Cloud microphysics and Climate

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Cloud microphysics and its significance to climate

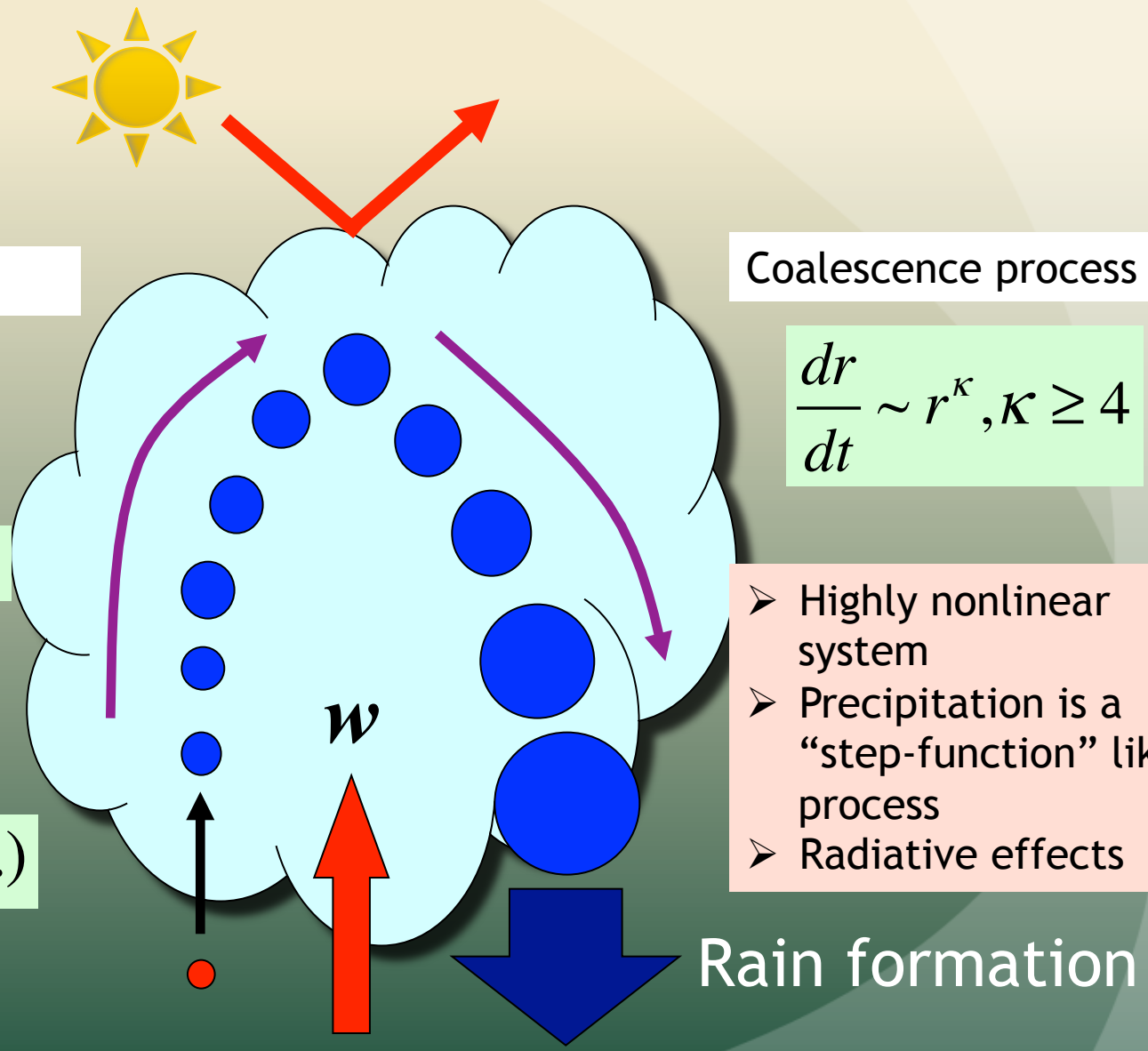
Condensational growth

$$\frac{dr}{dt} \sim \frac{S(w, N_c)}{r}$$

s: Supersaturation

Nucleation from aerosols

$$N_c = f(N_a, w, \ldots)$$

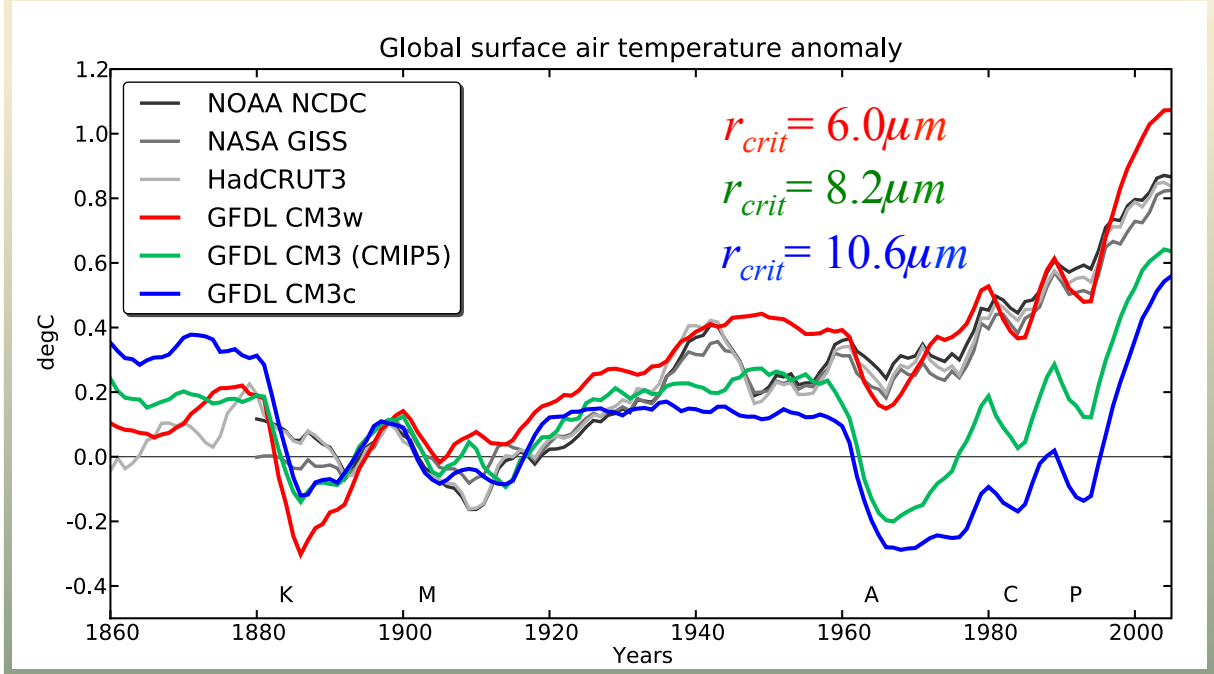


Coalescence process

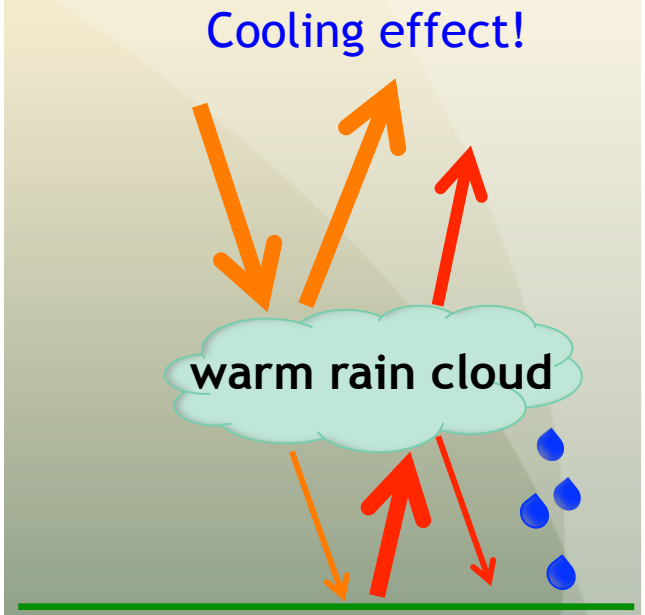
$$\frac{dr}{dt} \sim r^{\kappa}, \kappa \geq 4$$

- Highly nonlinear system
- Precipitation is a "step-function" like process
- Radiative effects

Implication for climate simulations



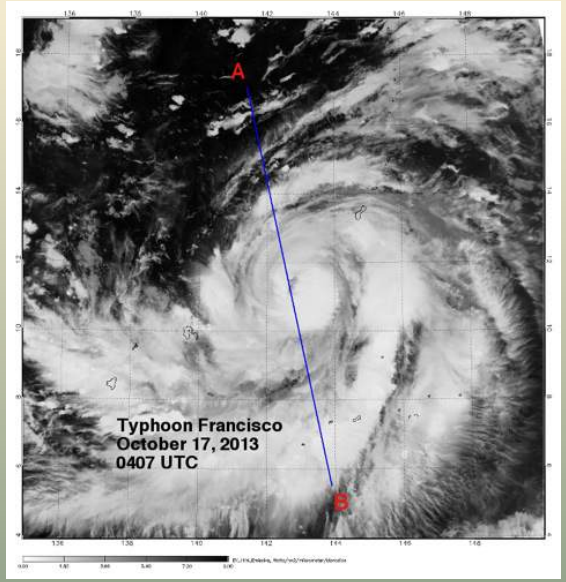
Golaz *et al.* (GRL '13)



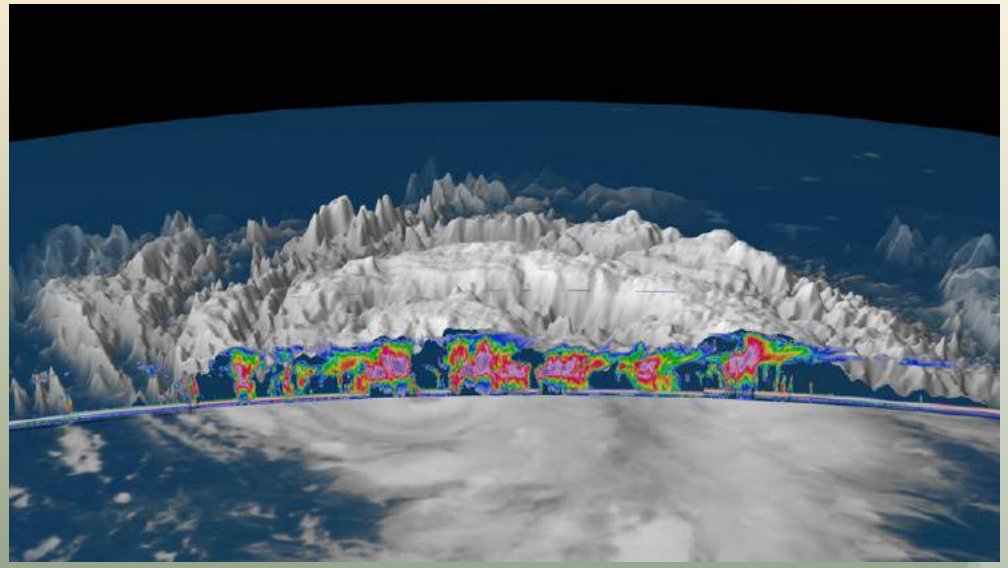
- r_{crit}: "switch" for rain formation (mimics the coalescence)
- One of the typical "tunable knobs" in GCMs
- Modulating the cooling magnitude via aerosol indirect effect
- Coalescence process representation links to global climate

New “era” of satellite observations

Passive (MODIS)



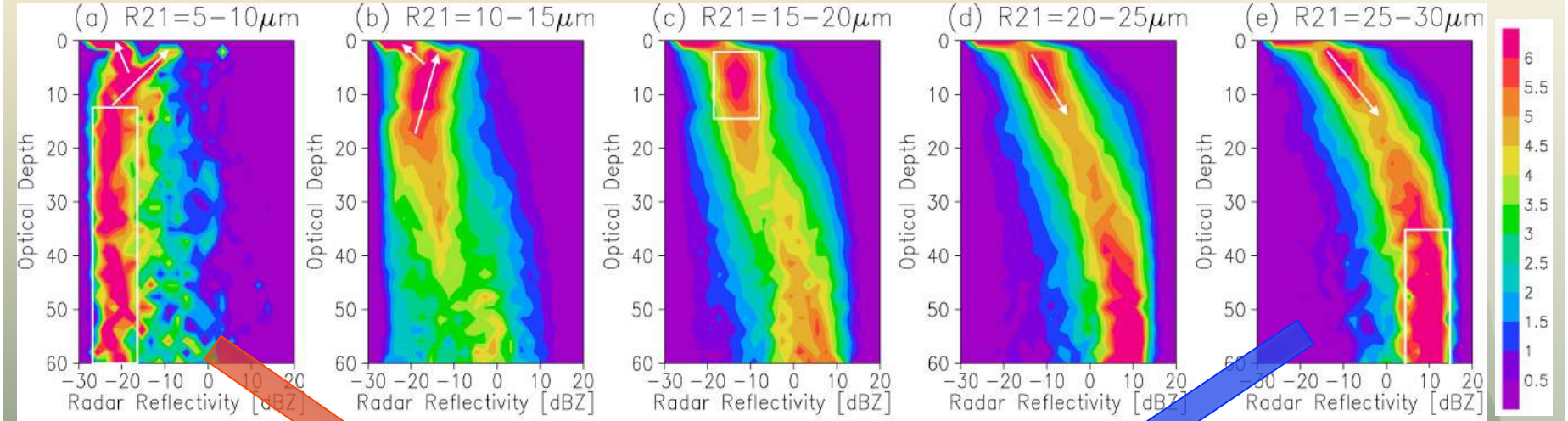
Active (CloudSat)



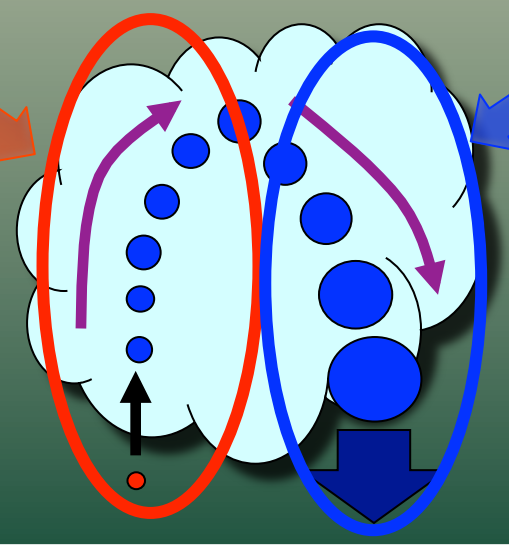
- Simultaneous obs of cloud and precip
- Novel measurement of cloud systems
- From “parameter-centric” view to “process-oriented” view
- Innovation for climate model diagnostics

Satellite-based "fingerprint" of μ-physical processes

r_{top}=5-10μm r_{top}=10-15μm r_{top}=15-20μm r_{top}=20-25μm r_{top}=25-30μm



Non-precip ← → ***Precip***

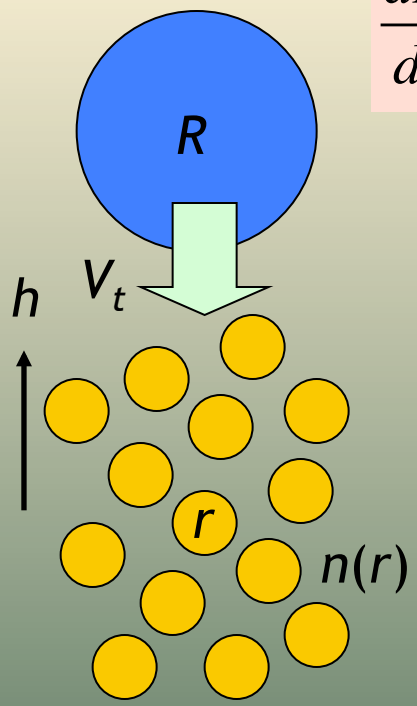


Suzuki *et al.* (JAS '10)
Nakajima *et al.* (JAS '10)

CloudSat+MODIS

Cloud process information found in CloudSat Obs

Continuous collection model



$$\frac{dR}{dt} = \frac{E_c V_t(R)}{4\rho_w} q_c$$

$$\frac{dR}{dh} = -\frac{E_c}{4\rho_w} q_c \qquad dh = -V_t(R)dt$$

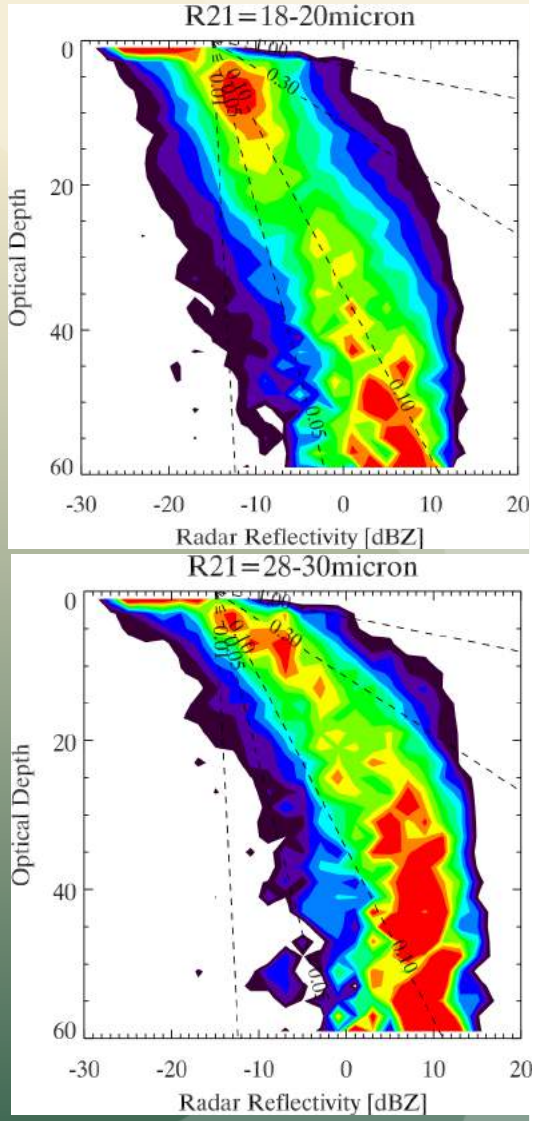
$$\frac{dR}{R} = -\frac{E_c}{4\rho_w}\frac{q_c}{R} dh$$

$$\frac{dZ_e}{Z_e} \approx \alpha \frac{dR}{R}$$: "collecting" drop

$$d\tau \approx -\frac{3}{2}\frac{1}{\rho_w}\frac{q_c}{R} dh$$: "collected" droplet

$$\therefore \frac{d\ln Z_e}{d\tau} \approx \frac{\alpha}{6} E_c$$

$$\alpha \approx 3-6$$

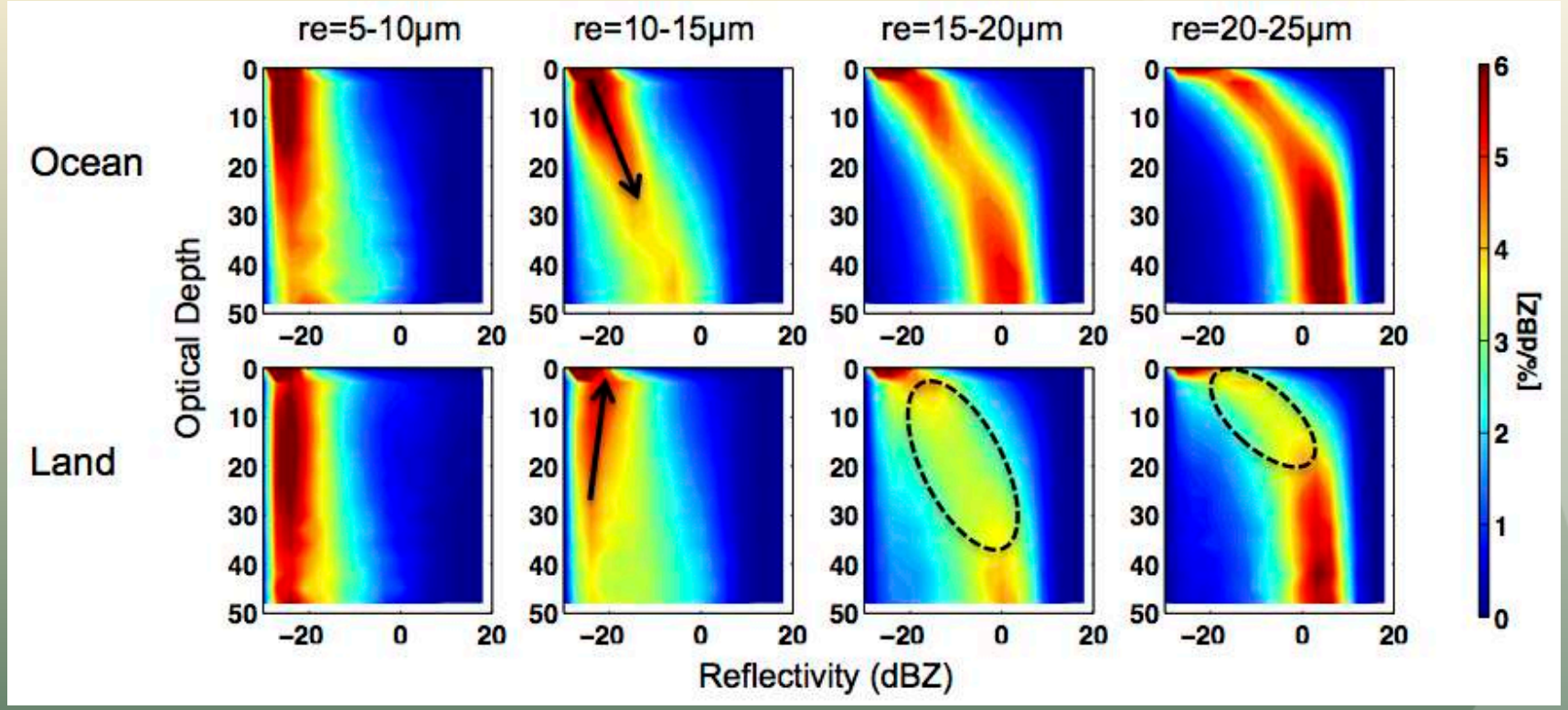


Suzuki *et al.* (JAS '10)

The slope in this diagram is a gross measure of collection efficiency E_c

Land-Ocean differences

CloudSat/CPR+Aqua/MODIS



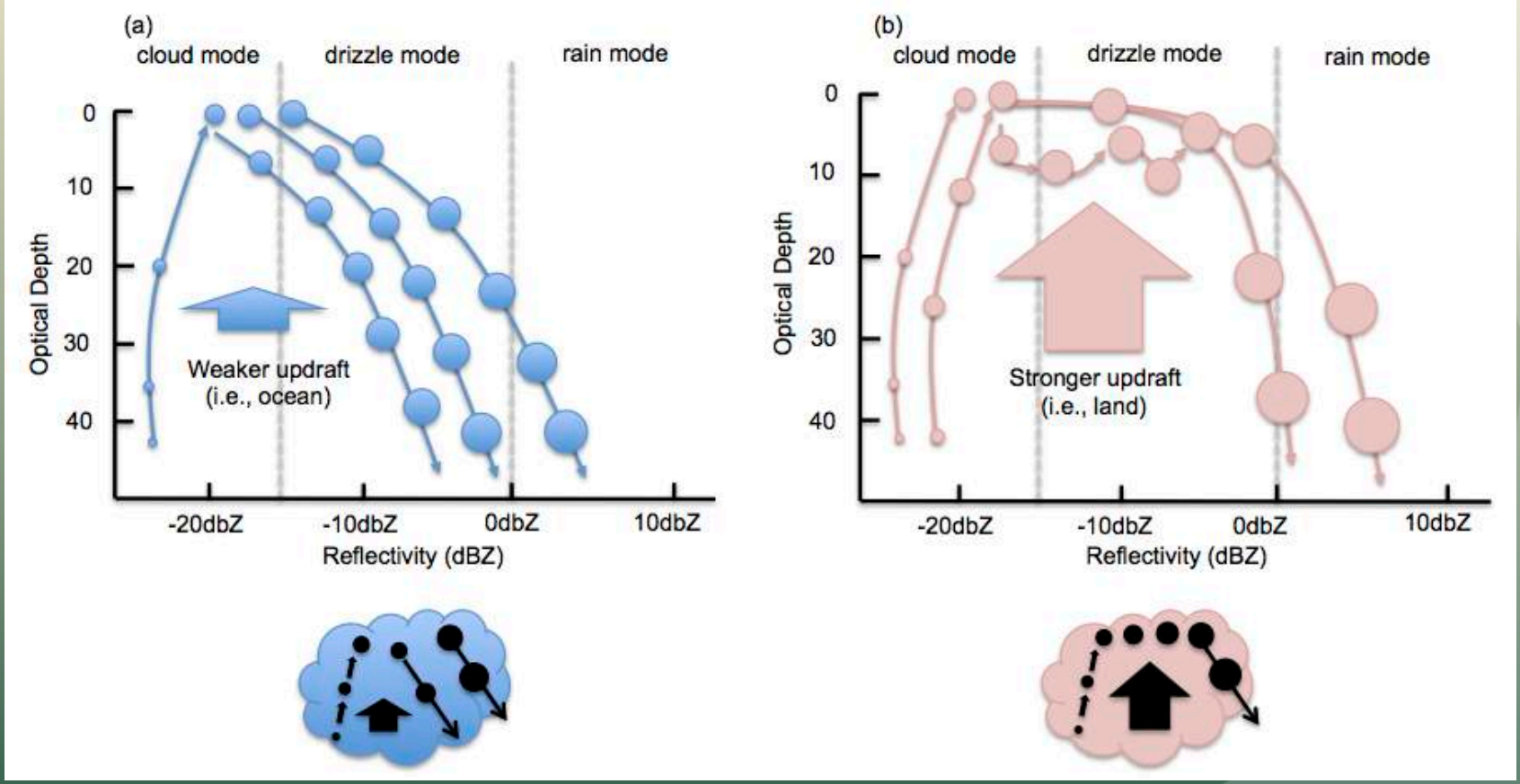
Takahashi *et al.* (submitted)

- Oceanic clouds tend to precipitate more "continuously"
- Continental clouds tend to "skip" drizzle ("drizzle disruption")

Hypothesis:
Effect of updraft on μ-physical structure

Oceanic clouds

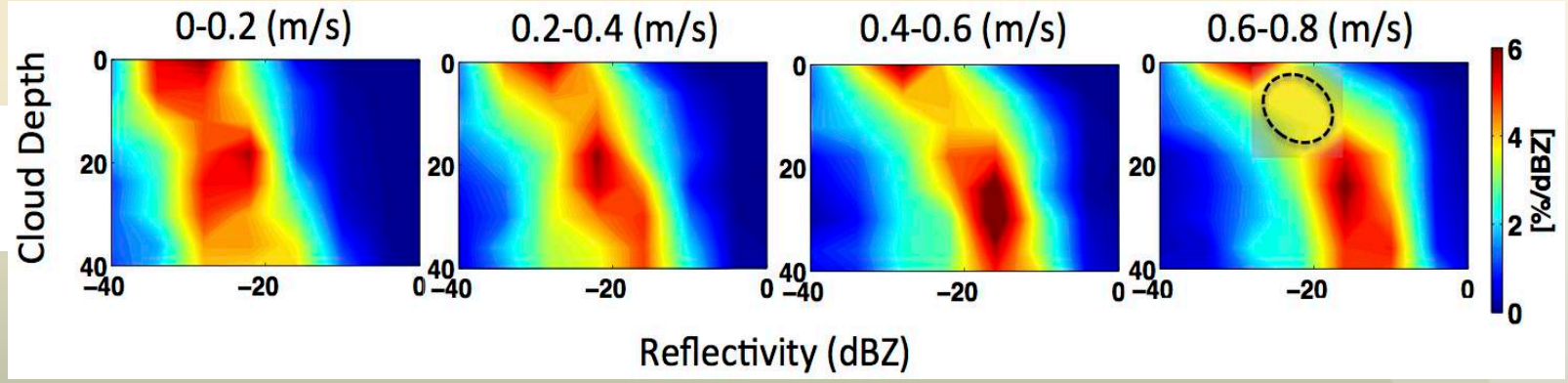
Continental clouds



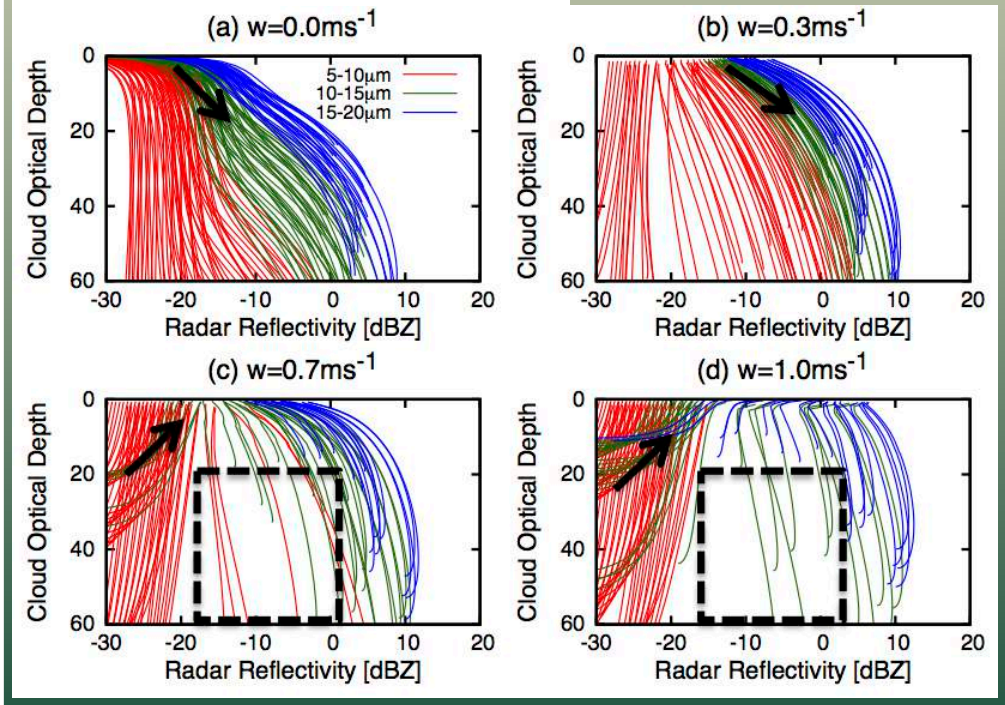
Takahashi *et al*. (submitted)

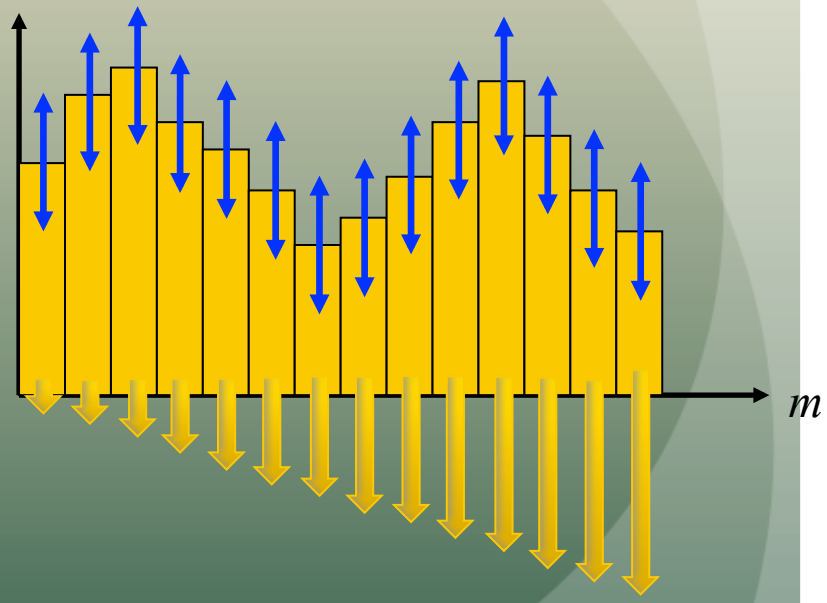
Testing the hypothesis: ARM and Bin model

ARM Azores



Spectral-bin model





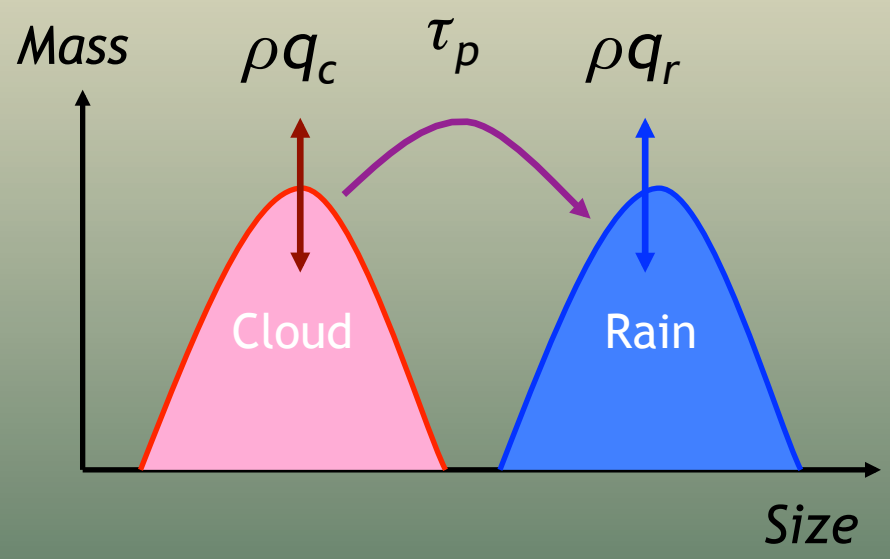
- Updraft measurement required

Takahashi *et al.* (submitted)

Climate model diagnostics

Sources of biases:

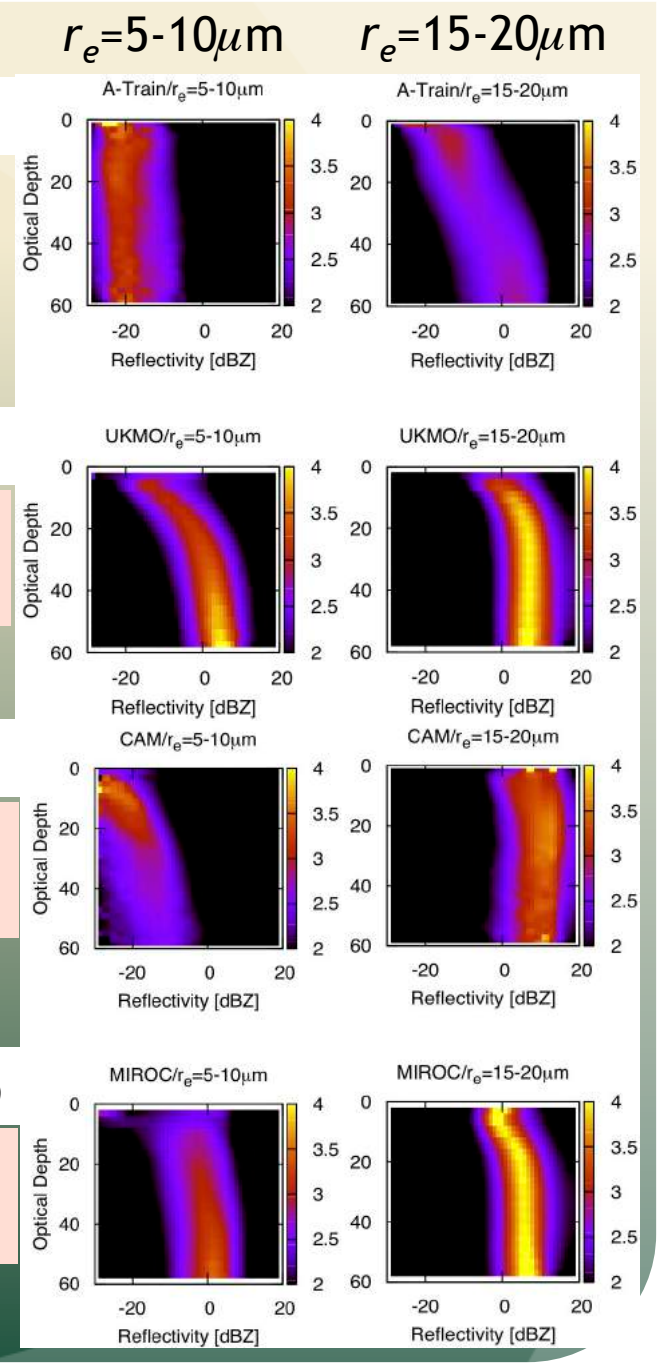
- Coarse resolution ~O(100km)
- Cloud process representation



$$\frac{\partial(\rho q_c)}{\partial t} = -\frac{\rho q_c}{\tau_p}$$

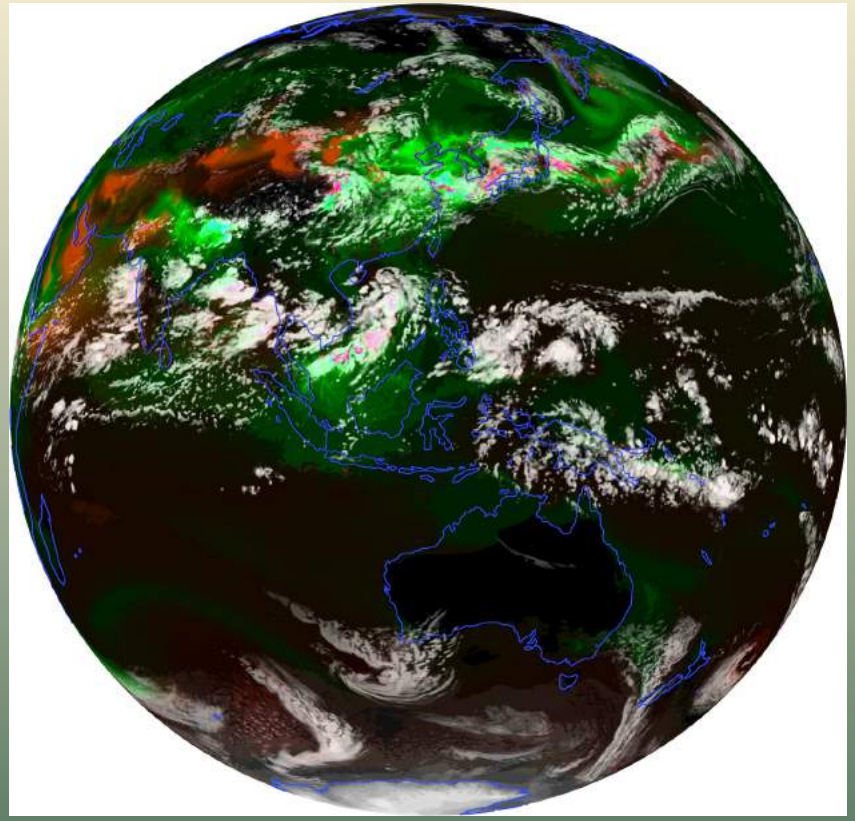
$$\tau_p \propto \frac{N_c^{\beta}}{(\rho q_c)^{\alpha}}$$

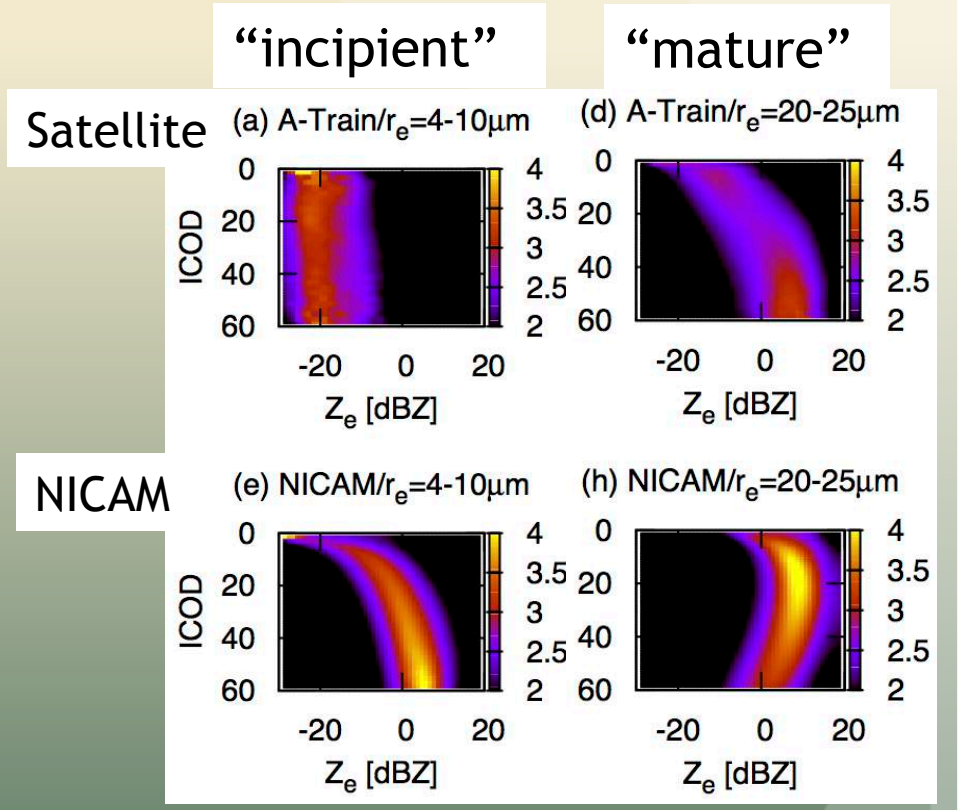
Suzuki *et al.* (JAS '15)



Does high-resolution help solve the problem?

NICAM-Chem dx=7km





Suzuki *et al.* (JAS '11)

- Red: Coarse aerosols (Dust/Sea Salt)
- Green: Fine aerosols (Sulfate/Carbon)
- White: Clouds

- Rain formation is still too fast
- Process representation is critical

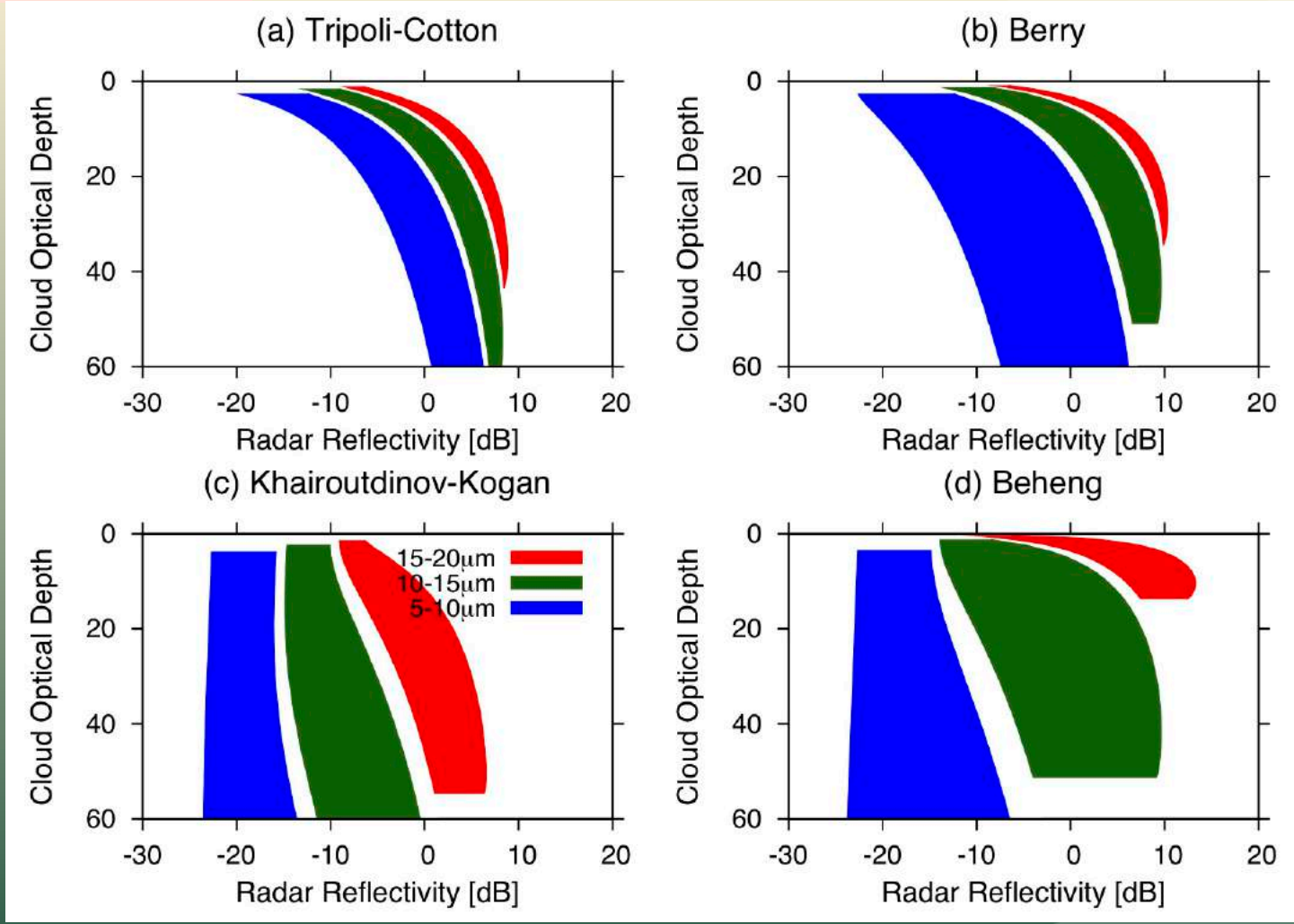
Biases traced back to auto-conversion schemes

$$\tau_p \propto (\rho q_c)^{-\alpha} N_c^{\beta}$$

1-dimensional model

α=1.33
β=0.33
UKMO, MRI

α=1.47
β=1.79
CAM5



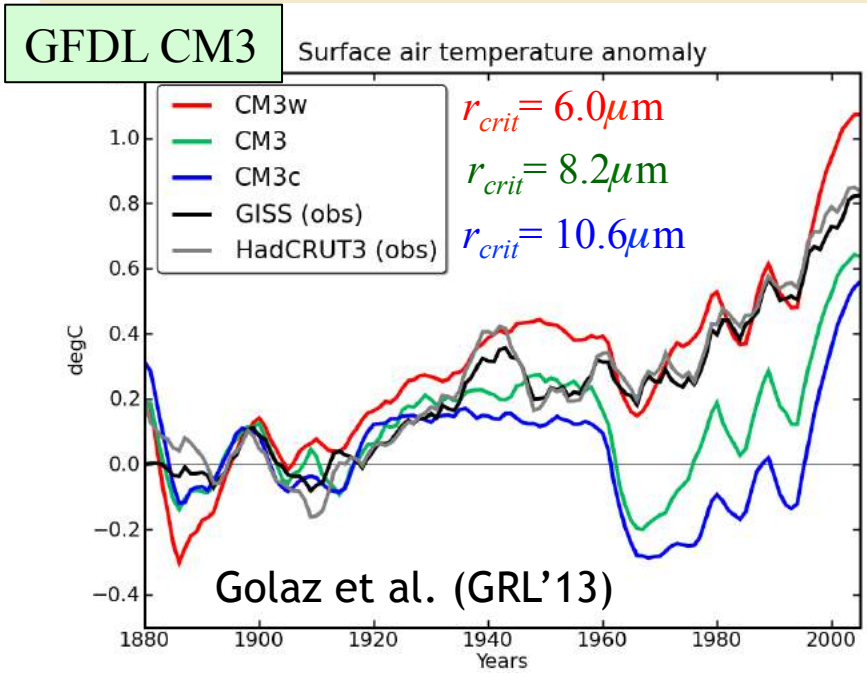
α=2.0
β=1.0
MIROC, NICAM

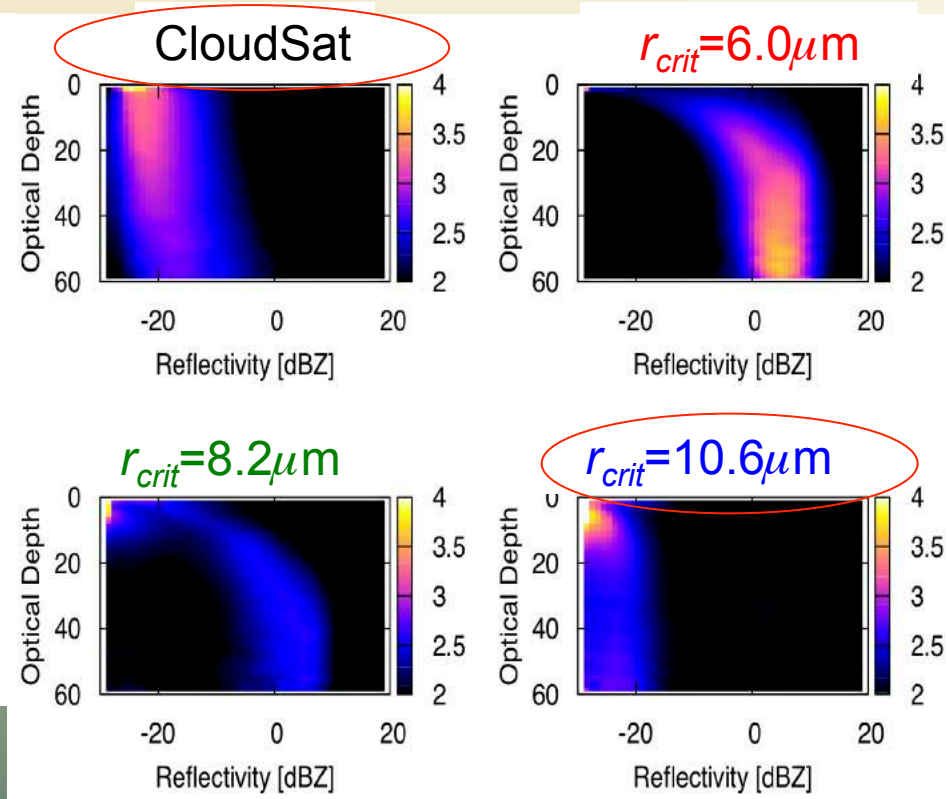
α=3.7
β=3.3

Implication of the "process-oriented" model constraint

Suzuki, Golaz and Stephens (GRL '13)

Satellite-based constraint on μ-physics





r_{crit}: "switch" for rain formation

- r_{crit}=6.0μm : Temperature trend is best, but rain forms too quickly.
- r_{crit}=10.6μm: Rain formation is best represented, but temperature is too cool.
- The model reproduces the correct temperature trend only with flawed physics
- The rain inhibition (matching satellite) causes too much cooling: Why?

What's missing in GCMs?

Buffering effect (Stevens–Feingold, Nature '09)

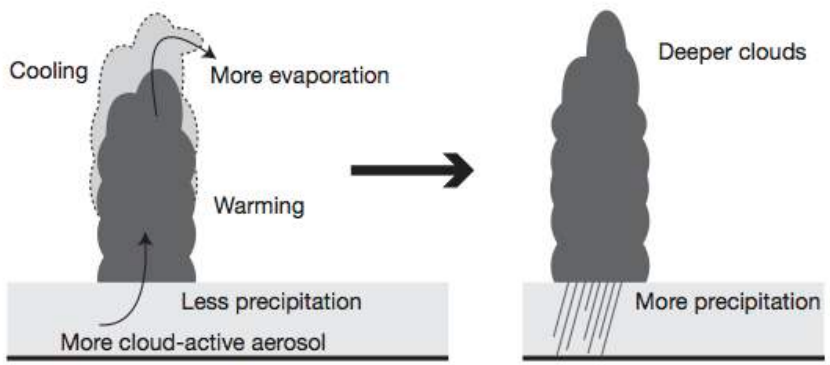
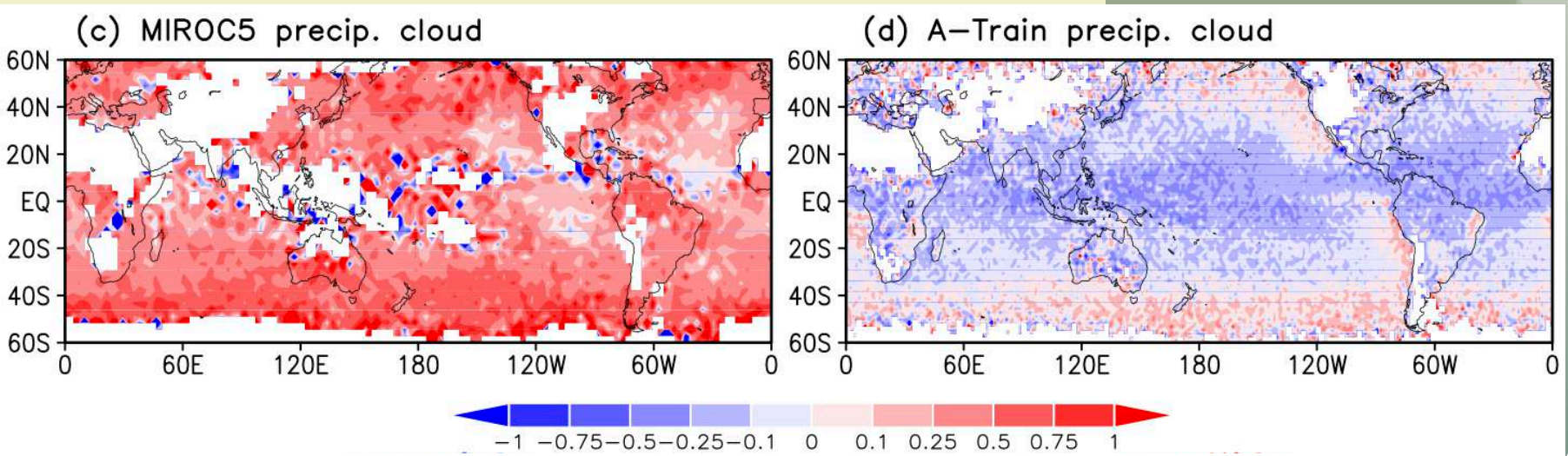


Figure 4 | The deepening effect. The local inhibition of precipitation helps precondition the environment for deeper convection, which then rains more.

- "Rapid adjustment" buffers the initial perturbation to the system
- Net RF drives climate change
  - ✓ Effective RF (IPCC AR5)
- Current GCMs may not represent this buffering effect appropriately
- Too strong indirect RF in current GCMs

Cloud susceptibility to aerosols (Michibata *et al*. in prep)



LWP decrease — d ln(LWP) / d ln(Nc) — LWP increase

Messages

- "Golden era" of satellite observation has started
  - ✓ Shift from "parameter-centric" view to "process-oriented" view of cloud systems
- Novel insight into microphysical processes with CloudSat/A-Train
  - ✓ Lifecycle view of the warm rain
  - ✓ Land-ocean difference associated with updraft velocity
- Innovation for climate model diagnostics
  - ✓ "Process-oriented" approach for model diagnostics
  - ✓ Contrasted against traditional "performance-oriented" metrics
  - ✓ Inconsistency b/w process-level and macroscopic behaviors
  - ✓ Missing in current GCMs: Buffering effect?