National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Investigation of Cloud-Topped Marine Boundary Layer Using V5 AIRS/AMSU Data

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AIRS STM 2014 Spring
California Institute of Technology

Outline:

- Motivation
- Sampling and yield
- Stratocumulus
- Transition from stratocumulus to trade cumulus
- Summary and limitations

Motivation 1: MBL clouds are important

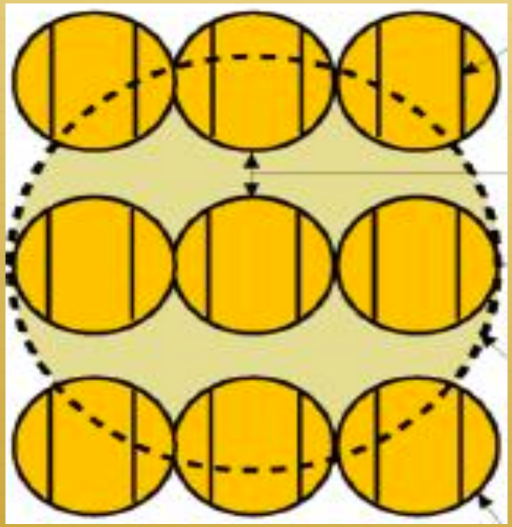
- Cover large area of the Earth's surface, large sensitivity of the earth's radiation budget to low cloud
- Transition of cloud-topped MBL from stratocumulus to trade cumulus regimes.
- Substantial uncertainty in the low cloud-climate feedback (Stephens 2005).
- Important to reduce the uncertainty of future climate projection.
- The response of low stratiform cloud to climate change requires the consideration of temperature and water vapor vertical structure in the low troposphere.

Motivation 2: We have the right tools, we need to know more about the tools

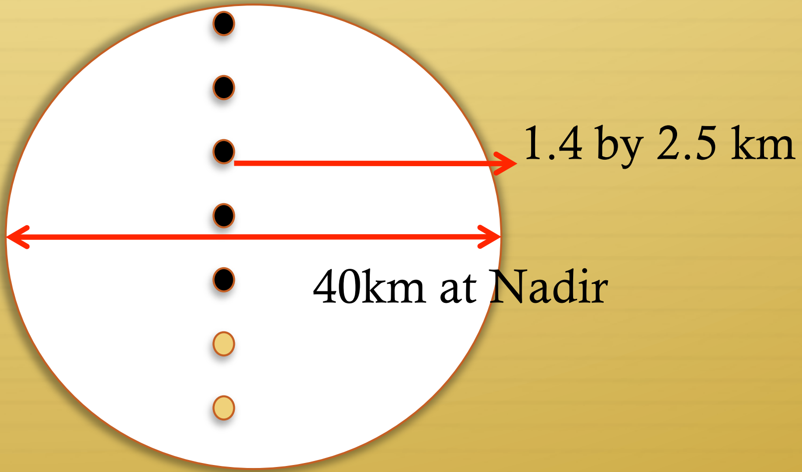
- The synergistic use of recent generation NASA's A-Train, NPP Suomi satellites provides nearly simultaneous observations on atmospheric thermodynamic vertical profiles, cloud, and radiation globally and daily.
- Combination of infrared/microwave radiances facilitates the retrieval of temperature and water vapor vertical structures.
- Correct and innovative application of these data can provide further observational constraint on the modeling of MBL cloud and the study of low cloud-climate feedback-> Limitations and strengths of the data and instruments.

Limitations and Strengths of AIRS/AMSU T and Q in PBL Study
NASA MEaSUREs Level 2 Data (PI: E. Fezter)

AIRS/AMSU FOV



AIRS/AMSU FOV with Collocated CloudSat Profiles

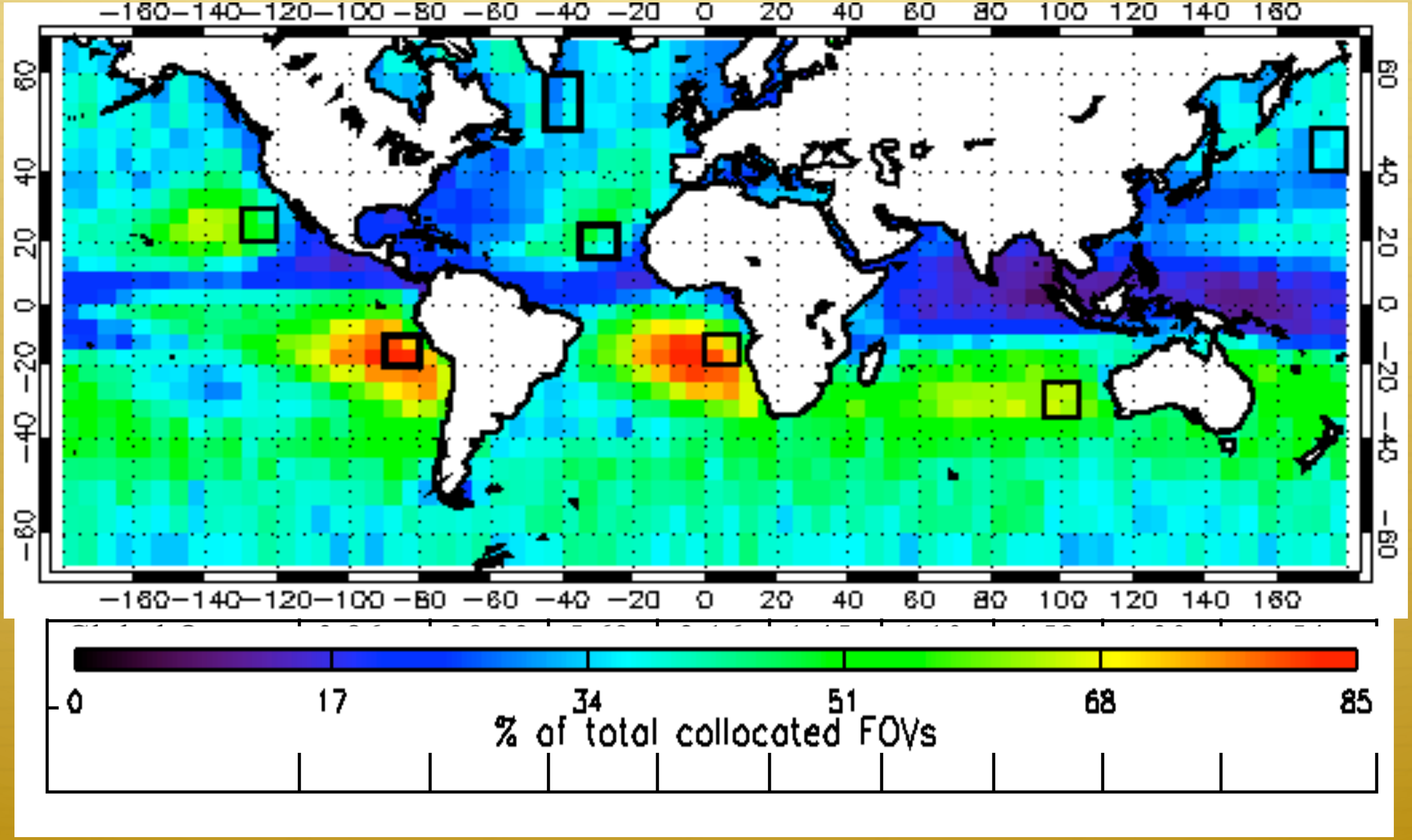


One Year of collocated data:
07/2006 ~ 07/2007
Over ocean from 65°S to 65°N

T(z), q(z):

AIRS quality controlled V5 L2 retrievals
Collocated ECMWF model analysis subsampled by AIRS quality flag
Collocated ECMWF model analysis

Frequency of Occurrence for Each Cloud Class



Global Mean AIRS Yield Vertical Profiles

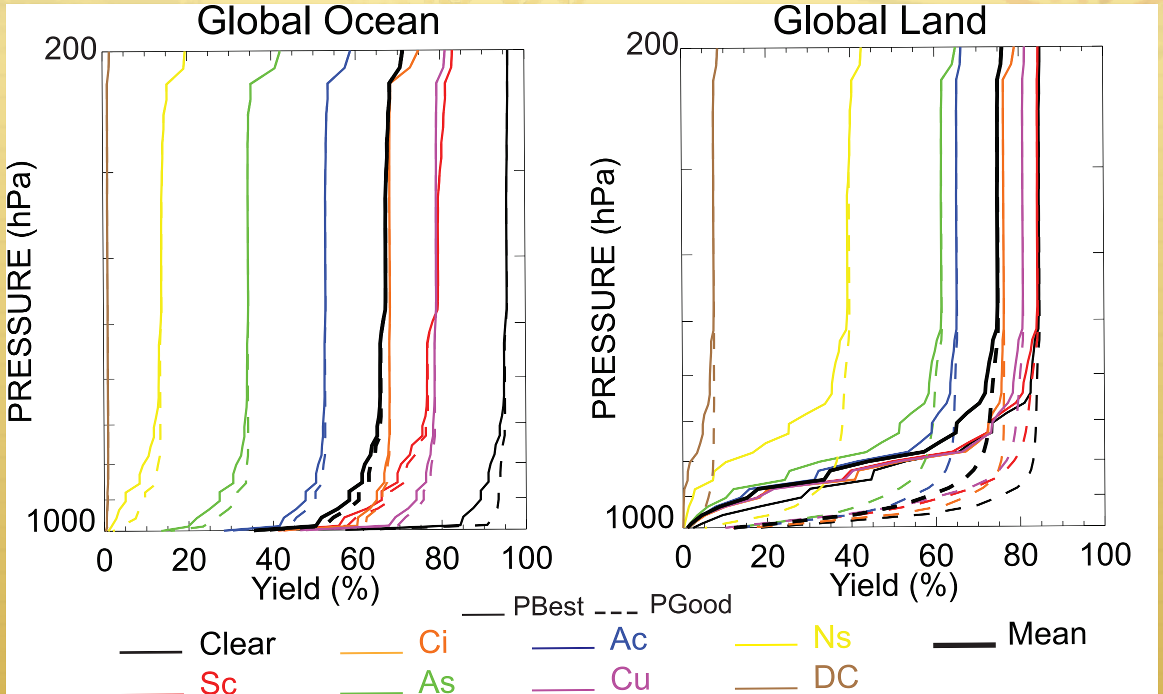


Figure 1. Mean profiles of the yield of AIRS over global ocean (left) and global land (right). The solid lines are for *PBest*, and dashed for *PGood*. Each color corresponds to a separate classification (see legend at bottom), and the bold black lines are for the mean profiles within the described region (land or ocean).

- Organized according to cloud classes (DC<Ns<As<Ac<Ci<Cu&Sc<Clear)
- Mean: 60-70%; ~50% near ocean sfc and at ~800 hPa over land.
- Cloudy scenes: Land > Ocean
- Clear scenes: Land < Ocean
- Decreasing as approaching the surface (more over land)

Cloud-State-Dependent Sampling of AIRS

Excellent Yield in Transition and Trade Cumulus Regimes

- **CloudSat Radar-only Cloud Fraction: CCF**
- **AIRS Yield: Percentage of AIRS PBest=Psurfstd retrievals**

All cases

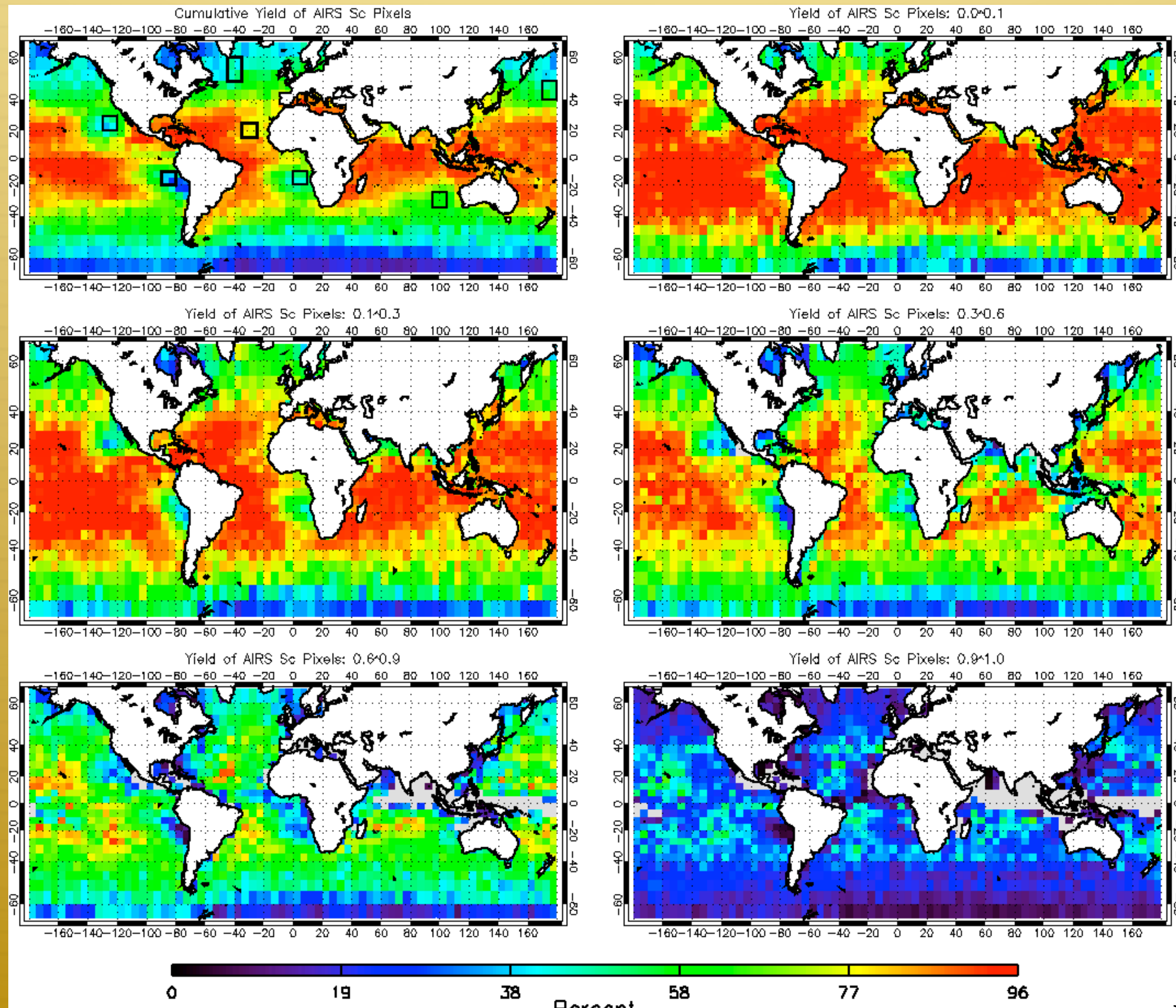
CCF: 0.0~0.1

CCF: 0.1~0.3

CCF: 0.3~0.6

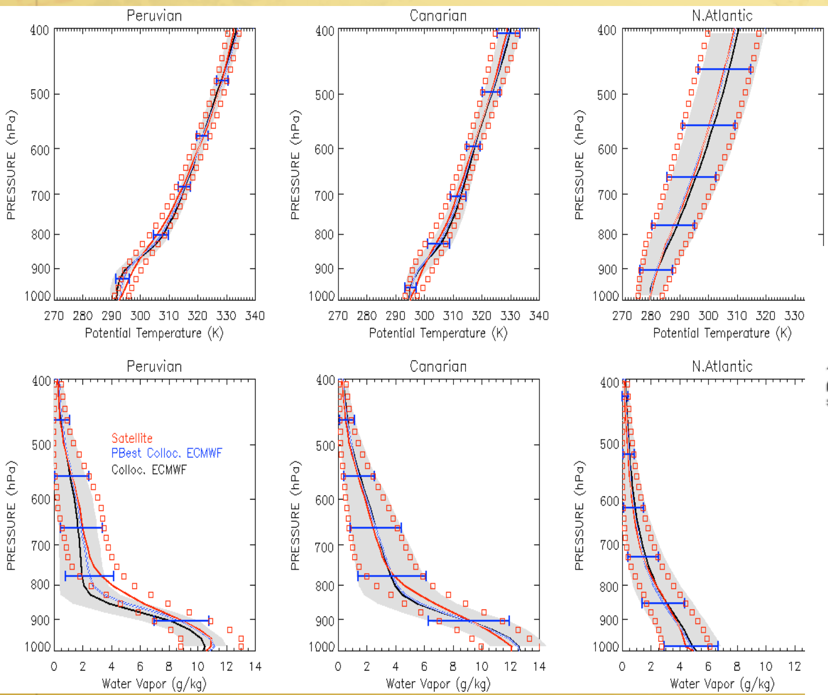
CCF: 0.6~0.9

CCF: 0.9~1.0



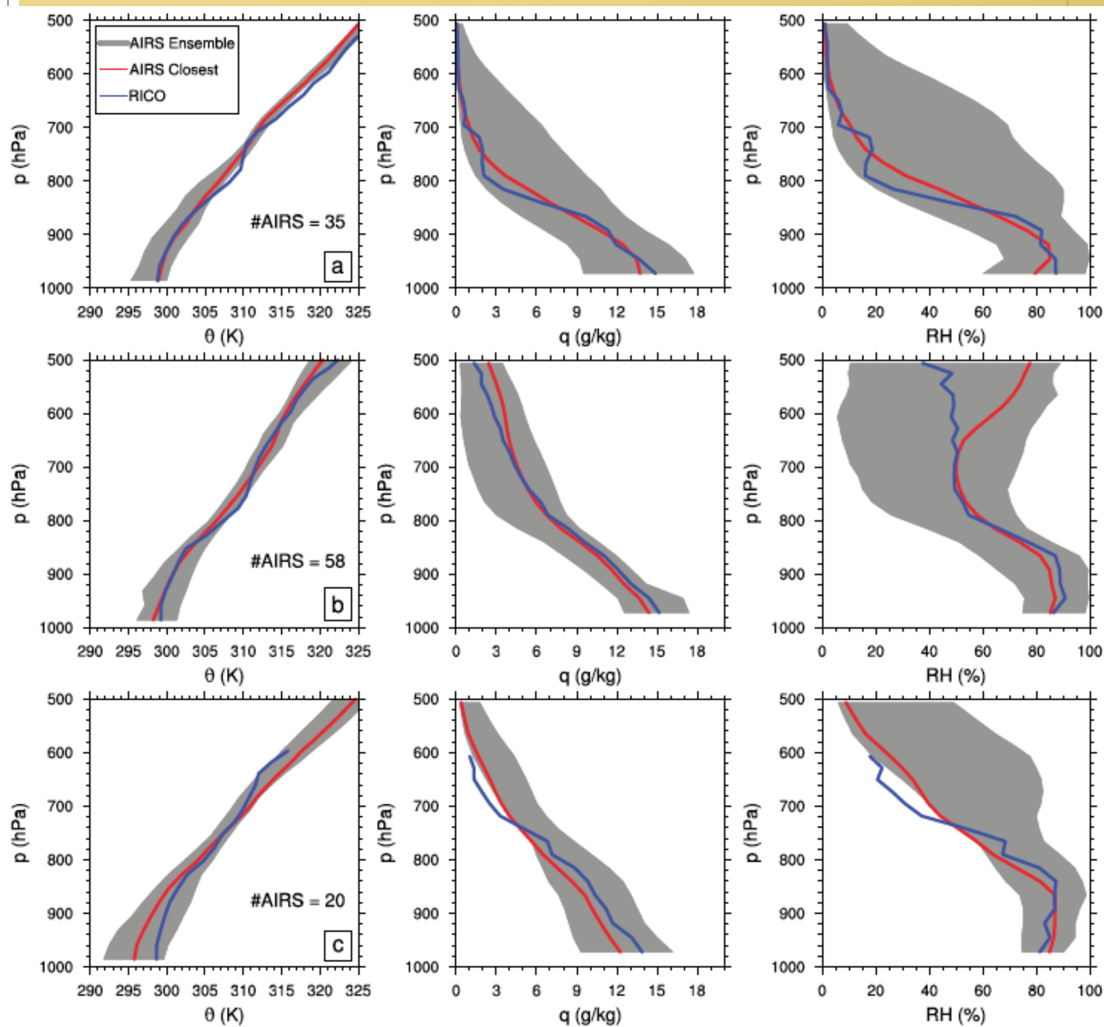
Yue et al. 2011

Smoothed Vertical Profiles from AIRS Retrieval



ECMWF model analysis: Yue et al. 2011

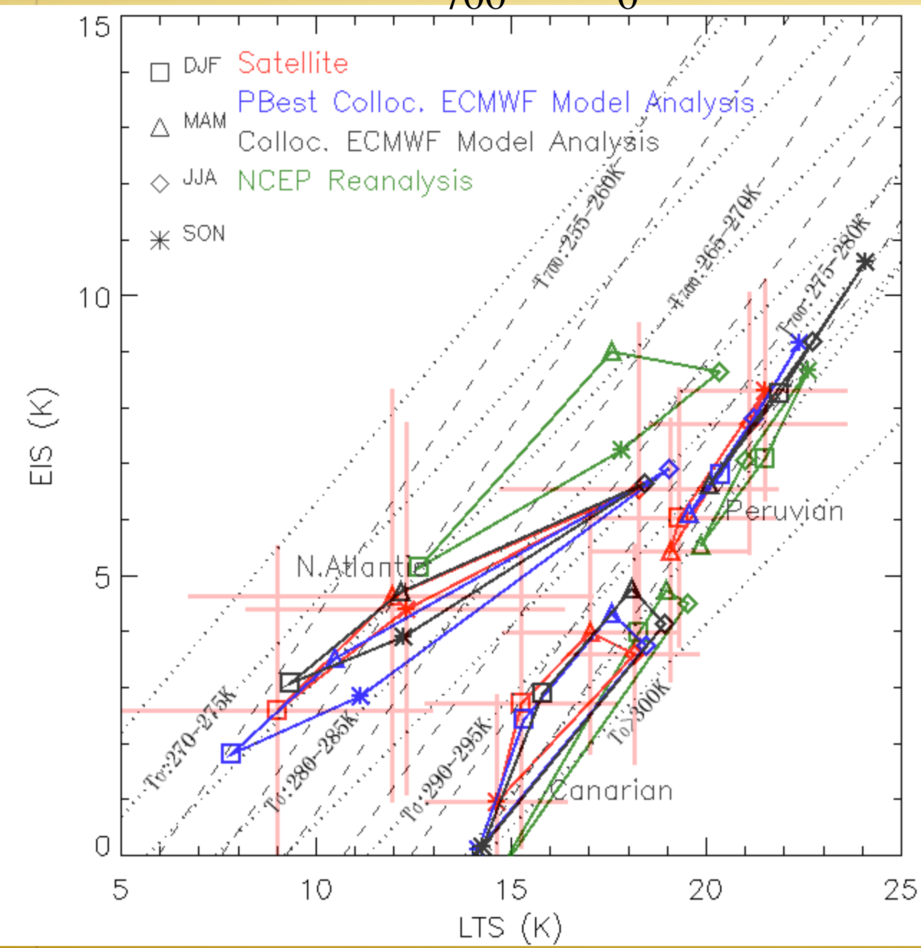
Rawinsonde and dropsonde: Martins et al. 2010



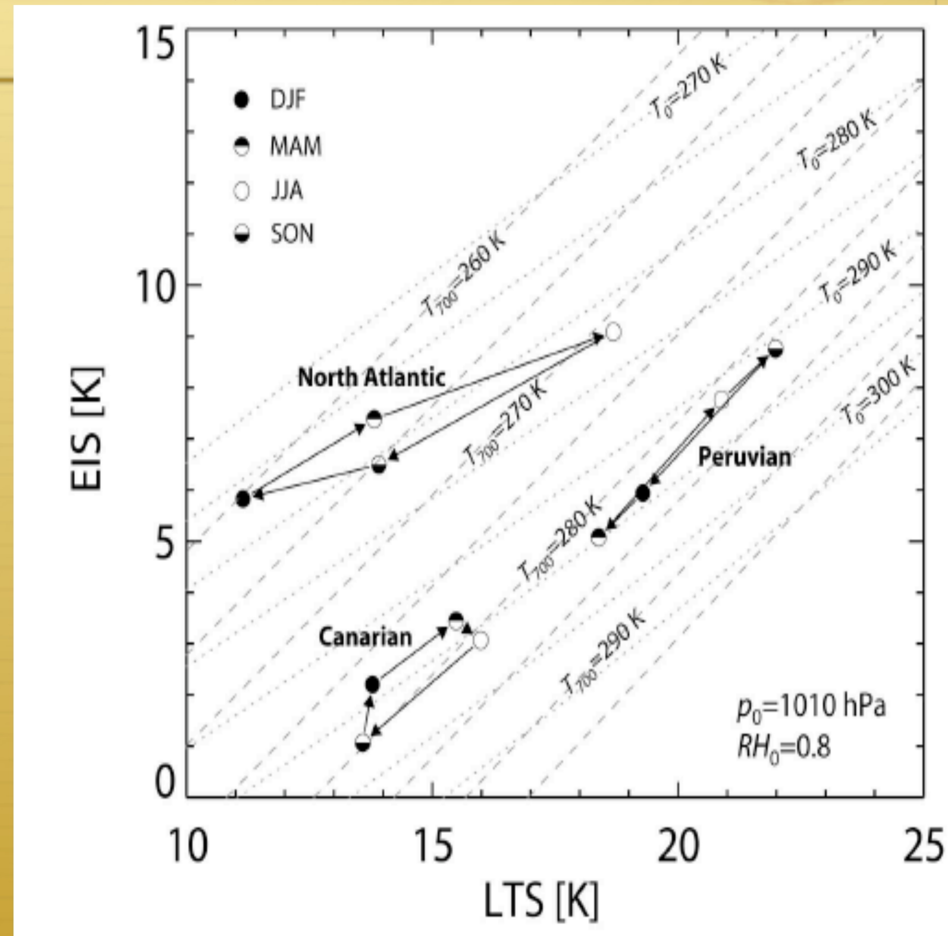
Regional Relationships Between EIS and LTS

N. Atlantic Box has both the lowest Sc frequency and lowest AIRS yield among the three boxes.

$$LTS = \theta_{700} - \theta_0 \qquad EIS = LTS - \Gamma_m^{850}(z_{700} - LCL)$$



EIS and LTS values calculated from AIRS data, collocated ECMWF, and NCEP reanalysis.

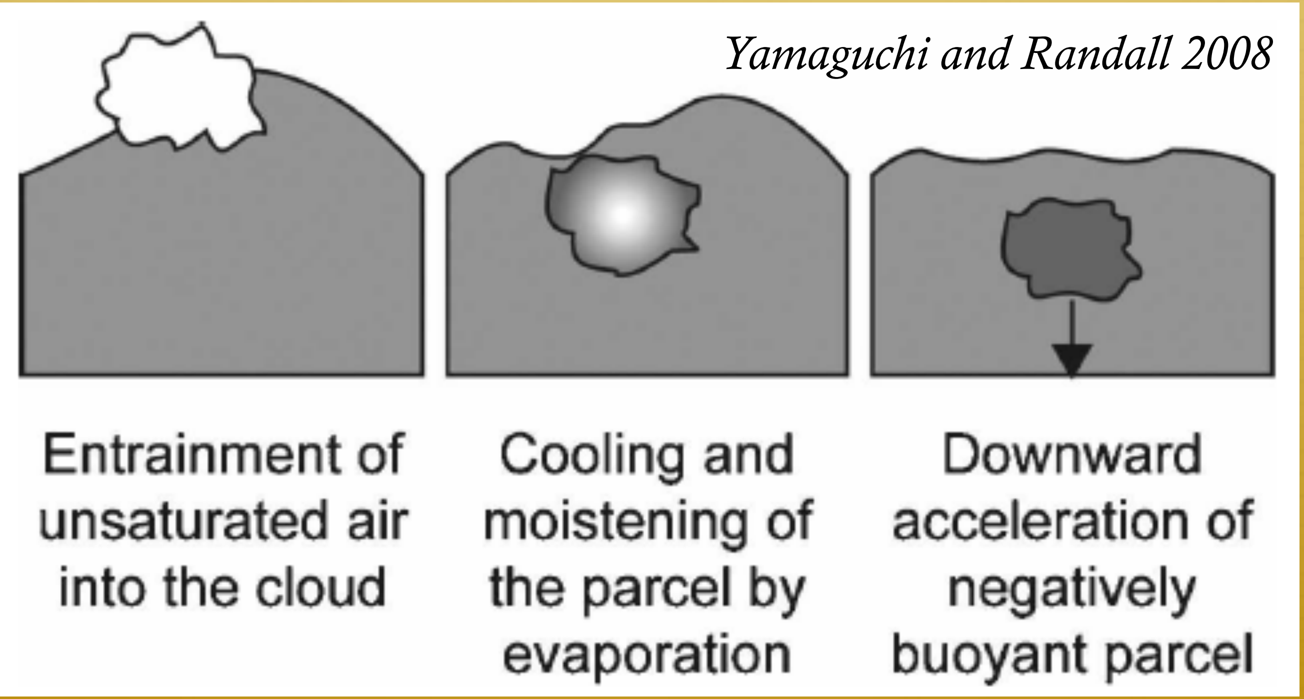


Data are from routine weather observation data in Warren et al. (1986, 1988). Dotted lines are EIS and LTS values derived from NCEP reanalysis (Wood and Bretherton, 2006).

Cloud Top Entrainment Instability (CTEI)

- If a parcel of the upper air is introduced into the cloud layer and mixed by turbulence, evaporation of the cloud droplets into the dry parcel will reduce its temperature. If the mixed parcel reaches saturation at a lower temperature than that of the cloud top it will be negatively buoyant and can then penetrate freely into the cloud mass. In such a case the evaporation and penetration process will occur spontaneously and increase unstably until the cloud is evaporated.

---- Lilly (1968)



CTEI and PBL Transition

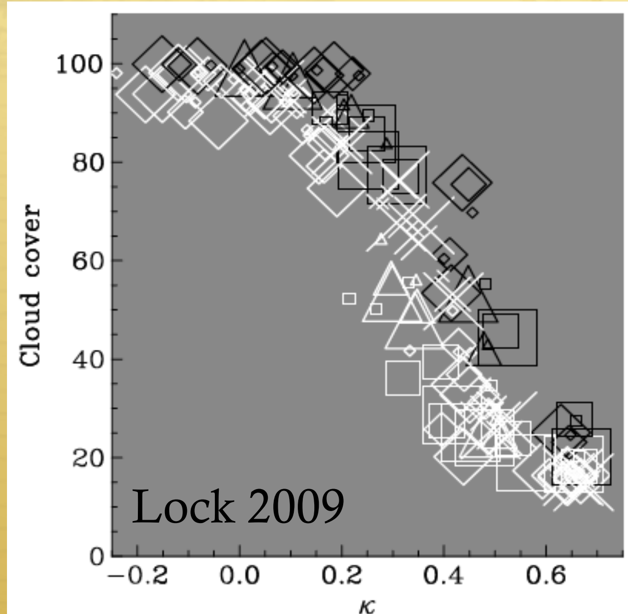
- Kuo and Schubert [1988]:

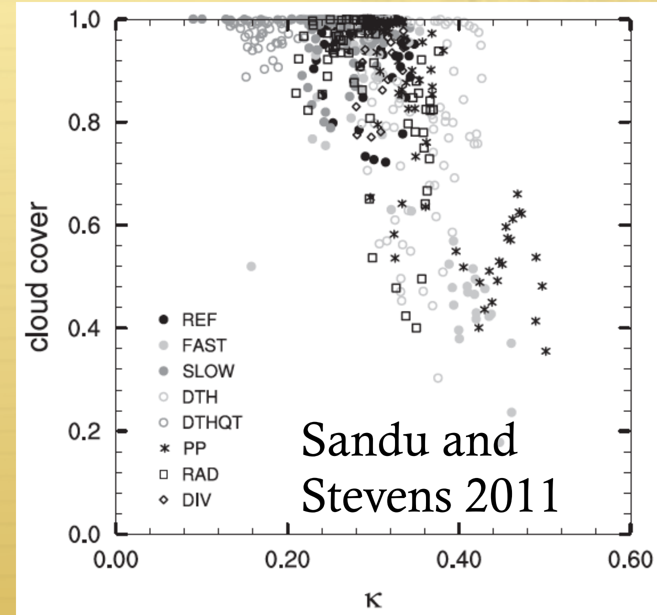
$$\kappa = \frac{\Delta\theta_e}{\left(L/c_p\right)\Delta q_t} > critical\_value$$

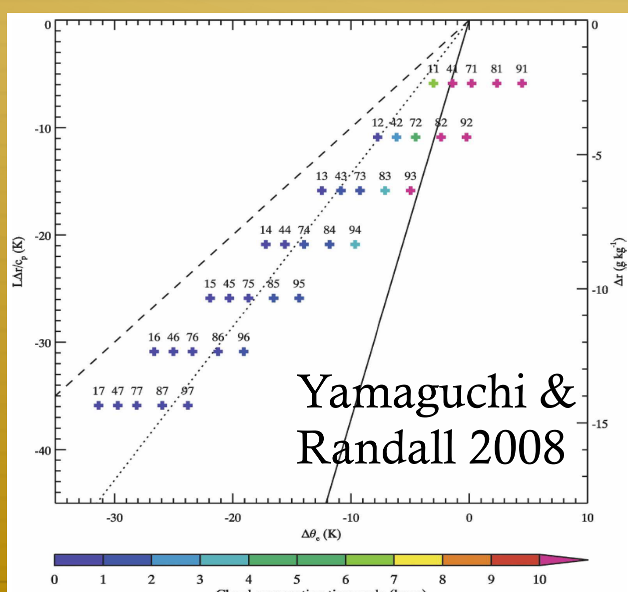
  - κ : CTEI parameter
  - Critical value: 0.23 (KS), 0.7 (MacVean and Mason 1990), 0.6 (Lilly 2002).
- LES: κ ←→MBL cloud fraction

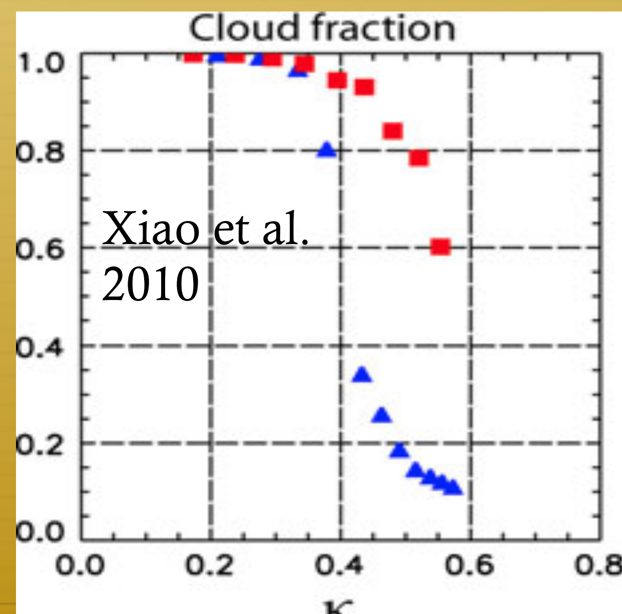
- Conflicting results from both numerical models and in-situ observations!
- Lack of observations and this is the first attempt to use satellite data to look at this.

Examples of Numerical Model Results

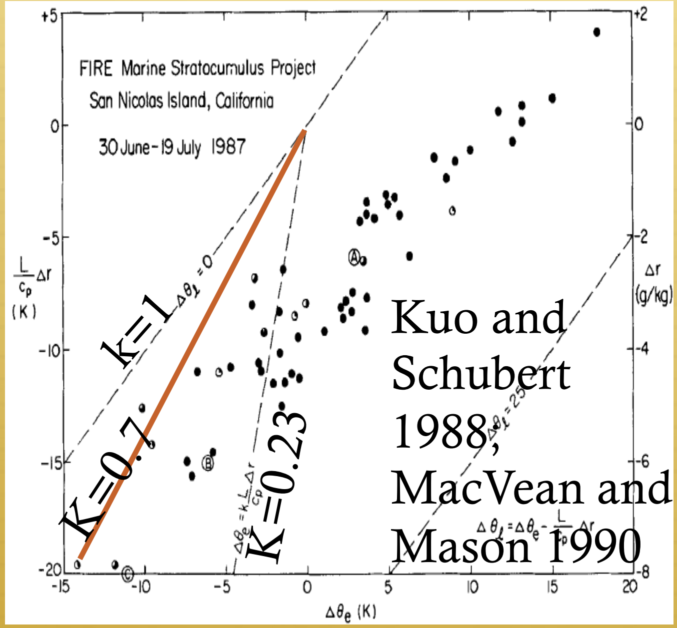


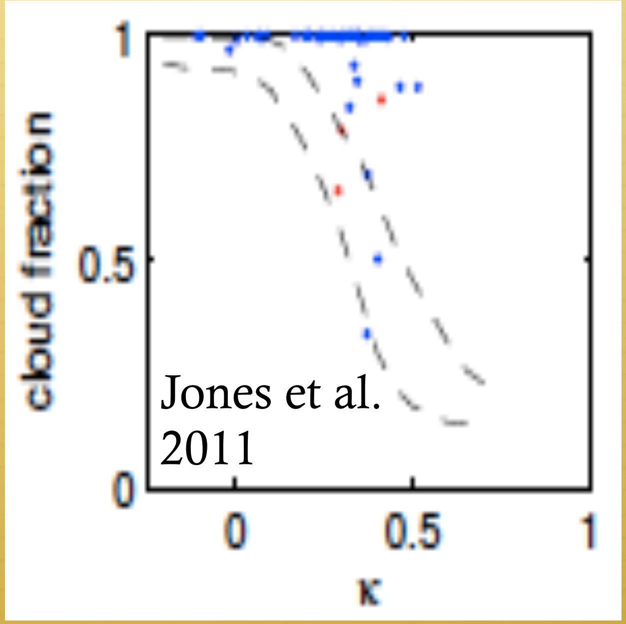






Observations: No satellite observation

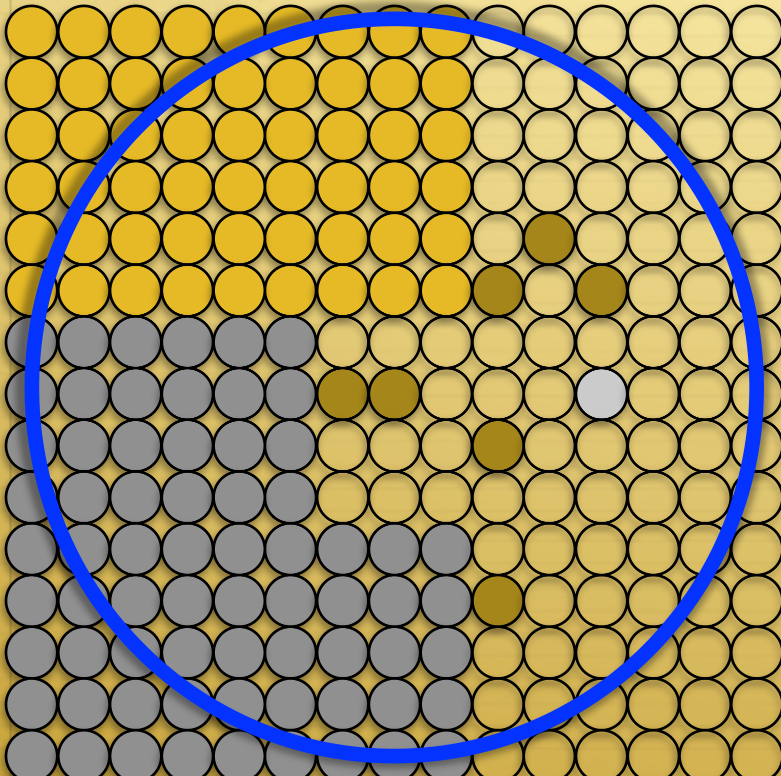


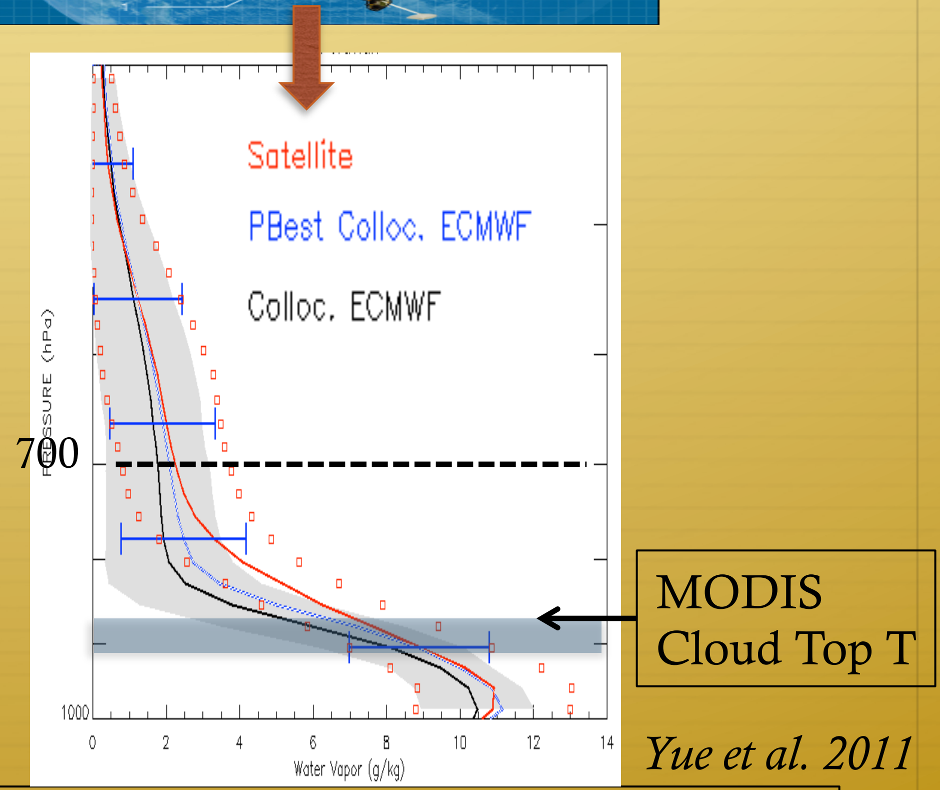


Lack of observations: satellite data may provide some insight

Simultaneous observation of atmosphere and clouds:

collocated MODIS and AIRS/AMSU data in the AIRS/AMSU FoV





Yue et al. 2011

- AIRS/AMSU ~ 45km (Temperature and water vapor profiles on 100 pressure levels)
- MODIS Cloud Fraction Daytime only ~ 1km
- MODIS Level 2 data ~ 5km

- The property jump is calculated from AIRS atmospheric profiles
- No liquid water information

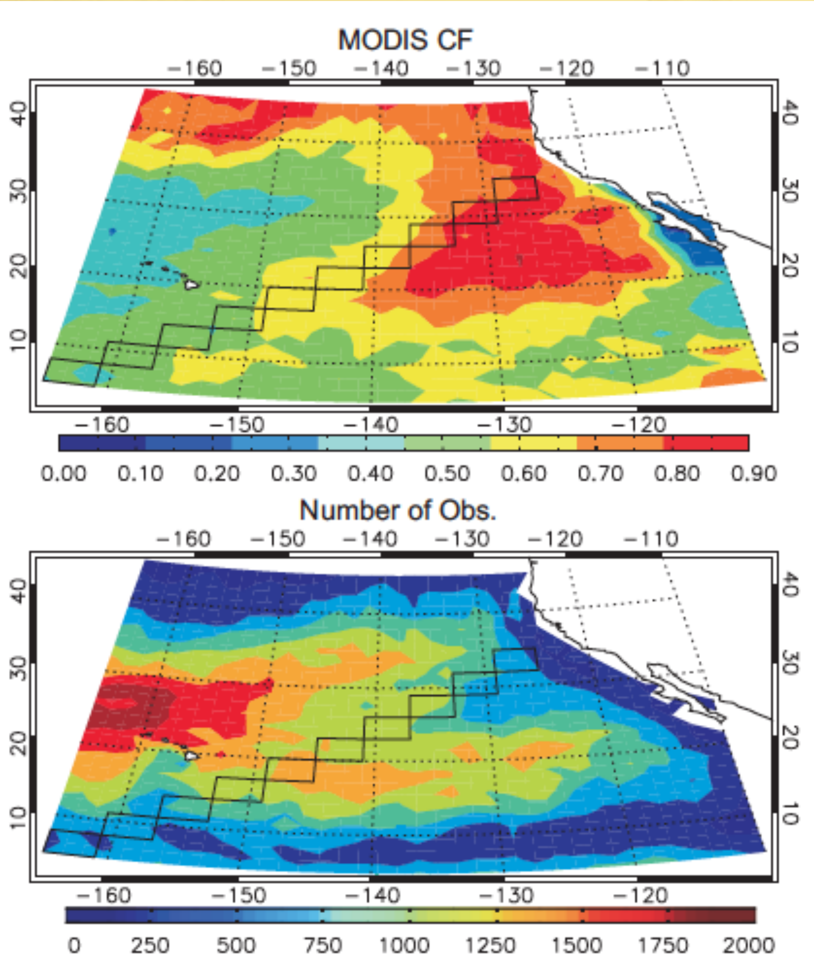
UCLA-LES

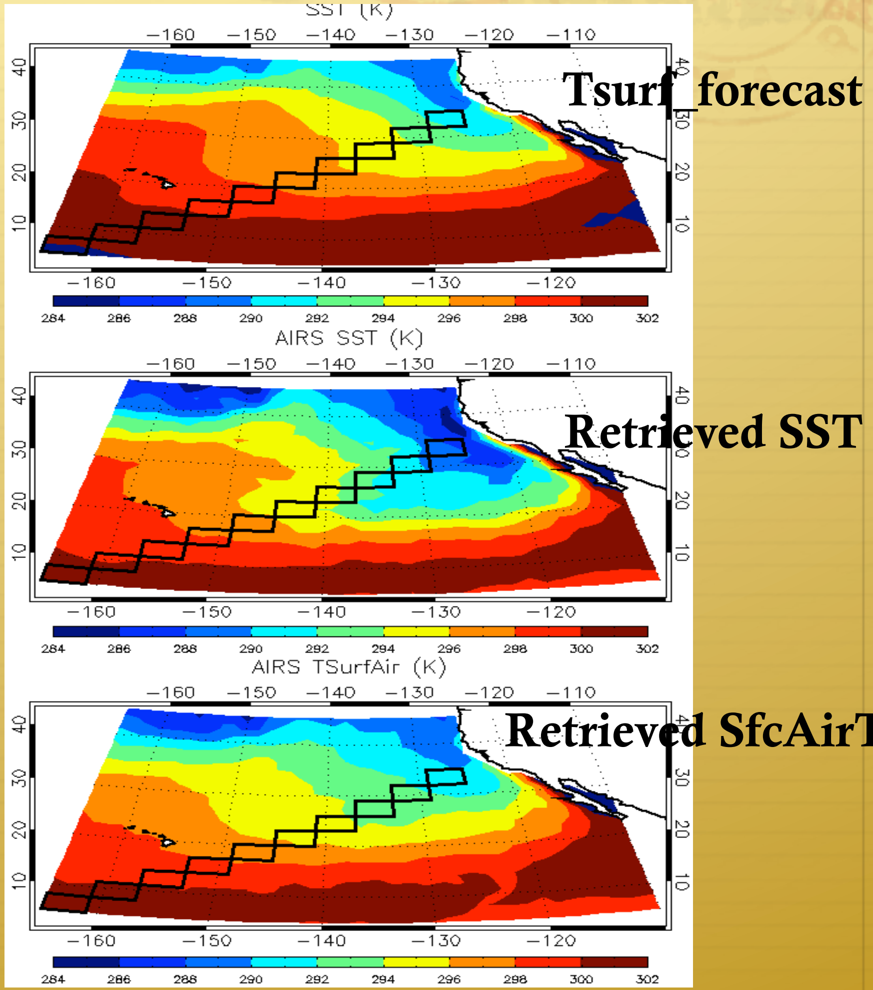
- Stevens et al. 1999, 2005; Stevens and Seifert 2008; Xiao et al. 2010.
- Model set-up:
  - MIXED series: DYCOMS-II RF01 case (Stevens et al. 2005) typical of shallow, well-mixed Sc topped MBL.
  - DECOUPLED series: ATEX (Stevens et al. 2001) generally with high Sc coverage but substantially deeper MBL and decoupled structure.
  - Multiple initial values of κ through varying total water content above cloud.

Single Column Model (SCM)

- Sušělj et al. (2011) developed a 1D SCM for representing moist convective boundary layer.
- Stochastic unified scheme for boundary layer and shallow convection based on eddy-diffusivity/mass-flux approach.
- Model set-up:
  - 20 m vertical resolution
  - Control case: ASTEX stratocumulus experiments (Duynkerke 1998), SST=293 K
  - Perturbed simulations: Step function increase of SST (2, 4, 6, 8, 10 K from control simulation), 5 days simulations until steady state has been reached

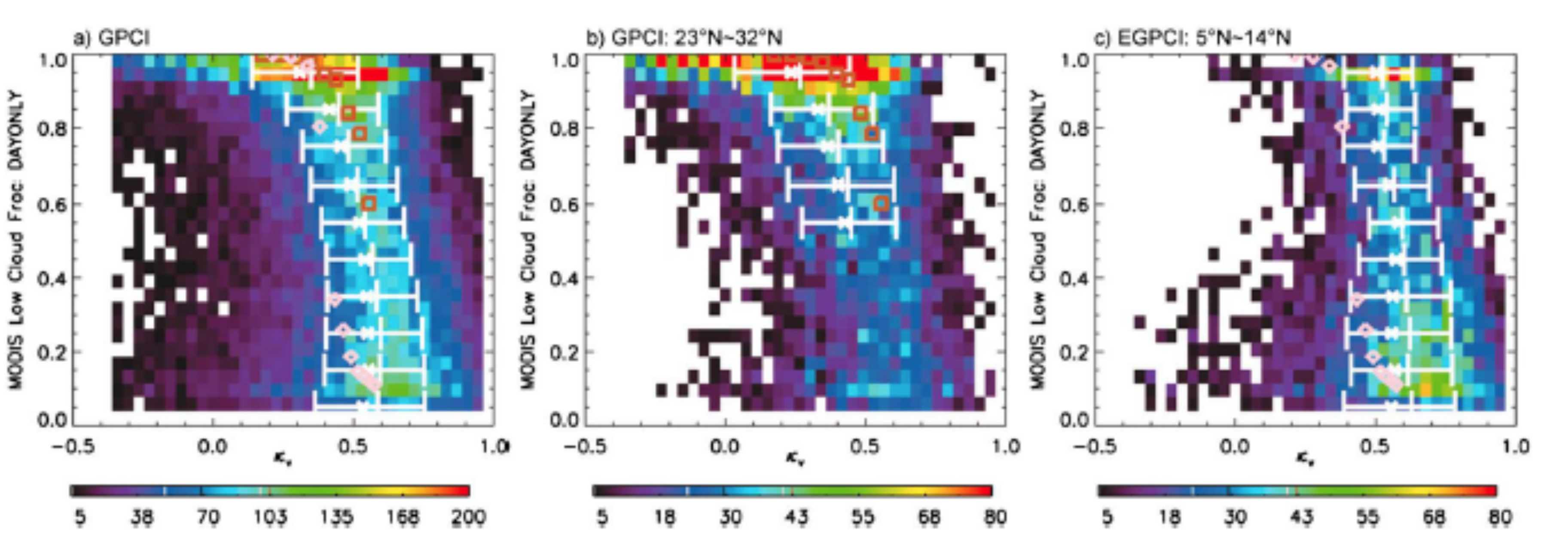
SST, CF and Number of Data Points





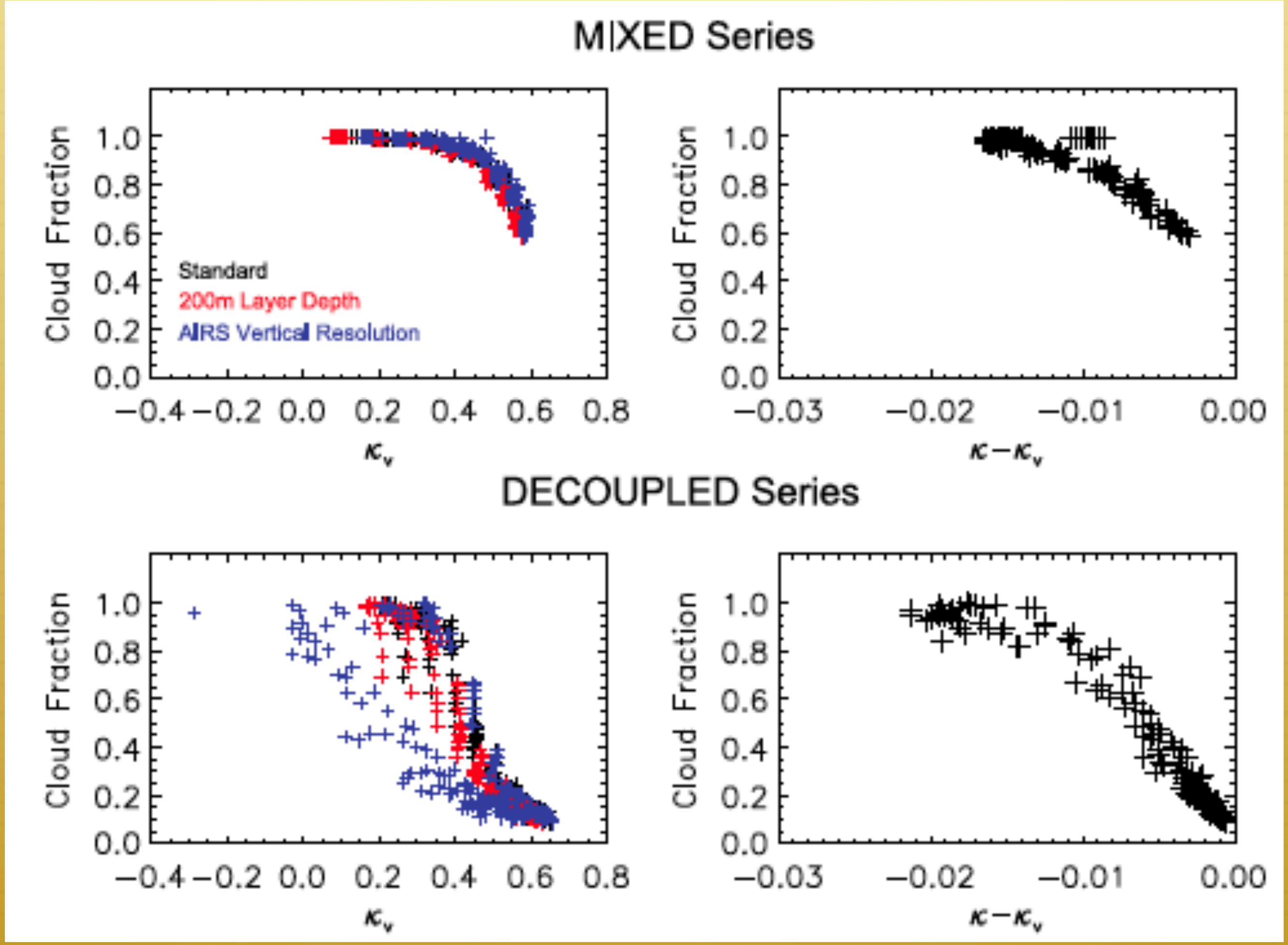
RTG SST collocated with AIRS FOV (right), mean MODIS cloud fraction (top left), the number of observations (bottom left) used from 01 July 2009 to 31 August 2009. Ten boxes of the GPCI transect are also shown in black.

Cloud Fraction and k: from satellite and LES

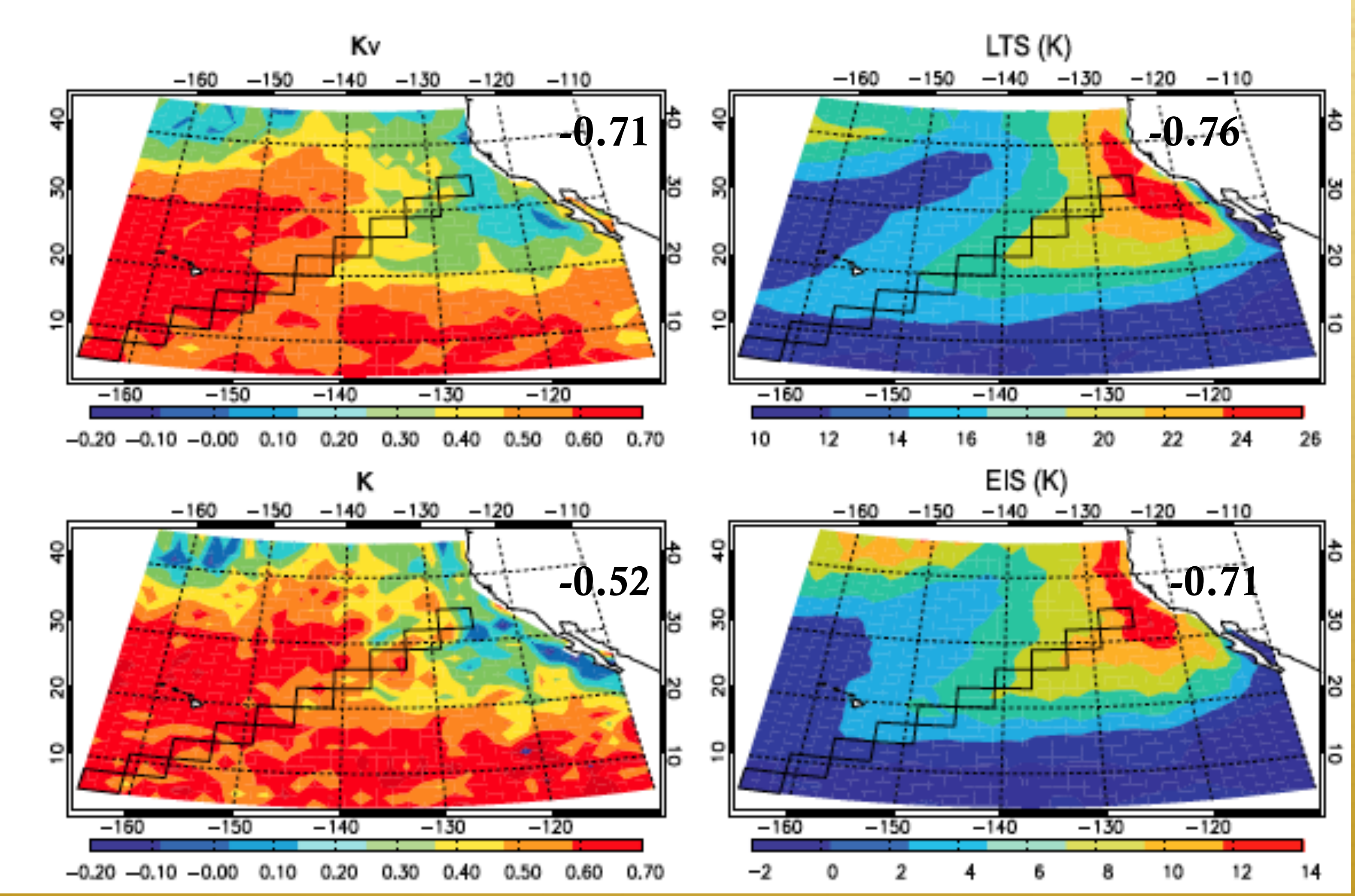


Correlation Coefficients with CF	All	MIXED	DECOUPLED
Pearson (r)	0.66	0.87	0.91
Spearman Rank (ρ/R)	0.65/0.0018	1.0/0.0	0.84/0.0013

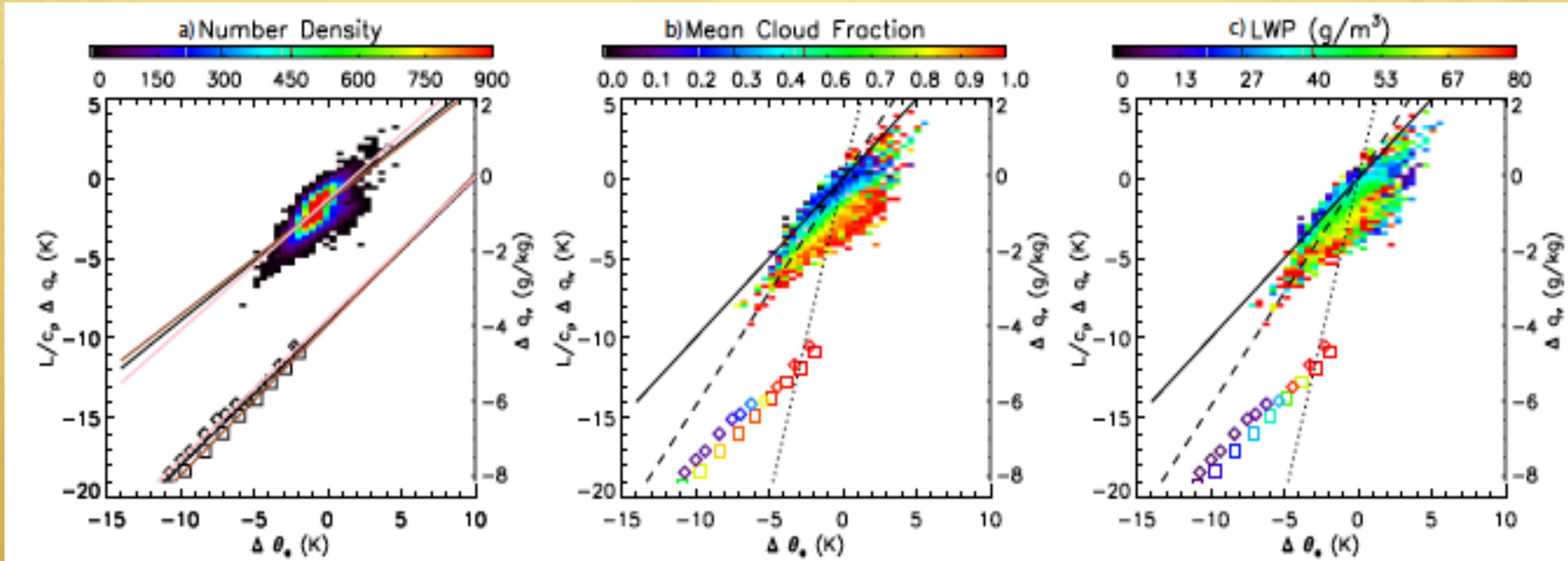
Sensitivity to Layer Depth and Liquid Water



Spatial patterns of Cloud Fraction and k



CTEI Diagram



Brown: MIXED
Pink: DECOUPLED

$$\kappa_{KS} = \frac{(1+\gamma)c_p\theta_0 / L}{1+(1+\delta)\gamma c_p\theta_0 / L} \approx 0.23 \quad \kappa_{MM} = \frac{[1+\gamma]\left[\theta_0 + \frac{L}{c_p}\left(1-\delta\frac{c_p\theta_0}{L}\right)\right]}{2\frac{L}{c_p} + \left(\frac{L}{c_p\theta_0} + 1 + \delta\right)\theta_0\gamma}$$

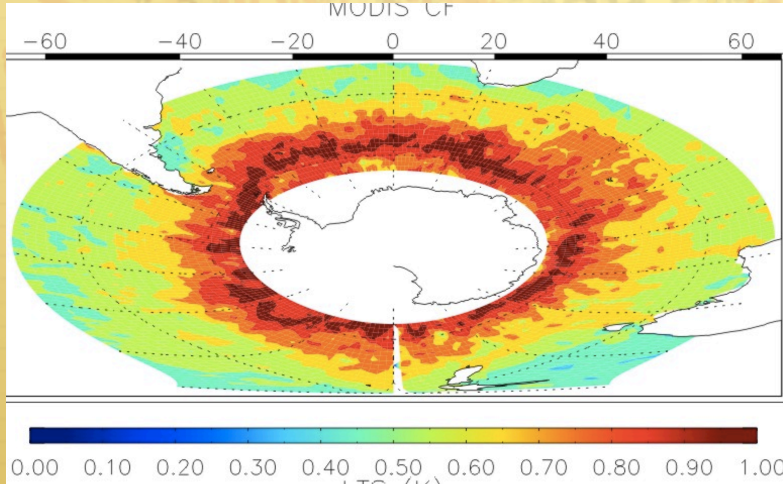
$$\kappa = \bar{\kappa}_{KS} = 0.25 \pm 0.026 \quad \kappa = \bar{\kappa}_{MM} = 0.70 \pm 0.02$$

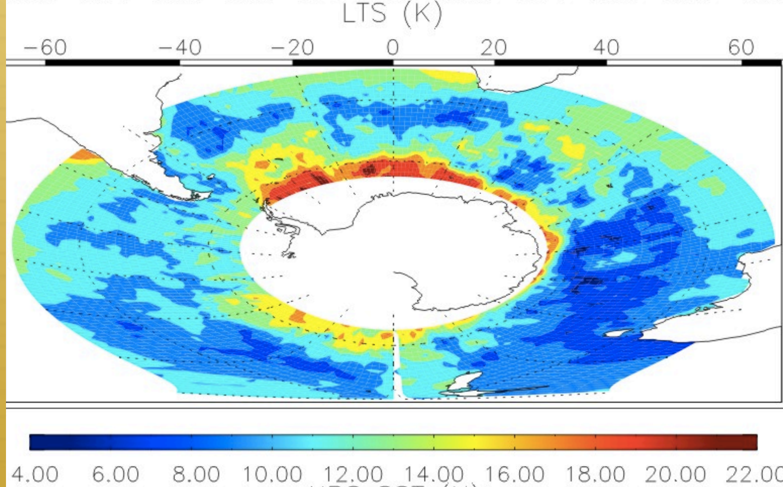
Summary

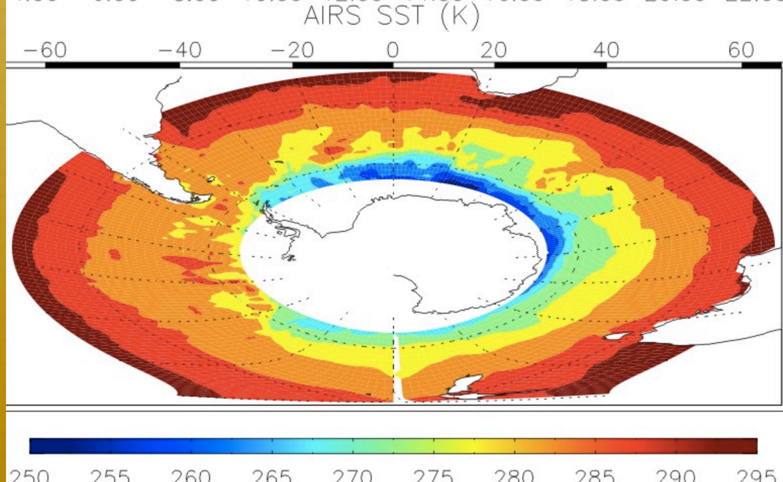
- We examined the strength and limitations of using AIRS thermodynamic profiles combined with satellite cloud observations to study MBL characteristics.
- We investigated the impact of satellite data limitation on Sc cloud scenes and transition of cloud-topped MBL
- From these snapshot-type observations, we find there is a correlation between the MBL cloud fraction and κ, which agrees with LES and SCM simulations.
- However, wide spread in the data indicates the effect from other physical processes (?) and limited satellite vertical resolution, which requires further study.

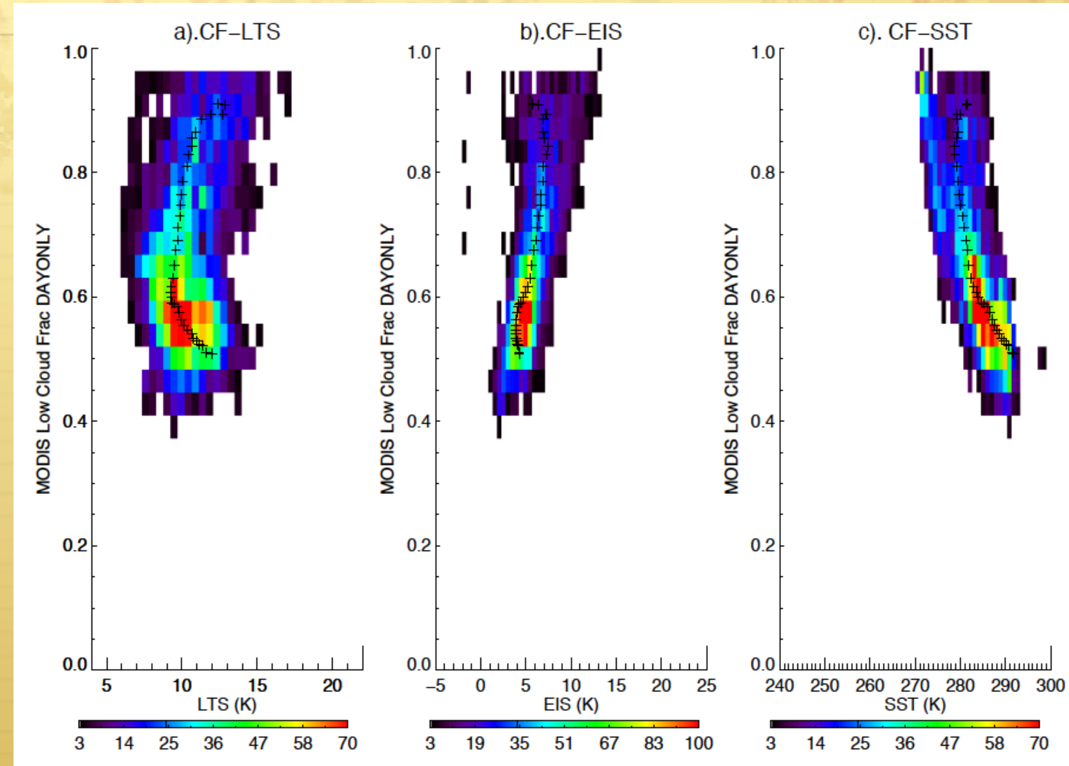
Discussion and Limitations

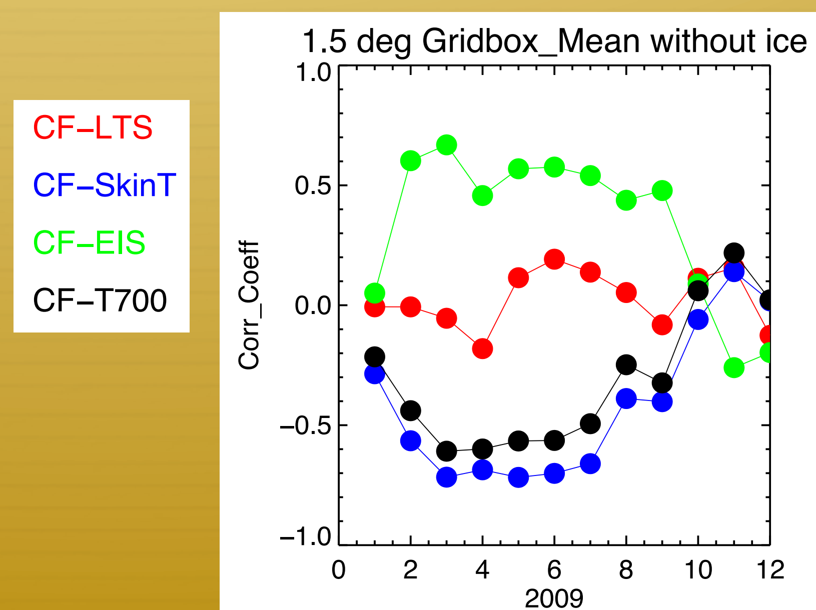
- Limited vertical resolution and lower sampling rate under stratocumulus condition in the AIRS L2 retrievals (Yue et al. 2011, Martins et al. 2010)
- Uncertainty of MODIS cloud product and impact on our study
- Lacking information on in-cloud liquid water vertical distribution and accurate water vapor measurement below the cloud
- K is related to the time scale of the cloud transition, satellite?
- More detailed model studies are necessary so that we can understand the potential and limit of using current satellite data on MBL studies.


MODIS CF
−60 −40 −20 0 20 40 60
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00


LTS (K)
−60 −40 −20 0 20 40 60
4.00 6.00 8.00 10.00 12.00 14.00 16.00 18.00 20.00 22.00

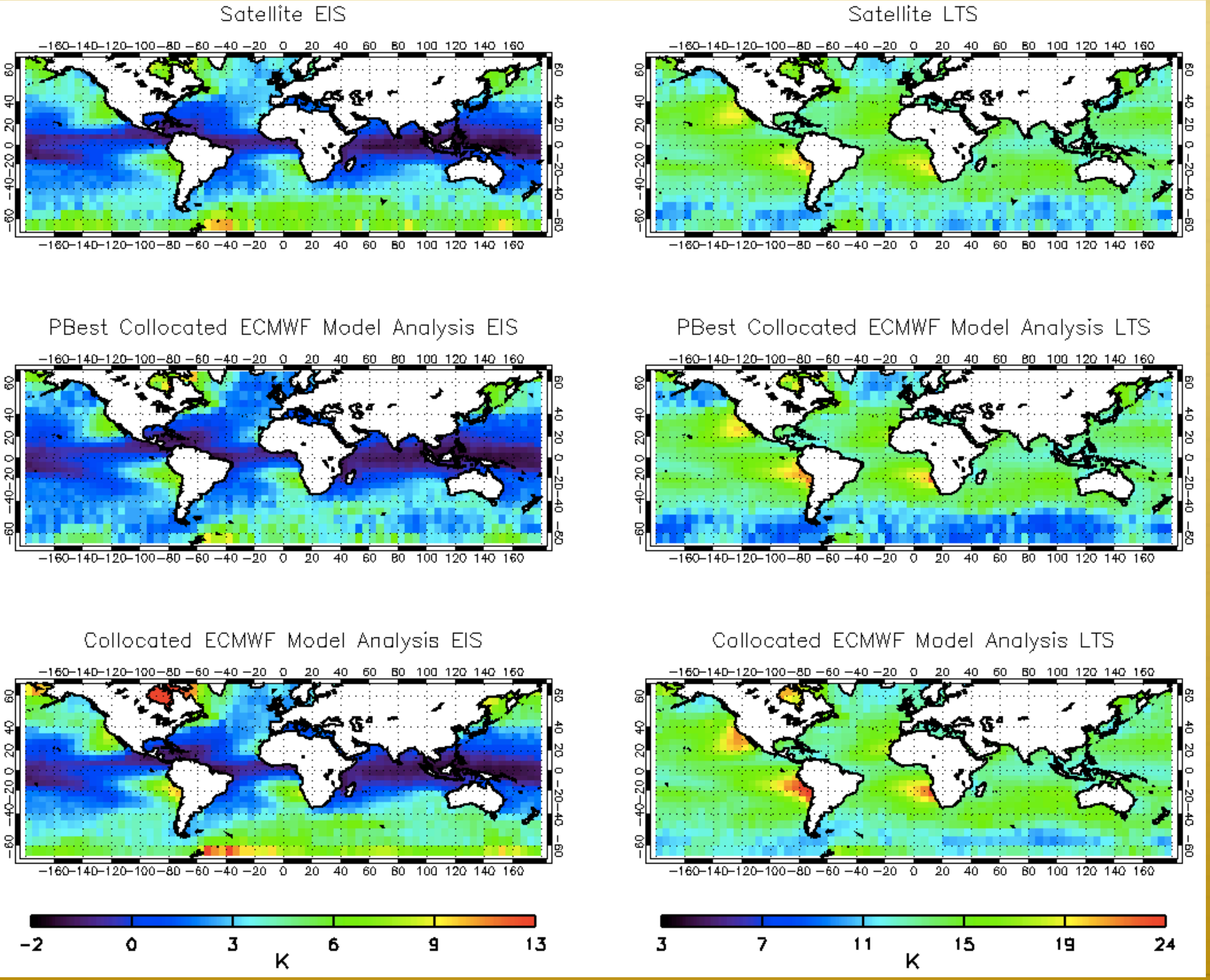

AIRS SST (K)
−60 −40 −20 0 20 40 60
250 255 260 265 270 275 280 285 290 295


a).CF−LTS
b).CF−EIS
c). CF−SST
MODIS Low Cloud Frac DAYONLY
LTS (K)
EIS (K)
SST (K)
3 14 25 36 47 58 70
3 19 35 51 67 83 100
3 14 25 36 47 58 70

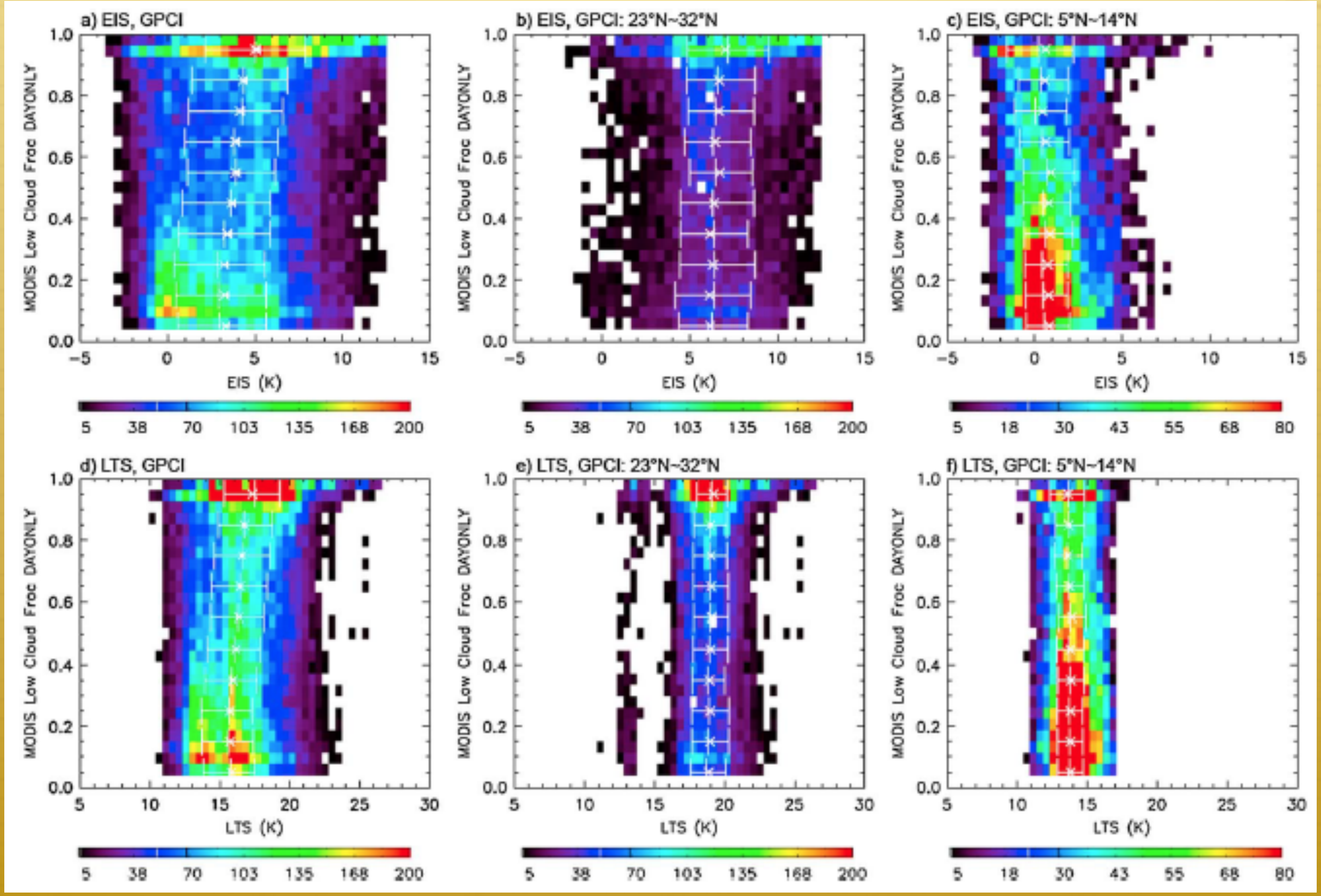

CF−LTS
CF−SkinT
CF−EIS
CF−T700
1.5 deg Gridbox_Mean without ice
Corr_Coeff
2009

EIS and LTS From AIRS and ECMWF

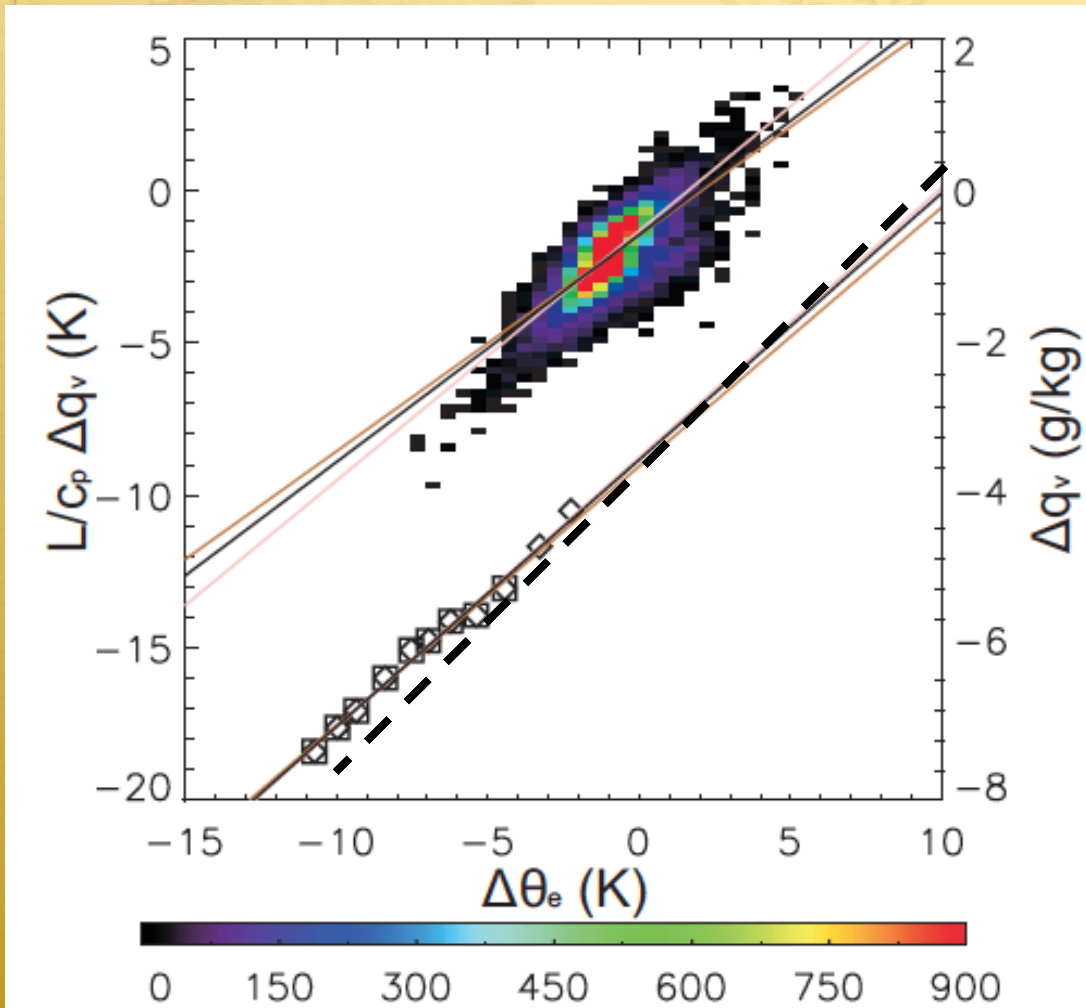
Both sampling bias and smoothed vertical structure contribute to the 1~3 K difference in Stratocumulus regime between AIRS and ECWMF, in which the sampling bias dominates.

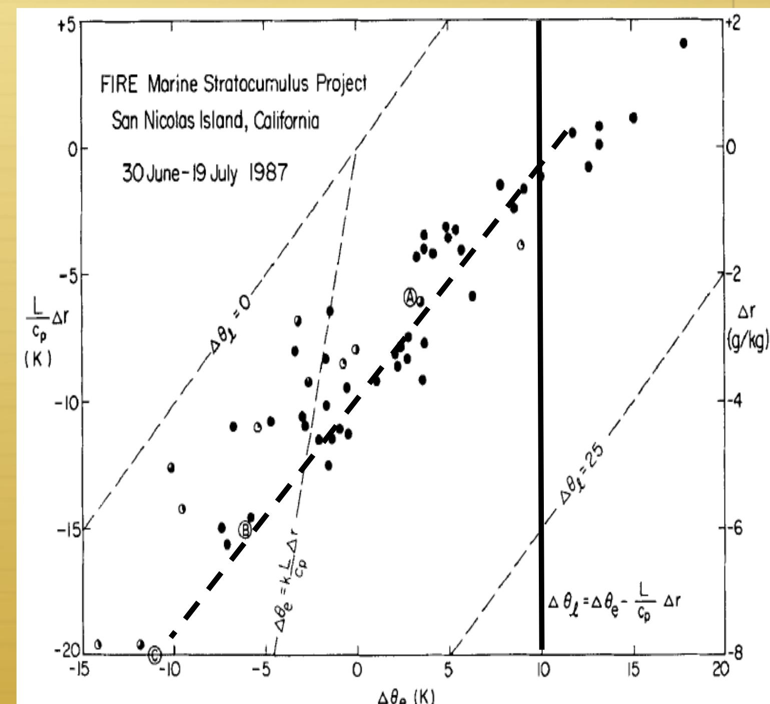


Cloud Fraction and EIS/LTS from Instantaneous Obs.



CTEI Diagram

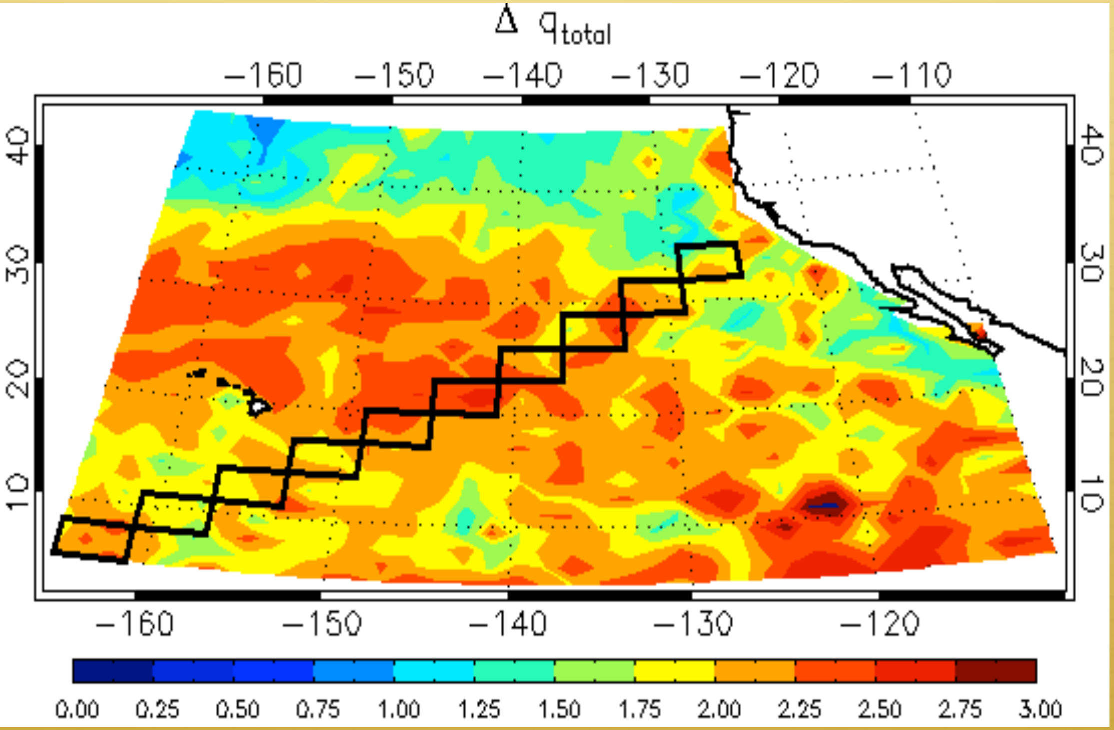




- AIRS underestimates the magnitudes of $\Delta\theta_e$ and Δq_v due to limited vertical resolution.
- Similar slopes (obs: 0.75; LES: 0.87): κ as a ratio between the property jumps, is less affected by the resolution issue.

Looking at Decoupling Rate from AIRS?

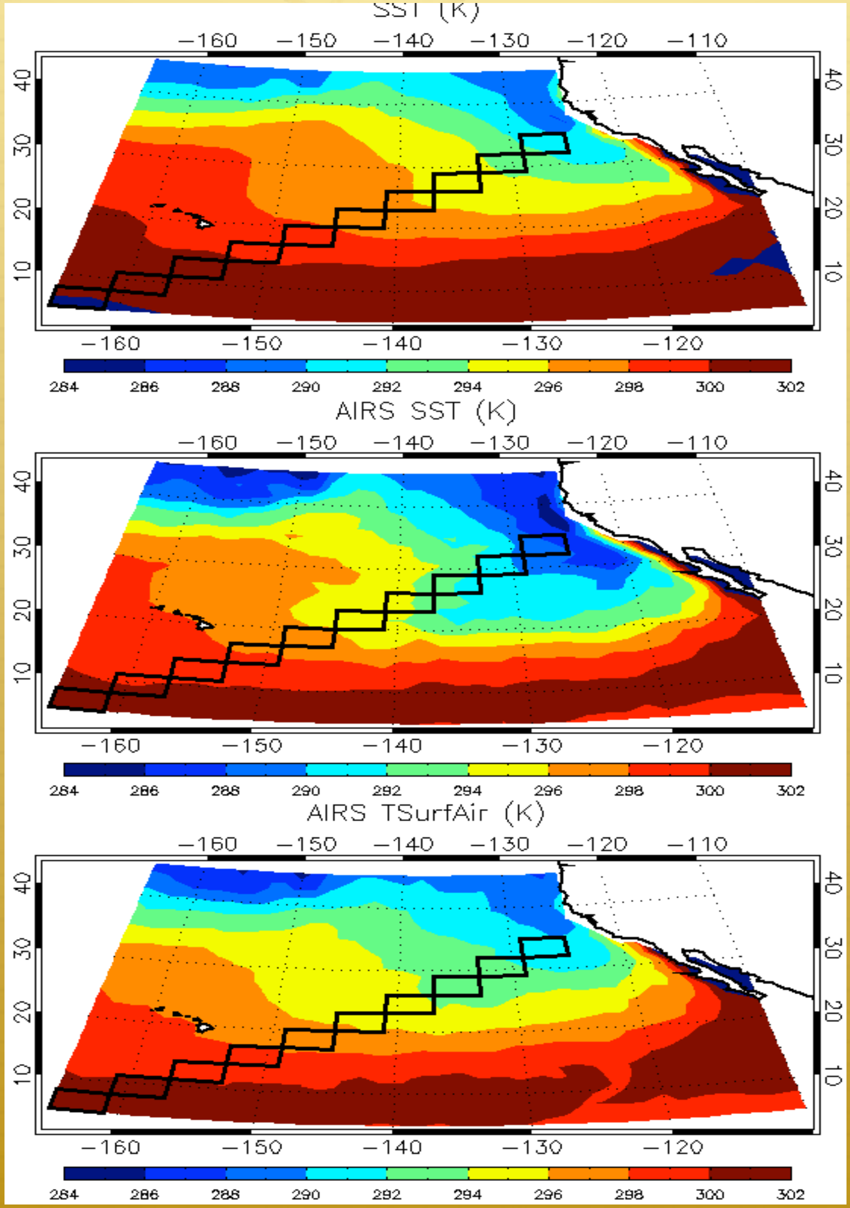
Need better water vapor measurements below the cloud!!!
Need accurate cloud liquid water content measurements!



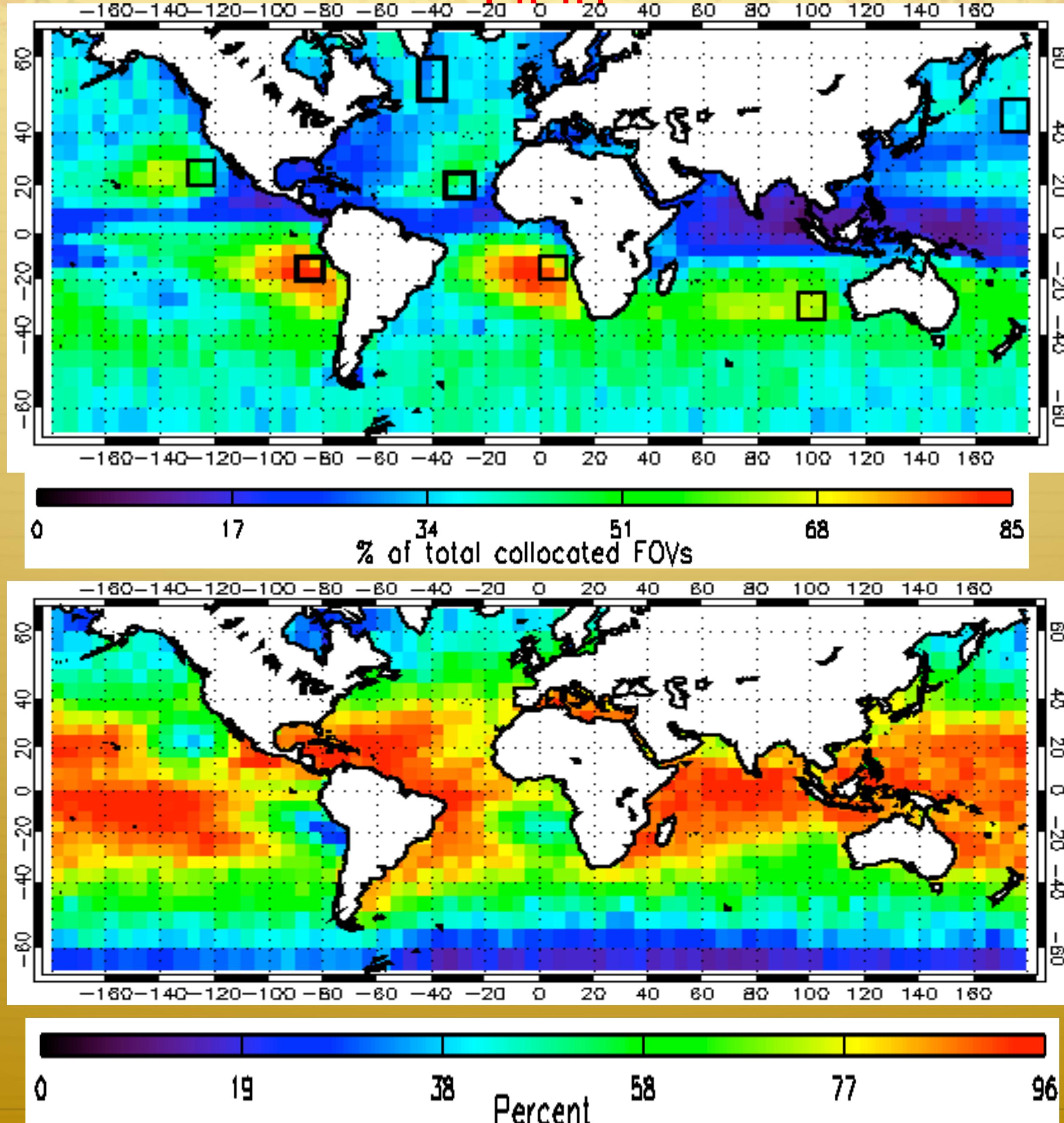
$\Delta q_{total} = q_{total}$ (bottom 25%) – q_{total} (top 25%)

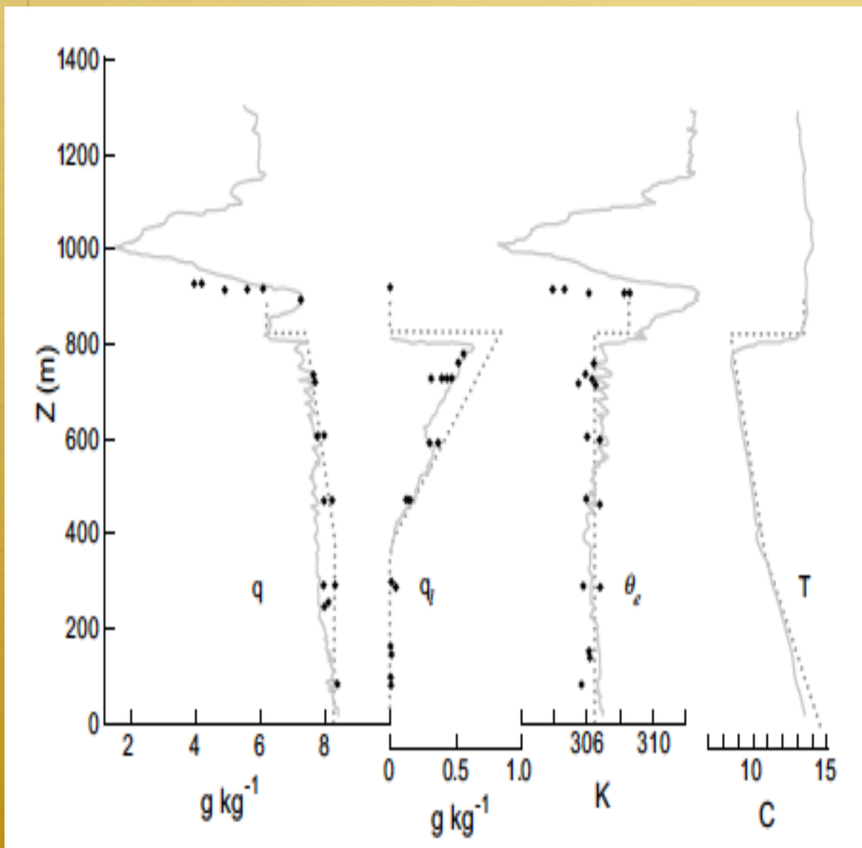
(Jones et al. 2011)

AIRS Cloud-State-dependent Sampling

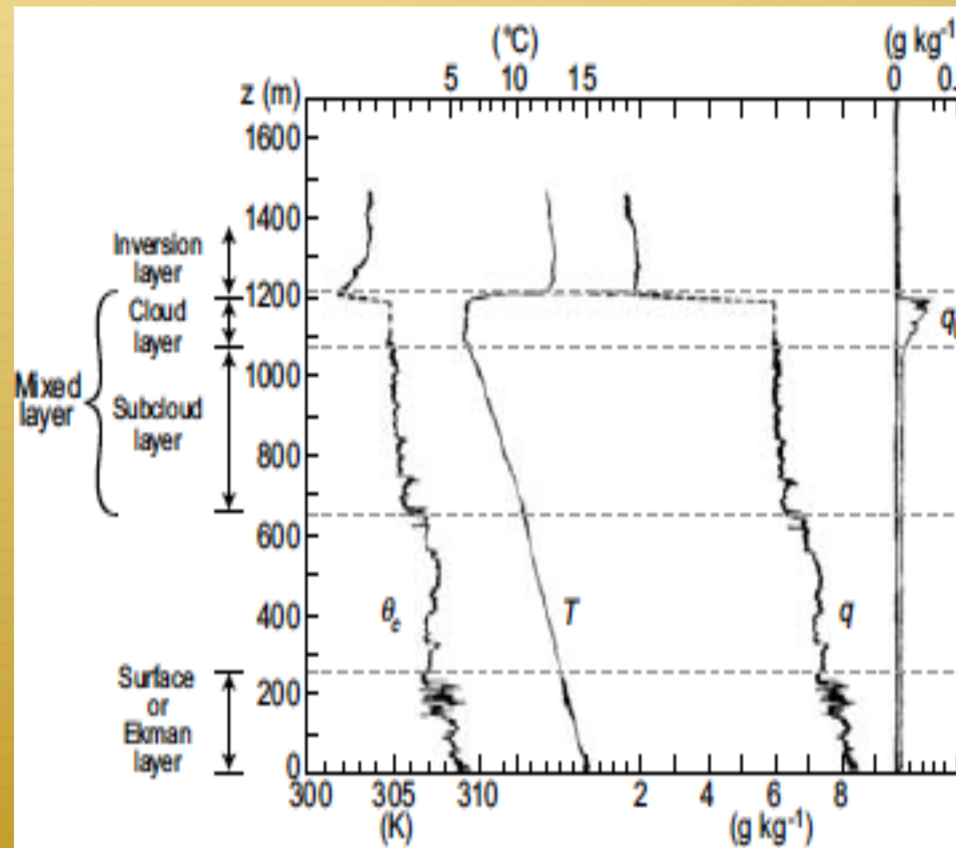


of Shallow Oceanic Clouds Events and AIRS Yield



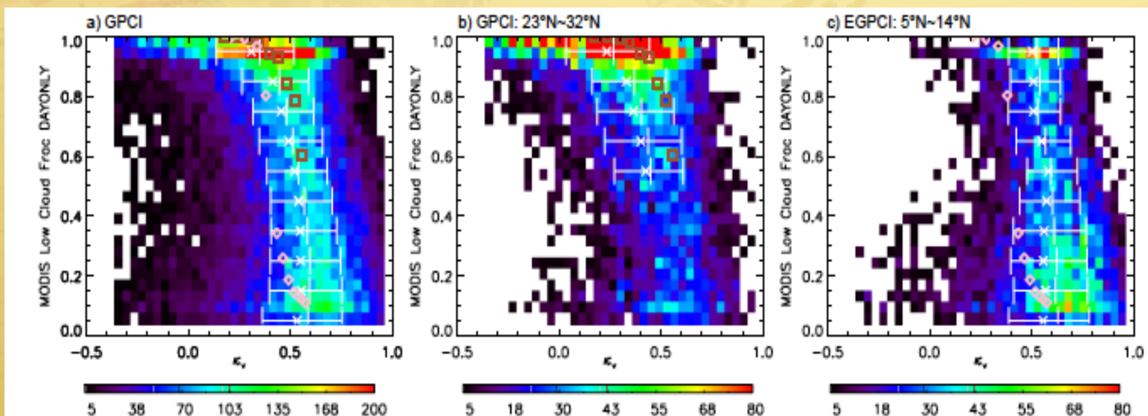


Z (m)
q
q_l
θ_e
T
g kg⁻¹
g kg⁻¹
K
C

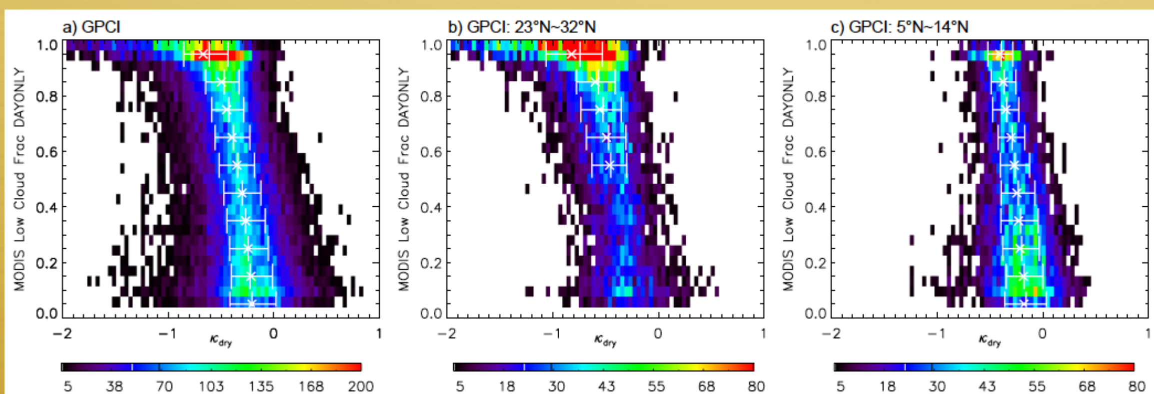


(°C)
(g kg⁻¹)
z (m)
Inversion layer
Cloud layer
Subcloud layer
Mixed layer
Surface or Ekman layer
θ_e
T
q
q_L
(K)
(g kg⁻¹)

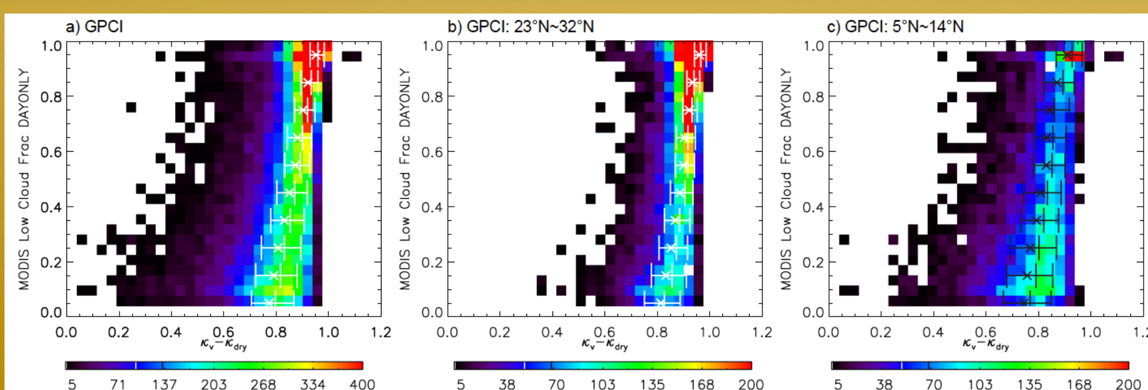
Uncertainty in the MODIS Cloud Top Pressure?



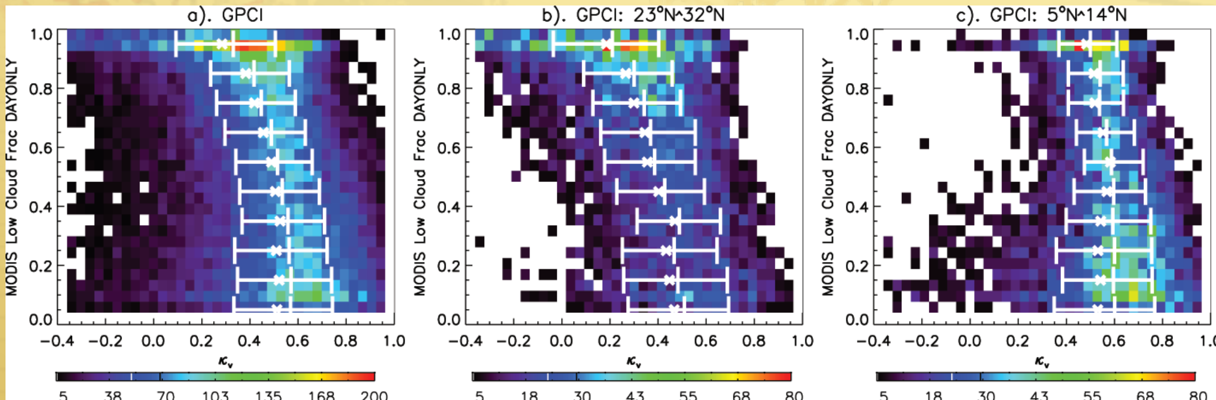
$$\kappa \cong \kappa_v \approx \kappa_{dry} + \frac{1}{\Pi}\left(1 - \frac{R_d}{c_p p}\frac{\Delta p}{\Delta q_v}\right)$$



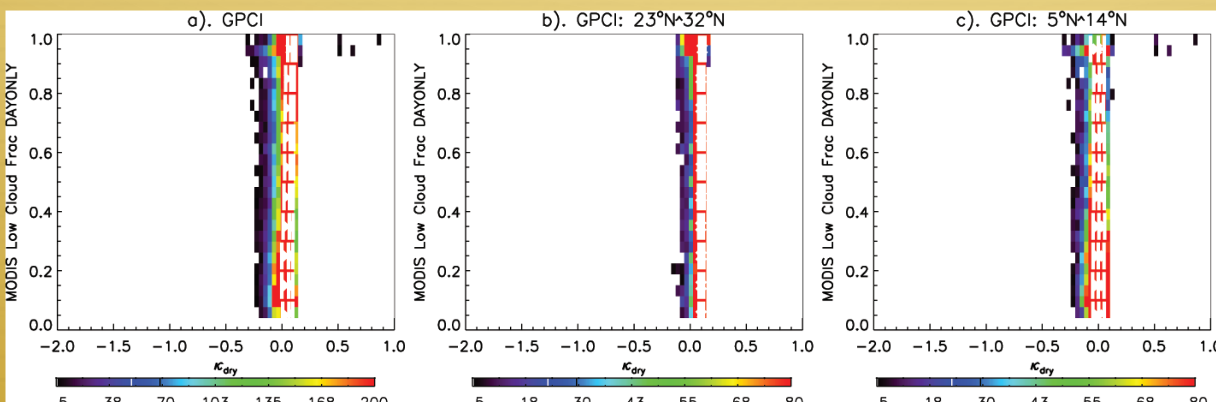
$$\kappa_{dry} \equiv \frac{\Delta\theta}{\left(L/c_p\right)\Delta q_v}$$



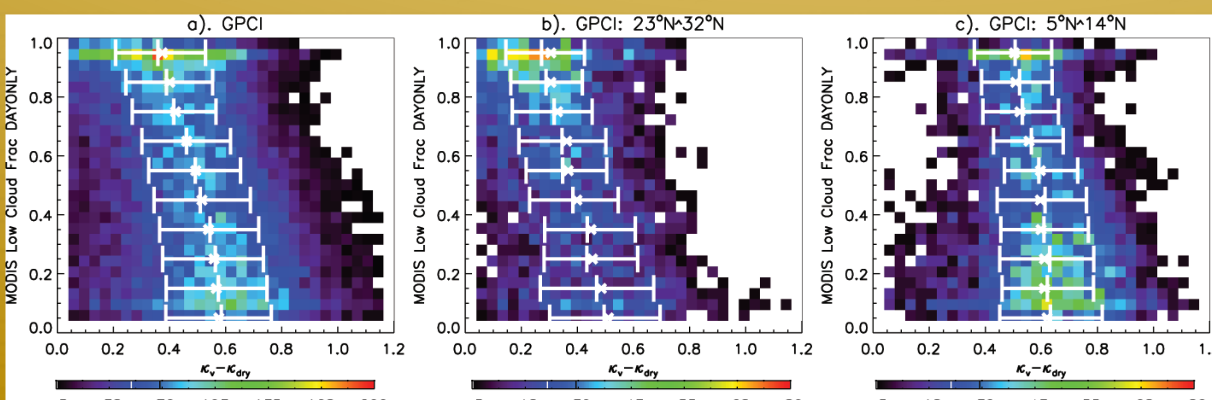
$$\kappa_{\text{v}} - \kappa_{\text{dry}}$$



κ_{v}

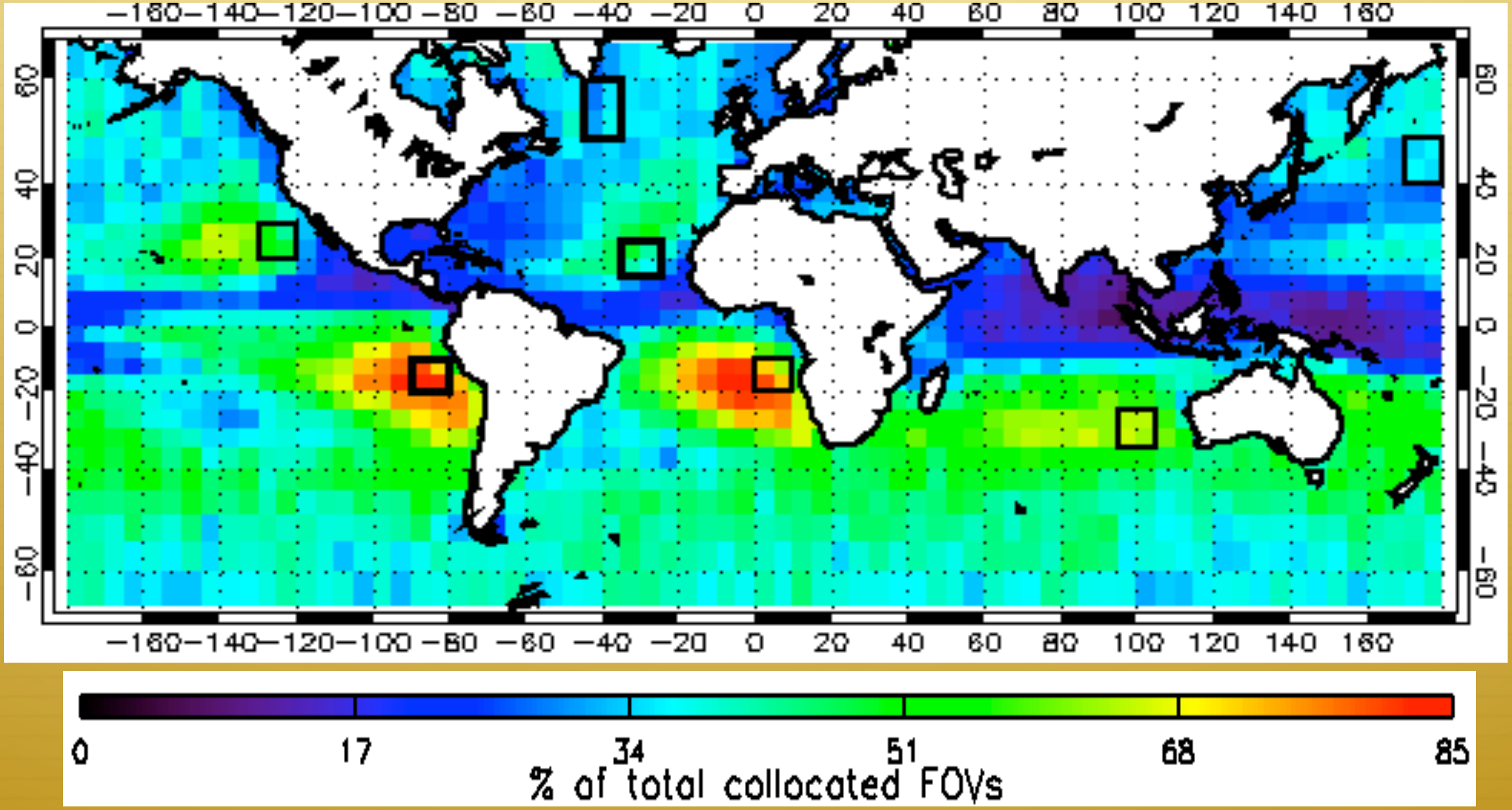


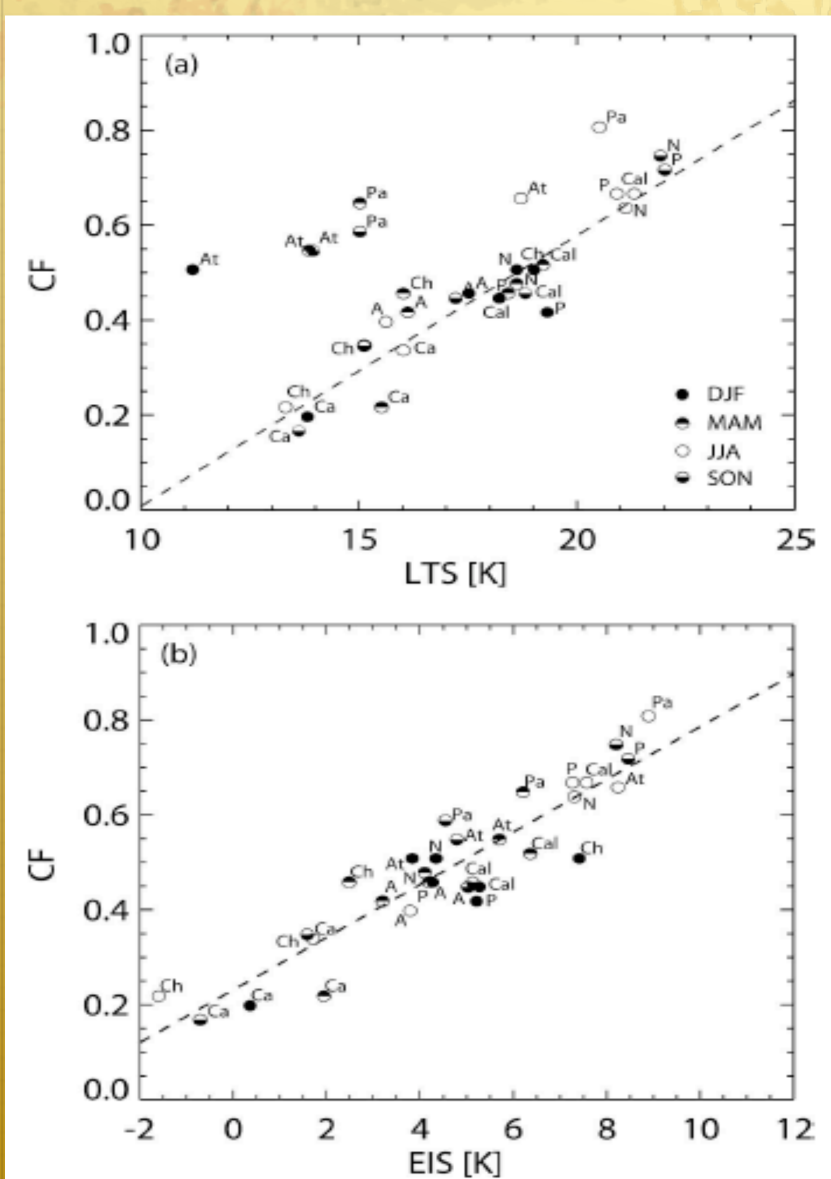
κ_{dry}



$\kappa_{v} - \kappa_{dry}$

CloudSat Sc Frequency of Occurrence

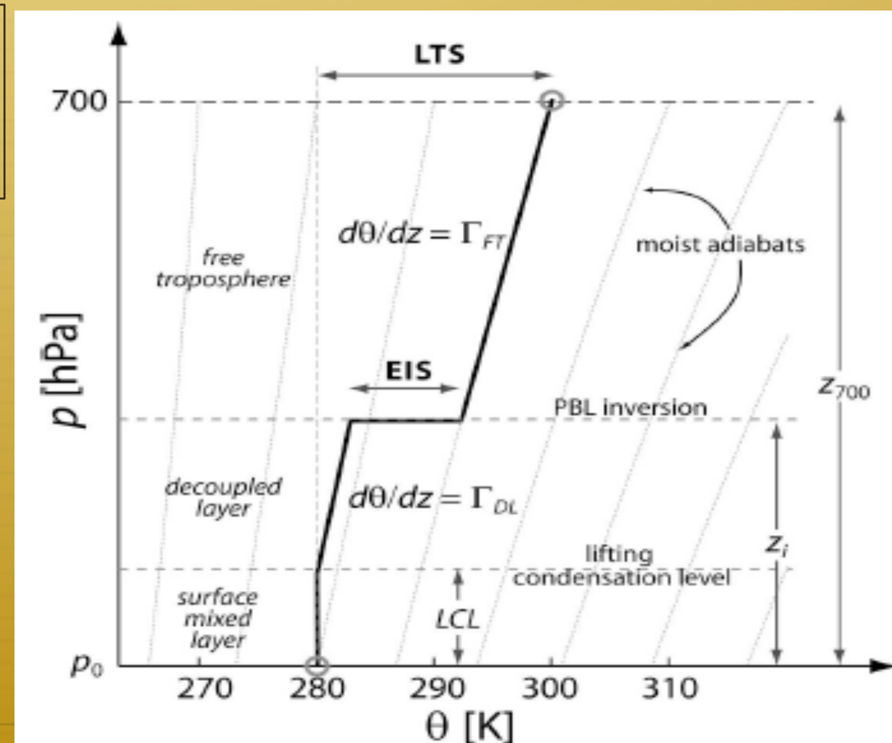




LTS and EIS

Lower-Tropospheric Stability (Klein and Hartmann 1993)

Estimated Inversion Strength (Wood and Bretherton, 2006)



For low cloud amount from ground observation and EIS/LTS from renalysis (Wood and Bretherton, 2006).

Cloud Liquid Water

Cloud liquid water path (LWP):

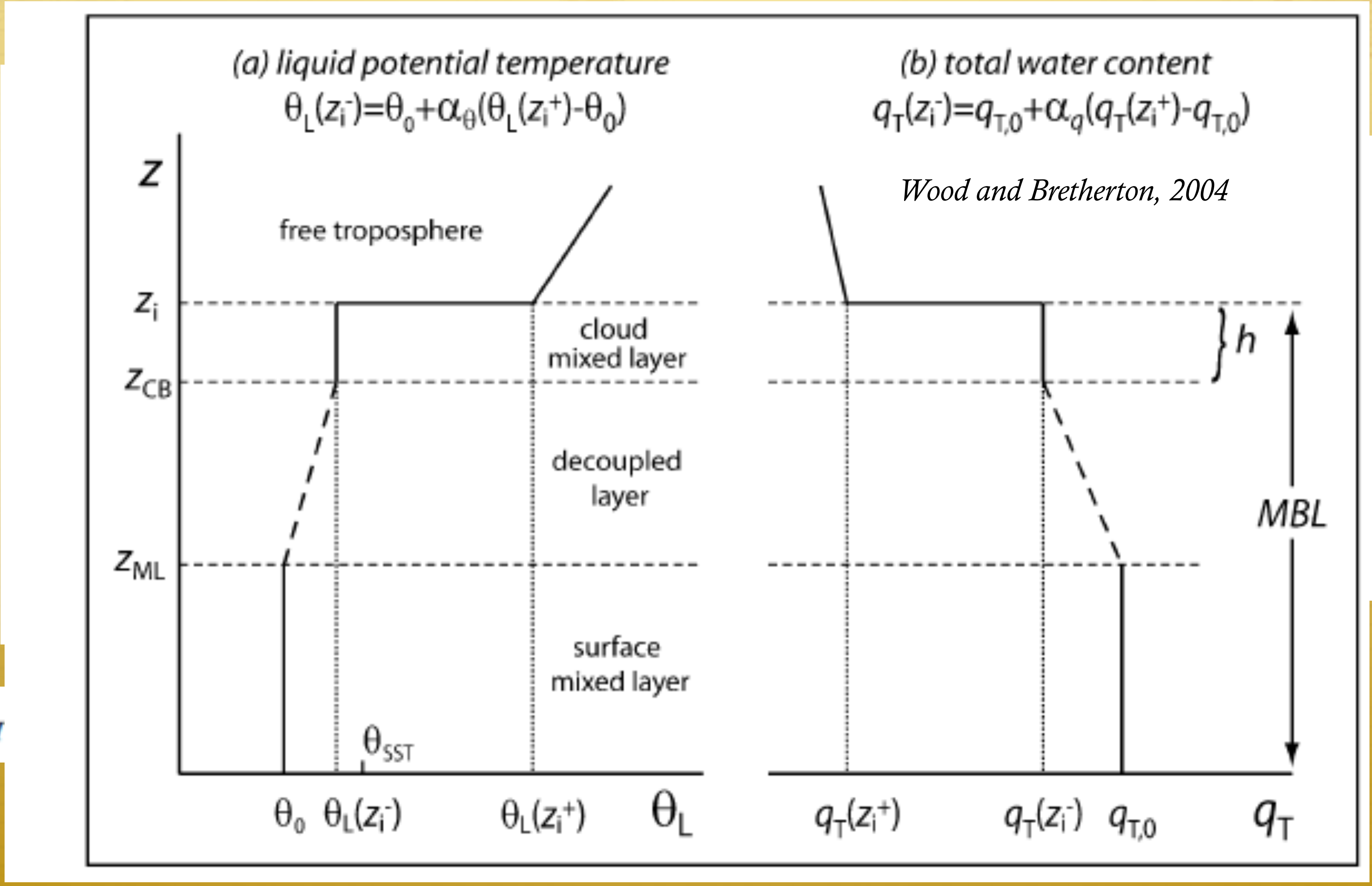
$$LWP = \frac{5}{9}\rho_l \tau r_{e,top},$$

Cloud liquid water content at the cloud top:
1) Adiabatic cloud so LWC increases linearly with in-cloud height
2) LCL=cloud_bottom

$$\Delta q_l = -q_{l,-} = -\frac{LWP \bullet g}{2\left(p_{cloud\_bottom} - p_{cloud\_top}\right)} = -\frac{LWP \bullet g}{2\left(p_{LCL} - p_{cloud\_top}\right)}$$

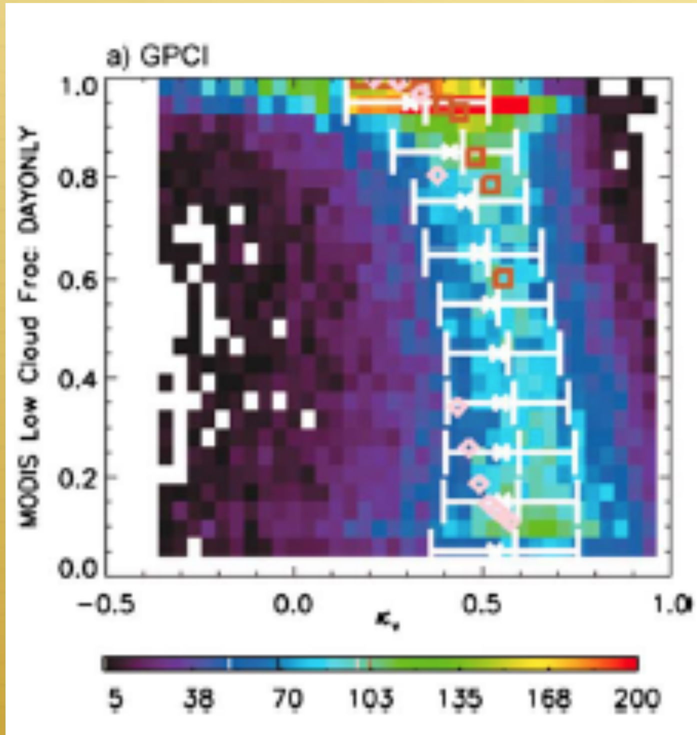
With liquid water contribution and without liquid water contribution

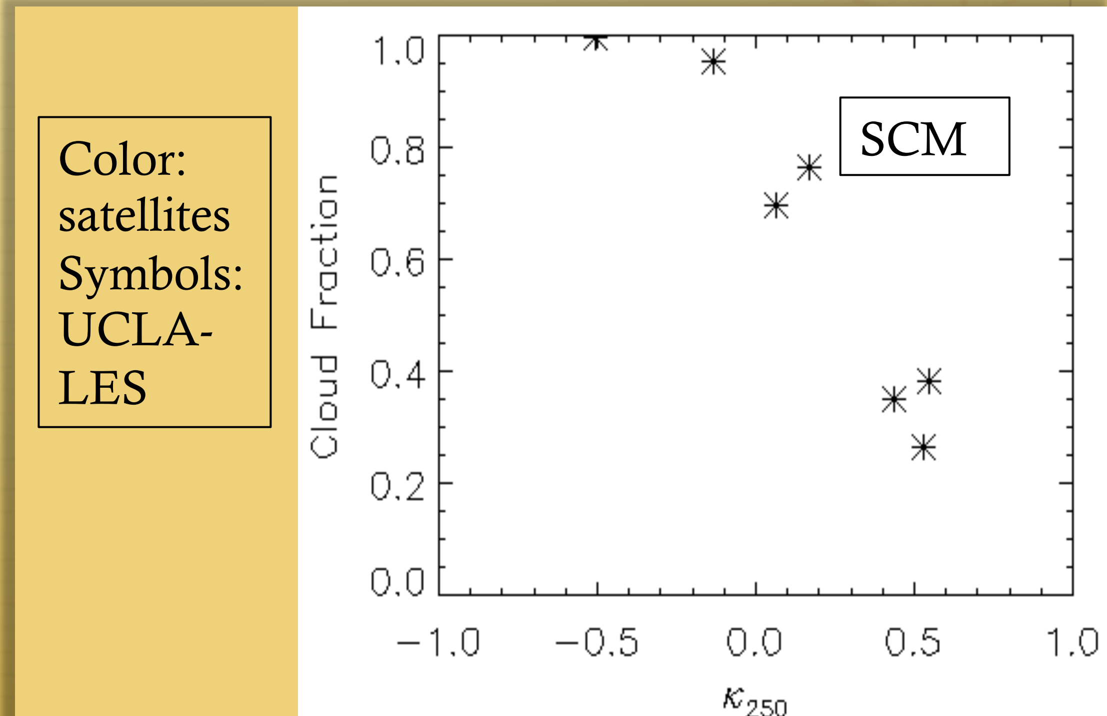
Decoupled and Well-Mixed



q_T

Cloud Fraction and k: from satellite and models





- correlation between MBL cloud fraction and κ from **snapshot** type of observations from satellite as in LES and SCM simulations.
- **Wide spread** may indicate the effect from other physical processes in addition to CTEI.

SCM results: Kay Suselj

CTEI and PBL Transition

- Lilly [1968]: $\Delta\theta_e < 0$,
  - Δ : jump operator (above cloud top – below cloud top)
- Randall [1980] and Deardoff [1980]:
  - s_v: virtual dry static energy
  - $(\Delta s_v)_{crit} > 0$

$$\Delta s_v < (\Delta s_v)_{crit}$$

- Kuo and Schubert [1988]:

$$\kappa = \frac{\Delta\theta_e}{(L/c_p)\Delta q_t} > critical\_value$$

  - κ : CTEI parameter
  - Critical value: 0.23 (KS), 0.7 (MacVean and Mason 1990), 0.6 (Lilly 2002).
- LES: κ ←→MBL cloud fraction

CTEI Parameter and PBL Transition

$$\kappa = \frac{\Delta\theta_e}{(L/c_p)\Delta q_t} = \frac{\Delta\theta_e}{(L/c_p)\Delta q_v}\frac{\Delta q_v}{\Delta q_t} = \kappa_v\left(1 - \frac{\Delta q_l}{\Delta q_t}\right)$$

$$\kappa_v = \frac{\Delta\theta_e}{(L/c_p)\Delta q_v}$$