# An Improved Understanding of the Boundary Layer and Vertical Cloud Structure in the Transition from the Tropical to Subtropical Pacific Cross Section

31 July 2009

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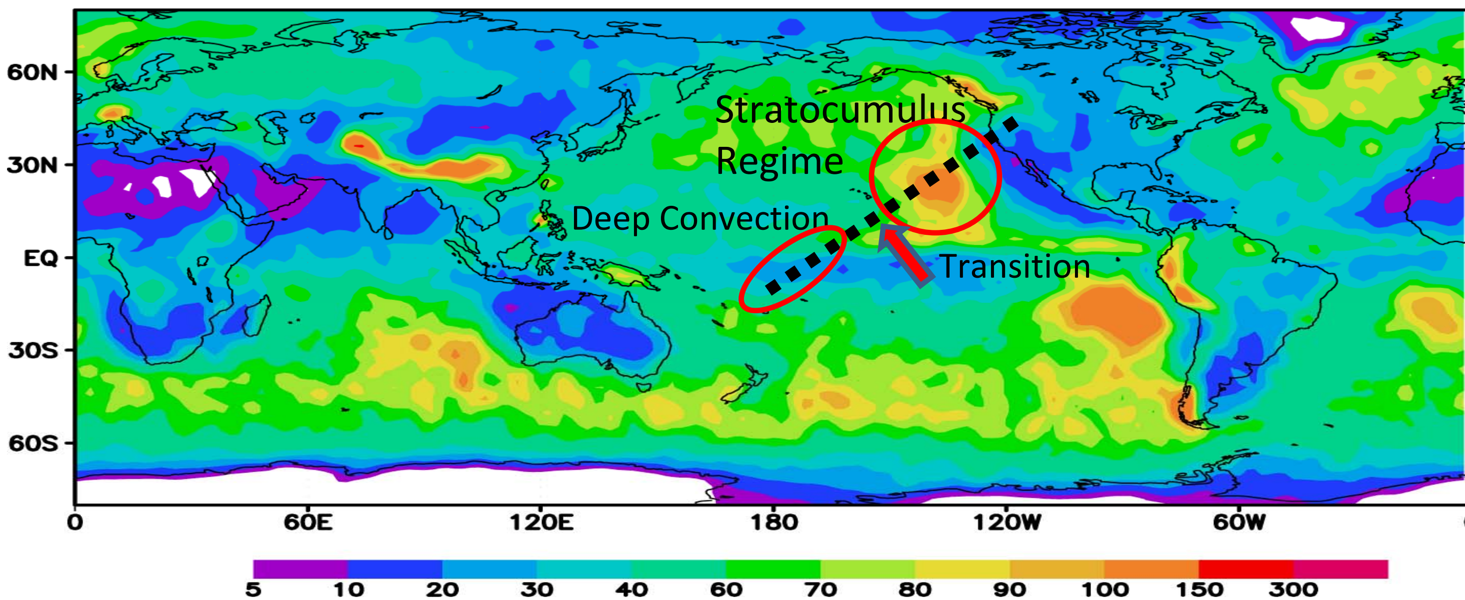
# Why Study Low-Level Clouds Across the Pacific Cross Section from 5°S, 180° to 35°N, 240°?

•This cross section encompasses a rich set of different **dynamic** and **thermodynamic** regimes associated with ascending and descending branches of the Hadley circulation, from deep convective cores near the ITCZ to trade cumuli and stratocumuli over lower SST regions




Liquid Water Path from CloudSat, g $m^{-2}$
(From Li et al., 2009)

# More about low clouds

- Marine boundary layer clouds are reflective and not much colder than the sea-surface, making their net cloud forcing strongly negative

- Given that a mere increase of 4% in stratiform low clouds could offset potential greenhouse warming of 2-3K, understanding their vertical structure and horizontal extent across widely varying meteorological regimes is critical (Randall et al. 1984)

# Data and a few Definitions

- **CloudSat 2B-Geoprof** dataset (radar reflectivity, cloud mask)

- Corresponding **MODIS 1km resolution cloud flags** collocated by the CloudSat Team

- **CloudSat-Calispo** Joint Dataset (2B-Geoprof-Lidar), with cloud boundary and flag information for up to **five** layers; Calipso resolution:

  **Horizontal: 333 m below 8.2 km, 1 km above 8.2 km**

  **Vertical: 30 m below 8.2 km, 75 m above 8.2 km**

- Corresponding **ECMWF** T & q profiles, from which many relevant thermodynamic and atmospheric profile quantities are calculated (more on next slide …)

# A few relevant thermodynamic variables

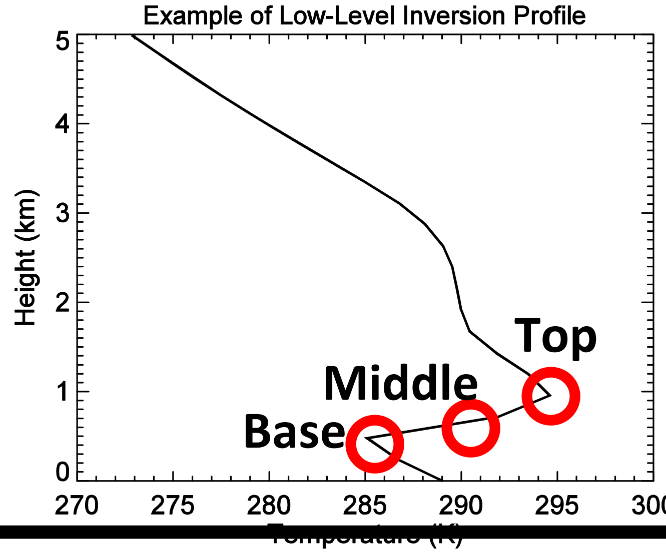
- **Moist Static Energy: $L_v q+gz+c_p T$ –** relevant for thermodynamic stability of atmosphere → an increase of MSE with height means stable stratification
- **Lifting Condensation Level (LCL)**

**Single-layer uniform low clouds** – Pixels in which MODIS flag indicates uniformity (clear or cloudy) around a given CloudSat pixel; other sensors are used diagnostically on these uniform clear/cloudy "footprints"

**ECMWF Inversion Heights:** Any layer in low-troposphere (pressure above 700mb) where the temperature increases with height

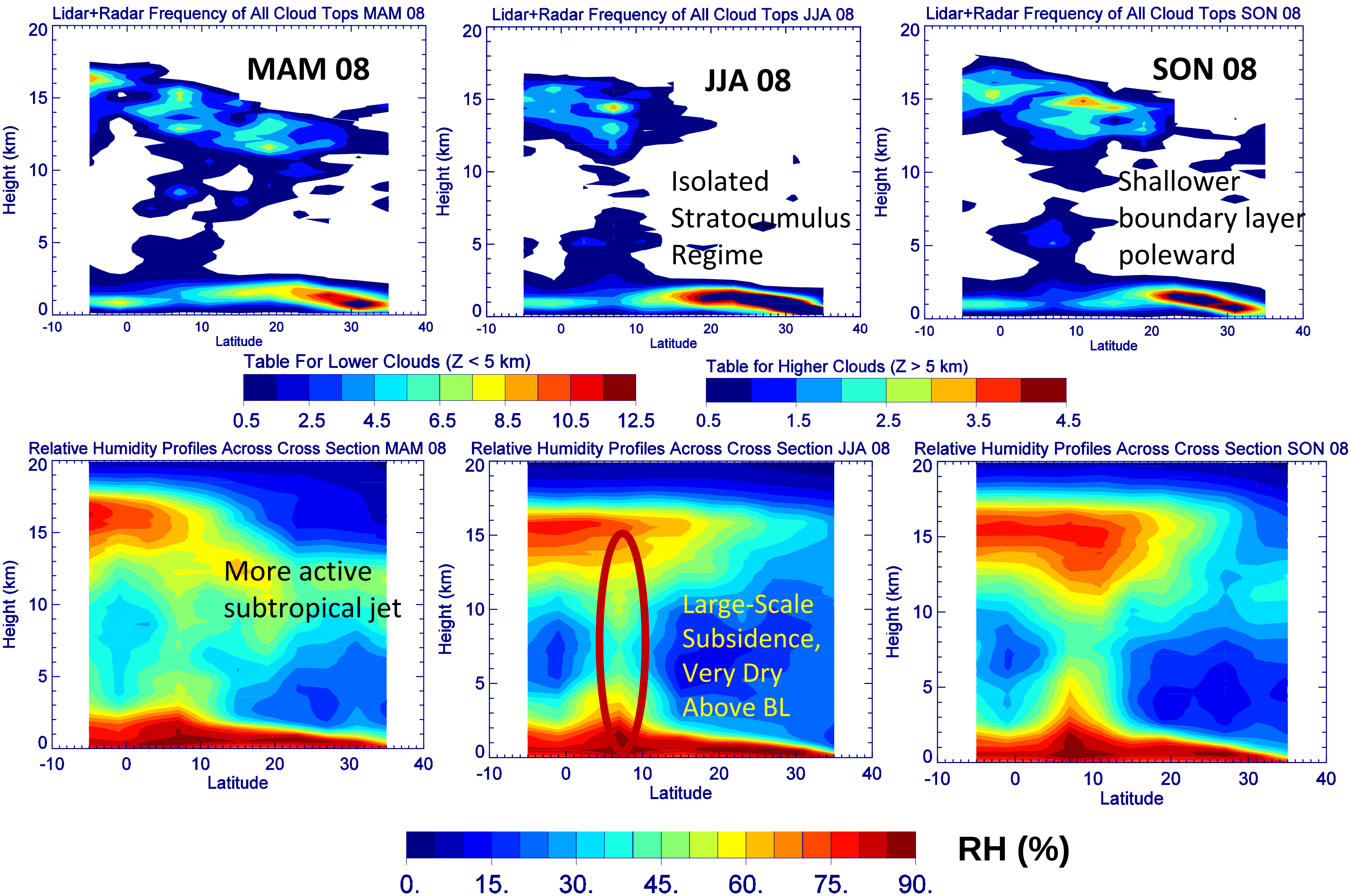
**ΔMSE: $\Delta MSE=MSE_{top}-MSE_{sfc}$**

Where **$MSE_{top}$**=MSE at 700mb (if no thermal inversion) or MSE at **inversion middle**



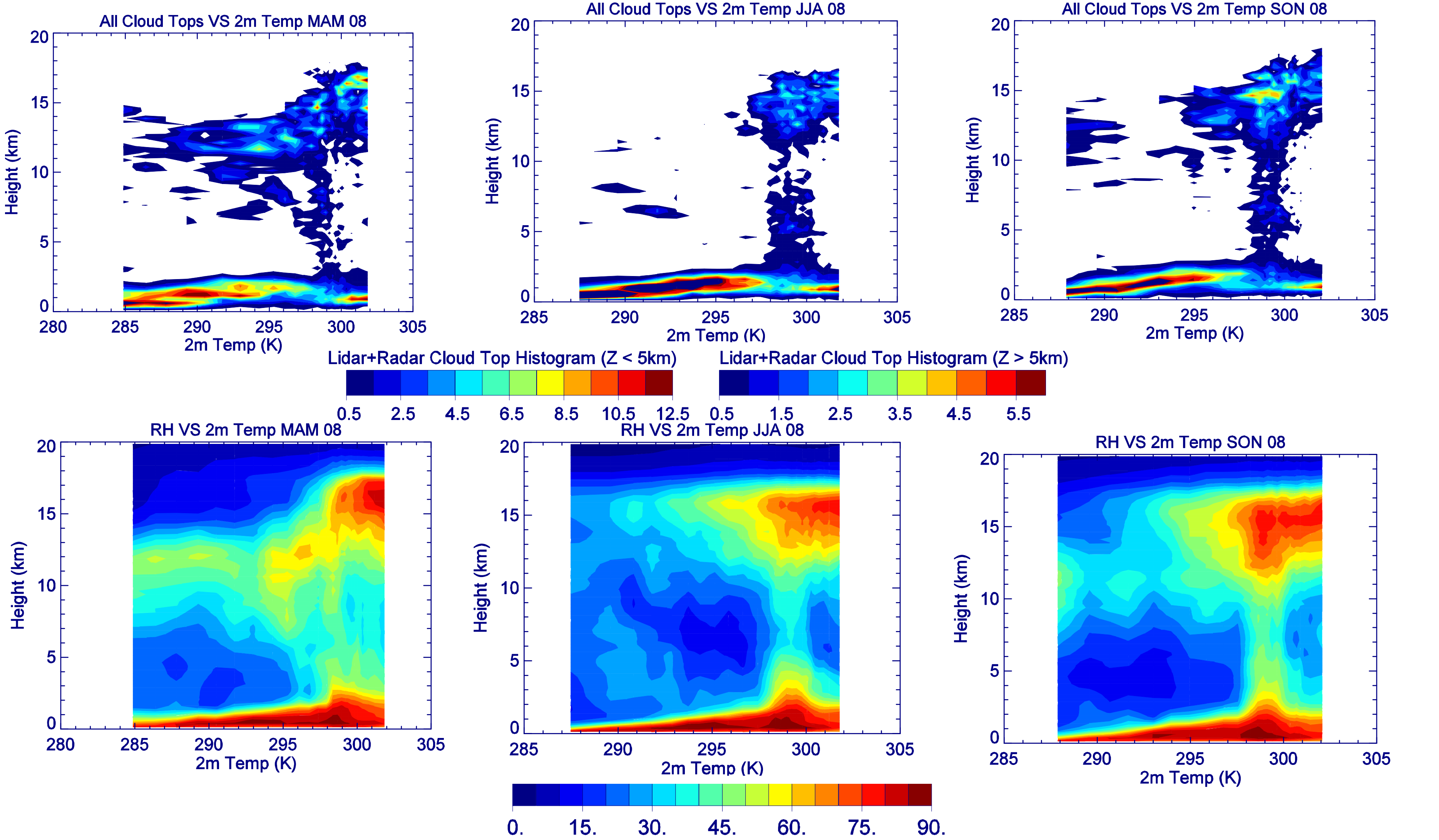
Before zooming in on the boundary layer, let's first look at the cloud top and RH profiles for our Pacific Cross Section from the Joint Calispo-CloudSat Product and ECMWF analysis

# Joint Lidar+Radar All Cloud Top PDFs and Relative Humidity Vs Location

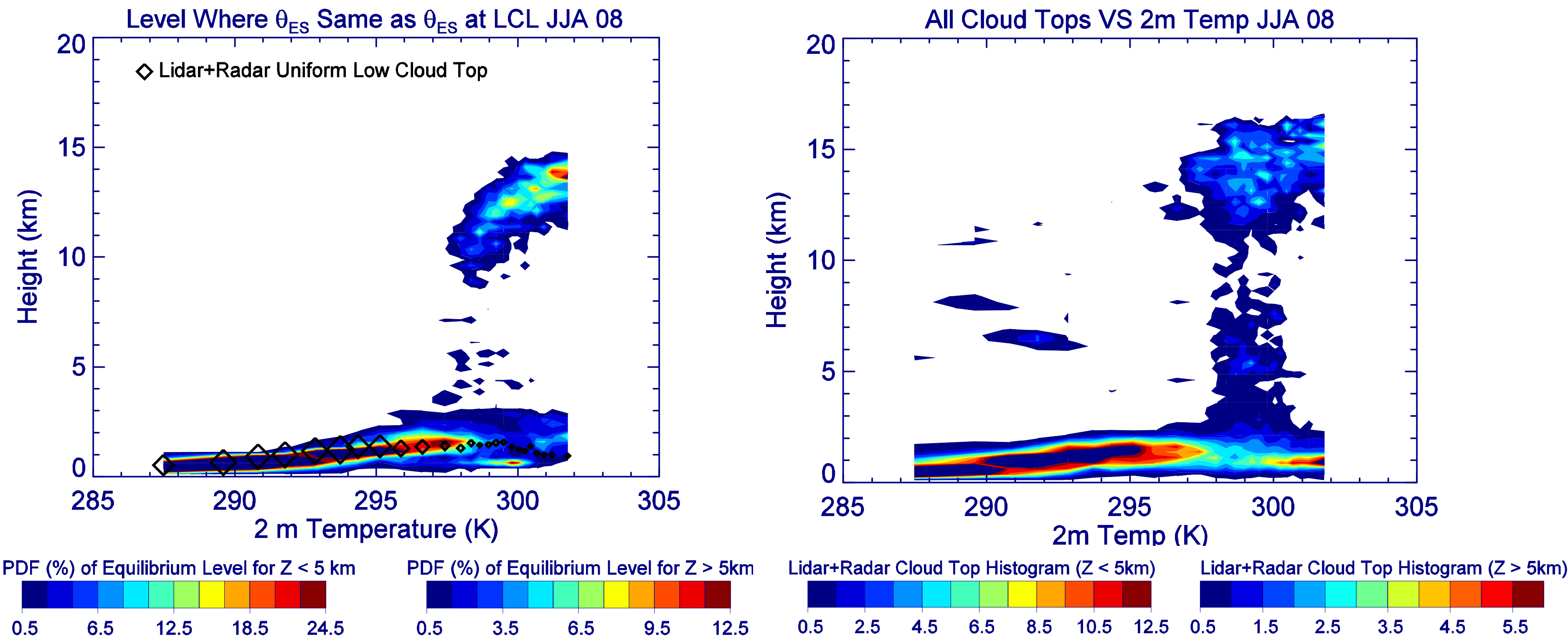


# Seasonal Joint Lidar+Radar Cloud Top PDFs and Relative Humidity vs $T_{SFC}$

- Mid and upper-level cloudiness mostly confined to high SSTs during JJA, and generally during SON, but mid and upper level cloudiness more pervasive over low SSTs during MAM (and even more during DJF, not shown) - low clouds are common in **isolation** over low SSTs especially during **JJA** (and somewhat less during MAM & SON)
- Transition from mainly shallow to mid/deep modes around 298 K

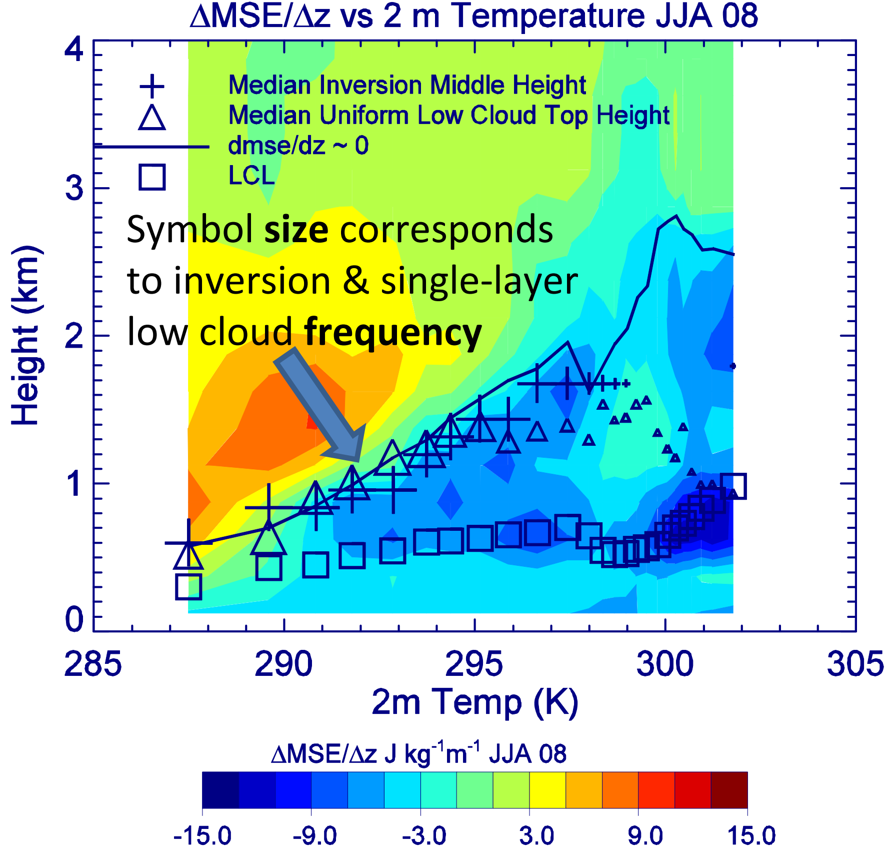


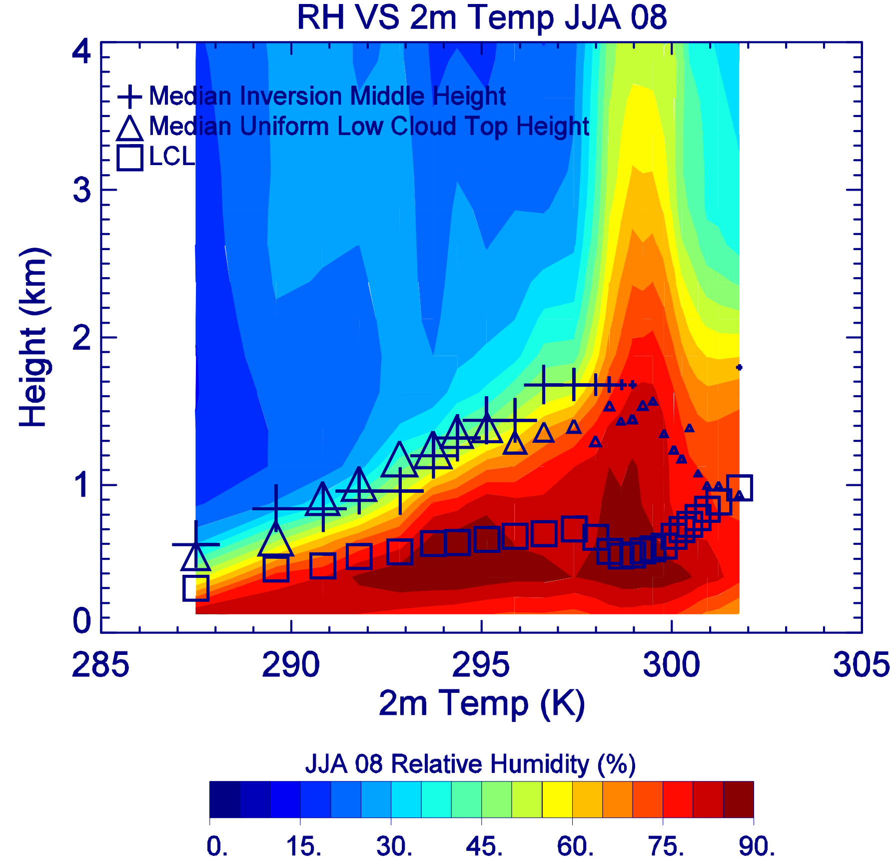
# Can a Simple Equilibrium Level PDF, the level where environmental $\theta_{ES}$ at the LCL matches $\theta_{ES}$ aloft, capture this transition at $T_{SFC} \approx 298K$?




- Qualitatively, equilibrium level PDF captures the transition around 298K, at least during JJA when tropical convection is well separated from the subtropics
- These simple calculations also show a continued low cloud mode over high SSTs, much like the cloud top histograms

Let’s now look more closely at how the boundary layer characteristics depend and change with surface temperature

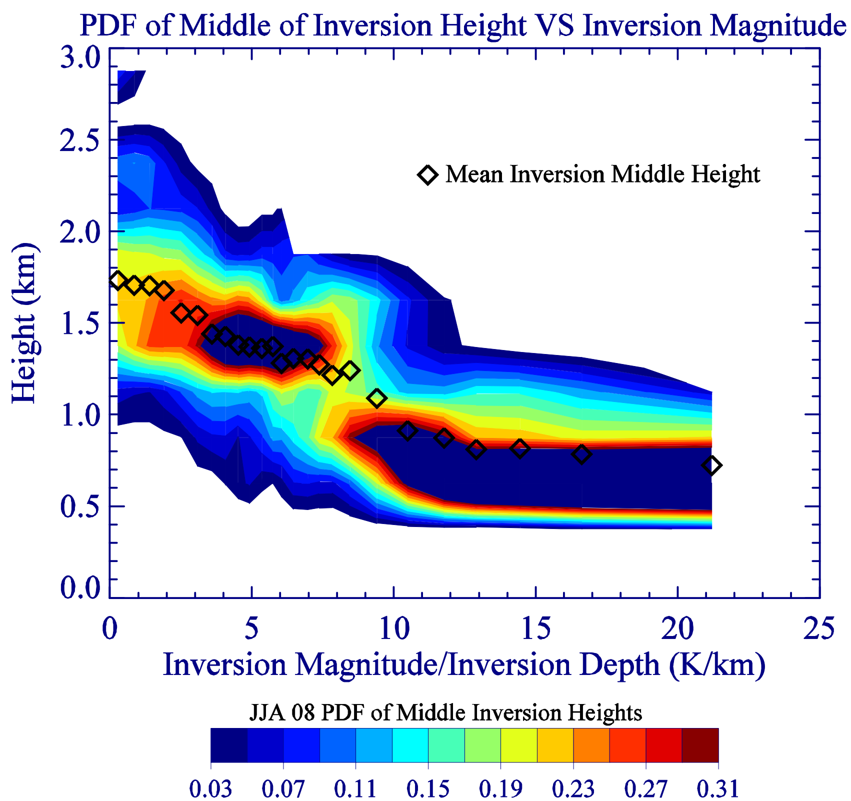


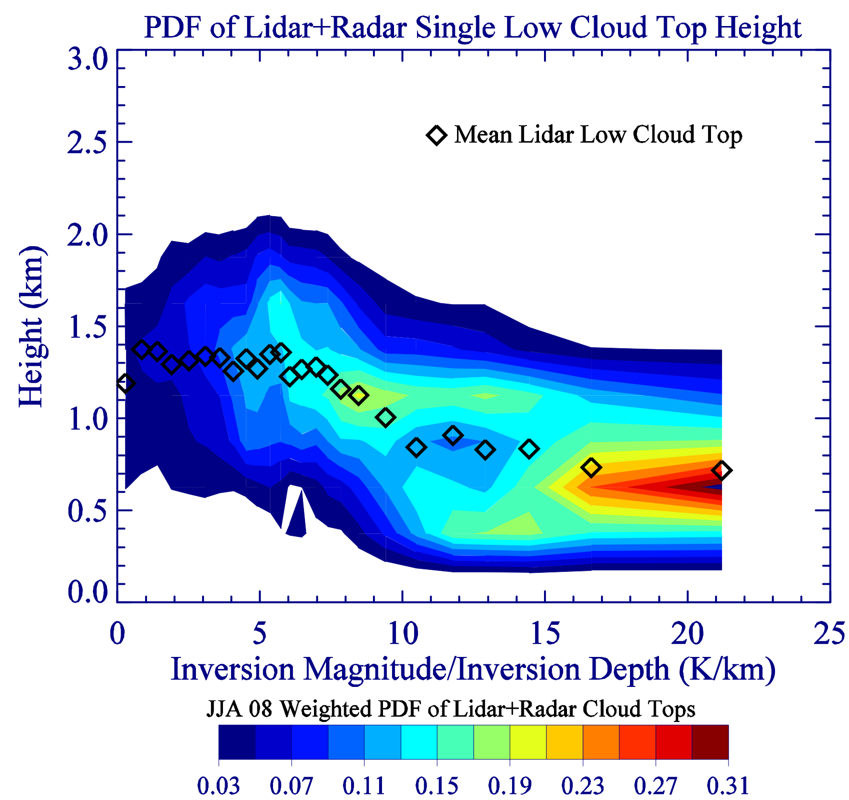




- Inversion height, low uniform cloud top height, and d(**MSE**)/dz~0 level increase with $T_{sfc}$; these BL parameters correspond closely with each other until above 295K
- Slight LCL increase with $T_{sfc}$ across stratocumulus region

- The sharp RH gradient corresponds to cloud top and inversion heights
- Single-layer low clouds become much less frequent as mid and deep convection increases near 298K
- In the deep convective regime around $T_{sfc}$ ~ 298K, the LCL lowers slightly due to a very moist near-surface layer

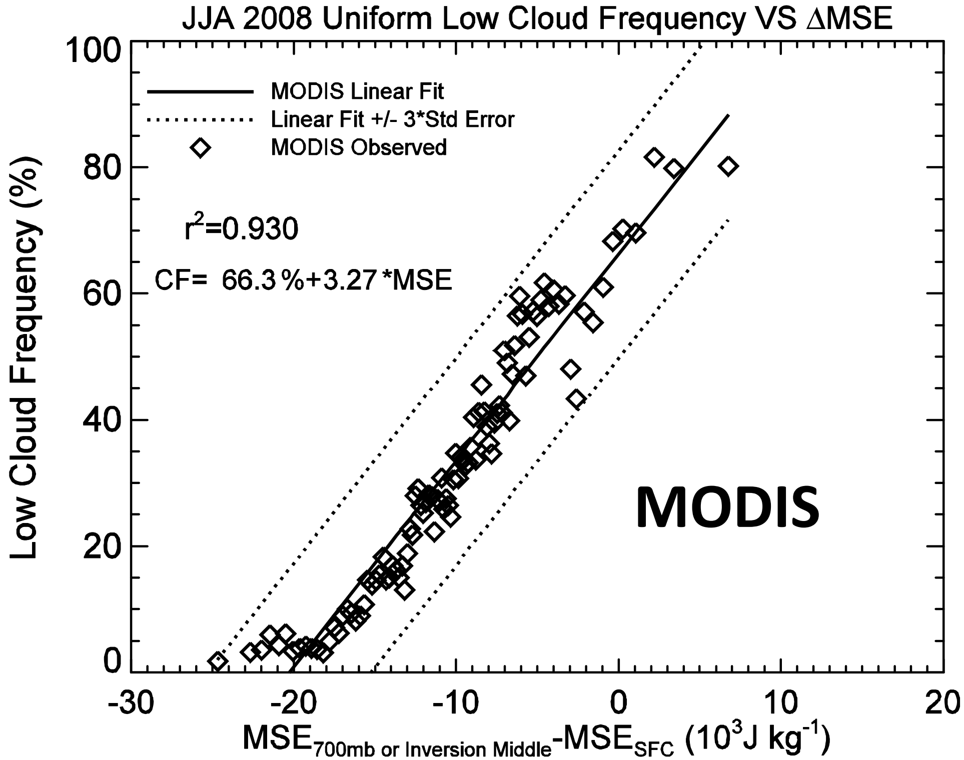
# Now, let's look at how the boundary layer becomes shallower with increasing inversion strength

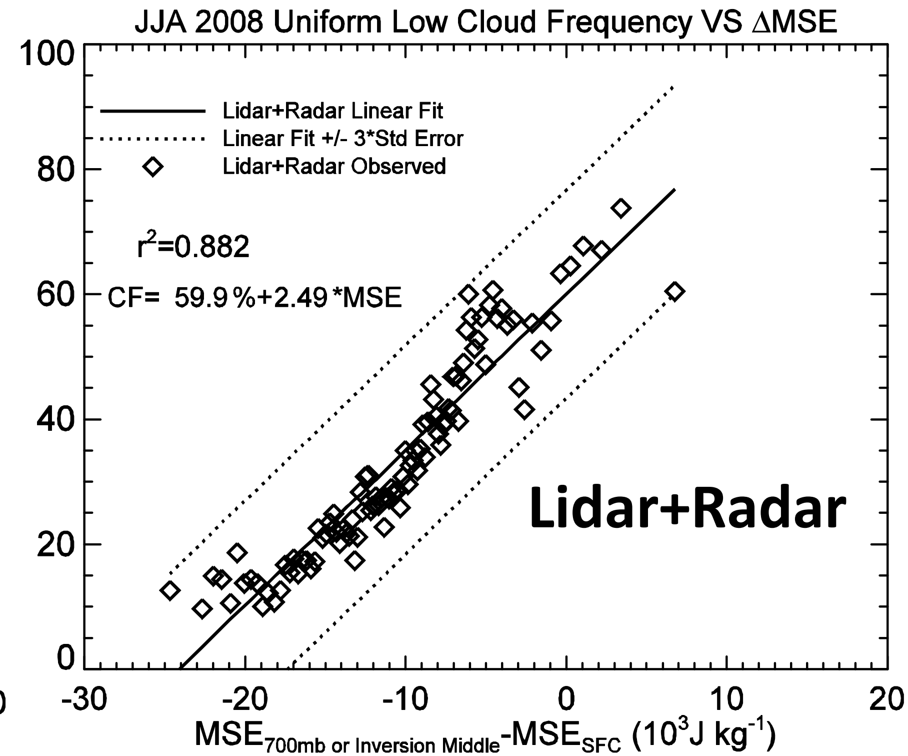



- Strengthening of inversion indicative of stronger subsidence
- Except for very weak inversions, single-layer uniform low cloud tops become shallower with increasing inversion strength (**right**)
- Low clouds are also more abundant under stronger inversion conditions
- Low cloud top PDF **(right)** closely resembles the inversion height PDF **(left)**

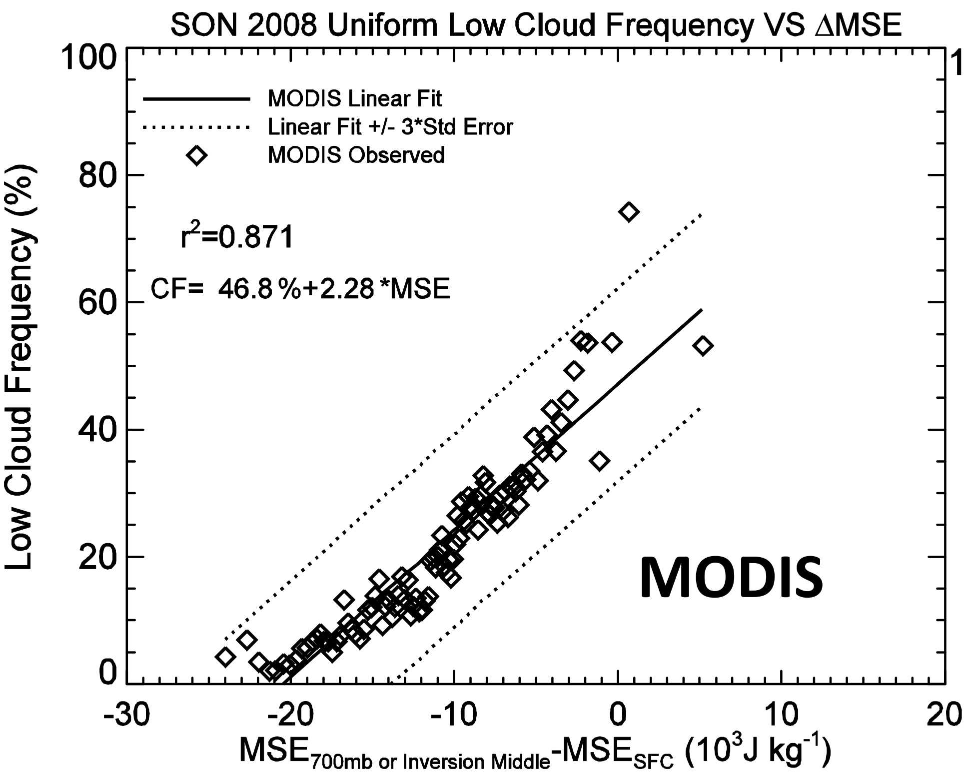
# Now, let's look at single-layer low cloud frequency vs ΔMSE for JJA 08

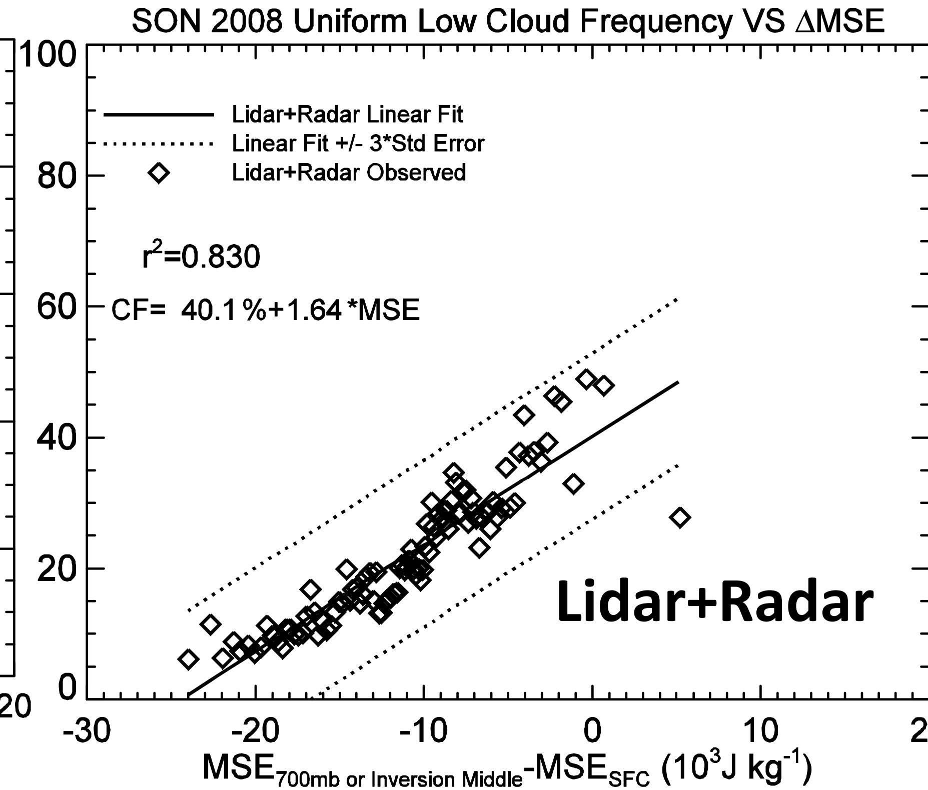



- Very high $r^2$ values between ΔMSE (**$MSE_{middle\ inversion}$ or $MSE_{700mb}$-$MSE_{surface}$**) and single-layer uniform low cloud frequency, especially for JJA (also a slightly higher slope for MODIS)
- Lidar+Radar see slightly more low clouds for unstable conditions, and MODIS slightly more over very stable conditions

# Same as previous slide, but now for **SON 2008**



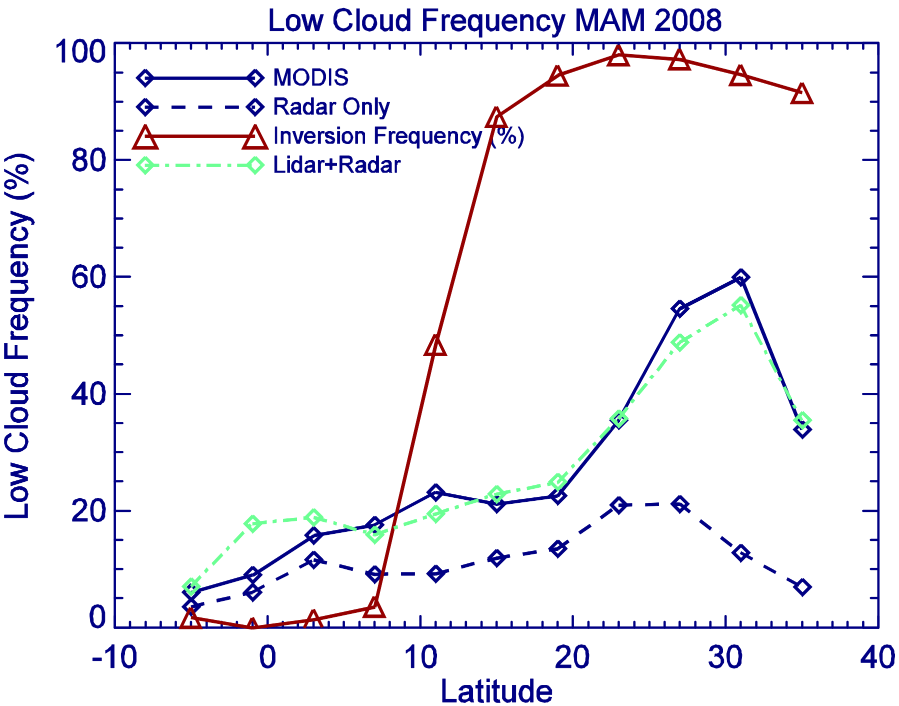

- Still fairly high $r^2$ values (0.87 for MODIS, 0.83 for Lidar+Radar), but with slightly reduced slopes, likely as a result of increased middle and overlying clouds over the subtropical regions

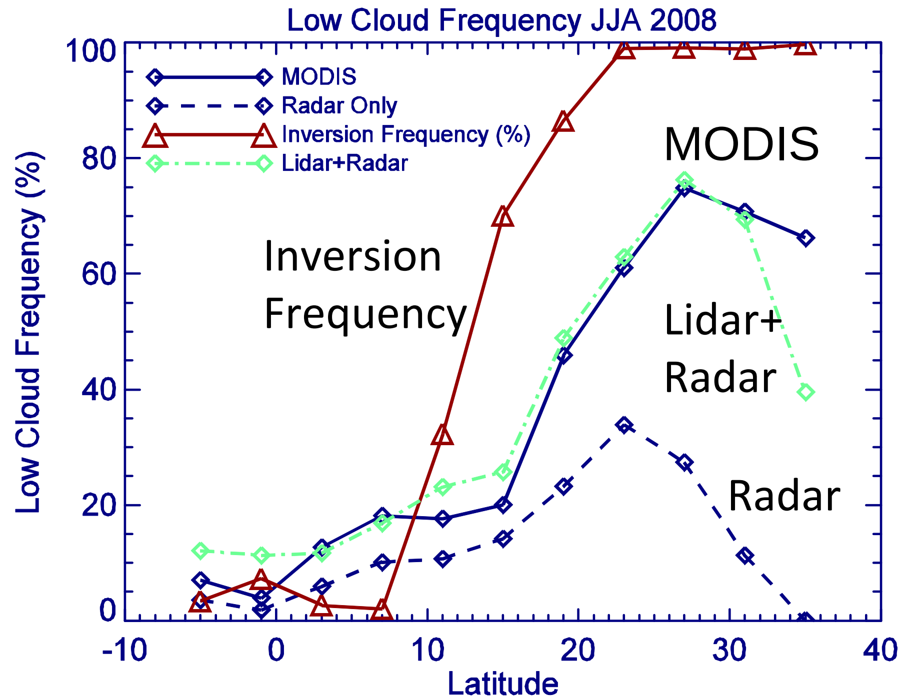
## Summary of ΔMSE /Low Cloud Frequency Results, with **Single-Layer Low Clouds** and **Random Overlap Assumption**

| | MAM 2008 | | JJA 2008 | | SON 2008 | |
|---|---|---|---|---|---|---|
| | Single-Layer $r^2$ | Random Overlap $r^2$ $\frac{LowCF}{1-HighCF}$ | Single-Layer $r^2$ | Random Overlap $r^2$ $\frac{LowCF}{1-HighCF}$ | Single-Layer $r^2$ | Random Overlap $r^2$ $\frac{LowCF}{1-HighCF}$ |
| MODIS | 0.85 | **0.91** | **0.93** | 0.91 | 0.87 | **0.88** |
| Lidar+ Radar | 0.68 | **0.85** | **0.88** | 0.86 | **0.83** | 0.77 |

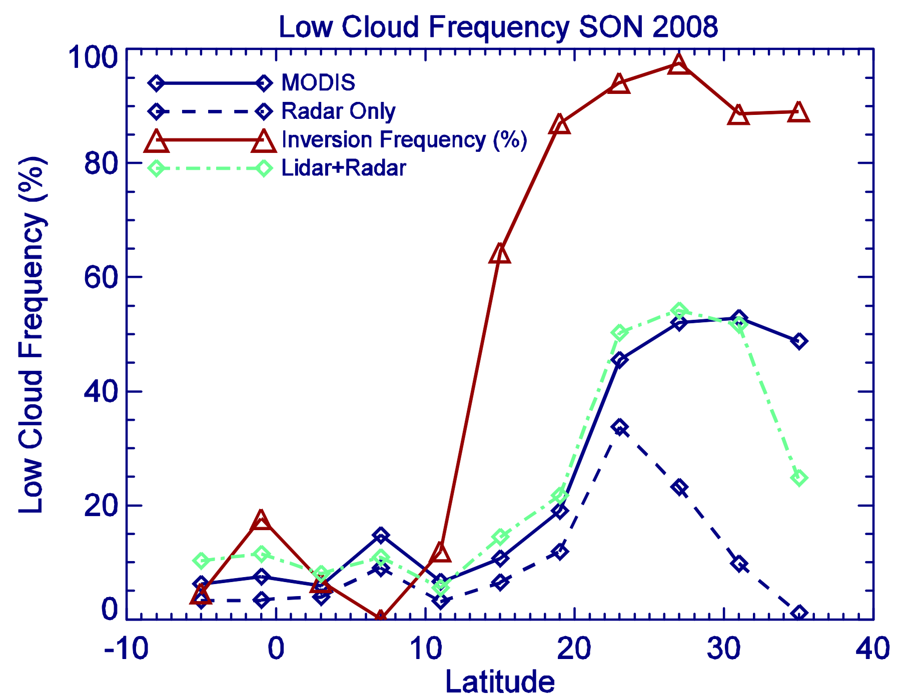
• Random overlap assumption sometimes improve correlation between ΔMSE and low cloud frequency, but not systematically so, such that large-scale dynamics are likely more important for differences among the different seasons

Let’s now do a more detailed comparison of low cloud frequency among the different A-Train sensors




- Low cloud frequency is a max in the subtropics ~25°N; 75% in JJA and 55% in **SON, MAM** (JJA max consistent with many previous studies)
- Joint *Lidar+Radar* agrees with MODIS remarkably well, except lidar+radar sees slightly more low clouds in tropics (perhaps these are trade cumuli) and also sees fewer clouds than MODIS at ~35°N
- Radar alone misses *MANY* subtropical low clouds, increasingly so north of 25°N



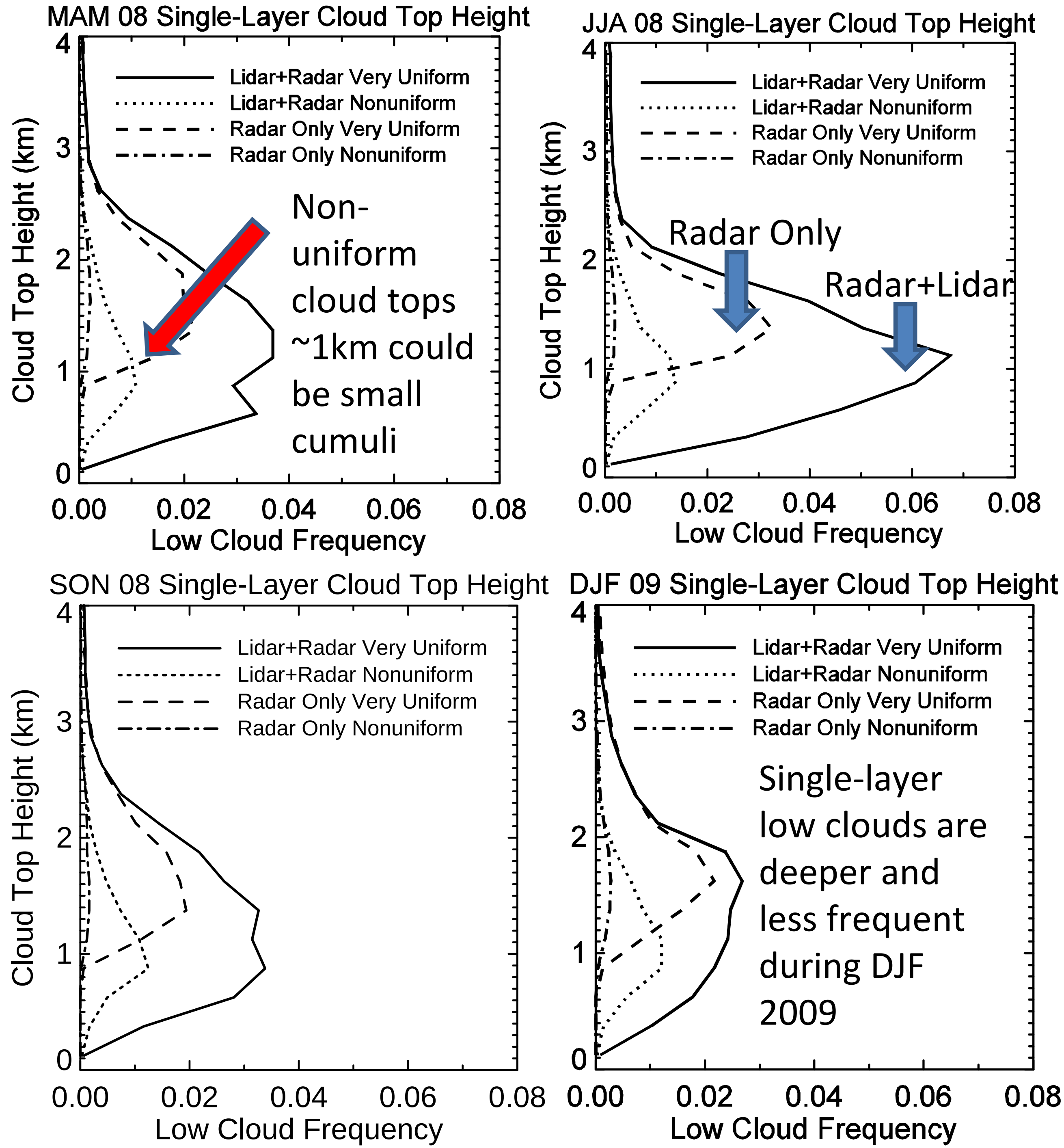
Seasonal Cycle of Single-Layer Uniform Low Cloud Frequency

| | MAM 2008 | JJA 2008 | SON 2008 | DJF 2009 |
|---|---|---|---|---|
| Radar Only | 11% | 12% | 9.3% | 9.7% |
| Lidar+Radar | 25% | 34% | 22% | 18% |
| MODIS | 25% | 32% | 22% | 17% |

Good Agreement

Which clouds are being missed by CloudSat? (Next Slide)

- Radar only sees few clouds with tops below ~1 km, whereas a large fraction of clouds is detected below 1 km by the lidar+radar during MAM, JJA, and SON
- The radar cloud top height mode is ~500m higher than the lidar+radar mode (except during DJF), which is logical as deeper low clouds are geometrically thicker and preferentially captured by the radar



# Summary

•Calipso Joint Lidar+Radar cloud top PDFs correspond to levels of high RH

•All boundary layer parameters grow sharply with $T_{SFC}$, including **low cloud tops**, **inversion height**, **height of sharpest vertical RH gradient**, level where **d(MSE)/dz is zero,** and the **Equilbrium Level** for $T_{SFC} < 298$K, above which middle and deep convection becomes pervasive

•Simple equilibrium level calculations, where the level where environmental $\theta_{ES}$ at the LCL matches $\theta_{ES}$ aloft, capture the transition to deeper convection at $T_{SFC} \approx 298$K

•Inversion height PDFs are consistent with the lidar+radar low cloud top height PDFs, which both become shallower with stronger inversions

•**ΔMSE** and low cloud frequency are highly correlated, especially during JJA ($r^2$=0.93, 0.88 for MODIS, Lidar+Radar respectively), and only slightly less so during spring and fall

•Very good agreement between MODIS and Lidar+Radar single-layer uniform low cloud frequency during all seasons; CloudSat sees fewer than half of single-layer uniform low clouds as it misses many clouds with tops lower than **1 km**

Thanks for your attention!

Please send any questions to
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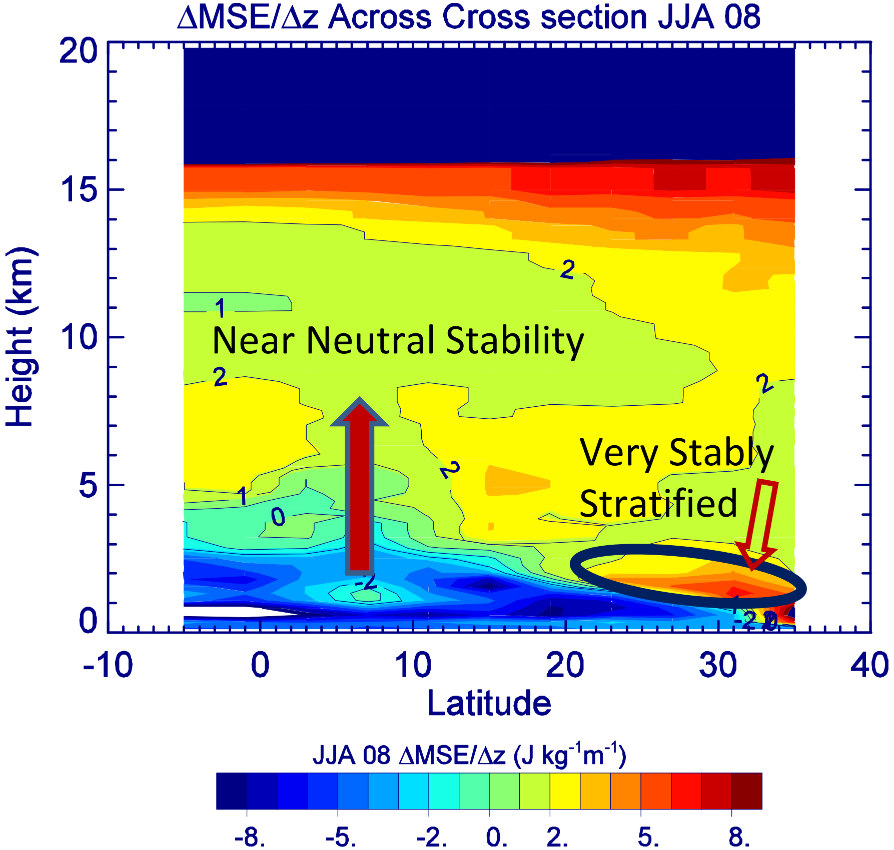
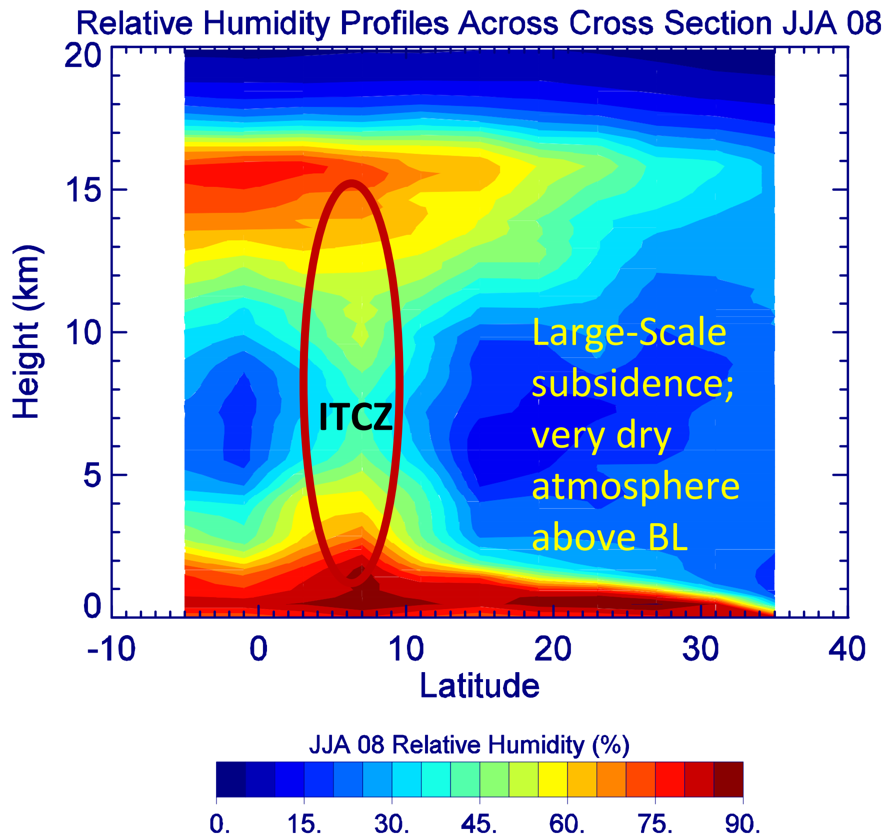
# Now, let's characterize the cross-section in terms of moisture and stability profiles



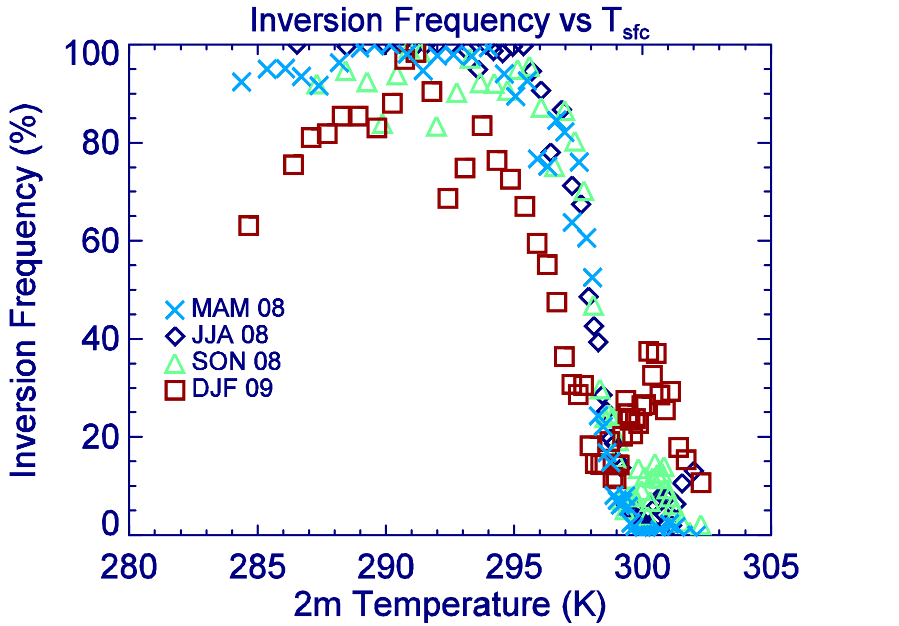



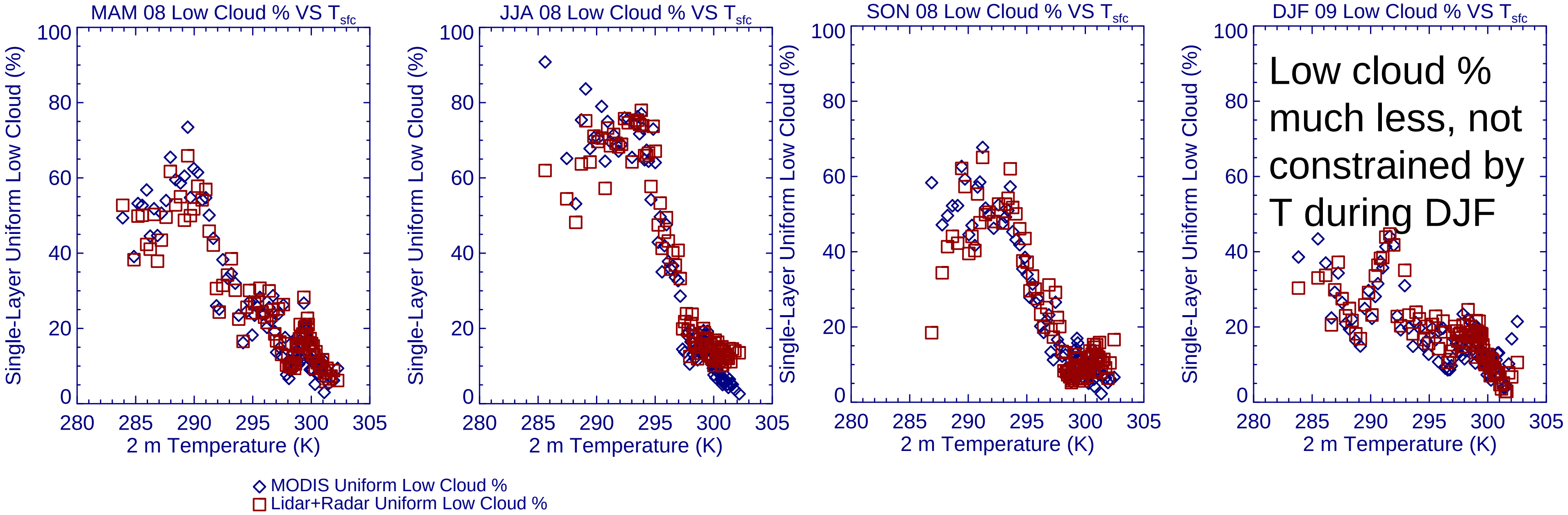

- South of ~10°N, deeper unstable layer (dmse/dz<0) – unstable layer becomes shallower towards the north – suggestive of shallower BL
- Near ITCZ, nearly neutral MSE stability in middle and upper troposphere

- Center of ITCZ ~8°N evidenced by deep layer of high low-level RH (only slightly drier in mid-troposphere) and high RH in upper troposphere
- MBL top can roughly be inferred by sharp gradient of high low-level RH values – this moist layer slopes dramatically downward poleward

# Inversion Frequency (TOP) & Uniform Single-Layer Low Cloud Frequency (Bottom) VS $T_{SFC}$

For a given $T_{SFC}$, inversions are more frequent from MAM thru SON, particularly for low temps in the Sc regime – corresponding single-layer low cloud frequency is higher as well



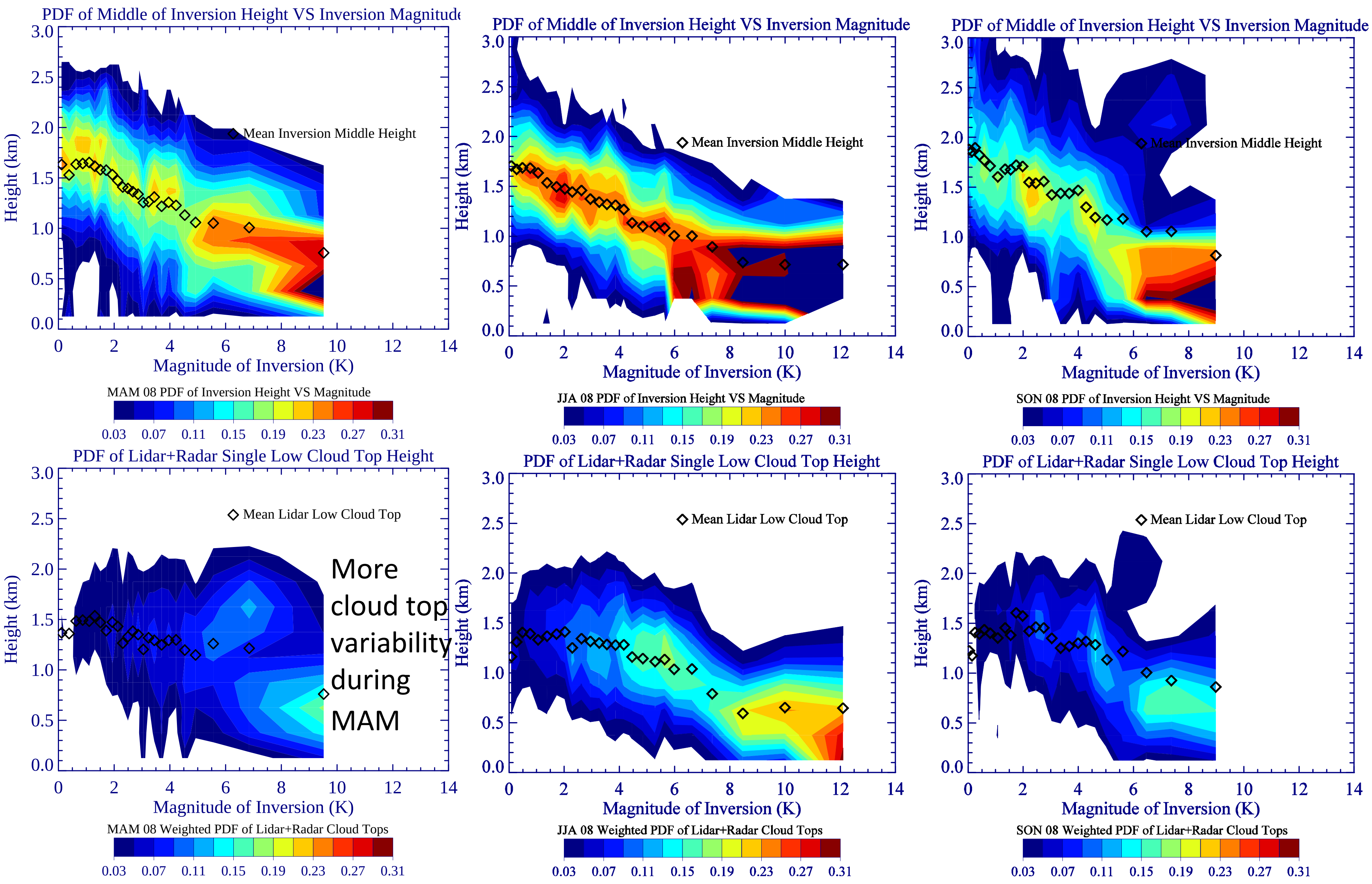




MODIS Uniform Low Cloud %
Lidar+Radar Uniform Low Cloud %

# How do inversion height and cloud height change with inversion strength?

## TOP: Inversion Strength VS Height, BOTTOM: Low Cloud Top VS Inversion Strength

### MAM 08 | JJA 08 | SON 08



Let's now turn our attention back to moist static energy (MSE), since it provides us with a good indication of the mean thermodynamic profile, and thus stability.

We remind ourselves that MSE encompasses three forms of energy:
MSE=sensible($\mathbf{c_p T}$)+potential($\mathbf{gz}$)+latent($L_v q$)

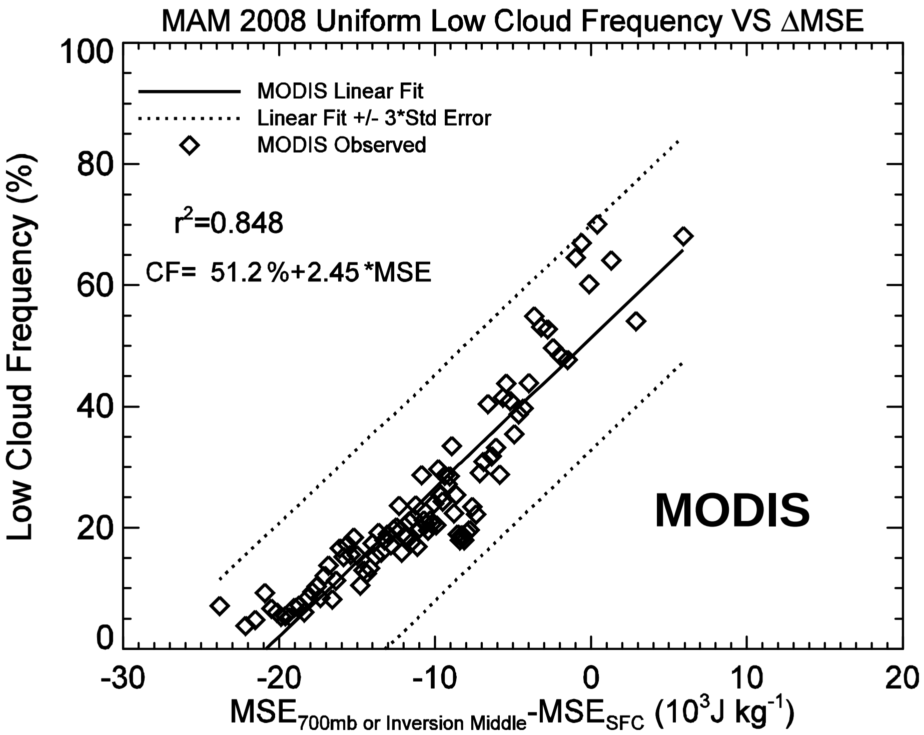
Since MSE increases with height in a stably stratified atmosphere, we believe the gradient of MSE in the lower troposphere should be well associated with low cloud frequency, perhaps even better than $T_{SFC}$, since moisture information is contained

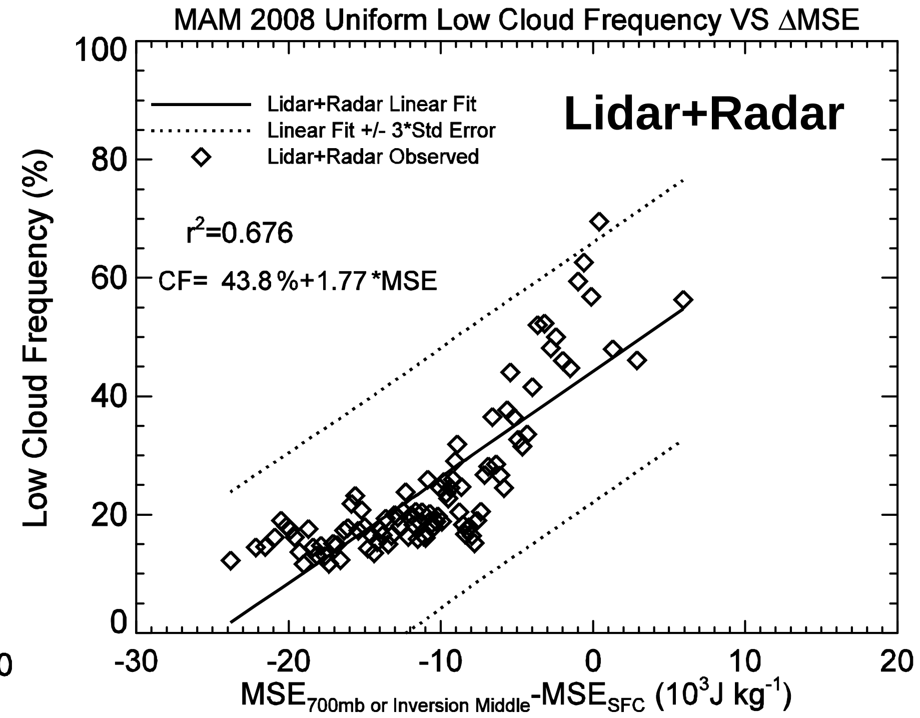
Our metric for determining ΔMSE is:

$$\mathbf{\Delta MSE = MSE_{top} - MSE_{sfc}}$$

Where $MSE_{top}$=MSE at 700mb (if no thermal inversion) or MSE at inversion middle

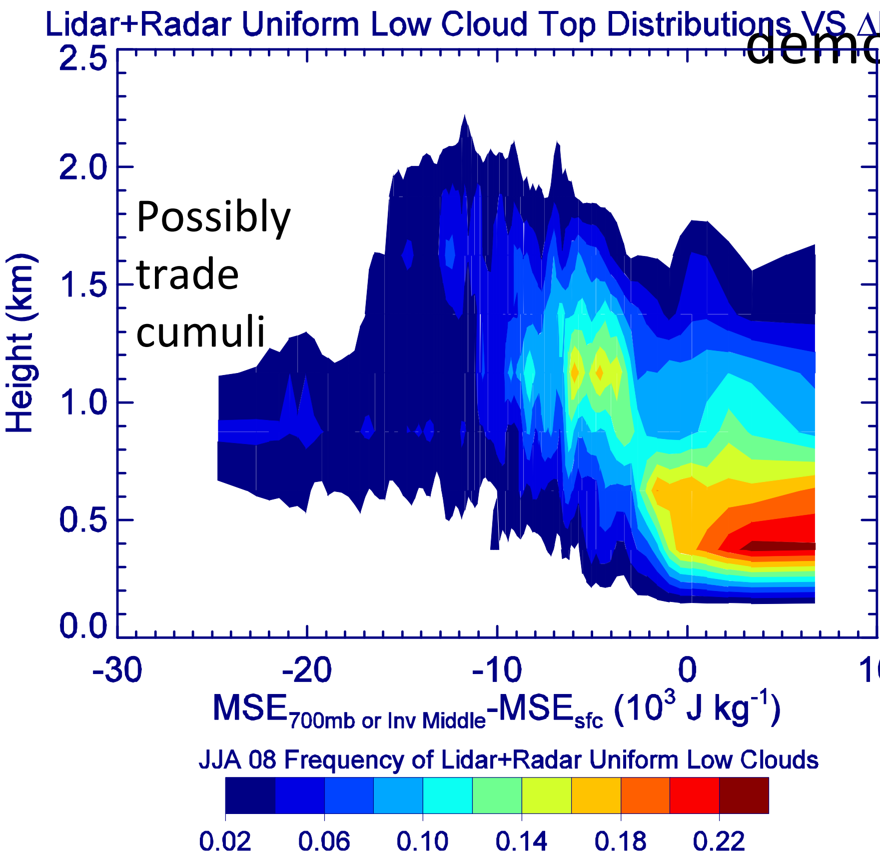
# MAM 08

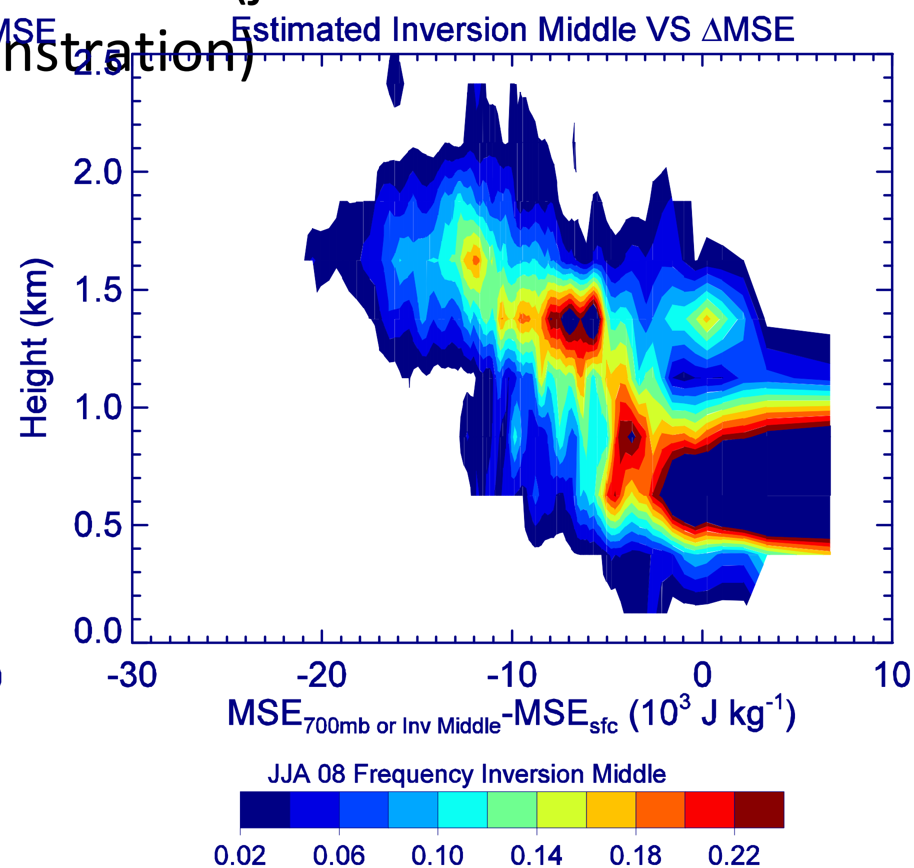



- Fairly high $r^2$ value for MODIS, but somewhat lower for Joint Lidar+Radar

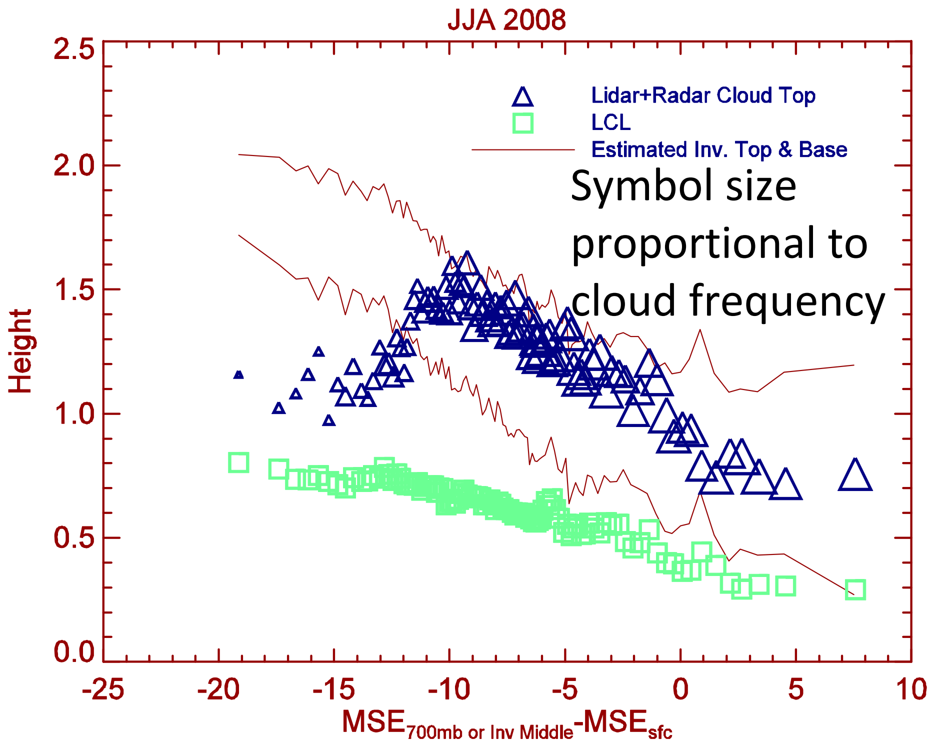
# We can also plot the cloud top height and inversion height histograms as a function of ΔMSE (just for JJA 2008 for demonstration)

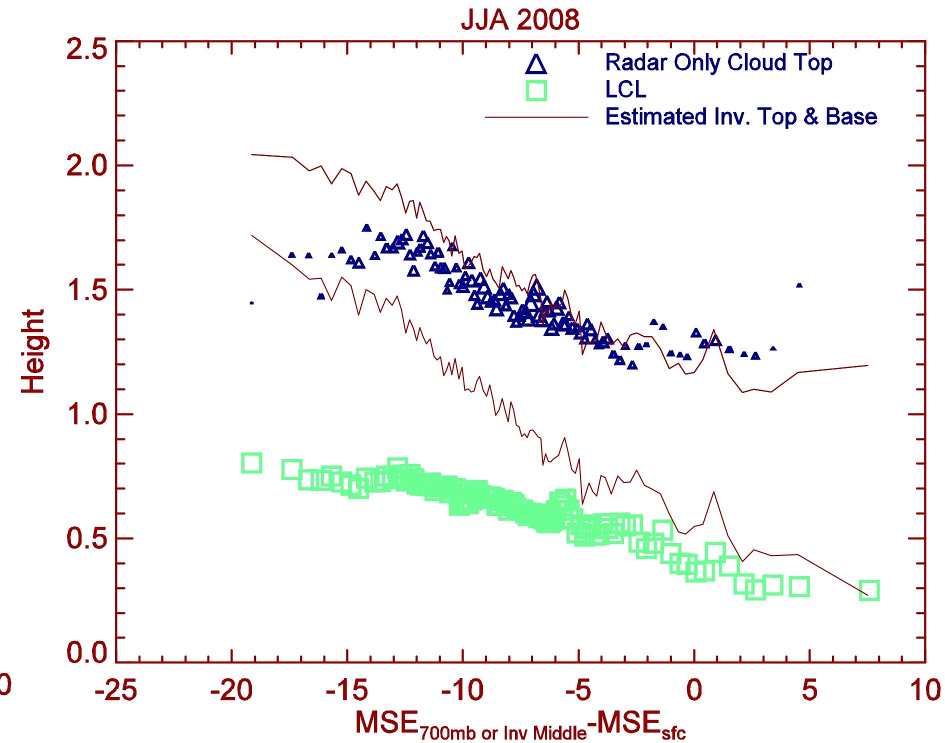



- These plots are fairly similar to ones presented earlier which showed that the boundary layer top grows with $T_{SFC}$ – not surprising since ΔMSE is closely connected to $T_{SFC}$

# Now, we compare cloud top properties as a function of ΔMSE for **lidar+radar** and **radar** only




- Lidar+Radar cloud tops are well-bounded by inversion boundaries once that static stability increases
- Since there are few low clouds when ΔMSE is very negative, these clouds may be either trade cumuli or perhaps in a developing stage to deeper convection
- Radar only cloud top are preferentially higher than lidar+radar, as we saw before, and radar single-layer uniform low cloud frequency vs ΔMSE is much lower