# Recent Progress on the Vertical Profiling of the Planetary Boundary Layer from GNSS Radio Occultations

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# Outline

- Overview of GNSS-RO
- PBL height estimation
- GCM comparison
- Decoupling parameter
- The “Negative N-bias” problem
- Improved retrieval methods
- Next-Gen instrument

# GNSS-RO Technique

- A GNSS-RO receiver measures the **phase delay** of the GNSS signal as the signal slices through different layers of the atmosphere.

Excess phase

↓

Bending angle profile

Abel inversion ↓

Refractivity profile

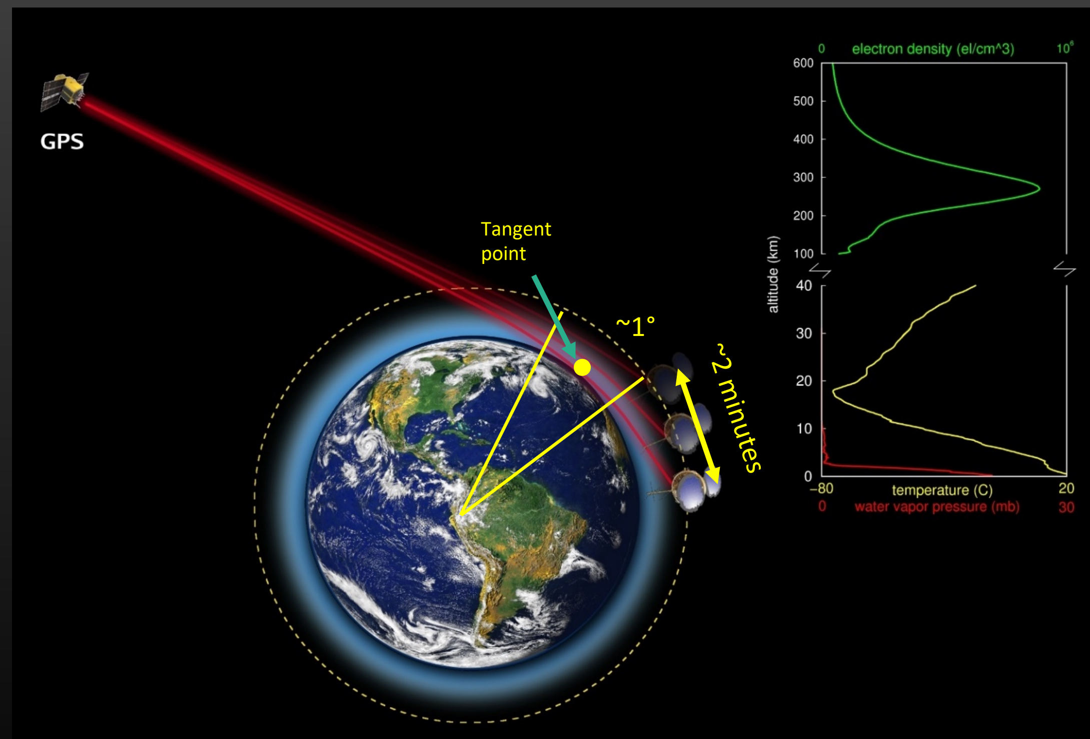
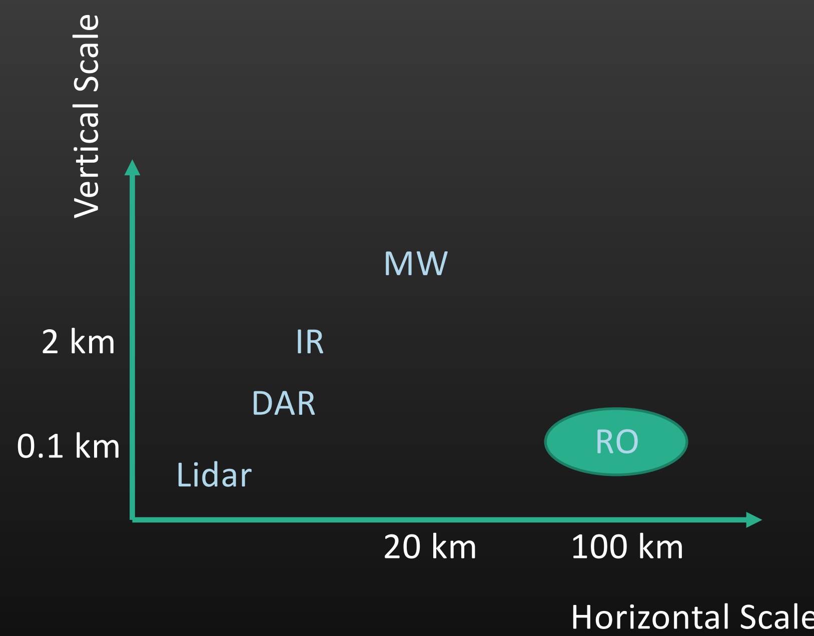



*Figure modified from UCAR*

# Why GNSS-RO is valuable for PBL

- High vertical resolution (< 200 m)
  - Limb geometry + phase observable
- All sky, all weather sensing (unaffected by clouds and precipitation)
  - L-band (1-2 GHz)
- All surface conditions (land, ocean, ice)
  - Active technique, "self-calibrating"
- Water vapor profiling



# Tropospheric water vapor retrieval

$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2}$$

$$\frac{dP}{dz} = -\frac{m_d g}{R}\frac{P}{T} - \frac{(m_w - m_d)g}{R}\frac{P_w}{T}$$

3 unknowns: ($P$, $T$, $P_w$)

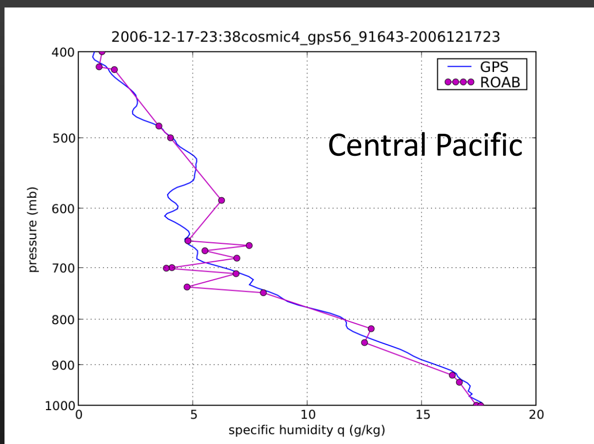
2 equations

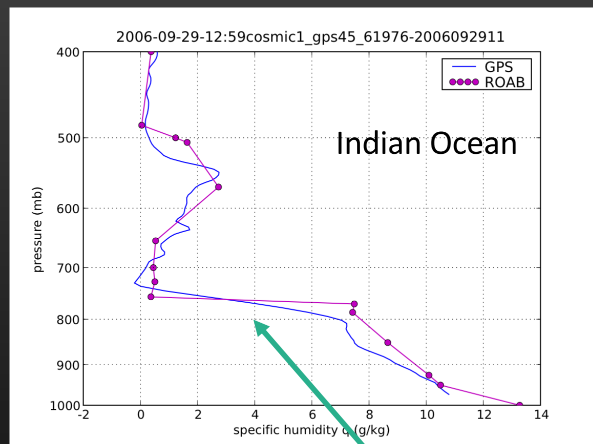
- **Direct method**: assume T(z) from analysis to remove the "dry" part of N(z) and solve for $P_w$(z).
- **1D Variational method**: Combine N(z) with "background" T(z), $P_w$(z) from analysis & error covariance estimates.

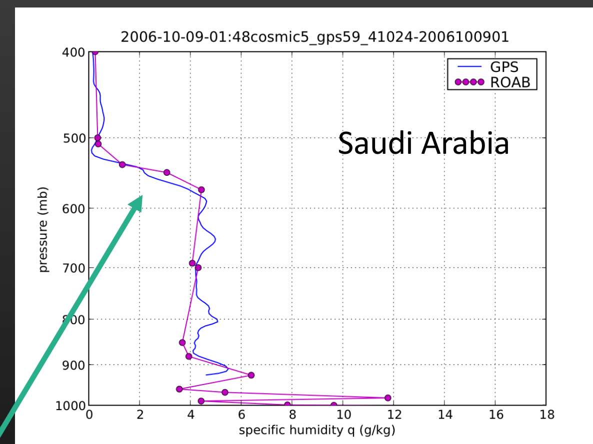
- **Direct method is not affected by humidity bias from the analysis. We prefer this approach in low to mid latitudes.**

# Comparison with radiosondes

Collocation criteria: < 100 km, 2 hr




Excellent agreements despite long horizontal averaging from RO

Large change in q is indicative of transition from PBL to FT

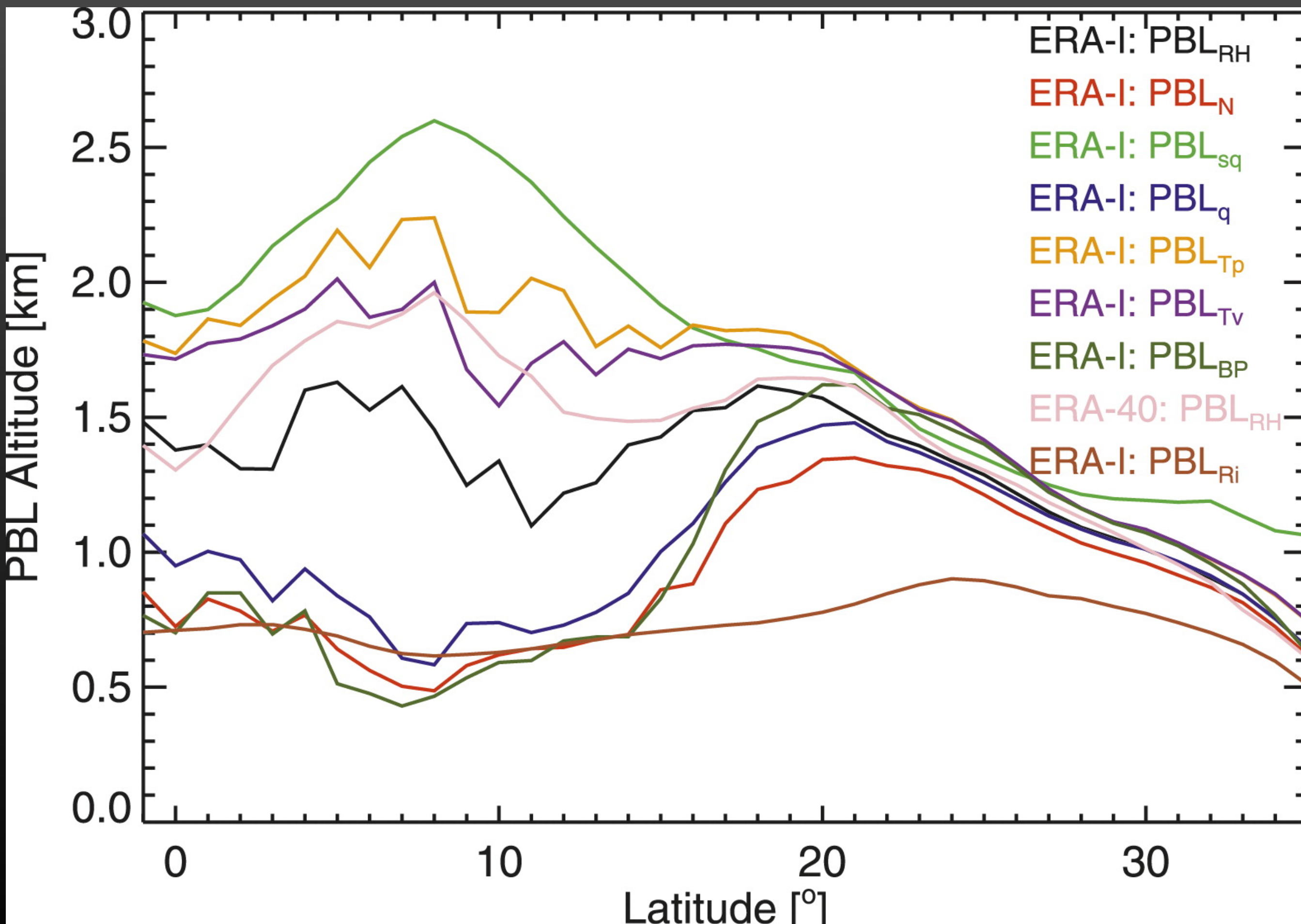
# Algorithms for estimating PBL height

Existing algorithms are based on detecting where large vertical change in an atmospheric variable occurs:

- Minimum of vertical gradient in refractivity, humidity, or bending angle [Ao et al. 2012; Xie et al. 2012; Ho et al. 2015]
- "Break point" [Sokolovskiy et al. 2006; Guo et al. 2011; Ho et al. 2015]
- Wavelet covariance transform (WCT) [Ratnam and Basha, 2010; Basha et al. 2018]

**Similar results when the PBL is capped by a strong inversion.**

**But... differences can be large elsewhere.**




PBL height estimated from ECMWF reanalysis interim profiles using different definitions along the GEWEX Pacific Cross Section Intercomparison region.

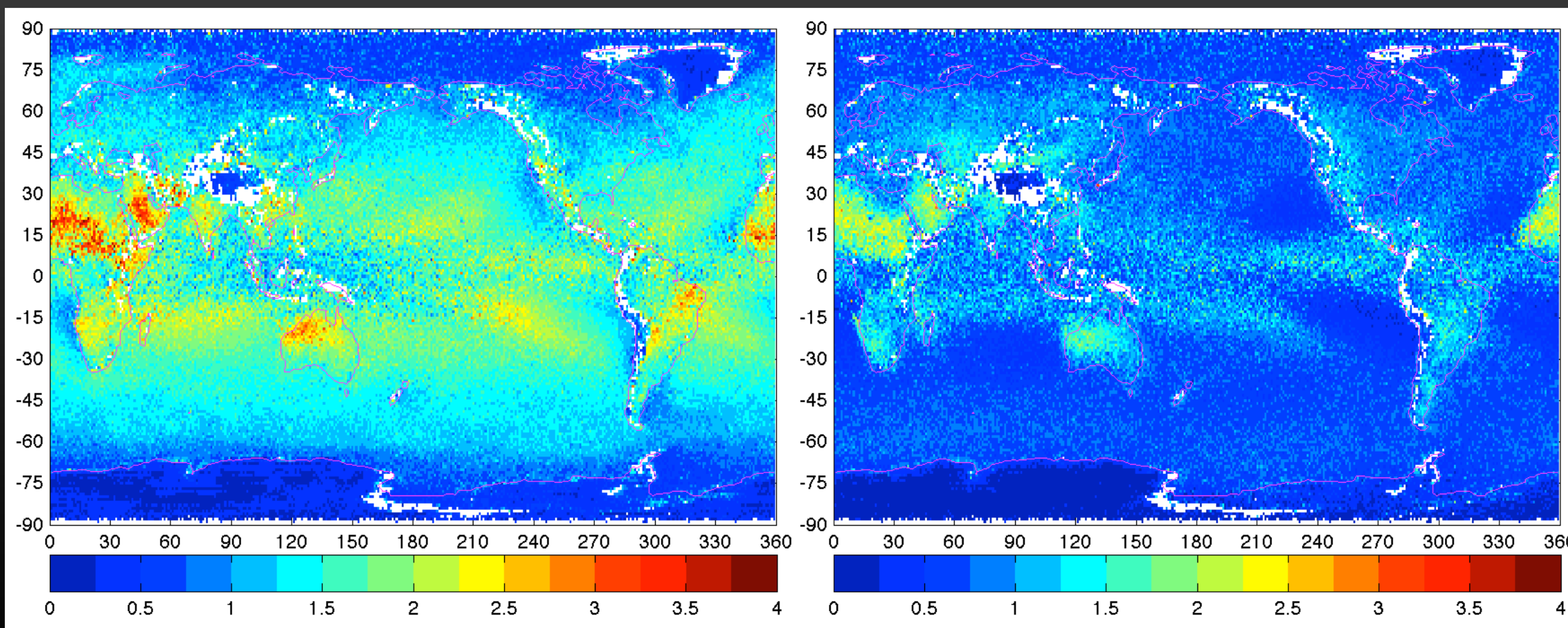
**Use the same definition if possible to ensure Apple to Apple comparison!**

*Figure from von Engeln and Teixeira (2015)*

# 1° x 1° PBL depth (~ 10 yrs COSMIC + TSX)

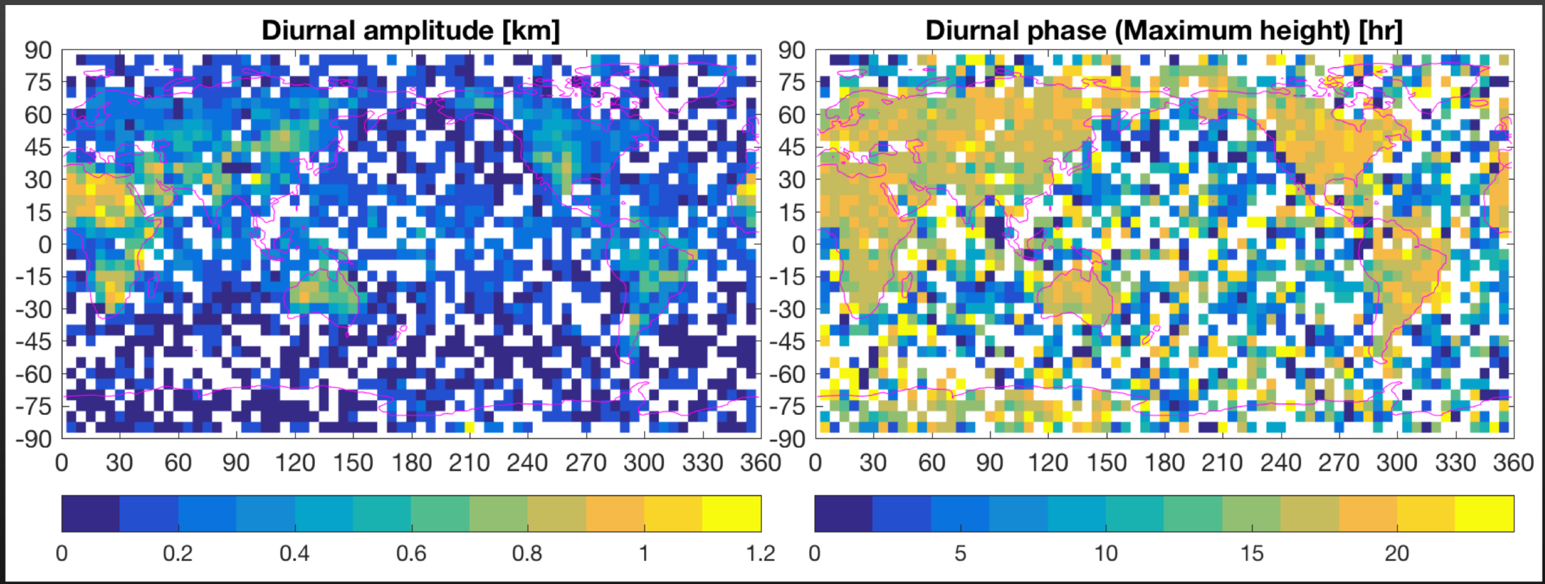
PBLH = z @ min(dN/dz)

**Mean** **Standard Dev**




[km] [km]

# Diurnal Cycle?




Only pixels with harmonic fit error < diurnal amplitude are shown

**Land**: Large diurnal amplitude allows for clear detection of the diurnal cycle. Maximum PBL height in late afternoon.
**Ocean**: Small diurnal amplitude makes it much harder to detect. Most peak in the early morning. (See also Ho et al., J Clim, 2015)

# Model evaluation

Kubar et al., *Geophys. Res. Lett.*, in preparation

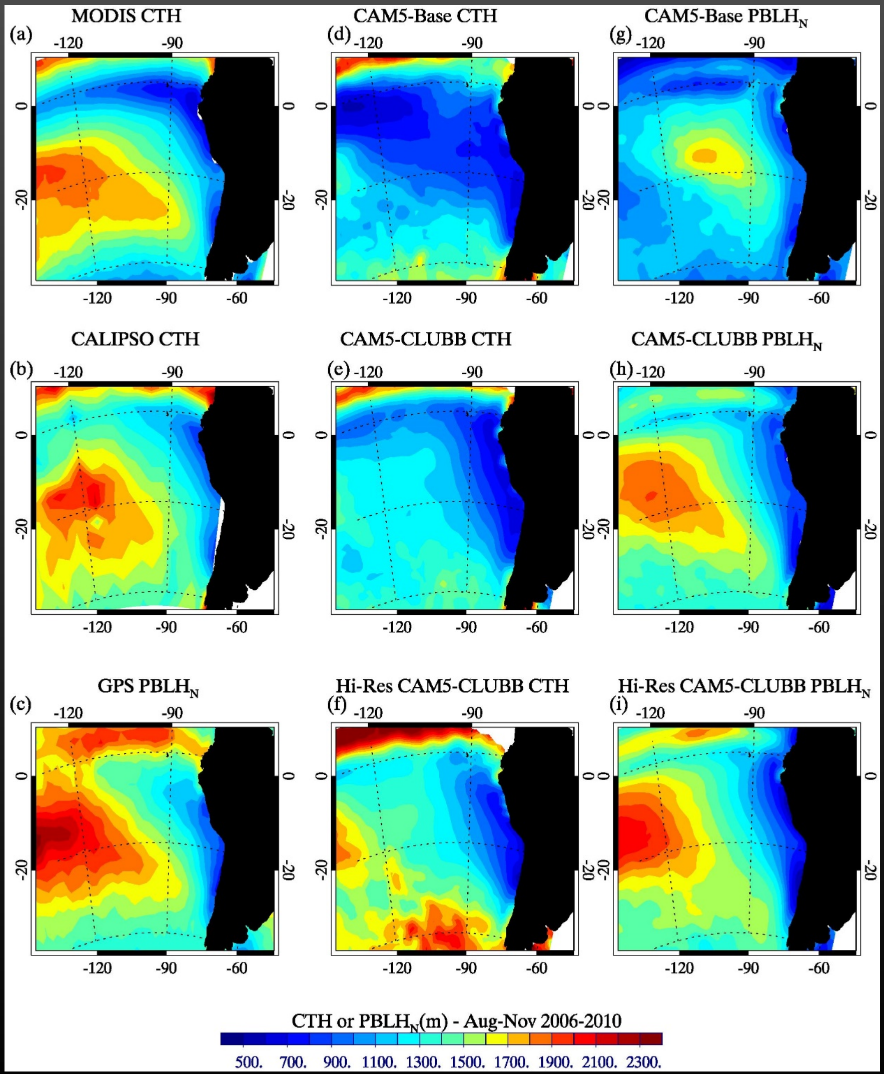
- PBL heights from RO can be used to assess GCMs with different PBL parameterizations and resolutions.
- Models: three versions of CAM5 (NCAR Community Atmosphere Model version 5)

1. **Base**
2. **CLUBB**: Cloud Layers Unified By Bi-normals, unified shallow cumulus and stratocumulus PBL schemes [Bogenschutz et al. 2013]
3. **Hi-Res CLUBB**: 60 vertical levels instead of 30

# Model/Observation comparisons over the Southeast Pacific

From RO and models:
**PBLH = PBL height estimated from min(dN/dz)**
From MODIS, CALIPSO, and models:
**CTH = Cloud top height**

- **CAM5-CLUBB agrees much better with observations than CAM5-Base. (Hi-res slightly better)**
- Good consistency between PBLH and CTH among the observations in the middle part of the domain.
- CTH and PBLH are quite different among the models. (better consistency for Hi-res)



# “Decoupling” of PBL

- The vertical structure of the PBL varies from a well-mixed layer where the specific humidity is relatively constant to a more complex structure with multiple layers.

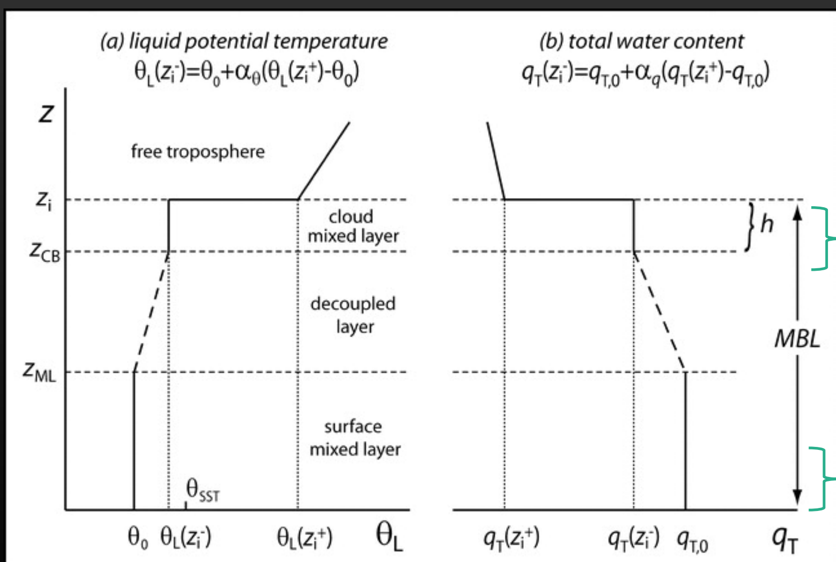


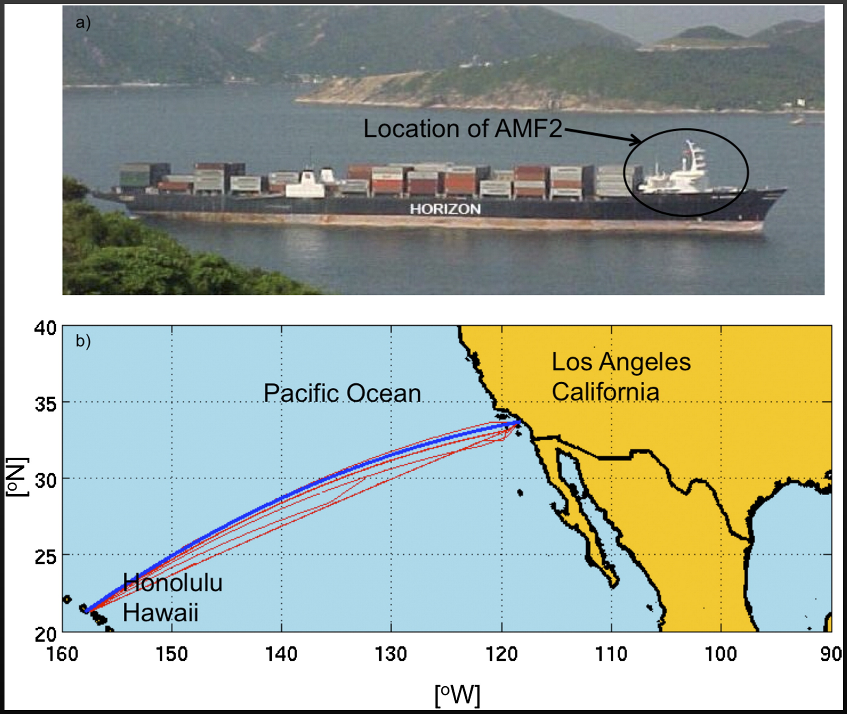

*Figure from Wood and Bretherton, J. Clim., 2004*

We define the decoupling parameter as [Jones et al., ACP, 2011]

D = q(bot)– q(top)

where bot, top = bottom (top) 25% of the PBL

# Comparison with MAGIC RAOB



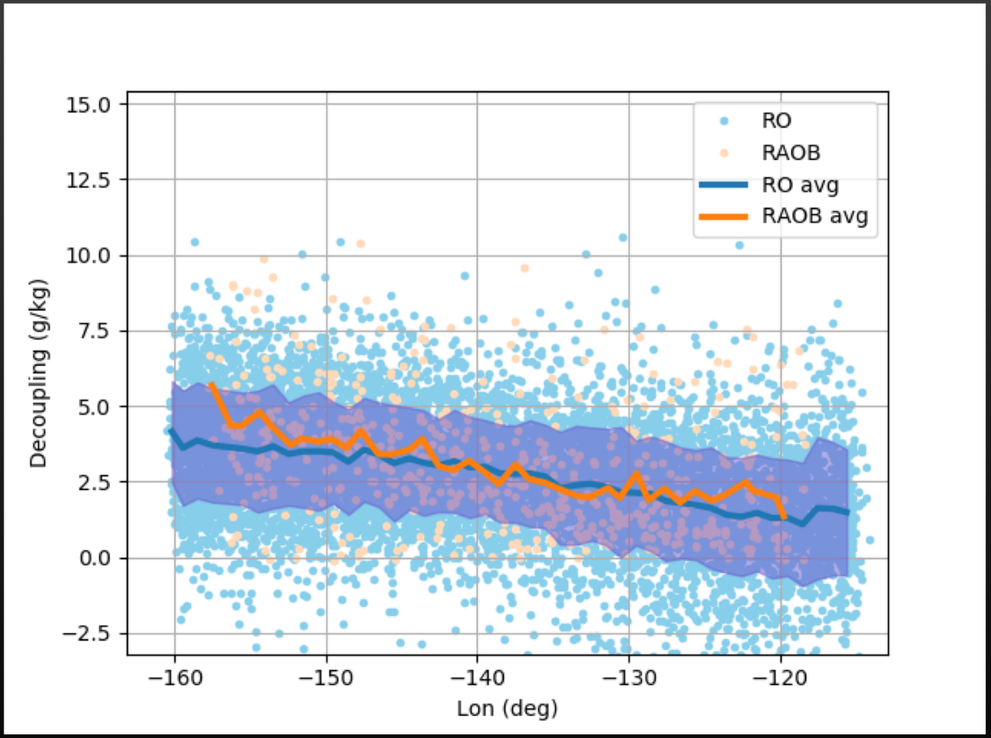
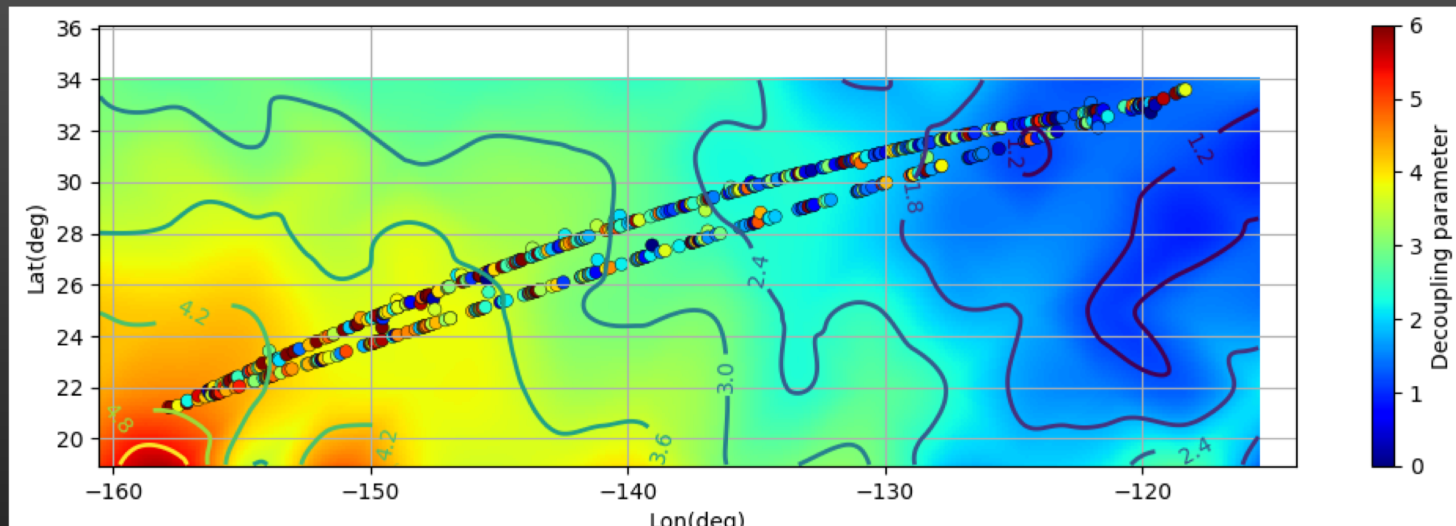
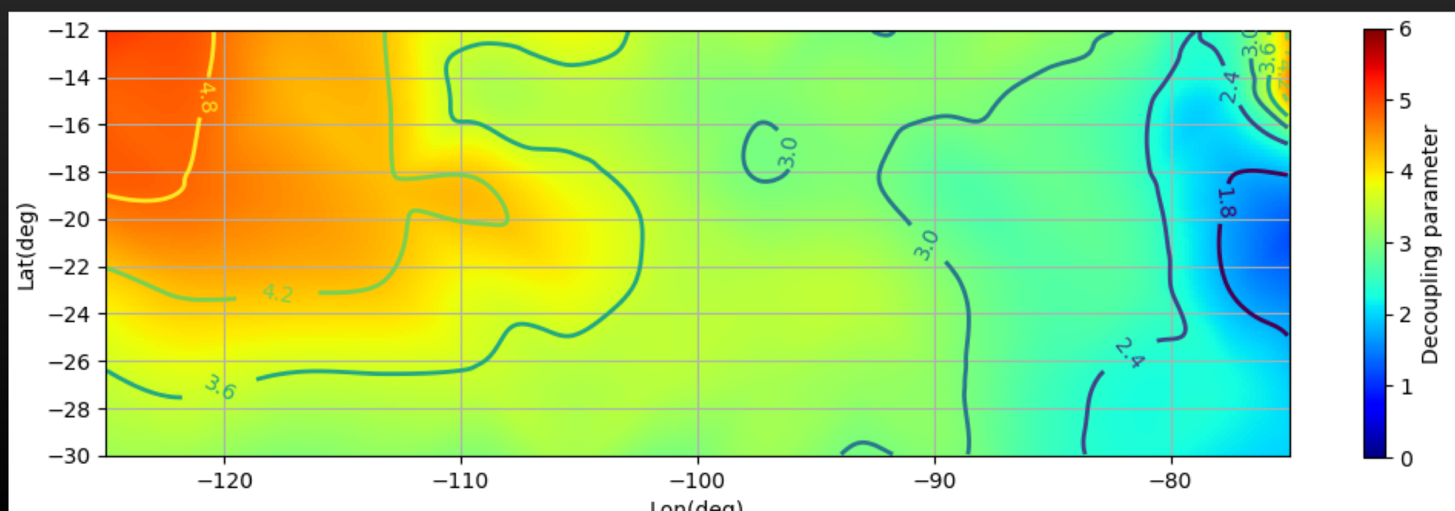




*Figure from Zhou et al., J Clim. 2015*

NE Pacific




SE Pacific



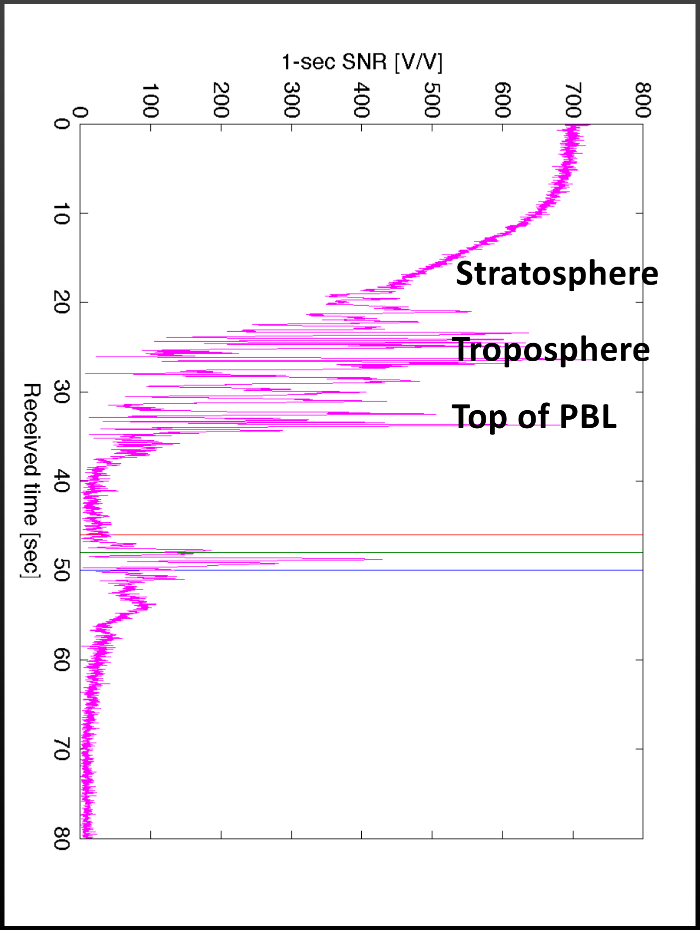
# Challenges in lower troposphere/PBL

- Large vertical gradient causes strong defocusing -> low SNR
- Diffraction and atmosphere multipath -> strong phase fluctuations

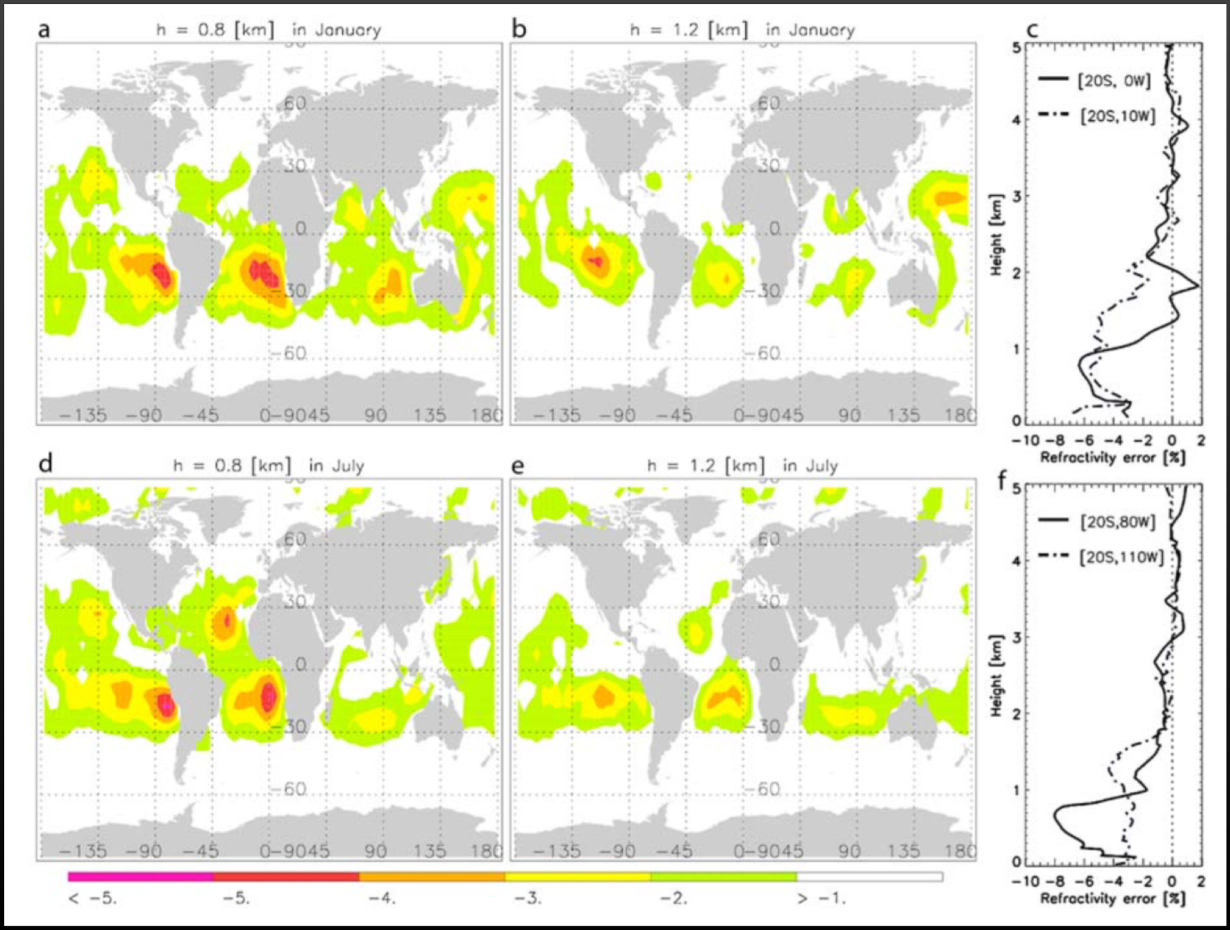
Which may lead to…

- Retrieval bias
- Profile truncation

These problems are most prevalent over moist regions.



# Negative N-bias




Fractional refractivity error in %:
[N(RO)-N(ECMWF)]/N(ECMWF)

Large negative bias under the stratocumulus cloud decks where large vertical refractivity gradient can form on top of the PBL, leading to elevated ducting layers.

*Figure from Xie et al., GRL, 2010*

# What is ducting?

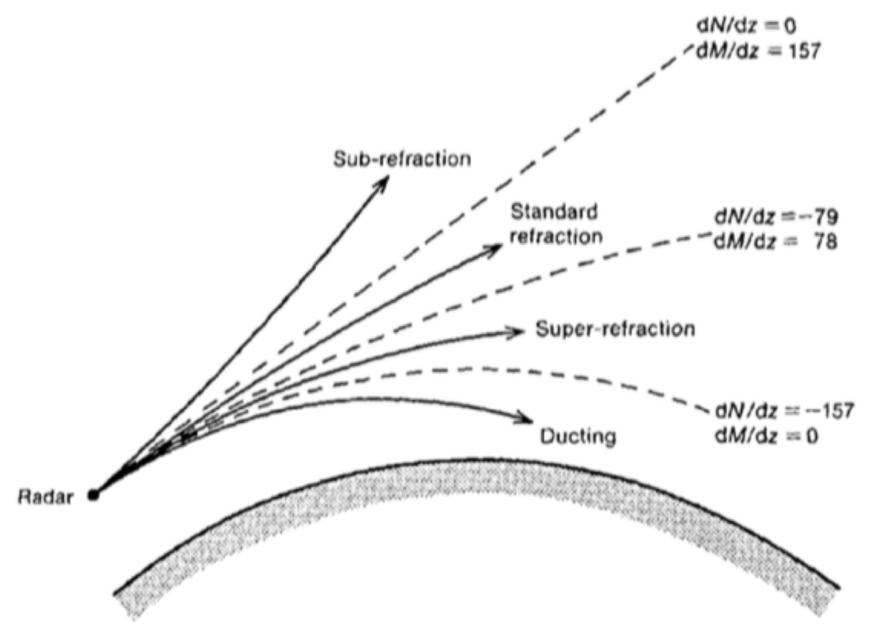


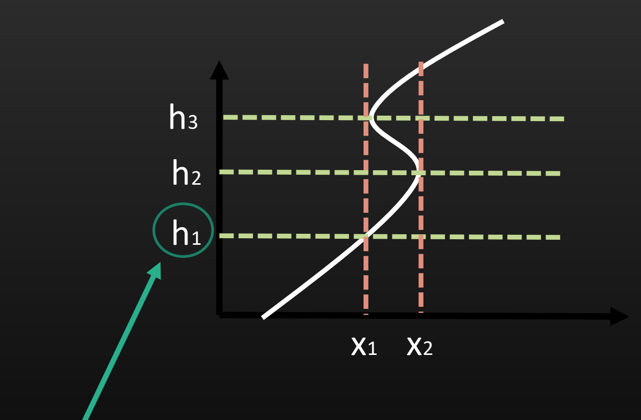

Figure 1. Categories of refractive propagation defined from the values of $dN/dz$ or $dM/dz$ (from Turtton et al. 1988).

In RO geometry, the transmitter is outside the atmosphere so the rays do not get trapped under ducting.

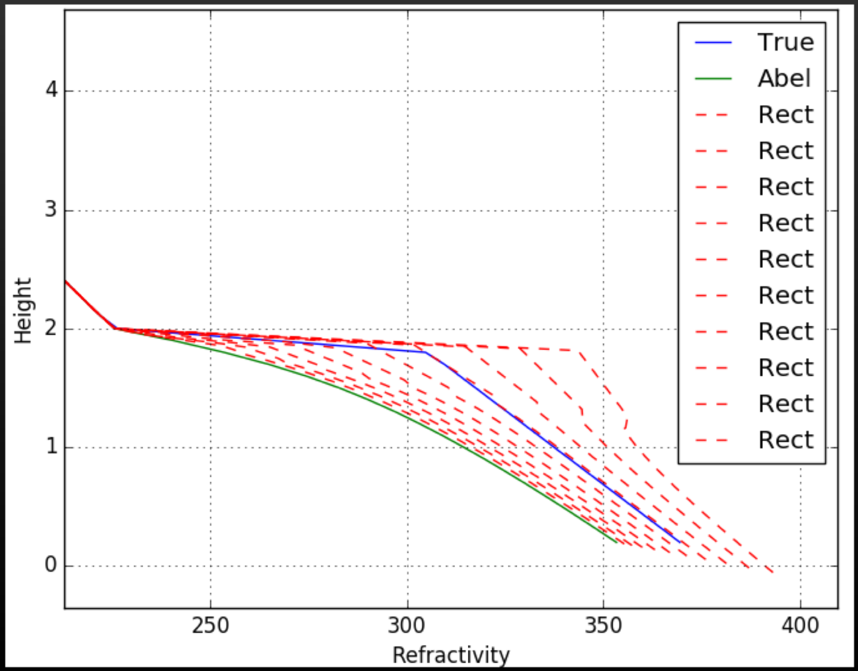
However, with ducting, there is a layer where there are no ray tangent points, violating a basic assumption in the Abel inversion that transforms bending angle to refractivity.

# Negative N-Bias from Ducting

- Under ducting, Abel inversion produces a smaller (non-ducting) refractivity below the duct [Sokolovskiy et al. 2003].
- **Bending angle profile no longer uniquely determines refractivity.**



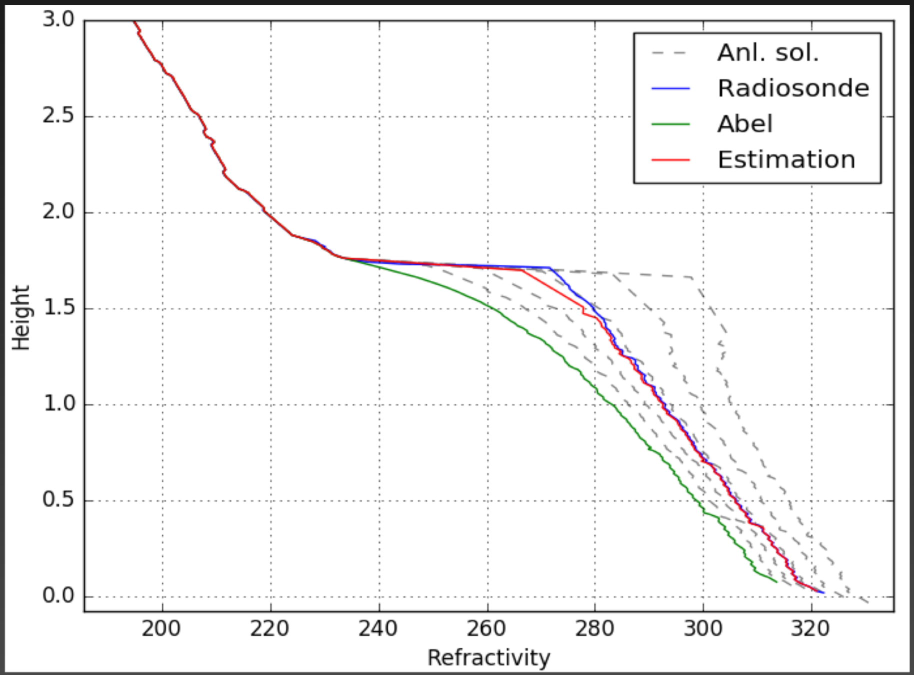

Family of refractivity solution can be reduced to a single parameter $h_1$ [Xie et al. 2006]

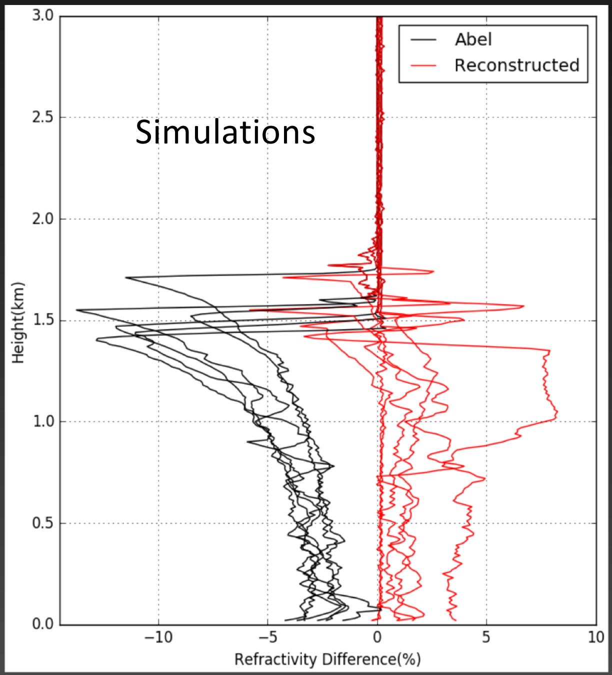


# Optimal estimation retrieval with PW

Wang et al., AMT, 2017

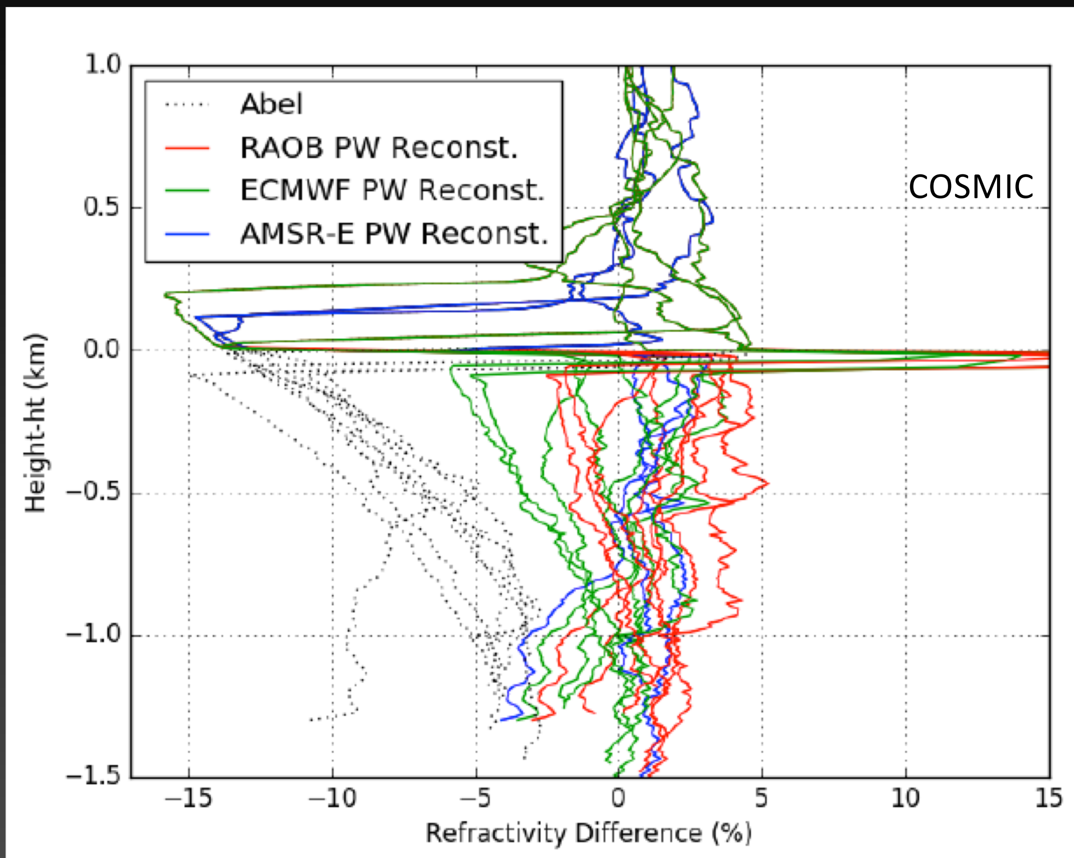
Precipitable water (PW) retrieved from collocated AMSR-E observations are used to constraint the PBL refractivity.



# Optimal estimation retrieval with PW

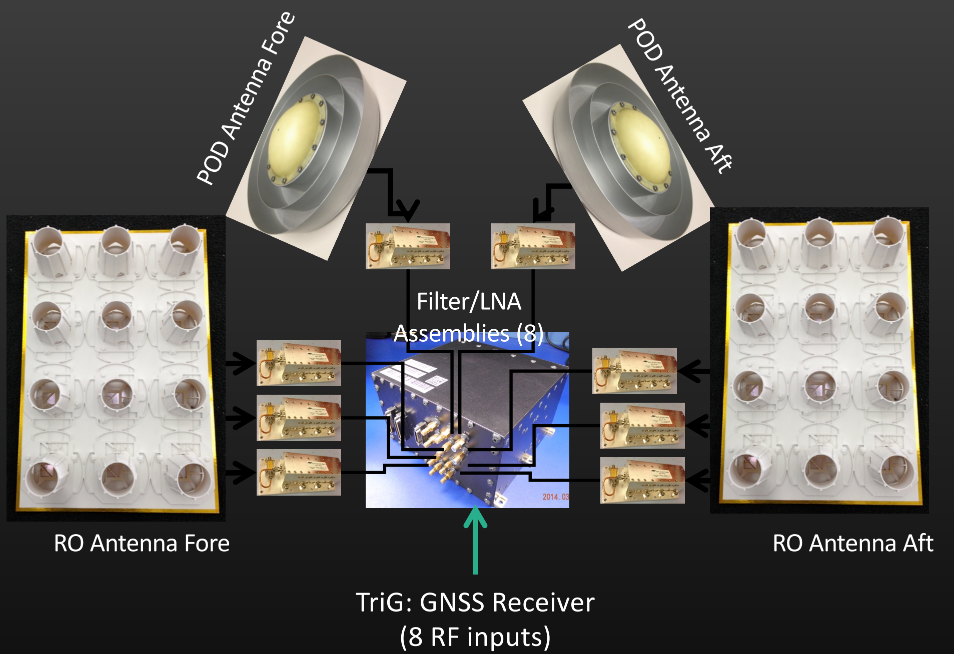
Wang et al., AMT, 2017




For real measurements, the results are not as perfect due to temporal and spatial separation between RO and RAOB. But significant reduction in the negative bias can be seen.

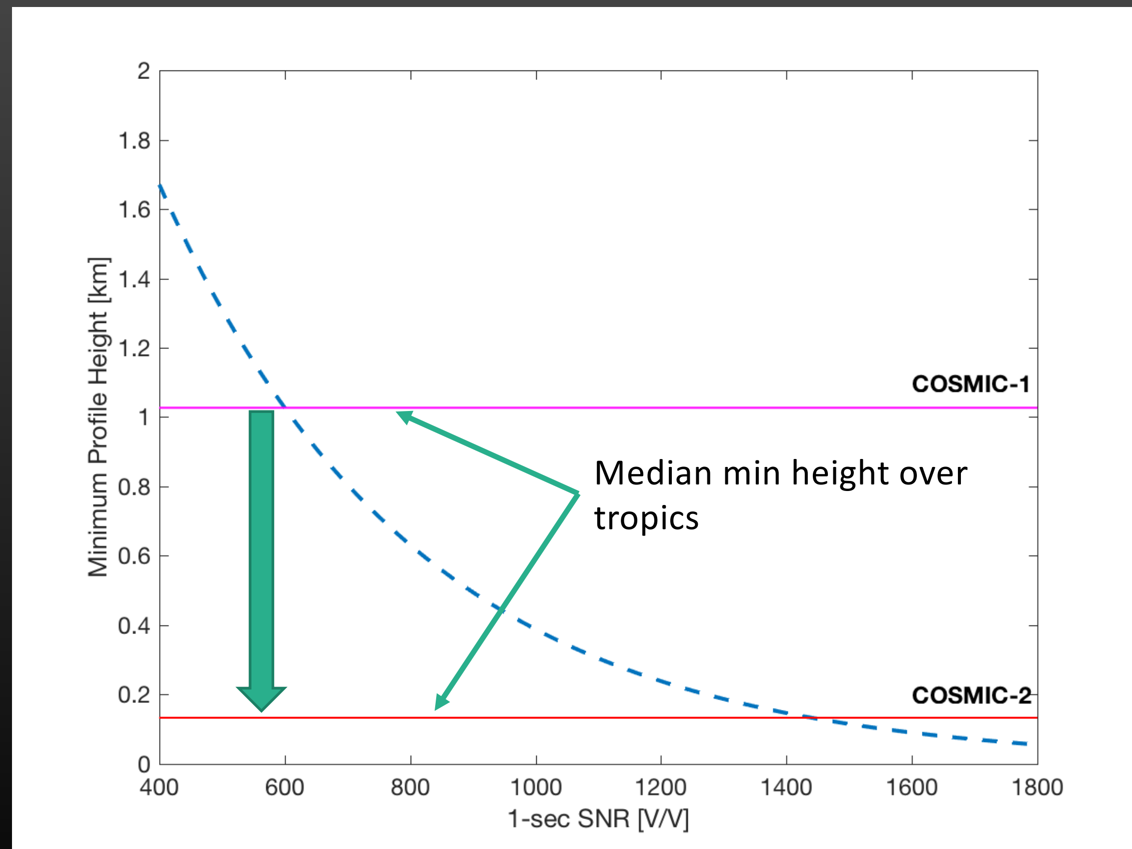
# Instrument developments since COSMIC

- JPL has developed the TriG GNSS receiver designed to track multiple GNSS constellations (more profiles per receiver) with a large beam-forming antenna array (higher SNR).
- The TriG receiver will be flying on COSMIC-2 (Early 2019) and Sentinel-6 (Late 2020).
- Besides higher SNR, additional open loop tracking channels + more processing capability should lead to much improved data quality in the PBL.




The TGRS payload on COSMIC-2

**With better SNR and increased tracking channels, we should get much better profile penetration.**



# Summary

- GNSS-RO provides unique information on the vertical structure of PBL globally
  - Most studies focus on MBL in the subtropics, but Arctic PBL has also been studied.
- Existing data can be used for GCM assessments and complements cloud/aerosol observations.
- Retrieval algorithms combining multiple sensors (e.g., RO+MW/IR) will lead to better products.
- Advanced instrument capability on COSMIC-2 and Sentinel-6 should yield enhanced data quality within the PBL.

COSMIC-2

Sentinel-6/Jason-CS
(video from ESA)

# Backups

# PBL and its importance

- The PBL is the bottom turbulent layer of the atmosphere (~ 2 km) that mediates the mass, energy, and momentum exchanges between surface and the troposphere.
- The PBL is identified as a "Targeted Observable" in the 2017 NAS Earth Science Decadal Survey:

  *"The planetary boundary layer (PBL) has broad importance to a number of Earth science priorities….*

  *Accurate and high-resolution measurements and better understanding of boundary layer processes are of key importance for improving weather and climate models and predictions."*

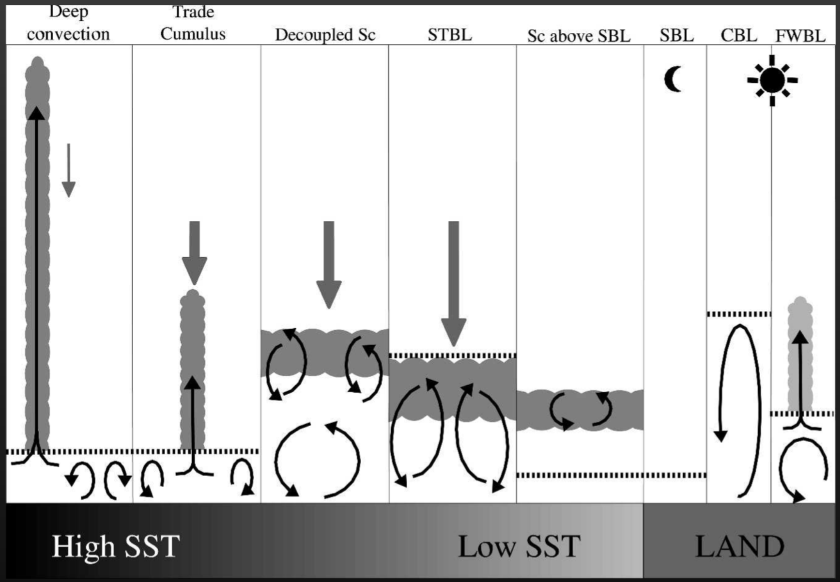
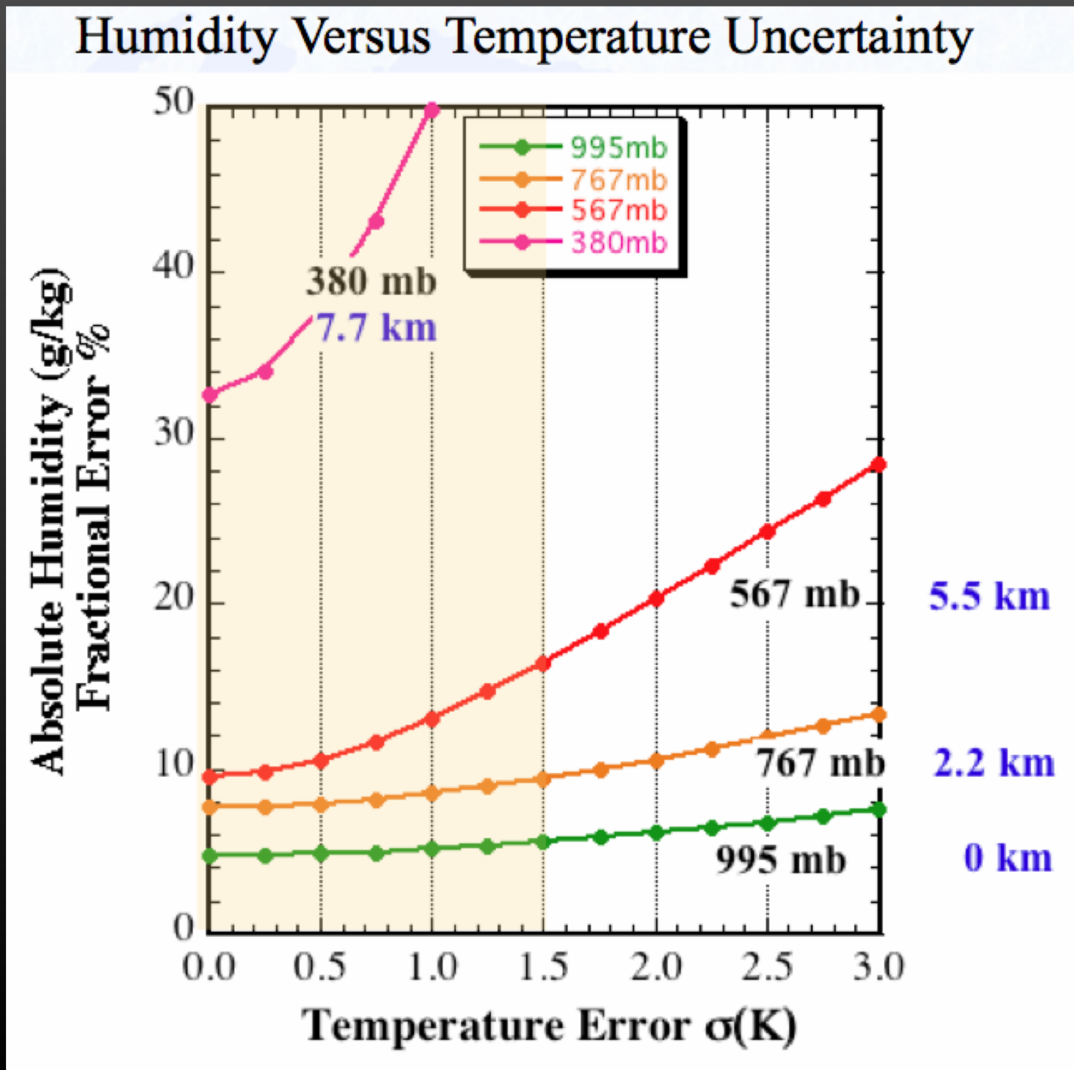


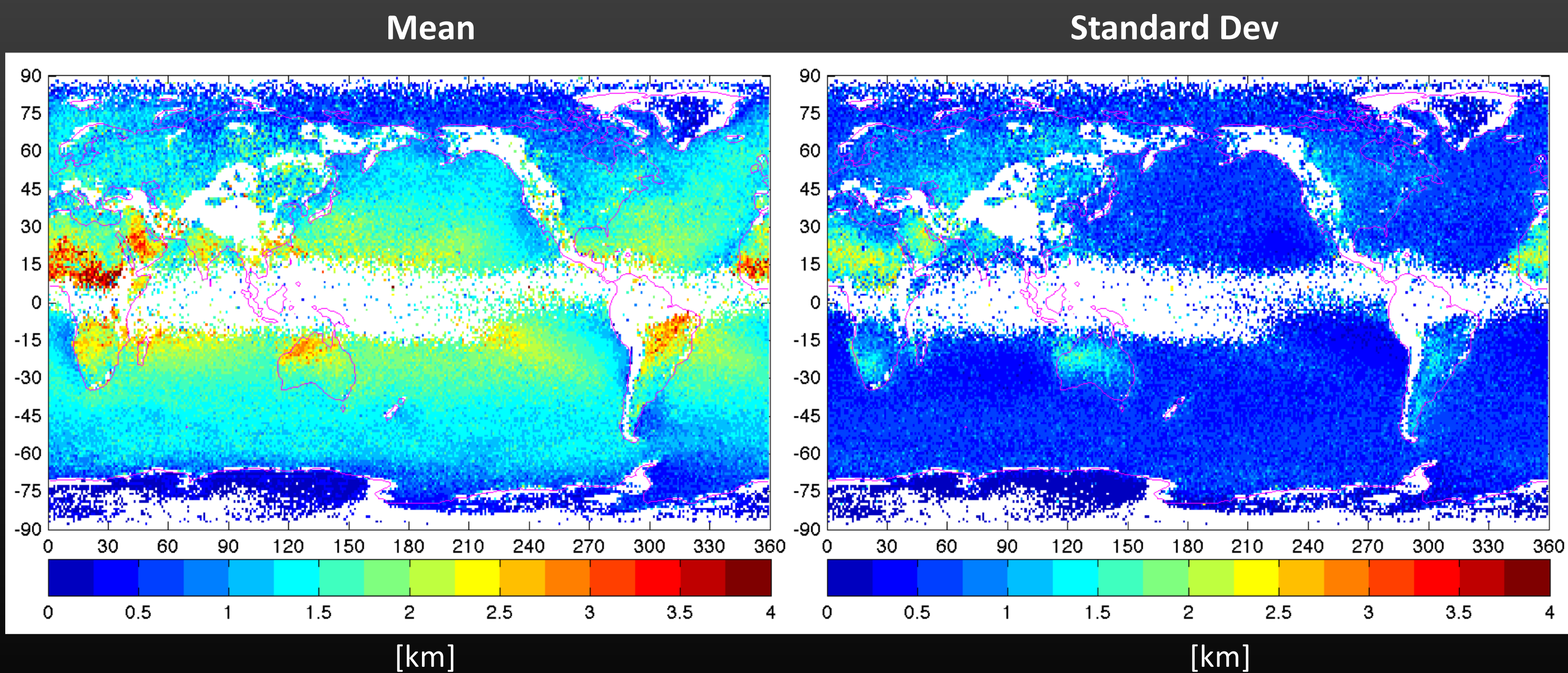

*Figure from Medeiros et al., J. Clim., 2005*




Applicable at low latitudes

In the PBL, the retrieved specific humidity is not very sensitive to the assumed temperature.

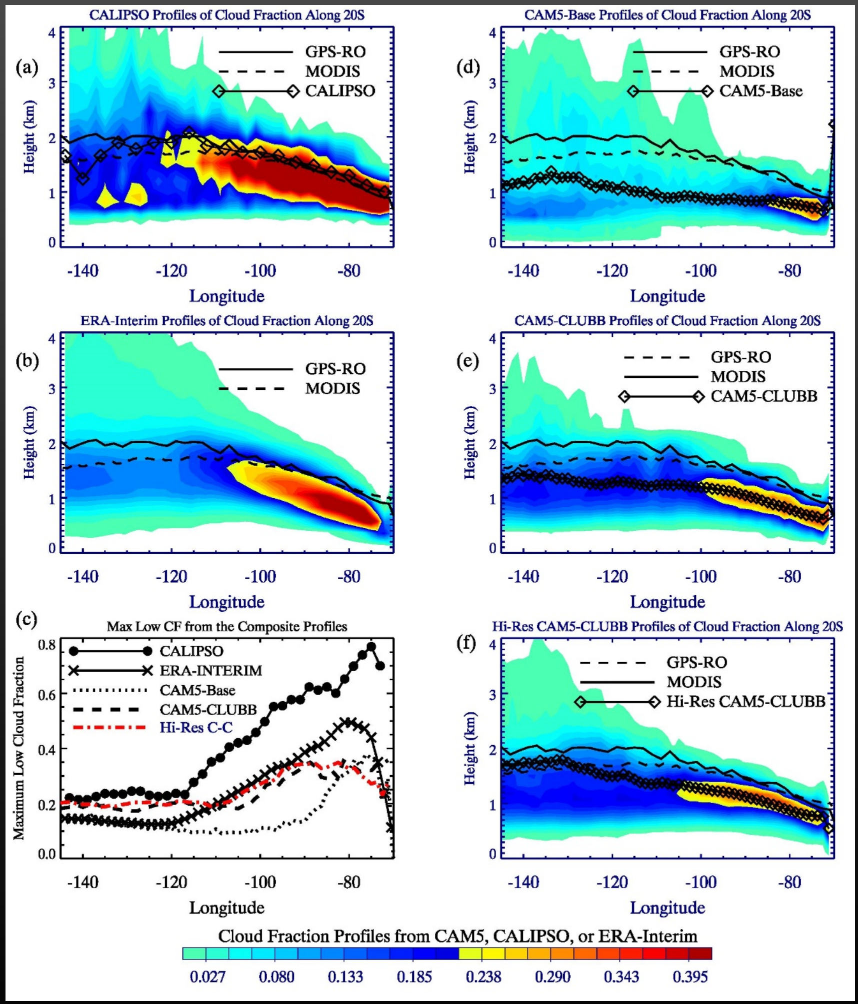
# 1° x 1° PBL depth (“Sharpness” > 2)



# Comparison at 20 deg S

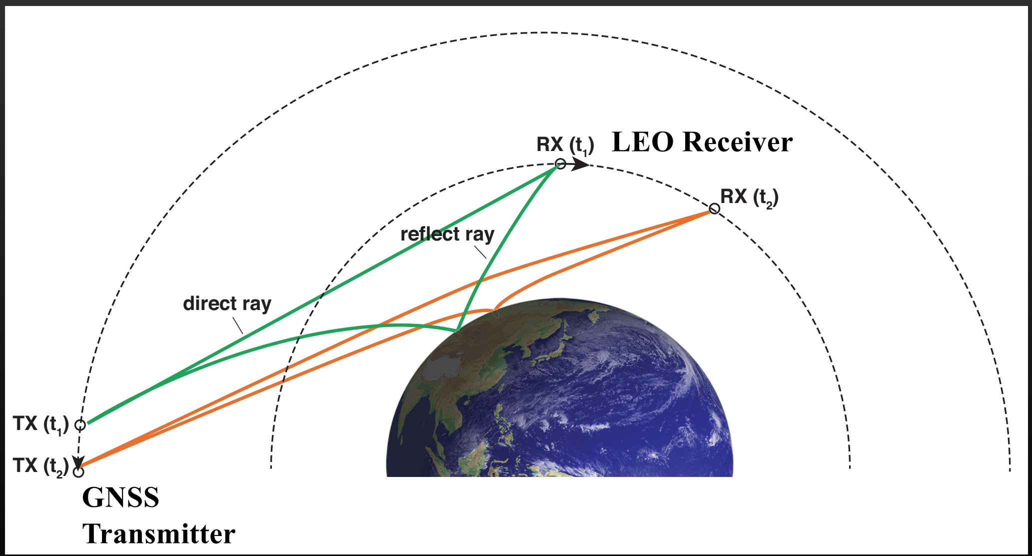
- **CAM5-Base severely underestimated cloud fraction and cloud height.**
- **Progressively better with CLUBB and Hi-res but biases can still be seen.**

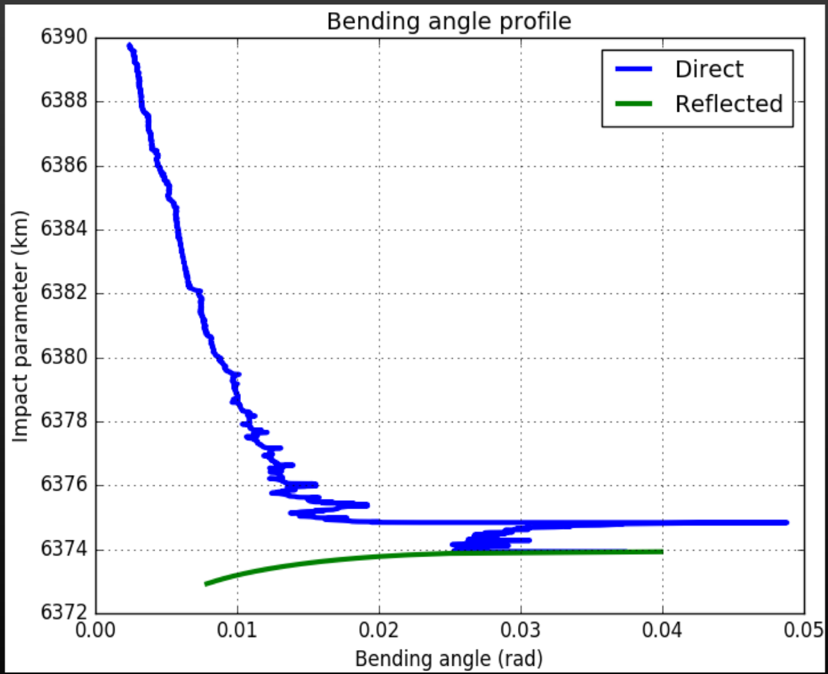
- The trade cumulus regime (apparent from the location of ∂CF/∂x ~ 0 and low values of "max low cloud fraction") near and west of ~120W is similar in ECMWF reanalysis and CALIPSO, but extends much too far east in CAM5-Base, with significant improvement with CLUBB and Hi-Res.



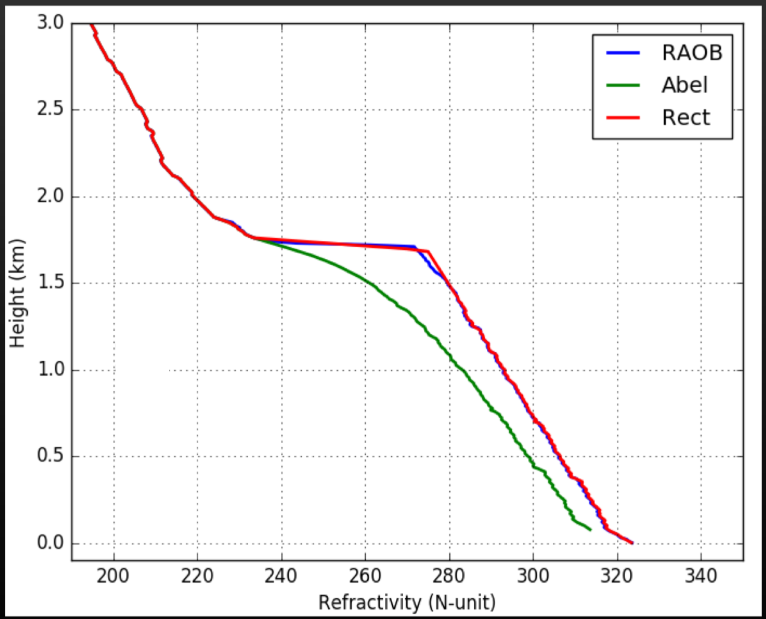
# Surface Reflections from GNSS-RO as constraint for PBL retrievals

Work led by Eric Wang

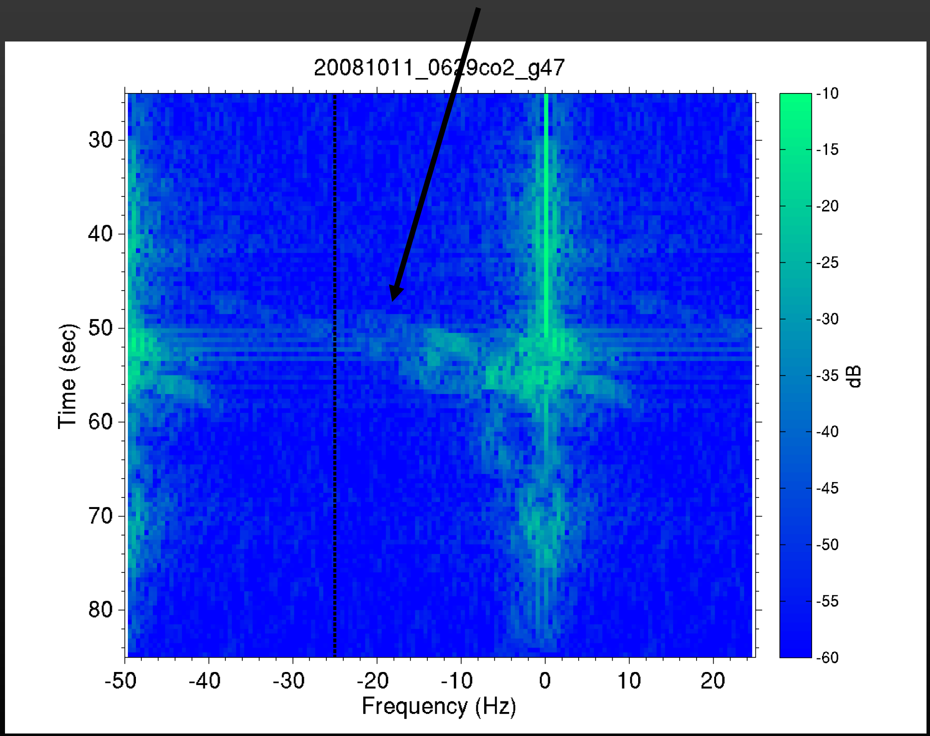


Idealized simulation results show that bending angle from reflected ray works just as well as PW as constraint…




However, applying this method to real data is challenging since reflection signals from real measurements are noisy…



# What about CubeSats?

- CubeSats provide an opportunity to greatly increase the number of RO measurements at a low cost.
- Several companies (Spire, GeoOptics, etc.) are vying to collect GNSS-RO data to sell to the govt.
- JPL has designed a CubeSat class receiver (Cion) which has flown on the GeoOptics CICERO 6-U CubeSats.
- To target PBL, bigger (deployable?) antennas than those currently in use are desirable.