Cloud microphysics and Climate

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Cloud microphysics and its significance to climate

Nucleation from aerosols

**Condensational growth**

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

**S**: Supersaturation

Nucleation from aerosols

$$N_c = f(N_a, w, ...)$$

**Coalescence process**

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

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

Rain formation
Implication for climate simulations

- $r_{\text{crit}}$: “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

Golaz et al. (GRL '13)
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 $\mu$-physical processes

$\rltop = 5-10\mu\text{m}$

$\rltop = 10-15\mu\text{m}$

$\rltop = 15-20\mu\text{m}$

$\rltop = 20-25\mu\text{m}$

$\rltop = 25-30\mu\text{m}$

CloudSat+MODIS

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

Non-precip

Precip
Cloud process information found in CloudSat Obs

**Continuous collection model**

\[
\frac{dR}{dt} = \frac{E_v V_t(R)}{4 \rho_w} q_c
\]

\[
\frac{dR}{dh} = -\frac{E_c q_c}{4 \rho_w} \quad dh = -V_t(R) dt
\]

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

\[
\frac{dZ_e}{Z_e} \approx \alpha \frac{dR}{R}
\]

\[
\tau \approx -\frac{3}{2} \frac{1}{\rho_w R} dh
\]

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

\[\alpha \approx 3 - 6\]

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

Suzuki et al. (JAS '10)
Land-Ocean differences

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

Takahashi et al. (submitted)
Hypothesis: 
Effect of updraft on $\mu$-physical structure

Oceanic clouds

Continental clouds

Takahashi et al. (submitted)
Testing the hypothesis: ARM and Bin model

Takahashi et al. (submitted)

 ARM Azores

Spectral-bin model

(a) $w=0.0\text{ms}^{-1}$  
(b) $w=0.3\text{ms}^{-1}$

(c) $w=0.7\text{ms}^{-1}$  
(d) $w=1.0\text{ms}^{-1}$

Updraft measurement required

Takahashi et al. (submitted)
Climate model diagnostics

Sources of biases:
- Coarse resolution \(~O(100\text{km})\)
- Cloud process representation

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

\[
\tau_p \propto \frac{N^\beta}{(\rho q_c)^\alpha}
\]

Suzuki et al. (JAS ’15)

Satellite

- \(r_e=5-10\mu m\)
- \(r_e=15-20\mu m\)

HadGEM2
- \(\alpha=1.33\)
- \(\beta=0.33\)

CAM5
- \(\alpha=1.47\)
- \(\beta=1.79\)

MIROC5
- \(\alpha=2.0\)
- \(\beta=1.0\)
Does high-resolution help solve the problem?

**NICAM-Chem dx=7km**

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

Rain formation is still too fast
Process representation is critical

**Suzuki et al. (JAS '11)**
Biases traced back to auto-conversion schemes

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

1-dimensional model

\[ \alpha = 1.33 \quad \text{UKMO, MRI} \]

\[ \beta = 0.33 \]

\[ \alpha = 2.0 \quad \text{MIROC, NICAM} \]

\[ \beta = 1.0 \]

\[ \alpha = 1.47 \quad \text{CAM5} \]

\[ \beta = 1.79 \]

\[ \alpha = 3.7 \quad \beta = 3.3 \]
Implication of the “process-oriented” model constraint

Suzuki, Golaz and Stephens (GRL ’13)

**Satellite-based constraint on µ-physics**

**GFDL CM3**

Surface air temperature anomaly

- $r_{\text{crit}} = 6.0 \mu m$
- $r_{\text{crit}} = 8.2 \mu m$
- $r_{\text{crit}} = 10.6 \mu m$

**Golaz et al. (GRL’13)**

$r_{\text{crit}}$: “switch” for rain formation

- $r_{\text{crit}} = 6.0 \mu m$: Temperature trend is best, but rain forms too quickly.
- $r_{\text{crit}} = 10.6 \mu m$: 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)

- “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)

![Figure 4: The deepening effect](image)

The local inhibition of precipitation helps precondition the environment for deeper convection, which then rains more.

![Maps](c) MIROC5 precip. cloud  (d) A–Train precip. cloud

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?