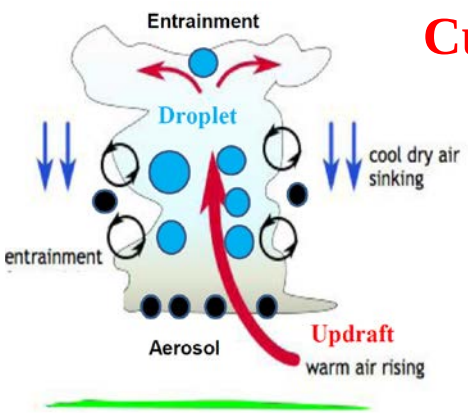
Exploring Entrainment-Mixing-Microphysics Relationships/Interactions in CAPI Context

Yangang Liu (BNL) and Chunsong Lu (NUIST)*

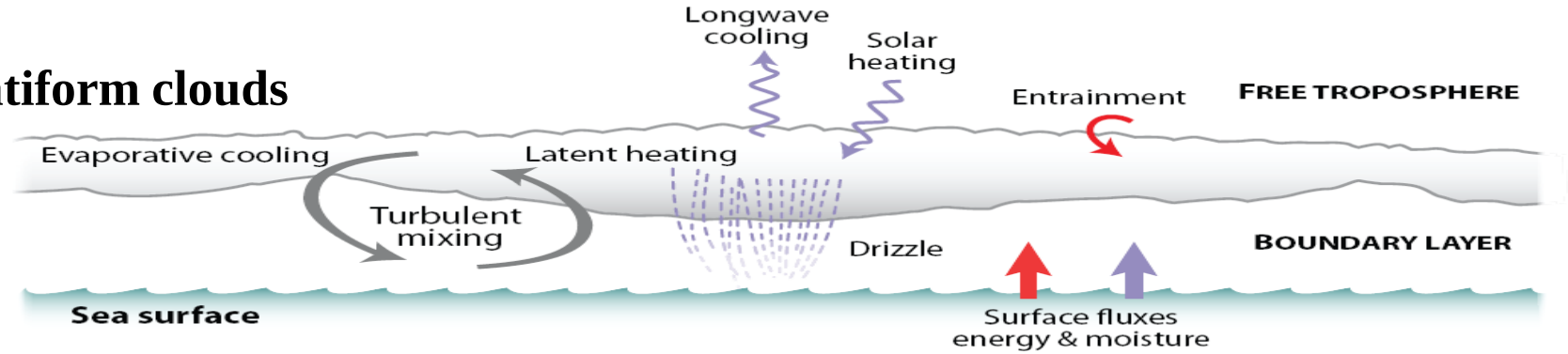
- **with contributions from many collaborators over the years and thanks To RACORO team**

ASR Fall WG Meeting
Nov 17-19, 2014



Cumulus clouds

Stratiform clouds



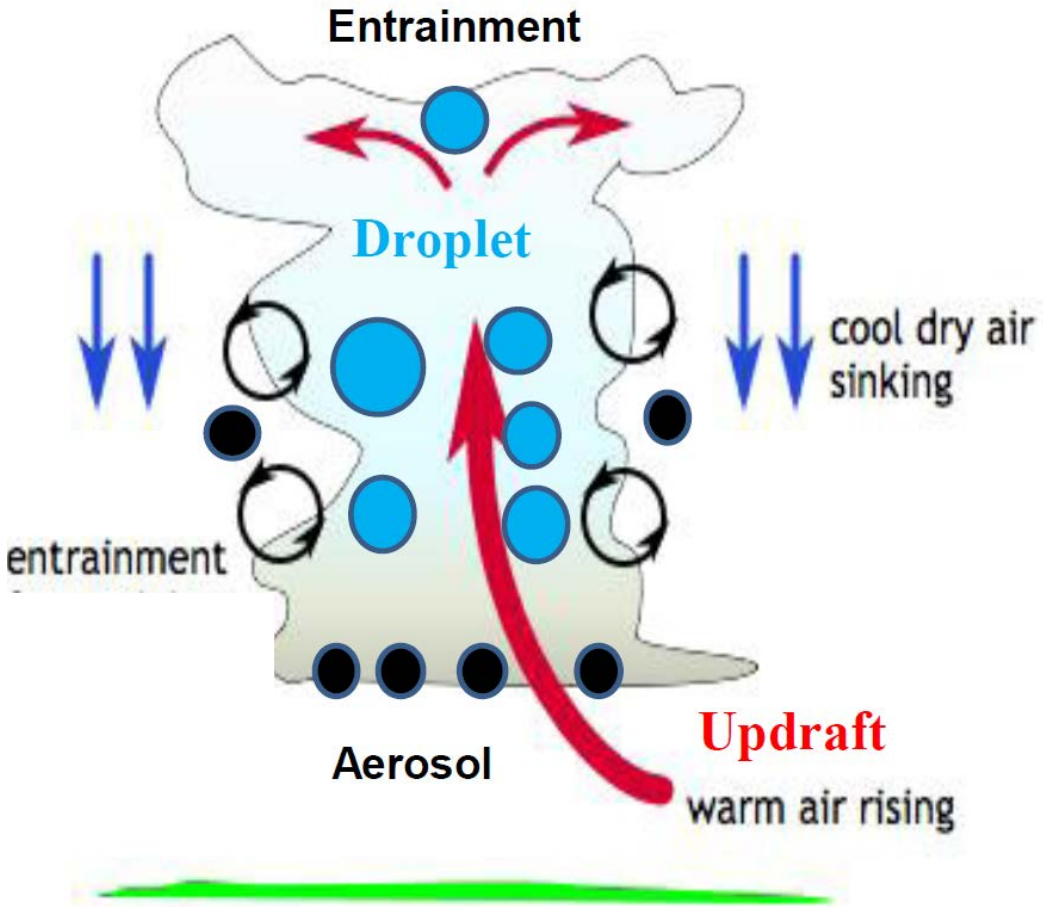
Why

- CAPI challenges

- Convection parameterization
-- Poor entrainment rate
-- Lacking microphysics

- Microphysics parameterization beyond adiabatic paradigm

- Observational analysis
-- verify hypothesis
-- guide para. development



Entrainment and subsequent mixing processes are critical links between microphysics, cloud dynamics, and environment, and key to improving parameterizations of convection and aerosol-cloud interactions.

What

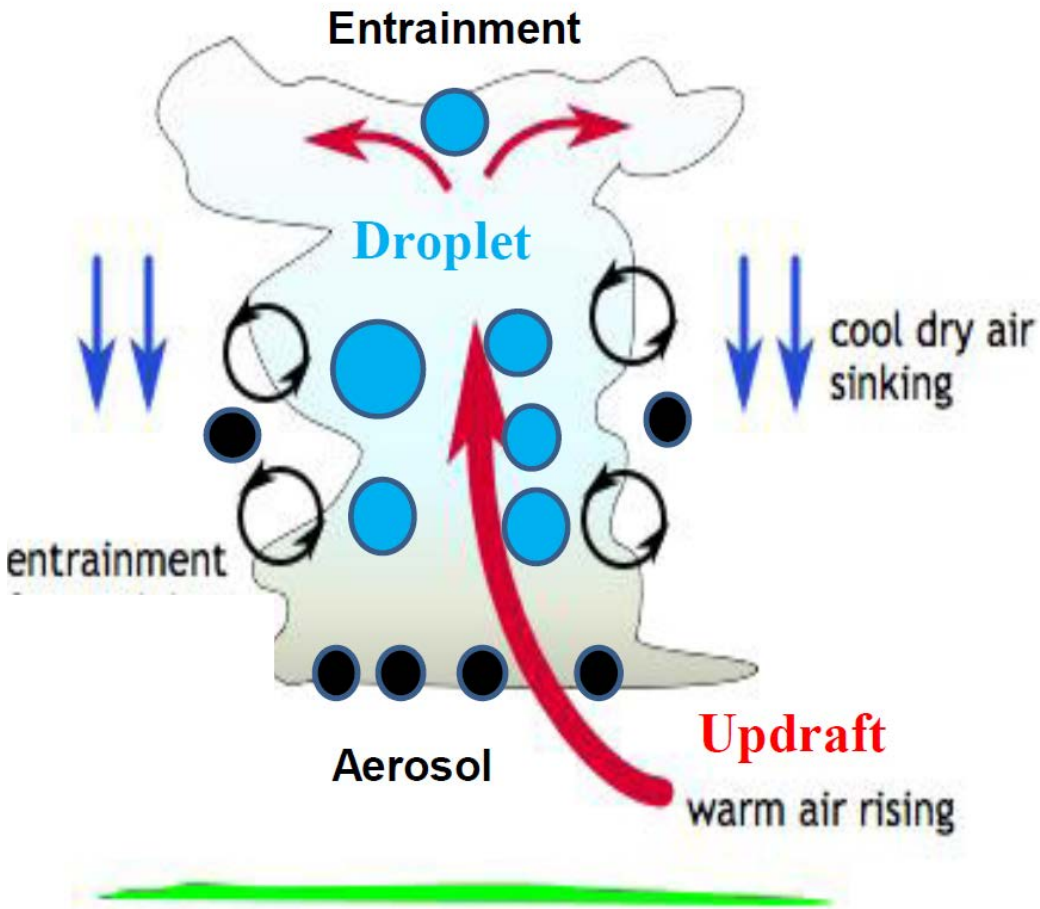
- Vertical velocity
- Buoyancy
- Dissipation
- Entrainment
- Turbulent mixing
- Microphysics

$$r_e = \beta \left(\frac{3}{4\pi\rho_w} \right)^{1/3} \left(\frac{L}{N} \right)^{1/3}$$

β is a function of relative dispersion

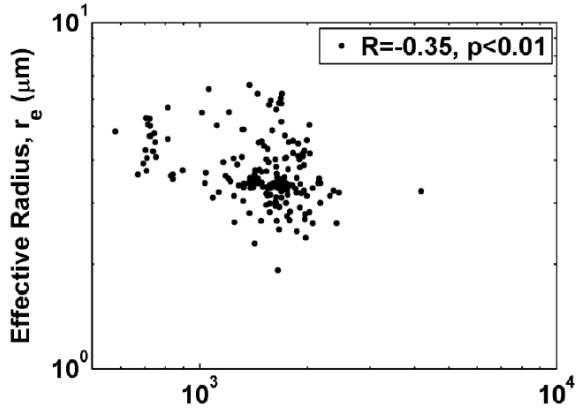
- Aerosol
- Environment RH
- Their relationships

(See Lu et al, 2011, 2012, 2013 and 2014 On entrainment method)

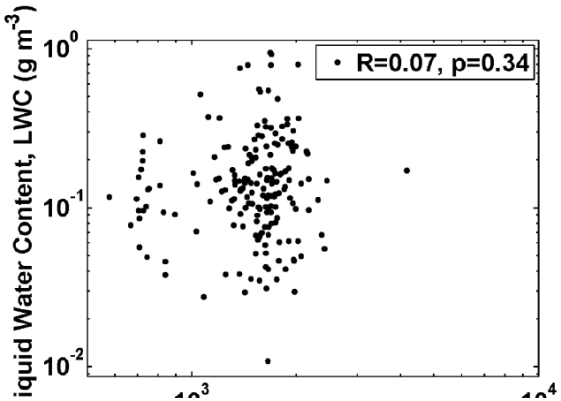


Results are for 186 growing non-precipitating shallow cumulus clouds collected during RACORO at SGP.

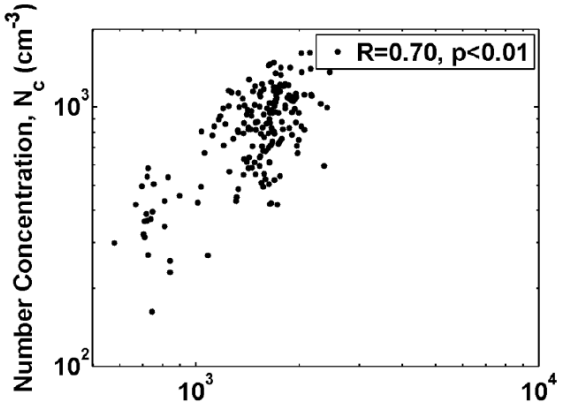
Aerosol vs.Microphysics



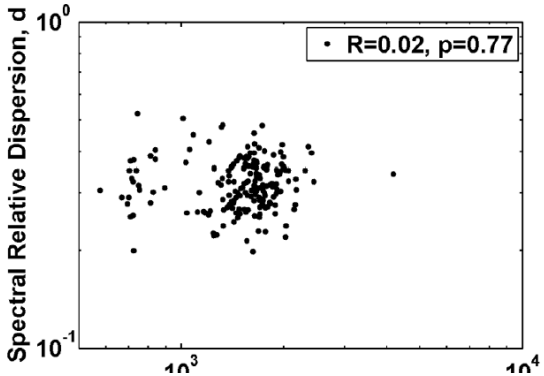
Aerosol Number Concentration (cm-3)



Aerosol Number Concentration (cm-3)



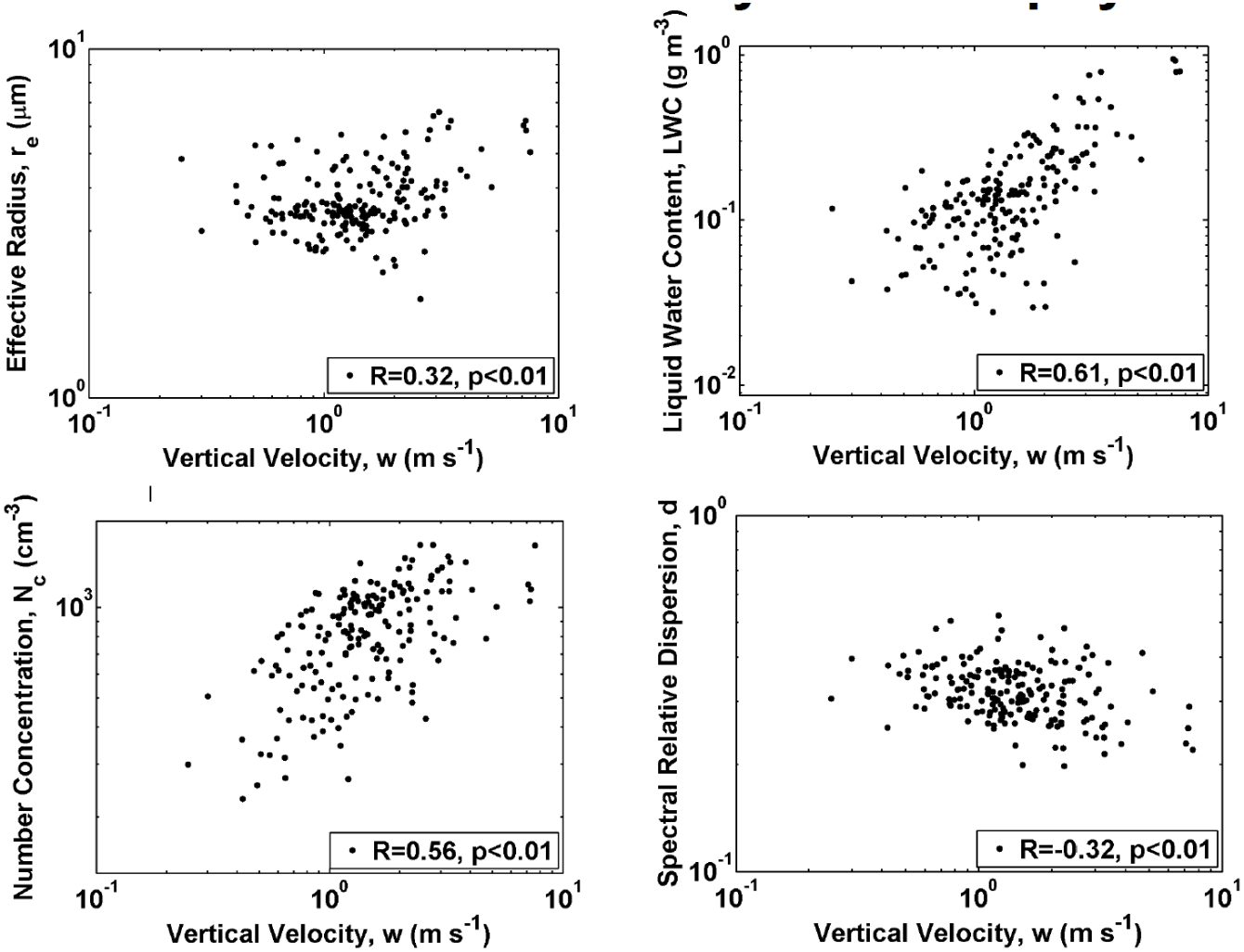
Aerosol Number Concentration (cm-3)



Aerosol Number Concentration (cm-3)

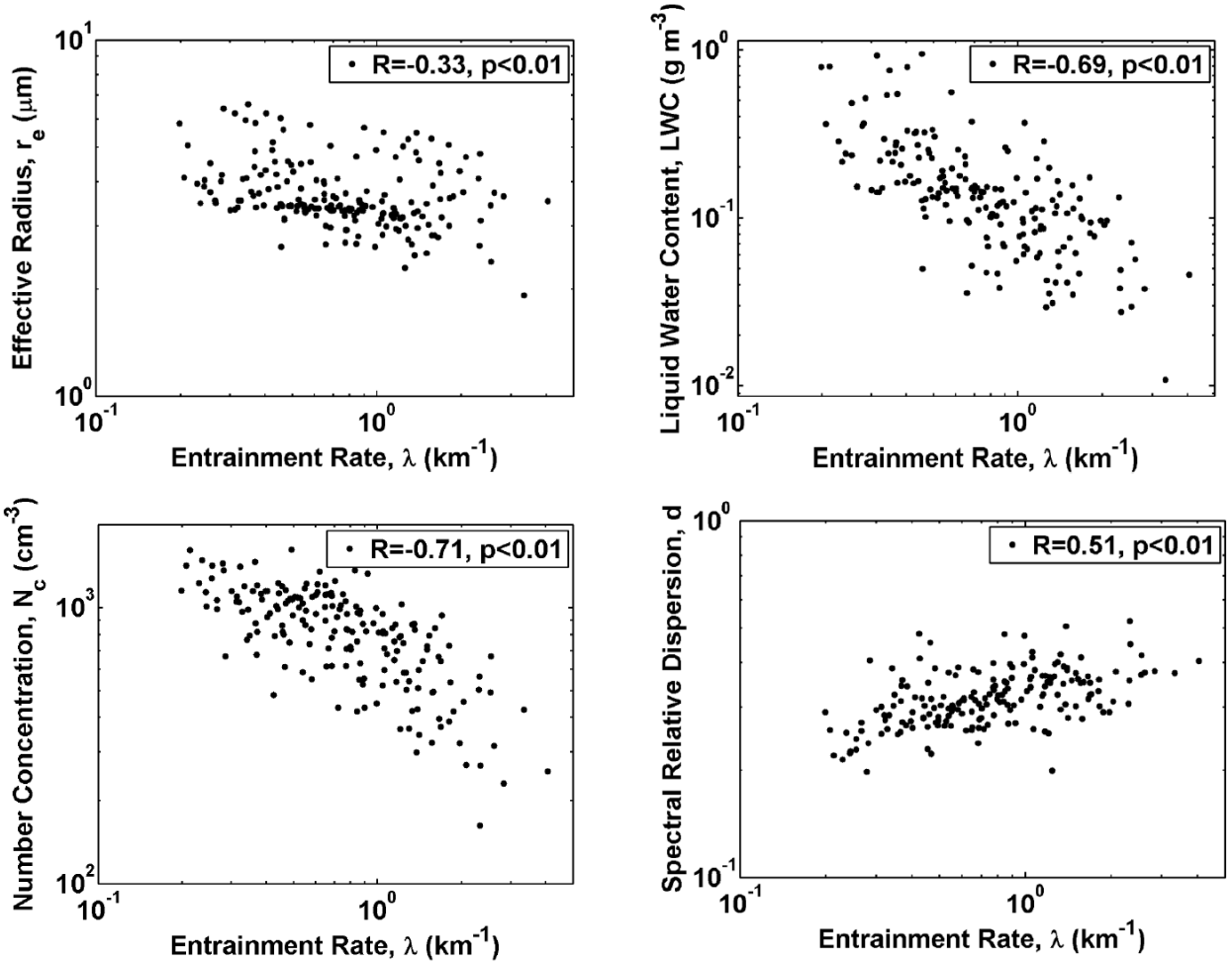
Except for dispersion, the relationships for effective radius and droplet concentration seem consistent with the first AIE, but result from complex interactions shown in next few slides.

Vertical Velocity vs. Microphysics



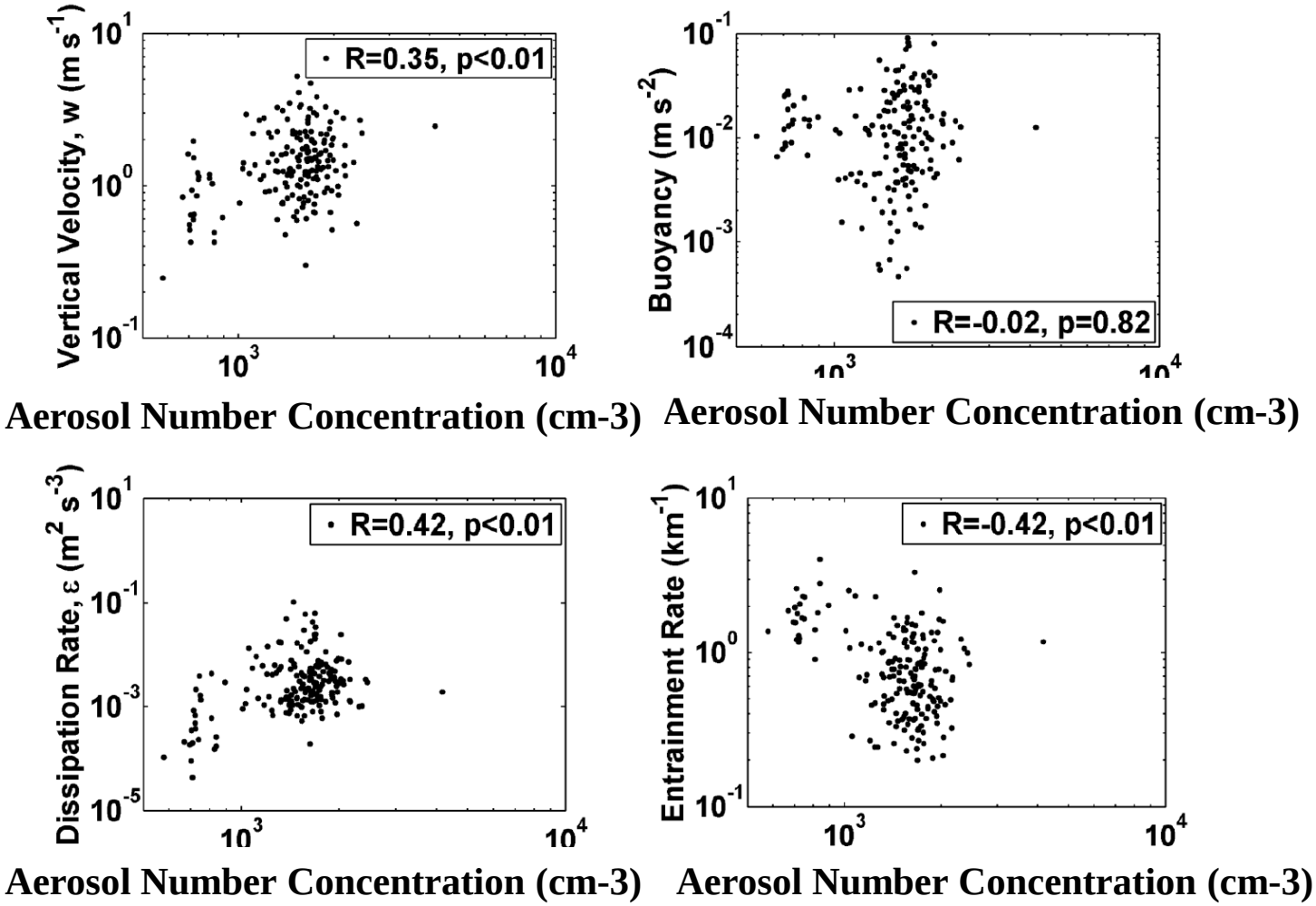
These relationships seem consistent with theoretical expectation in general, but with low correlation coefficients.

Entrainment Rate vs. Microphysics



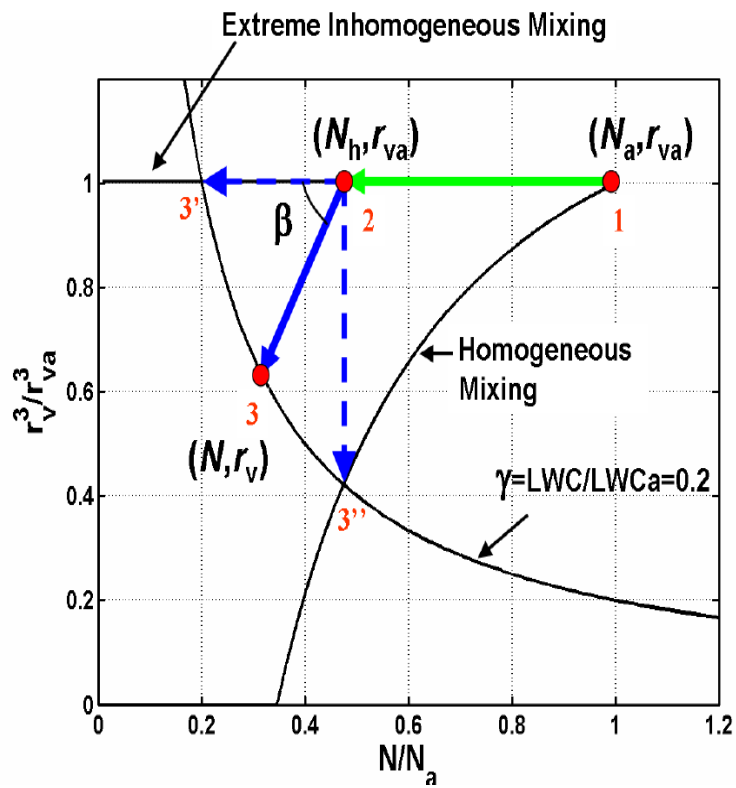
An increase in entrainment rate corresponds to decreases in LWC, droplet concentration, and droplet size but an increase in relative dispersion, largely consistent with homogenous mixing.

Aerosol vs. Dynamics

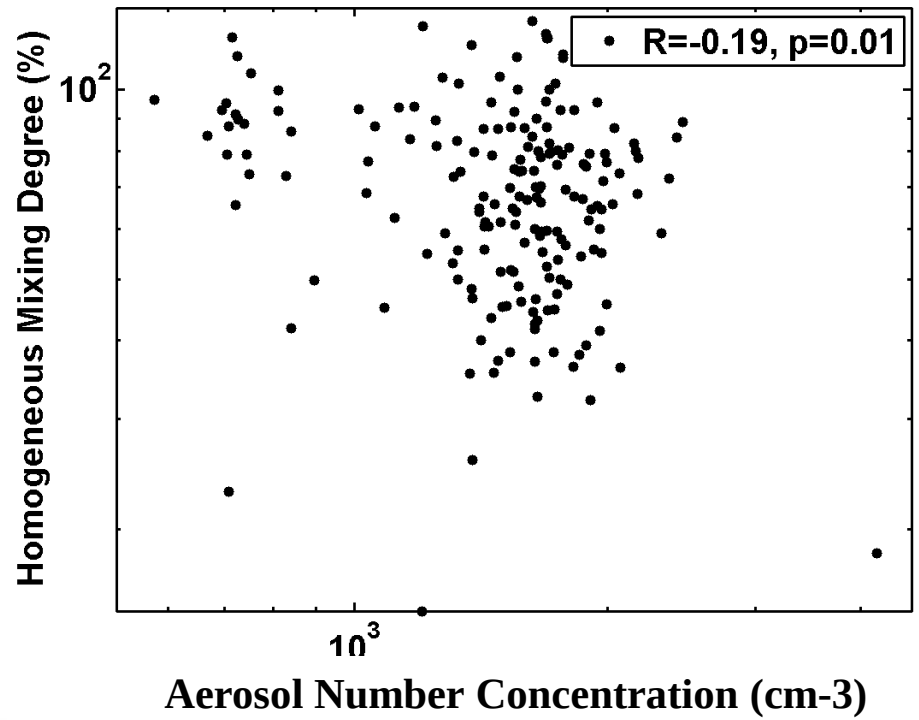


The increases of vertical velocity and turbulence dissipation rate agree with modeling studies (e.g., Ackerman et al 2004; Hue & Feingold 2006; Bretherton et al 2009)

Aerosol vs.Homogeneous Mixing Degree



(Lu et al., JGR 2013)



The result is marginally consistent with the expectation that a higher aerosol concentration would lead to a smaller homogeneous mixing degree (or more inhomogeneous) because faster droplet evaporation, OTHERS BEING EQUAL.

Take-Home Messages

- **There are (partial) correlations among all the quantities examined, suggesting complex couplings between aerosol, cloud microphysics, cloud dynamics and environment.**

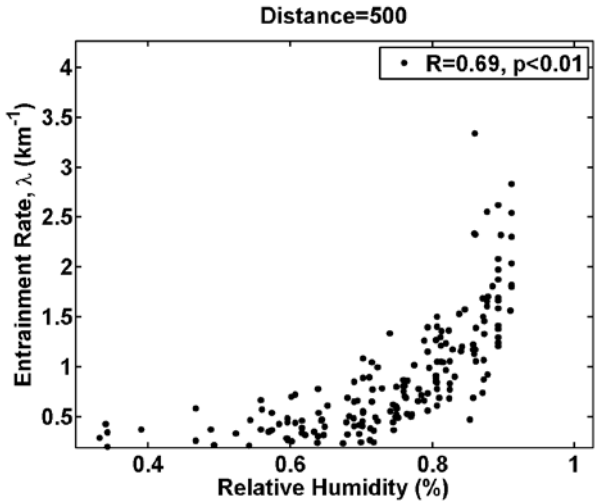
- **There appears to have AIE in terms of decreasing r_e with increasing aerosols, but as a result of complex chain of interactions.**

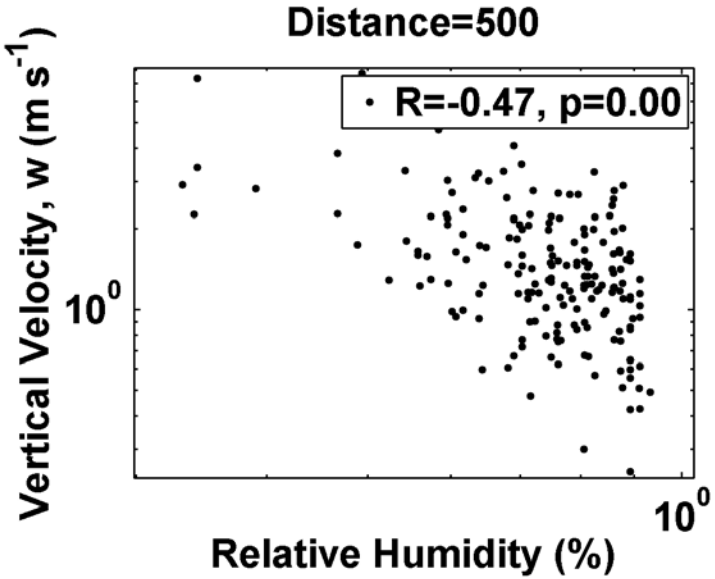
- **Disentangling these relationships is essential to improving parameterizations of aerosol-cloud interactions and convection.**

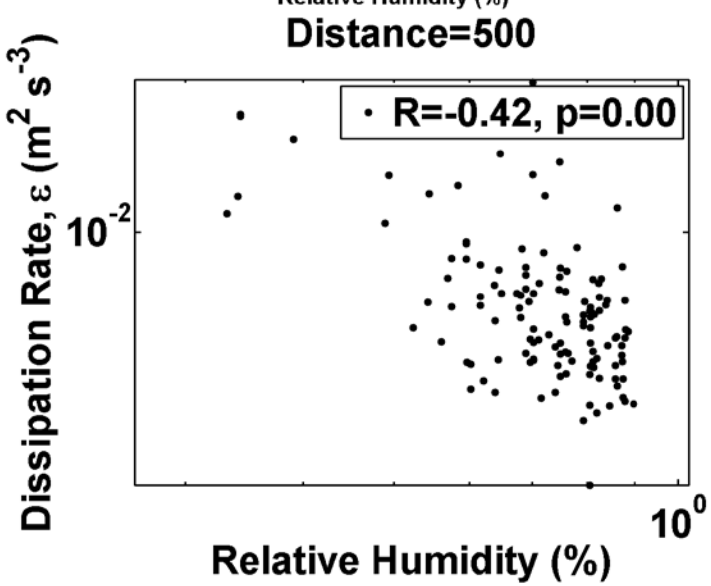
- **Just scratch surface; sc and precipitating clouds**

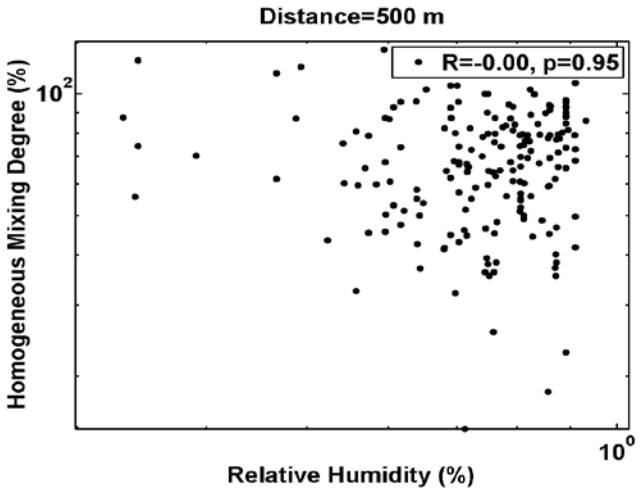
Backup Slides

RH vs. Dynamical Properties



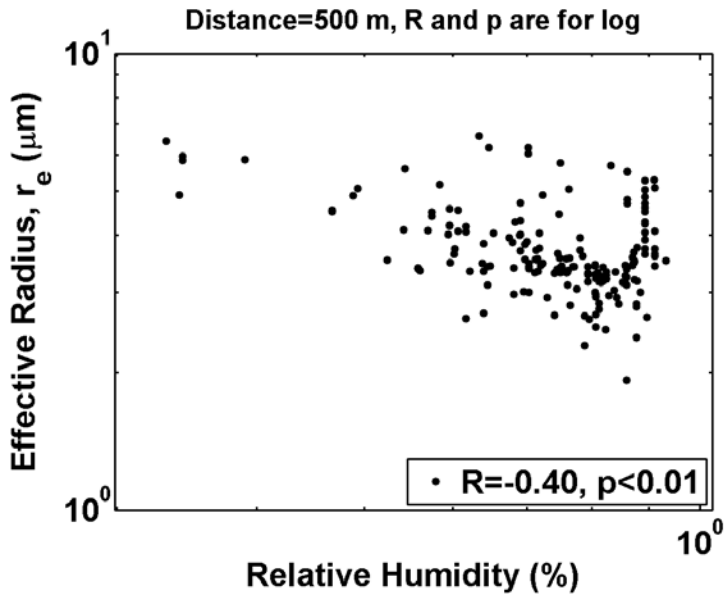


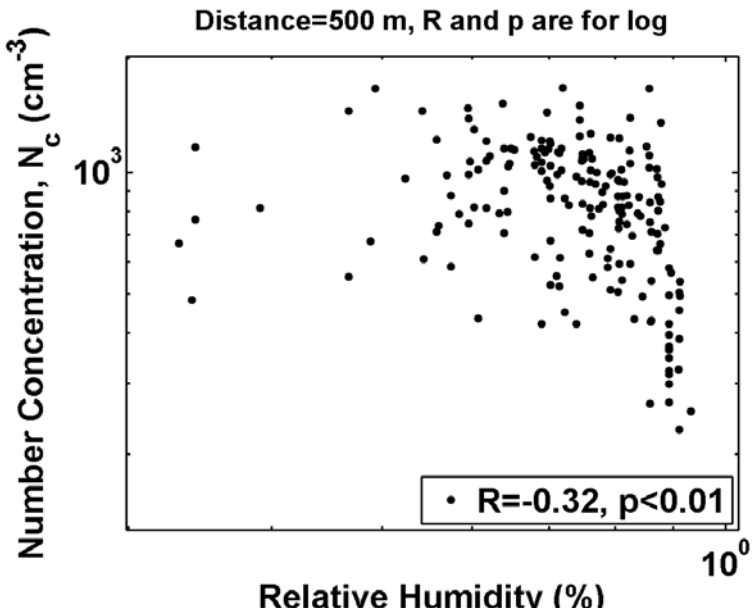


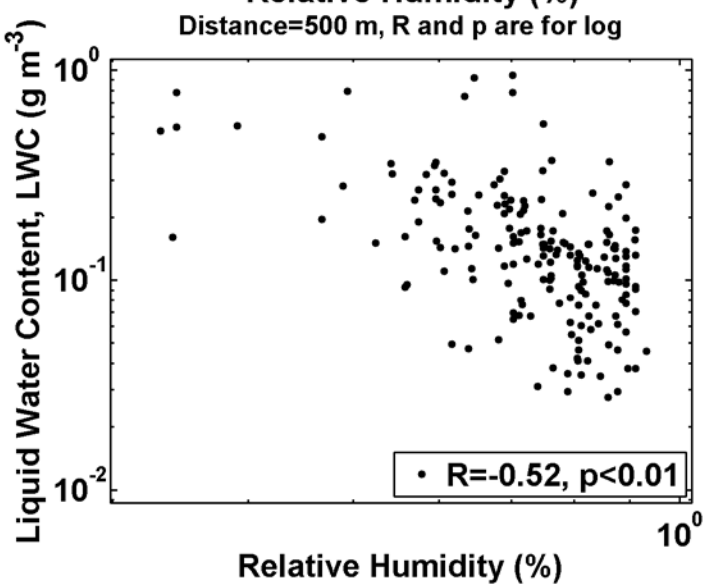


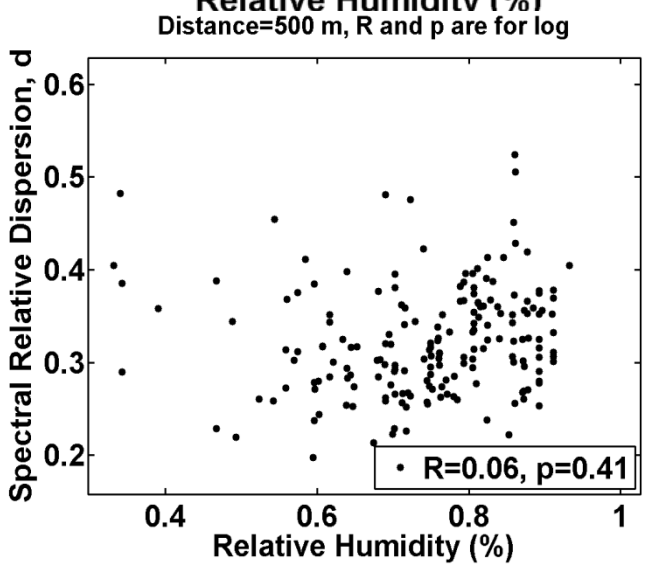
The results seem consistent with the modeling finding that entrained dry air enhances cloud dynamics, with puzzling entrainment rate and homogeneous mixing degree.

RH vs.Microphysics



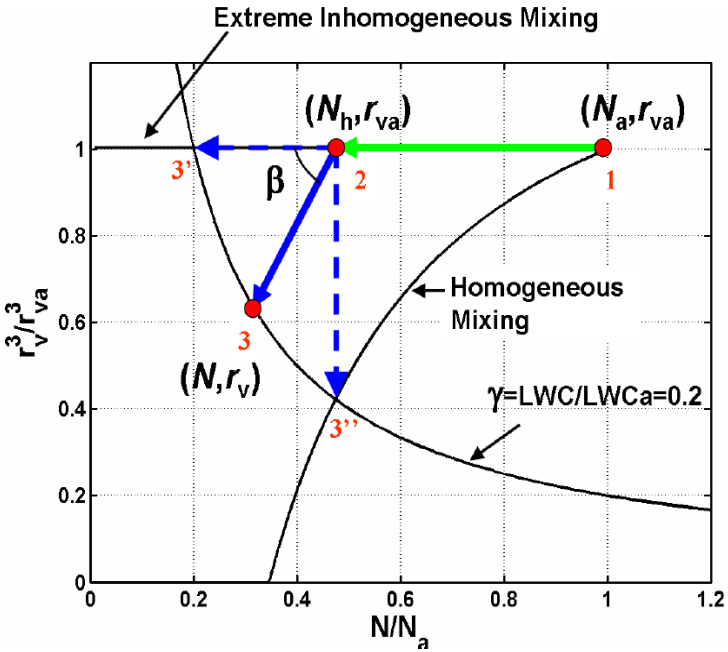


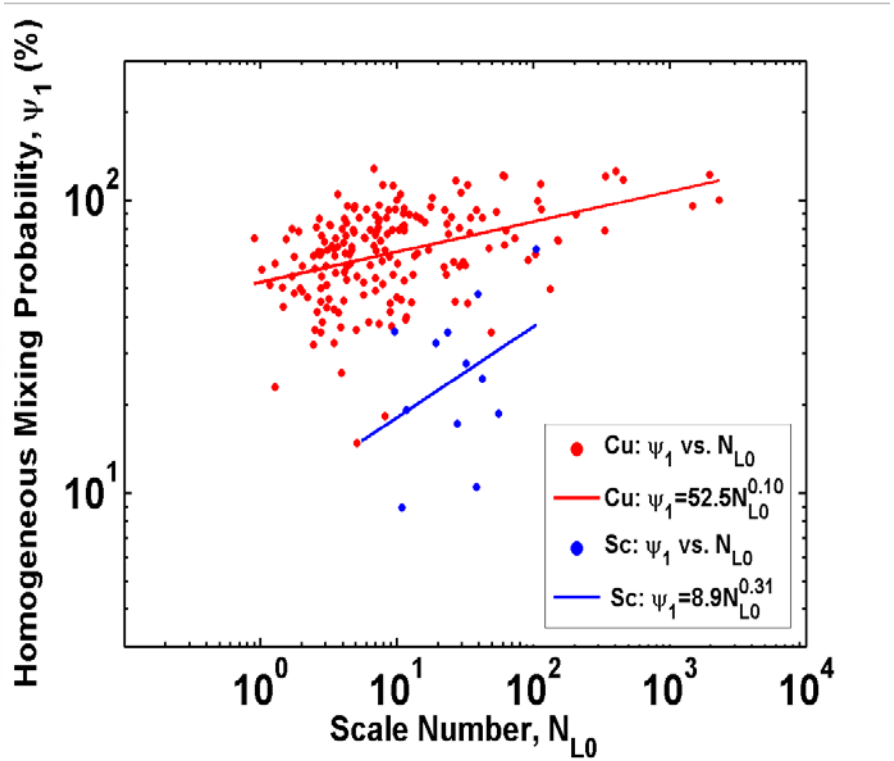




Contradict intuition first, but view together with RH-dynamics relationships

Parameterization of Mixing Mechanisms





Turbulent mixing processes in clouds often falls between the two extreme mechanisms; turbulent mixing in RACORO cumuli tend to be more homogeneous than stratiform clouds

(Lu et al., JGR, 2013).

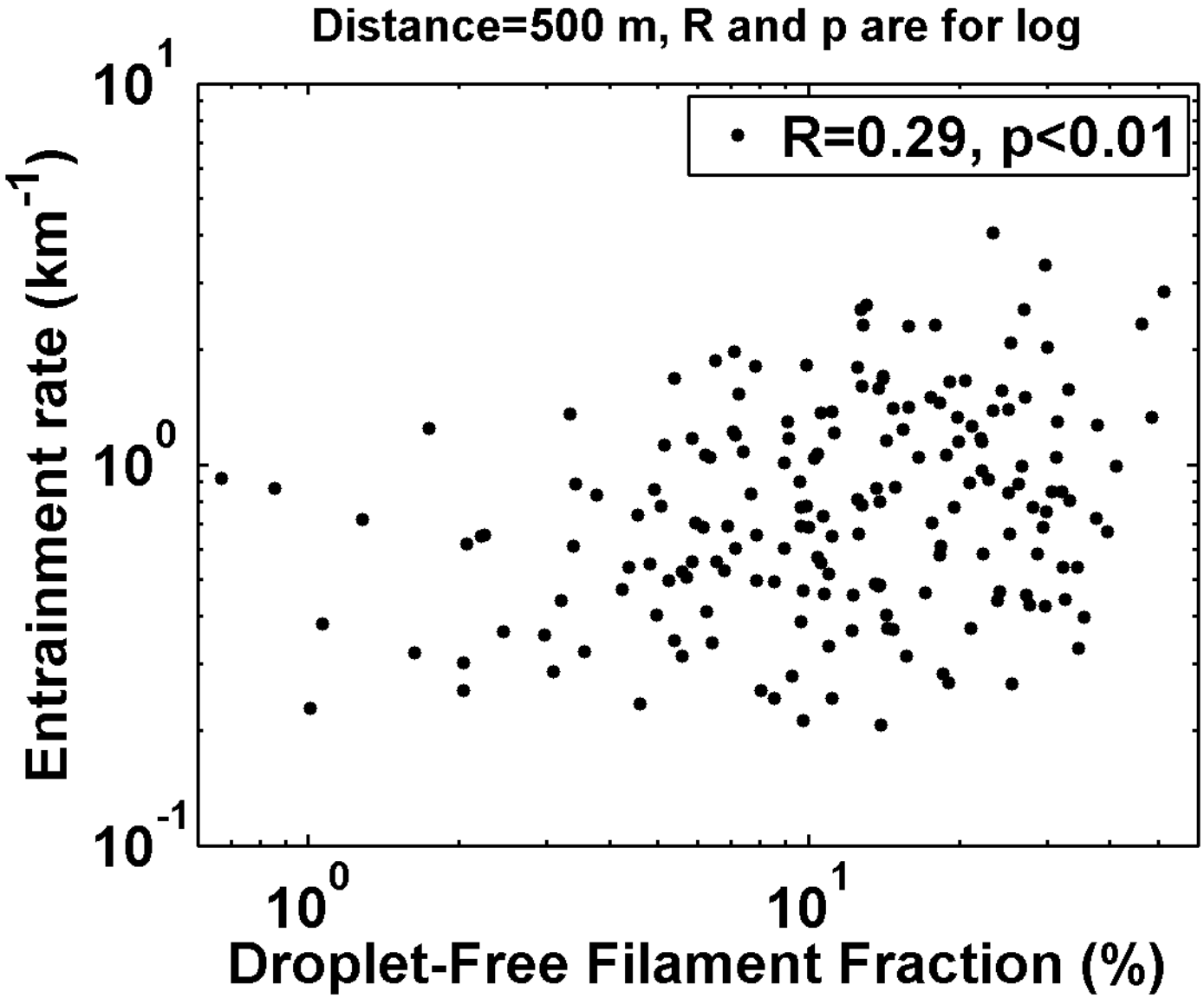
Addressing CAPI Challenges Is Merging Developments of Cloud Physics and Cu Parameterization

• Since Stommel (1947) introduced lateral entrainment into cloud parcel/plume model, entraining parcel model has been serving the backbone of convective parameterization; treating entrainment rate is still a challenge!

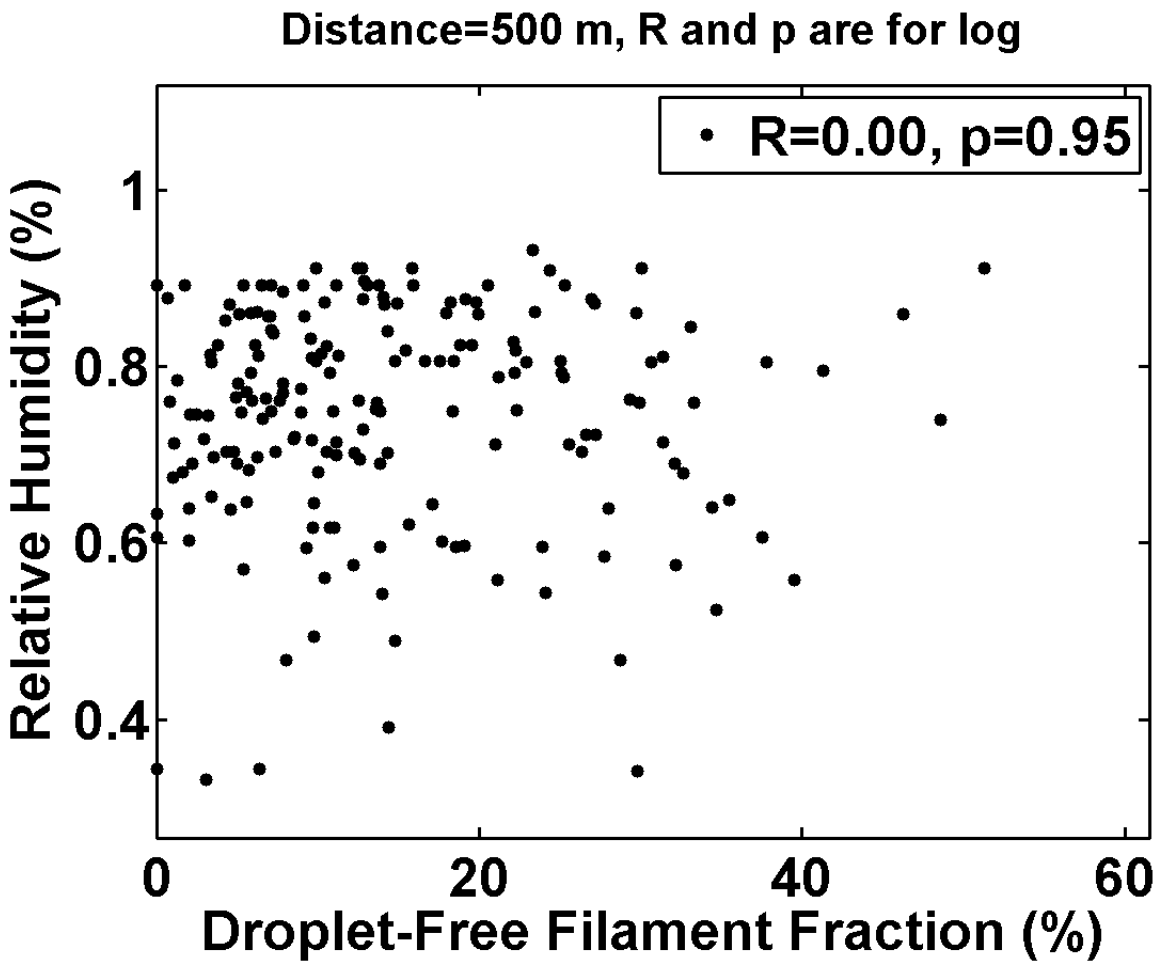
• Cloud physicists has been addressing the sources of entrained air (lateral vs. cloud-top), subsequent mixing mechanisms and turbulence-microphysics interactions; the fundamental challenges (e.g. spectral broadening and rain initiation) remain!

• The need to address CAPI challenges is converging the two areas on a NEW frontier of unifying entrainment-mixing processes and their interactions with microphysics.

Entrainment Rate vs Droplet-Free Filament Fraction

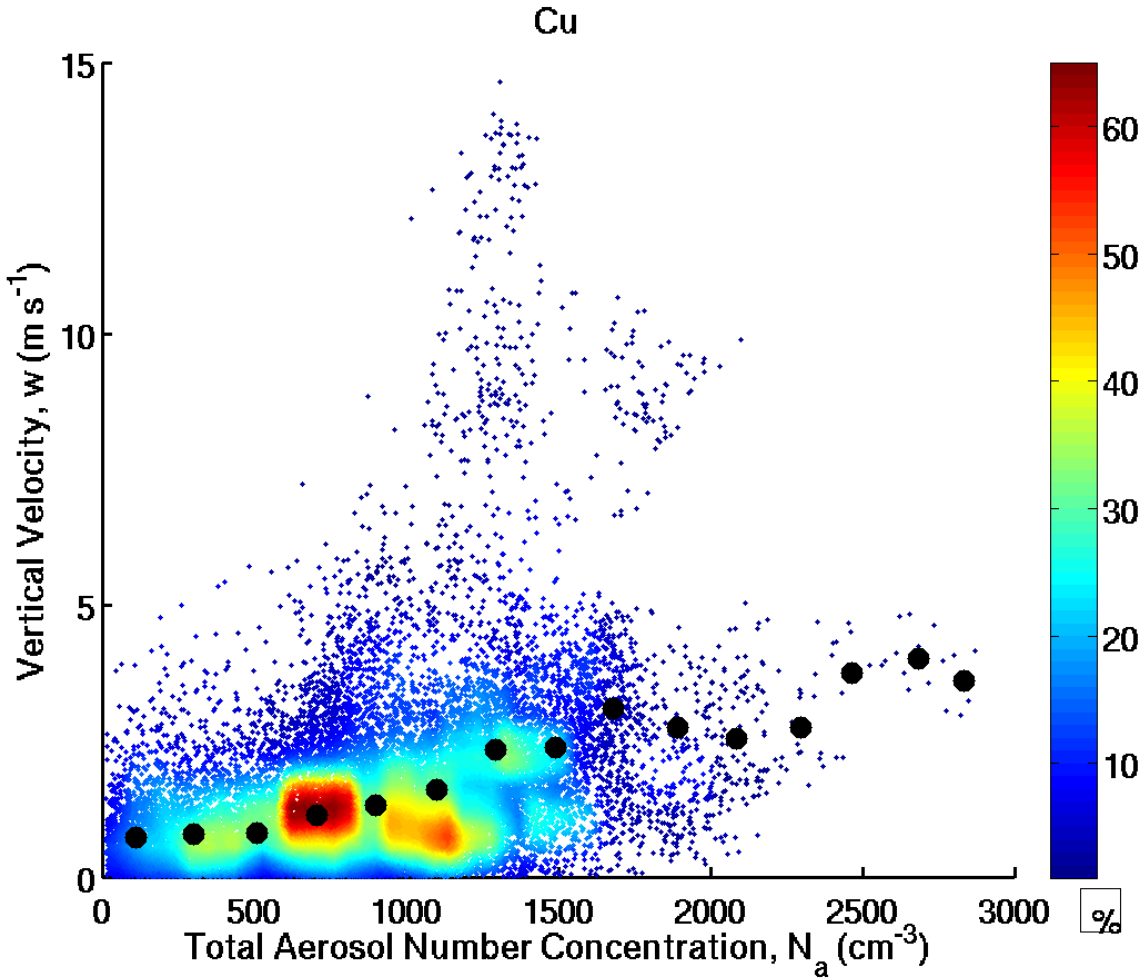


RH vs Droplet-Free Filament Fraction



The result suggests an independence of environmental RH and entrained dry air eddy size.

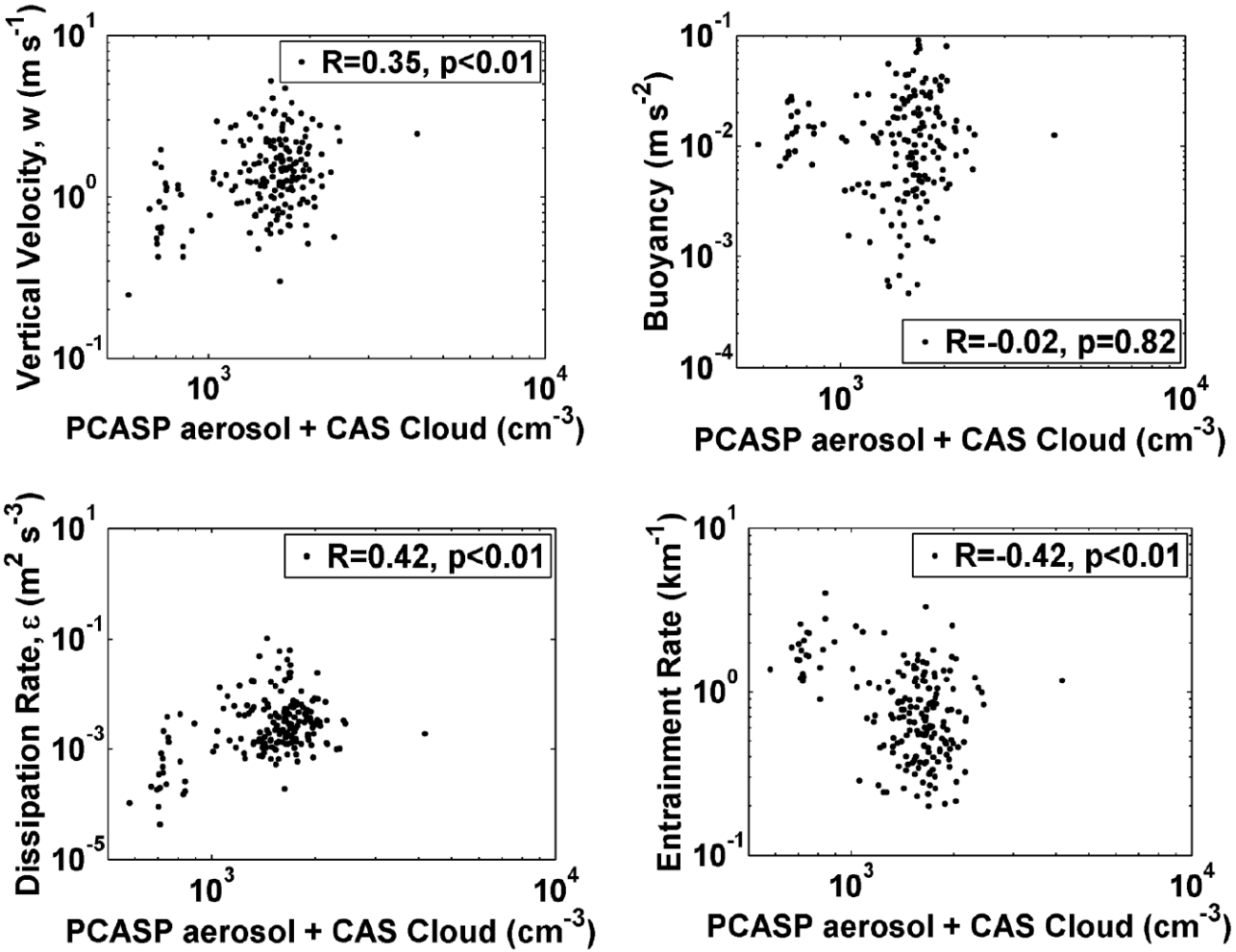
Another Dimension: Aerosol and Updraft Association



Dynamical Properties vs. Aerosol

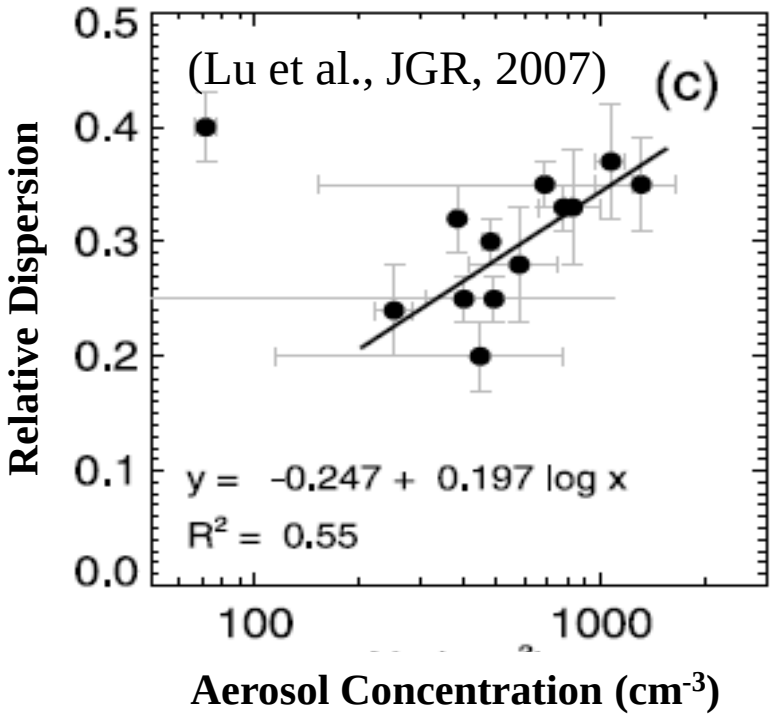
Aerosol-Dynamics Hypothesis

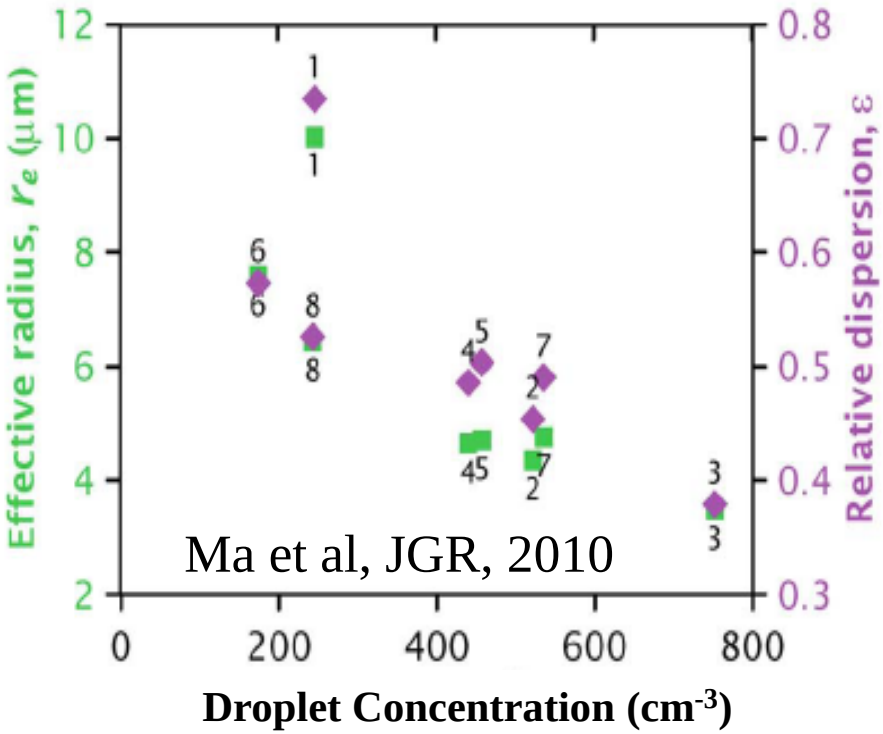
- Latent heat effect
- Sedimentation-entrainment
- Evaporation-entrainment



The increases of vertical velocity and turbulence dissipation rate agree with modeling studies (e.g., Ackerman et al 2004; Hue & Feingold 2006; Bretherton et al 2009)

Contrasting Results from Subsequent Studies





Warming dispersion effect
(Chen et al, ACP, 2012;
Pandithurai et al, JGR, 2012)

Cooling Dispersion Effect
(Martins et al, ERL, 2009;
Hudson et al, JGR, 2012)

These observational results suggest that dispersion effect can either mitigate or enhance the cooling from the number effect.

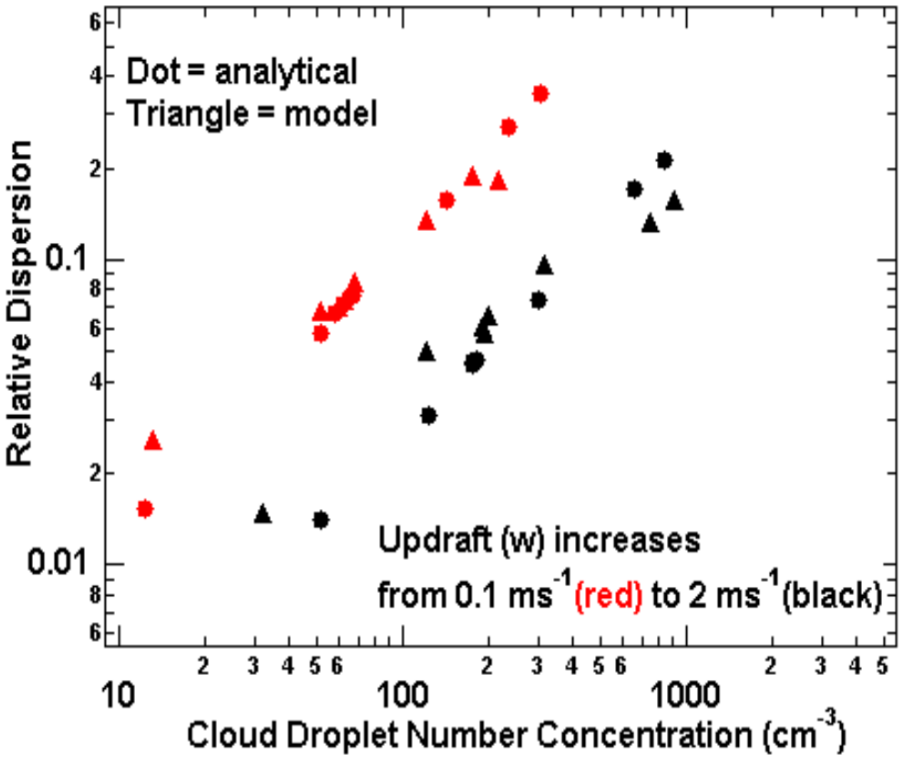
Analytical Formulation

(Liu et al. GRL, 2006)

$$N_{CCN} = CS^{K};$$

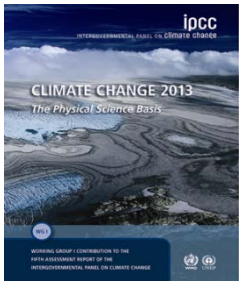
$$N \propto w^{3K/(2(k+2))} C^{2/(K+2)};$$

$$\varepsilon \propto w^{(K-1)/(K+2)} C^{2/(K+2)}$$



I thought then, "incorrectly", that the problem of dispersion effect was basically solved, and some studies reporting negative ε-N correlation were either about dynamical effect or for drizzling clouds … However, lately I realize that this view was too simplistic and we.need new understanding.

Science Drivers from IPCC-AR5



- **There is high confidence that aerosols and their interactions with clouds have offset a substantial portion of global mean forcing from well-mixed greenhouse gases. They continue to contribute the largest uncertainty to the total RF estimates.**

- **Warm clouds may typically be less sensitive to aerosol perturbation in Nature than in large scale models, which do not represent all of these compensating processes:**

  - Entrainment, mixing and their interactions with microphysics (in shallow cumulus clouds)
  - Droplet number and spectral dispersion
  - Non-monotonic response of cloud properties to aerosols
  - …