GPS RO Research on Water Cycle related issues & the Active Temperature Ozone and Moisture Microwave Spectrometer (ATOMMS)

E. Robert Kursinski

Department of Atmospheric Sciences
University of Arizona

August 19, 2009 JCSDA

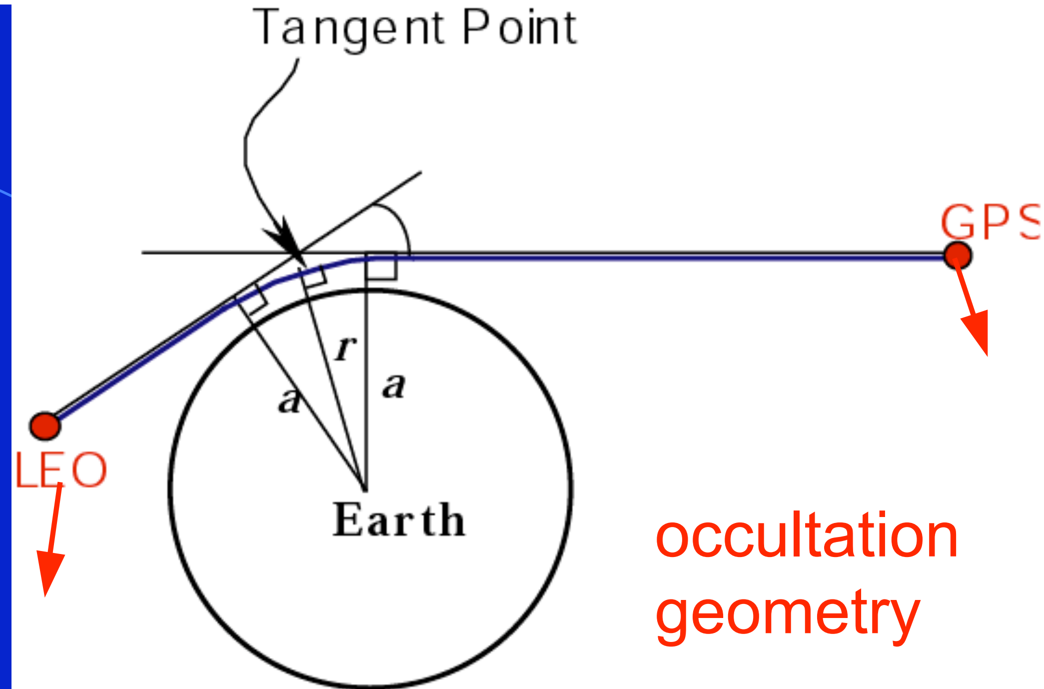
Outline

Three parts

- GPS RO water related results
- GPS RO data assimilation
- ATOMMS (next generation RO system under development)

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

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

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

1D Forward relation *1D Inverse relation*

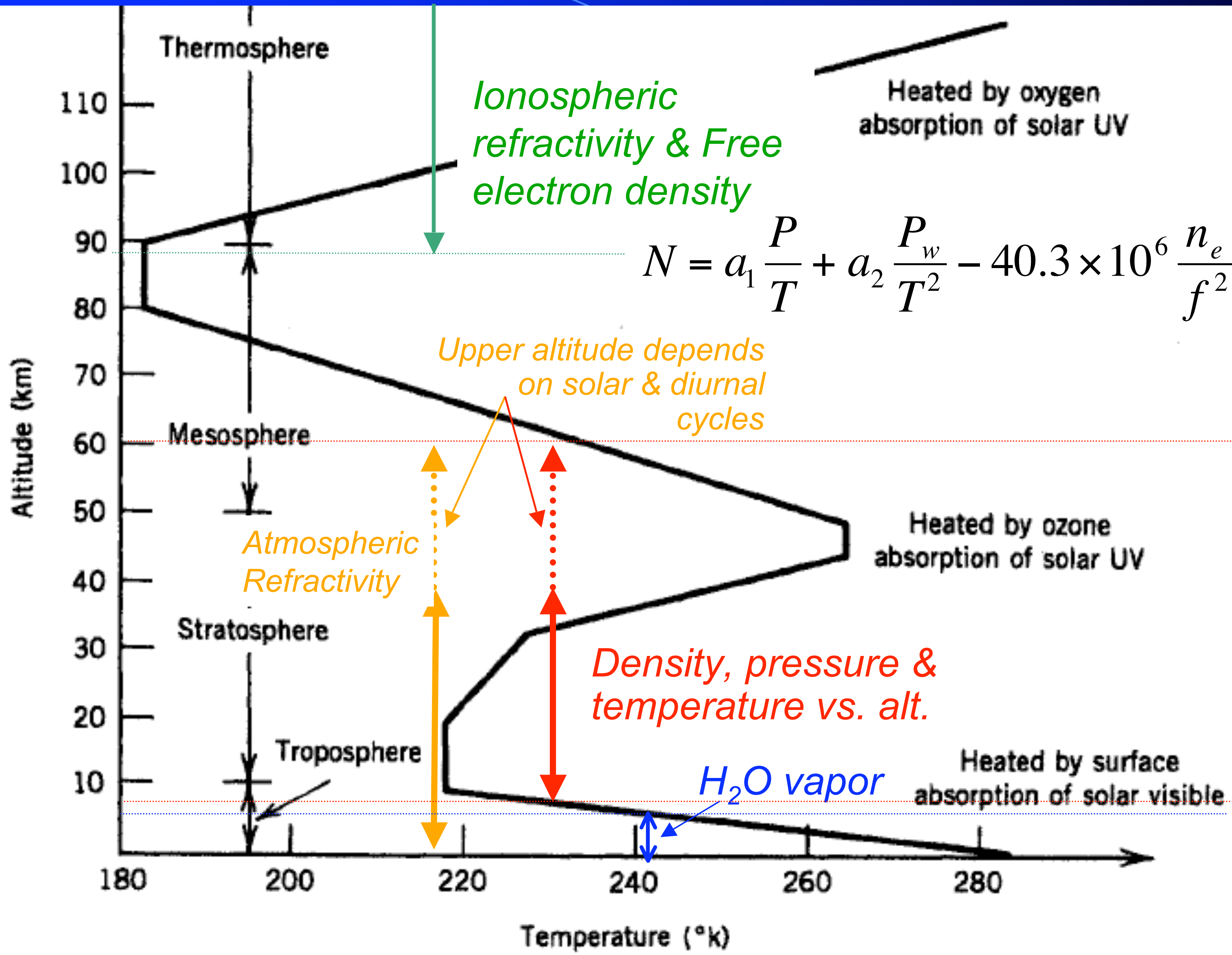
- Delay(t)=> bending angle(z) => refractivity(z)
  - Dry conditions: => dry density(z) => P(z) => T(z) via hydrostatic eqn
  - Wet conditions: refractivity + *T,p,q* (analysis) => better *T,p,q*

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

GPS RO Features Summary

- Least biased data set available?
  - Global coverage
  - Diurnal coverage with ≥ 6 satellite constellation like COSMIC
  - Works in clear and cloudy conditions (λ~20 cm)
  - Works over land and water (no surface emissivity sensitivity)
  - Unique relation between bending angle & refractivity (except super-N) insensitive to initial guess
- Resolution
  - Vertical resolution ~200 m
    - Capable of seeing stability related effects invisible to other sounders
  - Horizontal resolution
    - Along track horizontal resolution ~ 300 km
    - Cross track ~ 1.5 km (plus horizontal motion of raypath)
    - Inherent averaging good for climate (better horiz. res. desired for NWP)
- Water Vapor vertical range
  - Useful to ~240 K level in troposphere (~9 km alt. in tropics)
  - Extends down very close to surface in mid & high latitudes
  - If we can deal with ***super-refraction***, lower altitude can be the surface in the tropics

Information vs. Altitude from GPS RO



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

Part 1:

Low Latitude Water Vapor Variability Observed by GPS Radio Occultation

E. R. Kursinski, A. Kursinski

[1]*University of Arizona*

M. Evans[2], C. Ao[3], D. Rind[4], D. Ward[1]

[2]*UMd*, [3]*JPL*, [4]*GISS*

Funded by JPL DRDF

Tropical Moisture Variability Study

Data Sets

- CHAMP: ~150 occ per day from 2002 to mid-2008
- COSMIC: 6 satellite constellation ~1500 occ per day, mid-2006 to present
- Processed at JPL
  - GPS canonical transform data smoothed to 200 m vertically courtesy of Chi Ao at JPL
  - Interpolate the nearest ECMWF 12 hour, 22 level global temperature analysis to each occultation profile
- Low latitude, free tropospheric water vapor
  - Latitude range: 30°S and 30°N
  - Altitude range: 2.5 to 8.5 km
    - 2.5 km avoids super refraction problem in PBL
    - Good water vapor data 30°S and 30°N up to 8.5 km throughout year

Cluster Analysis

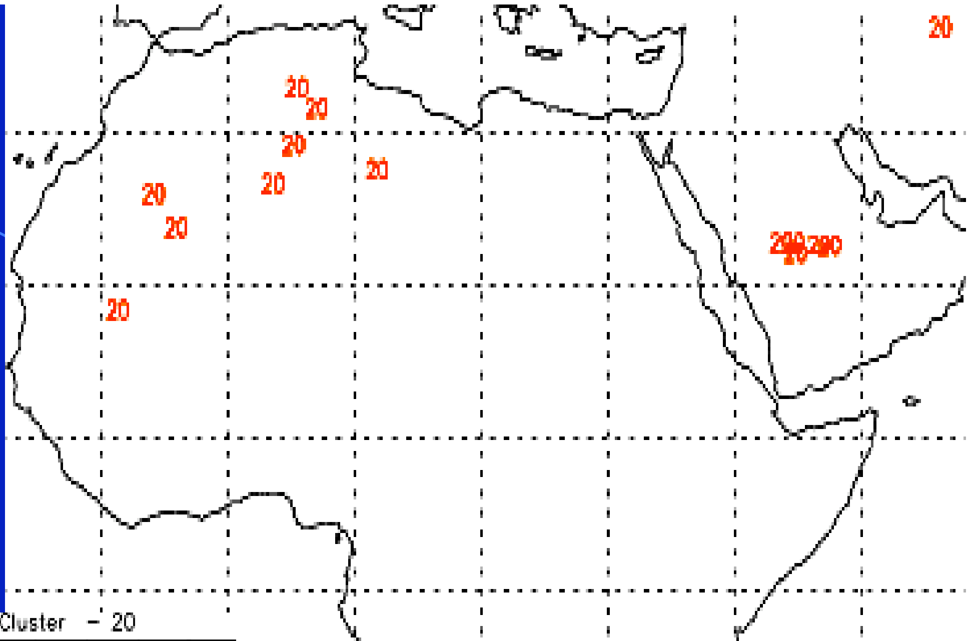
Use cluster analysis to

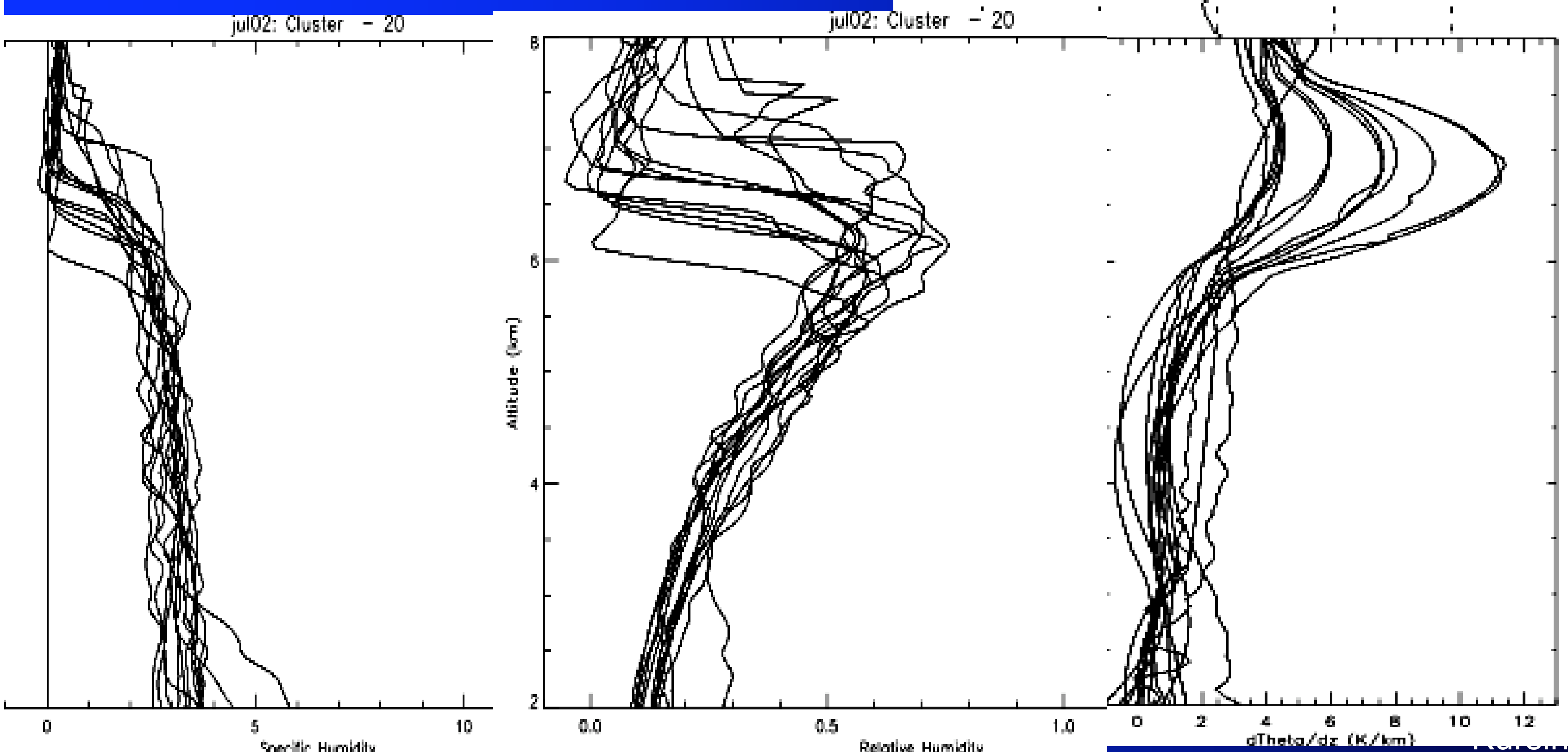
- extract patterns in the vertical structure of the GPS moisture profiles
- and reveal their horizontal distribution
- to help infer underlying processes

This led to identification of an ENSO related pattern and related research

Deep dry boundary layers over North Africa

- Deep well mixed layers to 6 to 7 km altitude in July
- Note 200-300 m vertical resolution across BL tops





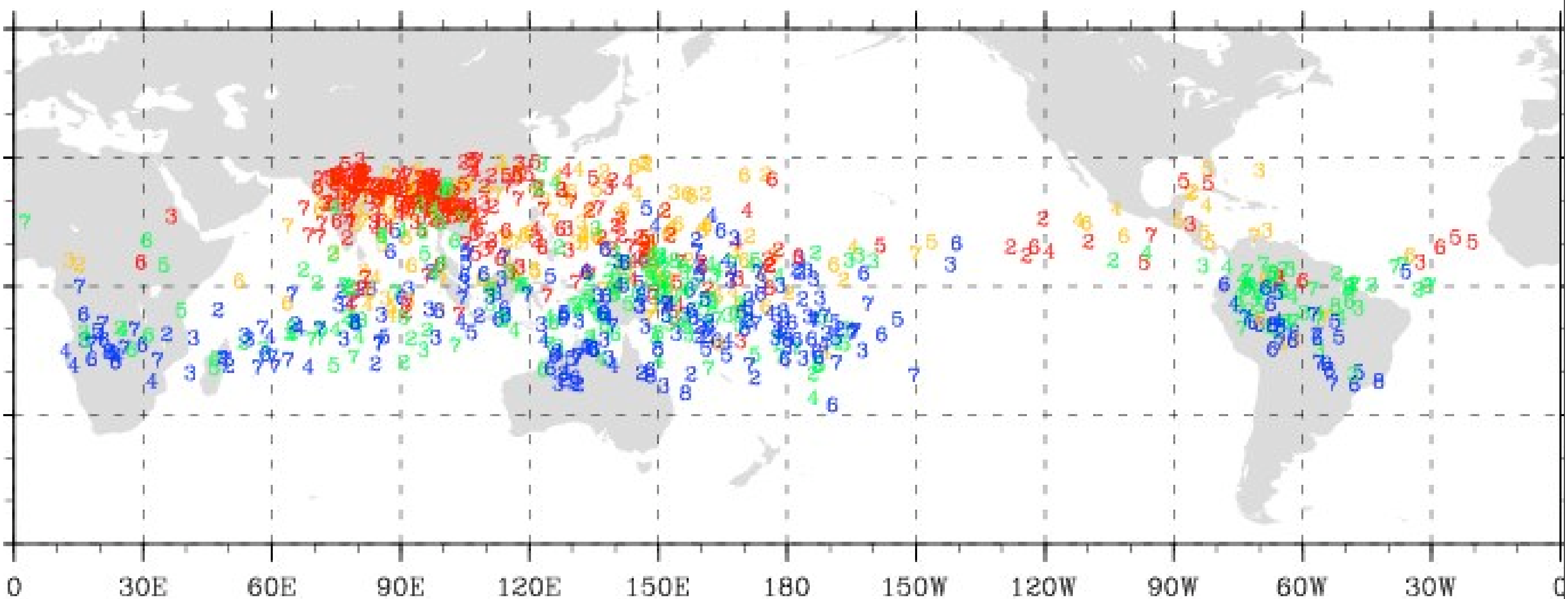
Location of Wettest Profiles vs. Season

Seasonal locations of the *CHAMP* GPSRO profiles between 30°S and 30°N with the largest free troposphere specific humidity amounts

DJF (blue), MAM (green), JJA (red), SON (orange).

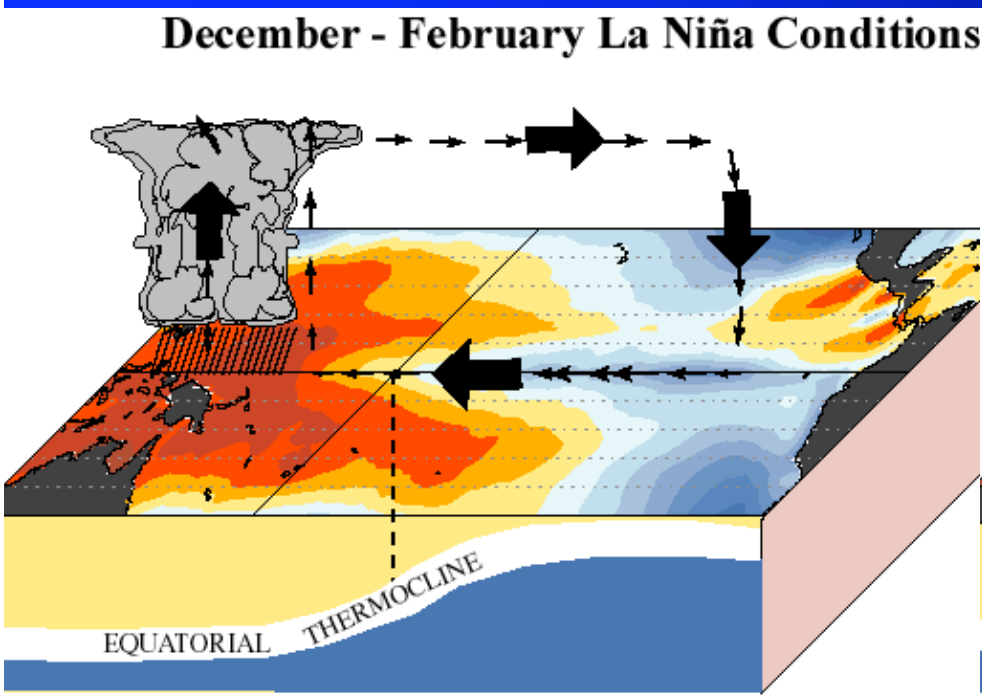
Numbers represent last digit of year in the 7-yr (2002-2008) dataset.

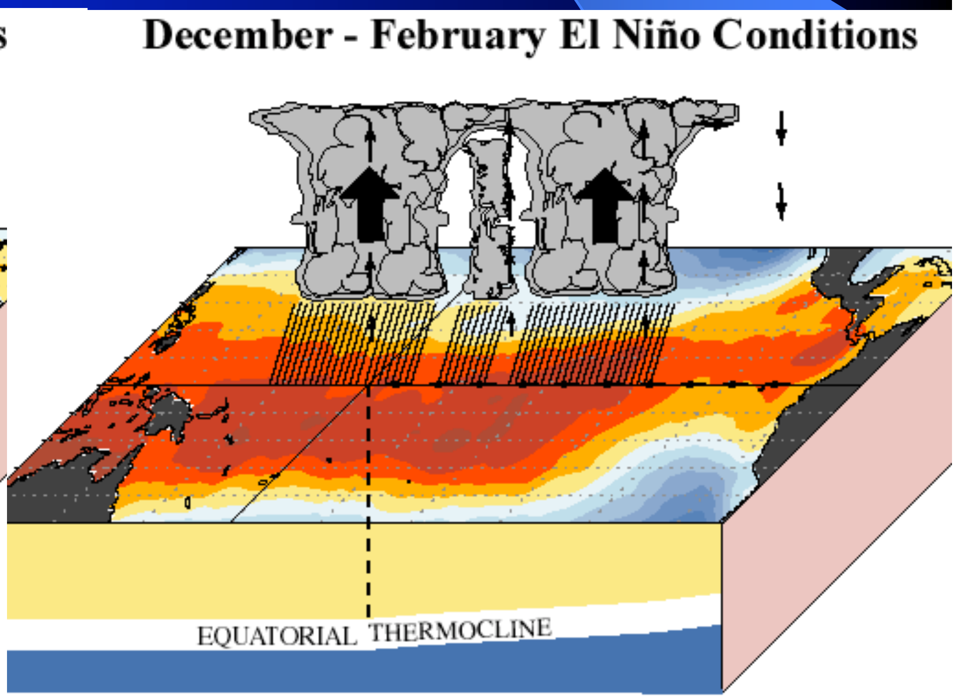
Seasonal cycle of water vapor is clearly evident



ENSO

- Coupled ocean-atmosphere mode of variability
- Dominates tropical variability
- Affects precipitation patterns around the globe
- Difficult to predict

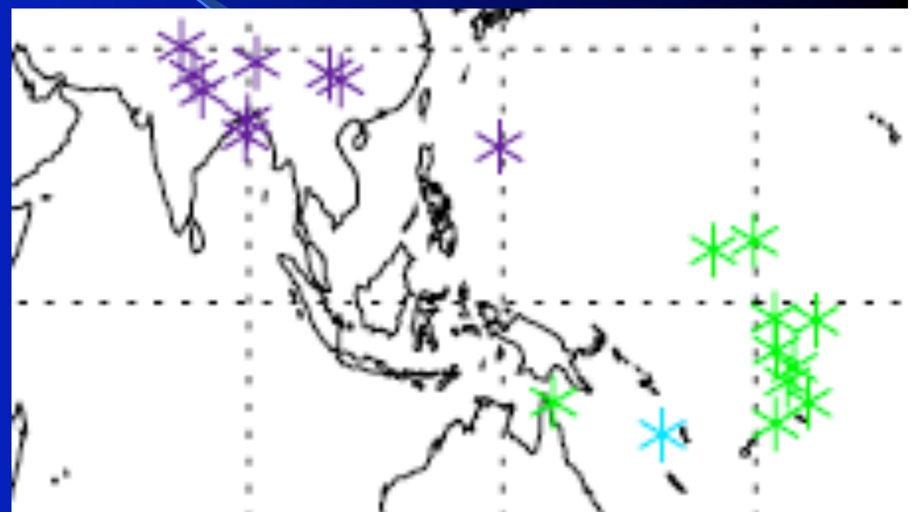


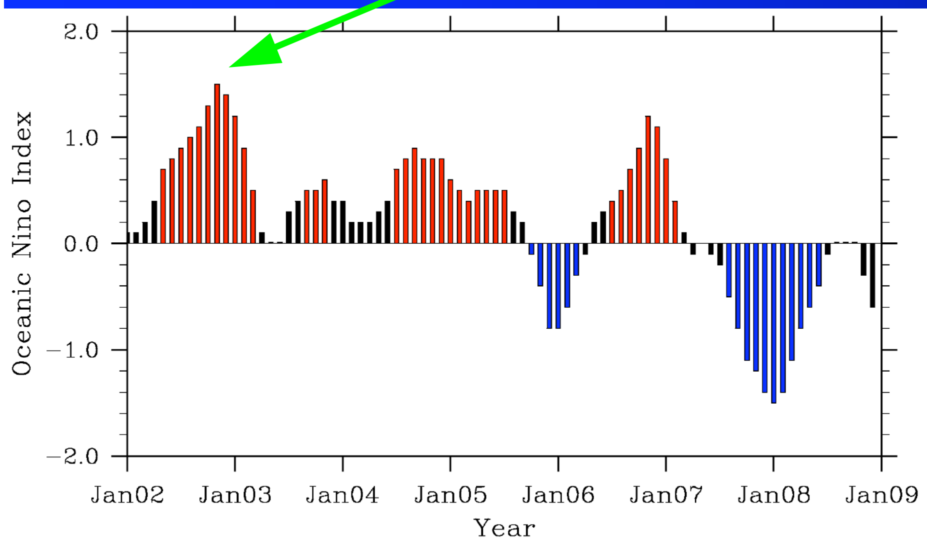


Initial Evidence of an ENSO Signature in GPSRO

- Found wettest *q* profiles in *July 03* in CHAMP data were located in Indian-Asian monsoon region
- Examined Austral summer for comparably wet profiles
  - only 1 profile *Jan 02* as wet
  - Similarly wet profiles ***did*** exist in *Jan 03* located over central Pacific

Jan 03 near El Nino peak



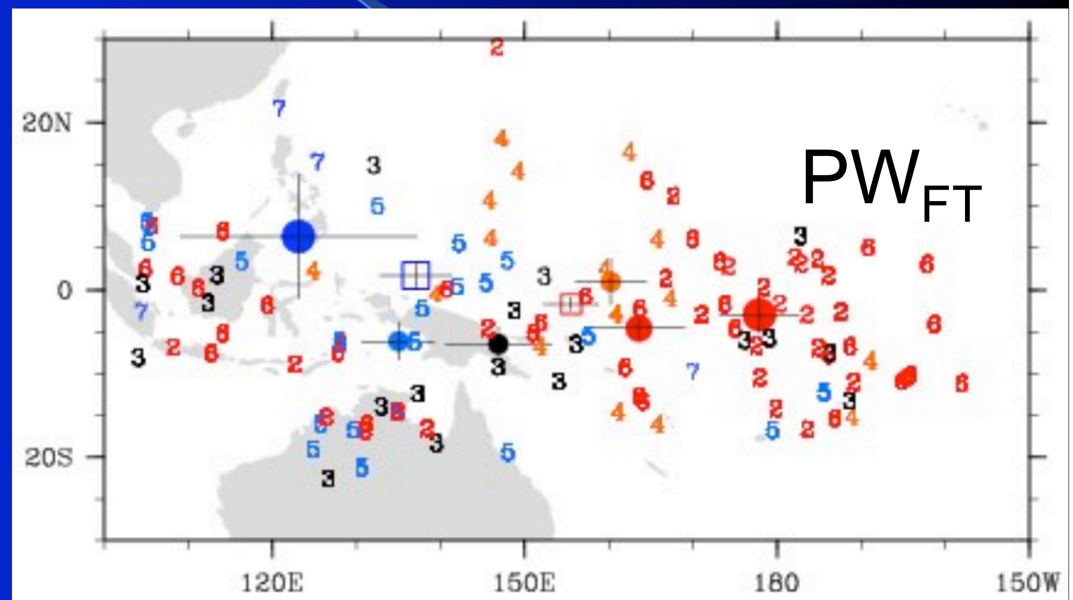


Wettest El Nino profiles have similar *q*'s but are slightly cooler than wettest monsoon profiles, (therefore higher RH)

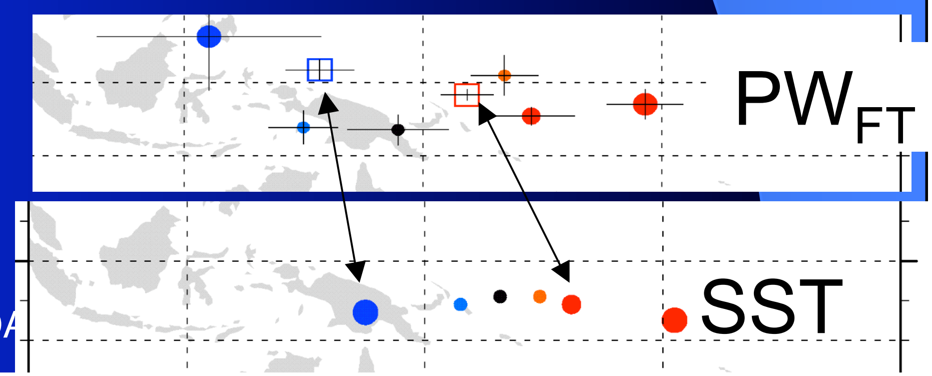
Free Troposphere Water Vapor-based ENSO Index

Centroids of 2 wettest Nov-Dec-Jan (NDJ) clusters from CHAMP & COSMIC track ENSO (SST) phase and intensity

- Tied to deepest, wettest convection, tracks max SST
- 3rd & 4th wettest clusters do ***NOT*** track the ENSO



- CHAMP centroids are noisier than COSMIC due to limited # of samples
- PW_{FT} centroids are shifted west of SST centroids
  - ➢ due to trade winds?



Blue La Nina
Black neutral
Red El Nino

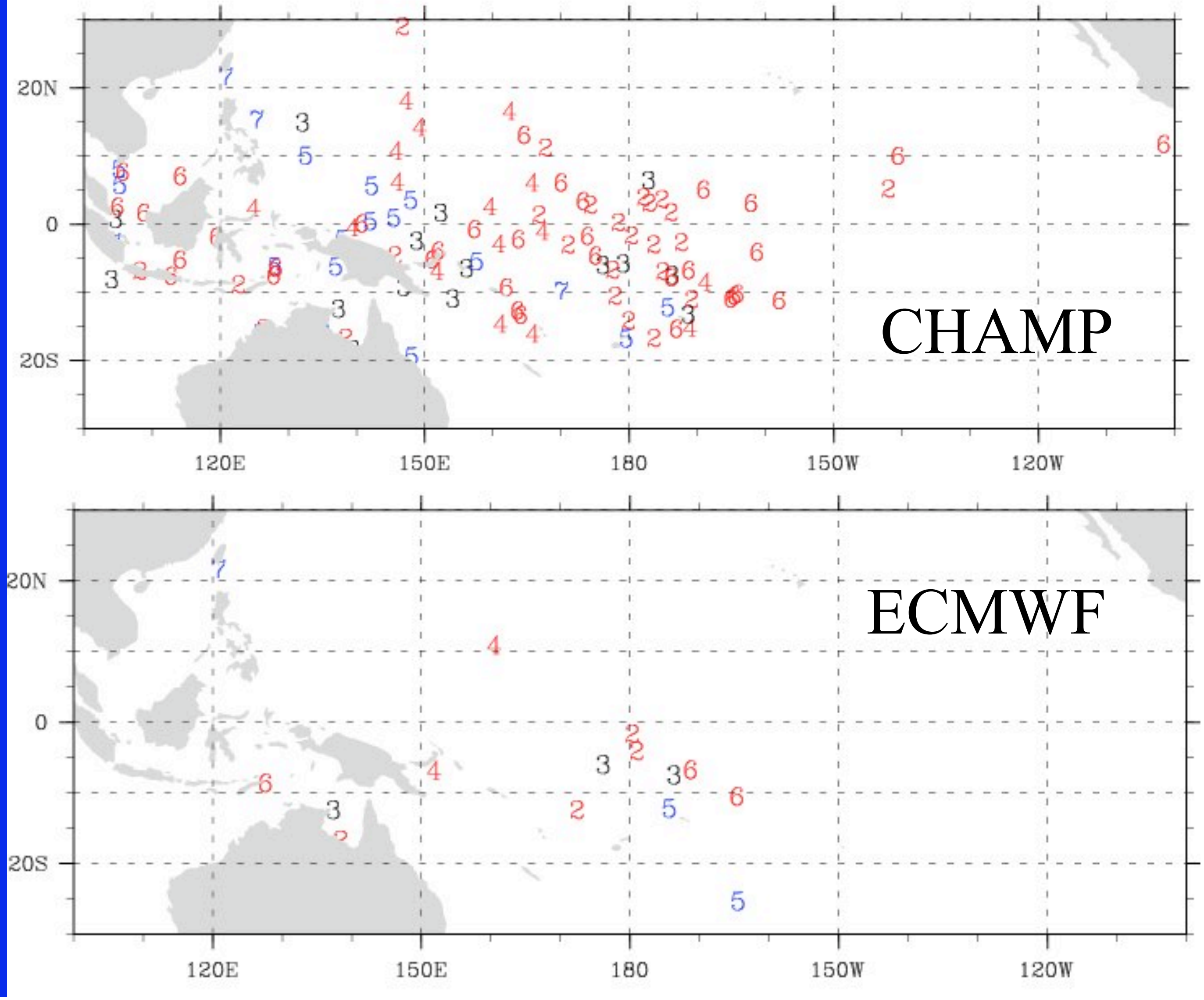
● CHAMP
■ COSMIC

Does ECMWF show this signature? ***NO***

Wettest cluster profiles: January CHAMP vs ECMWF

ECMWF analyses contain far fewer of the wettest profiles

Limits ability to perform similar research over a longer period using ECMWF

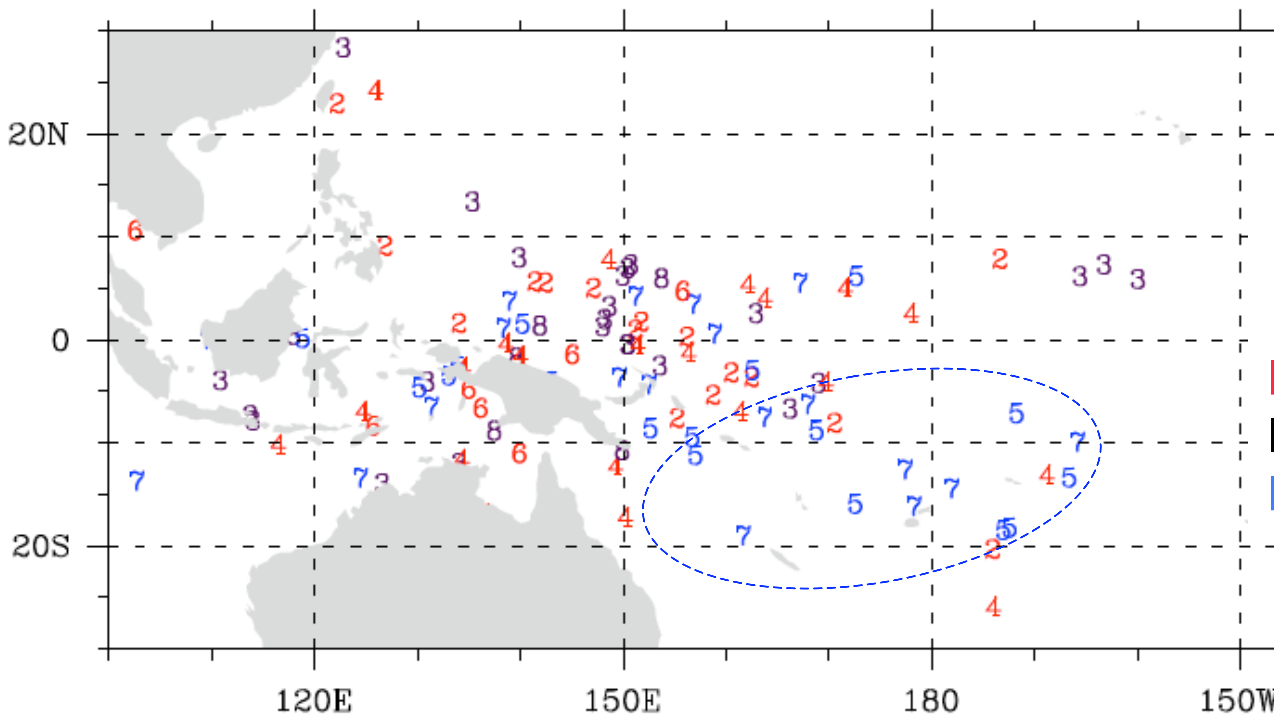


ENSO Predictive Skill from April-May SPCZ

During AM's of 2005 & 2007 that preceded two La Niñas, the SPCZ contained unusually large numbers of extremely wet profiles

- Implies that SPCZ in AM in 2005, 2007 experienced more extreme lifting than other years sampled by GPS
- Implies circulation with stronger convergence in SPCZ late in the (Southern Hemisphere) year

- Region is well to the south of latitudinal band of ocean ENSO indices



Wettest profiles from AM 2002-2008

Red following fall is El Niño
Black following fall is neutral
Blue following fall is La Niña

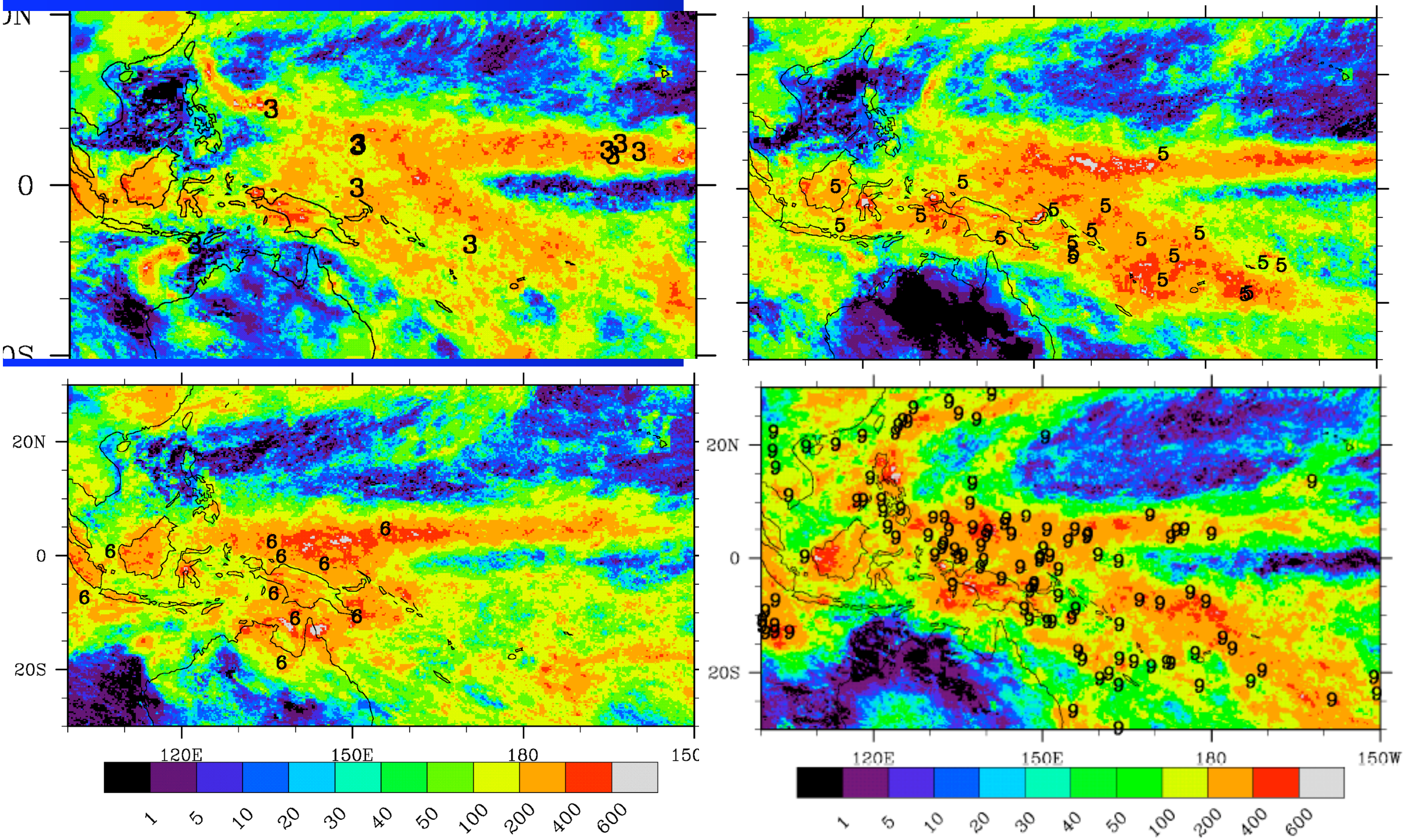
Adequacy of CHAMP Sampling?

Concern:

- Was the enhanced, extreme water vapor in AM 2005 & 2007 real or an artifact of the limited sampling by CHAMP?

- Considered surrogates that could confirm (or deny) the apparent enhancement
  - Looked at TRMM monthly rainfall

CHAMP & COSMIC sampling in SPCZ region overlain over TRMM rainfall in April



Gridded PWV_{FT} vs Rainfall

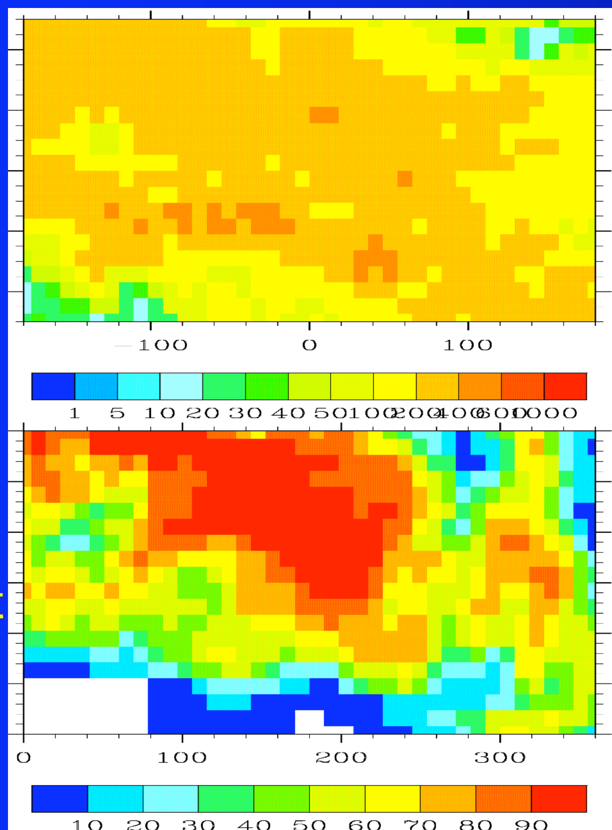
April-May SPCZ 0-20S, 150E - 170W

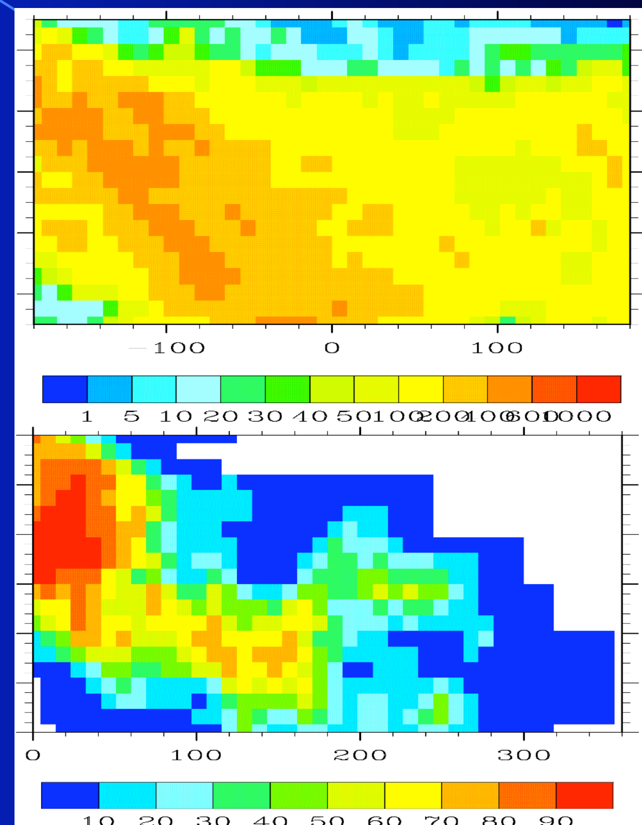
2007 | 2008

Precip monthly

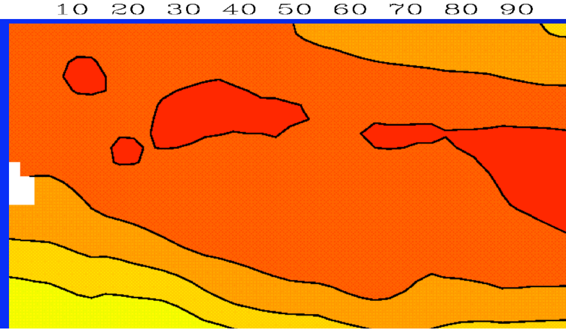
PW_{FT}

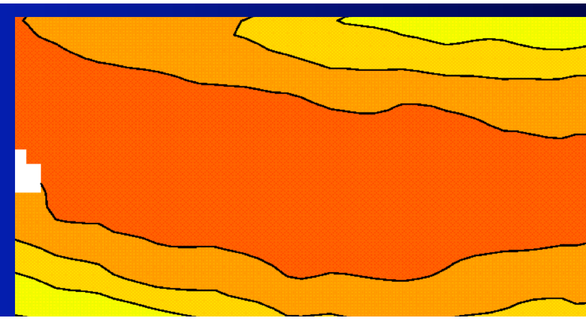
% time wettest cluster





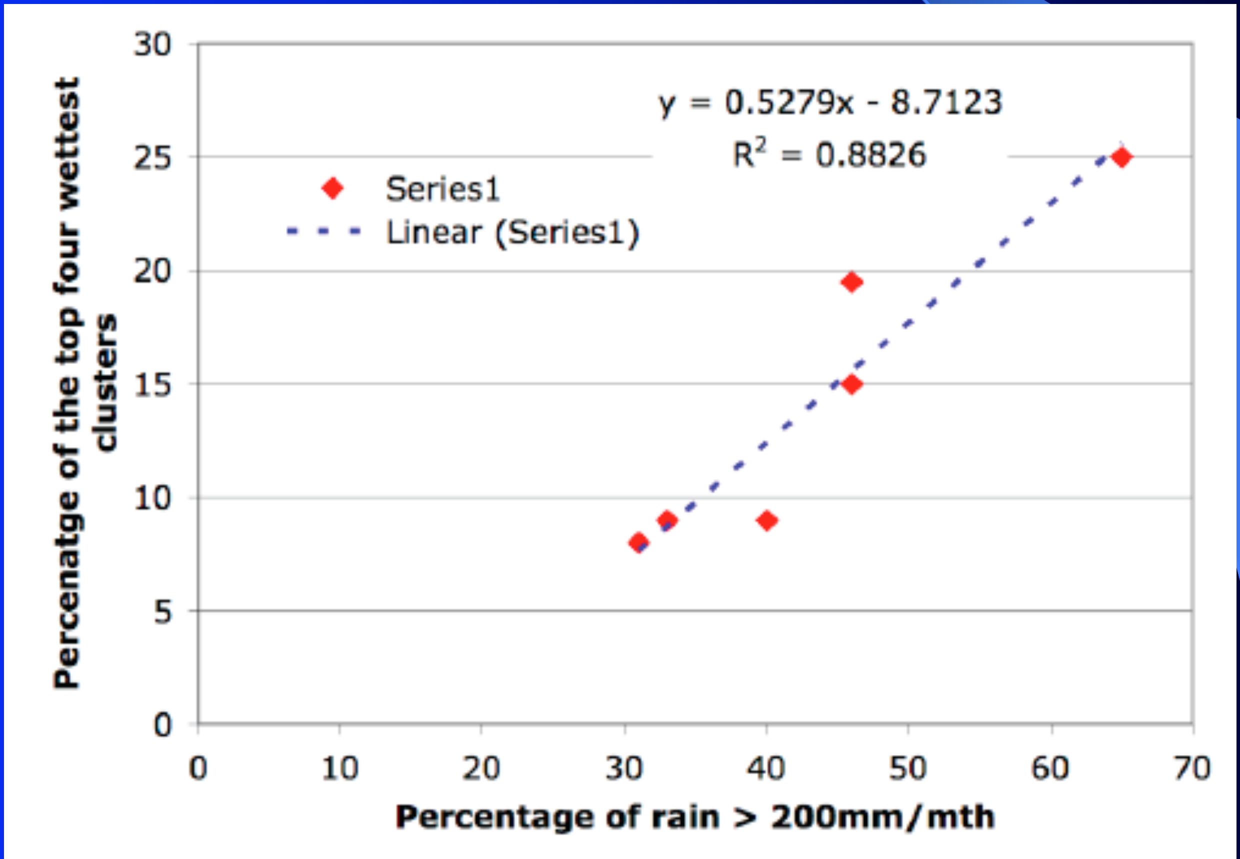
SST April





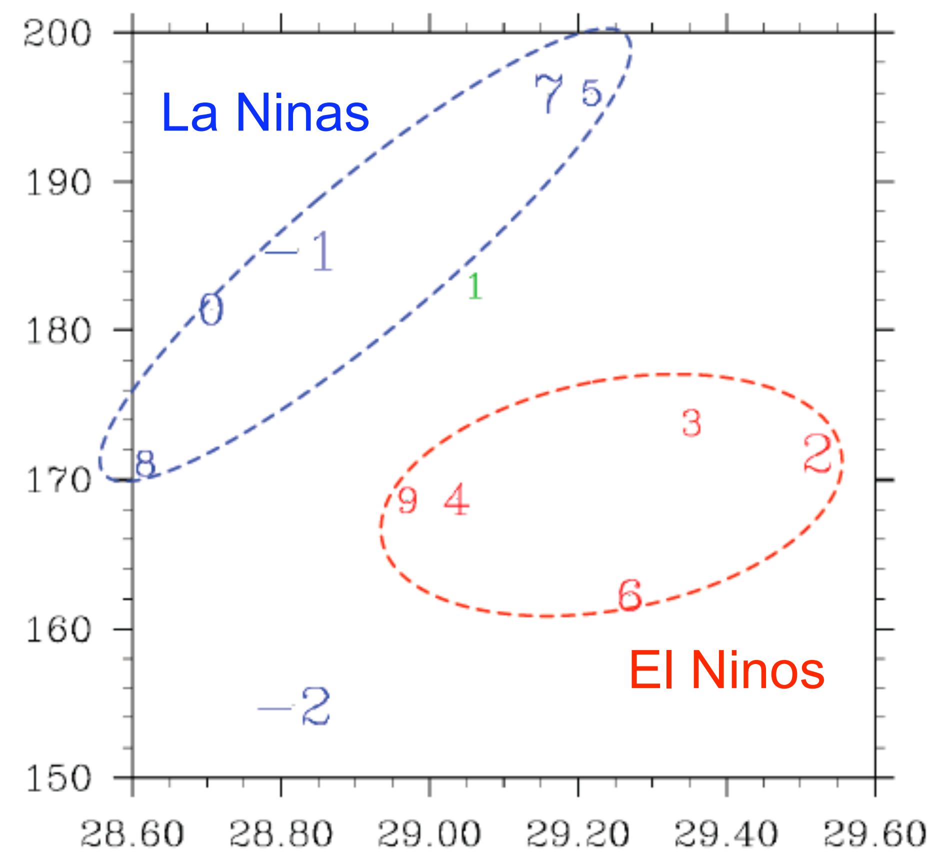
GPS RO & TRMM rainfall in SPCZ in April/May

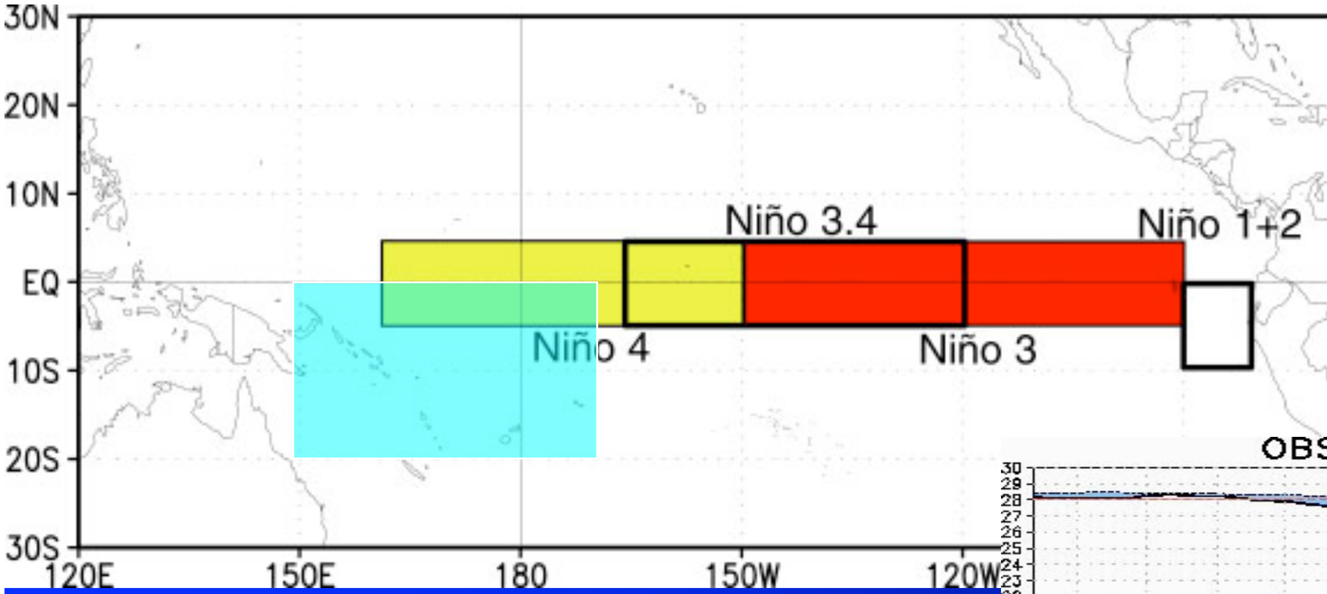
- High PW_{FT} is clearly correlated with high rainfall
- Compared 6 months of COSMIC with TRMM rainfall
- Best correlation between top 4 PW_{FT} clusters and area of rainfall $\geq$ 200 mm/month

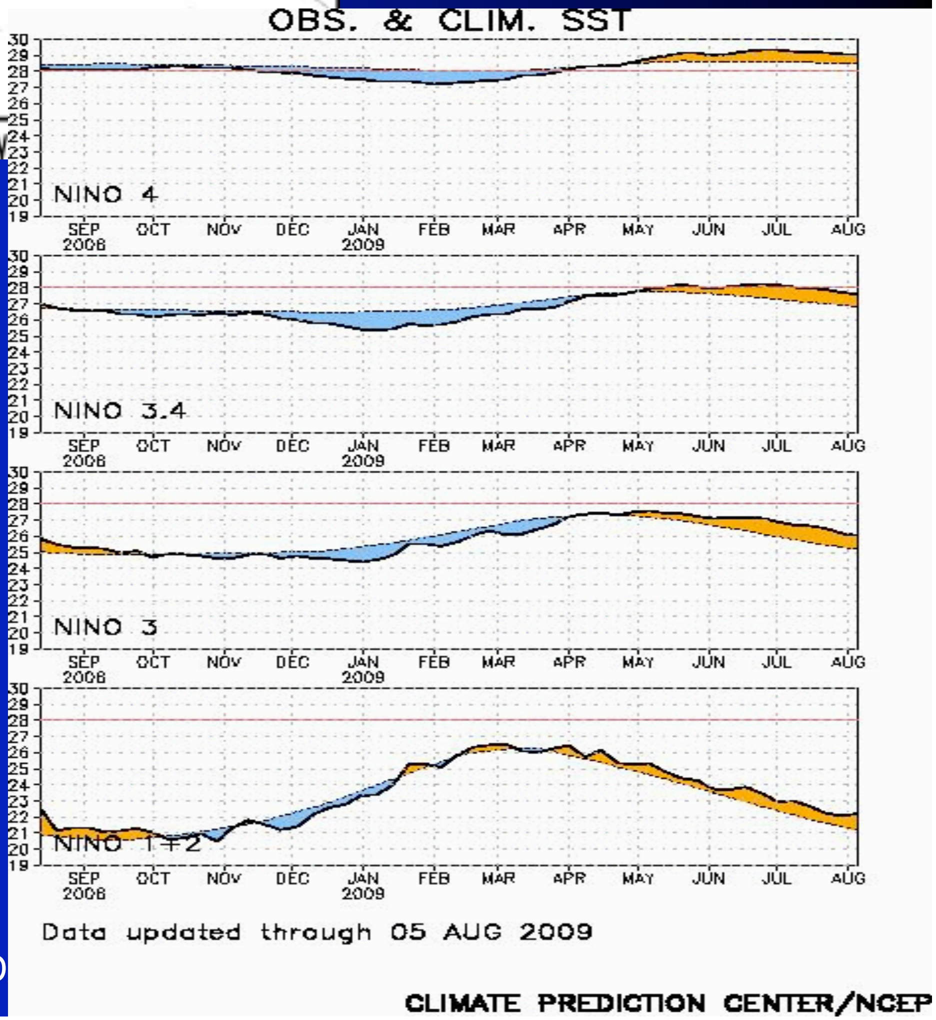


April-May Rainfall vs. SST in SPCZ region

- Figure shows SST and rainfall averaged over AM over the SPCZ region: 150ºE to 170ºW and 20ºS to 0º.
- Numbers are year minus 2000 (1998 = "-2")
  - Blue years are AM's that transition into La Nina later in the year
  - Red years transition to La Nina
  - Green year (2001) transitions to neutral conditions
- Size of number:
  - strength of ENSO index in subsequent boreal winter season
- 22%/^{o}C slope of pre-La Ninas >> Clausius Clapeyron (~slope of pre-El Ninos)
  - Suggests extra atmospheric instability in pre-La Ninas
- ***Predicts 2009 will move into El Nino phase***



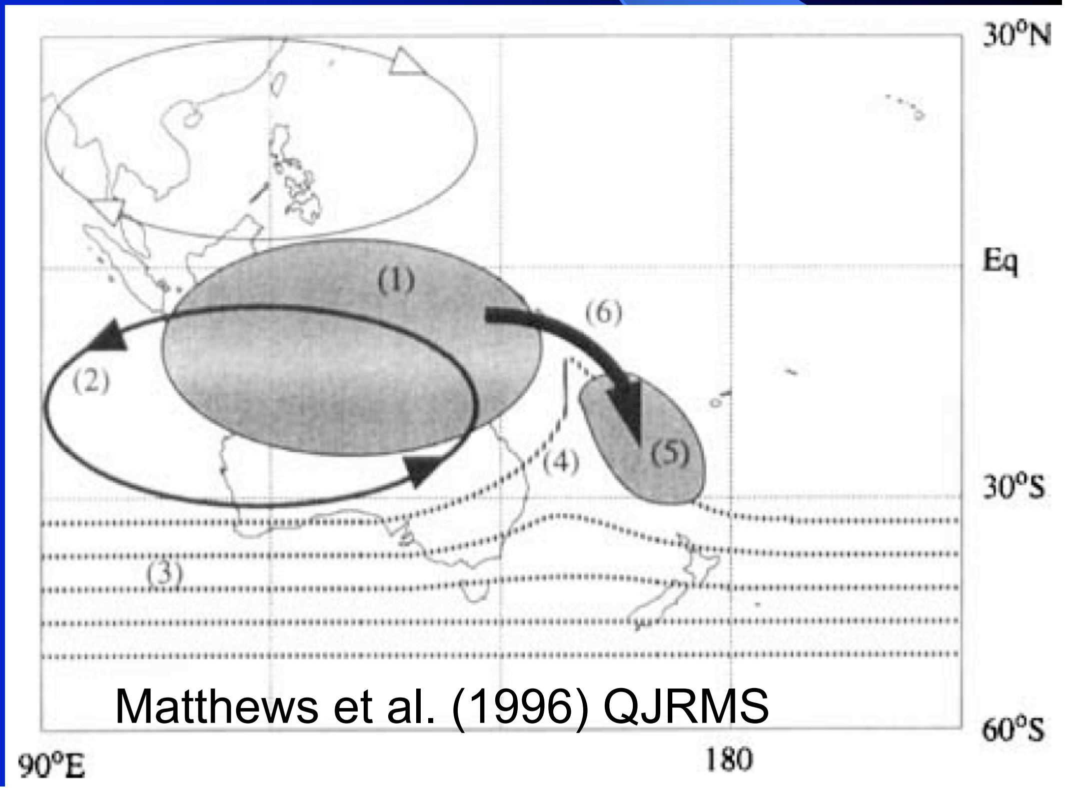




ENSO indices are moving to El Nino

Explanation for enhanced convective instability

1. Convection over indonesia associated with MJO passage
2. Creates upper tropospheric anticyclone
3. Creates large pressure gradient & subtropical jet, “high PV” air
4. Equatorward advection of high PV air leads to upper tropospheric trough
5. Induces instability to the east via cold air & divergence aloft which triggers deep convection
6. Subsidence inhibits eastward movement of warm pool water into central pacific



Matthews et al. (1996) QJRMS

Feedbacks over recent ENSO Cycle

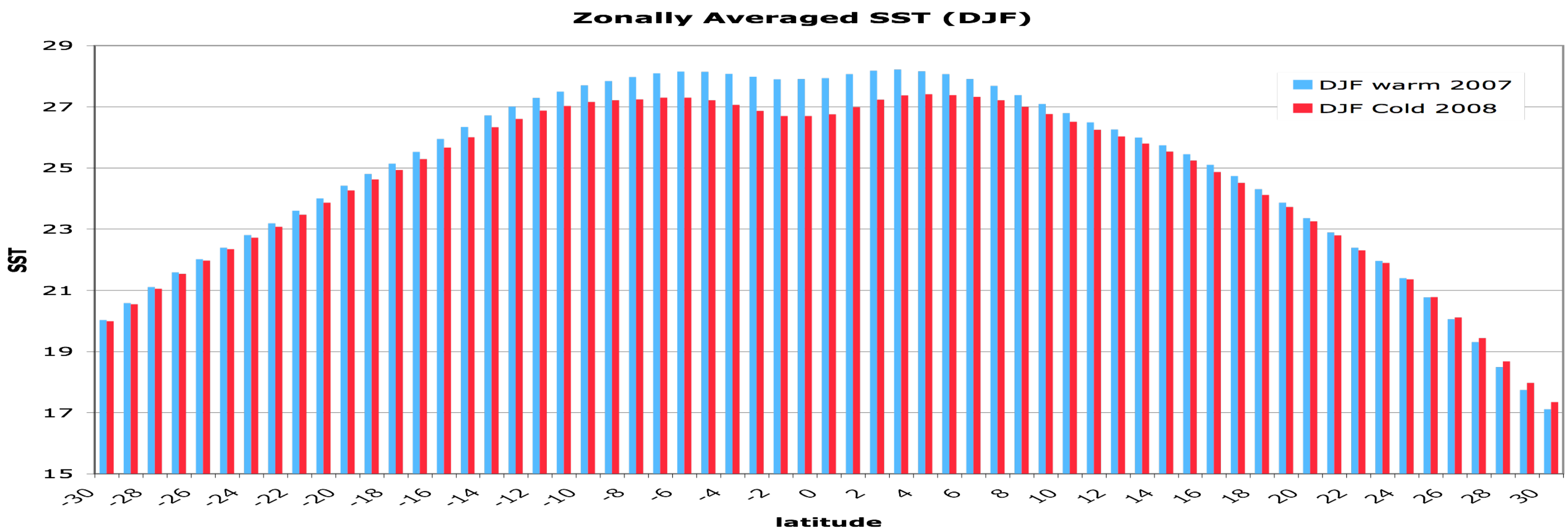
- Deceptively simple question from Earle Williams at 2009 AMS conference:
  - *Is free topospheric water vapor concentration higher during the warm phase of ENSO?*
  - Turns out to be tricky:
    - Wet regions are wetter ***but*** dry regions are drier
- Examined 3 month segments phase differences from

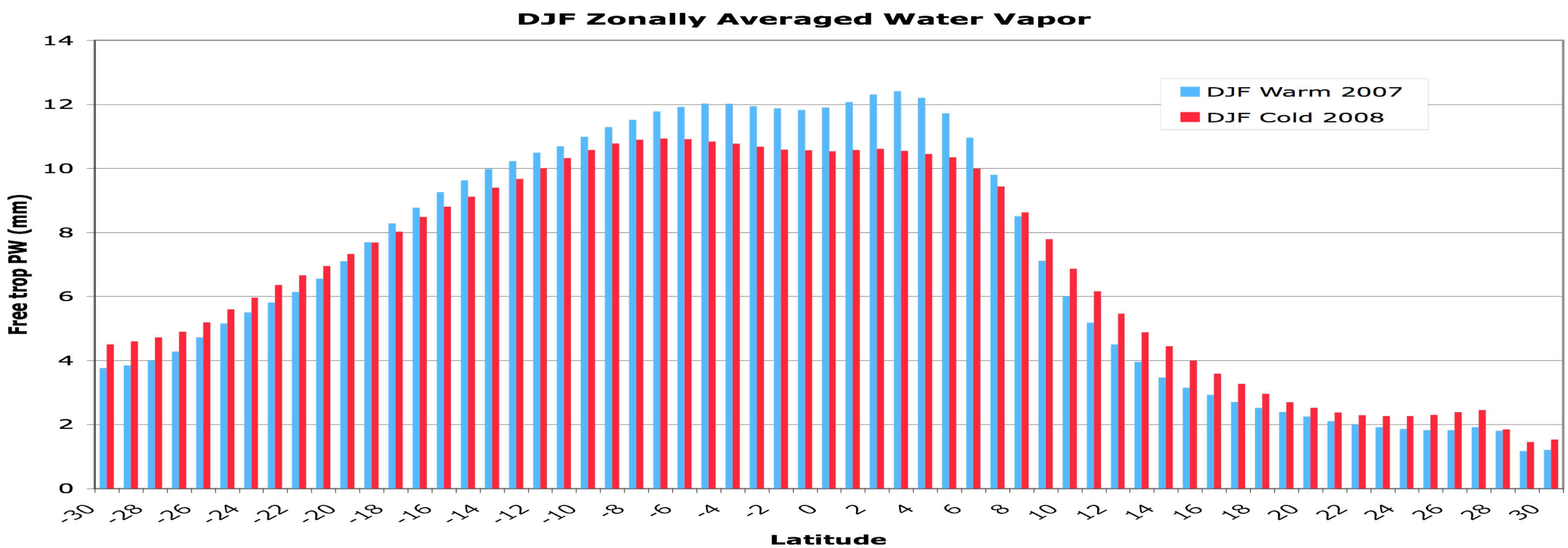
  WARM (Sept 2006 - May 2007) minus

  COLD (Sept 2007 - May 2008)

- Revealed signature of feedbacks

Zonally-averaged SST and PWV_{FT} for two COSMIC DJF

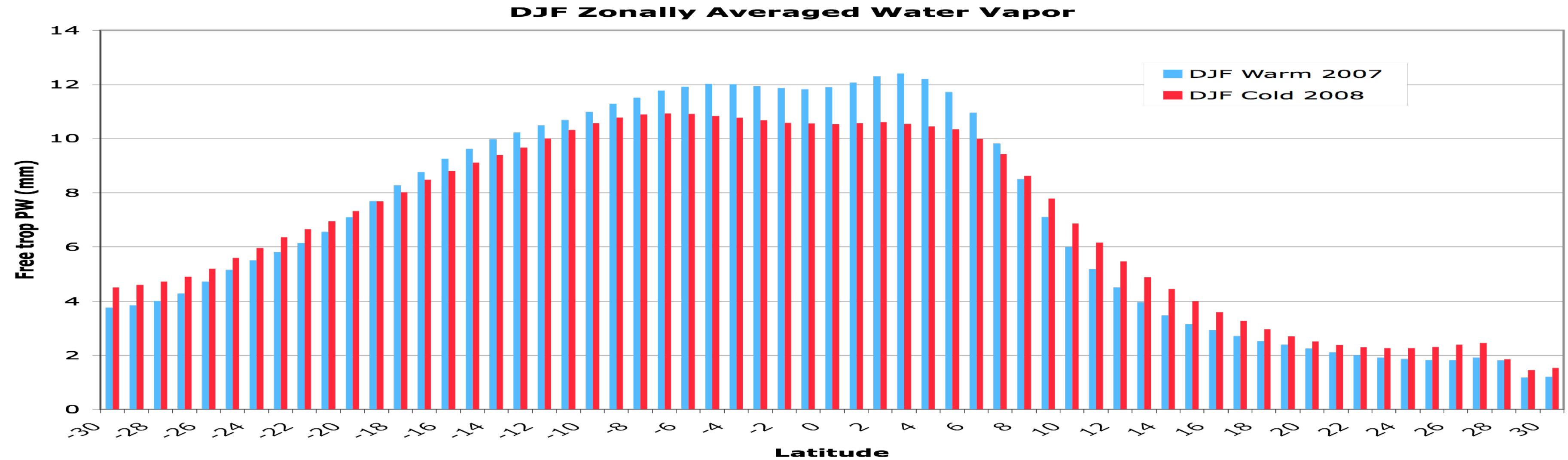


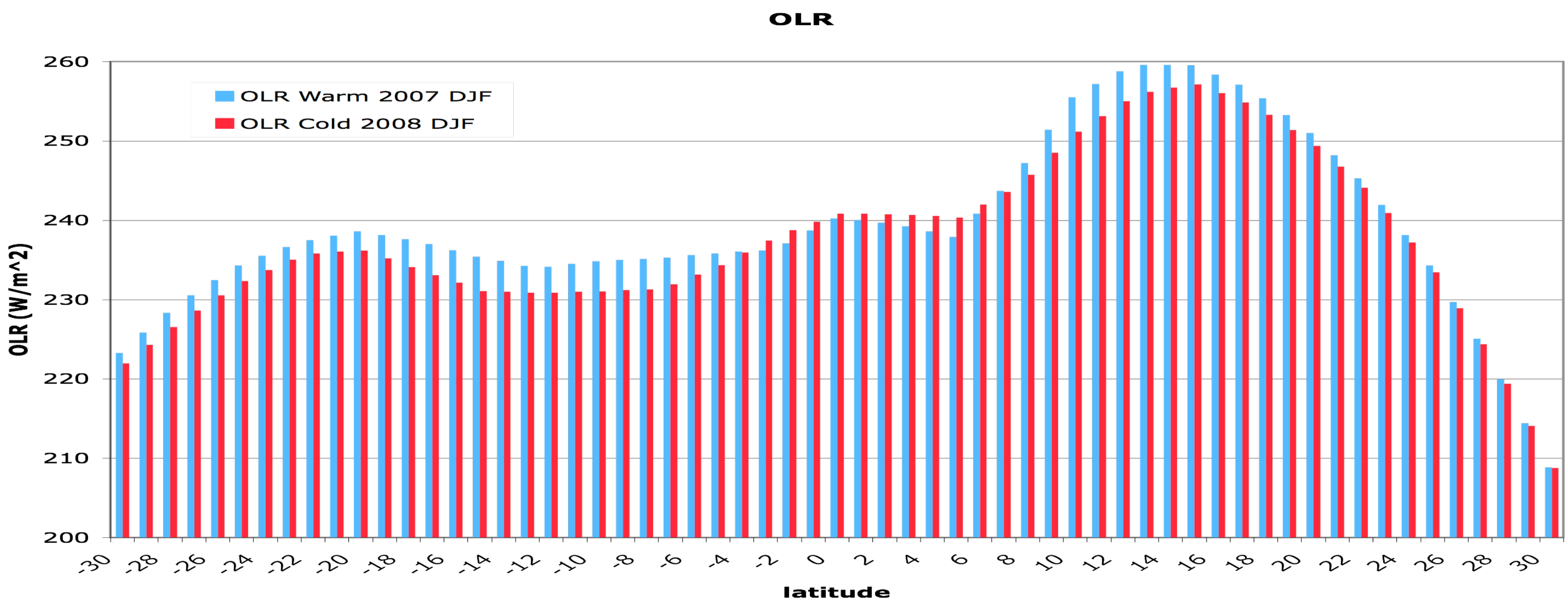


Key Features

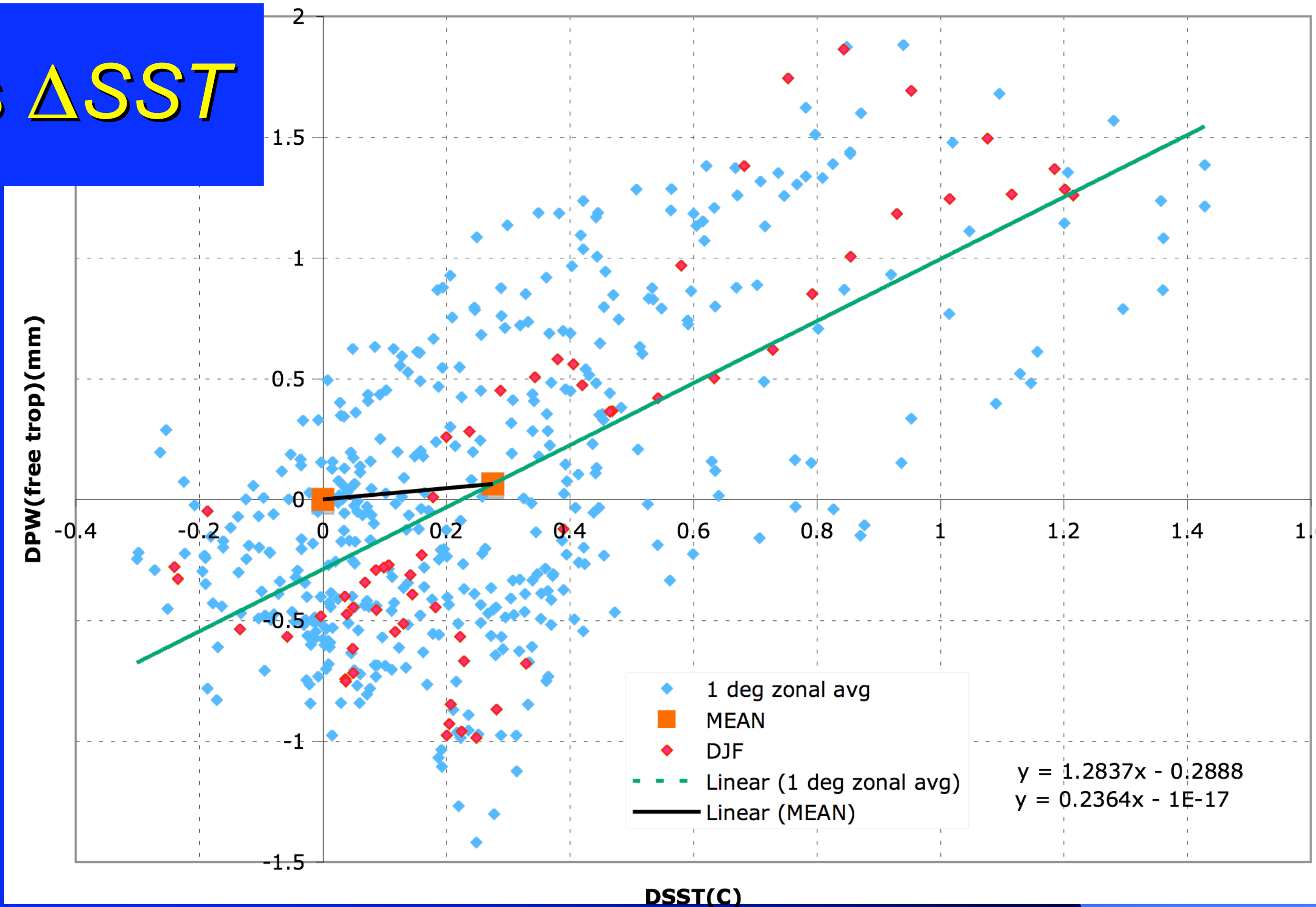
- Zonally averaged SST is far more symmetrical than water vapor distribution
- Warm phase is both wetter and drier than Cold phase in terms of extremes of PWV_{FT}
- Signature of stronger Hadley circulation during warm phase: larger meridional gradient of water vapor
- Location of peak PWV_{FT} shifts
  - warm phase ~ 5ºN
  - cold phase ~ 8ºS

PWV_{FT} vs. OLR for 2 COSMIC DJF





$\Delta PW_{free\ trop}$ vs ΔSST

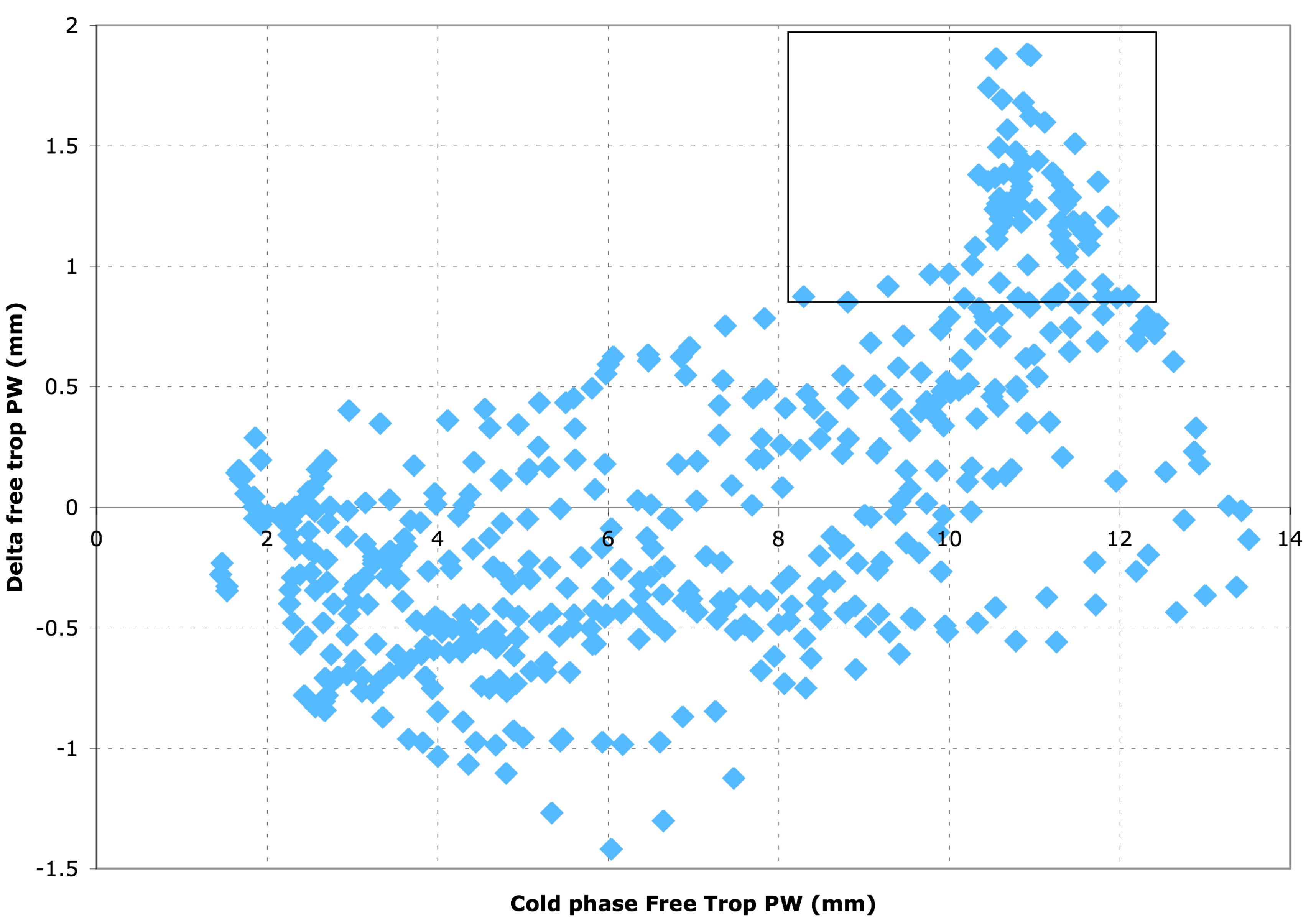


DATA:

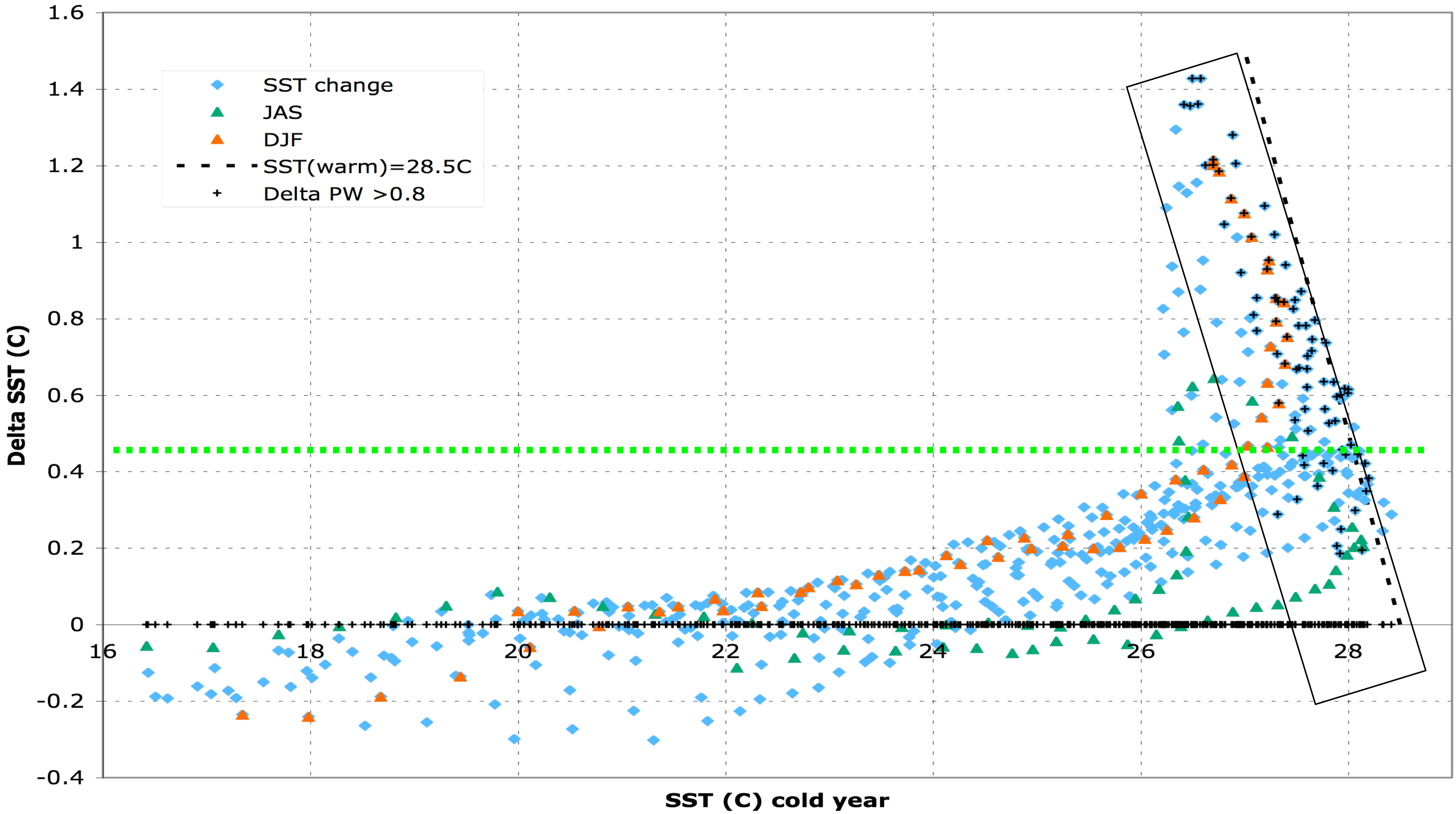
- Warm - Cold
- ASO thru MAM
- Each point is a 1º zonal mean

- Median $\Delta PW_{free\ trop}$ = -0.05 mm **< 0**
  - ⇒ For more than half of the zonal mean points, $PW_{free\ trop}$ *decreases* with the warm phase SST increase
- Mean $\Delta PW_{free\ trop}/\Delta SST$ = 0.065mm/0.28C = 0.24 mm/C
  - ⇒ Mean fractional $\Delta PW_{free\ trop}/\Delta SST$ = **3.3%/C** < Sat. Vap.(T)

Change in Free Tropospheric PW

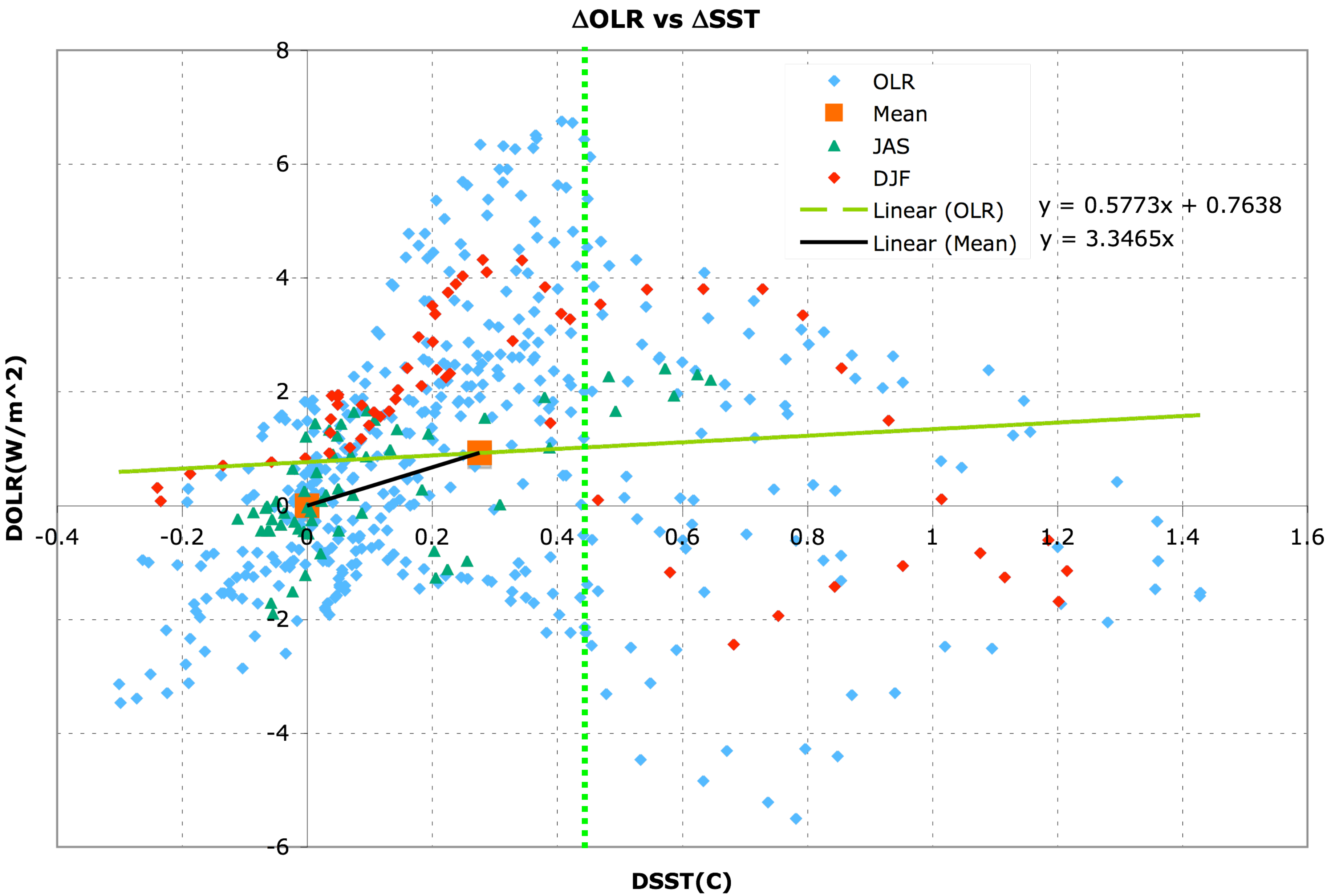


Change in *SST* Warm (2006-2007) vs Cold (2007-2008)

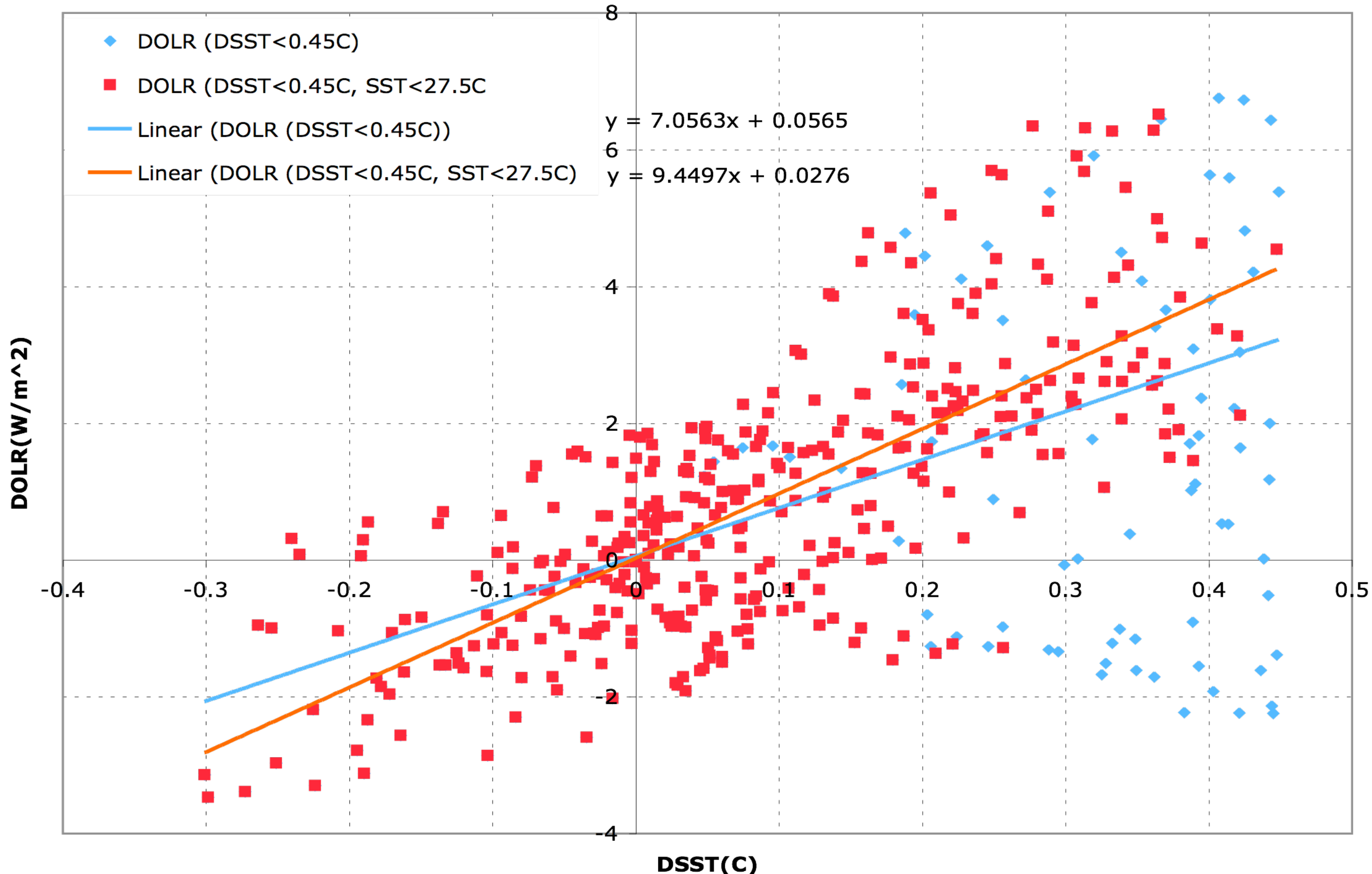


Indicates atmosphere-ocean SST (1) threshold trigger (zonally averaged) and (2) regulator/limiter (convective cooling?)

Changes in OLR vs SST



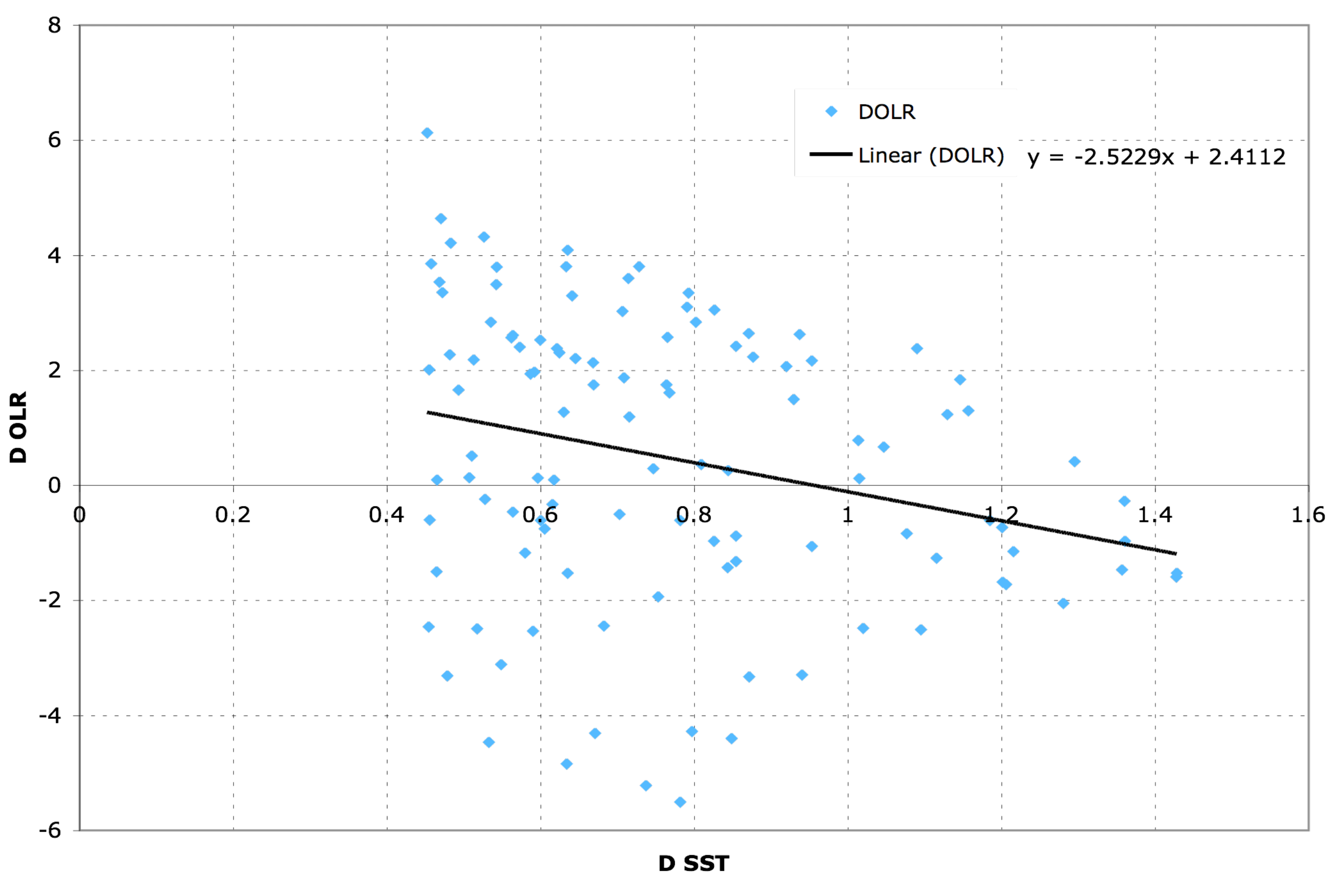
Changes in OLR for Smaller SST Changes



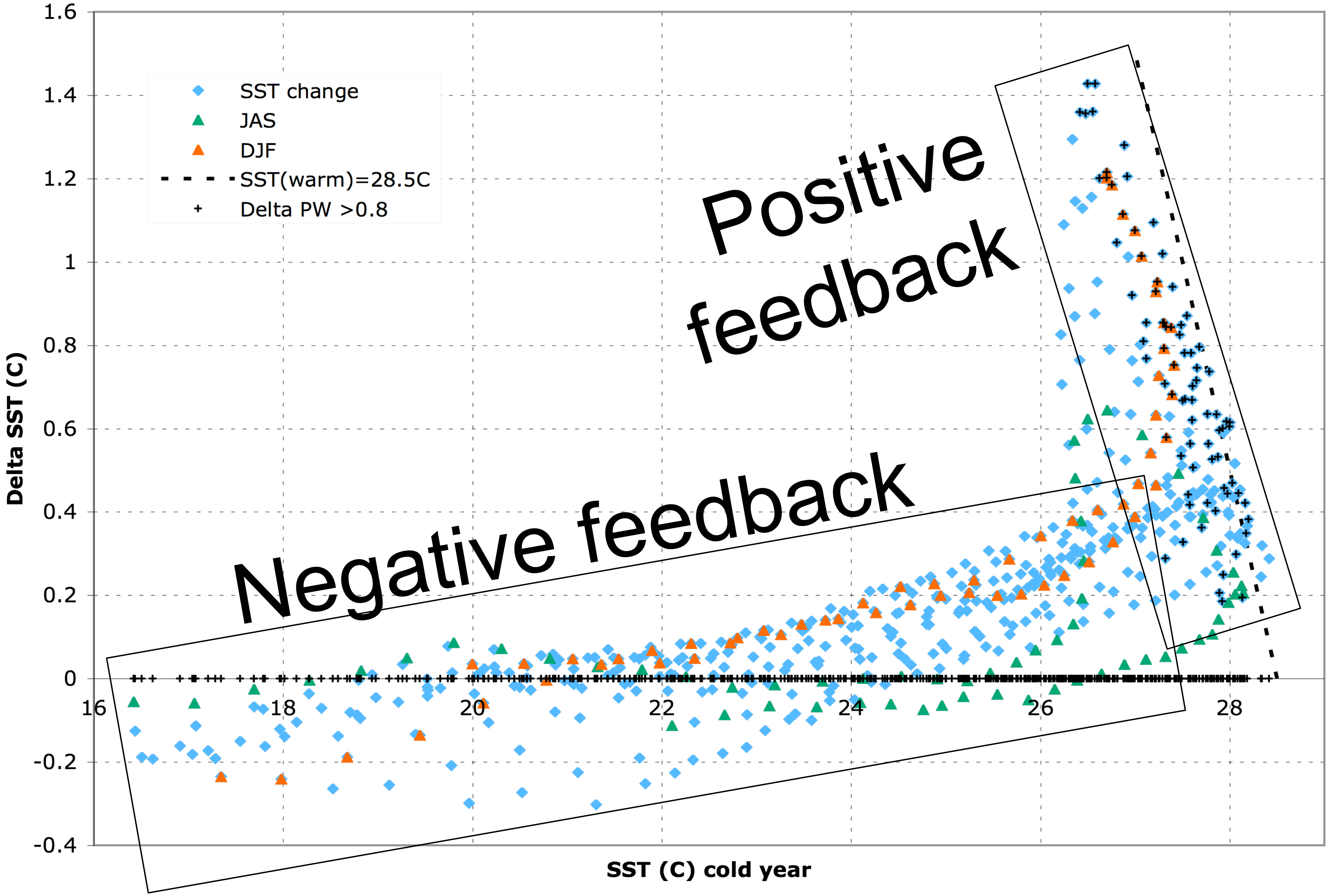
- Isolate behavior for ΔSST < 0.45C
  - => $\Delta OLR/\Delta SST$ = 7 W/m^2 / ºC
- Isolate behavior for ΔSST < 0.45C *and* SST_{warm} < 27.5C
  - => $\Delta OLR/\Delta SST$ = 9.5 W/m^2 / ºC
- For comparison, simple stephan boltzman scaling
  - => $\Delta OLR/\Delta SST$ = 4 W/m^2 / ºC

Δ*OLR* for Larger Δ*SSTs*

- A lot of scatter, but
- Overall SST increase causes OLR decrease => positive feedback



Change in *SST* Warm (2006-2007) vs Cold (2007-2008)



ENSO Feedbacks

- Two thresholds/limits evident
  - Minimum temperature for nset of deep convection
  - Evidence of limit to temperature in warm phase (due to convective cooling?)
- Strong negative feedback over recent ENSO cycle
  - Warm, El Nino phase dumps more OLR to space than the La Nina => cooling the tropics
  - If it weren't then it wouldn't be an oscillation
- Effect is stronger than water vapor effect which implies clouds are involved
  - Most important implications may be about clouds
- ENSO oscillations cool the Earth
  - May help explain why 2008 was a relatively cool year

Part 2

Improving the Impact of GPSRO Data Assimilation in NCEP

E. R. Kursinski, A. Otarola
University of Arizona

F. Xie, C. Ao
Caltech/JPL

working with S. Sokolovskiy L. Cucurull
UCAR NCEP

Funded by JCSDA

Scope of Data Assimilation Research

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

- Two areas of emphasis
  - Improve GPS RO error covariance
    - Create humidity dependent error covariance
    - Examine representativeness error
  - Correct for Super-refraction
    - Occurs at very sharp PBL top over oceans
    - Causes refractivity to be systematically underestimated via normal refractivity retrieval process

Error Covariance

- GPS RO provides much humidity information
- However, GPS RO does not influence the analyzed moisture fields as much as expected
- Why not?
  - Model relatively quickly removes moisture adjustments?
  - Error covariance may be suboptimal
    - Representativeness error?
      - GPS RO is a long horizontal average
      - Sonde humidity may be overweighted?
  - Least squares assimilation is limiting the extremes?

Representativeness Error

Figure: median of ratio of std dev of discrepancy between ***aircraft*** point measurements and horizontal averages of ***q*** normalized by mean of ***q***

– 288 and 301 hPa data from HIAPER START (courtesy of Laura Pan, NCAR),

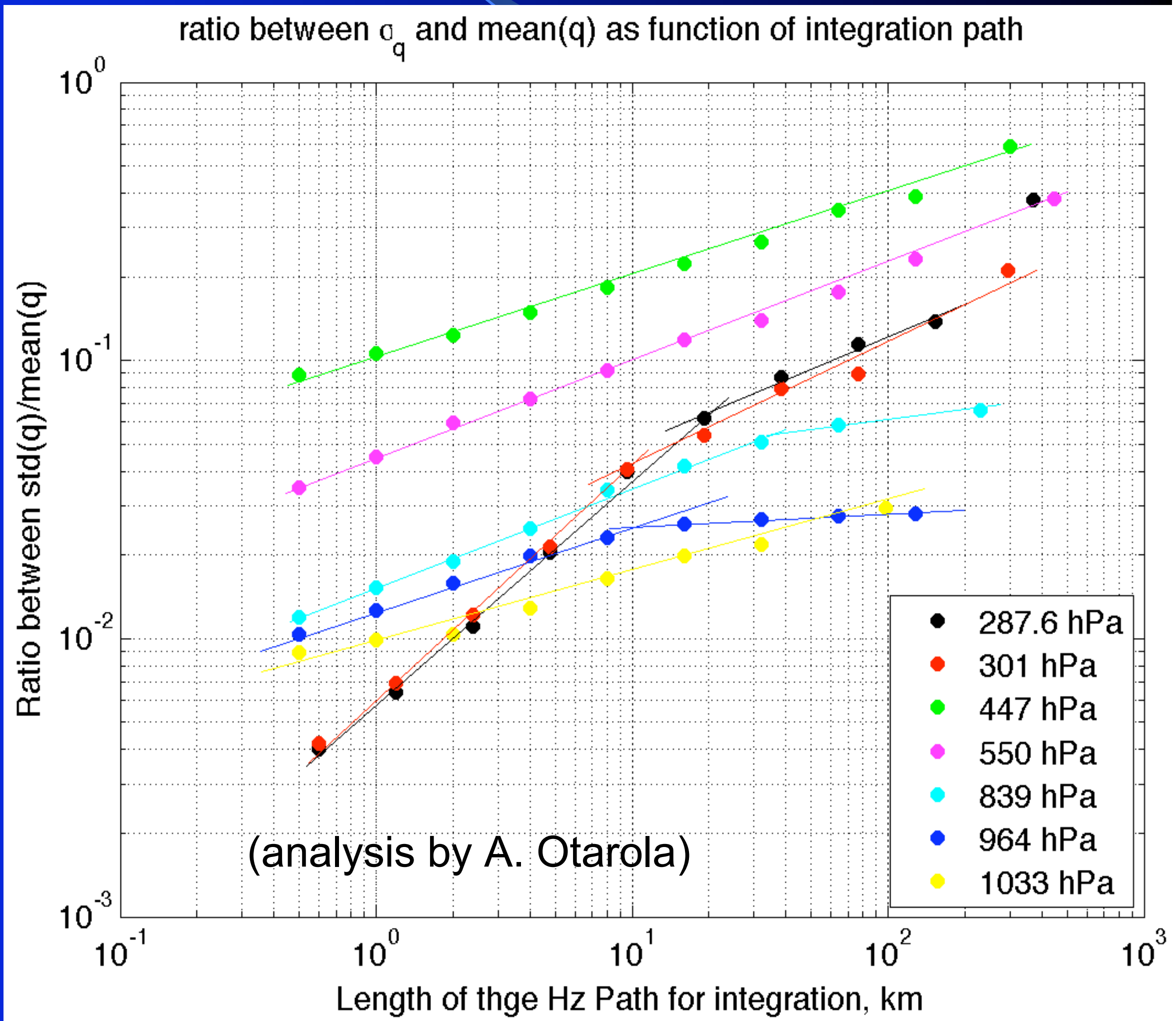
– Lower levels from TOGA COARE (provided by RAF)

$\sigma_q/\langle q \rangle$ exhibits ***power law*** dependence on horizontal averaging scale

3 different power law exponents (at least) :

- Most common: ~5/100 Kolmogorov?
- 964 & 839 mb exhibit almost flat dependence: saturation limited in PBL top/clouds?
- 301 & 290 mb exhibit highest slope: ~6/10 for scales smaller than 10-20 km

Highest $\sigma_q/\langle q \rangle$ values are mid troposphere (447 & 550 mb)
Most extreme mix of wet (from below) and dry (from above) air?

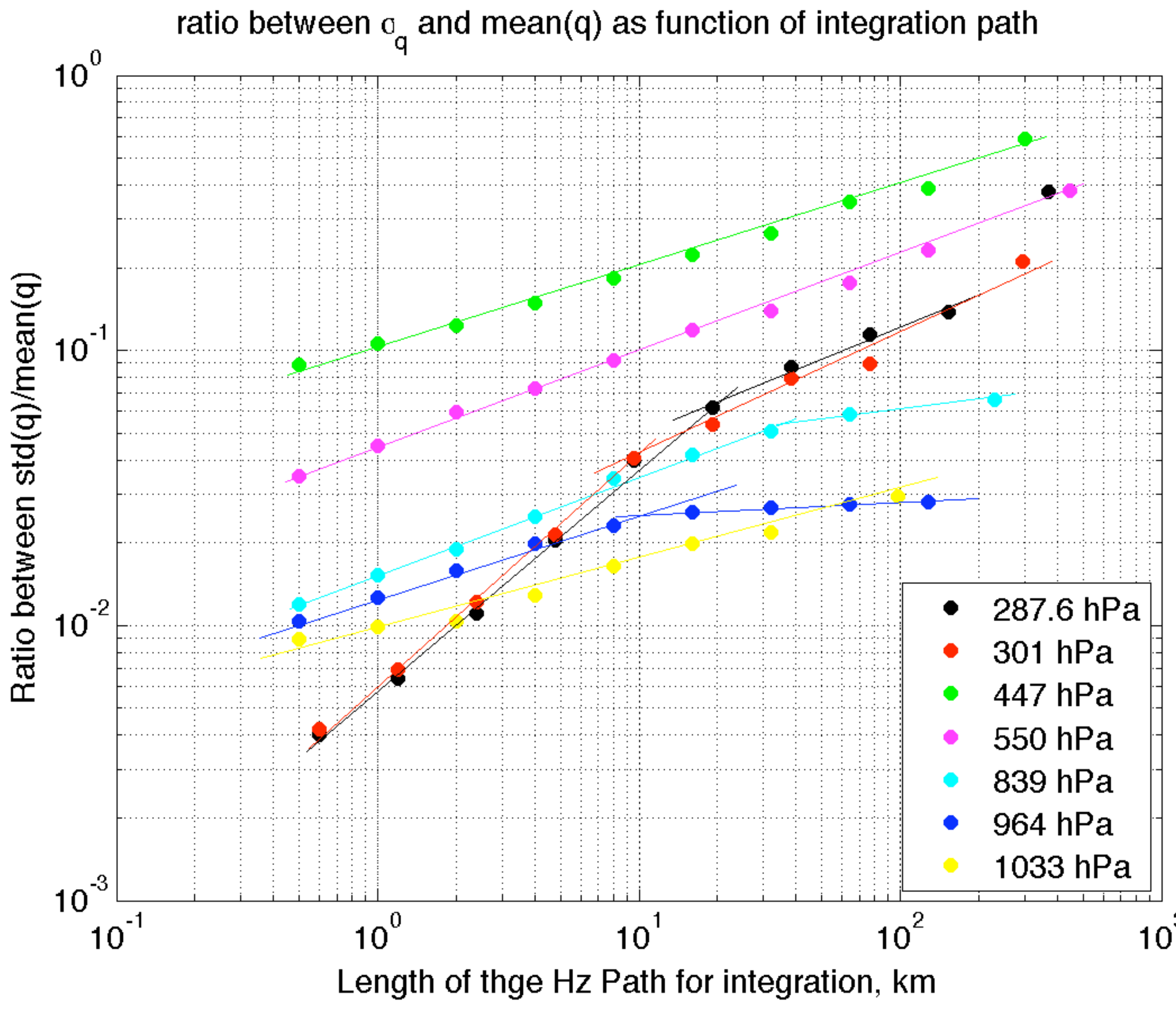


Representativeness Error

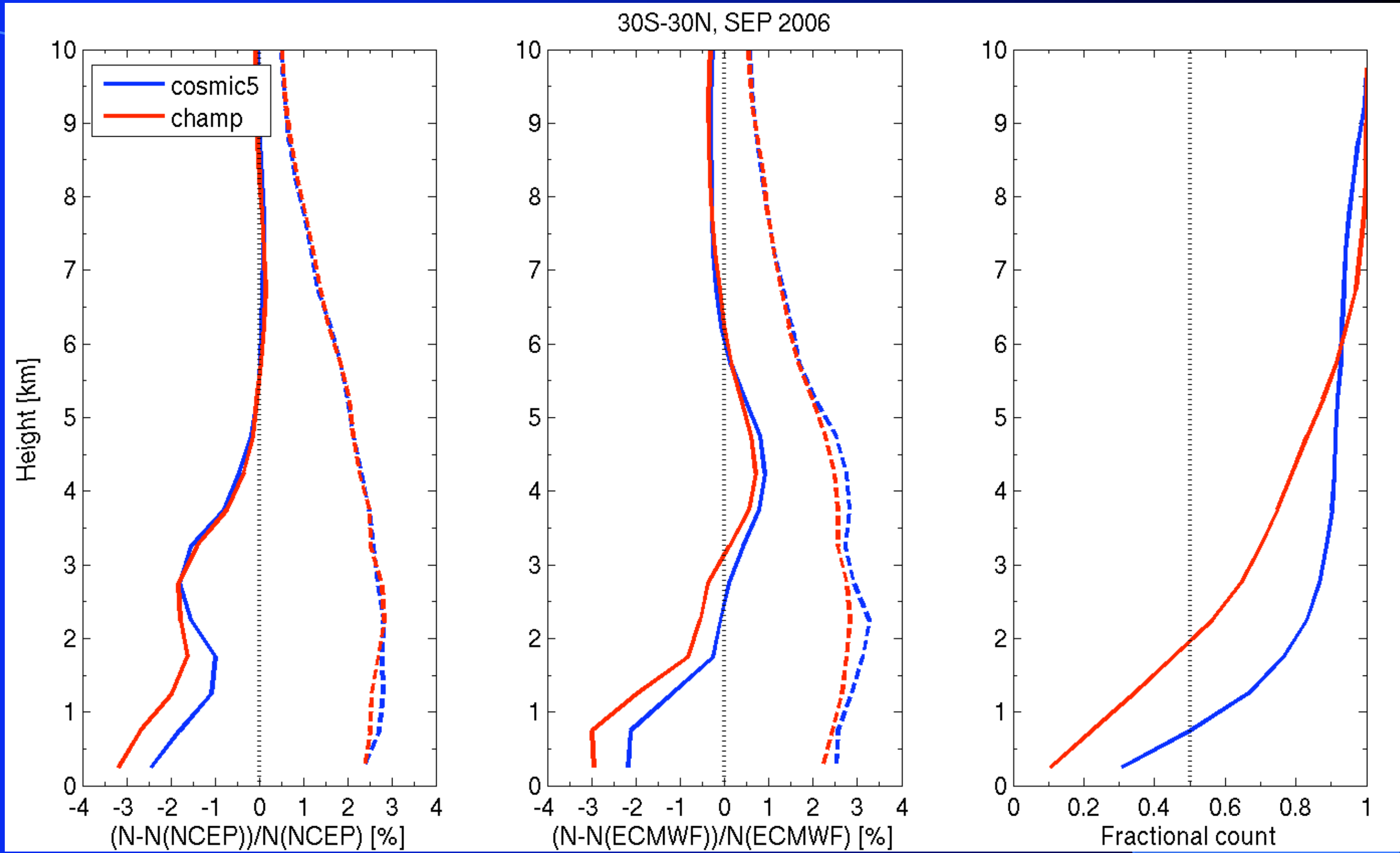
- Discrepancy between radiosonde (~point meas) and GPS RO (~300 km avg) ranges from 3% to 60%

- Discrepancy between radiosonde and NWP grid avg
  - 100 km: 3% to 40%
  - 50 km: 3% to 35%

- Does sonde humidity error covariance account for these discrepancies when sonde humidity is assimilated?
  - If not, sondes may be overweighted



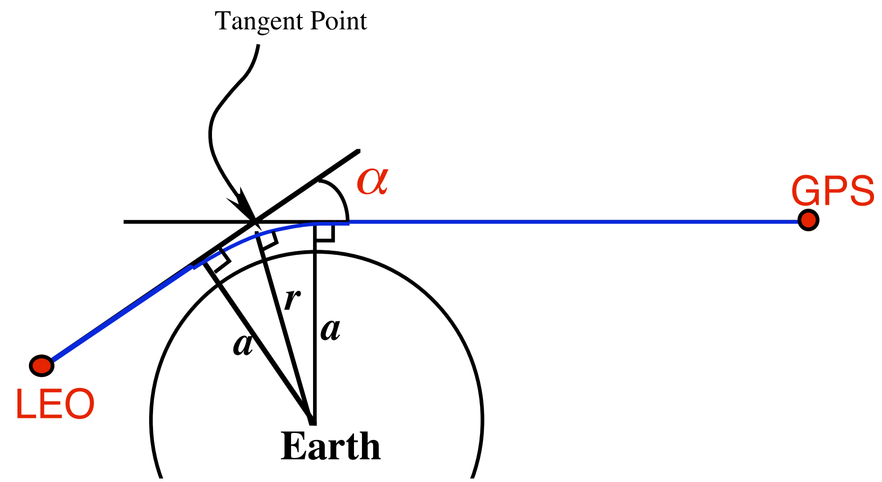
Super-refraction & “Negative N bias”



Low latitude, lowermost troposphere GPS refractivity is often underestimated

- Due to receiver tracking problems and “super refraction” (at least)
  - Receiver tracking improved with “open loop” tracking on COSMIC
  - Solving the super-refraction problem is a focus of our research

Normal 1D Bending Angle - Refractivity Relation



1st order approximation:

- no horizontal refractivity variation …
  - Leads to unique relation between
    - Observable: bending angle profile, $\alpha(a)$, and
    - Retrieved refractivity profile, $n(r)$

      via Abelian integral transform pair
  - Uniqueness is a strength of GPS RO technique

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

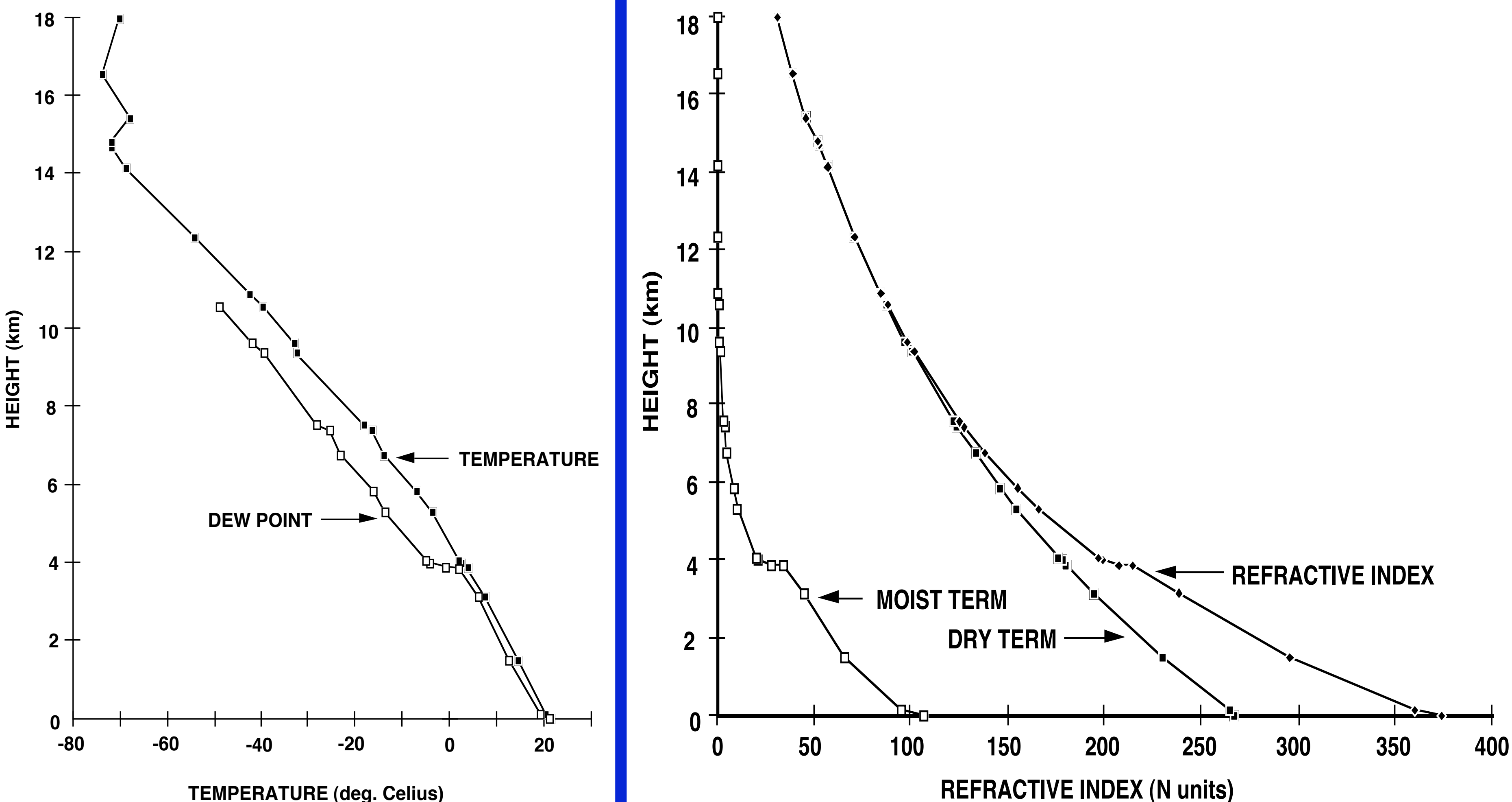
$$n(r_{01}) = \exp\left[-\frac{1}{\pi}\int_{a_1}^{\infty}\frac{\alpha(a)\,da}{\sqrt{a^2 - a_1^2}}\right]$$

Forward relation *Inverse relation*

Wet Contribution to Refractivity

Example: refractivity from Hilo radiosonde

- Water contributes up to one third of the total refractivity
- Sharp vertical gradients in water cause large bending angles



Super-refraction

Definition:

- Vertical refractivity gradient so large that radius of curvature of raypath < radius of the Earth
  - Occurs frequently at top of tropical and subtropical PBL

Problem:

- Creates non-unique relation between bending angle & refractivity
  - continuum of refractivity profiles are consistent with observed bending angle profile
  - Standard Abel transform yields the ***minimum*** refractivity profile that is consistent with bending angle profile
    - ⇒ systematic underestimate of actual refractivity profile
    - ⇒ Has limited utility of GPS RO below ~2.5 km altitude

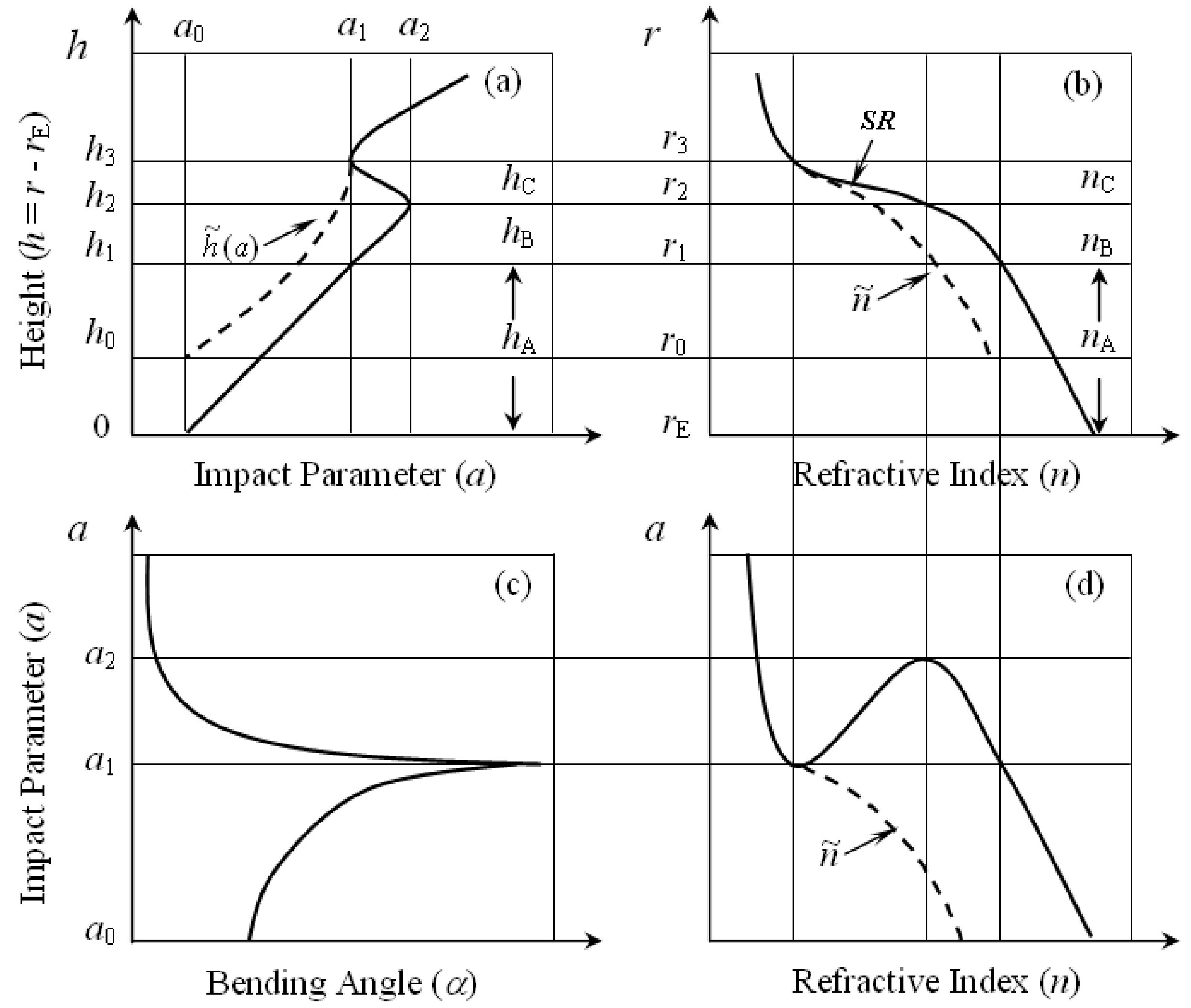
Solution:

- Xie et al. (2006) developed solution that
  - defines continuum of profiles consistent with bending angle profile
  - then selects "best" refractivity profile from that continuum
  - We are working to implement that solution in NCEP + …

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 tangent point
- 2 refractivity profiles produce identical bending angle profile Sokolovskiy (2003)



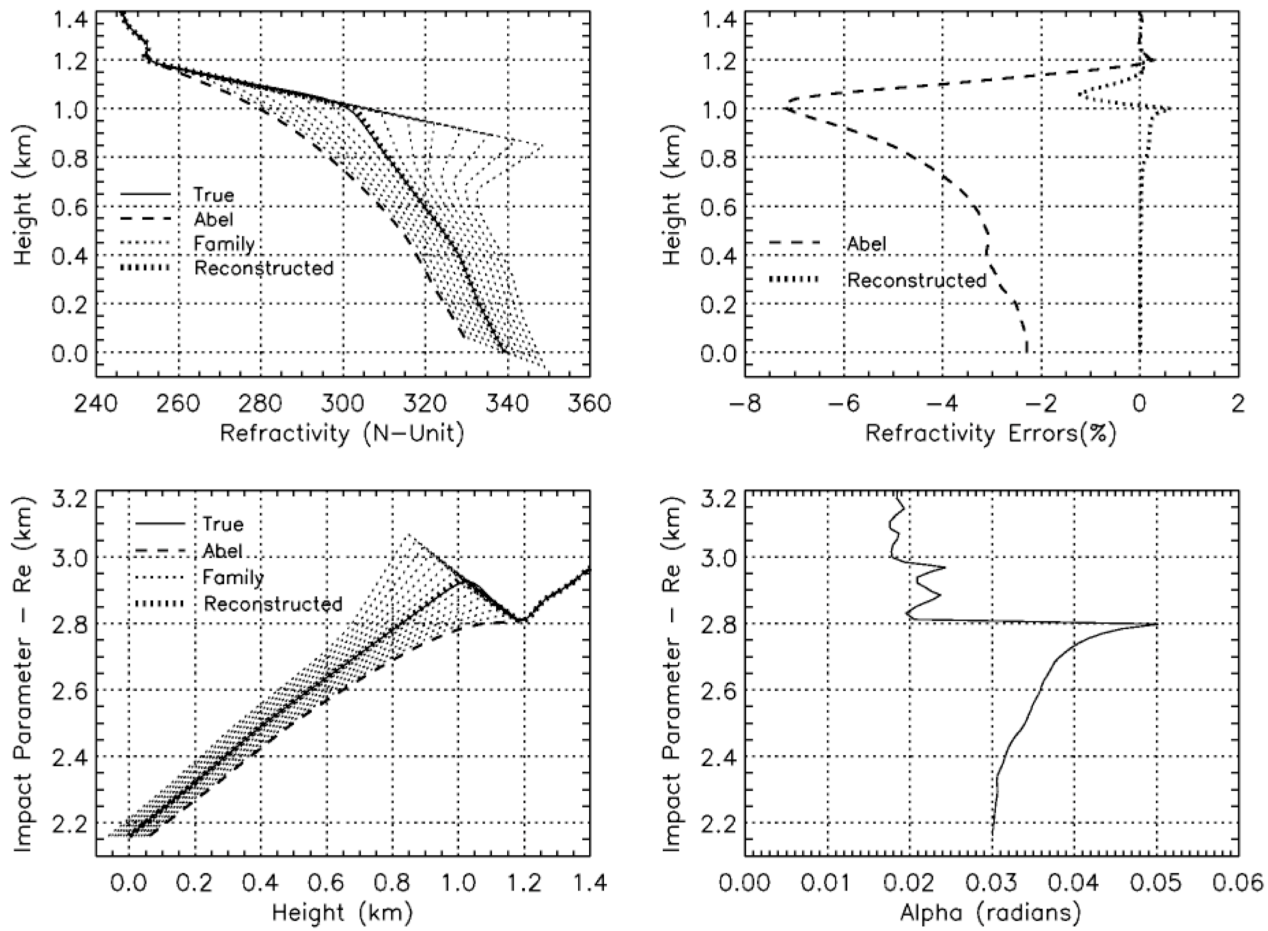
Super-refraction solution

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

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

This requires external Information, e.g.:

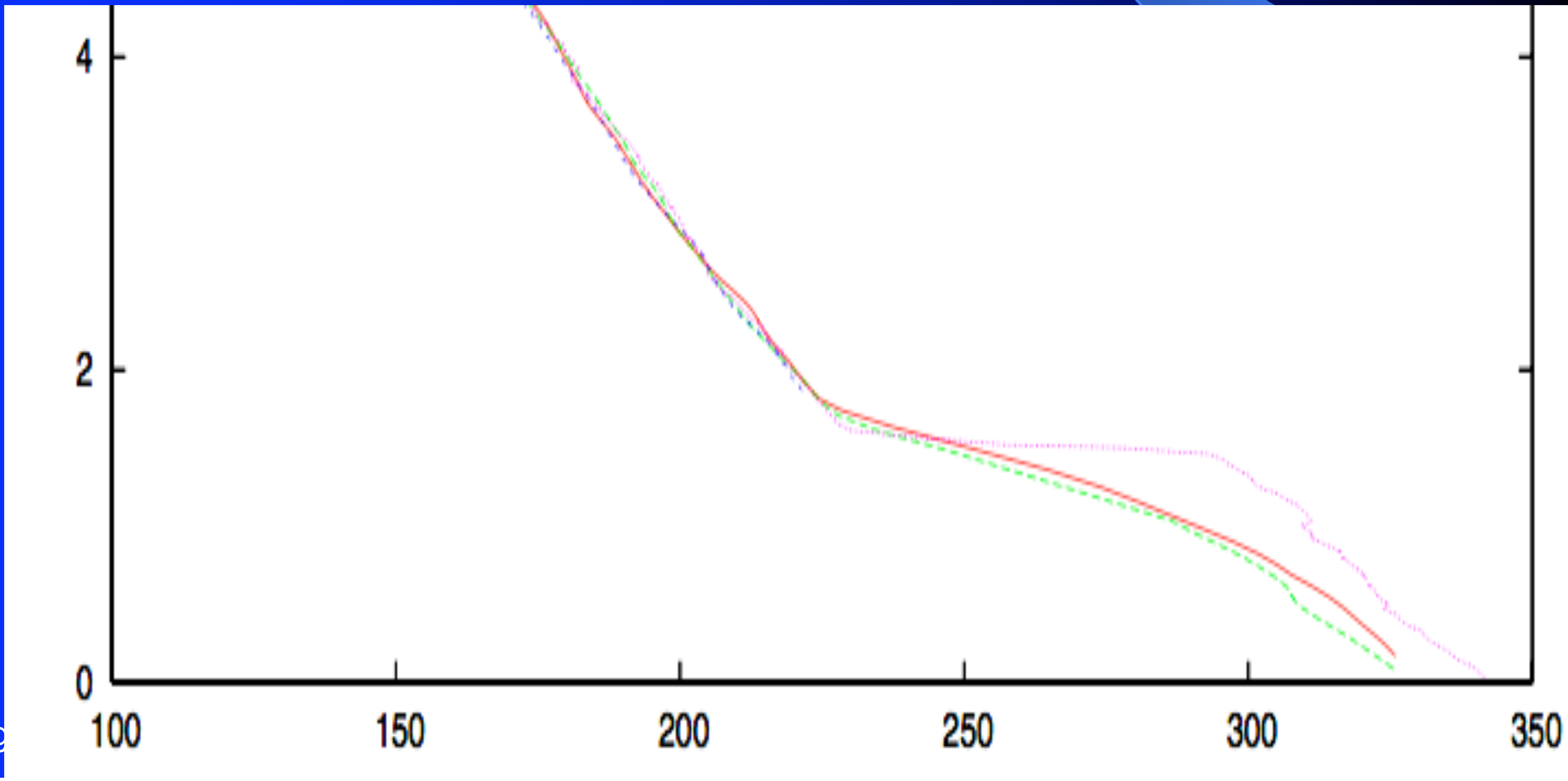
- Surface refractivity
- Column water vapor



Case Study: Observed Super-refraction

Example near Hilo, Hawaii sonde

- 2 COSMIC RO profiles that penetrate close to surface are very close to sonde time and location
- Classic signs of super-refraction



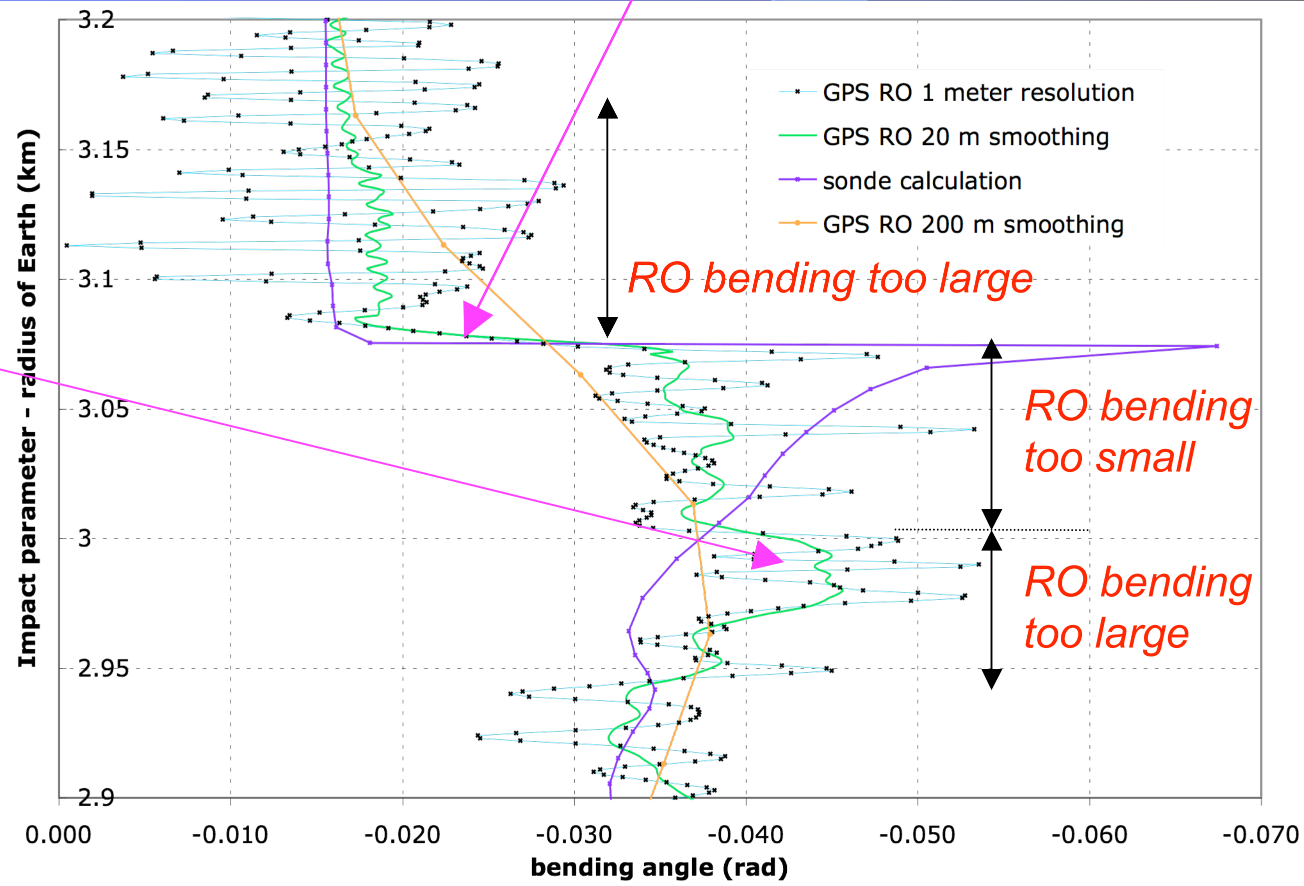
GPS RO bending angle profile assessment

High resolution (1m) RO profile sees very sharp PBL top

- implies ~10 m vertical resolution
- hi-res RO impact height of PBL top within 6m of the sonde
- Very good result: important for “reconstruction method”

Disagreement between RO & 1D sonde bending calculation

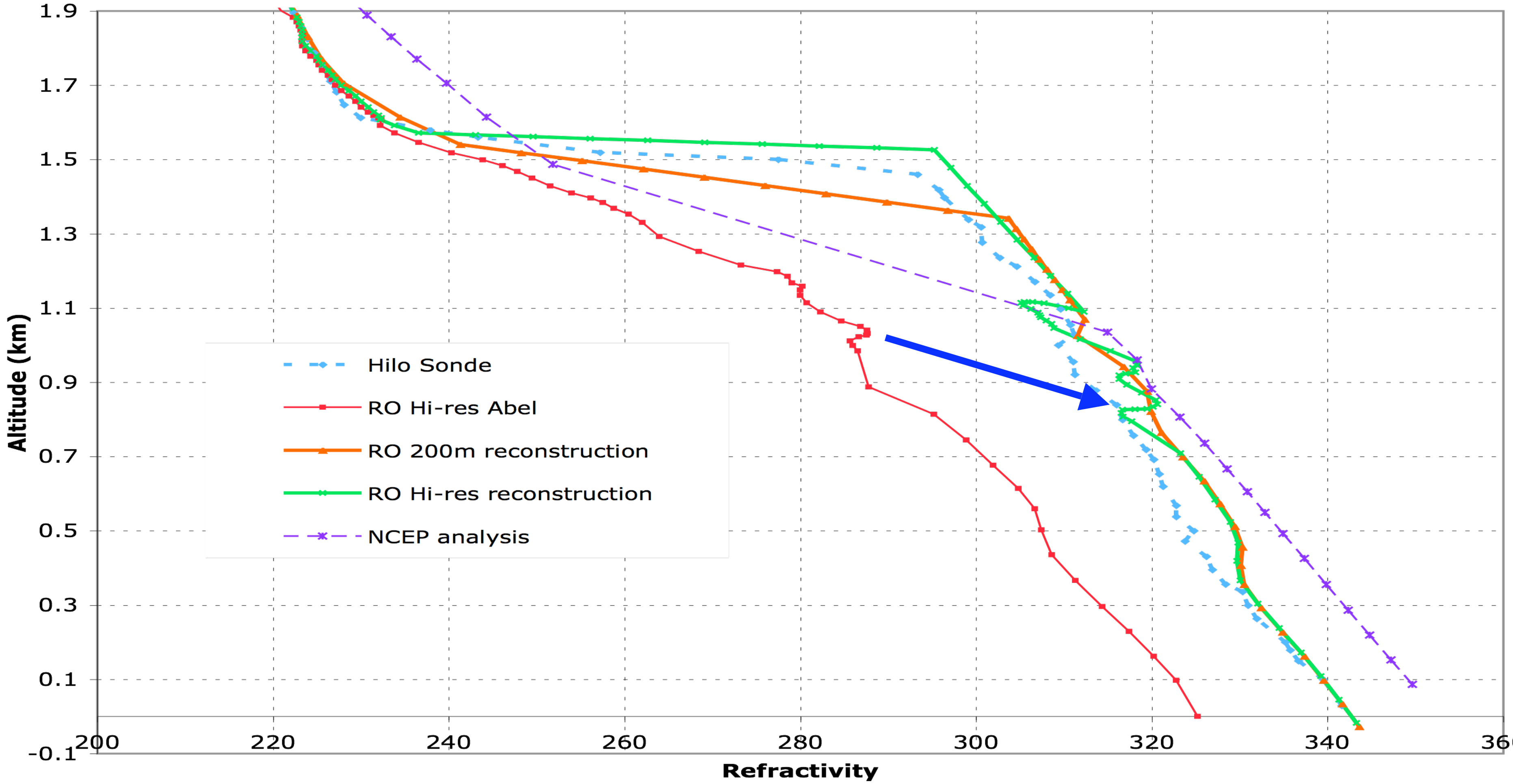
- Altitude of peak bending is shifted down by ~100 m relative to PBL top
- Extremely sharp 1D bending appears to be smeared vertically
  - Due to **horizontal variations in PBL top?**



August 19, 2009

Refractivity reconstruction method applied to GPS RO data

- Reconstruction method is definitely producing better refractivity profiles than Abel transform (Work in progress)
- Need to assess sensitivity to external constraints
  - Talk to JCSDA boundary layer group

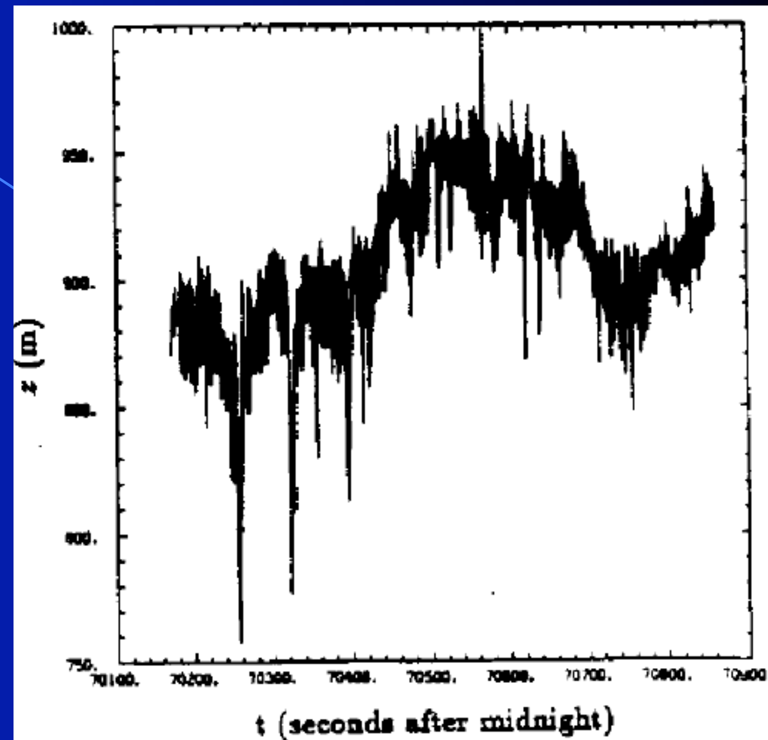


SR: Impact of Horizontal variations?

- Maximum observed bending angles are smaller than expected
- Several possibilities
  - Receiver tracking of GPS signals
    - No doubt contributing but has improved dramatically with open loop receivers on COSMIC
  - Horizontal variations in the PBL height?
    - We have begun to assess this via 2D signal propagation experiments

How larger are horizontal variations in MBL height?

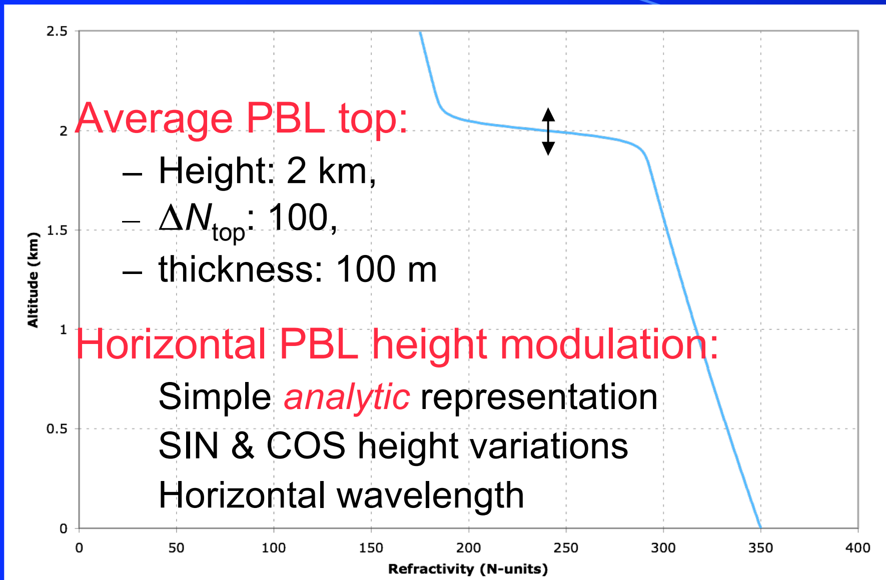
- PBL observations from So. California
  - Figure is lidar-measured cloud top structure from FIRE, a marine SC study off California coast (from D. Lenschow)

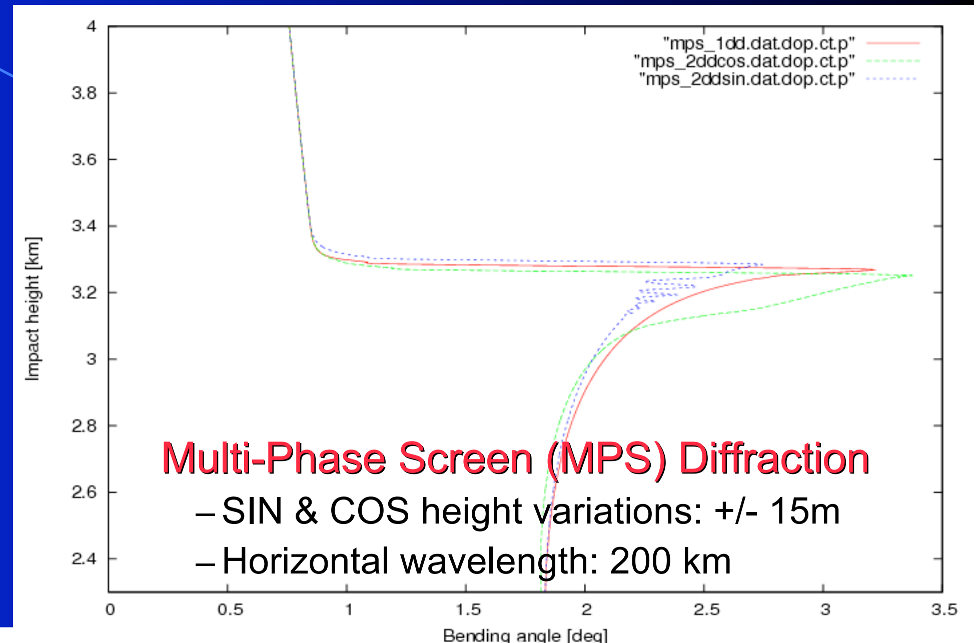


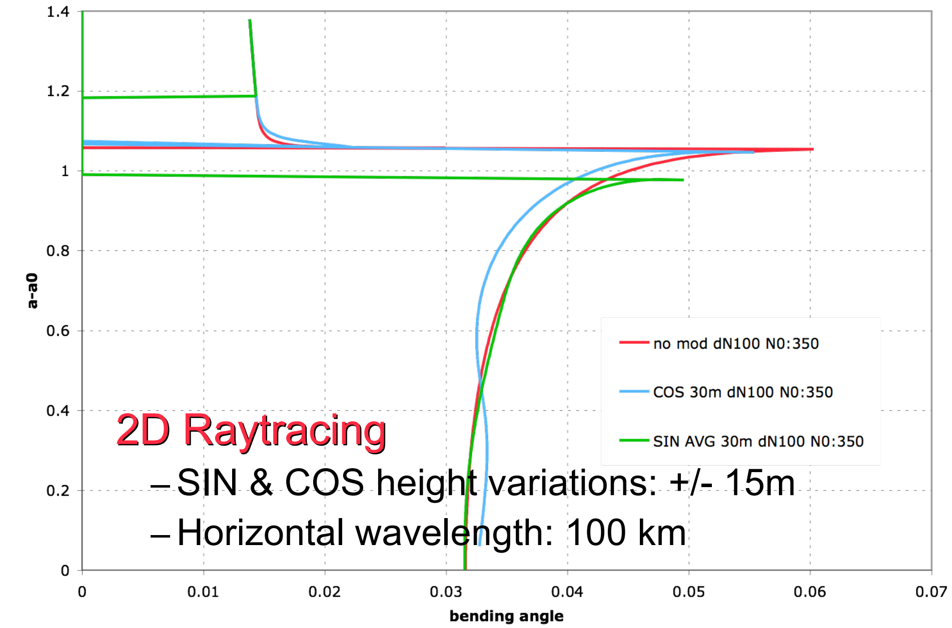
- MISR: working on a MISR high-res cloud top retrieval over stratocumulus region off So. Cal. coast, co-incident with a RO event.
  - Horizontal resolution of MISR high-resolution product can be ~1km
  - Preliminary result shows 60m height variations of popcorn-type cloud tops

- VOCALS observations west of South America
  - Representative scales 100 m height change over 100 km (Rob Wood)
  - Will obtain airborne cloud radar measurements from U. Wyoming

Preliminary Forward Simulations







- Have just begun these simulations
  - Raytracing results respond nonlinearly
  - Need MPS diffraction to assess
- Horizontal variations do tend to shift peak bending angle to lower altitude as observed
- Likely responsible for some of the observed behavior
- Need to simulate wide variety of conditions to understand effect

The Active Temperature, Ozone, and Moisture Microwave Spectrometer (ATOMMS) A LEO-LEO Occultation Observing System

E. R. Kursinski, D. Ward, A. Otarola, K. Sammler, M. Stovern, B. Herman
Department of Atmospheric Sciences, The University of Arizona, Tucson, AZ

C. Groppi, S. Albanna, M. Schein, C. Walker,
Department of Astronomy, The University of Arizona, Tucson, AZ

D. Rind
NASA GISS, NY, NY

Funded by NSF
Aircraft time from NASA

August 19 , 2009 JCSDA

Observational Needs

Climate models are wrong in ways that we don't know.

When you don't understand something, you measure it

Need observations as complete as possible and independent of models to determine what is actually happening

Can we do this via satellite to satellite occultations?

What can we achieve if we design a RO system from scratch

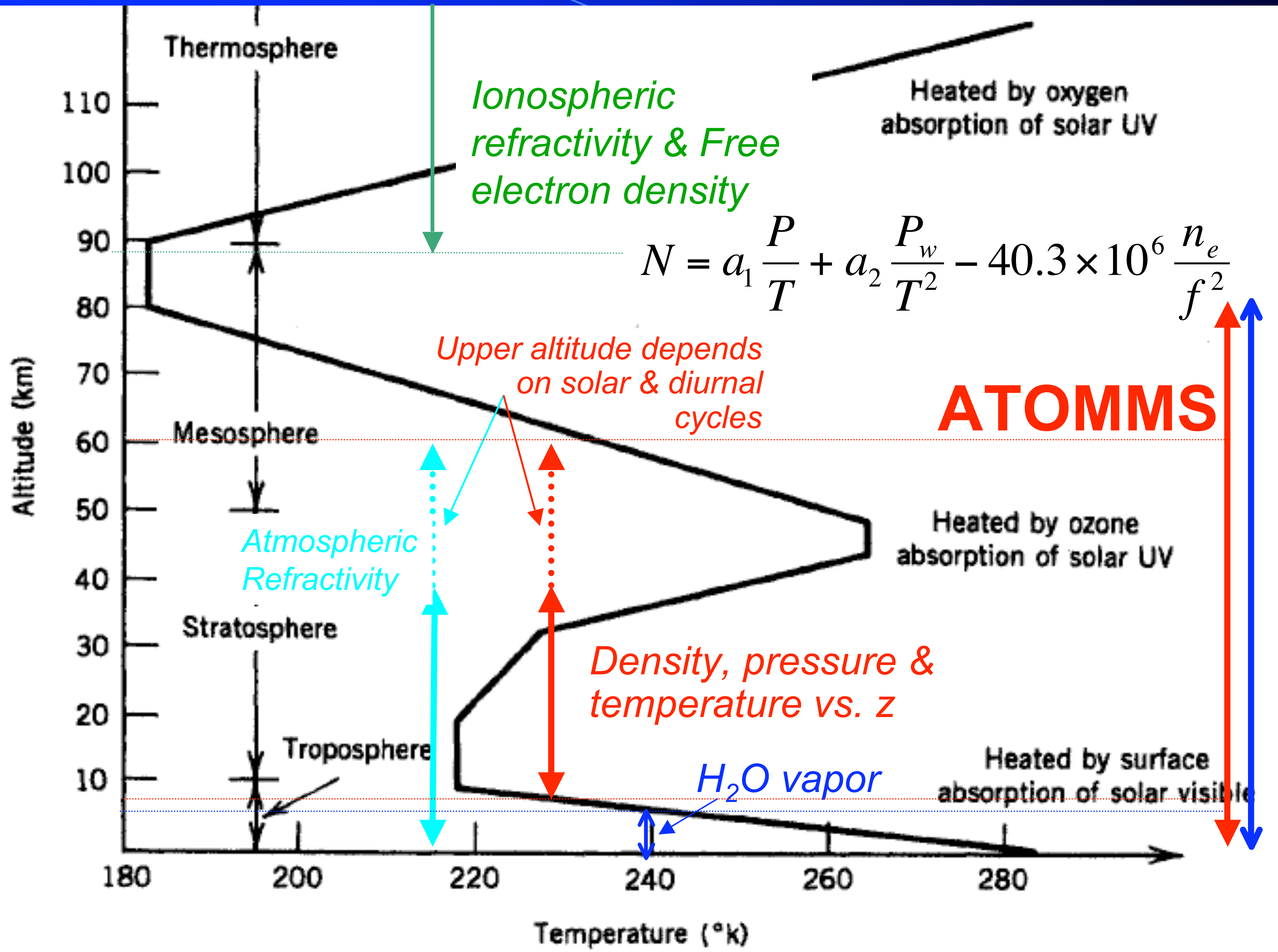
- Select occultation frequencies to measure absorption of interesting constituents:
  - H_2O absorption to break wet-dry ambiguity of refractivity
  - other constituents like O_3, $H_2{}^{18}O$, HDO via absorption
- Extend profiles to much higher altitudes
  - reduce GPSRO sensitivity to ionosphere using much higher freq’s
- No need for external hydrostatic boundary condition and use/weighting of middle atmosphere climatology/analyses:
  - measure high altitude temperature directly via Doppler broadening

Result is …

⇒ A cross between GPS RO & MLS

⇒ Standalone thermodynamic state estimator for climate and weather from near-surface to mesopause (& Mars)

Capabilities of GPS RO & ATOMMS



ATOMMS Capabilities

Features

- Global 4D coverage (at least statistically),
- All-weather sensing,
- Seasonal and diurnal coverage,
- High vertical resolution
- Sufficient sampling density
- High precision & absolute accuracy without biases & drifts,
- Independence from assumptions and models

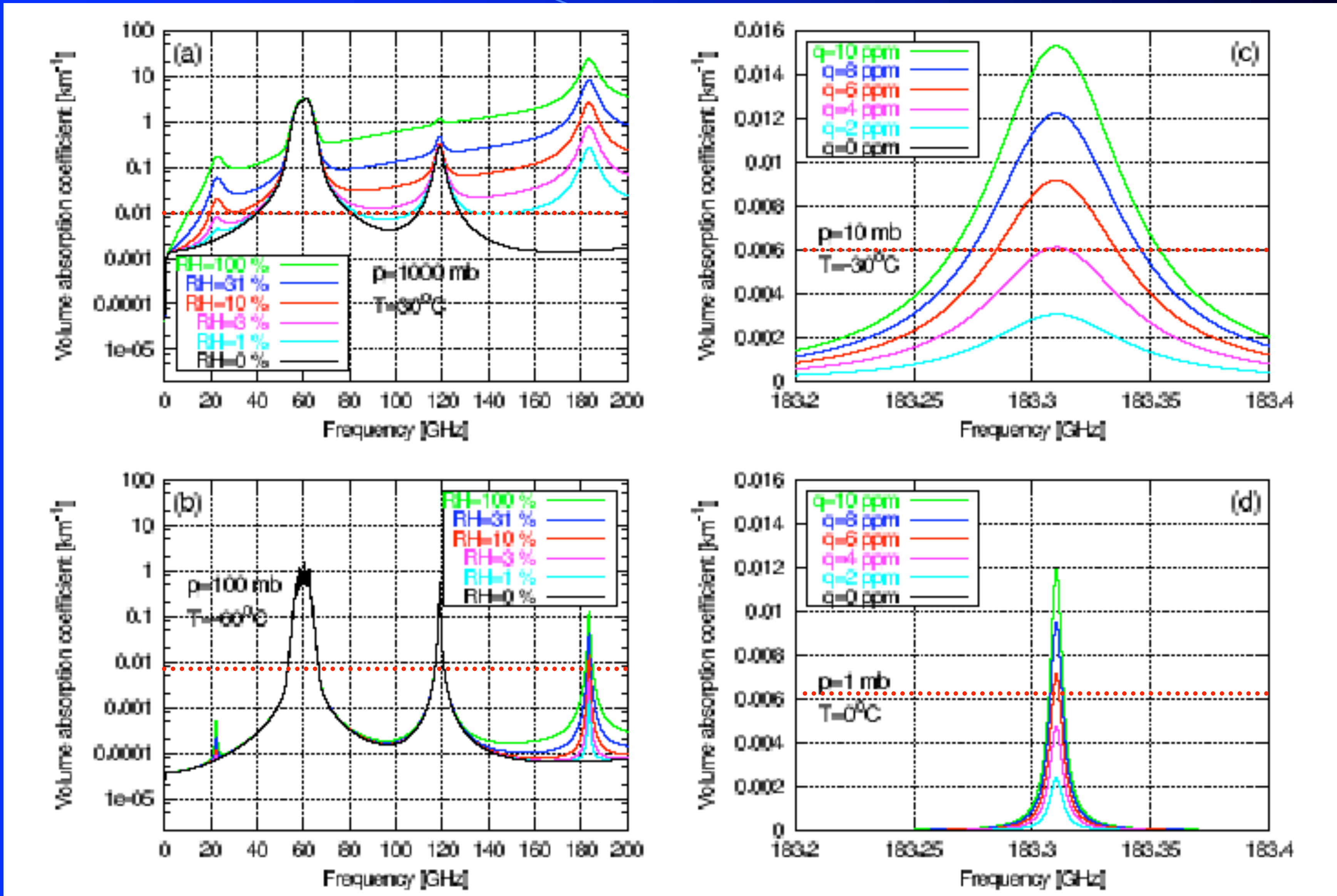
Determines

- Thermodynamic and dynamic state of the system
- Variability and trends
- Constraints on processes

Challenges:

- Requires new transmitters in orbit
- Pointing
  - high SNR requires directional antennas
- High amplitude stability
- Sampling density vs. cost of additional transmitters & receivers
- Enhanced sensitivity to turbulence
- Separate water vapor from liquid water clouds

Water and Oxygen Lines Below 200 GHz



Retrieval Overview: Deriving Extinction Coefficient Profiles

- For each wavelength, the observed intensity, *I*, equals the vacuum intensity (signal intensity with no atmosphere), I_0, times $e^{-\tau}$ where τ is the optical depth.

$$I = I_o \exp(-\tau) \quad or \quad \tau = \ln\left(\frac{I}{I_o}\right)$$

- measured optical depth is along the signal path whereas we want a ***radial*** profile of the extinction coefficient, *k*.
- Simplest solution is an abel integral transform pair for opacity and extinction coefficient: (**Note: *x = nr***)

absorption

$$\tau(a) = \int k\, dl = 2\int_{x=a}^{x=\infty} k \frac{x \, {}^{dr}\!/_{dx}\, dx}{\sqrt{x^2 - a^2}}$$

$$k = -\frac{1}{\pi}\frac{da}{dr}\bigg|_{a=a_0} \int_{a=a_0}^{a=\infty} \frac{d\tau}{da}\frac{da}{\left(a^2 - a_0^2\right)^{1/2}}$$

Forward relation | *Inverse relation*

bending

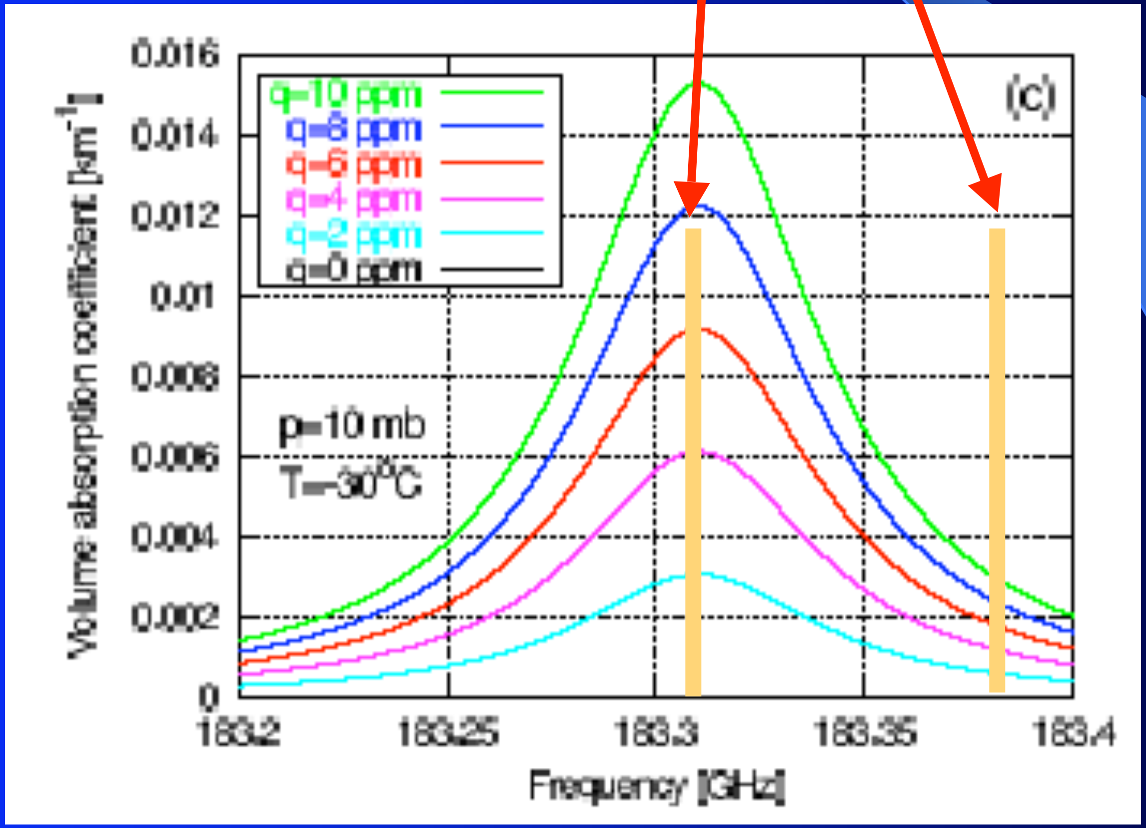
$$\alpha = \int d\alpha = 2a\int_{r_t}^{\infty} dr \frac{dn}{n\, dr}\frac{1}{\sqrt{n^2 r^2 - a^2}}$$

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

ATOMMS Differential Absorption

Measure occultation signal amplitude simultaneously at 2 or more frequencies,

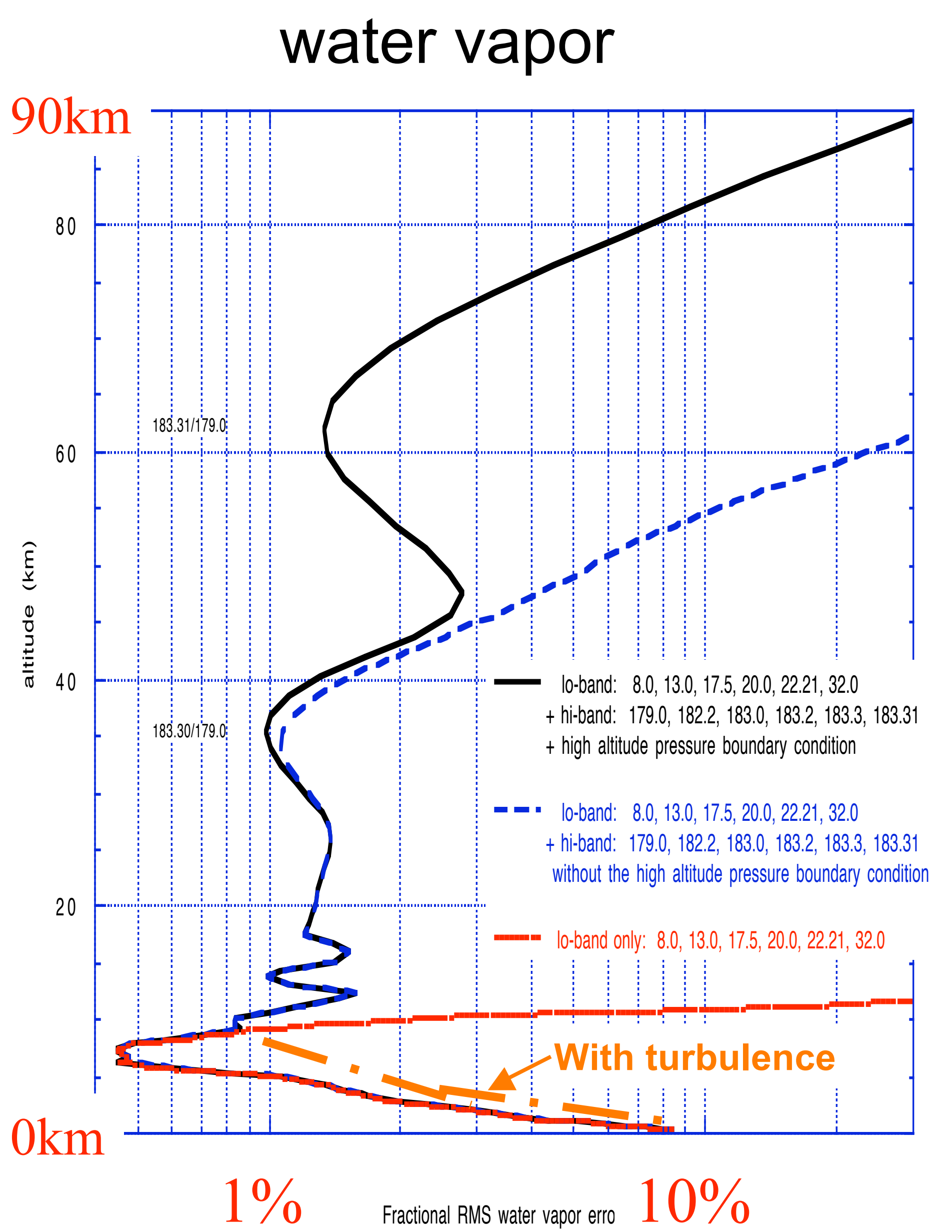
- One closer to line center to measure absorption
- Calibration tone farther from line center to ratio out unwanted effects

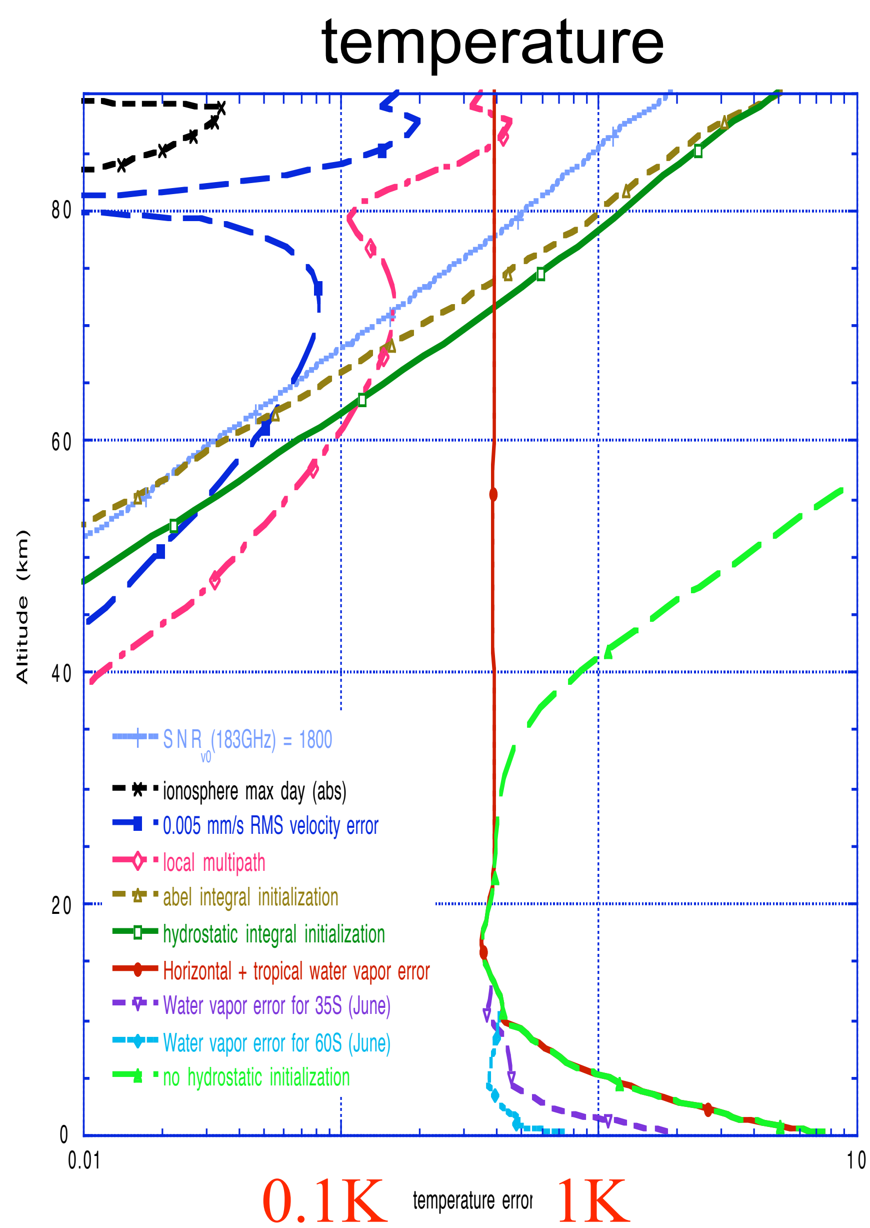


Sources and Mitigation of Error

Instrumental effects:	Finite signal to noise ratio,	Directional antenna
	Antenna gain and pointing,	Calibration tone
	Transmitter power fluctuations,	Monitor/Cal. tone
	Receiver gain fluctuations,	Cal. tone
	Local multipath	Directional antenna
Atmospheric effects:	Molecular oxygen absorption	Est. from T & P
	Defocusing	Cal.tone/Diff Corr
	Diffrac./M.P. from layering	Cal.tone/Diff Corr
	Scintillations from turbulence	**Cal.tone/Diff Corr**
	Liquid water clouds	**Spectr. Separation**
Retrieval errors:	Non-spherical distributions	Horiz. average
	Uncertainty in line parameters	Spectr. cal. in space

Precision of Individual ATOMMS Profiles





ATOMMS Performance vs. Latitude

Precision of individual temperature and water vapor profiles

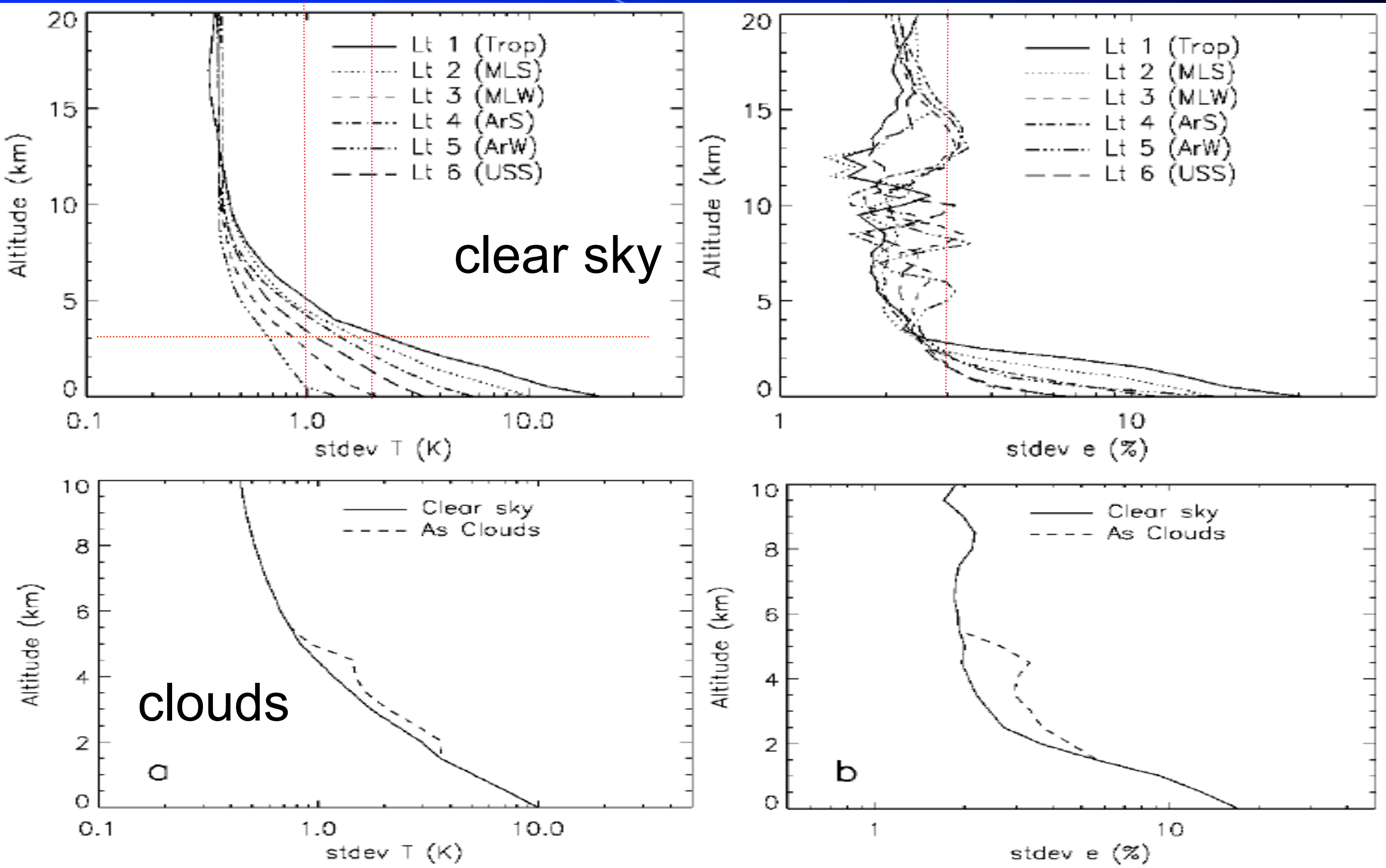
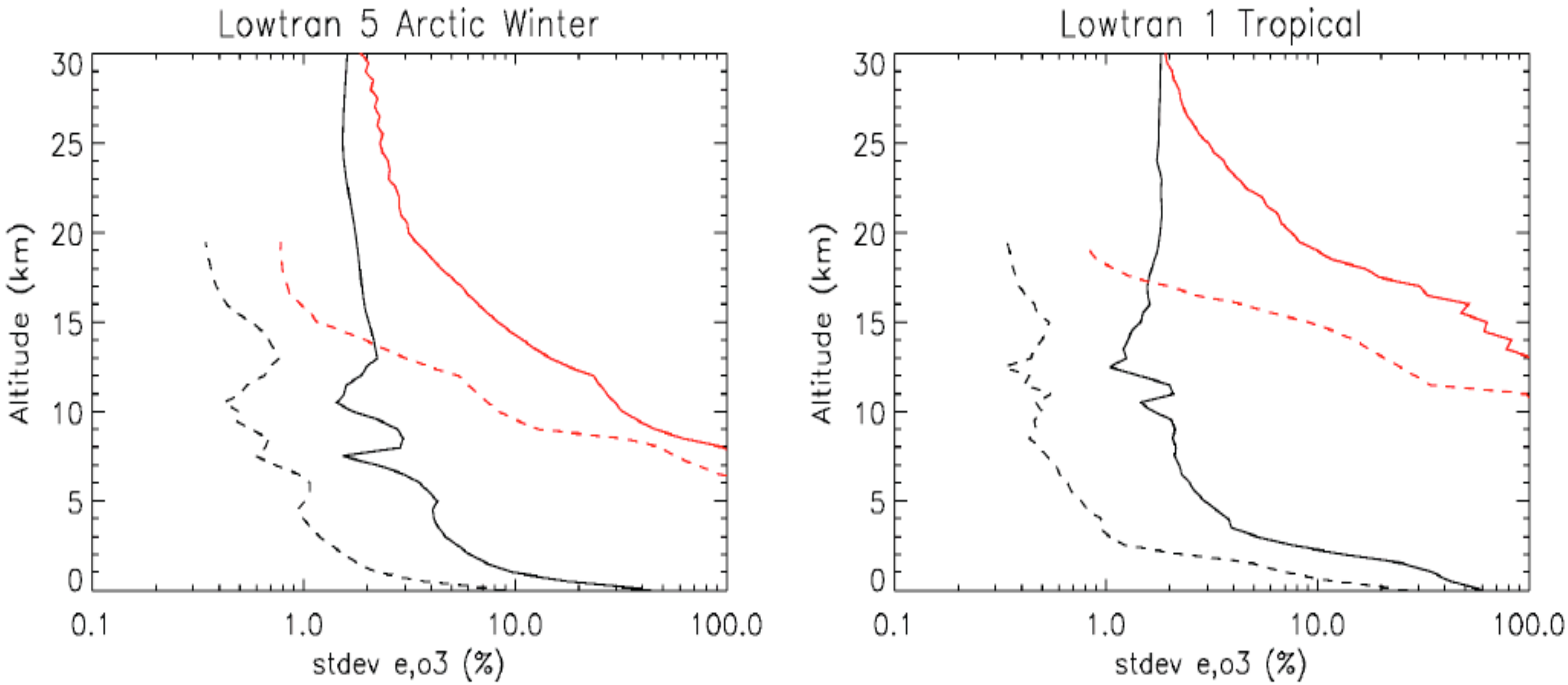


Fig. 7 Computed standard deviation of the errors in the retrievals of (a) temperature and (b) water vapor pressure using simulated ATOMMS observations. The background atmosphere is the Lowtran 2 mid-latitude summer profile. Solid lines are for clear sky conditions, while the dashed lines were computed after placing a broken deck of altostratus clouds between 4.5 km and 5.5 km altitude. The cloud field is highly non-symmetric about the local tangent point. Cloud elements have liquid water contents of 0.3 g m^{-3}.

Ozone & Water Vapor Retrieval Precision



- Standard deviation of simulated errors of water vapor (black) and ozone (red) from satellite (solid) and aircraft occultations (dashed).
- At altitudes below ozone peak, ozone retrieval error quickly increases
- Aircraft retrievals are more accurate than satellites & will be quite useful

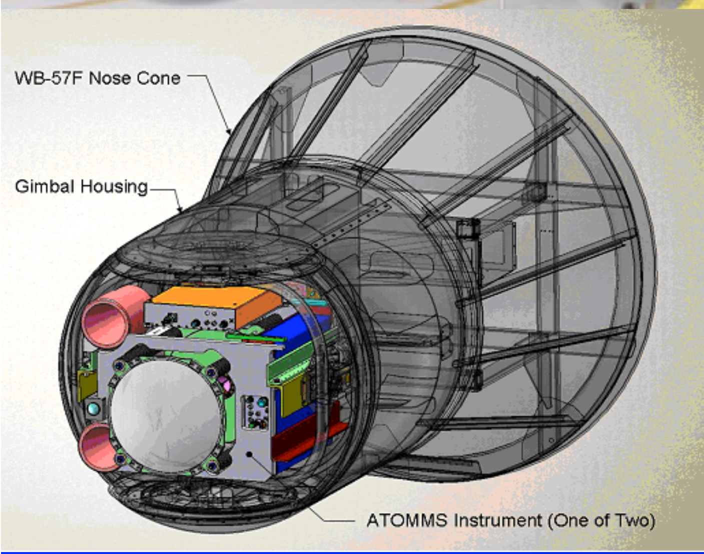
Concept Evolution

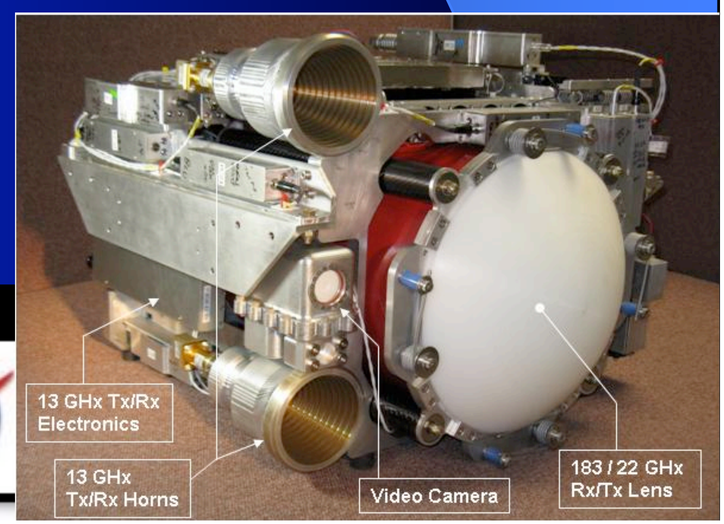
- Theoretical development (1998 - present)
- Aircraft to aircraft demonstration (2010)
- Satellite to satellite demonstration
- Constellation of microsatellites for climate and NWP
  - Satisfy (NOAA) climate monitoring needs
  - Provided by NASA, NSF, ESA, eventually NOAA, …

ATOMMS MRI Proposal

Aircraft-aircraft demonstration

- Occultation between 2 WB-57F aircraft flying near 19 km altitude
- Perform series of rising occultations
- Measure phase and amplitude at several wavelengths
- POD: GPS + accelerometers
- Pointing via WAVES





ATOMMS System Elements & Development

- ATOMMS occultation instrument (UA)
- ATOMMS precise positioning system (JPL)
  - < 0.1 mm/sec via GPS and seismic accelerometers
- WAVES pointing system (SRI)
- WB-57F Aircraft (JSC)
- Retrieval system (UA)
  - extended from JPL GPS RO
- Ground truth for evaluation (ARM SGP + A-Train + ….)

Occultation Instrument Overview

- 22 GHz water line
  - 8 tones space approximately 1 GHz apart between 18 and 26 GHz
  - Solve for water vapor mid-trop & below and liquid water content
- 183 GHz water and 195 GHz ozone lines
  - Presently 2 tones between 183 and 203 GHz
    - Add 2 more tones for turbulent variations in imaginary refractivity
  - Solve for water vapor in upper troposphere & above
  - Solve for ozone in upper troposphere and above
- 13 GHz phase tone(s)
  - Provide phase in lower troposphere where 183 GHz cannot penetrate to determine bending angle and real part of refractivity
- No cryogenics
- Build at UA