Profiling the Boundary Layer and Free Tropospheric Water Vapor with GPS Occultations

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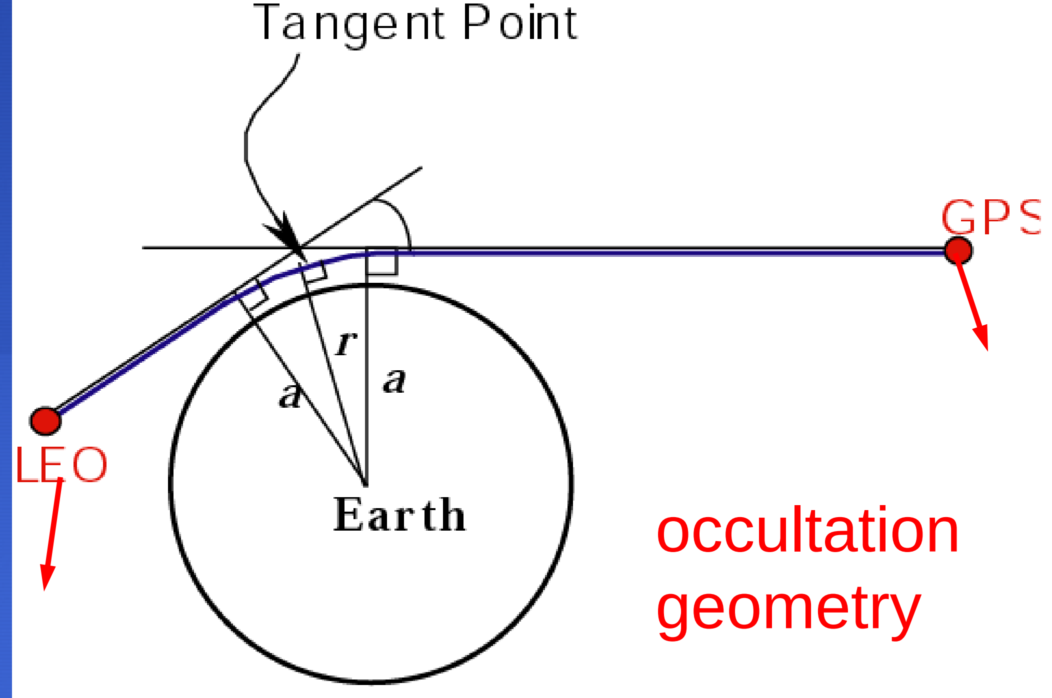
GPS Occultation Summary

- An occultation occurs when the orbital motion of a GPS SV and a Low Earth Orbiter (LEO) causes the LEO 'sees' the GPS rise or set across the limb
- This causes the signal path between the GPS and the LEO to slice through the atmosphere
- Atmosphere acts as a lens bending the signal path



occultation geometry

$$\alpha = \int d\alpha = 2a \int_{r_t}^{\infty} dr \frac{dn}{n\,dr} \frac{1}{\sqrt{n^2 r^2 - a^2}}$$

1D forward relation

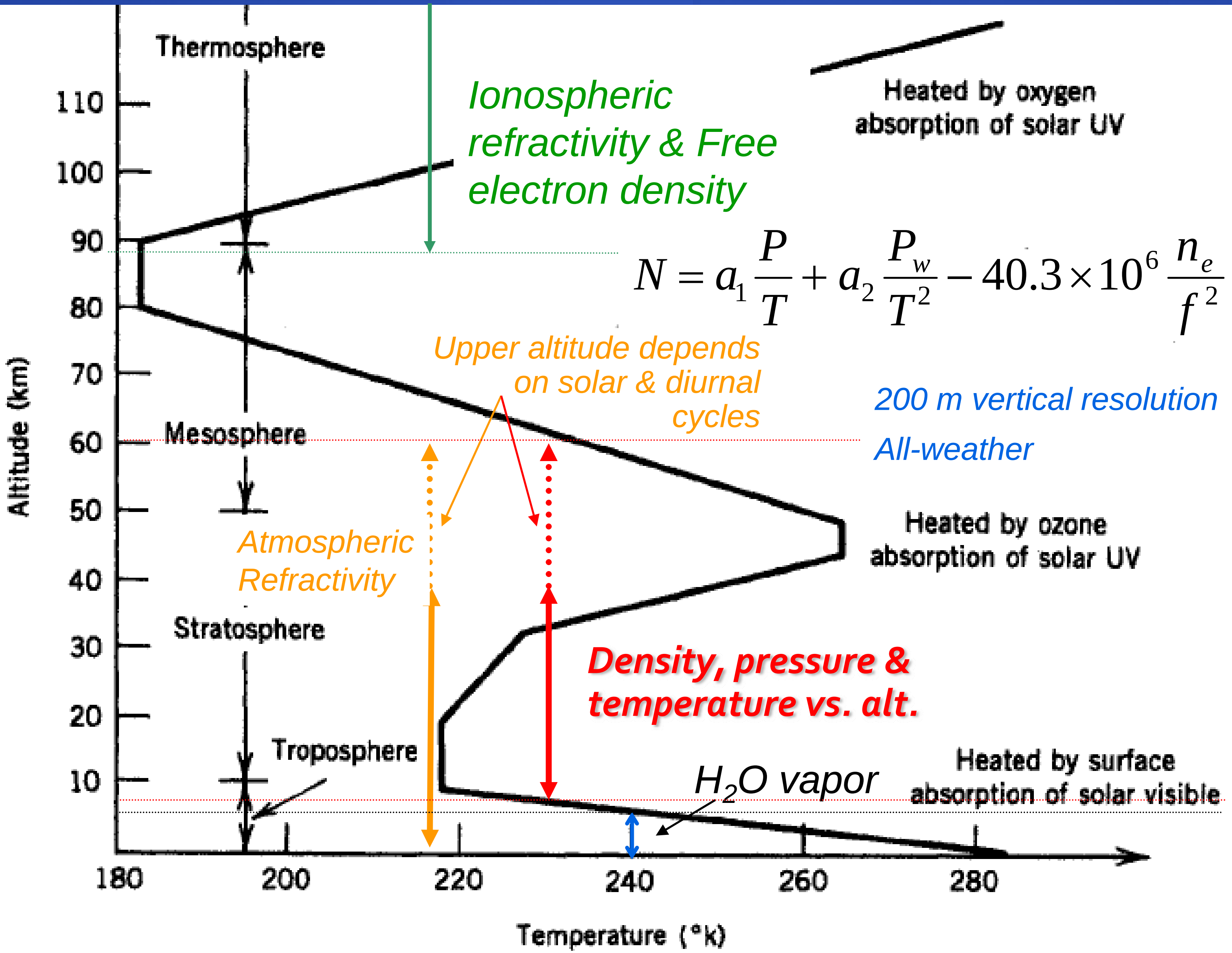
$$n(r_{01}) = \exp\left[-\frac{1}{\pi} \int_{a_1}^{\infty} \frac{\alpha(a)\,da}{\sqrt{a^2 - a_1^2}} \right]$$

1D inverse relation

- **Delay(t)=> bending angle(α) => refractivity(z) where *a=nr***
  - **Dry conditions: => dry density(z) => P(z) => T(z) via hydrostatic eqn**
  - **Wet conditions: refractivity + *T,p,q* (analysis) => better *T,p,q***

or refractivity + *T* (analysis) => water vapor(z)

Information vs. Altitude from GPS RO



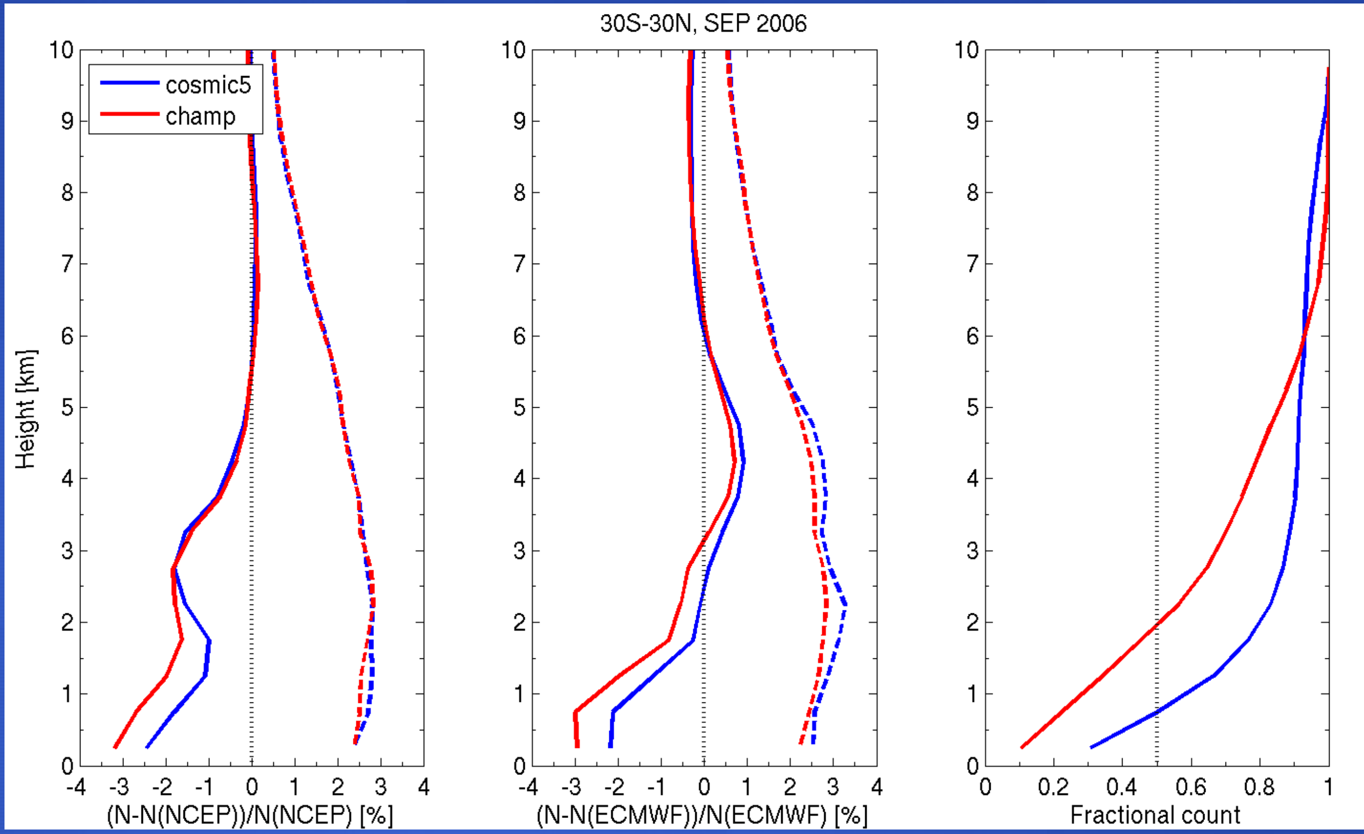
Scope of Data Assimilation Research

- GPS RO already has large impact in upper troposphere/Lower stratosphere
- GPS RO ***should*** have large impact in lower troposphere via water vapor, PBL top, PBL profile and surface pressure

***FOCUS*: improve impact of GPS RO, particularly in the lower troposphere**

- **Two main areas of emphasis**
  - **Develop ability to profile the (marine) boundary layer and assimilate information into NWP system**
    - **Correct for Super-refraction**
      - **Occurs at very sharp PBL top over oceans**
      - **Causes refractivity to be systematically underestimated via normal refractivity retrieval process**
      - **Assimilate refractivity rather than bending angle**
  - **Improve GPS RO error covariance and related quantities**
    - **Create humidity dependent error covariance**
    - **Examine representativeness error**
    - **Improve tropospheric water vapor**

Super-refraction & "Negative N bias"



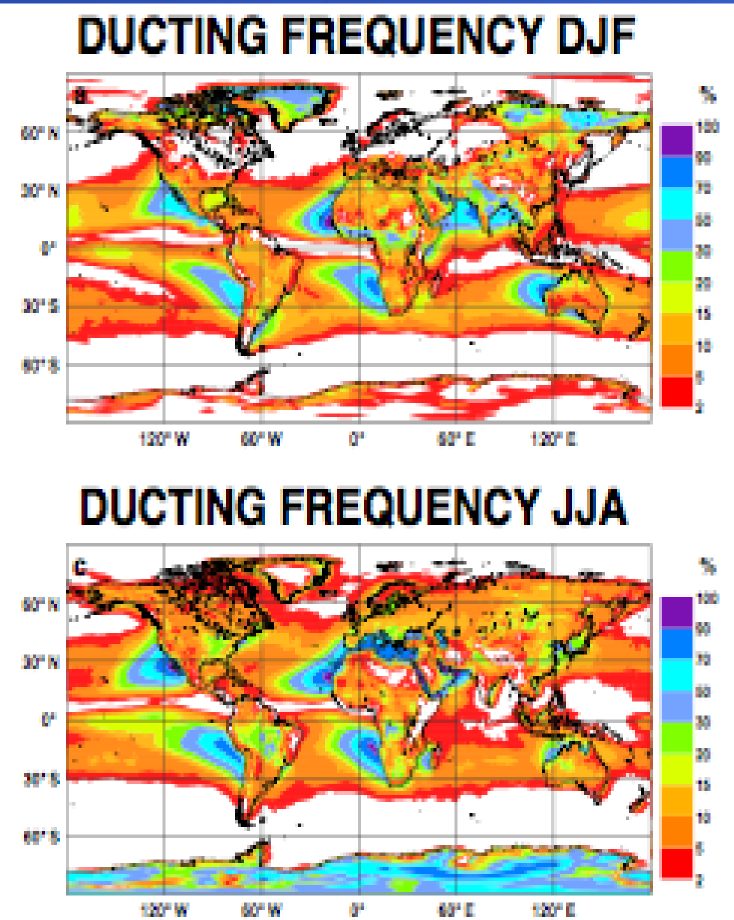
Low latitude, lower troposphere, GPS refractivity tends to be less than analysis

- Due in part to analyses being too moist?
- GPS problems:
  - Receiver tracking improved with "open loop" tracking on COSMIC
  - **Solving the super-refraction problem is a focus of our research**

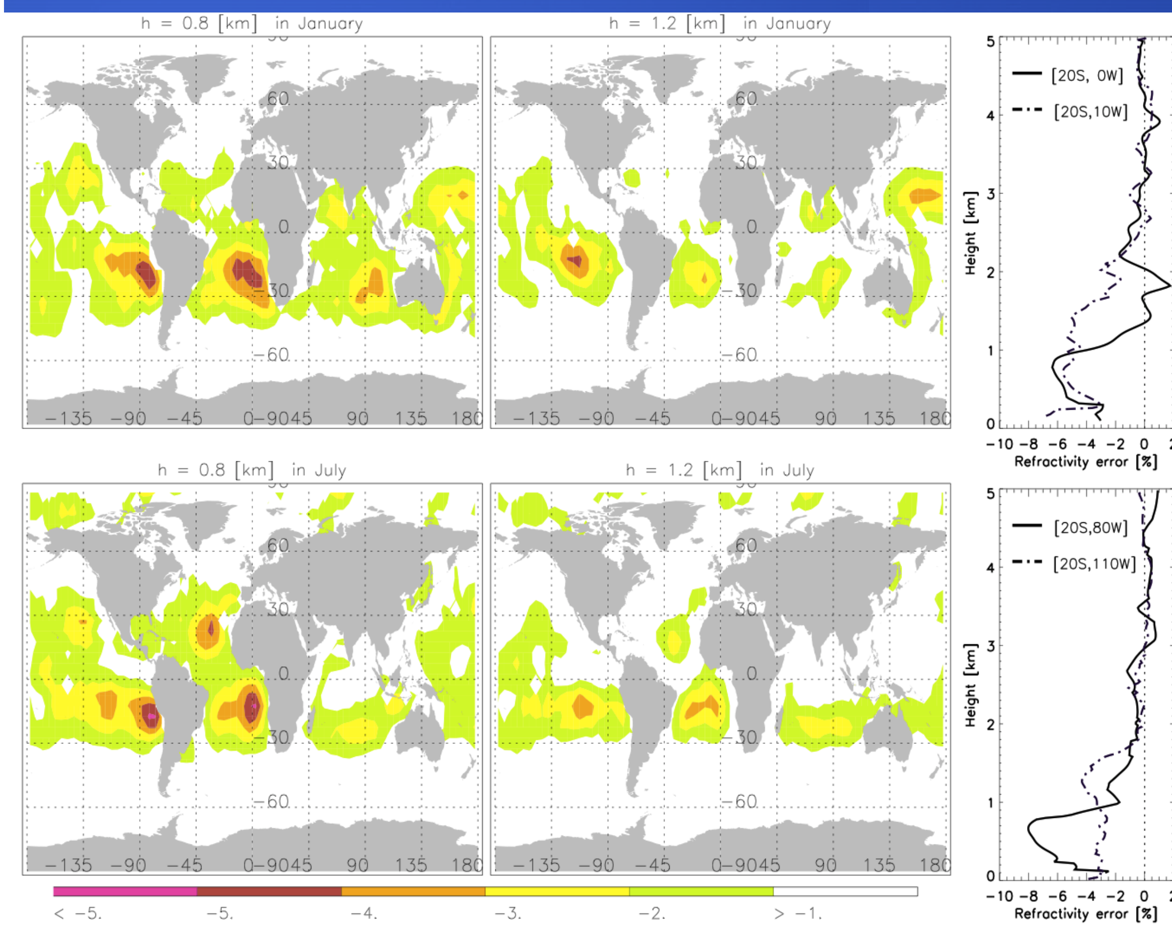
Super-Refraction and Negative N-bias

- Occurs with very high vertical gradient of water vapor across PBL top
- Causes raypath radius of curvature to be smaller than radius of Earth
- Result is no tangent raypath over a set of altitudes: "shadow interval"

Lopez, 2008, ECMWF Tech Memo 549



Xie, et al. (2010) GRL



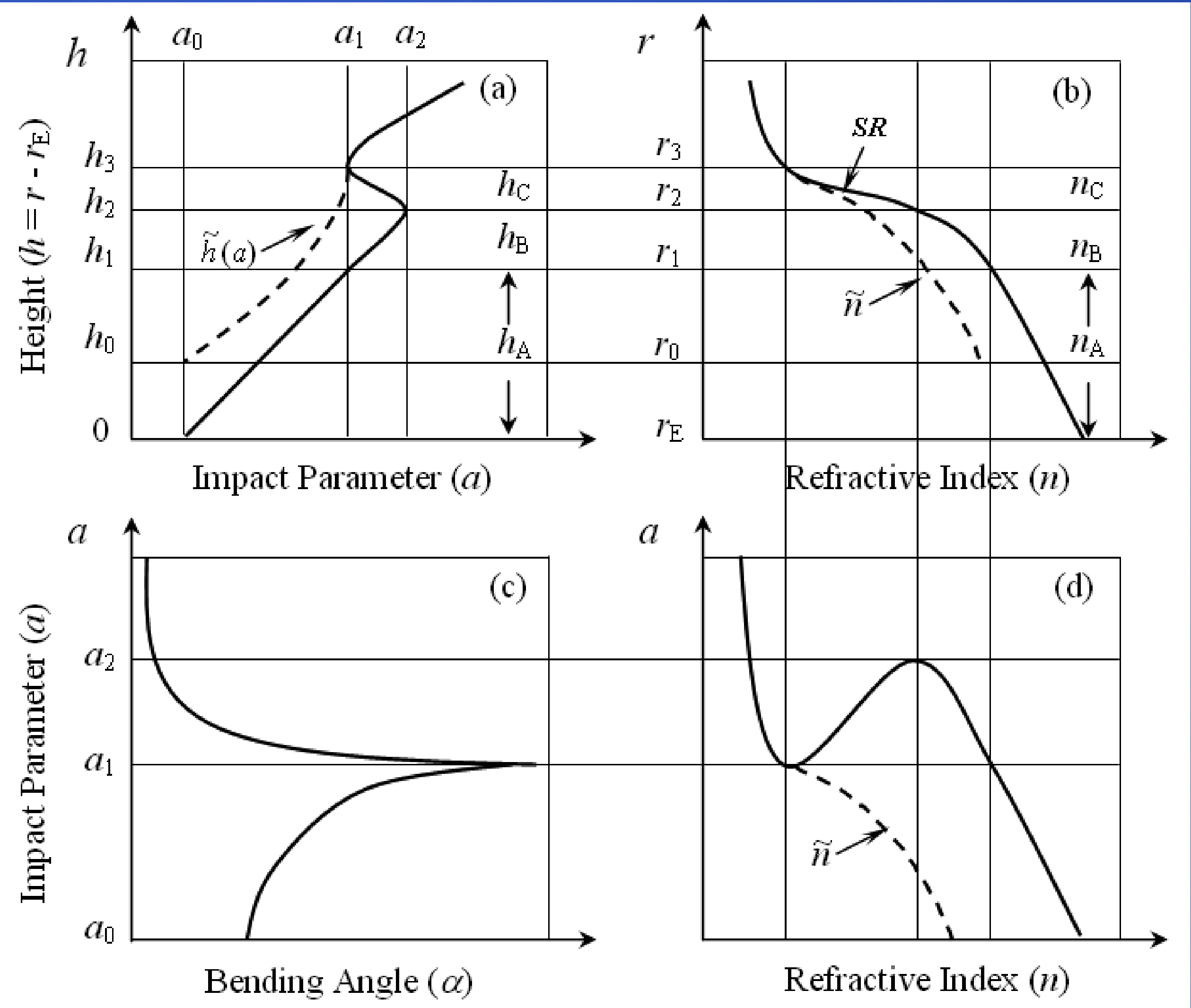
Super-Refractive Boundary Layer Profiling

- Super-refractivity creates a non-uniqueness problem
- Parameterize behavior in the "shadow interval"
- Yields continuum of refractivity profiles consistent with observed bending angle profile
- Use additional external constraint to select the best refractivity profile from the continuum of solutions

Super-Refraction: Non-uniqueness Problem

$$\alpha = \int d\alpha = 2a\int_{r_t}^{\infty} dr \frac{dn}{n\,dr}\frac{1}{\sqrt{n^2r^2 - a^2}}$$

- Large dN/dz creates interval in which *a=nr* decreases with height
- Shadow/ducting interval where no ray can have a tangent point
- 2 refractivity profiles produce identical bending angle profile Sokolovskiy (2003)

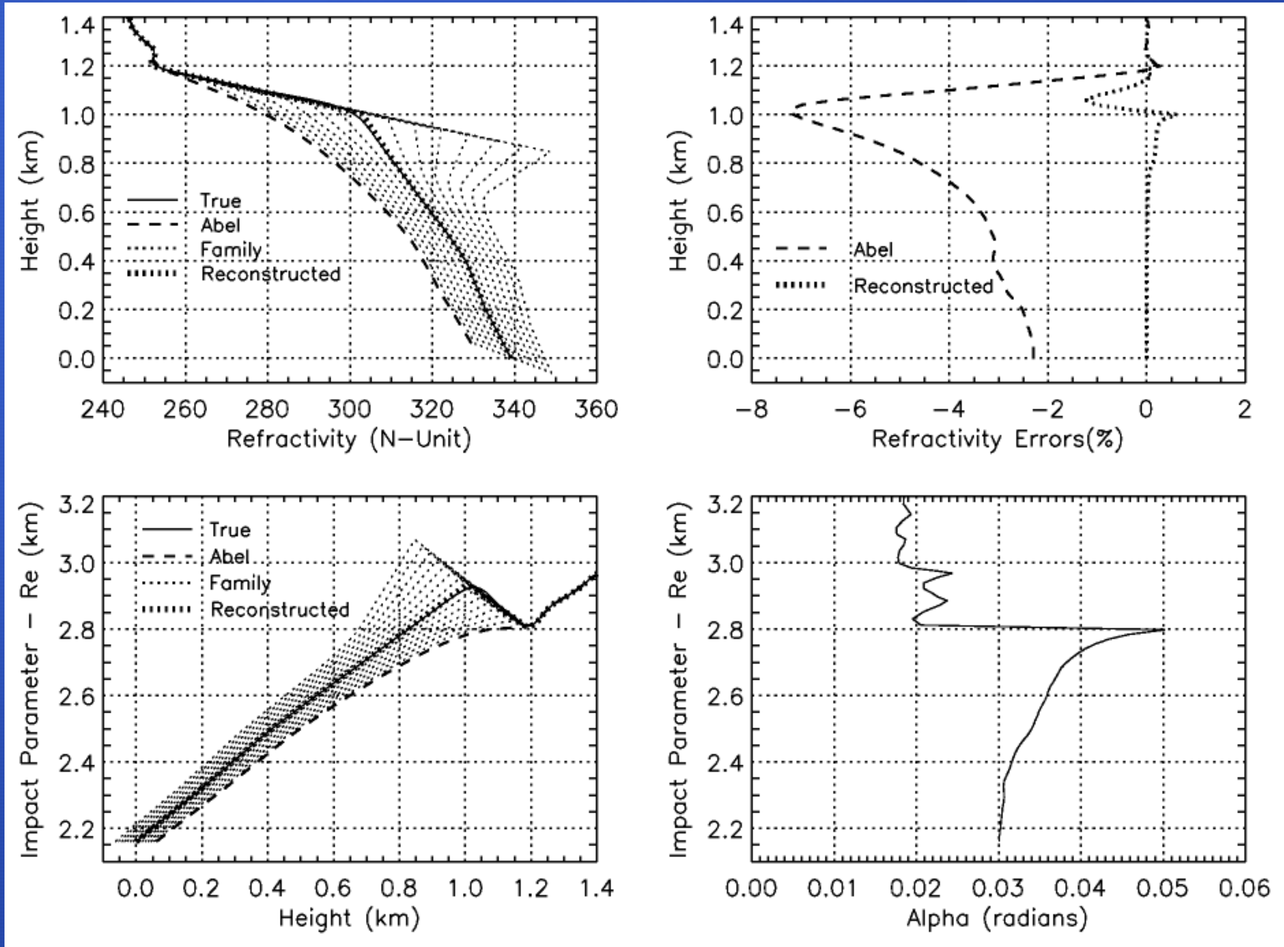


Super-Refraction Solution

- Xie et al. (2006) showed a continuum of refractivity solutions exists
- Developed parameterization: Assume impact parameter vs. height in "shadow region" can be represented by 2 linear segments
- Generate a continuum of refractivity profile solutions consistent with bending angle and Abel refractivity profiles

Then select "best" profile in the continuum and its uncertainty

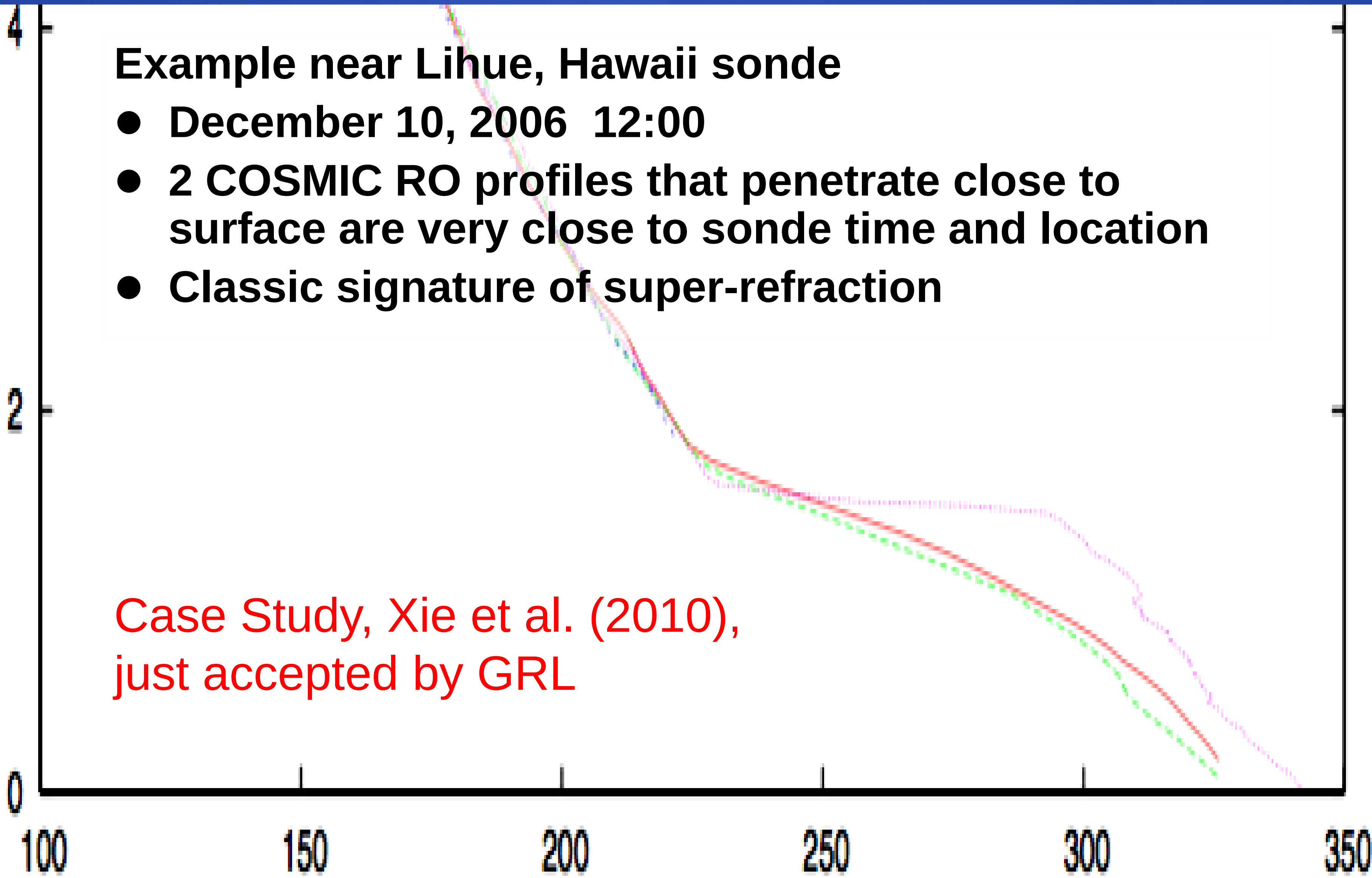
This requires external Information, e.g.:
- Surface refractivity
- Column water vapor
- Error covariance
- etc. ....



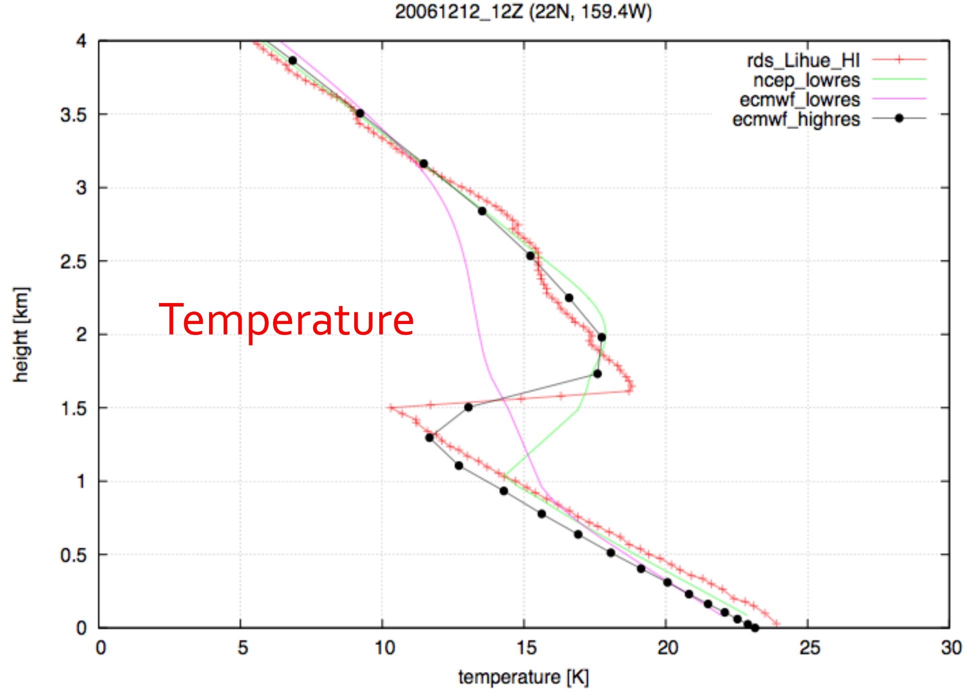
Case Study: Observed Super-Refraction

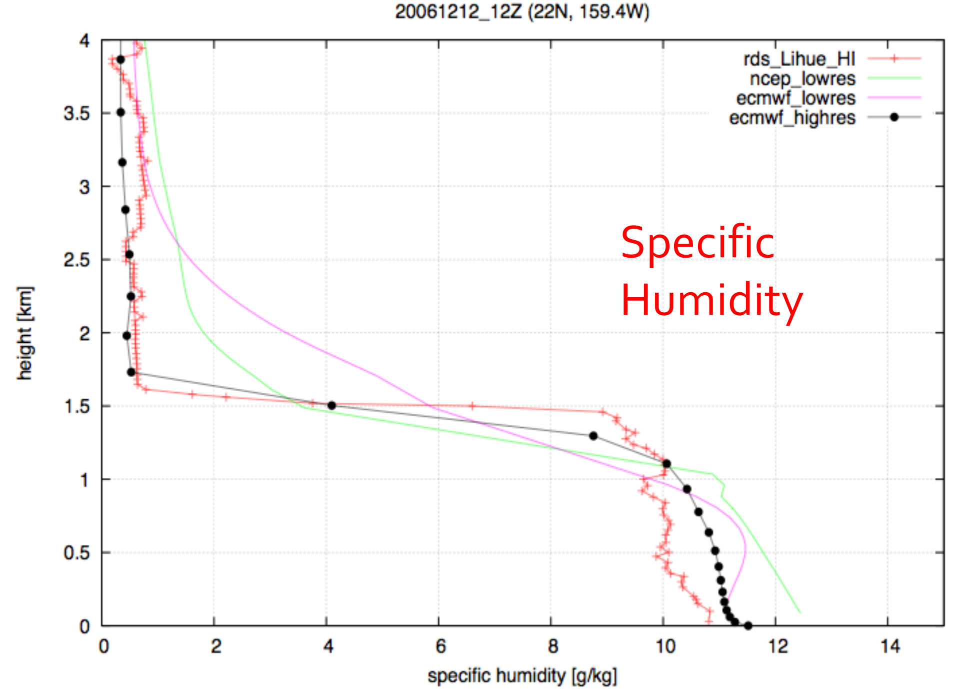
Example near Lihue, Hawaii sonde

- December 10, 2006 12:00
- 2 COSMIC RO profiles that penetrate close to surface are very close to sonde time and location
- Classic signature of super-refraction



Case Study, Xie et al. (2010),
just accepted by GRL

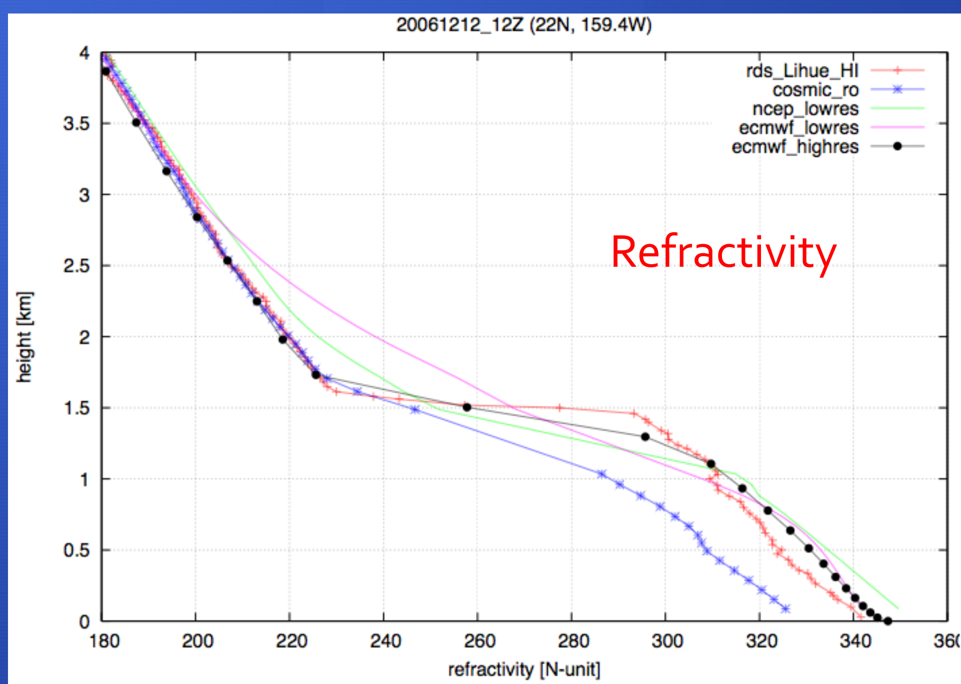




Profile Summary

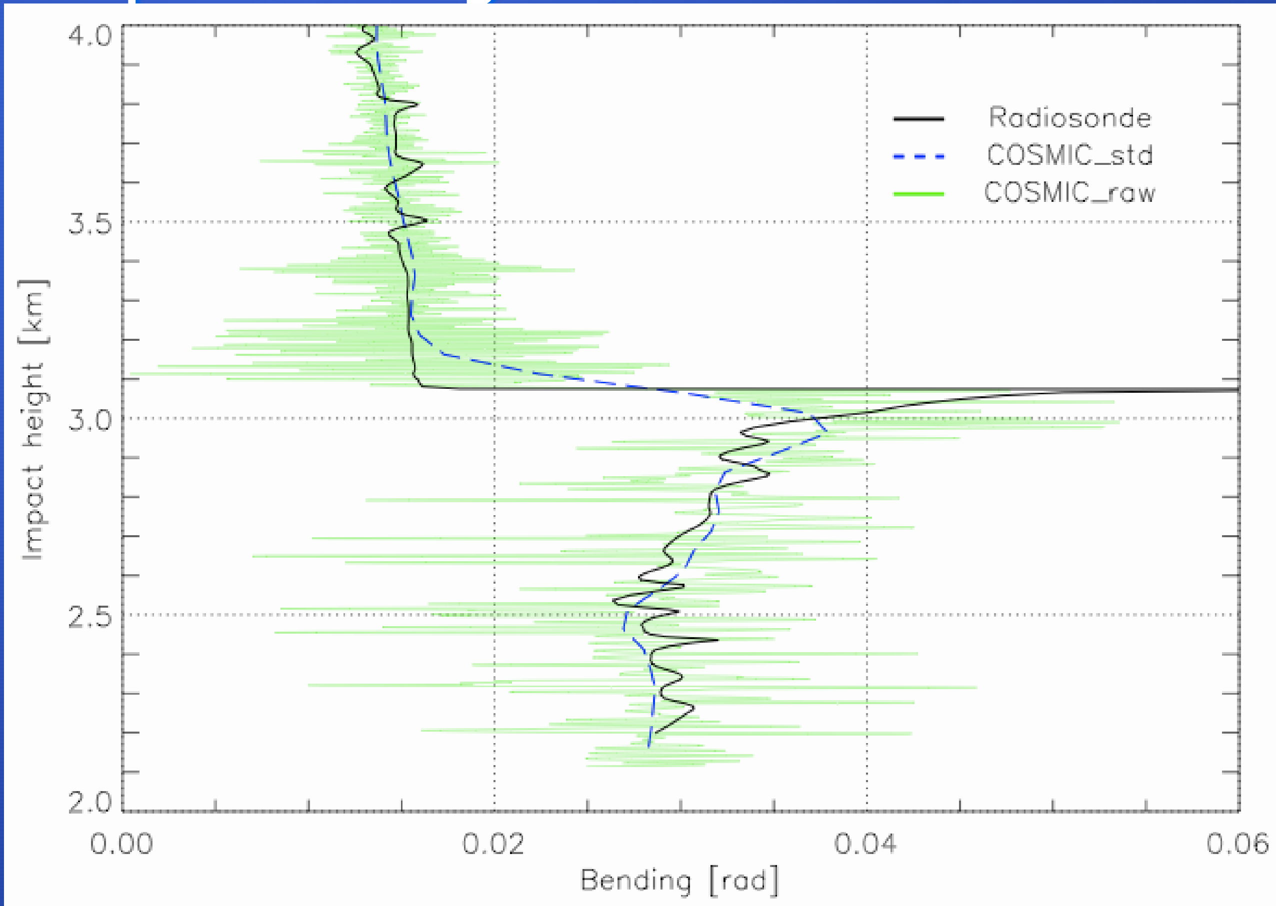
- Very strong thermal inversion
- Very low humidity above PBL
- Large super-refraction effect
- RH < 100%,
  - No cloud in sonde profile

JCSDA-Kursinski



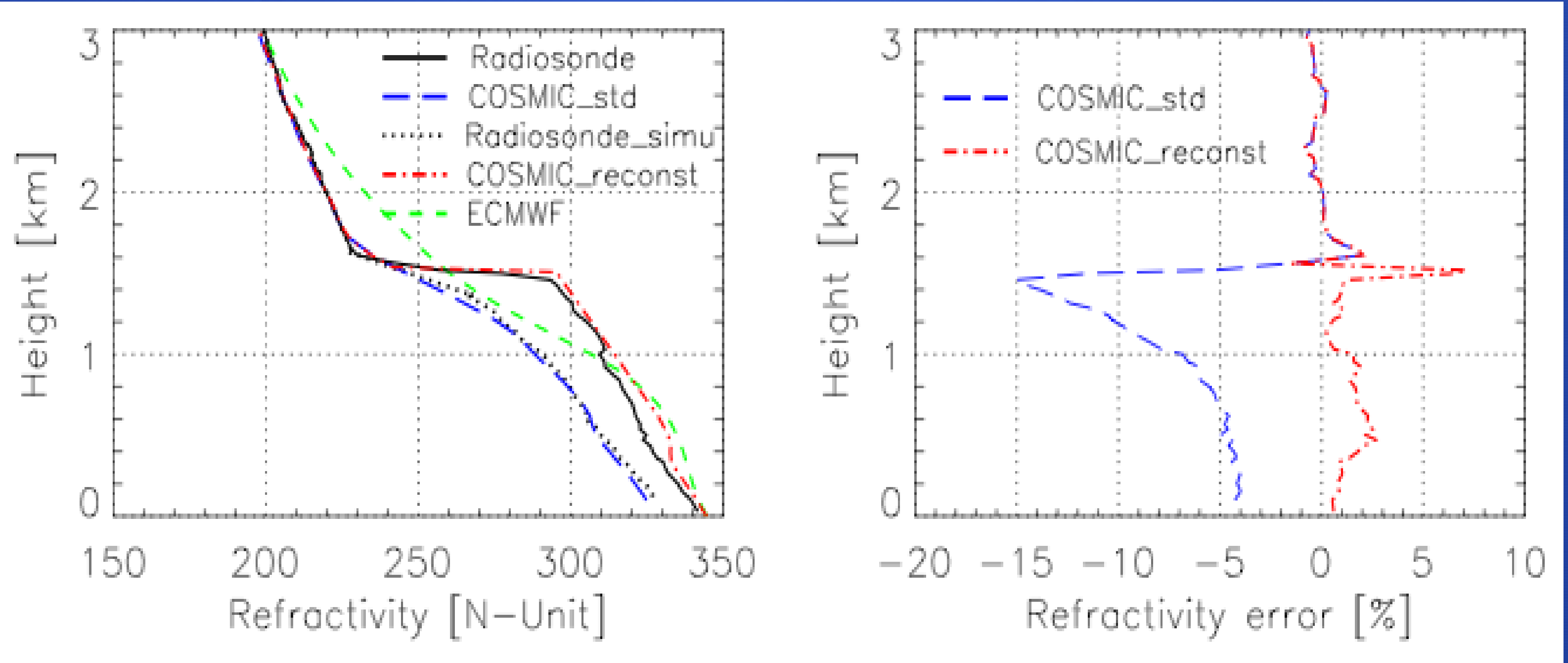
Vertical Resolution of GPS RO

- RO top of boundary layer agrees within few meters of sonde
- Very good news because reconstruction method is very sensitive to height of PBL top
- Issues with altitude of peak bending



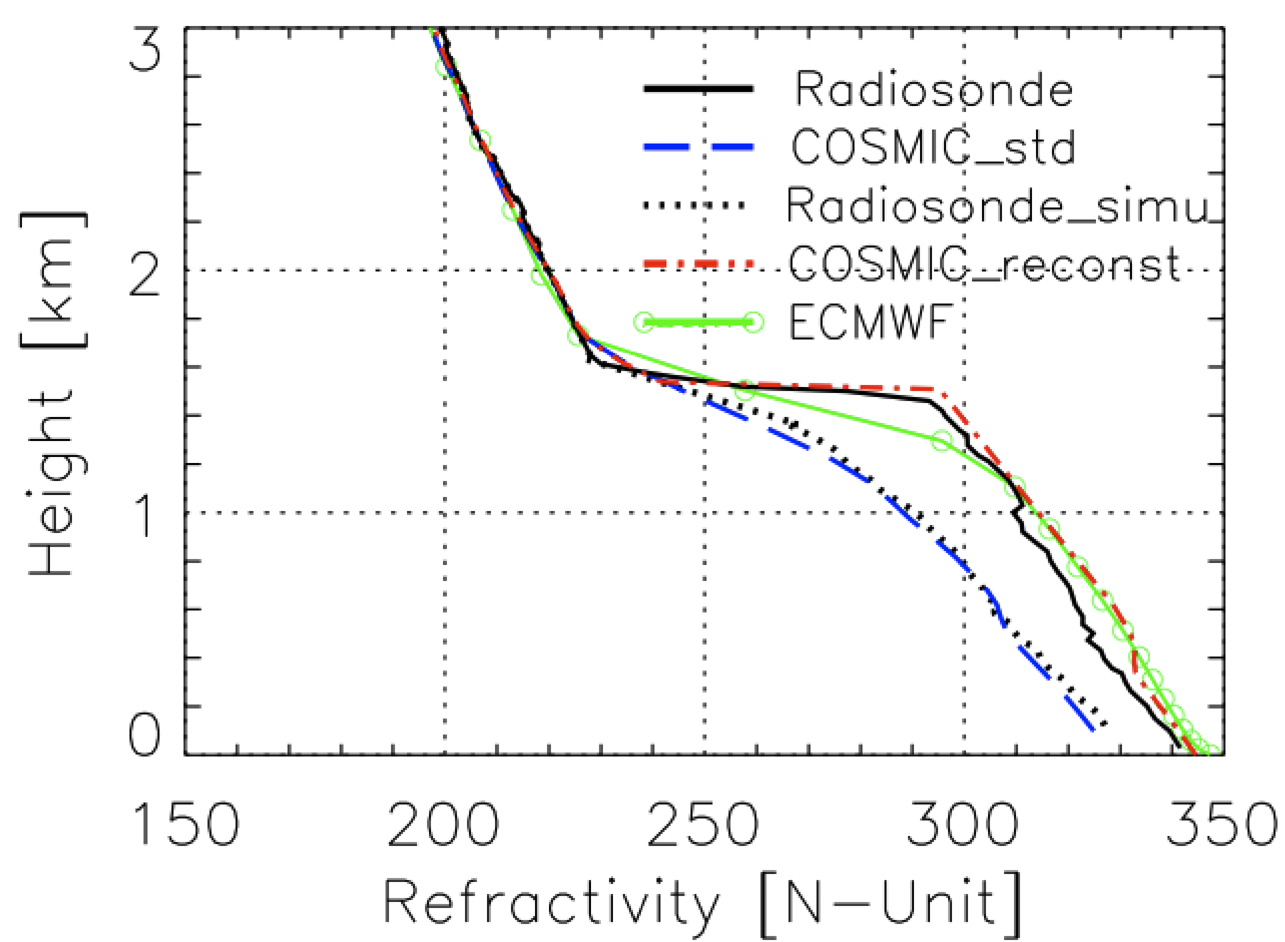
Case Study: Lihue Hawaii

- Construct the continuum of profiles
- "Best" profile selected from continuum used surface *N* constraint from ECMWF (low res)
  - Surface *N* from NCEP too high because water vapor is high



High Resolution 91-Level ECMWF

- High resolution ECMWF noticeably better than low resolution ECMWF
- Suspect ECMWF is so good because it assimilated the sonde



Future

- ECMWF evaluation: Plan to look at cases from VOCALS field campaign off west coast of South America where we have “truth” and ECMWF has not assimilated it
- Develop other constraints to choose “best” reconstruction profile
- Assess effects of horizontal refractivity gradients on bending angle profiles
- Automate reconstruction process
  - Automate super-refraction detection

PART 2

Two Methods for Extracting Water Vapor from GPS RO Refractivity Profiles

- **Simple Method**
  - Determine dry refractivity from analysis temperature profile and hydrostatic equation
  - Subtract dry refractivity from GPS refractivity => wet refractivity => water vapor
- **1D Variational Method**
  - Combine GPS refractivity with temperature & water vapor profiles and surface pressure from analysis
  - Overdetermined, least squares solution
- **Advantage of Simple Method:** it is not affected by biases in background water vapor analysis

SimpleMethod: Solving for water vapor given *N* & *T*

$$N \equiv (n-1)\times 10^{6} = a_1\frac{P}{T} + a_2\frac{P_w}{T^2} \quad (1)$$

- Use temperature from a global analysis interpolated to the occultation location
- To solve for *P* and P_w given *N* and *T*, use constraints of hydrostatic equilibrium and ideal gas laws and one boundary condition

Solve for *P* by combining the hydrostatic and ideal gas laws and assuming temperature varies linearly across each height interval, i

$$P(z_{i+1}) = P(z_i)\left(\frac{T_i}{T_{i+1}}\right)^{\frac{\bar{m}_i \bar{g}_i}{R\dot{T}_i}} \quad (2)$$

where:

z	height,
g	gravitation acceleration,
m	mean molecular mass of moist air
T	temperature
R	universal gas constant

Estimating the Accuracy of GPS-derived Water Vapor

The error in specific humidity, *q*, due to errors in *refractivity, N*, *temperature, T*, and *pressure, P*, from GPS is (Kursinski & Hajj, 2001)

$$\sigma_q = \left((C+q)^2 \left(\frac{\sigma_N}{N} \right)^2 + (C+2q)^2 \left(\frac{\sigma_T}{T} \right)^2 + (C+q)^2 \left(\frac{\sigma_{P_s}}{P_s} \right)^2 \right)^{1/2}$$

where $C = a_1 T m_w / a_2 m_d \sim 35$ g/kg

Similarly, the error in relative humidity, *U*, is

$$\sigma_U = \left[(B_s + U)^2 \frac{\sigma_N^2}{N^2} + \left(B_s + U(2 - \frac{L}{R_v T}) \right)^2 \frac{\sigma_T^2}{T^2} + B_s^2 \frac{\sigma_P^2}{P^2} \right]^{1/2}$$

where *L* is the latent heat and $B_s = a_1 TP / a_2 e_s$.

- The temperature error is particularly small in the tropics (~1.25 K)

Negative *q* and Error Deconvolution

Simple Method can and does produce negative *q* estimates
=> Produces an unphysical, negative tail in the *q* histograms

- Fix this by Deconvolving Error distribution from histograms
  - Linearize error model: $q_{measured} = q_{\mathrm{true}} + \varepsilon_q$
  - Measured histogram (PDF) is then the convolution of the true PDF and the error PDF

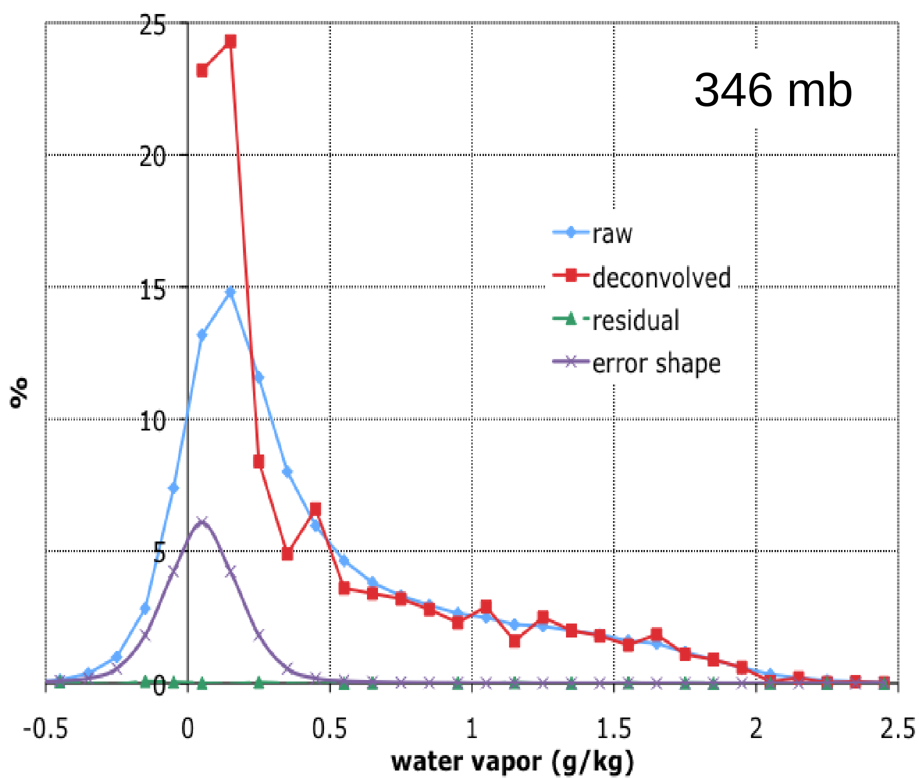
$$\mathrm{PDF}_{q\mathrm{meas}} = \mathrm{PDF}_{q\mathrm{true}} \otimes \mathrm{PDF}_{\varepsilon}$$

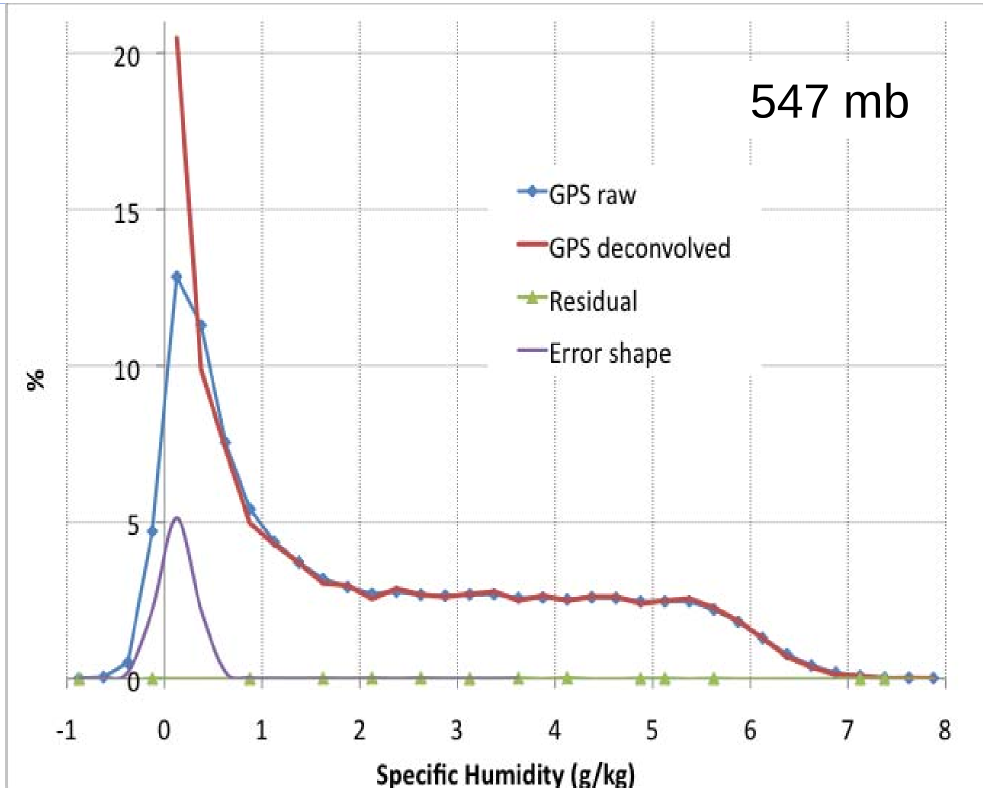
- *IF* we understand the error PDF, we can deconvolve it from the measured PDF to recover the true PDF
  - Negative tail tells us the shape & extent of the error distribution
    - Assuming shape of error distribution is symmetrical
- SOLUTION: Iteratively adjust Error PDF and Solution PDF to find best fit to observed PDF

Error Deconvolution Tropical, Full Annual Cycle (2007)

Very similar to errors predicted by Kursinski & Hajj (2001)

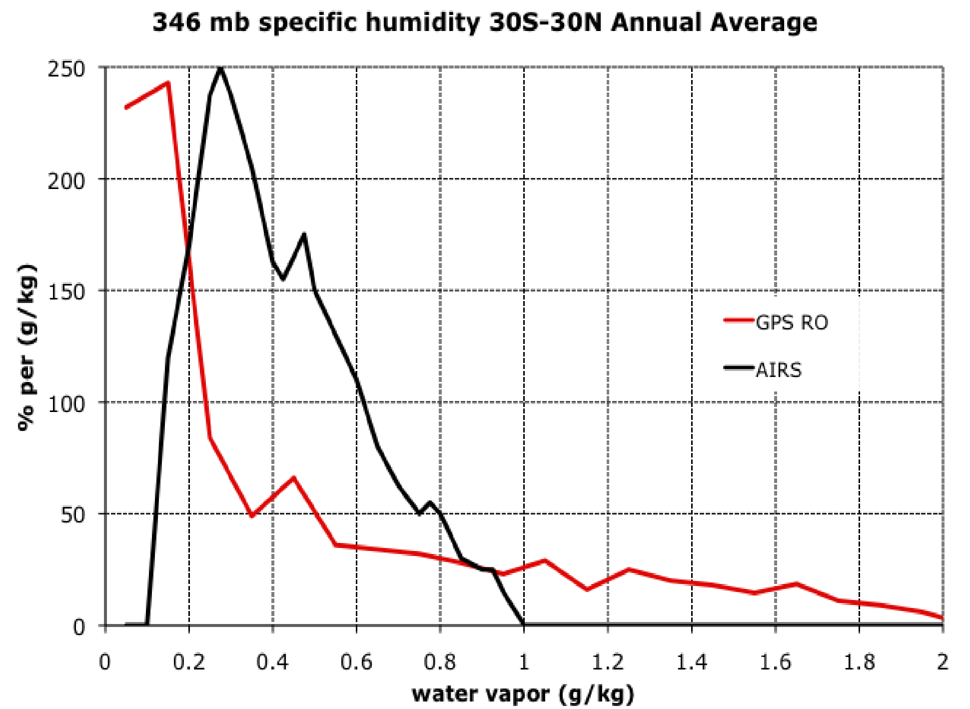
	346 mb		547 mb	
	Gaussian	Exponential	Gaussian	Exponential
Best fit error shape	74%	26%	94%	6%
Stdev of error	0.18 g/kg		0.27 g/kg	
Likely	N err	T err	N error	T error
Error contributions	0.2%	1.25 K	0.60%	1.25 K

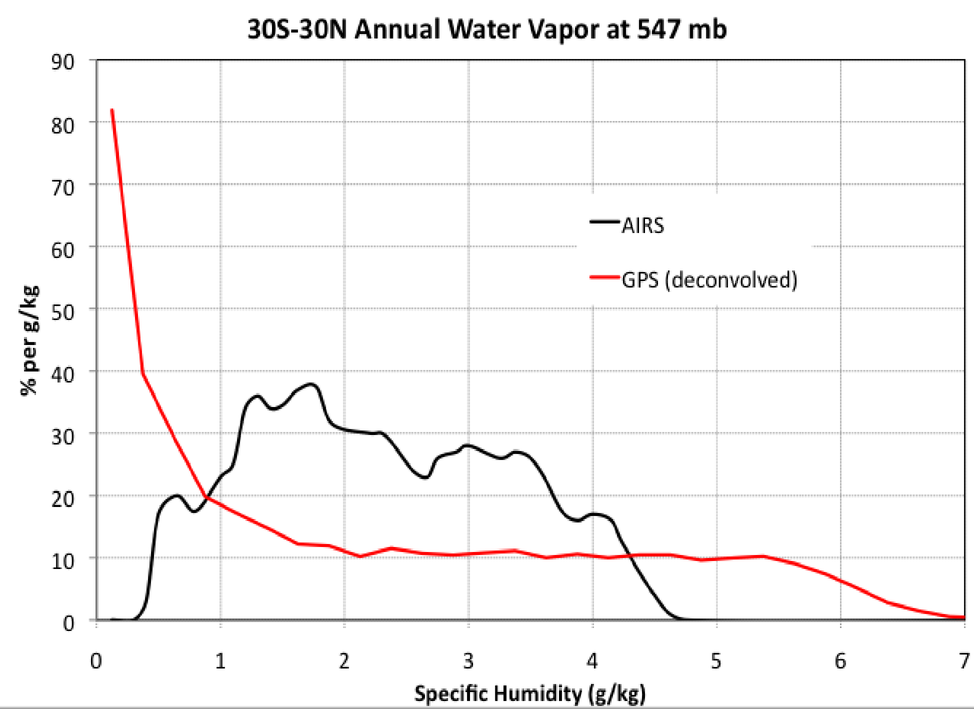




Water Vapor Distribution: GPS RO vs. AIRS

- AIRS from Dessler & Minschwaner (2007) eval. of moisture control
- AIRS vs GPS discrepancies much larger than GPS RO errors
  - AIRS missing high water portion, due in part to clouds + ?
  - AIRS missing dry part (< 0.2 g/kg) from anvil detrainment
    - ***Significantly different implications for free tropospheric moisture control***
  - Causes:
    - Limited vertical resolution?,
    - Biased initial guess from forecast?
- Means of GPS & AIRS are similar:
  - **0.47 vs. 0.42**
  - **2.0 vs. 2.3**





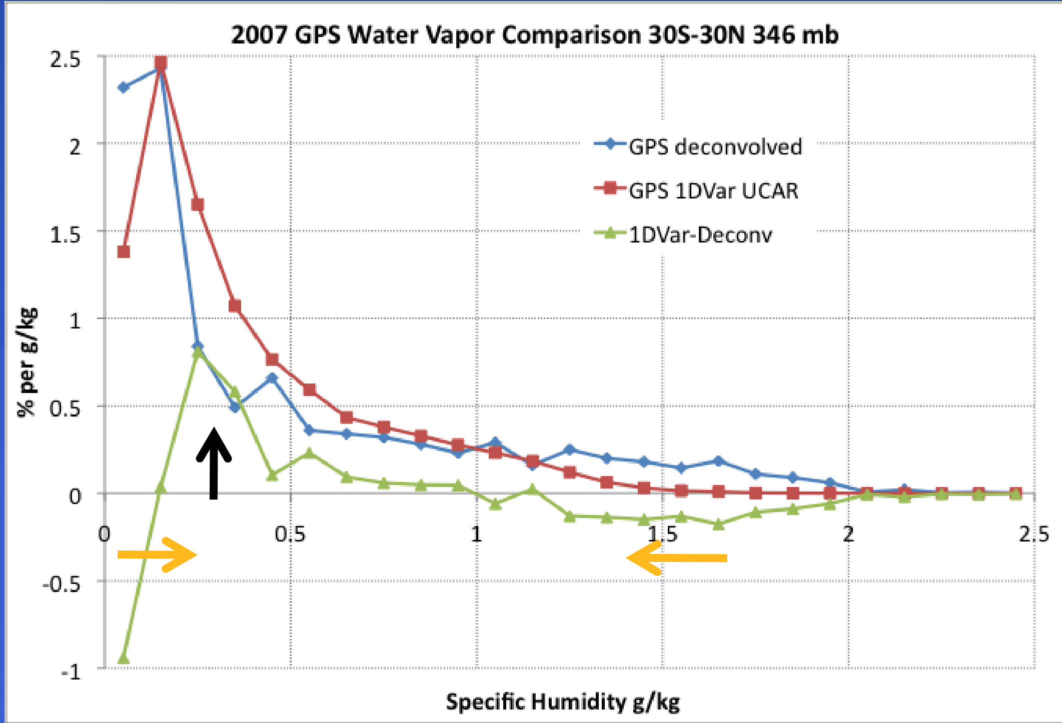
Effects of Model on GPS Water Vapor

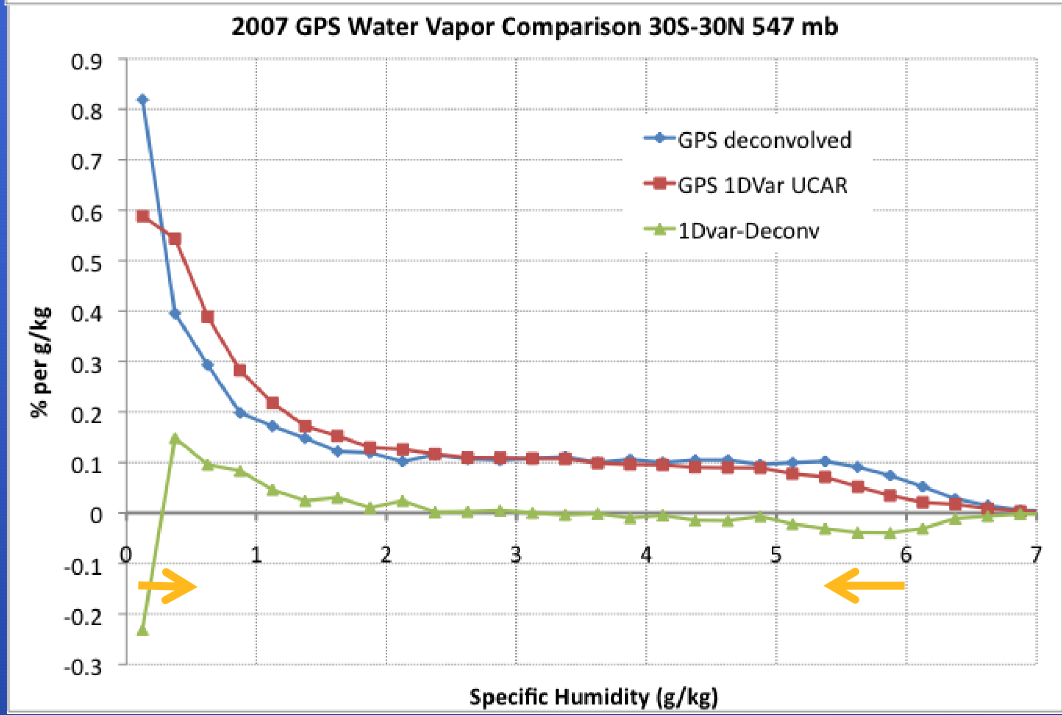
- Impact of model bias is evident in comparing Deconvolved & 1DVar GPS water vapor distributions
- 1DVar has pushed extremes toward center of distribution
  - Presumably because model distribution is narrower
  - Likely contributing to the narrow AIRS distribution
- Peak **increase** at 346 mb coincides with peak in AIRS distribution at 0.275 g/kg (black arrow).
- Positive portion of shift in distribution similar to AIRS distrib.

1DVar has shifted Means lower:

0.38 vs. 0.47 g/kg

1.89 vs. 2.03 g/kg





Climate Modeling of Tropical Water Distribution

Dessler & Minschwaner (2007) matched model & AIRS distributions

BUT* AIRS distribution is *incorrect

•To what extent are the AIRS and model data independent???

•Is agreement between AIRS & the model incestuous & not a robust indication of model's realism?

These results demonstrate the need to measure the atmospheric state independent of models

⇒ This is the reason we are developing the next generation ATOMMS RO system

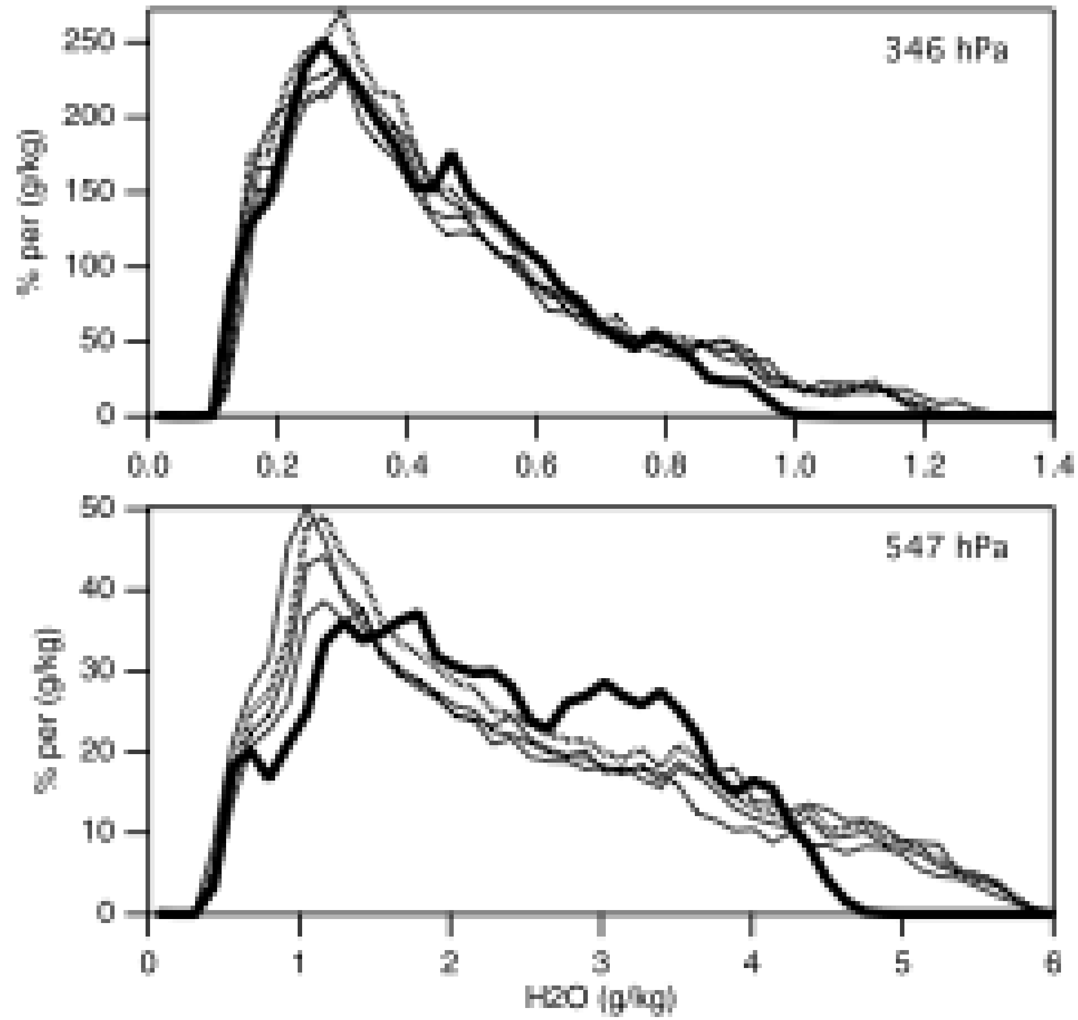


Figure 2. Histograms of annual average H_2O mixing ratio (g/kg) at 346 hPa (top) and 547 hPa (bottom). The thick solid lines are histograms of the AIRS data from Figure 1. The three thin solid lines are histograms from the trajectory model, each using a different convective threshold. The dotted line is obtained using the standard trajectory model with a RH limit of 90%.