



Differential absorption lidar (DIAL) for water vapor and aerosol profiling from airborne and space-based platforms

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Observational needs and challenges across scales



The 2017 Decadal Survey^(a) and the WCRP Grand Challenges^(b) highlight the need for **accurate, high vertical resolution measurements in PBL and aloft:**

- Water vapor (WV)
- PBL height
- Thermodynamics, aerosol, ...

Towards a deeper understanding of weather and climate systems **across scales:**

- Clouds,
- Air quality,
- ...

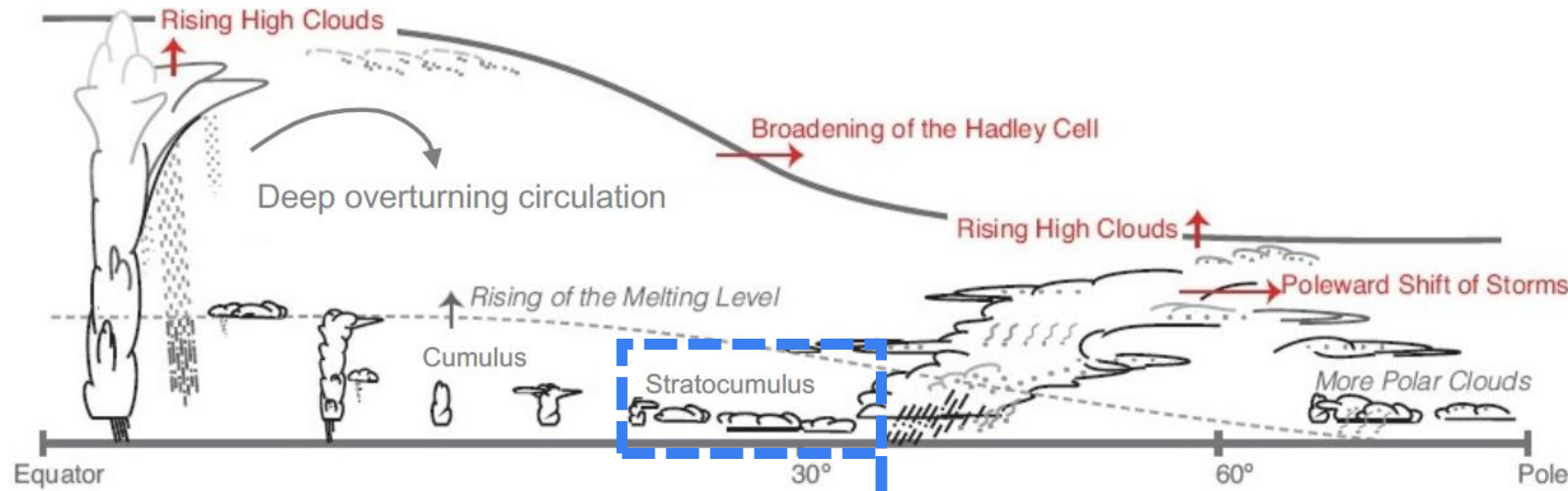
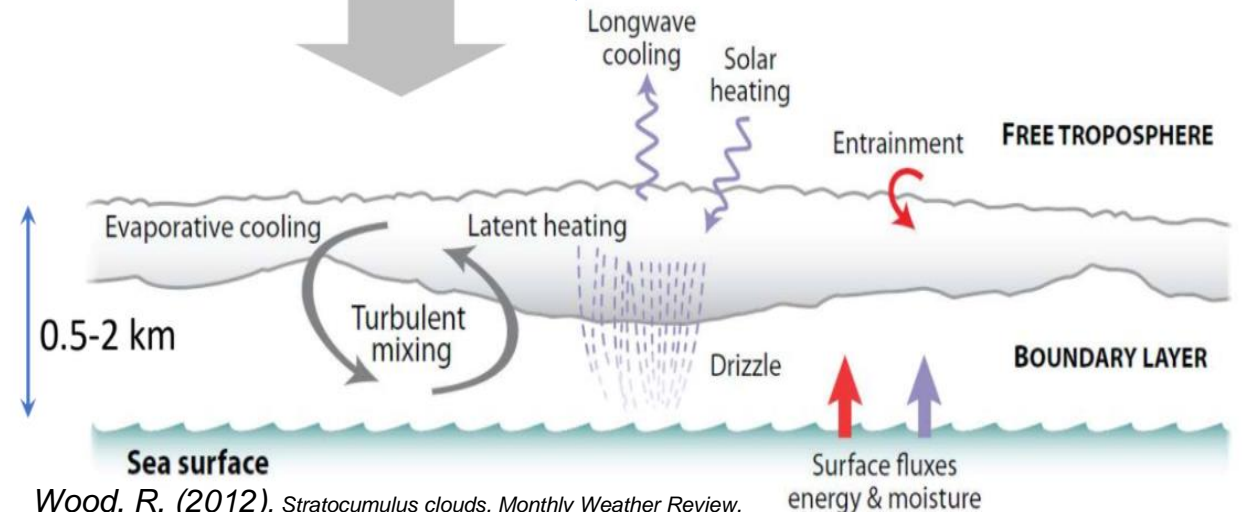


Fig. 7.11 of IPCC (2013)*

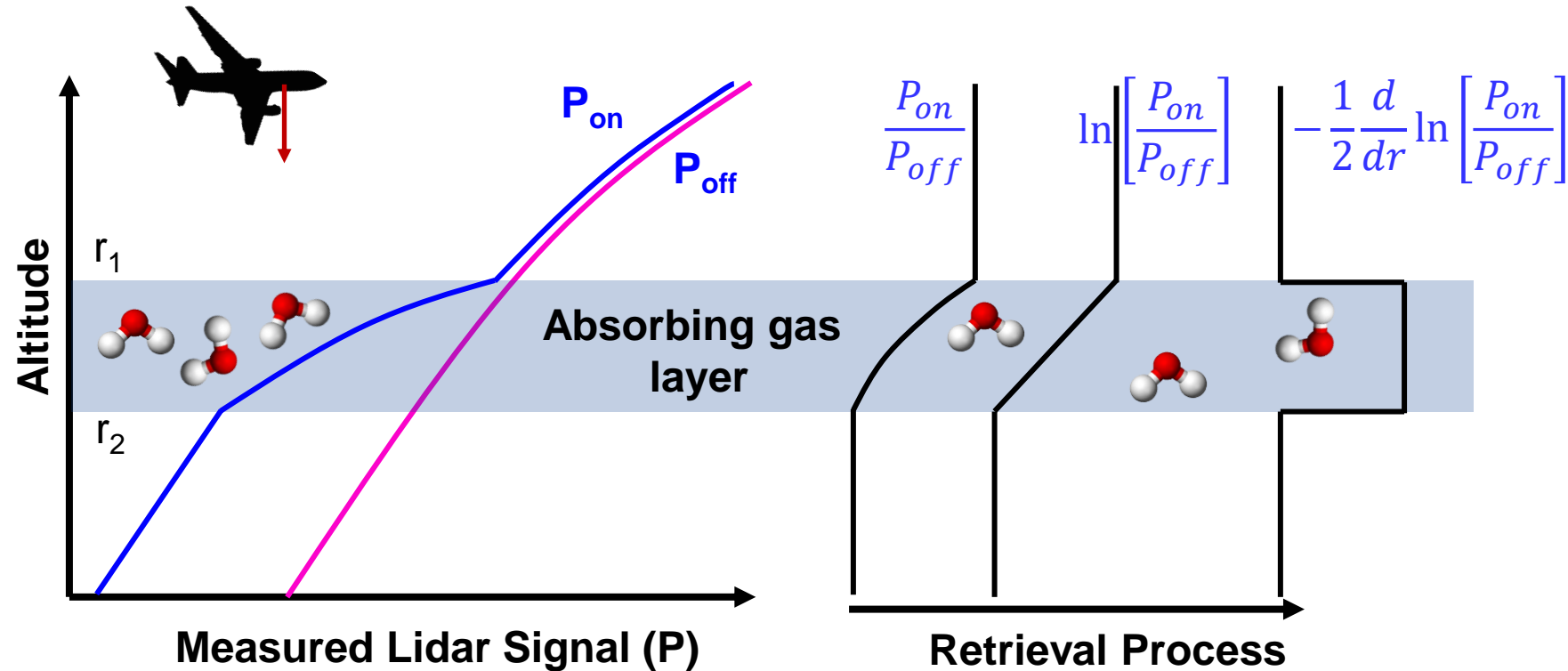
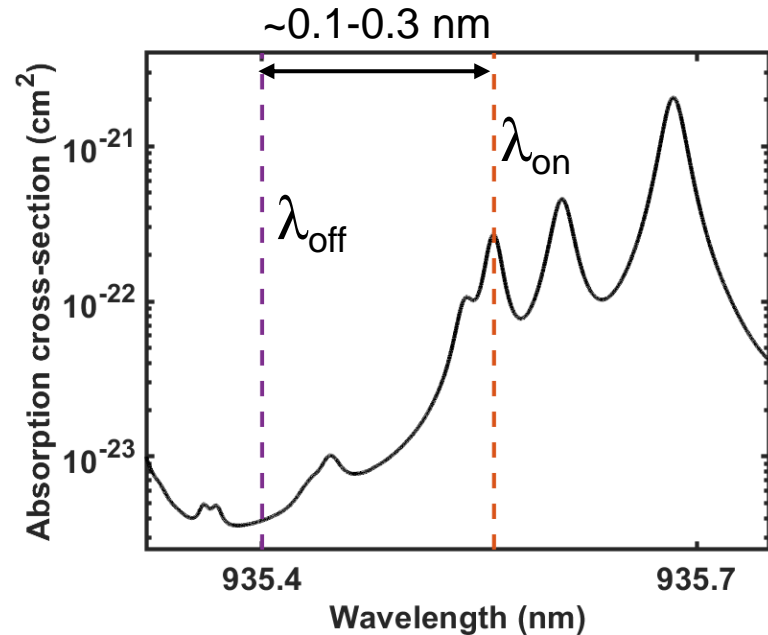
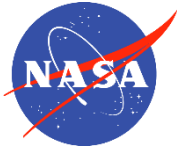
Large scale subsidence



Wood, R. (2012). Stratocumulus clouds. *Monthly Weather Review*, 140(8), 2373-2423. © American Meteorological Society. Used with permission.

* IPCC, 2013: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the IPCC*. Used with permission.

Differential Absorption Lidar (DIAL) – Principles and Characteristics



- WV number density is proportional to the differential absorption at two wavelengths
- **Direct, calibration-free** measurement of WV
- Measurements in lower atmosphere are independent of humidity and aerosol signals aloft
- Direct measure of uncertainty for every retrieval

Retrieved Number Density Profile:
$$n(r) = \frac{1}{2\Delta r \Delta \sigma(r)} \ln \left(\frac{P_{off}(r_2)}{P_{on}(r_2)} \cdot \frac{P_{on}(r_1)}{P_{off}(r_1)} \right)$$

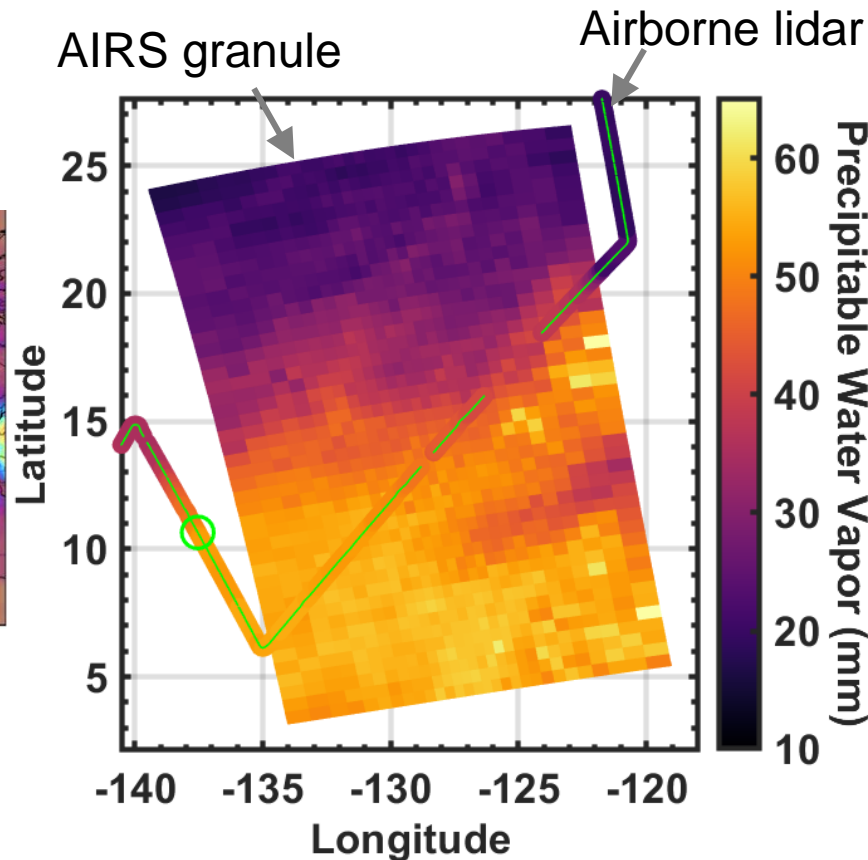
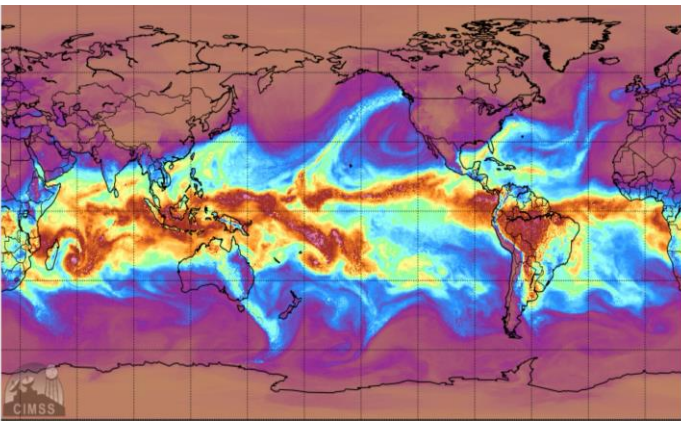
Random Error:
$$\frac{\Delta n}{n} \propto (\Delta t)^{-0.5} (\Delta r)^{-1.5}$$

Observing system capabilities



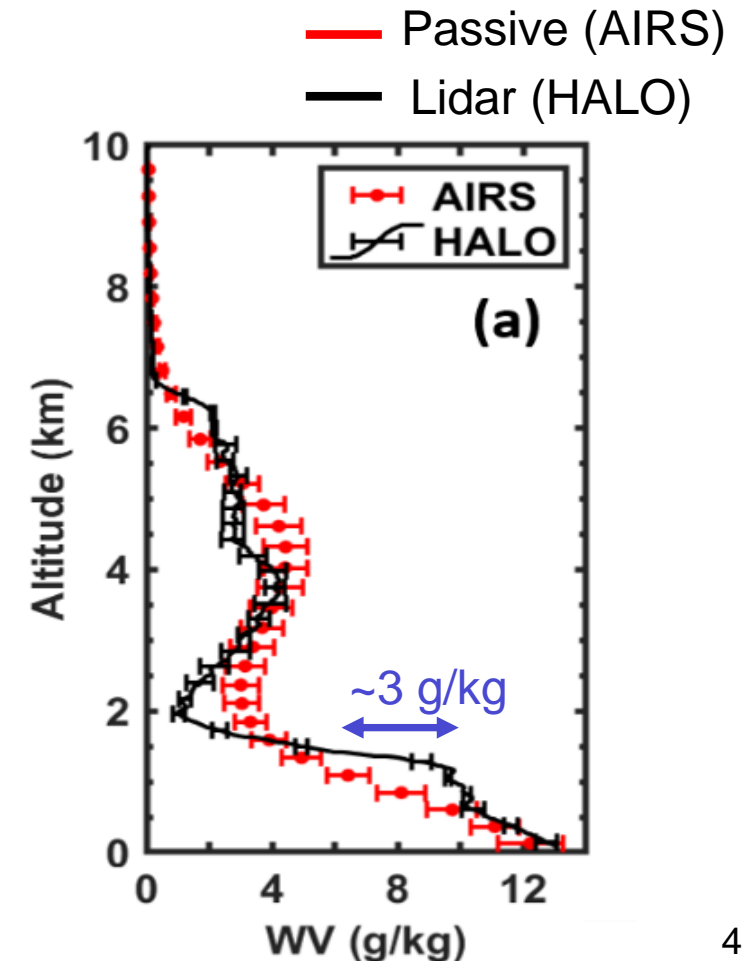
Passive sounders

Global coverage, poor vertical resolution especially in PBL / lower troposphere

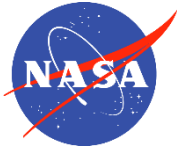


Lidar

Small footprint, high vertical resolution



High Altitude Lidar Observatory (HALO)

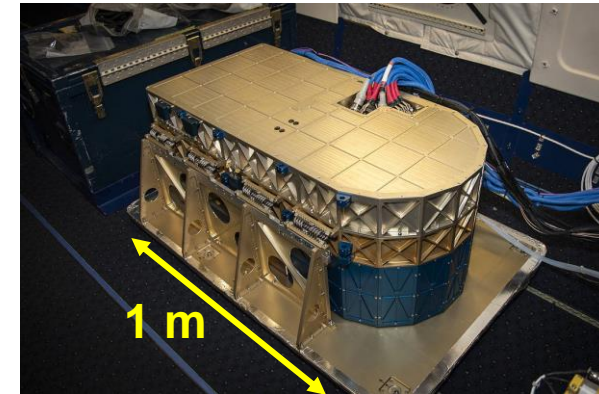


- Multi-functional, compact design compatible with most research aircraft
- Airborne observations of atmospheric dynamics, composition, radiation, & carbon cycle
- Technology testbed for future space-based DIAL

Differential Absorption Lidar
Water vapor DIAL

High Spectral Resolution Lidar
Aerosol/cloud/ocean HSRL

Integrated Path DIAL
Methane IPDA

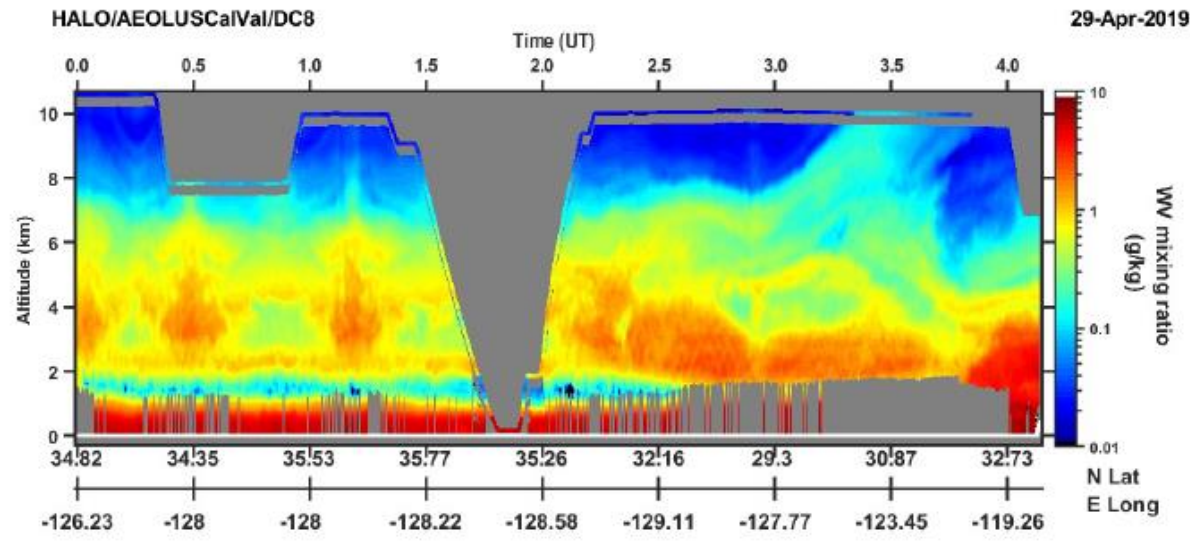
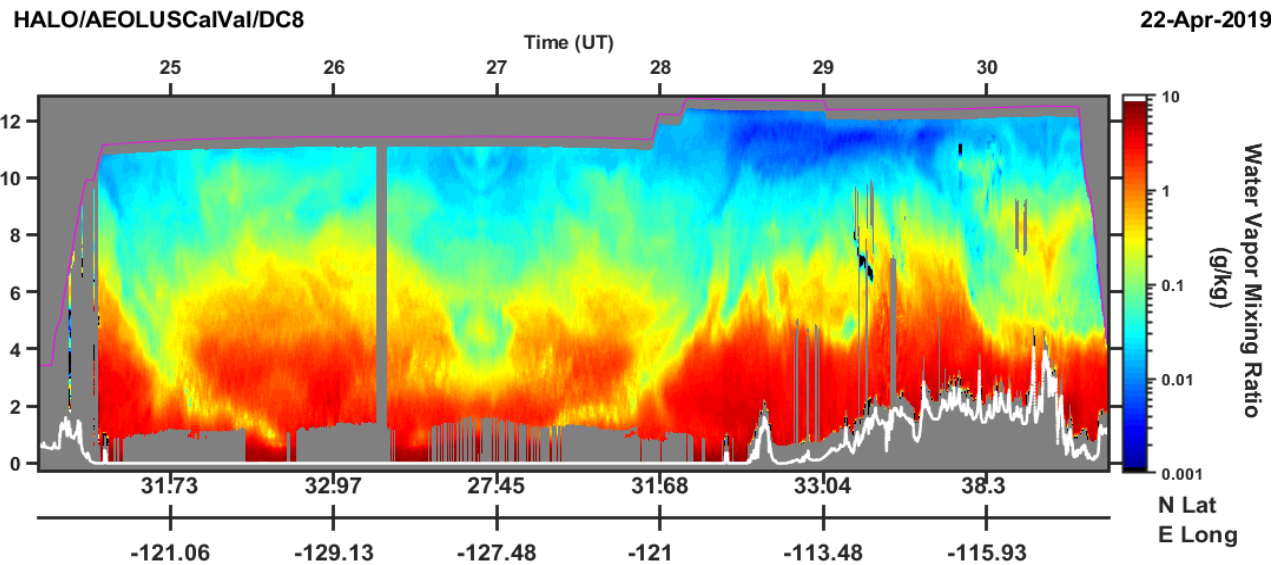
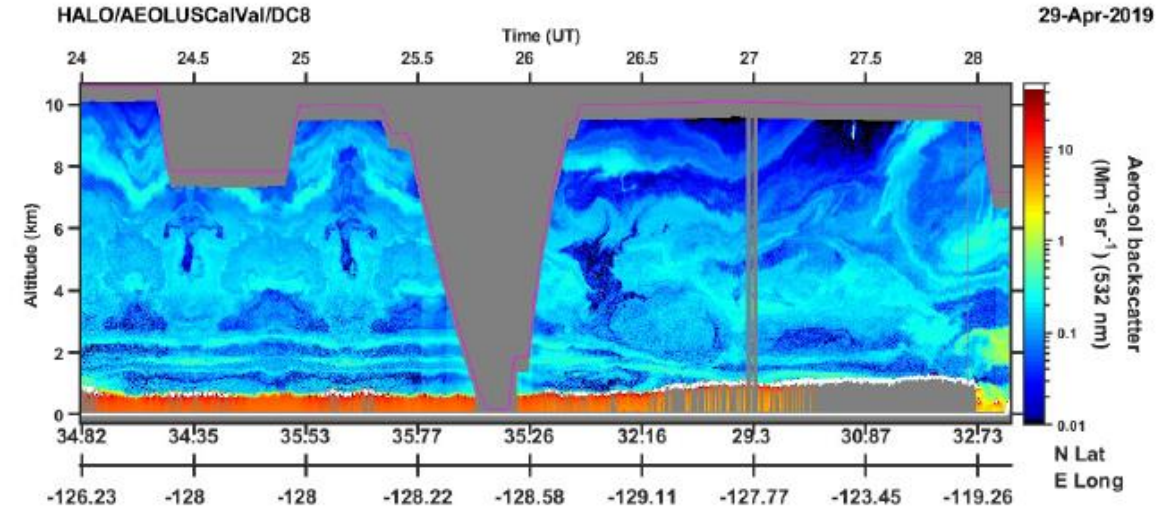
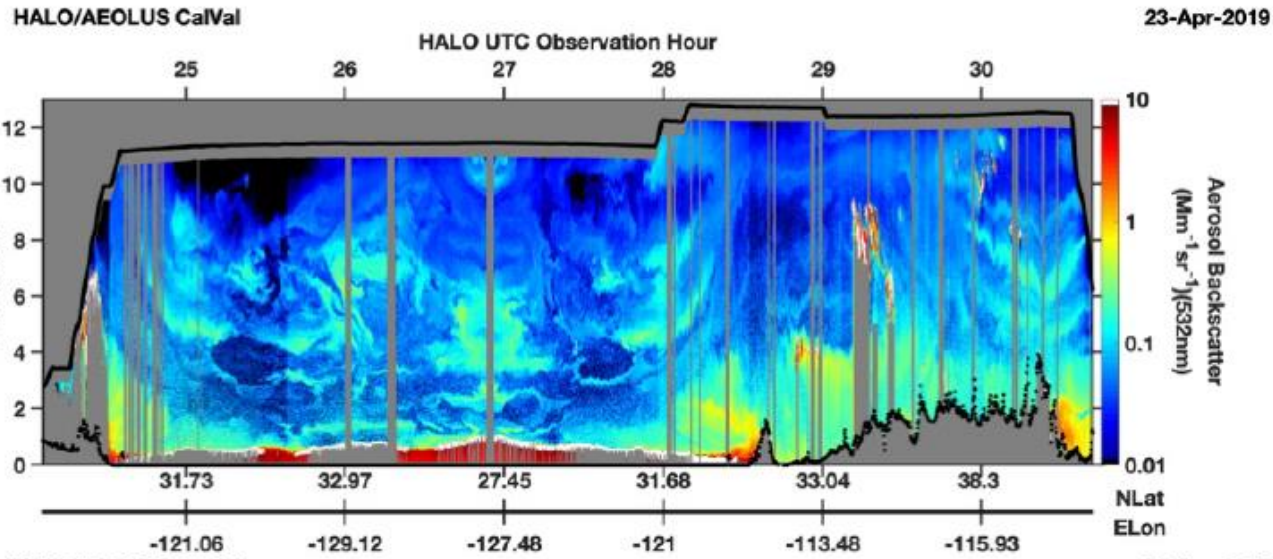
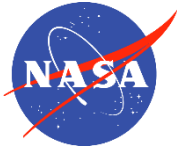


Parameter	Wavelength (nm)	Approximate Precision	Horizontal Resolution	Vertical Resolution
Water vapor mixing ratio	935	5% or .001 g/kg	1-12 km (variable*)	100-600 m (variable*)
PBL height	532/935/1645	< 50-100 m	200 m	N/A
Aerosol Backscatter	532/1064	0.2 Mm ⁻¹ sr ⁻¹	1 km	15 m
Aerosol Extinction	532	0.01 km sr ⁻¹	12 km	300 m
Depolarization	532/1064	0.01	1 km	15 m
Aerosol Type	N/A	Qualitative	12km	300 m
Methane column	1645	<8 ppb	1 km	column

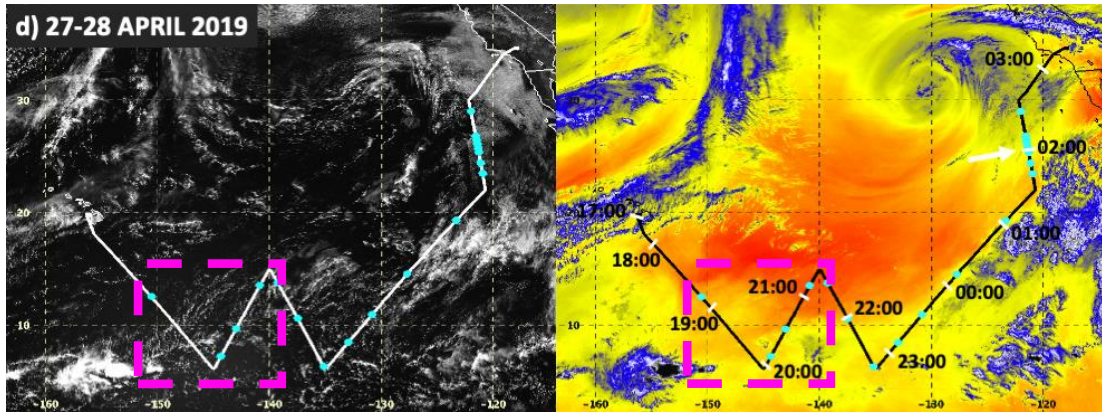
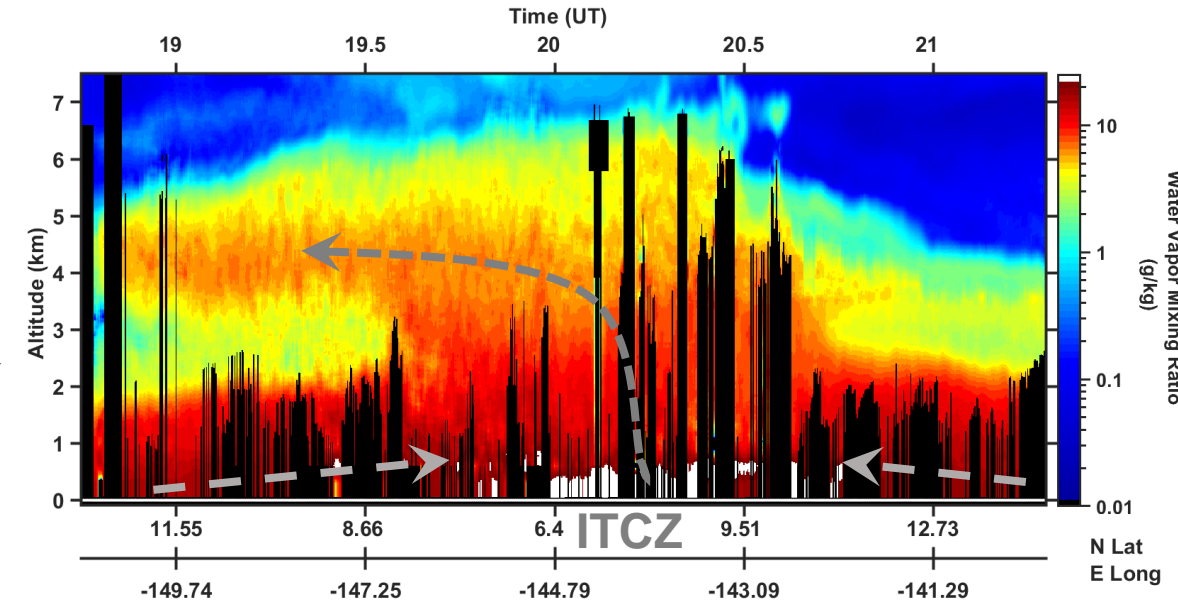
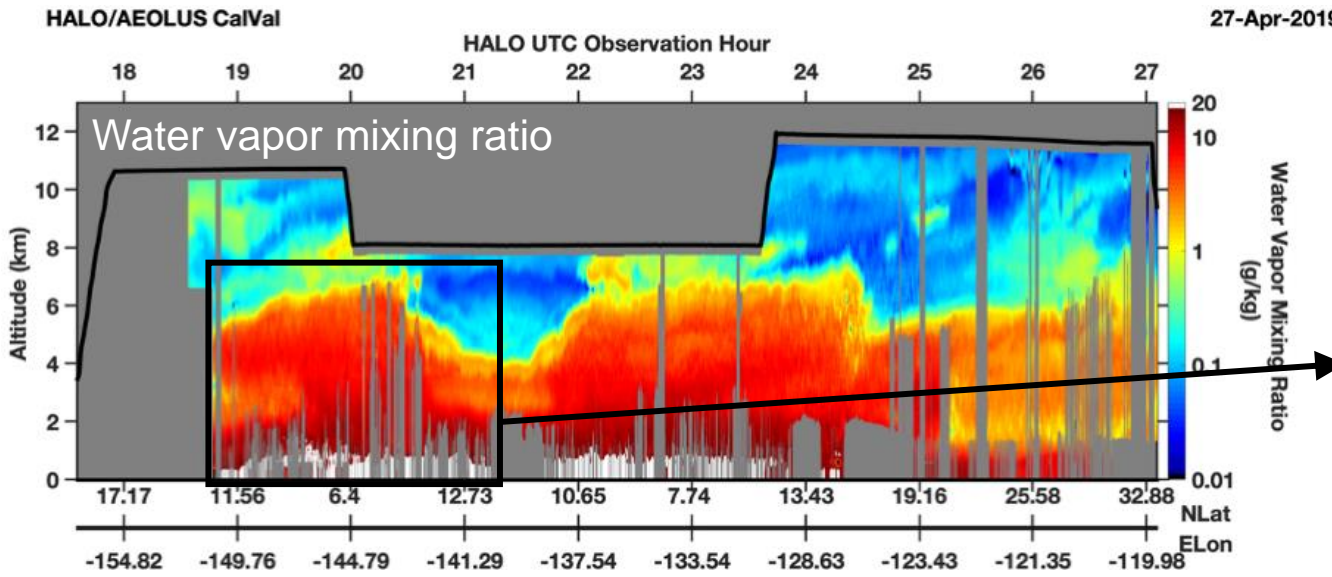
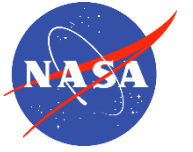


*DIAL resolution can be traded for precision to adapt for different applications.

HALO water vapor DIAL observations – Tropospheric coverage



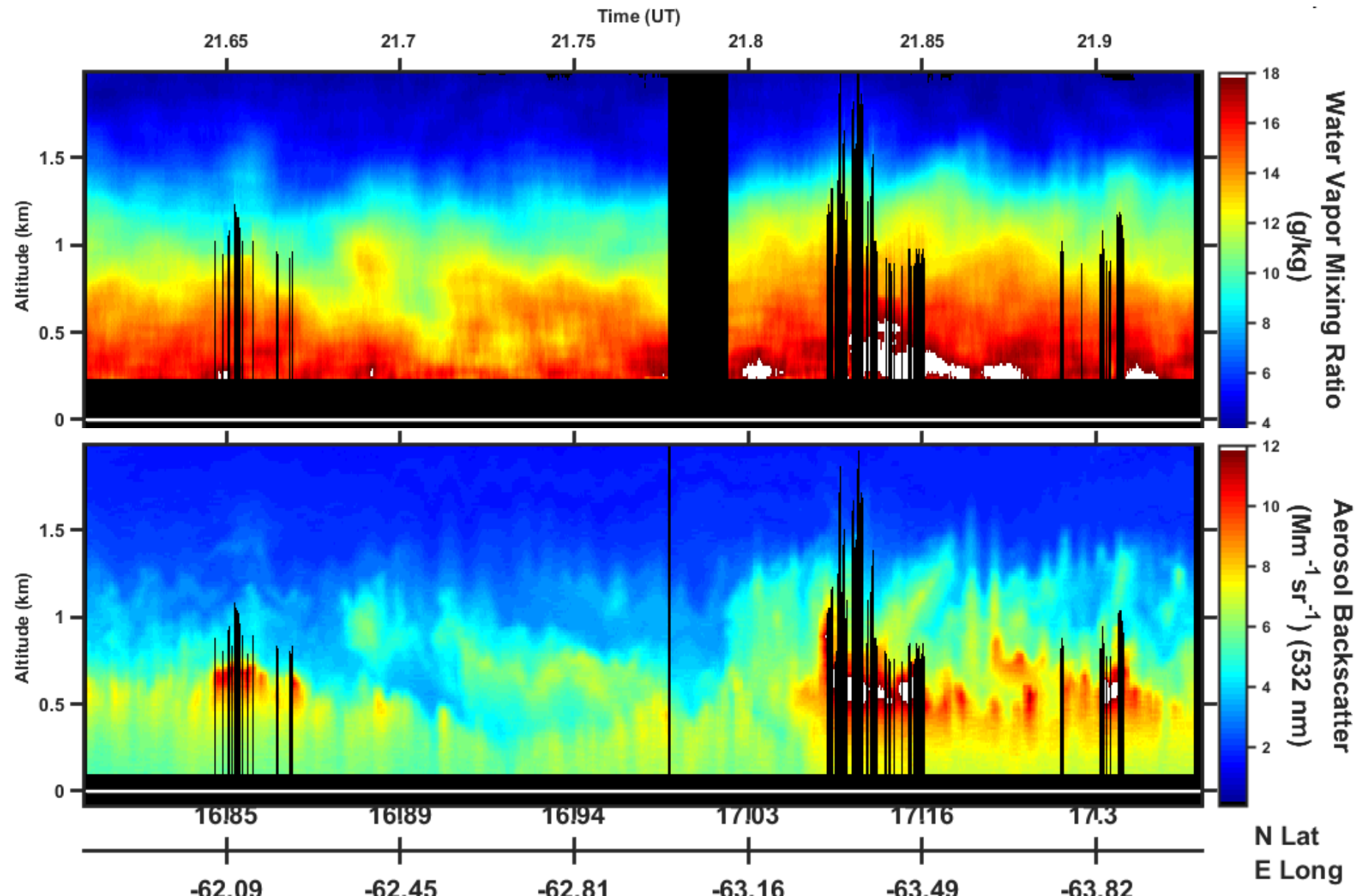
Moist tropical PBL and circulations



- Observing processes across scales that are coupled to the PBL
- Very moist ITCZ PBL
 - Moisture plume lofted ~4 km and advected northward, Hadley cell circulation
 - Higher cloud top heights in ITCZ

More water vapor causes more online signal attenuation, which is mitigated by tuning the online frequency.

High resolution



Will beautify these plots and fill in a few bullets of text later.

- Peaks ~20 sec apart (4km assuming 12km/minute... Check aircraft speed to do this math later)
- State WV resolution

Aerosol Extensive Parameters

Aerosol Intensive Parameters

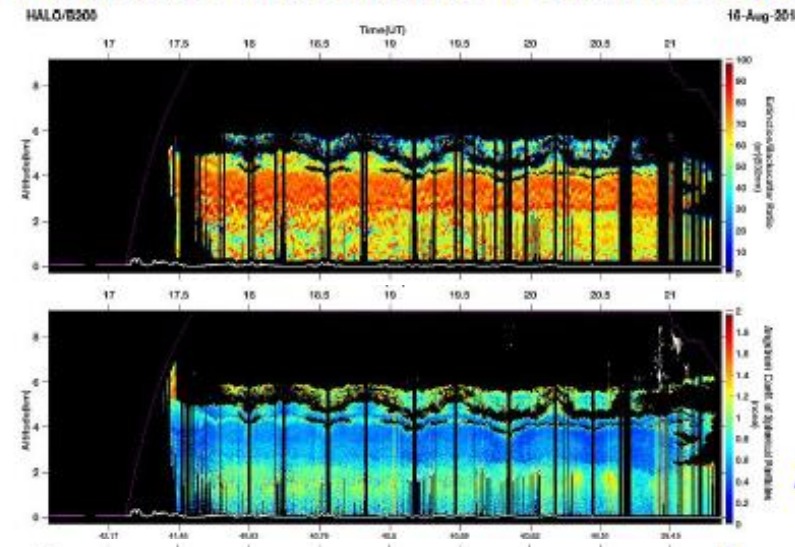
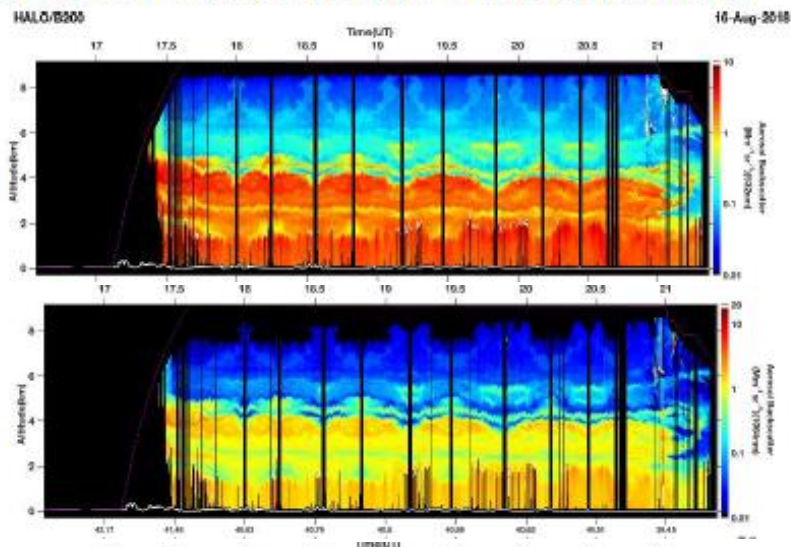
HSRL

532 nm
Backscatter

1064 nm
Backscatter

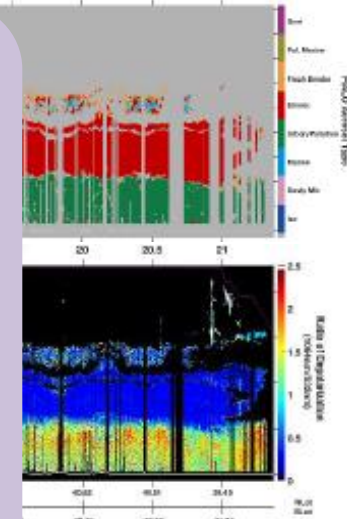
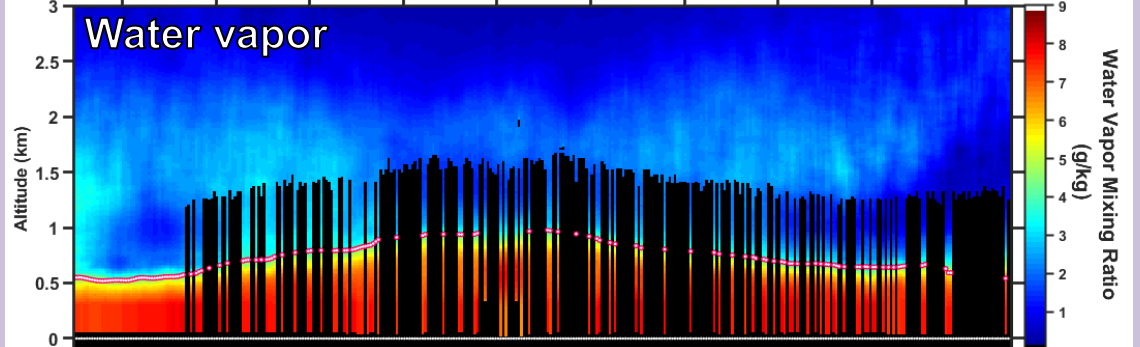
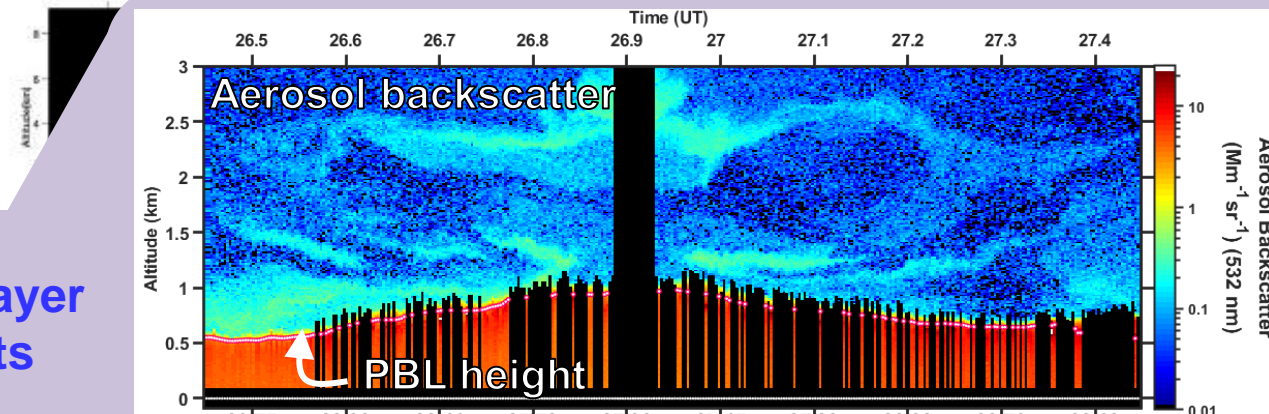
532 nm
Extinction

Mixed Layer
Heights



532 nm
Lidar Ratio

1064/532 nm
Backscatter
Angstrom Coeff.
(particle size)

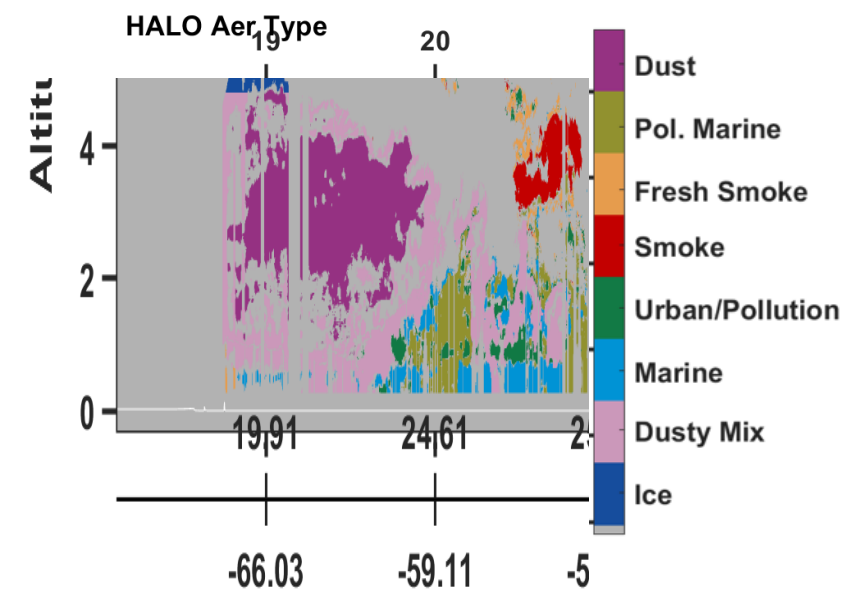
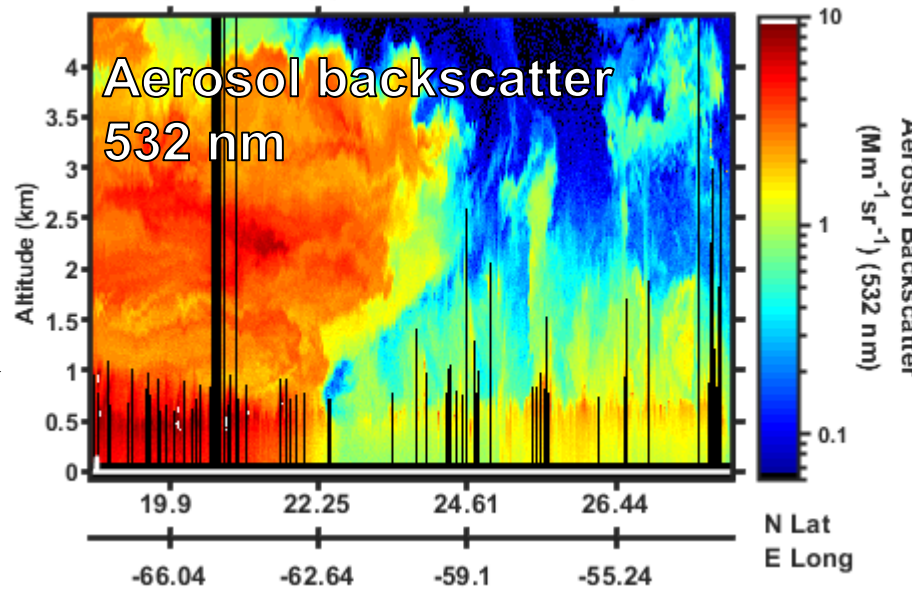
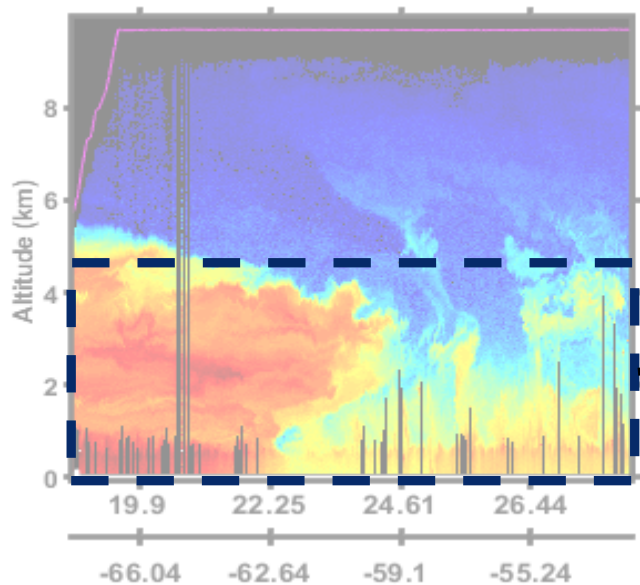
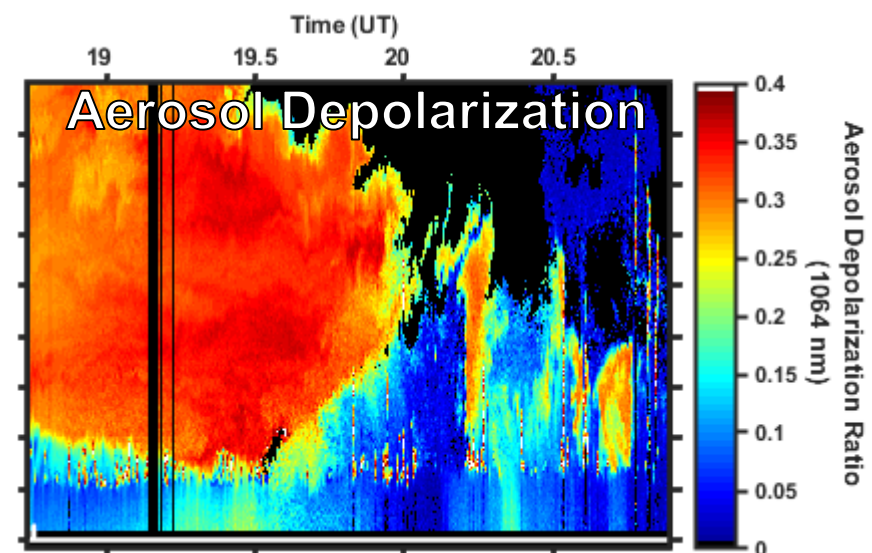
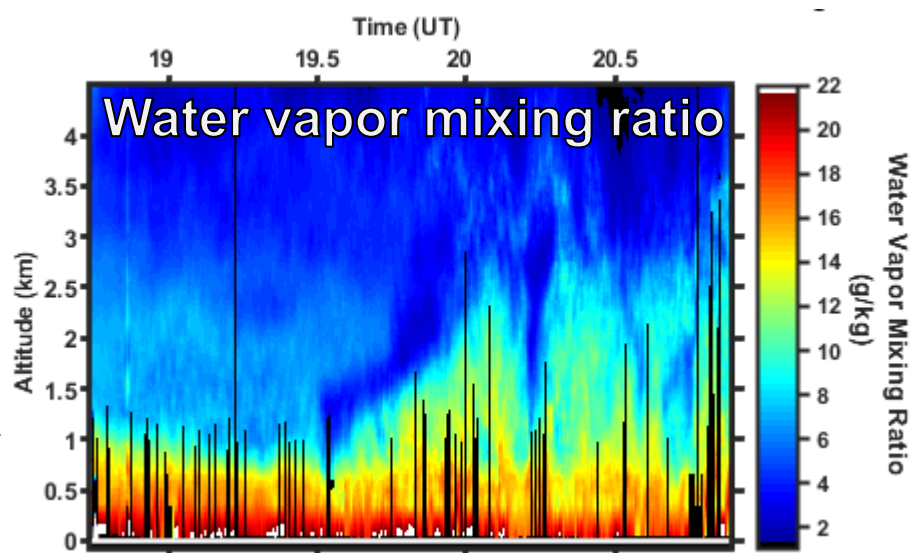
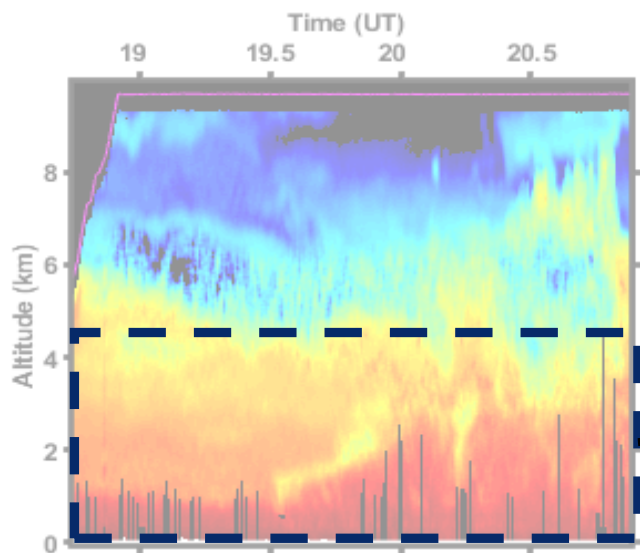


Aerosol Typing

1064/532 nm
Depolarization
Ratio

Other products may discern mixing/boundary layer height when aerosol backscatter is inconclusive

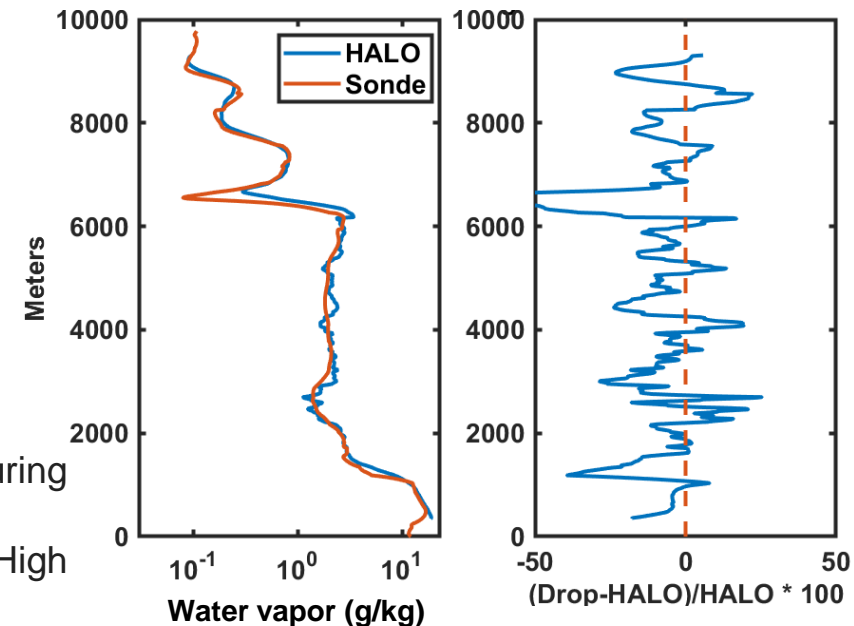
Analysis of complex scenes



Summary & path forward



- DIAL provides **direct measurements of water vapor with high accuracy**
- **Flexible resolution processing** and small footprint allows **measurement near clouds and the surface**
- Strengths of DIAL are **synergistic with other techniques**
- HALO is routinely supporting the NASA weather/dynamics, composition, radiation sciences, and carbon cycle programs *
- Airborne science bridges the gap between ground and space, providing intensive observations in hard-to-reach areas and a technology testbed for space
- Space-based missions are increasingly challenging, requiring extensive technology development towards space-based DIAL



* Bedka, K. M., et al. (2021). Airborne lidar observations of wind, water vapor, and aerosol profiles during the NASA Aeolus calibration and validation (Cal/Val) test flight campaign. *AMT*, 14(6), 4305-4334.

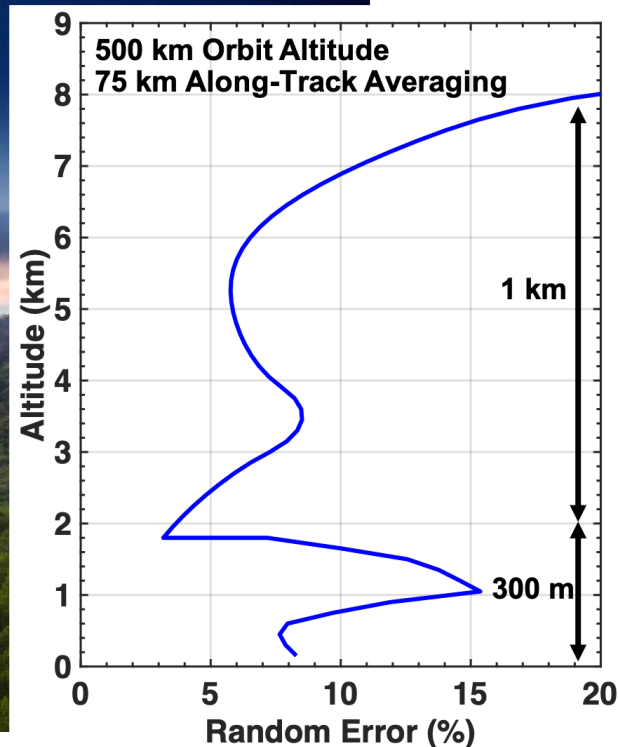
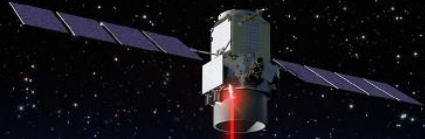
* Carroll, B. J., et al. (2021). Differential absorption lidar measurements of water vapor by the High Altitude Lidar Observatory (HALO): Retrieval framework and validation. *AMT Discussions*, 1-37.

Space-based DIAL development: ABLE



Atmospheric Boundary Layer Lidar Pathfinder (ABLE)

Water Vapor Profiles
PBL Heights
Aerosol/Cloud Profiles
Methane Columns



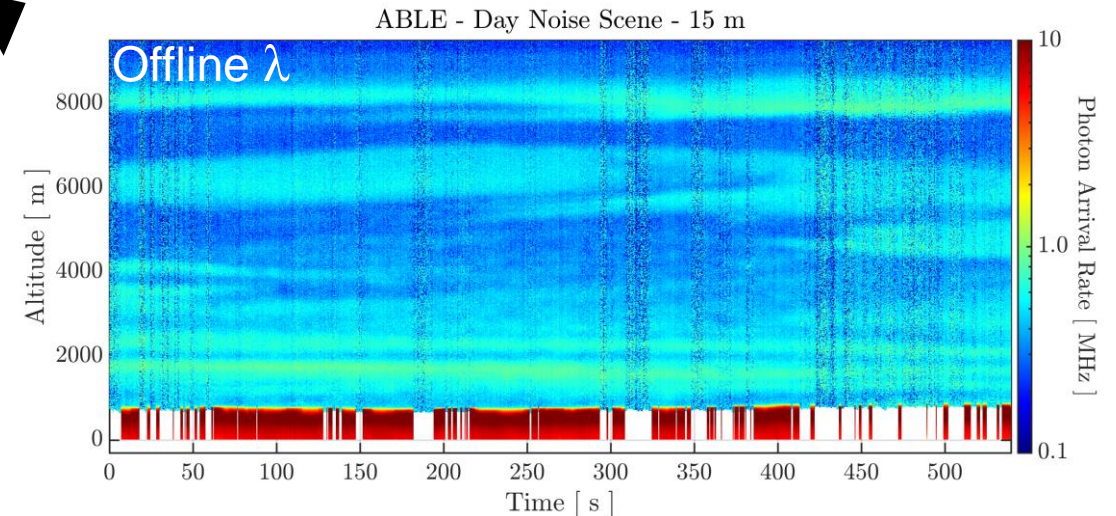
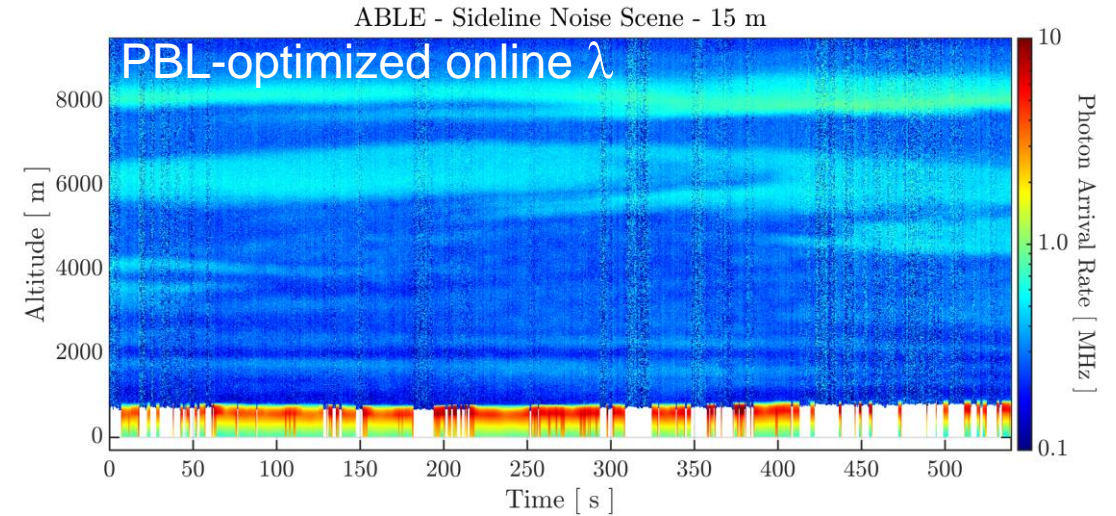
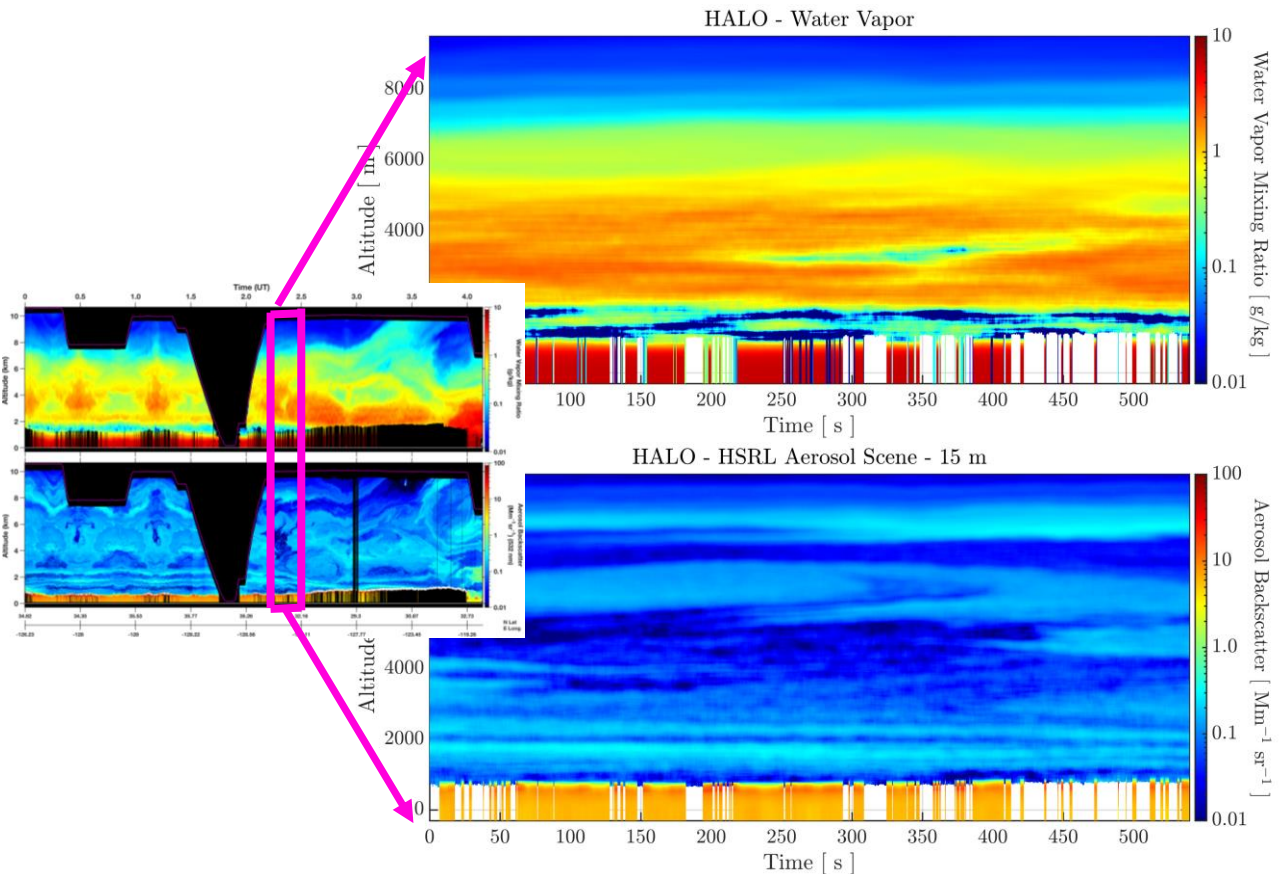
- Develop a pathfinder mission concept and advance associated technologies to **enable the first demonstration of DIAL in space**
 - Water vapor profiling from mid-troposphere to PBL
 - 200-400 m vertical resolution in PBL, 1km in mid-trop
 - 50-75 km along-track resolution
- **Novel laser technologies** enable crosscutting science spanning disparate science focus areas
 - Weather and dynamics (including PBL)
 - Atmospheric composition and radiation
 - Carbon cycle
- Set stage for synergistic observing system with backbone observations
 - Hyperspectral infrared sounders
 - Microwave sounders

ABLE simulator: HALO inputs

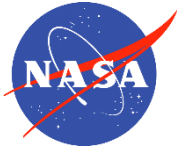


- HALO provides high-res “truth” water vapor & aerosol fields with a wide variety of conditions
- HALO data is input to a forward model lidar simulator

- Simulator produces observed photon counts at ABLE wavelengths

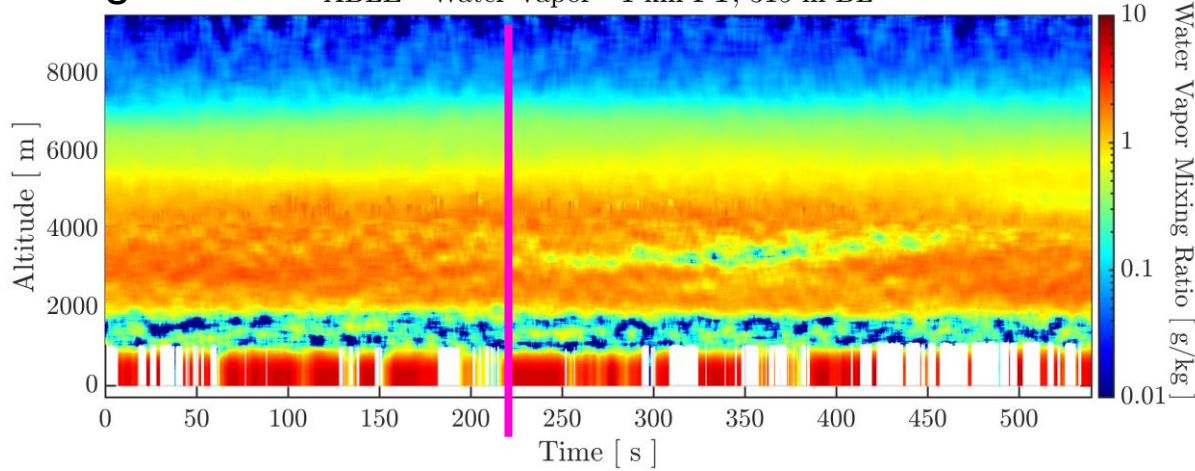


ABLE simulator: Retrieved water vapor profiles



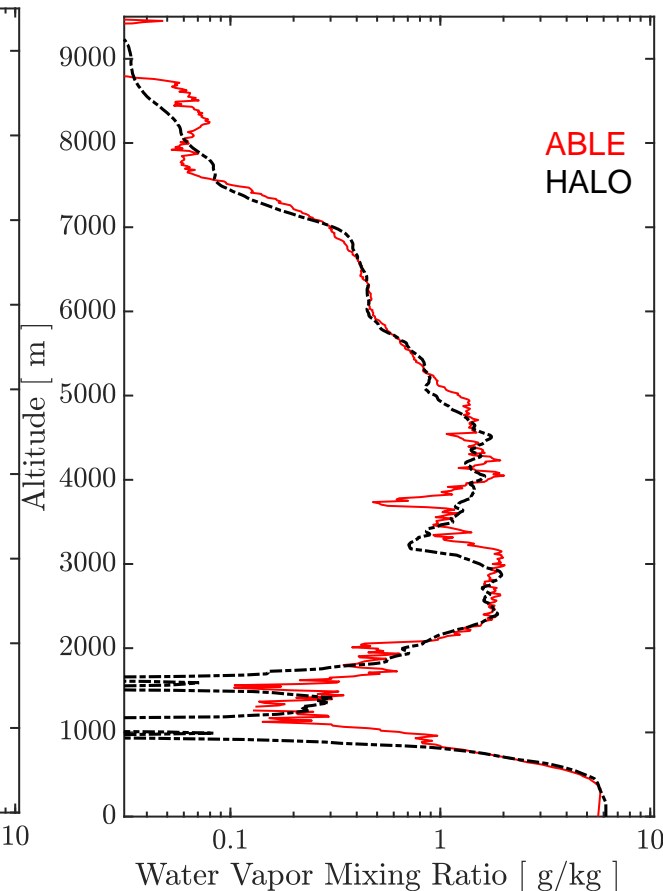
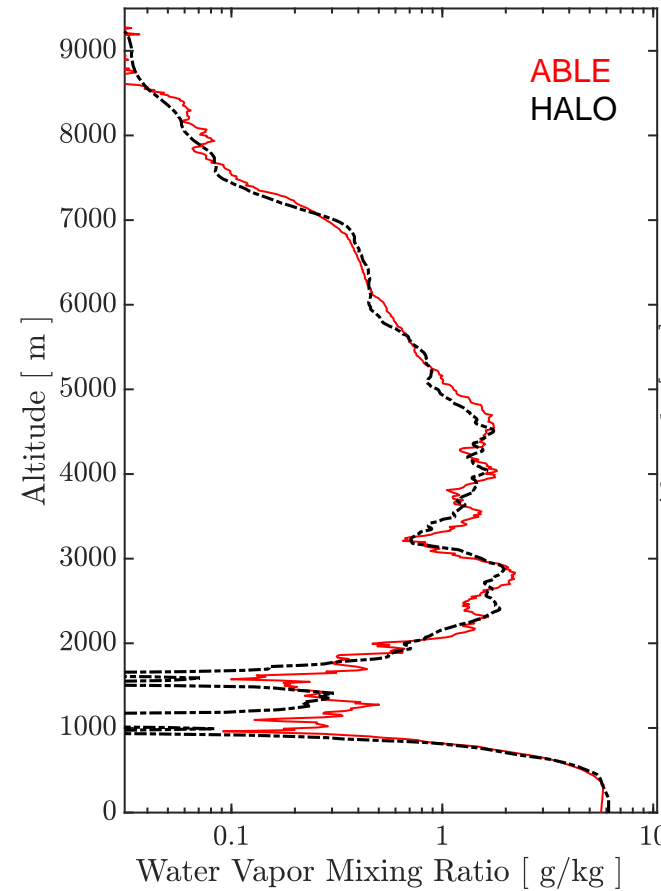
Nighttime

ABLE - Water Vapor - 1 km FT, 315 m BL



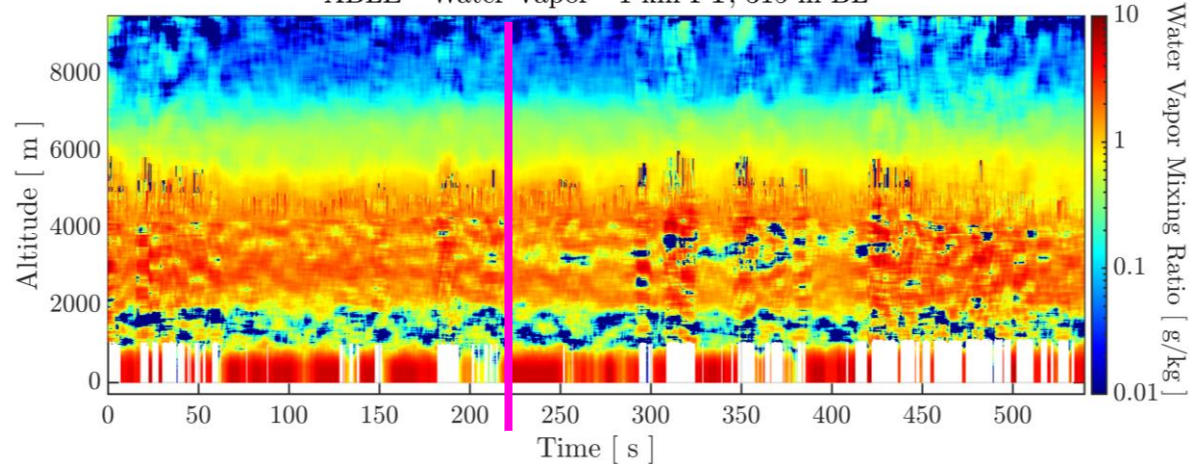
Nighttime

Daytime



Daytime (worst case)

ABLE - Water Vapor - 1 km FT, 315 m BL



50 km along-track averaging is shown here, but resolution can be increased at the cost of precision