Evaluating the lower stratospheric moist bias using airborne lidar and radiosonde observations

Andreas Schäfler[1], Konstantin Krüger[1], Noureddine Semane[2]

[1]Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

[2]European Centre for Medium-range Weather Forecasts, Reading, UK

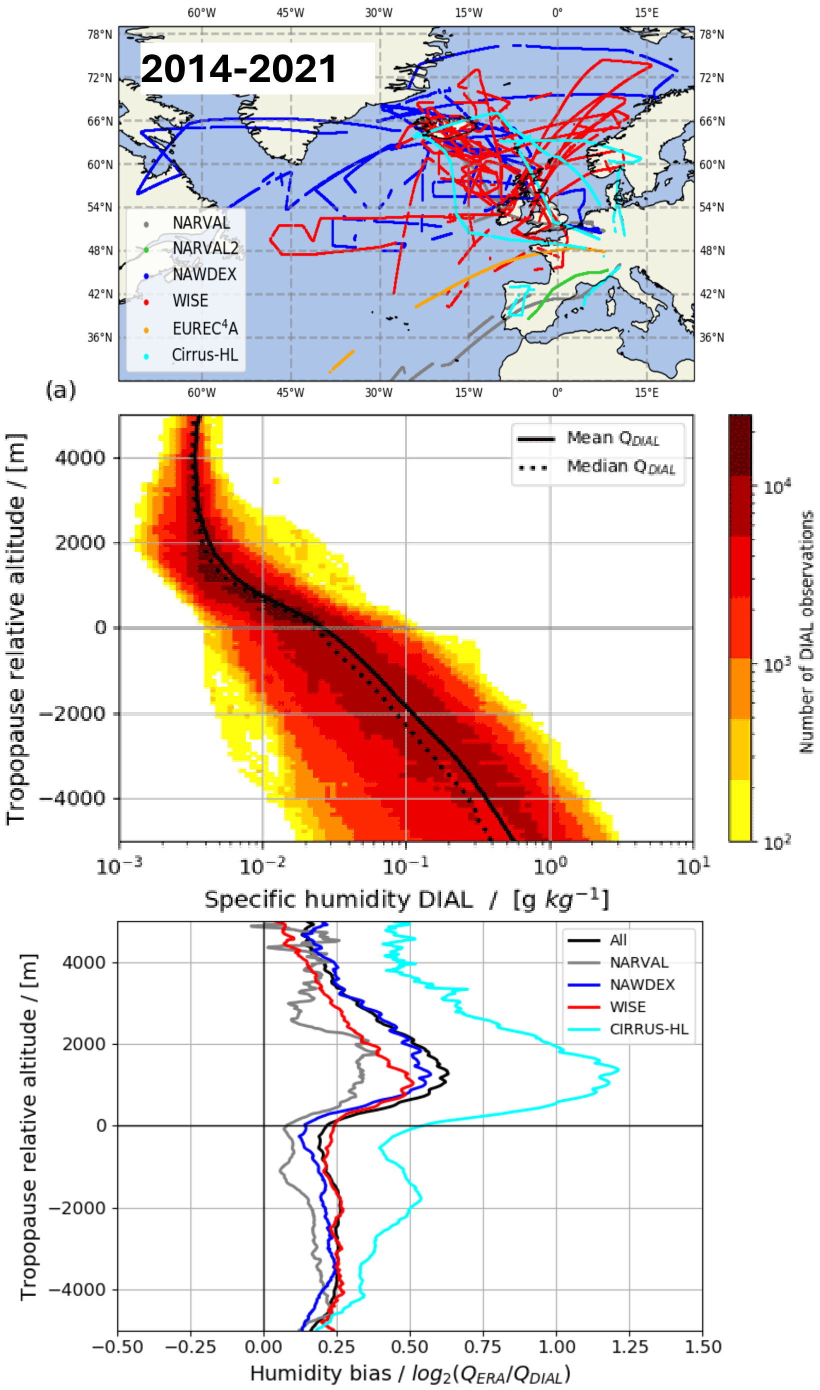
AR Recon workshop and 2nd Observational campaigns workshop for better weather forecasts
29 June – 3 July, Reading

North Atlantic Waveguide, Dry Intrusion and Downstream Impact Campaign

Background

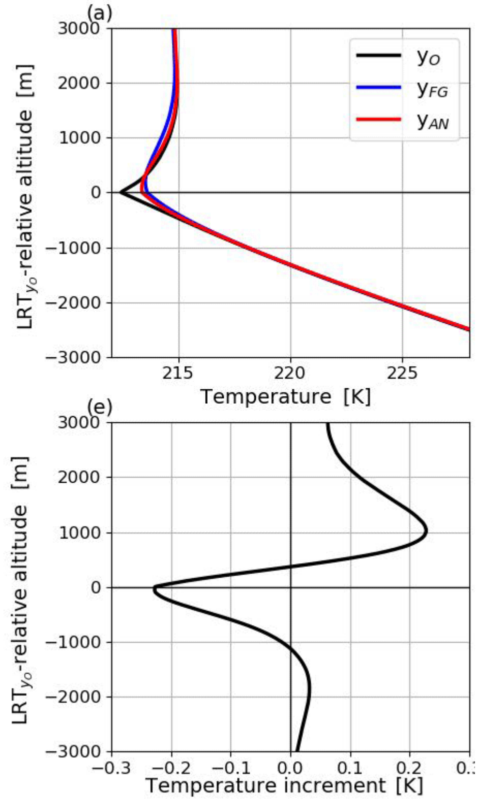
- **Since ~20 years :** campaign-based, range-resolved **airborne lidar water vapor (WV) profiles**
  - flight altitude to surface
  - **independent data for NWP validation**
  - **broad applications** in atmospheric dynamics and transport studies

- Vertical structure and magnitude **of the lower stratospheric moist bias** in ERA5 *(Krüger et al. 2022, ACP)*
  - Max. overestimation of ~55 % at ~1.5 km above the tropopause
  - Seasonal cycle peaking in summer (enhanced mixing across the tropopause)



Background

- Influence of NAWDEX radiosondes on the **sharpness and altitude of the midlatitude tropopause** in the IFS *(Krüger et al. 2024, WCD)*
  - Reduced background biases and improved tropopause sharpness
  - Positive influence on the analysis wind profile and vertical wind shear
  - **Humidity assimilated only in the troposphere**
- ECMWF introduces **stratospheric humidity assimilation** using RS41 radiosondes (+MLS) *(Semane and Bonavita, 2025, ECWMF newsletter)*
  - Operational implementation in Cycle 50r1 (May 2026)



Use observations to **validate UTLS humidity** and study **impact of radiosonde humidity assimilation**

- What is the seasonal cycle of the LS moist bias?
- Is the humidity bias reduced? How strong is the bias compared to 2014-2021?

1. **Radiosonde data** to study the impact on the analysis in tropopause-relative coordinates
2. **Campaign lidar data** for an independent validation of UTLS WV

Radiosondes
Data set

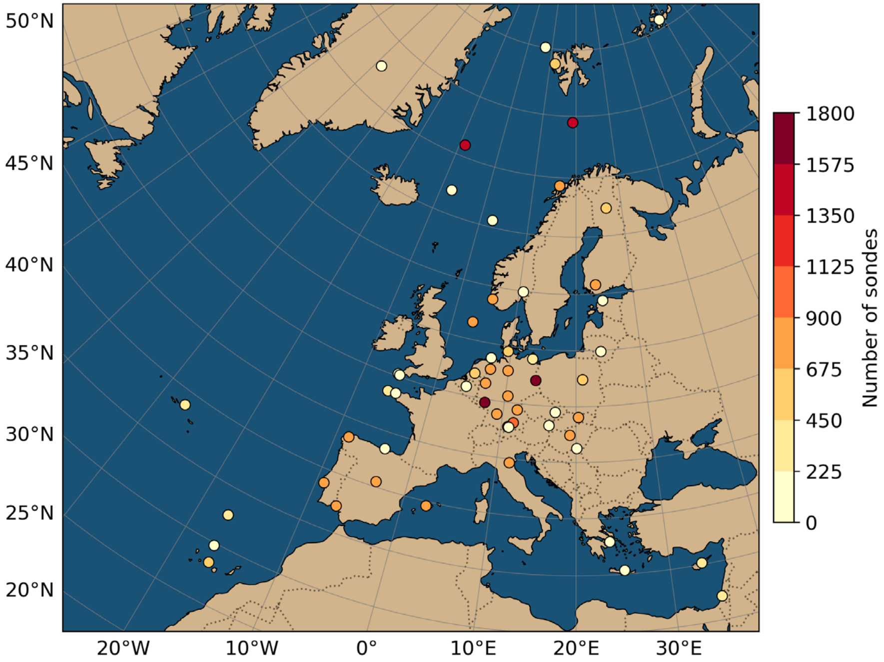
- **RS41 radiosonde** (+MLS) assimilated **up to 60 hPa**
  - Europe and North Atlantic
  - Pre-operational experiments Dec 2024 to Mar 2026, operational since May 2026 (Cycle 50r1)
  - 30 Nov 2024 to 22 Jun 2026: 464 days
  - 31978 radiosondes from 57 stations (max. 1781 radiosondes per station)

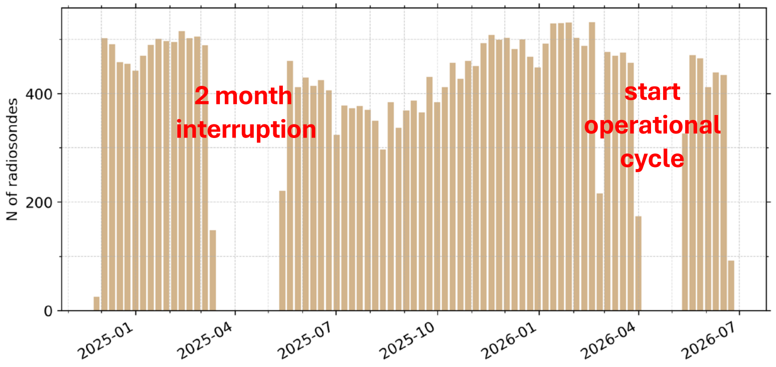
- **Observations** (O), **background** (first guess, B) and **analysis** (A)
  - **Innovation:** O – B | $\log_2[O/B]$
    (First Guess / background departure)
  - **Residual:** O – A | $\log_2[O/A]$
    (Analysis departure)
  - **Increments:** A – B | $\log_2[A/B]$

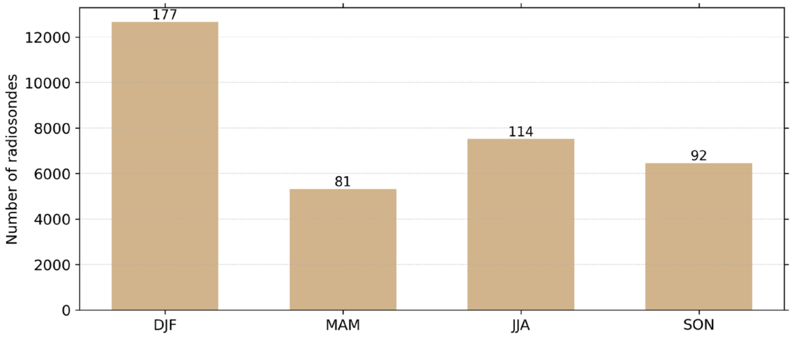
> 0
moist bias
q-decrease

< 0
dry bias
q-increase

Kunz et al. (2014)



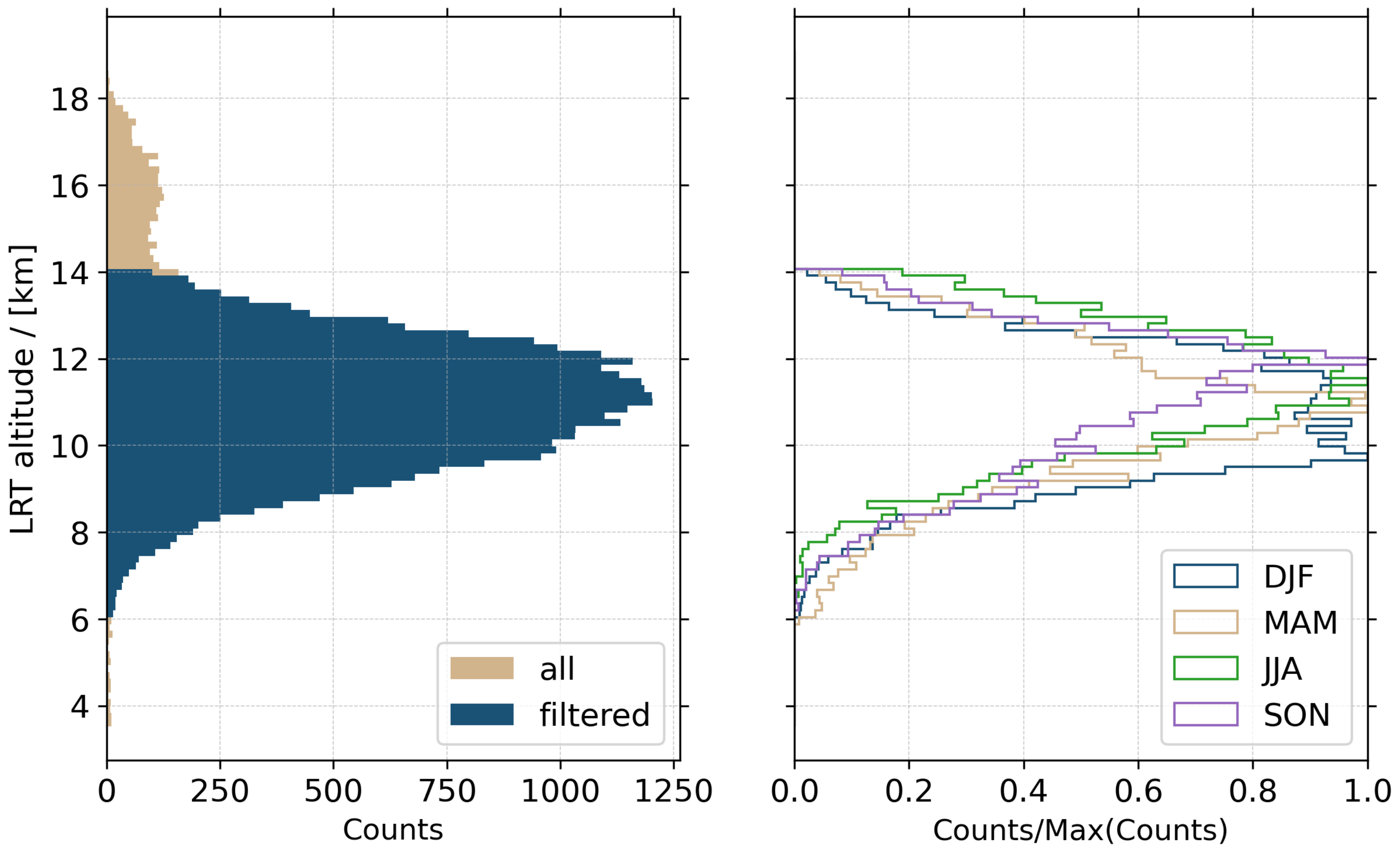




Radiosondes

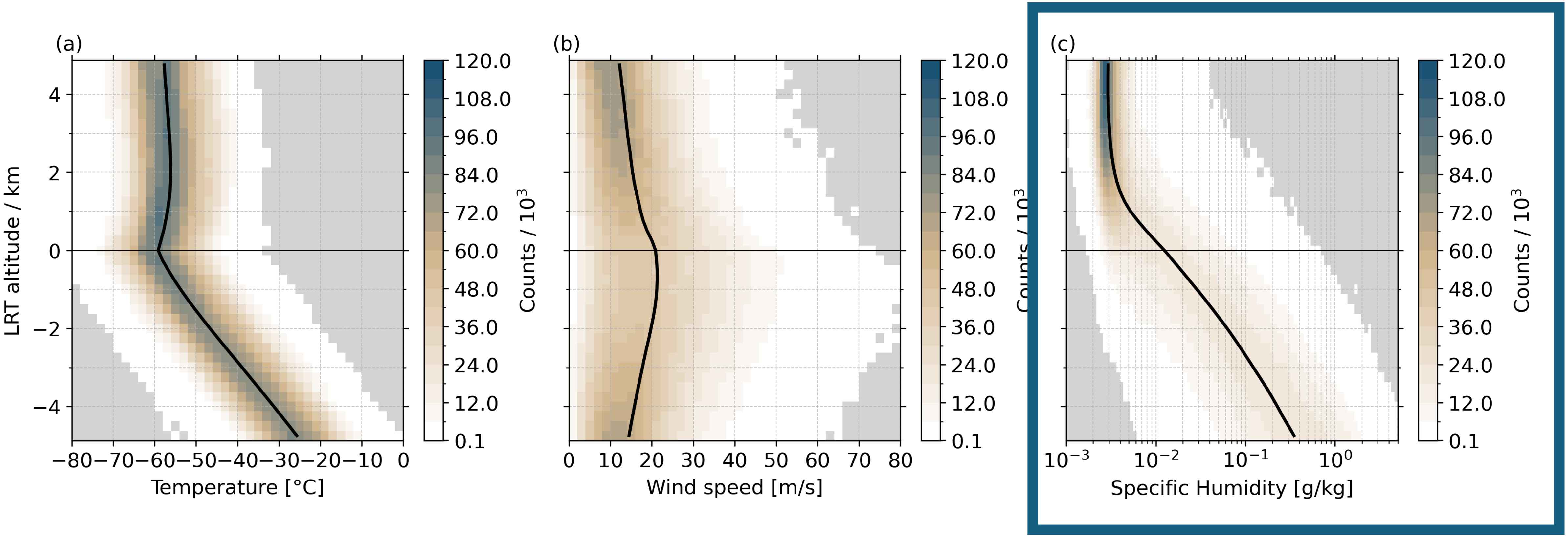
Data set

- Typical lapse rate tropopause (LRT) altitudes for the midlatitudes
  - 6 to 14 km
  - highest LRT in JJA/SON
- LRT > 14 km:
  - subtropical jet (STJ) or misdetections
  - 29501 profiles (92 %)
  - Most removed in summer → STJ



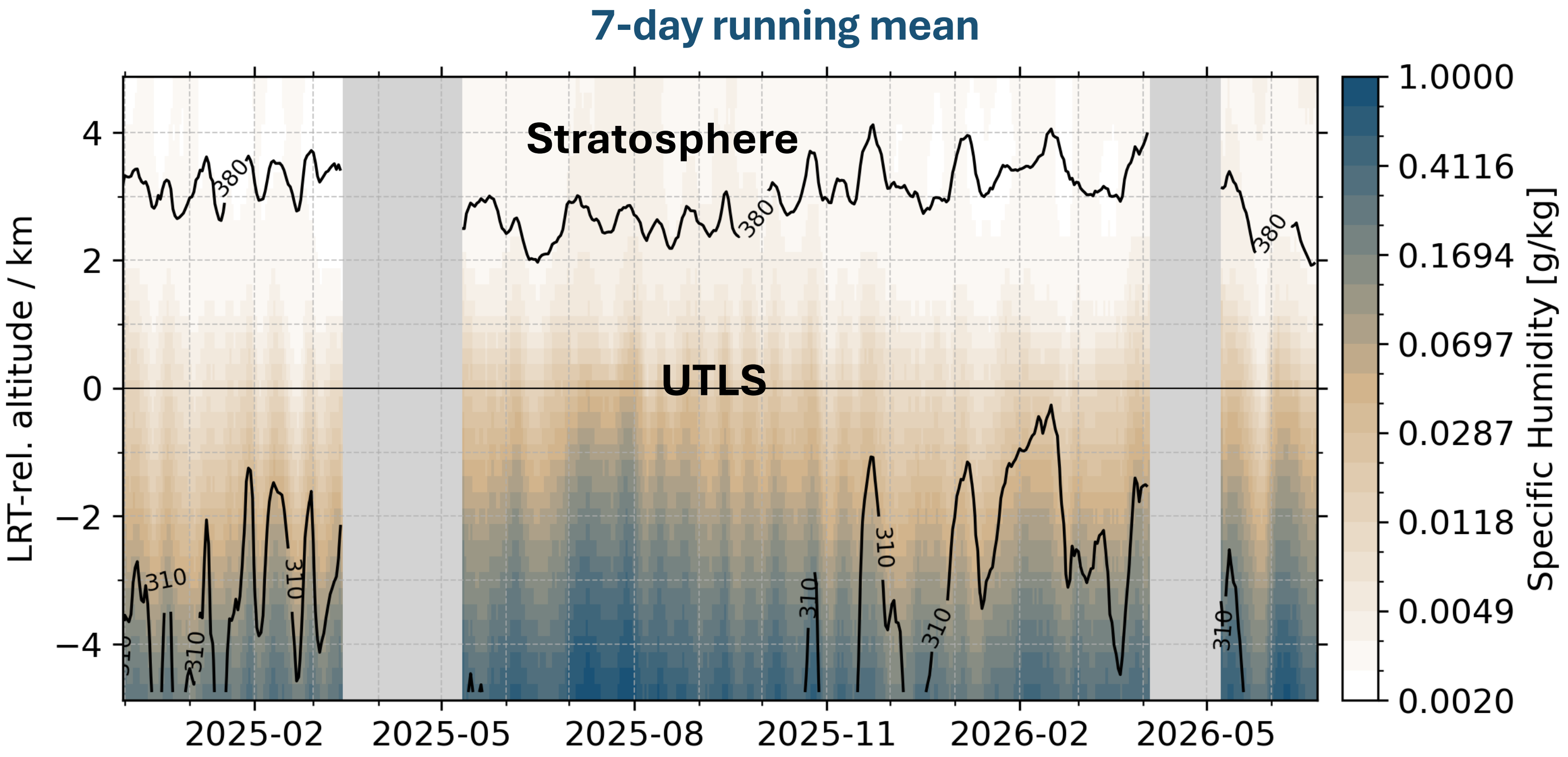
Radiosondes

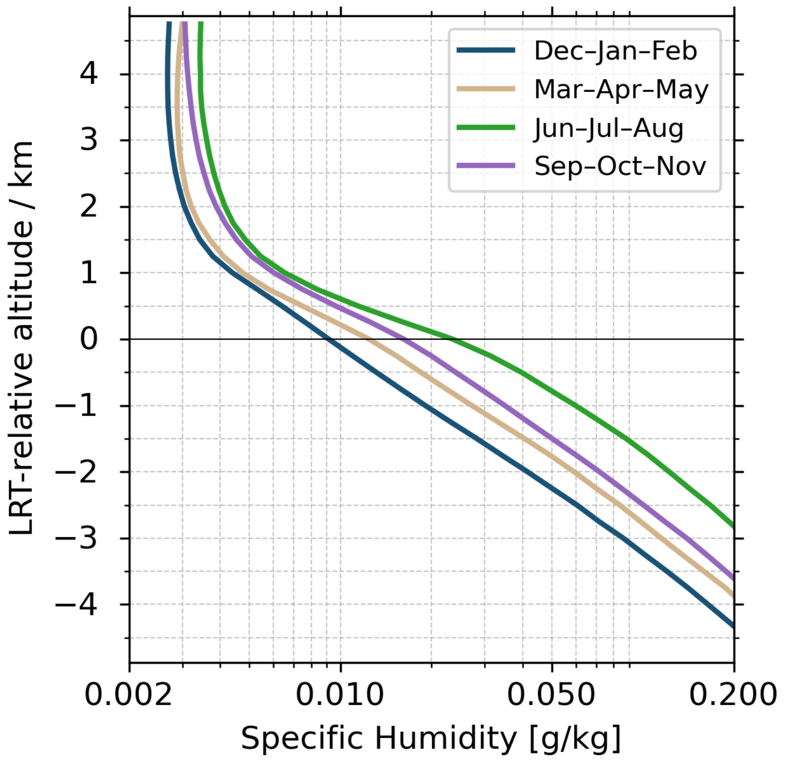
Observations – median distributions



Radiosondes

Observations – seasonality

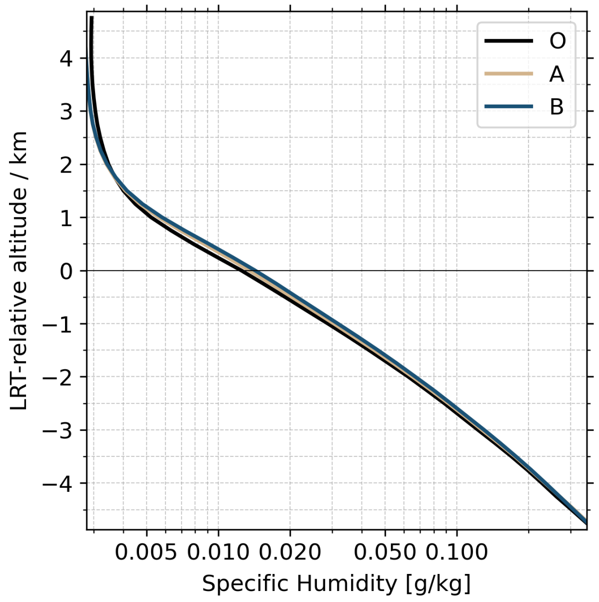


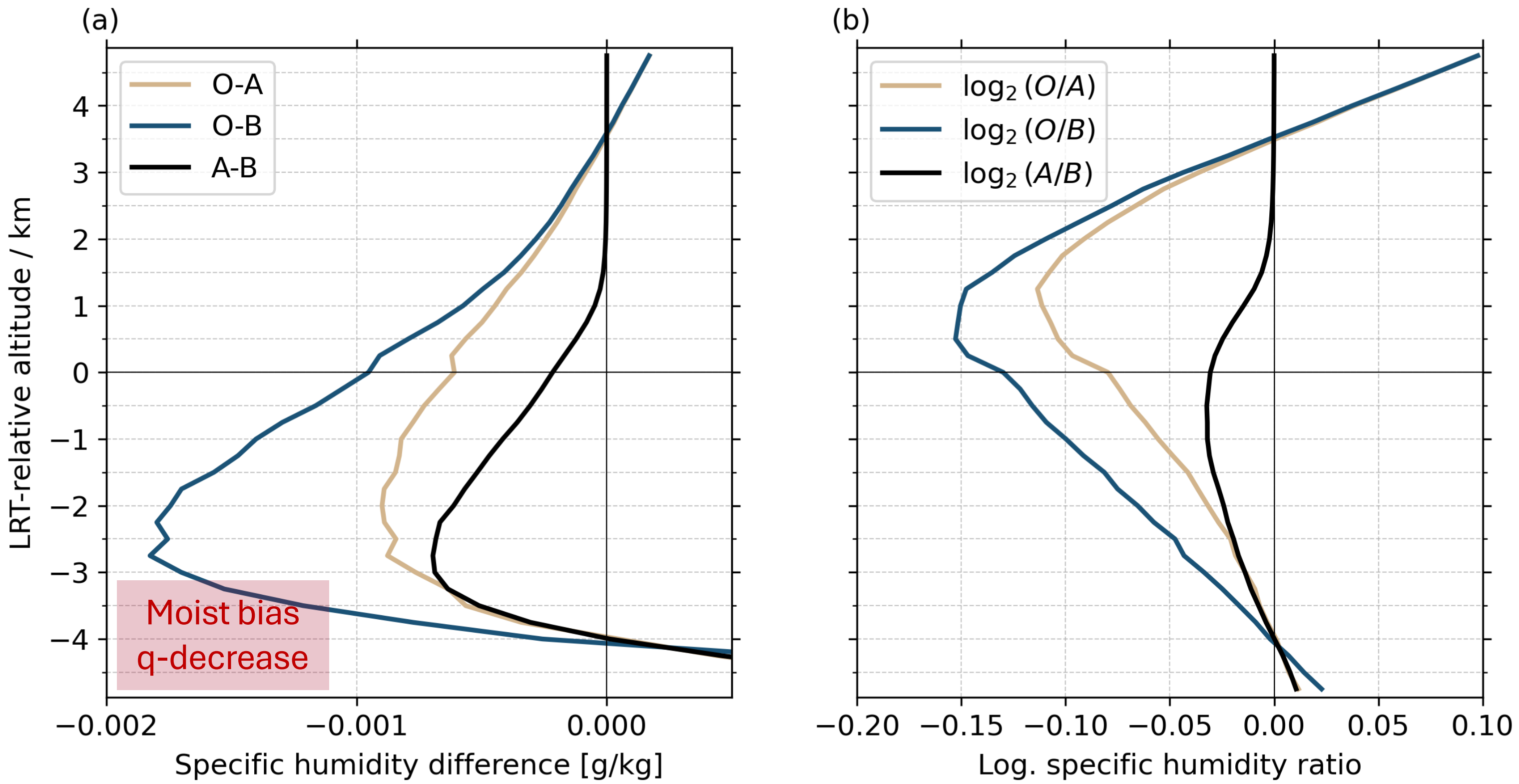


- Moist humid UTLS during summer
- Moist episodes extending into the LS

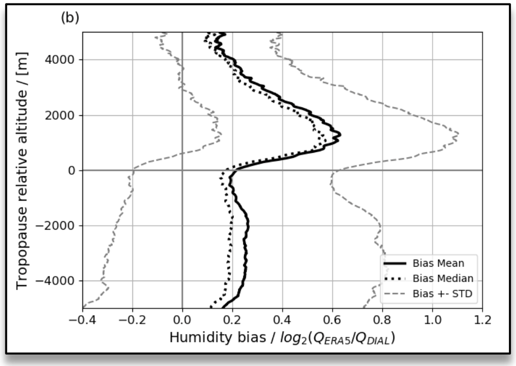
Radiosondes

Departures and increments - Median distributions





- Stronger UTLS moist bias in log metric
- Smaller FG departure than previously reported
- Bias reduction near tropopause; weaker increments aloft



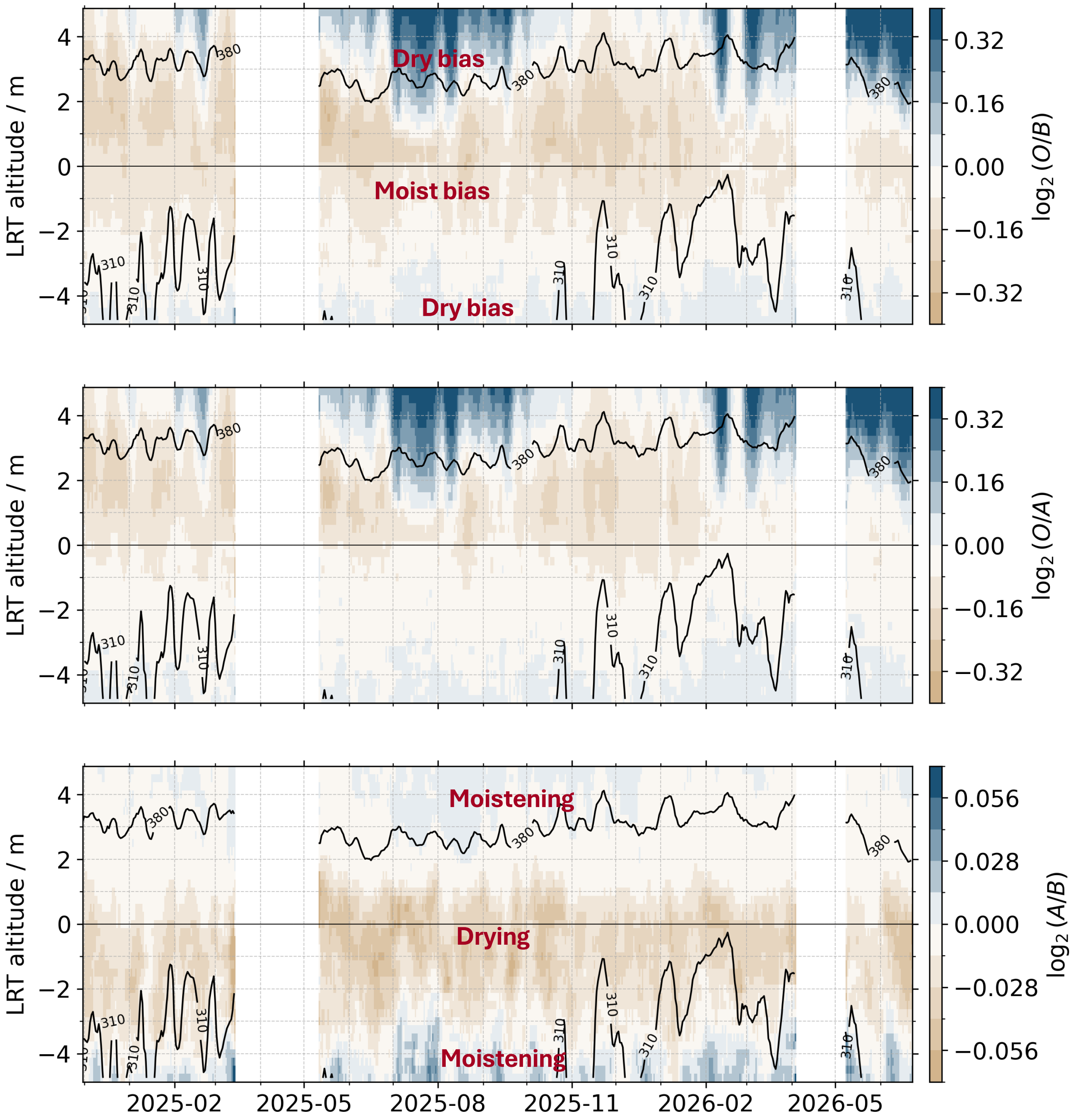
Radiosondes

Departures and increments - Seasonality

First Guess departure

Analysis departure

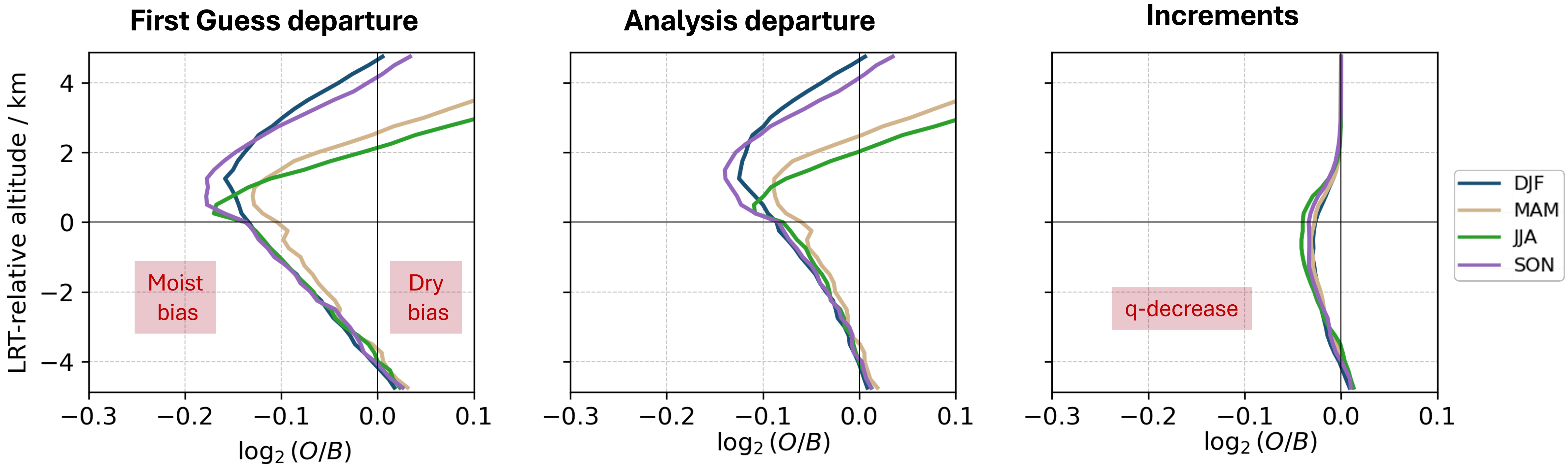
Increments

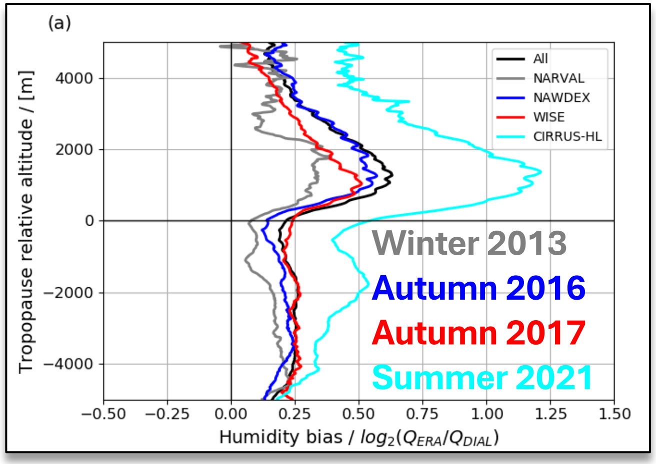


- Lower moist bias maximum in JJA and stronger dry bias aloft

Radiosondes

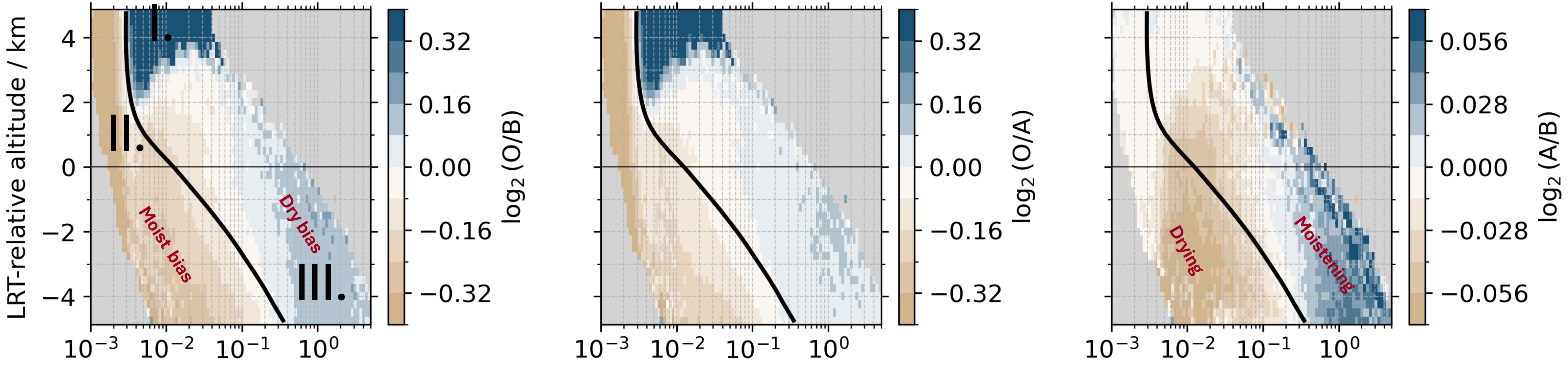
Departures and increments - Seasonality

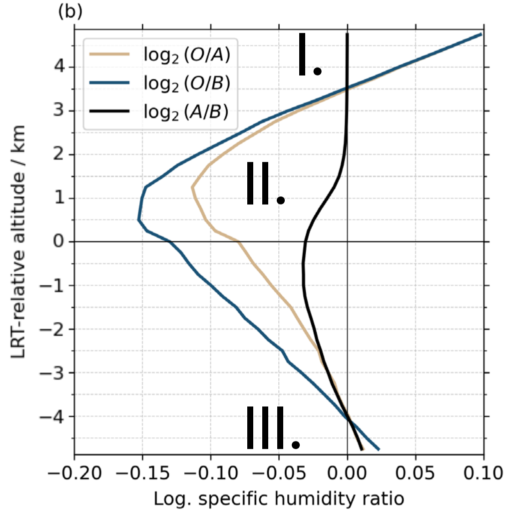




- No JJA bias maximum, lower altitude
- Consistent increments across seasons
- Greatest improvement during JJA

Radiosondes
Summary

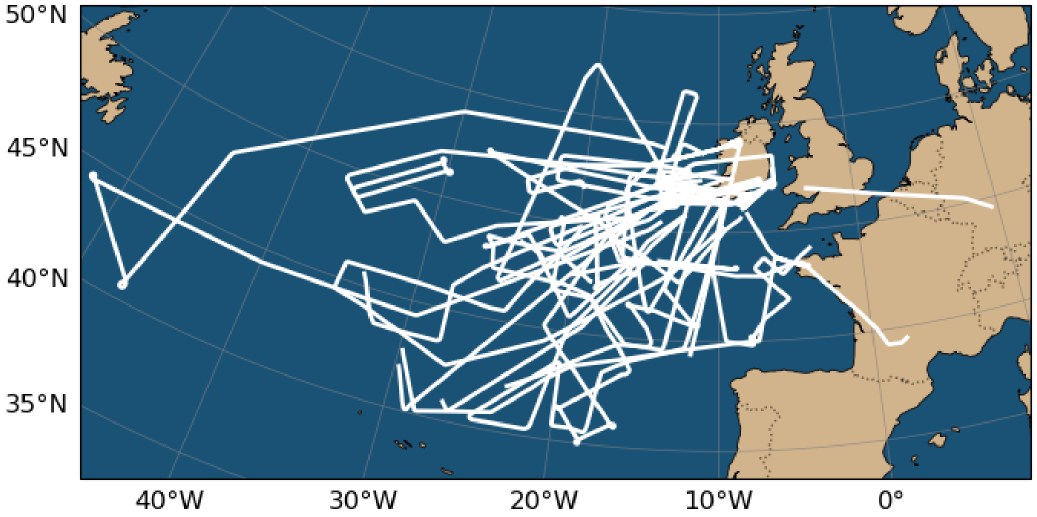




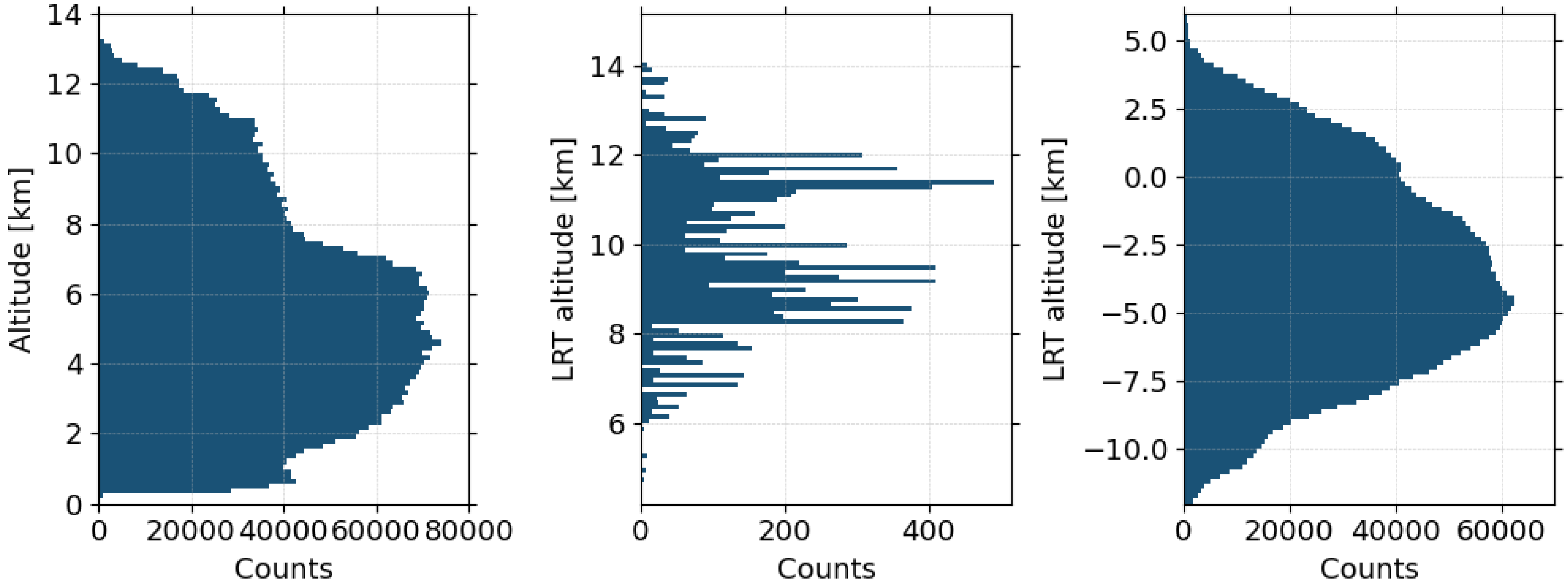
- **I. Stratosphere:** Dry bias linked to underestimated high humidity (mainly JJA)
- **II. UTLS:** Moist bias driven by overestimated low humidity (lower in JJA)
- **III. Troposphere:** Dry bias dominated by underestimated high humidity

Lidar
Dataset

North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign (NAWDIC)

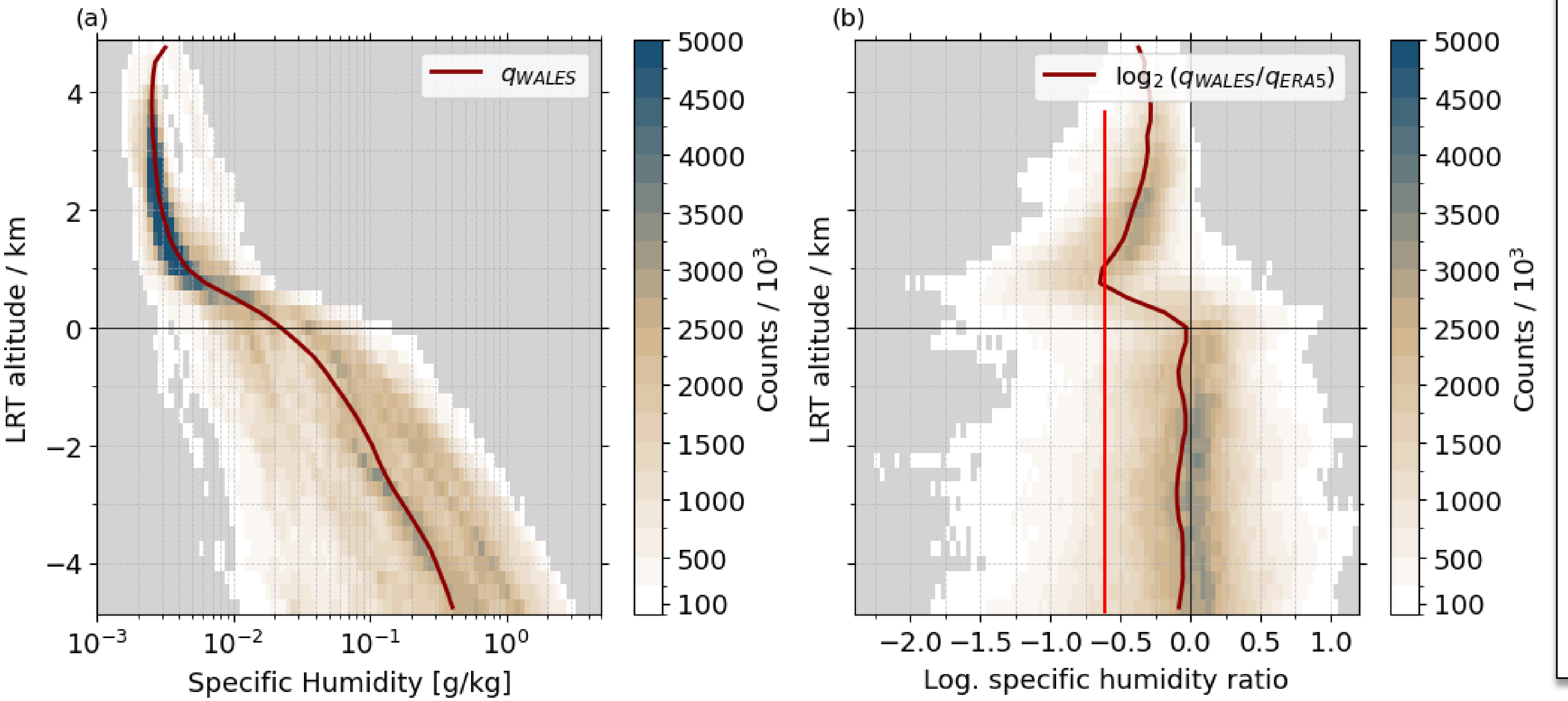


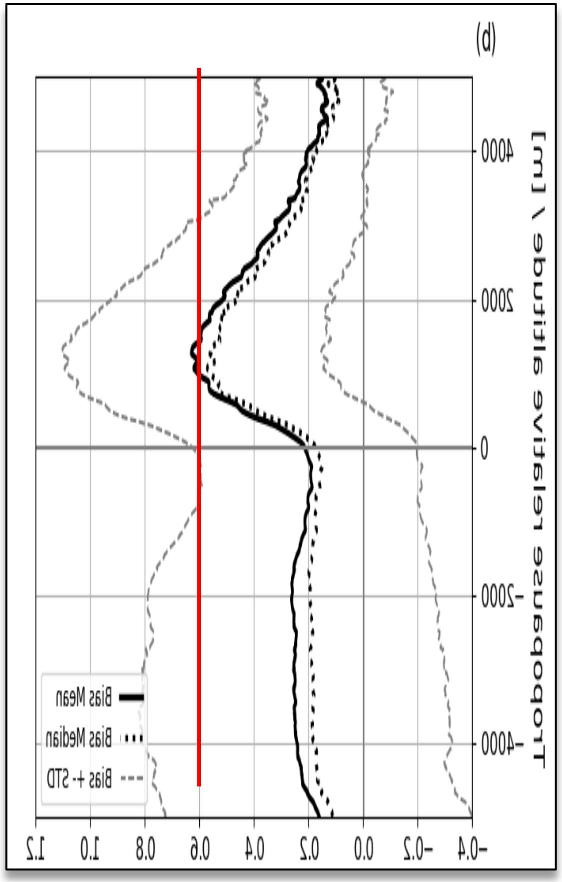
- 19 HALO flights between 13 Jan and 20 Feb 2026
- 14776 DIAL profiles at 24 s resolution (4-6 km distance)
- 4.296.872 WV observations



Lidar

Observations and ERA5 comparison



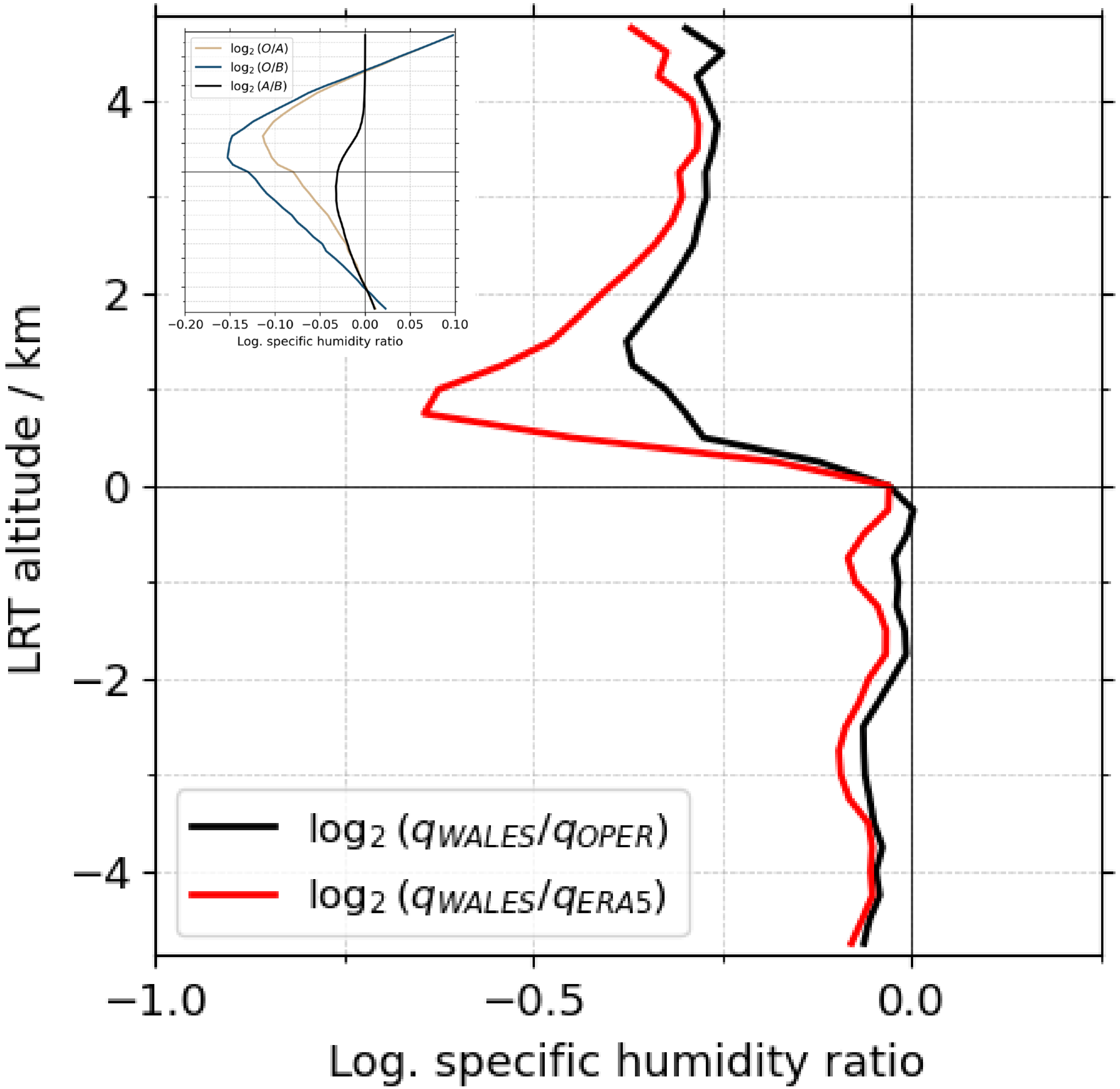


(Krüger et al. 2022, ACP)

- ERA5 UTLS moist bias similar to multi-campaign analysis 2014-2021

Lidar

Comparison with ERA5 and IFS OP AN/FC



- ERA5 / OPER: no LS WV assimilation
- Larger bias than IFS with LS humidity assimilation at radiosonde locations
- direct comparison with DA exp desirable
- Output too coarse for comparison (hourly FC needed)

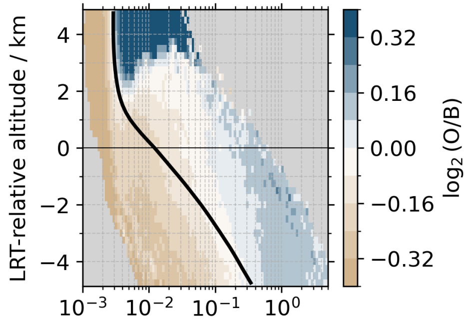
Summary

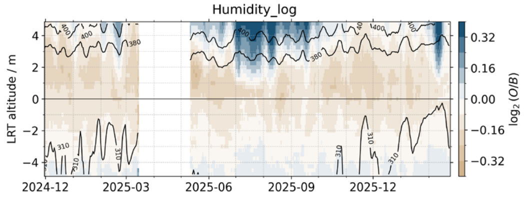
1) Radiosondes

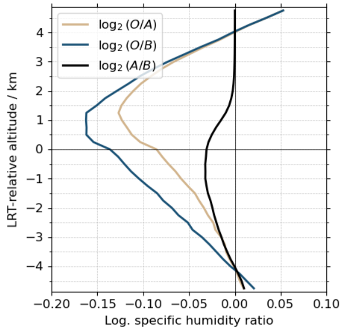
- **UTLS moist bias seasonality**
  - UTLS moist bias driven by overestimated low humidity
  - Previously reported JJA UTLS moist bias max not observed
  - Lower max. bias altitude in JJA, stratospheric dry bias aloft
- **Stratospheric humidity assimilation :**
  - UTLS moist bias reduced throughout the year
  - Overall UTLS bias smaller than previously reported

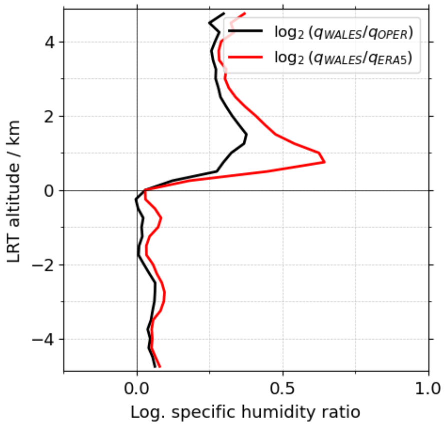
2) Lidar

- NAWDIC ERA5 bias similar to 2014-2021
- Smaller bias in operational AN/FC (Cycle 49r1, without WV DA)
- Comparison with DA experiment → higher FC output frequency needed









Summary

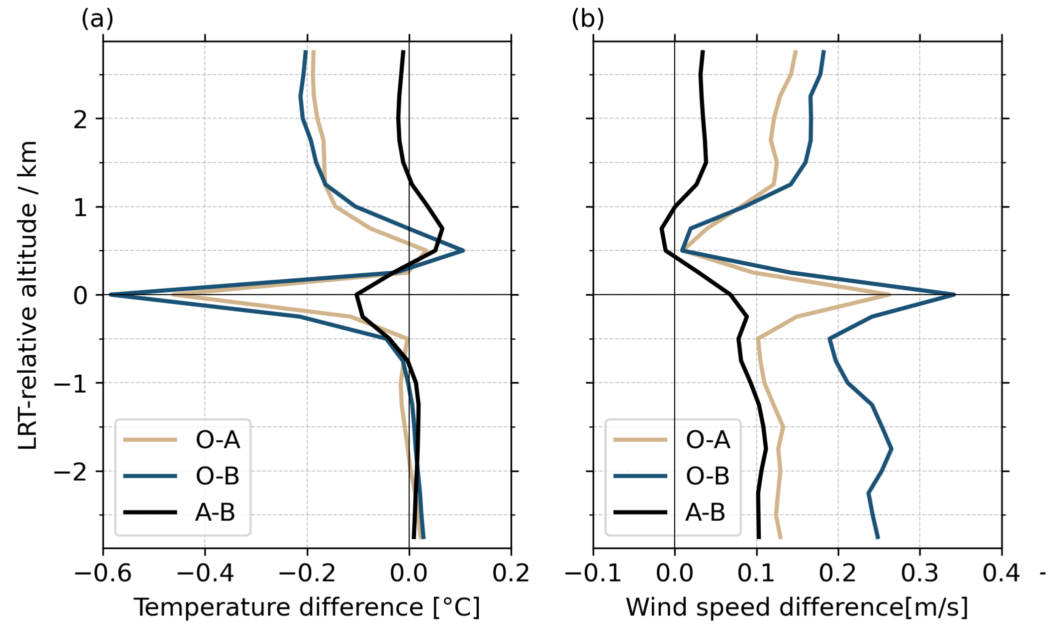
Other findings

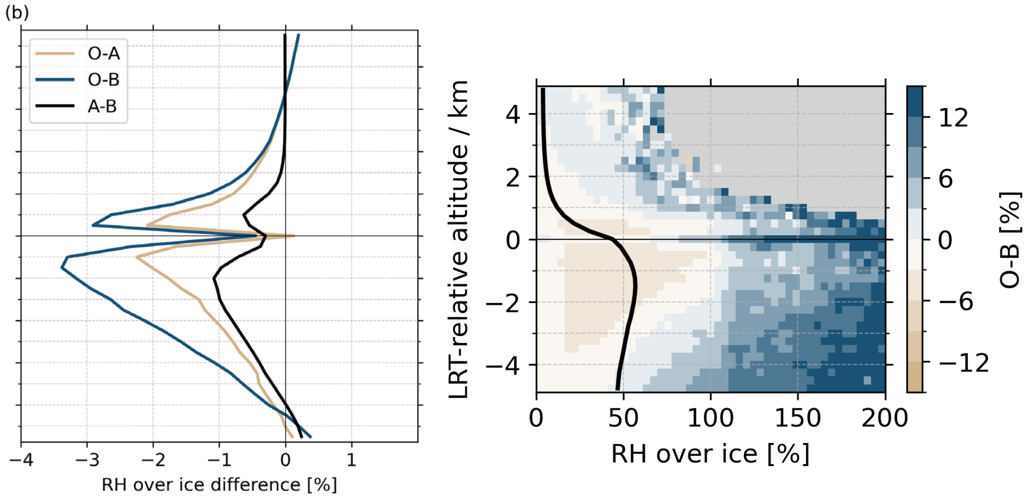
Temperature and Winds (similar positive influence on the tropopause structure as in *Krüger et al. 2024, WCD*)

- Tropopause sharpening, UT warm bias in summer and cold bias in winter
- Persistent slow wind bias (dominated by underestimated high wind speeds) → wind shear increase above LRT

Relative Humidity

- RH moist bias dominated by overestimated low relative humidities
- Improved representation through DA
- Striking: high RH near saturation systematically underestimated (5-12 %)





General remarks

- This work shows
  - how campaign observations can **support model improvements**
  - the need for **enhanced and improved UTLS humidity measurements**
- Beside the UTLS, **tropospheric humidity** plays a crucial role via latent heat processes
- Precise water vapor observations will remain scarce in the coming years
- NWP validation showcase the potential of differential absorption lidar, particularly for future space-borne use
- To advance future satellite (lidar) missions, **collaborations with weather centers** are essential to demonstrate the value of WV observations