# The ALBATROSS laser spectrometer for balloon-borne measurements of UTLS water vapor: Laboratory and in-flight validation

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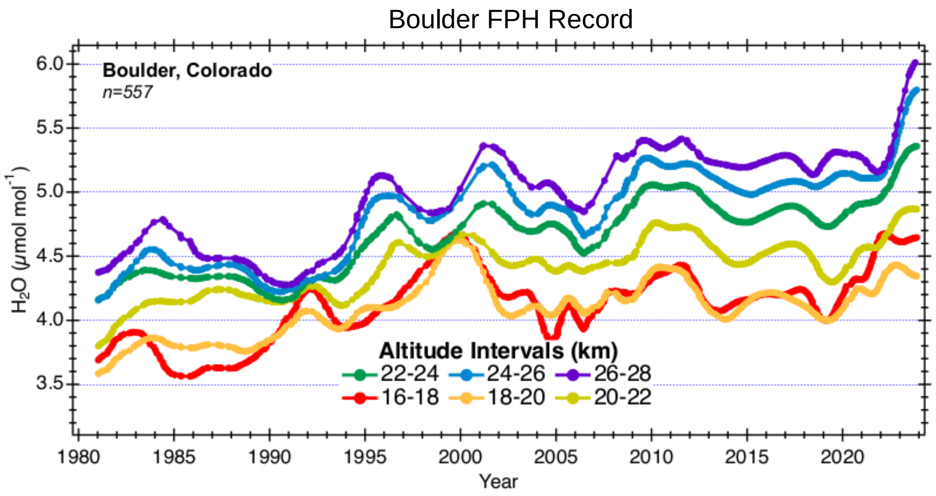
Materials Science and Technology

# Outline

- Motivation
- ALBATROSS instrument description
- Laboratory-based validation
- In-flight validation
- Conclusions and outlook

# UTLS water vapor and climate

- Water vapor (**$H_2O$**) is the strongest natural greenhouse gas in the Earth's atmosphere
- In the **UTLS** (upper troposphere−lower stratosphere):
  - Small changes in $H_2O$ have a strong impact on global surface warming (e.g., Solomon *et al.*, 2010)
  - Microphysical processes (cirrus clouds) determine the $H_2O$ content of the stratosphere
- **Accurate measurements** of UTLS $H_2O$ are crucial for reliable climate predictions




Hurst *et al.*, 2023

# Balloon-borne measurements of UTLS water vapor

## GCOS 2022 ECVs Requirements (GCOS-245)

2-σ uncertainty @ vertical resolution and long-term stability for quantity of interest

| | UT/LS | Middle Stratosphere & Mesosphere |
|---|---|---|
| **Goal**<br>2% MR @ 10 m | **0.5 %RHi @ 10 m**<br>**0.1 p**<br>*<0.5*<br>*<0.1 ppmv / decade* | *<0.2 ppmv / decade* |
| **Breakthrough**<br>5% MR @ 100 m | **1.0 %RHi @ 100 m**<br>**0.25 ppmv @ 100 m**<br>*0.5 %Rhi / decade*<br>*0.1 ppmv / decade* | **0.25 ppmv @ 1000 m**<br>*0.2 ppmv / decade* |
| **Threshold**<br>10% MR @ 250 m | **2.0 %RHi @ 250 m**<br>**0.5 ppmv @ 250 m**<br>*2.0 %*<br>*0.25 ppmv / decade* | **0.5 ppmv @ 3000 m**<br>*0.5 ppmv / decade* |

**ALBATROSS laboratory validation**
Brunamonti *et al.*, 2023

**CFH/FPH**

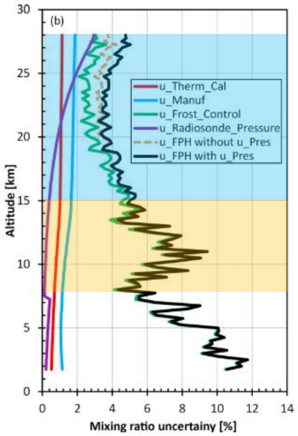
**CFH/FPH**

GCOS GLOBAL CLIMATE OBSERVING SYSTEM

## Cryogenic frostpoint hygrometer (CFH/FPH)

- Current reference instrument in GRUAN
- Ongoing transition from R23 to alternative low-GWP coolant (ethanol/dry ice)

EnSci, USA

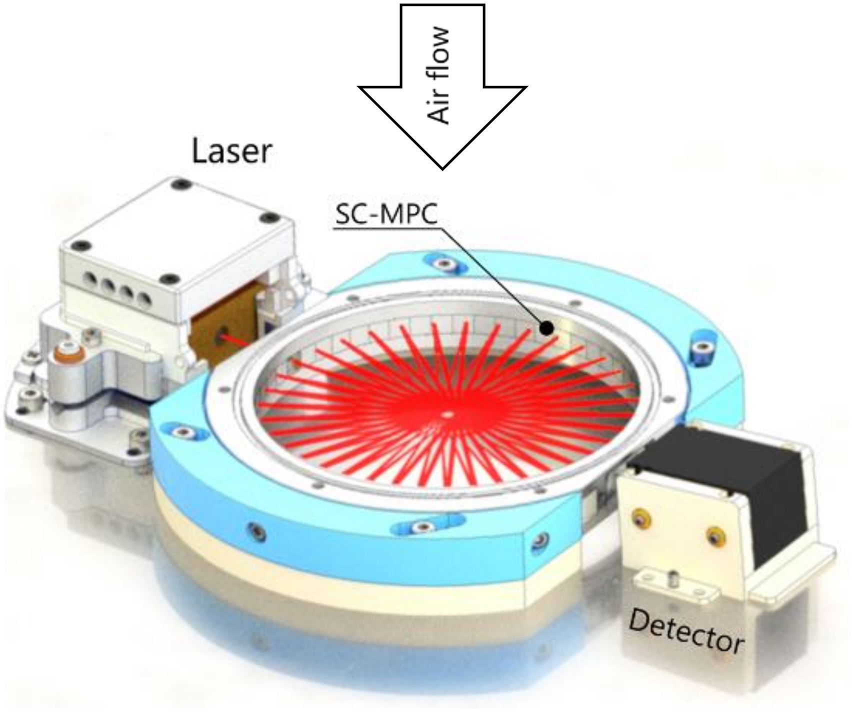



Hall et al., 2016

# ALBATROSS laser spectrometer for UTLS water vapor

- Mid-IR laser absorption spectroscopy
- Compact and robust optical design
- Lightweight (< 3.5 kg)
- Fast response (1 Hz)
- Calibration-free retrieval

| | |
|---|---|
| *SC-MPC diameter* | 10.8 cm |
| *Optical path length* | 6 m |
| *Sampling technique* | Open-path |
| *$H_2O$ transition used* | 1662.8 $cm^{-1}$ ($\lambda \approx 6$ µm) |
| *QCL tuning range* | ~1 $cm^{-1}$ (ICW driving) |
| *Acquisition rate* | 1 Hz |
| *Acquisition method* | 3000 co-averaged spectra |
| *Power consumption* | 15 W |
| *Total weight* | 3.45 kg (w/insulation) |




Graf *et al.*, 2021

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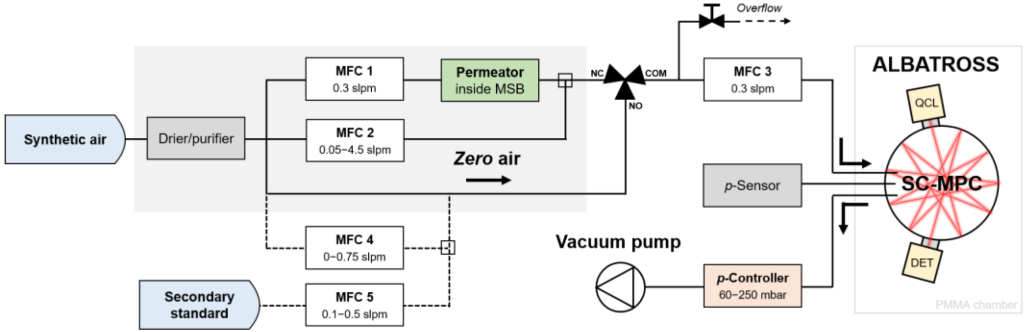
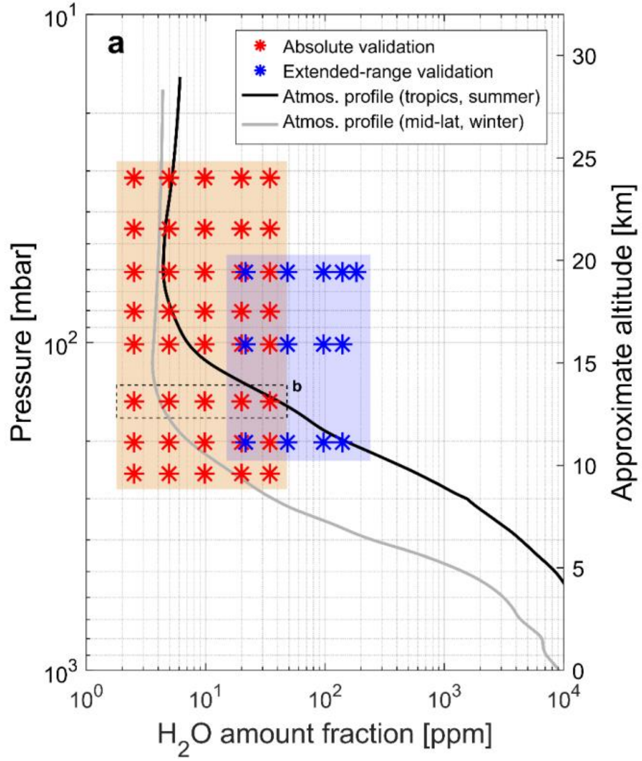
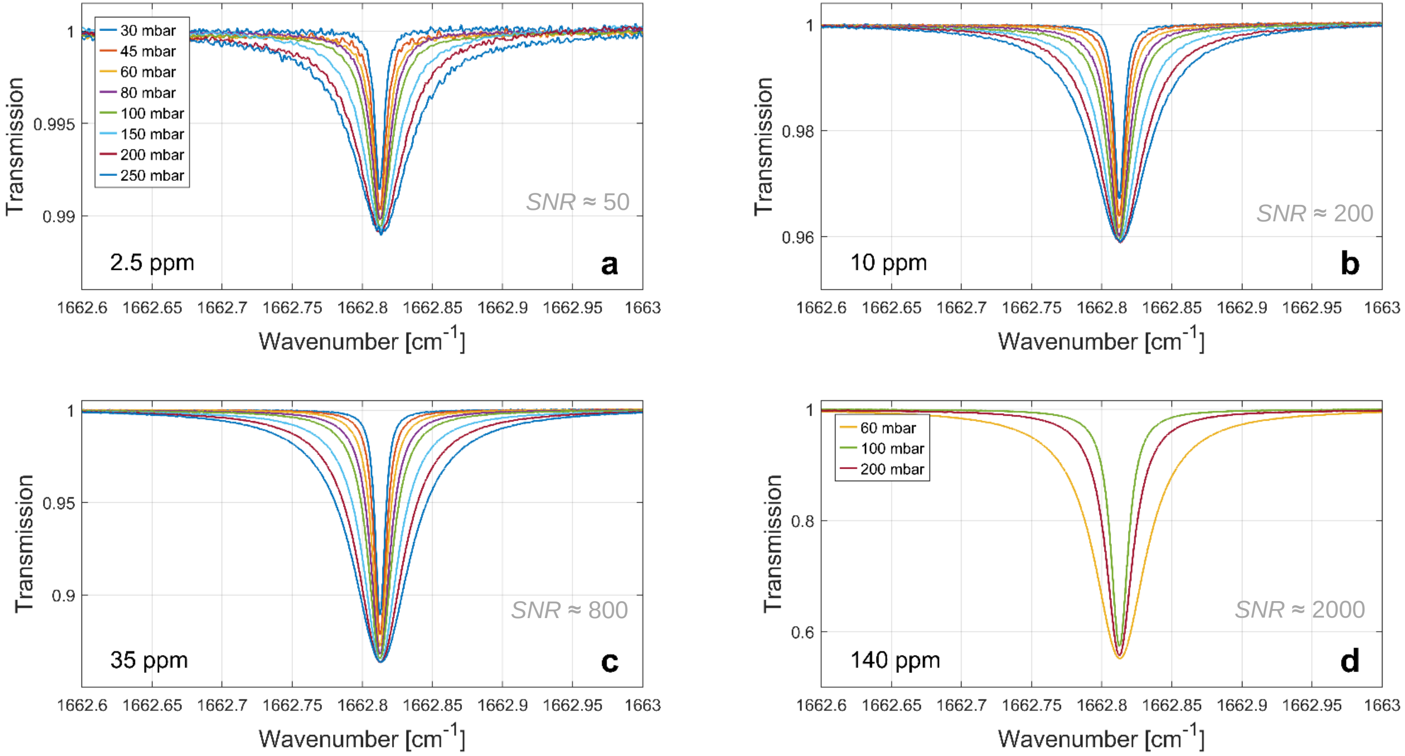
# Laboratory-based validation

- Collaboration with METAS (Swiss Federal Institute of Metrology)
- **SI-traceable** reference gases generated by dynamic-gravimetric permeation method
- **UTLS-relevant** conditions:
  - 2.5–35 ppm $H_2O$ (uncertainty < 1.5 %)
  - 30–250 hPa pressure



# Measured spectra




Integration time = 50 s

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# Spectroscopic retrieval

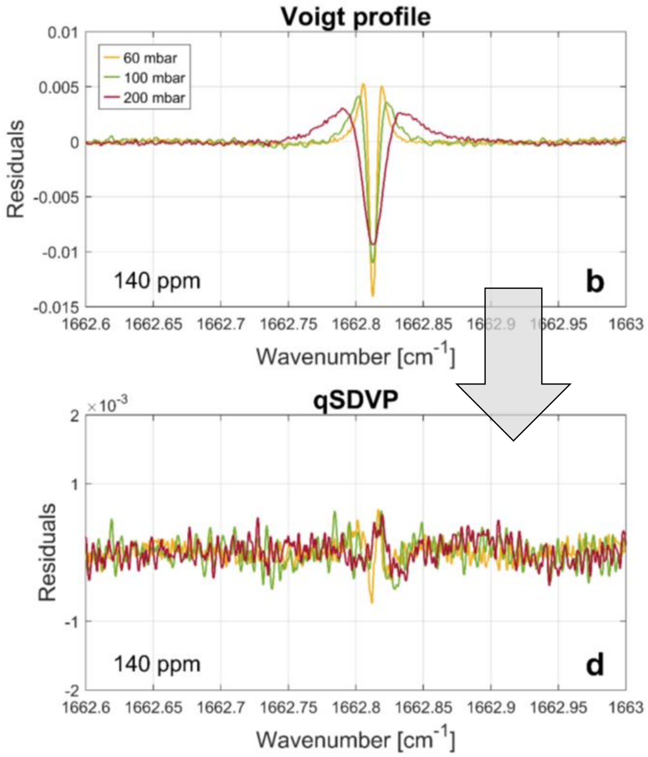
- $H_2O$ amount fraction retrieved by minimizing the **fitting residuals** (i.e., observed spectra – model function)
- Required input:
  - Environmental parameters (*p*, *T*, OPL)
  - Molecular parameters (line-specific)
  - Line shape model

**Voigt profile**

- Standard line shape model in spectroscopy
- Molecular parameters available in HITRAN database

**Quadratic Speed-Dependent Voigt profile (qSDVP)**

- Includes molecular-speed dependence of collisional broadening
- Molecular parameters *not available* in the literature → **Determined empirically**

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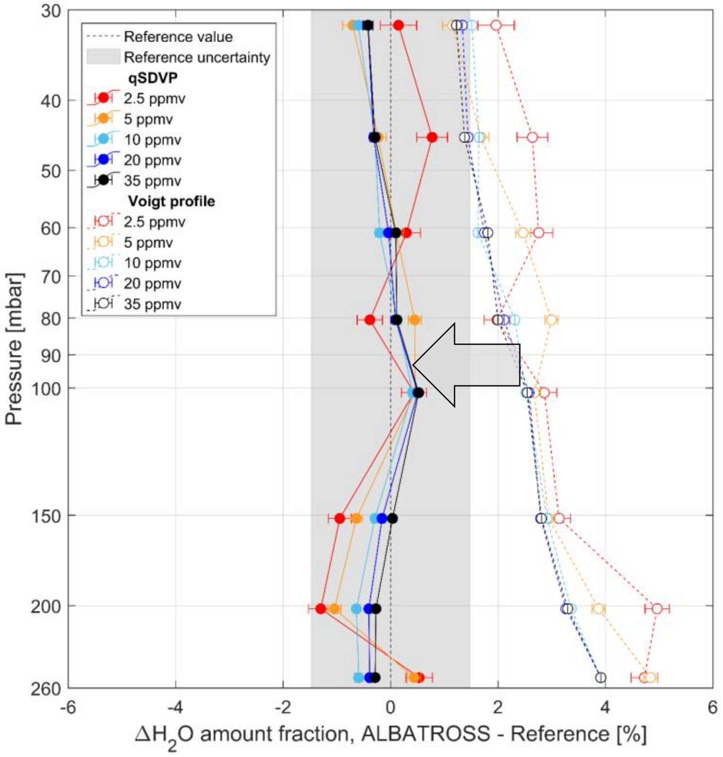
# Results: Accuracy

**Voigt profile**

- $H_2O$ amount fractions overestimated by up to **+5 %** compared to the reference
- Bias correlated with pressure

**qSDVP**

- All retrieved $H_2O$ amount fractions within the uncertainty range of the reference (**± 1.5 %**)
- No pressure-dependent bias

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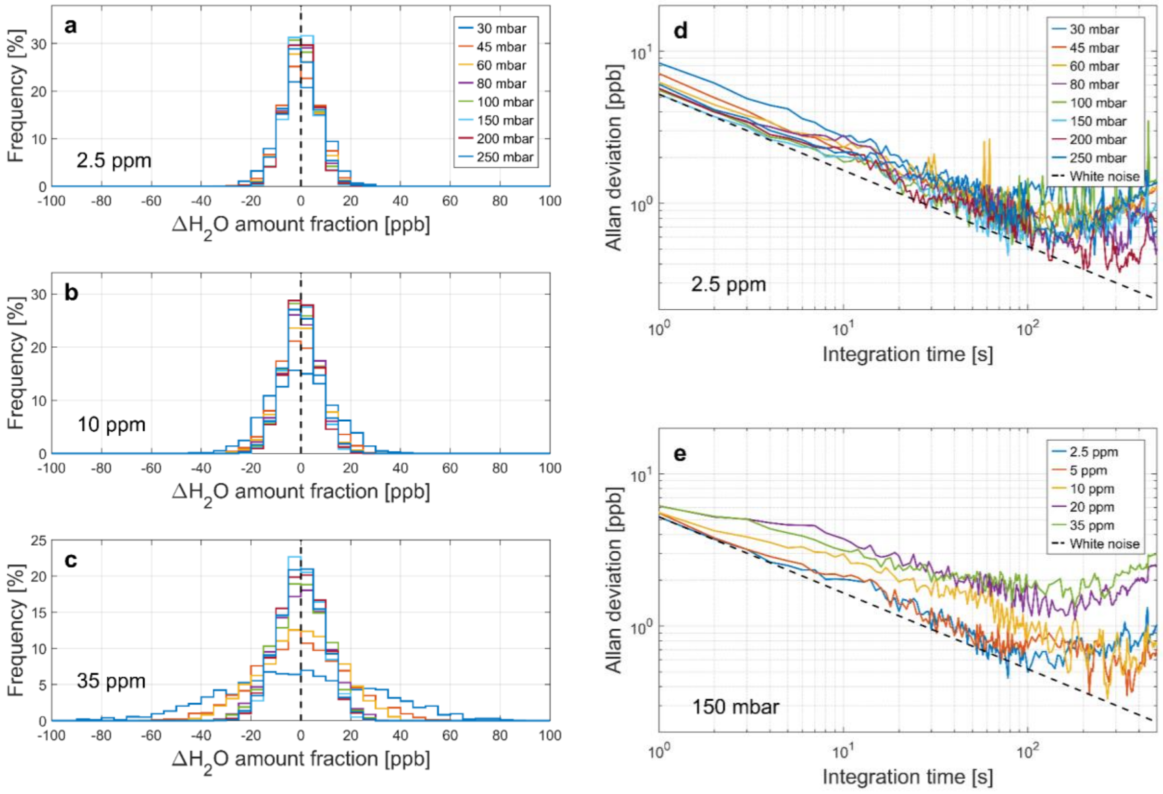
# Results: Precision and long-term stability




- Precision at 1 s resolution better than **30 ppb** $H_2O$ (i.e., 0.1 % at 35 ppm $H_2O$)
- Best precision of **5 ppb** $H_2O$ achieved by integrating in time ~50 s (Allan minimum)

Brunamonti *et al.*, 2023

# In-flight validation

- Two test flights performed with current prototype:
  - Lindenberg (DE), 7 Sept 2022
  - Payerne (CH), 17 Aug 2023 (*Swiss $H_2O$-Hub* project)
- Each consisting of two balloons flown simultaneously:
  - ALBATROSS / RS41
  - CFH / RS41 / Others (COBALD, PCFH)
- Burst altitude 28−30 km (balloon size 2000−3000 g)
- Payload **recovery mandatory** (no telemetry)
  - Careful flight planning and accurate landing point forecast required

ALBATROSS/RS41 payload

# In-flight validation

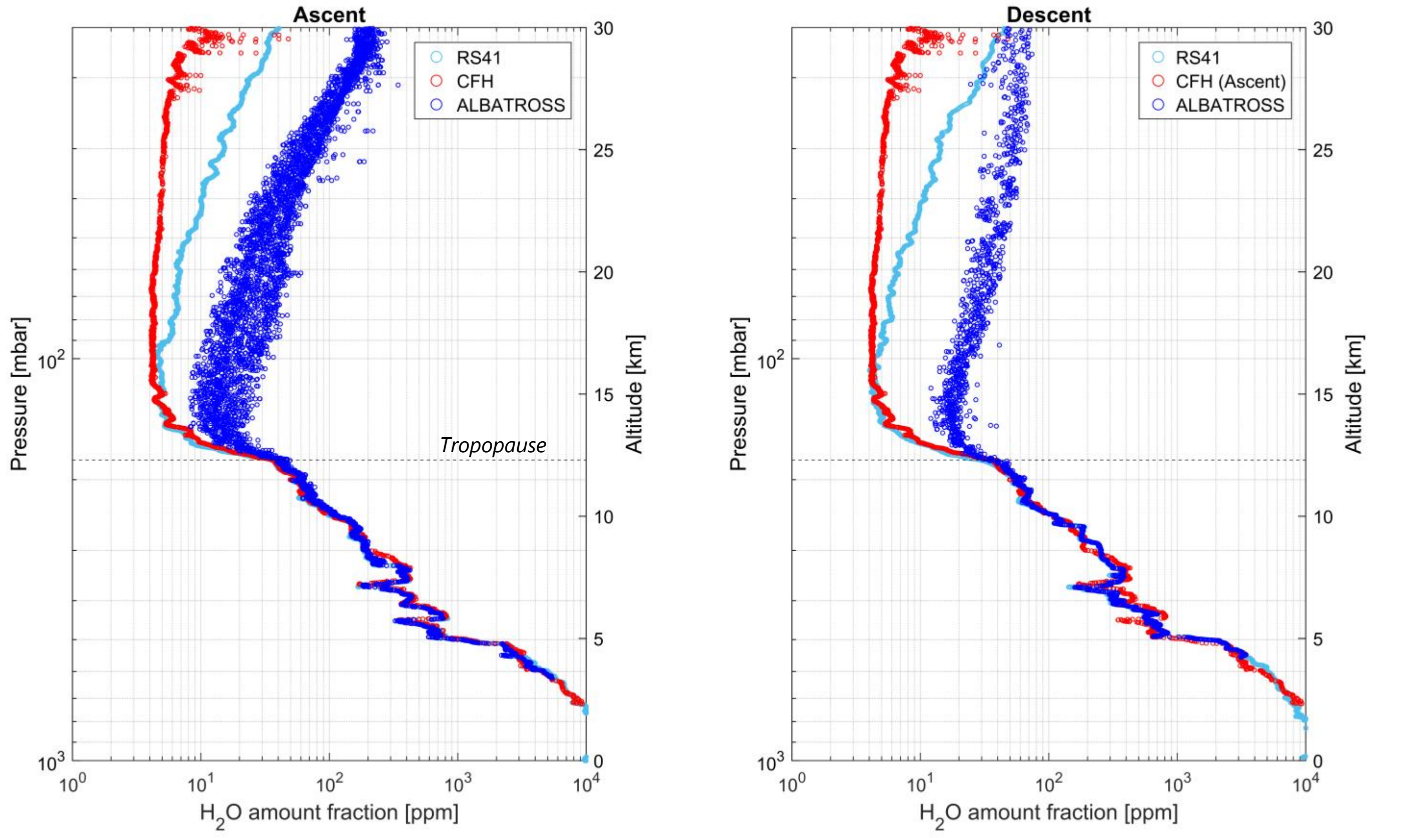

Lindenberg 2022


Payerne 2023

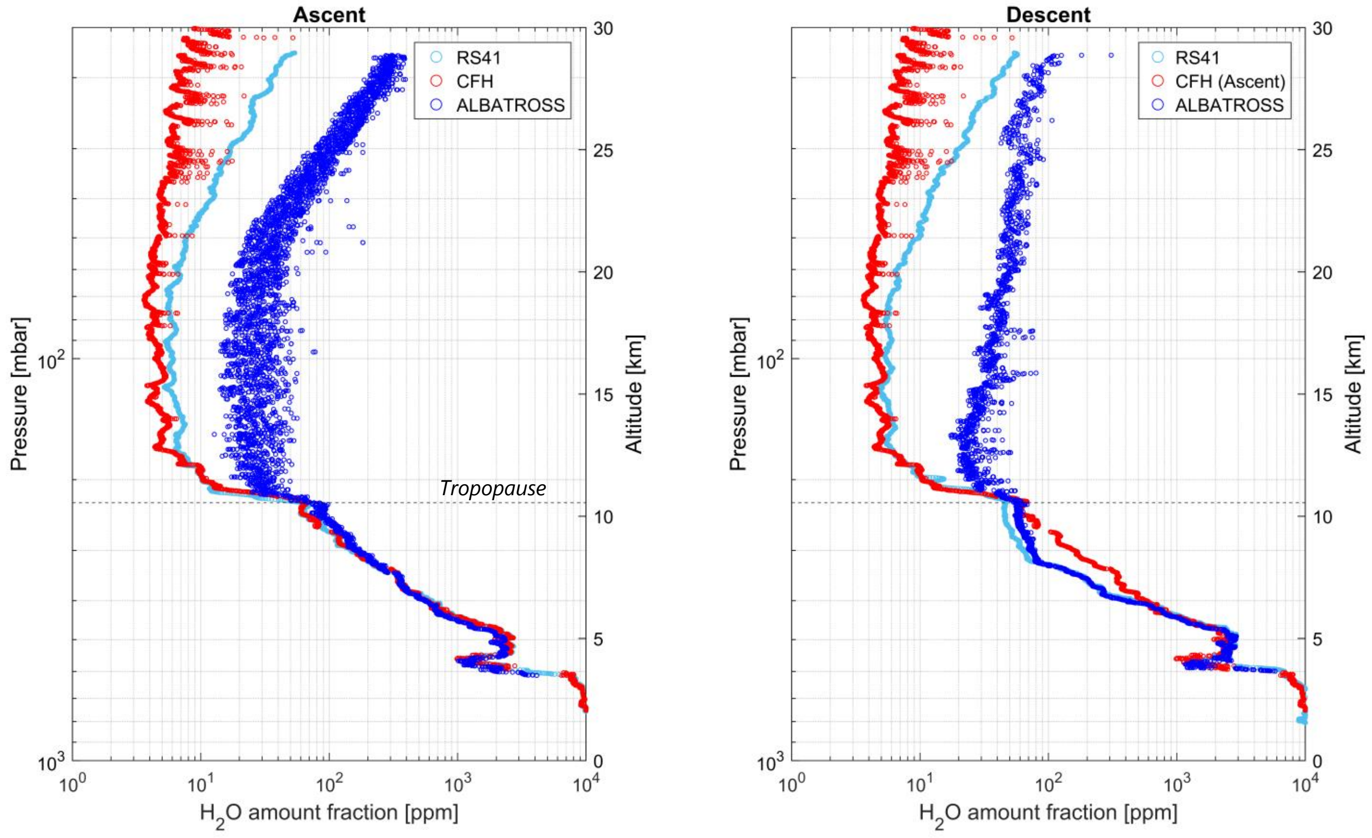

Recovery (Payerne 2023)


Recovery (Lindenberg 2022)

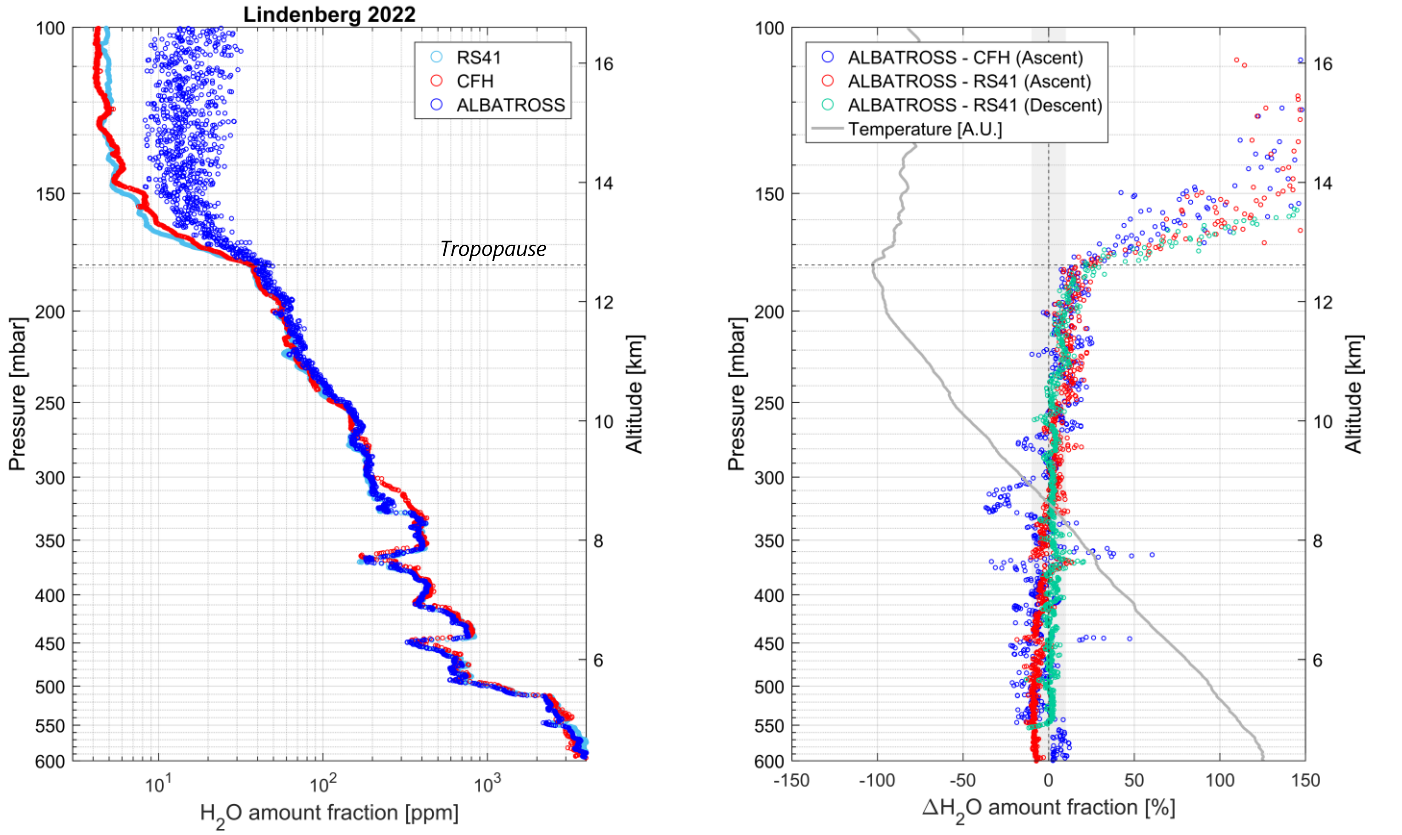
# Results: Lindenberg 2022



# Results: Payerne 2023



# Results: Comparison with CFH/RS41



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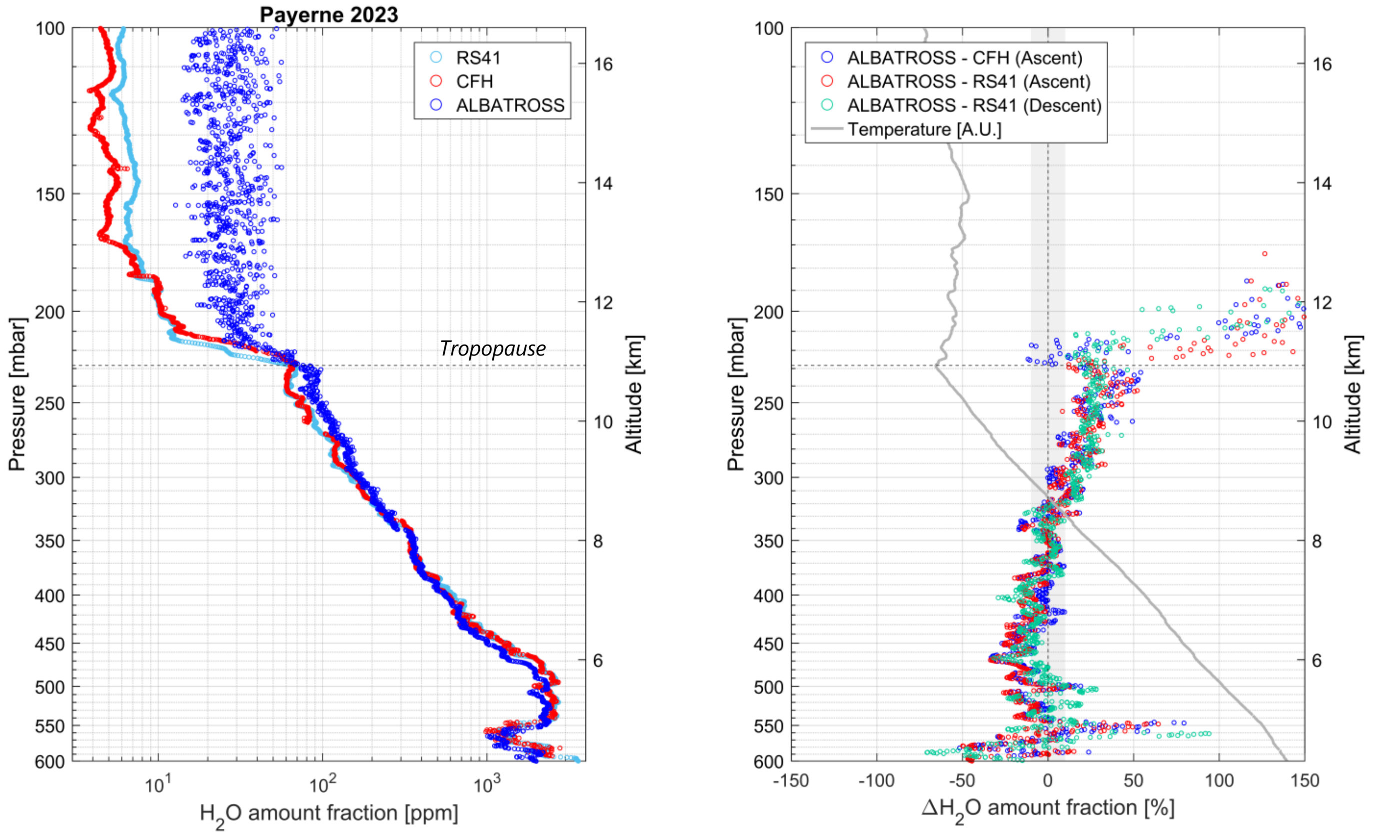
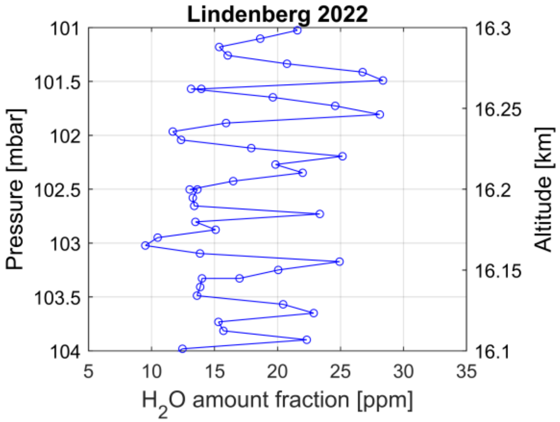
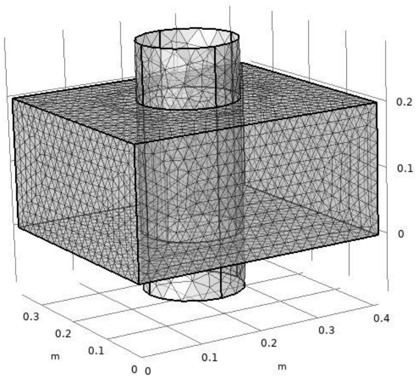
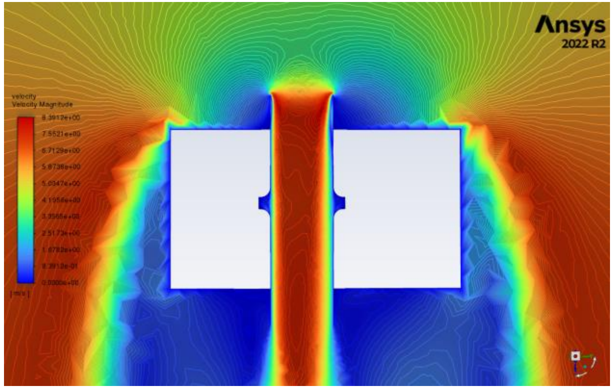


# Flight configuration optimization

- Stratosphere: moist bias and large fluctuations observed
  - **Real signal** (no instrumental artifact)
  - Attributed to **internal contamination** (i.e., "leakage" of air from instrument box into multipass cell)
- Ongoing design revision of instrument box and intake tube based on **CFD simulations**






# Conclusions and outlook

- We developed **ALBATROSS**, a lightweight (3.5 kg) mid-IR laser absorption spectrometer for balloon-borne measurements of UTLS $H_2O$

**Laboratory-based validation**

- SI-traceable reference gases generated by gravimetric permeation method
- Outstanding accuracy and precision at UTLS-relevant conditions:
  - **Accuracy < 1.5 %** at 2.5−35 ppm $H_2O$
  - **Precision < 0.1 %** at 1 s resolution
- Good performance during AquaVIT-4 intercomparison at AIDA chamber (*not shown*)

**In-flight validation**

- Troposphere: good agreement with CFH/RS41 (until ~12 km altitude)
- Stratosphere: moist bias, likely due to internal contamination (*work-in-progress*)
- New test flights planned in 2024-2025 within the *Swiss $H_2O$-Hub* project

# *Thanks for your attention!*


Acknowledgements

**METAS**
Tobias Bühlmann
Céline Pascale

**DWD Lindenberg**
Peter Oelsner
Susanne Meier
Ruud Dirksen

**MeteoSwiss Payerne**
Gonzague Romanens
Giovanni Martucci
Alexander Haefele

**Empa**
Manuel Graf
Philipp Scheidegger
Herbert Looser
Marco Ravasi

**ETH Zürich**
Yann Poltera
Frank Wienhold
Thomas Peter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