PBL Remote Sensing with GNSS-RO

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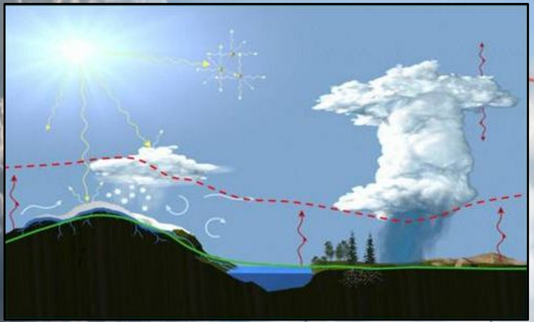
IROWG-10, Boulder, CO
Sept 11-18, 2024

PBL: What/Why

Teixeira et al., NASA PBL Incubation Study Team Report, 2021

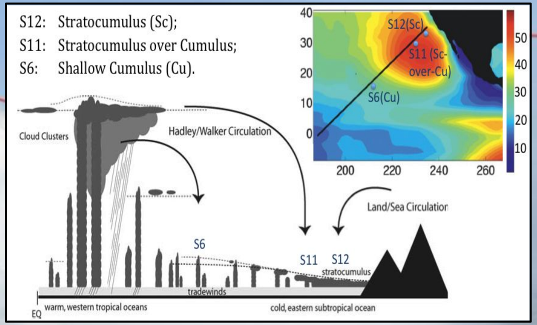
The planetary boundary layer (PBL) is the turbulent layer of the atmosphere adjacent to the Earth's surface (~ 1-2 km thick) which mediates the interactions between the surface and the free troposphere above, and responds to surface forcings within hours

Weather, Clouds, Storms



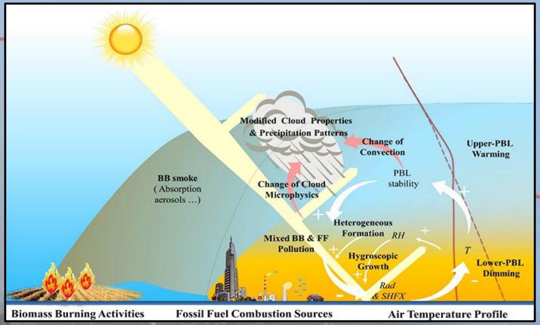
How do severe storms develop and where?

Cloud-Climate Feedback



How will low cloud coverage change under global warming?

Air Quality & Trace Gas Fluxes



What is the concentration of pollutants in the air we breathe?

Melbourne et al. 1994, p. 15:

"*The very sharp and large contrast in refractivity at the marine boundary layer between the moist air below and relatively dry air above induces dramatic changes in the amplitude and phase of the signal….*

knowledge of the height of the marine boundary layer obtained from occultation data will improve the interpretation of nadir-viewing measurements of water vapor."

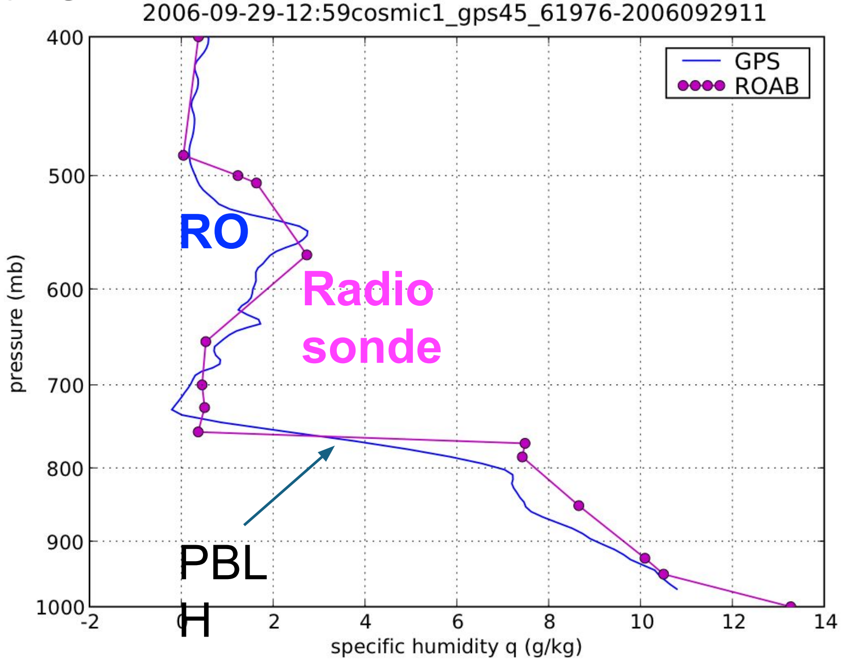
However, it was not until the development of radioholographic retrieval methods and implementation of open-loop tracking on SAC-C and COSMIC in early-mid 2000s, that such promise can be realized.

Topics

- PBL height from GNSS-RO
    - Research highlights using COSMIC
    - New era with COSMIC-2 and Commercial RO
- Joint RO & PS (passive sounder) characterization of the PBL
    - 1D and 3D approaches
    - Future PBL mission

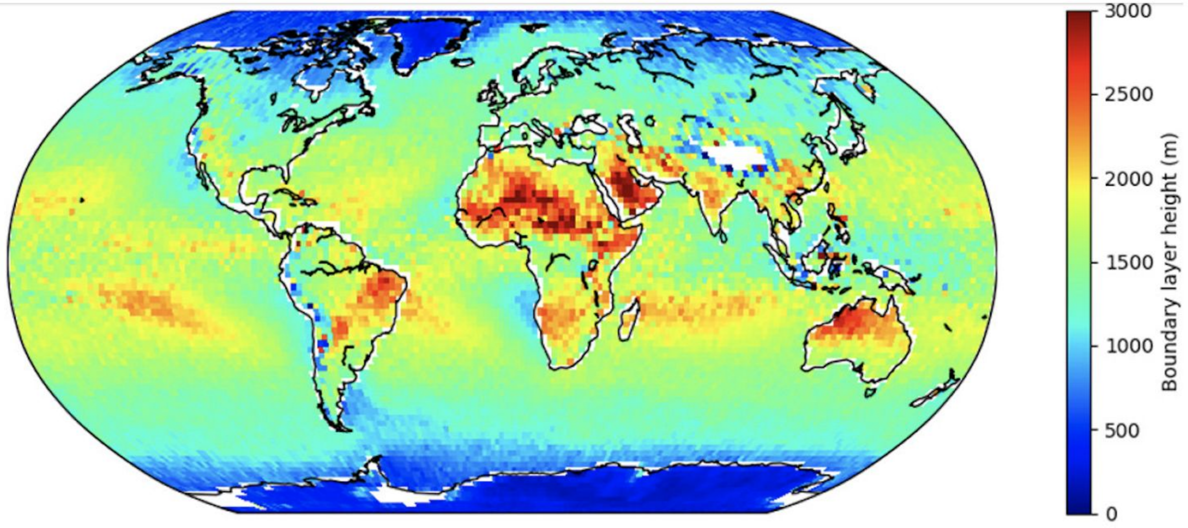
PBL height

GNSS-RO measurements are sensitive to sharp changes in refractivity (moisture and temperature) that can occur at the top of the PBL



PBLH = height where min(dN/dz) occurs

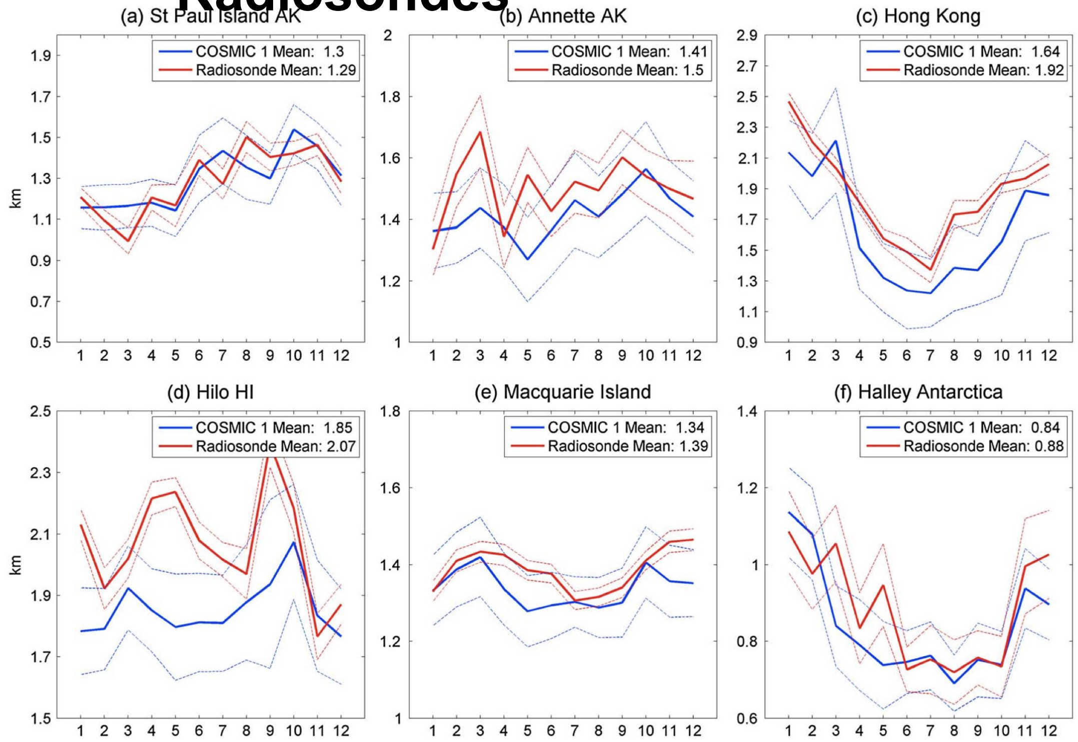
Relatively Insensitive to known bias within the PBL



2°x2° PBLH Climatology from over 12 years of GNSS-RO data (mainly COSMIC) [Kalmus et al. 2022]

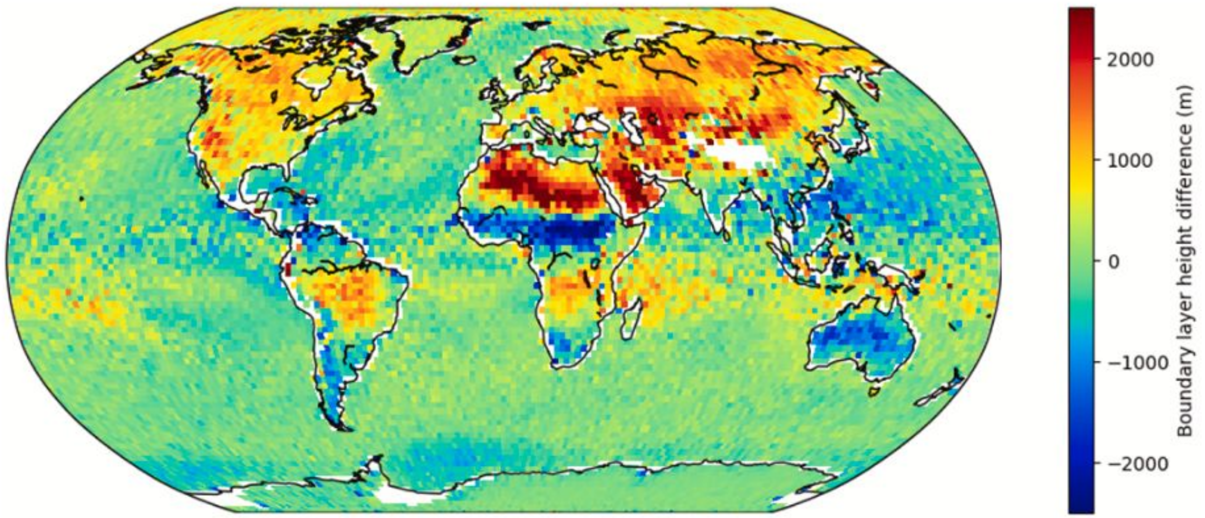
Seasonal Variability

Comparison with Radiosondes



Chan and Wood, JGR, 2013

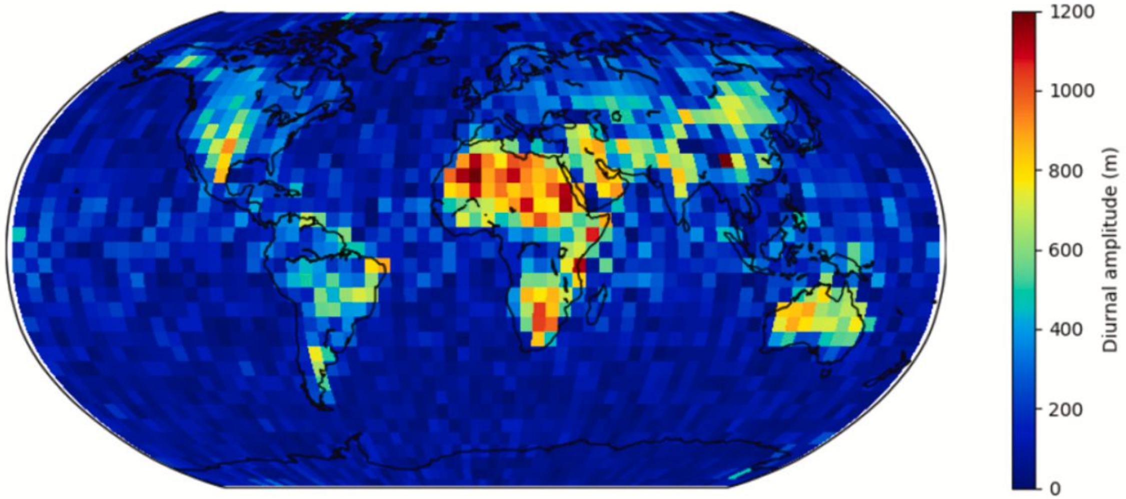
JJA-DJF



Kalmus et al. 2022

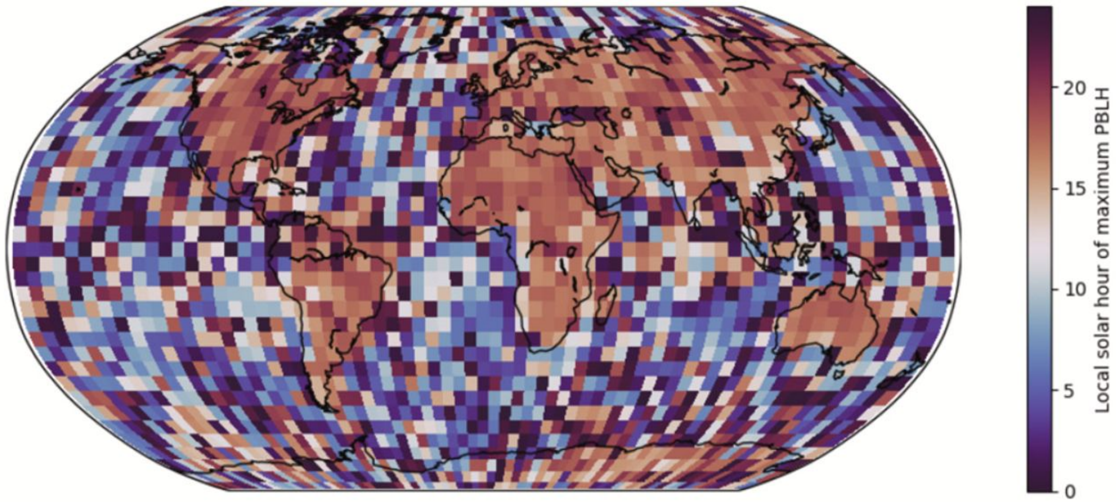
Diurnal Variability

Diurnal amplitude (half peak)



- Strong diurnal cycle over land

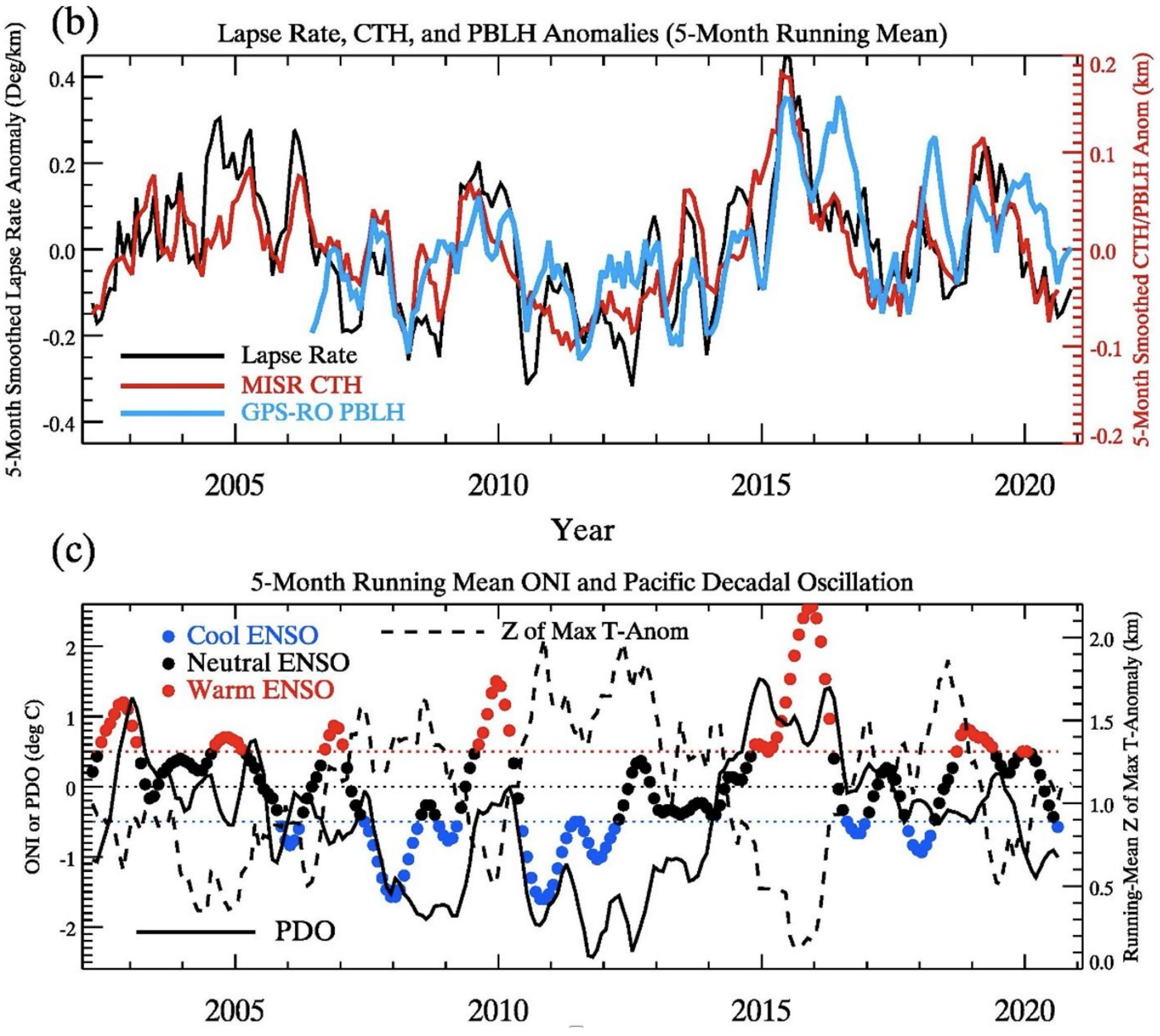
Local time at max



- PBLH is max in the afternoon over land
- PBLH is max in the early morning over oceans (but the results are noisy)

Kalmus et al. 2022

Interannual Variability



Monthly anomalies of PBLH from RO over the NE Pacific agree well with the MISR low cloud top height (top panel).

Both PBLH and CTH correlates positively with ENSO (bottom panel).

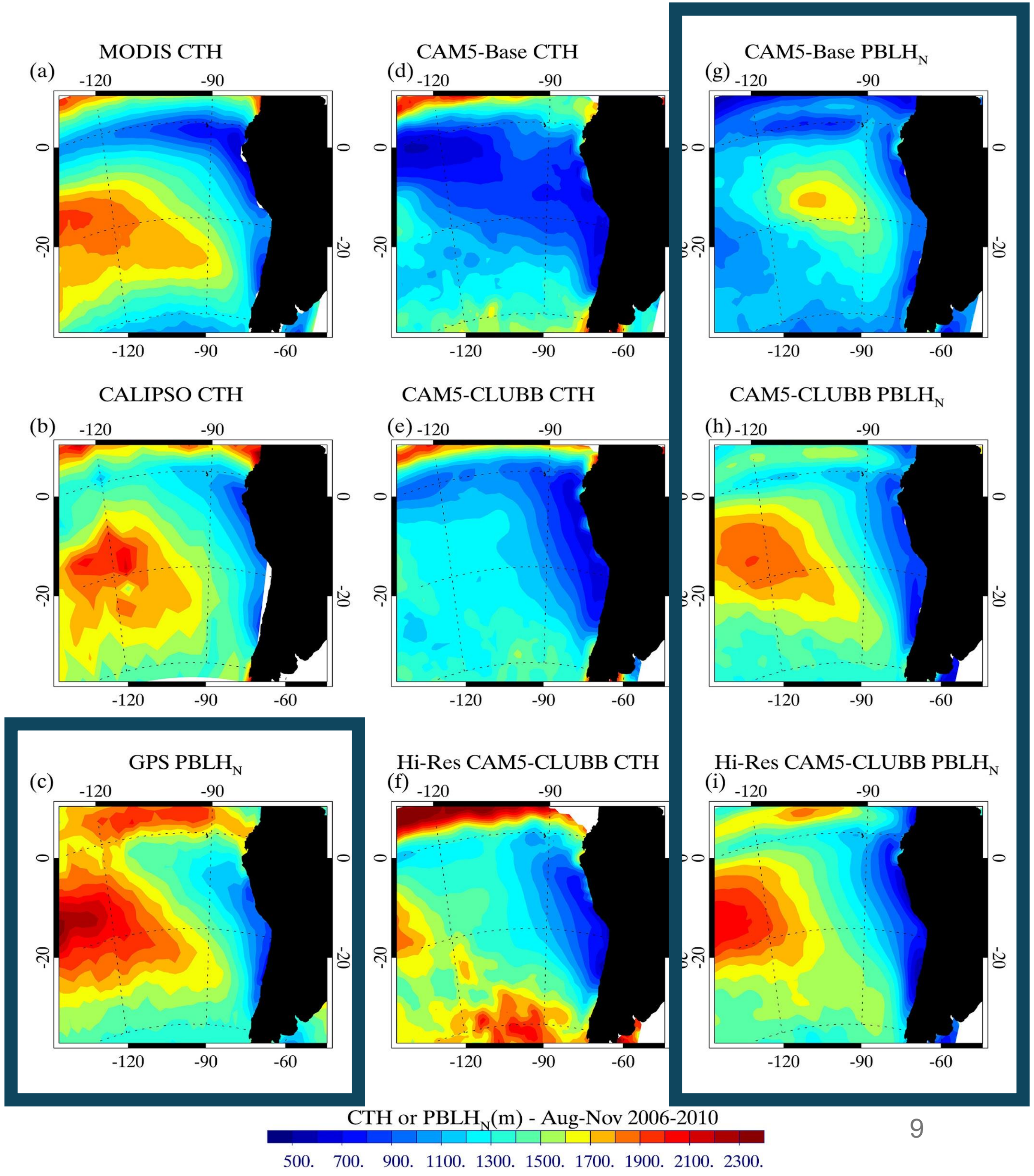
Kubar et al., JGR, in review

Model Assessment

PBLH from GNSS-RO provides a powerful observational constraint on GCM PBL parameterization schemes and model resolutions.

PBL heights from the CAM5 high resolution model with CLUBB PBL parameterization agree the best with GNSS-RO.

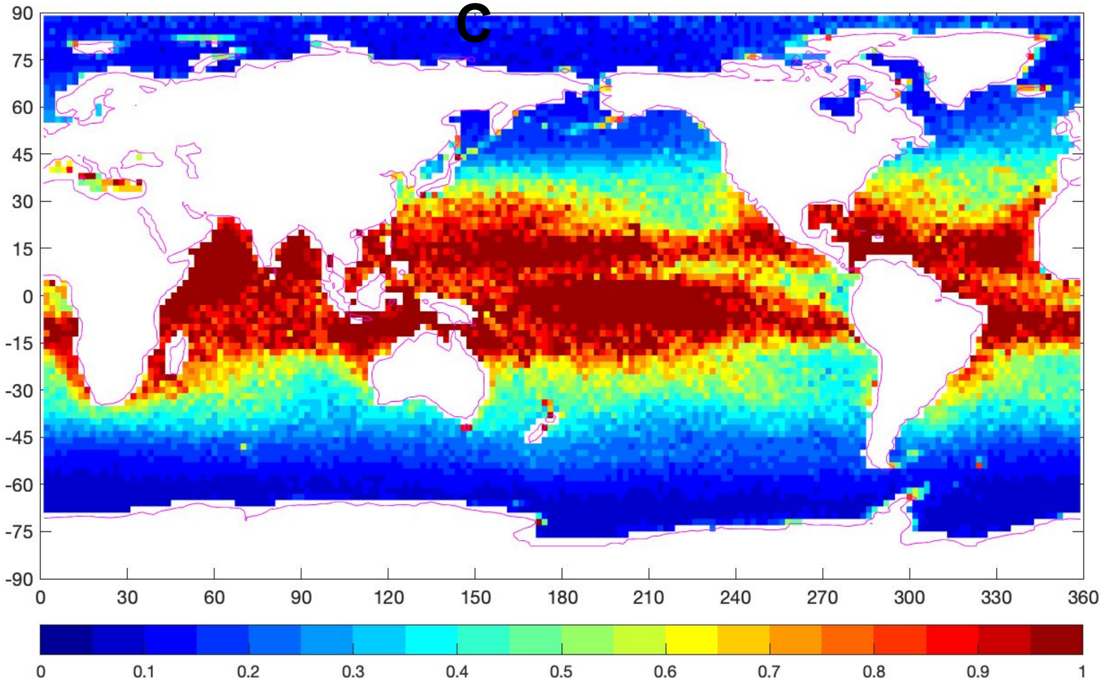
Kubar et al., GRL, 2020



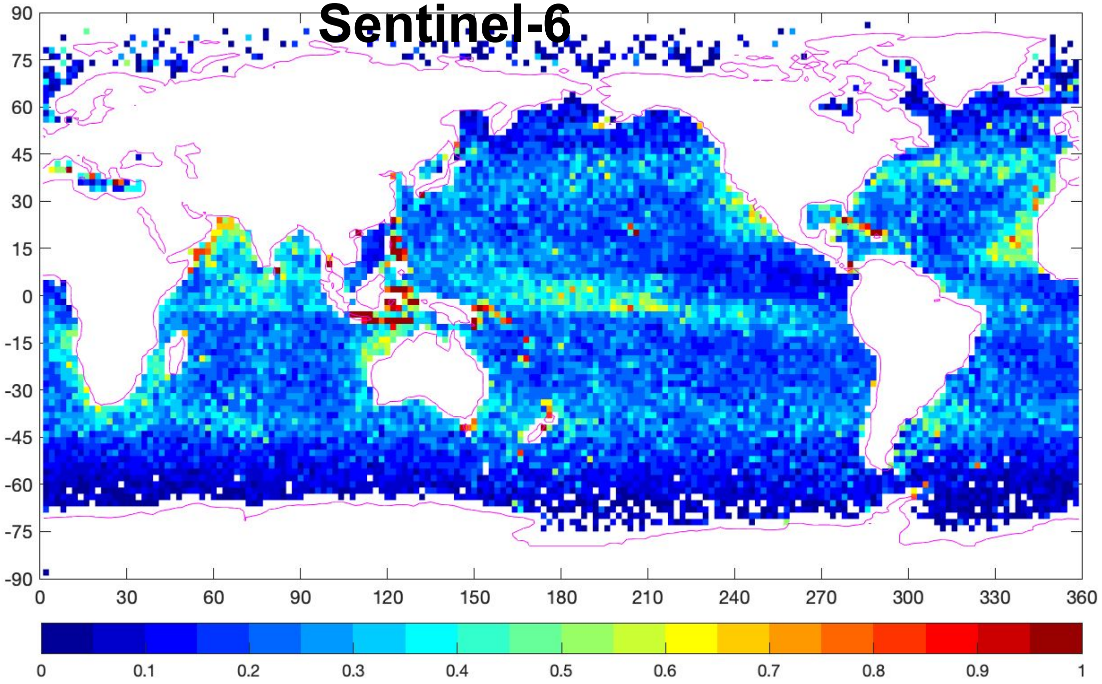
A New Era with C-2, S-6

Depth penetration was an issue with COSMIC at low latitudes…

COSMIC

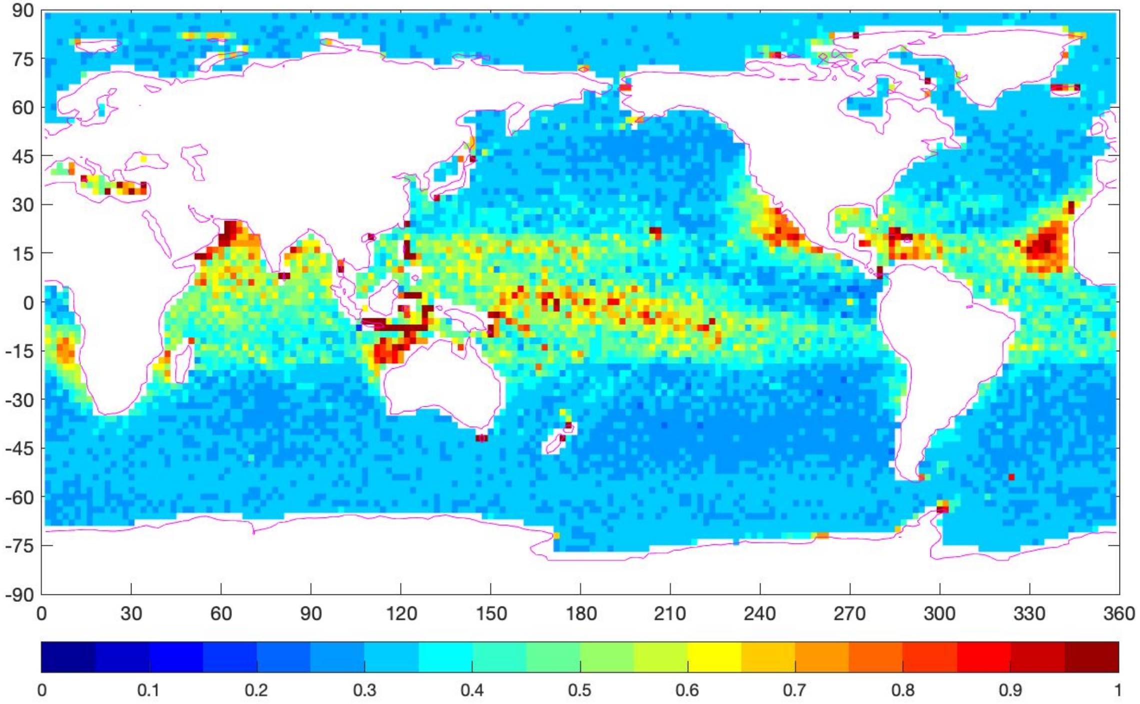


COSMIC-2 & Sentinel-6

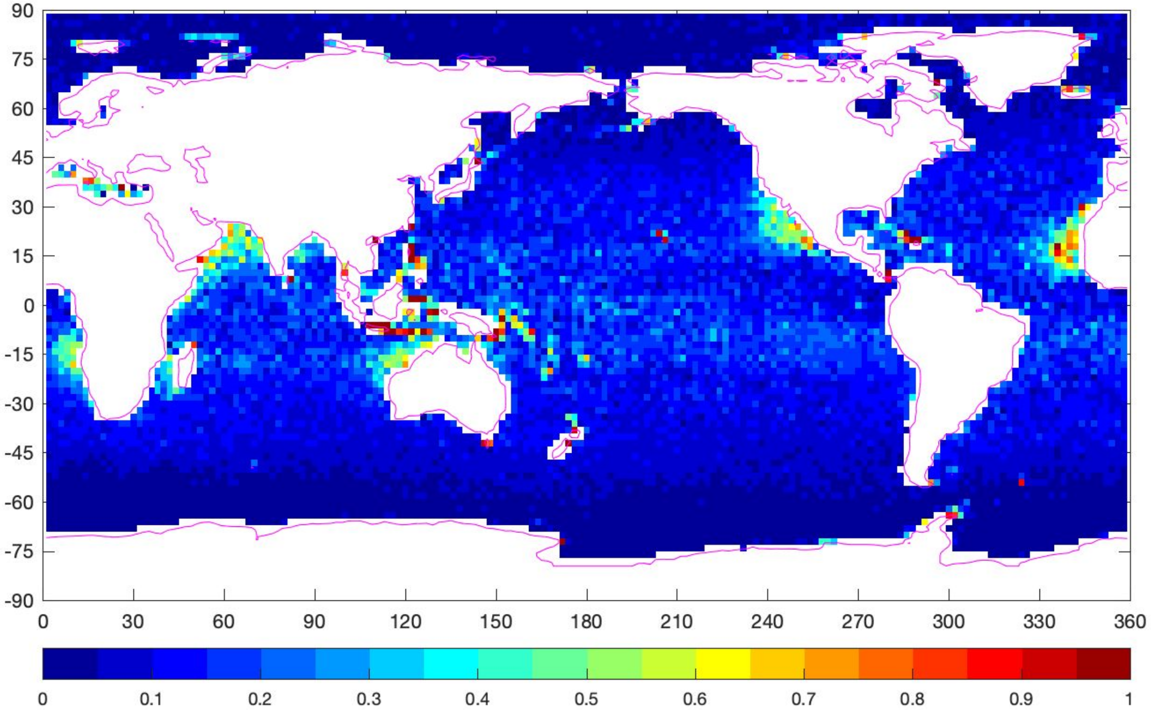


… and Commercial RO?

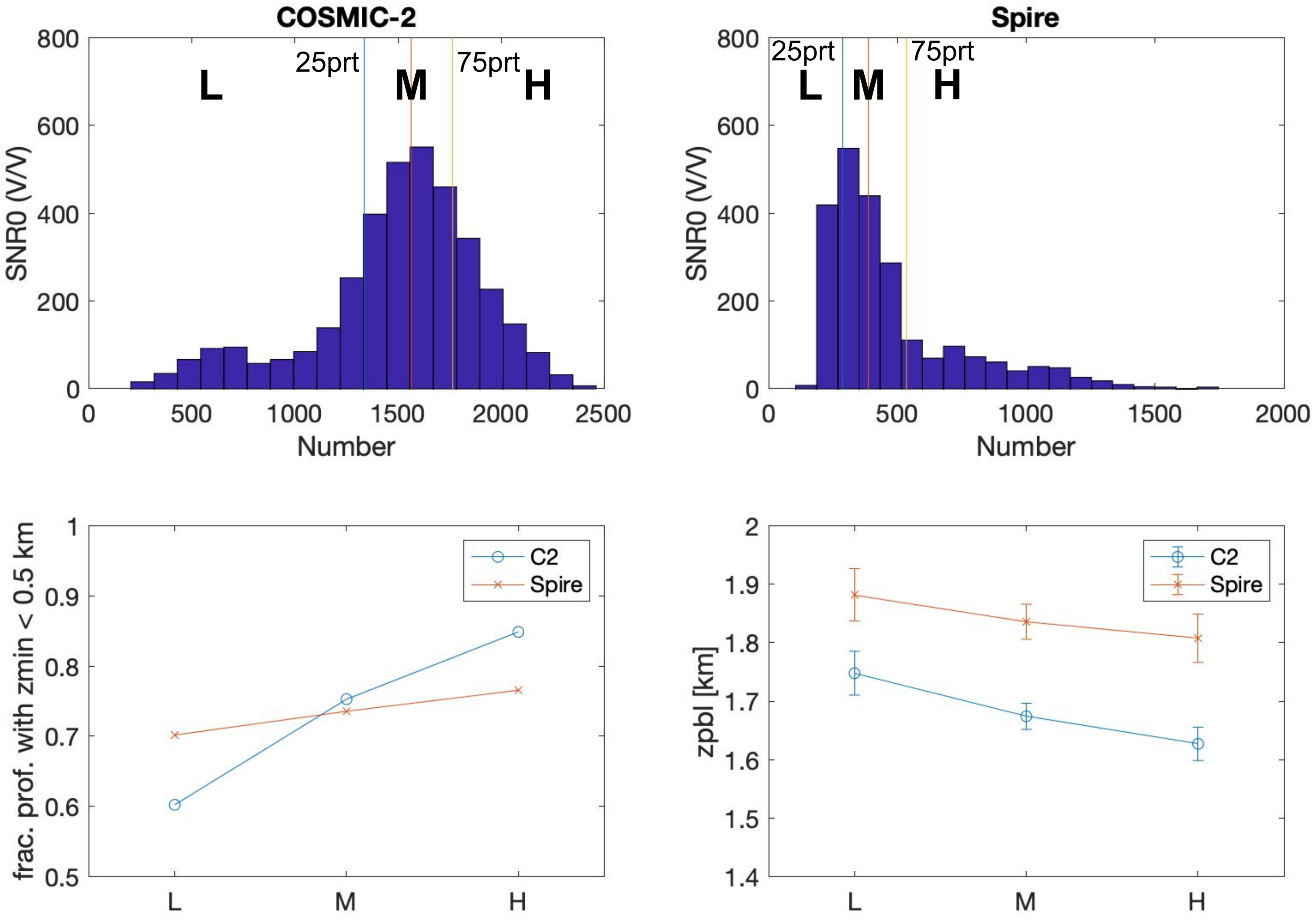
Spire L2 from NASA CSDAP



Spire L2 from UCAR CDAAC



C2 vs. Spire - Effect of SNR



Central
Pacific

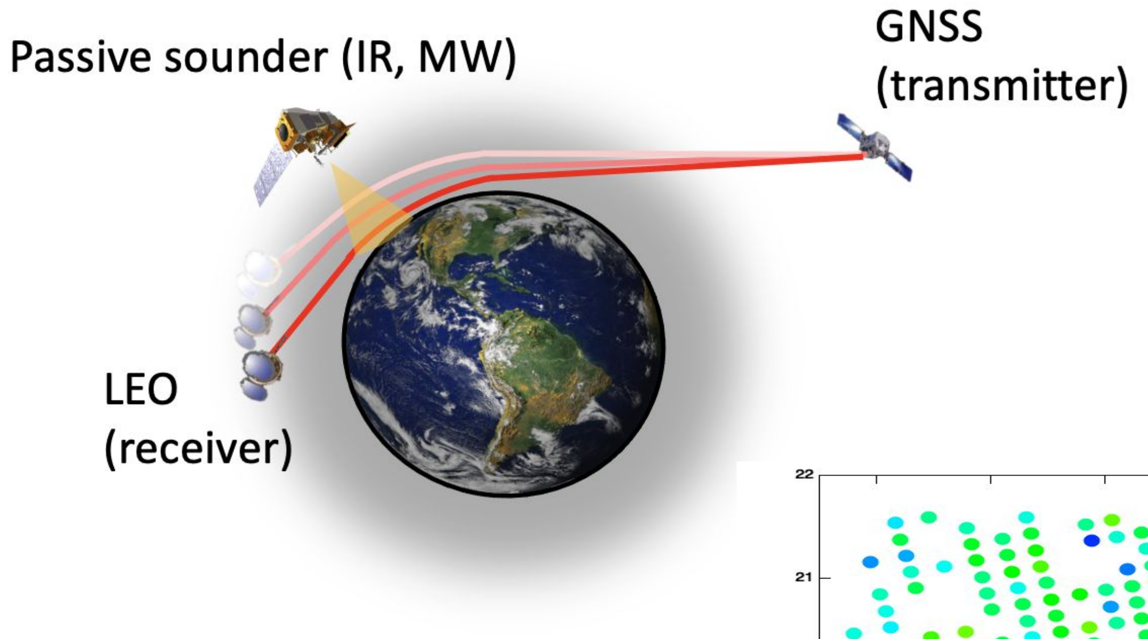
Outlook for GNSS-RO PBLH

- The improved penetration depth from GNSS-RO, together with the significant increase in the number of RO observations, allow us to study the PBLH in far greater spatial and temporal scales than before.
- Differences between the different instruments and processing methods need to be better understood.
- Better algorithm/more validation of PBLH beyond the subtropical oceans would be highly beneficial [e.g., Nelson et al., 2021; Ganeshan and Wu, 2015].
- Direct data assimilation of the PBLH in NWP models is being pursued [Yanqiu Zhu, GMAO], which could prove impactful for RO.

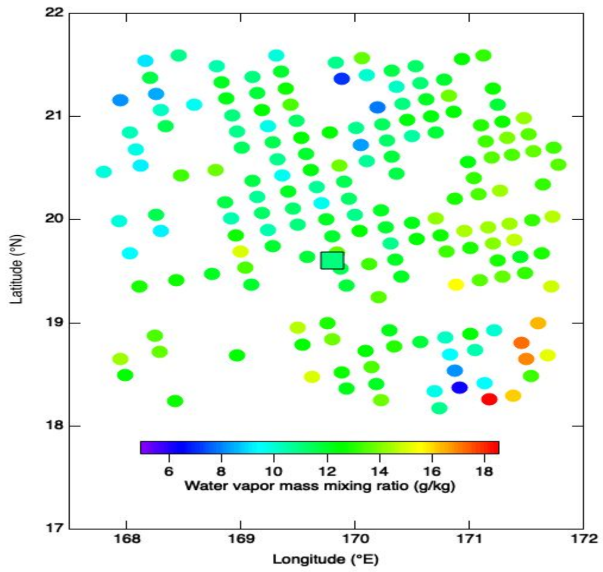
Beyond PBLH: Inherent Limitations in GNSS-RO

- Low horizontal resolution along raypath (~ 100 km)
- Wet/dry ambiguity, especially in drier regions
- Bending angle bias
- Ducting bias

RO+PS Joint PBL Characterization



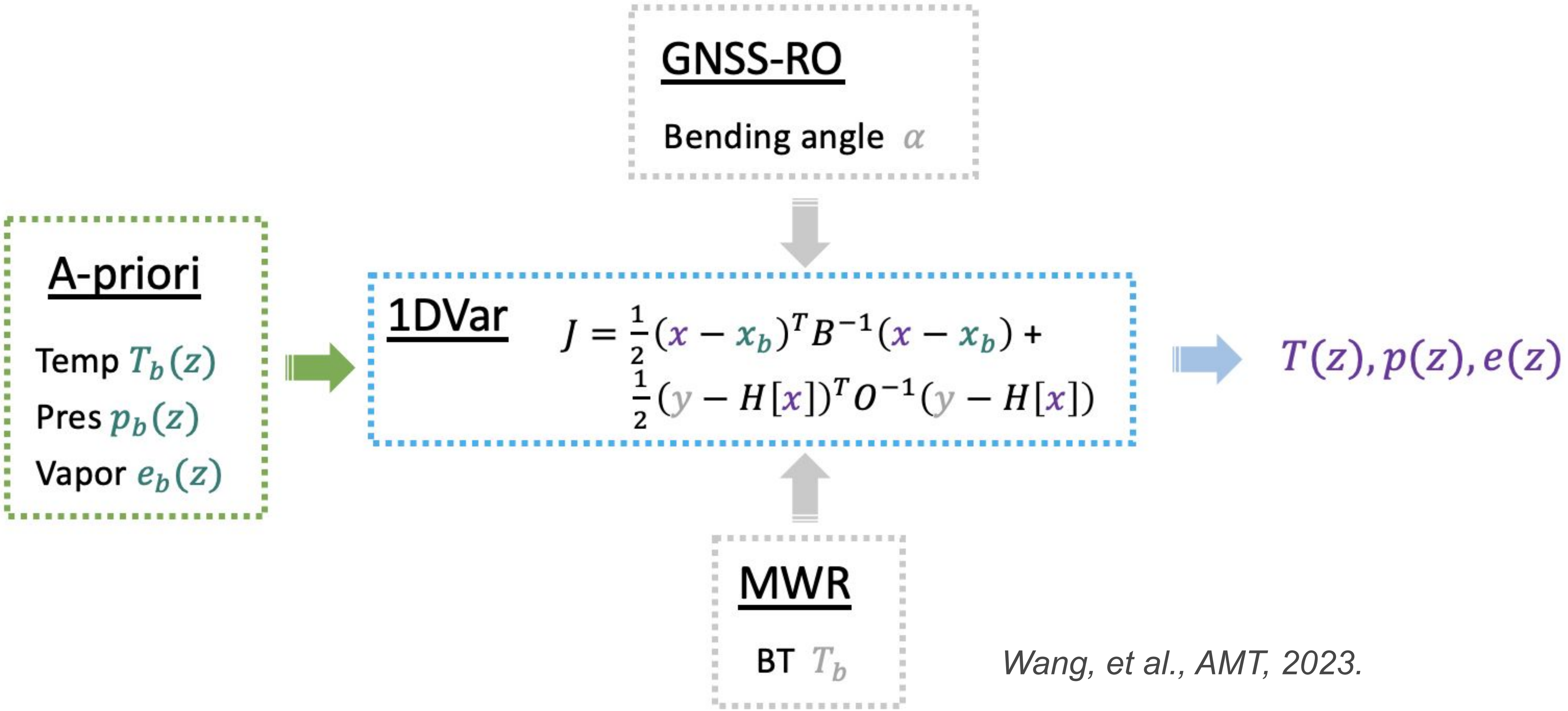
- Each provides information on vertical structure of temperature and water vapor
- Complimentary observing geometry
- Availability



Water vapor @815 hPa from IR soundings in vicinity of RO sounding (square)

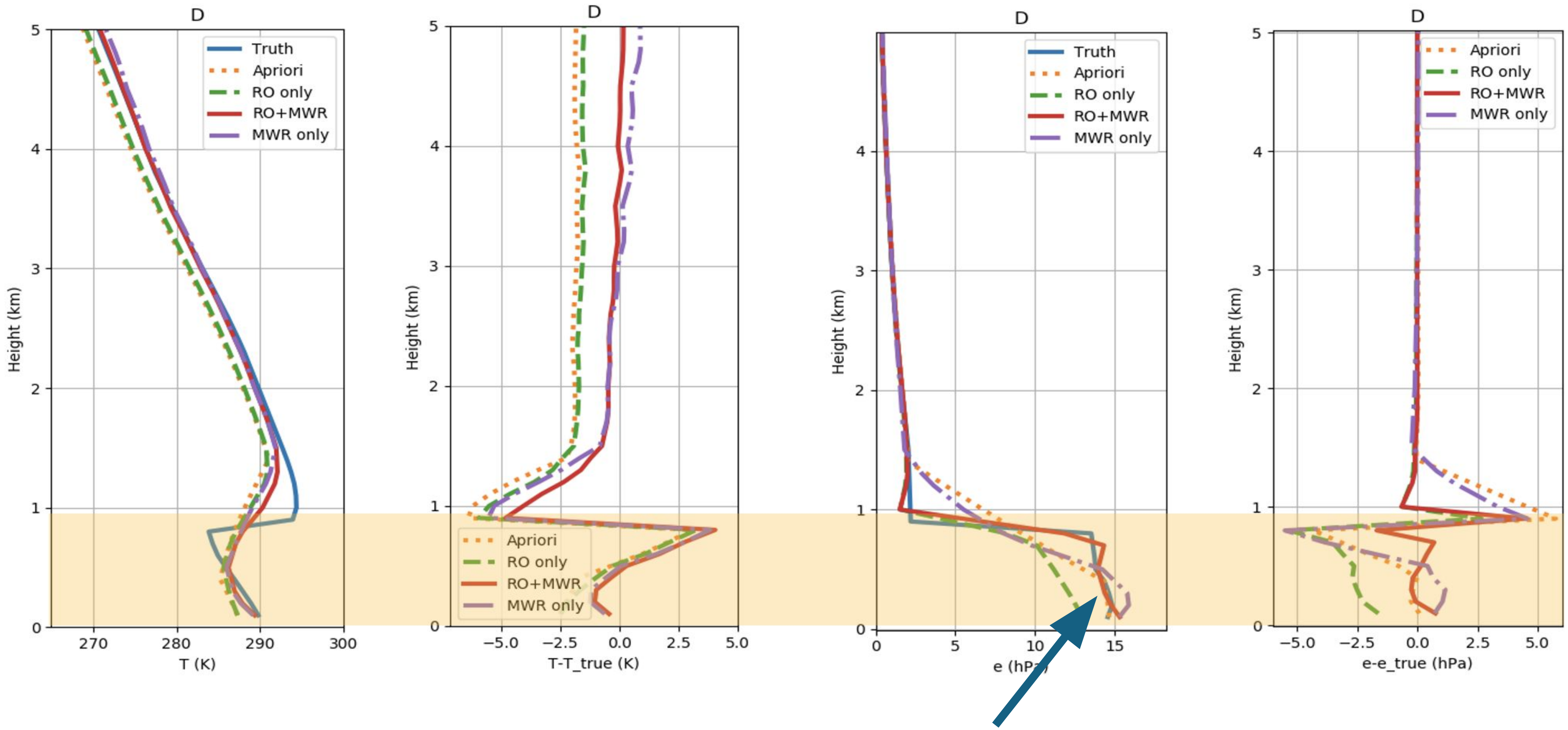
Courtesy of J. Teixeira (JPL)

Joint RO+MW Retrievals: 1D Var Approach



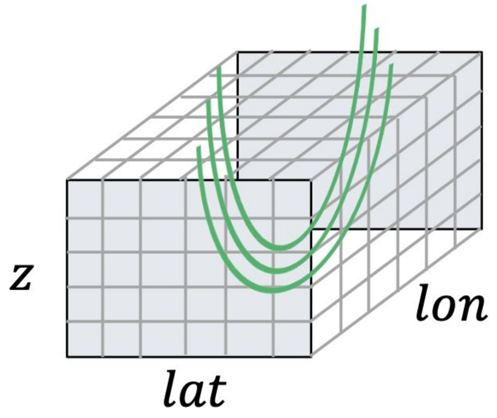
Wang, et al., AMT, 2023.

Simulation Result (Sc PBL)



Improved PBL retrievals (esp WV) with very little dependence on retrieval a priori, while retaining the high vertical resolution of GNSS-RO

Simplified 3D Tomography Approach



RO is used to solve for the vertical weighting of the smoothed 3D refractivity field determined from the MW/IR retrievals.

GNSS-RO

Excess Phase Φ

Ray path

Pseudo Inverse

$$\Phi_i(t) = \int N_{MWR}(z, lat, lon) \cdot w(z)\, dl$$

MWR

Temp, vapor (3D)

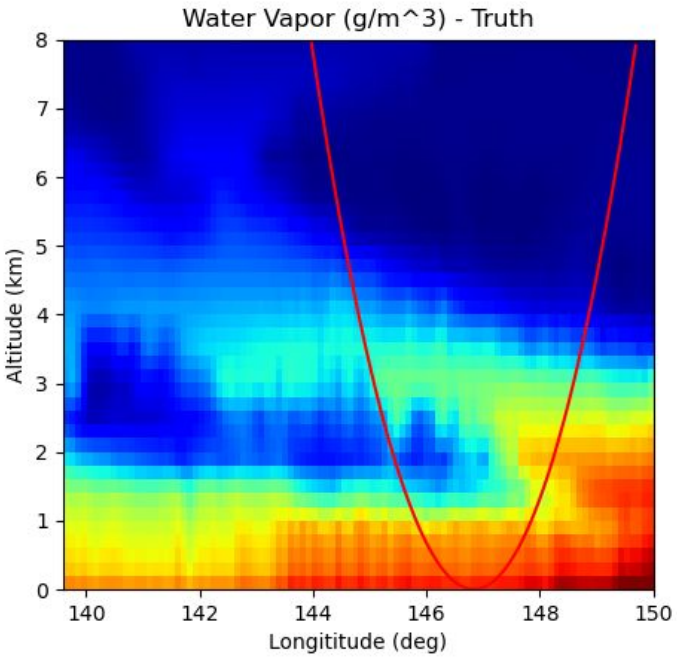
$w(z)$

Final 3D solution is:

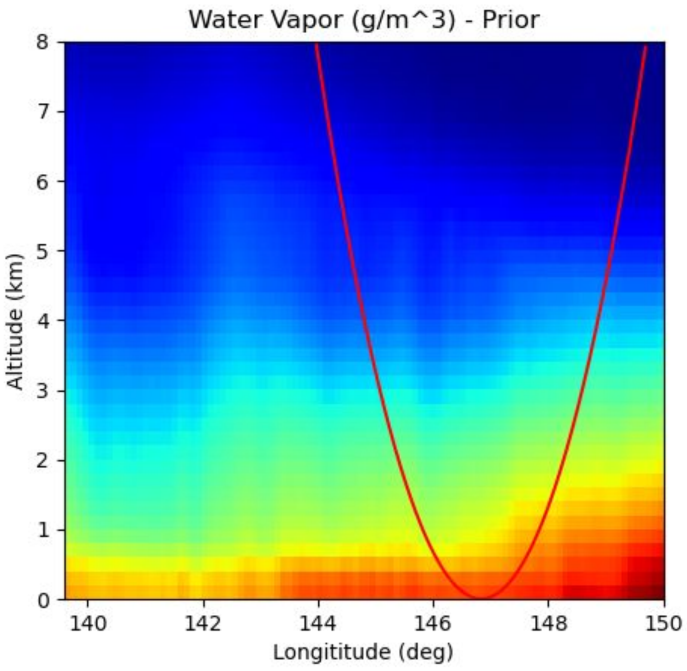
$N(z,lat,lon) = N_{MWR}(z,lat,lon) * w(z) * H_w(lat\text{-}lat\_tp, lon\text{-}lon\_tp)$

Simulation Results (1 RO)

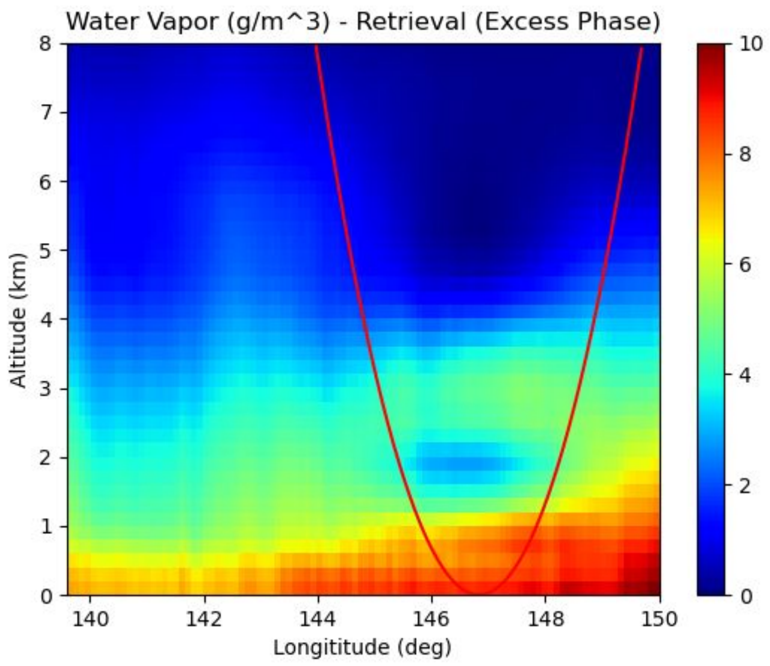
Input



MW (prior)

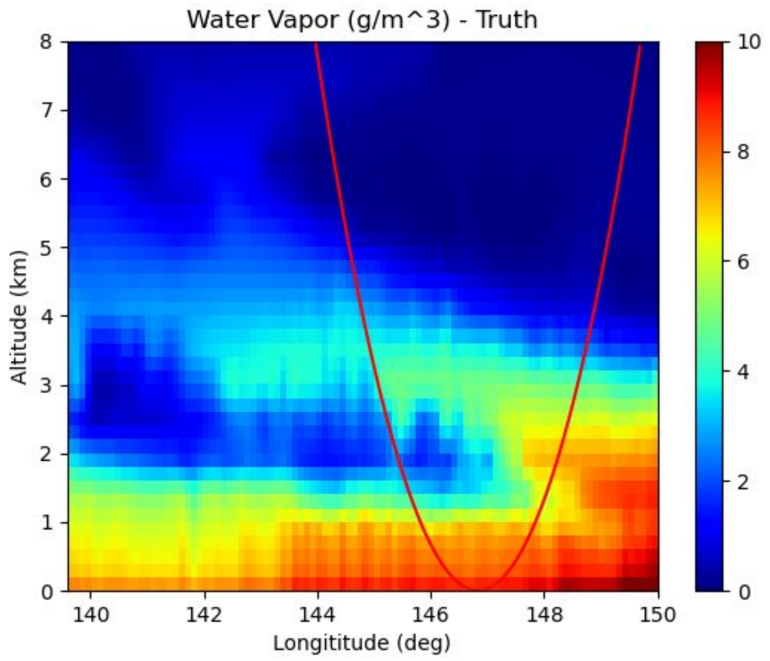


MW + RO

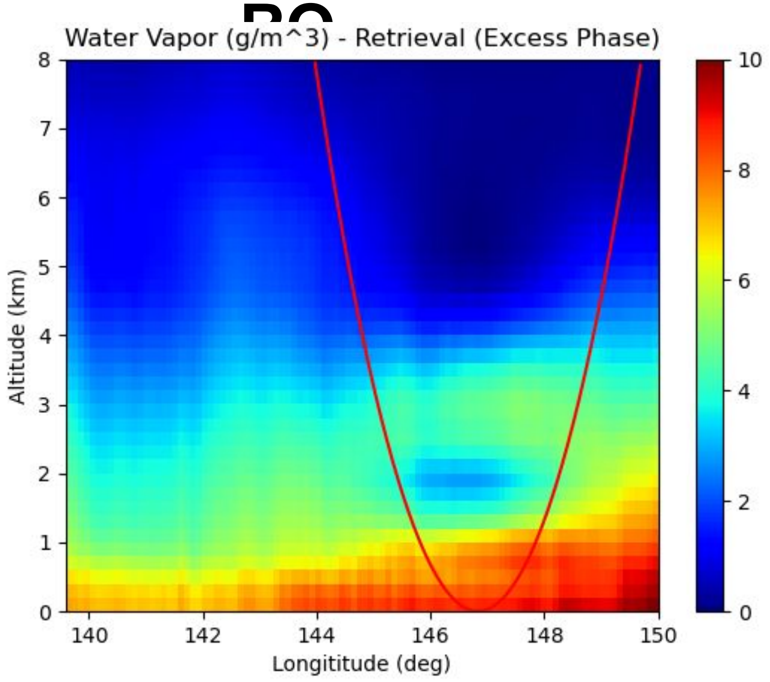


Simulation Results (2 ROs)

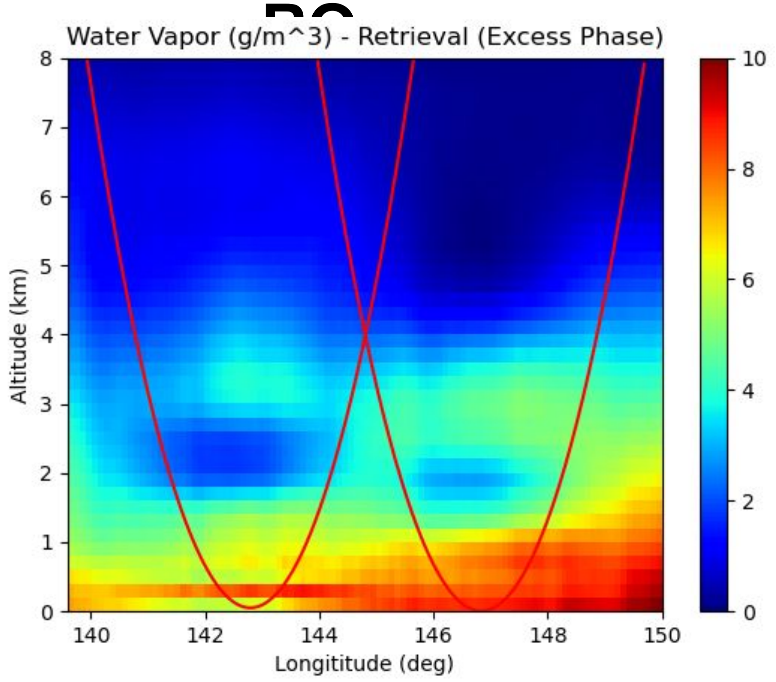
Input



MW + 1

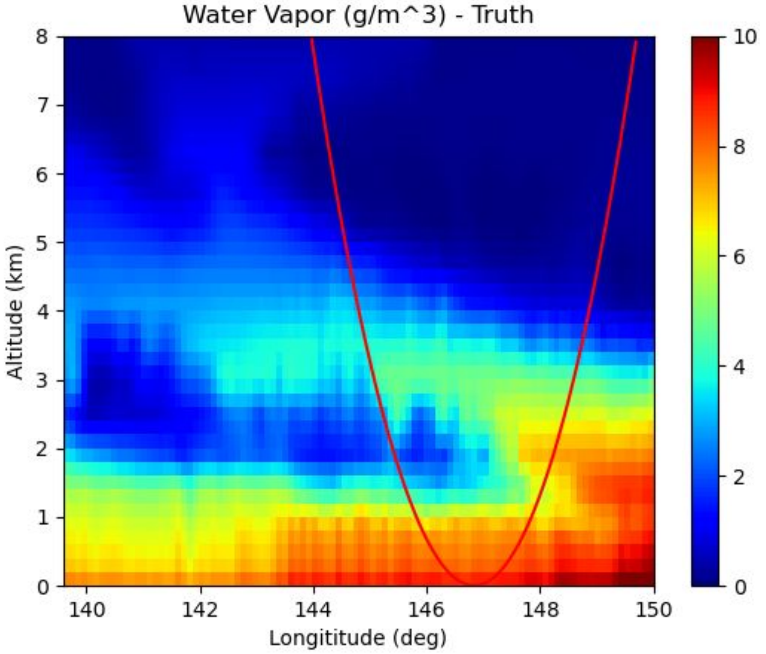


MW + 2

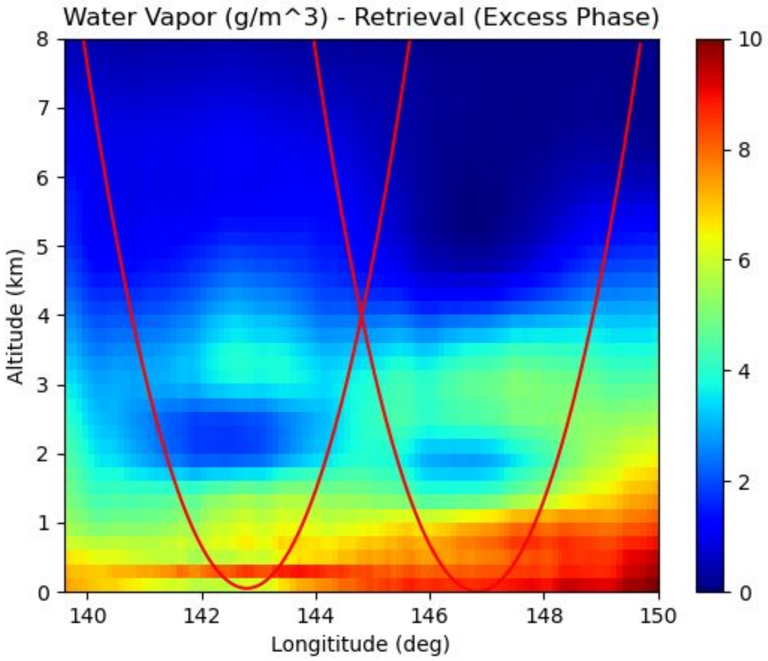


Simulation Results (20 ROs)

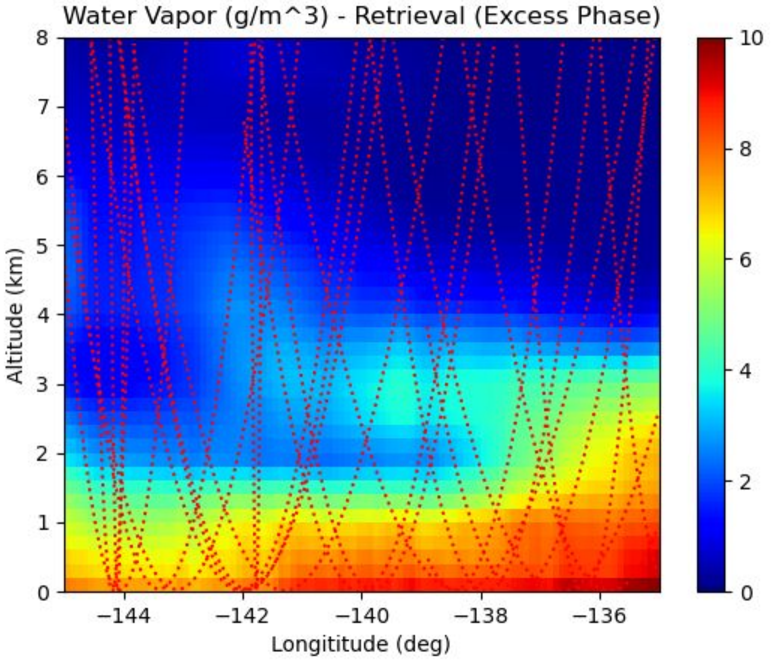
Input



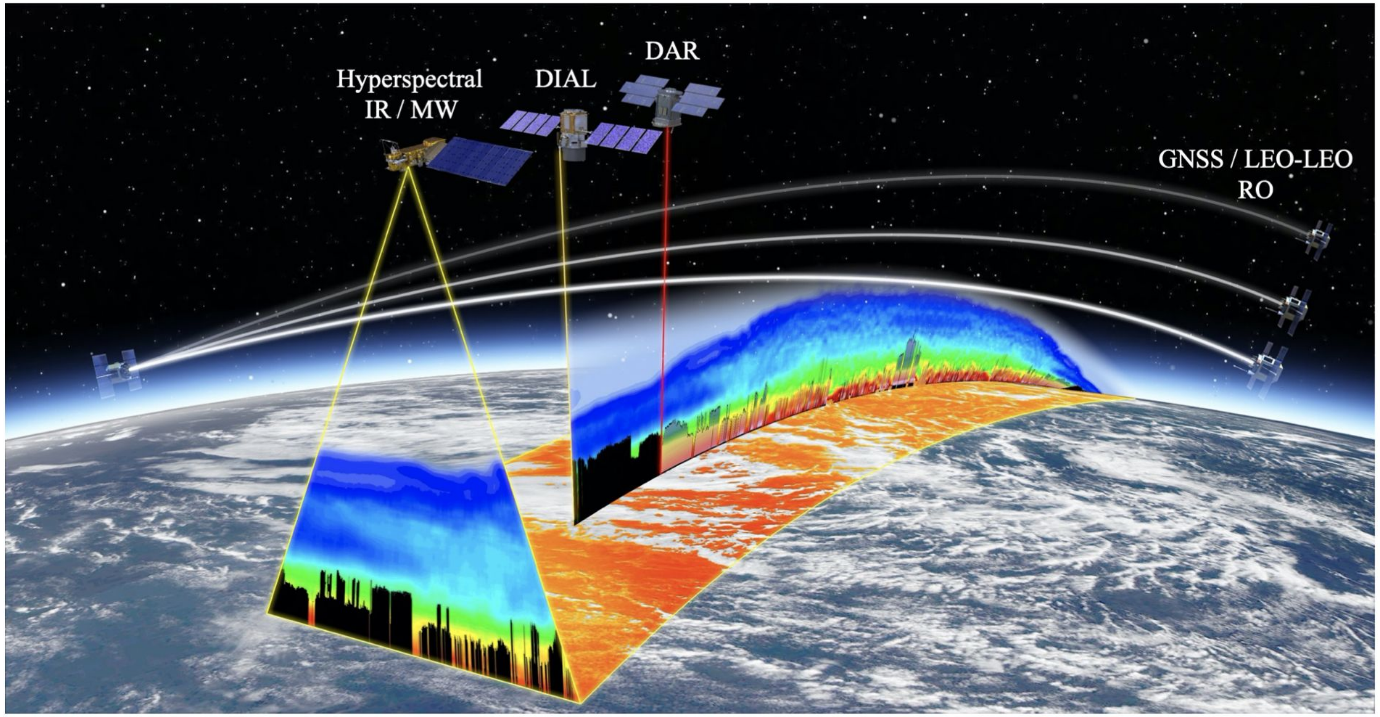
MW + 2 RO



MW + 20 RO



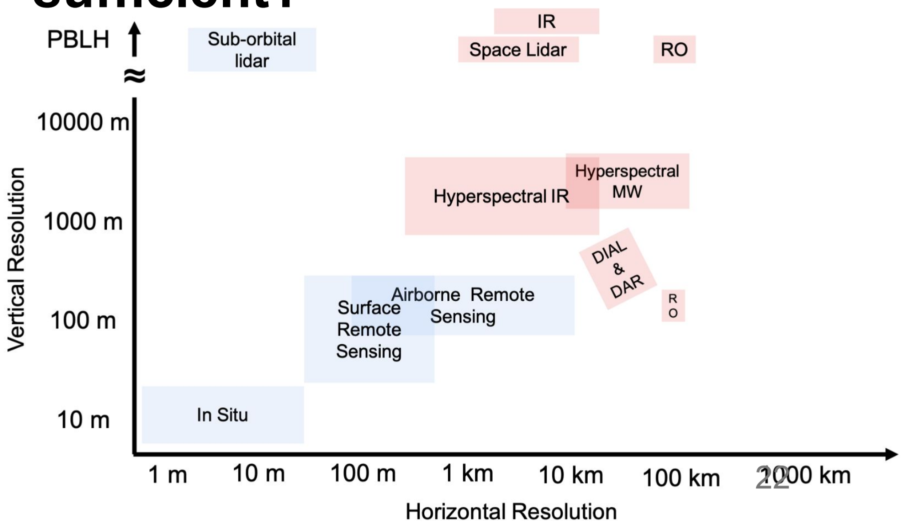
RO in a Future PBL Mission



Teixeira, J., J. R. Piepmeier, A. R. Nehrir, C. O. Ao, S. S. Chen, C. A. Clayson, A. M. Fridlind, M. Lebsock, W. McCarty, H. Salmun, J. A. Santanello, D. D. Turner, Z. Wang, and X. Zeng, 2021: Toward a Global Planetary Boundary Layer Observing System: The NASA PBL Incubation Study Team Report.

GNSS-RO is an indispensable component of a future PBL observing system, due to its high vertical resolution, esp. in absence of other active sensors.

What are the best ways to combine RO with PS from both instrumentation and retrieval point of views? How many ROs are sufficient?



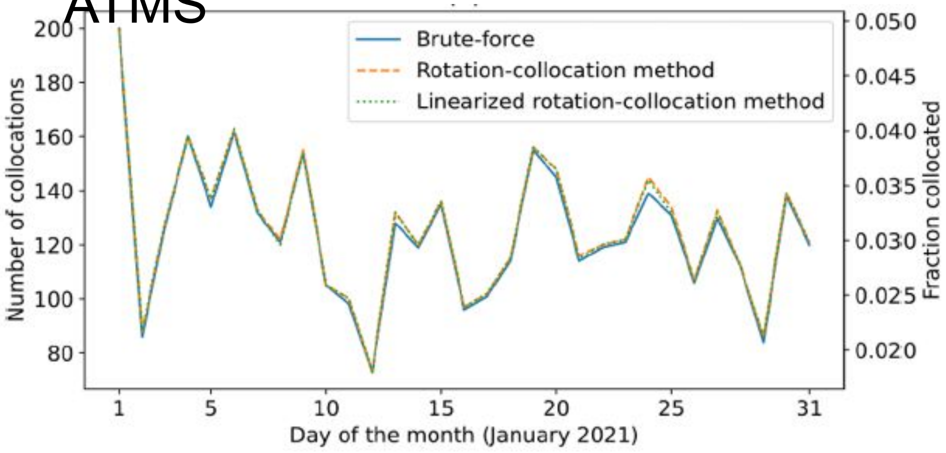
Backups

Optimizing RO + PS Collocations

There is significant advantage to have RO and MW/IR instruments on the same satellite platform or flying in close formation.

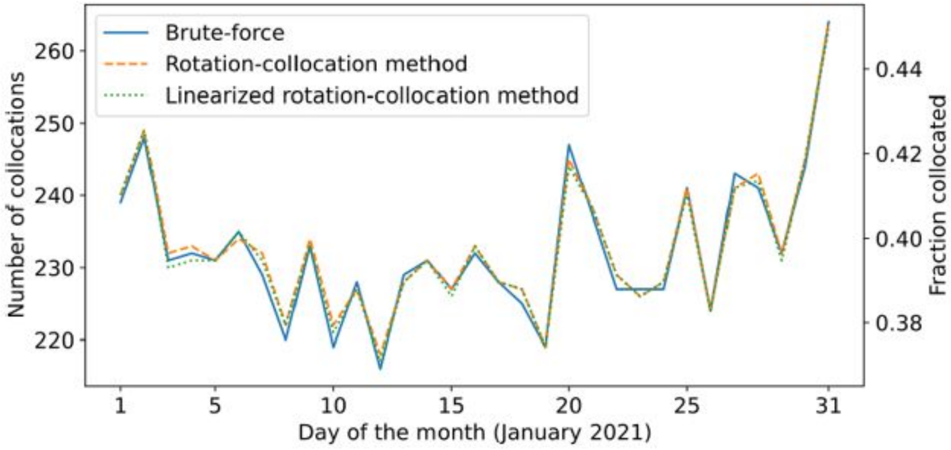
Total: 3859 / 125665 cases

COSMIC-2 (6 s/c) + NOAA-2 ATMS



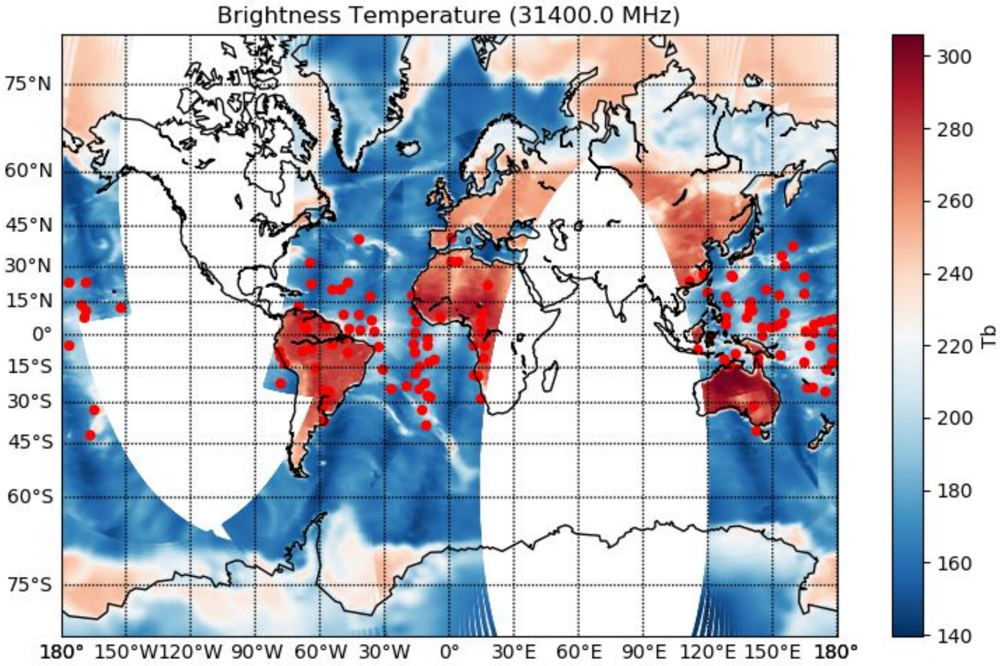
Total: 7206 / 18140 cases

Metop-B (RO+MWR on the same platform)

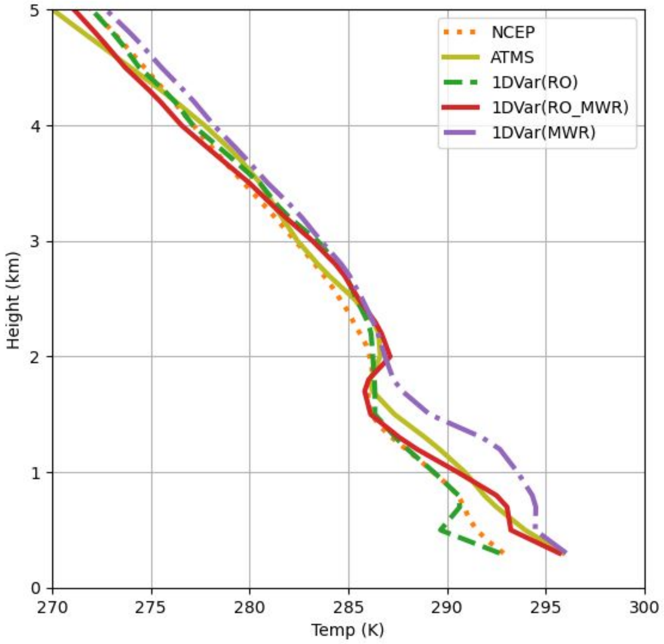


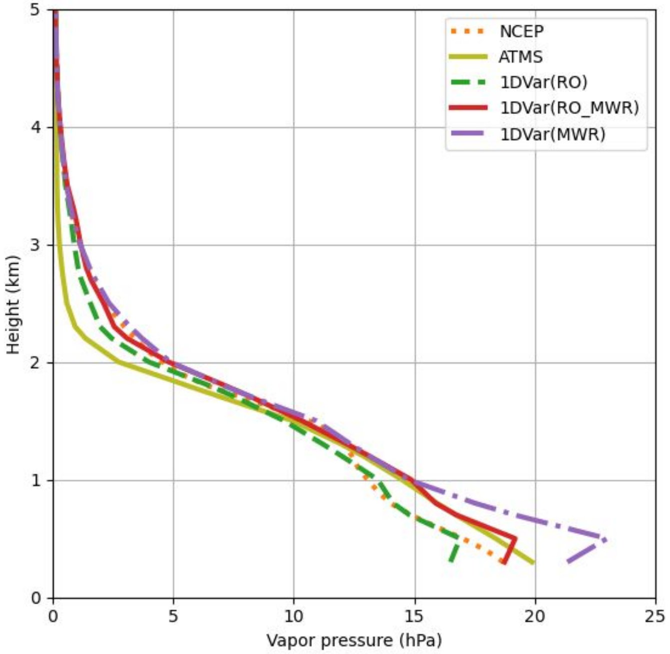
Meredith et al., AMT, 2023

C2 & SNPP/ATMS Collocation



17.91 N, 36.75 W





Validation is challenging!

The combined C2+ATMS solution (red lines) falls between RO-only and ATM-only solutions, independent of the NCEP a priori, and retains high vertical resolution of the RO-only resolution.