Process-oriented evaluation of warm cloud microphysics in global models with a synergistic use of multi-sensor satellite observations

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Thanks to collaborations with:
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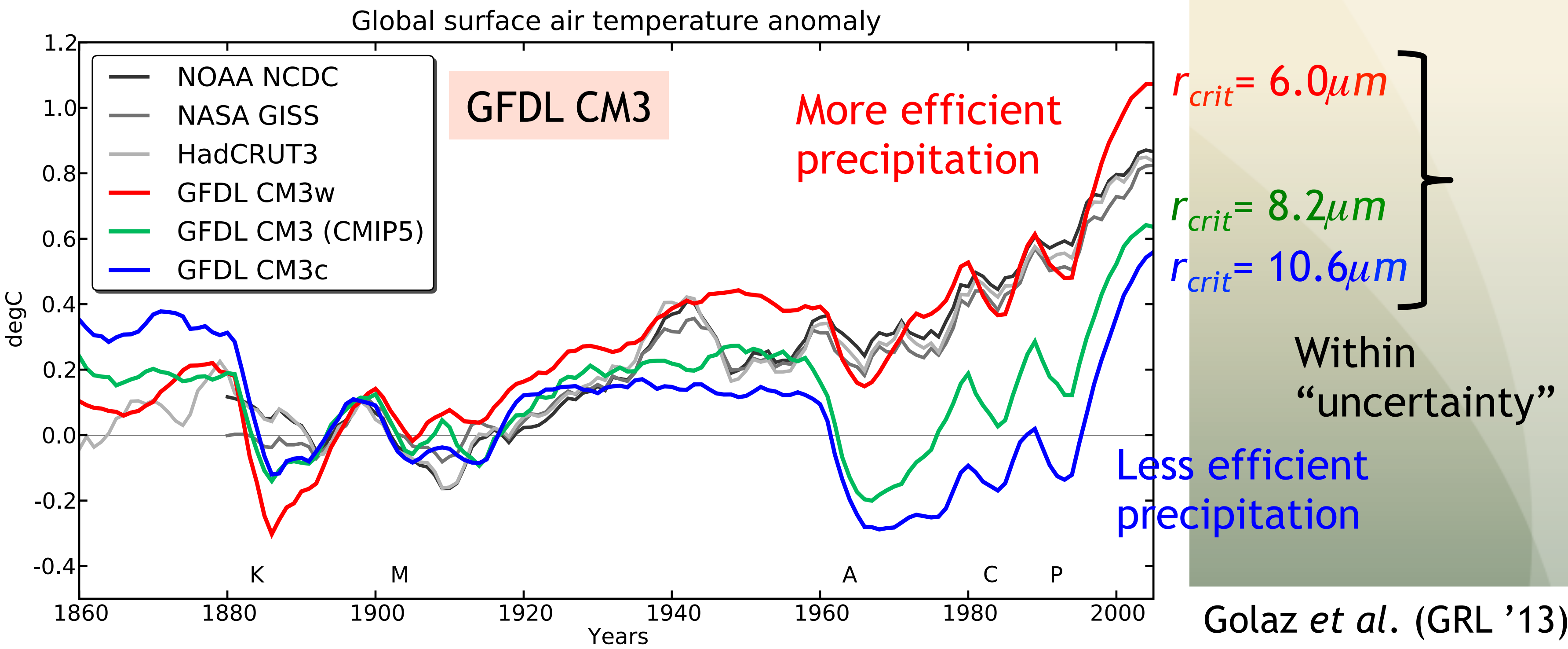
Cloud μ-physics: key uncertainty in climate simulation

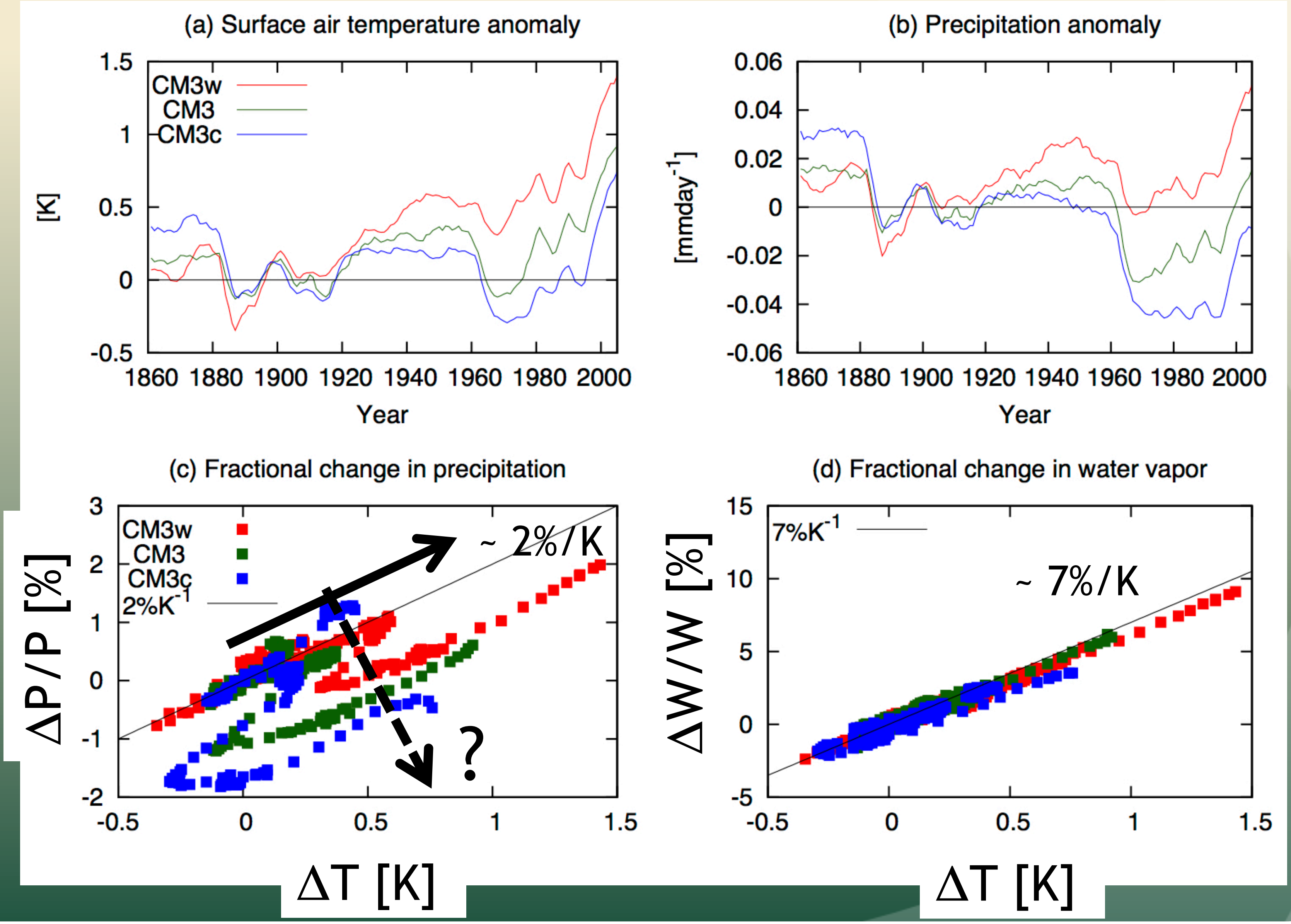


Golaz *et al.* (GRL ’13)

r_{crit}: Threshold particle radius for warm rain to occur

- A “tunable” parameter in (some) climate models
- Significantly modulates magnitude of the aerosol indirect forcing
- What is the impact on global climate/hydrologic cycle?
- How to use satellite observations to constrain this uncertainty?

Impact on the global-mean precipitation


(a) Surface air temperature anomaly

(b) Precipitation anomaly

(c) Fractional change in precipitation

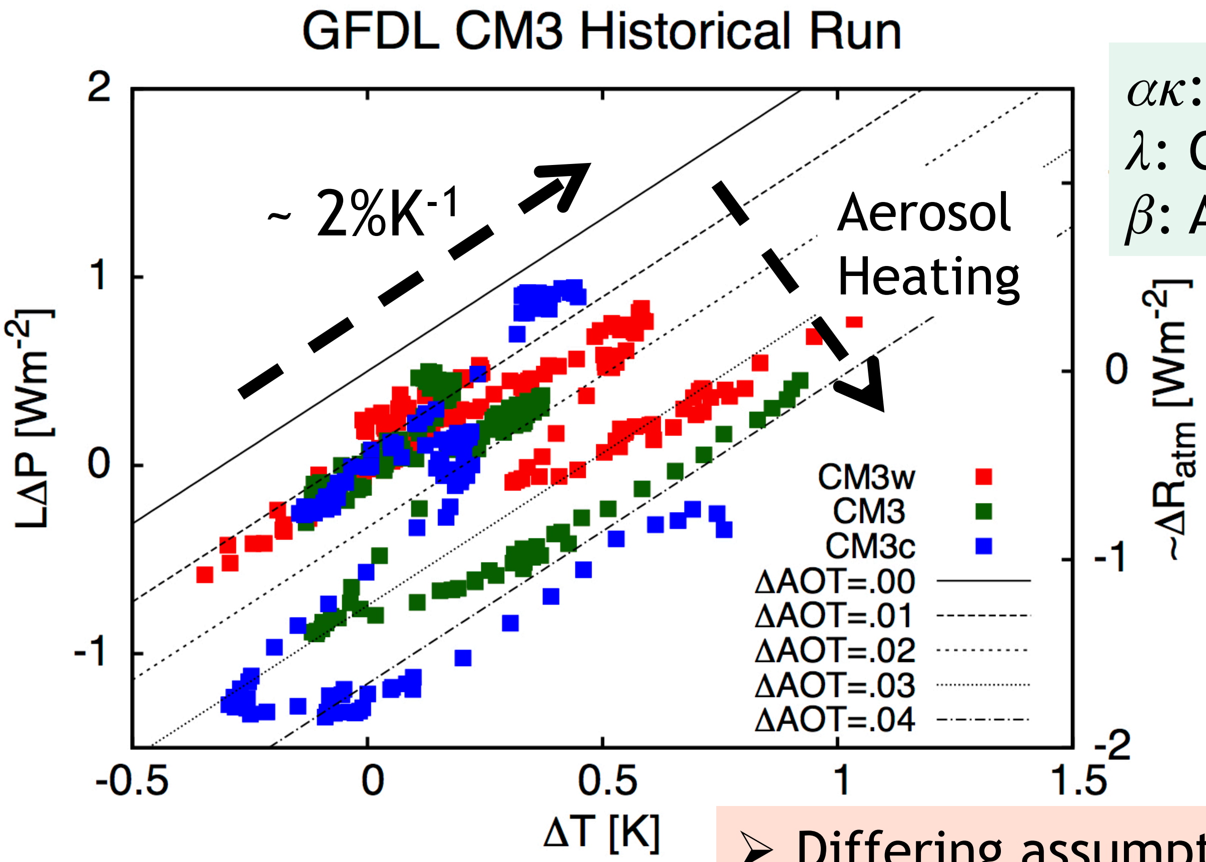
(d) Fractional change in water vapor

Energy balance controls on global precip change

$$L\Delta P \approx -\Delta S + (\alpha\kappa - \lambda)\Delta T - \beta\Delta\tau_a$$

Aerosol absorption

~0.5$\mathrm{Wm^{-2}}$ ~1.49$\mathrm{Wm^{-2}K^{-1}}$ ~41.5$\mathrm{Wm^{-2}}$ x O(0.01)



$\alpha\kappa$: Water vapor cooling
λ: Cloud radiative effect
β: Aerosol forcing efficiency

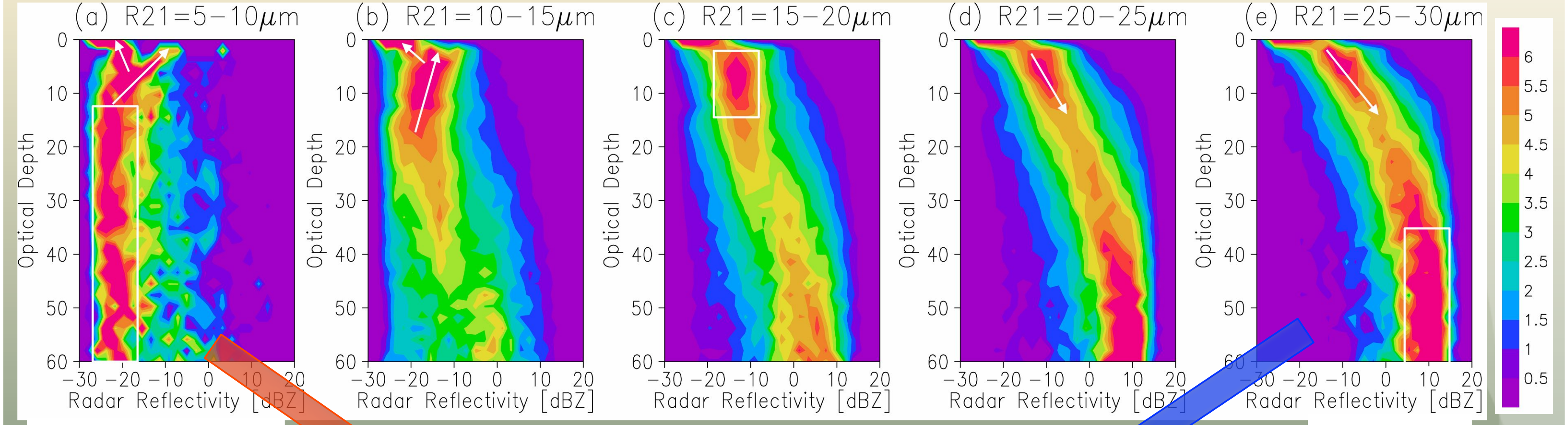
r_{crit}= 6.0μm
r_{crit}= 8.2μm
r_{crit}= 10.6μm

- Differing assumptions of cloud μ-physics cause different aerosol loadings
- This in-turn influences global precipitation via energy balance controls

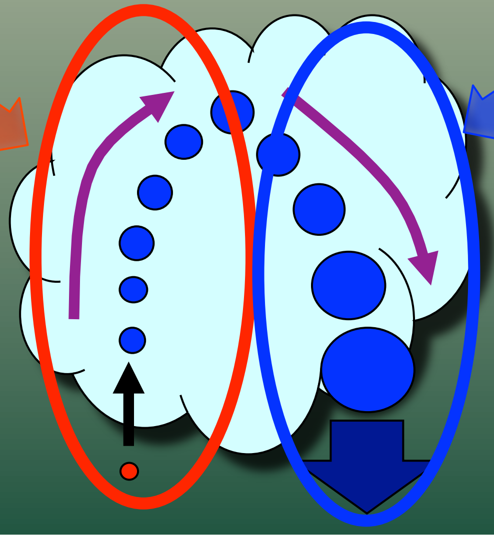
Warm rain process “fingerprint” in satellite obs

“incipient” ↔ “mature”

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



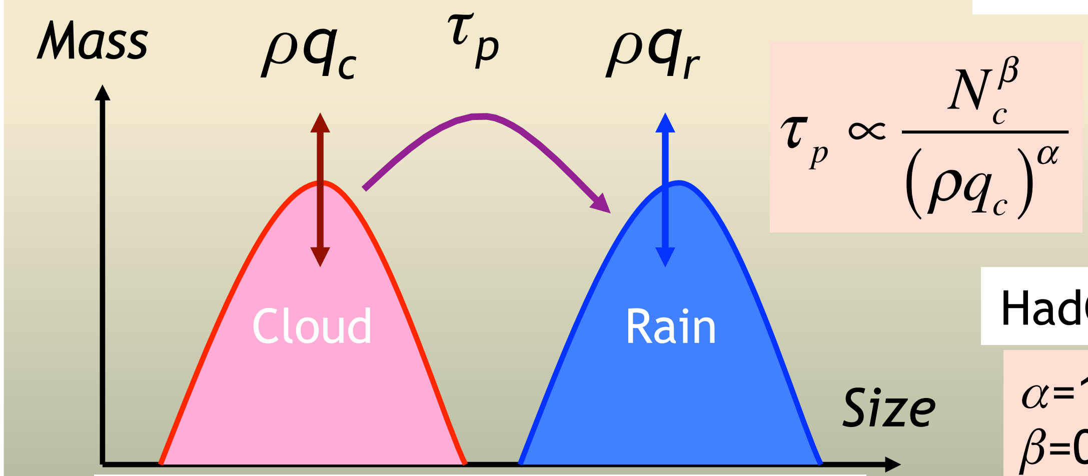
Non-precip ↔ ***Precip***



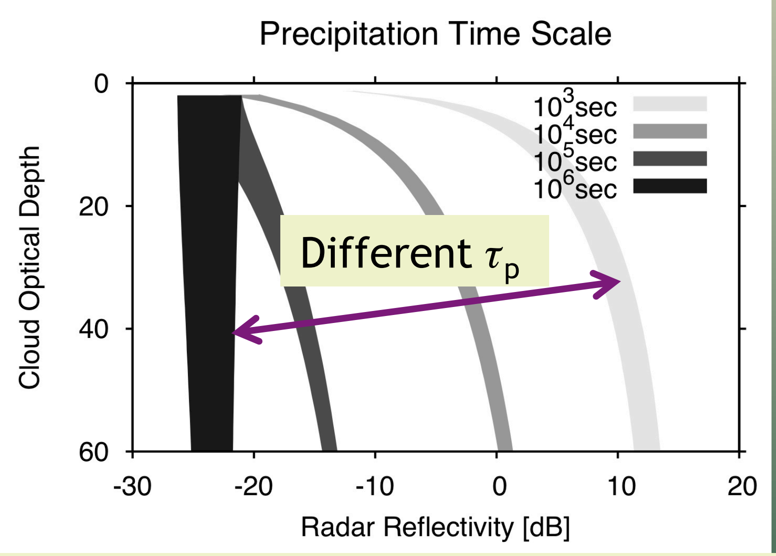
Contoured
Frequency by
Optical
Depth
Diagram

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

Climate model diagnostics



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



- Model μ-physics produces warm rain too efficiently

Suzuki *et al.* (JGR ’13; JAS ’15)

r_e=5-10μm r_e=15-20μm

Satellite

HadGEM2

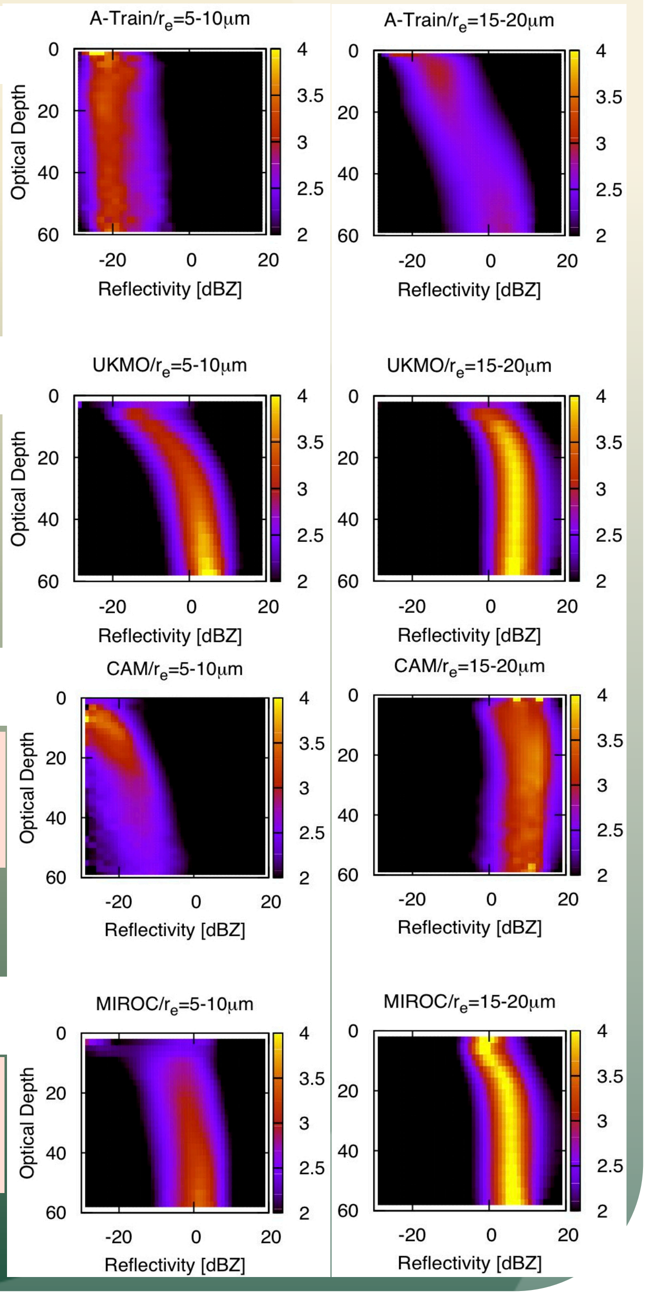
α=1.33
β=0.33

CAM5

α=1.47
β=1.79

MIROC5

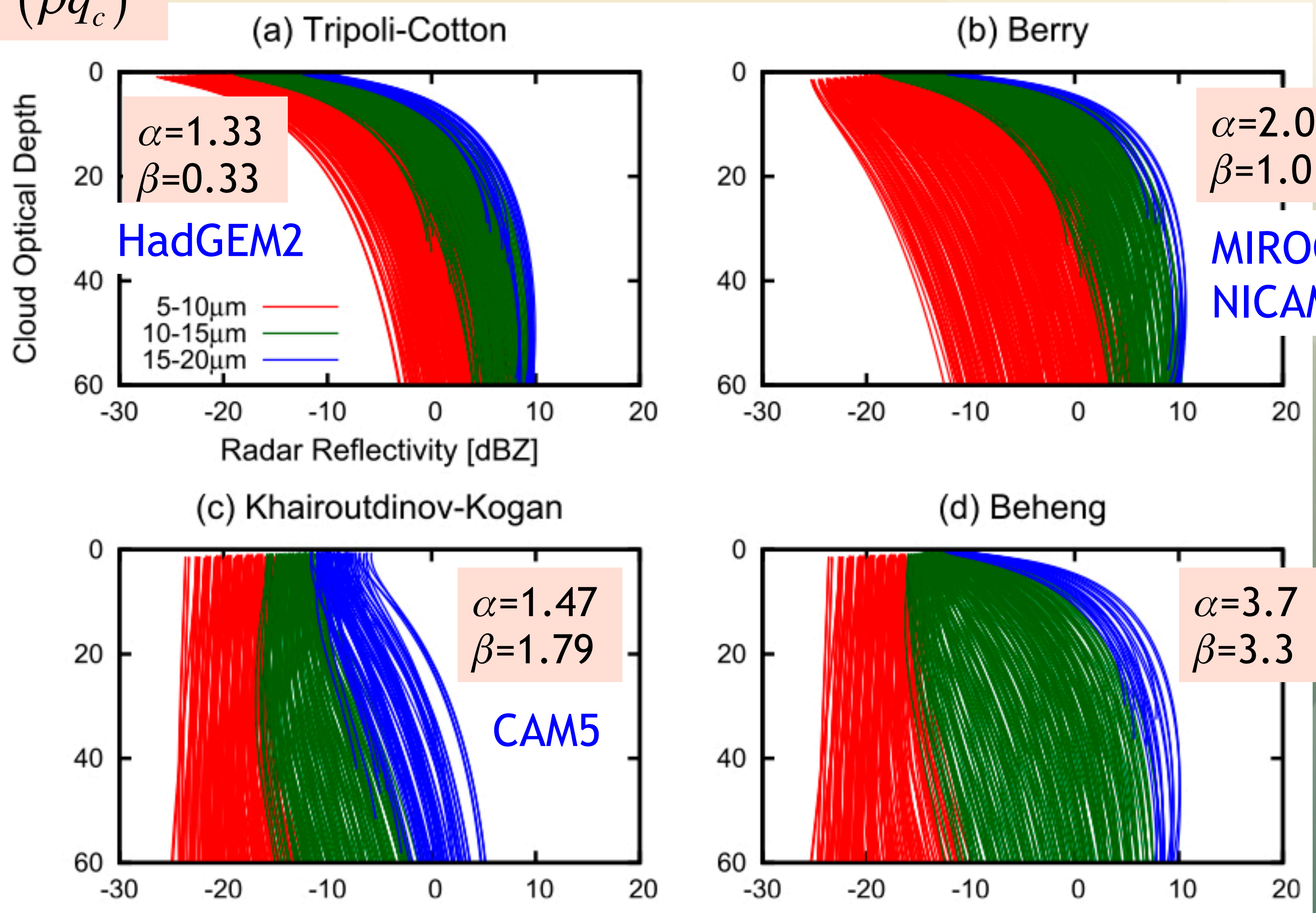
α=2.0
β=1.0



Behaviors of different schemes

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

Simple 1D model



α=1.33
β=0.33

HadGEM2

α=2.0
β=1.0

MIROC5,
NICAM

α=1.47
β=1.79

CAM5

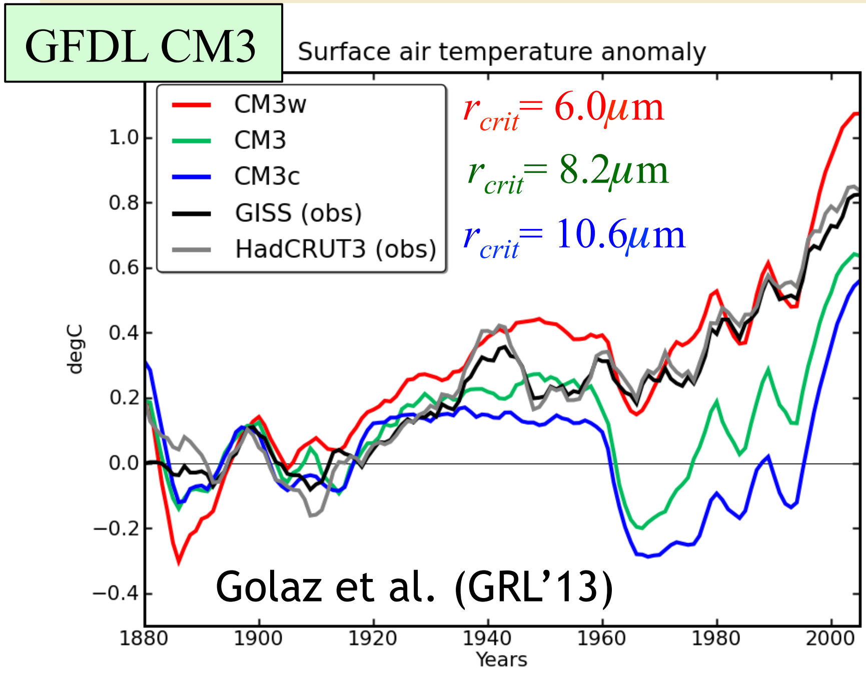
α=3.7
β=3.3

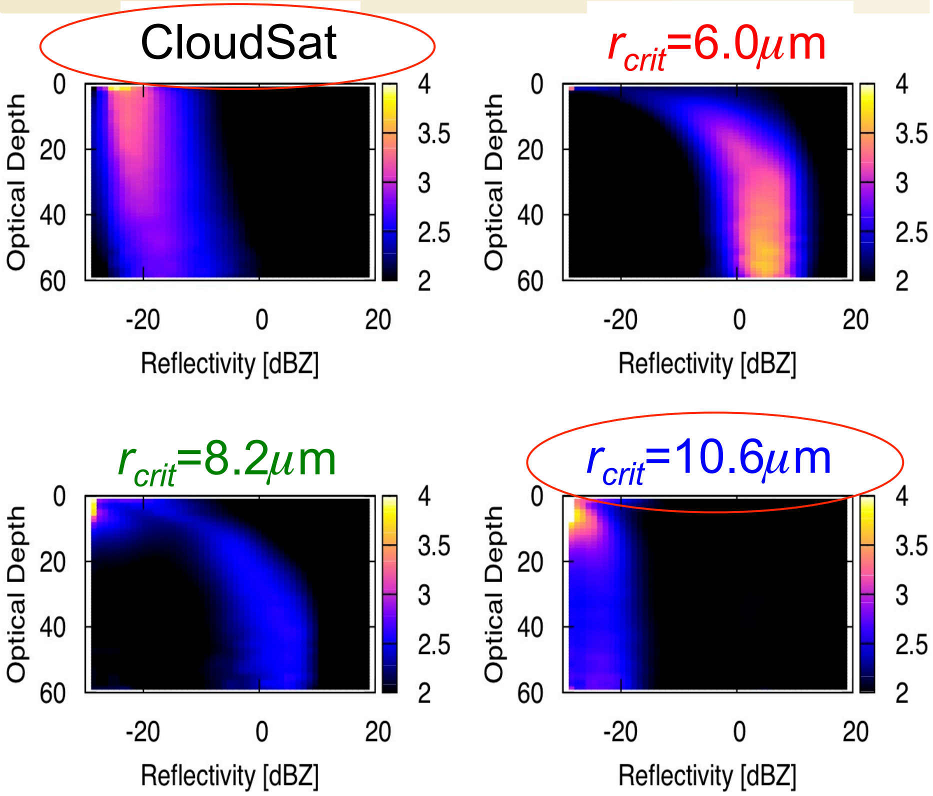
Suzuki *et al.* (JAS '15)

Implication of process-based constraint for climate projection

Suzuki, Golaz and Stephens (GRL ’13)

Comparisons of μ-physical “fingerprint”





r_{crit}: Critical particle size for rain to occur

- $r_{crit}=6.0\mu m$: Best reproduces the temperature trend but worst the μ-physics
- $r_{crit}=10.6\mu m$: Best captures microphysics but too much cooling
- Dichotomy b/w micro-process (microphysics) and macro-process (radiation)
- Exposes error compensation at a fundamental process level in the model

What’s missing in GCMs? – A speculation

Buffering effect (Stevens–Feingold, Nature ’09)

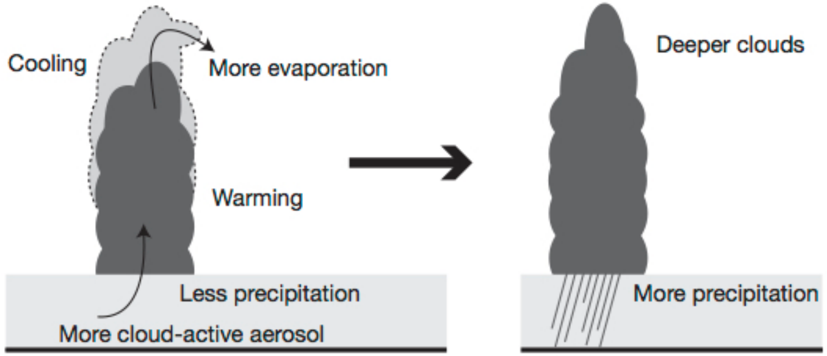
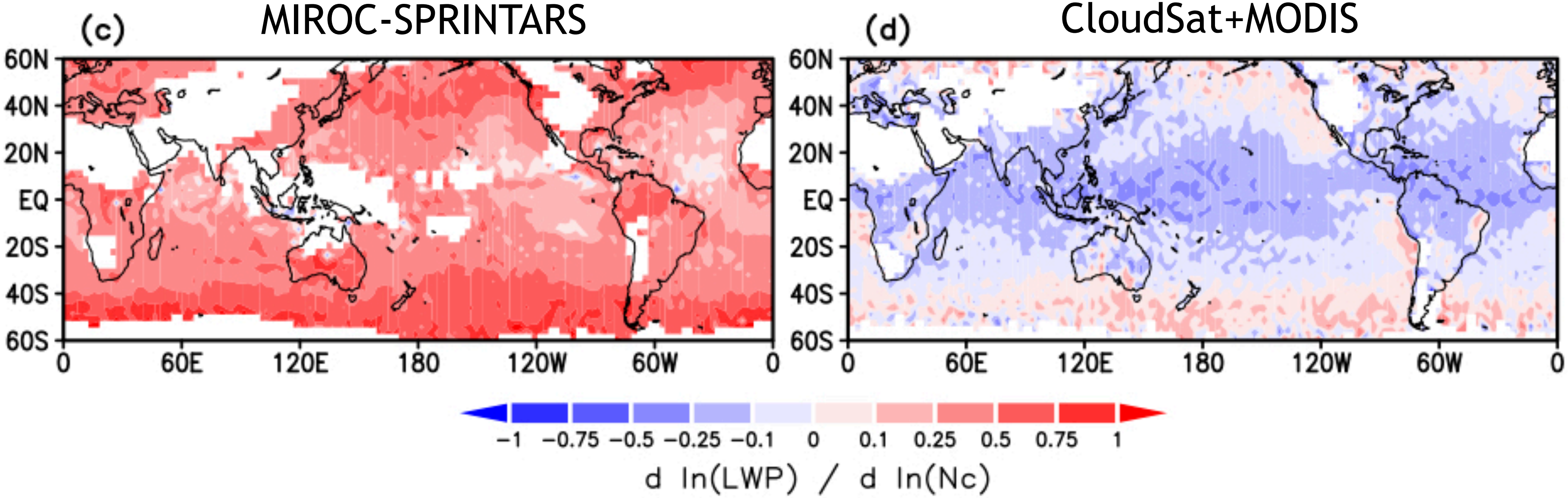


Figure 4 | The deepening effect. The local inhibition of precipitation helps precondition the environment for deeper convection, which then rains more.

- “Rapid adjustment” can buffer 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*. ACPD ’16)


MIROC-SPRINTARS

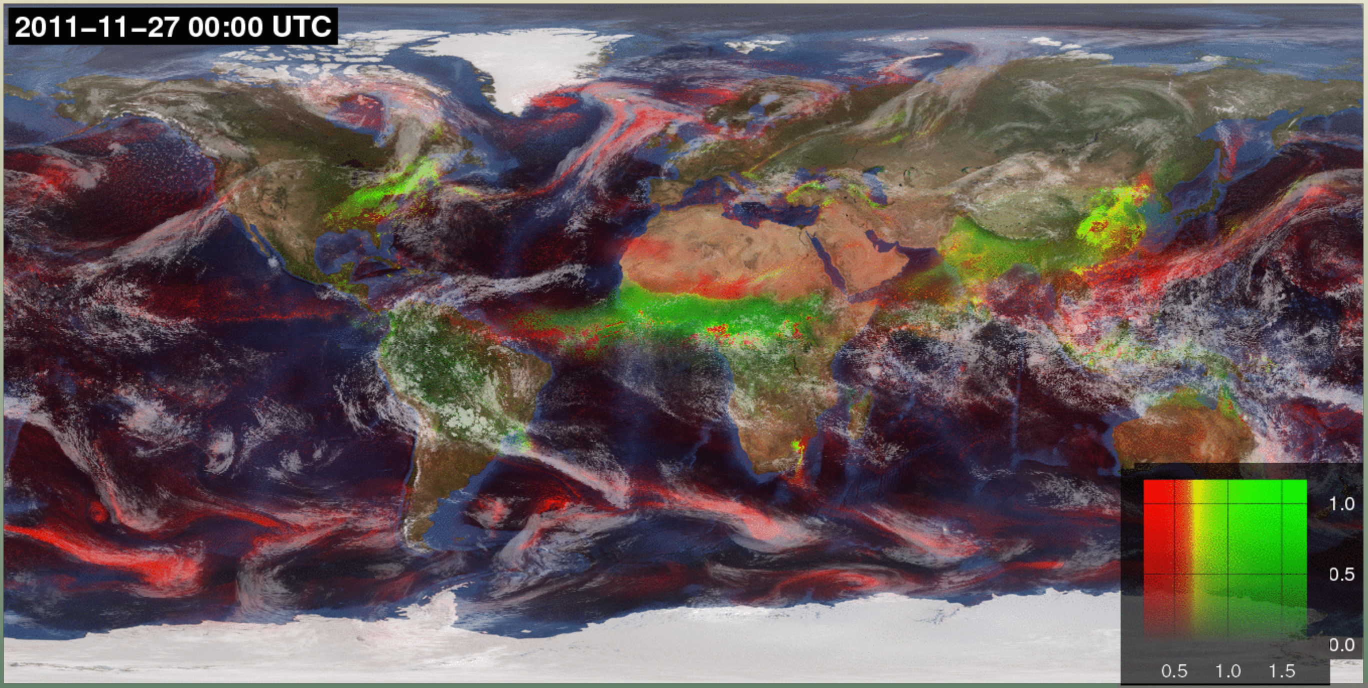
CloudSat+MODIS

Global non-hydrostatic modeling

NICAM-Chem

Goto et al. ('15); Suzuki et al. ('08)
Satoh et al. ('08; '14)

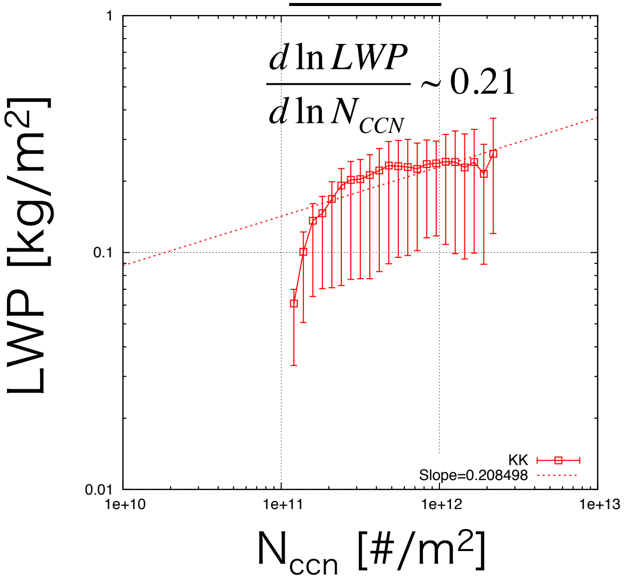
Red: Coarse aerosols (Dust, Sea salt)
Green: Fine aerosols (Sulfate, Carbon)
White: Clouds

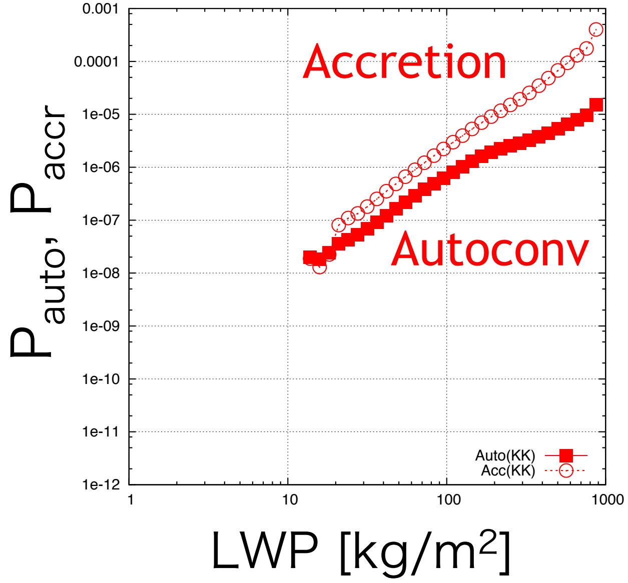


- Resolving clouds with a fine mesh (~3.5km)
- Exploiting a biggest computer in the world

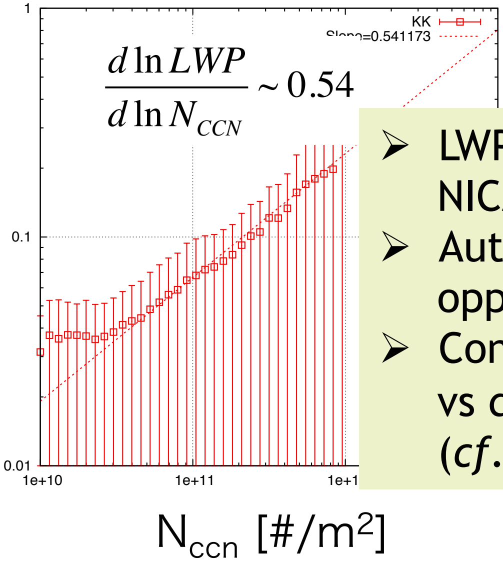
NICAM (global CRM) vs MIROC (traditional GCM)

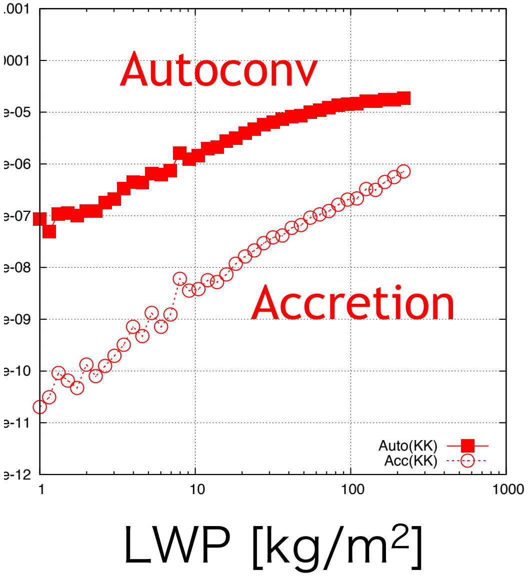
NICAM





MIROC





- ➢ LWP is less susceptible to N$_{CCN}$ in NICAM than in MIROC
- ➢ Autoconv/Accretion proportion is opposite b/w NICAM and MIROC
- ➢ Consistent with prognostic (NICAM) vs diagnostic (MIROC) rain schemes (*cf*. Gettelman et al. ’15)

Y. Sato et al. (in prep.)
[Do not re-distribute]

Summary

- Cloud microphysics has a profound impact on global climate through modulating the water budget of cloud.
- The water budget modulation also changes the energy budget to cause different scenarios of historical trends of global temperature and precipitation.
- Emergence of new satellite observations (particularly active sensors) provides a new tool for process diagnostics, which triggered a shift toward "process-oriented" approach for climate model diagnostics.
- The "bottom-up" model constraint contradicts the "top-down" constraint. Missing "buffering effect" might be relevant to this.