# Insights into the Hydrological Cycle Revealed by GPS RO & its future cousin, ATOMMS

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Special thanks to Feiqin Xie (Texas A&M) & Mark Ringer (Met Office)

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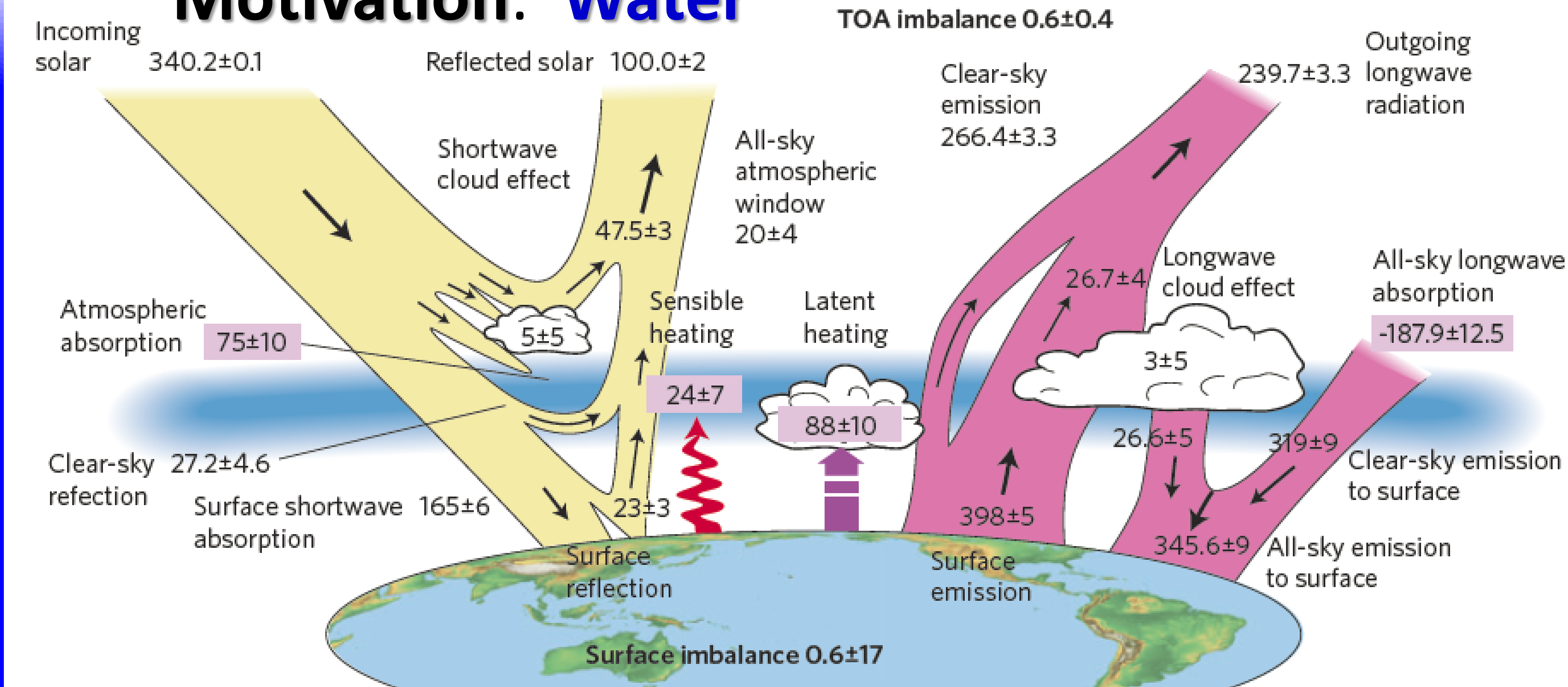
# Outline

- Motivation
- Background on GPS RO water vapor
- NWP impact
- Moisture histograms & comparisons
- Reduced climate prediction uncertainty?
- ENSO signatures
- ATOMMS overview

# Motivation: Water




## Water Vapor:

- Most important greenhouse gas
- Controlled by thermodynamics & dynamics
- Also drives dynamics
- Tied closely to clouds & precipitation

## Clouds:

Poorly understood, critical player in energy balance

## Precipitation:

Determines extent/type of continental biosphere

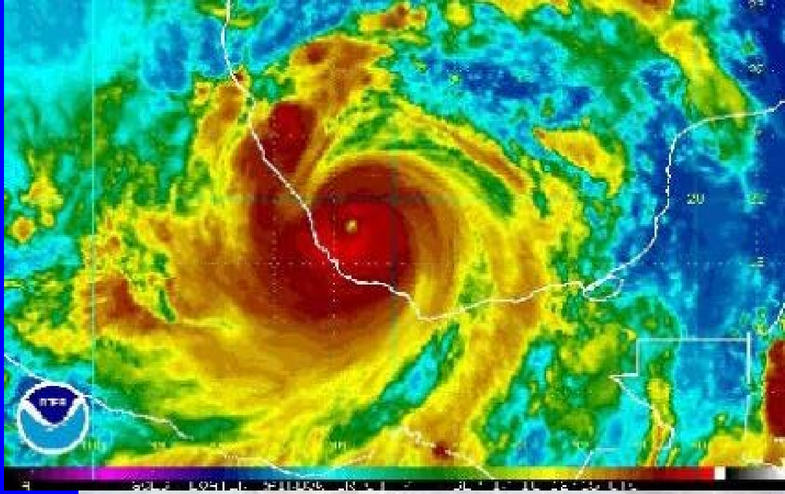
Vertical energy transport in the atmosphere

# Many concerns about climate change are water related

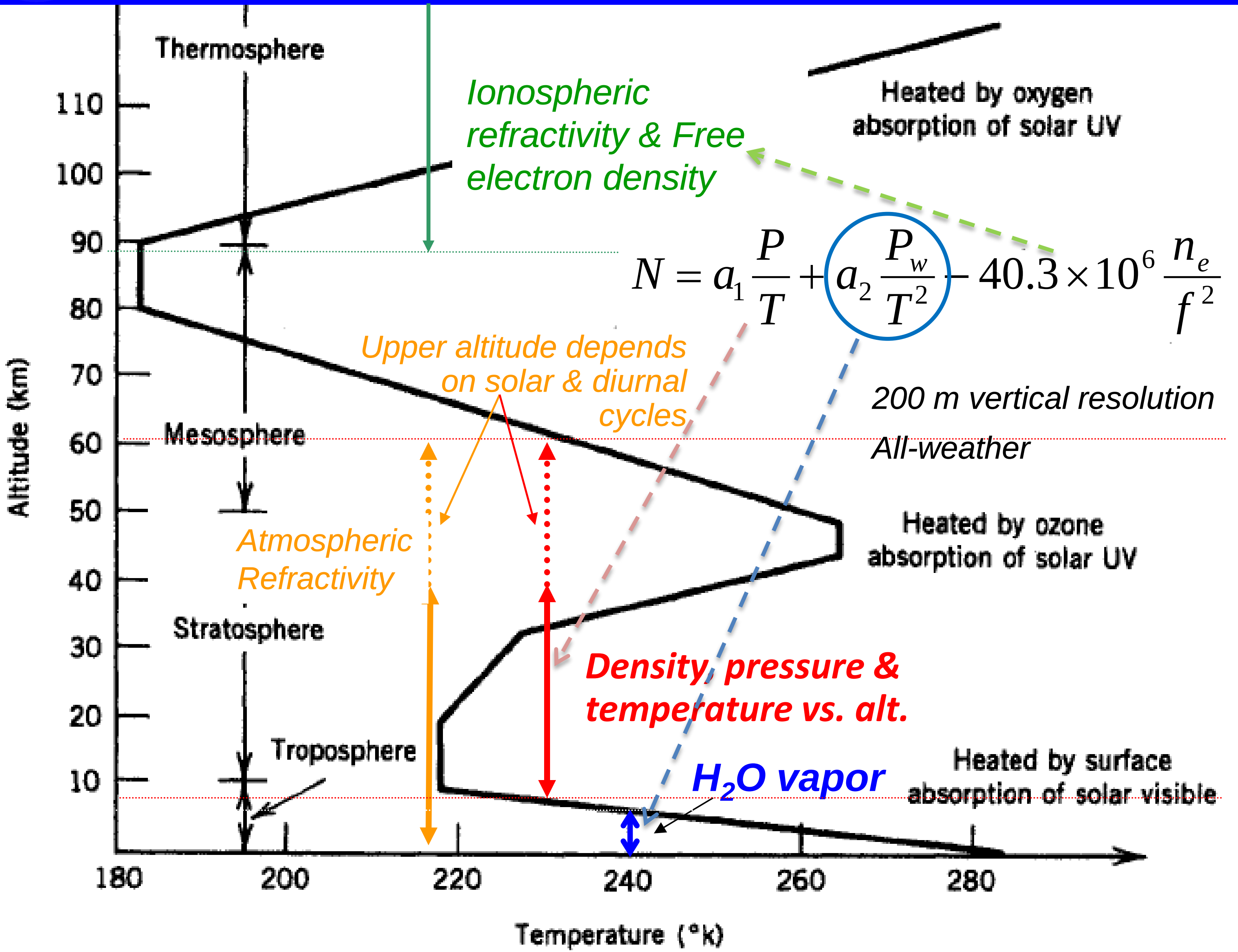
- Water vapor concentrations will increase (LT vs. UT),
- Changes in clouds are uncertain even in sign
- Continental ice melting => sea level rise
- Snow pack reduction: later freeze, earlier runoff
- More extreme weather, hurricane intensity increase
- Increase in intensity of extreme rainfall
- BUT time between rain events will also increase
    - More severe flooding

      ⇒Need to predict flash floods

  ⇒ Challenge: How do you keep water in reservoirs
- Soil moisture => nasty positive feedbacks



# GNSS RO Information vs. Altitude



# What does GNSS RO offer?

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

$$\alpha = \int d\alpha = 2a \int_{r_0}^{\infty} dr \frac{dn}{n\,dr} \frac{1}{\sqrt{n^2 r^2 - a^2}}$$

- Refractivity is sensitive to 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
  - Horizontal resolution is somewhat coarse (100-250 km)
- Profile thru clouds to observe very wet air in & below clouds
- Focus on free troposphere
  - Avoid super-refraction problem for the moment

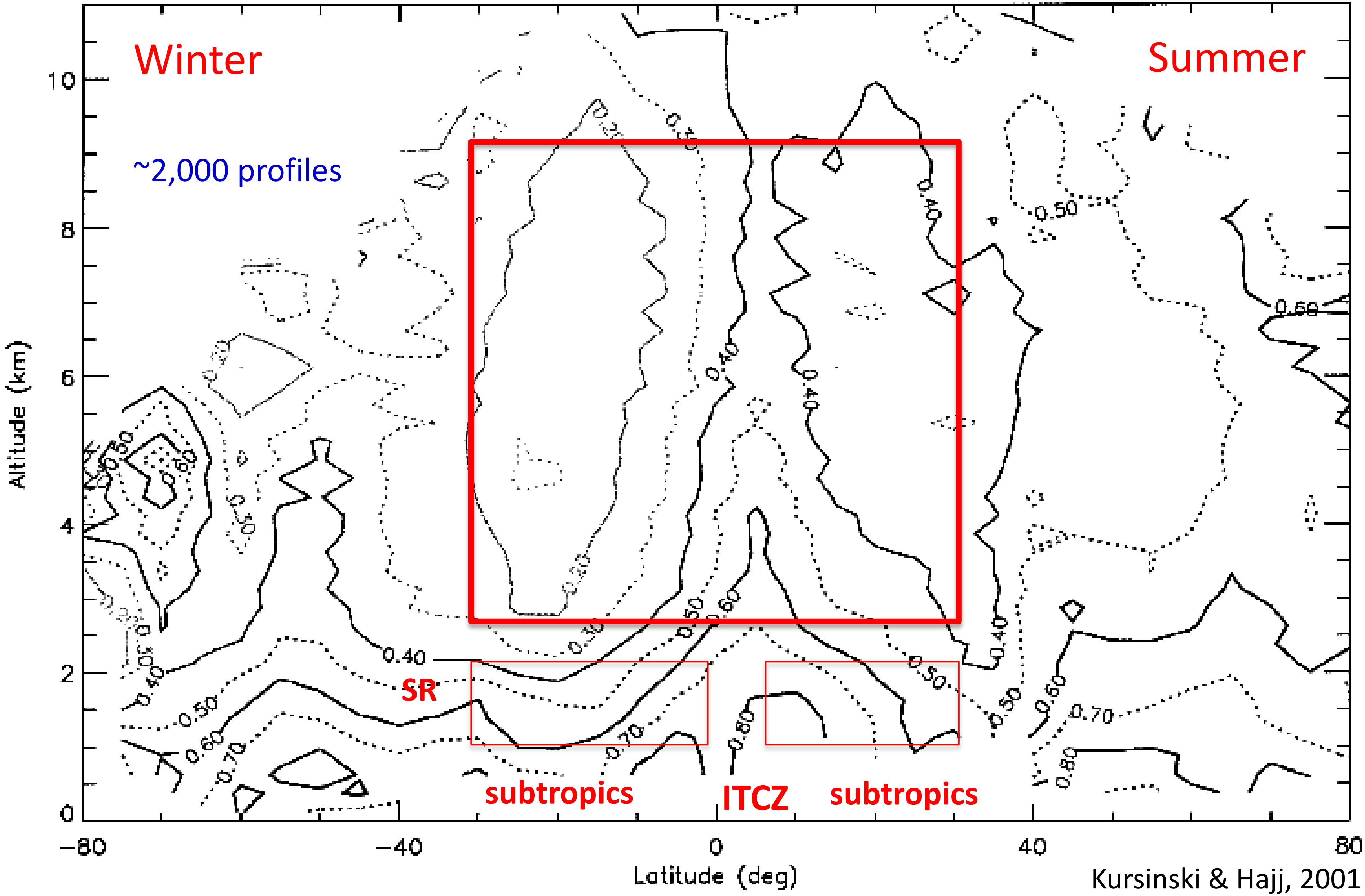
- Anticipated impact of GPS RO humidity information on NWP has not yet really materialized
- Will show there is a great deal of untapped, precise & unique information about water vapor in these RO data

# GPS RO Features Summary

- Least biased data set available?
  - Global coverage
  - Diurnal coverage with $\geq$ 6 satellite constellation like COSMIC
  - Works in clear and cloudy conditions ($\lambda$ ~ 20 cm)
  - Works over land and water
  - 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)
  - Extends down very close to surface in extratropics
  - 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




Kursinski & Hajj, 2001

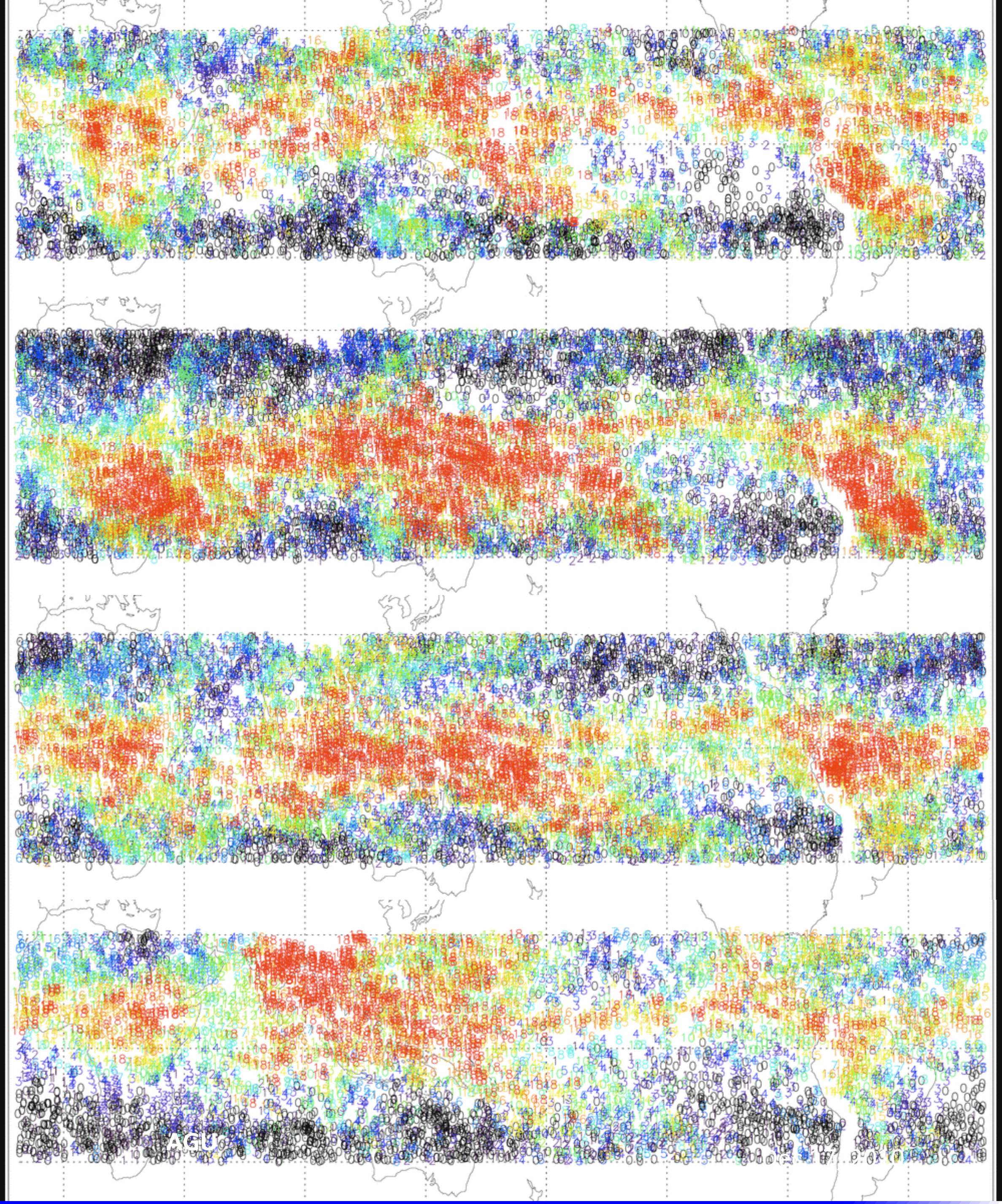
# **Free Tropospheric PW** from COSMIC

Oct 06

Jan 07

Apr 07

Jul 07

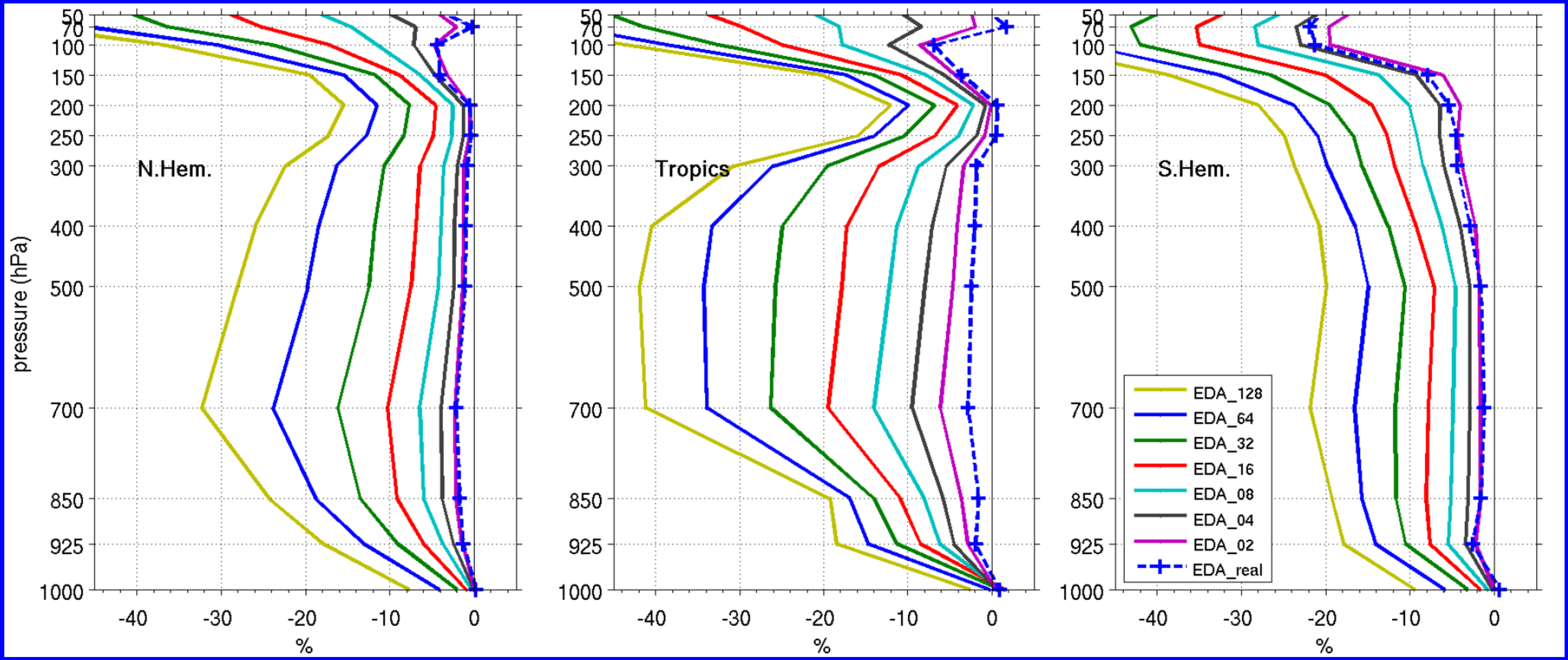


# NWP Impact

- GPS RO provides lots of information on water vapor
  - Global, all-weather sampling
  - Uniquely high vertical resolution
  - ~0.2 g/kg 1-sigma,
  - |bias| < 0.03 g/kg

# EDA Spread Reduction (%) for Relative Humidity Analysis

**From:** ***Estimating the optimal number of GNSS RO measurements for NWP &climate reanalysis applications-*** Florian Harnisch, Sean Healy, Peter Bauer (2012) ECMWF

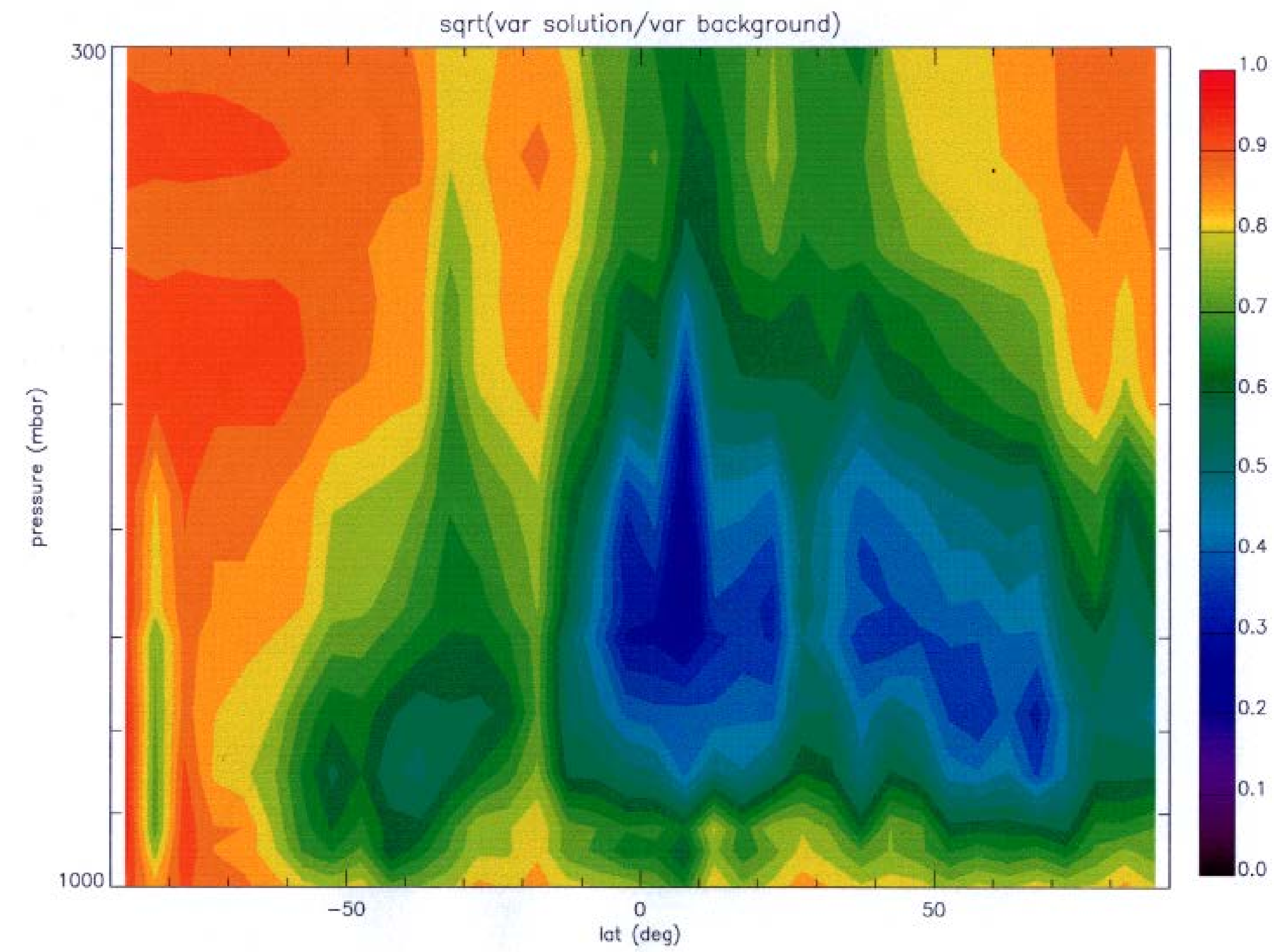



- Relative minimum of impact at 100 – 300 hPa
- Absolute humidity impact at altitudes below 300 hPa level
- Largest humidity impact on tropical troposphere (850 – 300 hPa)

# Early Prediction of RO Impact on NWP Humidity

- Kursinski, Healy & Romans (2000) in *Earth Planets and Space*
- 1DVar using refractivity

Essentially represents maximum impact, an occultation at every grid point at every NWP update




Kursinski et al., 12

# 6, 12, 100, 400 GNSS Occulting Satellites

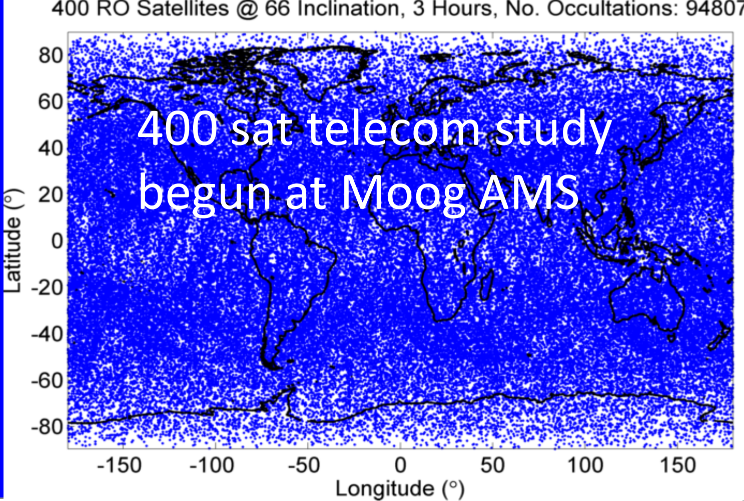
Present: 6 sats; GPS => < 3,000 occ/day

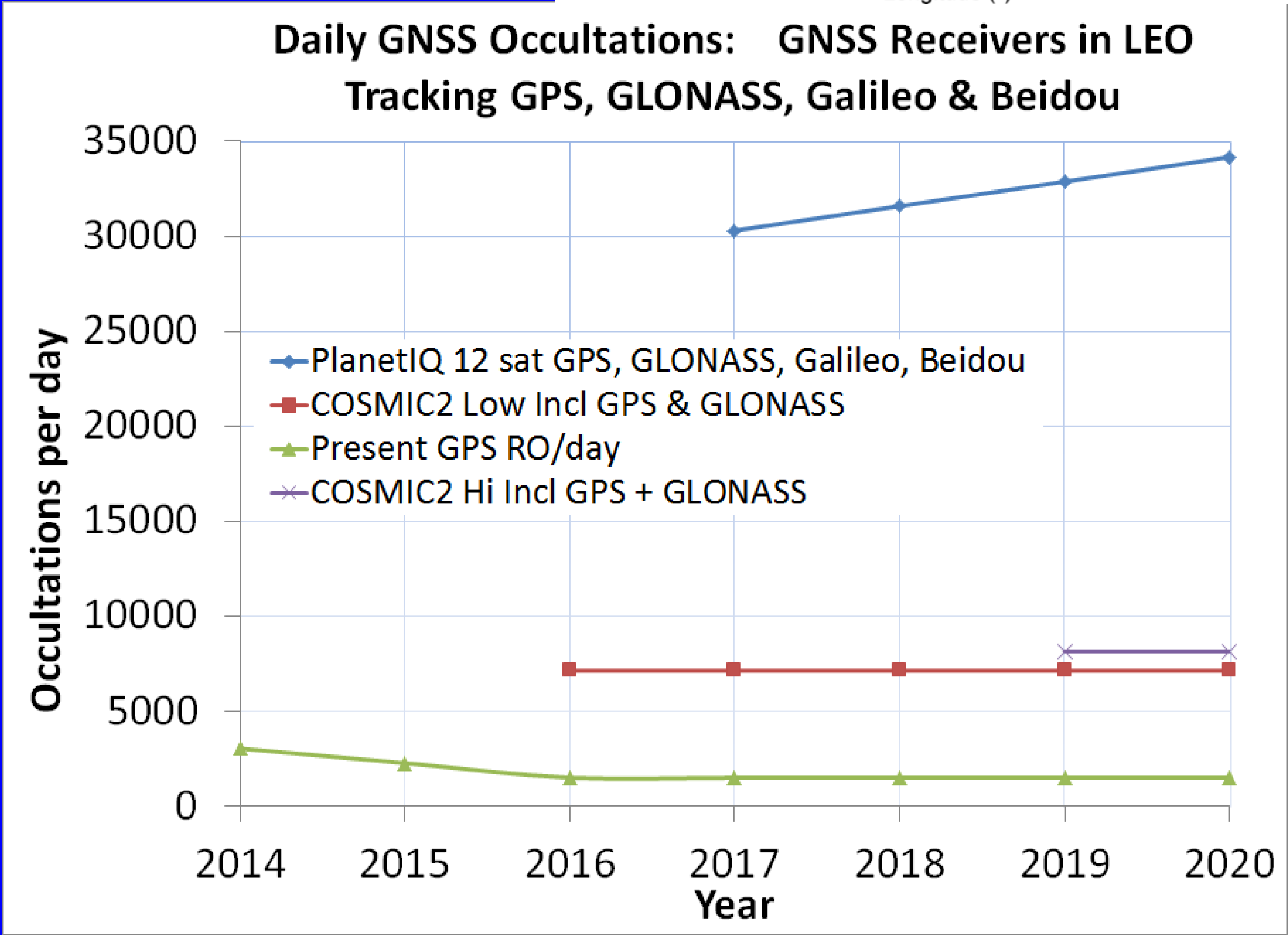
COSMIC2a: 6 sats; 2 GNSS => 7,000 occ/day

PlanetIQ: 12 sats; 4 GNSS => 34,000 occ/day

100 sats => 250,000 occ/day

400 sats => 1,000,000 occ/day




Kursinski et al., 13

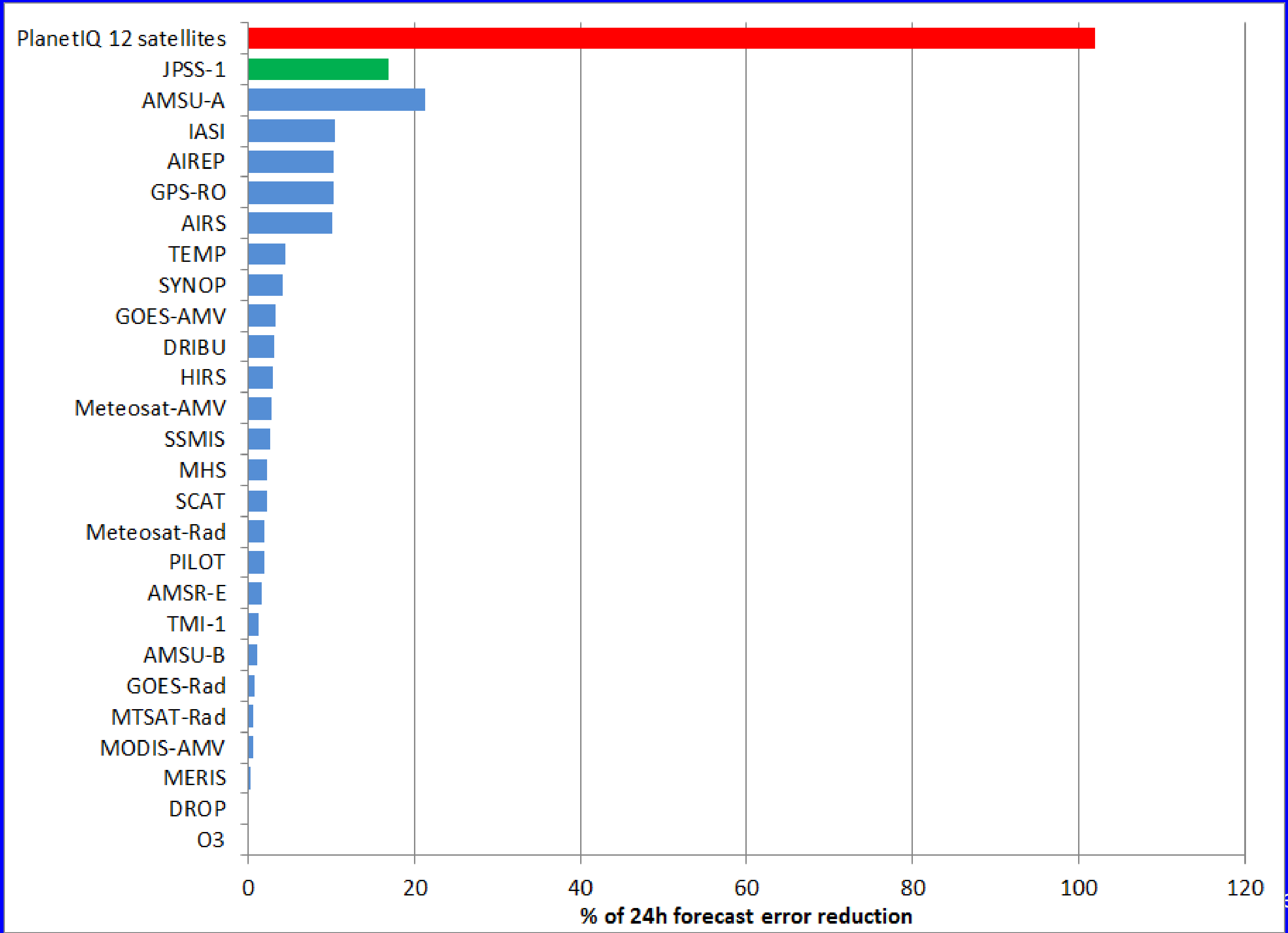
# NWP Impact

- Moisture climatology of NCEP does not match that observed by GPS RO
- Hi-resolution ECMWF is much better match to COSMIC results than low resolution ECMWF
- Assimilation of moisture observations will not work optimally until NWP model moisture climatology matches that of the observations.

- Present GPS RO sampling is sparse relative to water vapor correlation scales
- GNSS RO sampling should increase with time as new transmitter & receiver constellations come on line

# Estimated Impact of PlanetIQ

- Assume **linear** scaling of error variance
- PlanetIQ occultation FER ~ 2011 GCOS

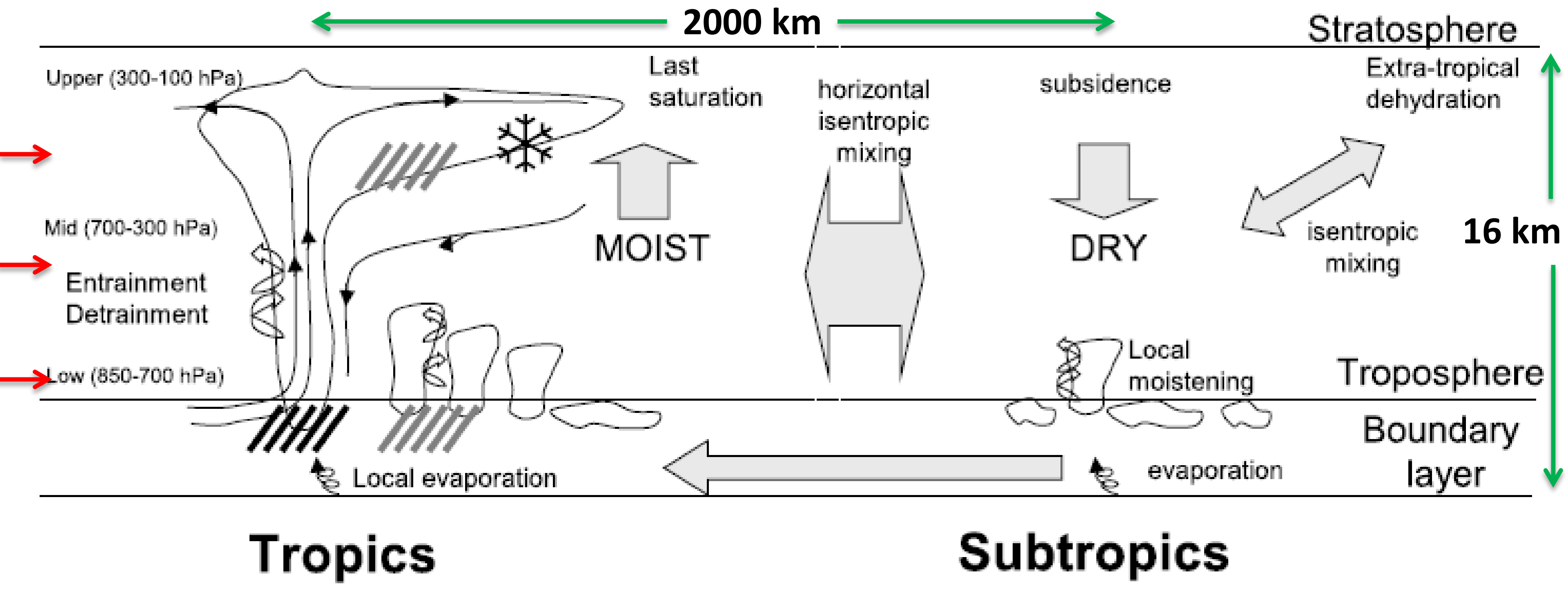


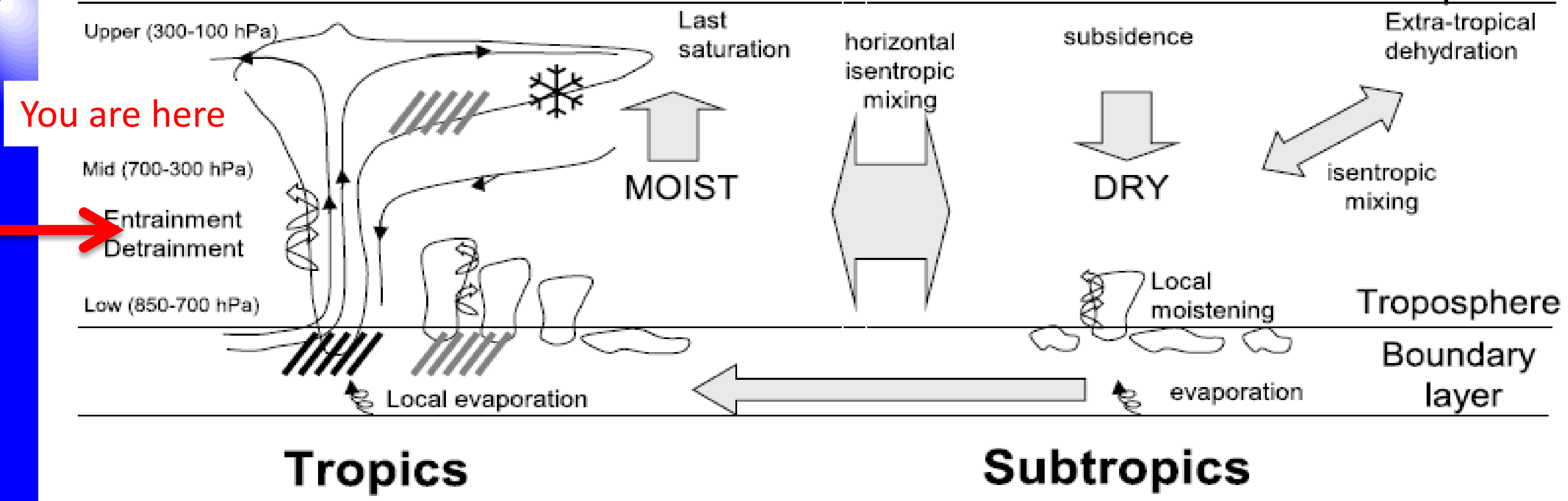
# Moisture Histograms

- Low order moments like mean and 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
- Plus insight into processes at work and adequacy of their representation in models

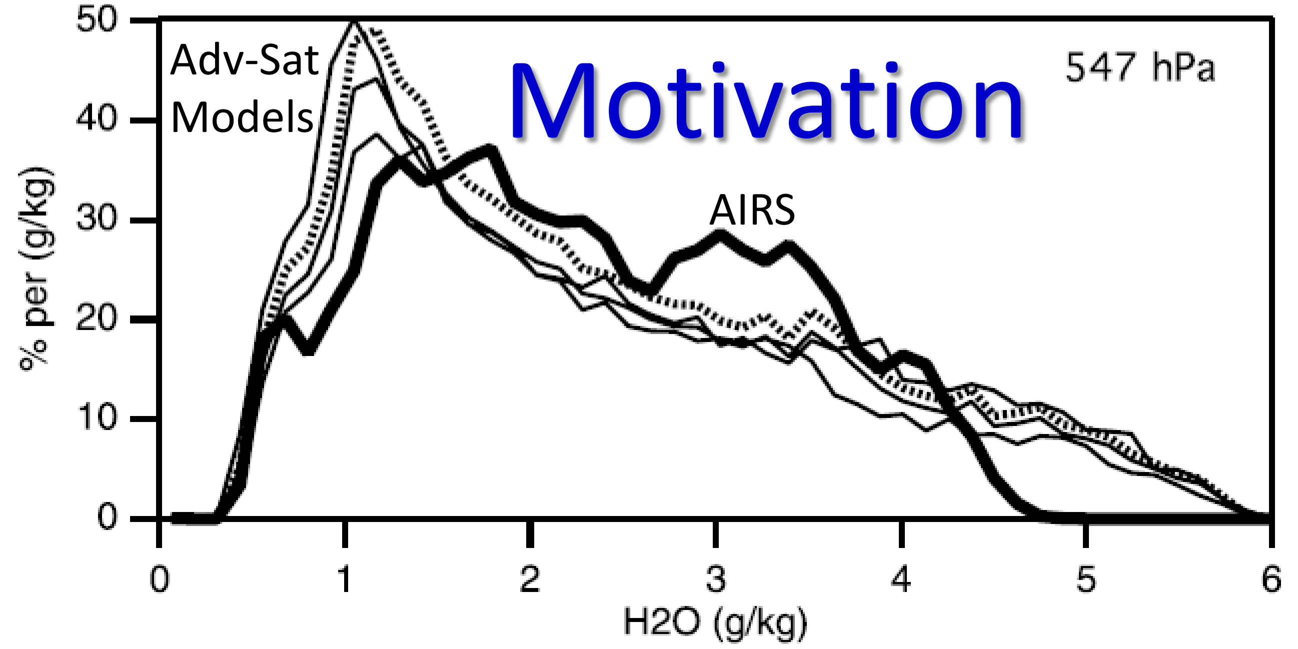
# Low Latitude Moisture Study

- 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***





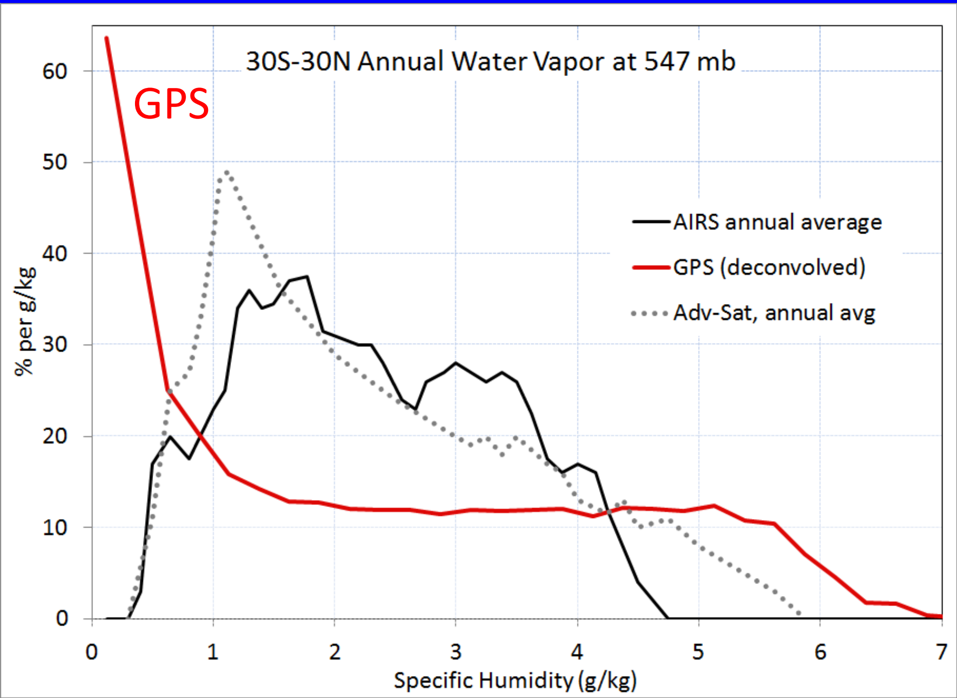

# Motivation

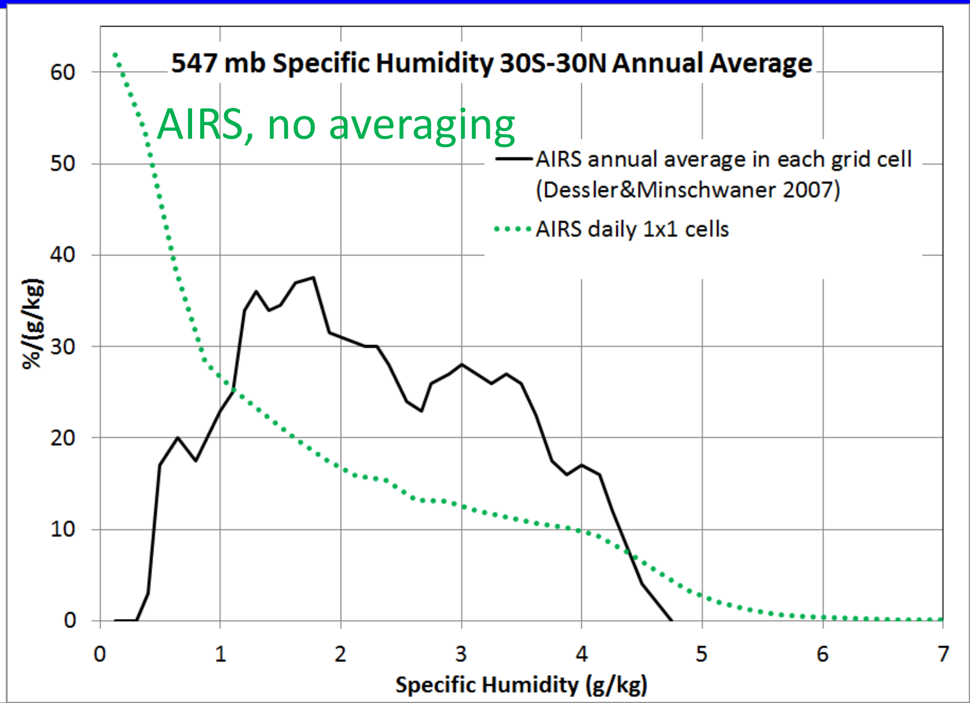



- Dessler & Minschwaner 2007 compared advection-saturation model results & AIRS
- **PROBLEM:** Model ~matches AIRS but neither looks like GPS RO. ***What's going on?***

# GPS vs. Adv. Sat. & AIRS (Dessler)

- Large disagreement between GPS RO and Dessler & Minschwaner (2007) versions of advection-saturation model and AIRS data.
- Largest discrepancies caused by an **annual average taken in each grid cell** by DM07 before calculating AIRS and Adv. Sat. histograms
  - Averaging removed extremes and compressed the histogram distributions.
  - Undesirable when trying to constrain & understand the processes at work



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

- 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
- (1D) Variational Method
  - Combine GPS refractivity with temperature & water vapor profiles and surface pressure from analysis and error covariance estimates
  - Overdetermined, least squares solution
- Advantage of Direct Method: Not affected by biases in background water vapor forecast/analysis

# Negative *q* and Error Deconvolution

Direct method can and does produce negative *q* estimates

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

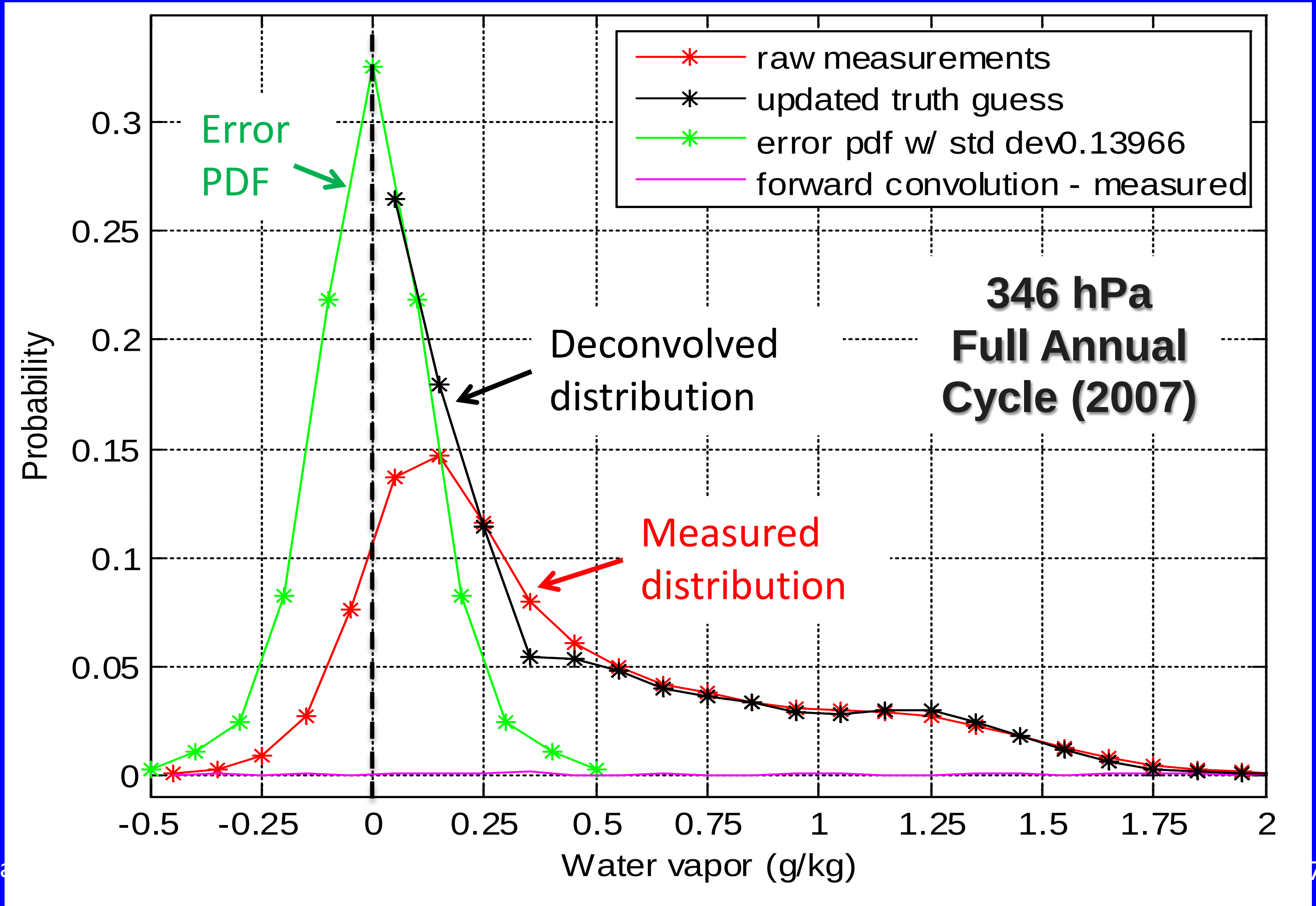
- This can be fixed by deconvolving the error distribution from histograms
  - Linearize error model: $q_{measured} = q_{true} + \varepsilon_q$
  - Measured histogram (PDF) is then the convolution of the true PDF and the error PDF

$$PDF_{q\,meas} = PDF_{q\,true} \otimes PDF_{\varepsilon}$$

- *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

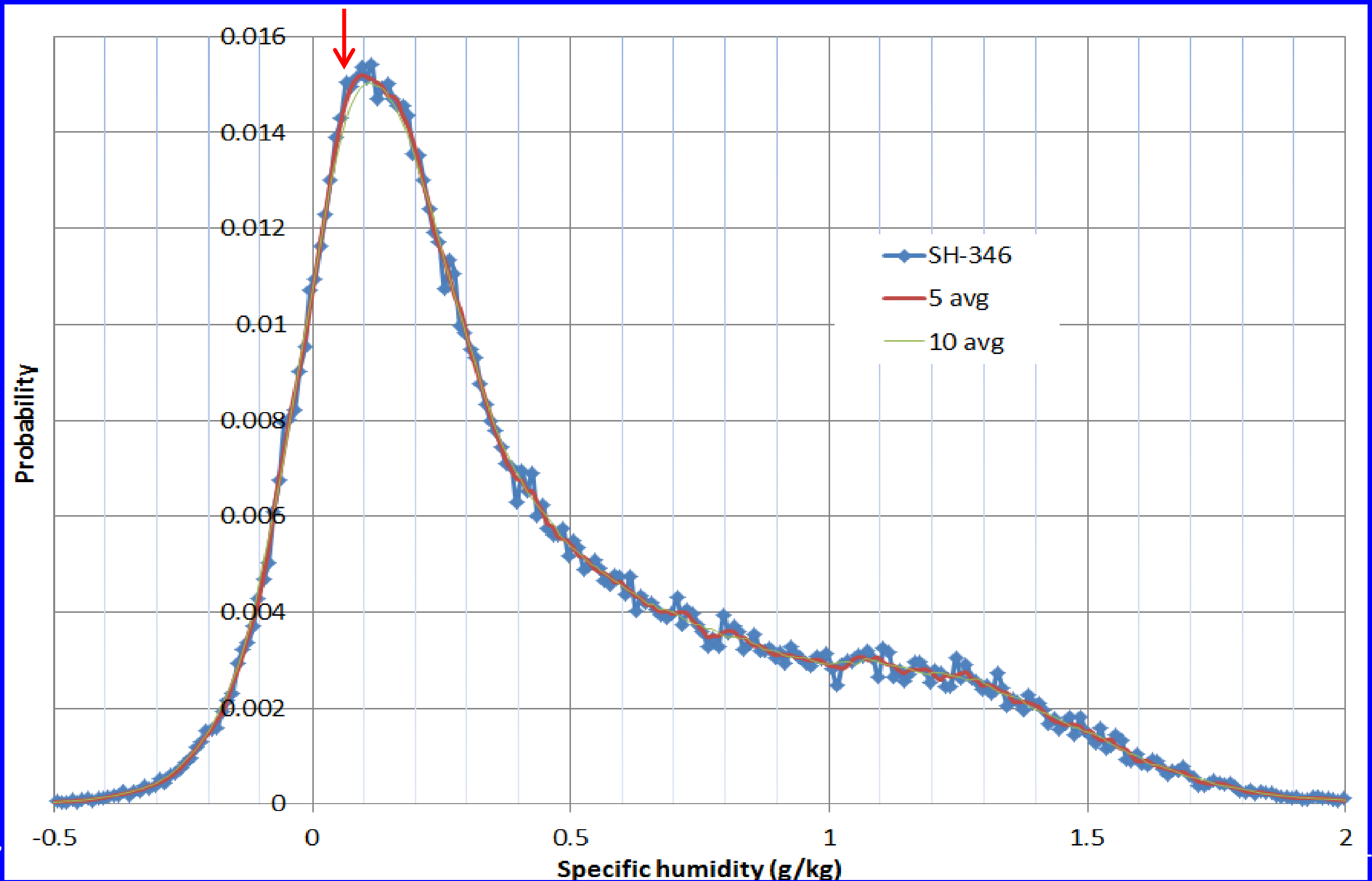
# *Automated,* Error Deconvolution Low Latitude

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



# How dry is the driest air at 346 hPa?

- 346 hPa raw histogram at **0.01** g/kg resolution
- Note that rapid falloff on the lower end begins distinctly above 0
- Indicative of water freeze dried at colder, higher altitude
- Raises question of can we tell how dry the driest air is



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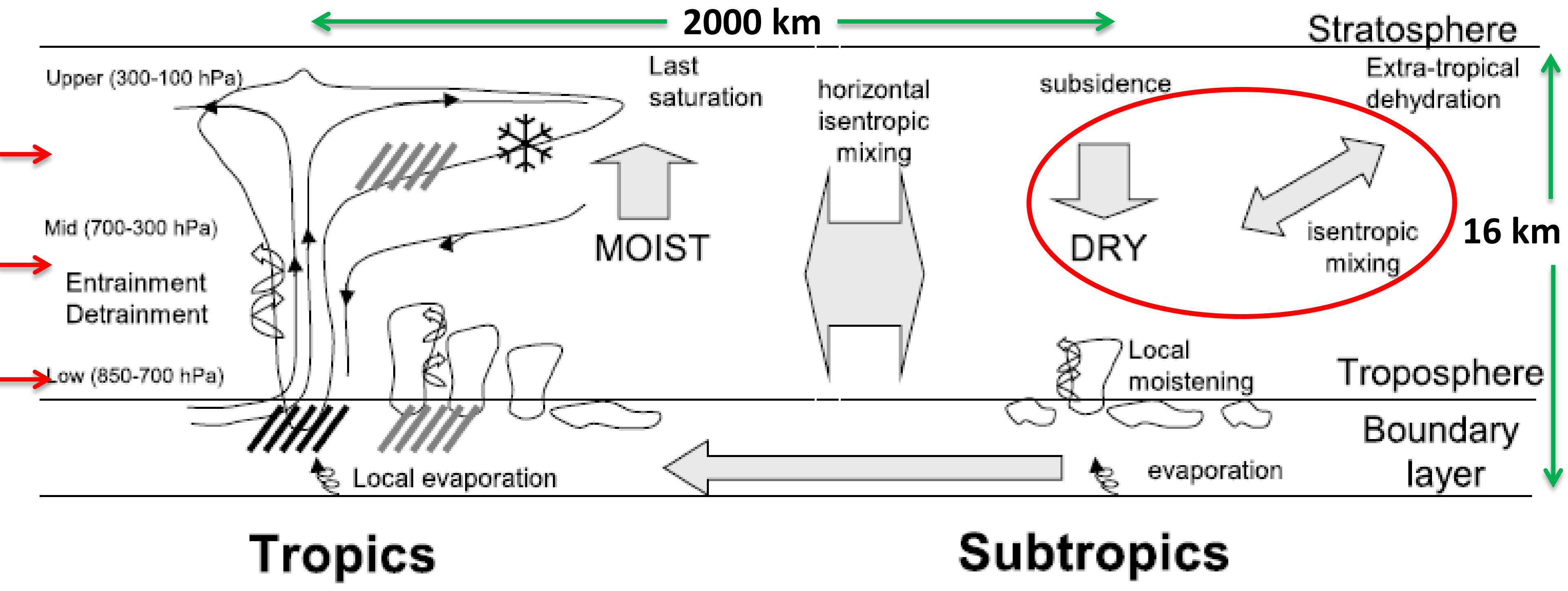
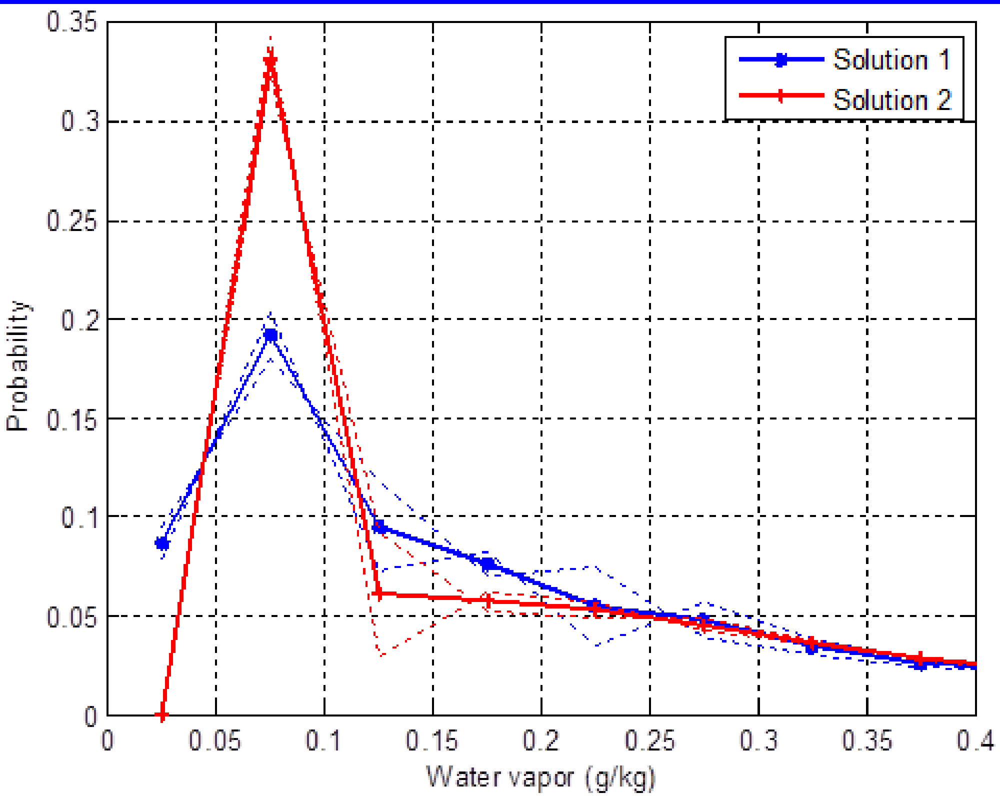


# *Automated,* Error Deconvolution Low Latitude

- Increased deconvolution bin resolution x2 from 0.1 to 0.05 g/kg
- Yielded 3 solutions (two physical, one unphysical)

  ⇒ ≤ 10% of air is ~0.025 g/kg

  ⇒ When bin resolution becomes too fine relative to error PDF, deconvolution solution becomes non-unique

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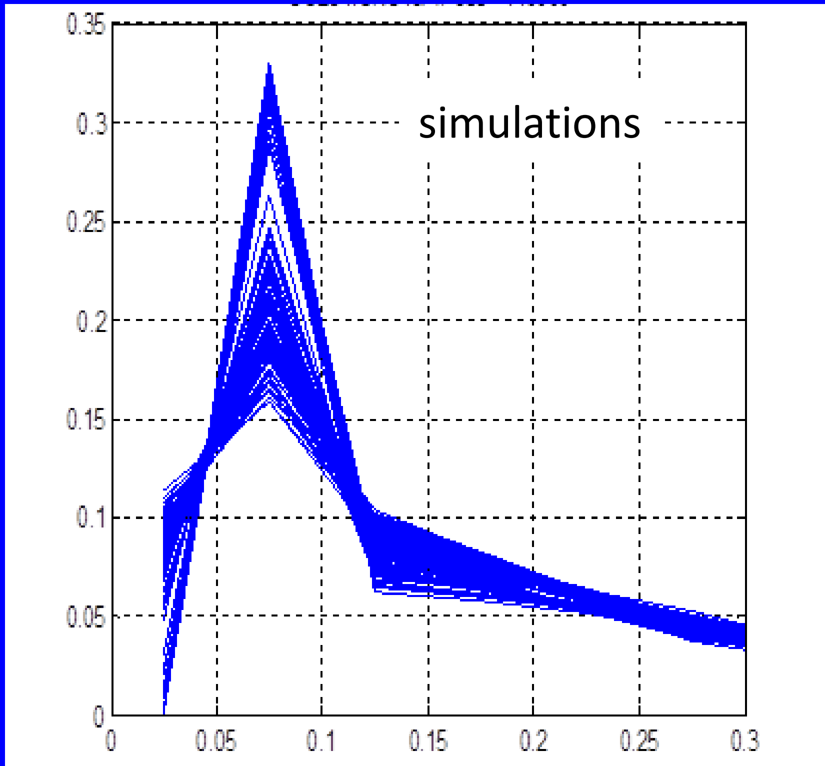


# Estimating the Accuracy of GPS-derived Water Vapor

- 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 $C = a_1 T m_w / a_2 m_d$ ~ 35 g/kg

$\sigma_q$ ~ 0.2 g/kg in mid & upper troposphere.

$\sigma_q$ ~ 0.5 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 $B_s = a_1 TP / a_2 e_s$.

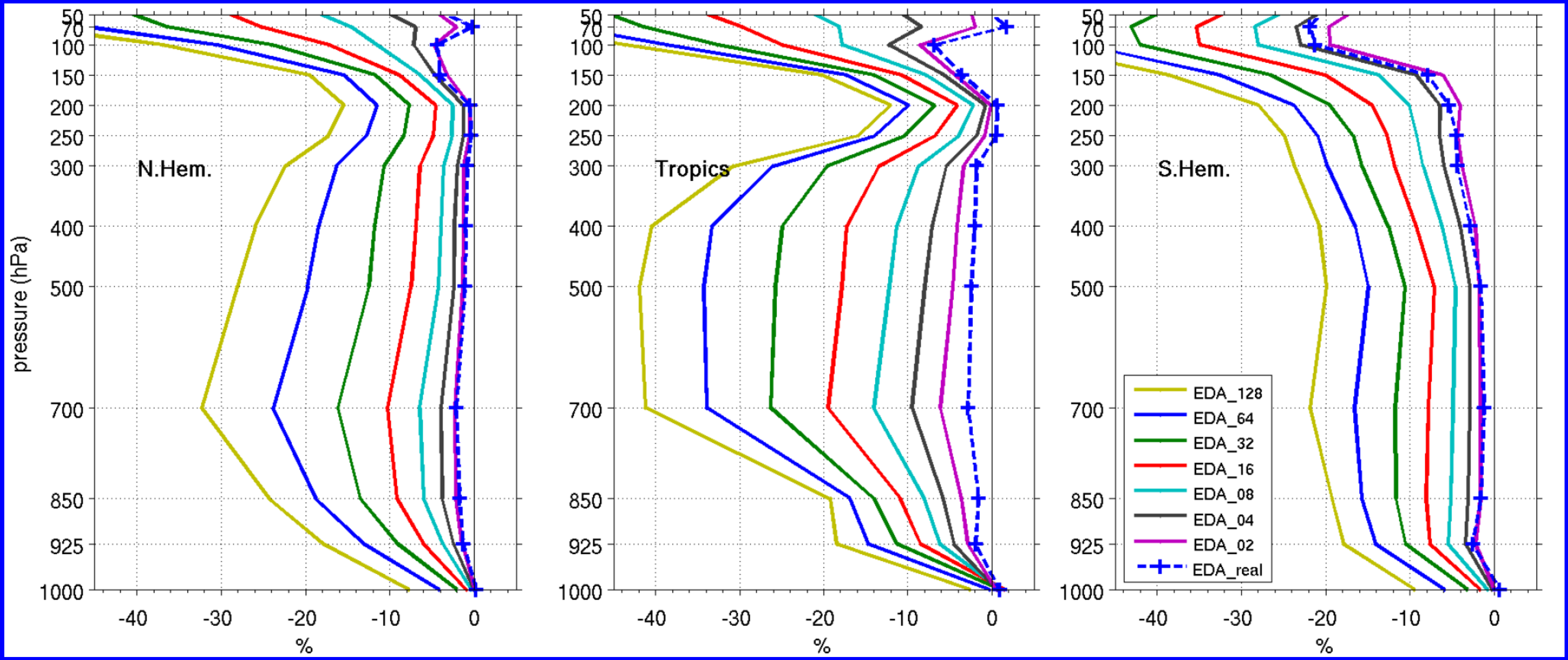
# Separating the Errors

- Estimate water vapor error from negative tail of distribution
- 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 | 0.9K | 0.3% | 0.15% |
| **547** | 0.31 | **0.25** | 0.5 | 0.6 | 1.5K | 0.9K | 0.3% | 0.15% |
| **725** | 0.47 | **0.39** | 0.9 | 1 | 1.5K | 0.9K | 0.3% | 0.15% |

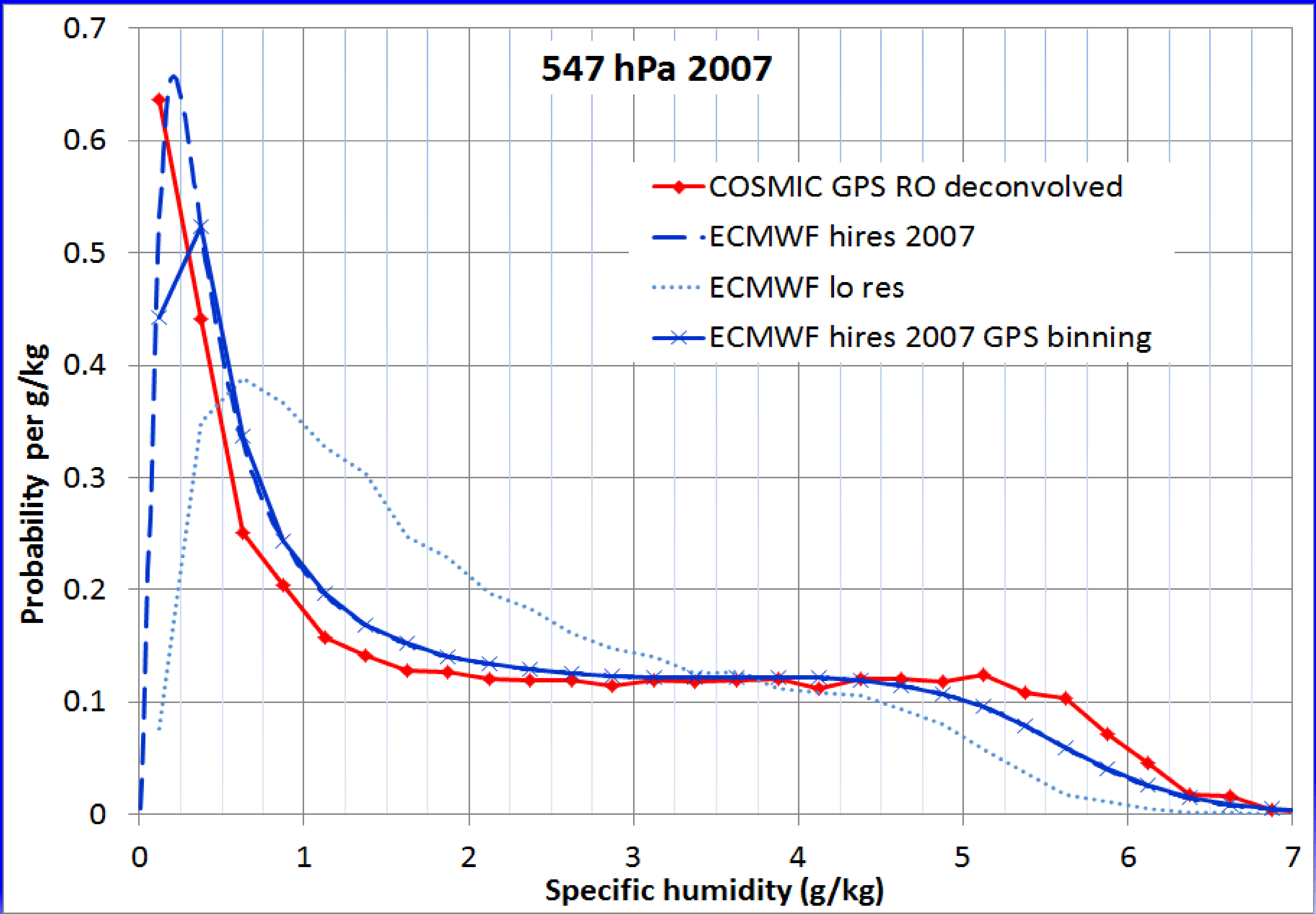
# EDA Spread Reduction (%) for Relative Humidity Analysis

**From:** ***Estimating the optimal number of GNSS RO measurements for NWP &climate reanalysis applications-*** Florian Harnisch, Sean Healy, Peter Bauer (2012) ECMWF

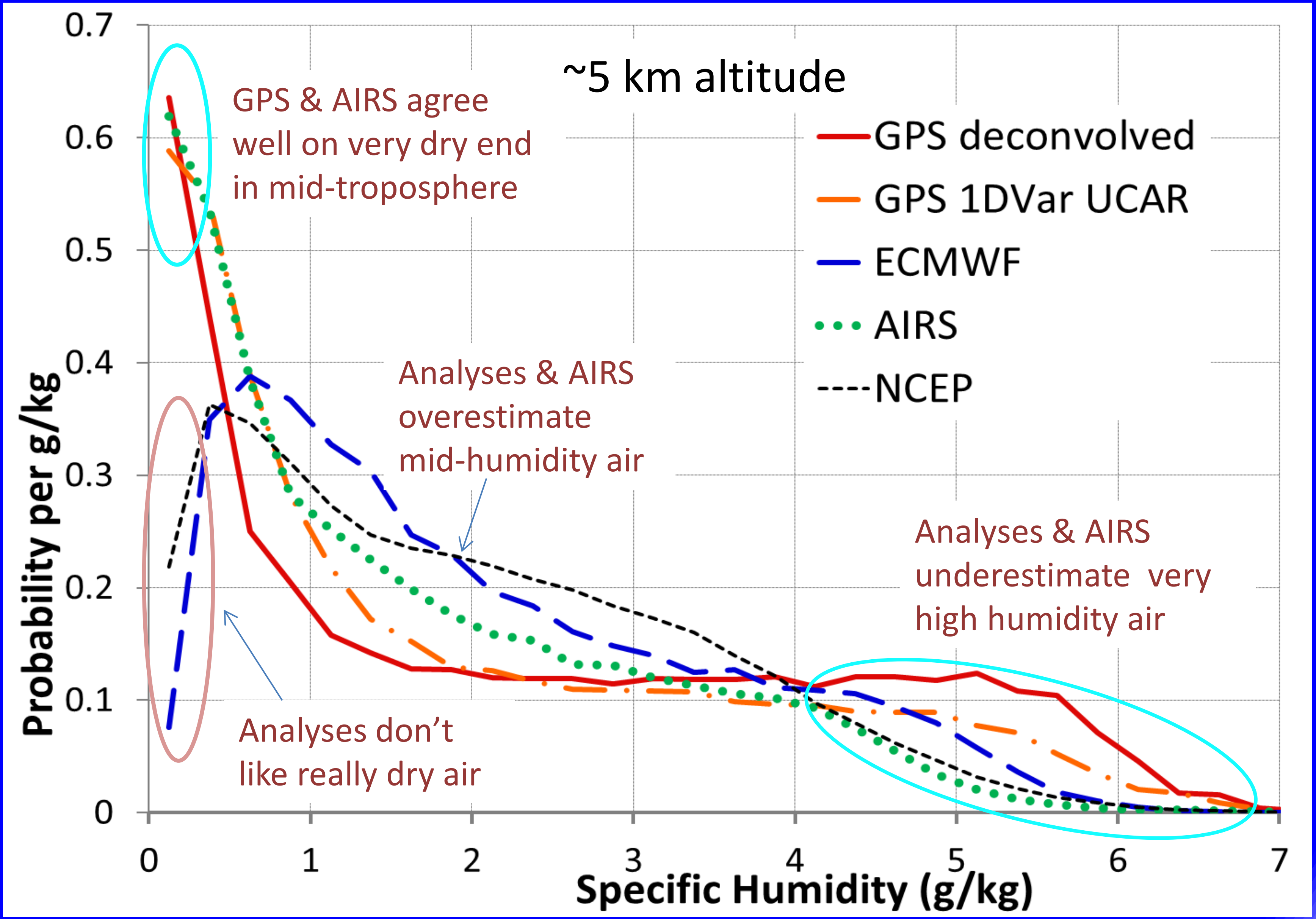


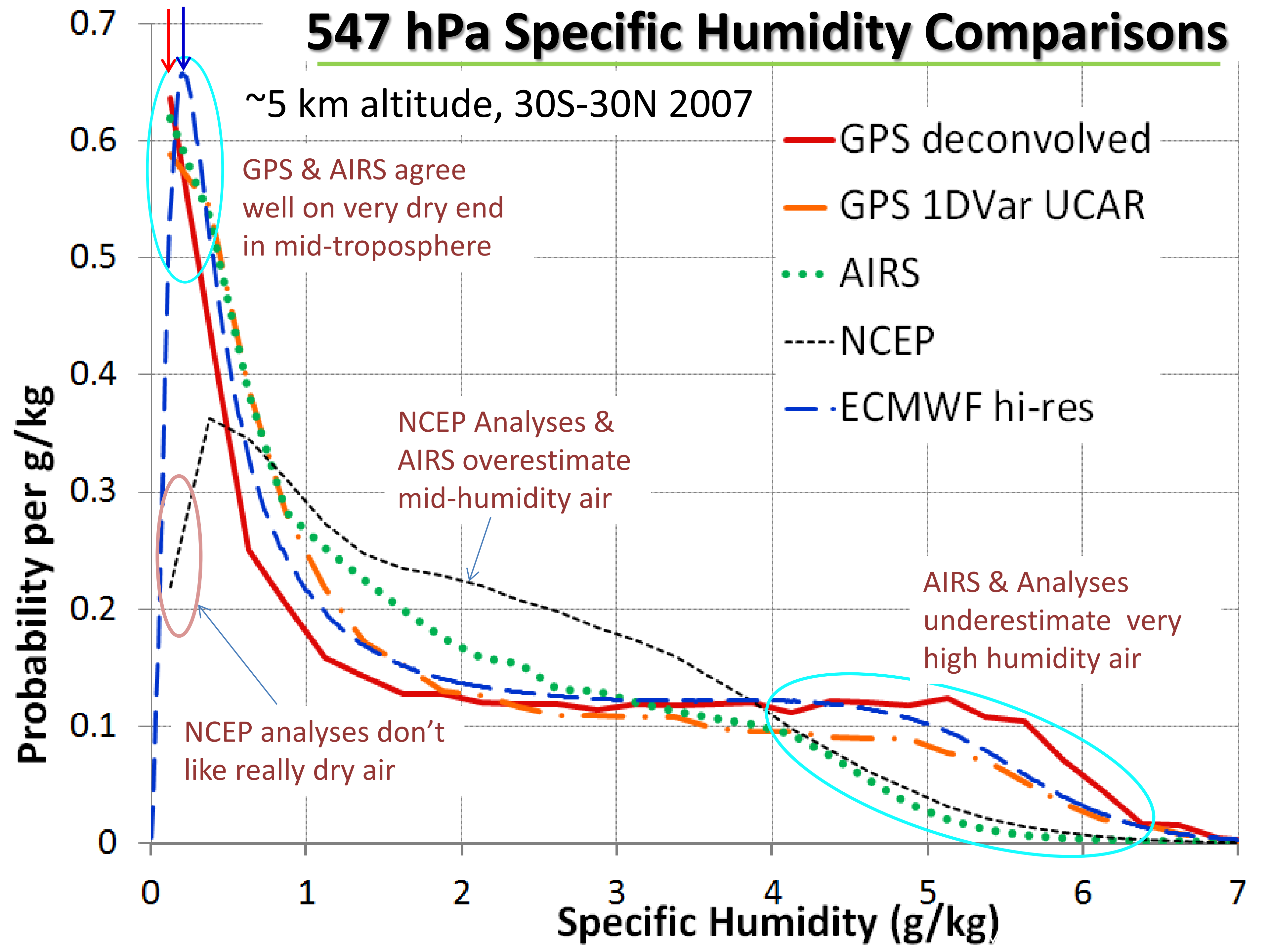

- Relative minimum of impact at 100 – 300 hPa
- Absolute humidity impact below 300 hPa
- Largest humidity impact on tropical troposphere (850 – 400 hPa)

# ECMWF Hi-Res 547 hPa Spec. Humidity Comparisons



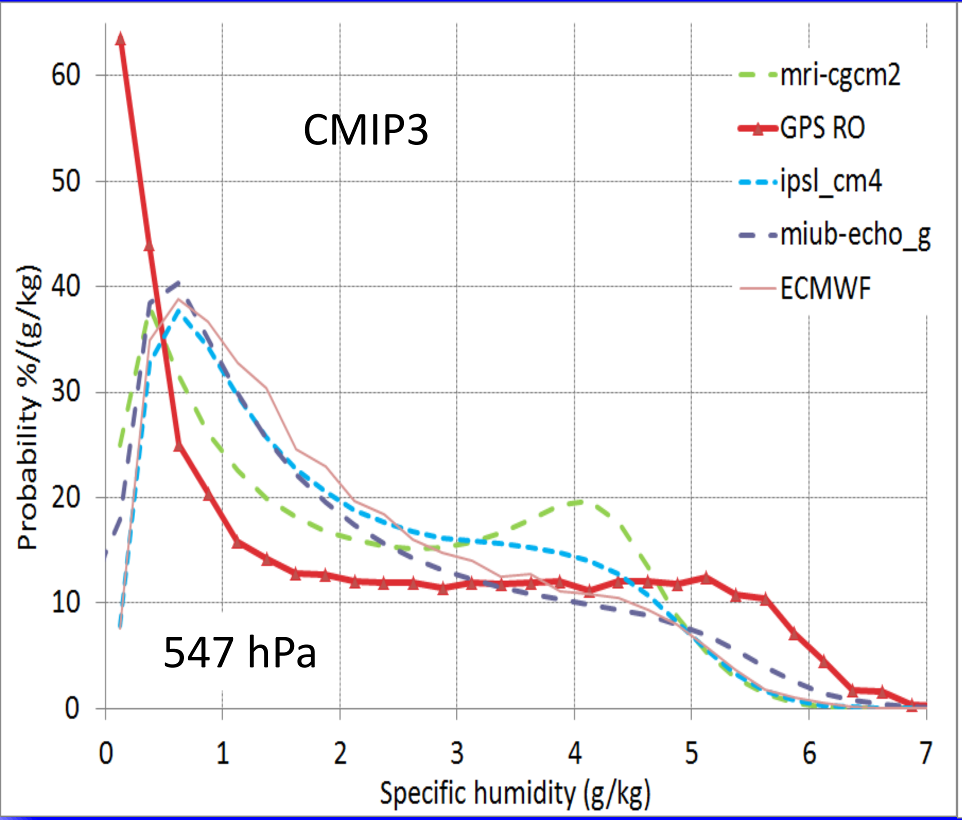
# Olde 547 hPa Specific Humidity Comparisons

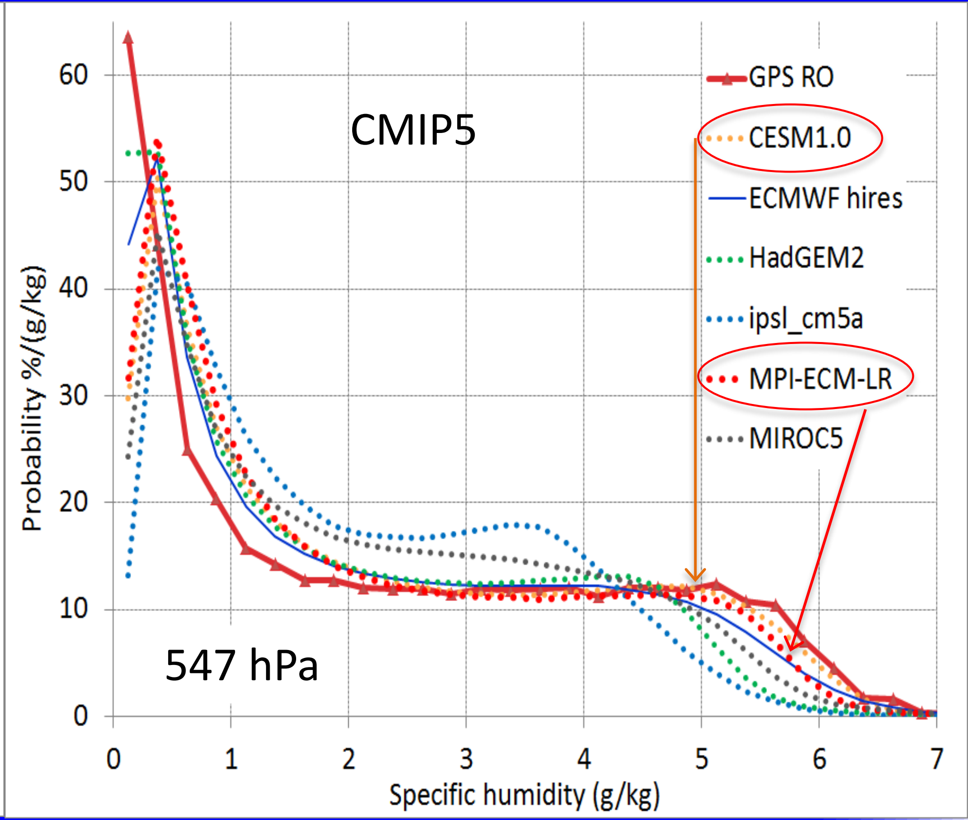



547 hPa Specific Humidity Comparisons
~5 km altitude, 30S-30N 2007
GPS deconvolved
GPS 1DVar UCAR
AIRS
NCEP
ECMWF hi-res
GPS & AIRS agree well on very dry end in mid-troposphere
NCEP Analyses & AIRS overestimate mid-humidity air
AIRS & Analyses underestimate very high humidity air
NCEP analyses don't like really dry air
Probability per g/kg
Specific Humidity (g/kg)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
1
2
3
4
5
6
7

# Comparison with CMIP 3 & 5 models

- Noticeable improvement in some AMIP5 models:
  - NCAR and MPI in particular
- Resolution contributing but definitely not the whole answer (MIROC 5 has highest resolution)

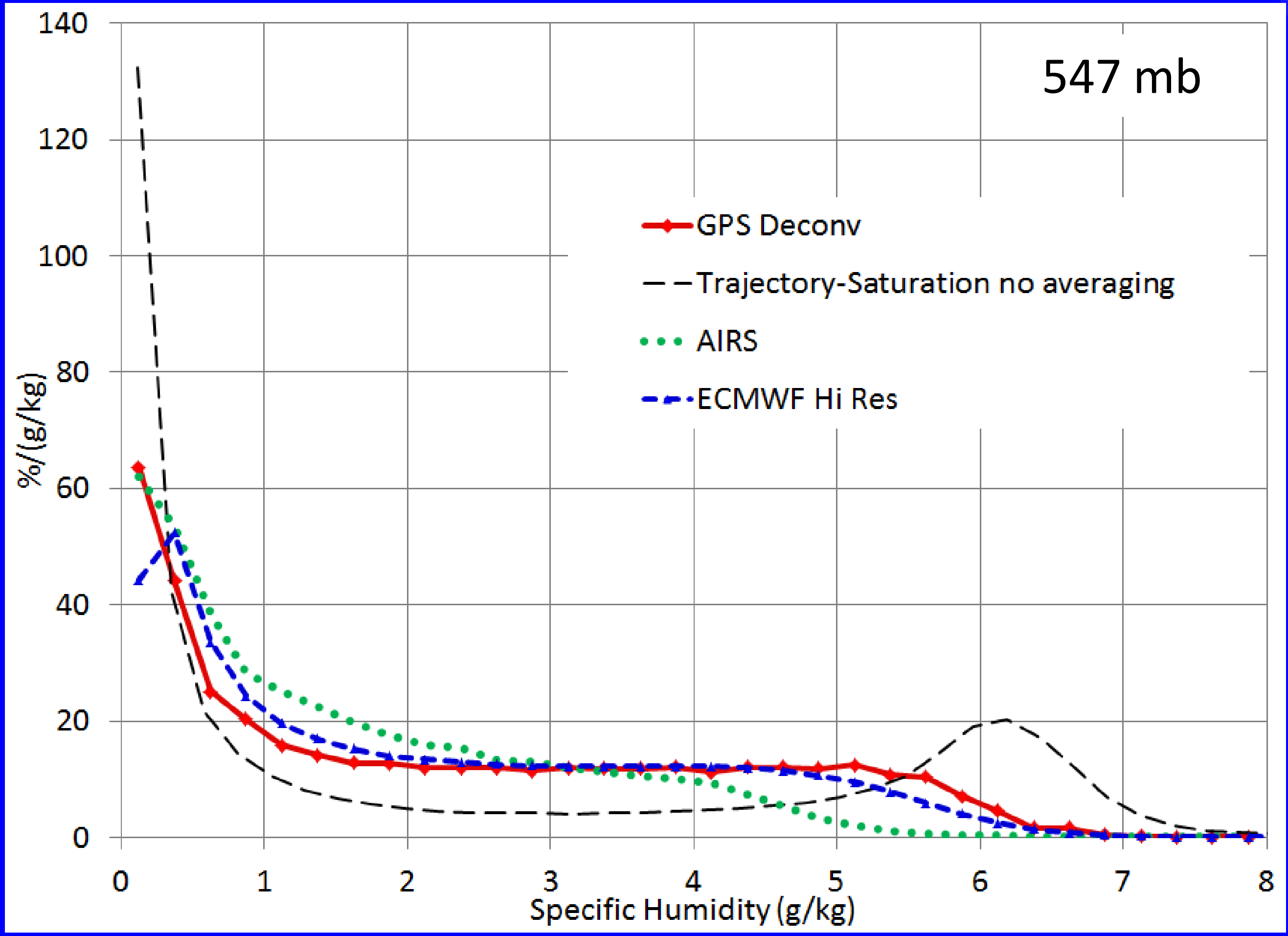


# Comparison with Advection- Saturation Model

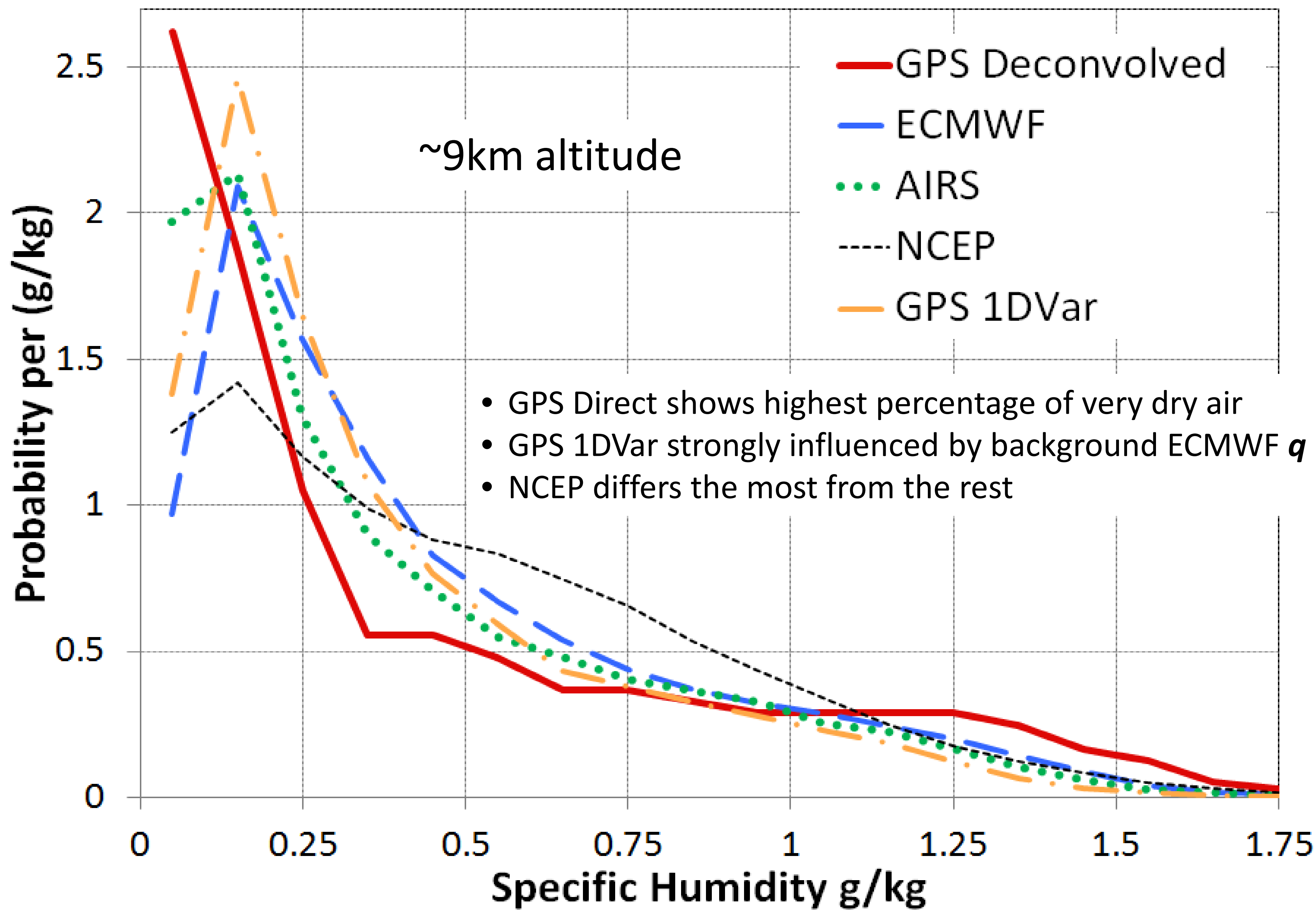
Model from Dessler & Minschwaner (2007)

- Initial moisture in air parcel from AIRS
- Advect parcel according to NCEP wind analyses
- Limit mixing ratio to the minimum saturation mixing ratio encountered along trajectory



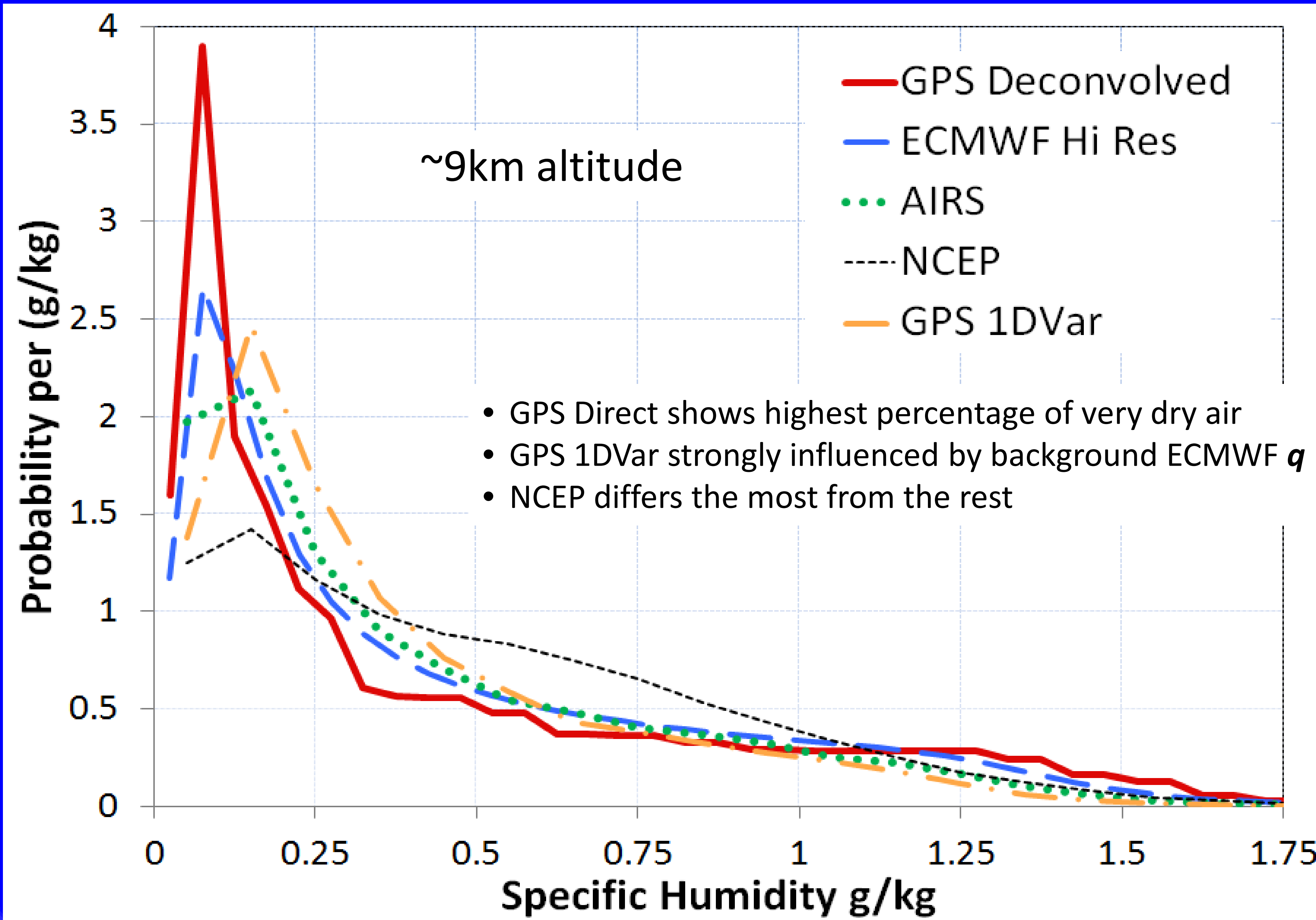

- Adv-Sat Model produces more very dry and very wet air than GPS RO observes
  - Adv-Sat Model's peak at the wet end is not observed
- Lack of mixing in Model likely explains model's higher extremes than observed

# Olde 346 hPa Specific Humidity 30S-30N 2007




- GPS Direct shows highest percentage of very dry air
- GPS 1DVar strongly influenced by background ECMWF ***q***
- NCEP differs the most from the rest

# 346 hPa Specific Humidity 30S-30N 2007




- GPS Direct shows highest percentage of very dry air
- GPS 1DVar strongly influenced by background ECMWF ***q***
- NCEP differs the most from the rest

# Comparison of Estimates of Low Latitude Humidity Means

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

| | GPS | AIRS | ECWMF lo-res | ECMWF hi-res | NCEP | Sat-Adv |
|---|---|---|---|---|---|---|
| 346 mb | 0.437 | 0.397 | 0.448 | 0.448 | 0.496 | 0.456 |
| 547 mb | 2.22 | 2.12 | 2.29 | 2.14 | 1.98 | 2.51 |

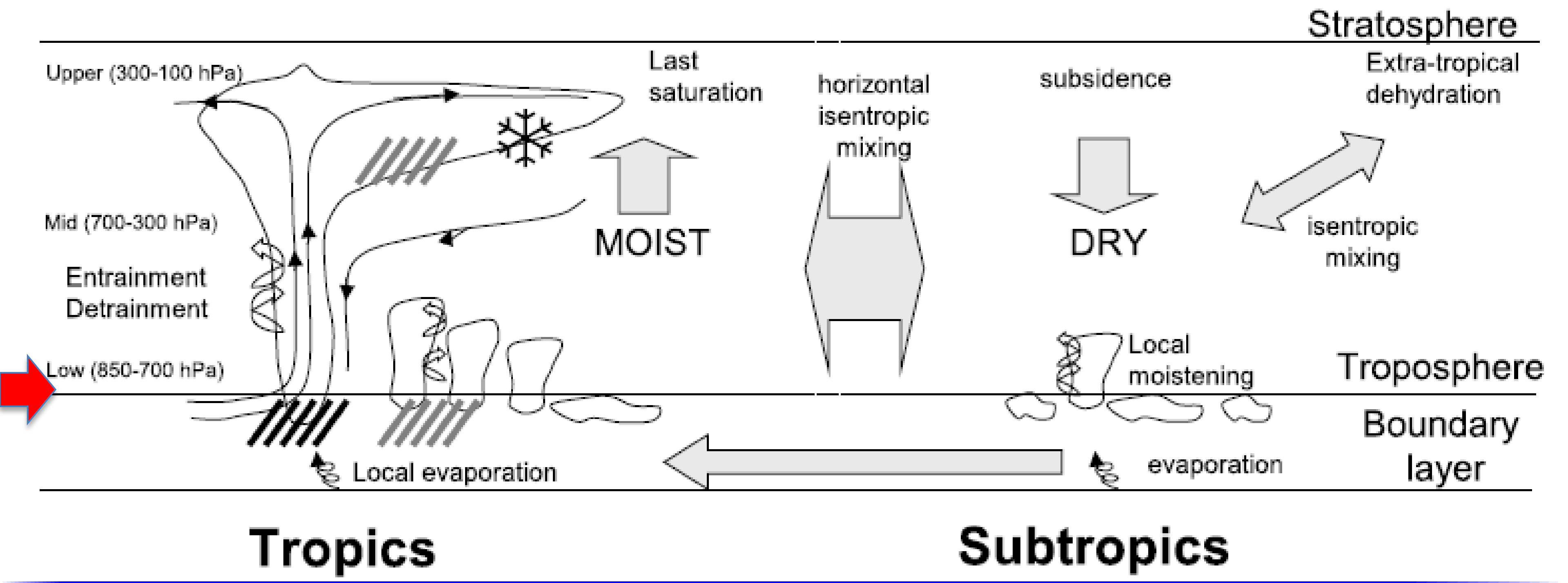
- Fractional Differences Relative to GPS RO

| | GPS | AIRS | ECWMF | NCEP | Sat-Adv |
|---|---|---|---|---|---|
| 346 mb | 0.0% | -9.1% | 2.5% | 13.5% | 4.3% |
| 547 mb | 0.0% | -4.6% | 3.2% | -10.8% | 13.1% |

Lots more going on than is captured in the means

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

- Low clouds are an important and variable element of Earth's albedo.
- Sherwood et al. found ~half the climate sensitivity variance across 43 climate models is associated with convective mixing between lower & mid- troposphere.



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

- As climate warms, models indicate stronger mixing dehydrates the BL

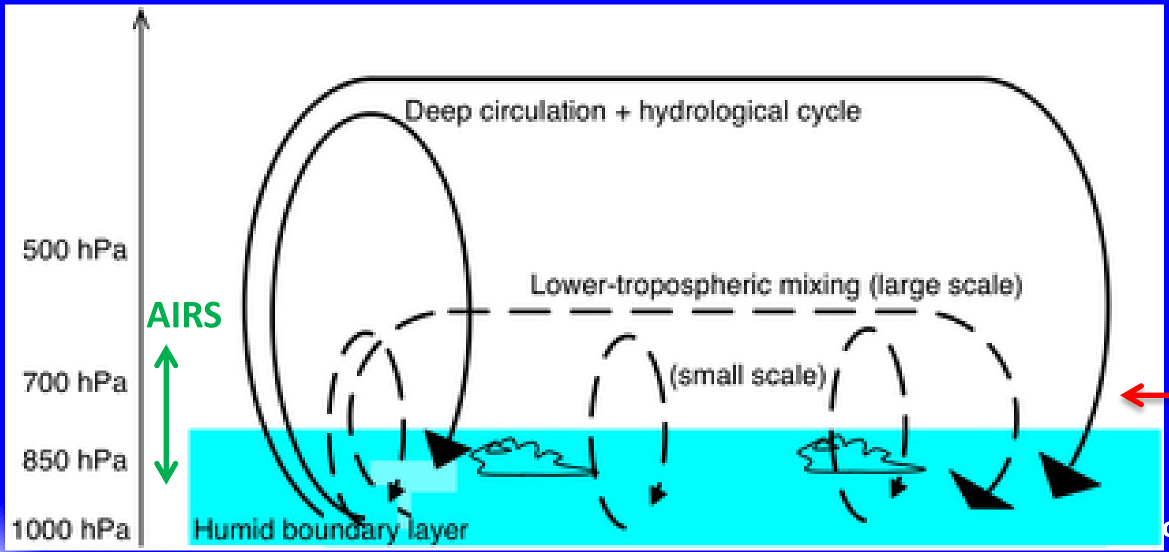
  ⇒ Reduces low cloud cover

- Rate of increased mixing & dehydration of low-cloud layer in warmer climate depends on initial mixing strength
- Evaluated model mixing against "observations" (= MERRA analyses)

  ⇒ Results imply a climate sensitivity **>** 3°C for $CO_2$ doubling.

- 3°C significantly higher than current lower bound of 1.5°C

⇒ **Relatively severe future warming**

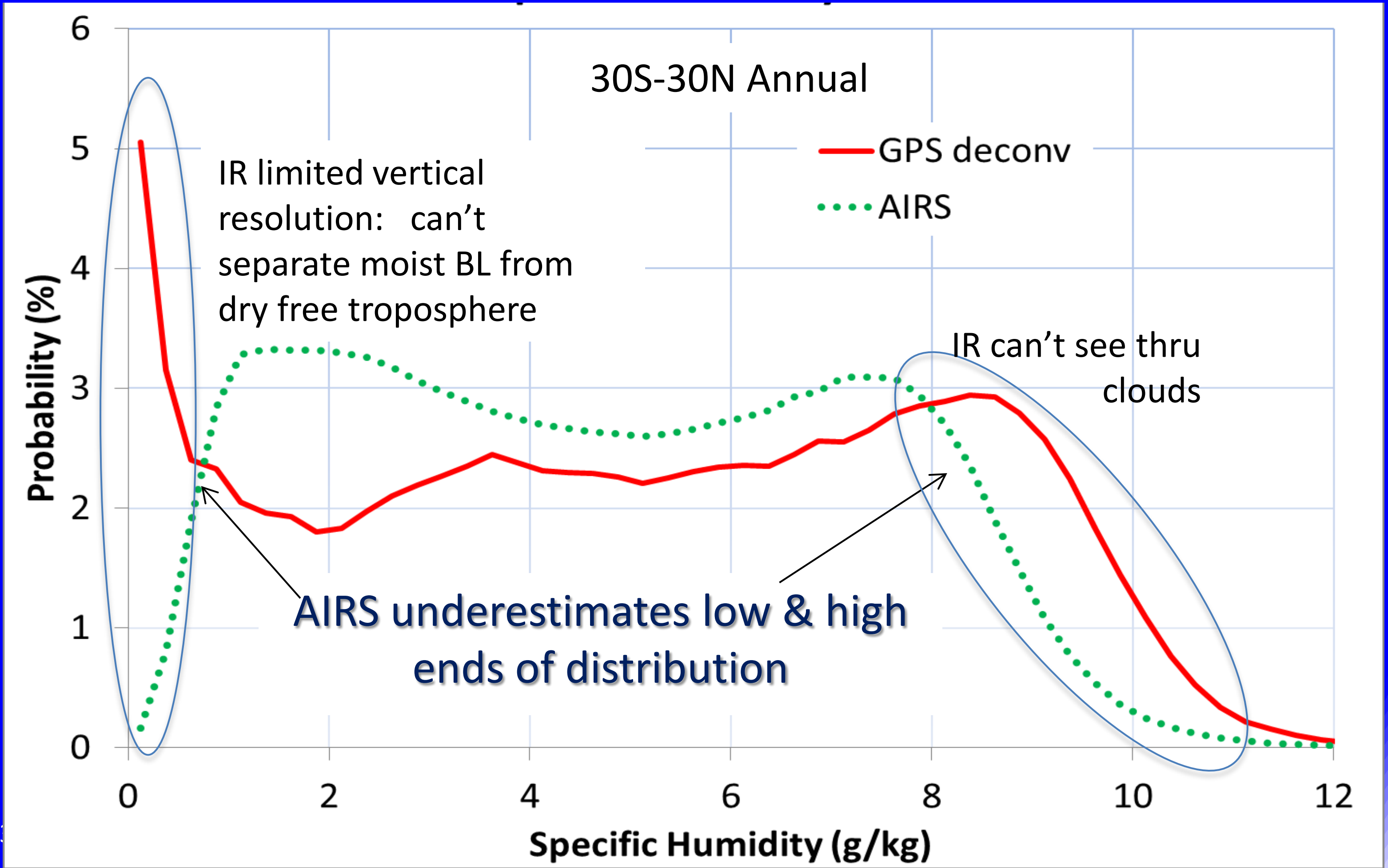



What can GPS RO tell us about this?

# GPS RO v. AIRS: 725 hPa Specific Humidity

- Data sets that most influence moisture analyses are passive microwave & IR
- Passive microwave has very limited vertical resolution
- AIRS ~2 km vertical resolution still coarse & limited ability to penetrate thru clouds

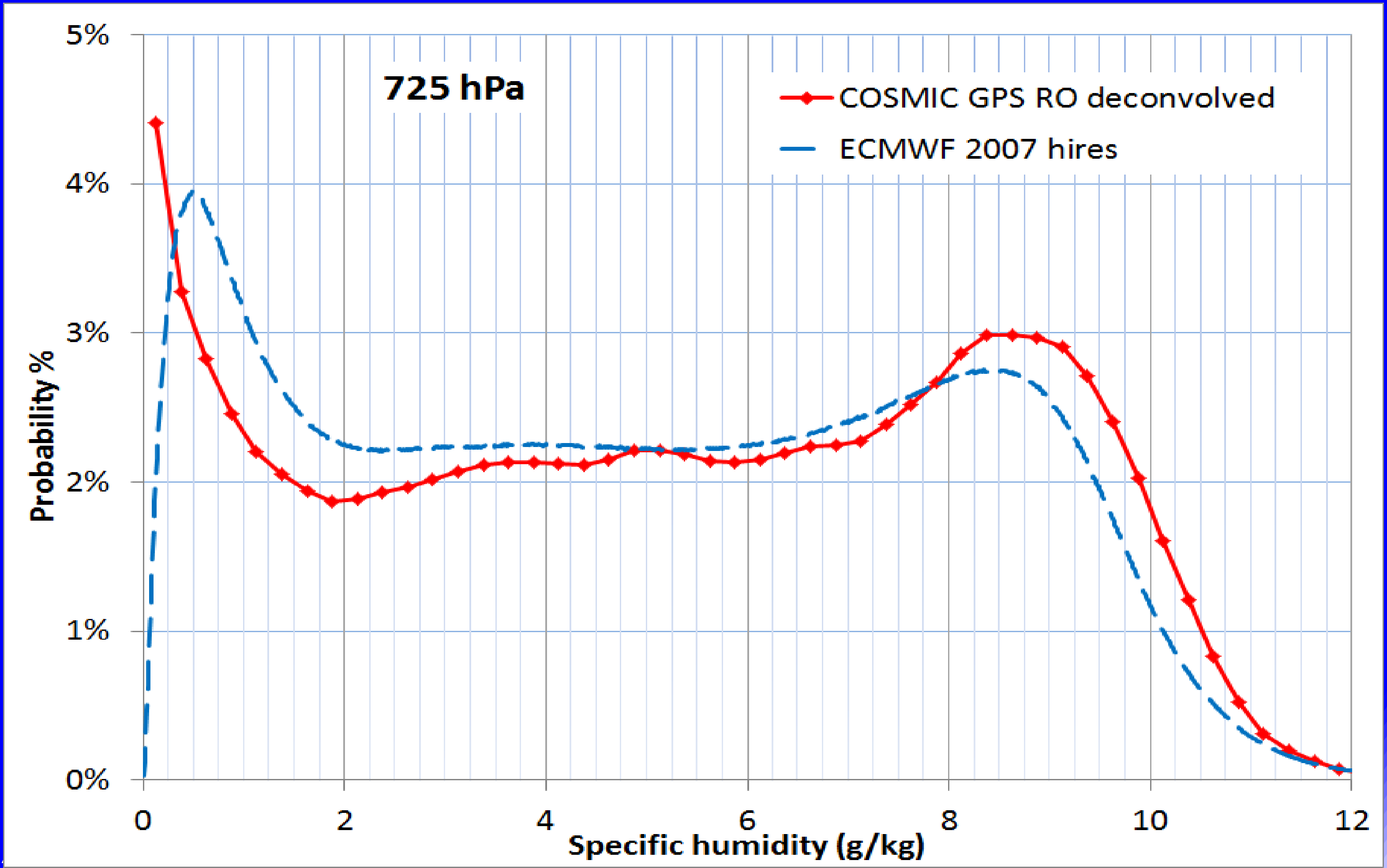
⇒ Passive data provides limited constraints on lower to mid troposphere mixing




Kursinski et al., 

# GPS RO v. ECMWF Hi-res: 725 hPa Specific Humidity

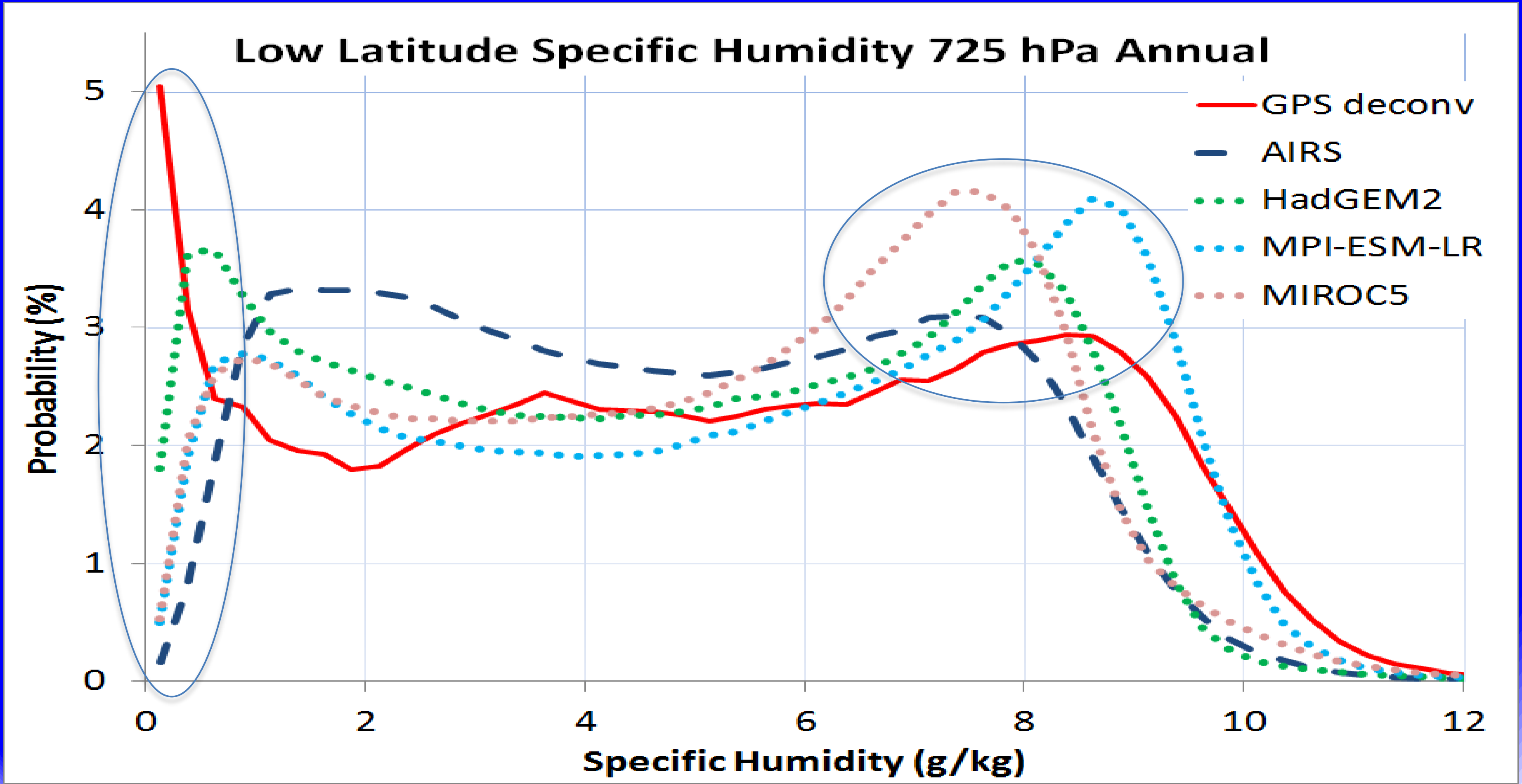
- ECMWF high-res much closer to GPS RO than ECMWF lo-res
- Still not enough extremely dry and wet air




Kursinski et al.

# Climate Model Comparison at 725 mb

- Model peak ***q*** on wet end is a bit small except in MPI
- Modeled % of wet air is too high
- Models miss the driest subtropical air



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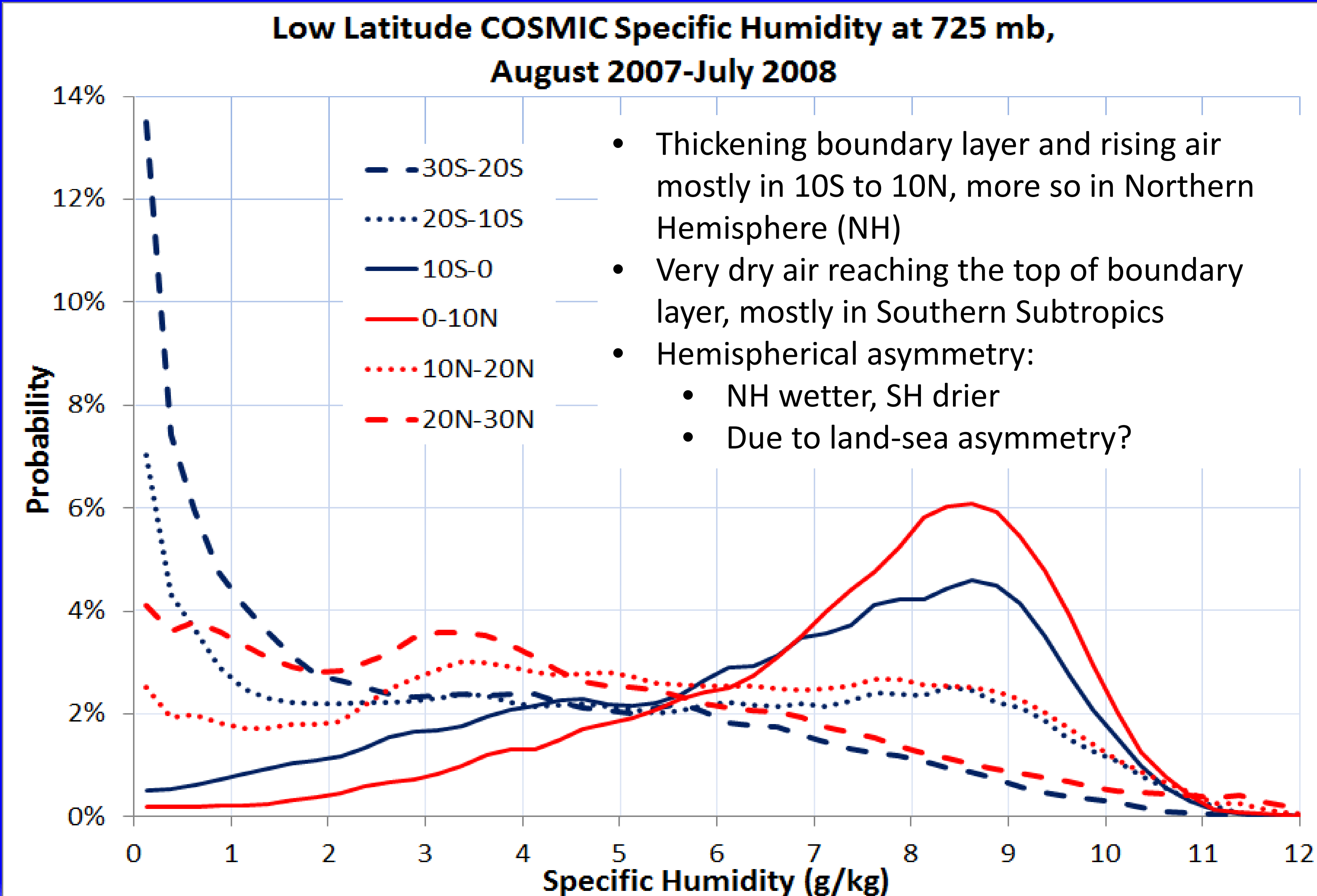
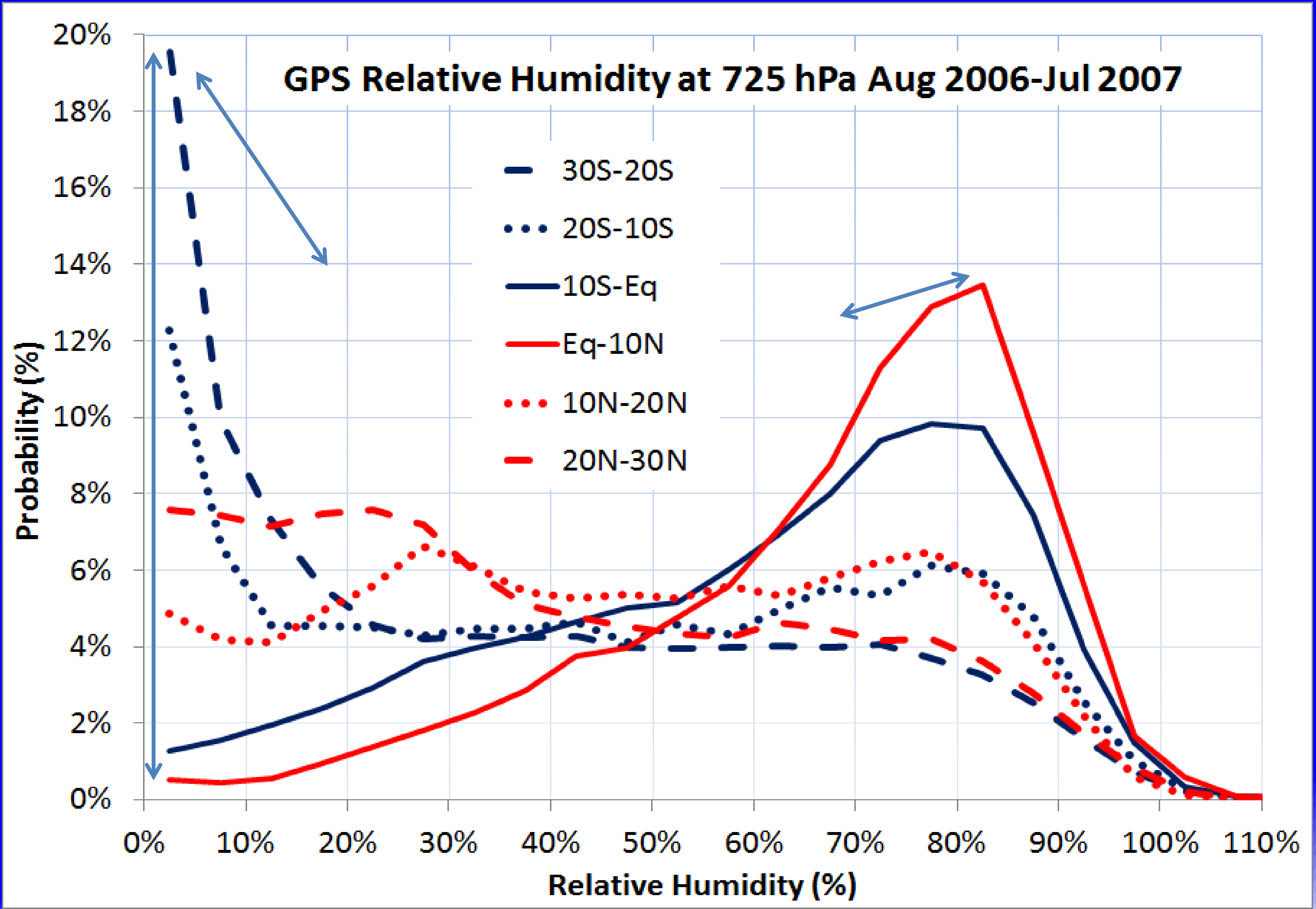
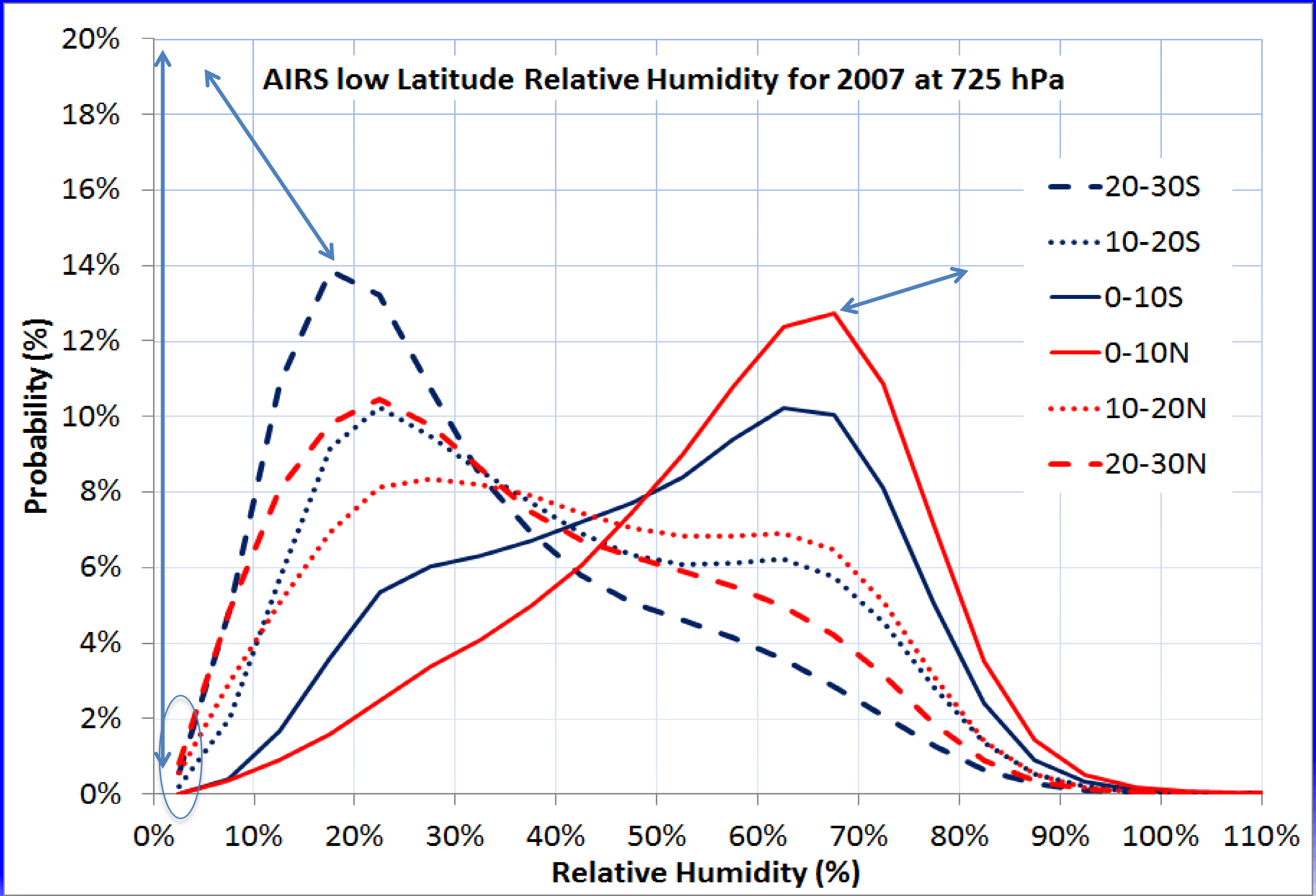


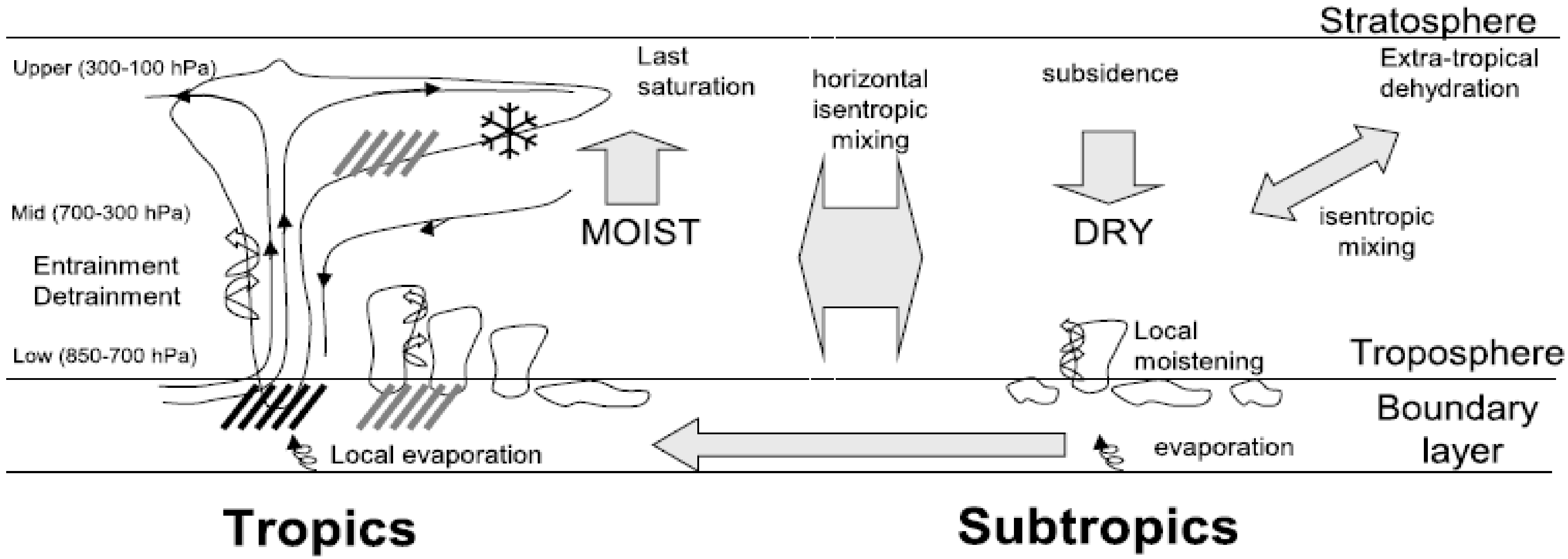

- Thickening boundary layer and rising air mostly in 10S to 10N, more so in Northern Hemisphere (NH)
- Very dry air reaching the top of boundary layer, mostly in Southern Subtropics
- Hemispherical asymmetry:
  - NH wetter, SH drier
  - Due to land-sea asymmetry?

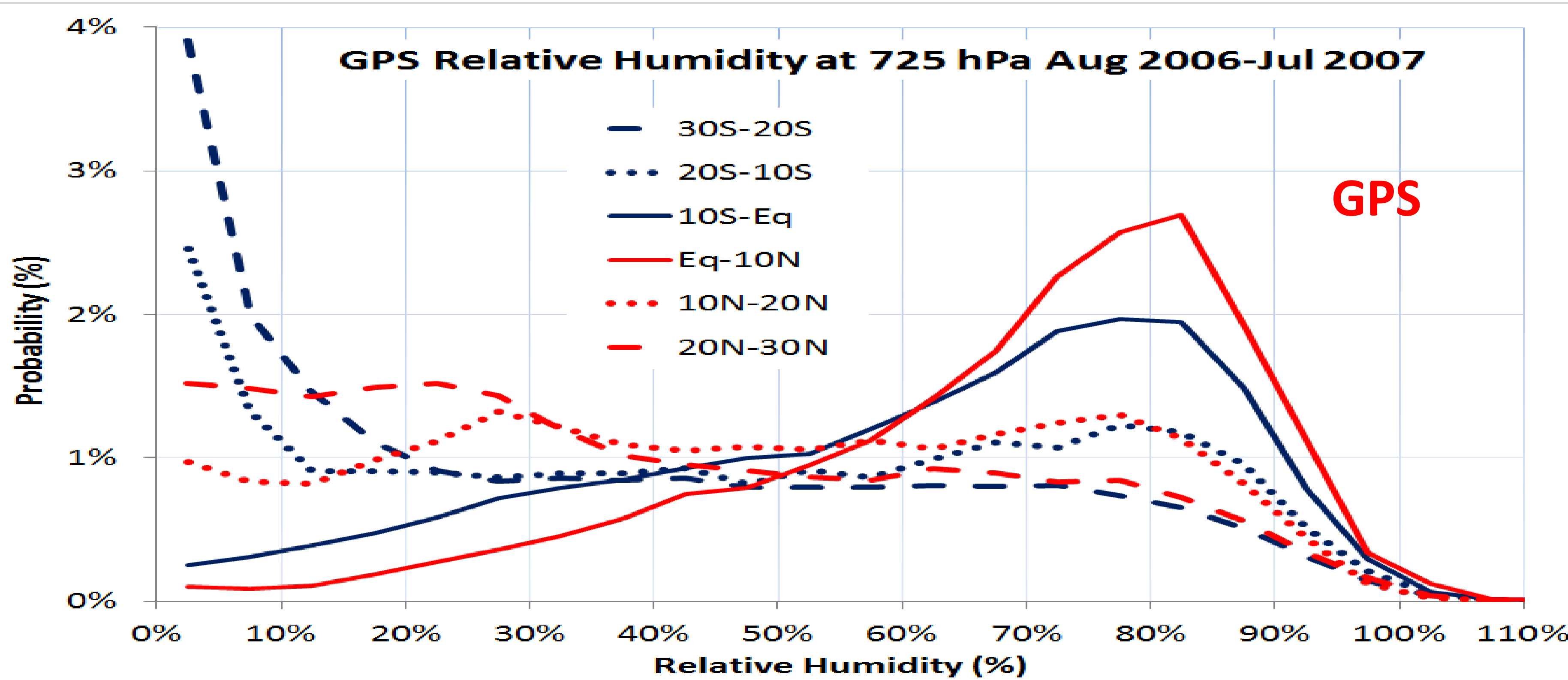
# GPS RO 725 hPa Relative Humidity

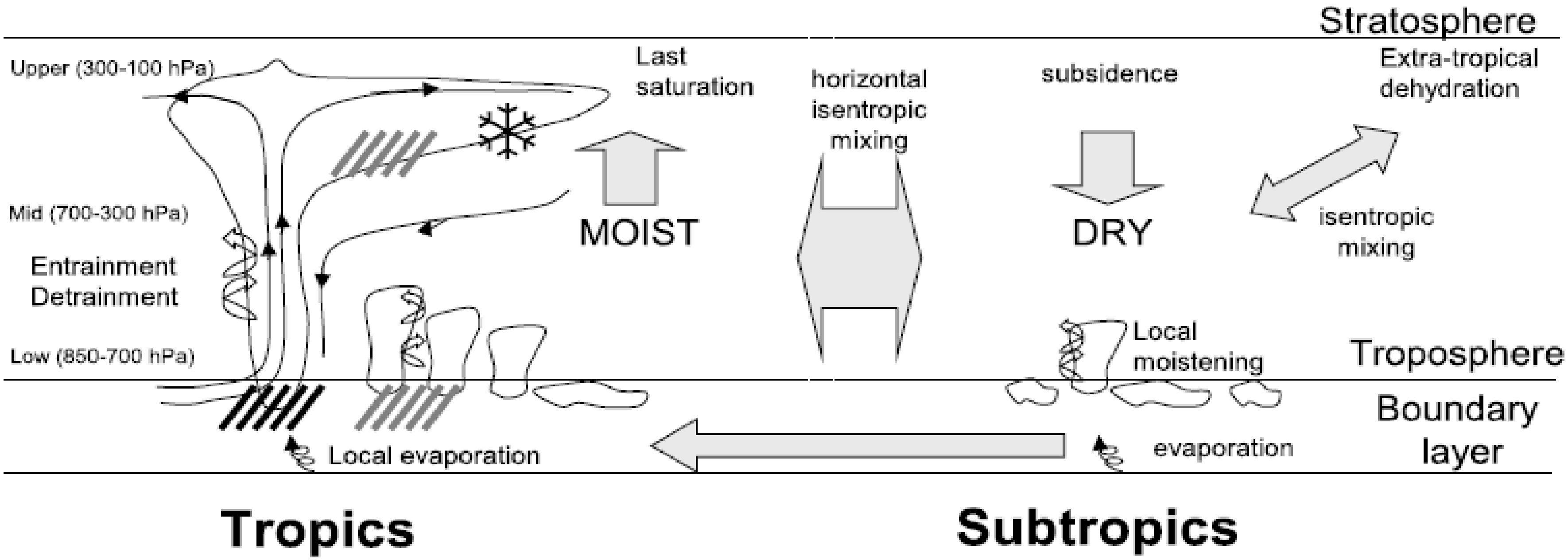


# AIRS 725 hPa Relative Humidity




Stratosphere
Upper (300-100 hPa)
Last saturation
horizontal isentropic mixing
subsidence
Extra-tropical dehydration
Mid (700-300 hPa)
MOIST
DRY
isentropic mixing
Entrainment
Detrainment
Low (850-700 hPa)
Local moistening
Troposphere
Boundary layer
Local evaporation
evaporation
Tropics
Subtropics


GPS Relative Humidity at 725 hPa Aug 2006-Jul 2007
30S-20S
20S-10S
10S-Eq
Eq-10N
10N-20N
20N-30N
GPS
Probability (%)
4%
3%
2%
1%
0%
0%
10%
20%
30%
40%
50%
60%
70%
80%
90%
100%
110%
Relative Humidity (%)


Stratosphere
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evaporation
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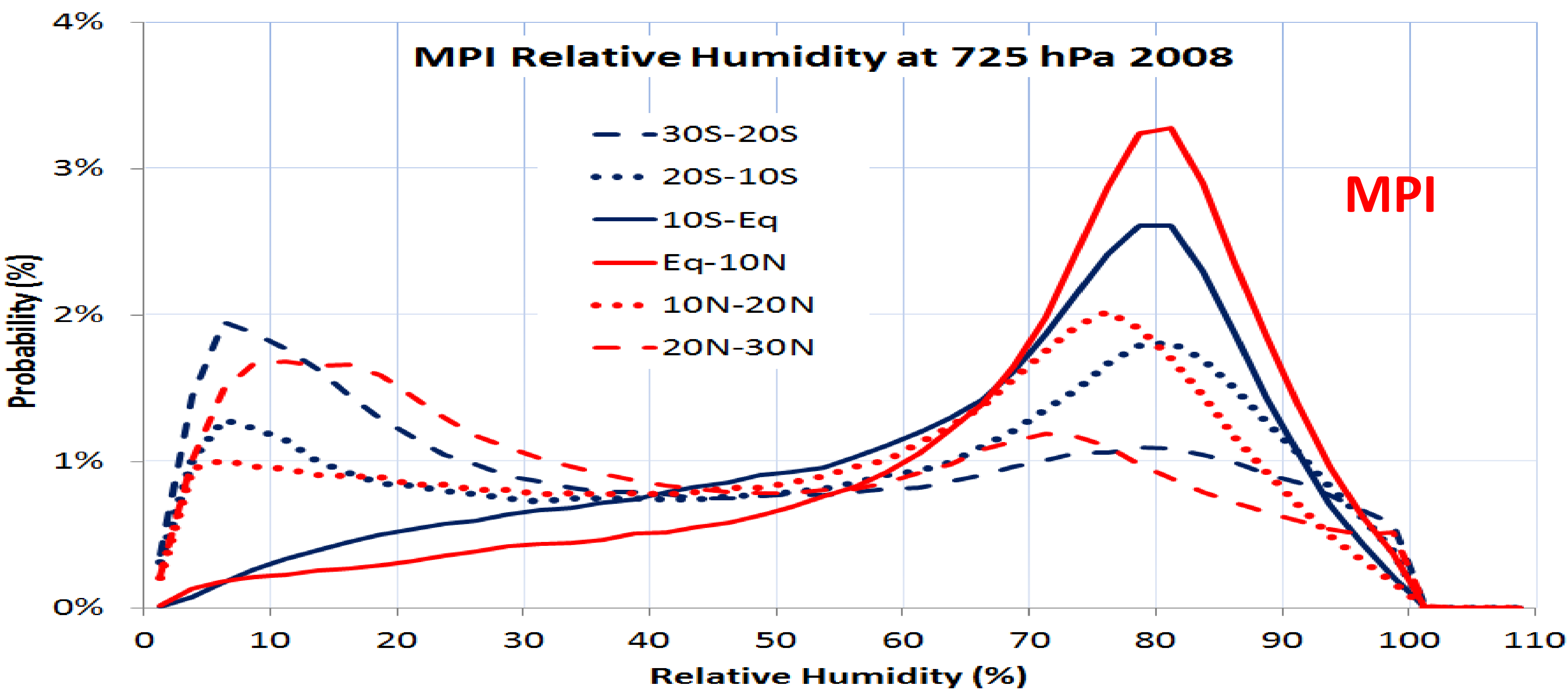
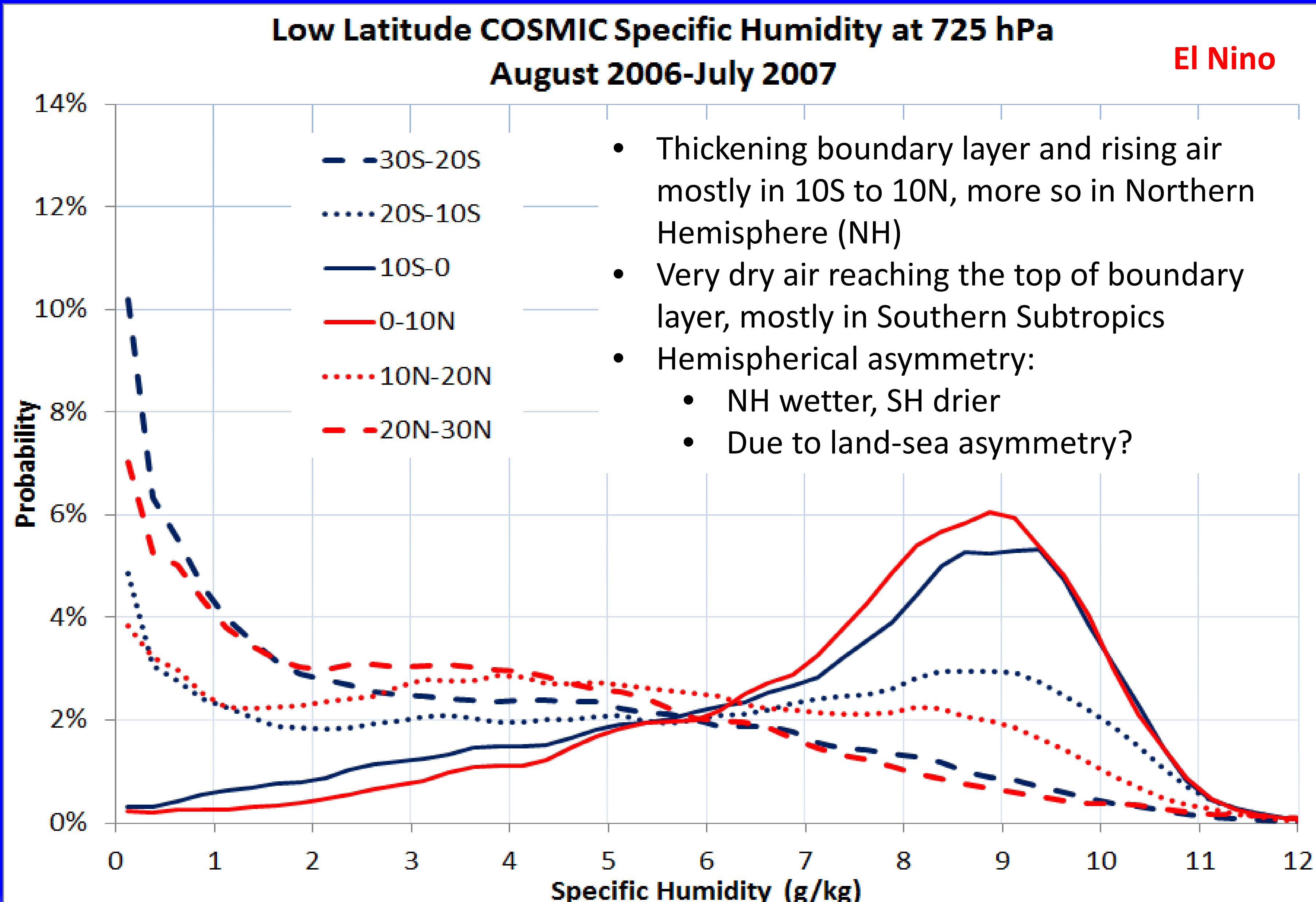
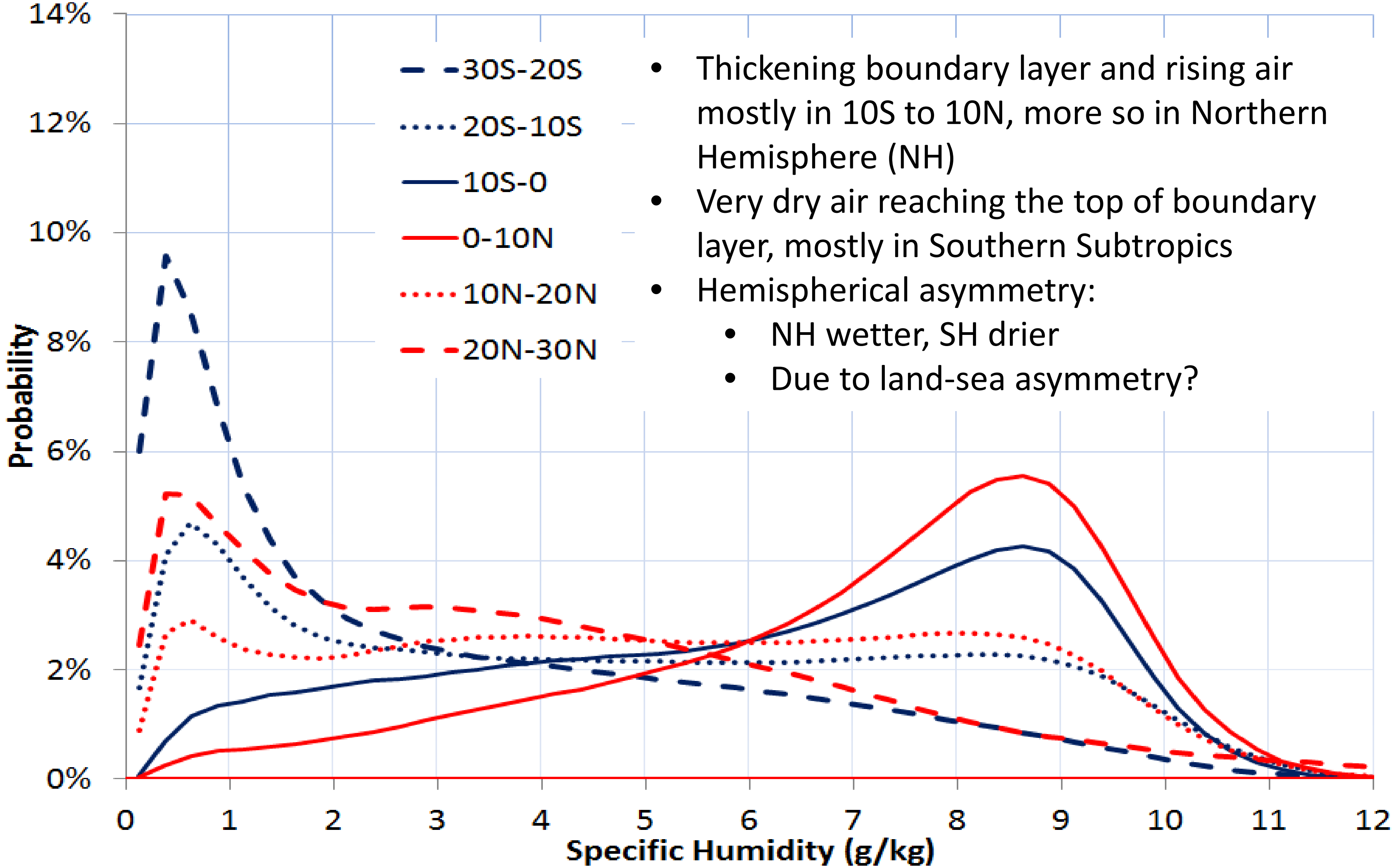

MPI Relative Humidity at 725 hPa 2008
30S-20S
20S-10S
10S-Eq
Eq-10N
10N-20N
20N-30N
MPI
Probability (%)
0%
1%
2%
3%
4%
0
10
20
30
40
50
60
70
80
90
100
110
Relative Humidity (%)

# GPS RO 725 hPa Specific Humidity




- Thickening boundary layer and rising air mostly in 10S to 10N, more so in Northern Hemisphere (NH)
- Very dry air reaching the top of boundary layer, mostly in Southern Subtropics
- Hemispherical asymmetry:
  - NH wetter, SH drier
  - Due to land-sea asymmetry?

# ECMWF 725 hPa Specific Humidity

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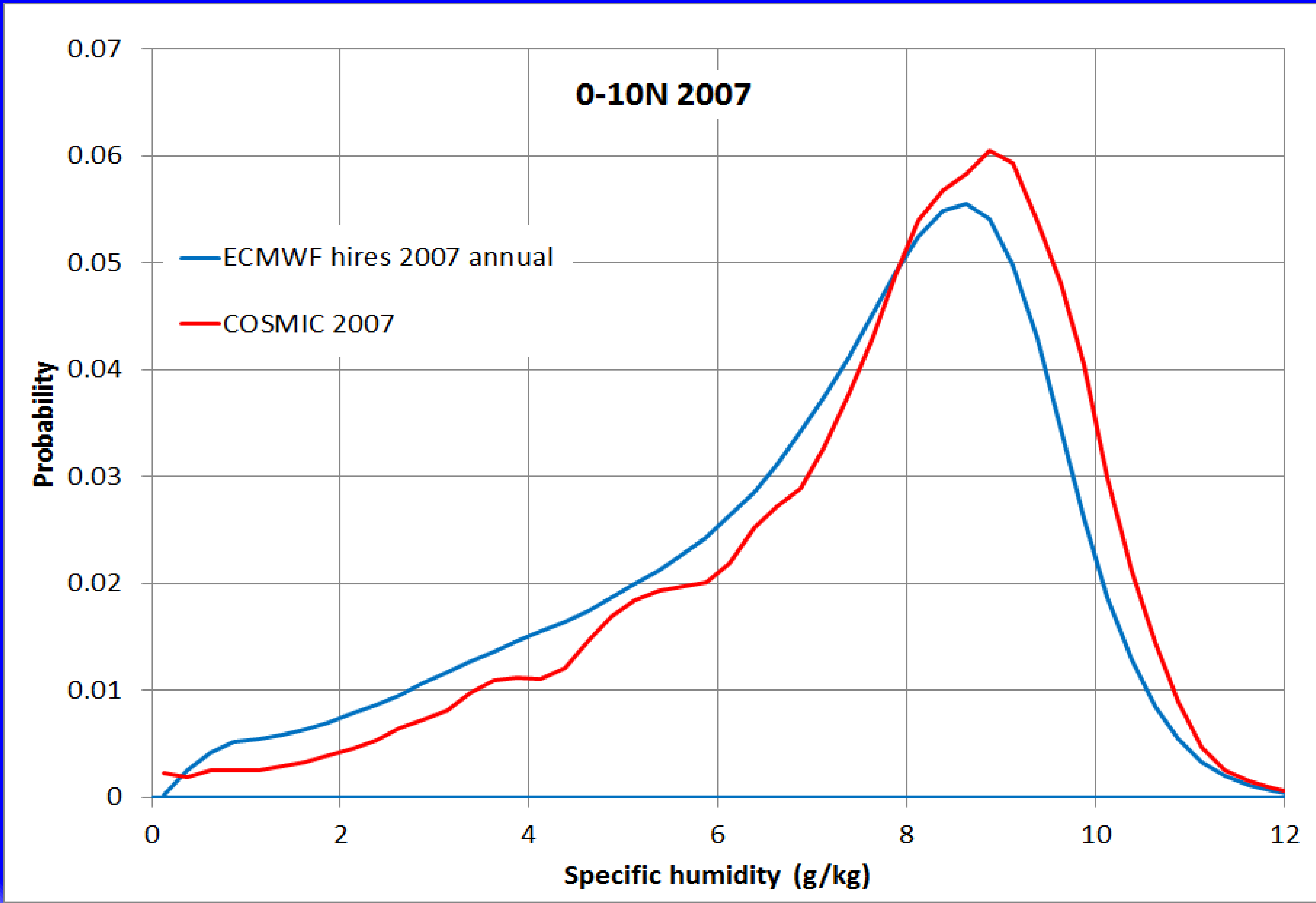
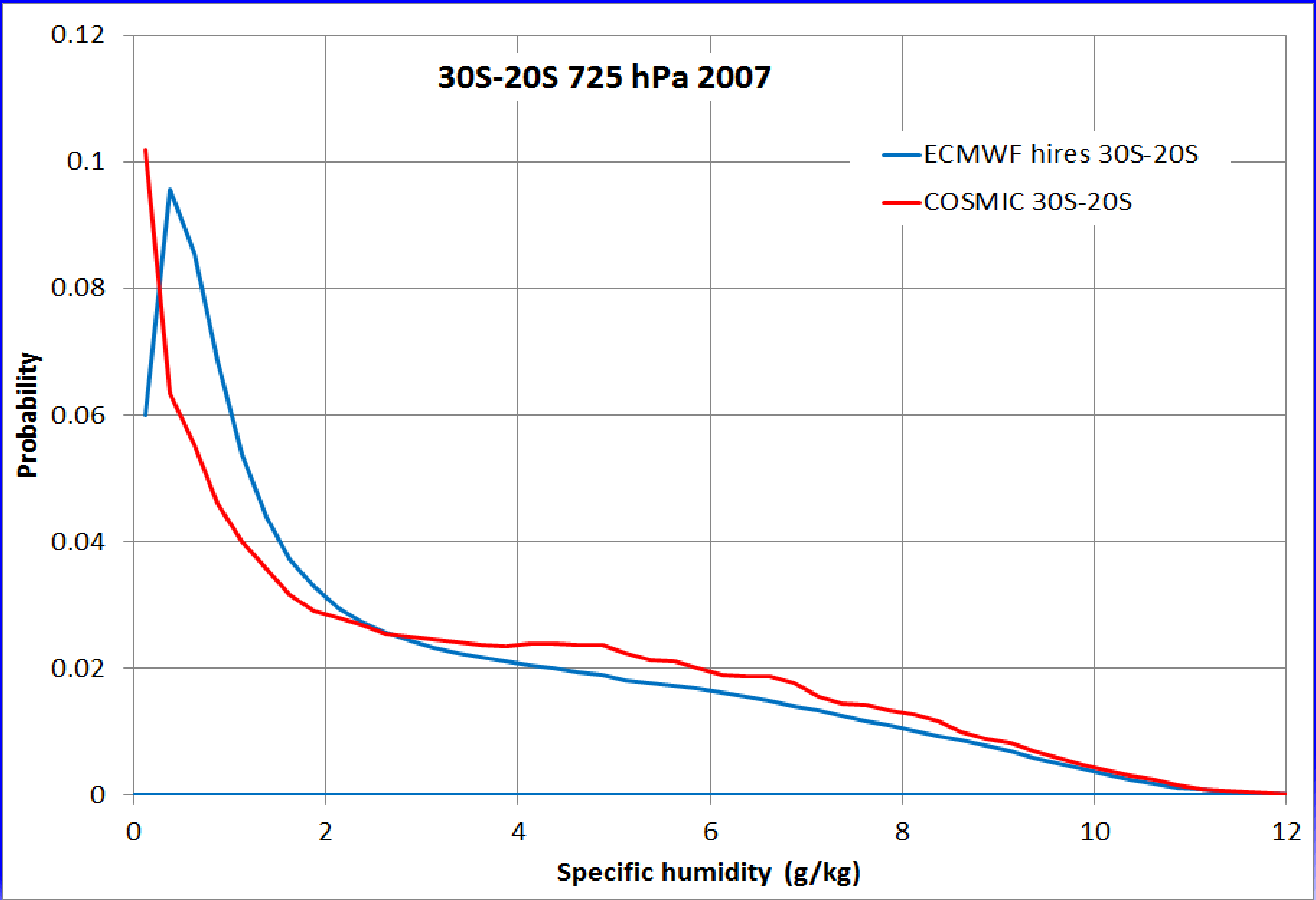
# ECMWF-COSMIC 725 hPa Specific Humidity



# ECMWF-COSMIC 725 hPa Specific Humidity



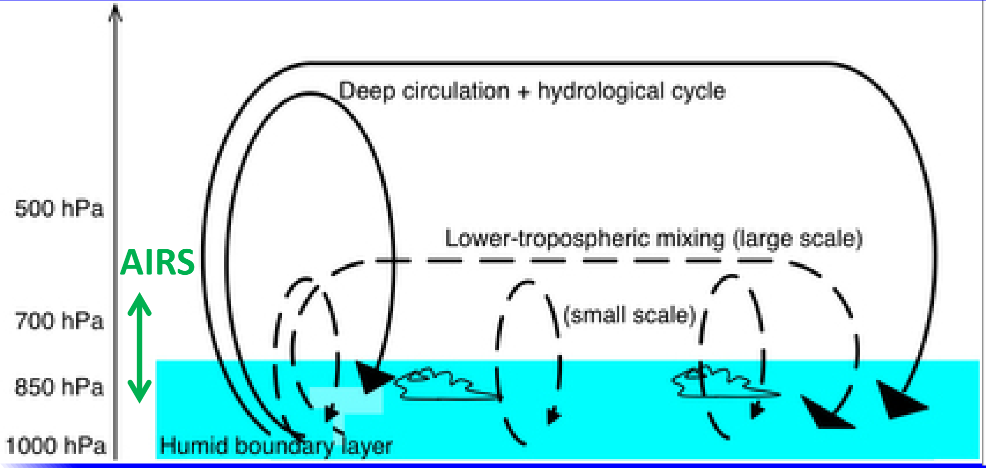
# Sherwood et al. (2014) Reduction in Climate Uncertainty?

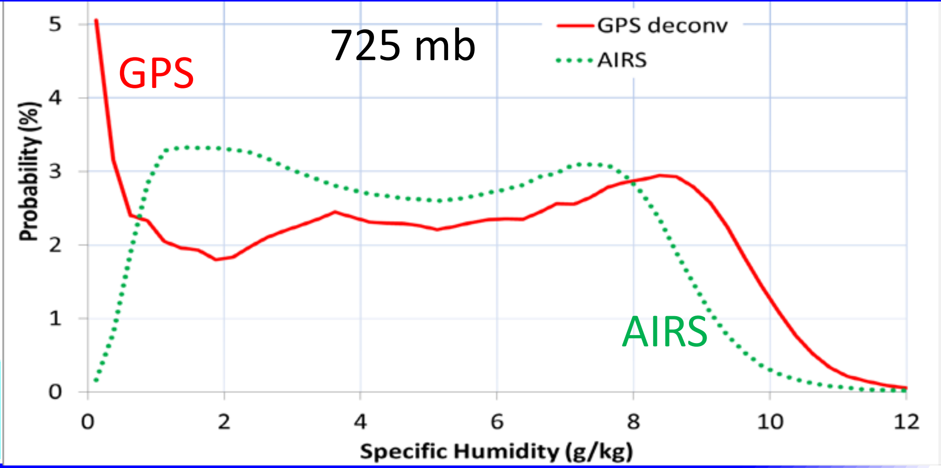
**PROBLEM with Sherwood et al. conclusion**:

- Other than GPS RO, tropical observational constraints on water vapor just above PBL are limited.
  - Radiometer vertical resolution coarse relative to sharp transition between PBL & free troposphere.

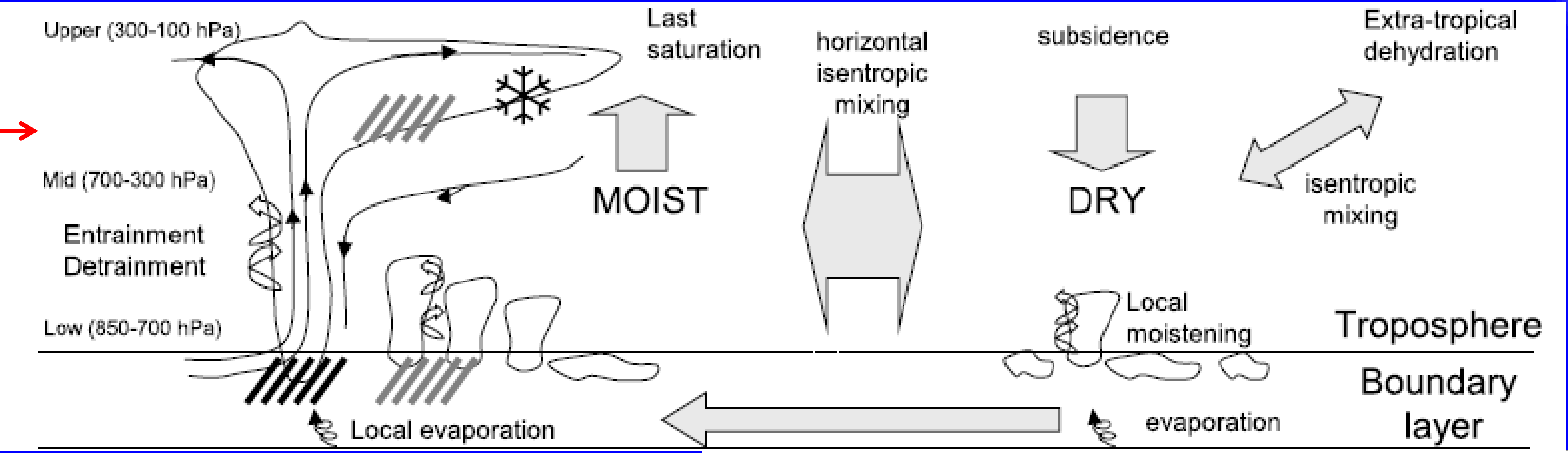
⇒ Comparison of GCMs with MERRA analyses just above the PBL is more of a model-to-model comparison than an observation-to-model comparison

⇒ Questionable to draw strong conclusions about model veracity based on present analysis-GCM comparisons

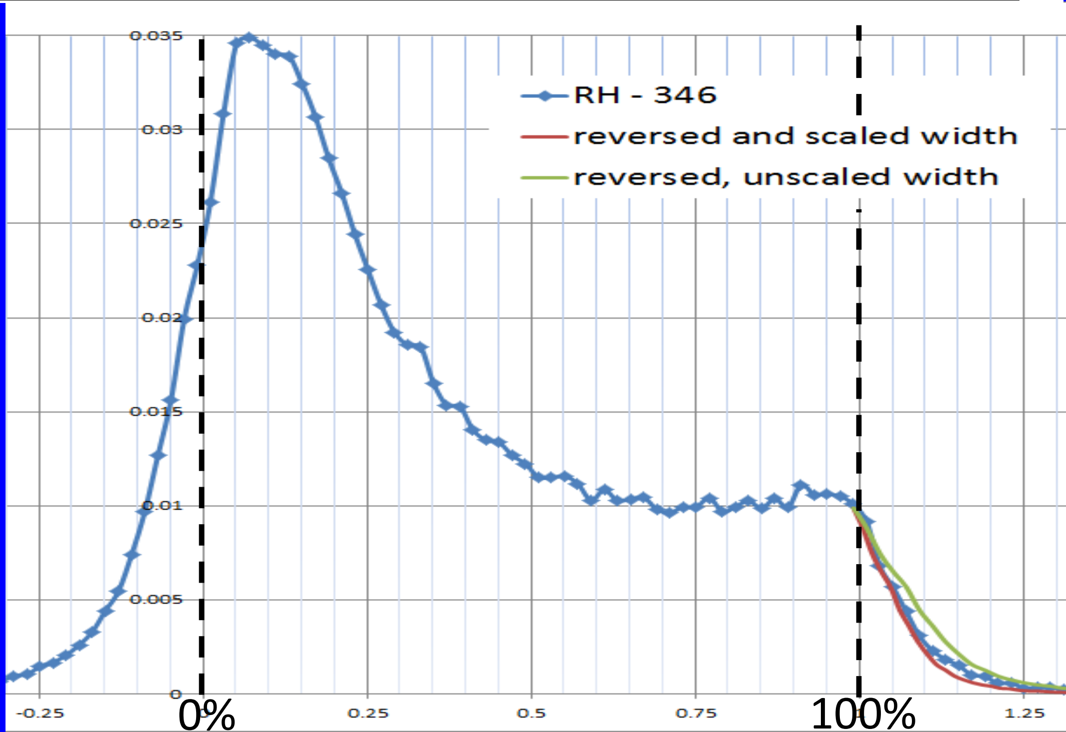


# 346 mb Relative Humidity Histogram




- Sharp fall off at 100% RH
- Asymmetry of upper & lower tails => T error = 0.8 K
- Suggestion of small % of supersaturation
- Apparently very little air drier than 0.065 g/kg (consistent with Hartmann et al., $H_2O$ rad cooling)



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

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

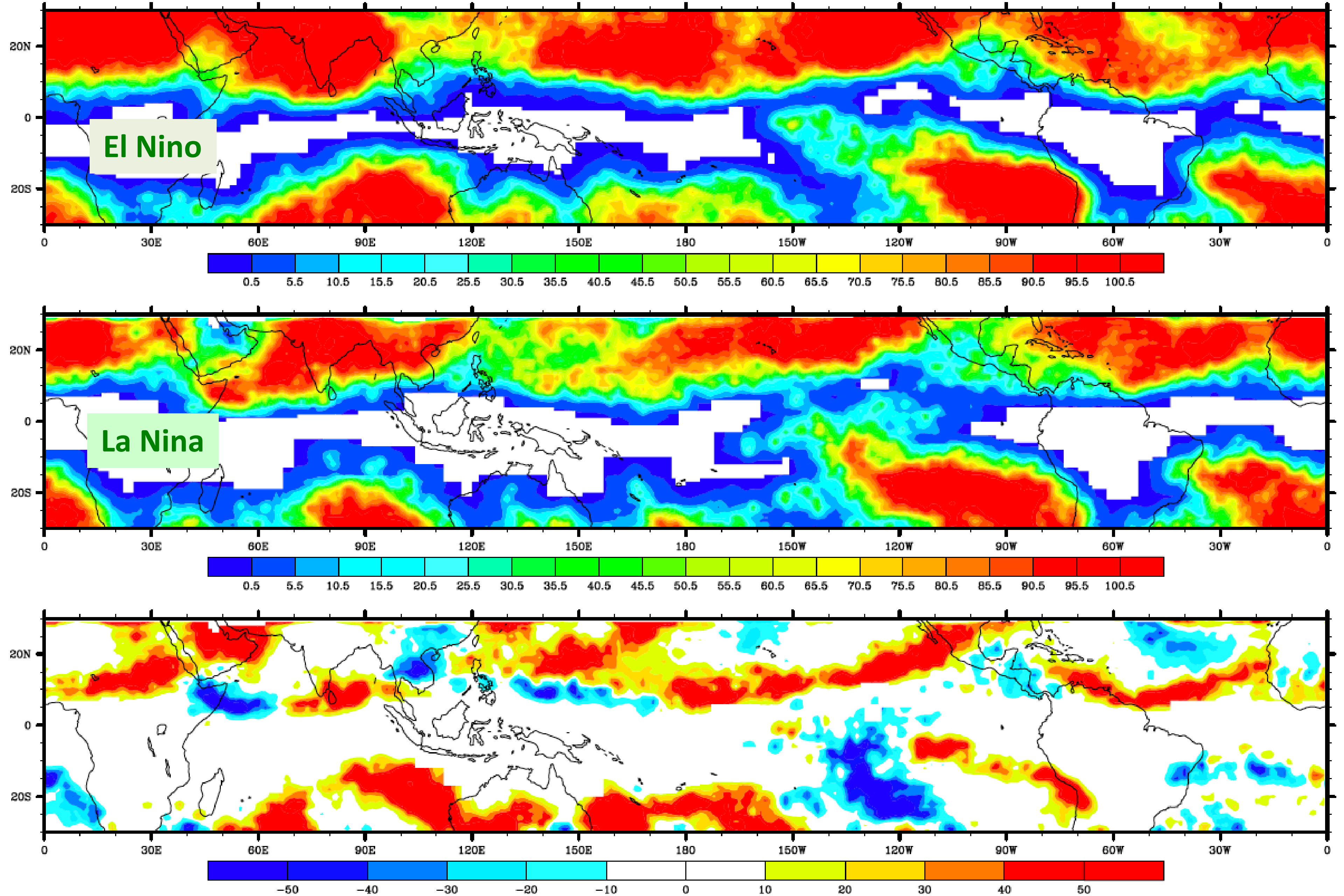
$\sigma_q \sim 0.5$ g/kg in lower troposphere

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

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

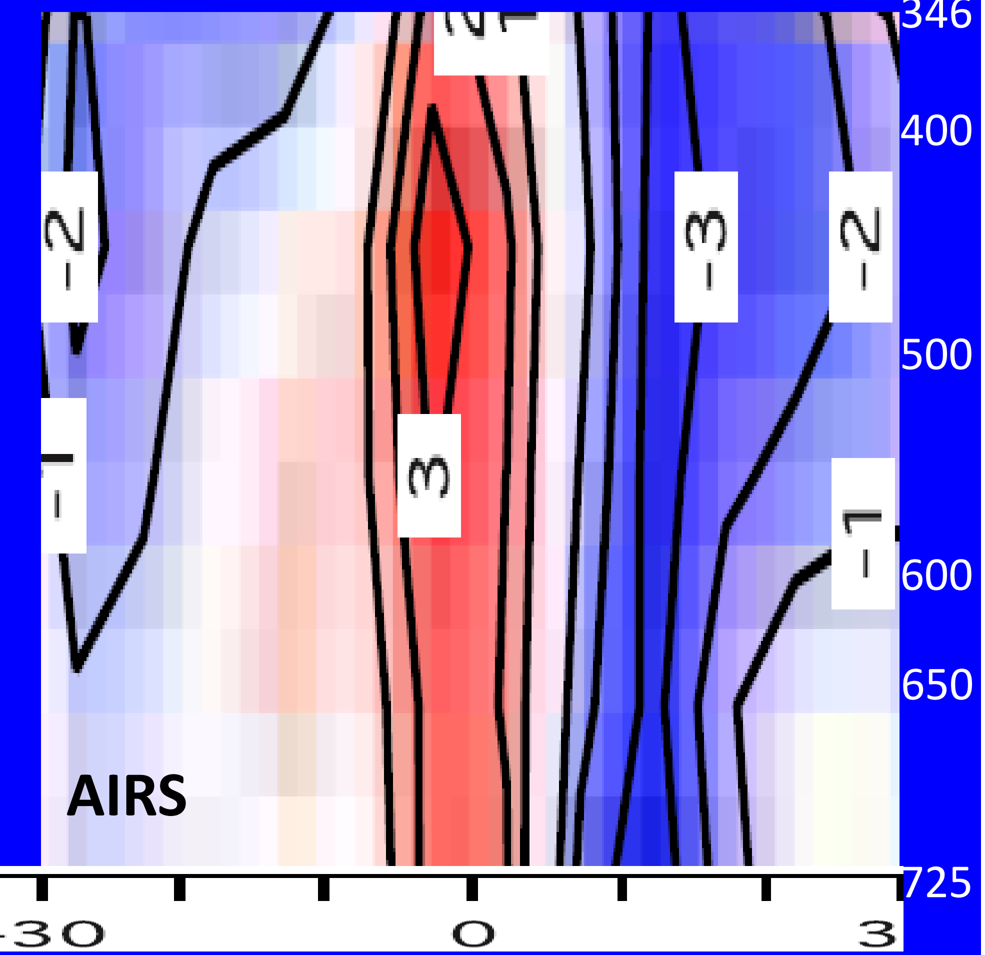
where *L* is the latent heat and $B_s = a_1 TP / a_2 e_s$.

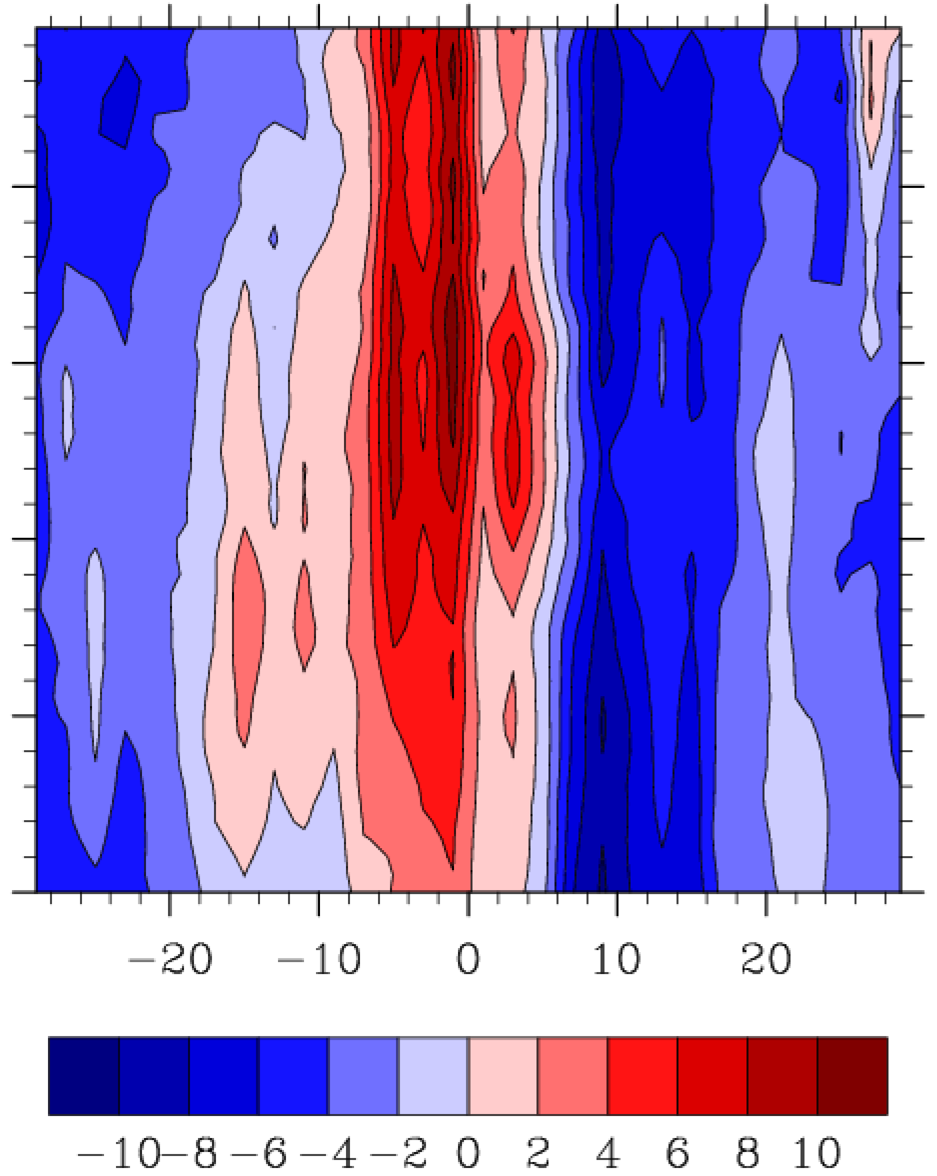
# Driest air PDFs January 2007 minus 2008



# GPS vs AIRS Fractional ΔRH vs. Altitude

## DJF 06-07 minus DJF 07-08 in %




- Similar patterns
- GPS is larger by x2-3

# Future cm & mm Wavelength Occultation System:

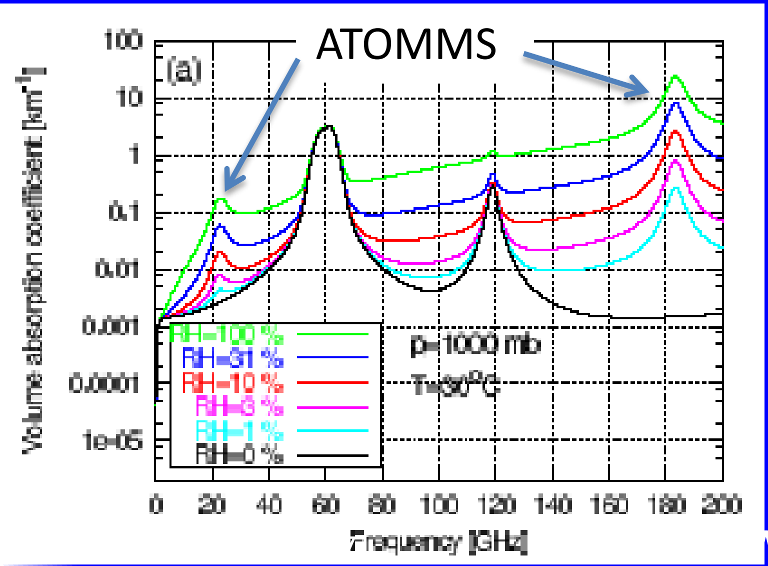
# Active Temperature, Ozone & Moisture Microwave Spectrometer (ATOMMS)

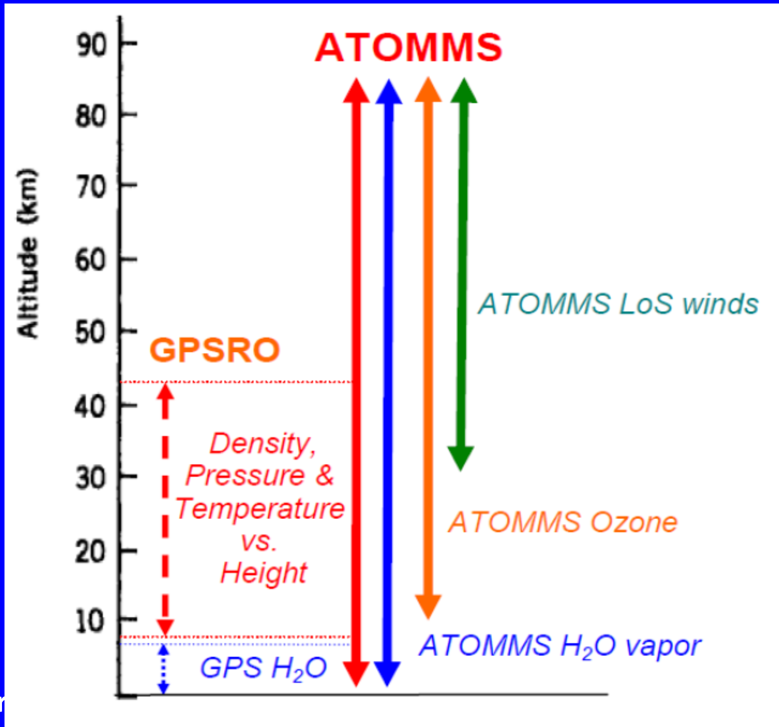
# ATOMMS Overview

- Actively probes $H_2O$ 22 GHz & 183 GHz absorption lines
  - Profile both speed of light and absorption of light
    - Profile water vapor & temperature simultaneously, which GNSS RO cannot do, to much higher altitudes
    - Works in clear air and clouds
- Also other constituents like $O_3$, $N_2O$, $H_2^{18}O$, HDO

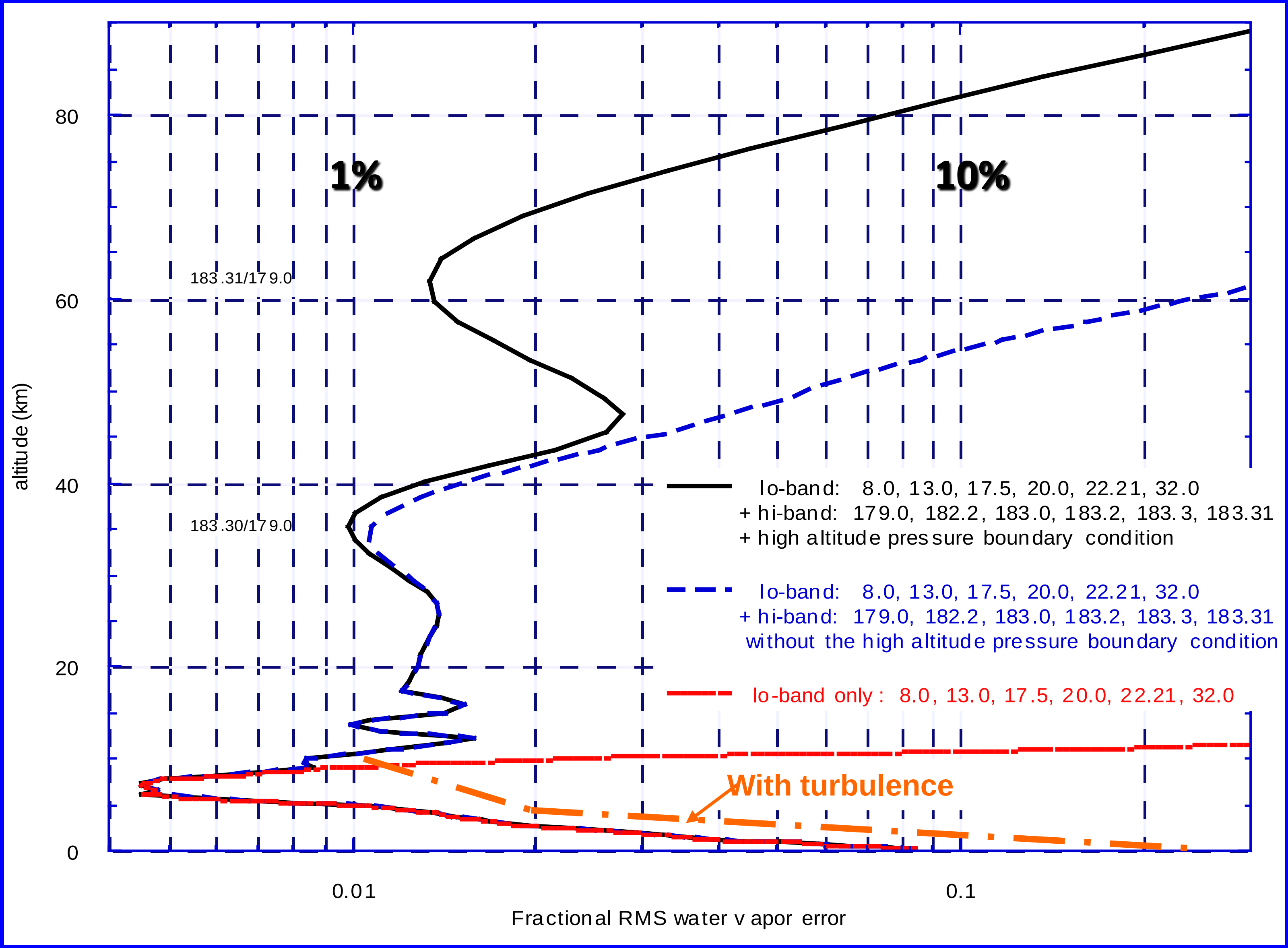
⇒ Cross between GPS RO & MLS

⇒ LEO Constellation of ATOMMS

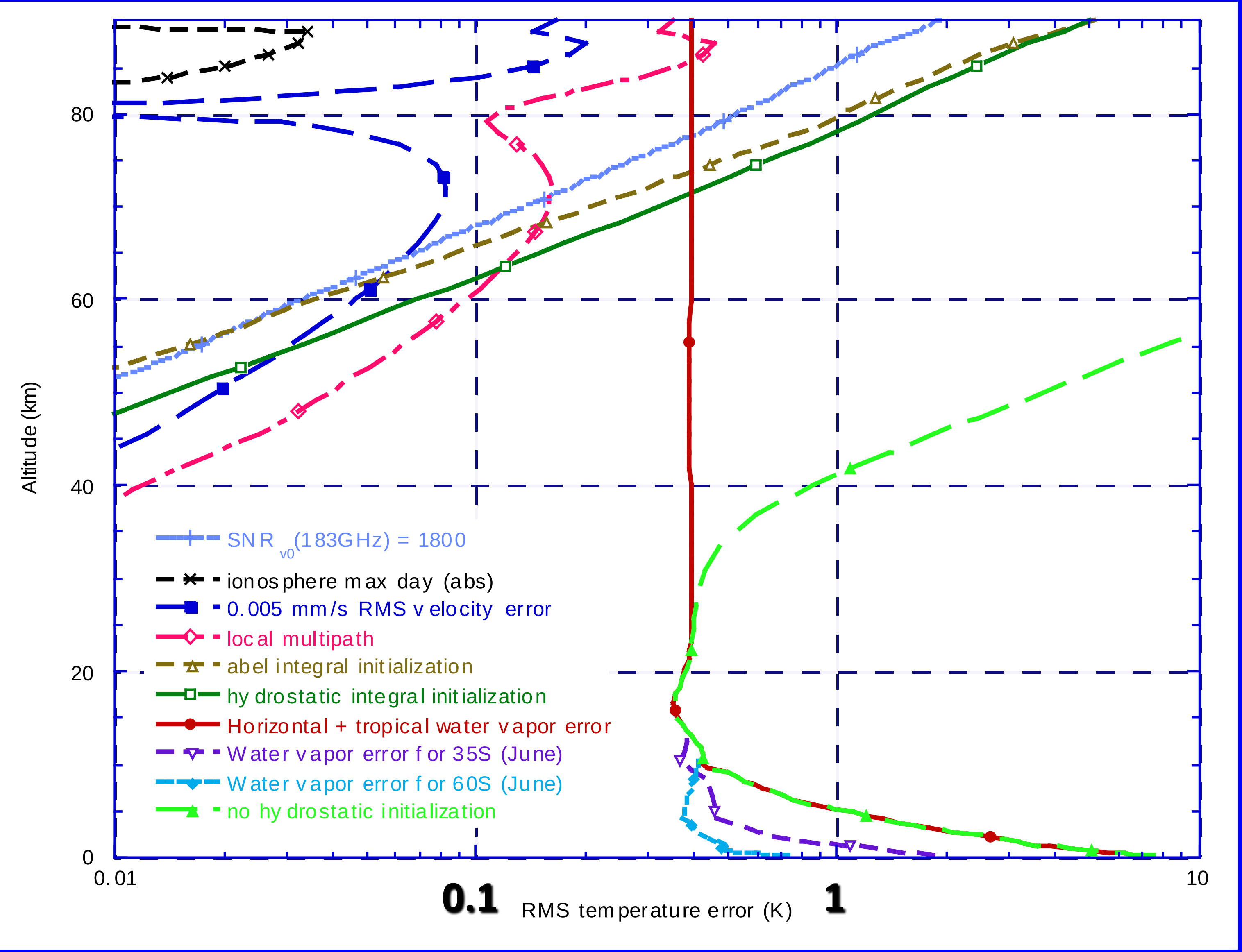


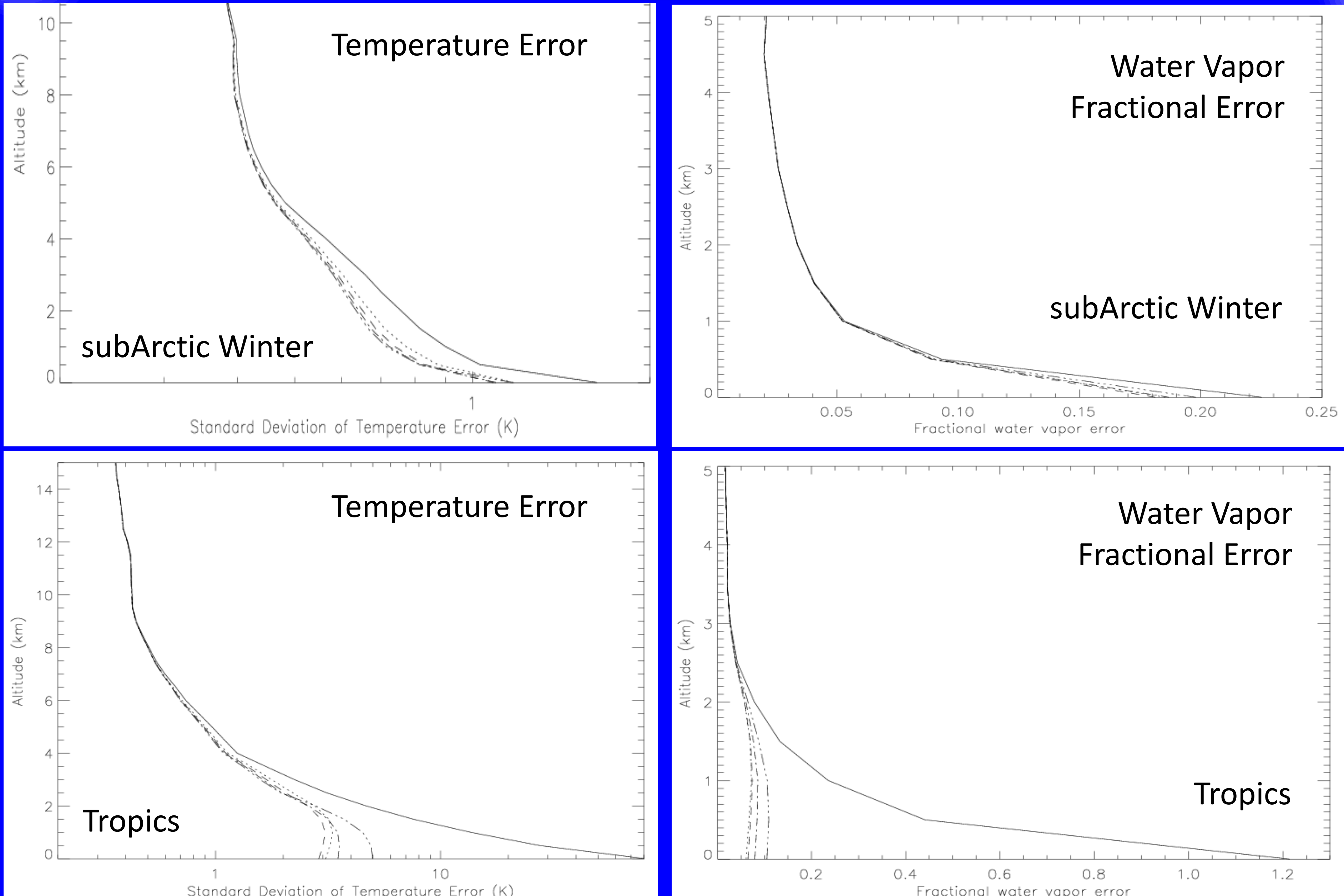
# Precision of Individual Water Vapor Profiles



# Precision of Individual Temperature Profiles



# Near-Surface Precision with 3, 22 & 183 GHz tones



# Water Vapor Retrievals: Clear, Cloudy & Rain

- Using mountaintop observations to demonstrate ability to retrieve water vapor spectra in clouds and rain
  - Enabled by calibration tone at 198 GHz
  - Figures show spectrum of amplitude ratios relative to calibration tone