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Cloudy Boundary Layers: PDFs and Vertical Structure

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Essence of turbulence, convection and cloud problem in climate models is the estimation of joint PDFs of model variables

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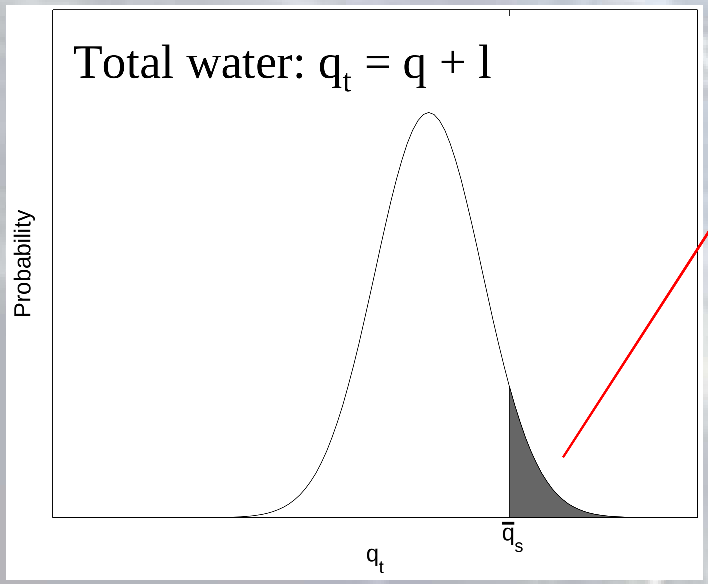
PDF-based Cloud Parameterizations

PDF-based cloud parameterizations are based on the pdf of q_t (in this simple example) or on the joint pdf of q_t and θ_l



Values larger than saturation are cloudy

$$a = \int_{q_s}^{+\infty} p(q_t)\,dq_t$$

$$\bar{l} = \int_{q_s}^{+\infty} (q_t - \overline{q_s})\,p(q_t)\,dq_t$$

With Gaussian distribution we obtain cloud fraction and liquid water as a function of Q:

$$a = \frac{1}{2} + \frac{1}{2} erf\left(\frac{Q}{\sqrt{2}}\right)$$

$$\frac{l}{\sigma} = aQ + \frac{1}{\sqrt{2\pi}} e^{-Q^2/2}$$

$$Q = \frac{q_t - q_s}{\sigma}$$

Characterizing PDF properties of total water content is essential for cloud parameterization development ➔ Can we use satellite observations?

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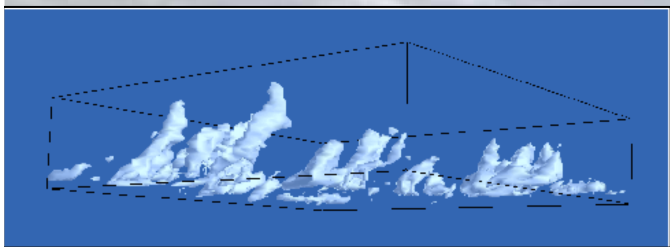
Climate model physics and satellite observations

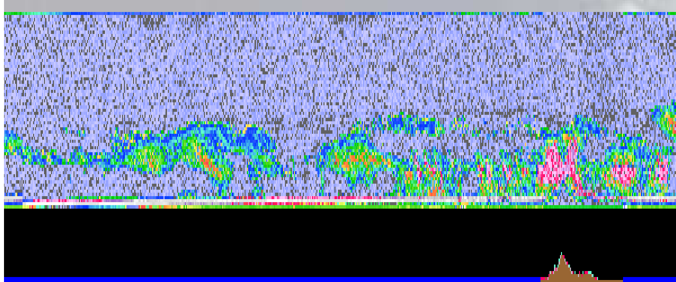
Strategy for climate model physics improvement/development



High-resolution model data:

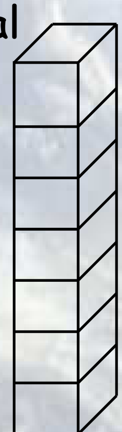
Large Eddy Simulation (LES) models

Cloud Resolving Models (CRMs)



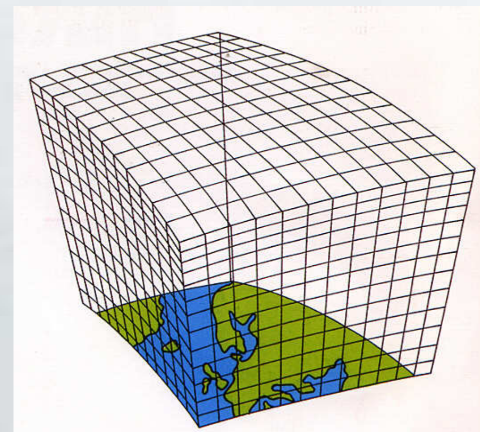
High-resolution satellite data

traditional



Testing in Single Column Models:

Versions of Climate Models



3D Climate/Weather Models:

Evaluation and Diagnostics with satellite observations

LES/CRM models do NOT provide a global perspective of physical regimes

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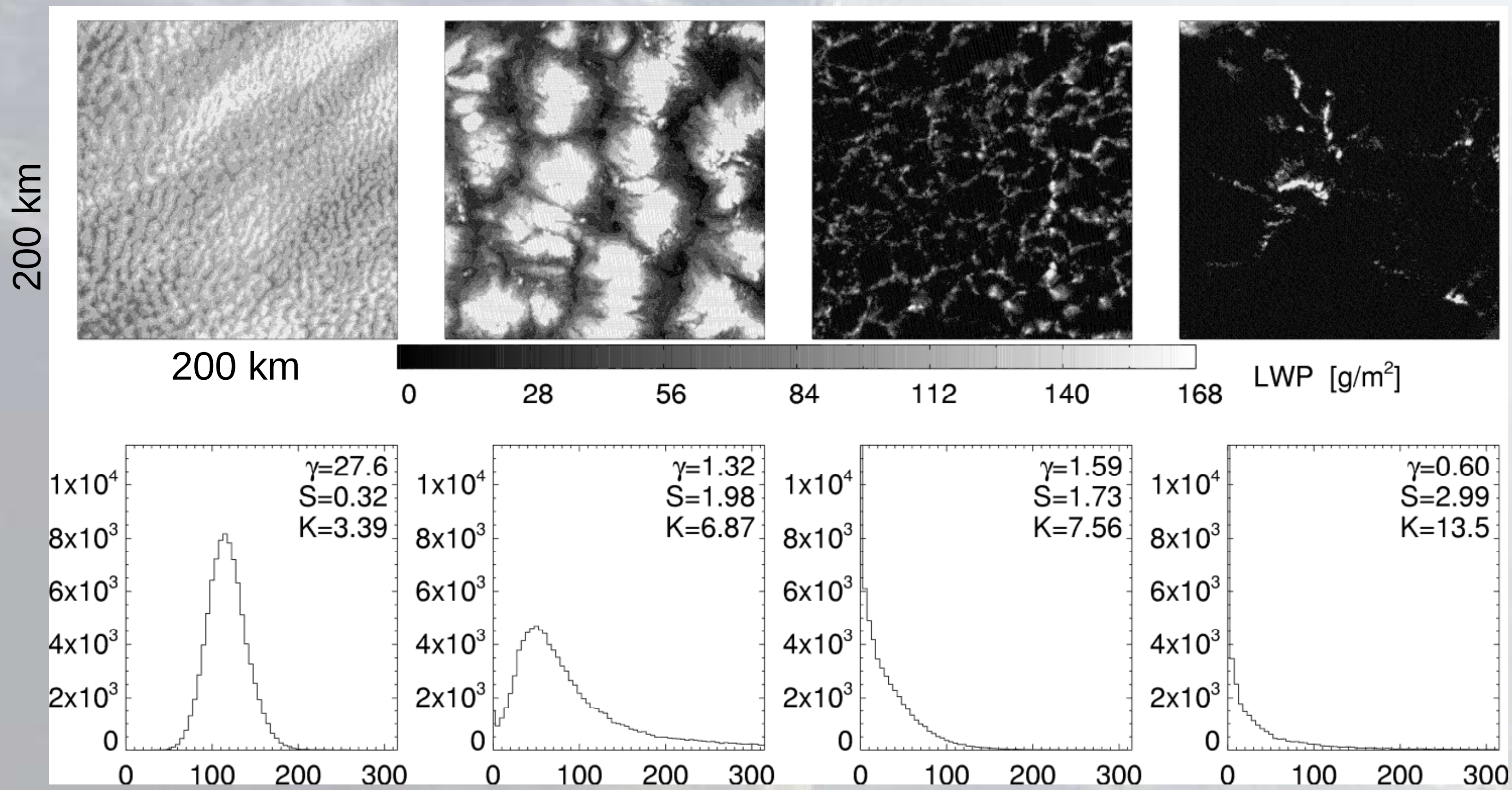
Liquid Water Path PDFs from GOES for different types of boundary layer clouds

LWP from visible channel, Δx=1km, Δt=30 min, 3 years of data (1999-2001) ➔ 100,000 snapshots of 200 km^2



From Gaussian stratocumulus to skewed cumulus regimes

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How do we relate PDFs of LWP to PDFs of total and liquid water content?

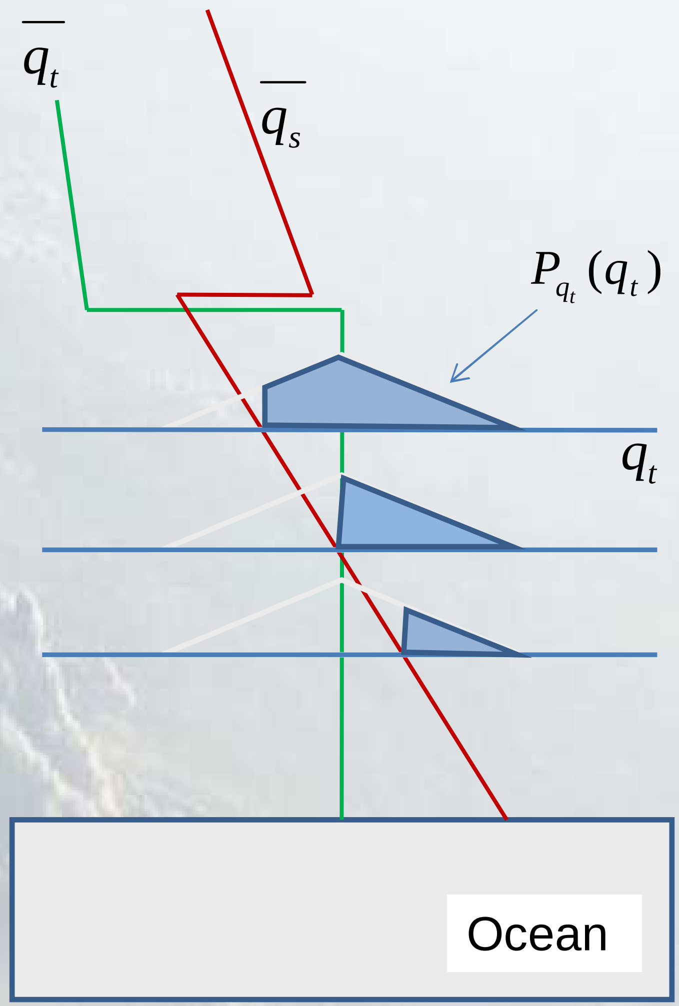
One possibility - Simplifying Assumptions:

(1) Mean total water content $\overline{q_t}$ is constant in well mixed boundary layer.

(2) PDF of total water content $P_{q_t}(q_t)$ is the same in the mixed layer.

(3) Saturation specific humidity $\overline{q_s}$ decreases linearly with height.

(4) Full vertical correlation for total water content PDFs.



See also Considine, JGR, 1997

Wood and Hartmann, JCLI, 2006

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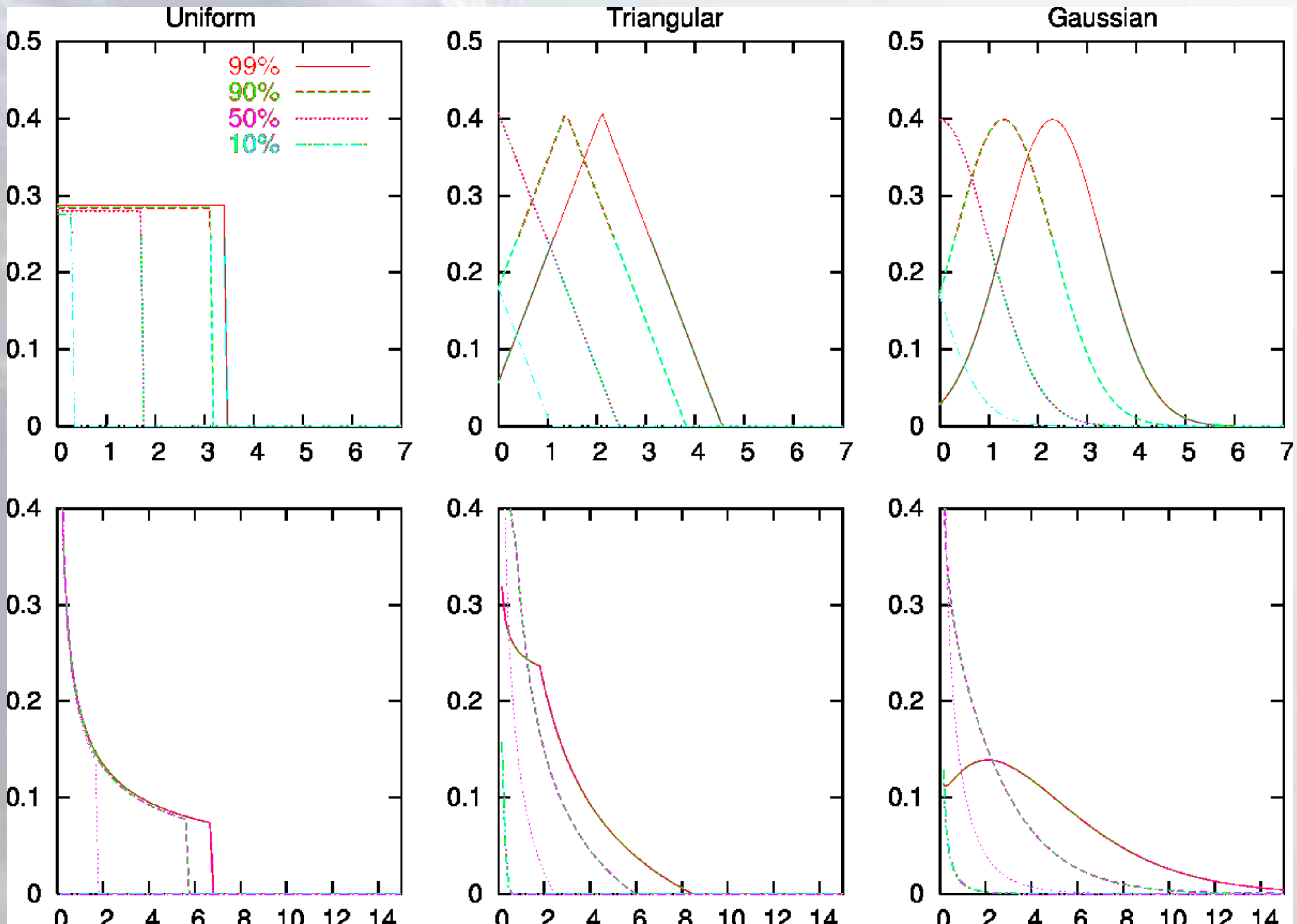
From PDFs of total water content to LWP PDFs

PDF of total water content

Uniform | Triangular | Gaussian

PDF of liquid water content (at the cloud top)

corresponding PDF of liquid water path



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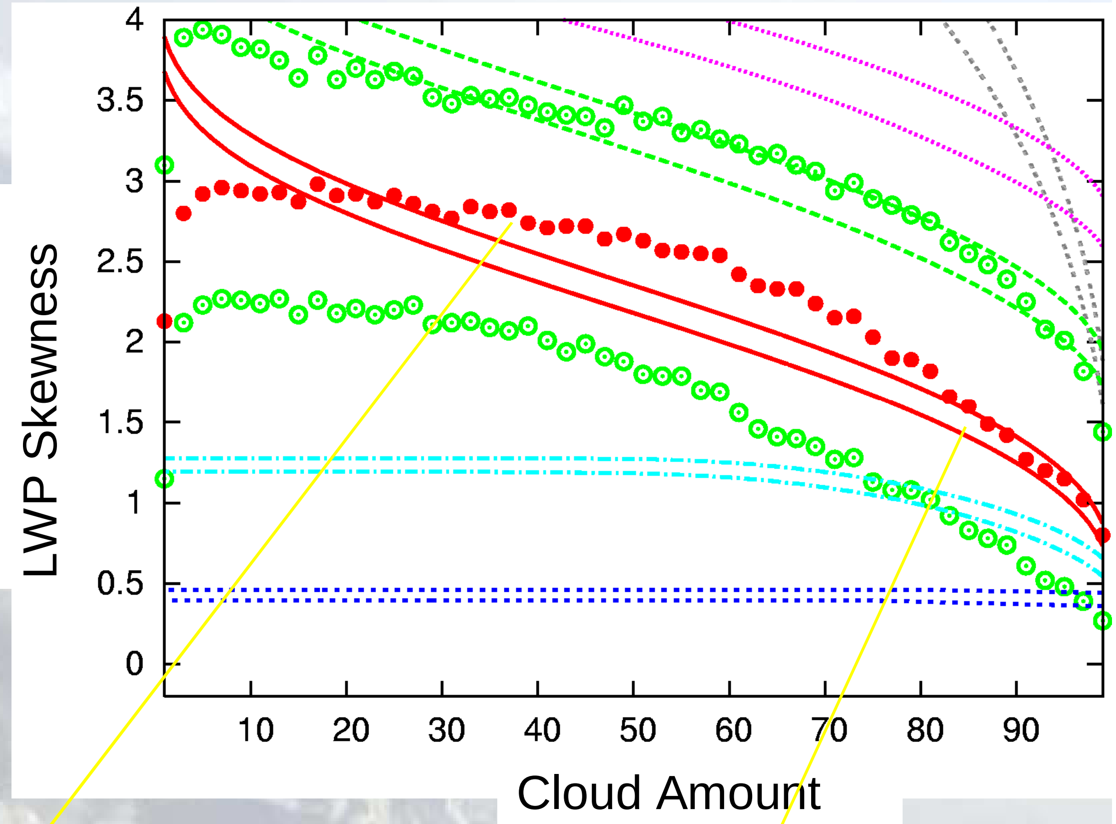
Cloud amount and skewness of LWP PDFs

Points : Observations (~100,000 snapshots)

● : median

○ : 25th & 75th percentile

Lines : Different PDFs (2 lines correspond to two virtual detection limits - 10% or 20% of mean LWP)



Gaussian PDF of total water does not reproduce observations (constant skewness) for cloud cover < 50%

Gaussian PDF of total water is realistic for cloud cover > 60%

Note: how much of this is due to the assumptions made?

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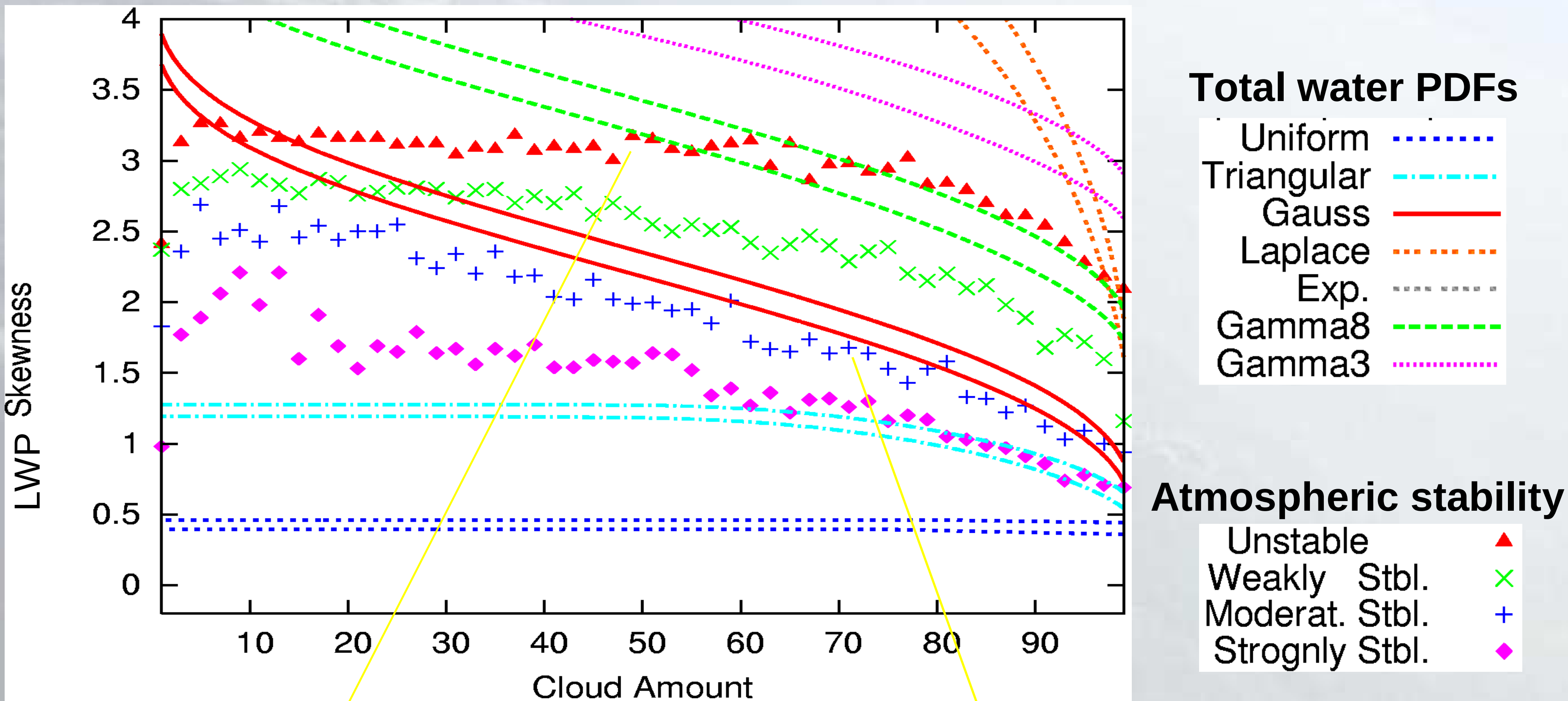
Cloud amount and skewness of LWP PDFs II



Gaussian PDF of total water is not realistic in unstable situations

Gaussian PDF of total water works very well in weak stability regimes

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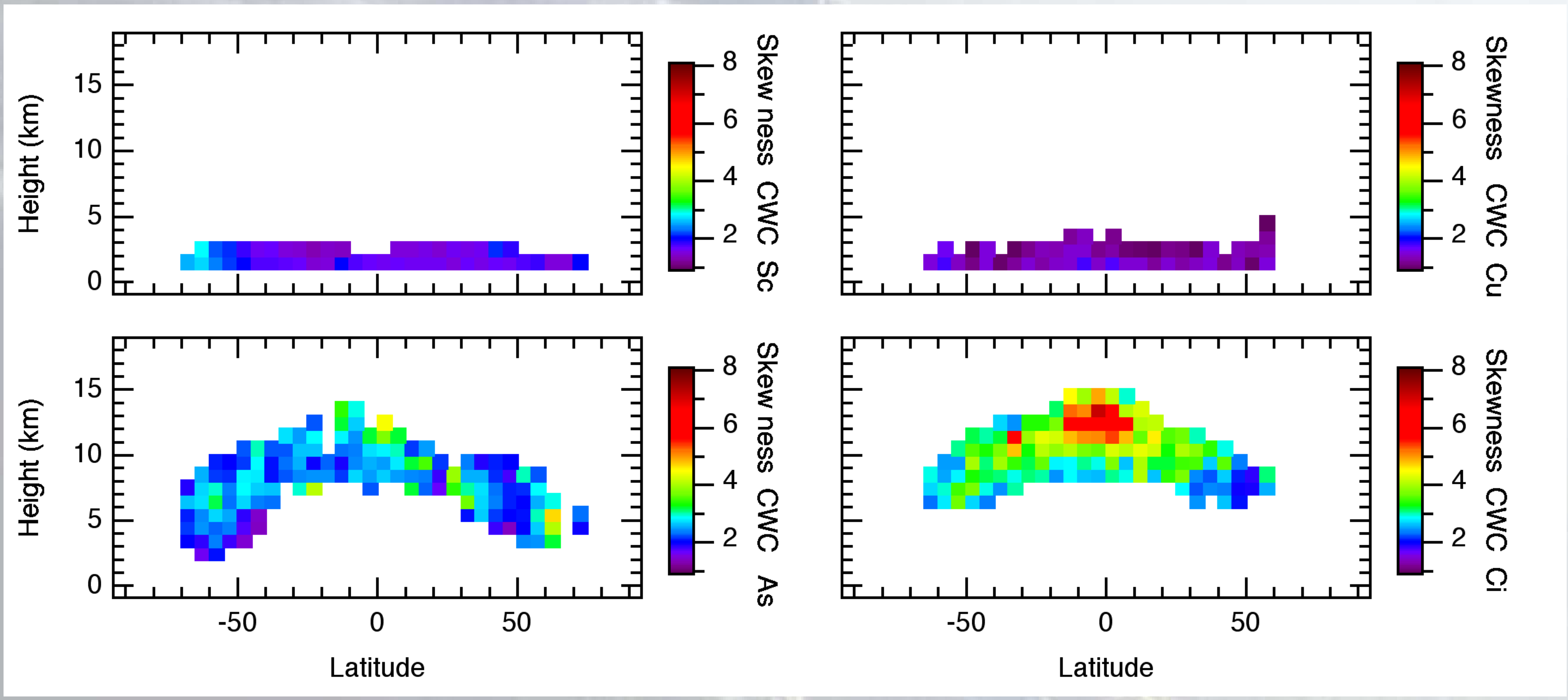
PDFs of cloud water content from CloudSat

Skewness of cloud water content (CWC) from CloudSat for different cloud types for SON 2006



CloudSat allows to study vertical structure of CWC PDFs

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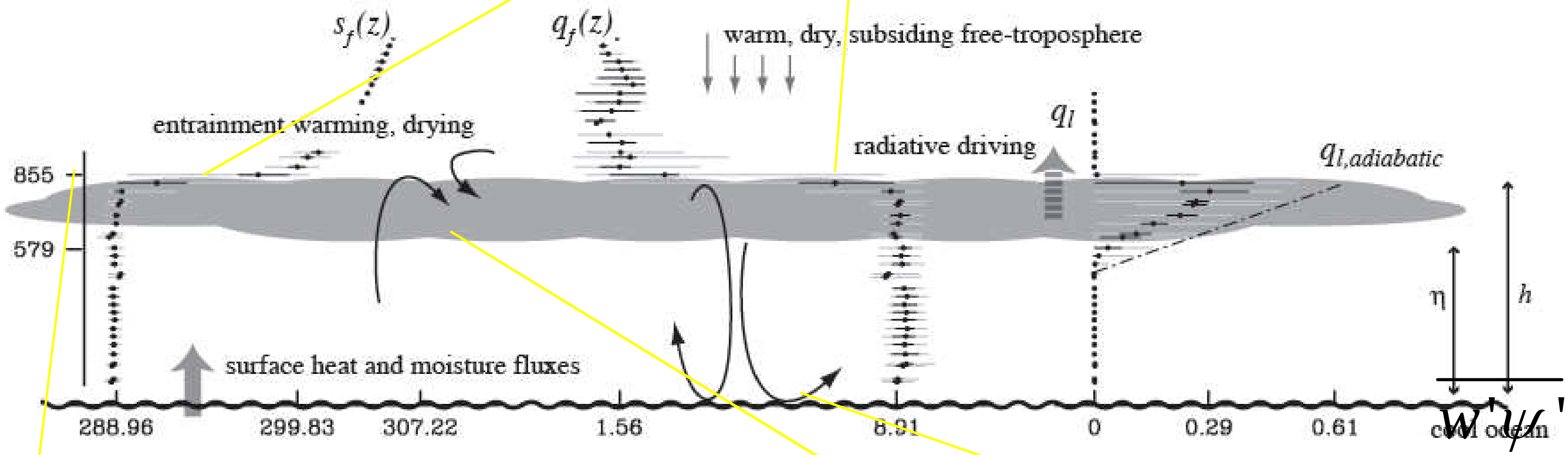
Cloudy Boundary Layer: Key Challenges for Models and Observations

Strong gradients of temperature and water

DYCOMS II composite

Courtesy: B. Stevens



Even just detecting accurately the height of the gradient is essential

PBL turbulent/convective structures and mixing

<u>Key observation and modeling challenges:</u>

a) Strong vertical gradients;
b) Turbulent/convective mixing.

Large cloud cover → major problem for IR/MW sounding

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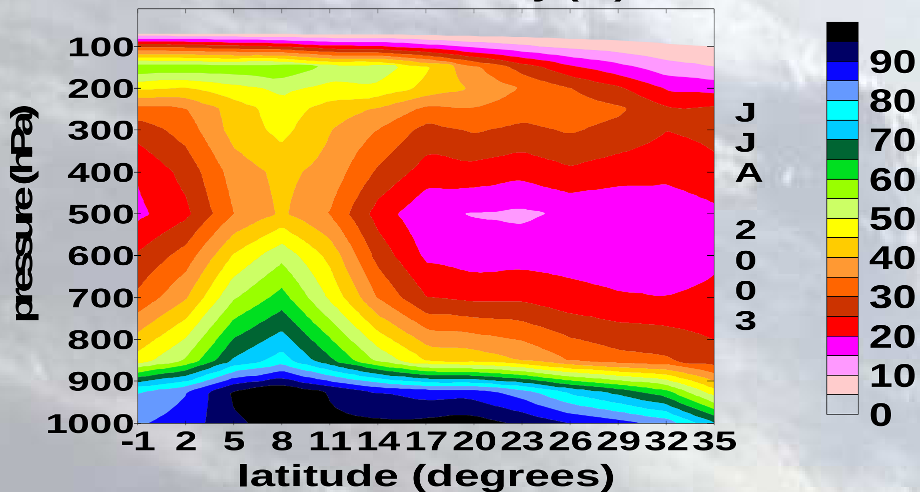
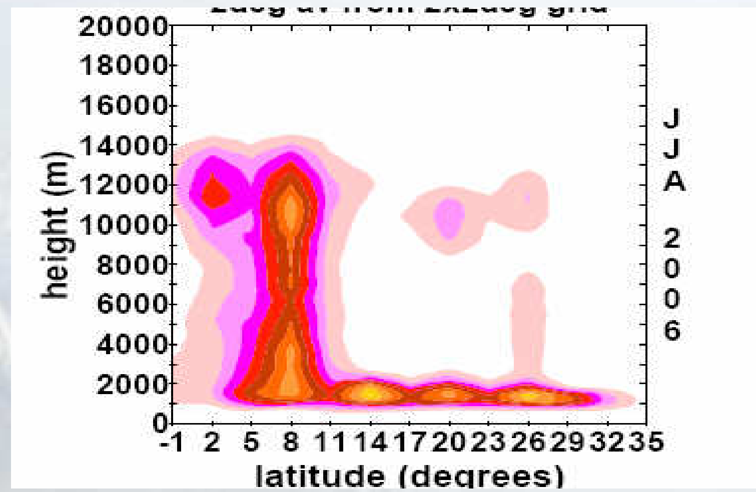
Satellite observations of cloud regime transitions along GPCI transect

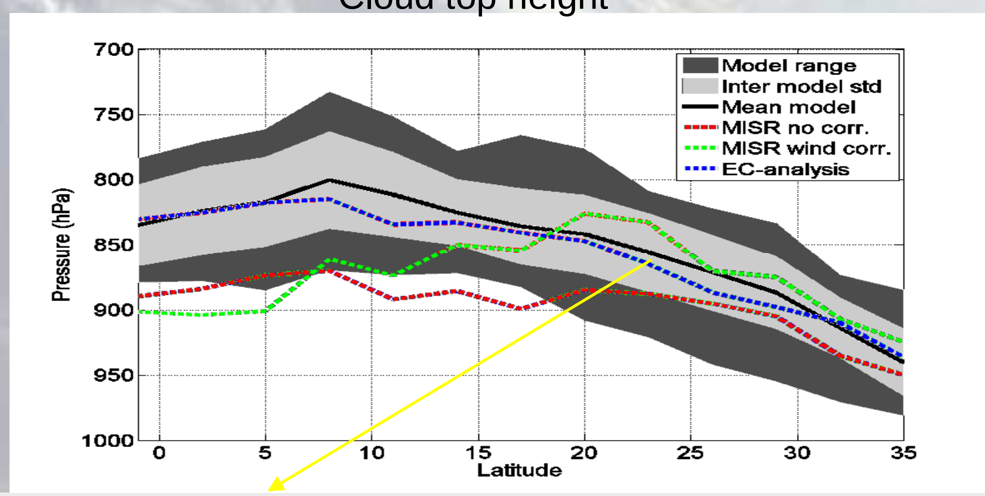
AIRS
relative humidity (%)



CloudSat cloud occurrence



Cloud top height



Model ensemble mean tracks MISR observations of cloud-top height ...
HOWEVER there is large variability among models

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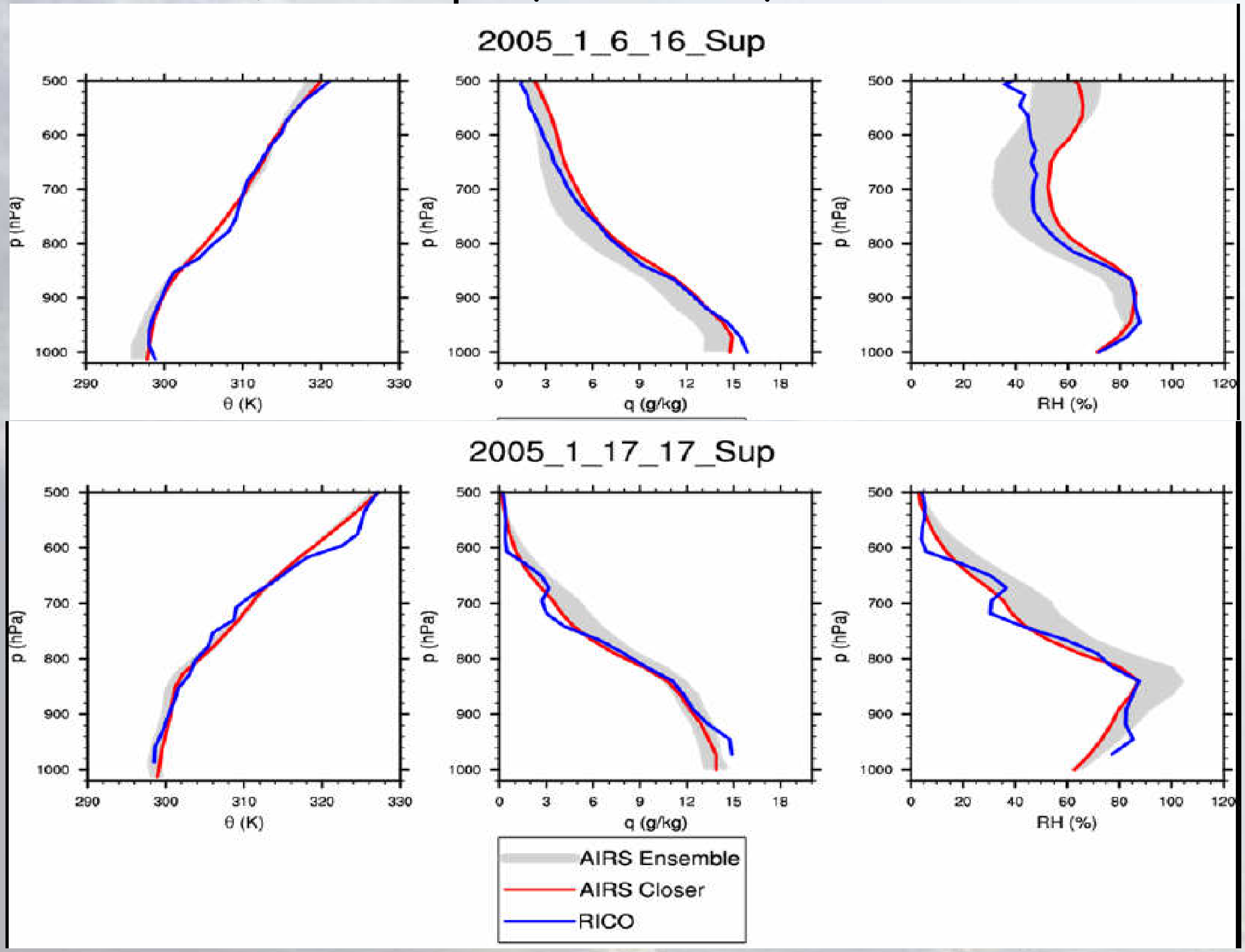
AIRS boundary layer versus RICO sondes

Two AIRS profiles out of 30 collocated sondes



Two successful examples of realistic AIRS boundary layer structure

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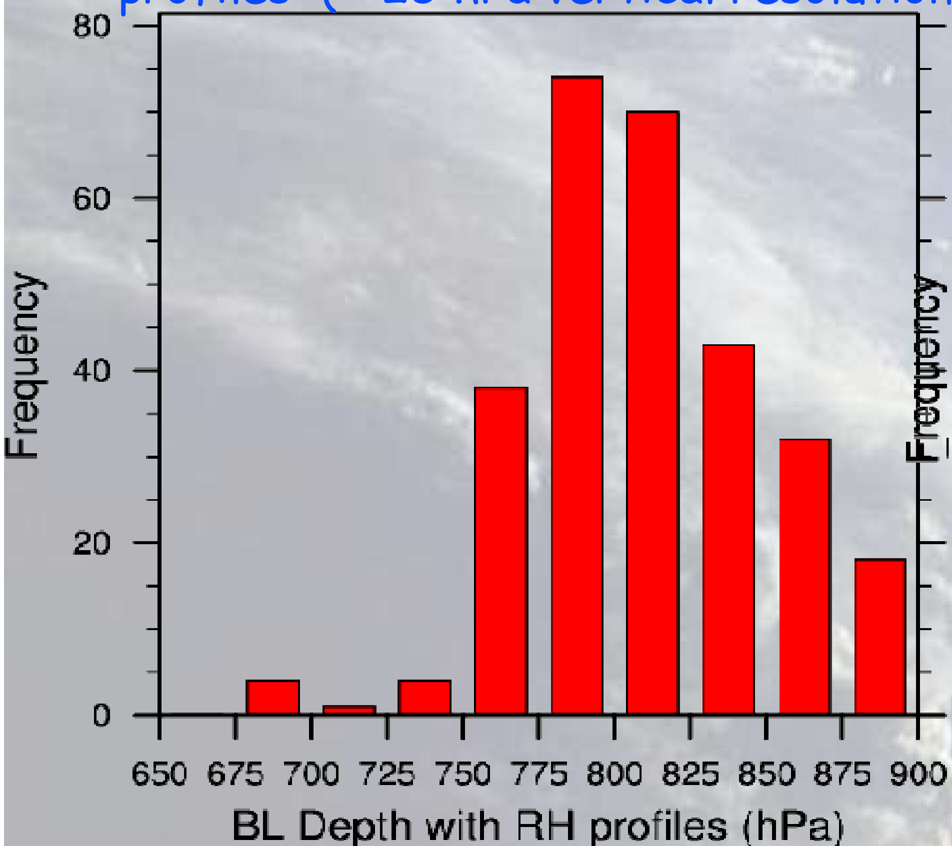
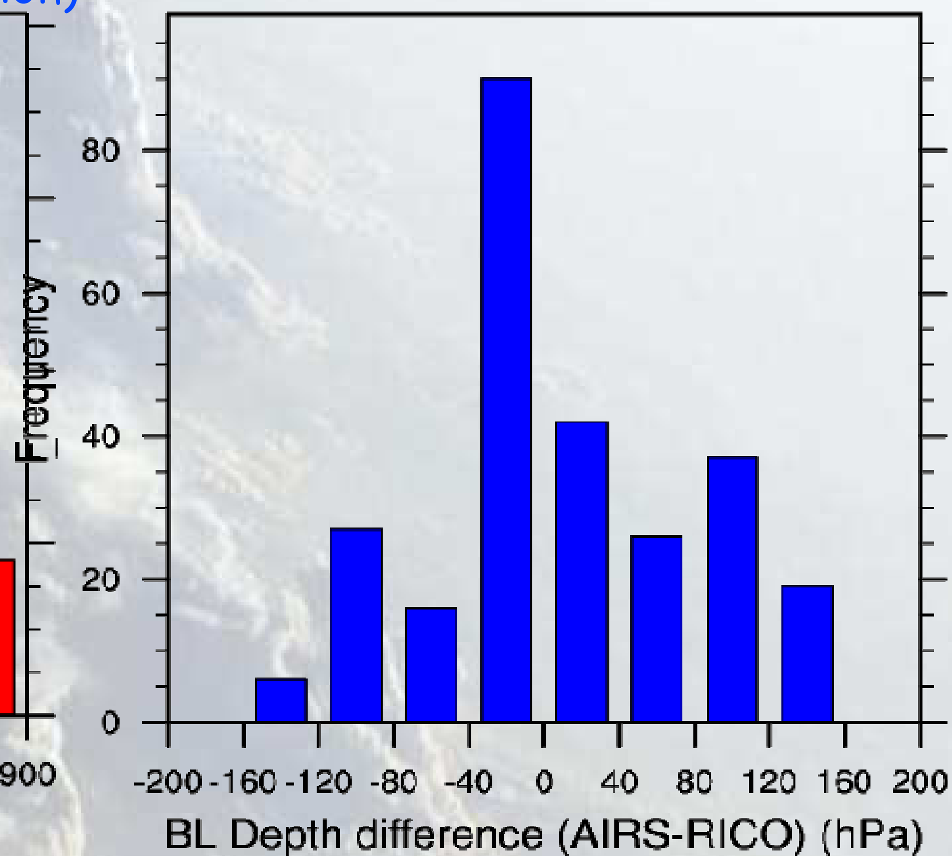
Estimates of PBL height (max. RH grad.) from AIRS during RICO

PBL height from all AIRS 'support' profiles (~ 25 hPa vertical resolution)



Error histogram: PBL height from all AIRS profiles versus RICO sondes



For cumulus regimes (low cloud cover, deep PBL, weak inversion) AIRS can provide realistic info on thermodynamic structure

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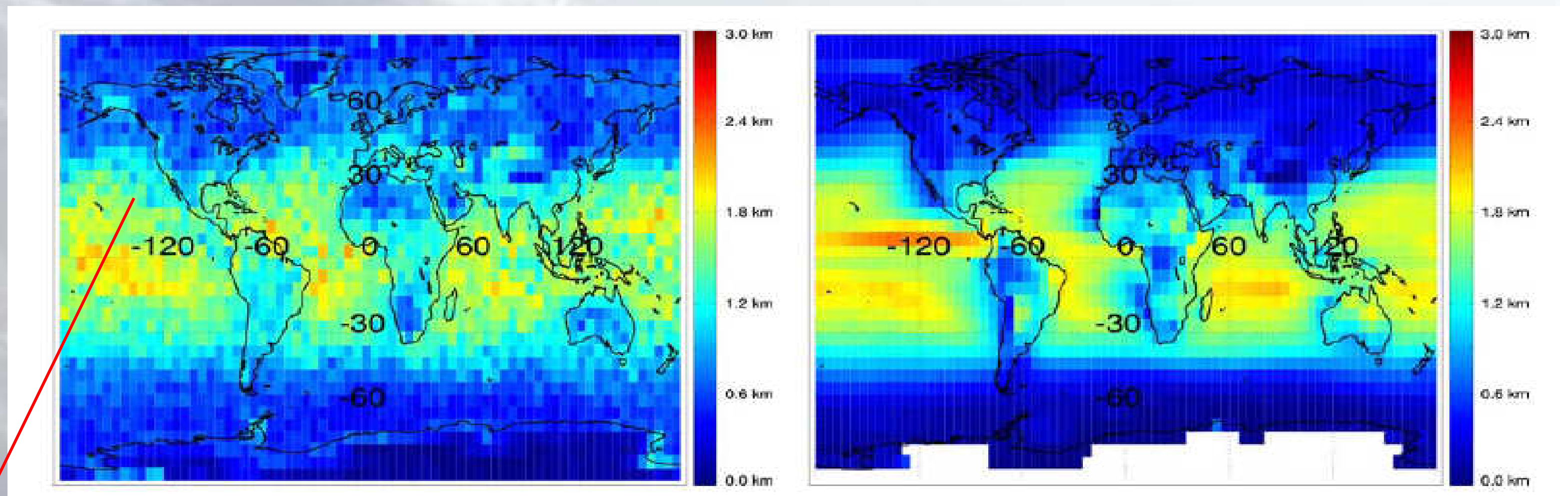
Boundary layer height from GPS RO observations

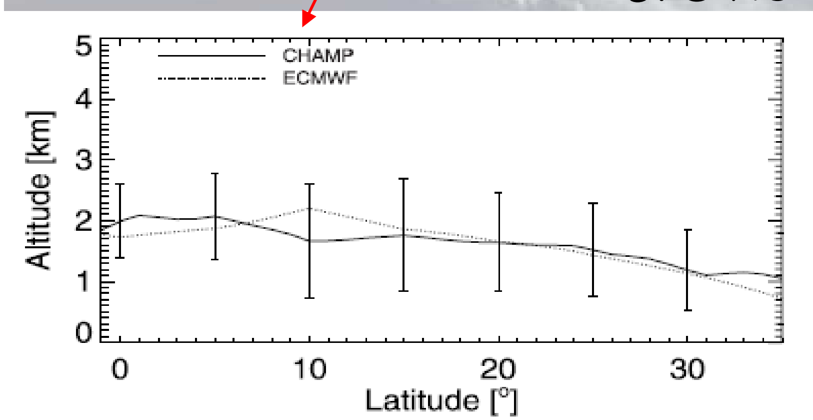
LEO satellite receives a signal from GPS satellite ➔ signal gets refracted trough atmosphere ➔ refractivity depends on temperature and water vapor

Boundary layer height (2001-2004)



GPS RO

ECMWF



Von Engeln et al, GRL, 2005

GPS RO retrievals:

- Profiles within/under clouds
- Vertical resolution ~100-200m
- Refractivity profiles only
- Horizontal resolution ~100km

GPS RO can provide unique info on boundary layer height from space

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Summary and the Future

- Global observations from space of boundary layer thermodynamic structure are essential for better understanding and prediction of low clouds
- Satellite observations (e.g. GOES, CloudSat) provide info on PDFs
- Satellite observations (e.g. AIRS, MISR, GPS RO) provide info on PBL height
- Traditionally we use local high-resolution models ➔ Global high-resolution satellite data could be directly used for model physics development

Future:

- IR sounders will have the potential to have horizontal resolutions of 1 km^2
- Cloud radars will have the potential to provide more realistic PBL CWC
- GPS RO will have the potential to provide full PBL profiles (down to surface)