

# GPS RO Water Vapor & GRUAN

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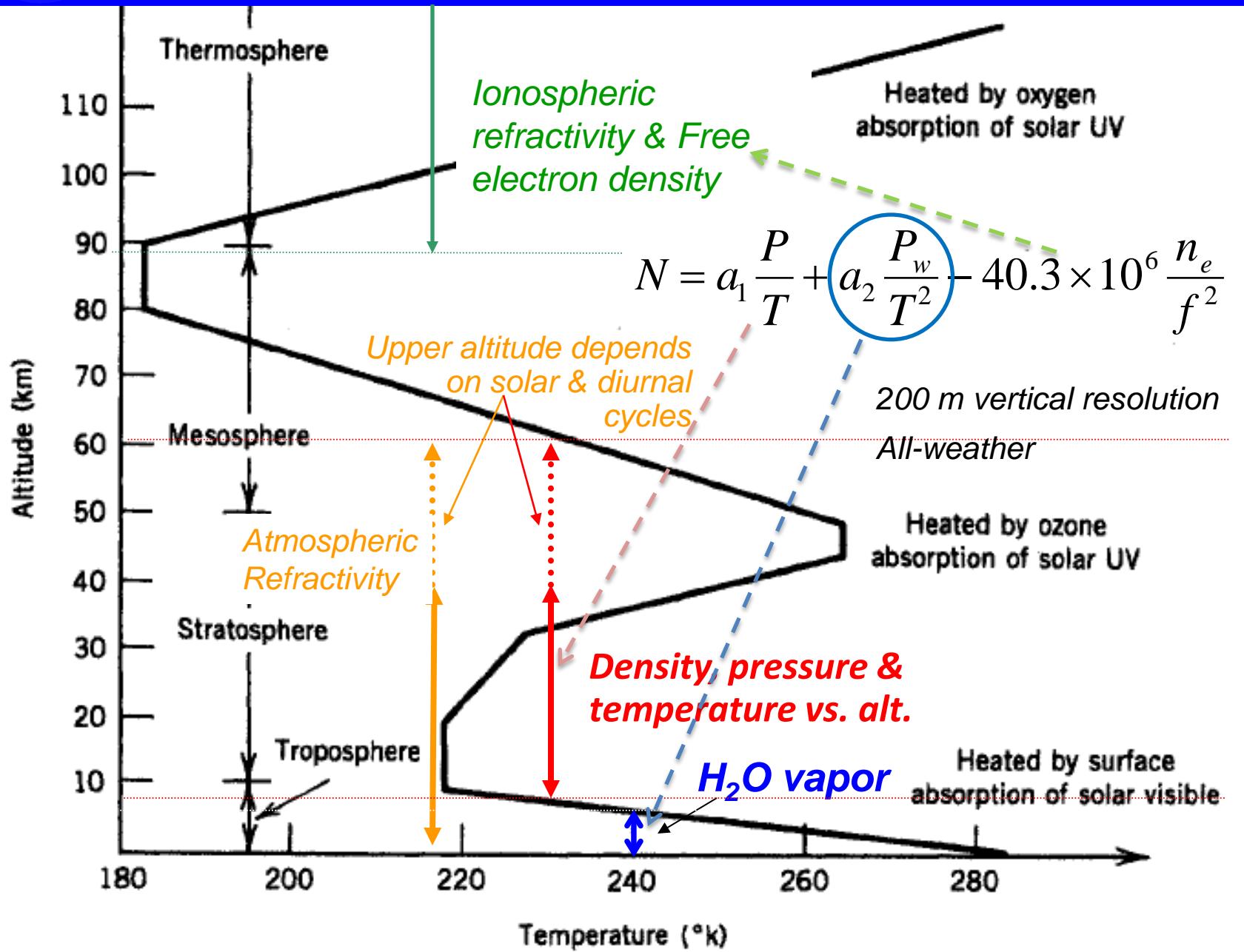
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# Outline

- Background on GPS RO water vapor
- Moisture histograms & Error estimates
- Moisture histogram comparisons
  - 346, 547 & 725 hPa

# GNSS RO Information vs. Altitude



# What does GNSS RO offer for H<sub>2</sub>O?

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

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

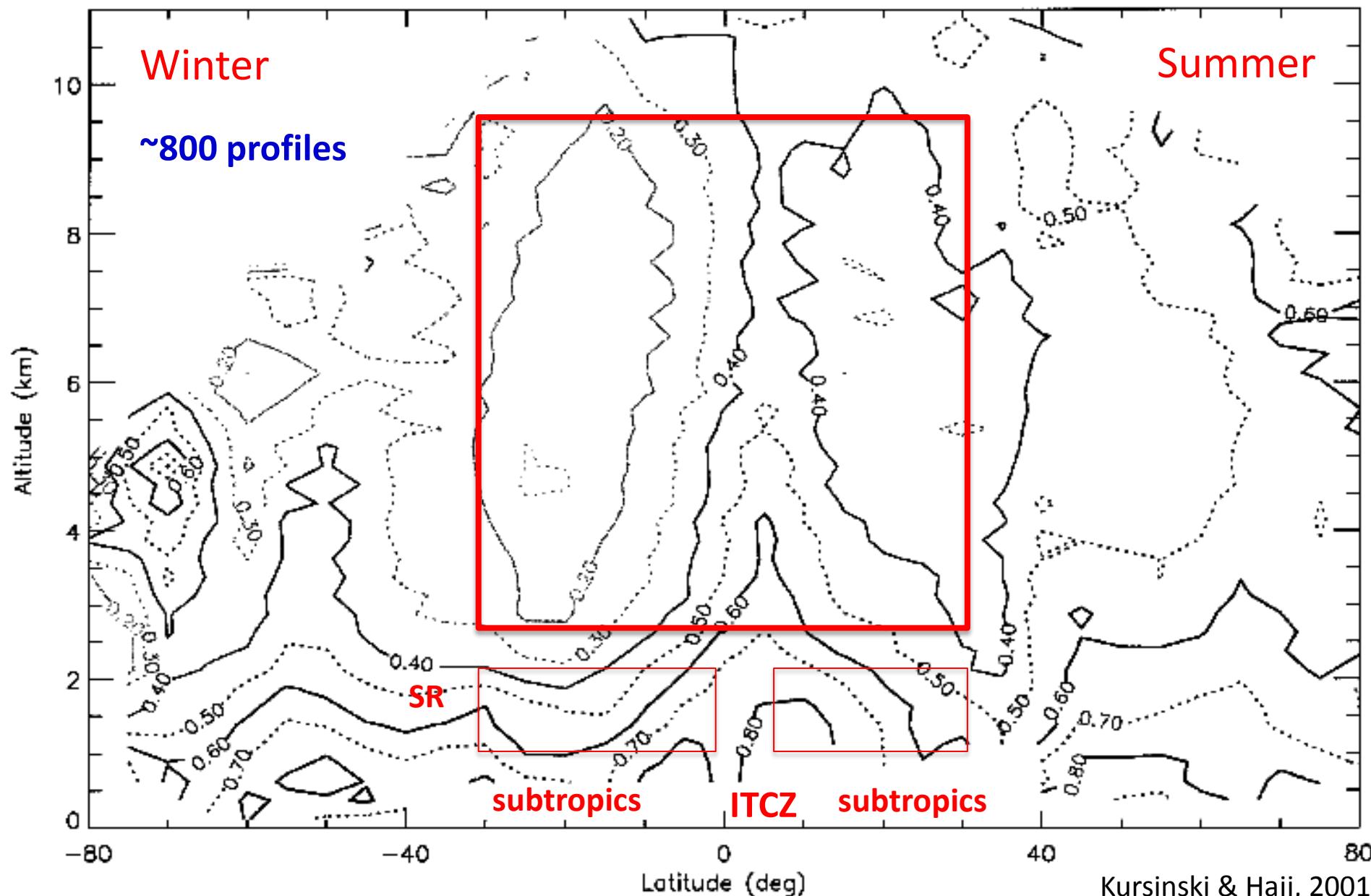
- Refractivity is sensitive to tropospheric water vapor
  - Bending angle particularly sensitive to water vapor
- Very high vertical resolution (~200 m) well matched to observing vertical scale variations of water vapor
  - Corresponding horizontal resolution is ~70 km
- Profile thru clouds to observe very wet air in & below clouds
- Focus on free troposphere
  - Avoid super-refraction problem for now
- Anticipated impact of GPS RO humidity information on NWP has not yet materialized
  - Reason: GPS RO sampling very sparse globally thus far

# GPS RO Features Summary

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- Least biased data set available?
  - Global coverage
  - Diurnal coverage with  $> 6$  satellite constellation like COSMIC
  - Works in clear & cloudy conditions ( $\lambda \sim 20$  cm)
  - Works over land & water (insensitive to surface emissivity)
  - Unique relation between bending angle & refractivity (except super-N) insensitive to initial guess
- Vertical range
  - Useful to ~240 K level in troposphere (~9 km alt. at low latitudes) (can go colder & higher if doing zonal averages)
  - Extends down very close to surface in extra-tropics
  - If we can deal with *super-refraction*, profiles can extend down to the surface at low latitudes

# Zonal Mean Relative Humidity GPS-MET Jun 21-Jul 4 1995



# Two Methods for Extracting Water Vapor from GPS RO Refractivity Profiles

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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
- ⇒ 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

# Moisture Histograms

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- Low order moments like mean & variance provide limited insight into water vapor distribution and the hydrological cycle
- Histograms of moisture on individual pressure levels provide much better indication of full range of behavior
- As well as insight into processes at work and adequacy of their representation in models

# Negative $q$ and Error Deconvolution

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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:  $q_{\text{measured}} = q_{\text{true}} + \varepsilon_q$

- Measured histogram (PDF) is then the convolution of the true PDF and the error PDF

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

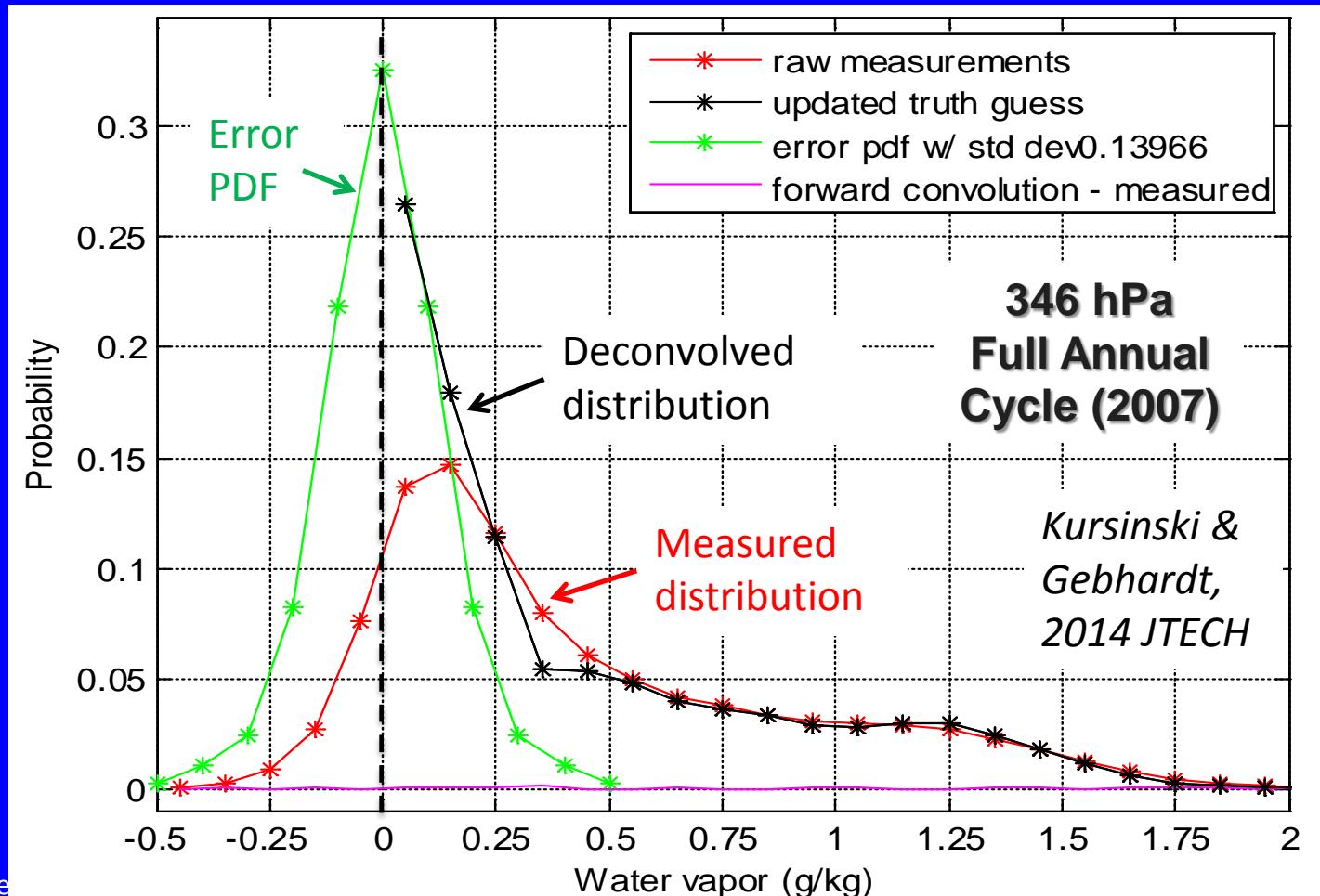
- If we understand the error PDF, we can then deconvolve it from the measured PDF to recover the true PDF

- 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



# Estimating the Accuracy of GPS-derived Water Vapor

- Kursinski et al. 1995: Initial estimate of GPS water profile accuracy
- Kursinski & Hajj, 2001: Error in specific humidity,  $q$ , due to errors in *refractivity, N, temperature, T, and pressure, P*, from GPS

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

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

$\sigma_q \sim 0.2 \text{ g/kg}$  in mid & upper troposphere.

$\sigma_q \sim 0.4 \text{ g/kg}$  in lower troposphere

Analogously, the error in relative humidity,  $U$ , is

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

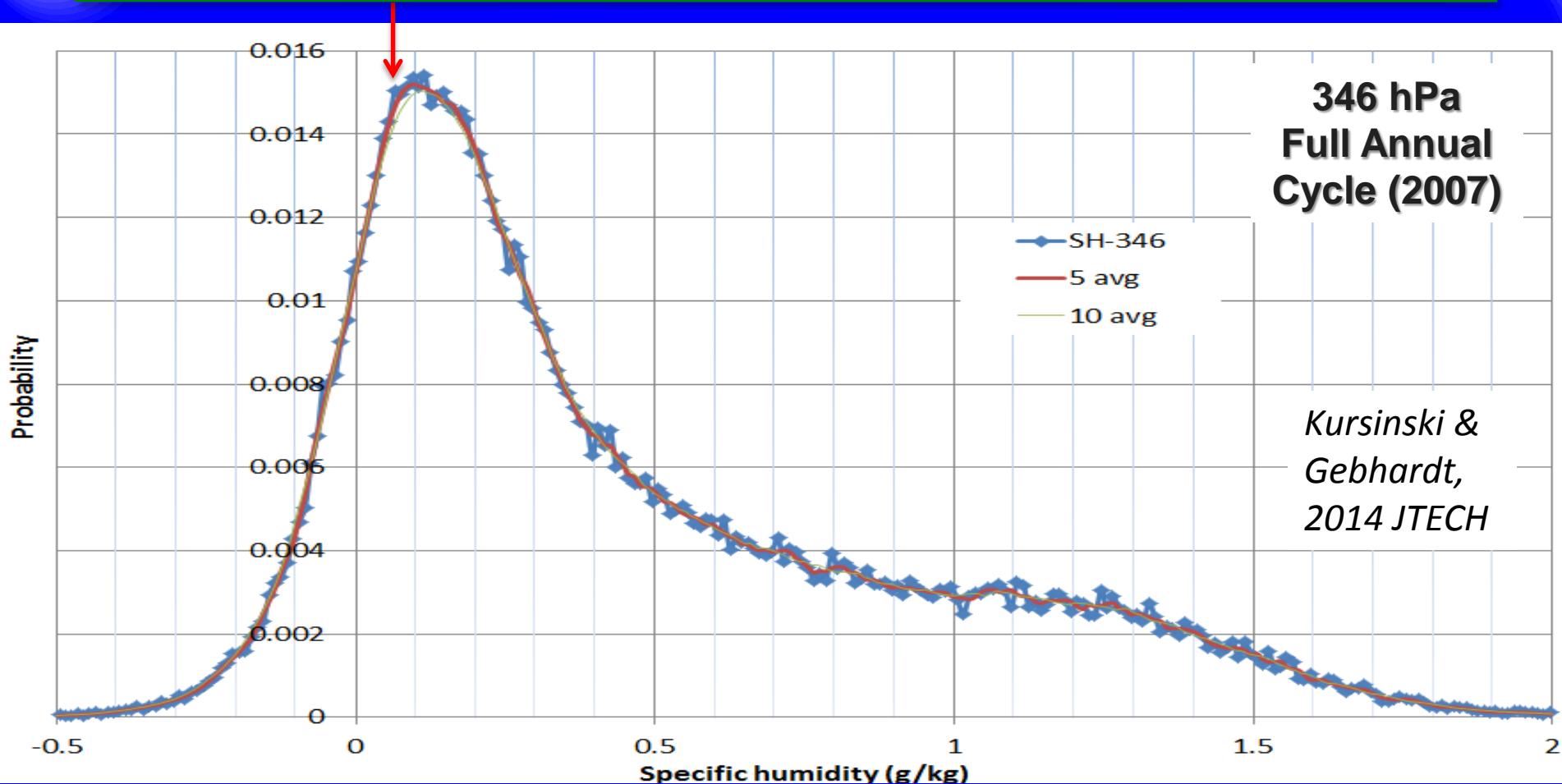
where  $L$  is the latent heat and  $B_s = a_1 T P / a_2 e_s$ .

# 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%

# Constraining the GPS RO H<sub>2</sub>O Vapor Bias



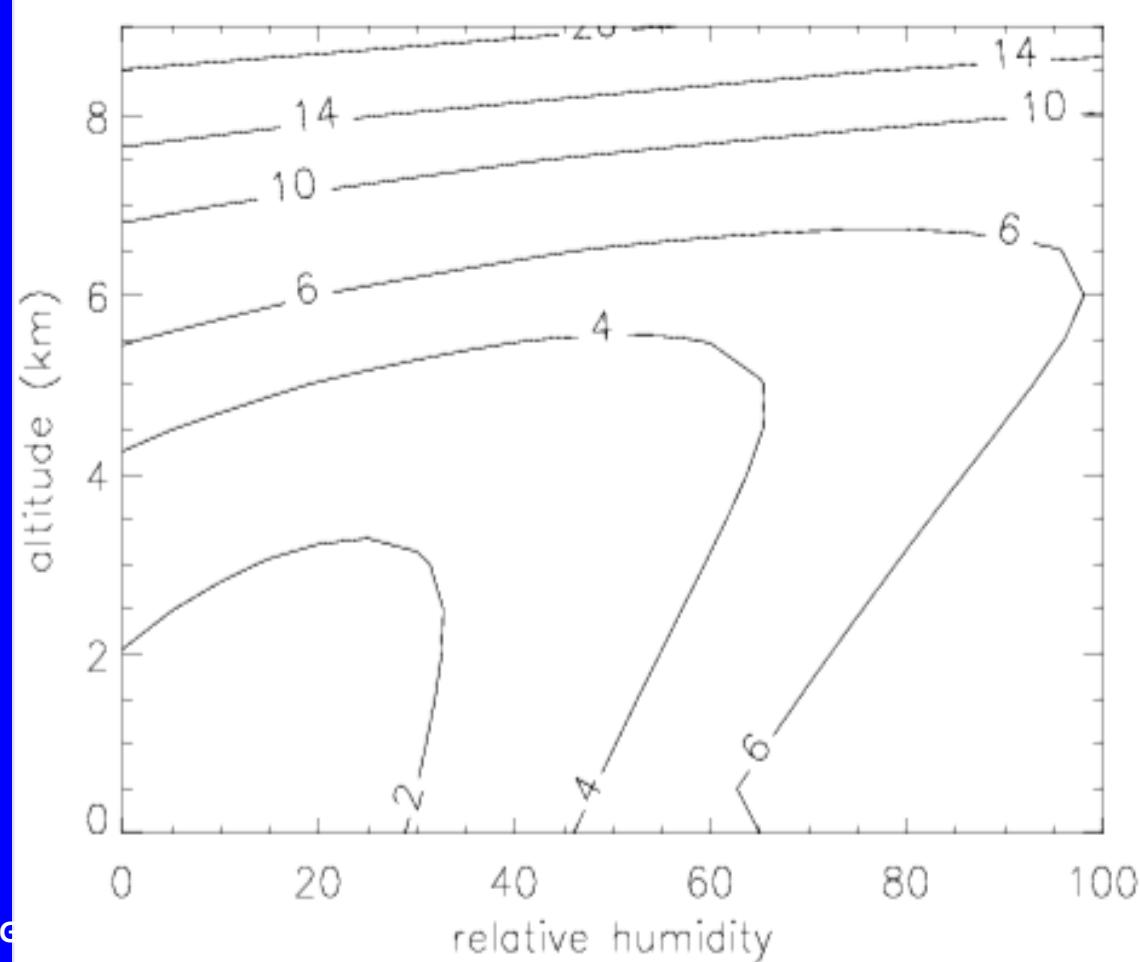
- 0.01 g/kg wide bins at 347 hPa => Sharp roll-off below 6<sup>th</sup> positive bin
- Expected due to coldest detrainment near 200 mb that returns to troposphere (Hartmann et al., 2001)
- Suggests bias is no more than 0.03 g/kg (Kursinski & Gebhardt 2014)

# Expected Relative Humidity Errors

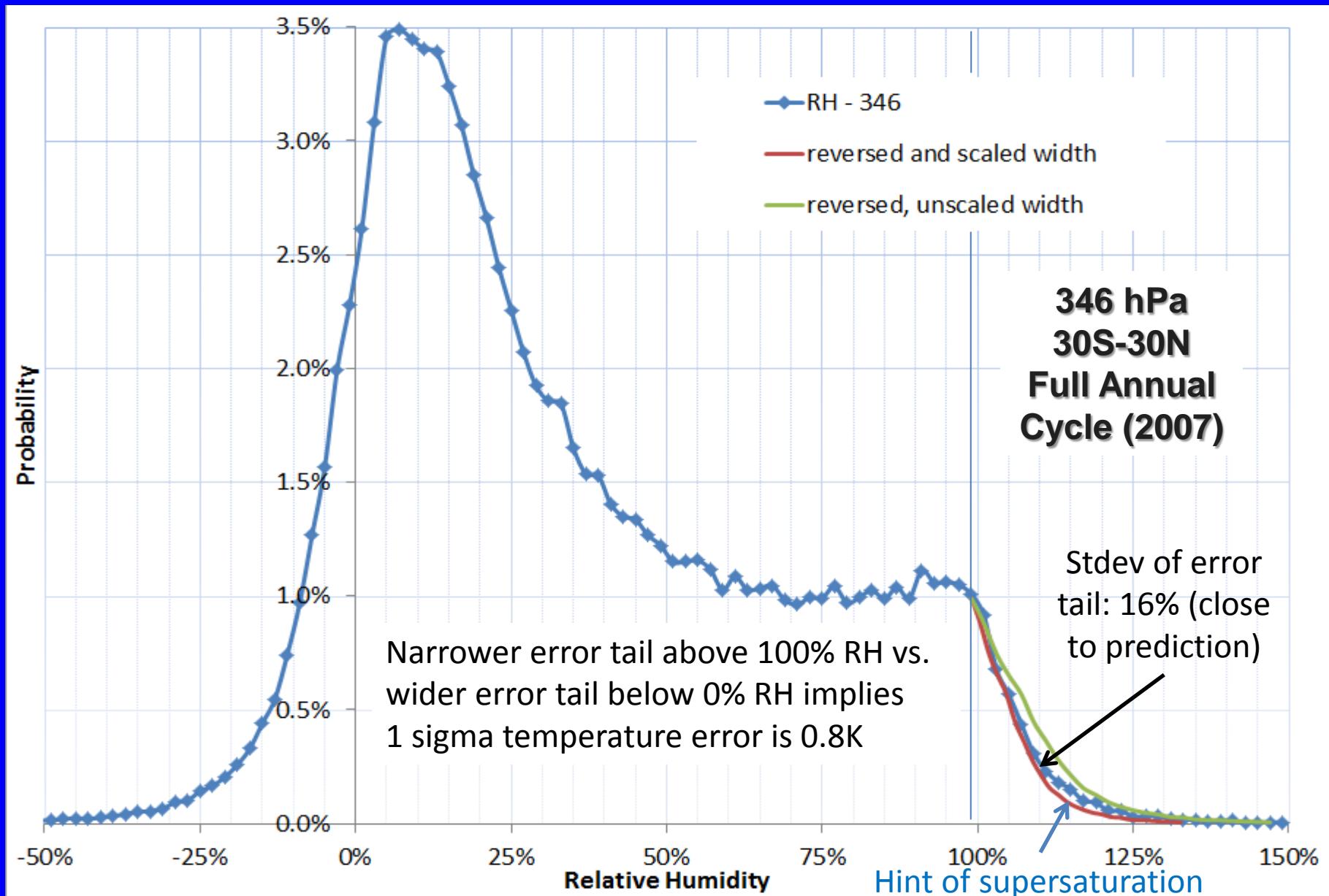
$$\sigma_U = \left[ (B_s + U)^2 \frac{\sigma_N^2}{N^2} + \left( B_s + U \left( 2 - \frac{L}{R_v T} \right) \right)^2 \frac{\sigma_T^2}{T^2} + B_s^2 \frac{\sigma_P^2}{P^2} \right]^{1/2}$$

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

Figure shows  
predicted low  
latitude, 1-sigma  
errors vs. altitude &  
relative humidity

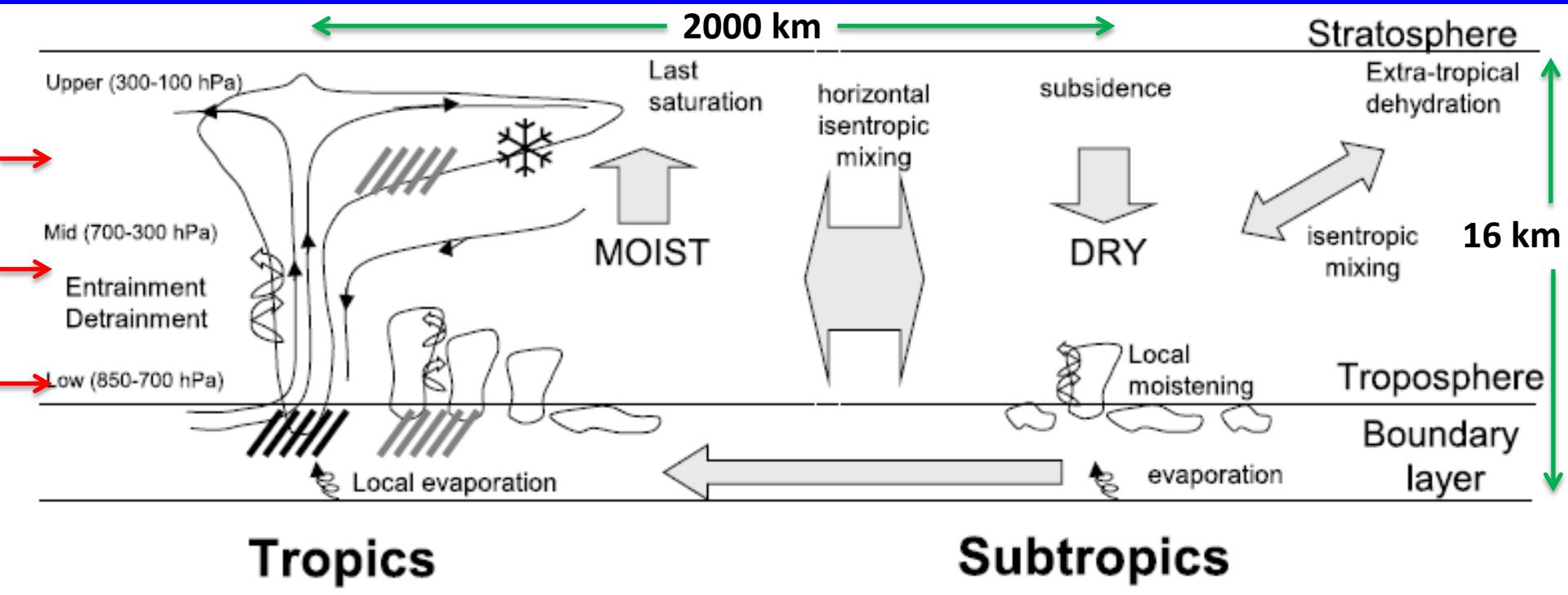


# Relative Humidity Histogram 346 hPa



# Low Latitude Moisture

- Convection creates extremes, stretching the H<sub>2</sub>O 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

GPS, MERRA & AIRS

agree well on very  
dry end in mid-  
troposphere

NCEP & AIRS  
overestimate mid-  
humidity air

ECMWF & NCEP  
analyses don't like  
really dry air

GPS deconvolved

GPS 1DVar UCAR

AIRS v5

NCEP

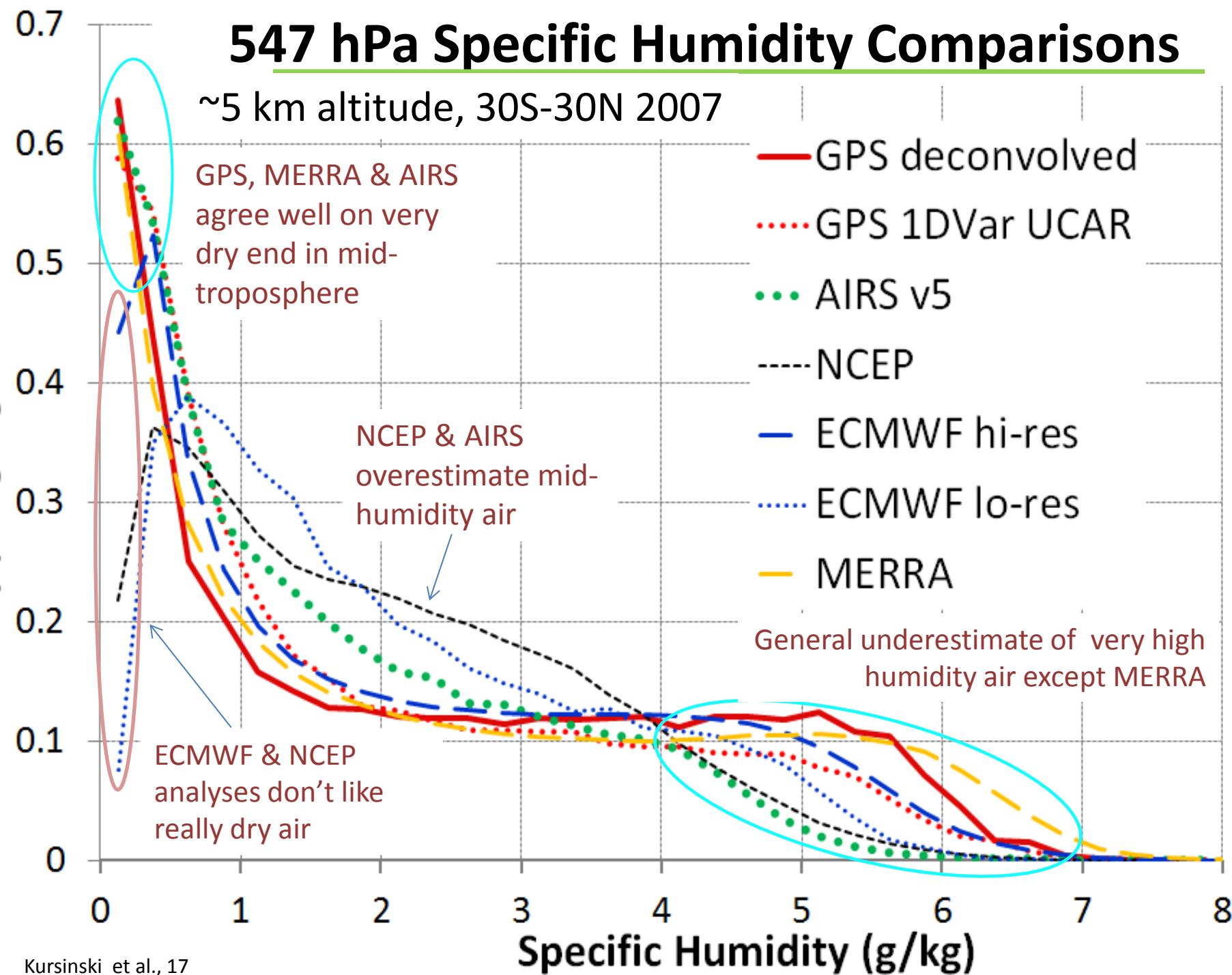
ECMWF hi-res

ECMWF lo-res

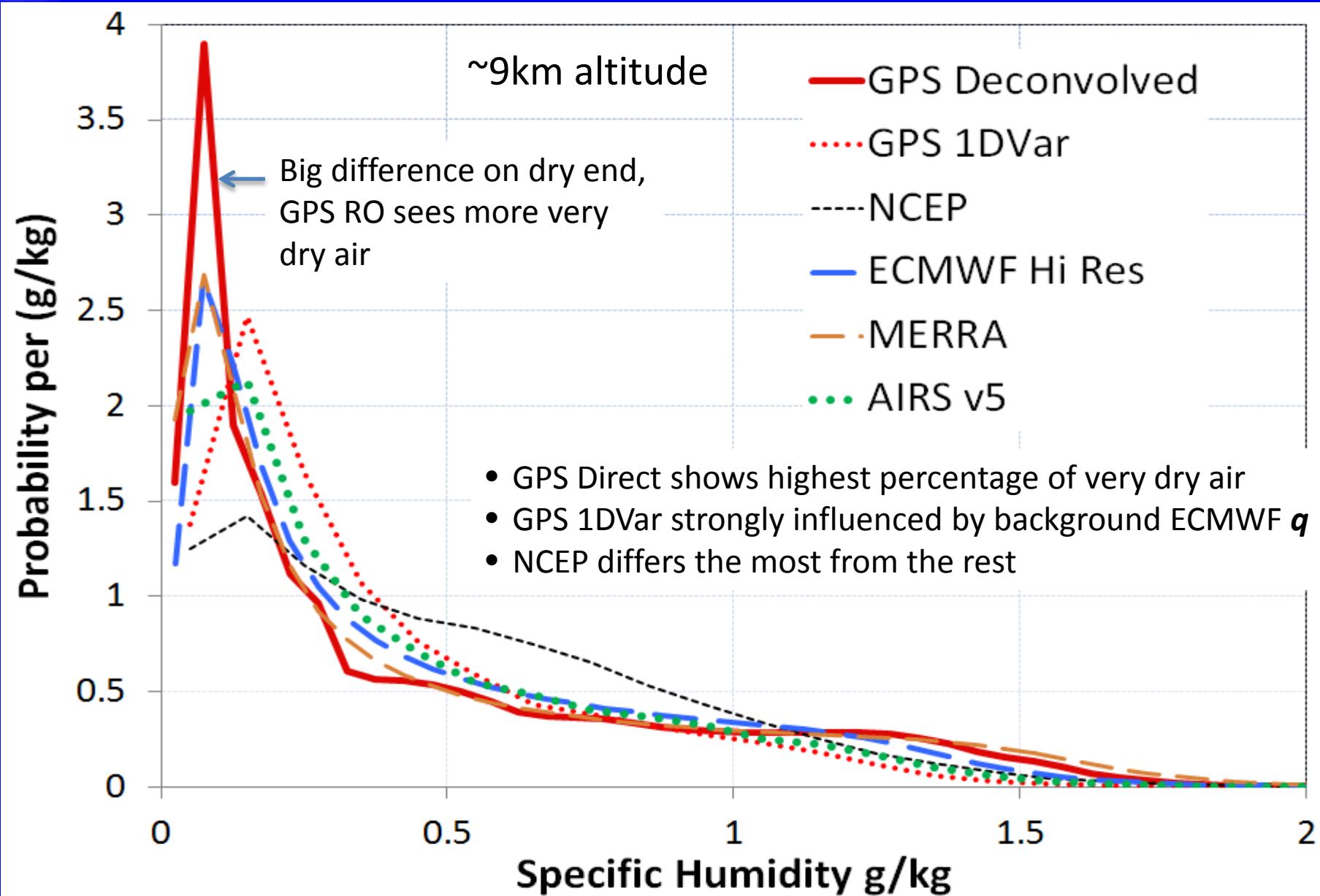
MERRA

General underestimate of very high  
humidity air except MERRA

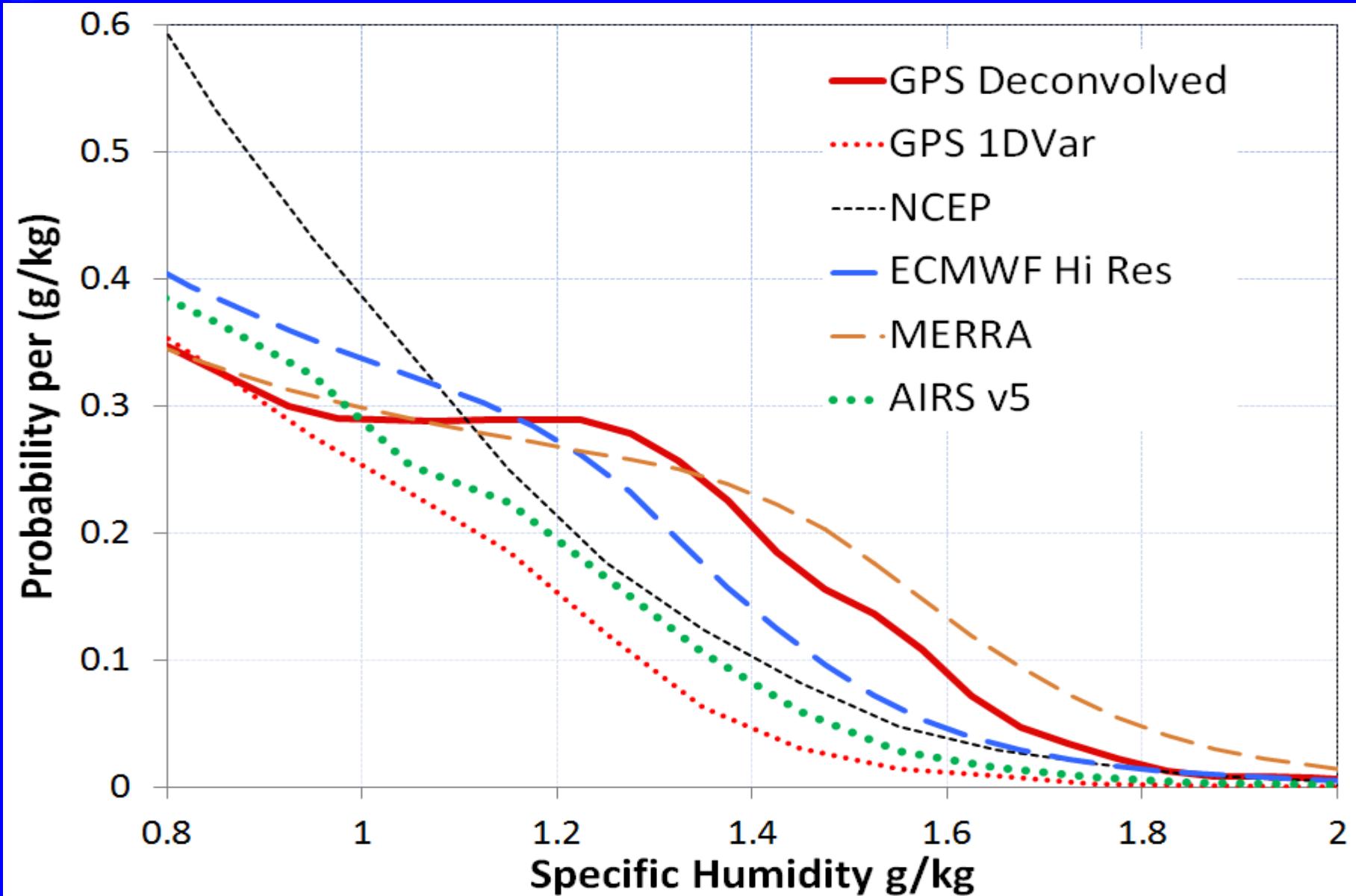
Probability per g/kg



# 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	ECWMF lo-res	ECMWF hi-res	MERRA	NCEP	Sat-Adv
346 mb	0.44	0.397	0.448	0.448	0.48	0.496	0.456
547 mb	2.22	2.12	2.29	2.14	2.43	1.98	2.51

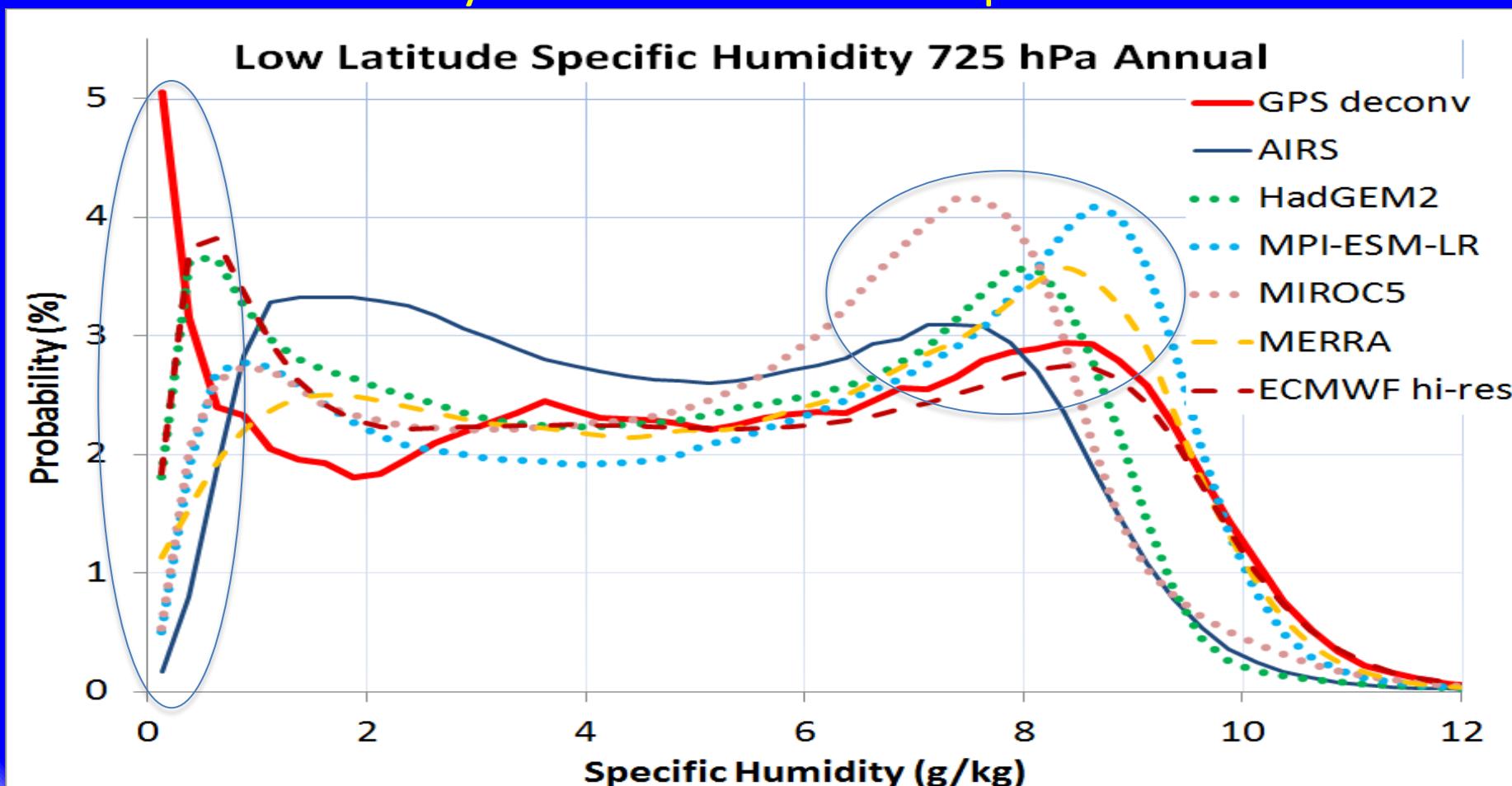
- Fractional Differences Relative to GPS RO

	GPS	AIRS v5	ECWMF lo-res	ECMWF hi-res	MERRA	NCEP	Sat-Adv
346 mb	0.0%	-9.1%	2.5%	2.5%	<b>9.0%</b>	13.5%	4.3%
547 mb	0.0%	-4.6%	3.2%	-3.6%	<b>9.5%</b>	-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

# 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
- Models & analyses miss driest subtropical air



# Vertical & Horizontal Resolution Near 725 hPa

