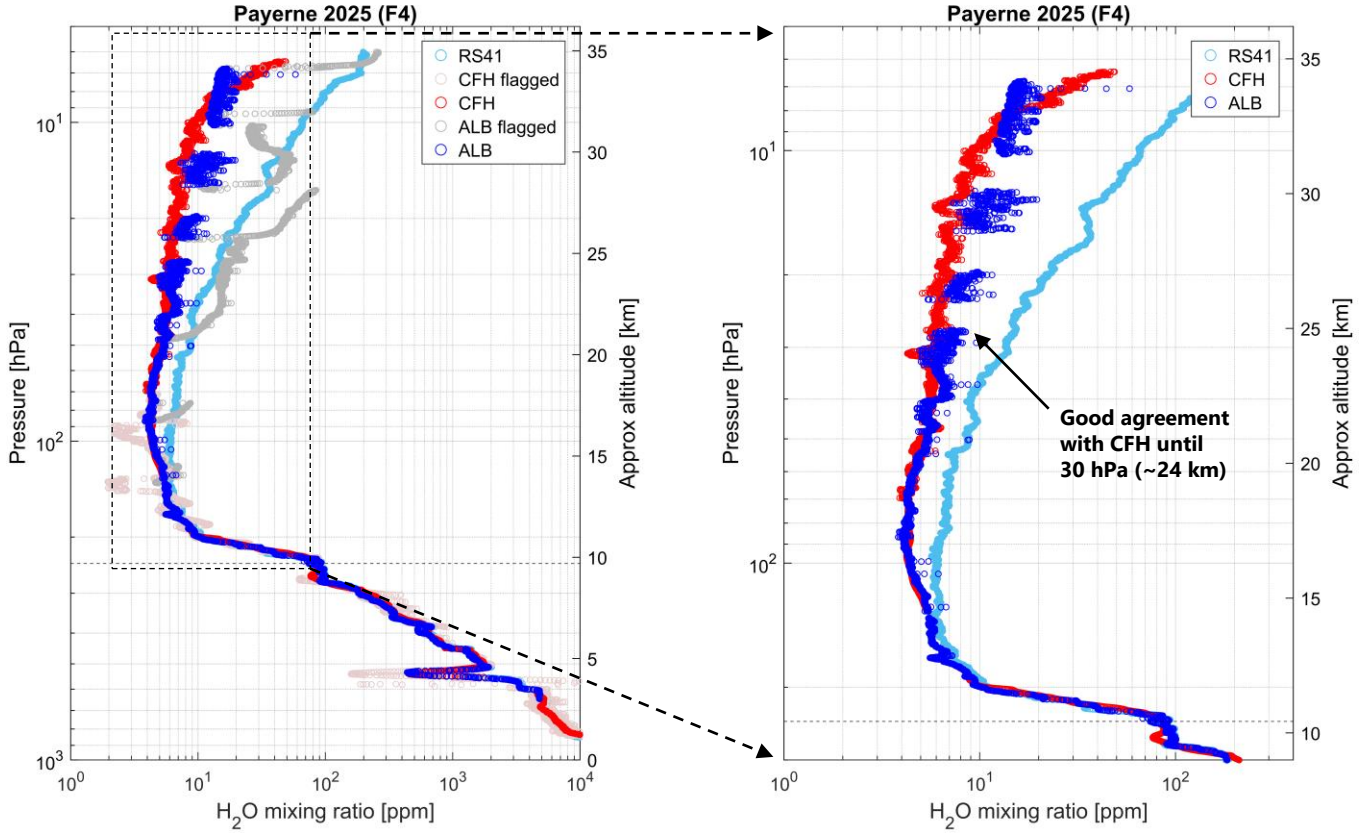
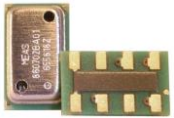


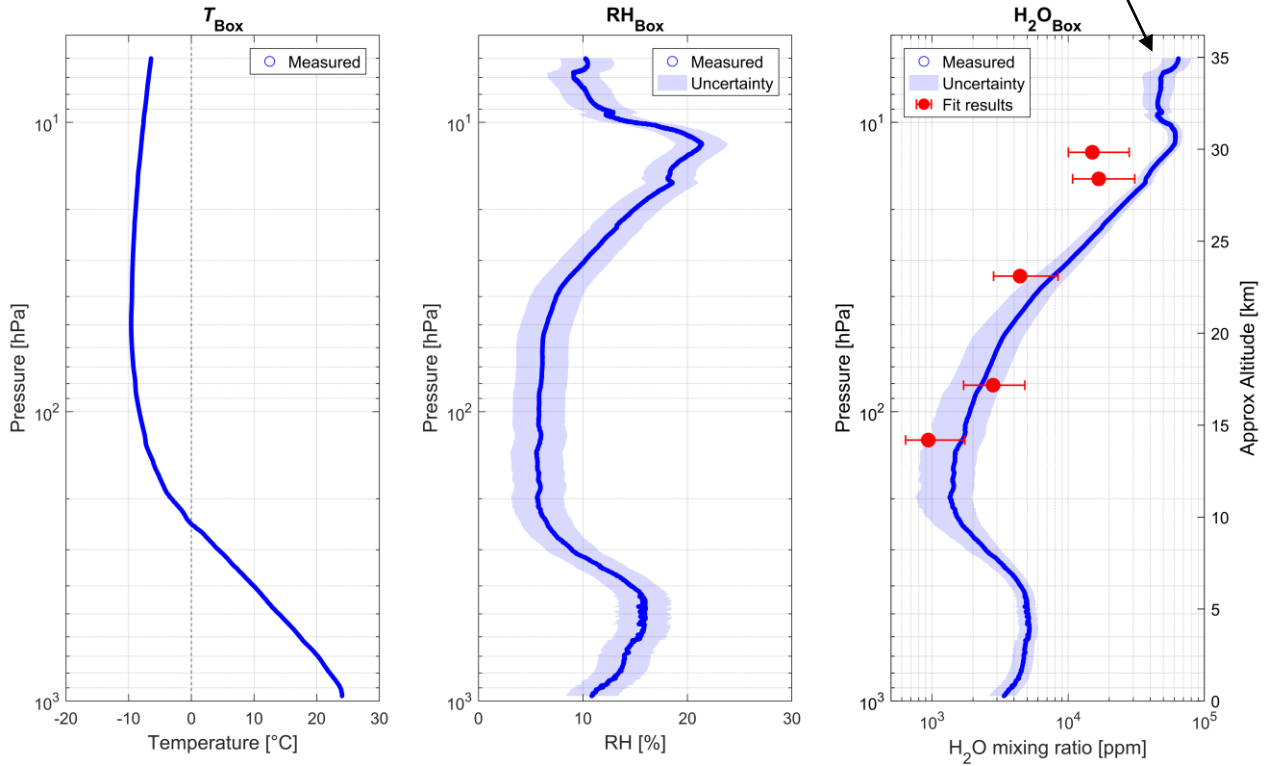
Flight 19 Sept 2024 (F4)

- Housekeeping parameters (p, T, RH) inside ALBATROSS box measured by PCB sensor



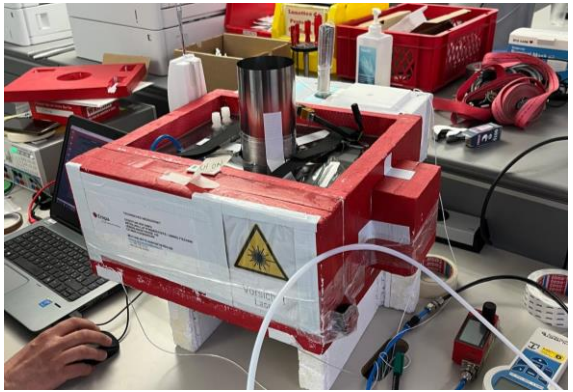
MS8607 (TE Connectivity, USA)
https://www.te.com/en/product-MS860702BA01-50.html

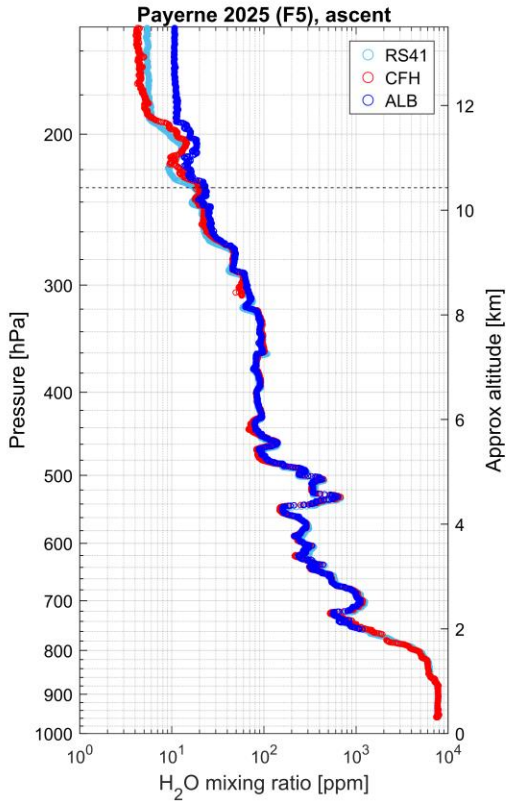
- PCB RH data calibrated using lab measurements against Vaisala HMP110 sensor
- Reasonable agreement between H_2O_{Box} measured by PCB sensor and diffusion model results

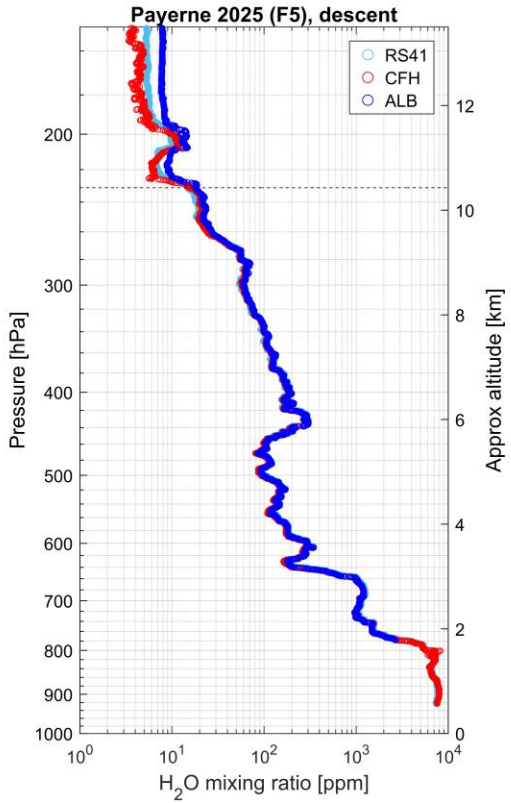


Flight 27 March 2025 (F5)

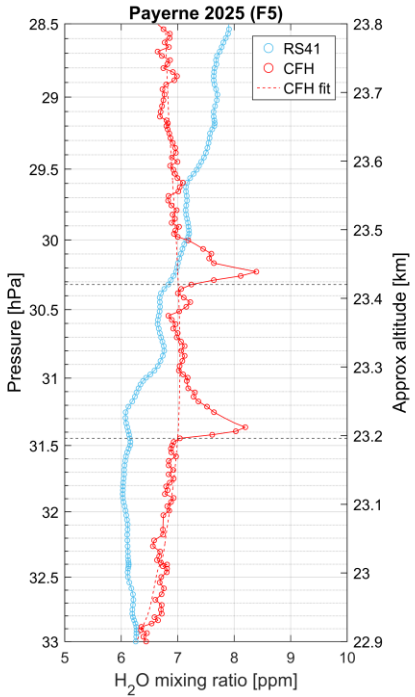
- First time ALBATROSS and CFH on the **same balloon** (payload weight ~6 kg)
- Purge gas flow stopped at ~9 km ascent → No good stratospheric data
- Excellent agreement with CFH in troposphere, both ascent and descent

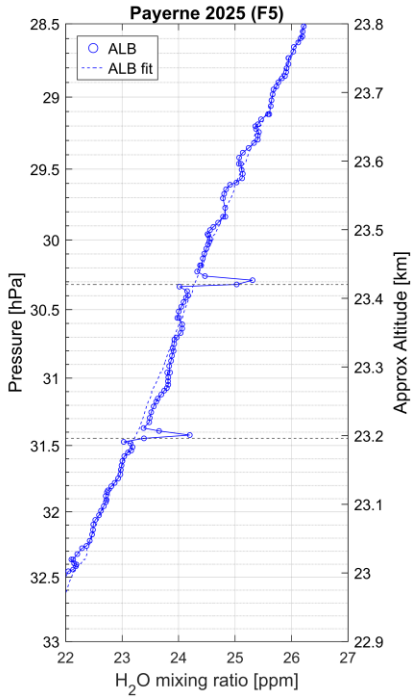


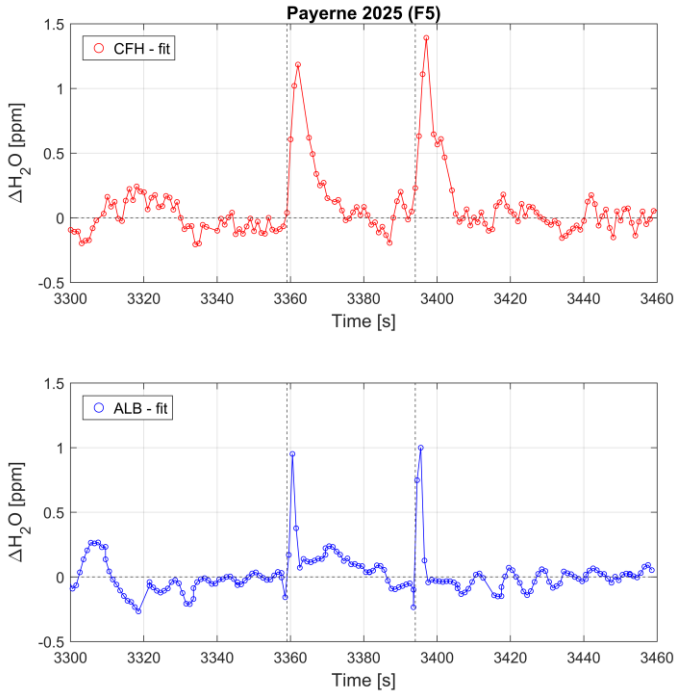




Flight 27 March 2025 (F5)



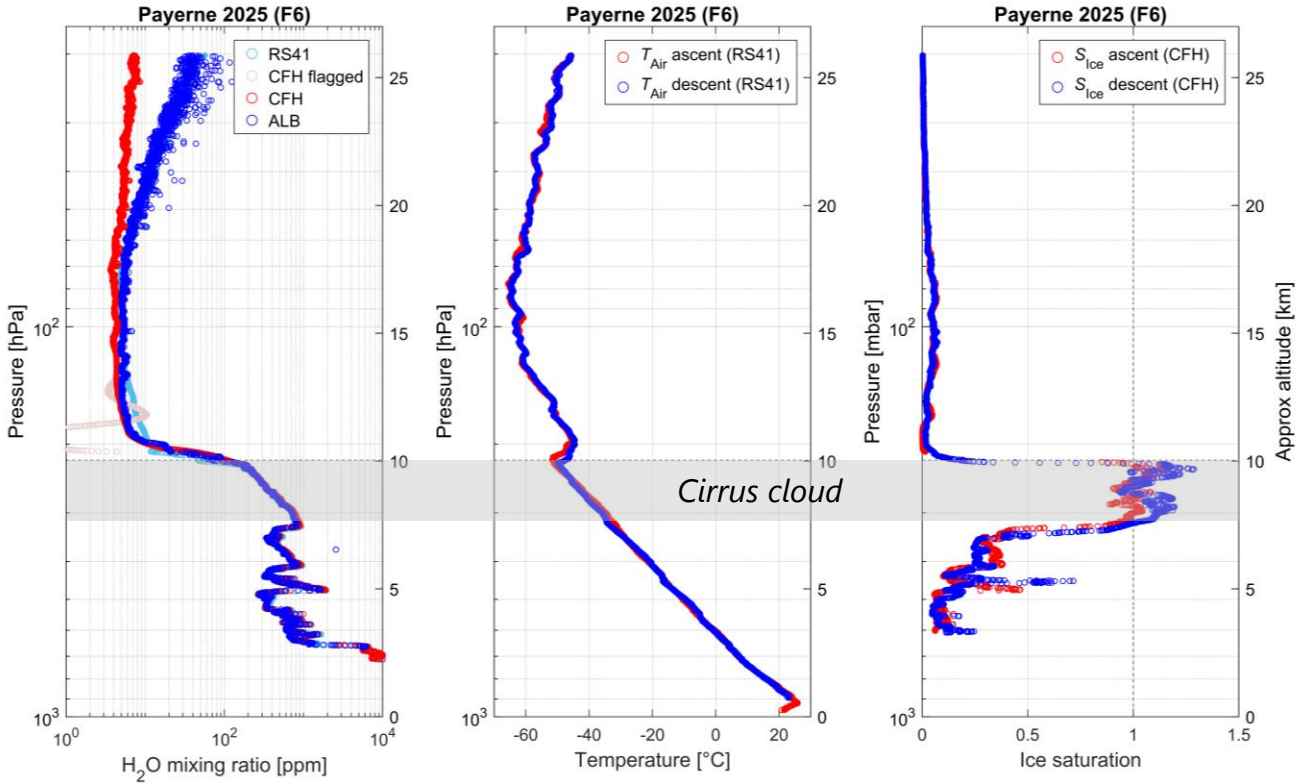




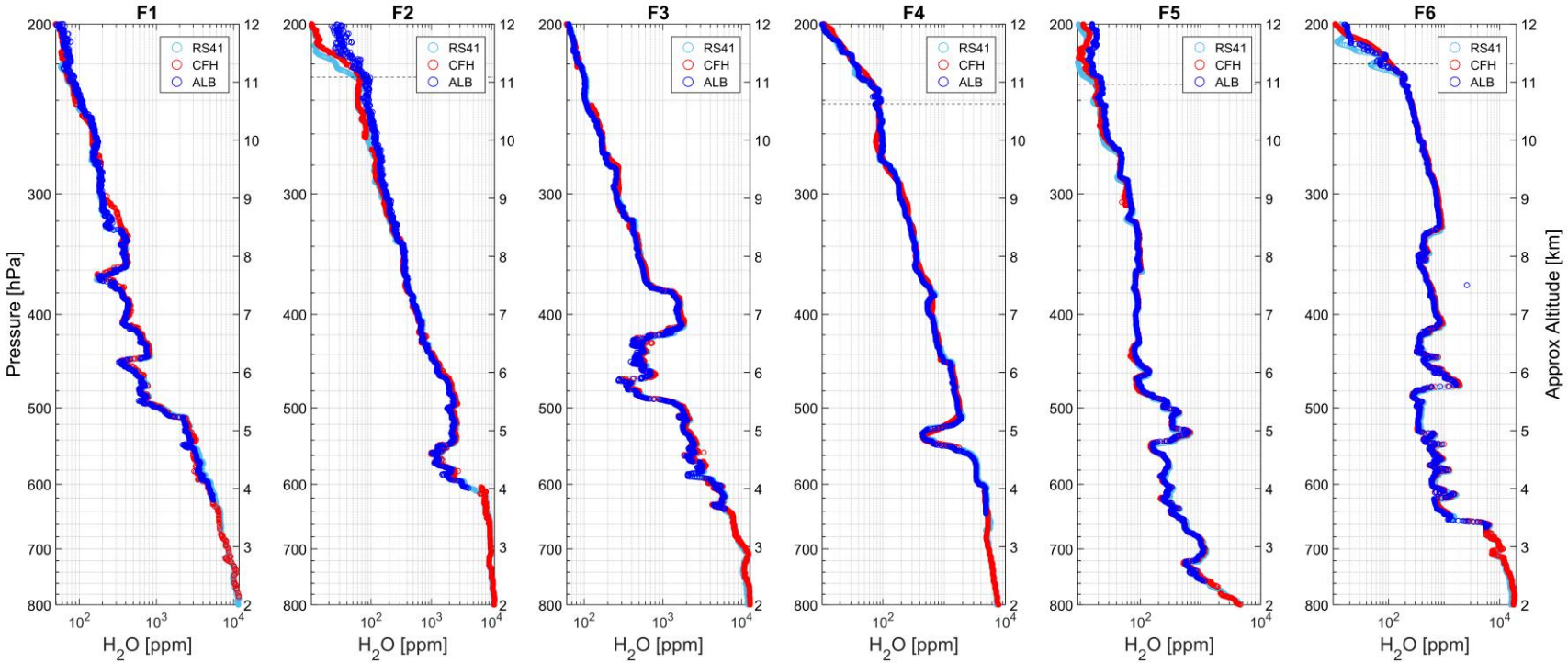
- Two consecutive **"balloon spikes"** (~1 ppm) observed by both ALBATROSS and CFH at ~23 km altitude
- ALBATROSS shows **3× faster response time** (~3 s) compared to CFH (~10 s)

Flight 1 July 2025 (F6)

- **Cirrus cloud** crossed below the tropopause (thickness ~2 km)
- Cloud bottom temperature **−32°C** → Likely presence of supercooled water
- **Contamination** observed in the stratosphere: due to cirrus cloud?



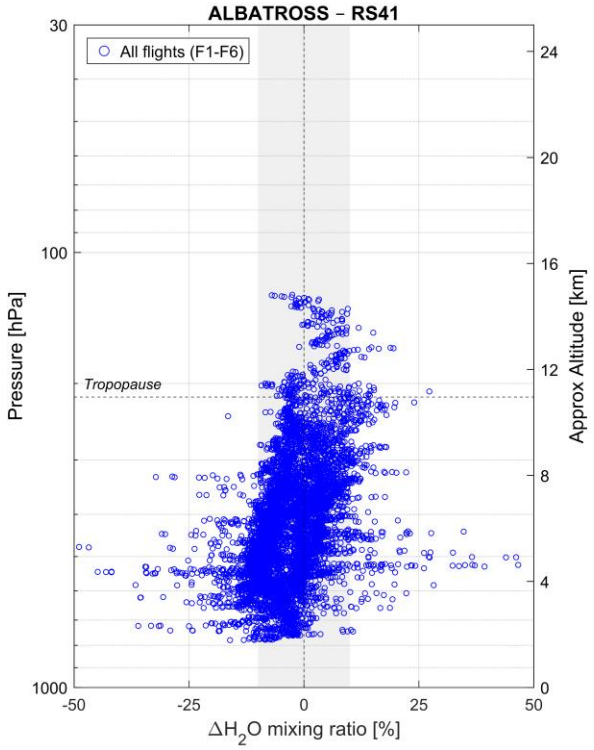
Statistical comparison

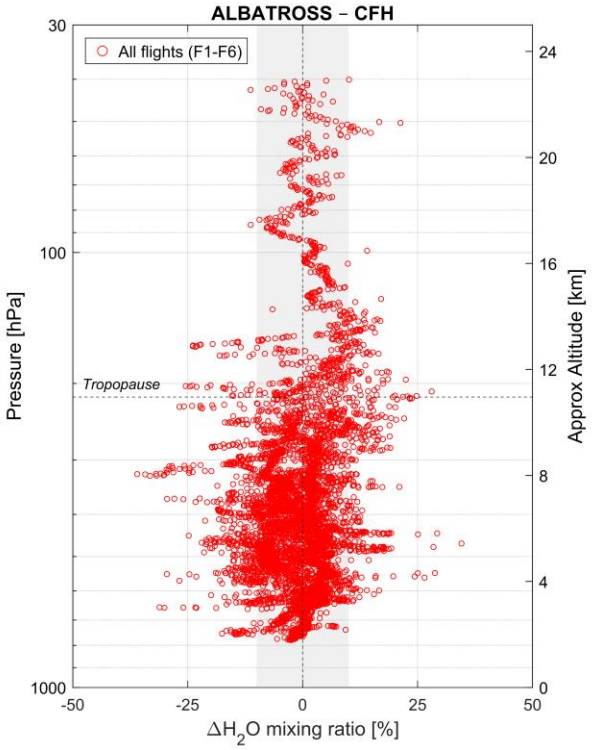


Statistical comparison

- All flights (F1-F6), both ascent and descent
- Excluded: ALBATROSS contaminated intervals, CFH flagged intervals, RS41 stratospheric data below limit of detection
- Mean deviations:

ALBATROSS – RS41	
Troposphere (0-12 km)	−3 ± 8 %
ALBATROSS – CFH	
Troposphere (0-12 km)	−1 ± 8 %
Stratosphere (12-24 km)	+3 ± 7 %





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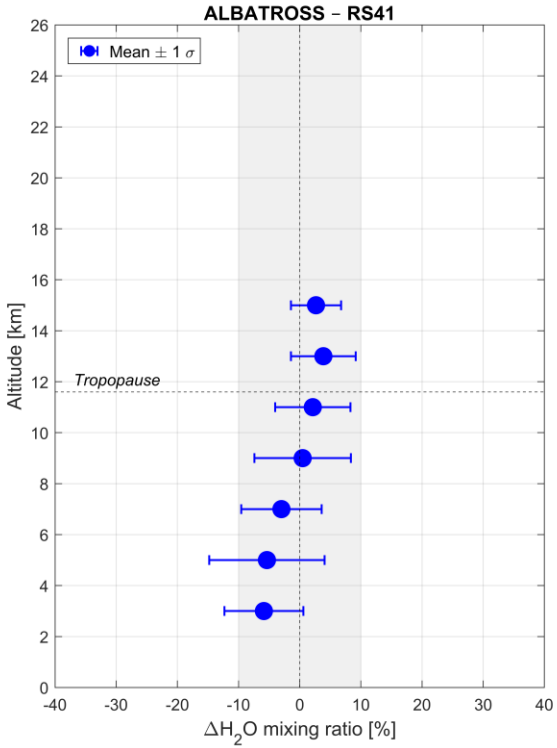

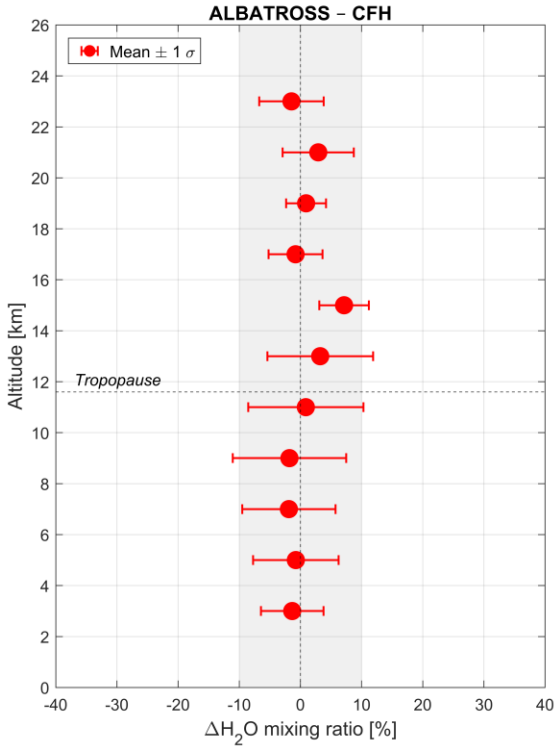

Summary and conclusions

- **ALBATROSS** is a lightweight (3.5 kg), mid-IR laser absorption spectrometer for balloon-borne measurements of **UTLS H_2O**
- Outstanding performance achieved in laboratory-based validation (**SI-traceable, *AquaVIT*-4**) at UTLS-relevant conditions (accuracy < 1.5 %, precision < 30 ppb)
- **In-flight validation** ongoing in Payerne (Switzerland) within the *Swiss H_2O-Hub* project:
  - Five successful test flights conducted in 2023-2025
  - **Good agreement** (±10 %) with CFH until ~25 km altitude
  - "Balloon spikes" analysis reveals **faster response time** of ALBATROSS compared to CFH
  - Self-contamination still to be minimized (in-flight purging system)
  - Fingers-crossed for more test flights in 2025–2026!

Thanks for your attention!

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