Airborne lidar observations of tropospheric and lower stratospheric H_2O demonstrate the potential of a space-borne DIAL (to create future CDRs)

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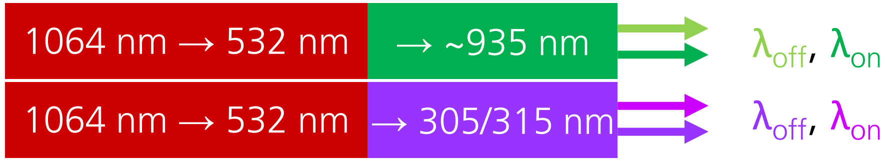
DLR

The airborne DIAL WALES
The instrument

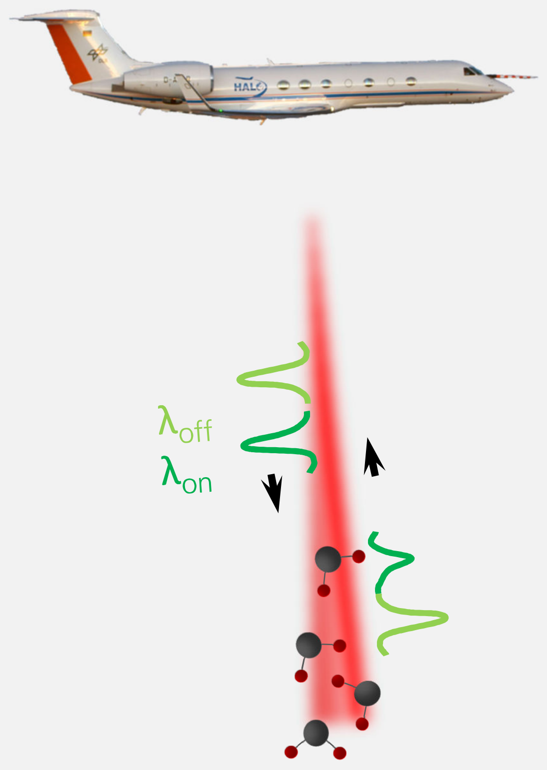
2007: WALES airborne demonstrator developed for ESA EarthExplorer mission proposal for an H_2O differential absorption lidar (DIAL) in space.

→ 4λ-DIAL to measure H_2O from the ground to the UTLS

2017: option to measure O_3 and H_2O profiles



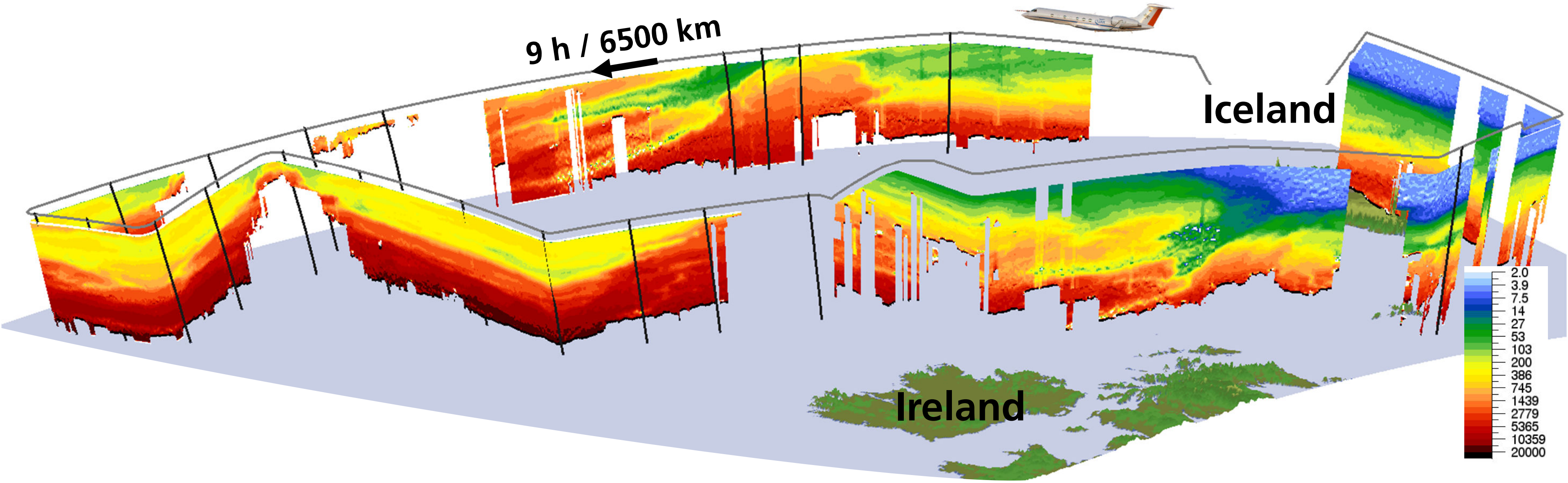
(Wirth et al. 2009, Appl. Opt., Fix et al. 2019, Appl. Opt.)



$$n(r) \approx \frac{1}{2\Delta\sigma \cdot \Delta R} \ln\left[\frac{P_{off}(R_2) \cdot P_{on}(R_1)}{P_{on}(R_2) \cdot P_{off}(R_1)}\right]$$

DIAL measurement principle

The airborne DIAL WALES
Deployment



Measurement example from NAWDEX 2016

- Arctic: NARVAL (2014), POLSTRACC (2016), Cirrus-HL (2021), HALO-AC^3 (2022)
- Midlatitudes: ML-Cirrus (2014), NAWDEX (2016), WISE (2017)
- Tropics: NARVAL (2013), NARVAL II (2016), EUREC^{4}A (2019), PERCUSION (2024)

The airborne DIAL WALES
Scientific focus

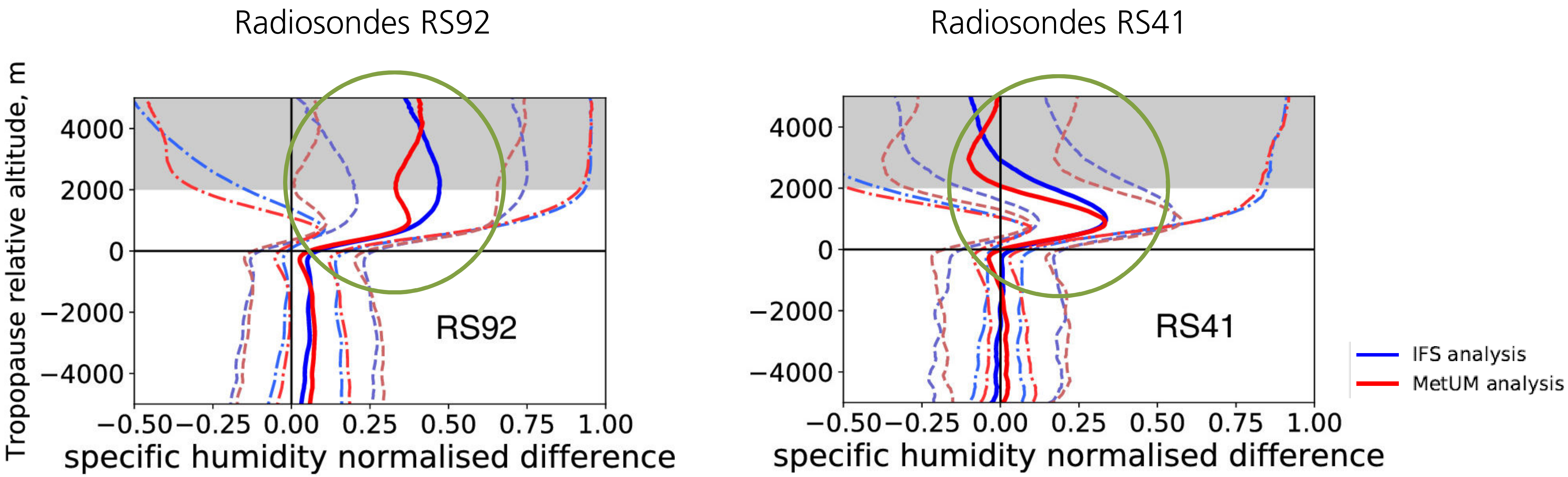
- **Cirrus cloud studies:**
  - RH in Arctic and midlatitude cirrus *(Dekoutsidis et al. 2022, ACP and 2024, ACP)*
  - Optical properties of midlatitude cirrus *(Groß et al. 2022, ACP)* and effects of aviation-induced cirrus *(Urbanek et al. 2018, GRL)*
  - Cirrus life cycles *(Urbanek et al. 2017, AMT)*
- **Radar-lidar synergies**
  - Cloud microphysical properties *(Ewald et al. 2021, AMT)*
- **Aerosol**
  - Saharan dust transport *(Gutleben et al. 2022, ACP)*
  - and its radiative effect *(Gutleben et al. 2019, GRL & 2020, ACP)*
- **EarthCARE validation** *(Groß et al. 2015, ASL)*
- **Atmospheric dynamics and transport studies**
  - H_2O transport in warm conveyor belts *(Schäfler et al. 2010, JTECH & 2011, QJ; Schäfler and Harnisch, 2014, QJ)*
  - H_2O lidar profile data assimilation *(Harnisch et al. 2011, QJ)*
  - UTLS mixing of H_2O and O_3 *(Schäfler et al. 2021, ACP & 2023, ACP)*
  - LS moist bias *(Krüger et al. 2022, ACP)*

WAVES TO WEATHER

DFG Transregional Collaborative Research Center (2015-2024): ***Model error and uncertainty at the midlatitude tropopause***

LS moist bias in ERA5
Scientific background

Moist bias *(e.g., Woiwode et al., 2020)* ⟶ cold bias in LS *(Bland et al., 2021)*



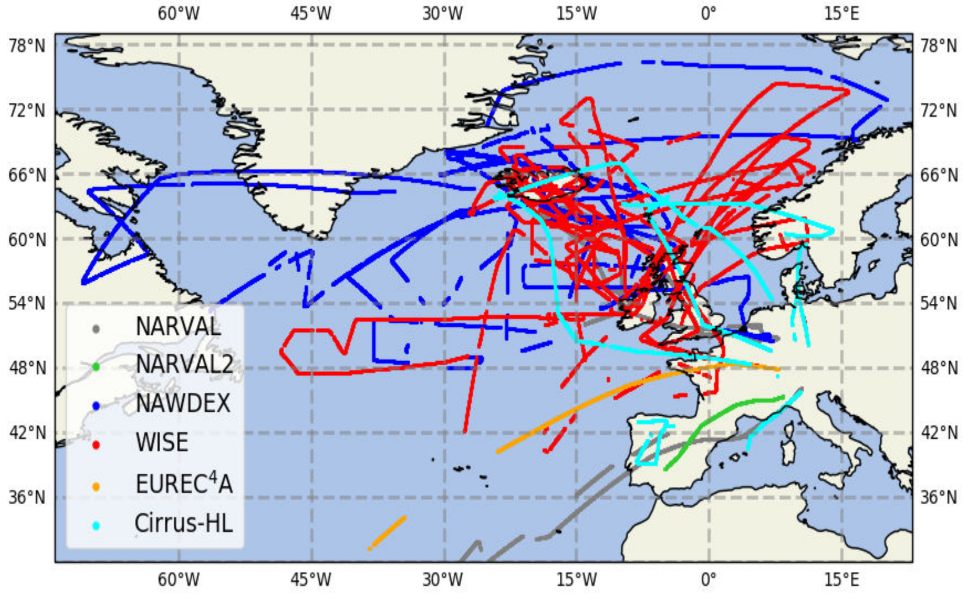
(Bland et al. 2021, QJ)

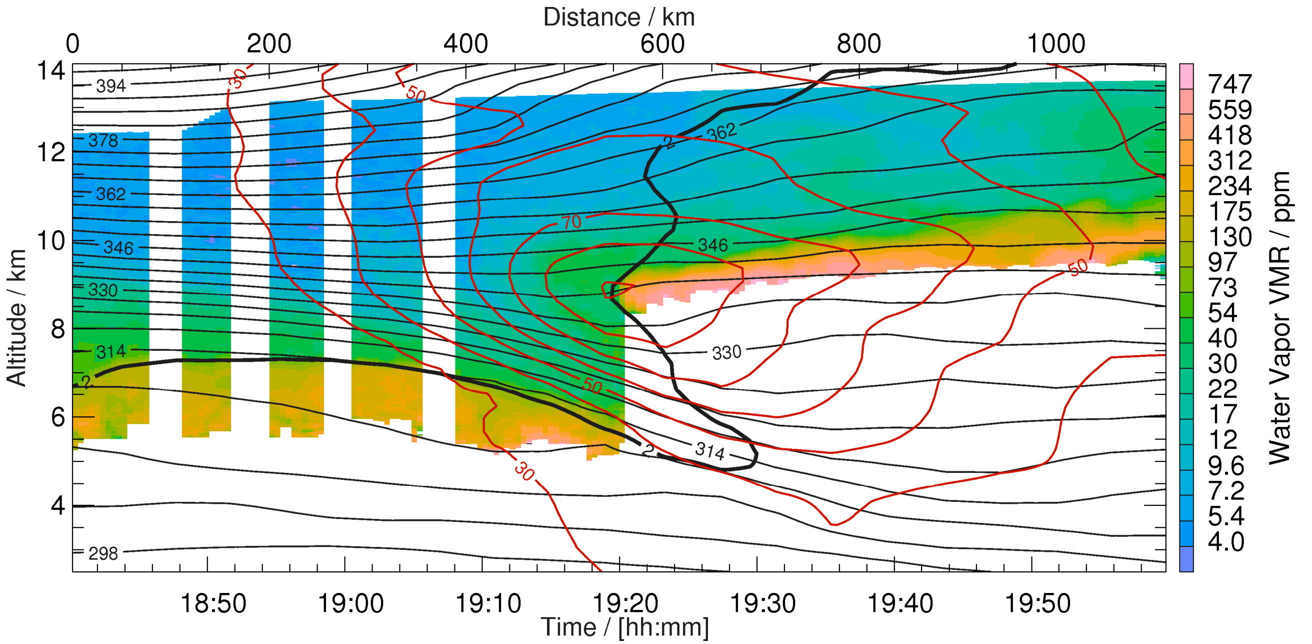
- Vertical structure of the LS moist bias?
- Origins of the LS moist bias?

LS moist bias in ERA5

Approach

- 2013-2021: 41 midlatitude HALO flights, ~210.000 km, ~33000 WALES profiles
- Comparison against 1-hourly ERA5 ML analyses



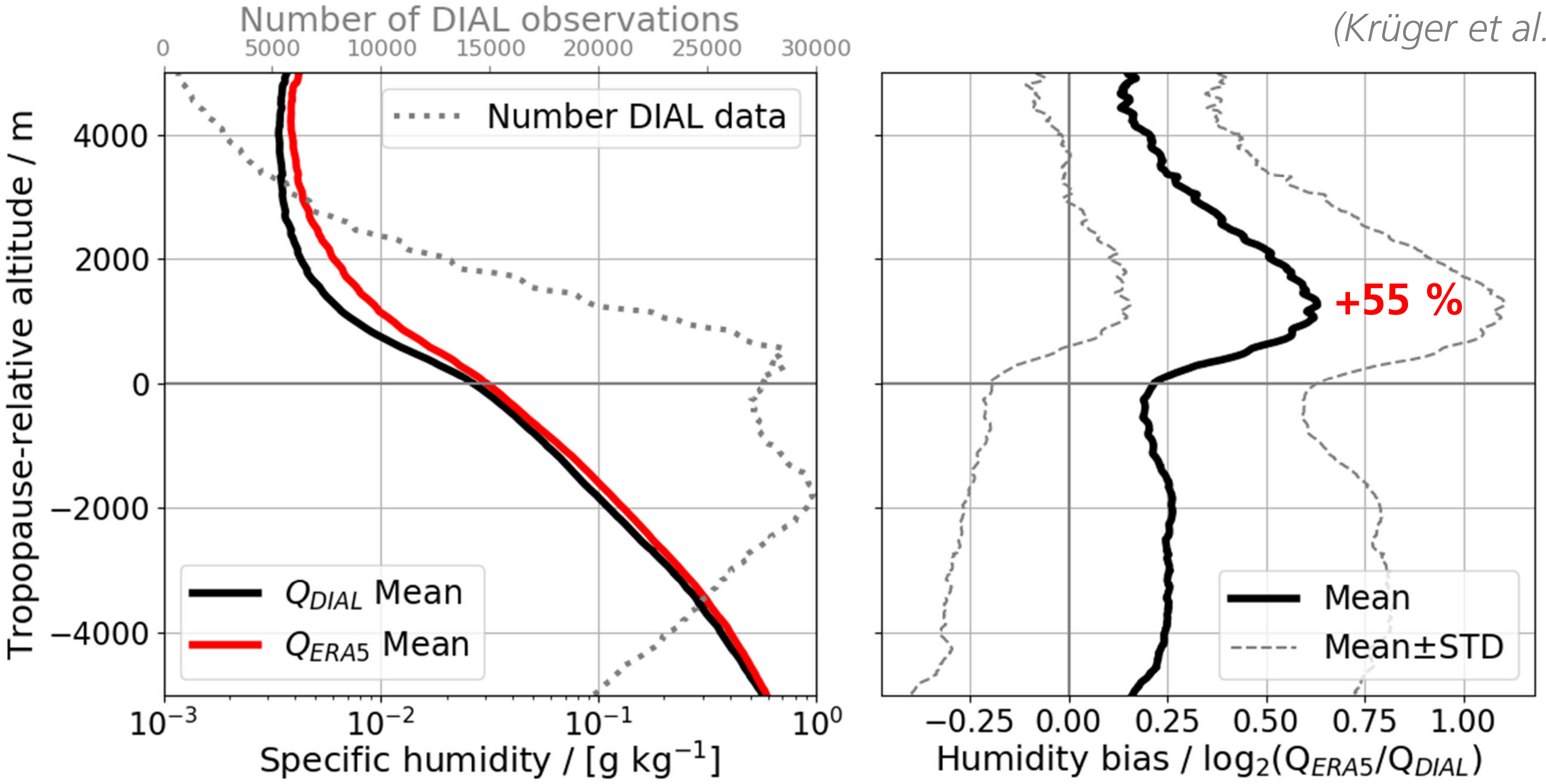


- Independent high precision and accuracy data → not assimilated by NWP models
- Capturing strong vertical gradients at the tropopause

LS moist bias in ERA5

Statistical evaluation: vertical structure

(Krüger et al. 2022, ACP)

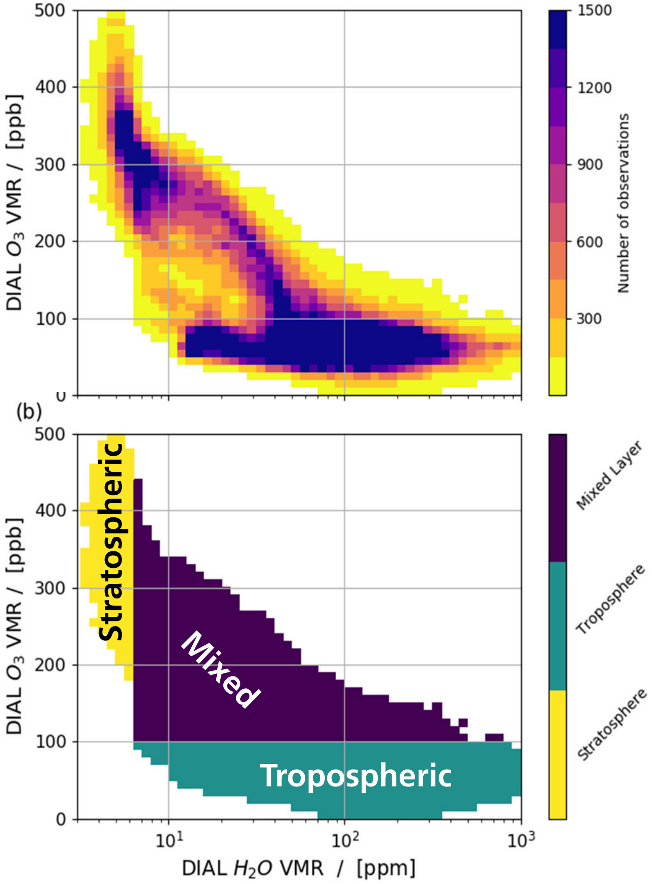


- Robust signal of decreasing bias 1.5 km above TP
- Stronger moist bias in summer (by factor of 2-3)

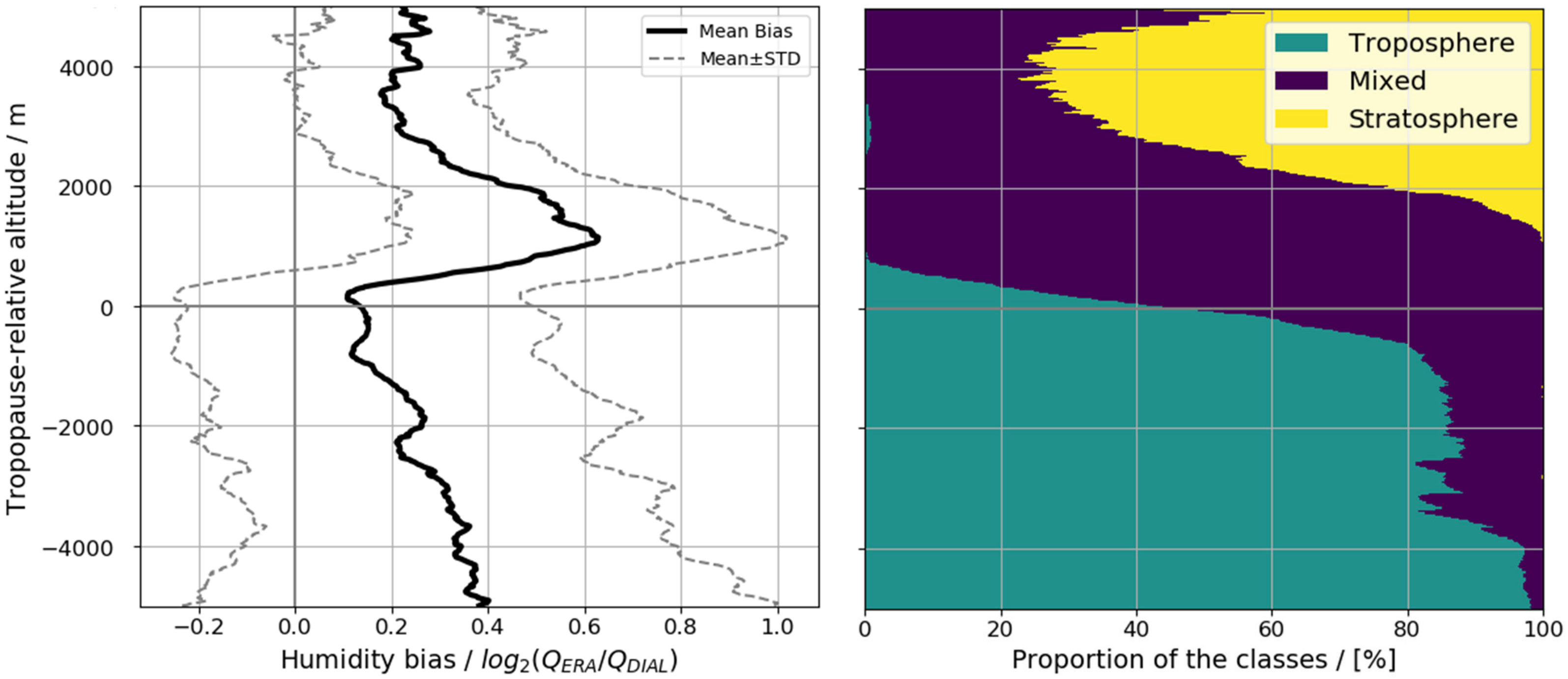
LS moist bias in ERA5

Origin of the bias

H_2O – O_3 data for 4 flights



(Krüger et al, 2022, ACP)

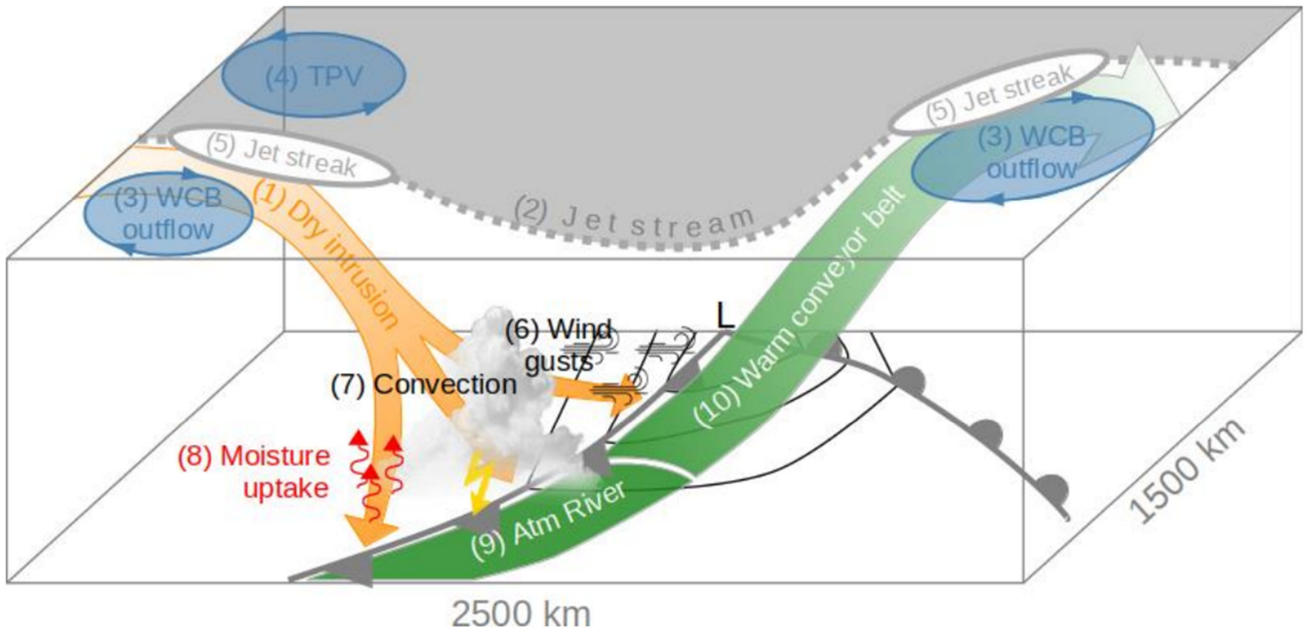


- moist bias correlated with mixed air: overestimated mixing processes involved in bias formation

Future campaigns: Individual mixing processes, seasonality, data assimilation

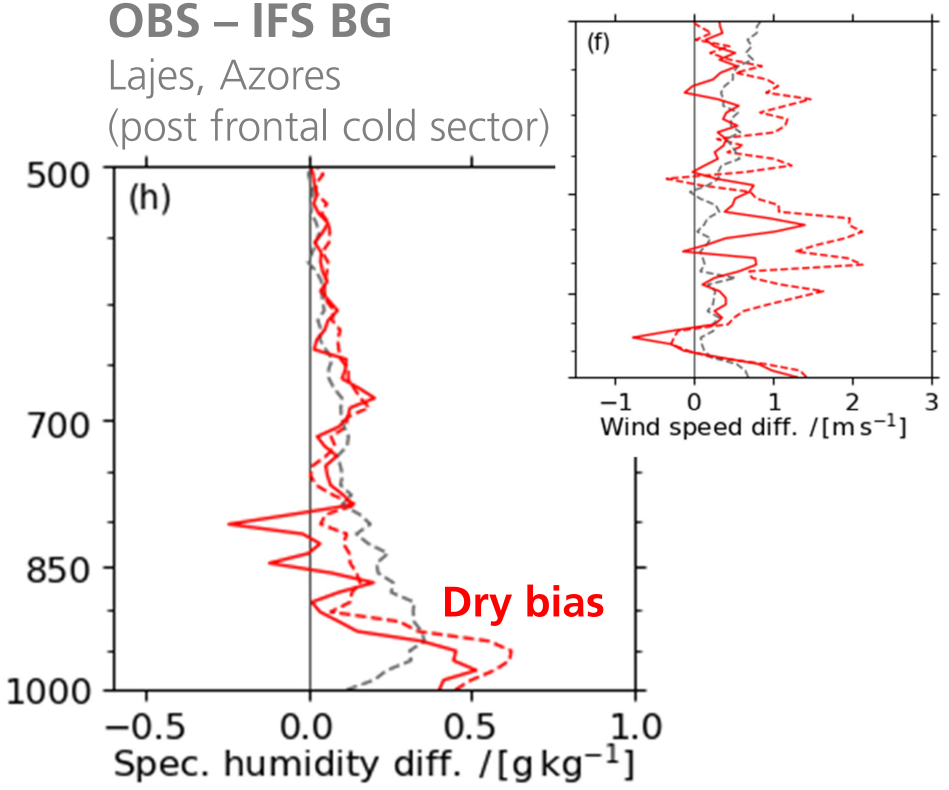
Outlook

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



Campaign idea from NAWDIC science plan

- January /February 2026
- International coordination



(Schäfler et al. 2024, GRL)

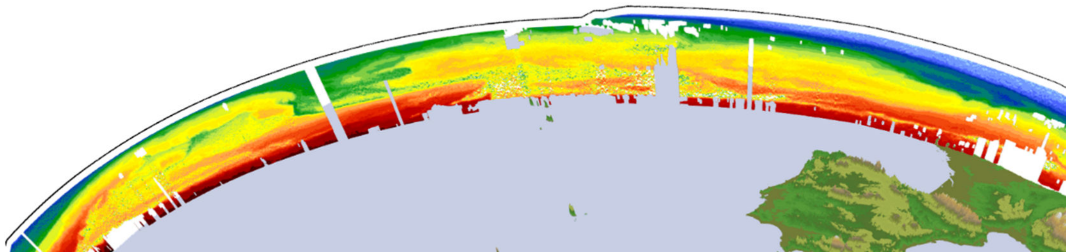
Collocated H_2O, O_3 and wind lidar observations to derive horizontal and vertical moisture fluxes in the PBL (post-frontal moisture sources) and UTLS

Spaceborne H_2O DIAL

The right time

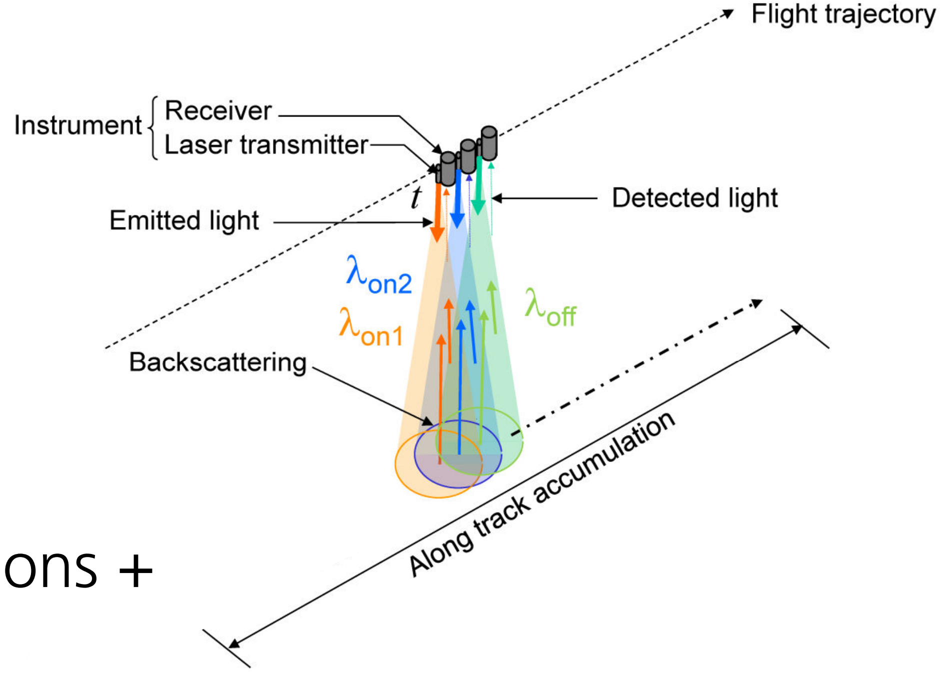
- **Broad applicability of airborne DIAL observations** in process studies from ground to the UTLS and inside and outside clouds
- **Technological innovation** in the past decades and the recent success with operating European **space lidars** (EarthCARE, Aeolus)
- Long standing **gap in the observing system**: little precise information on the vertical distribution of (tropospheric) WV
- **Global circulation** on weather and climate time scales largely depends on the **H_2O distribution** and impact it, weather and climate modelling relies on H_2O data

→ QLEO for monitoring global H_2O

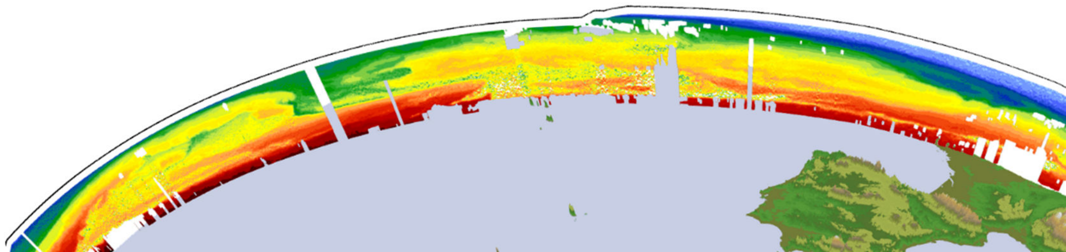


Spaceborne H_2O DIAL
QLEO characteristics

- Active optical DIAL technique, basic characteristics from WALES
  - 4 λ at 935 nm H_2O absorption band
  - Eff. vertical res.: 0.5 (PBL) to 1.5 km (10-16 km)
  - Horizontal res.: 25 (PBL) to 200 km (10-16 km)
  - Dynamic range: 0.005-25 g kg^{-1}
  - Precision: <10 %, accuracy (bias): <5%
  - Lifetime: 3-4 years, from low Earth orbit satellite

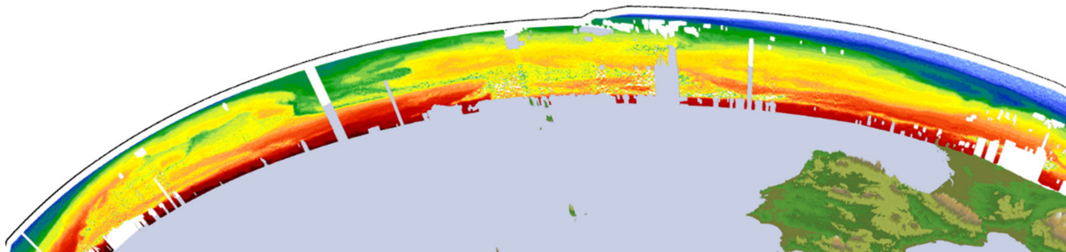


- High resolution H_2O profiles in clear and cloudy regions +
  - Boundary layer depth, structure and humidity
  - Vertical aerosol profiles and aerosol optical depth estimates
  - Cloud boundaries
  - Optical depth of cirrus and optically thin mid-level clouds
- Retrieval free of a priori information



Spaceborne H_2O DIAL
QLEO challenges

- Submission to ESA EE11 and EE12 calls failed despite
  - Components are modifications of space missions (AEOLUS, EarthCARE, MERLIN)
  - Cost optimization options: Reduced power consumption (lower horizontal resolution) and number of emitted wavelengths (focus on defined layers)
- Lidar missions remain expensive and technologically demanding
- Future ESA activities to increase technology readiness level would be appreciated
- Benefits of ESA’s 5th EE Aeolus to European stakeholders and society: 3.5 billion €



Spaceborne H_2O DIAL
QLEO expected achievements

DLR

Enhance our understanding of the H_2O distribution with focus on the troposphere:

- **Tropics:** coupling of deep convection to its environment, influence on tropical cyclones
- **Subtropics**: control on shallow cumulus distribution, cloud feedbacks and climate sensitivity
- **Extratropics**: predictability of weather on a variety of scales, control on high impact weather related to storms and connection to long-range moisture transport
- **Globally:** quantification of the surface energy budget, land-atmosphere and ocean-atmosphere interactions, moisture sources
- **NWP:** origin of biases, improvement through usage of range-resolved H_2O information

WV_cci community: reference data for vert. resolved CDRs

- QLEO limited life time, limited spatial resolution in UTLS
- But: low systematic error, identification of UTLS biases in NWP

→ WV_cci project highlights the need of H_2O profile data for climate applications