Unveiling water cycle processes in the troposphere using stable isotopic composition measurements

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Scientific context

- **Water vapor – an Essential Climate Variable**
  - for understanding the global hydrological cycle,
  - for improving operational weather forecasting,
  - to better predict extreme weather events,
  - to understand climate change and GES radiative forcing.
- **The need for precise water vapor observations is acute still**
  - especially in the lower troposphere in spite of currently available space-borne and surface-based observations,
  - because water phase changes make it challenging for instruments to consistently monitor 4D WV variability over several orders of magnitude,
  - … but WV concentration alone does not provide information on the role different processes may play in its variability.
- **Water vapor stable isotopes ($HD^{16}O$, $H_2{}^{18}O$)**
  - indicators of meteorological processes on a broad range of scales,
  - reflect evaporation, condensation, and air mass mixing processes.

Stable water vapor isotopes & processes

- Main isotopologue $\mathbf{H_2^{16}O}$ (99.731%)
  - *lightest molecule*
  - *tendency towards evaporation*
- Semi-heavy water $\mathbf{H_2^{18}O}$ (0.2%)
- Semi-heavy water $\mathbf{HD^{16}O}$ (0.0038%)
  - *heavier molecules*
  - *tendency towards condensation*
- Isotopic ratio (δD-notation):

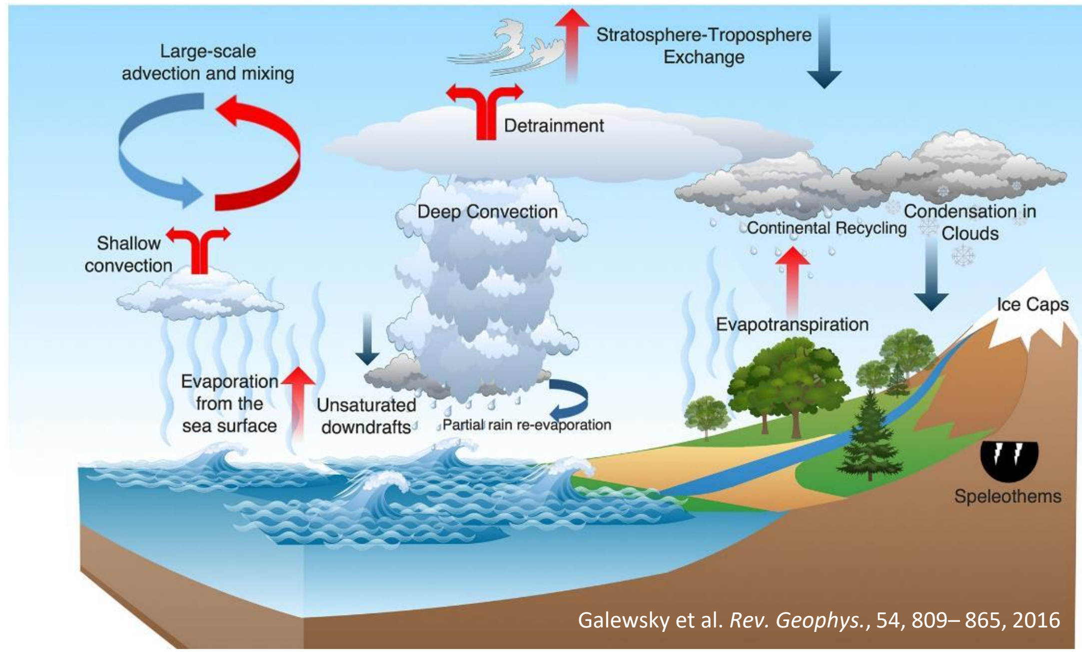
$$\delta\mathrm{D} = \left[\frac{[HDO]/[\mathrm{H_2O}]}{R_{\mathrm{VSMOW}}} - 1\right] \cdot 1000\ [‰]$$

$$R_{\mathrm{VSMOW}} = 3.1152 \times 10^{-4}$$

(Vienna standard mean ocean water)

increases δD (isotopic enrichment)

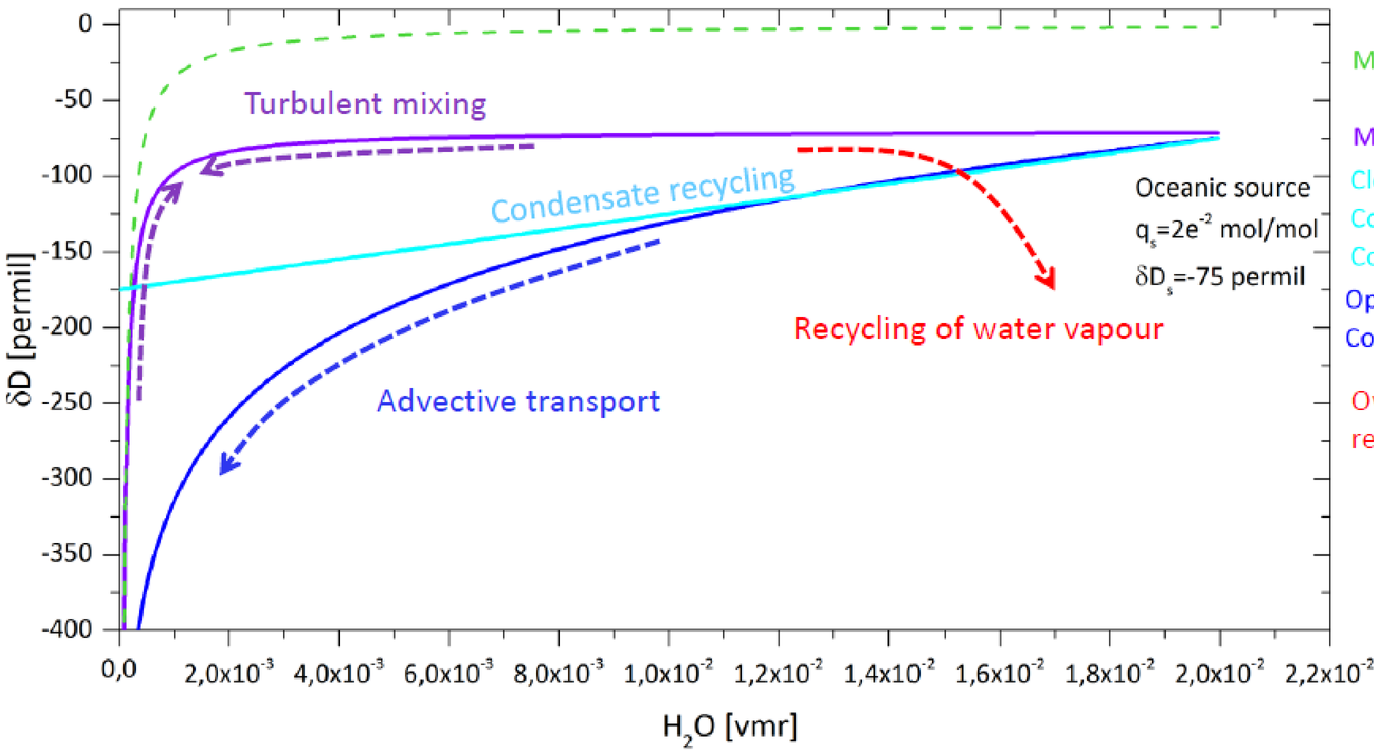
decreases δD (isotopic depletion)



Galewsky et al. *Rev. Geophys.*, 54, 809– 865, 2016

- Isotopic composition of water vapour is:
  - closely related to atmospheric transport as well as source (evaporation) and sink (condensation) processes,
  - can be seen as an integrating tracer of the water Lagrangian transport history.
- Isotope fractionation altering δD and δ^{18}O is:
  - driven by T at which phase change occurs,
  - due to the heavier isotopes preferring the more tightly bound phase,
  - Condensation/rain out: depletion of heavy isotopes.

Stable water vapor observations interpretation framework



Mixing with land source

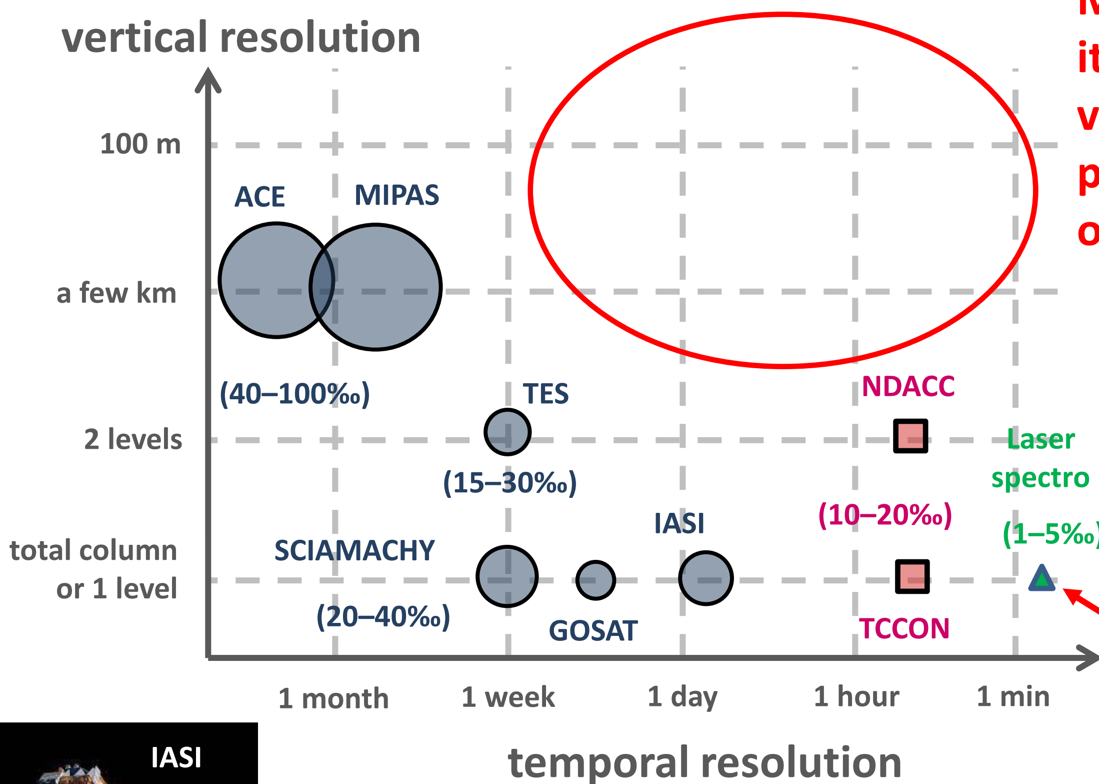
Mixing with oceanic source

Closed system
Condensate exchanges with the vapour
Condensate recycling

Open system (Rayleigh)
Condensate is removed from the system

Over-depleted -> Rain-reevaporation

Stable water vapor observations: existing instruments/techniques



Major observational gap when it comes to monitoring water vapor variability and underlying processes throughout the depth of the boundary layer!!

Laser-based spectrometer
Cavity-ring-down spectrometer (CRDS)

Regional scale studies

Local scale studies
Near surface processes &
Profiles with airborne CRDS (scarce)

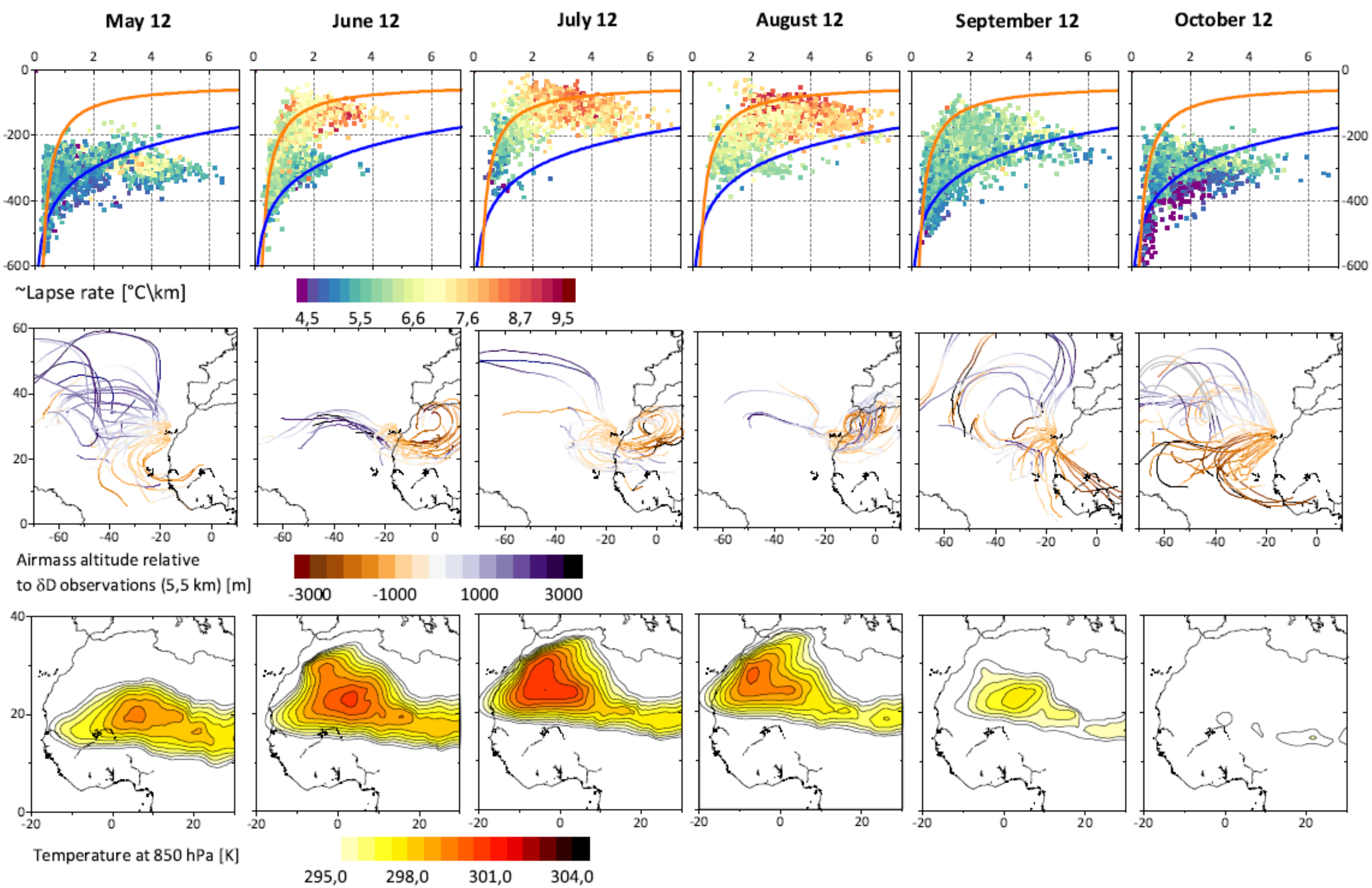
Stable water vapor observations: Regional scale studies

Importance of the Saharan Heat Low on the control of the North Atlantic free tropospheric humidity deduced from IASI δD observations (Lacour et al. ACP 2017).

IASI observations in the q-δD framework

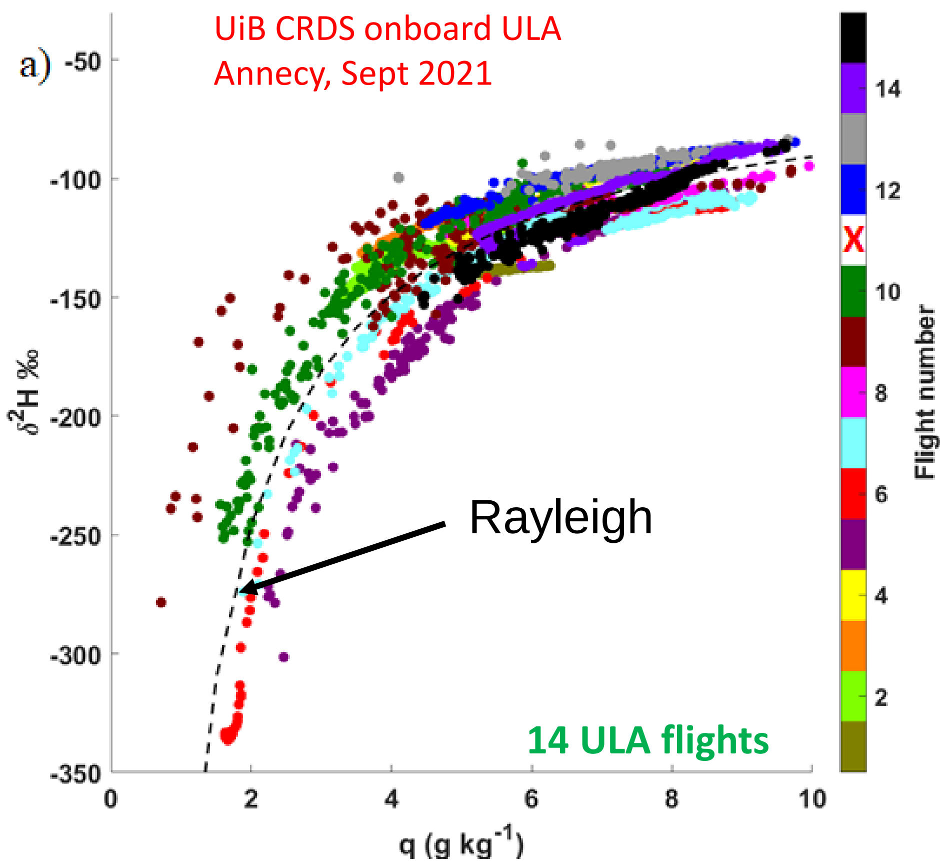
Airmass trajectories arriving in Tenerife, Canaries

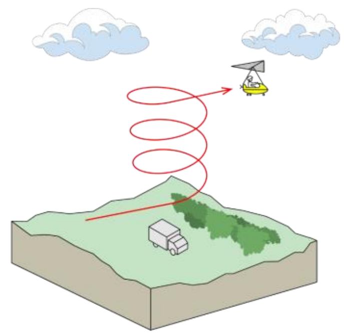
T at 850 hPa from ECWMF = proxy of the locatin of the SHL

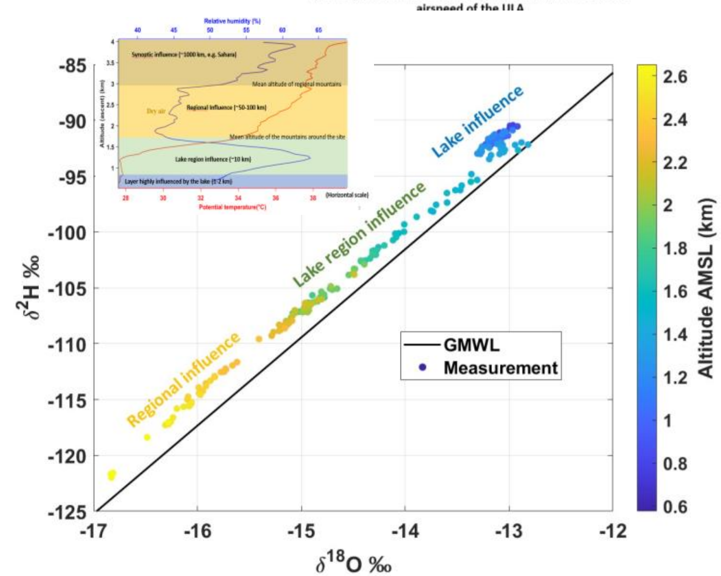


Stable water vapor observations: Local scale studies

Experimental investigation of the stable water isotope distribution in an Alpine lake environment (L-WAIVE) (Chazette et al., ACP 2021).



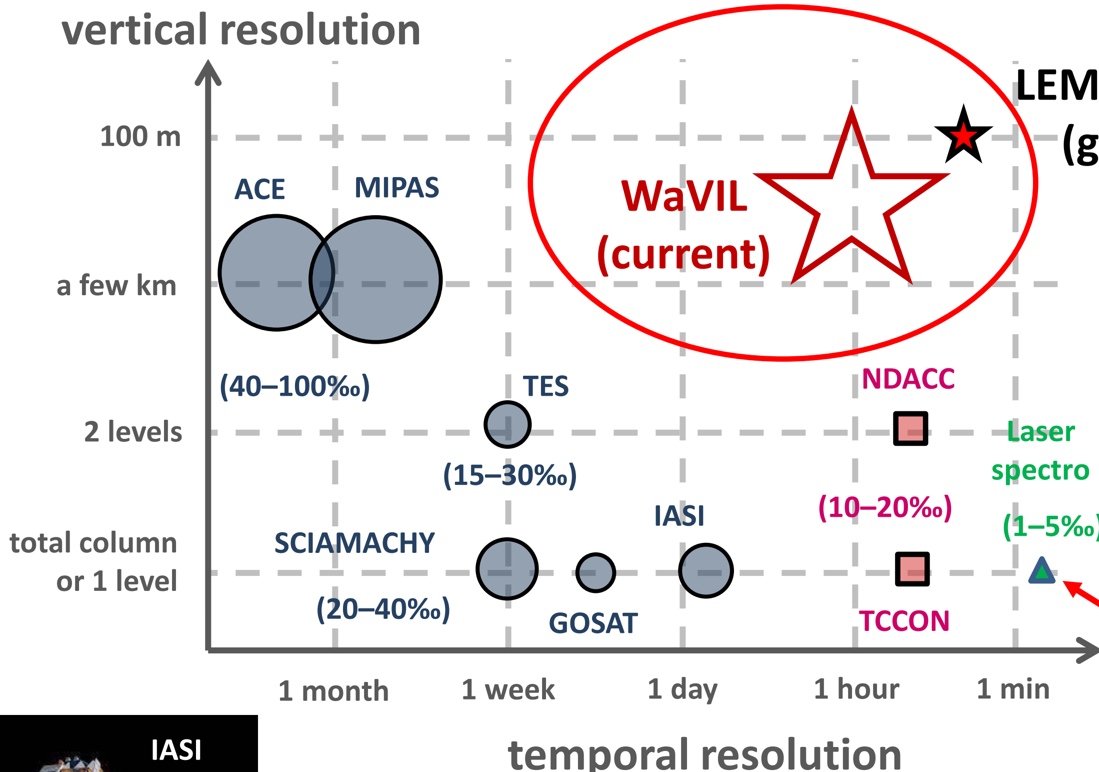


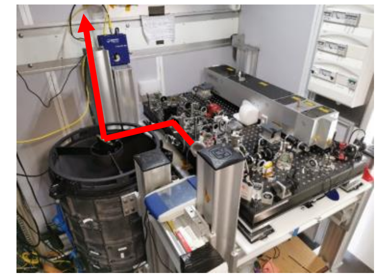


Stable water vapor observations: LEMON and WaVIL heritage

LEMON (2019-2023)

WaVIL 2017-2022)





Passive remote sensing:

- space-borne
- ground-based

Laser-based spectrometer
Cavity-ring-down spectrometer (CRDS)

Regional scale studies

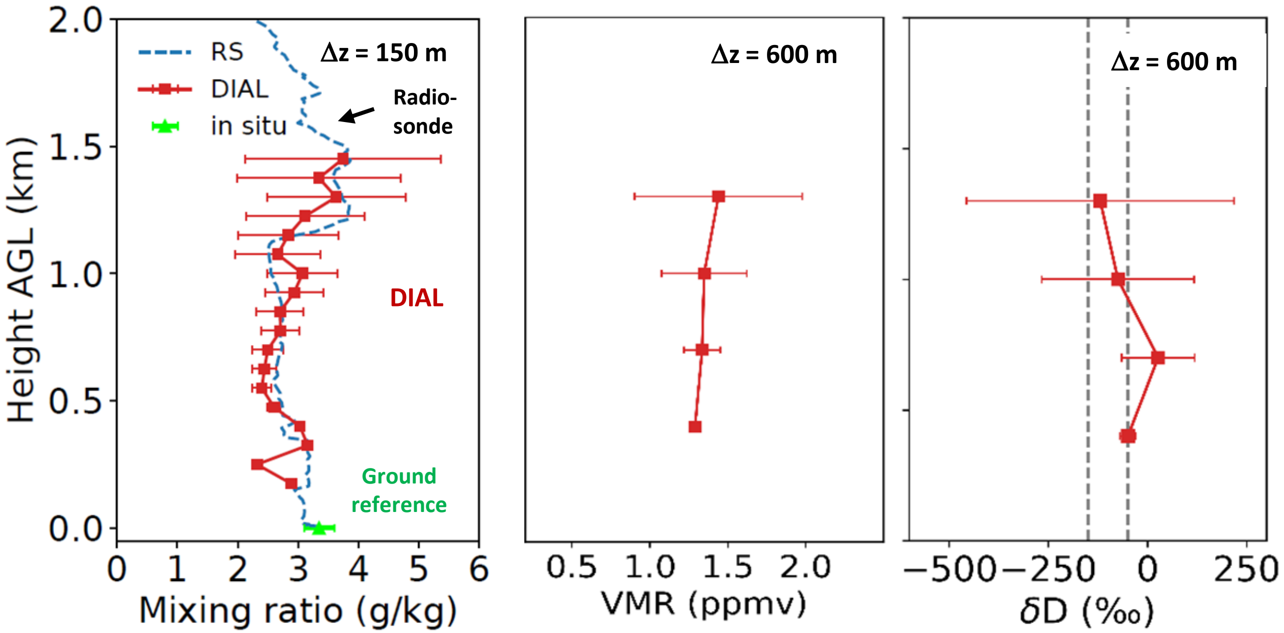
Local scale studies
Near surface processes &
Profiles with airborne CRDS (scare)

Vertical DIAL measurements of H_2O and HDO with WaVIL

Range-resolved detection of boundary layer stable water vapor isotopologues using a ground-based 1.98 µm differential absorption LIDAR (Hamperl et al., Optics Express 2022).

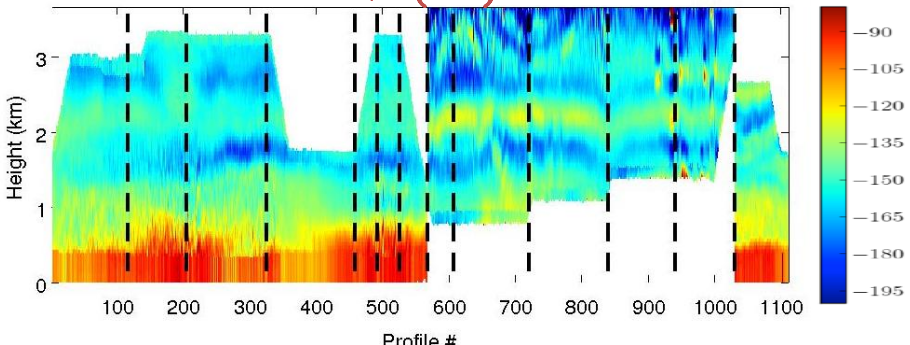
Separate measurements of H_2O and HDO at ONERA on 23/03/2022

25 min averaging, E ≈ 5 mJ



Towards continuous monitoring of the lower troposphere

LEMON: an innovative remote sensing tool capable of measuring water vapour and isotopic abundance profiles of HDO to enhance our knowledge of the water cycle at scale relevant for meteorology and climate.



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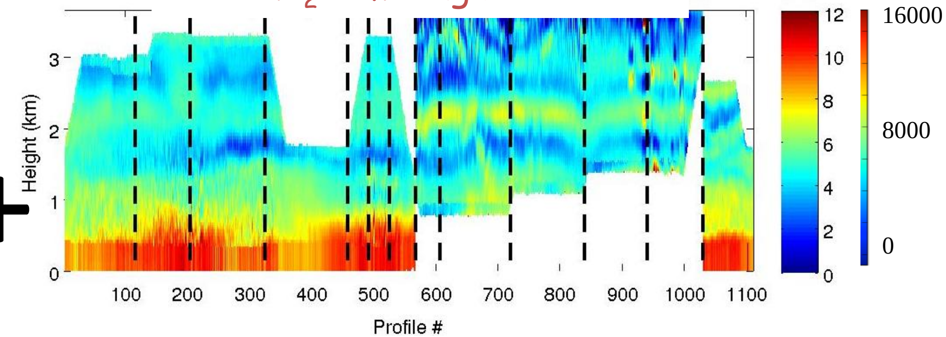
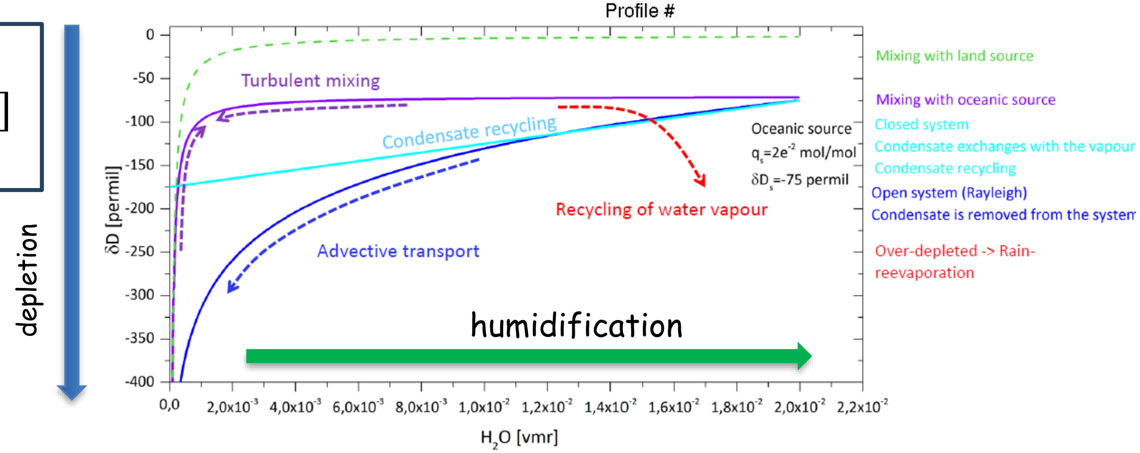


$$\delta \mathrm{D} = \left[\frac{[HDO]/[\mathrm{H_2O}]}{R_{\mathrm{VSMOW}}} - 1 \right] \cdot 1000\ [‰]$$

+

"Simple" q-dD interpretation framework (Noone et al., 2012)



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