GCMs with Implicit and Explicit cloud-rain processes for simulation of extreme precipitation frequency

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Content

1. Conventional GCM precipitation processes

2. Precipitation processes in a Cloud Resolving Model (CRM)

3. The GCM with cloud microphysics

All results with AGCM

- 50km horizontal resolution
Thermodynamic equations & Reynolds averaging

- Governing equations for dry static energy (s) and water vapor (q)

\[
\frac{\partial s}{\partial t} + (\mathbf{u} \cdot \nabla)s = LC + R
\]

\[
\frac{\partial q}{\partial t} + (\mathbf{u} \cdot \nabla)q = -C
\]

- After Reynolds averaging (over a grid)

\[
\frac{\partial \bar{s}}{\partial t} + \bar{u} \cdot \nabla \bar{s} = -\frac{\partial}{\partial p} \omega' \bar{s}' + L\bar{C} + \bar{R}
\]

\[
\frac{\partial \bar{q}}{\partial t} + \bar{u} \cdot \nabla \bar{q} = -\frac{\partial}{\partial p} \omega' \bar{q}' - \bar{C}
\]
Conventional GCM precipitation processes

1. Convective rain (sub-grid scale)
   - Convective parameterization based on a quasi equilibrium condition

2. Large-scale condensation (grid scale)
   - Function of relative humidity with auto-conversion time scale

\[ l_u = q_u - q_{cv} \]

Precipitation rate: \( R(z) \)

Condensation \((\bar{q} + q' > q_s)\)

- T>0
- T<0

Cloud water

Falling down without Time scale

Cloud ice

Precipitation
Annual mean (50km) precipitation

TRMM

BULK scheme without triggering

BULK scheme with triggering ($w_{cb} > 0.2 \text{ m s}^{-1}$)

Ratio of convective to total precipitation

No convective parameterization (NOCONV) to total precipitation
Frequency of 3-hourly precipitation

- **Frequency (%)**
- **Precipitation (mm/day)**

- **TRMM**
- **BULK_Original**
- **BULK_Triggering**
- **No convection**
Precipitation processes in a cloud resolving model (CRM)

CRM experiments

- Goddard Cumulus Ensemble (Tao et al. 1993)
- Two-dimensional model with cyclic boundary conditions
- 1km horizontal resolution with 41 vertical level and 256km domain size
- TOGA-COARE forcing data
Precipitation – CRM vs. OBS

✓ Goddard Cumulus Ensemble model (Tao et al. 1993) simulation with TOGA-COARE forcing for boreal winter
CRM Microphysics

Cloud Microphysics

Condensation → Cloud water
Freezing → Cloud ice
Accretion → Snow
Melting → Rain
Deposition → Graupel

AGCM parameterization

Convective rain

Cloud water, \( l_u = q_v - q_{ev} \)

Precipitation rate: \( R(z) \)

Convective adjustment

Time scale

Large-scale condensation

Condensation (\( q_v + q_e > q_e \))

\( T > 0 \)

Cloud water

Auto-conversion

Time scale

\( T < 0 \)

Cloud ice

Falling down

Without

Time scale

Precipitation
Budget of microphysical processes

(a) Light precipitation (0 – 10 mm day⁻¹)

(b) Heavy precipitation (> 60 mm day⁻¹)

Cloud species: g/g
Processes: g/g/s
Relationship between precipitation and graupel

Rainfall vs. Graupel

Rainfall vs. Accretion of cloud water to graupel
Development of GCM with cloud microphysics

Convective parameterization + Large-scale condensation → Cloud microphysics

Model resolution: 50km
Dynamical core: Spectral -> Finite volume methods
Climatological SST, 4 year integration
The GCM with cloud microphysics
Global model with CRM physics

- **Superparameterization**

- **Explicit global CRM**

- **GCM with cloud microphysics** (50 km, CRM & Parameterization combined)
Required computing resources for climate simulation

* Computing resources: 1,000 CPU

- **IPCC model (200km)**: 2 hours for 10 years simulation
- **Explicit global CRM (1km)**: 50 years for 10 year simulation
- **GCM with cloud microphysics (50km)**: 2 weeks for 10 years simulation

This is suitable for climate researches as a next generation model.
Modification of cloud microphysics

1. Less condensation due to relatively coarse horizontal resolution (50km)
   => Modification of condensation process by using the parameterization used in the large-scale condensation scheme (Le Treut and Li 1991)

2. Insufficient accretion due to weak vertical motion
   => Decrease of the terminal velocity of cloud hydrometers (Satoh and Matsuda 2009)
Biases of vertical structure of cloud water

- Adding vertical mixing
  - Diffusion type of convective scheme

Too excessive cloud water
Annual mean precipitation

TRMM

Modified Microphysics

Modified Microphysics + Convection
Frequency of 3-hourly precipitation
Global distribution of 3-hourly light & heavy precipitation

TRMM

- **(a)** Light precipitation (0–10 mm/day)
- **(b)** Heavy precipitation (>60 mm/day)
- **(c)** Total precipitation

BULK+LSC

- **(d)** Light precipitation (0–10 mm/day)
- **(e)** Heavy precipitation (>60 mm/day)
- **(f)** Total precipitation

Microphysics+
shallow convection

- **(g)** Light precipitation (0–10 mm/day)
- **(h)** Heavy precipitation (>60 mm/day)
- **(i)** Total precipitation
Hovmuller diagram of daily mean precipitation (10°S-10°N)
Summary

GCM requires Cloud Microphysics for Simulation of heavy and extreme precipitation reasonably well

- The GCMs with convective parameterization produce too much light rain but less heavy precipitation compared to the observed.
- Graupel and Accretion are important hydro-meteor and hydor-process for heavy precipitation.

A paper submitted to Climate Dynamics
Thank you!
Global distribution of 3-hourly light & heavy precipitation

TRMM

(a) Light precipitation (0–10 mm/day)

(b) Heavy precipitation (>60 mm/day)

(c) Total precipitation

BULK+LSC

(d) Light precipitation (0–10 mm/day)

(e) Heavy precipitation (>60 mm/day)

(f) Total precipitation

NOCONV

(g) Light precipitation (0–10 mm/day)

(h) Heavy precipitation (>60 mm/day)

(i) Total precipitation
Increase of vertical mixing

- Deep convective parameterization
  - BULK scheme without precipitational processes

- Diffusion type of shallow convection scheme
  - Vertical mixing of temperature and moisture
  - No precipitation processes

\[
\begin{align*}
\left( \frac{\partial \bar{s}}{\partial t} \right)_{shc} &= \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \left\{ \bar{\rho} K \frac{\partial}{\partial z} \left( \bar{s} - L \bar{l} \right) \right\}, \\
\left( \frac{\partial \bar{q}}{\partial t} \right)_{shc} &= \frac{1}{\bar{\rho}} \frac{\partial}{\partial z} \left\{ \bar{\rho} K \frac{\partial}{\partial z} \left( \bar{q} + L \bar{l} \right) \right\}.
\end{align*}
\]

- \( s \): dry static energy
- \( q \): specific humidity
- \( l \): cloud water
- \( L \): latent heat of condensation
- \( \rho \): density of air
- \( z \): altitude
- Over bar: grid average value
- Prime: perturbation from grid average value

Vertical profile of \( K \):

- Cloud Top
  - Top -1: K=0.5
  - Top -2: K=1.5
- 3~4 levels
  - 3~4 levels: K=2.5
- Cloud Bottom
  - K=0.75
  - K=0

\( K \): eddy diffusion coefficient
Modification of cloud microphysics

- **Condensation using sub-grid scale variability**

![Diagram showing condensation process](image)

Parameterization of sub-grid scale variability

\[
C_{frc} = \begin{cases} 
0 & (1 + b)\bar{q} \leq \bar{q}^s \\
\frac{(1 + b)\bar{q} - \bar{q}^s}{2b\bar{q}} & (1 - b)\bar{q} < \bar{q}^s < (1 + b)\bar{q} \\
\frac{1}{1} & (1 - b)\bar{q} \geq \bar{q}^s 
\end{cases}
\]

(Le Treut and Li 1991)

- **Accretion processes**

  - Less accretion due to coarse resolution
  - Increase of collection efficiency
  - Increase of accretion

- **Terminal velocity**

  - At coarse resolution, accretion processes is weak
  - Decrease of terminal velocity
    - Increase of cloud hydrometer
    - Increase of accretion

\[
P_{RACW} = \frac{\pi}{4} q_{eRW} n_{QO} \left(\frac{\rho_0}{\rho}\right) \left[\frac{a_0 \Gamma(3)}{\lambda^3_R} + \frac{a_0 \Gamma(4)}{\lambda^5_R} + \frac{a_0 \Gamma(5)}{\lambda^5_R} + \frac{a_0 \Gamma(6)}{\lambda^5_R}\right]
\]

- \(E_{RW} \Rightarrow 1.0 \text{ g g}^{-1} \text{ to } 2.0 \text{ g g}^{-1}\)

\[
U_R = \frac{a \Gamma(4 + b)}{6 \lambda^b_R} \left(\frac{\rho_0}{\rho}\right)^{1/2}, \quad \lambda_R = \left(\frac{\pi \rho_w n_{QO}}{\rho q_R}\right)^{0.25}
\]

- \(a \Rightarrow 2.14 \text{ m/s}^{-1} \text{ to } 1.8 \text{ m s}^{-1}\)
Wheeler-Kiladis diagram

GPCP (20yrs)

Parameterization (6yrs)

Modified microphysics and convection (6yrs)
GCM simulation with cloud microphysics (50km)

- Annual mean precipitation
- Animation of 3-hourly precipitation

TRMM

GCM with parameterizations

GCM with microphysics

TRMM

GCM with parameterization

GCM with microphysics
Coupled model with cloud microphysics

- CGCM with microphysics and convection (ongoing)

* 4 years average
Global distribution of 3-hourly light & heavy precipitation