2008 January 15-18th, CMMAP team meeting

Development of a cumulus scheme with vertically variable entrainment rate

Minoru Chikira

Frontier Research Center for Global Change, JAMSTEC, Japan

Introduction

< CRMs and LESs >

- Entrainment rate of both deep and shallow cumuli has large values near cloud base and top (Lin and Arakawa, 1997; Lin, 1999; Cohen, 2000; Stevens et al., 2001).
- Vertical profiles of entrainment rate is not sensitive to vertical wind shear, but is sensitive primarily to thermodynamic fields (Lin, 1999).

< Parameterization >

- Lin (1999) discussed an empirical relation between entrainment rate and buoyancy of updraft air and developed a modified AS scheme where entrainment rate is expressed by a function of buoyancy.
- Gregory (2001) used an equation of updraft energy to diagnose vertical profile of entrainment rate and developed a modified Gregory scheme where entrainment rate depends on buoyancy and updraft velocity.
- There are no GCM studies where entrainment rate vertically changes depending on large scale field.

Outline of new cumulus scheme

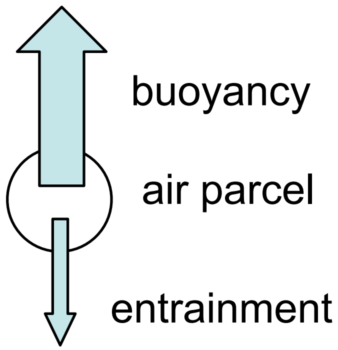
1. Based on plume-entraining model

2. Entrainment rate vertically changes depending on buoyancy and vertical velocity of updraft air parcel following Gregory (2001).

3. Updraft ensemble is spectrally represented following the spirit of Arakawa-Schubert scheme. But cloud types are represented according to updraft velocity at cloud base.

4. Cloud base mass flux is determined by the same method as the prognostic Arakawa-Schubert scheme.

Gregory (2001)'s method



buoyancy

air parcel

entrainment

vertical component of momentum equation and continuity eq.

$$\frac{1}{2}\frac{\partial \overline{w}^{c2}}{\partial z} = g\overline{\left(\frac{T'_v}{\overline{T}_v} - l\right)}^{c} - \frac{1}{\sigma\rho}\left(\frac{\partial \sigma\rho\overline{w'^2}^{c}}{\partial z}\right) - \frac{1}{\rho}\overline{\left(\frac{\partial p'}{\partial z}\right)}^{c} - g\overline{\left(\frac{p'}{\overline{p}}\right)}^{c} - \varepsilon\overline{w}^{c2}$$

cloud vertical velocity — buoyancy — turbulent kinetic energy — pressure perturbation — entrainment

$$\varepsilon = \frac{1}{M}\frac{\partial M}{\partial z}$$

hypothesis: some fraction of kinetic energy generated by buoyancy is reduced by entrainment

(First proposed by Grant and Brown (1999) and successfully applied for shallow convection)

$$\boxed{\varepsilon\overline{w}^{c2} \cong C_\varepsilon \times g\overline{\left(\frac{T'_v}{\overline{T}_v} - l\right)}^{c}}$$

constant value from 0 to 1

$$C_\varepsilon = 0.2$$

Interpretation of the hypothesis

$$\varepsilon \overline{w}^{c\,2} \cong C_{\varepsilon} \times g \overline{\left(\frac{T'_v}{\overline{T}_v} - l \right)}^{c}$$

multiplying mass flux and integrating vertically,

$$\int_{Z_B}^{Z_T} E \overline{w}^{c\,2}\, dz \cong C_{\varepsilon} \underbrace{\int_{Z_B}^{Z_t} BM\, dz}_{\text{cloud work function}}$$

where $E = \varepsilon M$: entrainment

Some fraction of cloud work function is used to accelerate entrained air to mean updraft velocity.

$$\varepsilon \cong C_\varepsilon \frac{B}{\overline{w}^{c\,2}}$$

If updraft velocity is large, large amount of buoyancy-generated energy must be used to accelerate entrained air. In this situation, convective flow tries to reduce entrainment rate and efficiently transform potential energy into mean updraft kinetic energy.

If buoyancy is large enough, it is easy to apply buoyancy-generated energy to acceleration of entrained air even if entrainment rate is large.

Convective flow prefers efficient transformation from potential energy into kinetic energy

$$\varepsilon \cong C_\varepsilon \frac{B}{\boxed{\overline{w}^{c\,2}}}$$

vertical profile of updraft velocity is necessary

$$\frac{1}{2}\frac{\partial \overline{w}^{c\,2}}{\partial z} = B - \frac{1}{\sigma\rho}\left(\frac{\partial \sigma\rho\,\overline{w'^2}^{c}}{\partial z}\right) - \frac{1}{\rho}\overline{\left(\frac{\partial p'}{\partial z}\right)}^{c} - g\overline{\left(\frac{p'}{\overline{p}}\right)}^{c} - \varepsilon\overline{w}^{c\,2}$$

$$= (1 - C_\varepsilon)B \boxed{- \frac{1}{\sigma\rho}\left(\frac{\partial \sigma\rho\,\overline{w'^2}^{c}}{\partial z}\right) - \frac{1}{\rho}\overline{\left(\frac{\partial p'}{\partial z}\right)}^{c} - g\overline{\left(\frac{p'}{\overline{p}}\right)}^{c}}$$

$$\frac{1}{2}\frac{\partial \overline{w}^{c\,2}}{\partial z} = (1 - C_\varepsilon)B - \boxed{\frac{1}{\tau_z}\left(\frac{\overline{w}^{c\,2}}{2}\right)}$$

updraft velocity is damped with a certain length scale

$$\tau_z = 2.0\,[km]$$

Spectral representation of updraft types

entrainment

$$\varepsilon = C_{\varepsilon} \frac{B}{\overline{w}^{c\,2}}$$

$$\frac{1}{2}\frac{\partial \overline{w}^{c\,2}}{\partial z} = (1 - C_{\varepsilon})B - \frac{1}{\tau_z}\left(\frac{\overline{w}^{c\,2}}{2}\right)$$

in-cloud properties

$$\frac{\partial}{\partial z}\left(\eta\, h\right) = \varepsilon\, \overline{h} \qquad \frac{\partial M}{\partial z} = \varepsilon\, M$$

$$\frac{\partial}{\partial z}\left(\eta\, q_w\right) = \varepsilon\, \overline{q}_w$$

In-cloud properties depend on updraft velocity at cloud base.

small (large) updraft velocity at cloud base

↓

large (small) entrainment rate

↓

shallow (deep) convection

- Obviously, updraft velocity at cloud base has wide range of values because of different strength of thermals, gravity waves, topography-induced lifting etc.

- If you accept Gregory (2001)'s hypothesis, it logically leads to the conclusion that different cloud heights can be generated by different vertical velocities at cloud base.

- Although wide range of entrainment rate has been traditionally linked with cloud sizes, Gregory's hypothesis suggests a different view.

- In this scheme, updraft types are spectrally represented according to updraft velocity at cloud base. It is assumed that updraft velocity at cloud base is distributed in a certain range.

$$\overline{w}^{C}{}_{\min} < \overline{w}^{C}\Big|_{z=zb} < \overline{w}^{C}{}_{\max}$$

$$\overline{w}^{C}{}_{\min} = 0.3\,[m/s] \qquad \overline{w}^{C}{}_{\max} = 1.0\,[m/s]$$

Cloud base mass flux

Cloud base mass flux is determined by the same method as prognostic AS.

$$\frac{\partial K}{\partial t} = AM_B - \frac{K}{\tau}$$

$$K = \alpha M_B{}^2$$

Some behaviors of this scheme

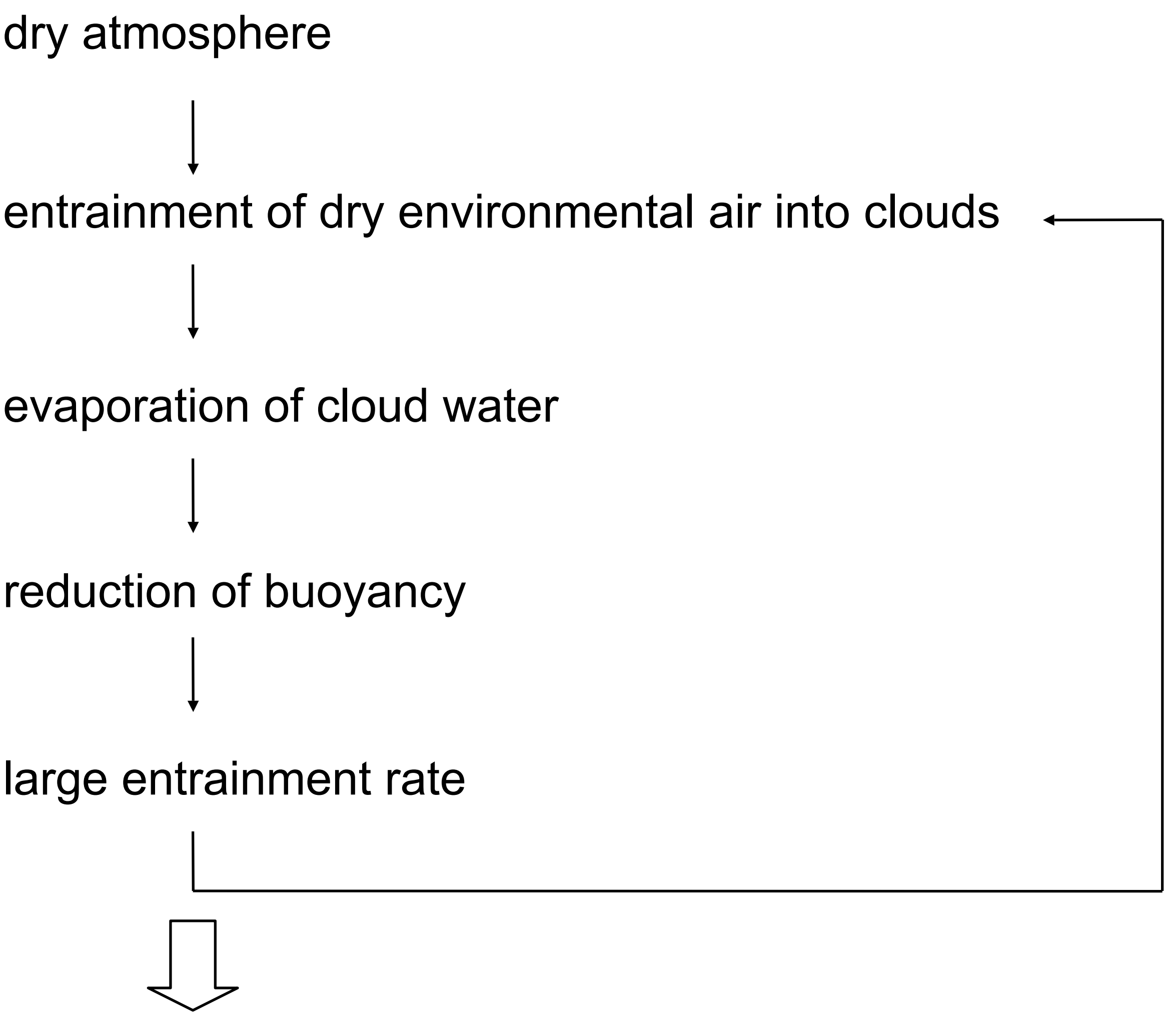
$$\begin{cases} \varepsilon = C_\varepsilon \dfrac{B}{\overline{w}^{c2}} \\[2ex] \dfrac{1}{2}\dfrac{\partial \overline{w}^{c2}}{\partial z} = (1 - C_\varepsilon)B - \underline{\dfrac{1}{\tau_z}\left(\dfrac{\overline{w}^{c2}}{2}\right)} \end{cases}$$

supress updraft velocity when buoyancy is small

small (large) buoyancy → small (large) updraft velocity
→ large (small) entrainment rate

Buoyancy is generally small at both cloud base and top
→Entrainment rate tends to be large at both cloud base and top
consistent with results of CRMs and LESs.

Behavior under dry atmosphere



dry atmosphere

entrainment of dry environmental air into clouds

evaporation of cloud water

reduction of buoyancy

large entrainment rate

Deep convection is suppressed under dry condition consistent with observations and model studies.

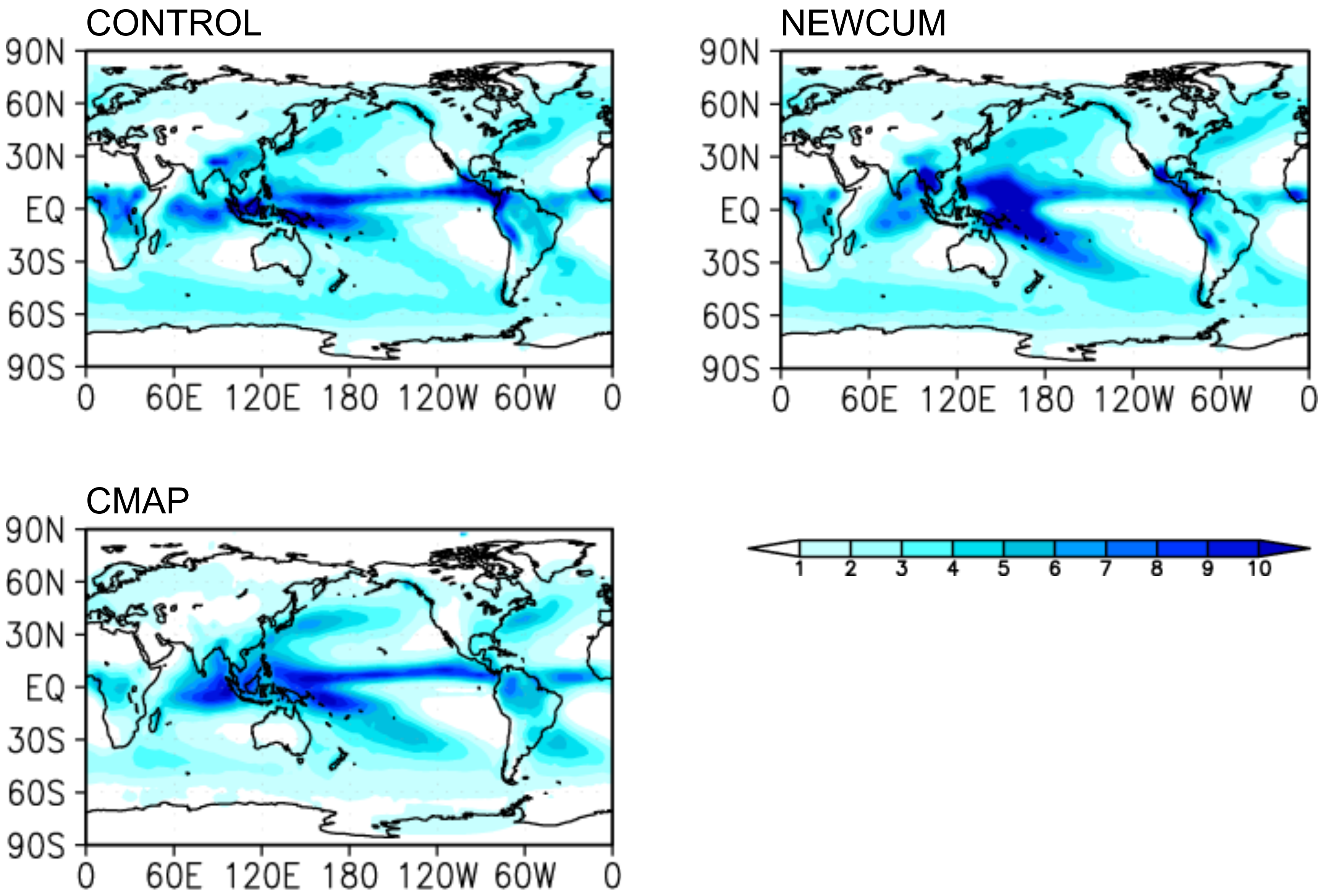
Experimental design

Model : MIROC4.0
Resolution : T42L20
SST : climatology
Integration : 5yeas (spin up) + 10years

CONTROL: Arakawa-Schubert scheme
with cumulus supression mechanism
based on relative humidity

NEWCUM : New cumulus scheme
without cumulus supresstion mechanism

Annual mean precipitation [mm/day]

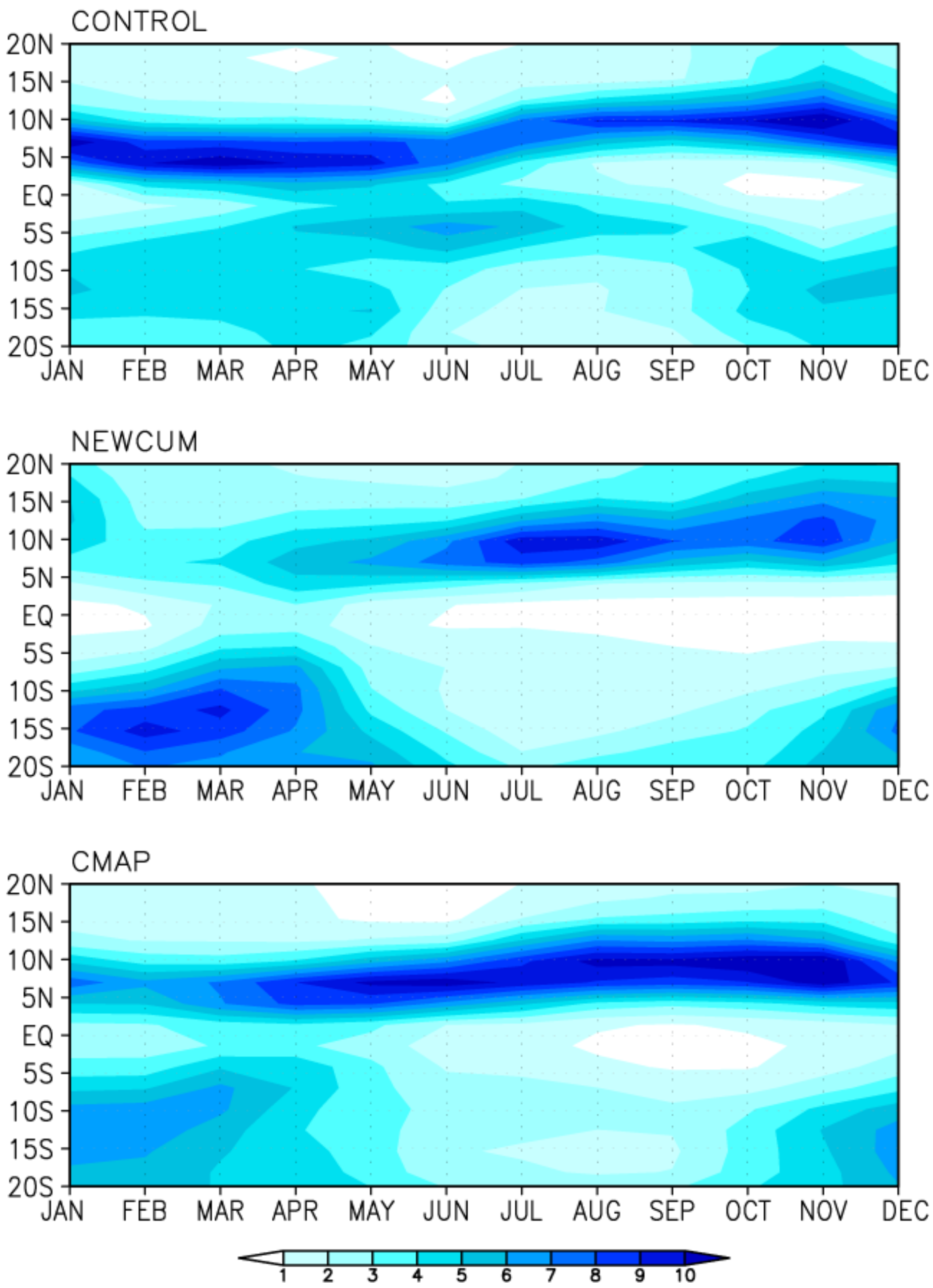


CONTROL

NEWCUM

CMAP

Precipitation averaged between 180E–120W [mm/day]

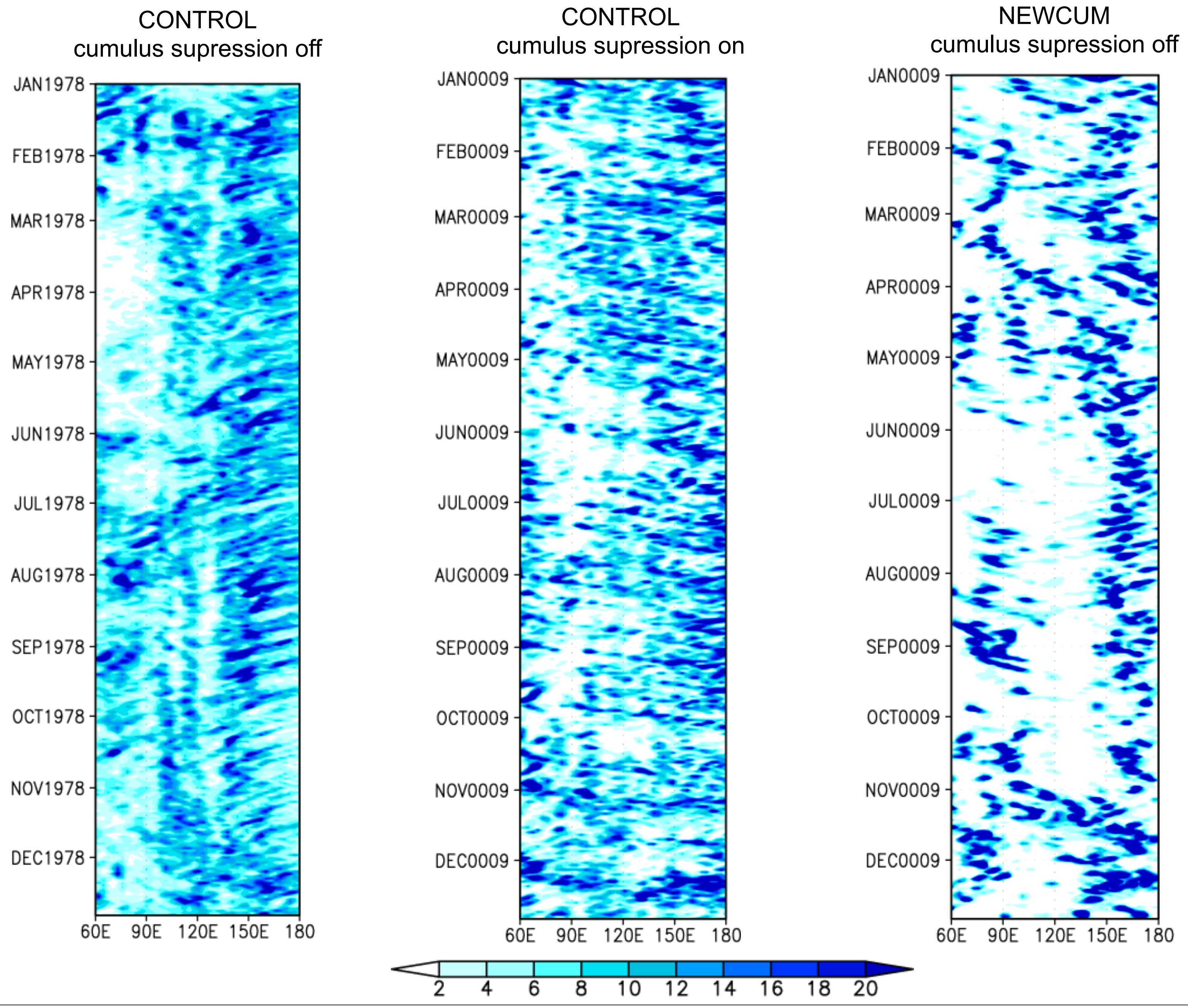


CONTROL

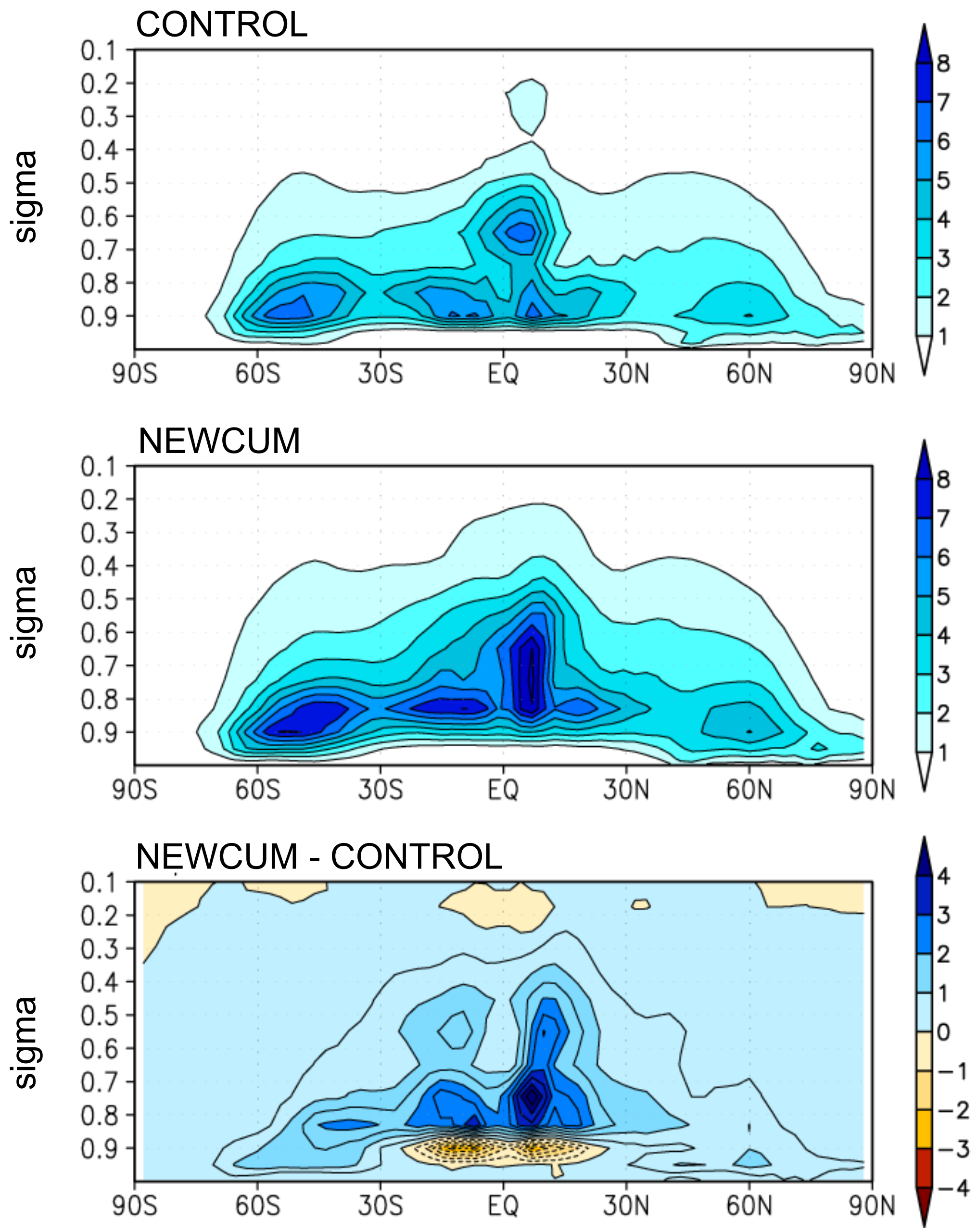
NEWCUM

CMAP

Precipitation averaged between 5S - 5N [mm/day]



Zonally averaged annual mean liquid+ice cloud [10^(−2)g/kg]

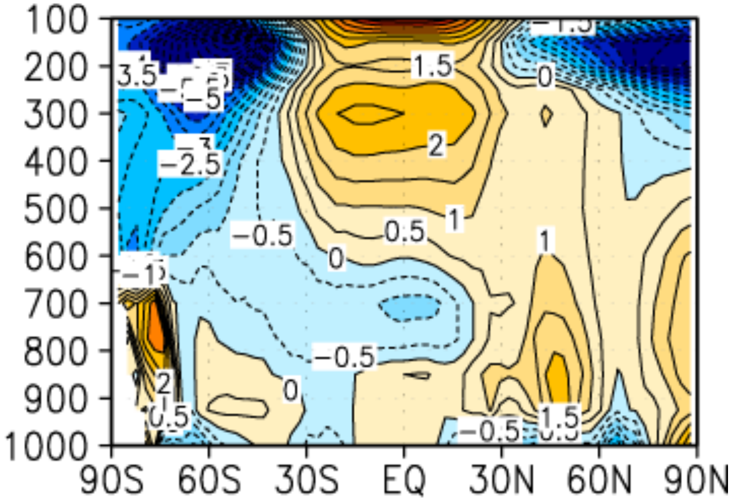

CONTROL

NEWCUM

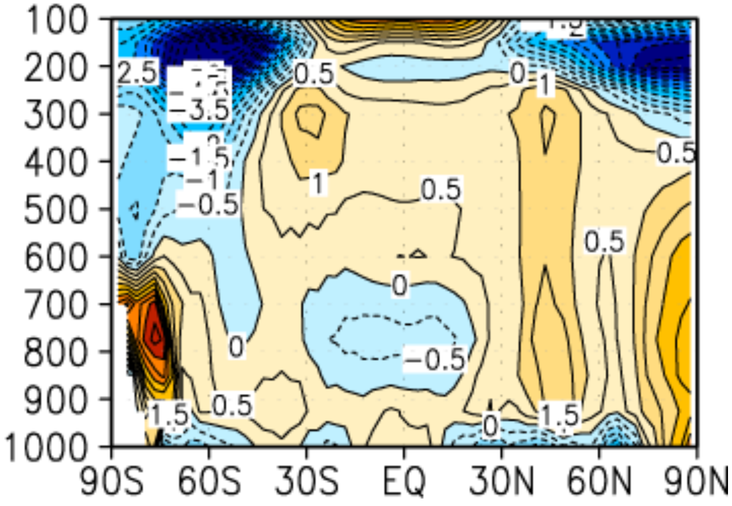
NEWCUM - CONTROL

Zonally averaged
annual mean temperature bias [K]

CONTROL

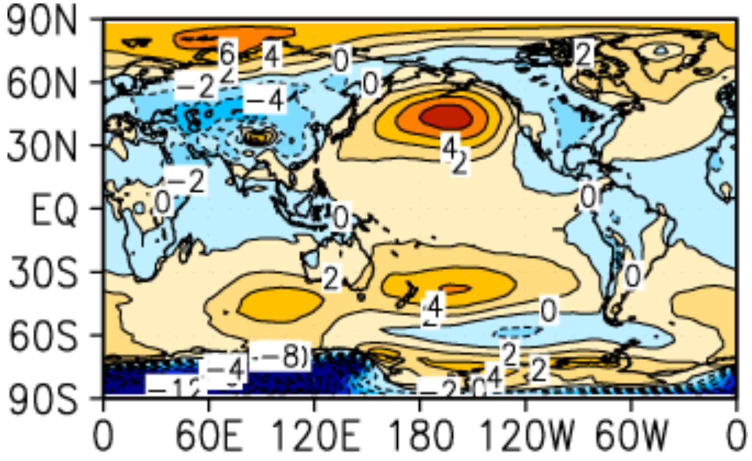


NEWCUM

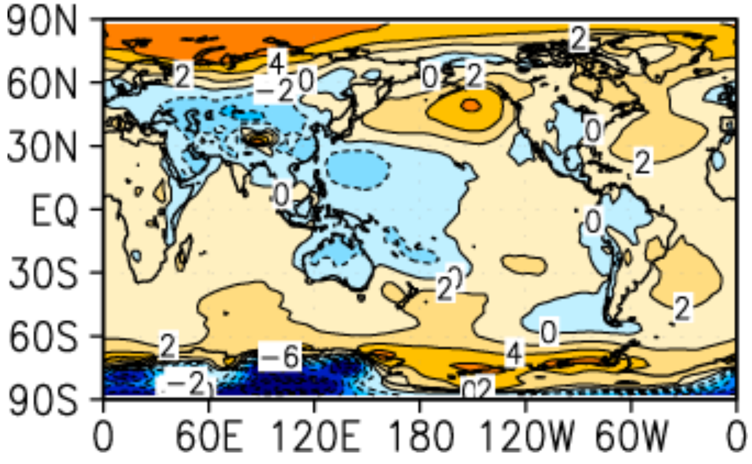


Annual mean
sea level pressure bias [hPa]

CONTROL



NEWCUM



Summary

■A new cumulus scheme is developed. Its characteristecs are the following.

- ･Lateral entrainment rate vertically changes depending on buoyancy and updraft velocity.
- ･Updraft types are spectrally represented according to updraft velocity.
- ･Cloud base mass flux is determined following the prognostic AS.

■ Although the hypotheses used in this scheme seem to be crude and controvertial, it has interesting characteristics and leads to a better result in some points.

- •Double ITCZ disappears in the eastern Pacific.
- •SPCZ is better represented.
- •Moist equatorial Kelvin waves and MJO-like waves are represented without any empirical triggering mechanisms.
- •Increased population of shallow and middle level convection.

Discussion

- Equatorial moist Kelvin waves and MJO might be regulated by change in entrainment rate.
- Verification of the hypothesis on entrainment is NOT enough. it should be carefully examined by CRMs and LESs.