Ducting Detection and Reconstruction with COSMIC-I/II GNSS Radio Occultation Observations

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Acknowledgement:

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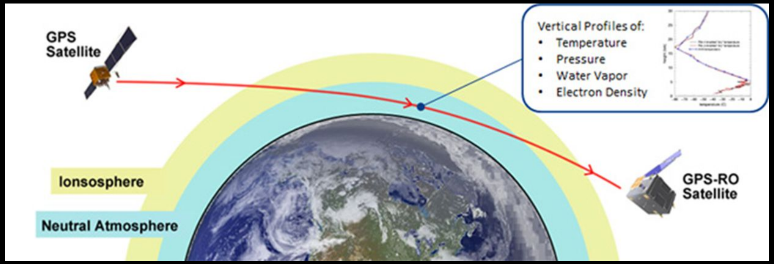
Motivation

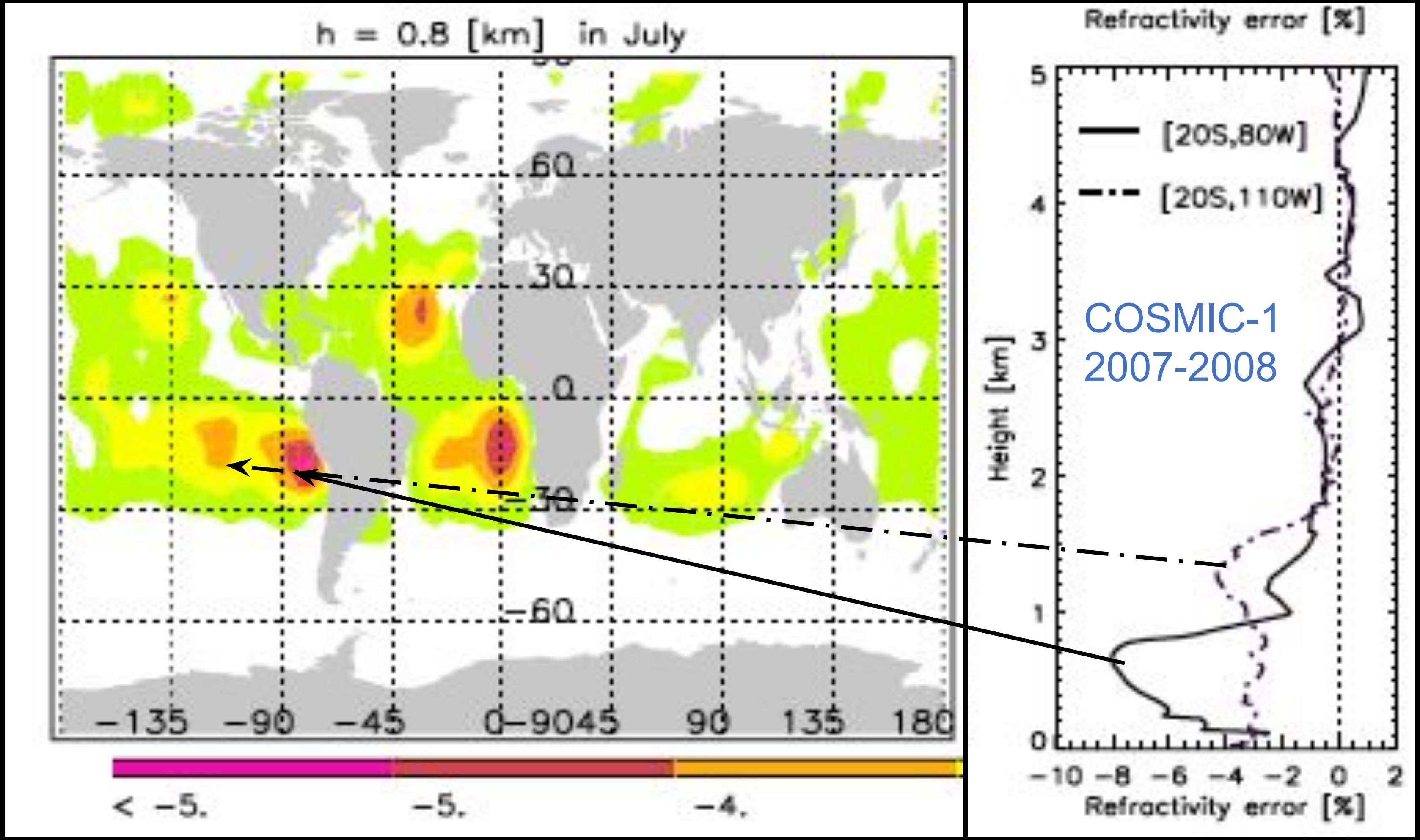
- **Planetary Boundary Layer (PBL)**
  - Key component of the weather and climate system, an interface between Earth's surface and the free troposphere (affect energy, moment, and mass fluxes), of prime importance to climate, weather, and air quality research
  - Governing the evolution of low clouds (large uncertainty in climate feedback according to IPCC-2007/2013 report). PBL is a top priority in the 2017 NASA Decadal Survey PBL incubation.
  - PBL height (PBLH) – or mixing height (MH): fundamental parameter characterize the vertical extent of mixing within the boundary layer
- **Unique Capabilities of GNSS-RO PBL Sensing**
  - Sensitivity to vertical structure of water vapor and temperature inversion with high vertical resolution (~100 m)
  - All-weather (not degraded by clouds or precipitation)
  - Diurnal cycle coverage (e.g., COSMIC-I&II)



- **Challenges Facing GNSS RO PBL Sensing**
  - Relative coarse horizontal resolution (~ 100 km)
  - Negative refractivity bias (dry bias) under certain conditions (Ducting etc?)

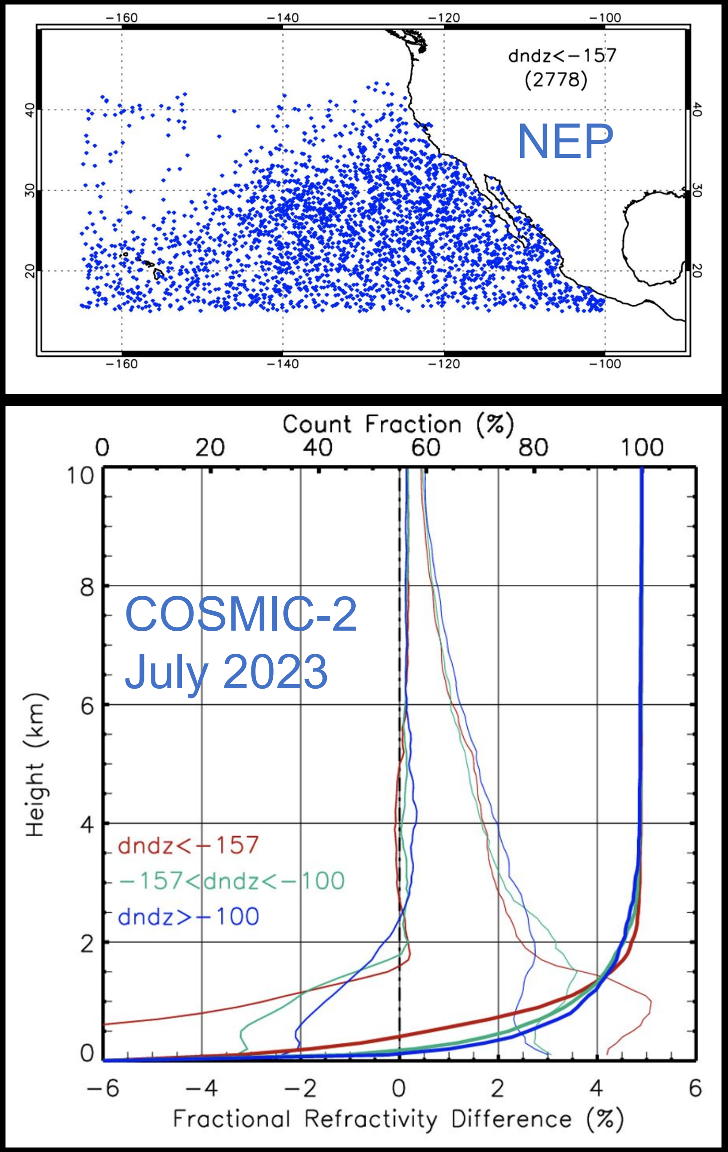
Refractivity Biases in GNSS-RO

COSMIC-1(2007) & /COSMIC-2 (2023)



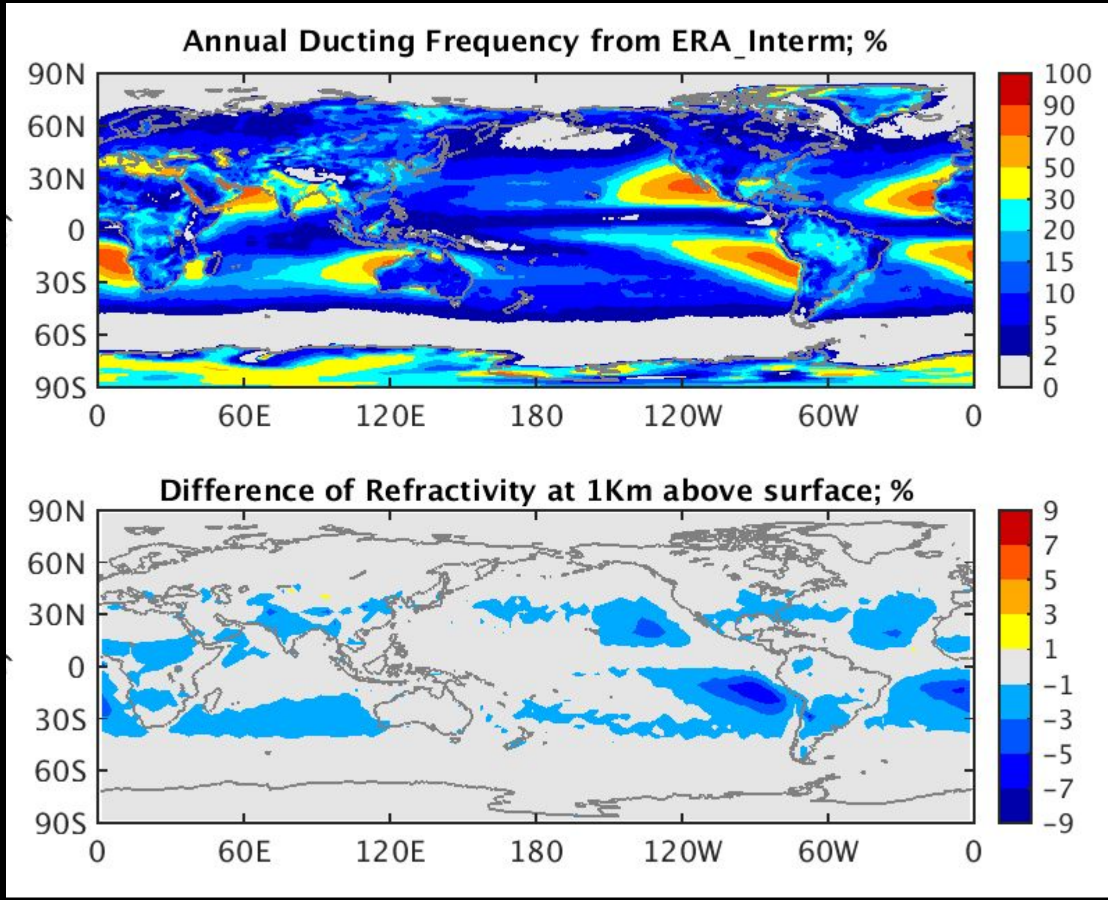
$(N_{ro} - N_{ecmwf}) / N_{ecmwf} \times 100$ [%]

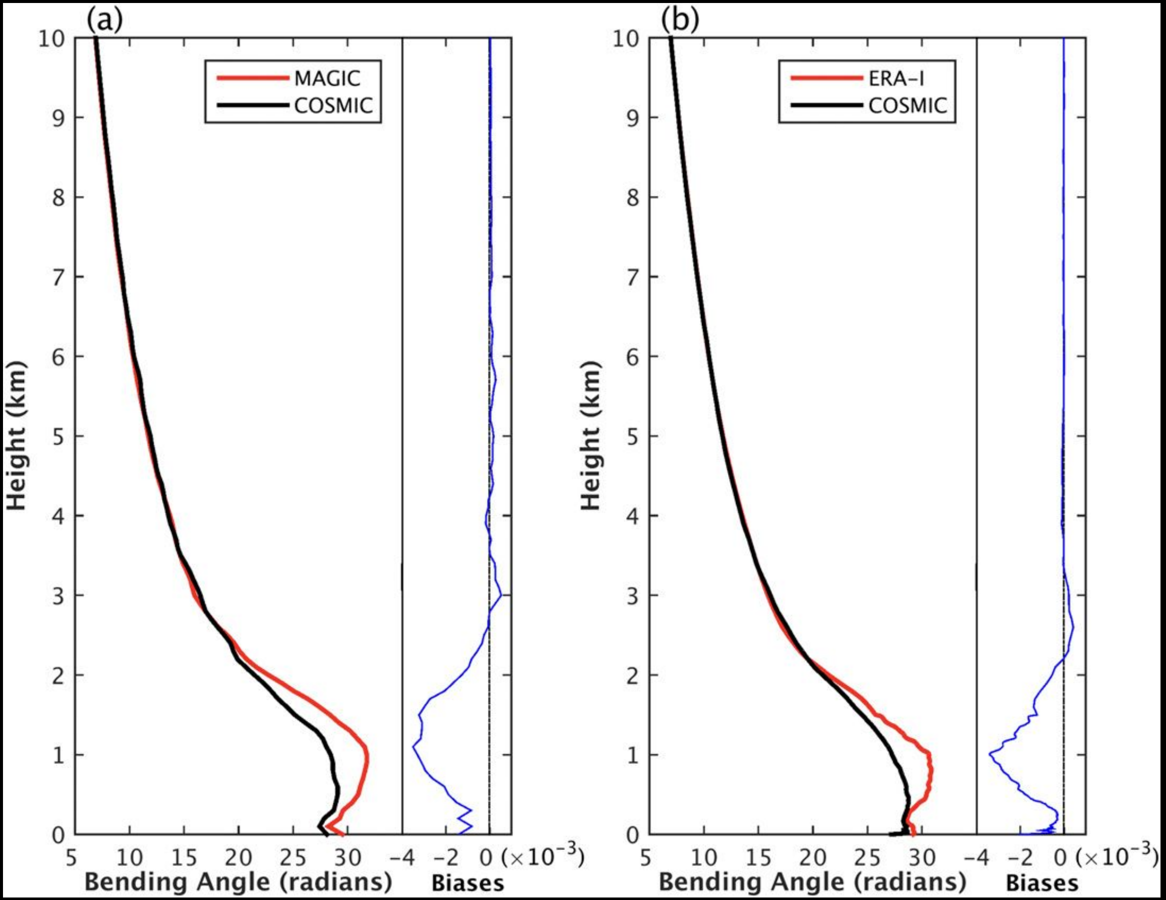
Xie et al., GRL 2010



Systematic Negative *N*-bias over Subtropical Eastern Oceans inside the PBL

Global Ducting Frequency and COSMIC-RO Bending/*N*-biases



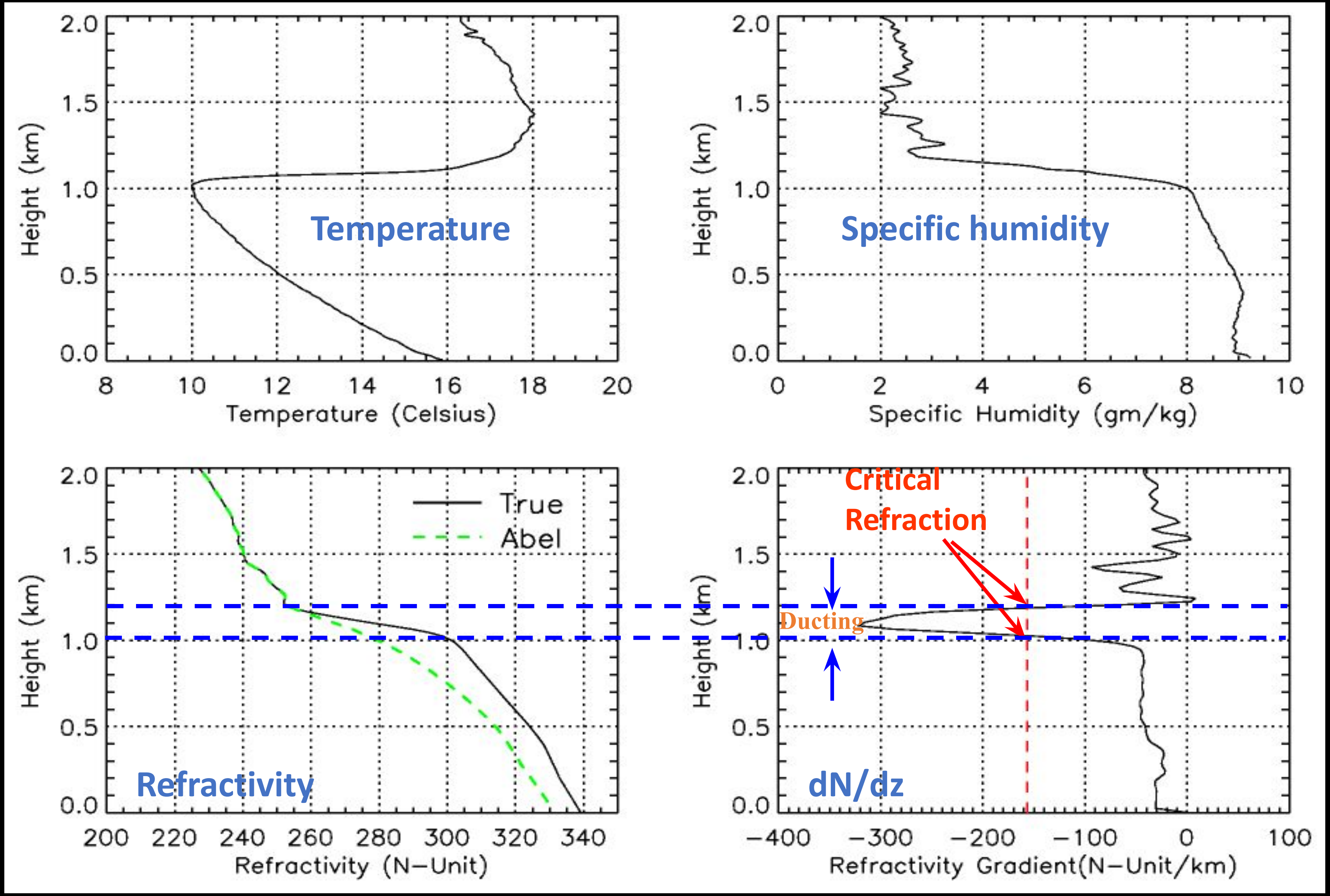


(Top) Ducting frequency: clustered in subtropical eastern oceans. **(Bottom) Fractional N-bias**: Similar to ducting pattern, with maximum up to ~-10%.

Mean bending angle profile and biases (Left): COSMIC vs collocated MAGIC radiosondes; (Right): COSMIC vs ERA5

Feng et al., JTECH 2020

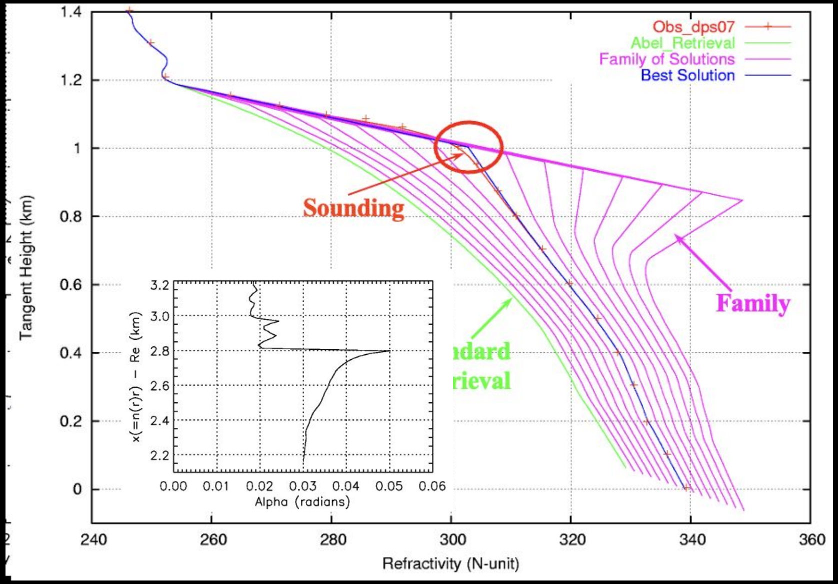
GNSS-RO Refractivity Bias due to Ducting



Dropsonde from DYCOMSII (Bjorn Stevens)

An ill-posed Abel Inversion problem

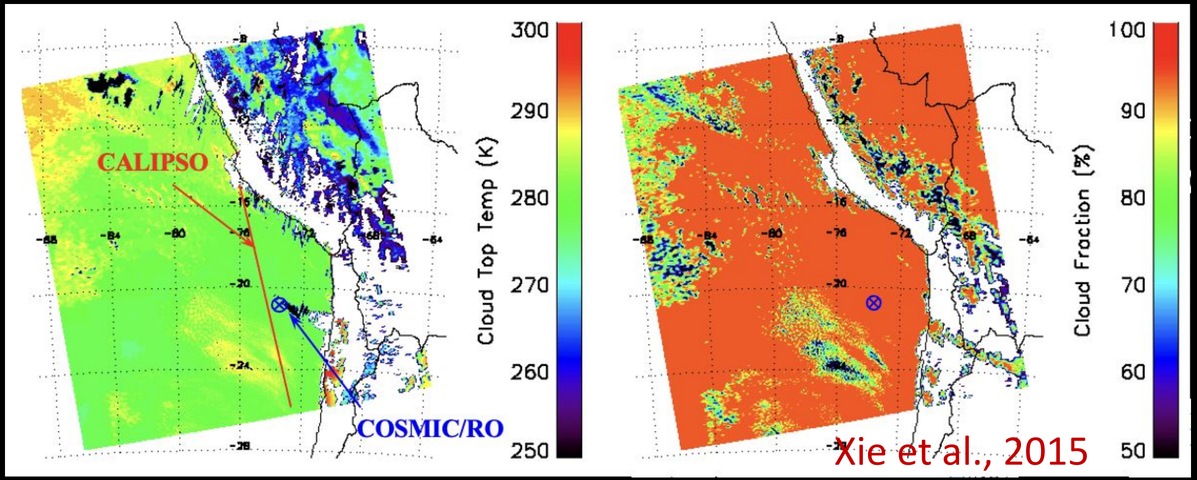
One bending angle corresponds to a continuum of refractivity profiles.

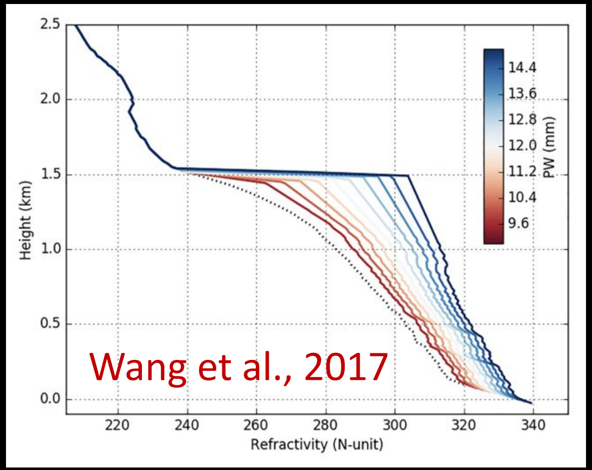


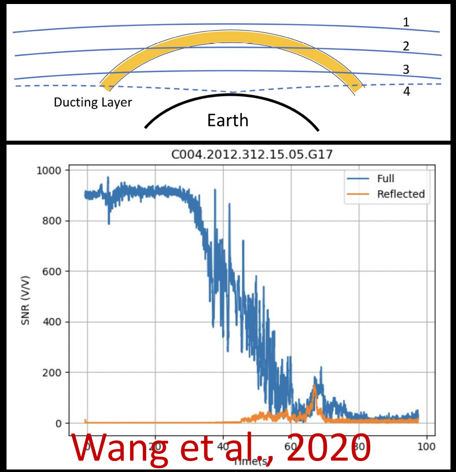
Xie et al., 2006, JTECH

Ducting PBL Reconstruction - Constrained Inversion

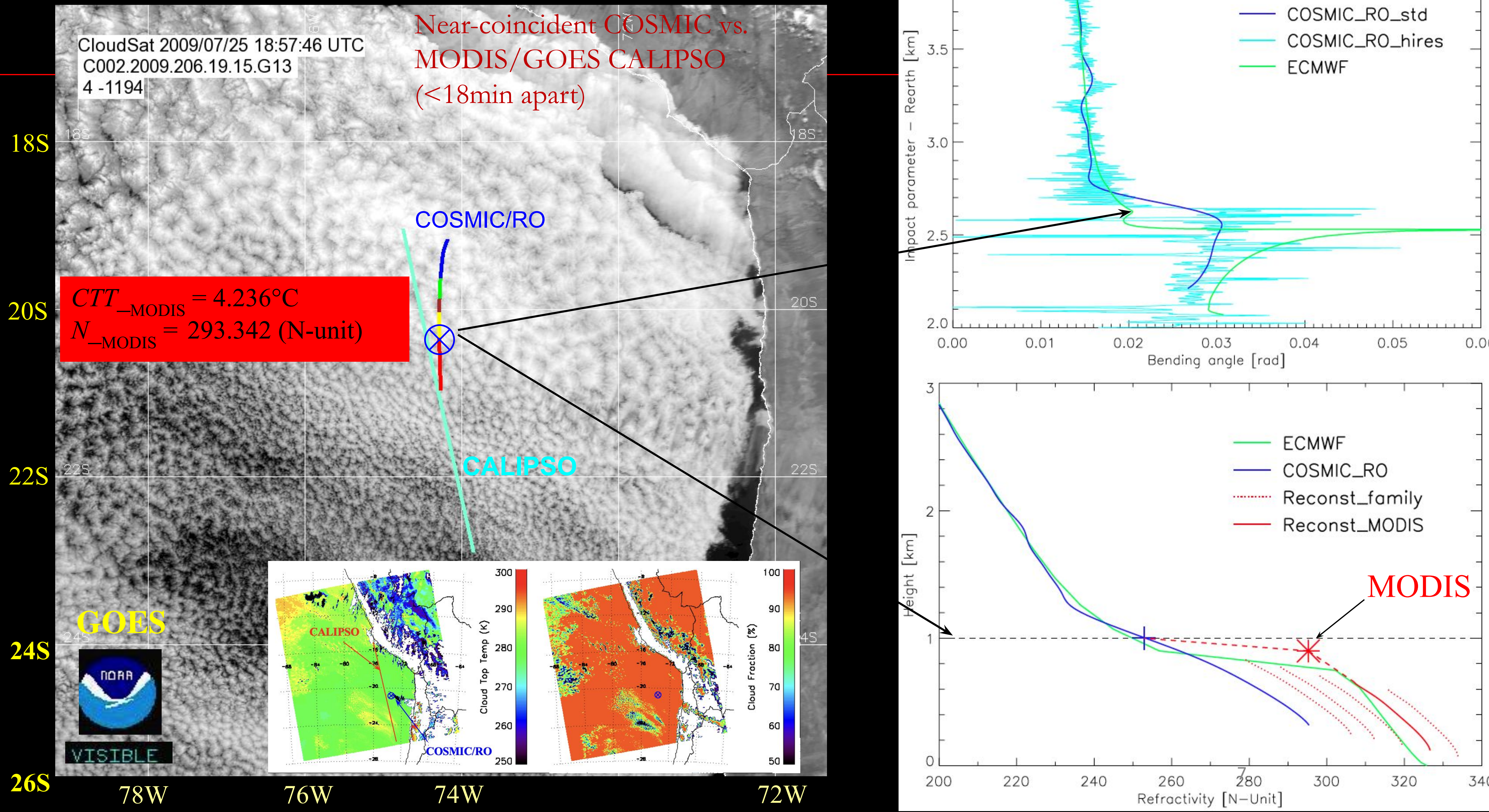
- A constrained Abel inversion using additional information was proposed by Xie et al. (2006, JTECH).
- Potential independent constraints colocated with RO measurements
  - Cloud-Top-Temperature (CTT) from MODIS/GOES (Xie et al., 2015, AGU)
  - Precipitable water vapor (e.g., Wang et al., 2017, AMT)
  - Grazing RO Reflection Signal (Wang et al., 2020, RS)
  - Surface measurements and others?





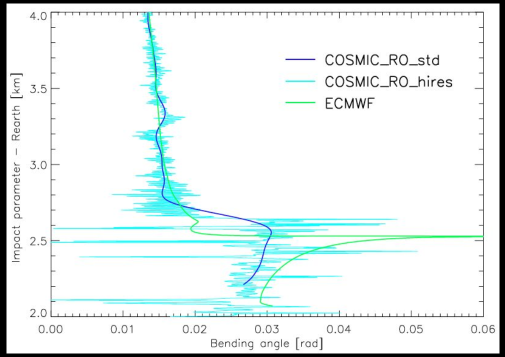


COSMIC vs. MODIS-CTT

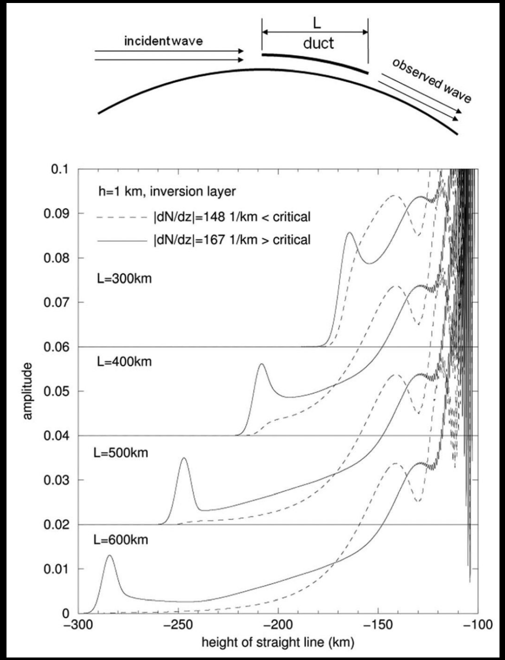


Ducting PBL Refractivity Reconstruction

- **Ducting Reconstruction Challenges**
  - Uncertainty in constrained reconstruction method
    - Standard Abel refractivity retrieval
      - High-rate bending angle retrieval will be needed (Xie et al., 2010)
      - Bending angle biases
    - Ducting height (critical refraction)
      - Sub-100 m precision needed (Xie et al., 2006)
    - Linear parameterization within ducting layer
    - External constraints
- Ducting detection
  - Ducting existence
    - Deep signal detection (Sokolovskiy et al., 2014)
    - Horizontal inhomogeneity
    - Other signal interference
  - Ducting height/PBLH detection
- Uncertainty related to the physical constraints
  - Colocation successfully rate
  - Precision & accuracy of constraint, e.g., CTT (dependent on cloud fraction/optical depth)

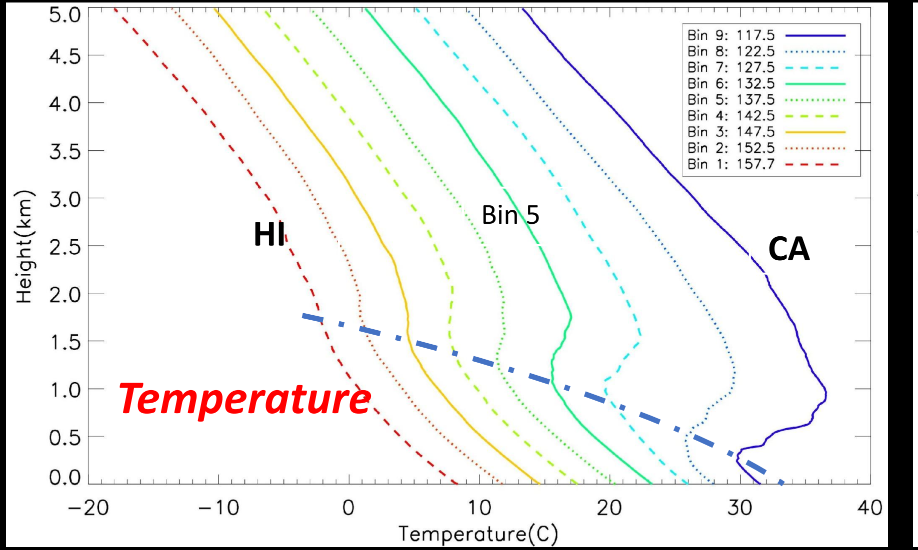


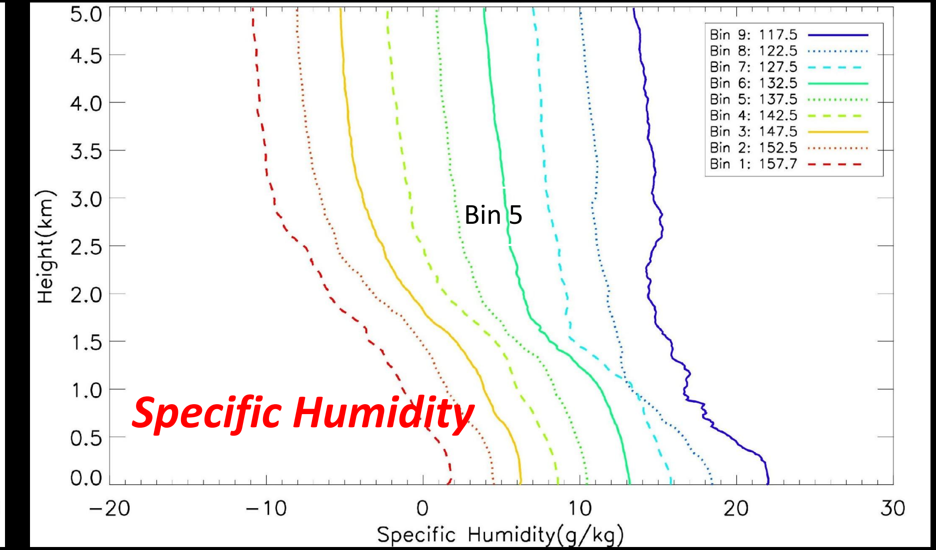
Xie et al., 2010



Sokolovskiy et al., 2014

PBL Variation along the MAGIC Transect

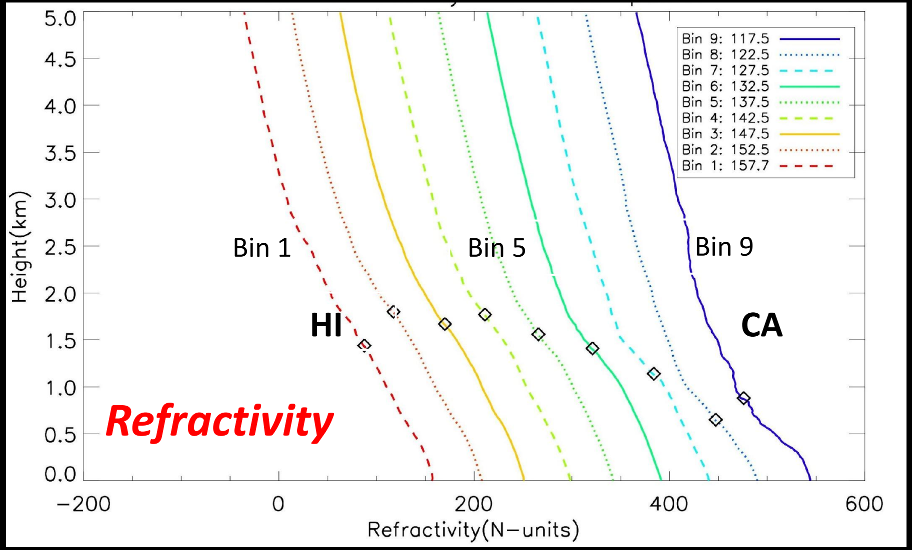




Radiosonde:

Marine ARM GPCI Investigation of Clouds (MAGIC) field campaign

Location: 20 round trip between Los Angeles, CA (34.05°N, 118.24°W) and Honolulu, HI (21.31°N, 157.86°W) ~ 500 rds (2012.10 – 2013.9)



- PBLH, SST, N_{sfc}, increase westward
- Westward decrease of max refractivity gradient, sharpness parameter, PBLH; and increase in SST & PBLH

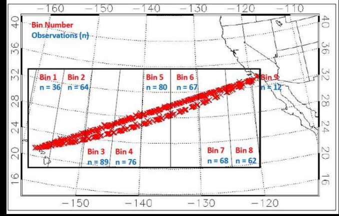
Presence of Horizontal Inhomogeneity

ERA-5 (ECMWF Reanalysis Version-5)

0.25 deg x 0.25 deg, 1-hour temporal resolution, and 137 vertical levels from the surface to 0.01 hPa (Hersbach et al., 2020).

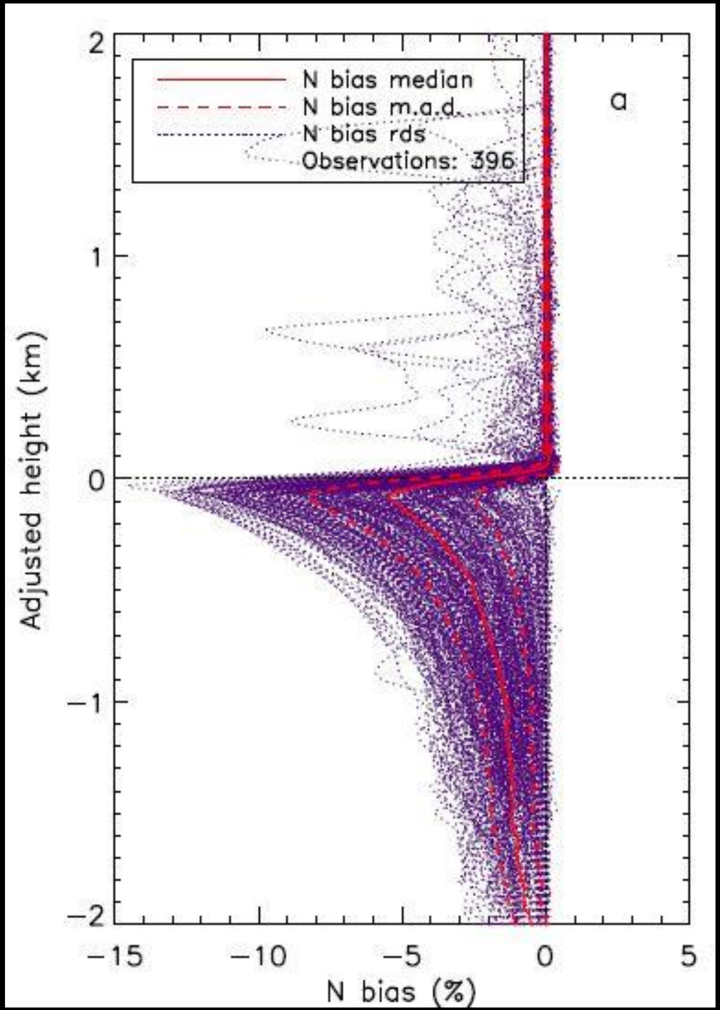
~19 model levels below 2 km

Ducting inducted *N*-Bias Along the Transect

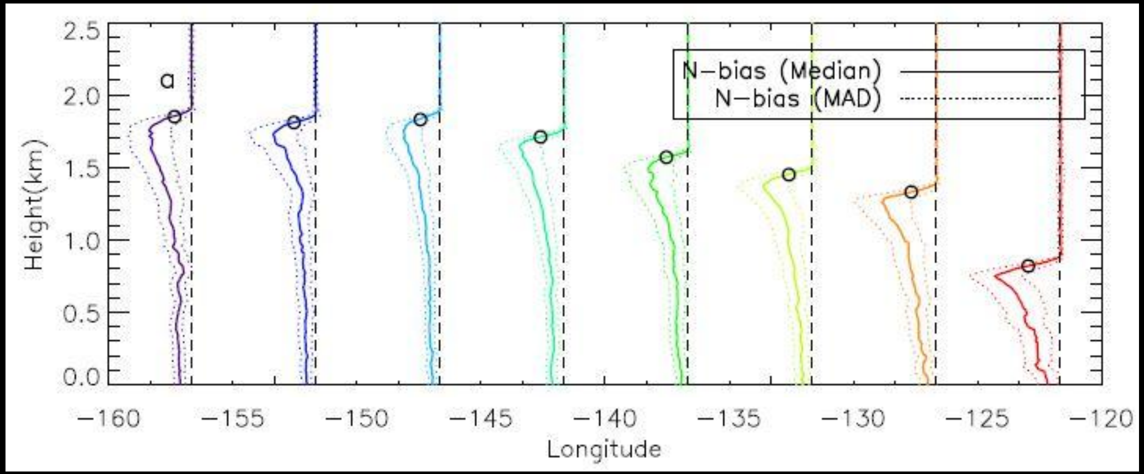


Largest *N-bias* near ducting height

Median *N*-bias from -1% to −5.4%



MAGIC Radiosonde *N*-bias Normalized to PBL Height



HI

CA

PBLH increase from east to west

MAGIC *N*-bias maximum near California, with minimum near center of transect

2D Refractivity Model & Asymmetry Index (AI) - Inhomogeneity

- Cross section total refractivity (CSTR)

$$CSTR(lon,h) = \int_{LBT}^{RBT} N(h_i)ds = \int_{LBT}^{MPT} N(h_i)ds + \int_{MPT}^{RBT} N(h_i)ds$$

- Cross section asymmetry (CSA)

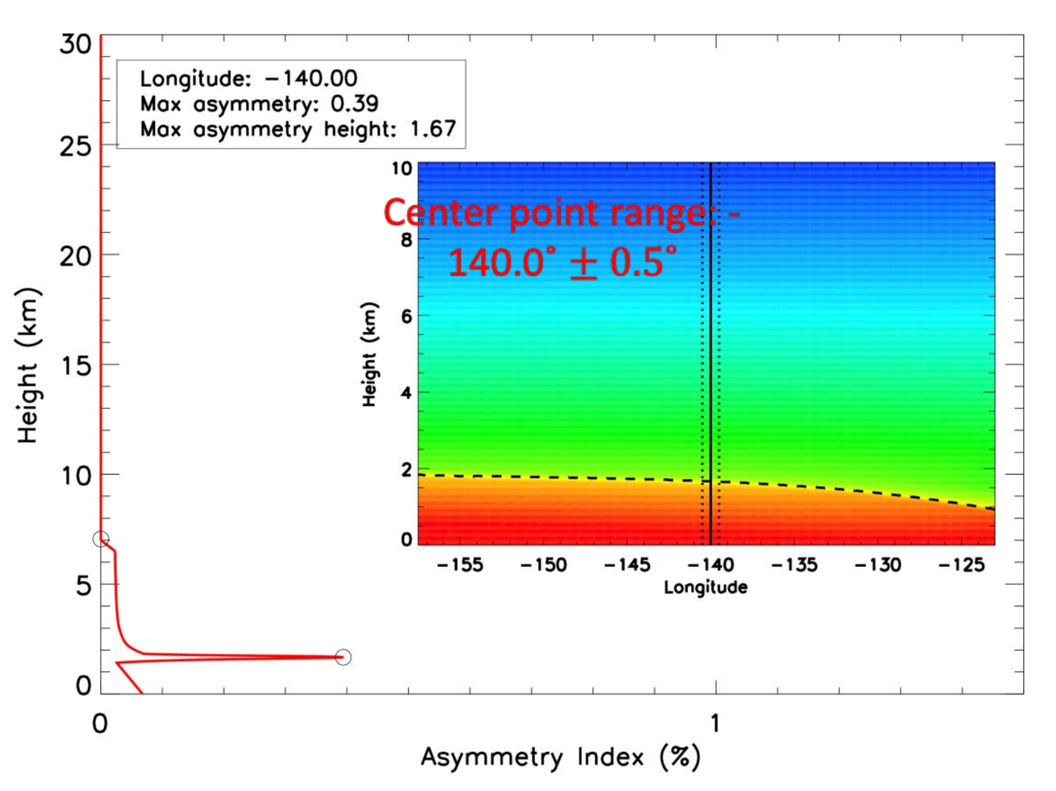
$$CSA(lon,h) = \left| \int_{LBT}^{MPT} N(h_i)ds - \int_{MPT}^{RBT} N(h_i)ds \right|$$

- Cross section asymmetry index (CSAI)

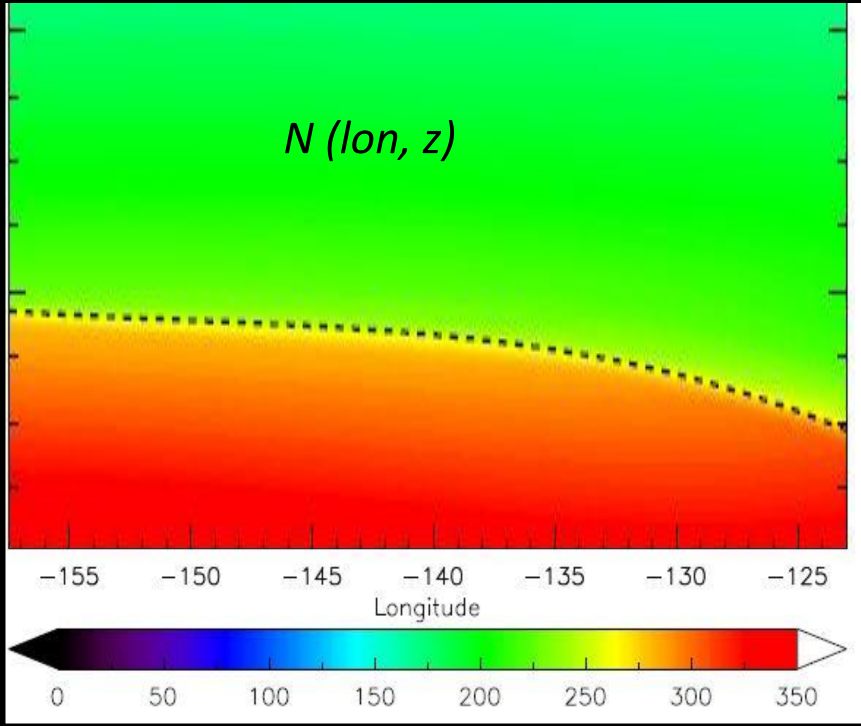
$$CSAI = \left(\frac{CSA}{CSTR} \right) 10^2$$

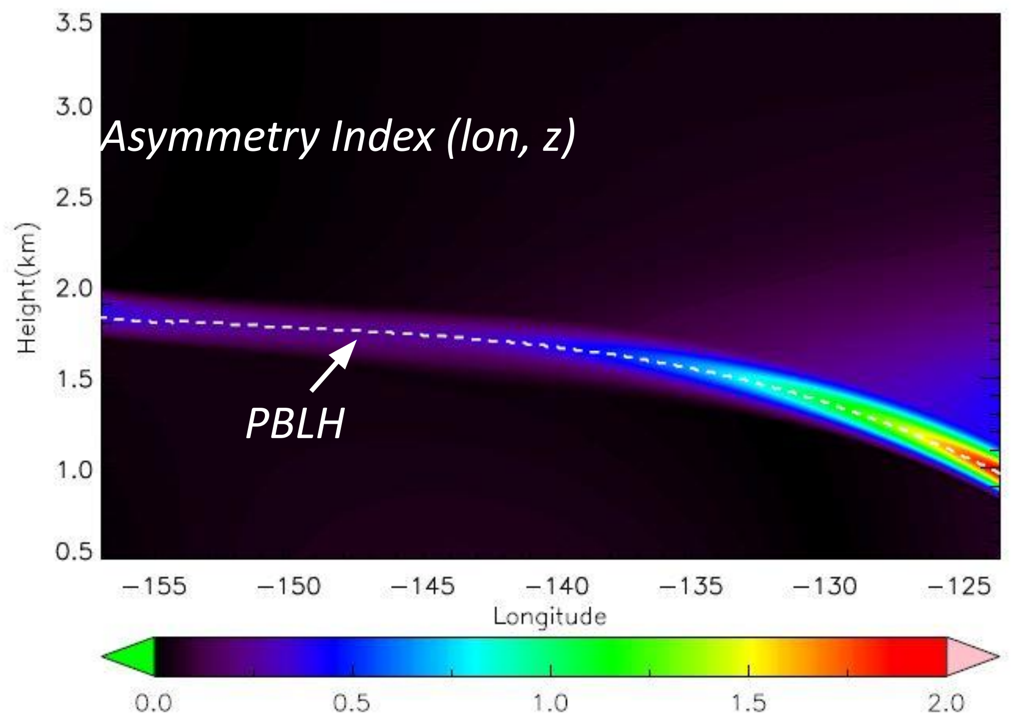
  - where: $0 \leq CSAI \leq 10$

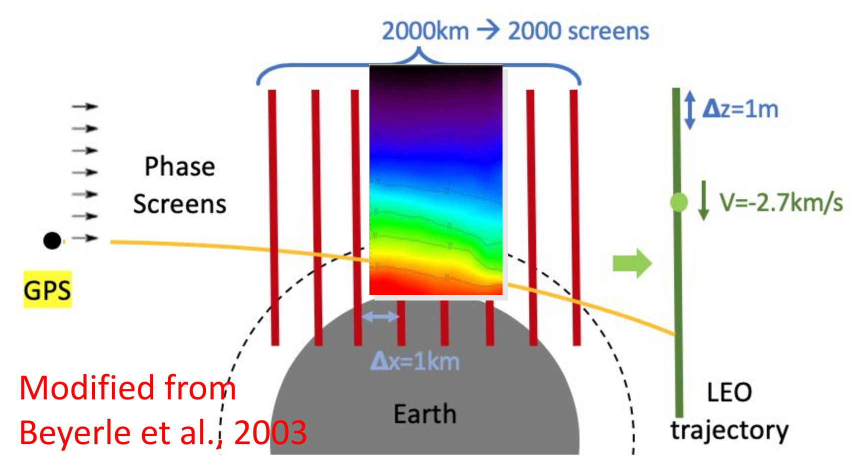
- Determine asymmetry at a location by calculating along an equidistant area from a defined center point. (*Adapted from Shaikh et al., 2014*)



2-D PBL Asymmetry & MPS Simulation



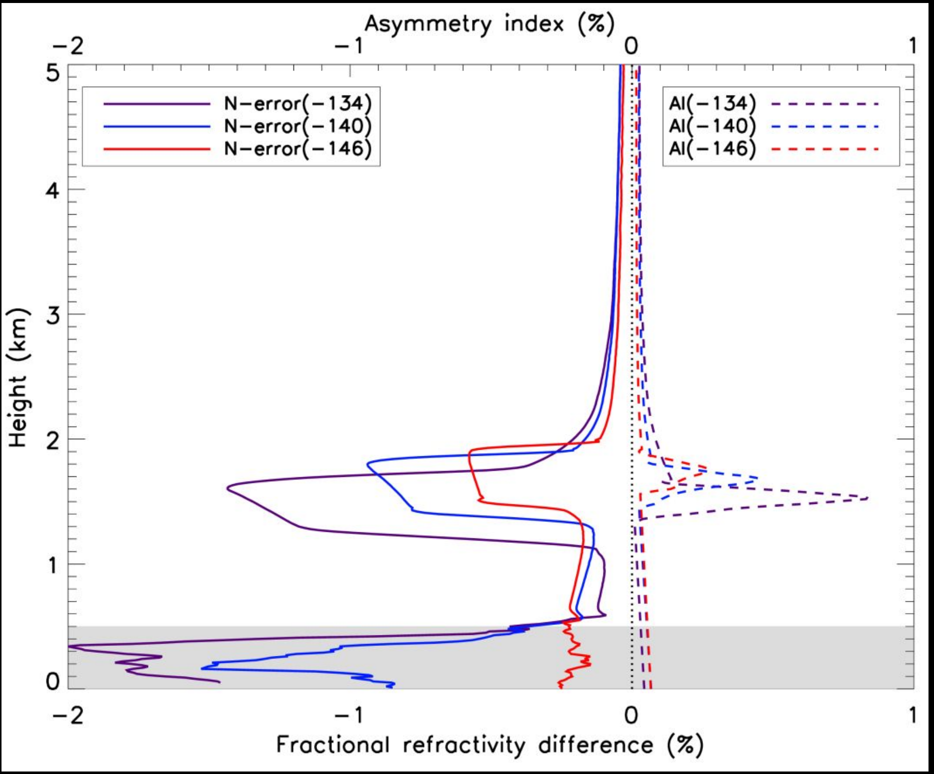


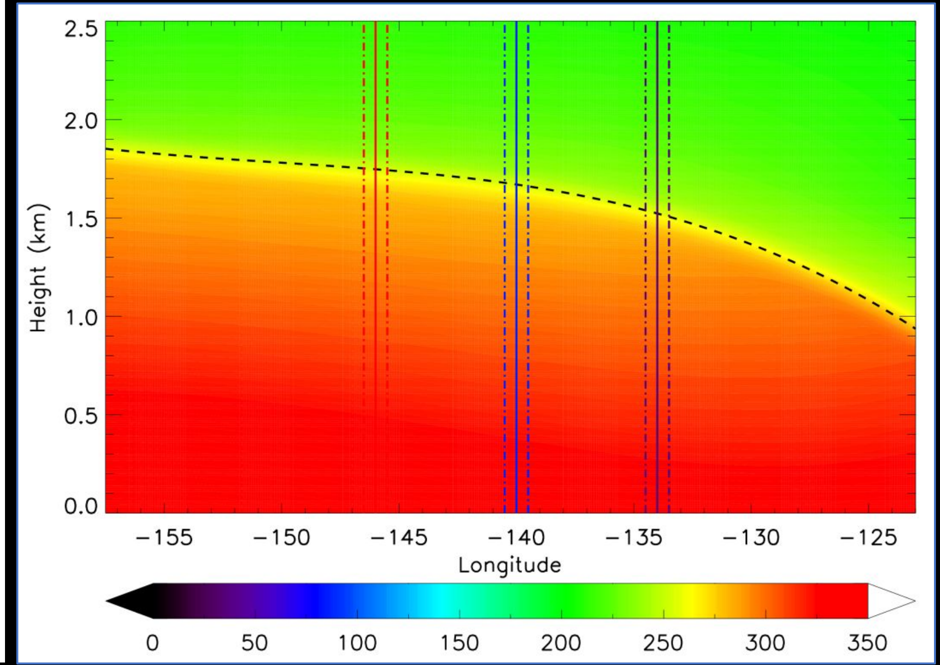


Multiple Phase Screen (MPS) Simulation

Center longitude: -140˚
Longitude range: x=-1000 to x=1000
corresponding to x= -150˚ to x= -130˚
Screen interval (Δx): 1 km
Total number of screens: 2000
Vertical range: -250 m to 60 km

N-bias due to Horizontal Inhomogeneity
(Three case studies with different Asymmetry Index)





- MPS centered at three longitude
- Retrieval error
  - $N_{error} = ((N_{2D}\text{-}N_{1D})/N_{1D})$
- Asymmetry Index
  - *AI(-140˚) = 0.45% at 1.67 km*

Center longitude	Maximum Asymmetry Index	Maximum *N*-bias due to horizontal inhomogeneity
-134˚	0.83%	-1.43%
-140˚	0.45%	-0.94%
-146˚	0.27%	-0.60%

Conclusions and Future Works

- COSMIC-I/II GNSS RO soundings show large *N*-biases in the moist lower troposphere, clustering over the subtropical eastern oceans, which are mainly caused by ducting.
- The PBLH increases from ~1 km near the South California coast to ~2 km in Hawaii. Such strong horizontal inhomogeneity over the NE Pacific are observed from both in-situ radiosonde and RO observations.
- Preliminary simulation shows extra negative refractivity biases (up to about -1.5%) are caused by the PBL horizontal inhomogeneity.
- Potential usage of independent constraints (e.g., MODIS/GOES CTT, AMSR-E PW, and Grazing RO reflections) will allow the maximum benefit of reconstructing RO refractivity inside PBL.
- The higher SNR RO receivers (e.g., COSMIC-II, PlanetiQ etc.) offer opportunity for ducting detection through the deep signals but will still require further studies.
- The sensitivity analysis of RO refractivity reconstruction method and the accuracy of the independent physical constraints & derived reconstruction profiles warrant further attentions.

Acknowledgements

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- The ERA5/ERA-I reanalysis data were acquired from ECMWF. The MAGIC radiosonde data were provided by the Atmospheric Radiation Measurement program (ARM) Climate Research Facility sponsored by the U.S. Department of Energy (DOE). MOIDS data were obtained from GSFC LAADS Distributed Active Archive Center (DAAC).

Motivated MS/PhD Students needed, Please contact: Feiqin.Xie@tamucc.edu

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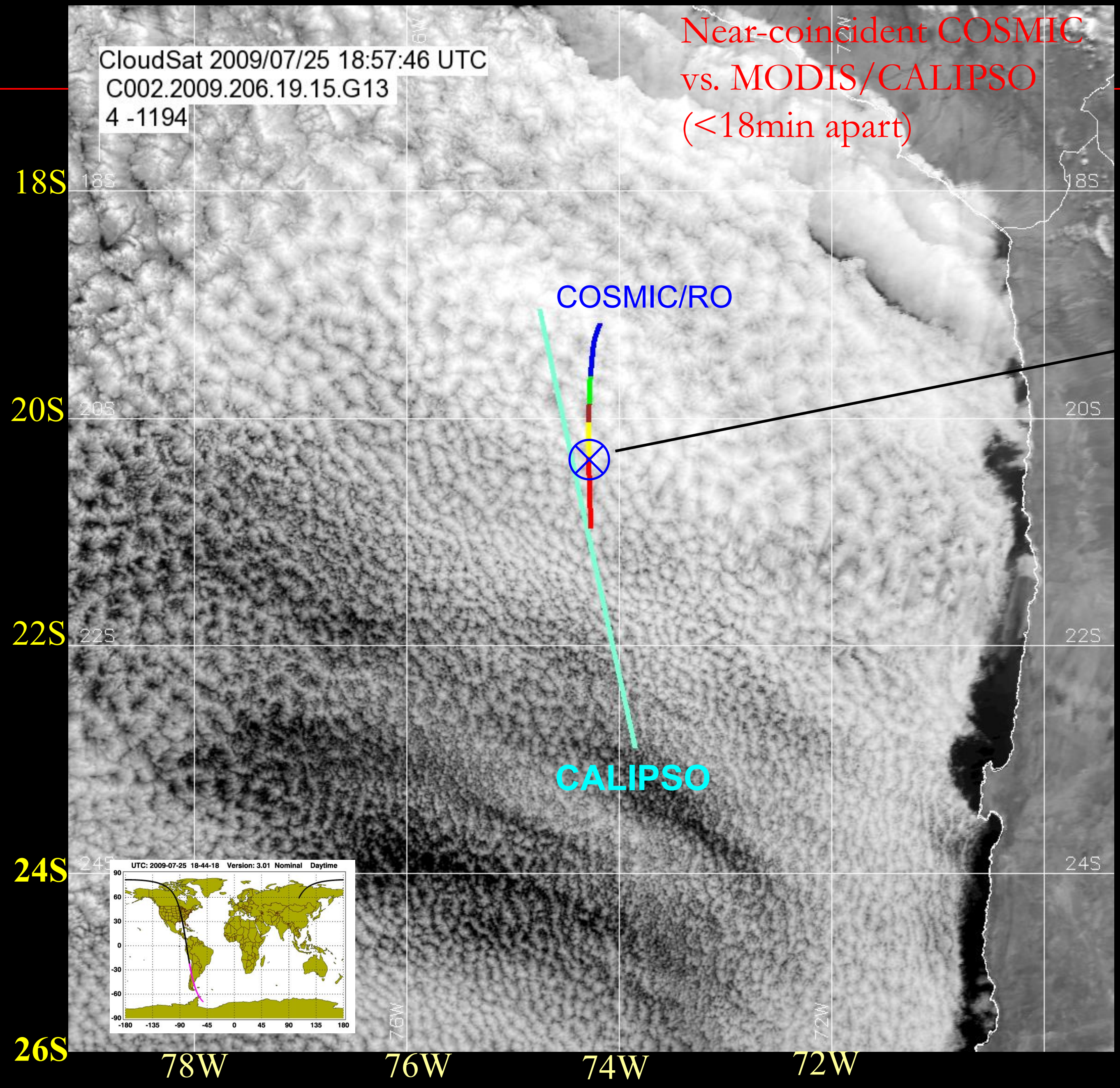
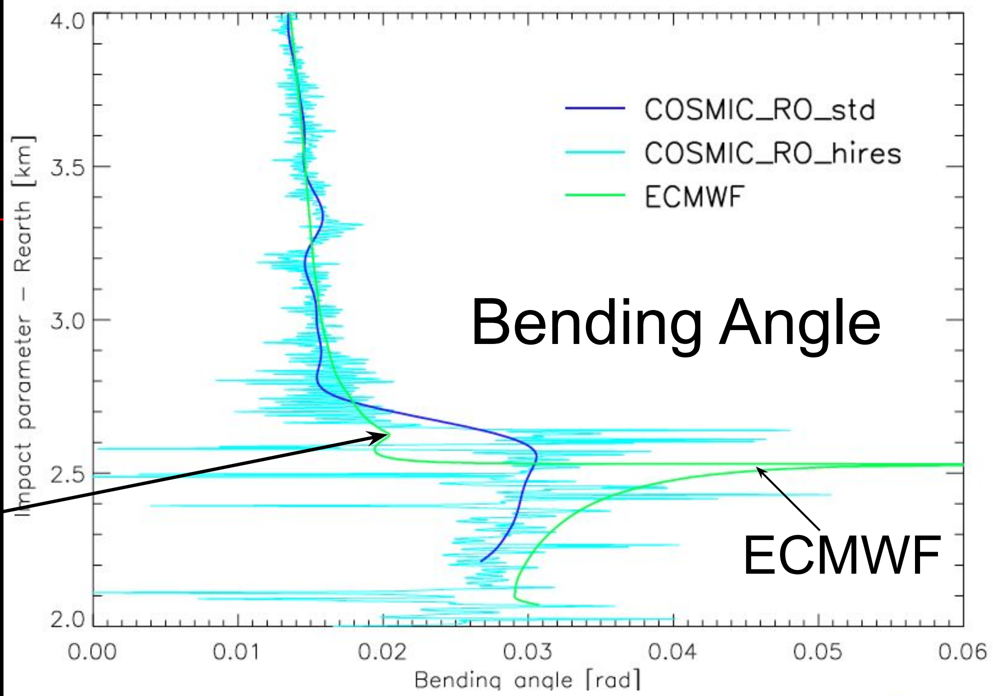
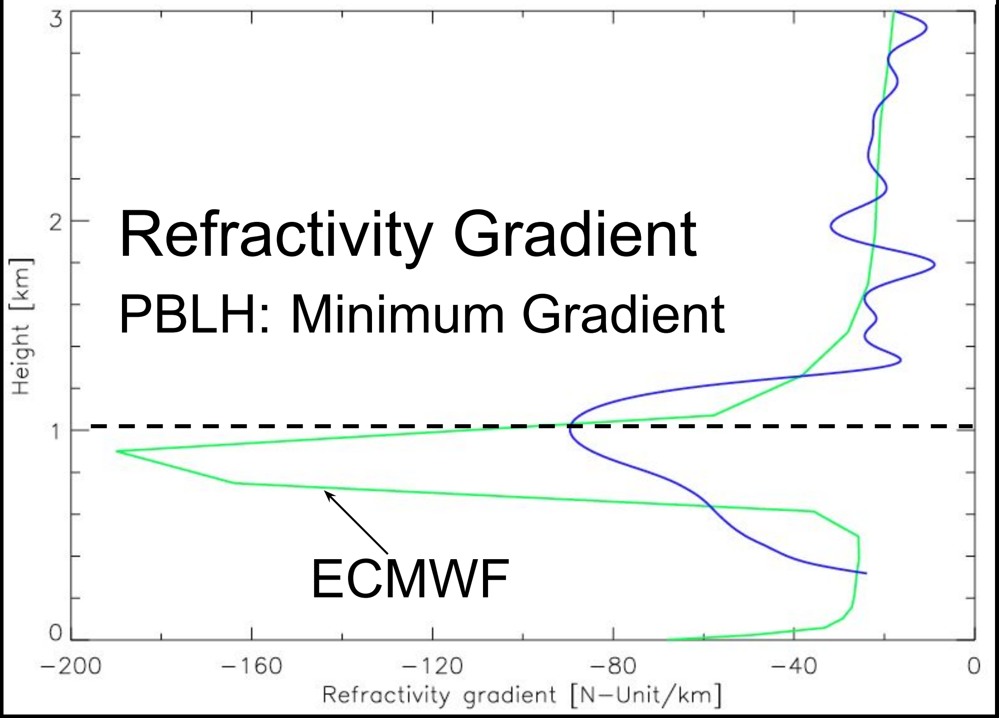
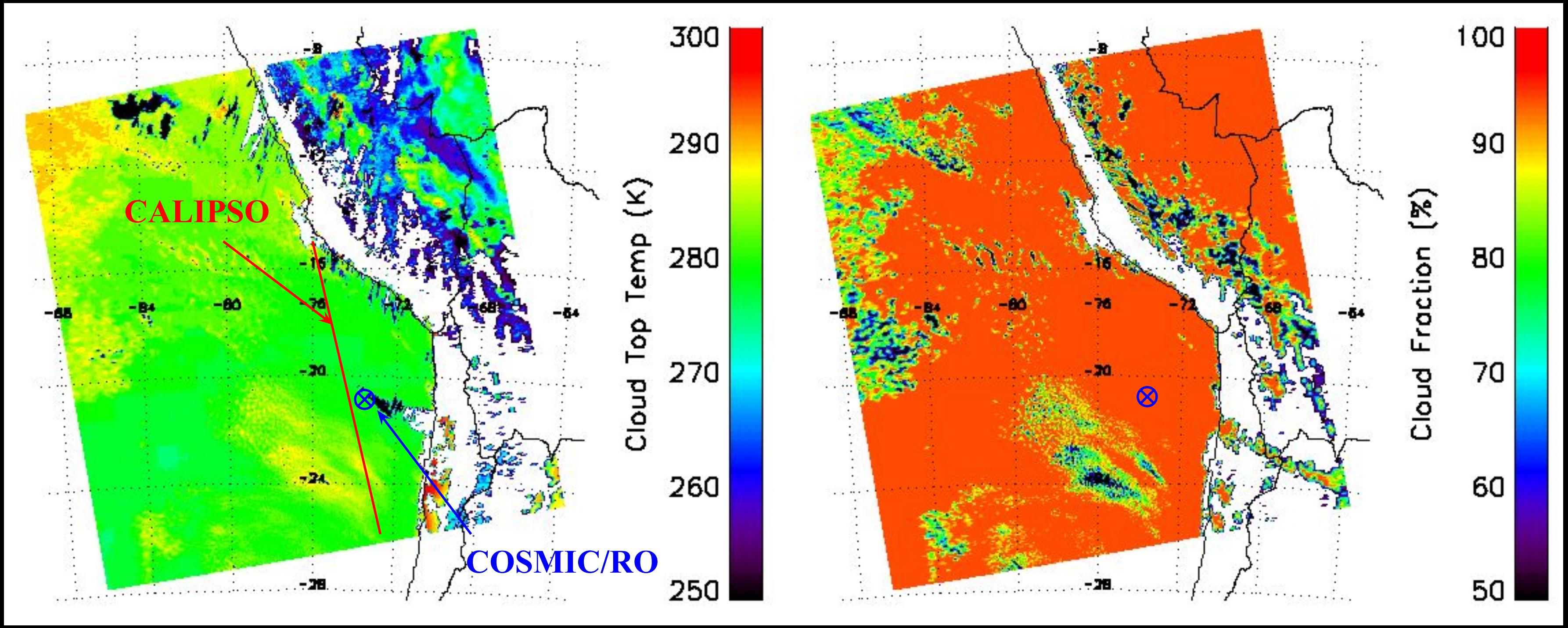
COSMIC vs. MODIS & CALIPSO



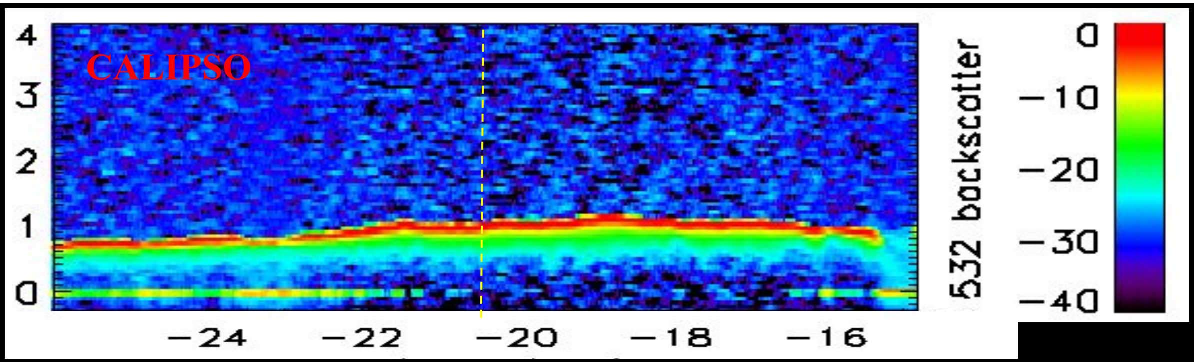




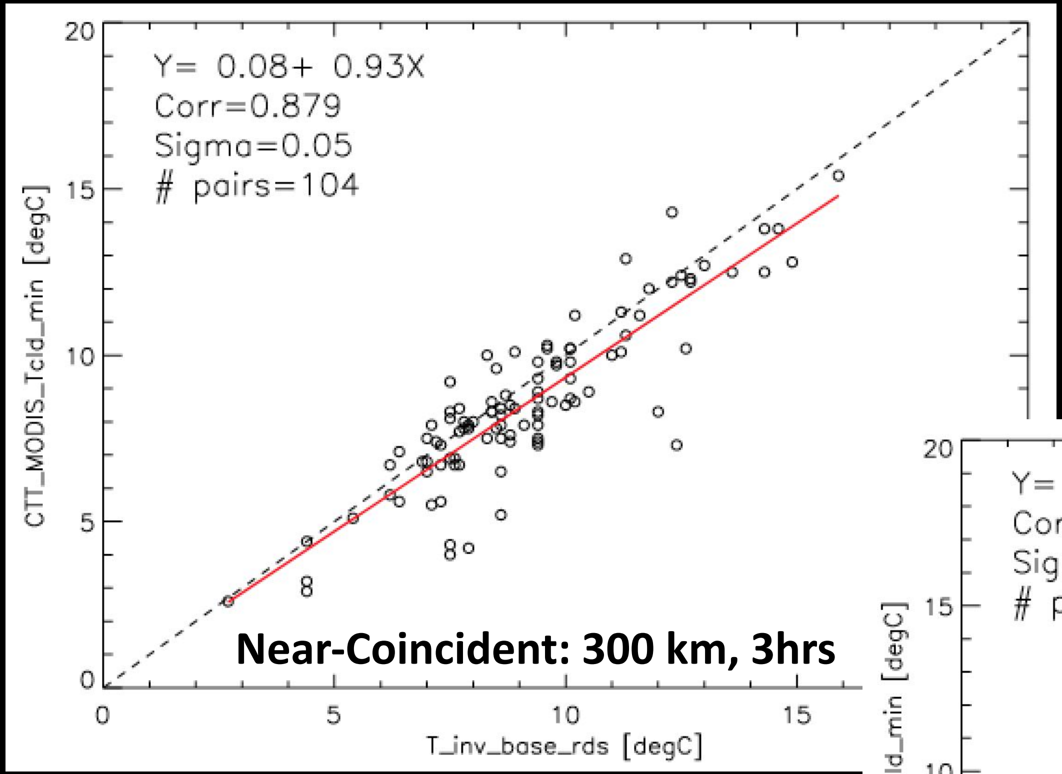
MODIS/CALIPSO Cloud Measurement

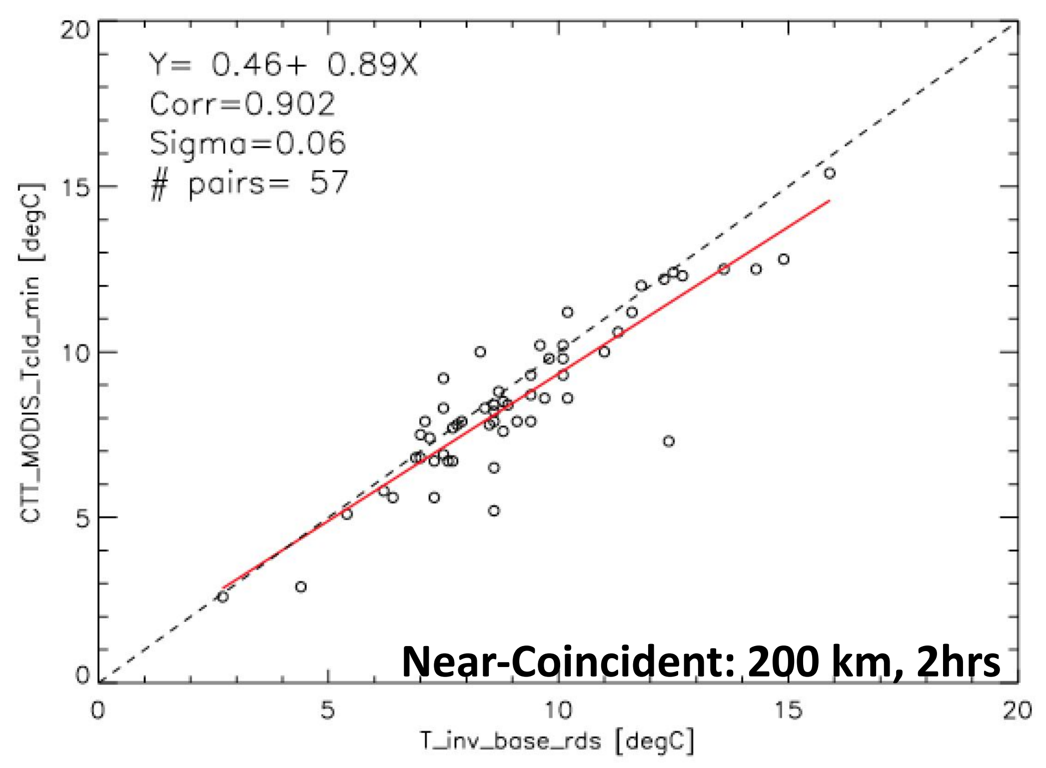


Near-coincident COSMIC vs. CALIPSO (<18min apart)



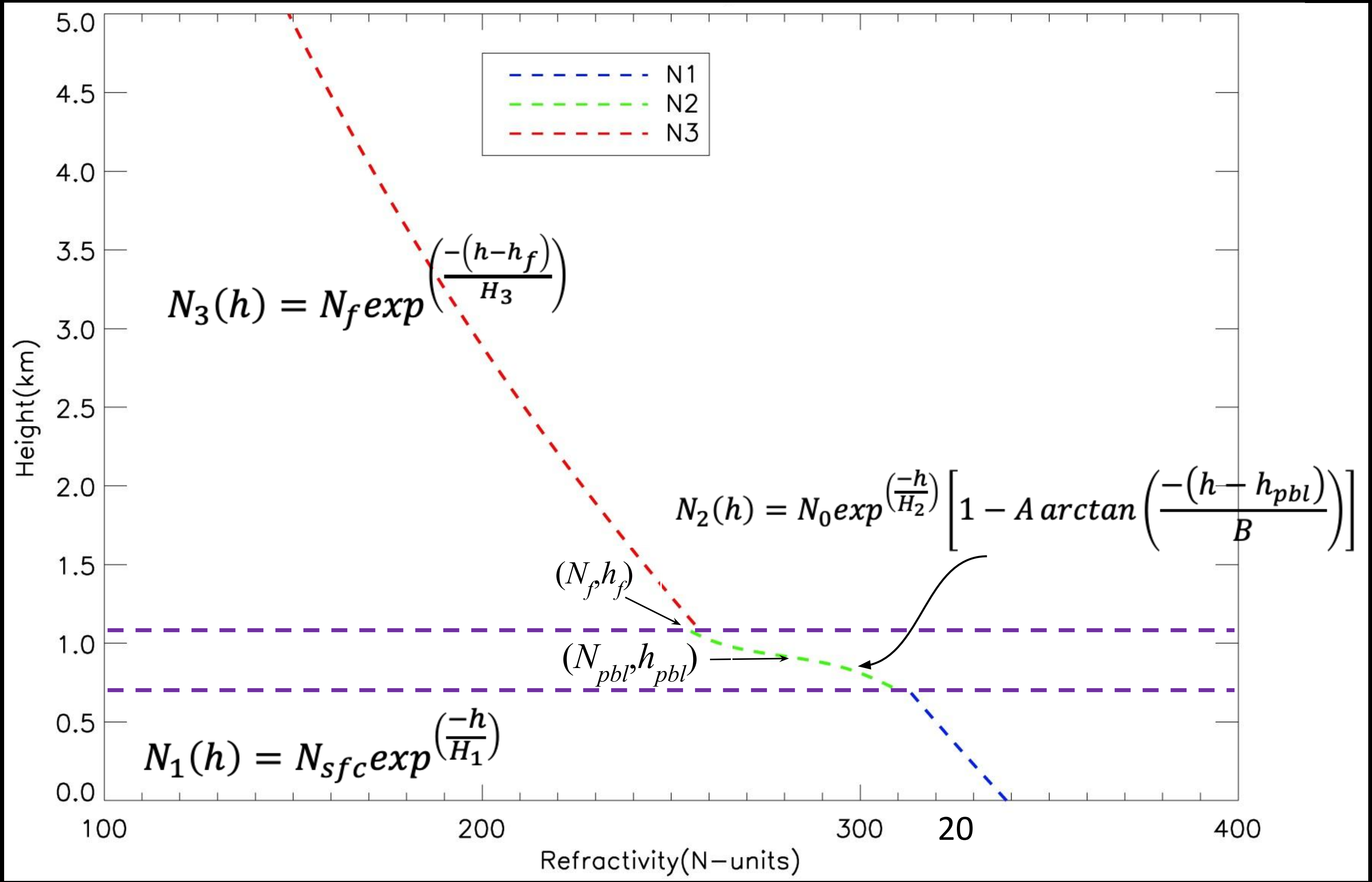
MODIS Cloud Top Temp. vs. Inversion Base Temp. (T_{IVB})



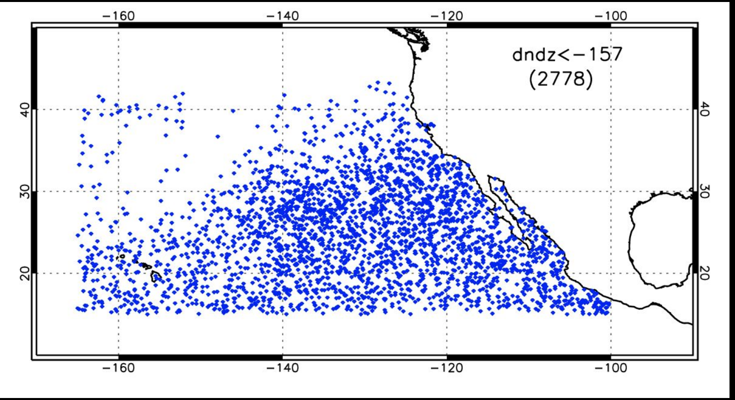


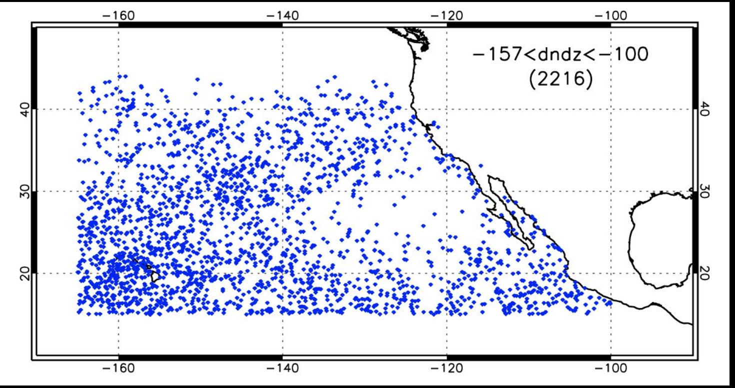
CTT > 0 °C
CF > 90%
CTT_{min} – 5x5 Footprint
Longitude [-118°W, **140°W**]

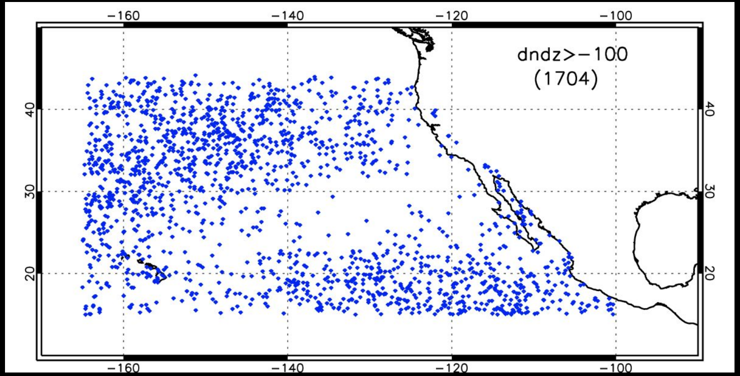
1D Refractivity Model (3-segment)

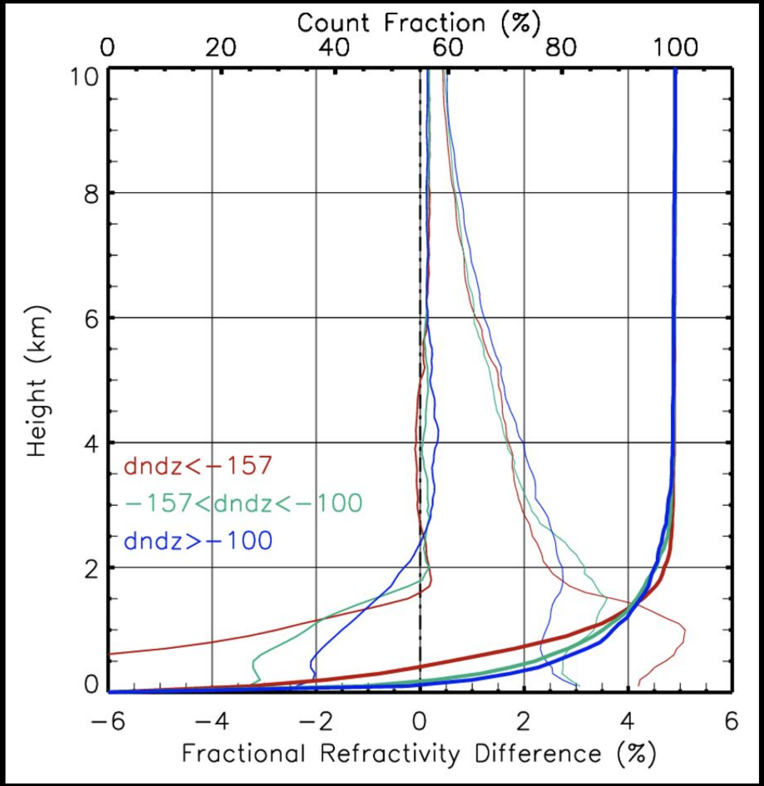


COSMIC-2 Profiles over Northeastern Pacific (July 2023)



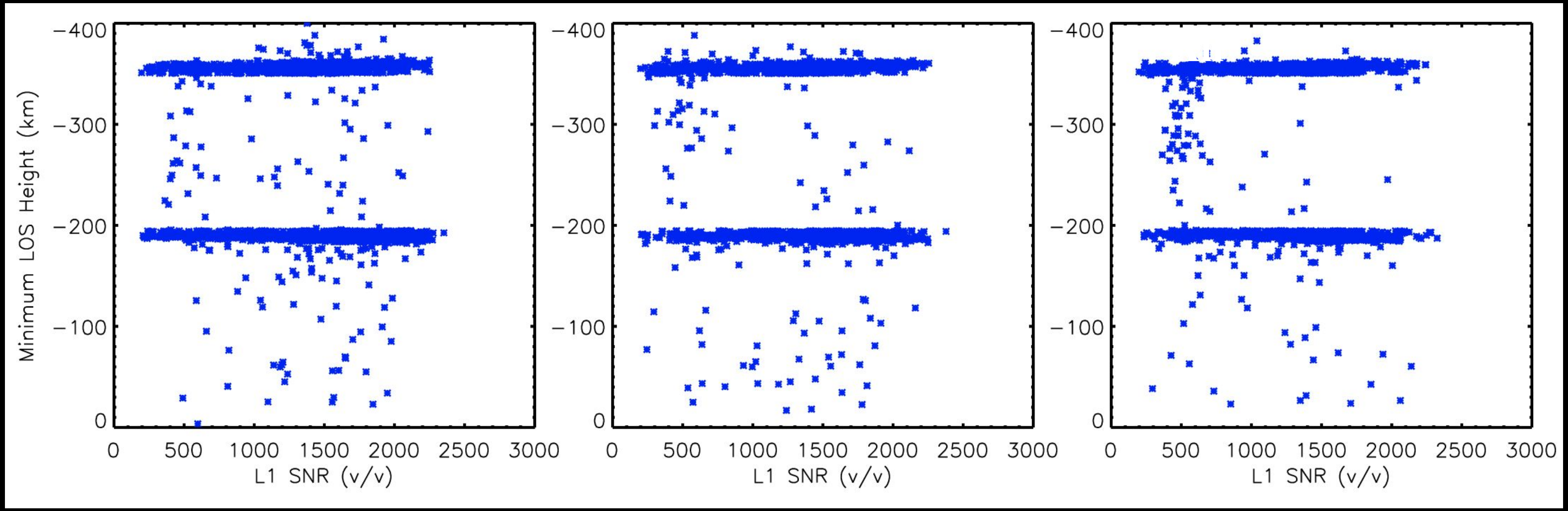


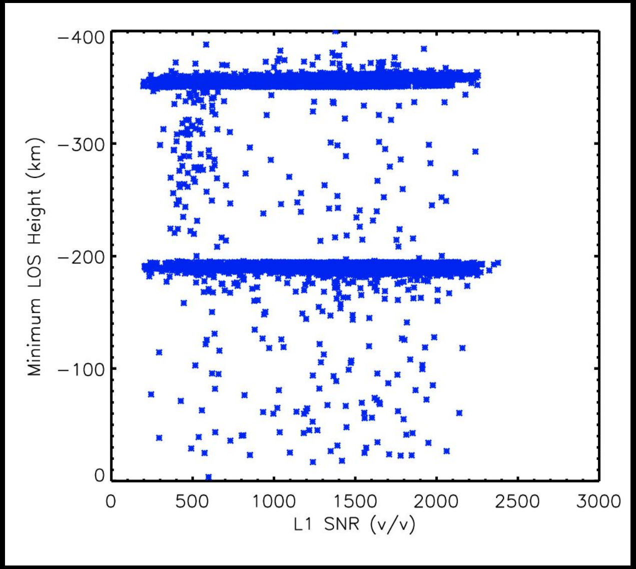




- Region: (160W – 100W, 15N – 45N)
- Colocation between COSMIC2 and ERA-5
- Separated into three group based on the minimum refractivity gradient of the colocated ERA5 refractivity (within 300m – 5000m)

Relationship between ERA-5 dN/dz and COSMIC-2 penetration Depth





dN/dz < -157 **-157<dN/dz < -100** **dN/dz > -100**