A Grey Zone GCM

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Young-Min Yang (2014) & Min-Seup Ahn (2017)

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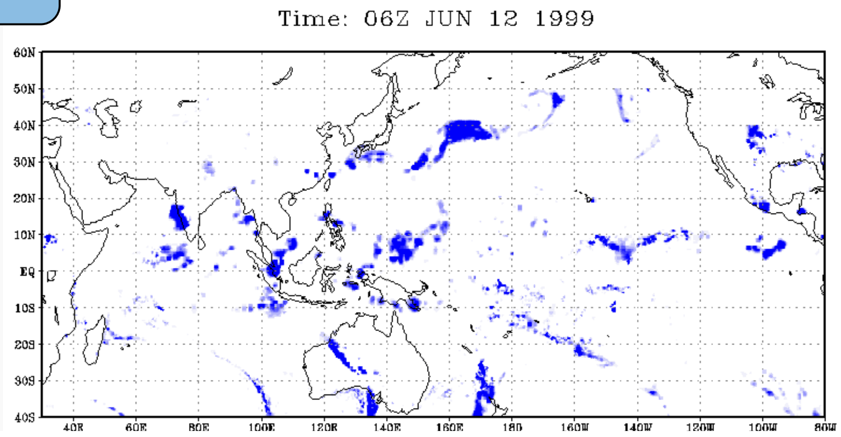
High resolution modeling

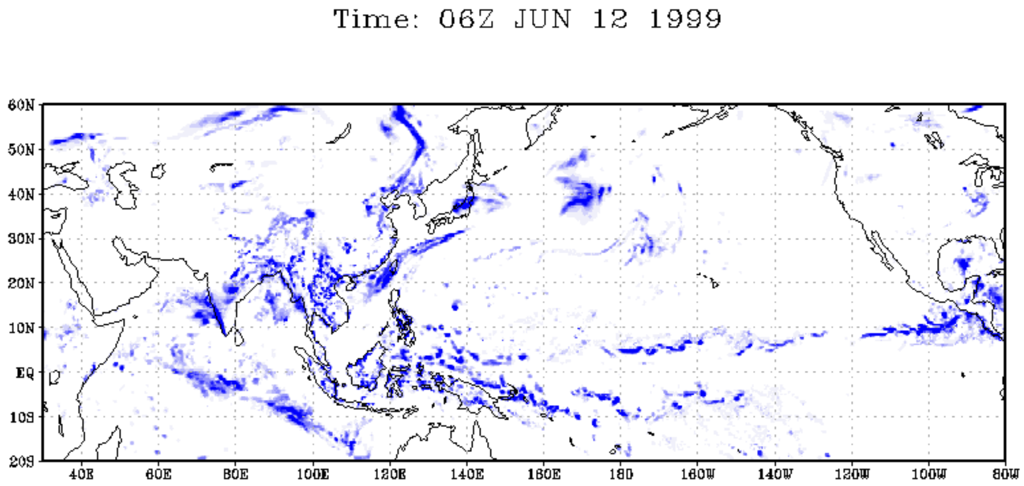
June 1999 – 20km resolution

Satellite observation

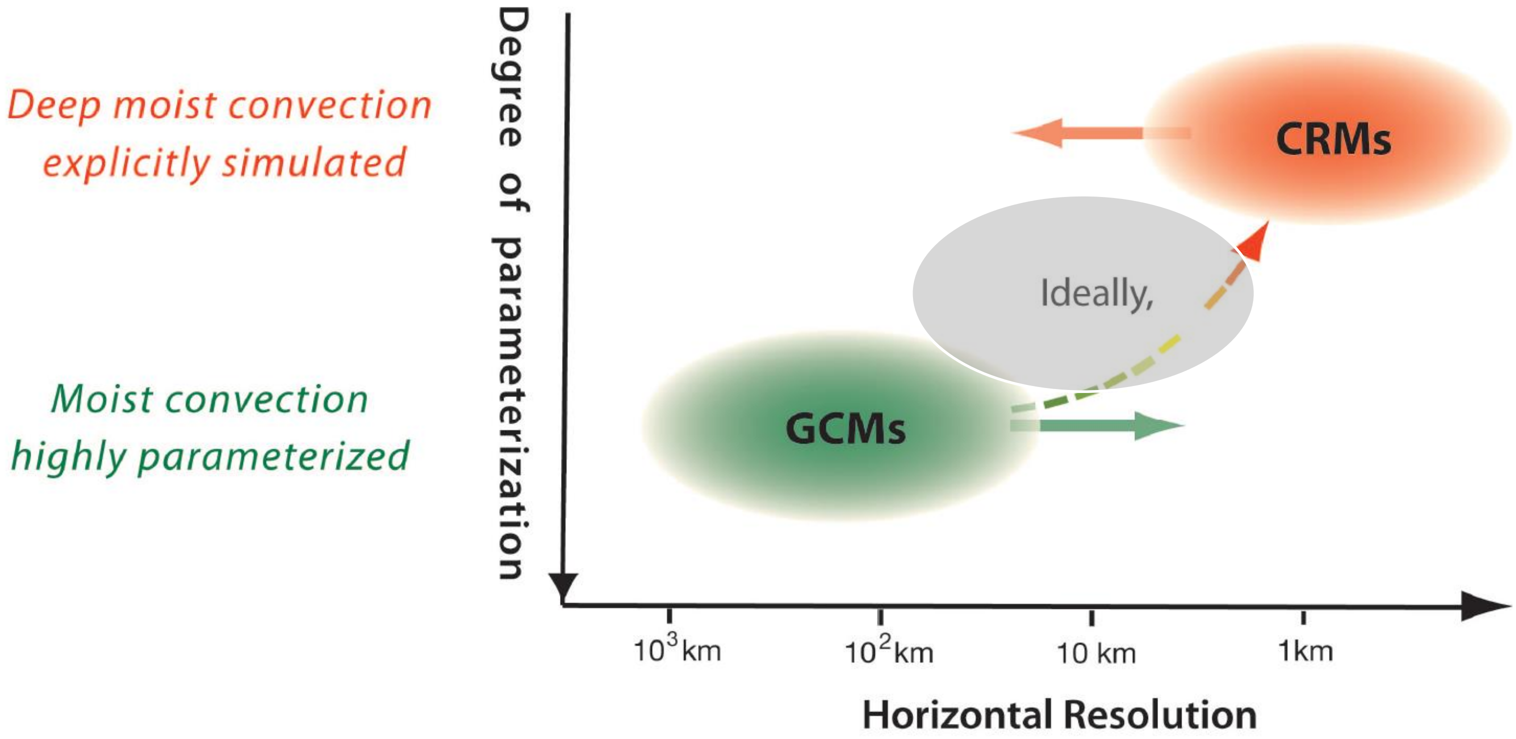


High resolution

Finite volume GCM

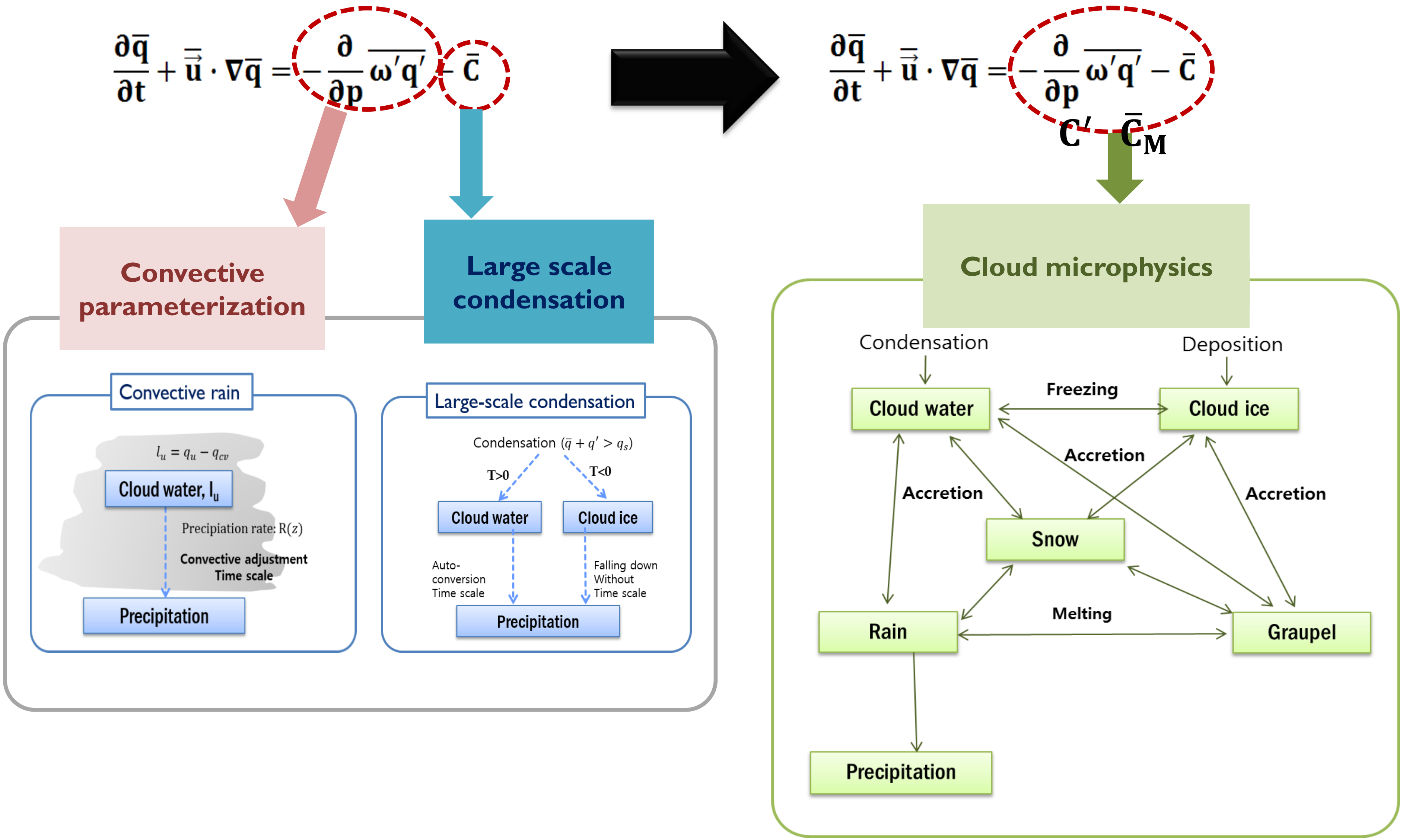


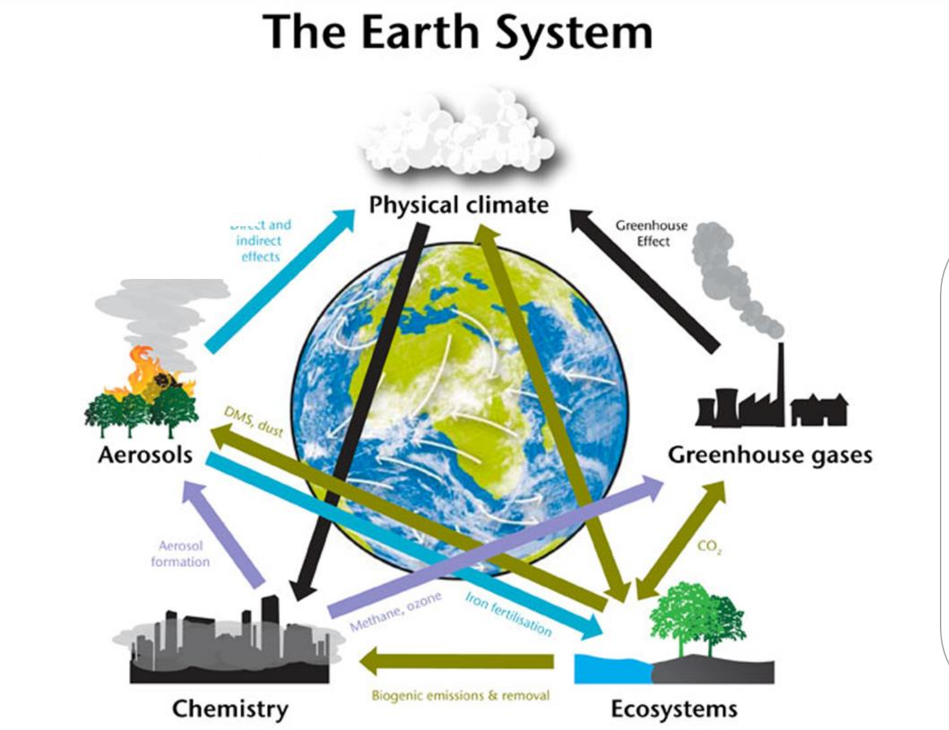
Degree of parameterization depending on horizontal resolution



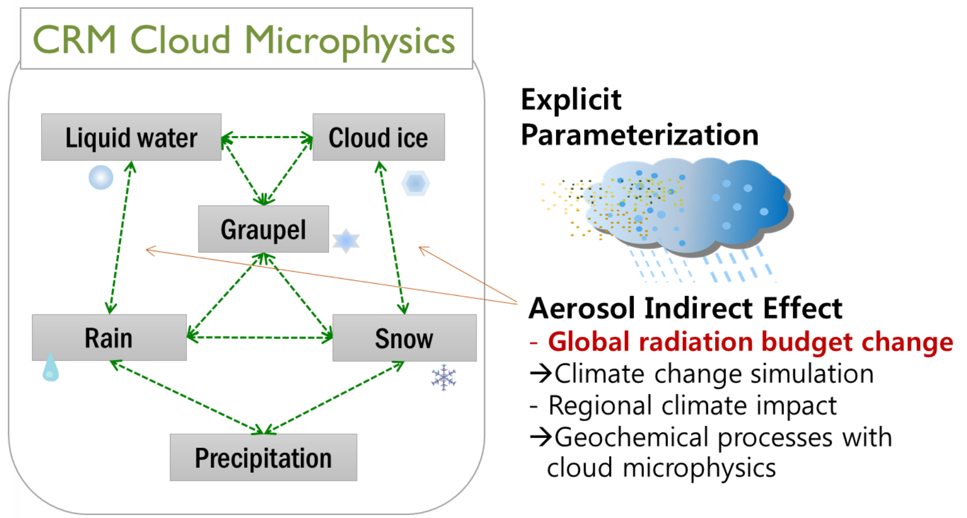
Arakawa et al. (2011)

Moisture Equation in a GCM





Schematic figure of HadGEM2-ES and the earth system interactions it represents
http://www.metoffice.gov.uk/research/news/cmip5



The Earth System Modeling requires Cloud Microphysics for the reasonable representation of **Precipitation process, Cloud-Radiation interaction, Cloud-Aerosol interaction (aerosol indirect effect)**

Contents

1. **Conventional GCM with a convective parameterization**

2. **Precipitation processes in a Cloud Resolving Model – Cloud Microphysics**

3. **A GCM with cloud microphysics (MP-GCM)**

4. **MP-GCM with scale-adaptive convective parameterization**

All results with AGCM

- 50km horizontal resolution

Thermodynamic equations & Reynolds averaging

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

$$\frac{\partial s}{\partial t} + (\vec{u} \cdot \nabla)s = LC + R$$

$$\frac{\partial q}{\partial t} + (\vec{u} \cdot \nabla)q = -C$$

- C: condensation-evaporation
- R: Radiative heating

❖ After Reynolds averaging (over a grid)

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

$$\frac{\partial \bar{q}}{\partial t} + \bar{\vec{u}} \cdot \nabla \bar{q} = -\frac{\partial}{\partial p}\overline{\omega' q'} - \bar{C}$$

Mass flux-type convection scheme

❖ Mass flux-type (e.g. Arakawa-Schubert, Tiedtke and many other schemes)

$$\frac{\partial}{\partial p}\overline{\omega' s'} \sim g\frac{\partial M_c(s_c - \bar{s})}{\partial p}$$

$$\frac{\partial}{\partial p}\overline{\omega' q'} \sim g\frac{\partial M_c(q_c - \bar{q})}{\partial p}$$

- M_c: mass flux
- s_c, q_c : in-cloud (by cloud model)

❖ Cloud budget equation (cloud model)

$$0 = -D + E - g\frac{\partial M_c}{\partial p}$$

$$0 = -Ds_c + E\bar{s} - g\frac{\partial M_c s_c}{\partial p} + LC_c$$

$$0 = -Dq_c + E\bar{q} - g\frac{\partial M_c q_c}{\partial p} - C_c$$

*Stationary assumption

$$\frac{\partial \sigma}{\partial t} = \frac{\partial \sigma s_c}{\partial t} = \frac{\partial \sigma q_c}{\partial t} = 0$$

Unknown: M_c, s_c, q_c

$D, E, C_c = f(s_c, \bar{s}, q_c, \bar{q})$

- σ: cloud fraction
- D: detrainment
- E: entrainment

❖ Determination of M_b

$M_c = M_b \mu$ ➔ closure of the convection scheme

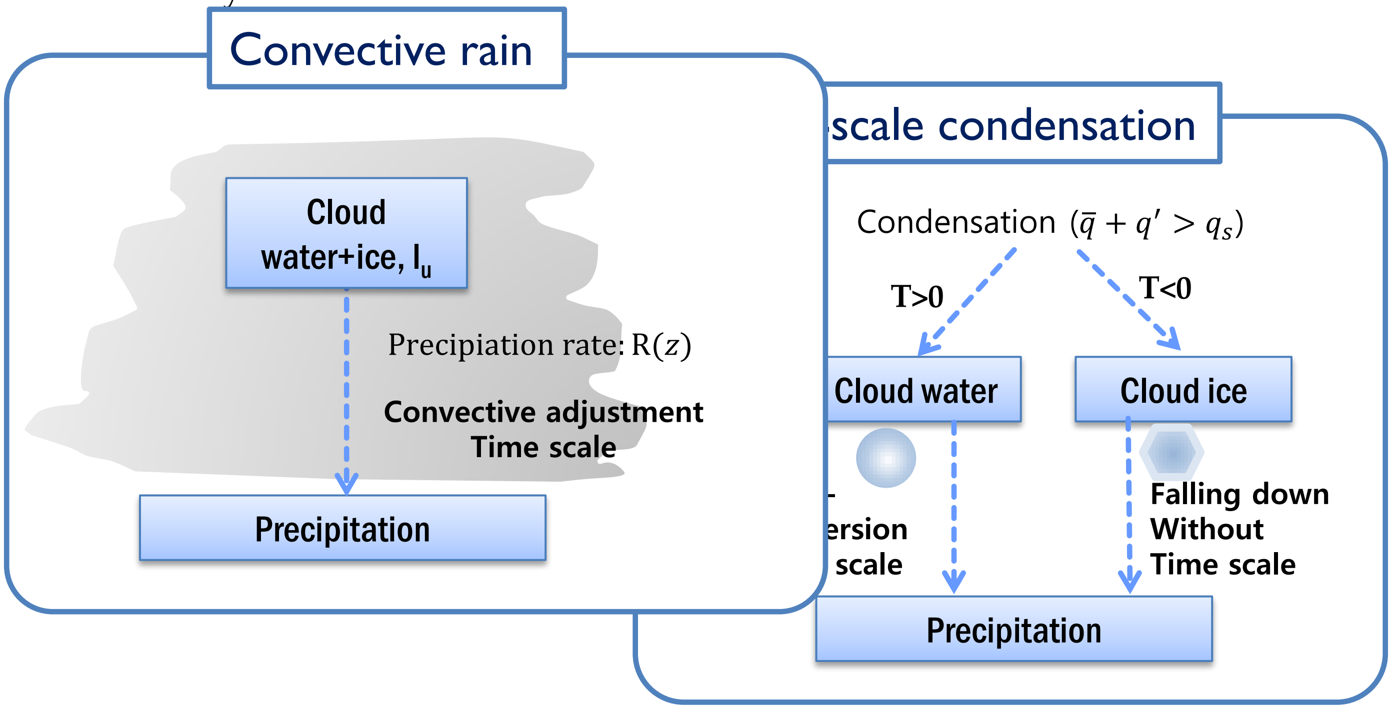
Conventional GCM precipitation processes

1. Convective rain (sub-grid scale)

- Convective parameterization based on a quasi equilibrium condition

2. Large-scale condensation (grid scale)

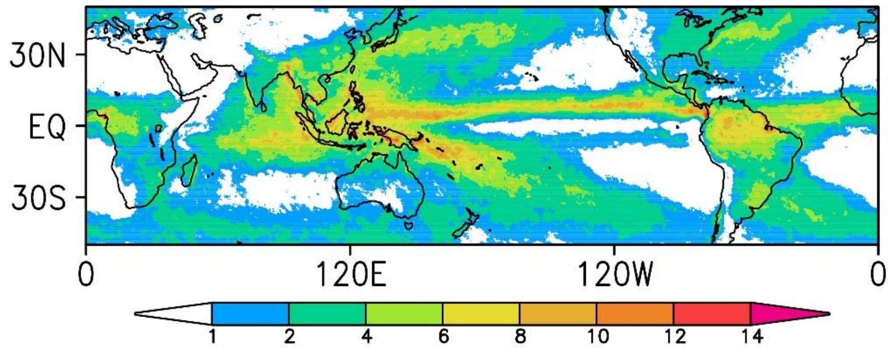
- Function of relative humidity with auto-conversion time scale



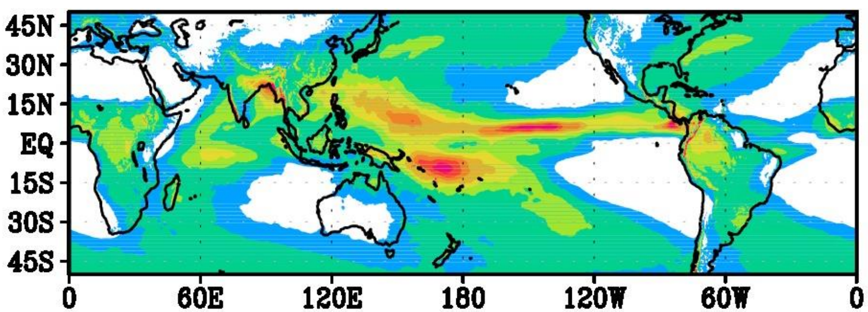
Annual mean (50km)

precipitation

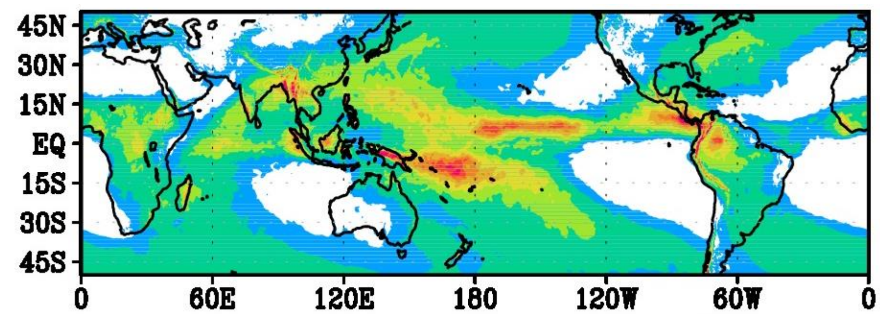
TRMM



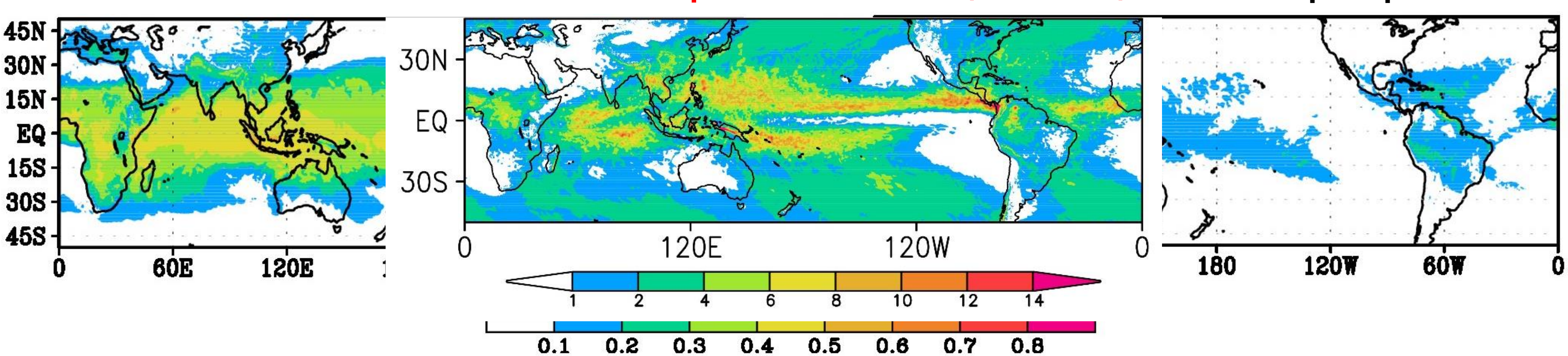
SAS scheme with Tok 0.075



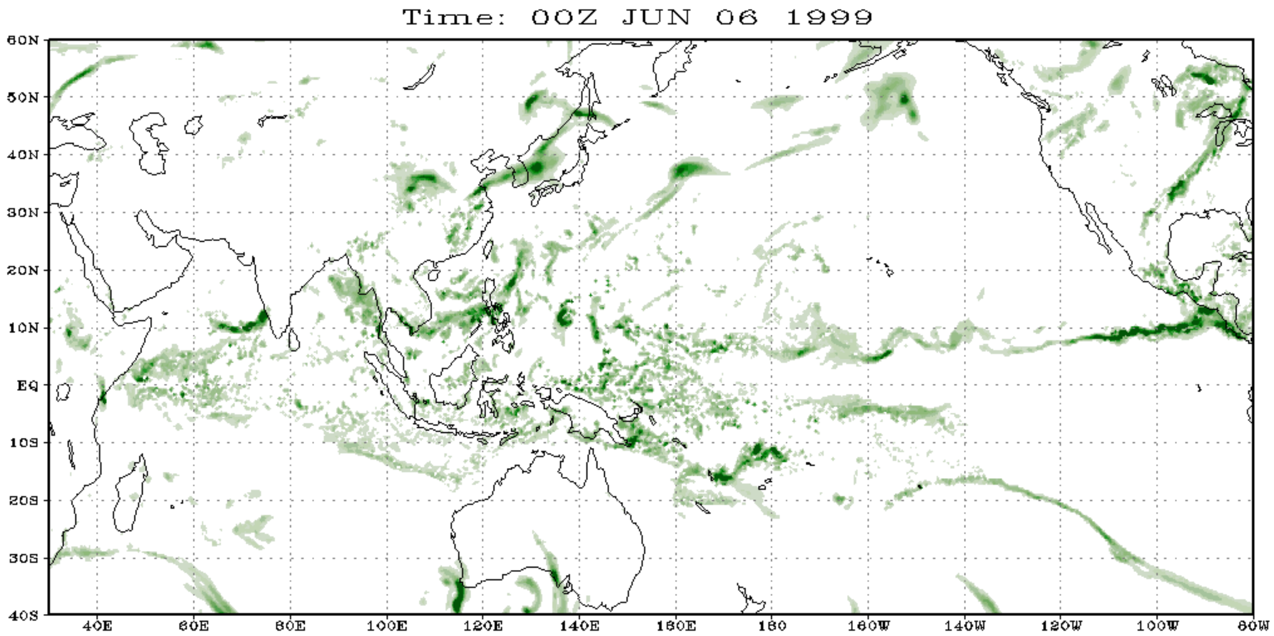
SAS scheme with Tok 0.45



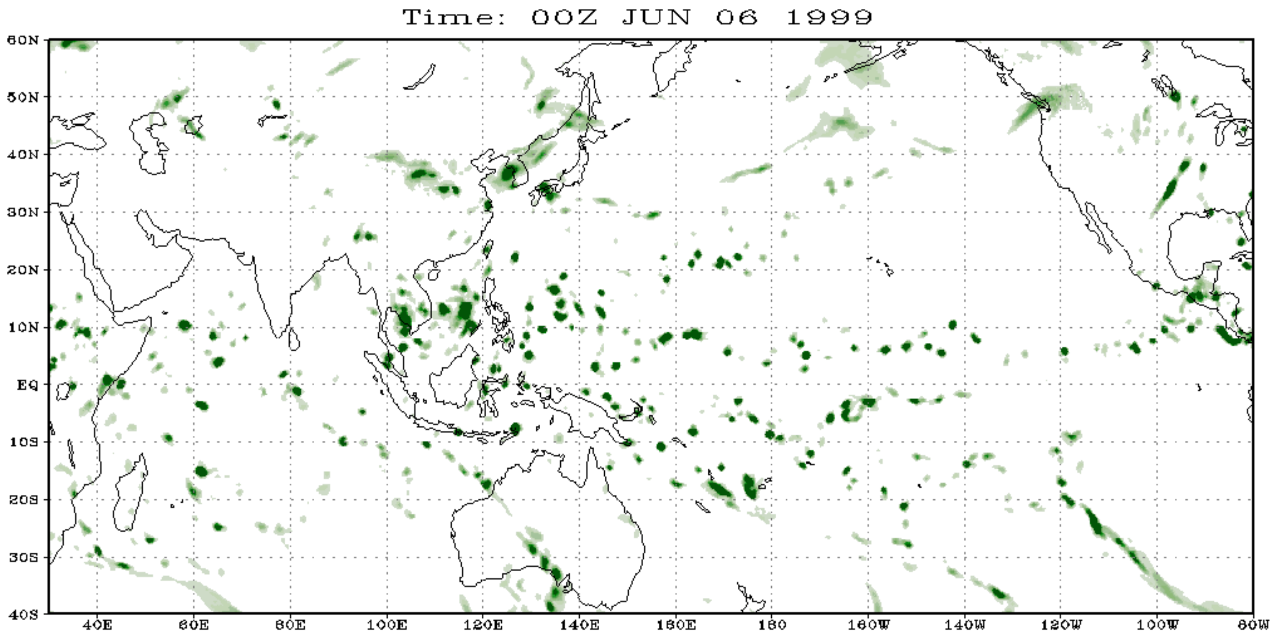
Ratio of convective to tot **No convective parameterization (NOCONV)** ve to total precipitation



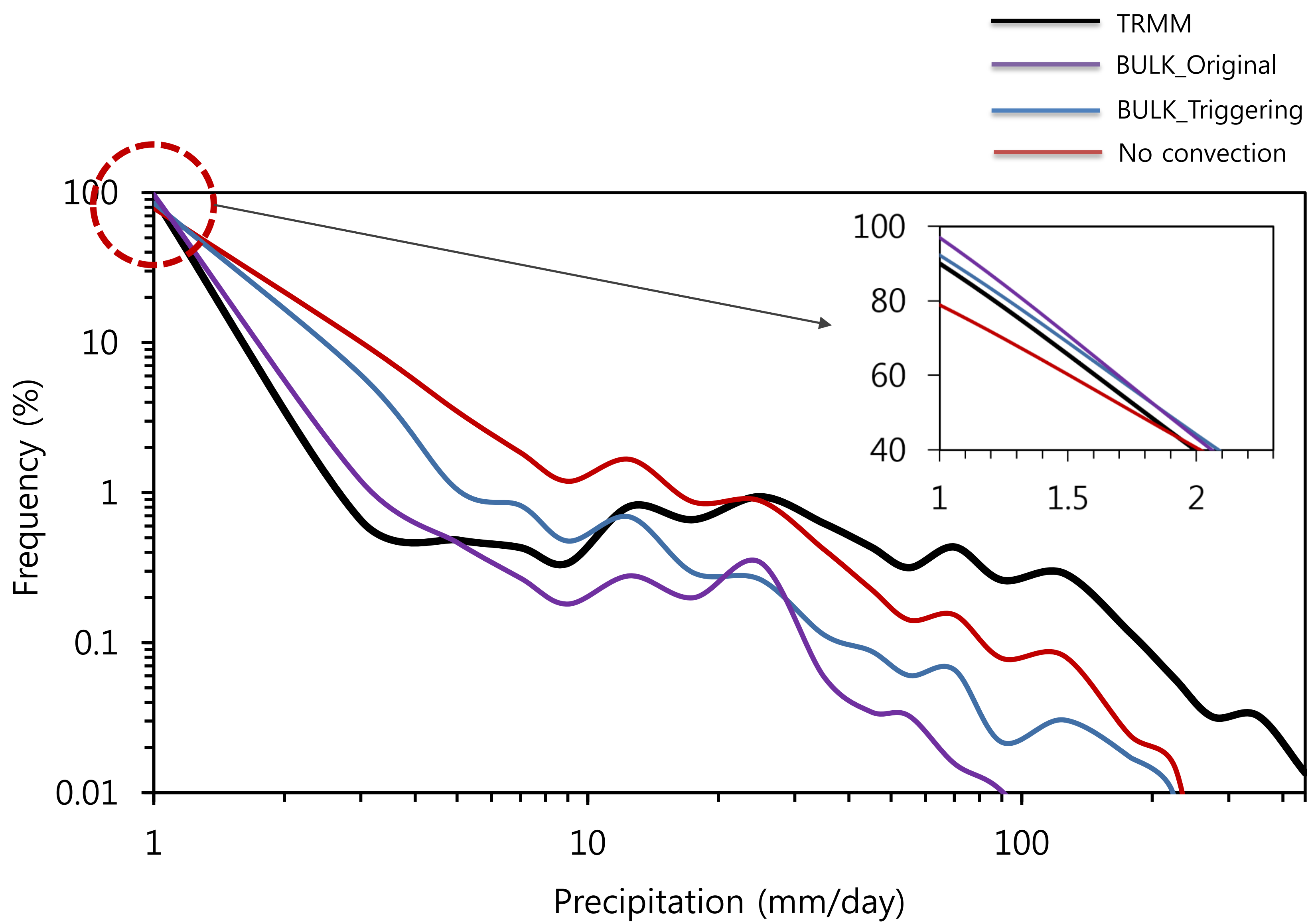
With cumulus parameterization



Without cumulus parameterization



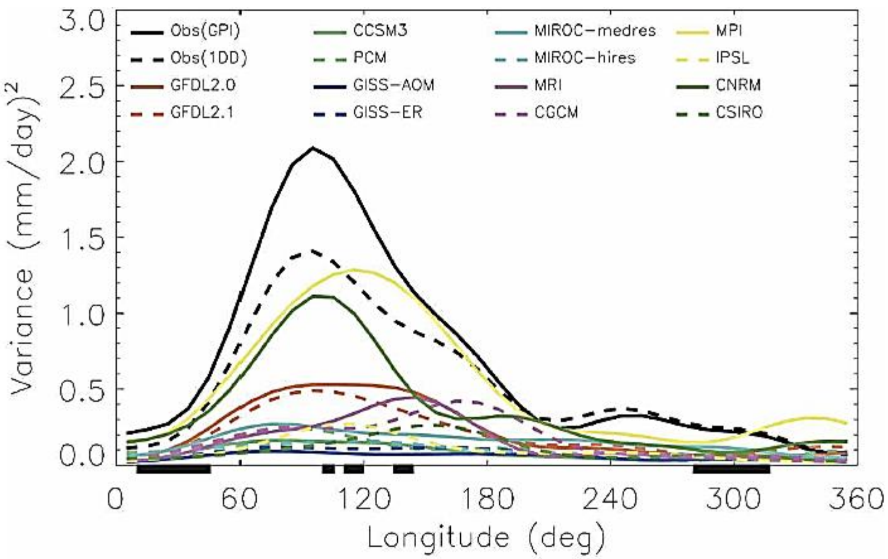
Frequency of 3-hourly precipitation



IPCC AR4 and AR5 Models

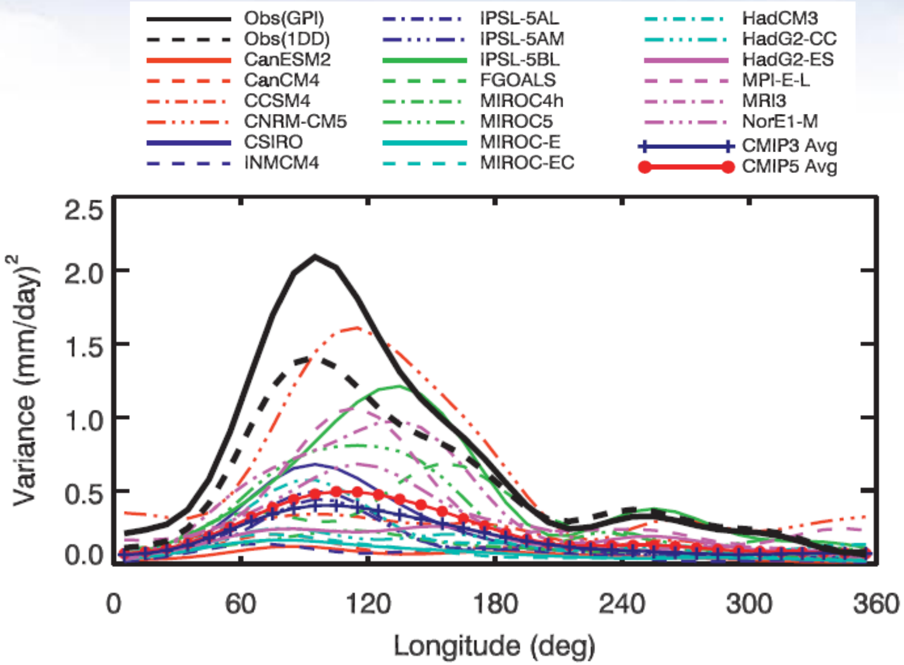
MJO Variance (15°N-15°S)

AR4 models



(Lin et al. 2006)

AR5 models



(Hung et al. 2013)

STILL

Problems of Current GCMs

- Too much light rain and
  Lack of extreme precipitation

- Poor simulation of moisture related phenomena

Lack of physics and Wrong assumptions

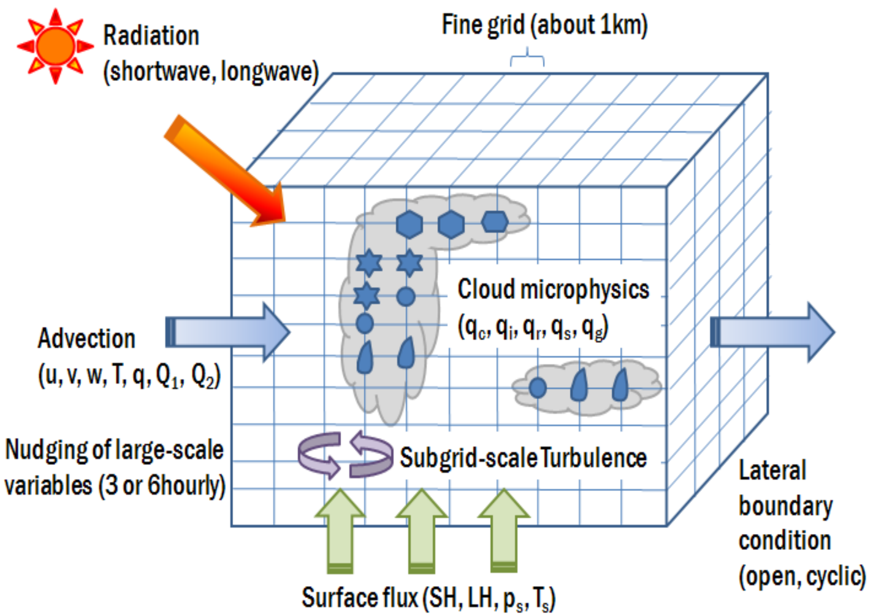
Precipitation processes in a cloud resolving model (CRM)

CRM experiments

- Goddard Cumulus Ensemble (GCE) (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

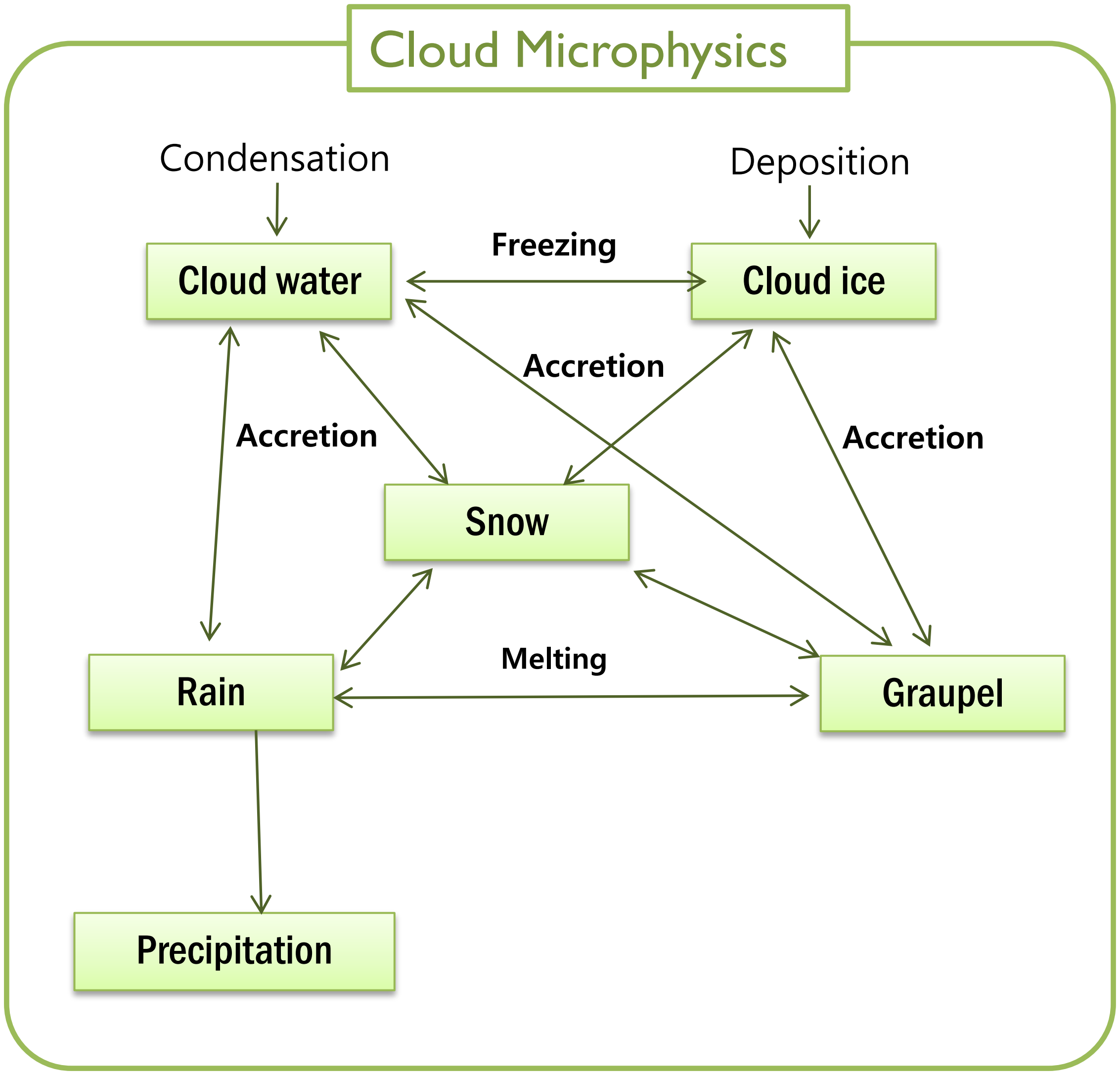
Cloud resolving model

Goddard Cumulus Ensemble model (NASA/GSFC)



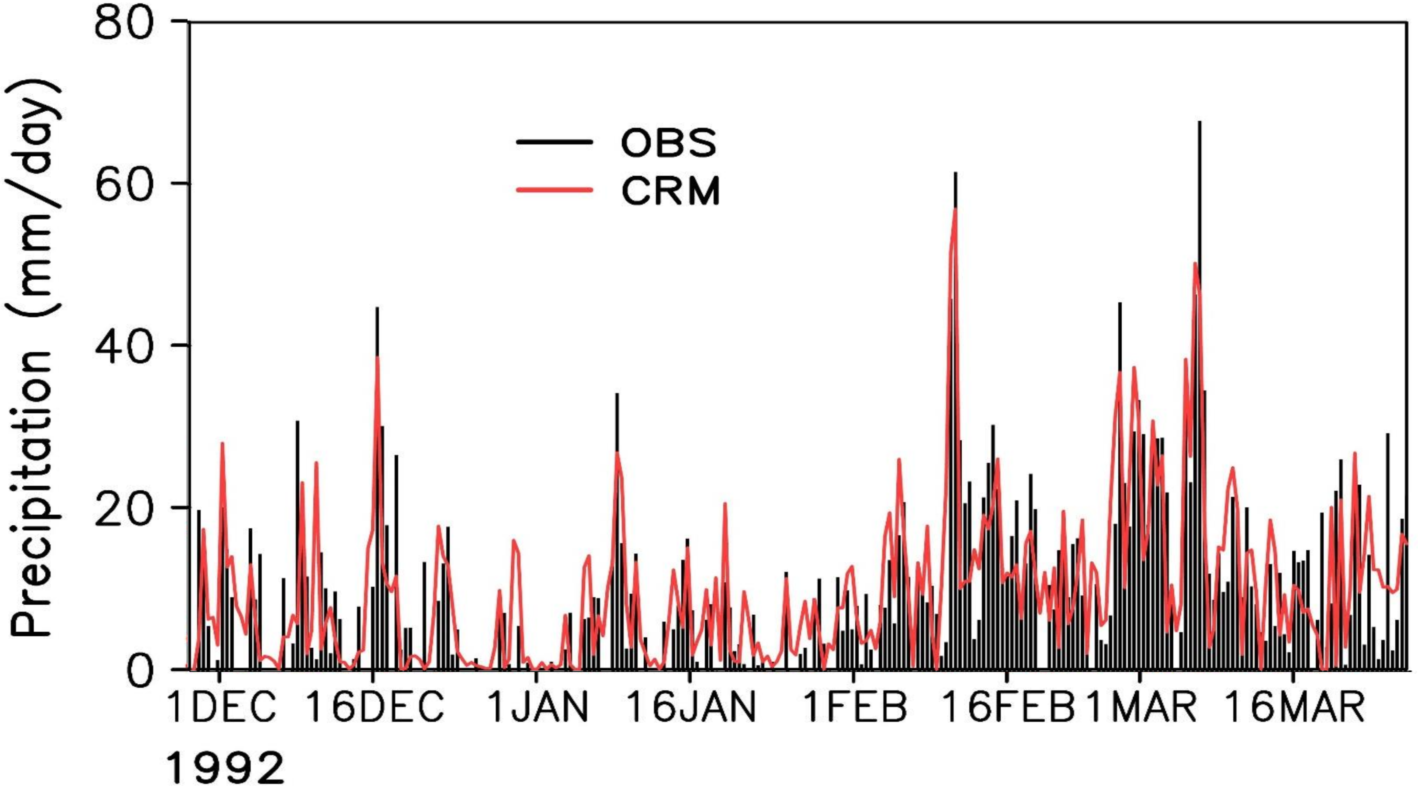
Parameters/ Processes	GCE Model
Dynamics	Anelastic or Compressible 2D (Slab- and Axis-symmetric) and 3D
Microphysics	2-Class Water & 3-Class Ice Single momentum
Numerical Methods	Positive Definite Advection for Scalar Variables; 4th-Order for Dynamic Variables
Radiation	k-Distribution and Four-Stream Discrete-Ordinate Scattering (8 bands) Explicit Cloud-Radiation Interaction
Sub-Grid Diffusion	TKE (1.5 order)
Surface Energy	TOGA COARE Flux Module

CRM Microphysics



Precipitation – CRM vs. OBS

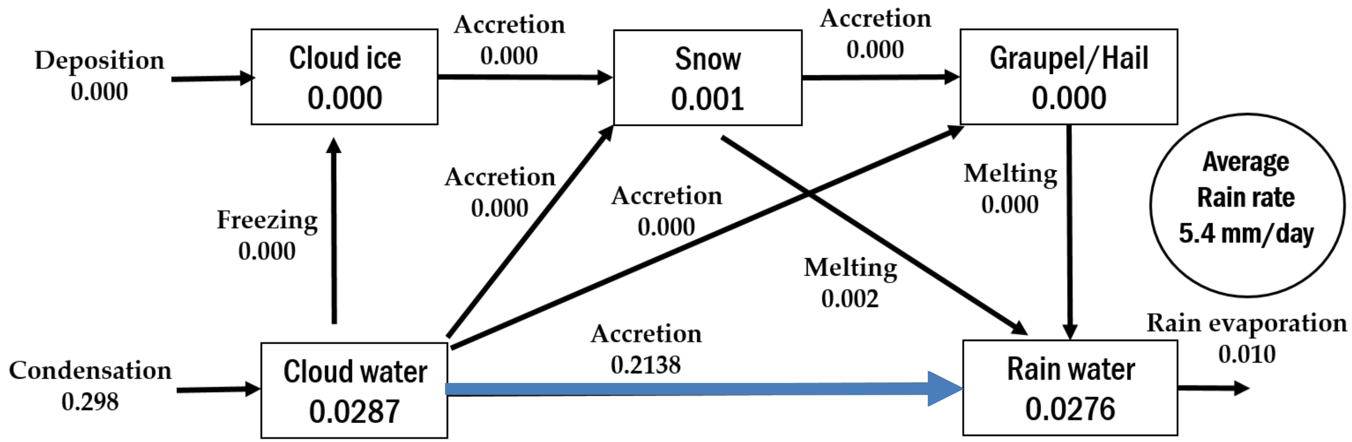
6-hour mean precipitation (mm day^{-1})



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

Budget of microphysical processes

(a)Light precipitation (0 – 10 mm day^{-1})

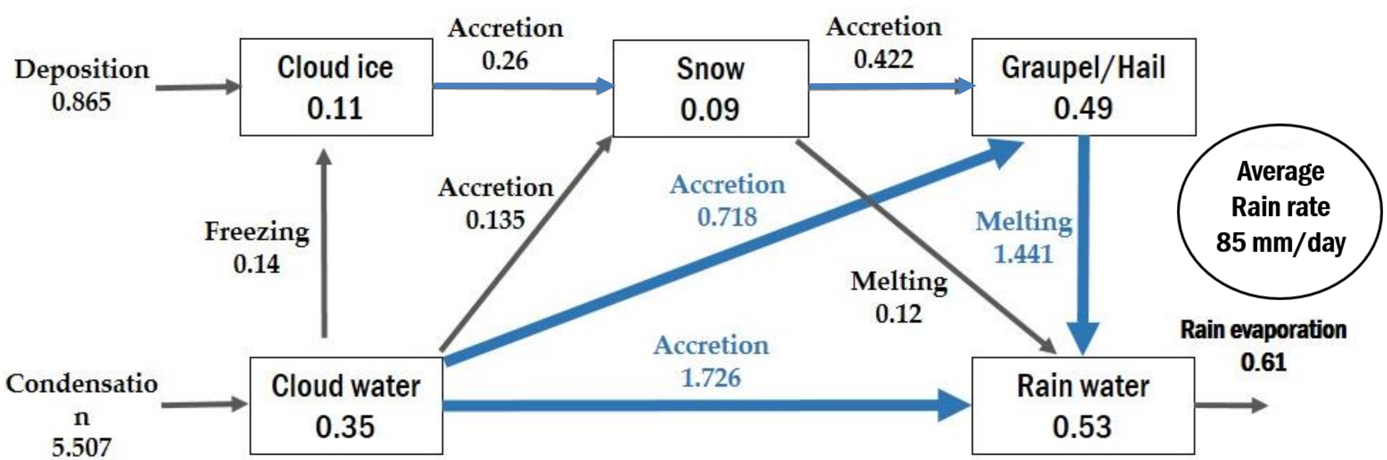


<Unit>

Cloud species : g/g

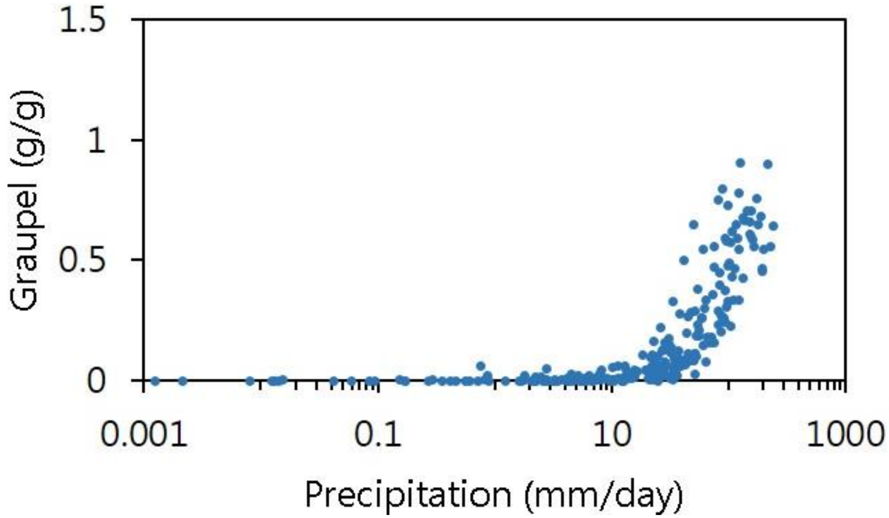
Processes : g/g/s

(b) Heavy precipitation (> 60 mm day^{-1})

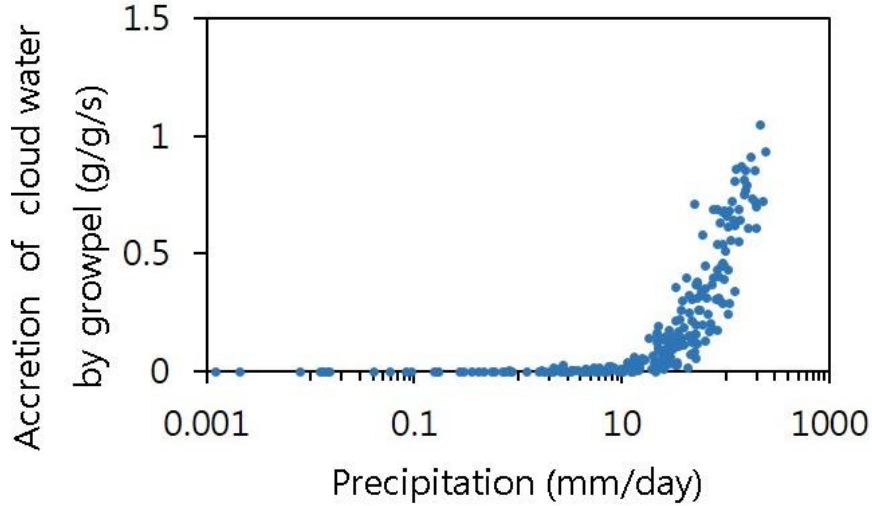


Relationship between precipitation and graupel

Rainfall vs. Graupel



Rainfall vs. Accretion of cloud water to graupel



A GCM with cloud microphysics

❖ Problems of CRM for applying it to a global model of 50km Resolution

- Resolution dependent physics

  - Modified Cloud Micropysics

- Less vertical mixing

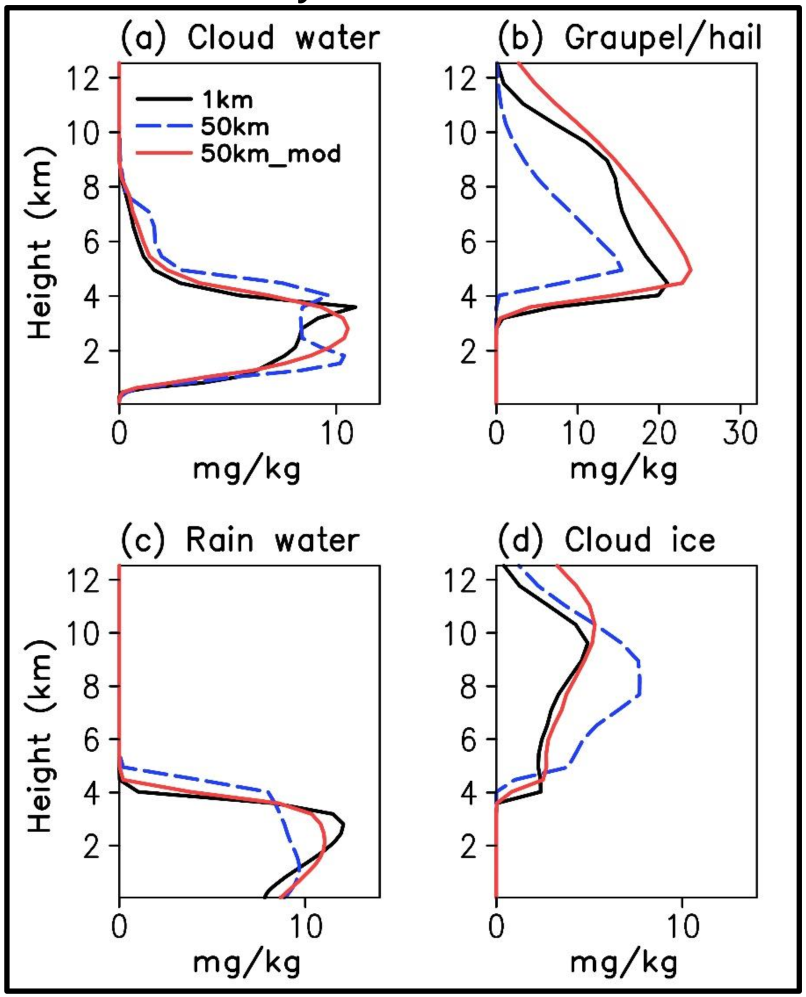
  - Adding convective mixing

CRM simulations with modified microphysics

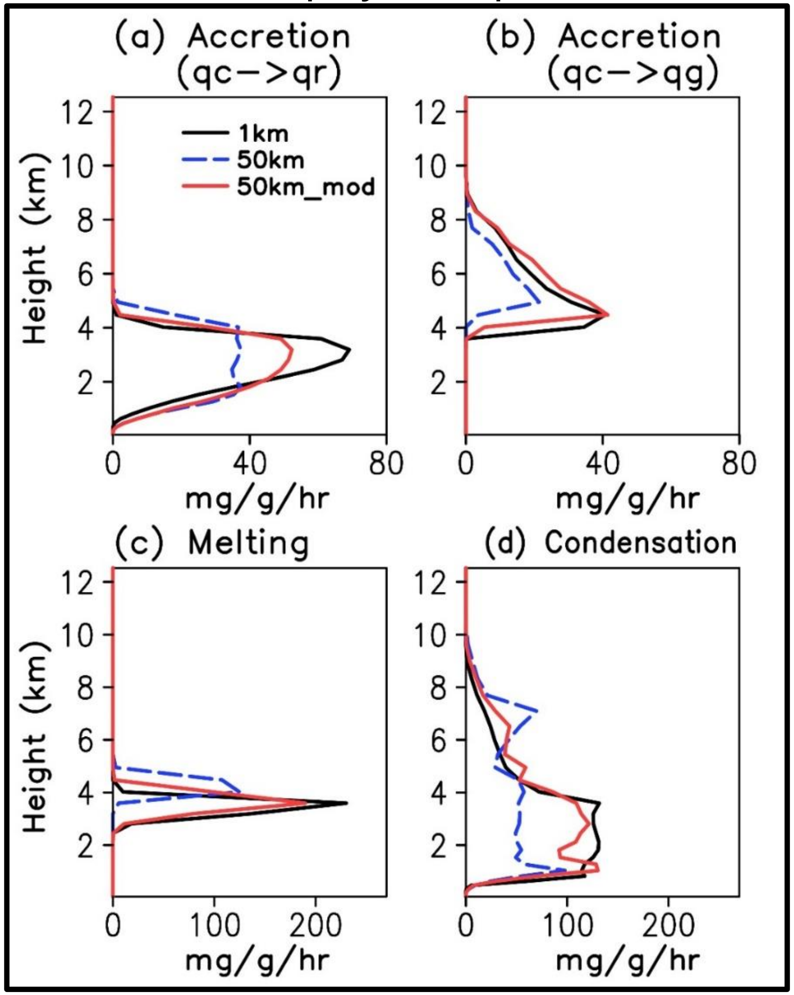
- **Condensation (GCM formula,** Le Treut and Li 1991**)**
- **Terminal velocity (50% reduction)**

(Kang et al. 2015)

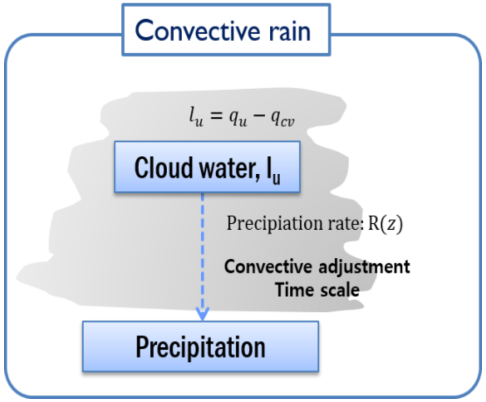
Hydrometeors



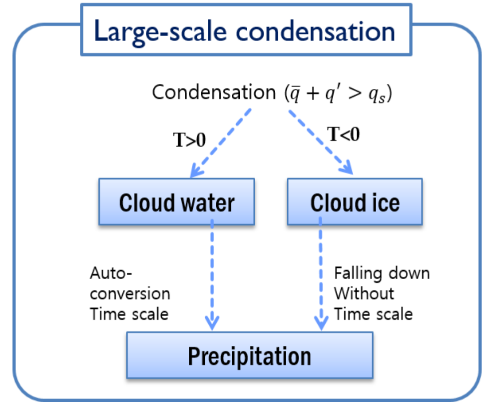
Microphysical process



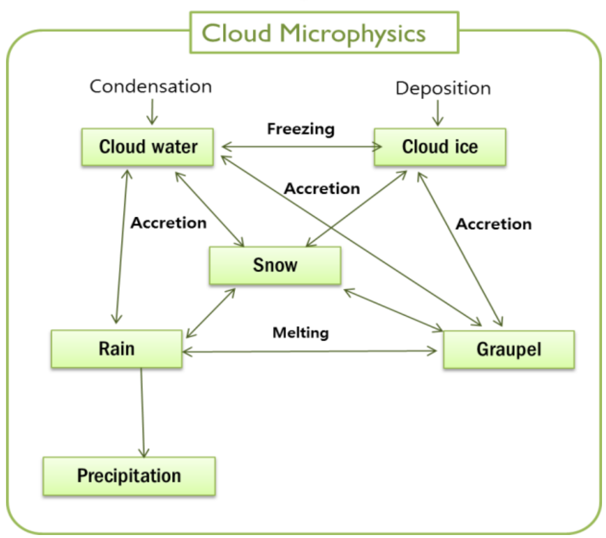
Development of GCM with cloud microphysics



Convective parameterization



Large-scale condensation



Cloud microphysics

- Model resolution : 50km
- Dynamical core :
  Spectral -> FV methods
- Climatological SST
- 4 year integration

Governing equations for Temperature and Hydrometeors in GCM

	Conventional GCM	MP-GCM
Thermodynamic	Thermodynamic $\frac{d\bar{T}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' T'}) + \left[\frac{L_v}{C_p}(\bar{c} - \bar{e})\right] + Q_R$	Thermodynamic $\frac{d\bar{T}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' T'}) + \left[\frac{L_v}{C_p}(\bar{c} - \bar{e_l}) + \frac{L_s}{C_p}(\bar{d_i} + \bar{d_s} + \bar{d_g} - \bar{s_i}) + \frac{L_f}{C_p}(\bar{f} - \bar{m})\right] - \left[\frac{L_v}{C_p}\bar{e_r} + \frac{L_s}{C_p}(\bar{s_s} + \bar{s_g})\right] + Q_R$ Cloud Microphysics and Macrophysics
Hydrometeors	Water vapor $\frac{d\bar{q_v}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_v'}) - (\bar{c} - \bar{e})$	Water vapor $\frac{d\bar{q_v}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_v'}) - (\bar{c} + \bar{d_i} + \bar{d_s} + \bar{d_g} - \bar{e_l} - \bar{s_i}) + (\bar{e_r} + \bar{s_s} + \bar{s_g})$
	Cloud water (liquid+ice) $\frac{d\bar{q_c}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_c'}) + (\bar{c} - \bar{e})$	Cloud liquid $\frac{d\bar{q_l}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_l'}) + (\bar{c} - \bar{e_l}) + \overline{T_{ql}}$
		Cloud ice $\frac{d\bar{q_i}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_i'}) + (\bar{d_i} - \bar{s_i}) + \overline{T_{qi}}$
		Rain $\frac{d\bar{q_r}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_r'}) - \bar{V_r}\frac{\partial \bar{q_r}}{\partial p} + (\bar{m_s} + \bar{m_g} - \bar{f_s} - \bar{f_g}) - \bar{e_r} + \overline{T_{qr}}$
		Snow $\frac{d\bar{q_s}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_s'}) - \bar{V_s}\frac{\partial \bar{q_s}}{\partial p} + (\bar{d_s} - \bar{m_s} + \bar{f_s}) - \bar{s_s} + \overline{T_{qs}}$
		Graupel $\frac{d\bar{q_g}}{dt} = -\frac{\partial}{\partial p}(\overline{\omega' q_g'}) - \bar{V_g}\frac{\partial \bar{q_g}}{\partial p} + (\bar{d_g} - \bar{m_g} + \bar{f_g}) - \bar{s_g} + \overline{T_{qg}}$

Increase of vertical mixing

✓ Diffusion type of shallow convection scheme

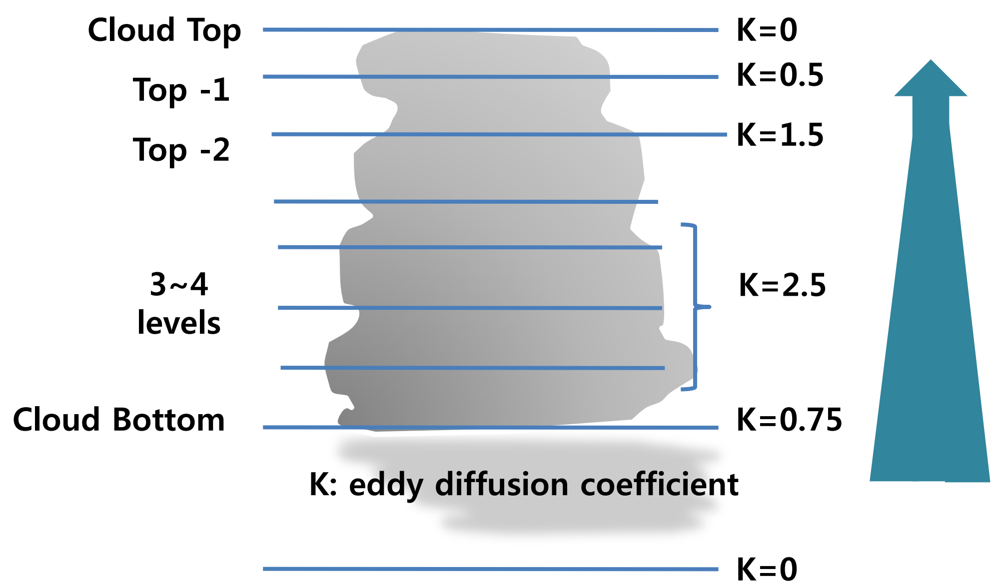
- Vertical mixing of temperature and moisture
- No precipitation processes

$$\left(\frac{\partial \bar{s}}{\partial t}\right)_{shc} = \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left\{\bar{\rho}K\frac{\partial}{\partial z}\left(\bar{s} - L\bar{l}\right)\right\}$$

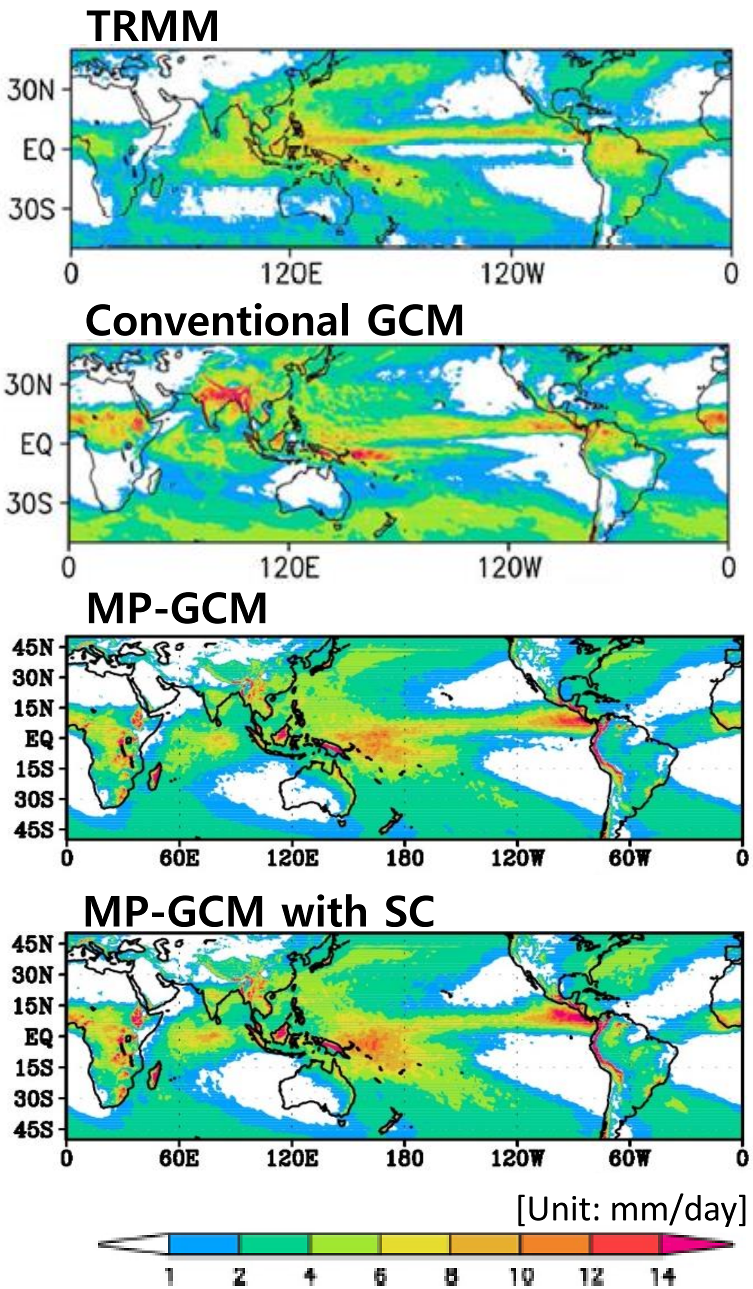
$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{shc} = \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left\{\bar{\rho}K\frac{\partial}{\partial z}\left(\bar{q} + L\bar{l}\right)\right\}$$

s : dry static energy
q : specific humidity
l : cloud water
L : latent heat of condensation
ρ : density of air
z : altitude
over bar : grid average value
prime : perturbation from grid average value

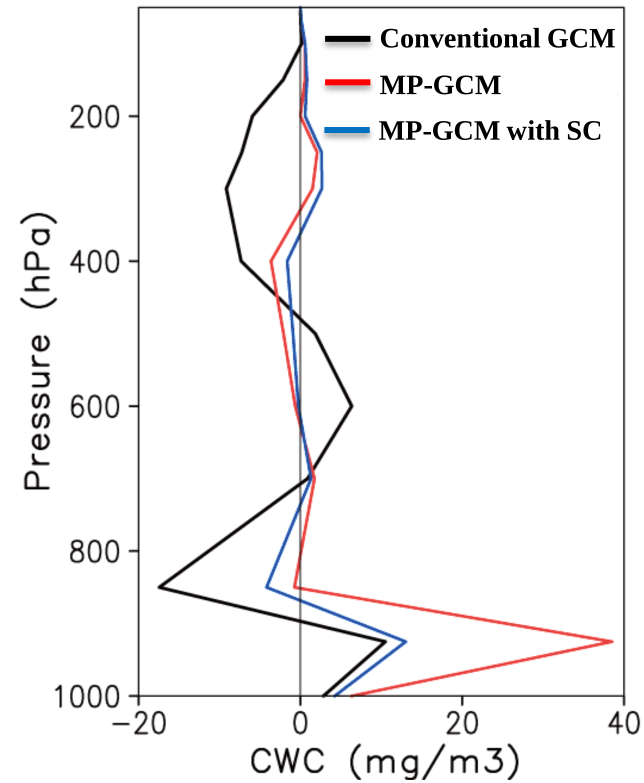
Vertical profile of K



Precipitation and cloud water content simulation



Biases of cloud water from Cloudsat over the tropics (0E-360E, 30S-30N)

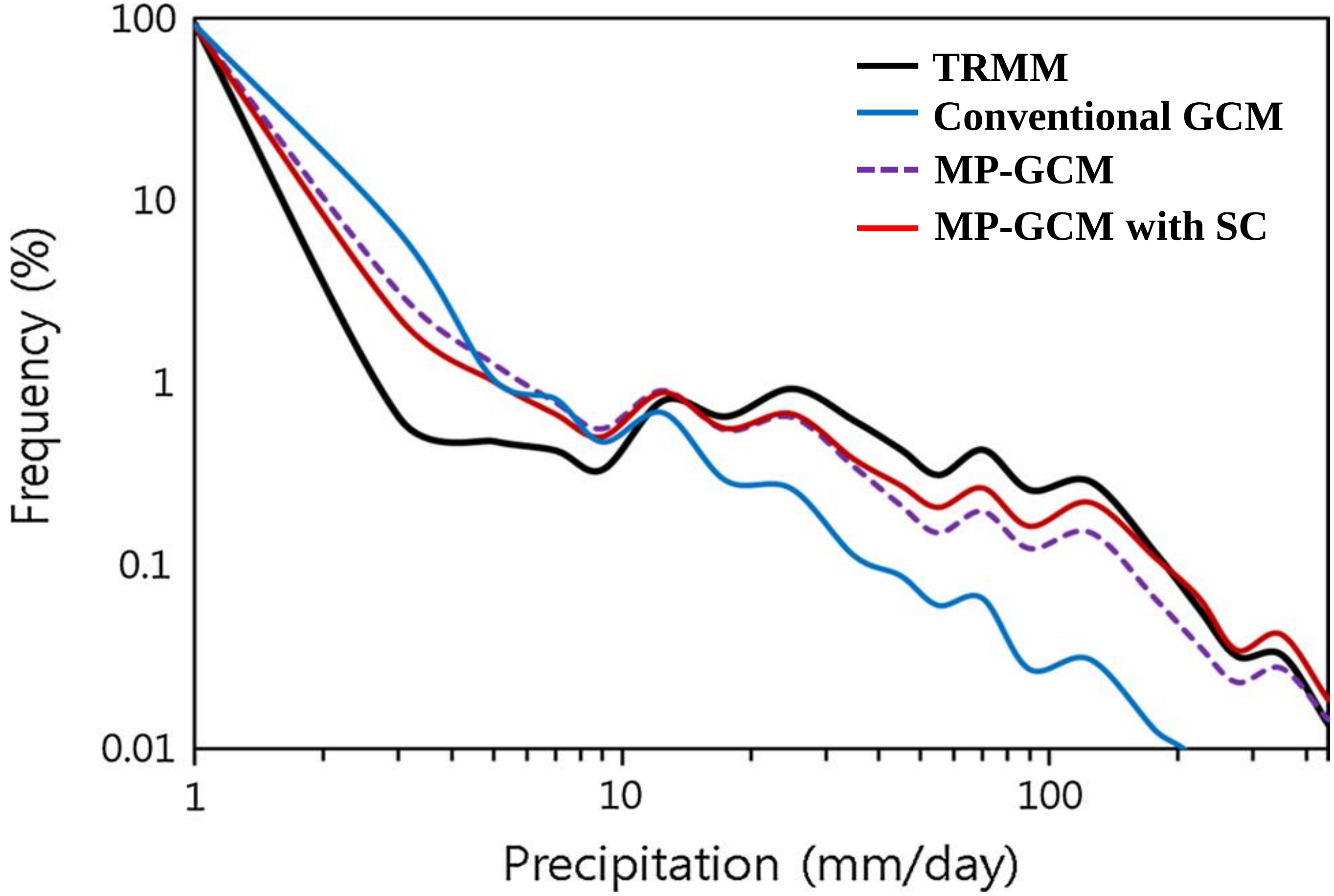


Description of Simulations:

- **Time step: 600s**
- **MPS sub-time: 600s**
- **MPS tv sub-time: 20s**
- **RHC: 90%**
- **Terminal velocity reduce factor: tv*0.5**
- **Additional vertical mixing:**
  Shallow convection (diffusion type)

Frequency of 3-hourly precipitation simulation

(Kang et al. 2015, Climate Dynamics)



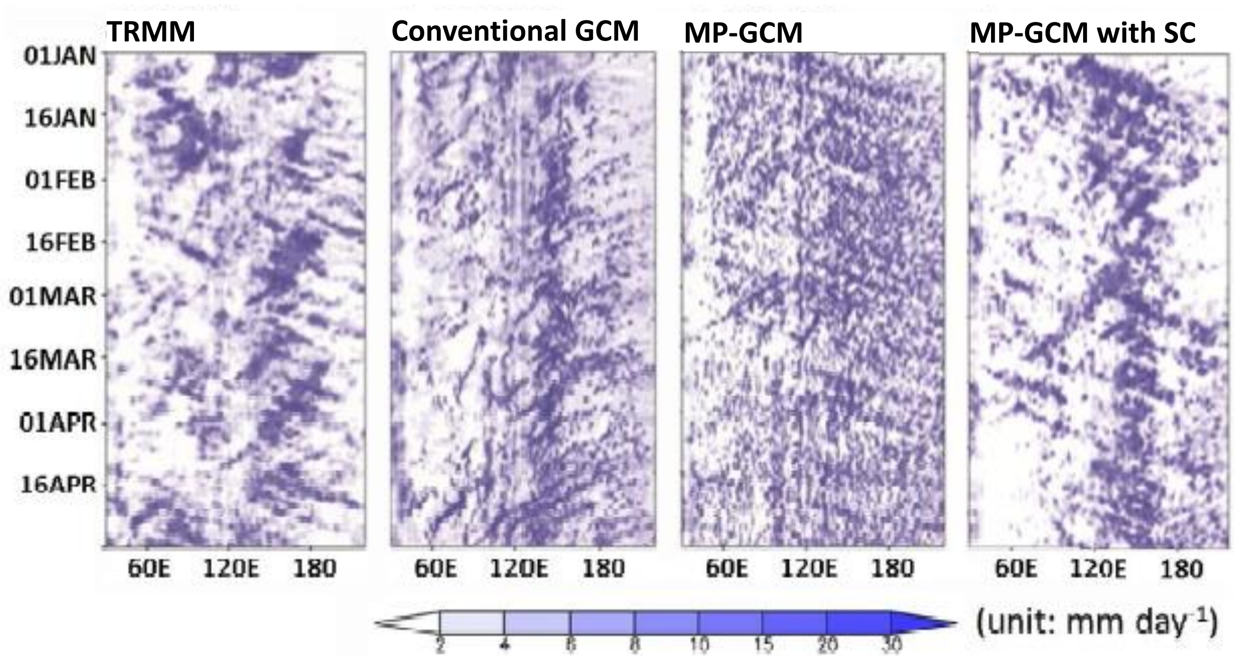
GCM requires Cloud Microphysics for simulation of heavy and extreme precipitation statistics

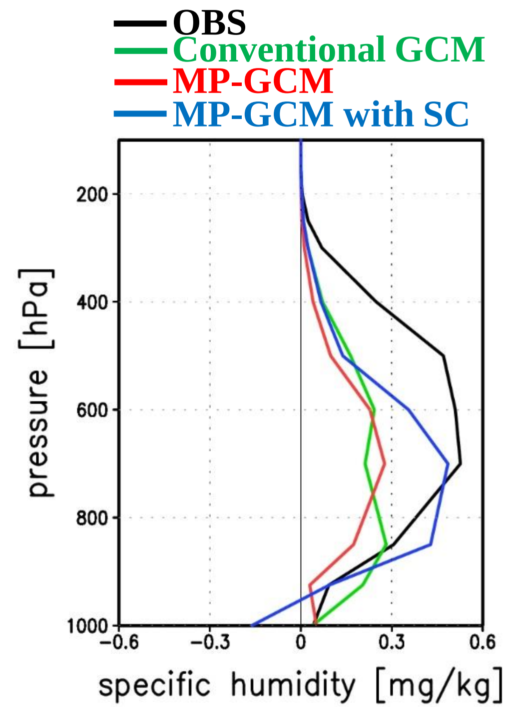
- The GCMs with convective parameterization produce too much light rain but less heavy precipitation compared to the observed.
- Graupel and Accretion are important hydro-meteor and hydor-process for heavy precipitation.

MJO and specific humidity simulation

(Kang et al. 2016)

Hovmuller diagram of PRCP (10S-10N)



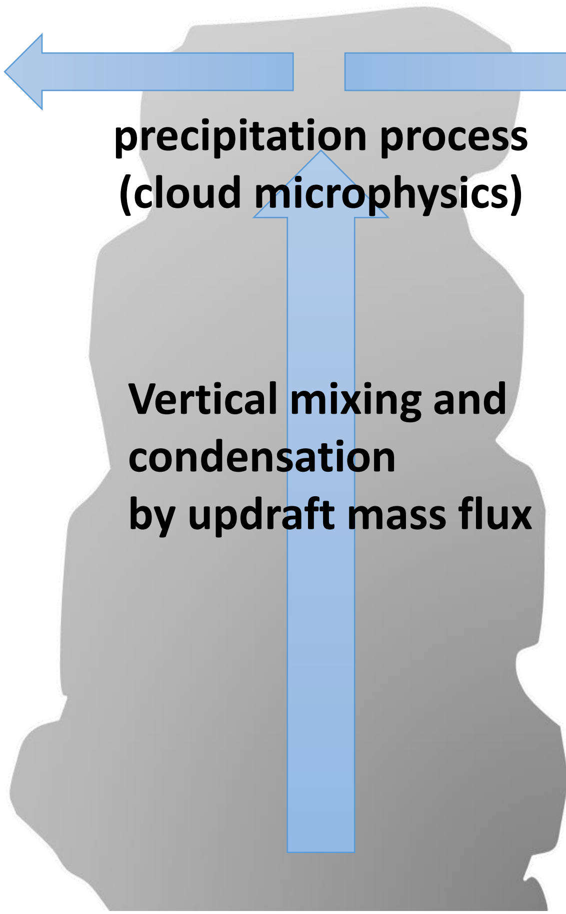


30-90day specific humidity composite when 30-90day precipitation ≥ 1STD over the I.O.

Description of Simulations:

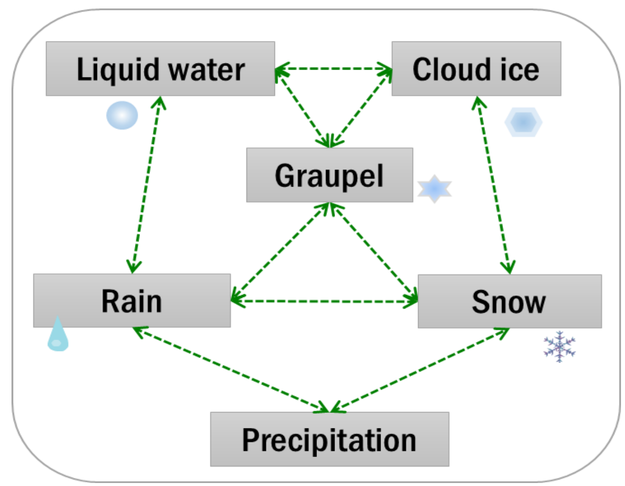
- **Time step: 900s**
- **Terminal velocity sub-time: 20**s
- **RHC: 95%**
- **Terminal velocity reduce factor: tv*0.5**
- **Additional vertical mixing:**
  Shallow convection (diffusion type)

Adding deep convective parameterization in MP-GCM



cumulus detrainment
(environmental heating and moistening)

Adding cloud liquid and ice from convective parameterization to cloud microphysics



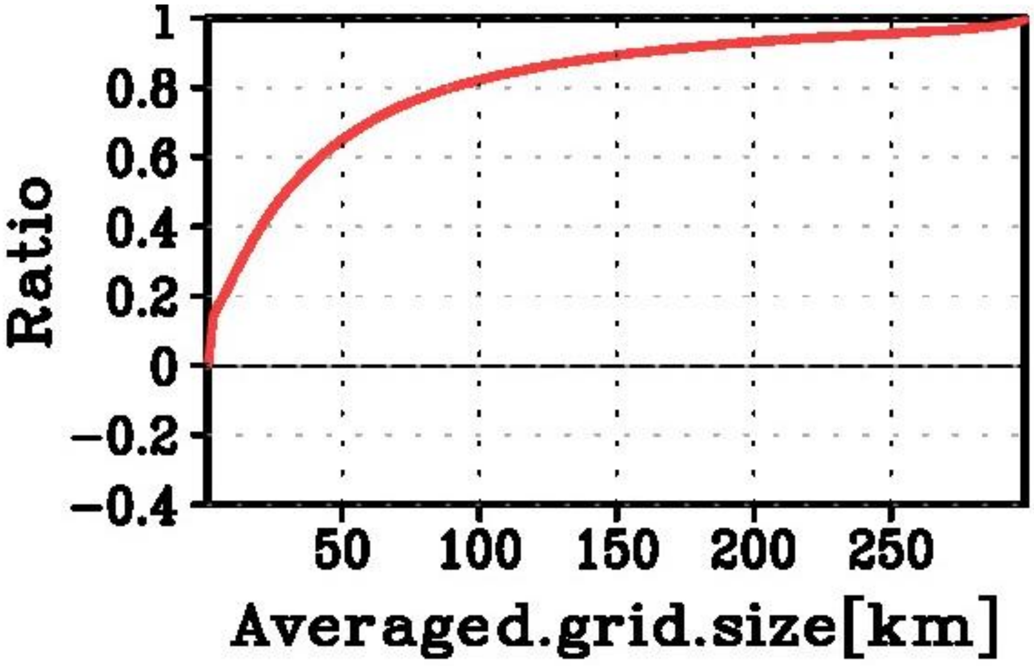
Resolution dependency of MSE850 sub-grid scale vertical mixing ratio to total mixing

From 1km 3-d CRM simulation

$$\overline{w' \frac{\partial h'}{\partial z}} \Big/ \overline{w \frac{\partial h}{\partial z}}$$

—: mean over target domain

′ : anomaly from target domain mean



only updraft $\left(\overline{w} > 0, \frac{\partial \overline{h}}{\partial z} < \mathbf{0}\right)$ domains are used

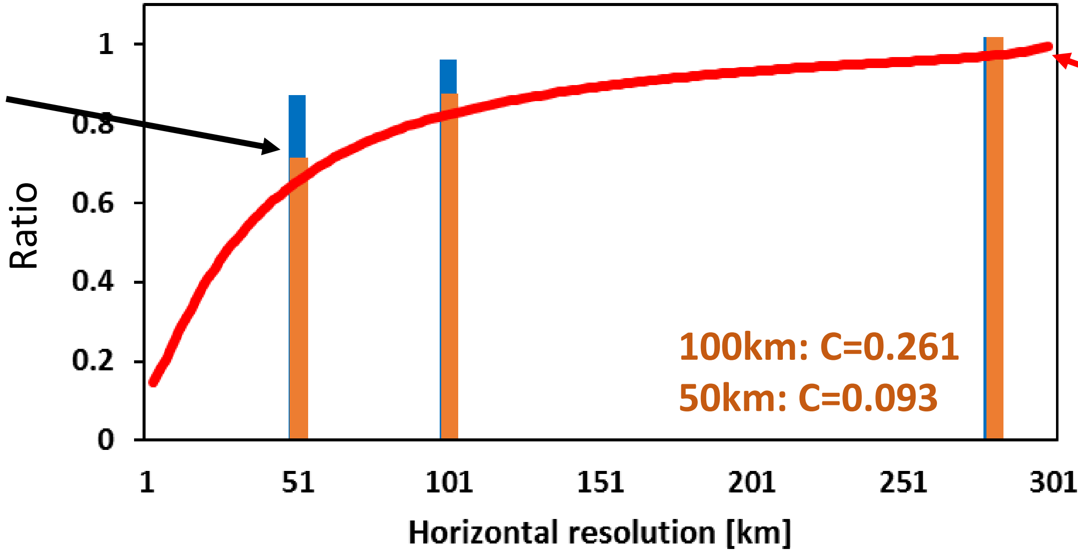
Resolution dependency of cumulus mixing

scale-adaptive cumulus base mass flux (M_B)

$$(M_B)_s = M_B \times C$$

From GCM

$$\frac{\left(\frac{\partial \overline{\omega' h'}}{\partial p}\right)}{\bar{\omega}\frac{\partial \bar{h}}{\partial p} + \left(\frac{\partial \overline{\omega' h'}}{\partial p}\right)}$$



From CRM

$$\frac{\overline{w' \frac{\partial h'}{\partial z}}}{\overline{w \frac{\partial h}{\partial z}}}$$

: original GCM normalized by 280km simulation

: cumulus base mass flux control GCM normalized by 280km simulation

: resolution dependency of sub-grid scale MSE850 vertical mixing from 3d CRM simulation

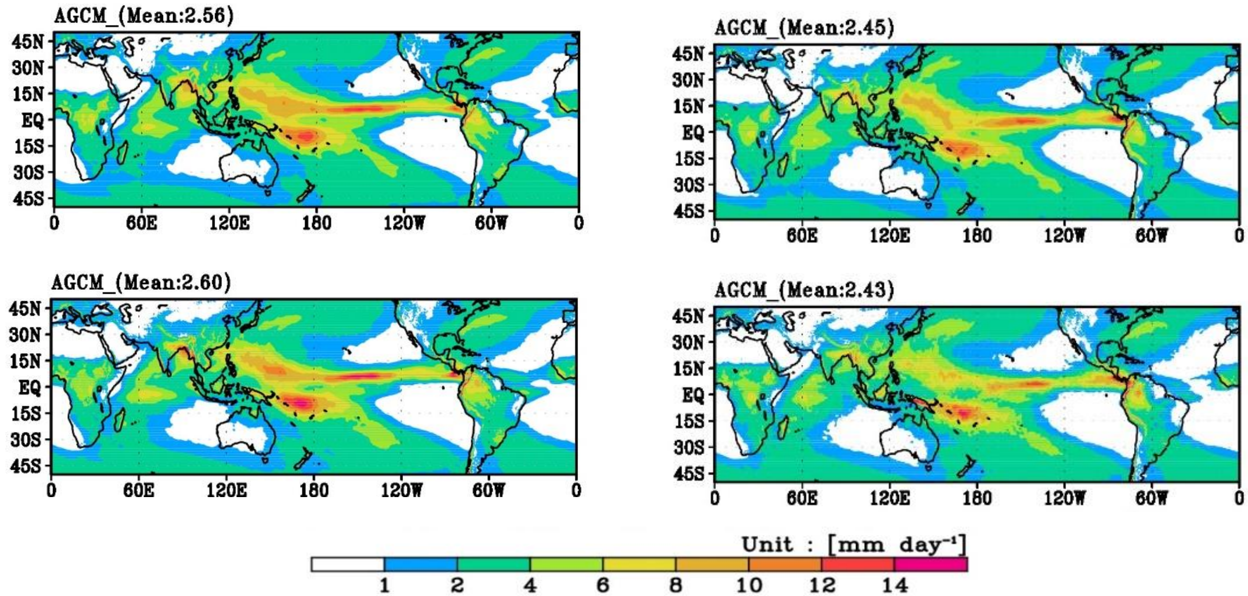
PRCP mean state of scale-adaptive simulations (5years)

Original GCM | Cumulus base mass flux control

PRCP mean state

360x181 (100km)

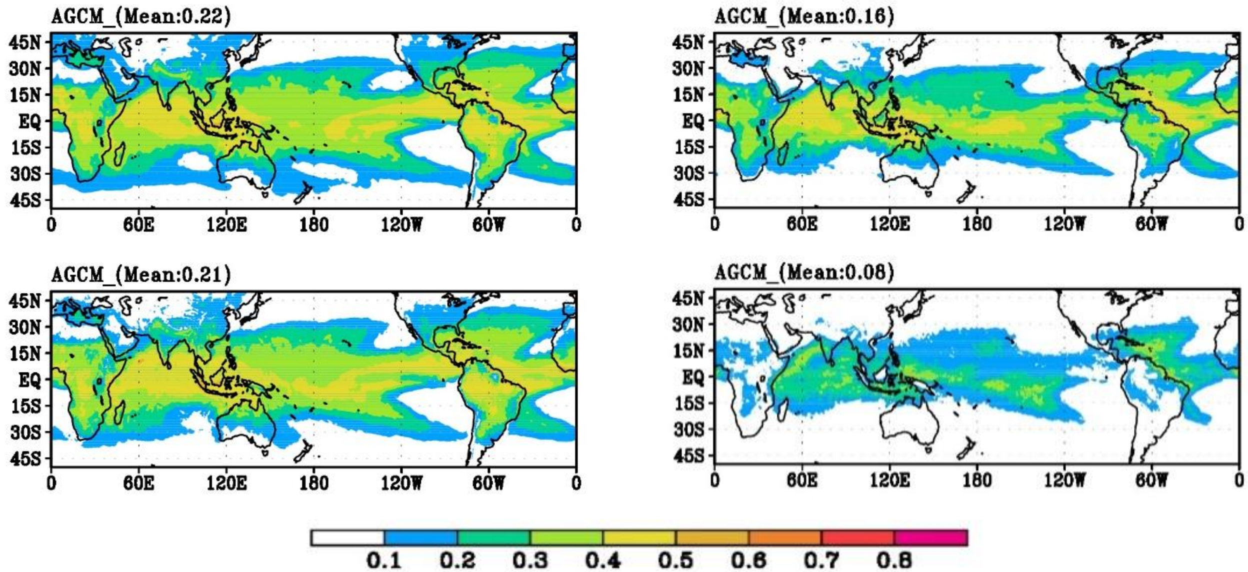
720x361 (50km)



Convective PRCP ratio

360x181 (100km)

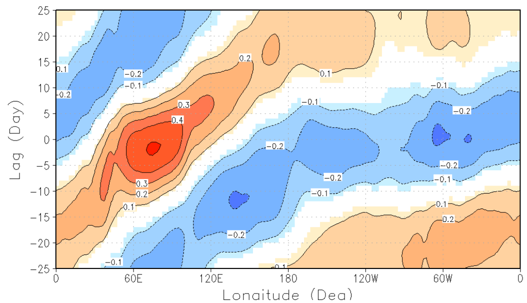
720x361 (50km)



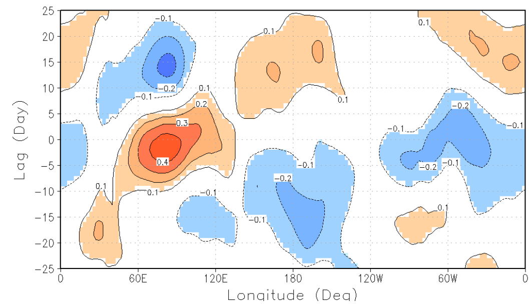
MJO eastward propagation of various simulations (5years)

Lag-longitude diagram of 10S-10N averaged U850 over the Indian Ocean

OBS (NCEP)



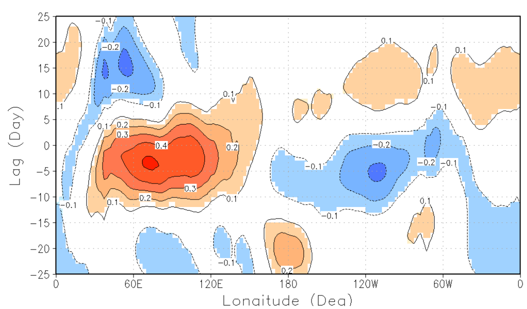
128x65 (280km)

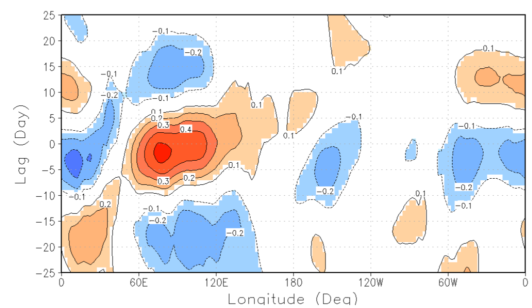


Original GCM

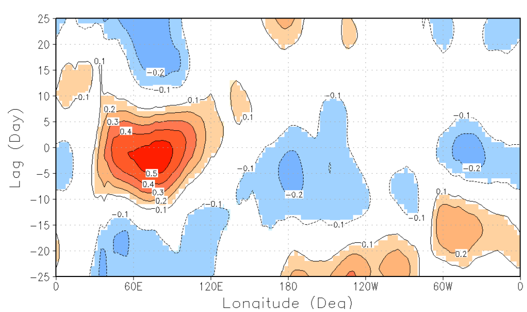
Cumulus base mass flux control

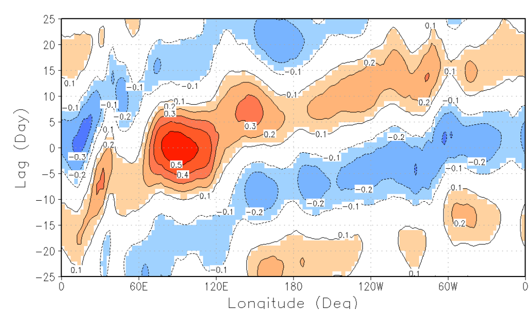
360x181 (100km)

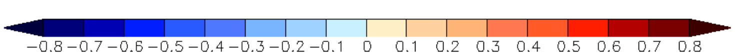




720x361 (50km)



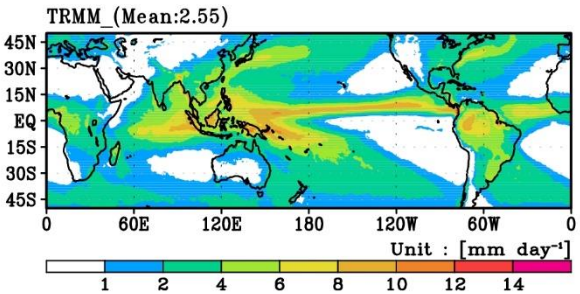




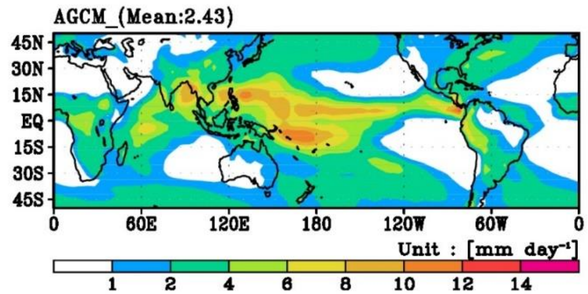
Comparison between MP-AGCM and conventional AGCM

PRCP mean state (5years)

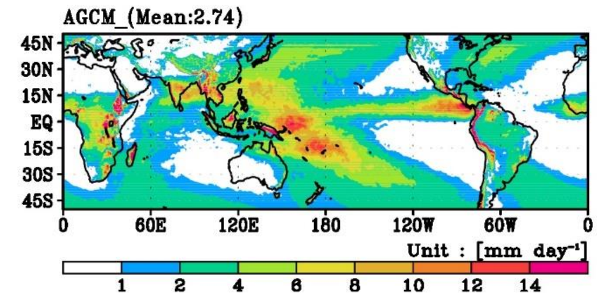
OBS(TRMM)
(10years mean)



conventional AGCM

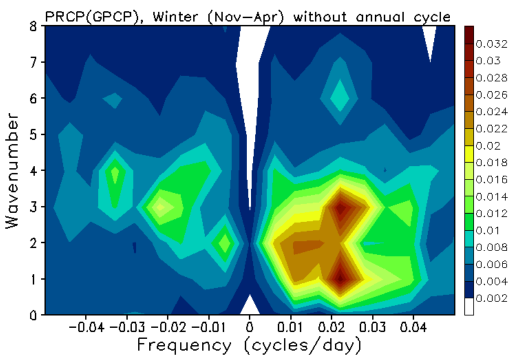


MP-AGCM with SC&DC
(scale-adaptive DC)

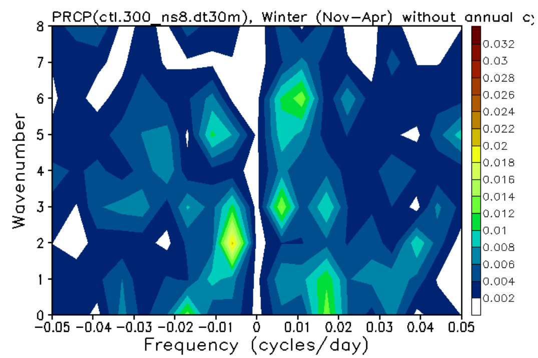


Space-time power spectrum (PRCP, 5years, NOV-APR)

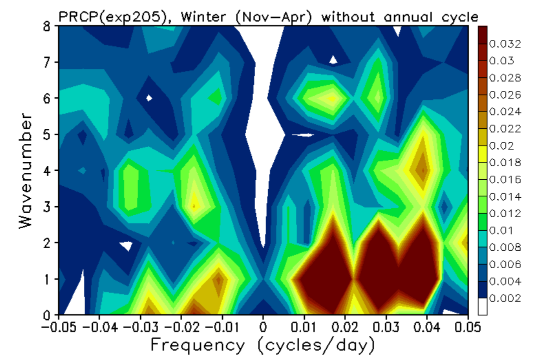
PRCP(GPCP, 14yrs)



conventional AGCM



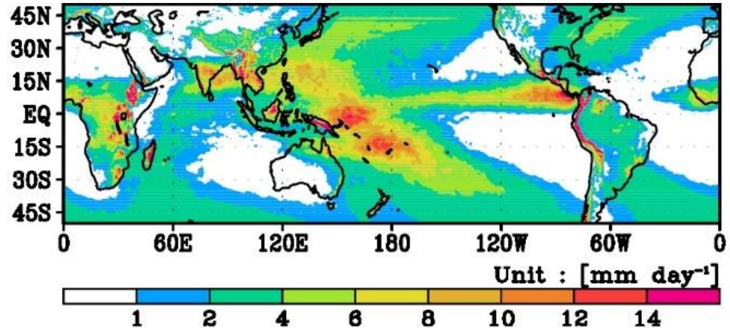
MP-AGCM with SC&DC
(scale-adaptive DC)



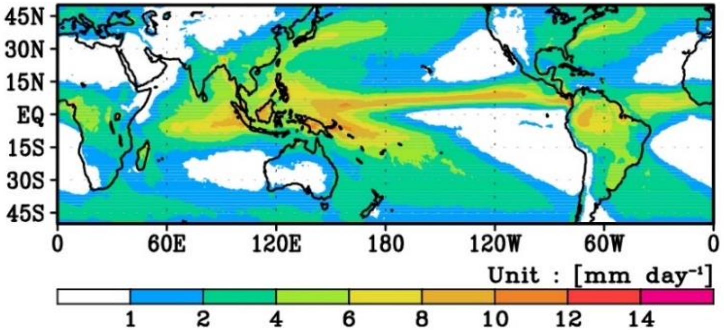
A coupled GCM with comprehensive cloud microphysics

Comparison between MP-AGCM and MP-CGCM (5yrs)

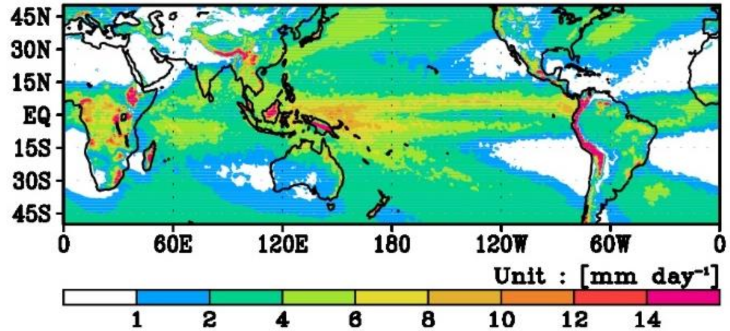
MP-AGCM with SC&DC (scale-adaptive DC)



TRMM (10yrs)

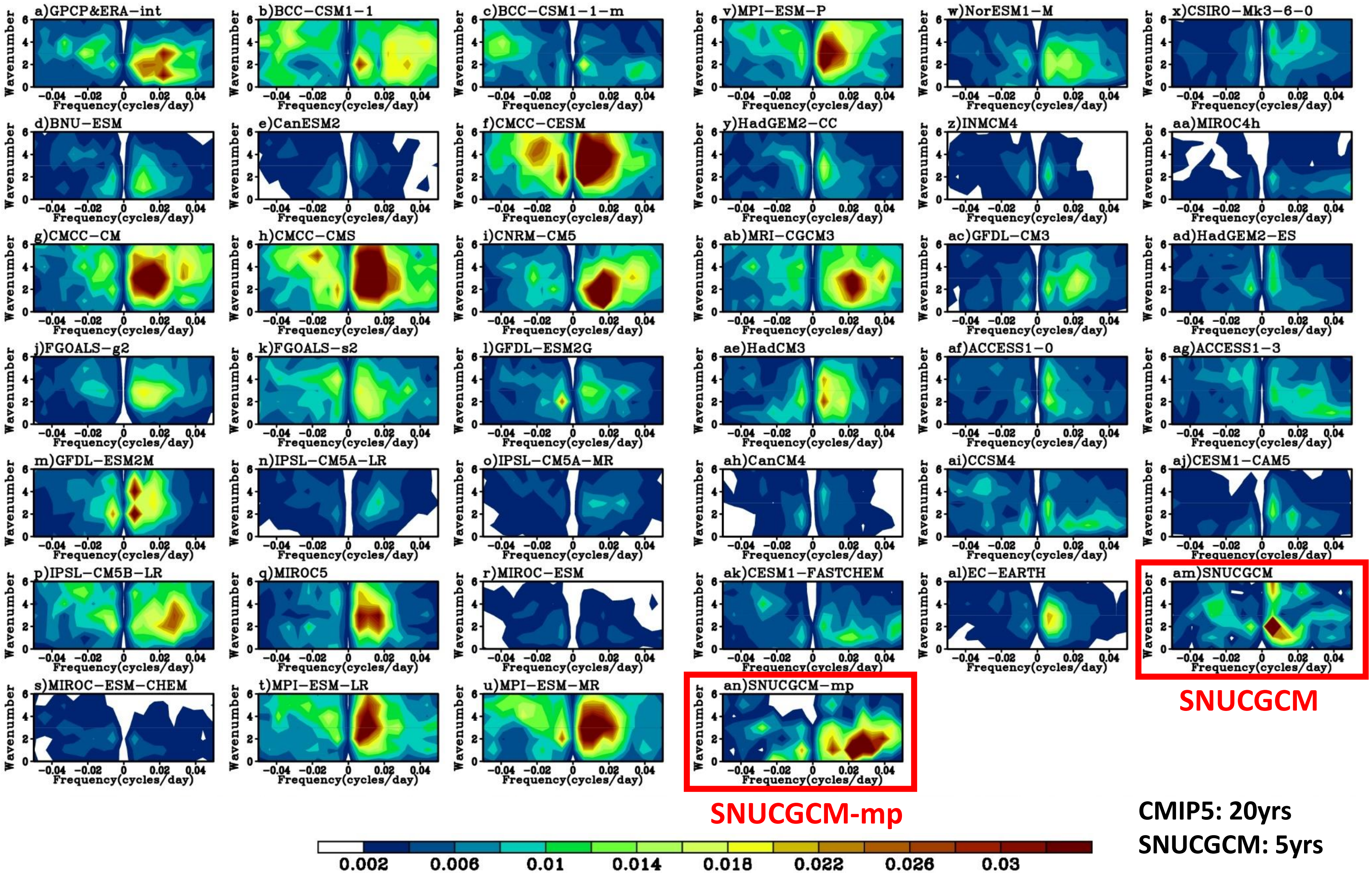


MP-CGCM with SC&DC (scale-adaptive DC)



Comparison MP-CGCM with CMIP5 models

Space-time power spectrum (PRCP, NOV-APR)



Summary

• GCM requires comprehensive cloud microphysics for reasonable simulation of observed precipitation properties (e.g., extreme and MJO)

• GCM with comprehensive cloud microphysics requires appropriate vertical mixing (scale-adaptive cumulus parameterization)

- Strengthening eastward propagation

- Improved vertical moisture profile

Thank you!

Kang et al. (2015, *Climate Dynamics*)
"GCMs with Implicit and Explicit cloud-rain processes for simulation of extreme precipitation frequency"

Kang et al. (2016, *Geoscience Letters*)
"A GCM with cloud microphysics and its MJO simulation"

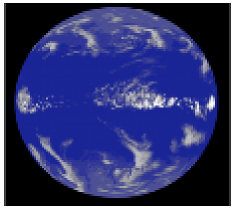
Yang, Young-Min (2014, Ph.D. thesis)

Ahn, Min-Seop (2017, Ph.D. thesis)

Global model with CRM physics

❖ **Explicit global CRM**

Satoh et al. (2005)

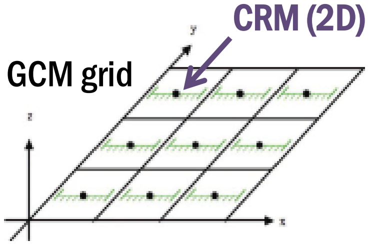


NICAM (Japan)

14, 7, 3.5km

❖ **Superparameterization**

Grabowski and Smolarkiewicz (1999)
Khairoutdinov and Randall (2001)
Tao et al. (2009)



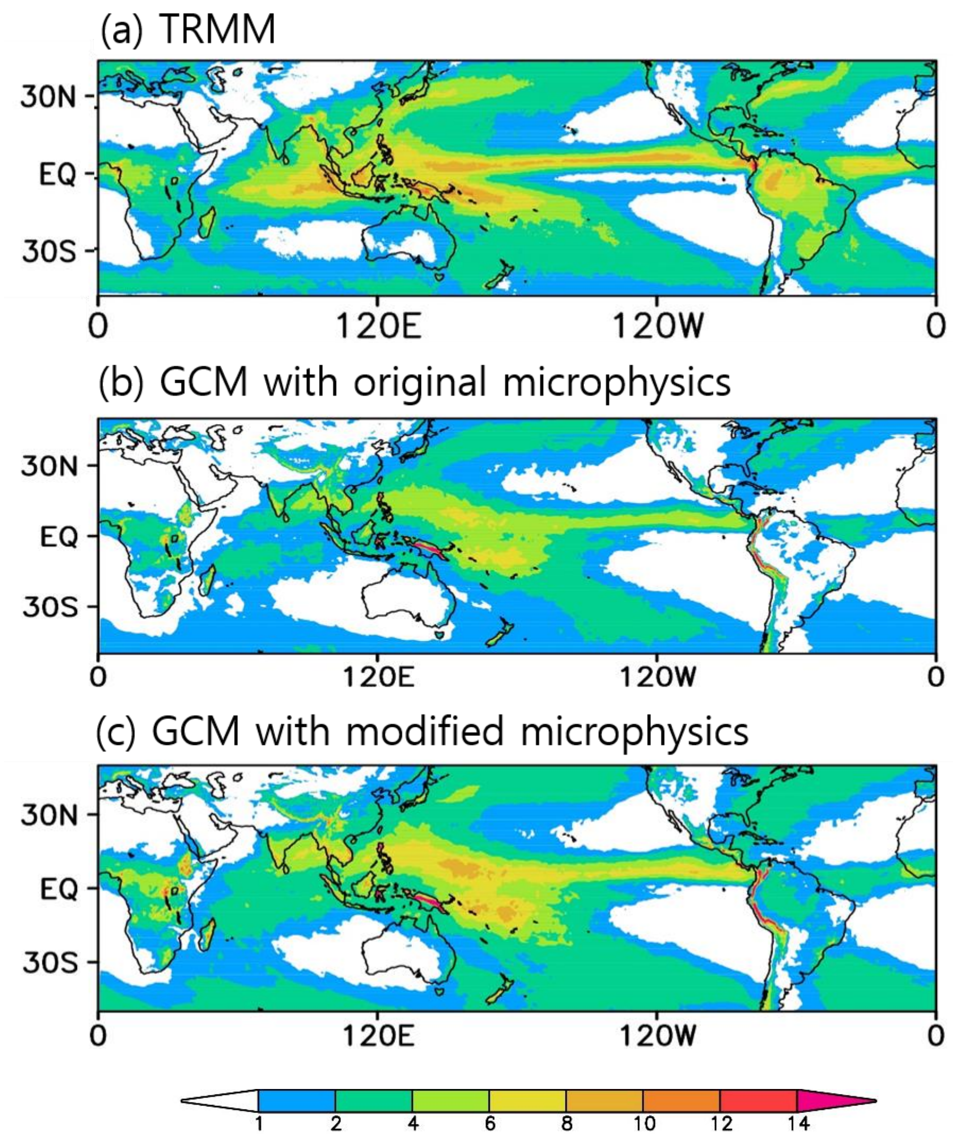
NASA/GSFC, CSU

Horizontal Resolution of CRM: **4km**

❖ **GCM with CRM cloud microphysics**
(50 km, CRM & Parameterization combined)

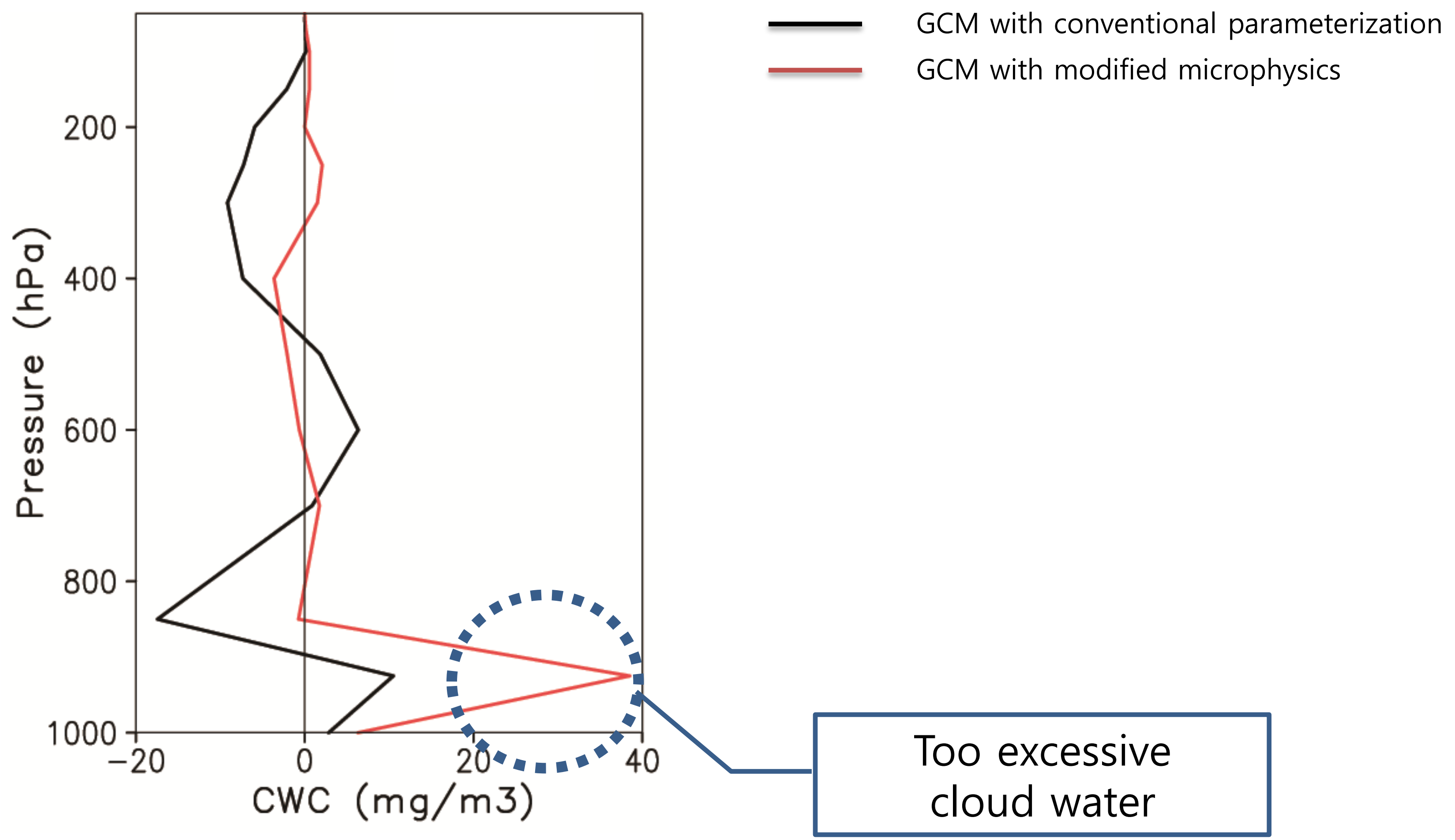
Kang et al. (2015)
Kang et al. (2016)

GCM with modified microphysics - Annual mean precipitation (50km)



microphysics modified by **RH criteria 75%** and **Terminal velocity 50% reduction**

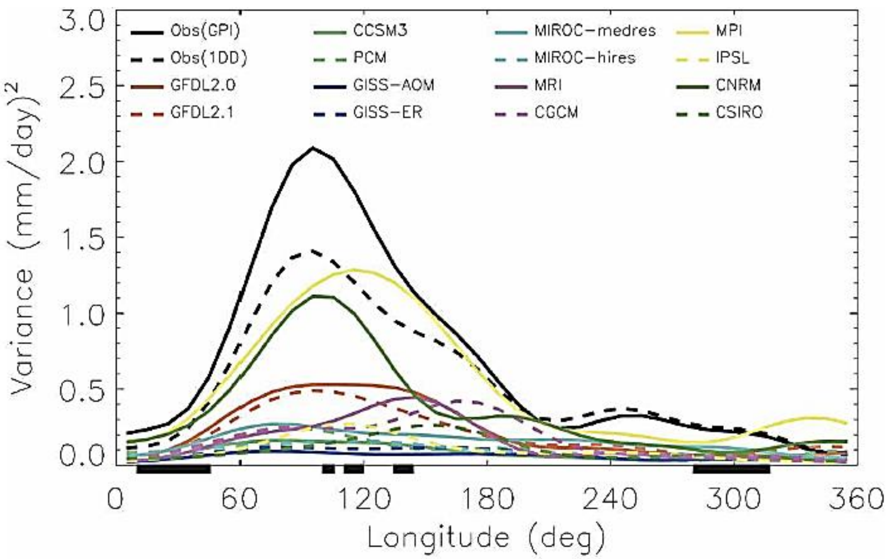
Biases of cloud water (GCM, tropics)



IPCC AR4 and AR5 Models

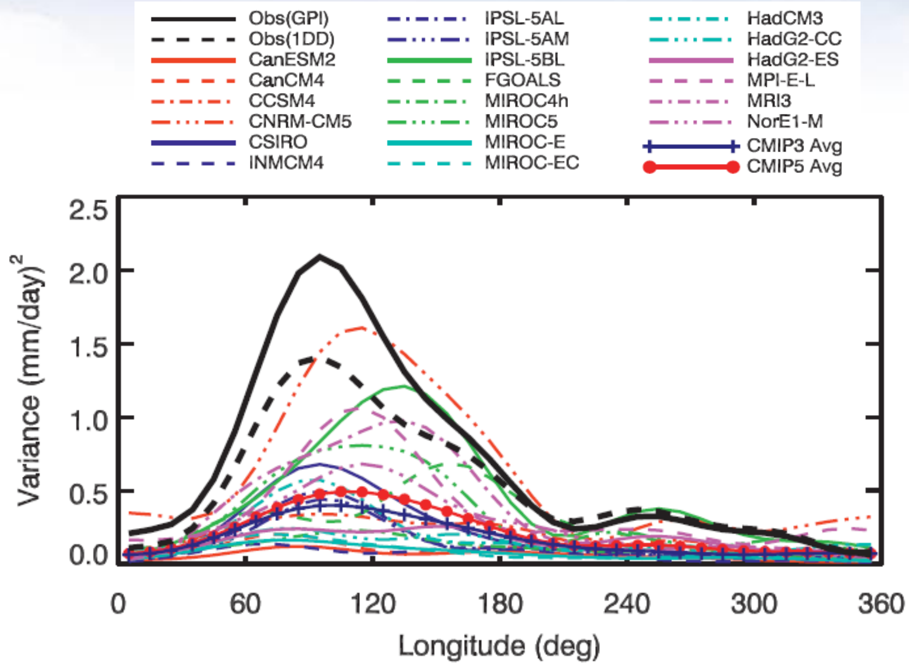
MJO Variance (15°N-15°S)

AR4 models



(Lin et al. 2006)

AR5 models

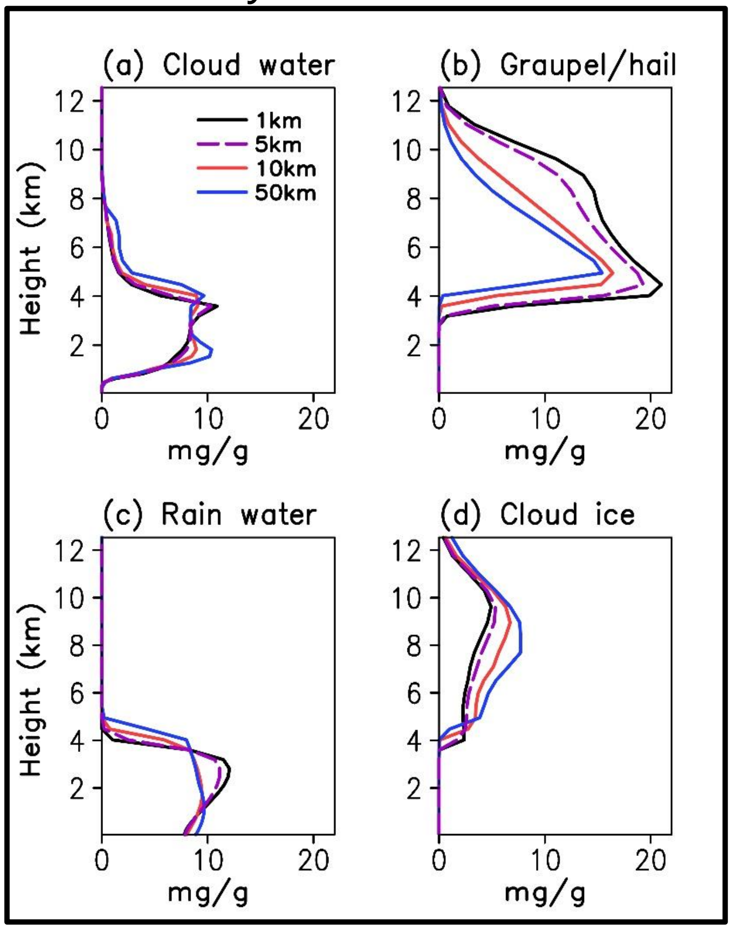


(Hung et al. 2013)

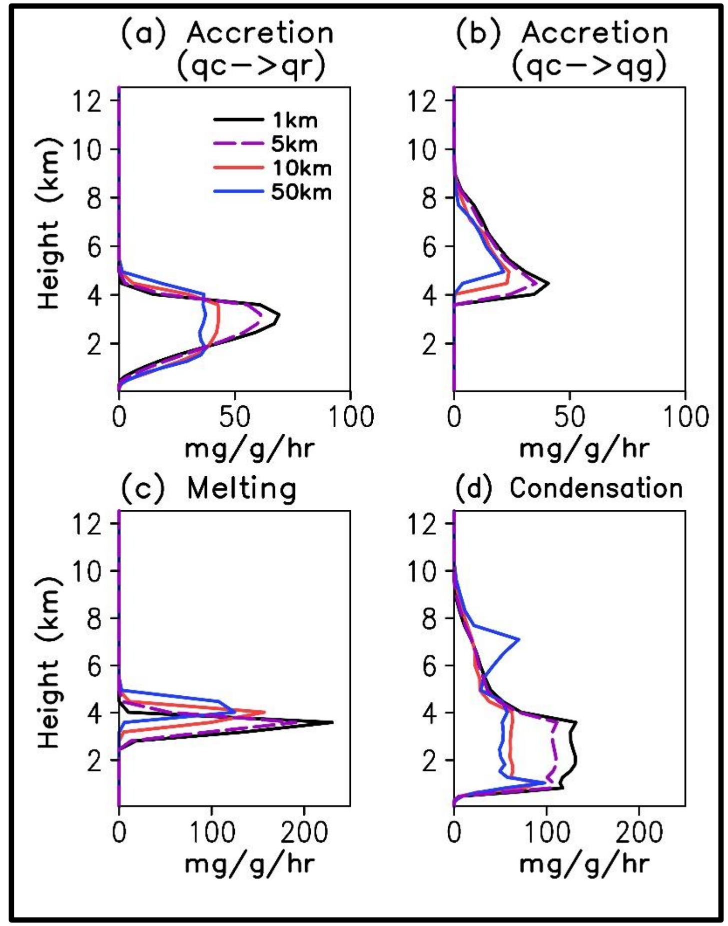
STILL

Resolution dependency of cloud microphysics in GCE

Hydrometeors



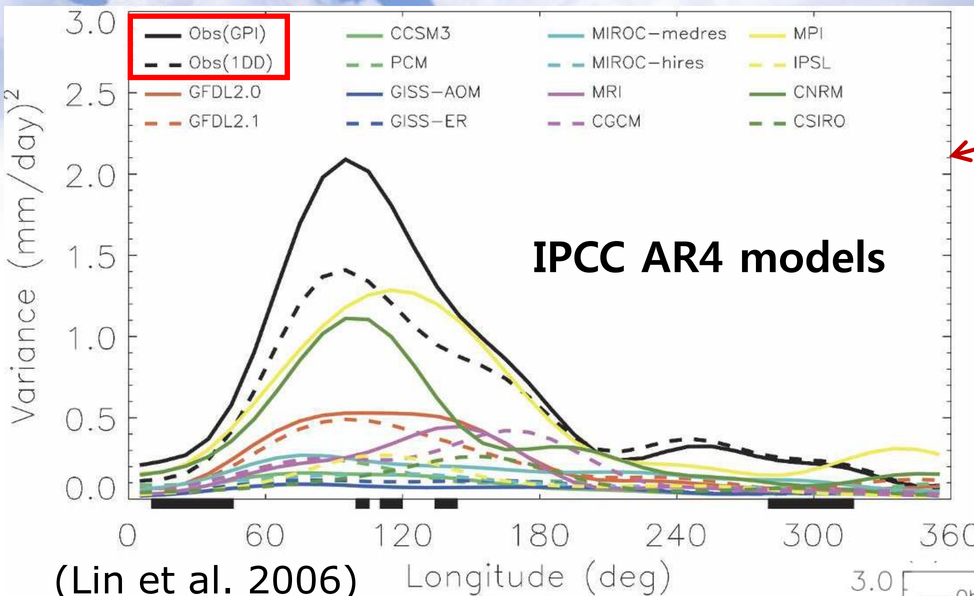
Cloud microphysical process



In the low resolution:

-Less condensation and accretion
-Less rain water & graupel
-More cloud ice

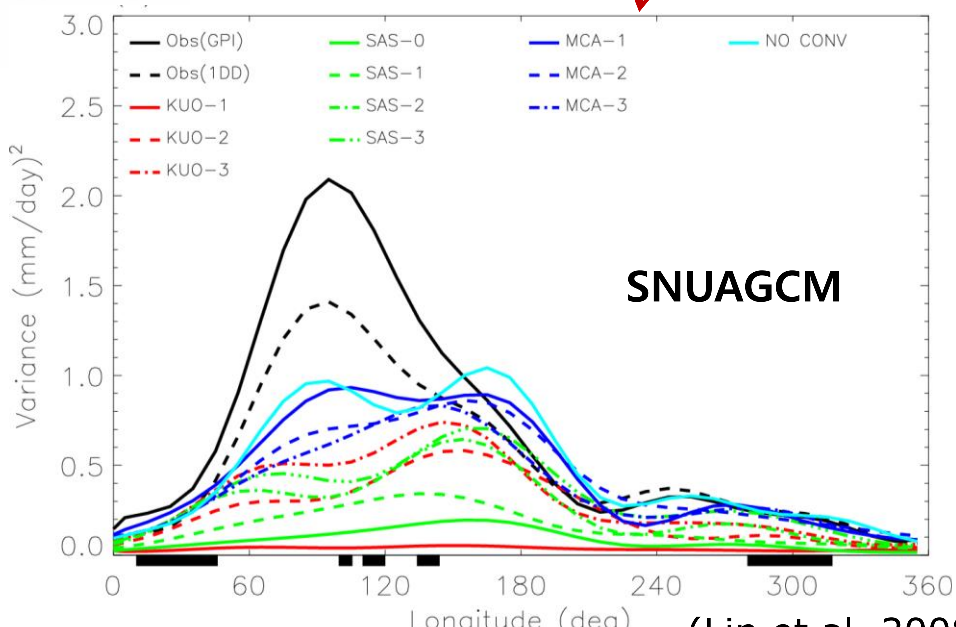
MJO Variance (eastward wavenumber 1-6, periods 30-70days)



(Lin et al. 2006)

different colors
- different climate models

different colors
- different convection schemes



(Lin et al. 2008)

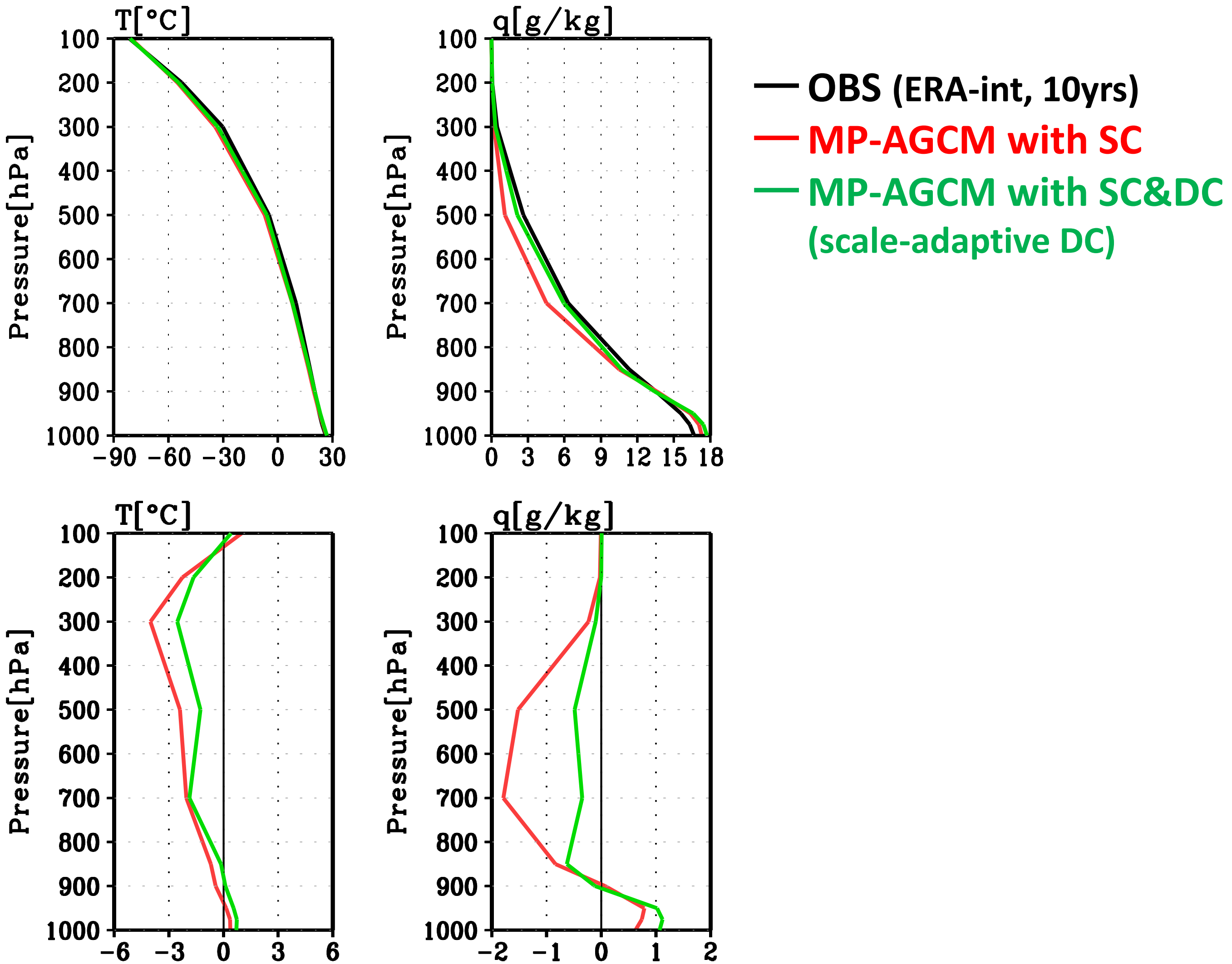
Convection scheme

: represent model diversity in MJO variability

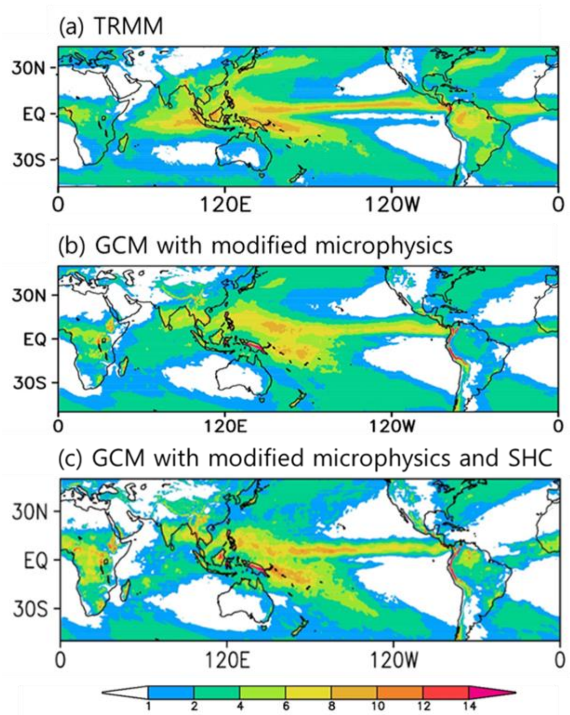
Vertical profile of specific humidity and temperature (5years)
(60E-180E, 15S-15N)

Total

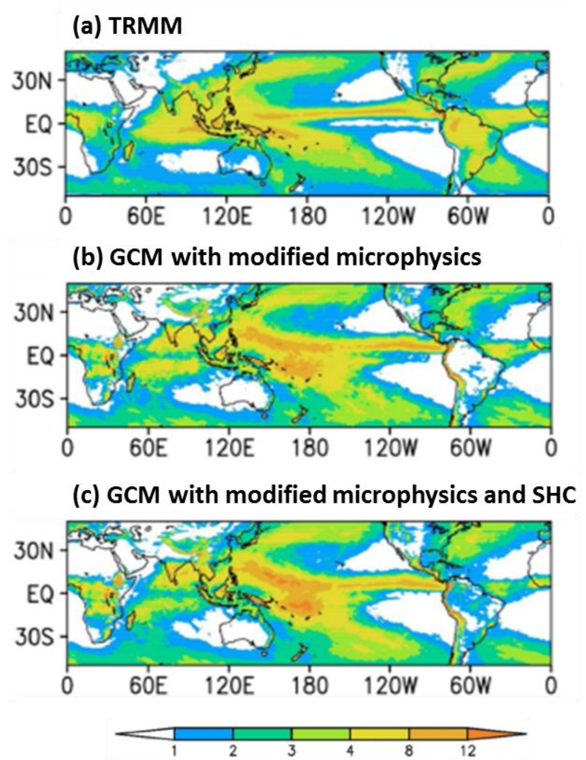
Bias
(model-obs)



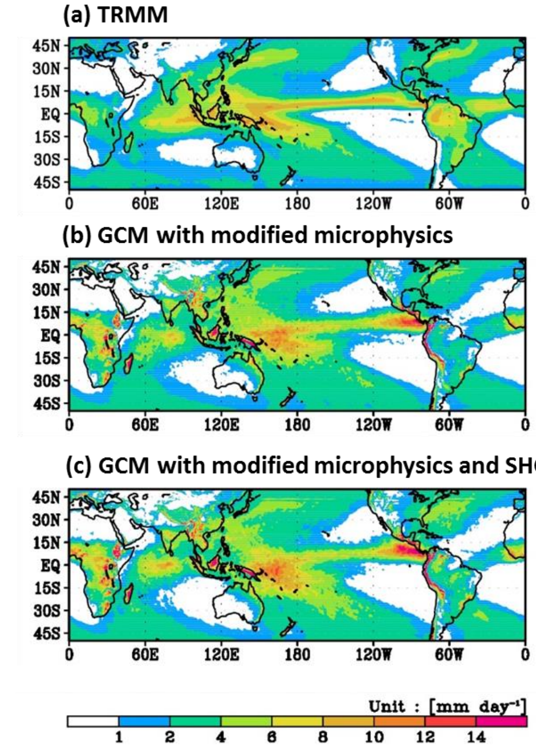
Various results with different treatments of cloud microphysics



Kang et al. (2015)
RHC: 75%
TV: 50%
1800s time step
300s MP sub-time
1s tv time step



Kang et al. (2016)
RHC: 95%
TV: 50%
900s time step
900s MP sub-time
20s tv time step



RHC: 90%
TV: 50%
600s time step
600s MP sub-time
20s tv time step

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

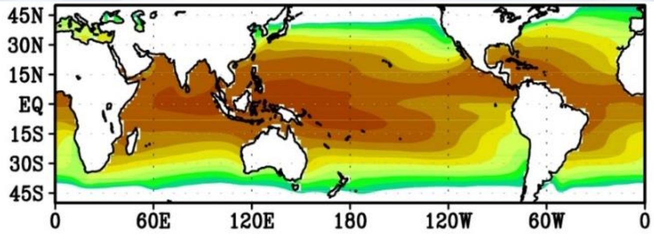
GCM with cloud microphysics (50km)	2 weeks for 10 years simulation

This is suitable for climate researches as a next generation model

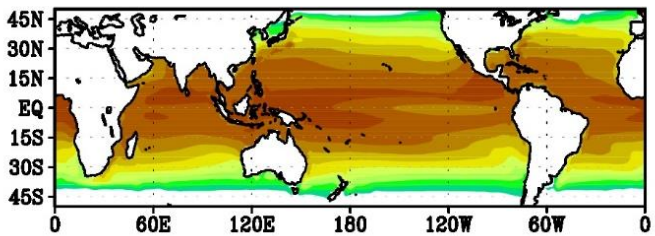
Comparison between MP-CGCM and conventional CGCM

SST

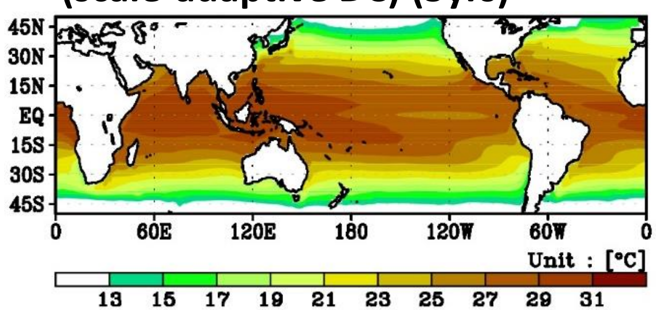
ERSST (10yrs)



conventional CGCM (5yrs)

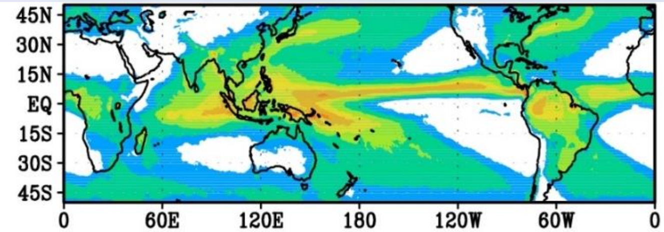


MP-CGCM with SC&DC (scale-adaptive DC) (5yrs)

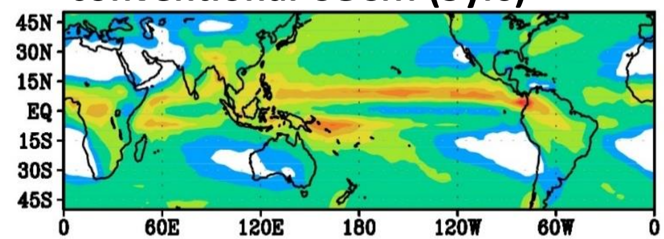


PRCP

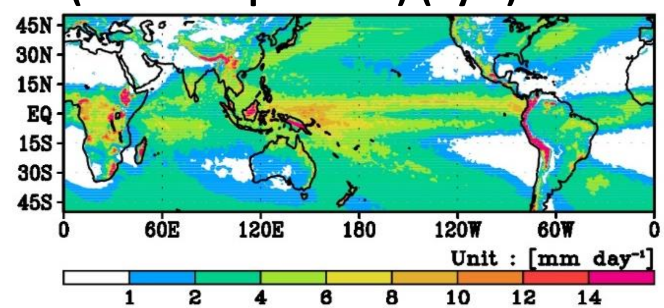
TRMM (10yrs)



conventional CGCM (5yrs)



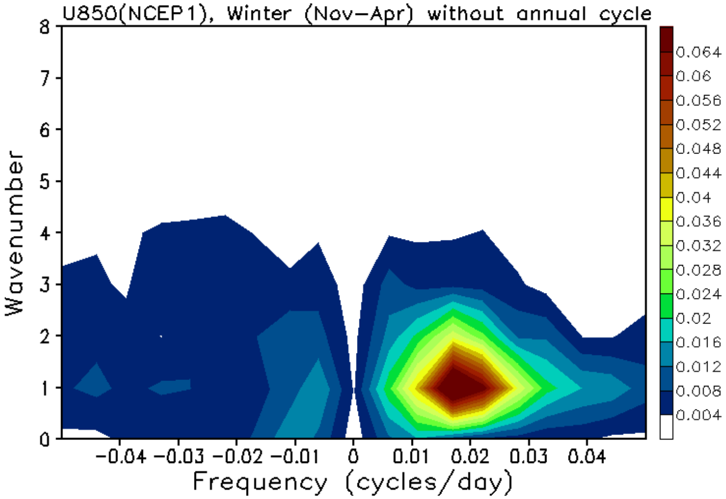
MP-CGCM with SC&DC (scale-adaptive DC) (5yrs)



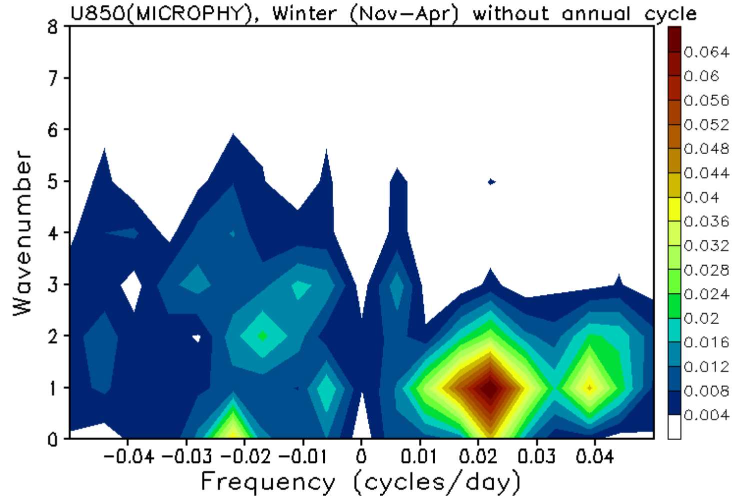
Frequency-wavenumber power spectrum (10S-10N)

U850 Winter(NOV-APR)

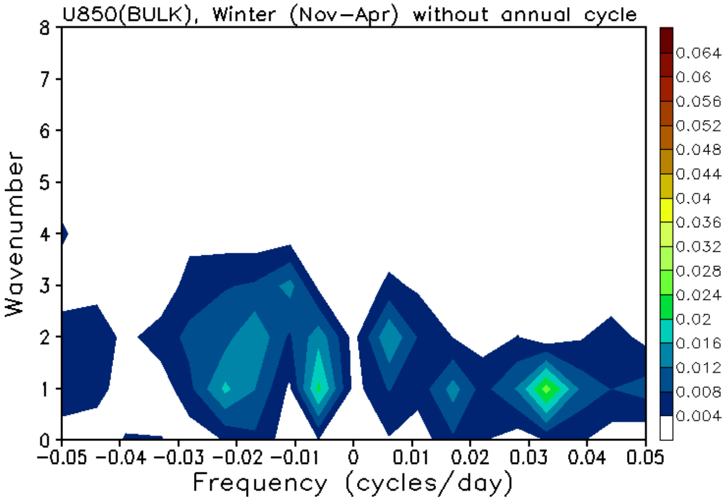
NECP1 (20yrs)



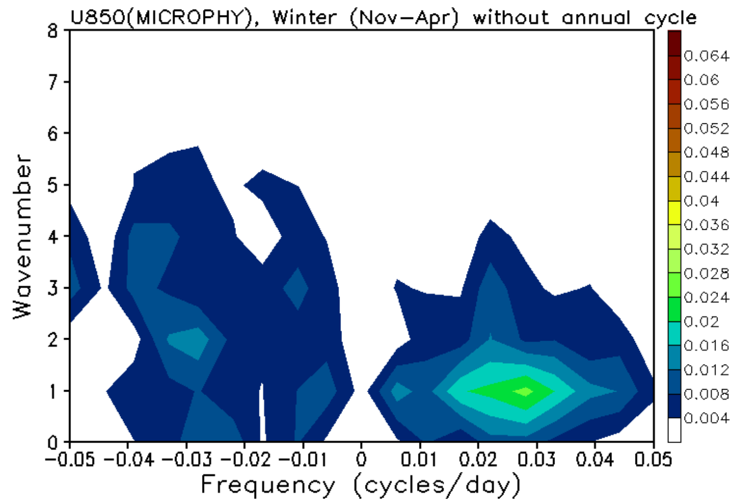
Modified microphysics and shallow convection



Parameterization (BULK scheme)



Modified Microphysics



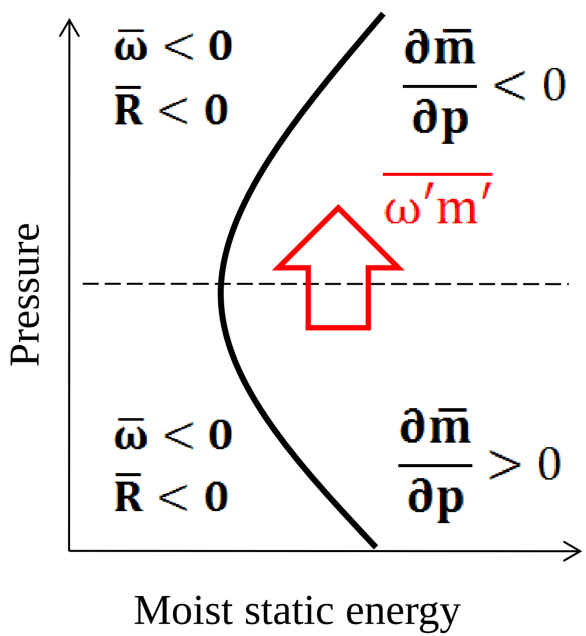
Dynamical consideration on convection

❖ Reynolds averaged m equation (time-mean, averaged over the tropics)

MSE mean advection   MSE turbulent flux

$$0 = -\bar{\omega}\frac{\partial \bar{m}}{\partial p} - \frac{\partial}{\partial p}\overline{\omega' m'} + \bar{R}$$

Radiative cooling (<0)



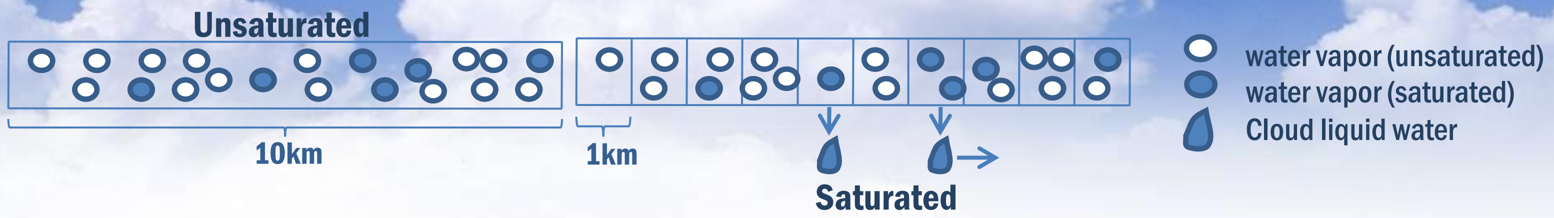
Mean MSE advection < 0
Radiative cooling < 0

MSE turbulent flux >> 0
➔ convective overturning

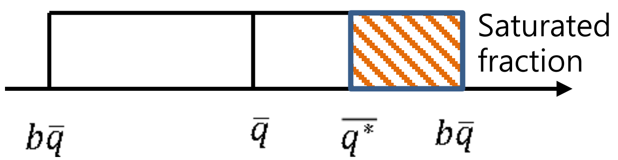
Mean MSE advection > 0
Radiative cooling < 0

Modification of cloud microphysics

✓ Condensation using sub-grid scale variability



Parameterization of sub-grid scale variability



$$C_{frc} = \begin{cases} 0 & ,(1+b)\bar{q} \le \overline{q^*} \\ \dfrac{(1+b)\bar{q} - \overline{q^*}}{2b\bar{q}} & ,(1-b)\bar{q} < \overline{q^*} < (1+b)\bar{q} \\ 1 & ,(1-b)\bar{q} \ge \overline{q^*} \end{cases}$$

(Le Treut and Li 1991)

✓ Terminal velocity

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

$$U_R = \frac{a\Gamma(4+b)}{6\lambda_R^b}\left(\frac{\rho_0}{\rho}\right)^{1/2}, \qquad \lambda_R = \left(\frac{\pi\rho_w n_{oR}}{\rho q_R}\right)^{0.25}$$

- a =>2.14 m/s^{-1} to 1.8 $m\ s^{-1}$

Global distribution of light & heavy precipitation (annual)

(Kang et al. 2015)

TRMM | GCM with conventional parameterization | GCM with microphysics and shallow convection