GNSS & ATOMMS RO and GRUAN

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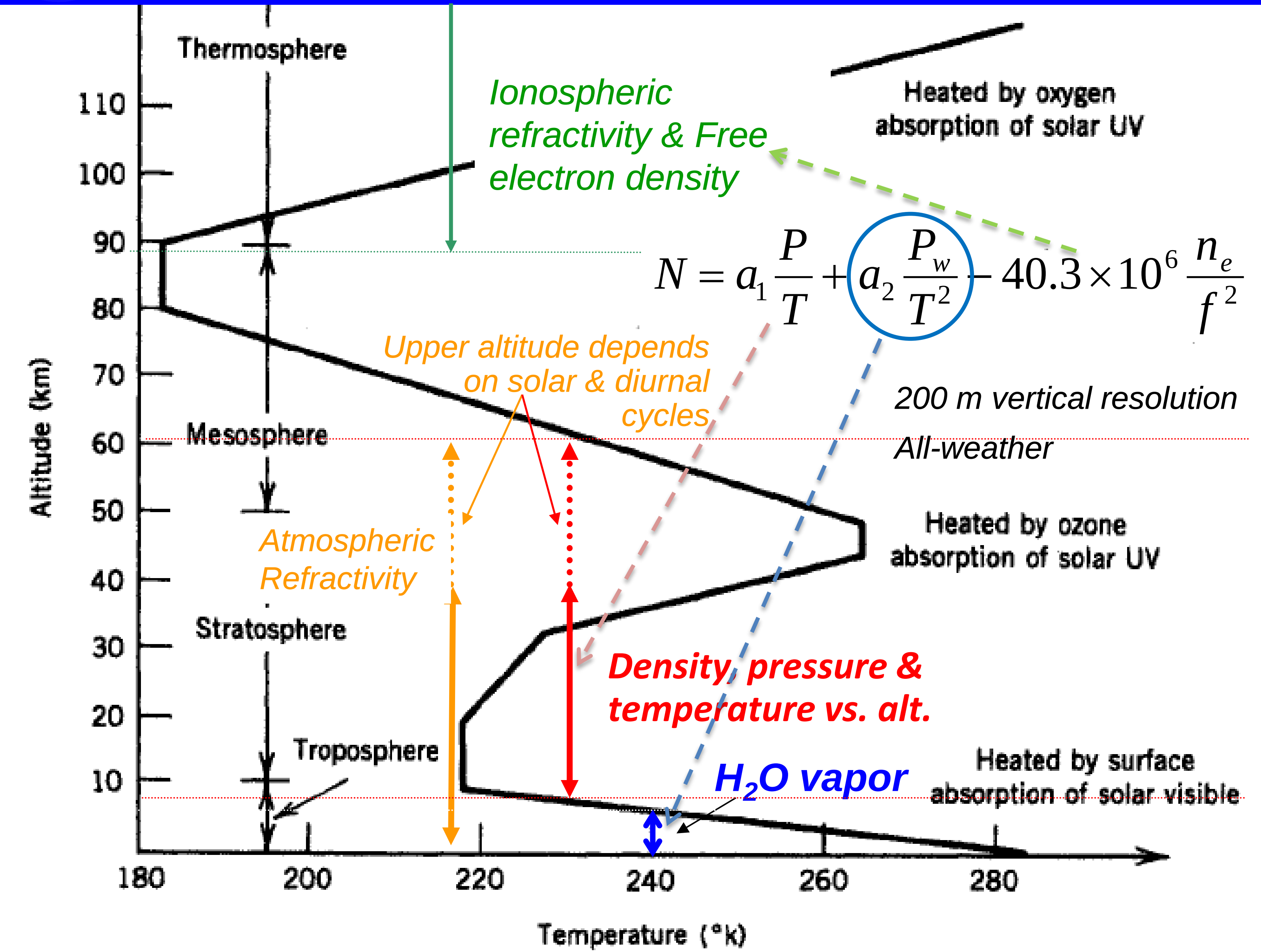
Outline

- GPS RO temperature items
- GPS RO error deconvolution
  - Description
  - Specific & relative humidity
  - Temperature dependence of negative tails
- 183 GHz spectroscopy
- Challenge of validating water vapor

GNSS RO Information vs. Altitude



$$N = a_1 \frac{P}{T} + a_2 \frac{P_w}{T^2} - 40.3 \times 10^6 \frac{n_e}{f^2}$$

Upper Altitude Boundary Condition

density ← **retrieval** — **bending angle**

$$n(a) = \exp\left[\frac{1}{\pi}\int_a^\infty \frac{da'}{\sqrt{a'^2 - a^2}}\alpha(a')\right]$$

Refractive index

Impact parameter
a = n(r) r

Bending angle

Old way:

E.g. higher than 50 km

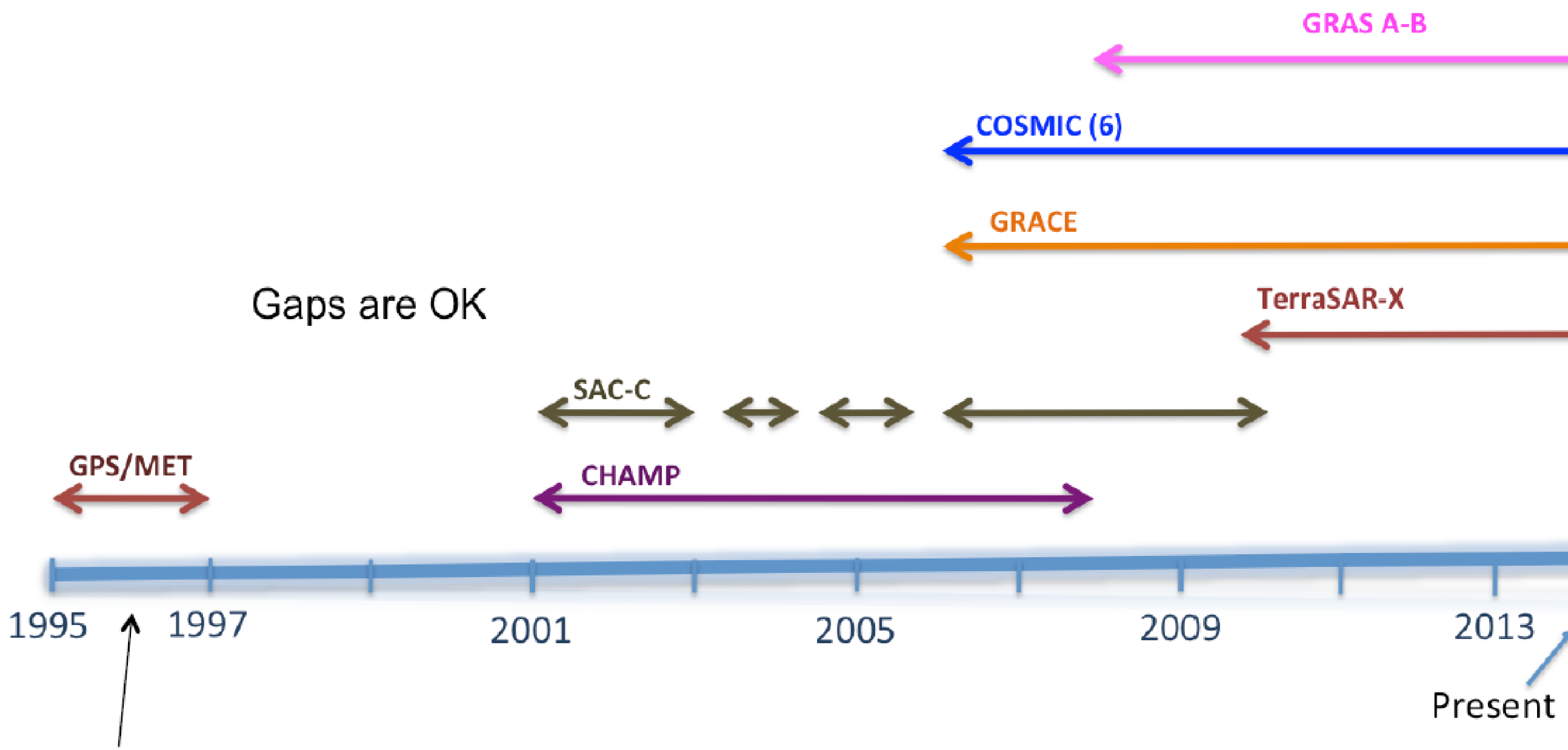
- Calculate density by extrapolating noisy measurements vertically, or using a model
- Form monthly means of density

New way:

- Calculate monthly means of bending angle
- Extrapolate monthly mean bending angle vertically

Ao, C. O et al., GRL 2012

Plans for A GNSS-RO Data Set



Developing single-frequency processing

Two Methods for Extracting Water Vapor from GPS RO Refractivity Profiles

1. Direct Method: $N_{wet} = N_{tot} - N_{dry}$
   - Determine dry refractivity (N_{dry}) from analysis temperature profile and hydrostatic equation
   - Scale N_{wet} to get water vapor

2. (1D) Variational Method
   - Combine GPS refractivity with
   - Analysis temperature & water vapor profiles and surface pressure
   - and error covariance estimates

   $\Rightarrow$ Over-determined, least squares solution

Advantages of Direct Method:

- Not affected by biases in background water vapor forecast/analysis
- Can derive water vapor information to higher altitudes

Negative q and Error Deconvolution

Direct Method can and does produce negative q estimates

=> Produces an unphysical, negative tail in the q histograms

- This can be fixed by deconvolving the error distribution from histograms
  - Linearize error model: $q_{measured} = q_{\text{true}} + \varepsilon_q$
  - Measured histogram (PDF) is then the convolution of the true PDF and the error PDF

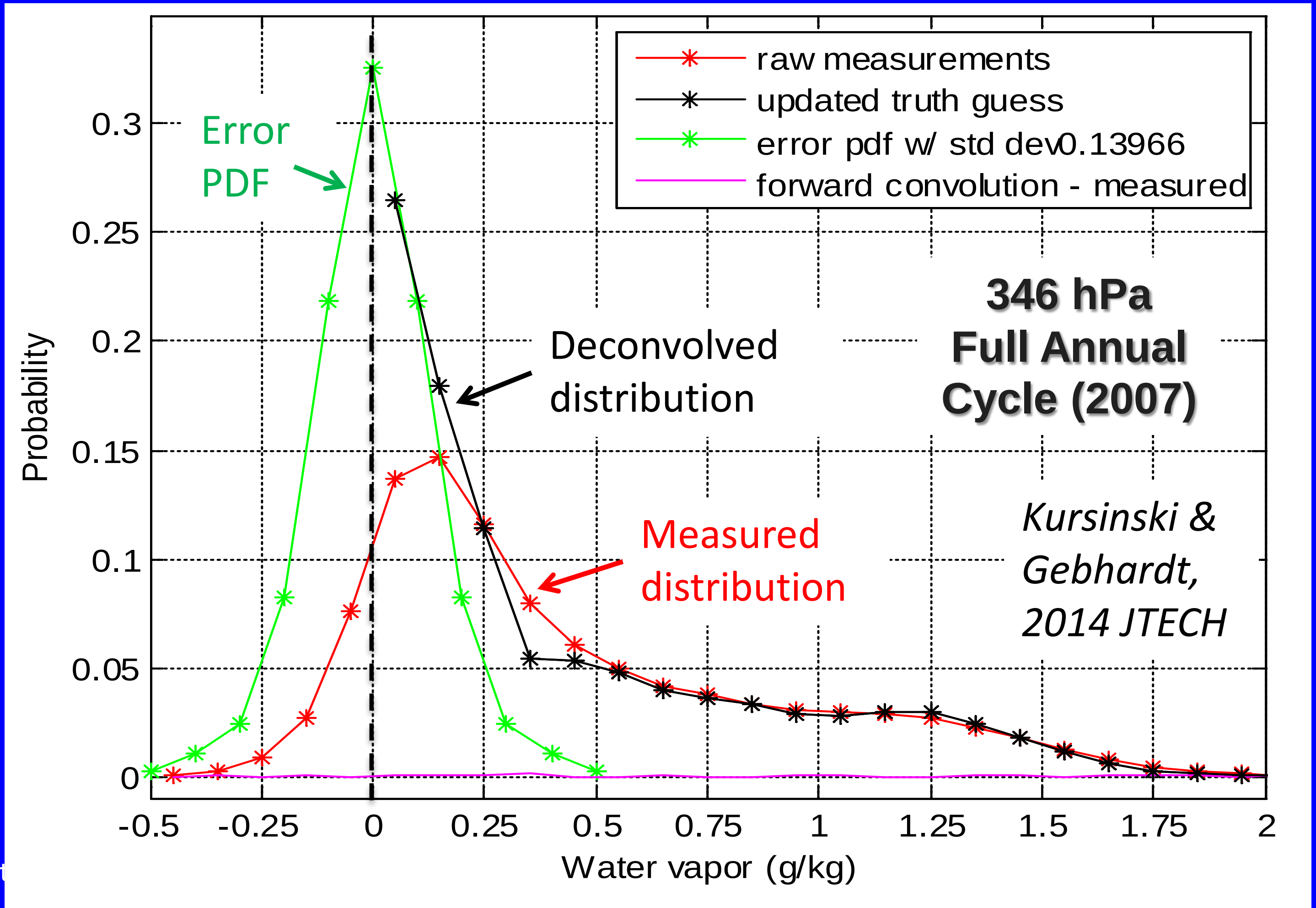
$$\text{PDF}_{q\text{meas}} = \text{PDF}_{q\text{true}} \otimes \text{PDF}_{\varepsilon}$$

- *IF* we understand the error PDF, we can then deconvolve it from the measured PDF to recover the true PDF
  - Negative tail tells us shape of the error distribution

- Described in Kursinski & Gebhardt (2014) in JTECH

Error Deconvolution Low Latitude

- Adjust (1) (symmetric) Error PDF & (2) "true" *q* distribution PDF,
- Convolve them to generate estimate of "measured" PDF,
- Iterate adjustments until best fit to measured PDF is achieved



Random Error Deconvolution Method

- X = true water vapor distribution
- D = measured water vapor distribution
- A = convolution process that maps true distribution to measured distribution

$$D = A(X)$$

- Linearize the problem writing it as

$$D = A\, X$$

- A is now a matrix such that $A\, X$ represents the process of convolving the true moisture PDF with the error PDF.
- We want to find a forward convolved D' that closely approximates the measured D
- To find D', we minimize the difference between D' and D by iteratively adjusting A and X

Random Error Deconvolution Method

- Expand D' around most recent estimate, $D'_0 = A_0 X_0$

$$D' = (A_0 + \Delta A)(X_0 + \Delta X) = A_0 X_0 + A_0 \Delta X + \Delta A X_0 + \Delta A \Delta X$$

- Linearize: drop last term which is 2nd order
- Want to minimize the difference: $D'-D$

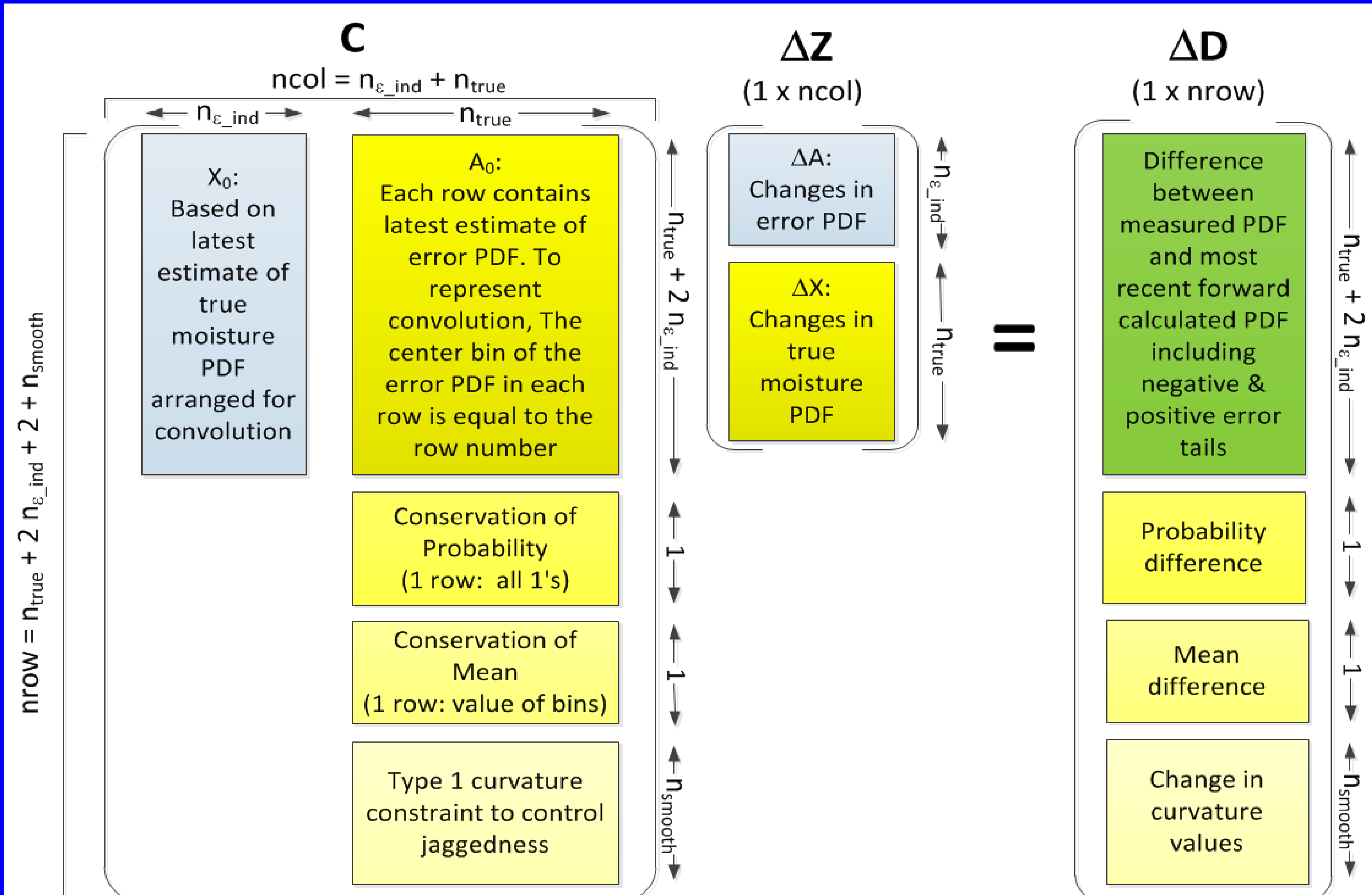
$$D' - D = A_0 X_0 + A_0 \Delta X + \Delta A X_0 - D$$

- Each iteration, find ΔX and ΔA such that

$$D - D'_0 = \Delta D = A_0 \Delta X + \Delta A X_0$$

- Each iteration, find least squares solutions for ΔX and ΔA
- Then update D'_0 and do the next iteration

Random Error Deconvolution Method



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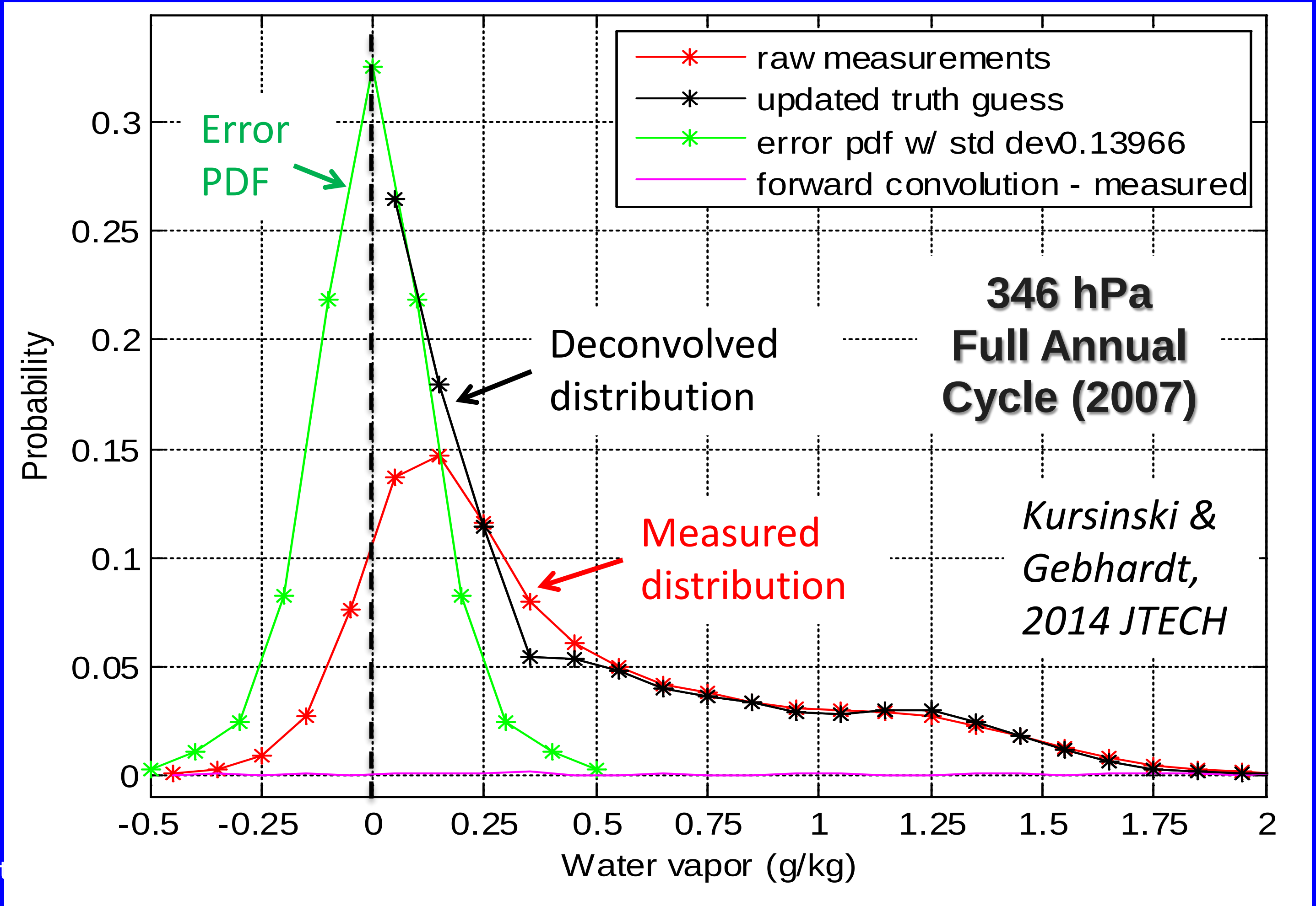


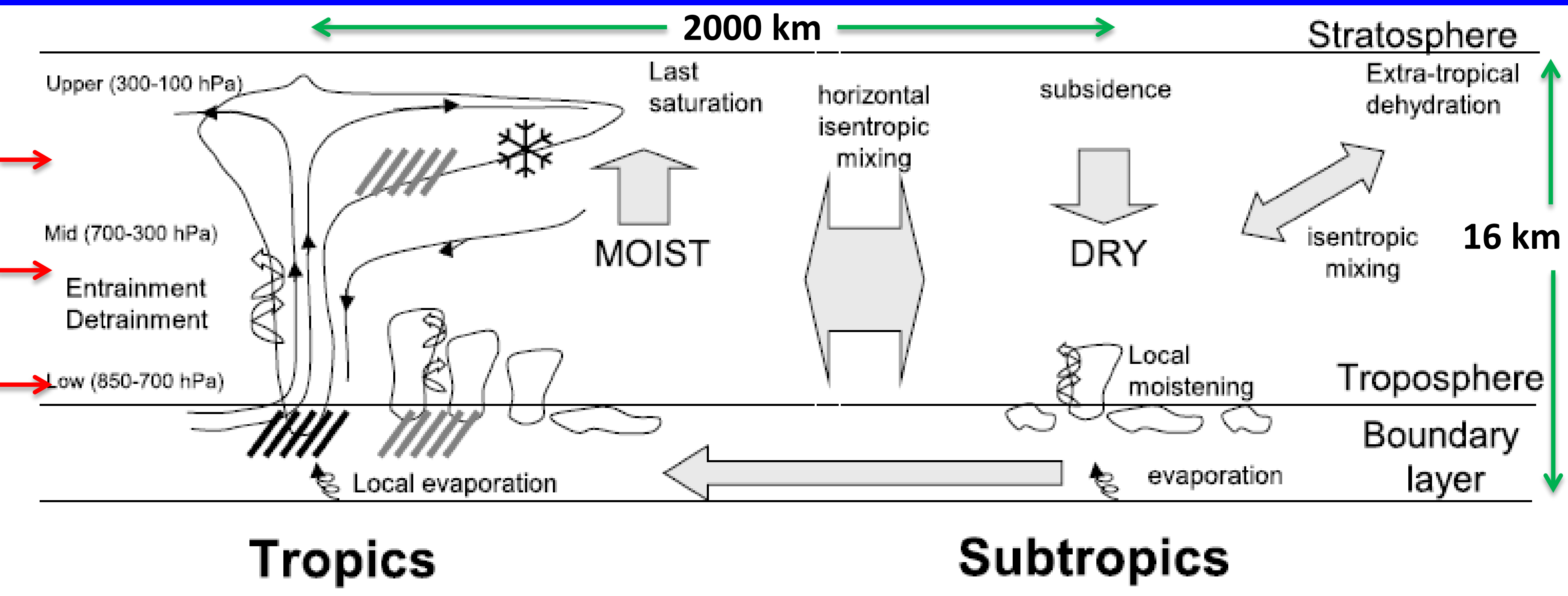
Separating the Errors

- Estimate water vapor error from negative tail of distribution (Kursinski & Gebhardt, 2014)
- Resulting errors somewhat smaller than predictions of Kursinski & Hajj, 2001
  - In part because low lat. analysis temperature errors are smaller

	Specific Humidity Error (g/kg)		Fractional Refractivity Error (%)		Temperature Error (K)		Reference Pressure Error (%)	
Pressure level (hPa)	KH01	Error deconv	KH01	Error deconv	KH01	Error deconv	KH01	Error deconv
346	0.24	**0.14**	0.2	0.2	1.5K	0.85K	0.3%	0.19%
547	0.31	**0.25**	0.5	0.6	1.5K	0.85K	0.3%	0.19%
725	0.47	**0.39**	0.9	1	1.5K	0.85K	0.3%	0.19%

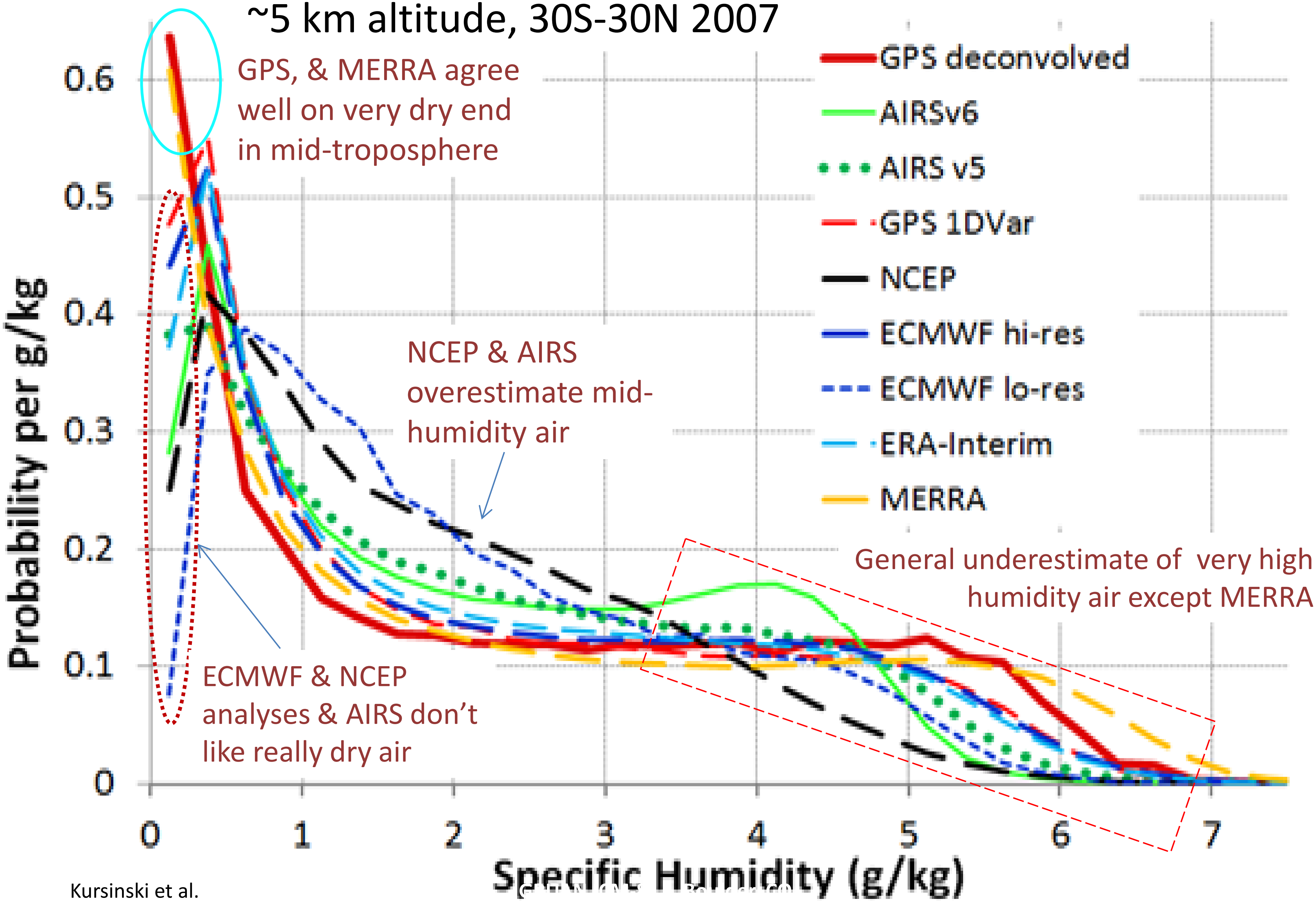
Low Latitude Moisture

- Convection creates extremes, stretching the H_2O vapor distribution
- Mixing & diffusion compress distribution toward its center
- Specific humidity is conserved in the absence of sources & sinks => ***tracer***
- Relative humidity important for conversion between vapor & condensed phases => ***clouds & precipitation***



547 hPa Specific Humidity Comparisons

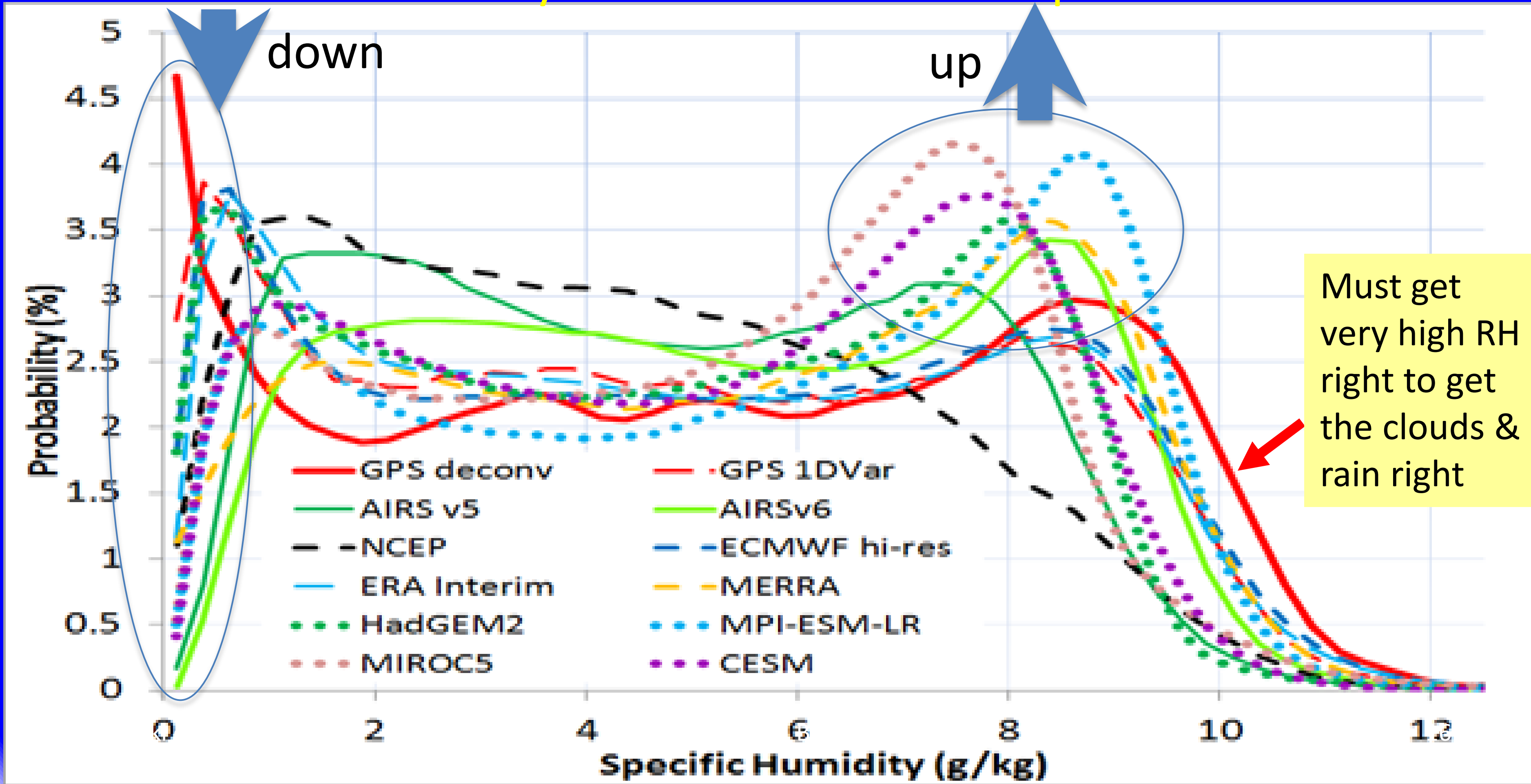
~5 km altitude, 30S-30N 2007



Kursinski et al.

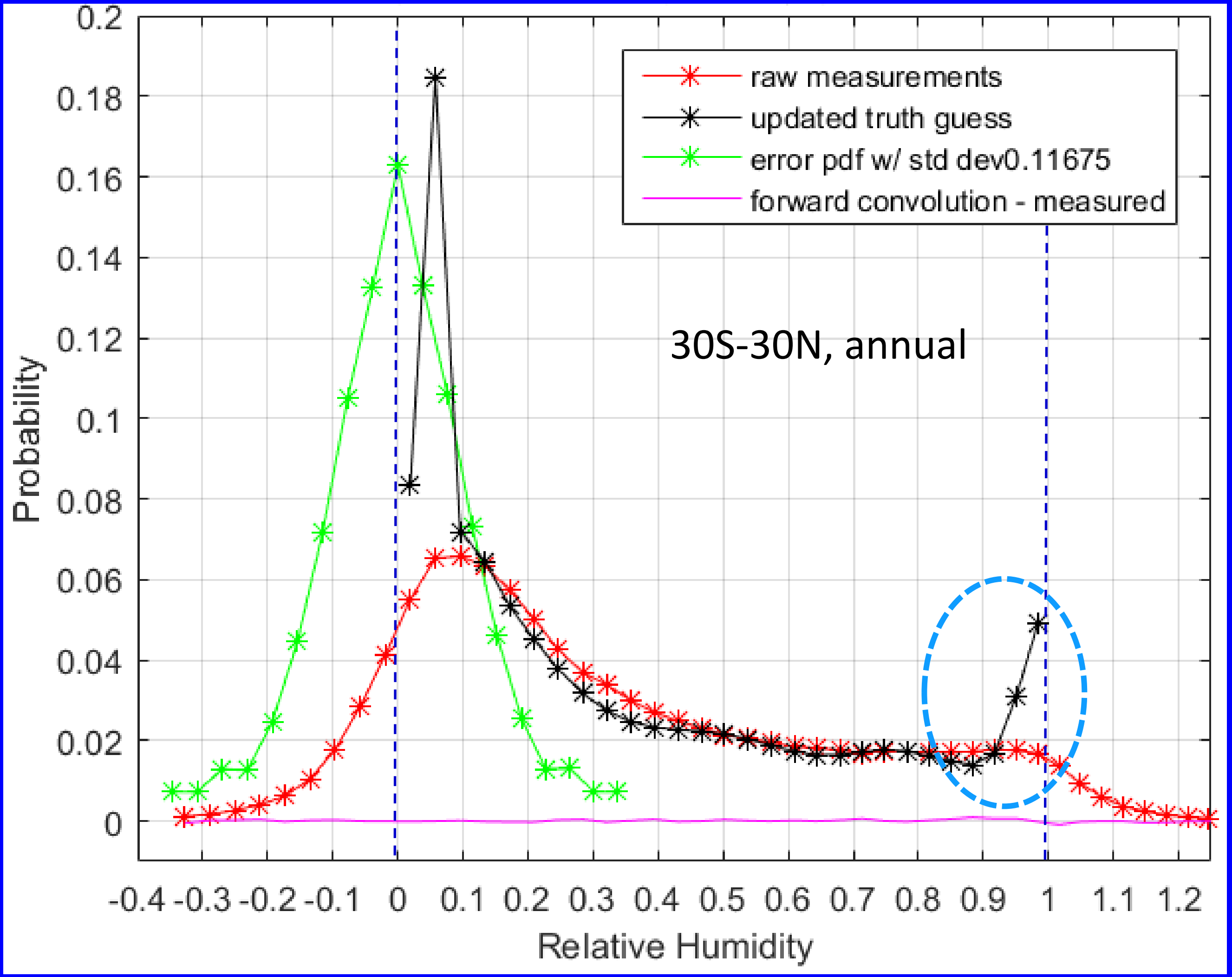
Climate Model & Analysis Comparison 725 mb

- Model peak ***q*** on wet end is a bit small except in MPI
- Modeled % of wet air near the peak is too high
- MERRA % too high; ECMWF slightly too low
- All models & analyses miss driest subtropical air



Relative Humidity Deconvolution Results at 346 mb

- Deconvolution indeed yields a peak near 100% RH



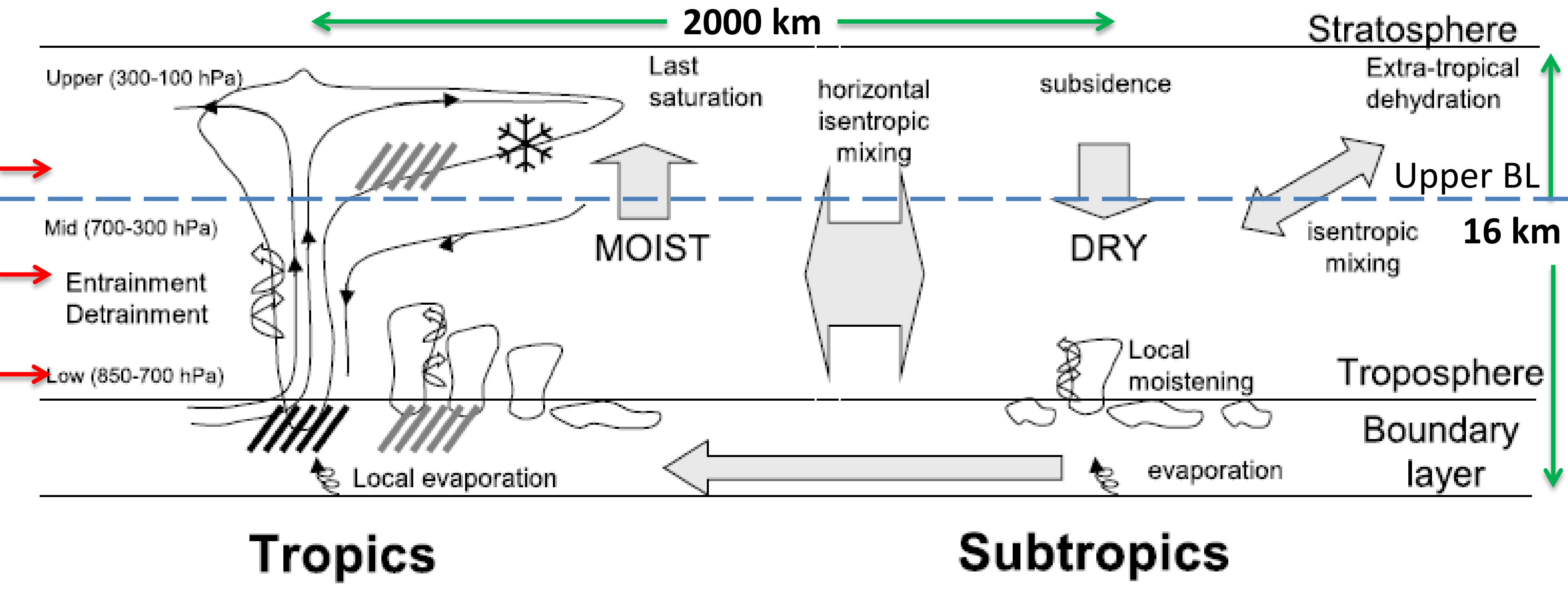
Signature of Convective Boundary Layers

Classical convection: "hot" boundary layer at the bottom bringing heat into the system + "cold" boundary layer at the top removing heat from the system

In Earth's atmosphere,

- The bottom boundary layer is heated by the hot surface heated by the sun
- The upper boundary layer in the UT cools the atmosphere by radiating IR to space
- Air rising into this upper layer diverges and spreads out horizontally

The observed peak near 100% RH in the 346 mb histogram is a signature that this air is in the upper boundary layer

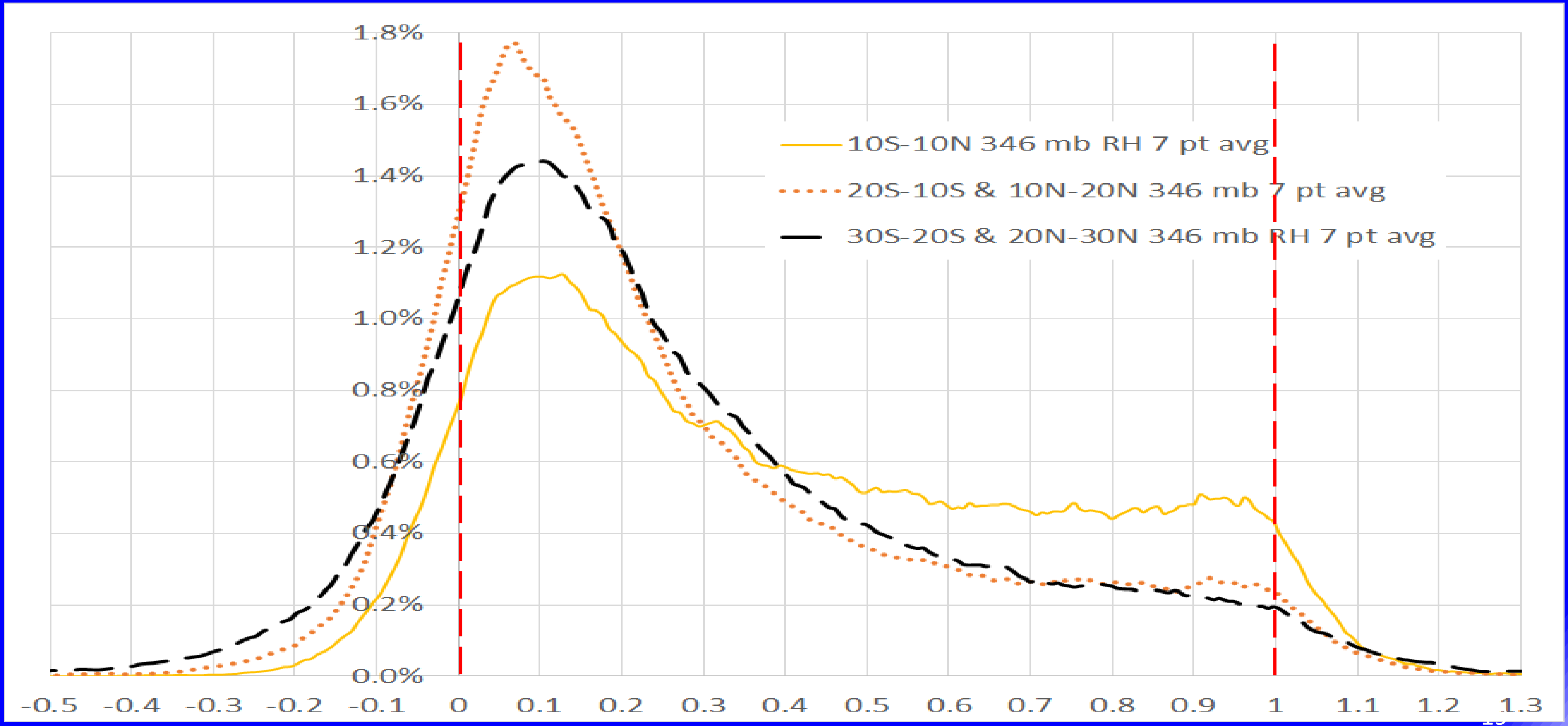


Temperature Error Influence on RH Histograms

Width of unphysical tails varies with latitude

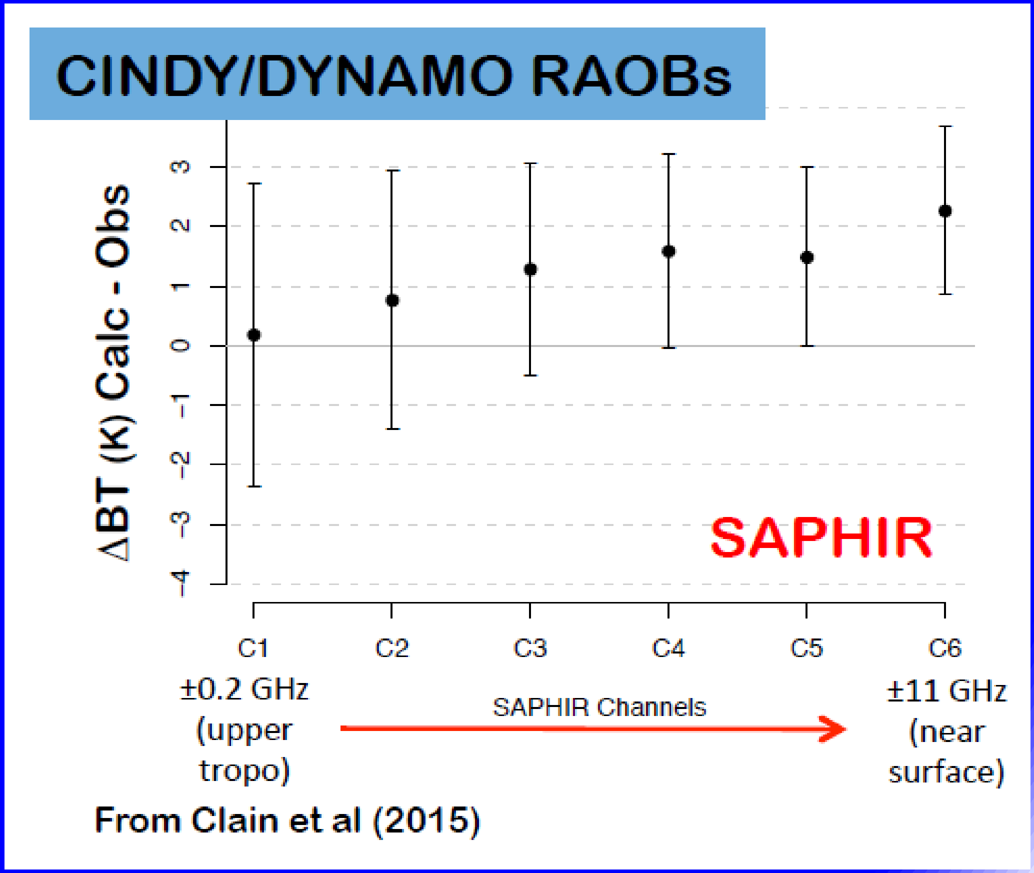
- Narrower in the 10S to 10N interval (where Coriolis is ~0)
- Widest in the 20 to 30 interval

Due primarily to analysis temperature error variation with latitude



183 GHz Problem

- Mismatch in the wings of 183 GHz line between measured radiances & forward radiative transfer calculations: Too little opacity in the modeled wings
- June 2015 Workshop in Paris
- Brogniez et al. in review in *AMT*



22 & 183 GHz RO Active Spectrometer

- Profiles speed of light (like GPS RO) + attenuation of light (unlike GPS RO)

⇒ Profiles H_2O vapor, temperature & pressure versus height **simultaneously**, unlike GPS RO

in clear & cloudy air, over land & water

- 22 GHz: surface into upper troposphere
- 183 GHz: upper troposphere to mesopause

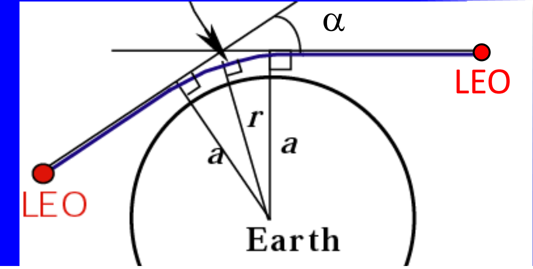
⇒ Also cloud LWC, O_3, NO_2, water isotopes, turbulence, LoS winds above 10 mb level

RO: Self calibrating, **no drift**

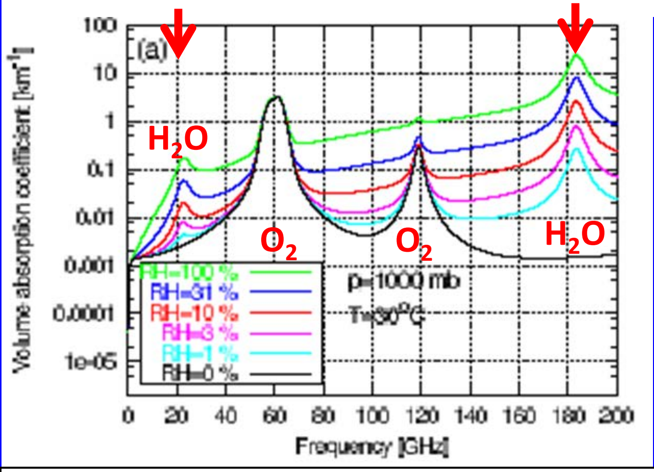
Resolution: ~100 m vertical, ~70 km horiz.

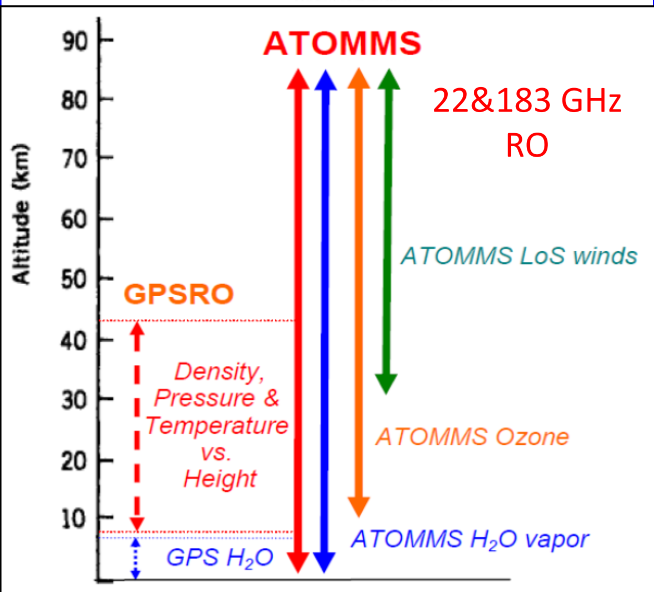
H_2O vapor: < 3% precision, < 1% accuracy

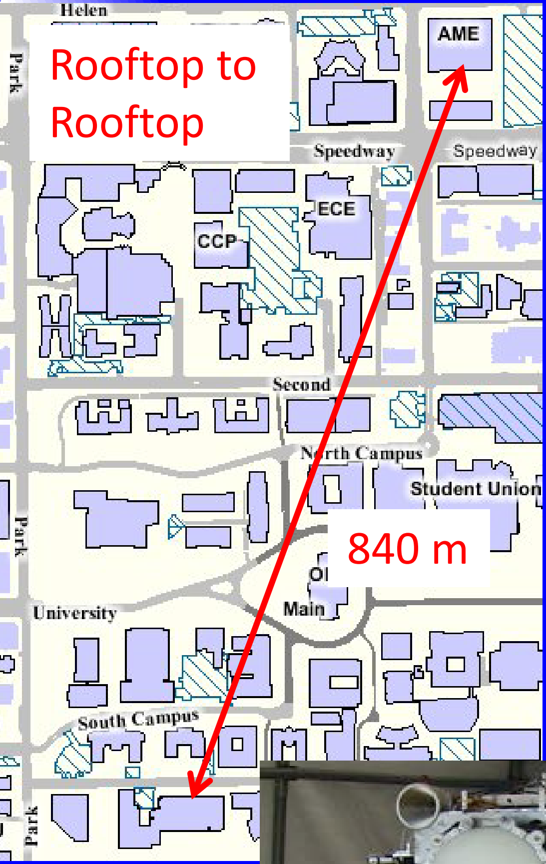
Temperature: 0.4K precision, < 0.05 K accuracy



RO geometry: Transmit & Receive

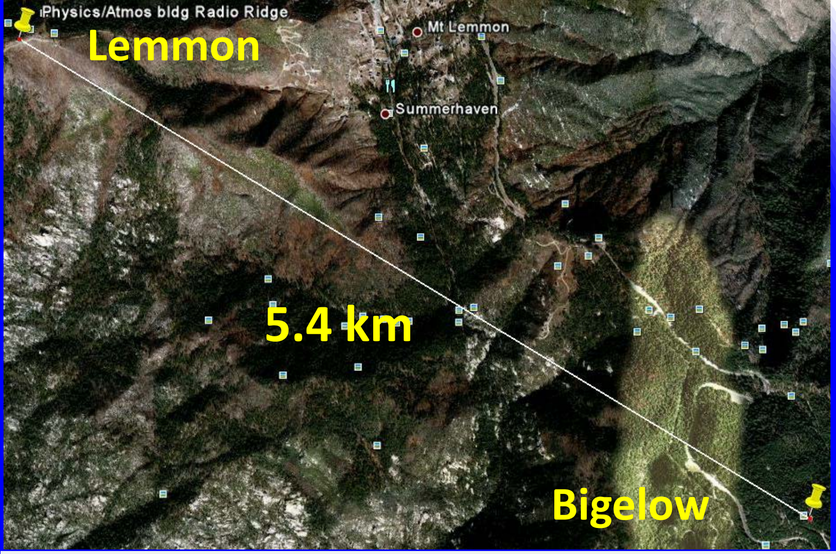


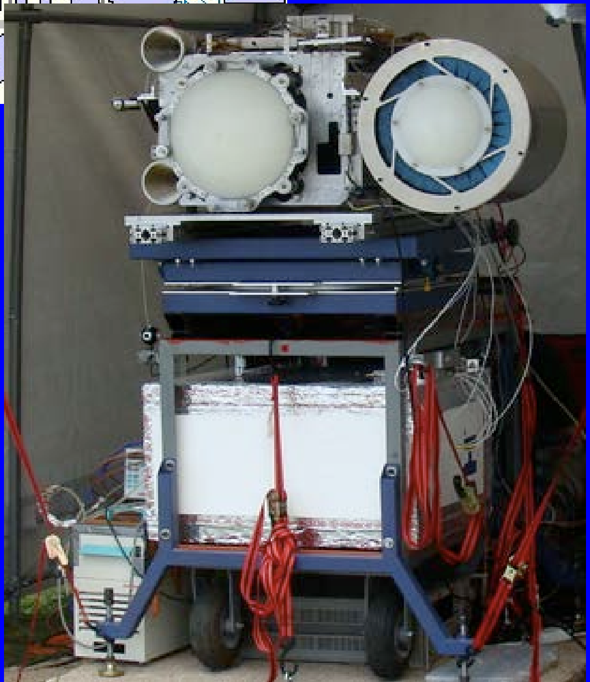




3 Field Test Geometries

- Rooftop: 840 m
- Lemmon to Bigelow: 5.4 km
- Hopkins to Lemmon: 84 km

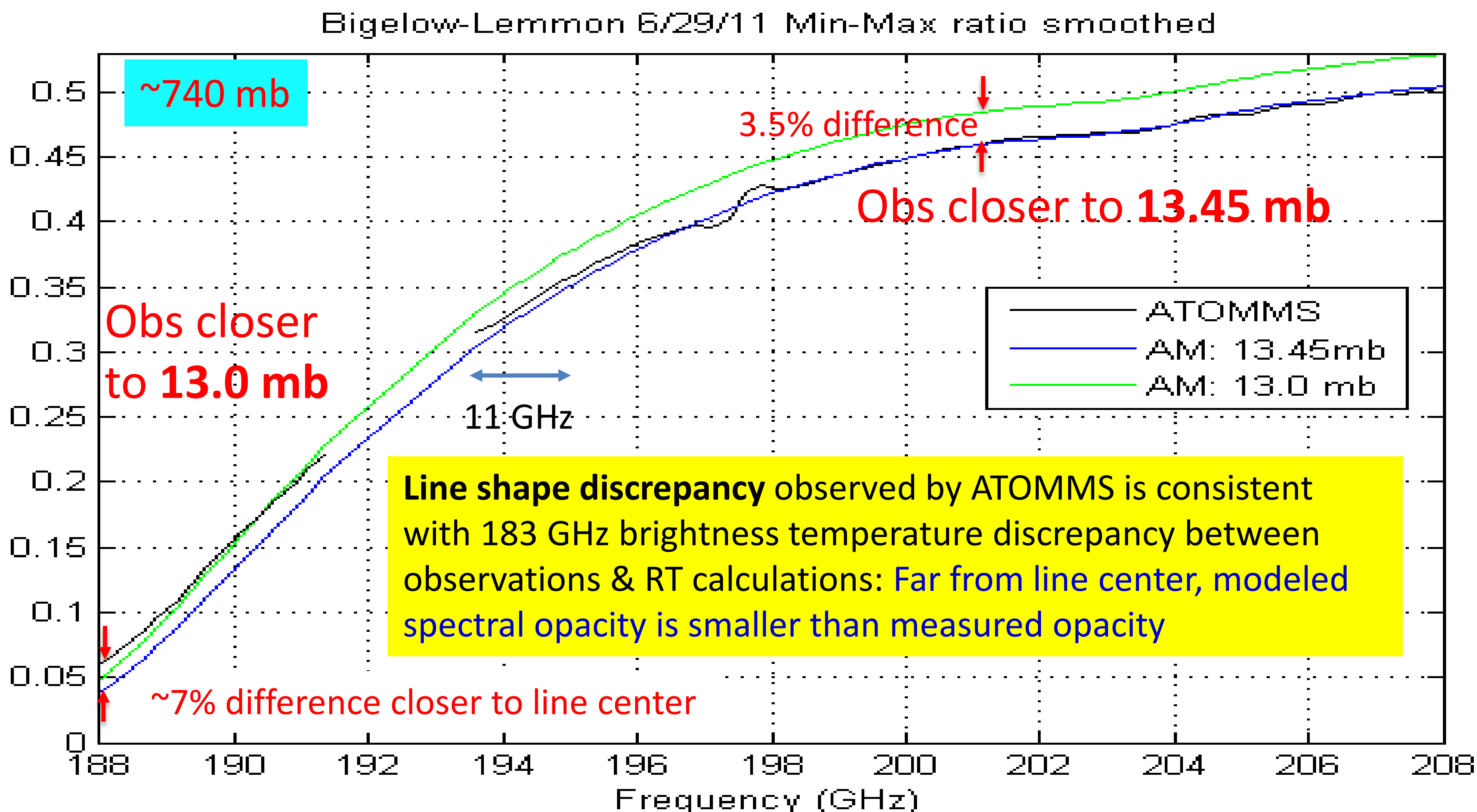




View of Mt. Lemmon from Mt. Bigelow

5.4 km Path Spectrum Reveals Spectral Discrepancy

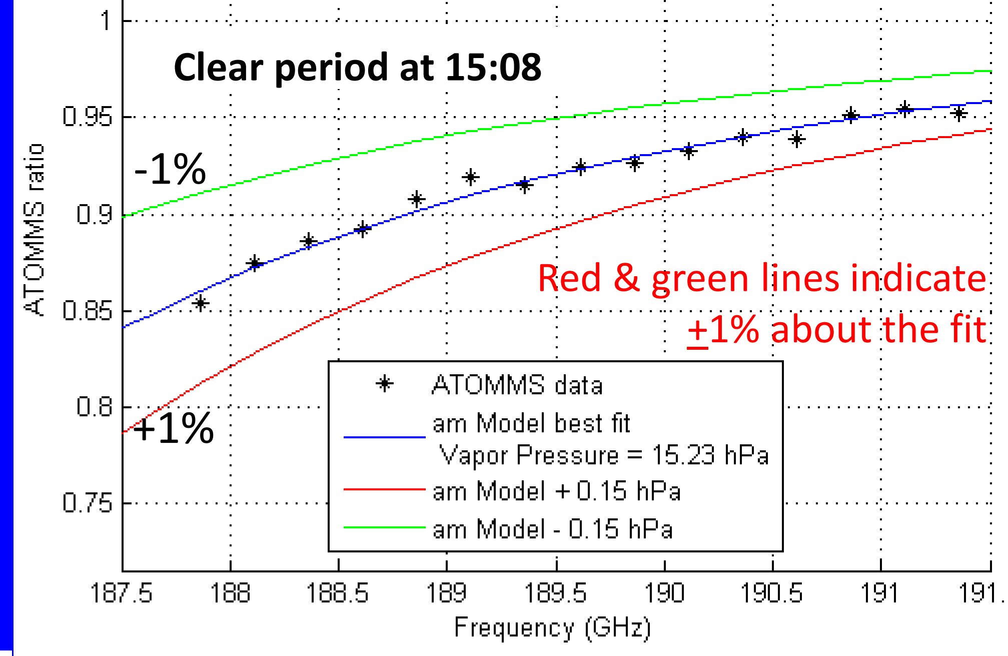
- Spectral model AM6.2 of Scott Paine based on HITRAN and uses the MT_CKD water vapor continuum model

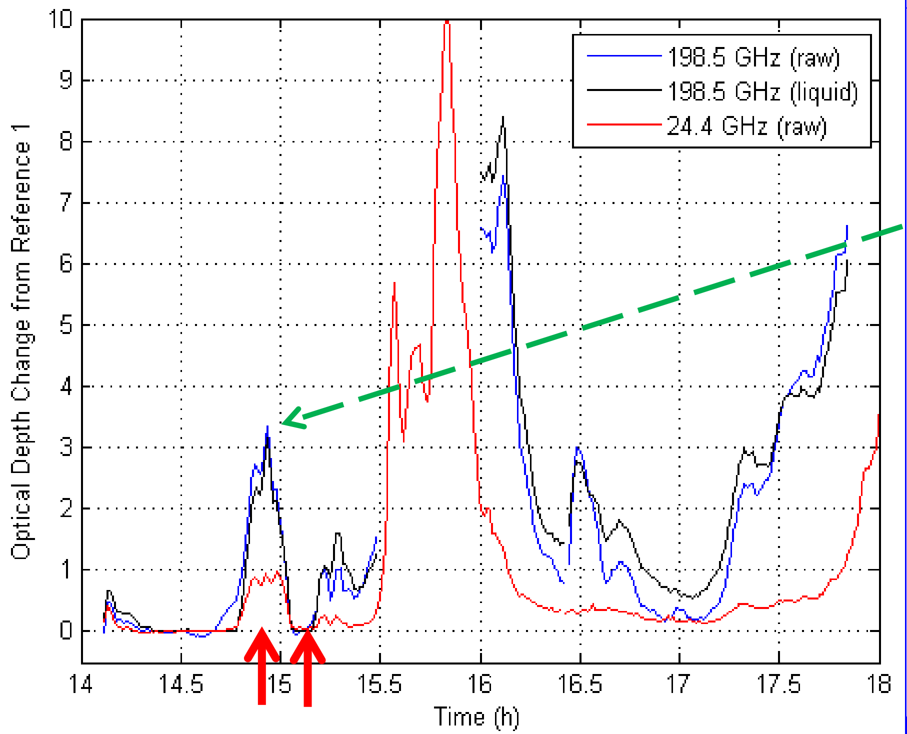


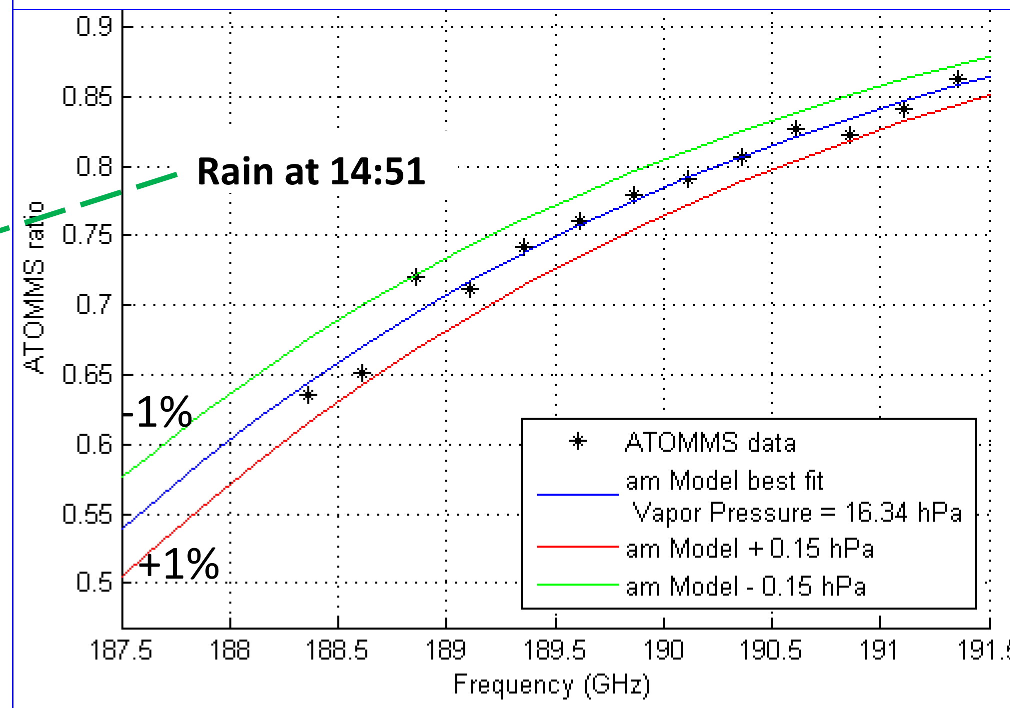
ATOMMS Mountaintop Water Vapor Retrievals

During clear and rain

Random uncertainties <1%







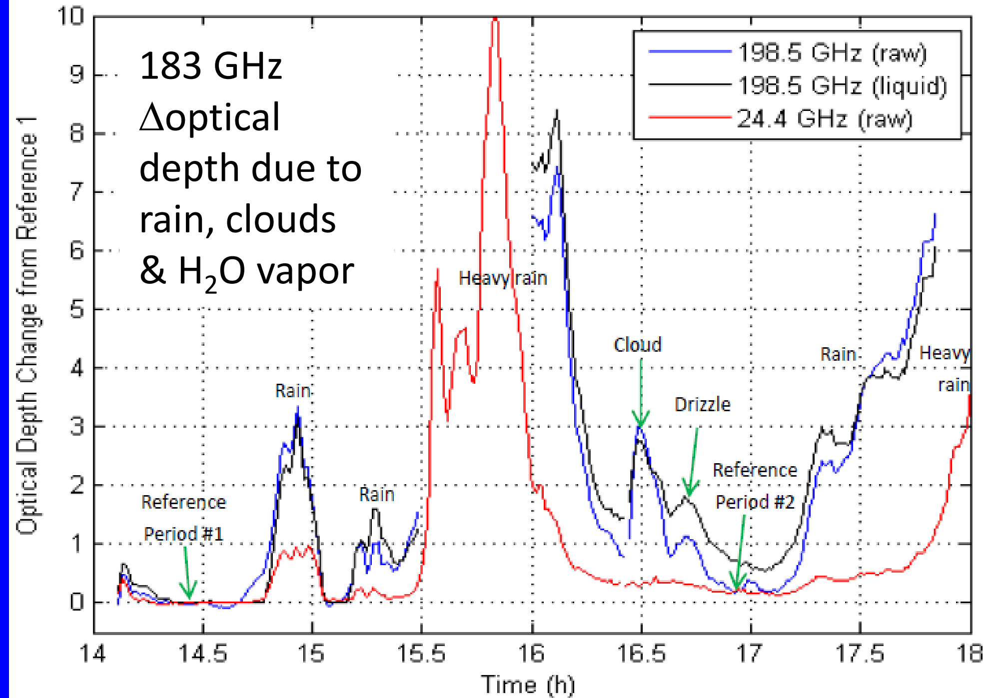
ATOMMS Mountaintop Results Summary

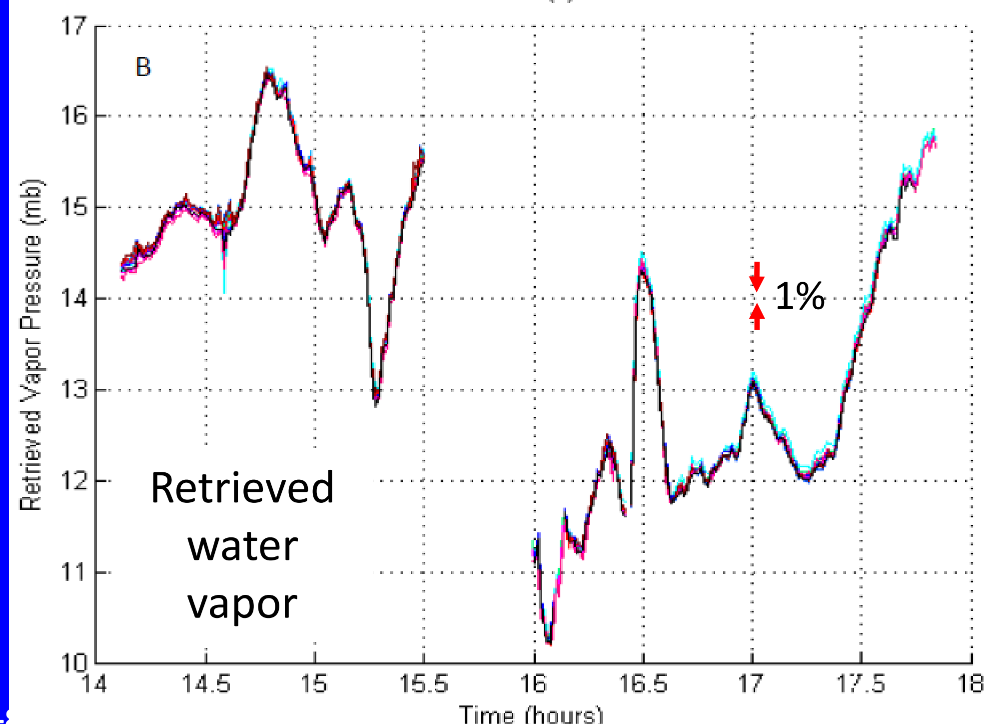
Mtn-top retrievals

- In clear, cloud & rain
- Optical depth up to 17

Water vapor retrievals

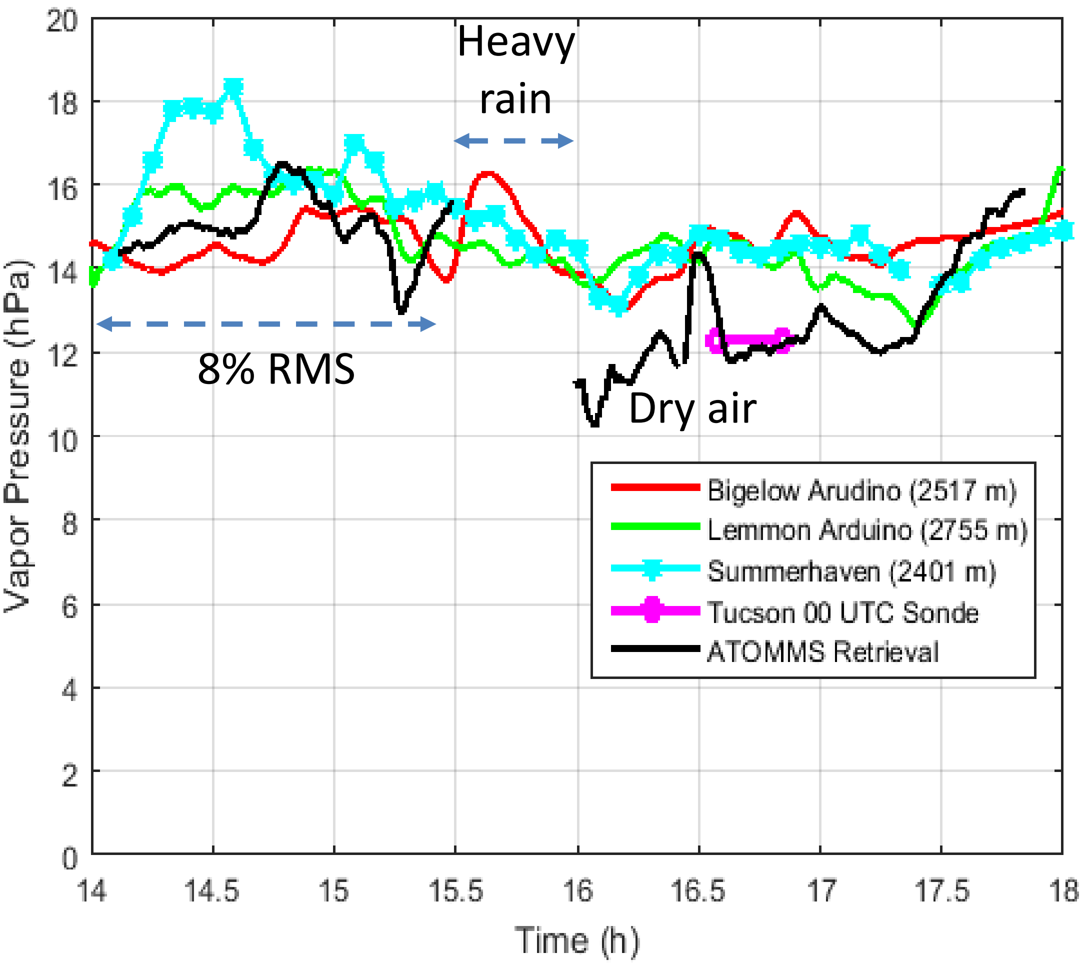
- **Extremely little ambiguity even in rain**
- **Stdev < 1%**
- Ward et al. (2015) resubmitting to GRL

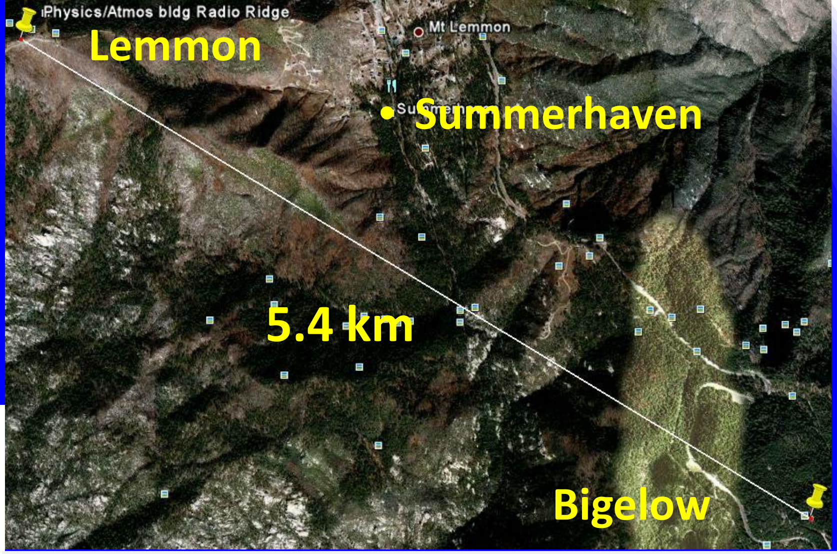


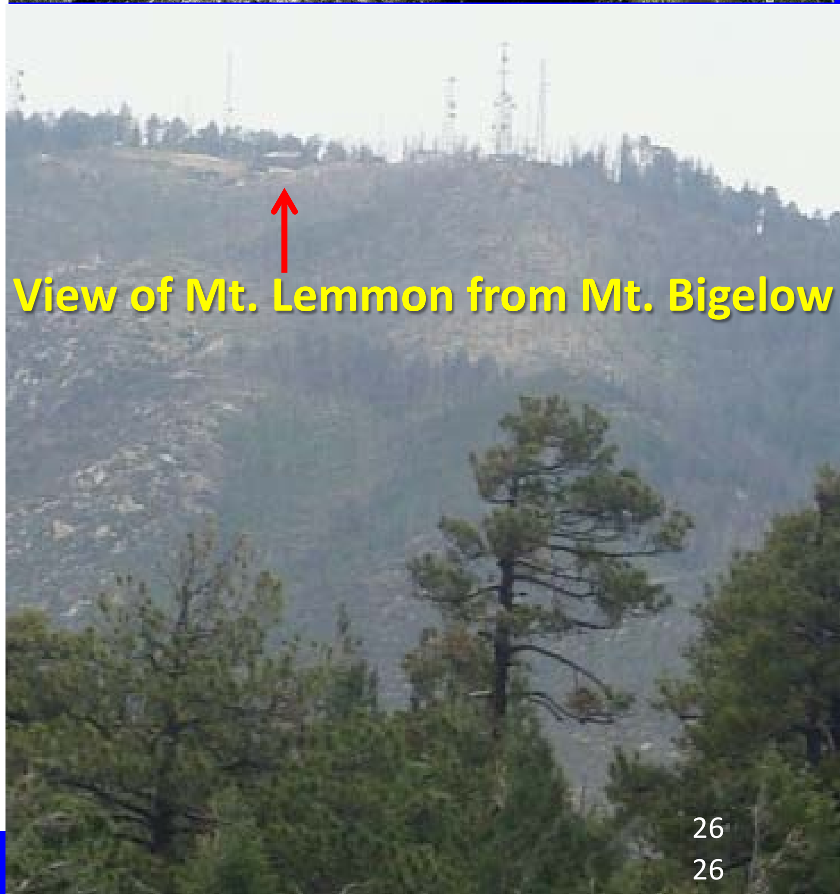


ATOMMS - *in situ* Water Vapor Comparison

- 3 nearby in situ sensors







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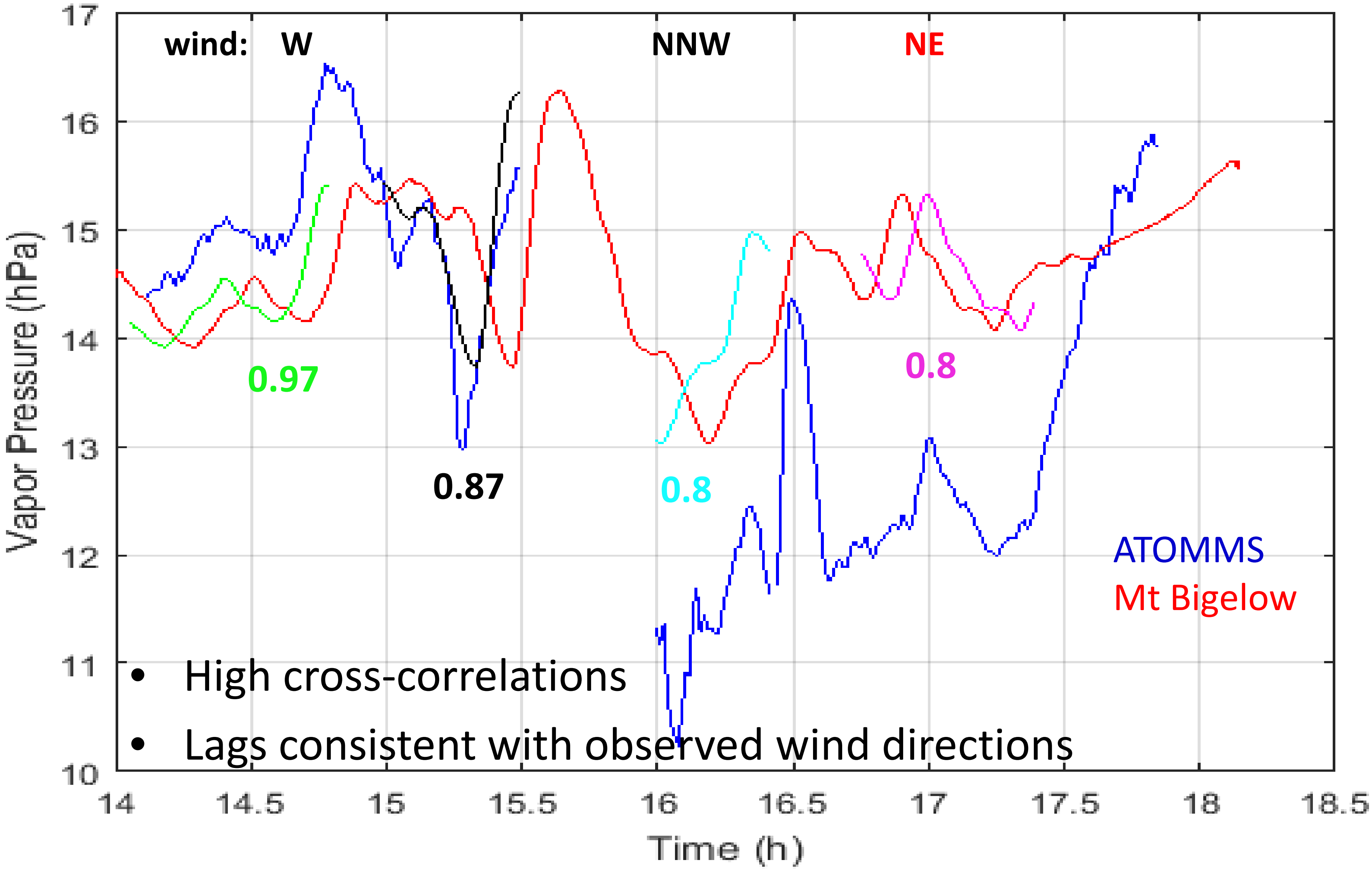
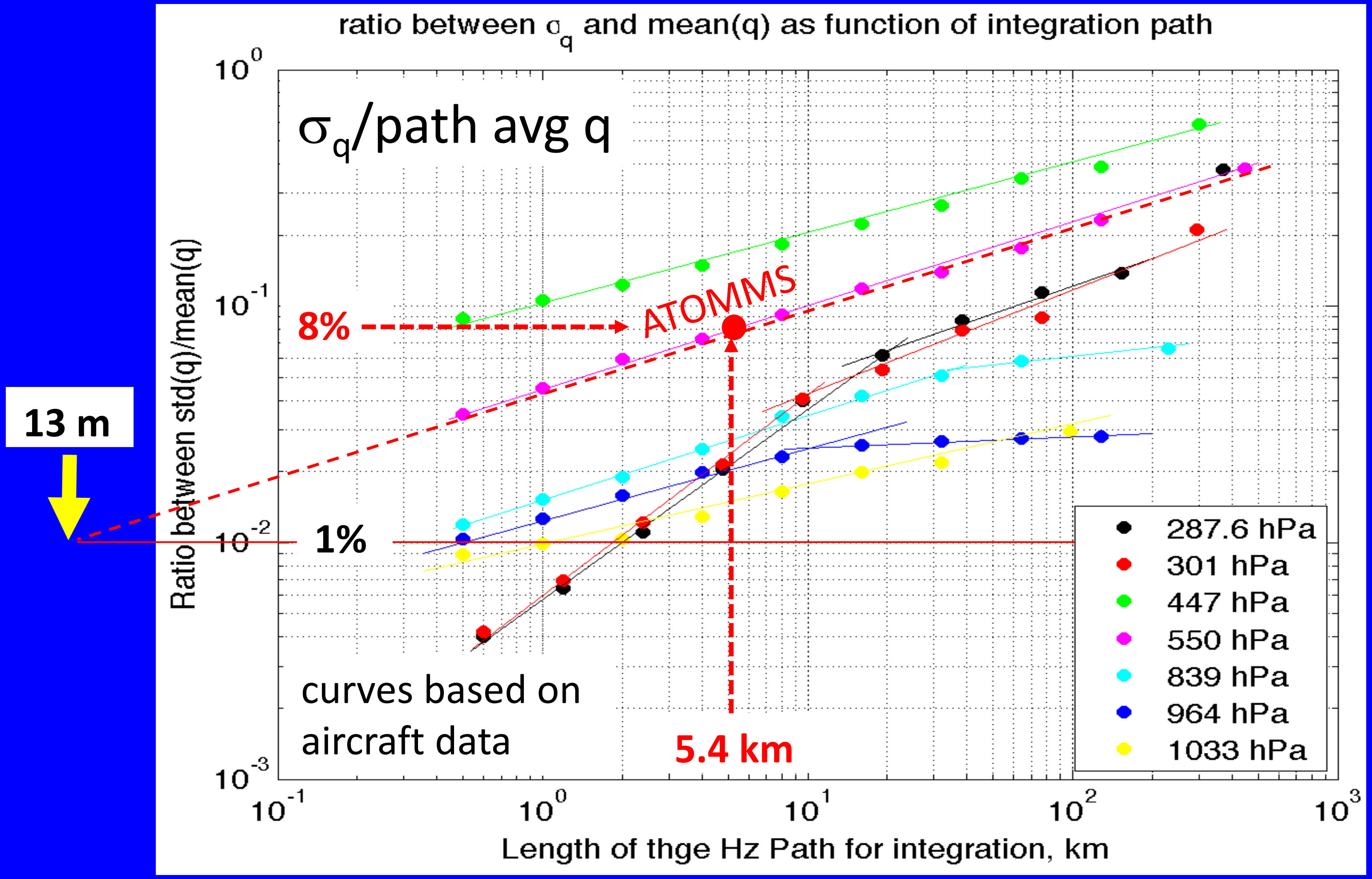
Correlations: ATOMMS vs. Mt Bigelow *in situ*



- High cross-correlations
- Lags consistent with observed wind directions

Challenge: How to validate a 5.4 km path average to 1%

- Requires ~400 1% *in situ* sensors, placed every 13 m along the **elevated** path, that operate to 1% in intense thunderstorms
  - **Is this realistically doable**?



Backup slides

Example: High Latitude Profiling

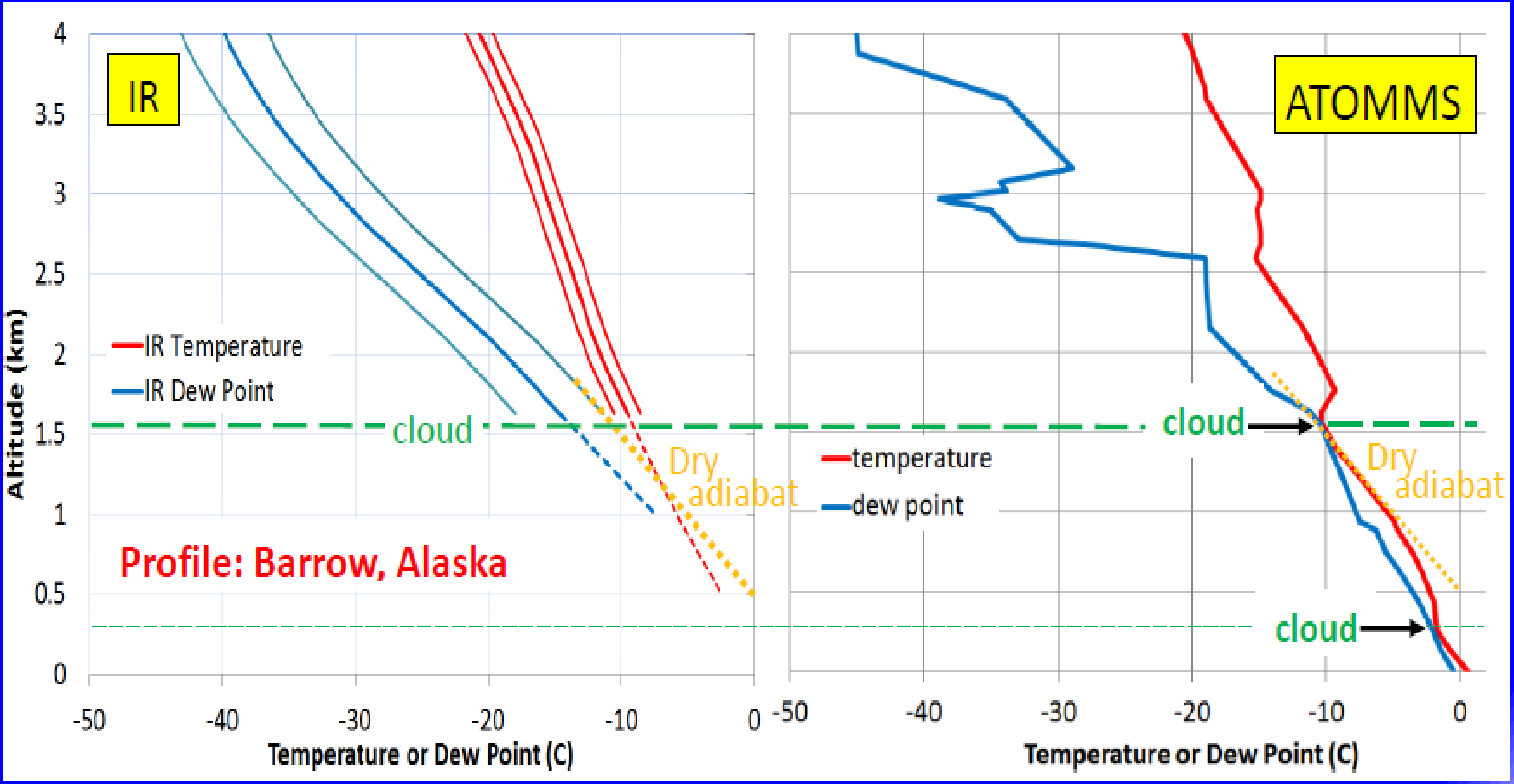
Large spread among sea ice melting predictions

- Uncertainties in modeled clouds & energy fluxes

Passive obs limited utility due to vertical resolution & sensitivity to surface emissivity & clouds

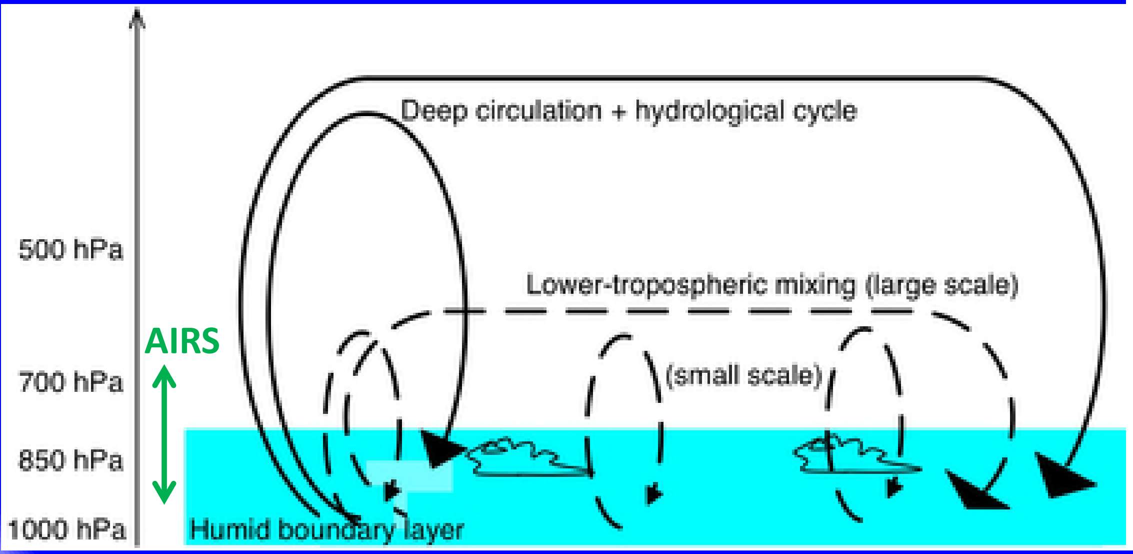
ATOMMS: routinely profile atmospheric structure to surface, **sonde-like with better accuracy**

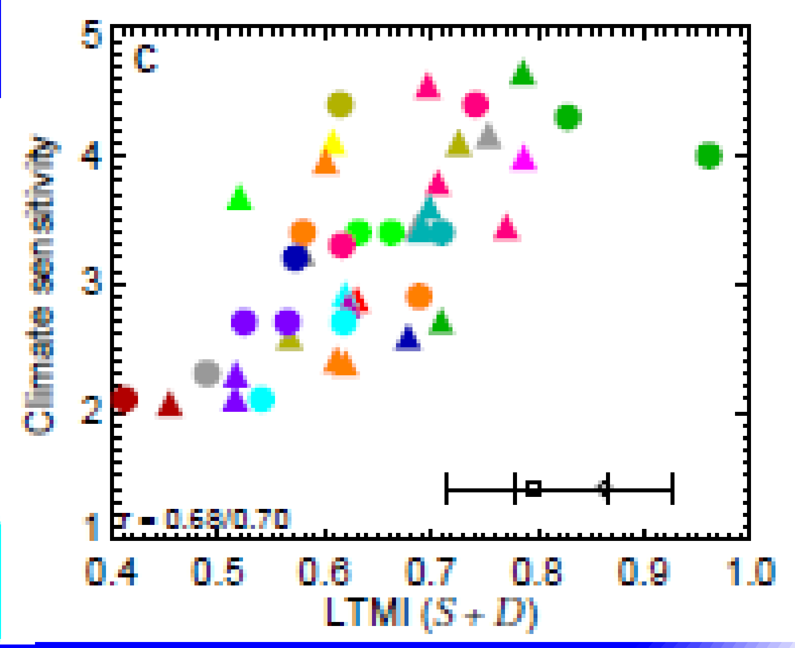
- **Resolve near surface temperature, stability, water vapor & cloud LWC structure**



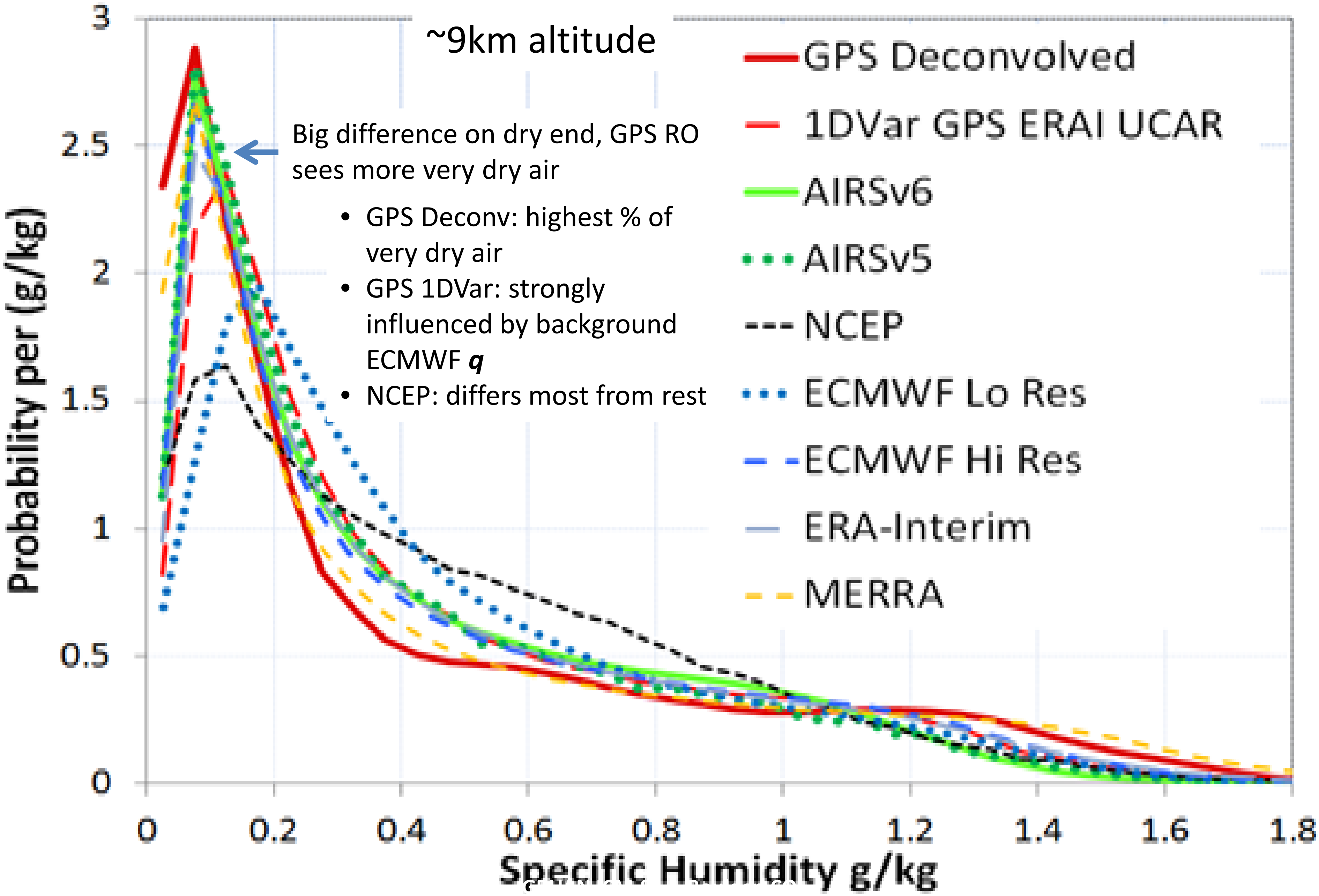
Sherwood et al. (2014) Reduction in Climate Uncertainty?

- As climate warms, models indicate stronger mixing => dehydrates BL
  - $\Rightarrow$ Reduces low cloud cover => lowers albedo => more SW absorption
- Increase in mixing & dehydration of low-cloud layer in warmer climate proportional to mixing strength in present climate
- Evaluated model mixing against "observations" (= MERRA analyses)
  - $\Rightarrow$ High climate sensitivity **>** 3°C for CO_2 doubling.

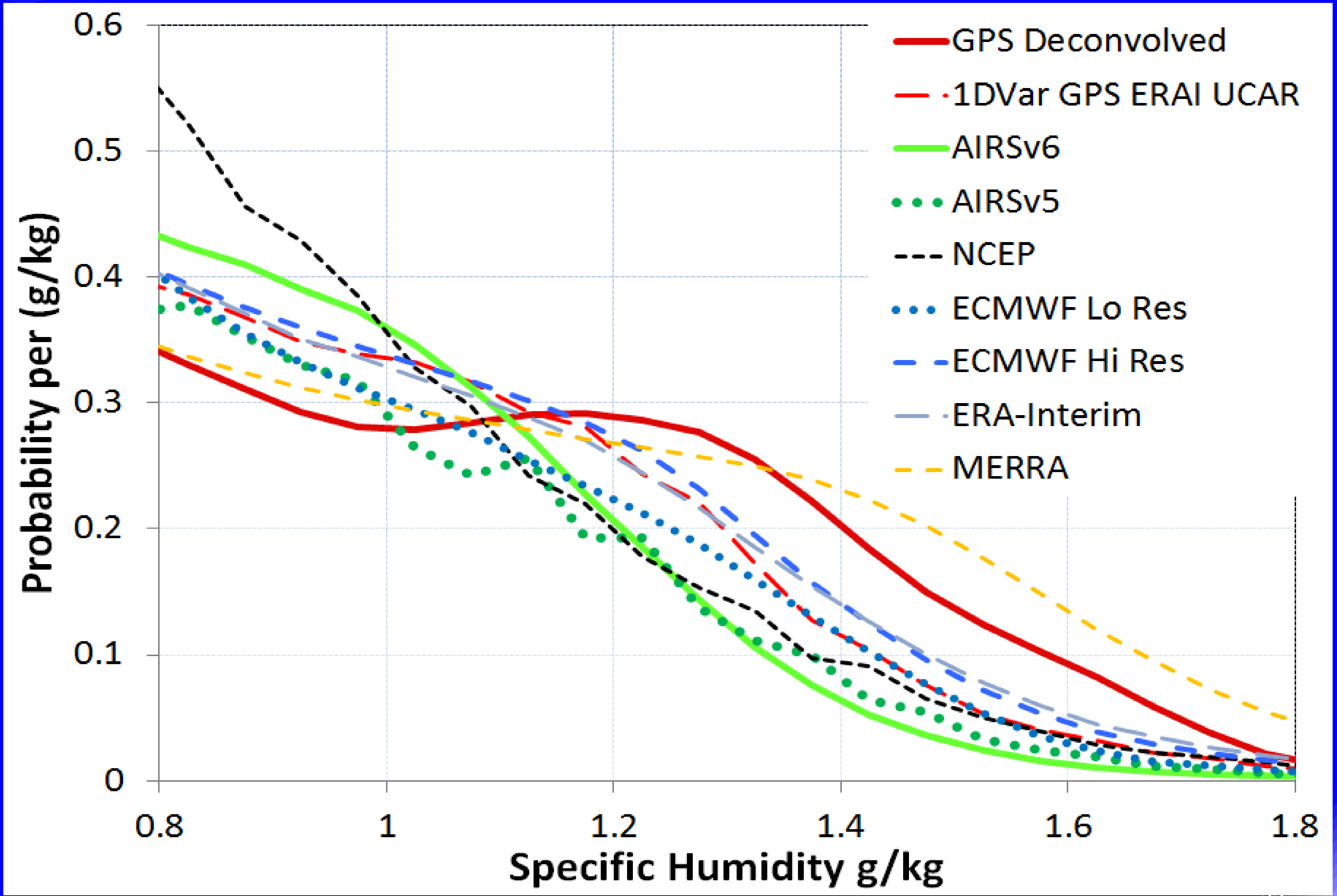




0.05 g/kg res. **346 hPa** Specific Humidity 30S-30N 2007



346 hPa Low Latitude Comparison (2007)



Comparison of Estimates of Low Latitude Humidity Means

- Specific humidity: 30S-30N annual averages
- Means

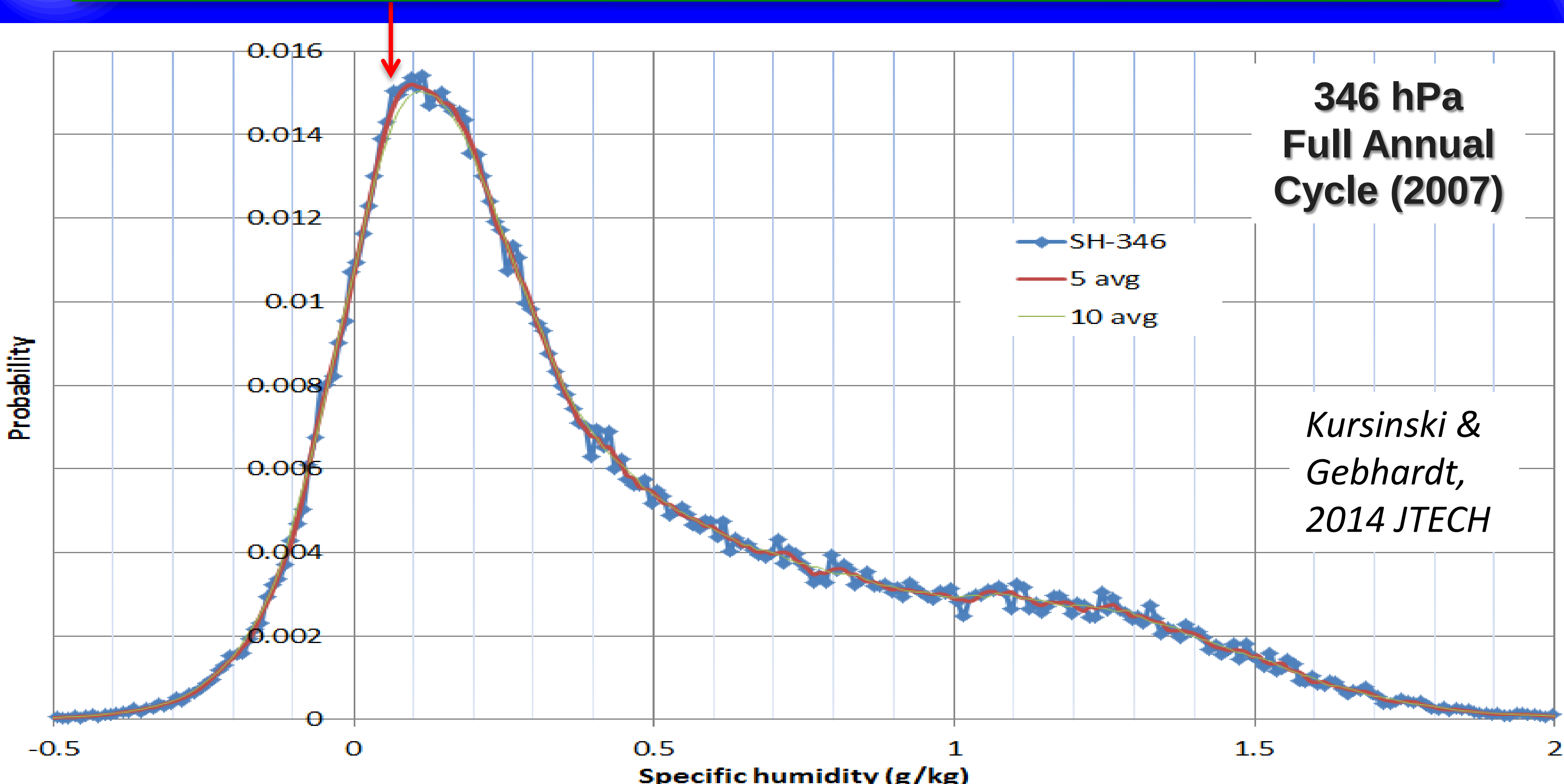
	GPS	AIRS v5	AIRS v6	ECWMF lo-res	ECMWF hi-res	MERRA	NCEP	Sat-Adv
346 mb	0.439	0.397	0.411	0.448	0.448	0.48	0.496	0.456
547 mb	2.22	2.12	2.12	2.29	2.14	2.43	1.98	2.51

- Fractional Differences Relative to GPS RO

	GPS	AIRS v5	AIRS v6	ECWMF lo-res	ECMWF hi-res	MERRA	NCEP	Sat-Adv
346 mb	0.0%	-9.6%	-6.4%	2.5%	2.5%	**9.0 %**	13.5%	4.3%
547 mb	0.0%	-4.6%	-4.6%	3.2%	-3.6%	**9.5 %**	-10.8%	13.1%

- Lots more going on than is captured in the means
  - MERRA histogram shapes closest to GPS but biased high in terms of mean

Constraining the GPS RO H_2O Vapor Bias



- 0.01 g/kg wide bins at 347 hPa => Sharp roll-off below 6th positive bin
- Expected due to coldest detrainment near 200 mb that returns to troposphere (Hartmann et al., 2001)
- Suggests **bias is no more than 0.03 g/kg** (Kursinski & Gebhardt 2014)