WHY DO WE NEED TO UNDERSTAND ENTRAINMENT? WHY DON'T WE?

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NASA/GISS

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Two different but related problems:

Convective clouds

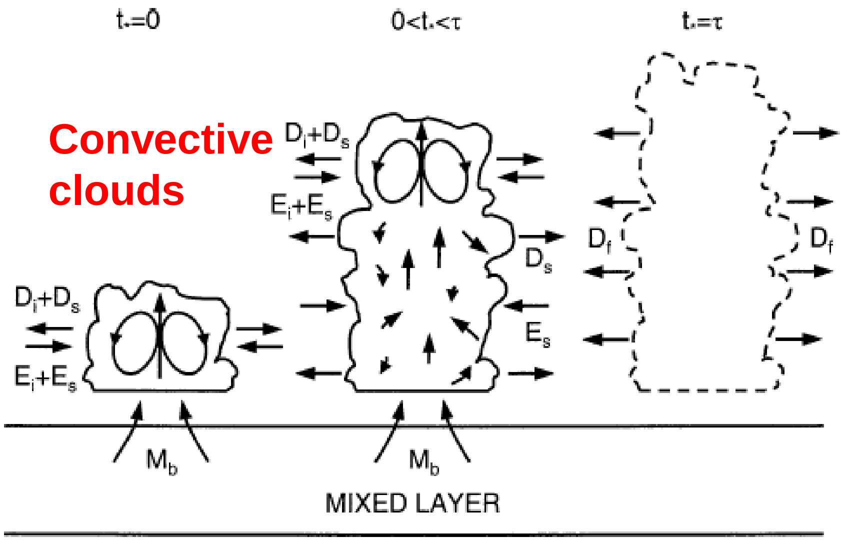


FIG. 1. Simplified life cycle of a shallow cumulus cloud. The cloud begins to form at time $t_* = 0$ and collapses at $t_* = \tau$. The air in the cloud is modified by entrainment and detrainment at the top of the cloud (E_i and D_i) and at the lateral boundaries (E_s and D_s). Final and complete detrainment (D_f) occurs at $t_* = \tau$.

Stratocumulus

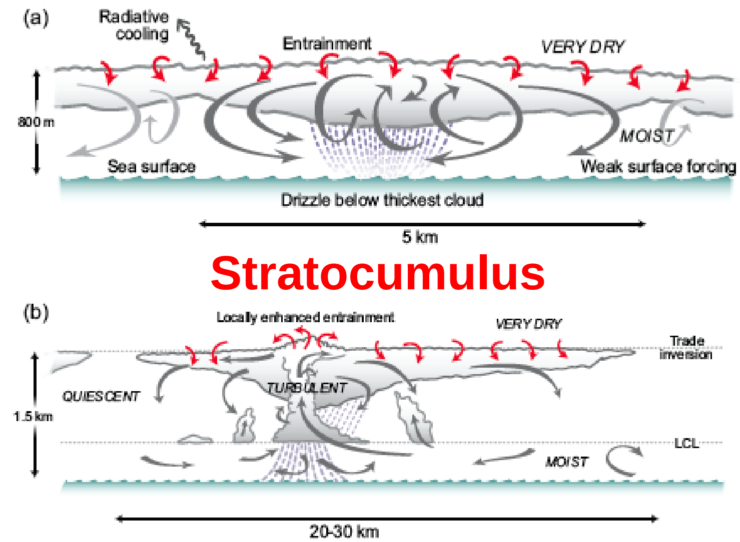


FIG. 11. Schematic showing structure of marine stratocumulus in (a) the shallow, well-mixed boundary layer; (b) deeper, cumulus-coupled boundary layers. Gray arrows indicate the primary motions on the scale of the boundary layer, while smaller red arrows indicate the small-scale entrainment mixing taking place at the inversion atop

And two different parts to the problem:

- **Dynamics/thermodynamics of entrainment, effect on mixing rate, buoyancy, vertical velocity, … (CLWG)**
- **Microphysics of entrainment, effect on nucleation, particle size distribution, … (CAPI)**
- **Even a small ALWG component via semi-direct effects**

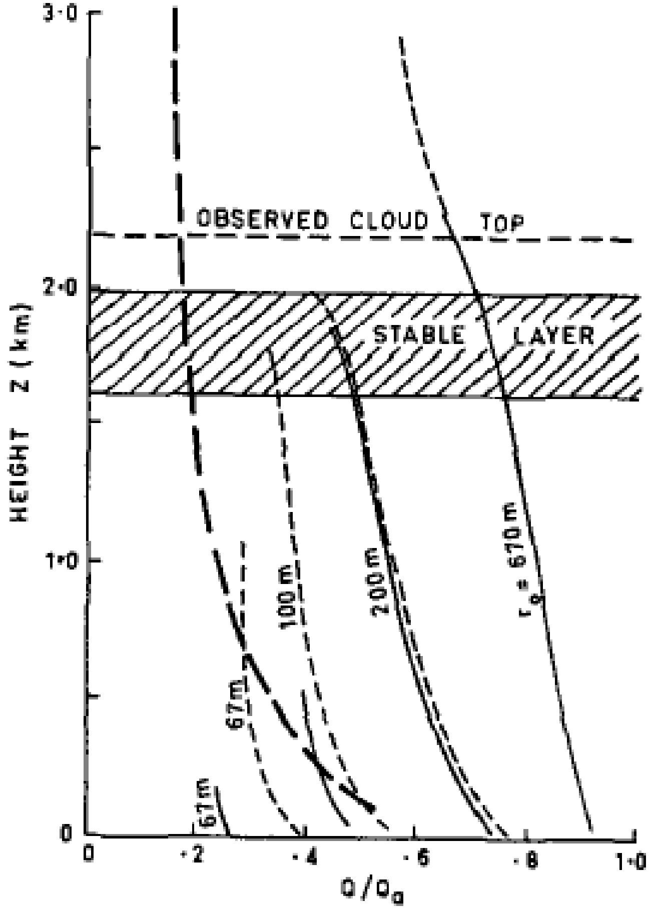


FIG. 2. Predicted ratio of liquid water content to its adiabatic value as a function of height for plumes of different initial radii obeying Eqs. (1)–(4) and growing in the environment listed in Table 2. Full lines are for zero initial updraft and temperature excess, dotted lines for initial values of 1 m sec^{-1} and 1C. The lines terminate at the maximum heights reached by the plumes. The heavy dashed line represents observed values of Q/Q_a.

"Warner paradox" (1970):

Difficult to get observed convective cloud top height and liquid water content right at the same time using the lateral entraining plume paradigm; also does not explain inhomogeneity

GCMs have traditionally opted to get cloud top right -> weak entrainment within lateral entrainment framework

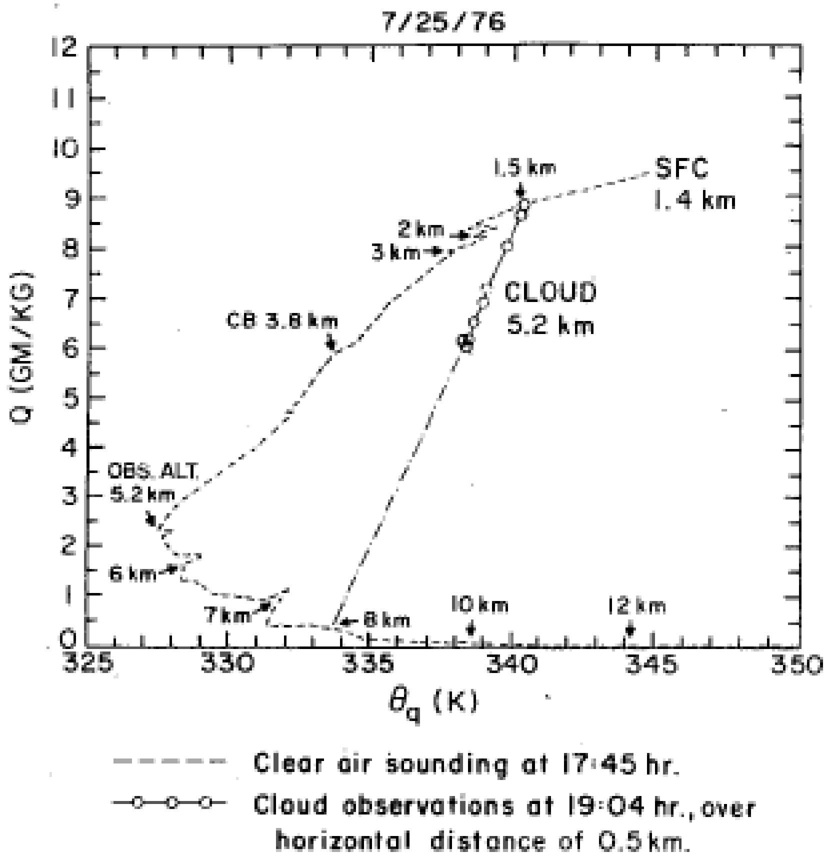


FIG. 4. Comparisons of the total mixing ratio Q and the wet equivalent potential temperature θ_q computed from data collected inside a growing cumulus cloud with Q and θ_q values of a representative sounding. The dashed line refers to the sounding; the points connected by lines represent the in-cloud observations. The data correspond to the first half-kilometer shown in Fig. 3. Air with the observed properties could have been formed by mixing air from the surface levels with air from ~8 km as indicated by the dot-dashed line. The observation level was 5.2 km (−2°C). Cloud base (CB) was at 3.8 km.

"Paluch diagram" (1979):

Conserved variable analysis apparently showing that observed properties of air within convective clouds can be interpreted as a series of mixtures of cloud base air and cloud top air

Entrainment through top rather than sides, leading to penetrative downdrafts

Parameterized by Emanuel (1991)

Adding to the confusion…

- Maybe both cloud top and lateral entrainment occurring at the same time? (e.g., Blyth et al. 1988, Raga et al. 1990, Taylor and Baker 1991) – Dependence on RH of air outside cloud?

- Much talk about undilute air in early aircraft observations, but little if any evidence in more recent observational and CRM studies (e.g., Zipser 2003; Khairoutdinov and Randall 2006; Romps and Kuang 2010)

- LES model inferences:

  - Particle tracking implying lateral entrainment yet conserved variables produce Paluch diagram behavior (Heus et al. 2008)

  - Inhomogeneity from deterministic entrainment by pdf of cloud base properties (Neggers et al. 2002) vs. intermittent stochastic entrainment from uniform cloud base properties (Romps and Kuang 2010)

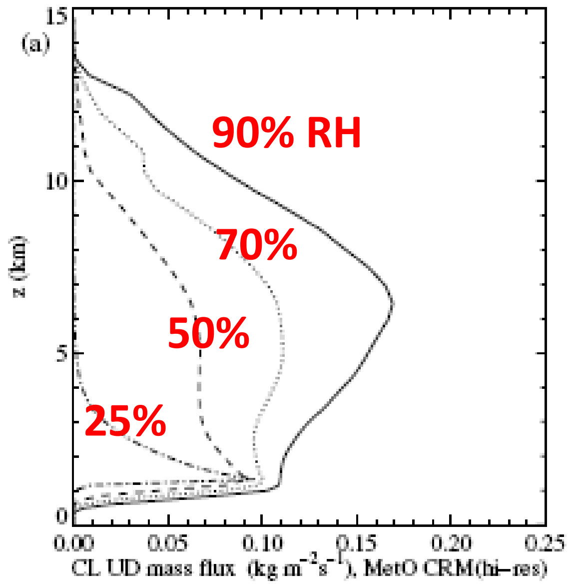
GCM cumulus parameterizations are not sensitive enough to free troposphere humidity to capture the transition from shallow to midlevel to deep convection; ruins diurnal cycle over land, MJO

(Derbyshire et al., 2004; Guichard et al. 2004)

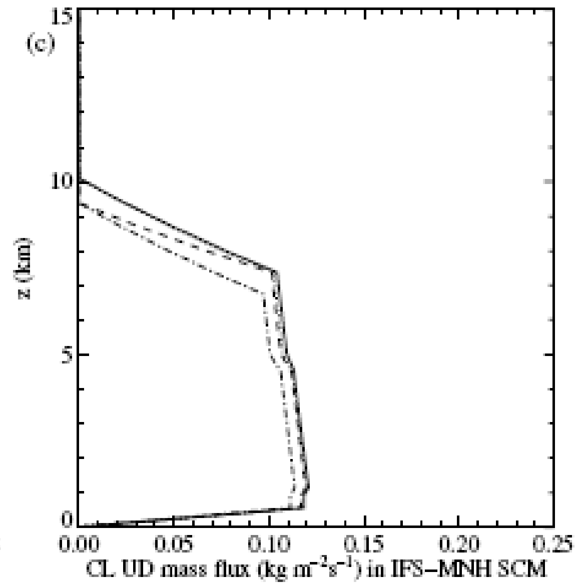
Need stronger entrainment, decreasing as convection deepens

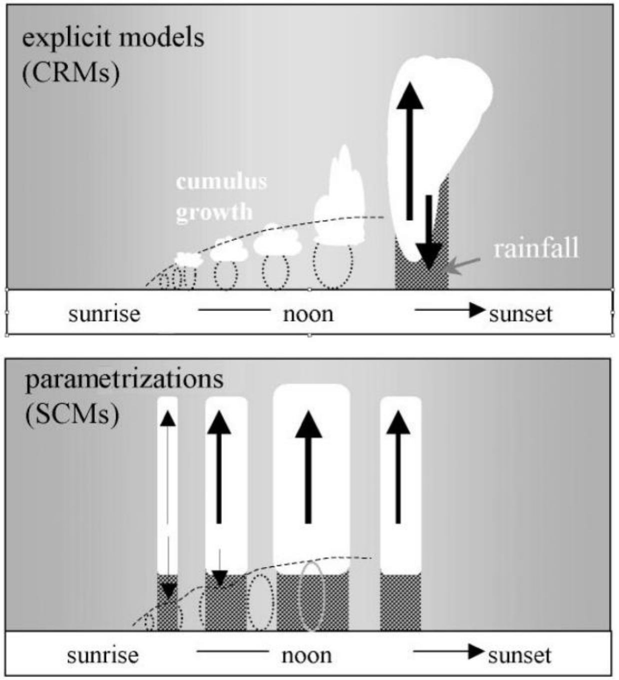
(Grabowski et al., 2006; Kuang and Bretherton, 2006; Khairoutdinov and Randall, 2006; Del Genio and Wu 2010)

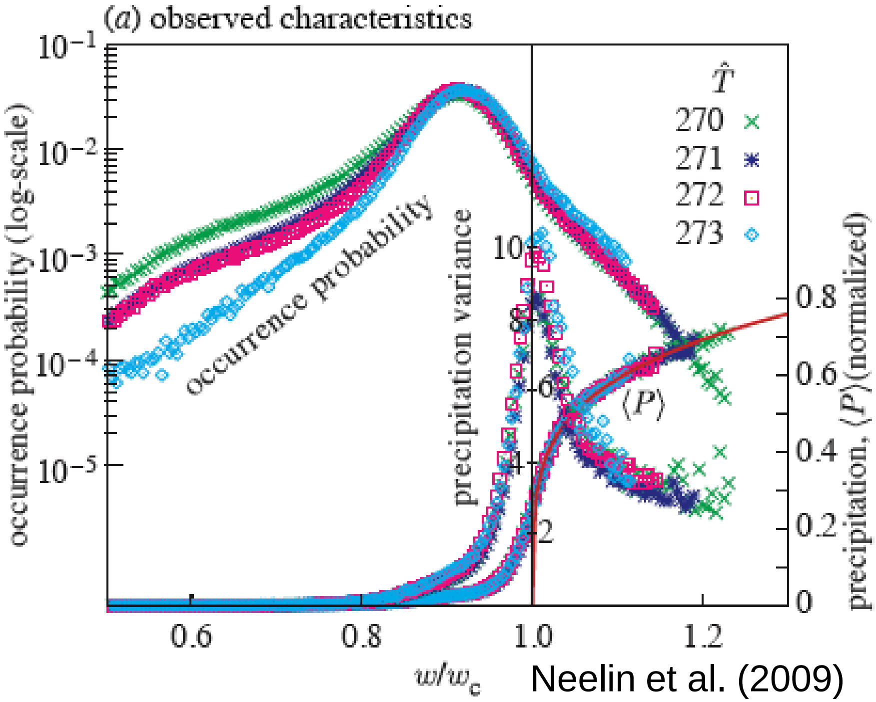
Cloud-Resolving Models



Single Column Models





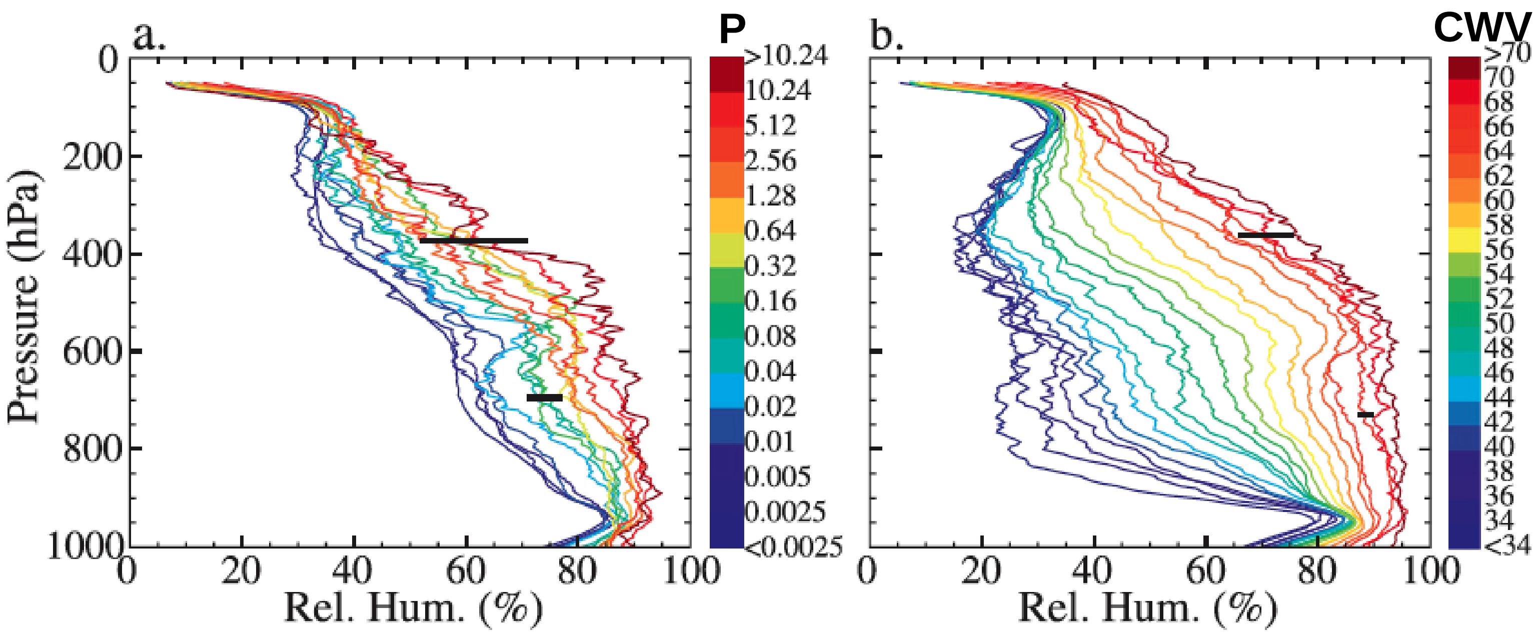


Neelin et al. (2009)

- Precipitation increases sharply above a critical value (~50 mm) of column water vapor

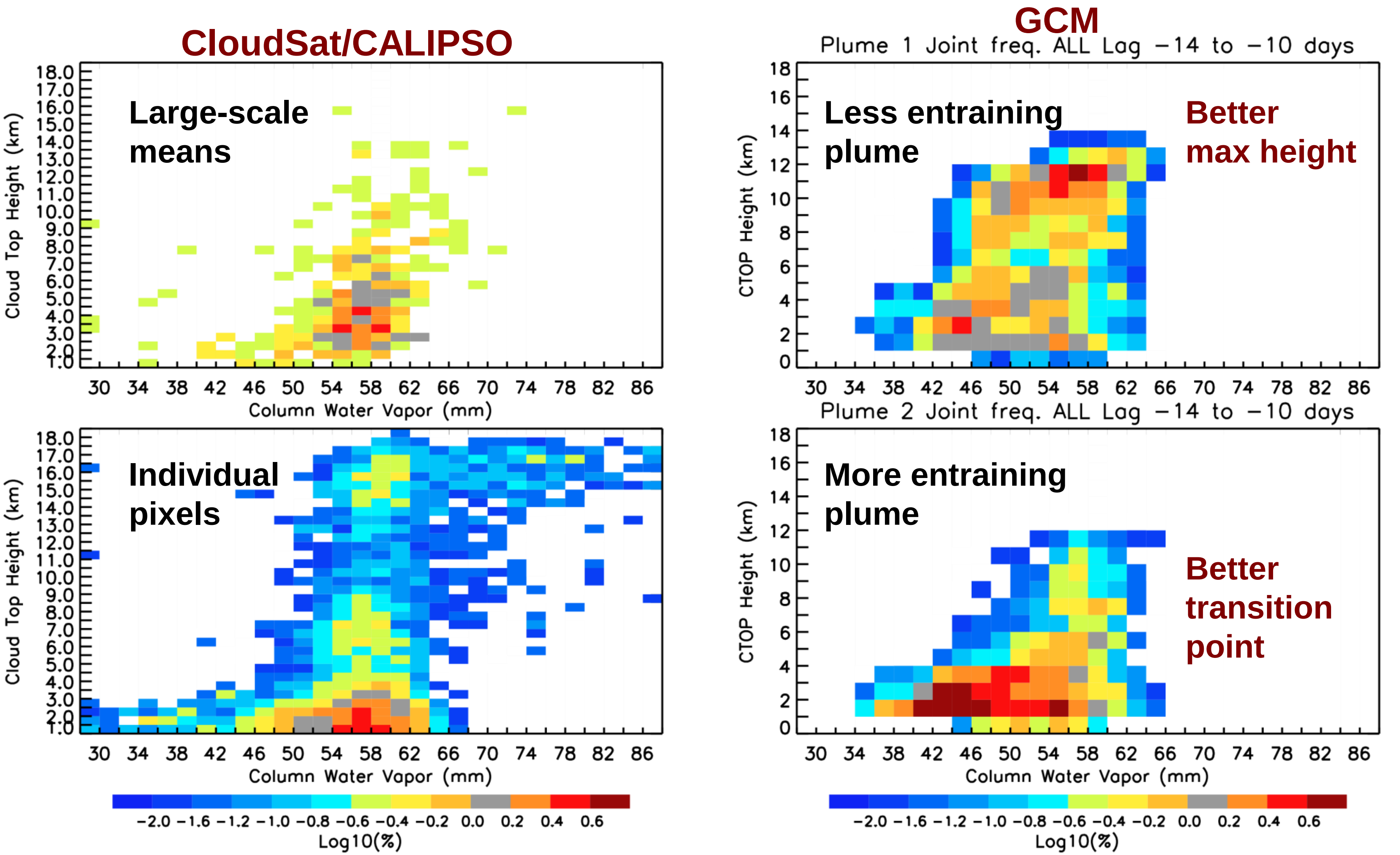
-Large variance in P near the critical value, where atmosphere spends most of its time

- Behavior primarily due to increasing humidity of middle troposphere as CWV increases



Holloway and Neelin (2009)

Convective cloud top height vs. column water vapor in MJO shallow-deep transition, CloudSat/CALIPSO vs. GISS GCM



Challenge to a possible Entrainment FG: Can you do better than this?

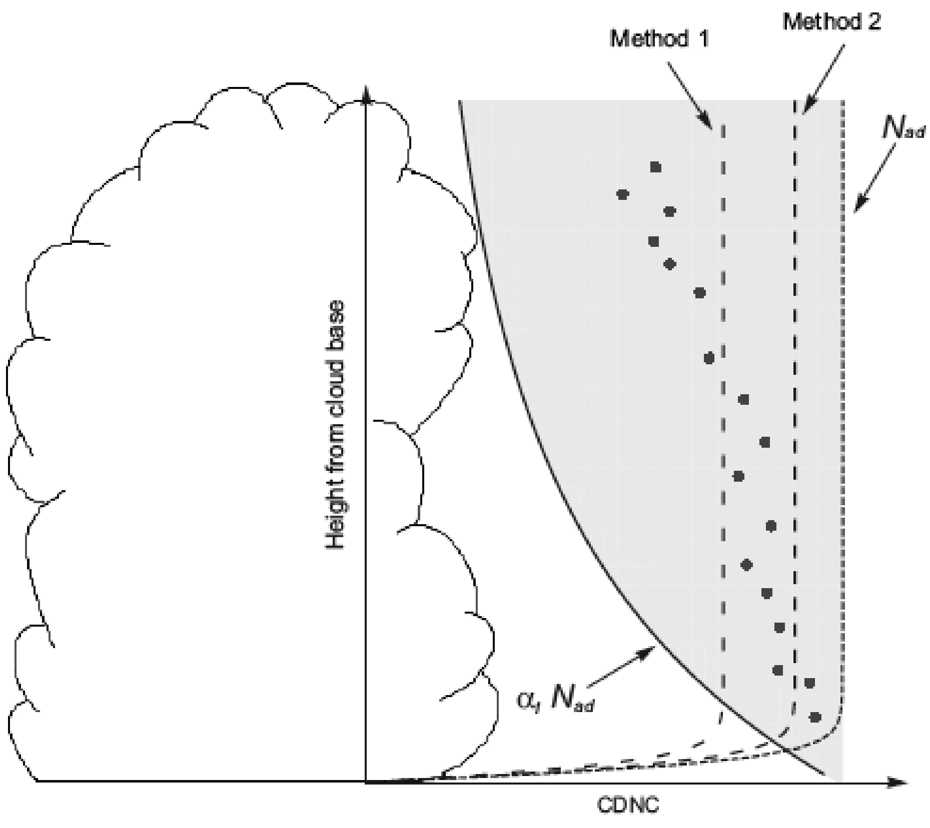


Figure 1. Schematic of the expected impact of predicted CDNC with the different approaches discussed in the text. The points represent actual observed CDNC, while the shaded area represents the region bounded by the adiabatic (N_{ad}) and inhomogeneous mixing limits ($\alpha_l N_{ad}$). Dashed lines represent CDNC predicted with BN07 when: $(1 - e/e_c) \sim \alpha_{l,avg}$, and, $(1 - e/e_c)$ derived from least square fits to observed α_l profiles.

Morales et al. (2011)

Entrainment effect on CDNC, particle size distribution:

Effective supersaturation seen during nucleation

Homogeneous (constant CNDC) vs. inhomogeneous (variable CDNC) mixing

Depends on ratio mixing time/evap time

Krueger et al. (1997)
Lehmann et al. (2009)
Lu et al. (2011)

Stratocumulus: Many issues, especially at cloud top interface

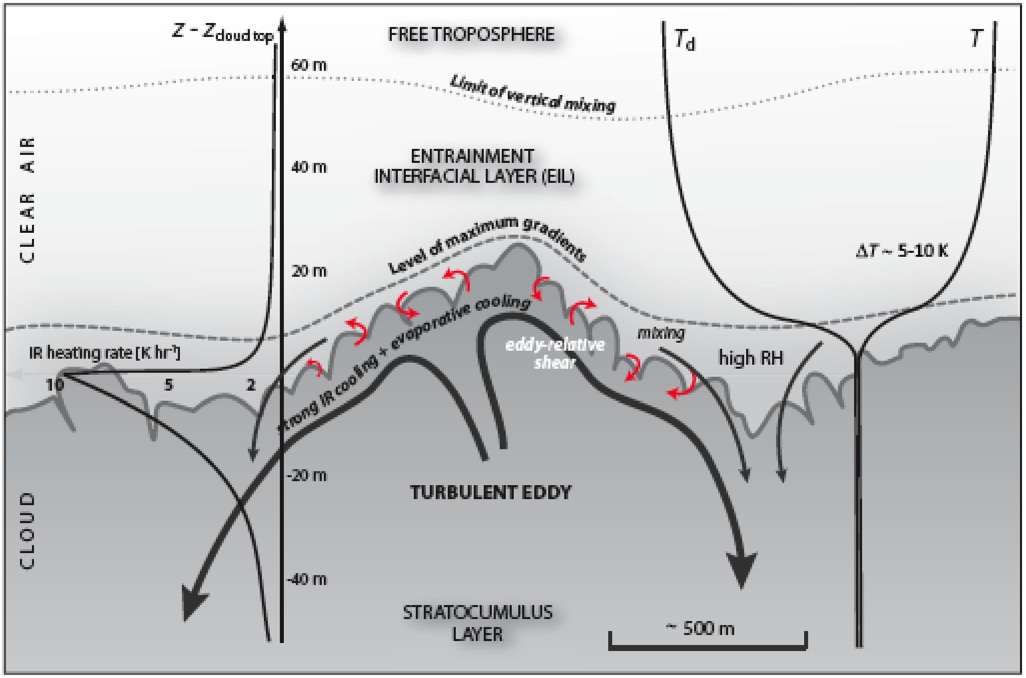
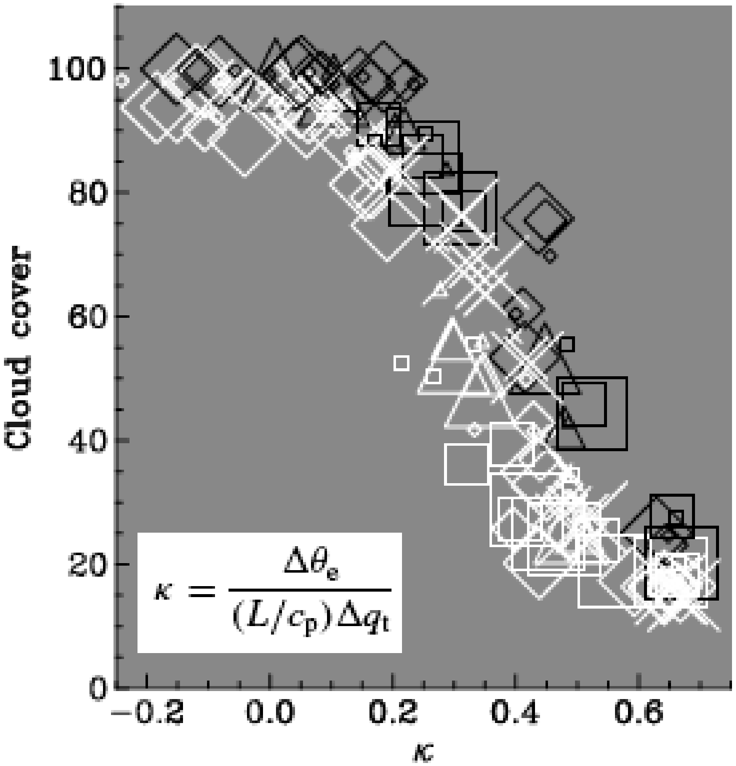


FIG. 13. Schematic of the entrainment interfacial layer (EIL) ato[illegible] a layer of marine stratocumulus.

Wood (2011)



Lock (2009)

- Vertical resolution (~5 m needed)
- Relative contribution of LW cooling and evaporation to buoyancy
- Droplet sedimentation
- Drizzle evaporation decoupling
- Humidity above inversion

Thermodynamic structure differences between overcast and clear are subtle – a tremendous challenge for GCMs

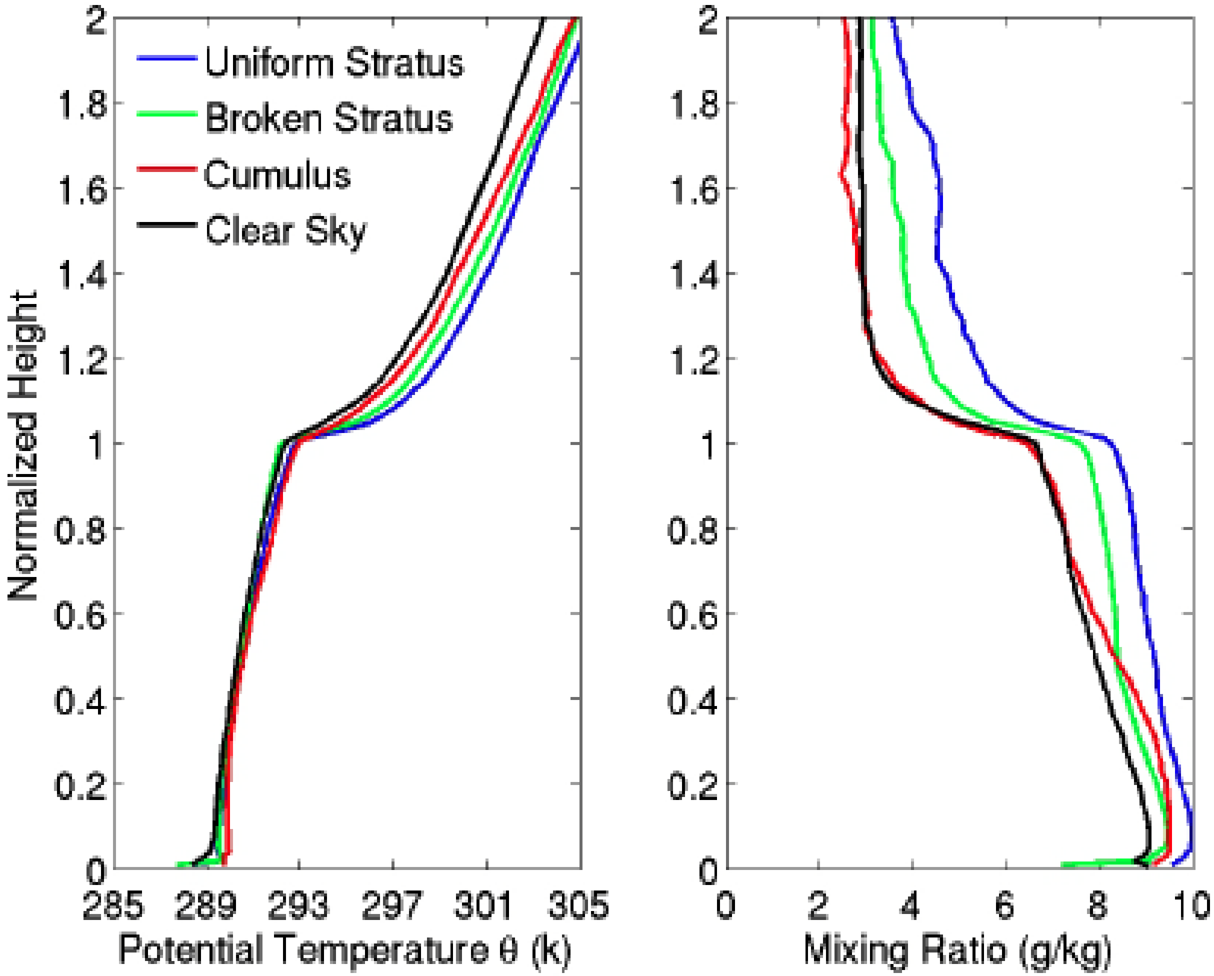
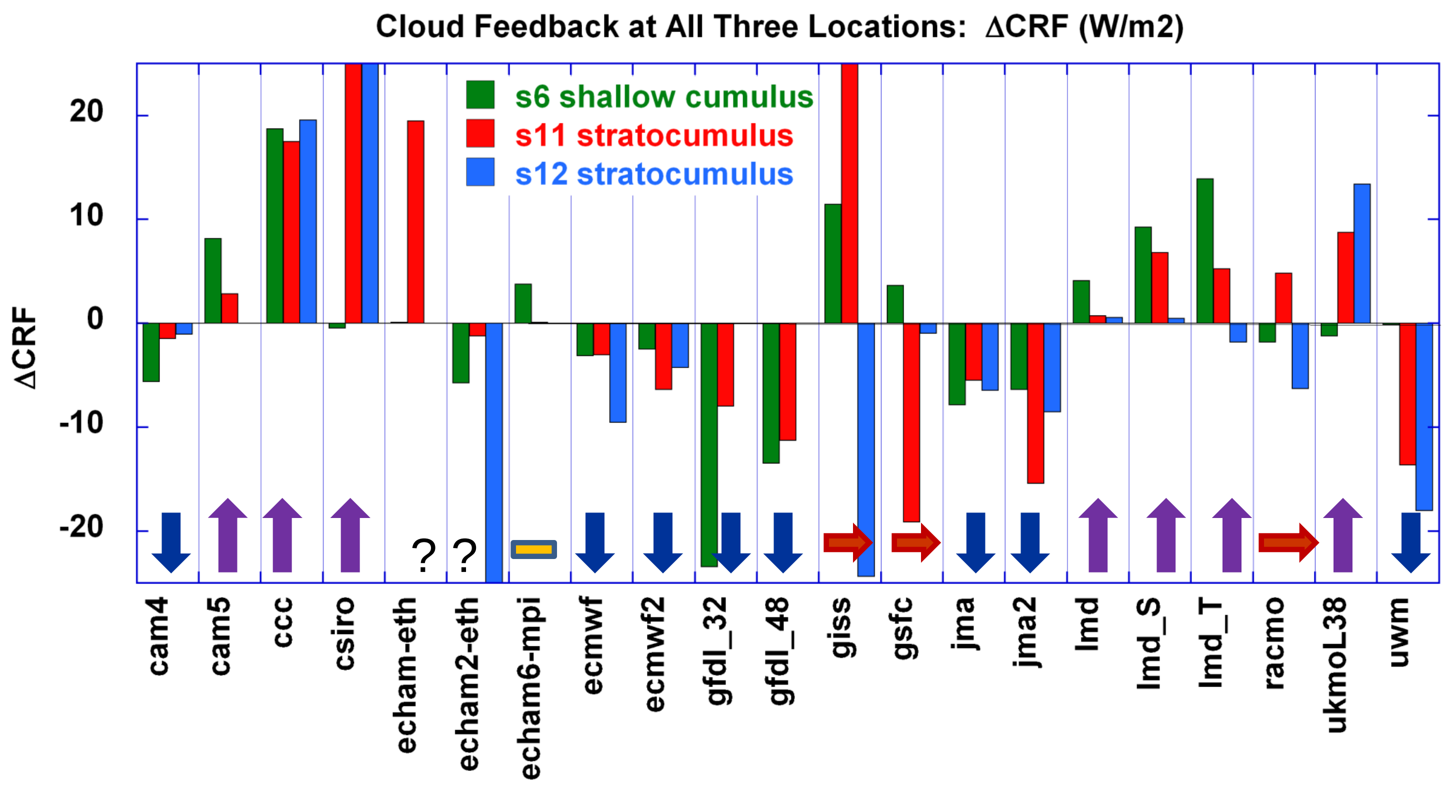


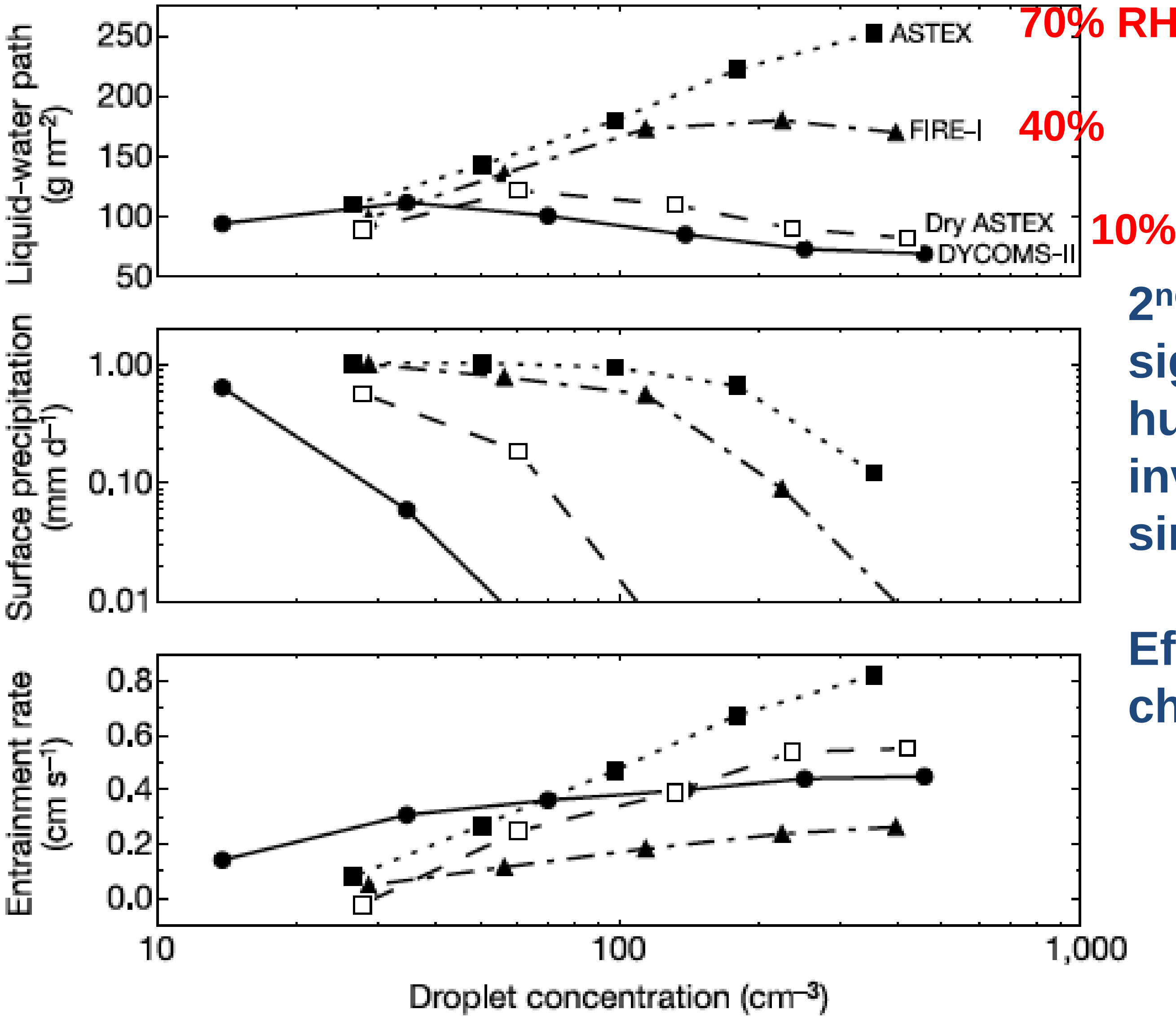
Figure 3: BL depth normalized profiles of potential temperature and mixing ratio for different BL cloud regimes.

Ghate and Miller (2011)

CGILS (Zhang, Blossey): SCMs all over the place in low cloud feedback; SCMs ~agree in equilibrium cloud but differ in feedback



- ⬆ **5 models with positive feedback: CAM5, CCC, CSIRO, LMD, UKMO**
- ⬇ **5 model with negative feedback: CAM4, ECMWF, GFDL, JMA, UWM**
- ▬ **1 with little feedback: ECHAM-MPI; ? 1 to equilibrate ECHAM-MPI**
- ➡ **3 models with different signs at the three locations: GISS, GSFC, RACMO**

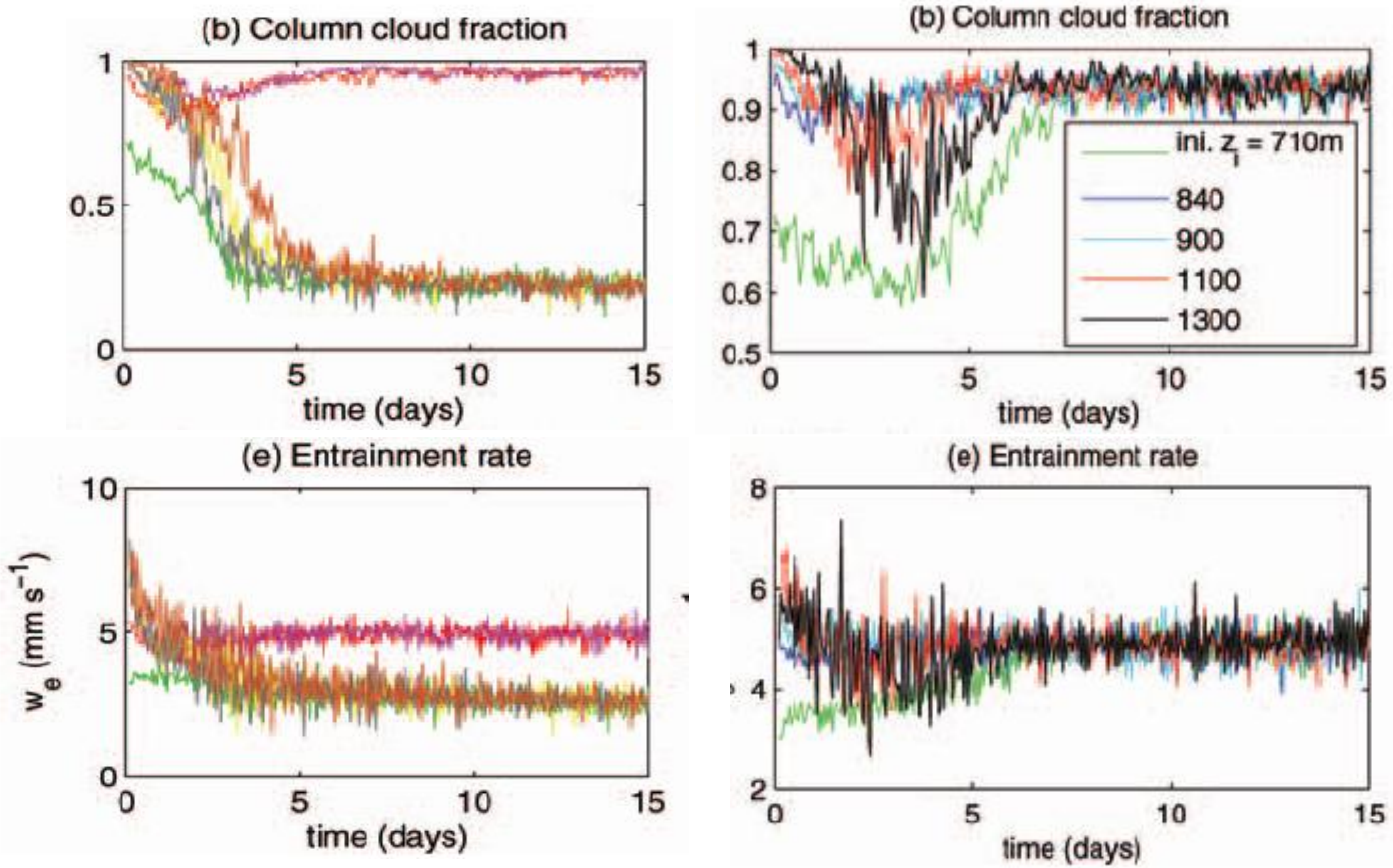


2nd AIE can change sign depending on humidity of air above inversion in LES simulations of Sc

Effect on precip also changes entrainment

Ackerman et al. (2004)

LES model sensitivity to inversion height, droplet number



CDNC = 150

CDNC = 30

Bretherton et al. (2010)

Summary

- Entrainment a problem for > half a century – we are not going to solve it. Can we take a couple of steps forward?
- Observational constraints? From existing IOPs or AMF deployments?
- Fundamentals of entrainment important…but implications for GCMs important too -> What matters? How well can we simulate large-scale relationships?
- LES/CRM intercomparisons…Are humidity, buoyancy reversal, CDNC dependences robust across LES/CRMs?
- Who will lead? Rounding up the usual suspects not an attractive option