Workshop on Tropical Dynamics and the MJO
January 14-16, 2014, University of Hawaii

Eastward propagating ISO represented by Chikira-Sugiyama cumulus parameterization: Understanding moisture variation under weak temperature gradient balance

Minoru Chikira

Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Japan
Visiting CSU (Nov2012-Oct2014)

Introduction

- Recently, the initiation and propagation of the MJO came to be viewed from a viewpoint of moisture variation (Discharge-recharge and moisture mode).
- But, our understanding of the variation is not sufficient.
- The goal of this study is to provide useful information for simplified models of the MJO through the analysis of the MJO-like waves represented by the Chikira-Sugiyama cumulus scheme.

- A popular method for analyzing the moisture variation is to use vertically integrated moist static energy and Gross Moist Stability (GMS). (e.g. Peters et al. 2008; Maloney 2009)
- We want to understand the moisture variation at specific levels such as the lower troposphere which is known to be particularly important for cumulus convection.
- This study proposes a new approach which enables to understand the variation of moisture profile (not column integrated moisture).

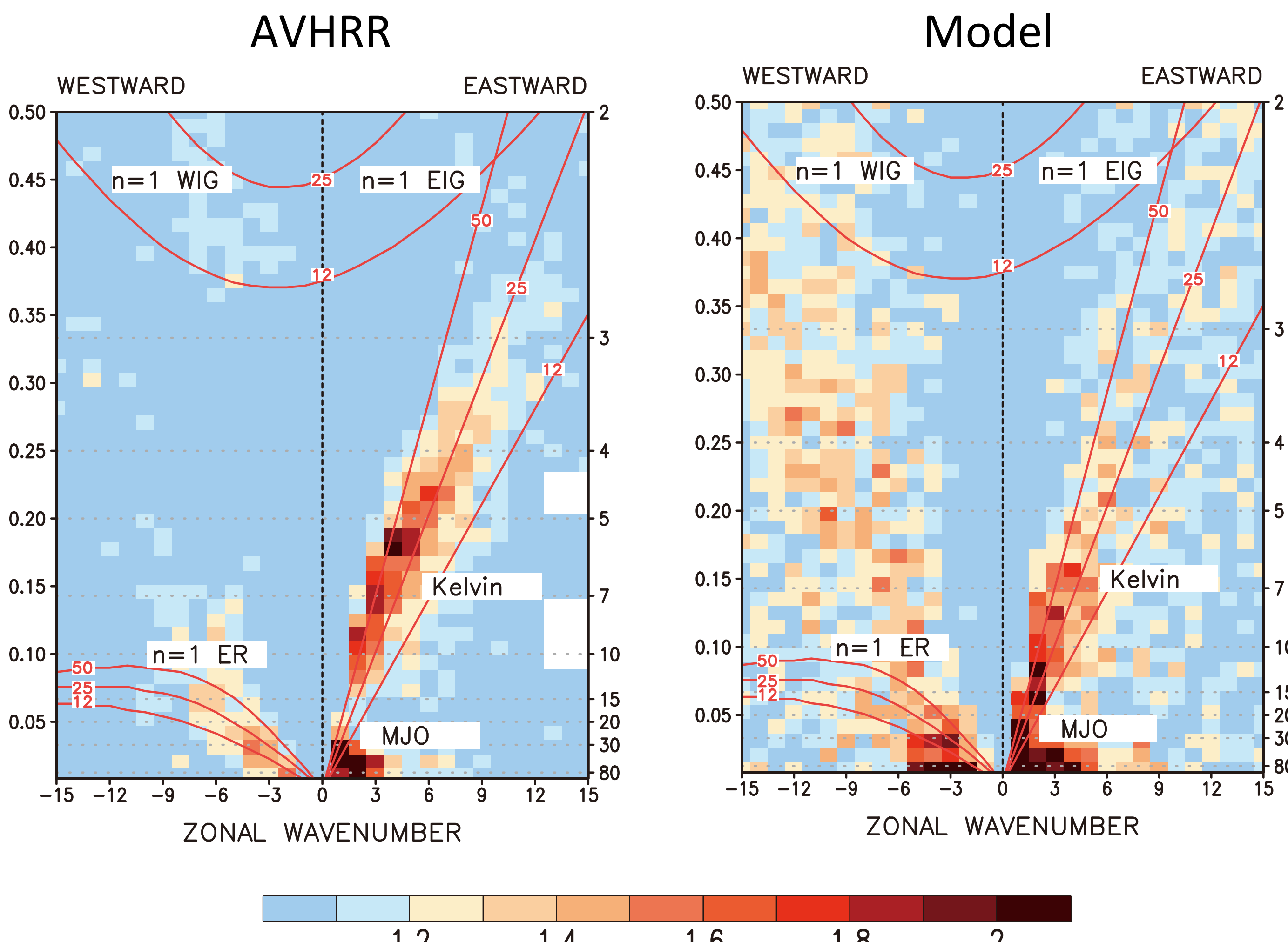
This presentation picks up higlights from

Chikira, M., 2013: Eastward propagating intraseasonal oscillation represented by Chikira-Sugiyama cumulus parameterization. Part II: Understanding moisture variation under weak temperature gradient balance, Journal of the Atmospheric Sciences, in press

Experimental design

- The atmospheric component of MIROC5 with the horizontal resolution of T42 (approximately 250km) and 56 levels
- Cumulus scheme is based on Chikira and Sugiyama (2010) with the entrainment formulation of Gregory (2001).
- The scheme can represent the moisture effect on convection through the change in entrainment rate without using any empirical triggering schemes.
- Climatological SSTs
- 10 years integration after 5-years spin-up

Wheeler-Kiladis diagram for OLR (Symmetric Component)



A thorough comparison with observation and reanalysis data was made in Chikira and Sugiyama (2013)

Analysis of moisture variation

Data for comparison

- Outgoing longwave radiation observed by AVHRR (1989-2005)
- ERA-Interim (1989-2005)

Composite method

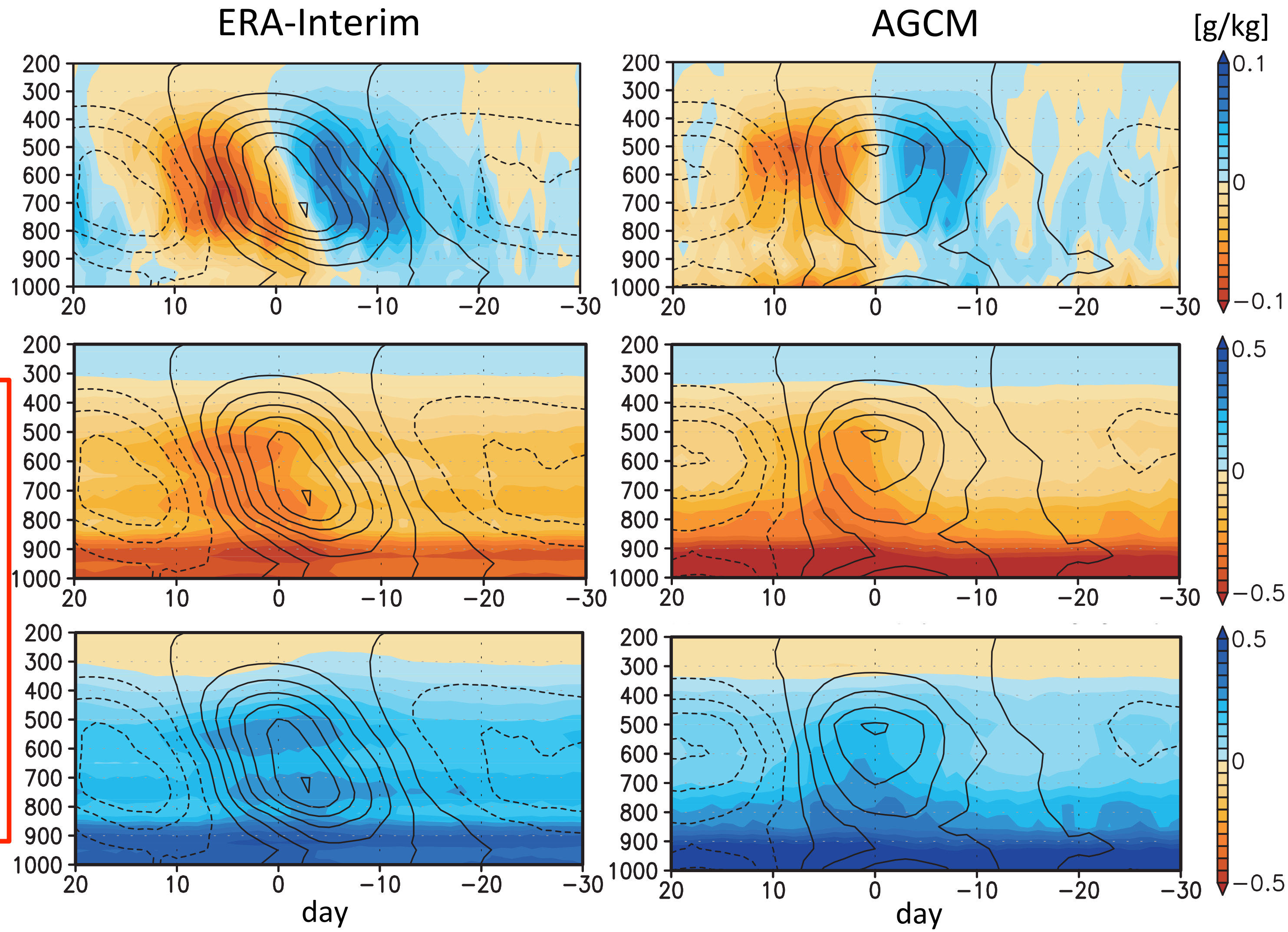
- Base points of the composites are the minimum values of OLR anomaly bandpass-filtered between 20-100days in period and 1-5 in wavenumber. Some criteria were applied to pick up clear MJO-like events.

Moisture tendency

Horizontal advection

+

Vertical advection
+ physical process



*Moisture anomaly is indicated by contours

- Horizontal advection strongly dries the western side of the convective area.
- The net effect of vertical advection and cloud process amplifies the positive moisture anomaly, consistent with the moisture mode theory.
- These two effects in total propagate the moisture anomaly eastward.

Understanding of moisture variation reduces into two problems

1. Why does the horizontal advection particularly dry the western side of the convective area?

→ Due to the horizontal advection by Rossby waves

2. Why does the effect of the vertical advection plus cloud processes amplify the positive moisture anomaly?

How to understand the effect of vertical advection plus cloud processes

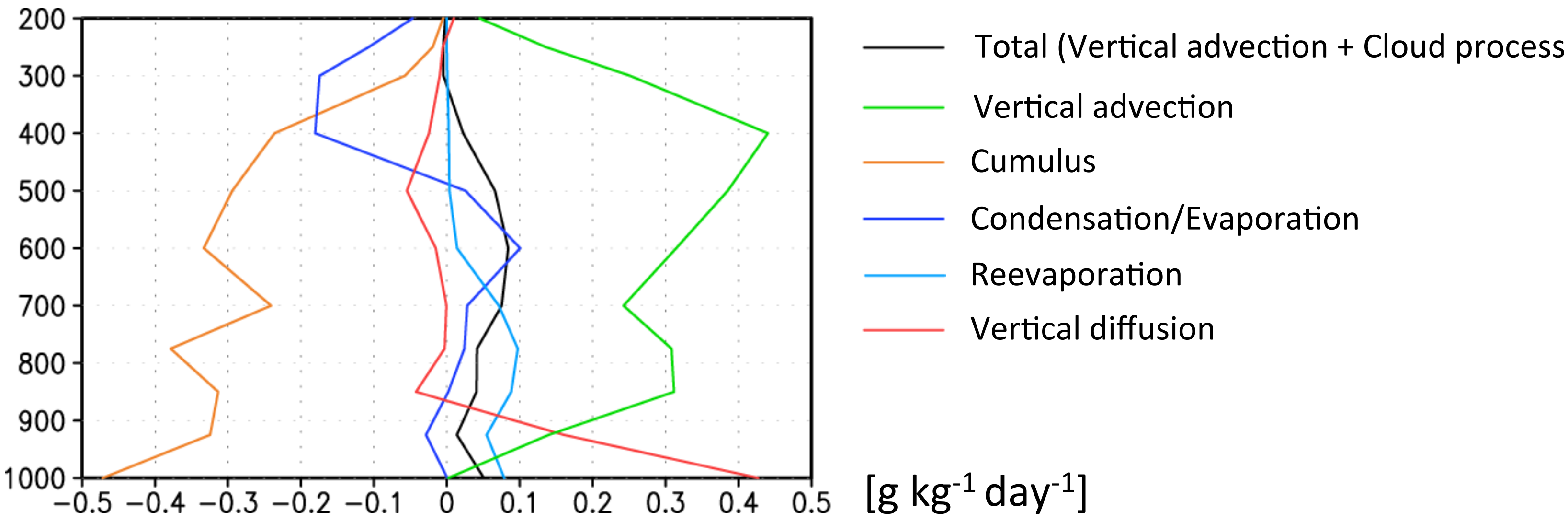
Prognostic equation of moisture (omitting horizontal advection)

$$\frac{\partial q}{\partial t} = -\omega \frac{\partial q}{\partial p} + S_{cu} - \tilde{C} + \tilde{R}_v + S_{df}$$

Vertical advection; Cumulus; Large-scale condensation /evaporation; Re-evaporation; Vertical diffusion

$\tilde{(\ )}$: Mean values in environment outside cumuli

Composited anomalous values of each term over the mature phase (-5〜5 days)



Approach of this study

Prognostic equation of moisture (omitting horizontal advection)

$$\frac{\partial q}{\partial t} = -\omega \frac{\partial q}{\partial p} + S_{cu} - \tilde{C} + \tilde{R}_v + S_{df}$$

Cumulus

$$\frac{\partial q}{\partial t} = -\omega \frac{\partial q}{\partial p} + D_q - \omega_c \frac{\partial q}{\partial p} - \tilde{C} + \tilde{R}_v + S_{df}$$

Vertical advection | Cumulus detrainment | Cumulus subsidence

$$\frac{\partial q}{\partial t} = -\tilde{\omega} \frac{\partial q}{\partial p} + D_q - \tilde{C} + \tilde{R}_v + S_{df}$$

Environmental vertical advection

$$\tilde{\omega} = \omega + \omega_c$$

Environmental vertical velocity outside cumuli

$$\frac{\partial q}{\partial t} = -\langle \tilde{\omega} \rangle \frac{\partial \langle q \rangle}{\partial p} + D_q - \tilde{C} + \tilde{R}_v + S_{df} + S_{hf}$$

Environmental vertical advection by low-frequency fields

$\langle\ \rangle$: Low frequency field where Fourier components less than 20days are removed

$$S_{hf} = -\langle \tilde{\omega} \rangle \frac{\partial q'}{\partial p} - (\tilde{\omega})' \frac{\partial \langle q \rangle}{\partial p} - (\tilde{\omega})' \frac{\partial q'}{\partial p}$$

Effect of high-frequency waves

$(\ )'$: Departure from $\langle\ \rangle$

Prognostic equation of potential temperature

$$\frac{\partial \theta}{\partial t} + \mathbf{V_h} \cdot \nabla \theta + \omega \frac{\partial \theta}{\partial p} = \frac{1}{C_p \pi}\left[Q_{cu} + L_v(\tilde{C} - \tilde{R}_v) + Q_r + \tilde{Q}_i + Q_{df} \right]$$

weak temperature gradient balance

Horizontal advection

Vertical advection

Cumulus

Large scale condensation/ evaporation

Re-evapo-ration

radiation

Freezing /Melting

Vertical diffusion

$$\omega \frac{\partial \theta}{\partial p} = D_\theta - \omega_c \frac{\partial \theta}{\partial p} + \frac{1}{C_p \pi}\left[L_v(\tilde{C} - \tilde{R}_v) + Q_r + \tilde{Q}_i + Q_{df} \right]$$

Vertical advection

Cumulus detrainment

Cumulus subsidence

$$\tilde{\omega} \frac{\partial \theta}{\partial p} = D_\theta + \frac{1}{C_p \pi}\left[L_v(\tilde{C} - \tilde{R}_v) + Q_r + \tilde{Q}_i + Q_{df} \right]$$

Environmental vertical advection

$$\langle \tilde{\omega} \rangle \frac{\partial \langle \theta \rangle}{\partial p} = D_\theta + Q_{hf} + \frac{1}{C_p \pi}\left[L_v(\tilde{C} - \tilde{R}_v) + Q_r + \tilde{Q}_i + Q_{df} \right]$$

Negligible

Environmental vertical advection by low-frequency fields

$$Q_{hf} = -\langle \tilde{\omega} \rangle \frac{\partial \theta'}{\partial p} - (\tilde{\omega})' \frac{\partial \langle \theta \rangle}{\partial p} - (\tilde{\omega})' \frac{\partial \theta'}{\partial p}$$

Effect of high-frequency waves

$$\langle \tilde{\omega} \rangle = \frac{1}{C_p \pi}\left[L_v(\tilde{C} - \tilde{R}_v) + Q_r + \tilde{Q}_i + Q_{df} \right] \left(\frac{\partial \langle \theta \rangle}{\partial p} \right)^{-1}$$

$$\frac{\partial q}{\partial t} = -\langle\tilde{\omega}\rangle\frac{\partial\langle q\rangle}{\partial p} + D_q - \tilde{C} + \tilde{R}_v + S_{df} + S_{hf}$$

$$\langle\tilde{\omega}\rangle = \frac{1}{C_p\pi}\left[L_v(\tilde{C} - \tilde{R}_v) + Q_r + \tilde{Q}_i + Q_{df}\right]\left(\frac{\partial\langle\theta\rangle}{\partial p}\right)^{-1}$$

$$\frac{\partial q}{\partial t} \simeq (\alpha - 1)(\tilde{C} - \tilde{R}_v) + \frac{\alpha}{L_v}(Q_r + \tilde{Q}_i + Q_{df}) + D_q + S_{df} + S_{hf}$$

Large-scale condensation/evaporation | Reevaporation of precipitation | Radiation | Freezing/Melting | Heating by vertical diffusion | Detrainment | Vertical diffusion | High-frequency waves

Nondimensional parameter

$$\alpha \equiv -\frac{L_v}{C_p\pi}\left(\frac{\partial\langle q\rangle}{\partial p}\right)\left(\frac{\partial\langle\theta\rangle}{\partial p}\right)^{-1} = -L_v\left(\frac{\partial\langle q\rangle}{\partial z}\right)\left(\frac{\partial\langle s\rangle}{\partial z}\right)^{-1} > 0$$

s: dry static energy

Vertical velocity is eliminated. It is clear what factors really moisten or dry the free-troposphere.

$$\frac{\partial q}{\partial t} \simeq (\alpha - 1)(\tilde{C} - \tilde{R}_v) + \frac{\alpha}{L_v}(Q_r + \tilde{Q}_i + Q_{df}) + D_q + S_{df} + S_{hf}$$

Large-scale condensation/ evaporation | Reevaporation of precipitation | Radiation | Freezing/ Melting | Heating by vertical diffusion | Detrainment | Vertical diffusion | High-frequency waves

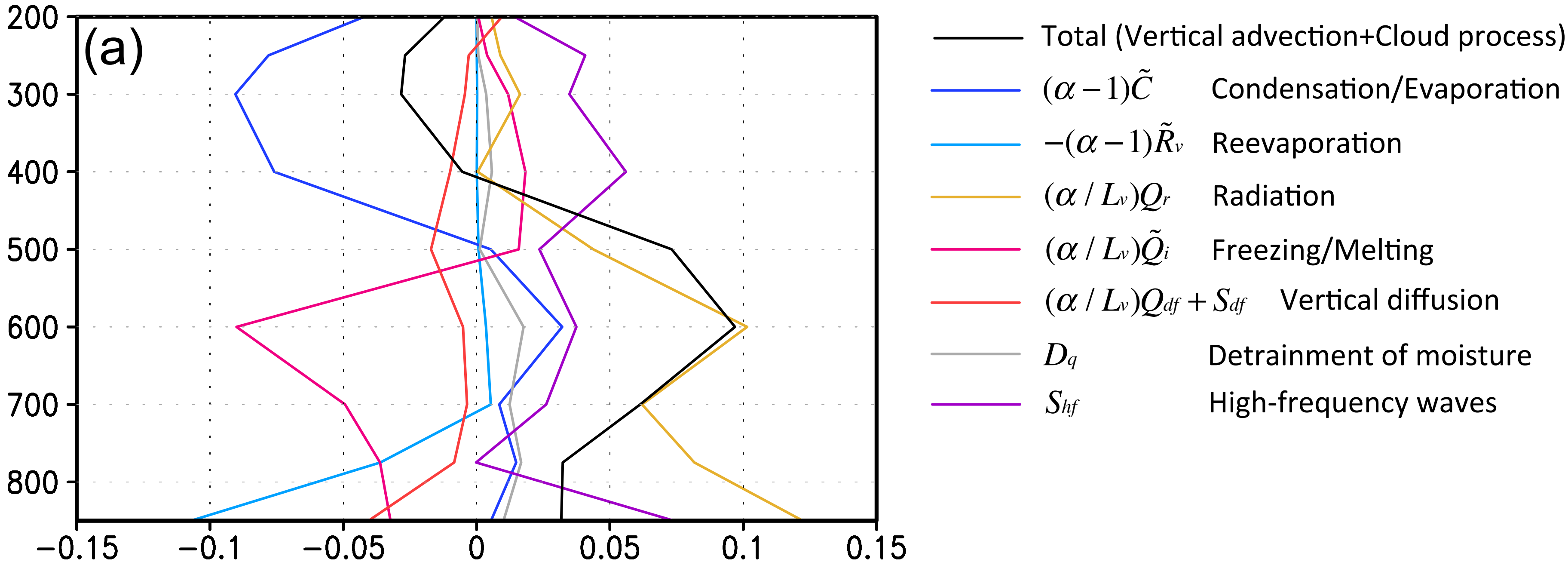
- Terms with alpha represent their effect through environmental vertical velocity.

  e.g. Radiative warming anomaly induces upward anomalous vertical velocity, thereby moistens the atmosphere.

$$\alpha - 1 = -\left(\frac{\partial\langle h\rangle}{\partial z}\right)\left(\frac{\partial\langle s\rangle}{\partial z}\right)^{-1} \begin{cases} > 0 & \text{in the lower-troposphere} \\ < 0 & \text{in the upper-troposphere} \end{cases}$$

- In the lower-troposphere, large-scale evaporation (both clouds and precipitation) always dries the atmosphere, since the drying effect of downward vertical velocity induced by its cooling always overcomes its direct moistening effect.

Composited anomalous moistening by each of the terms over the mature phase (-5～5days）



- Primary moistening factor: radiative warming anomaly
- Primary drying factor: Snow melting and reevaporation

Moistening is enhanced with ...

(1) Larger radiative warming anomaly
= Smaller radiative cooling (by higher clouds)

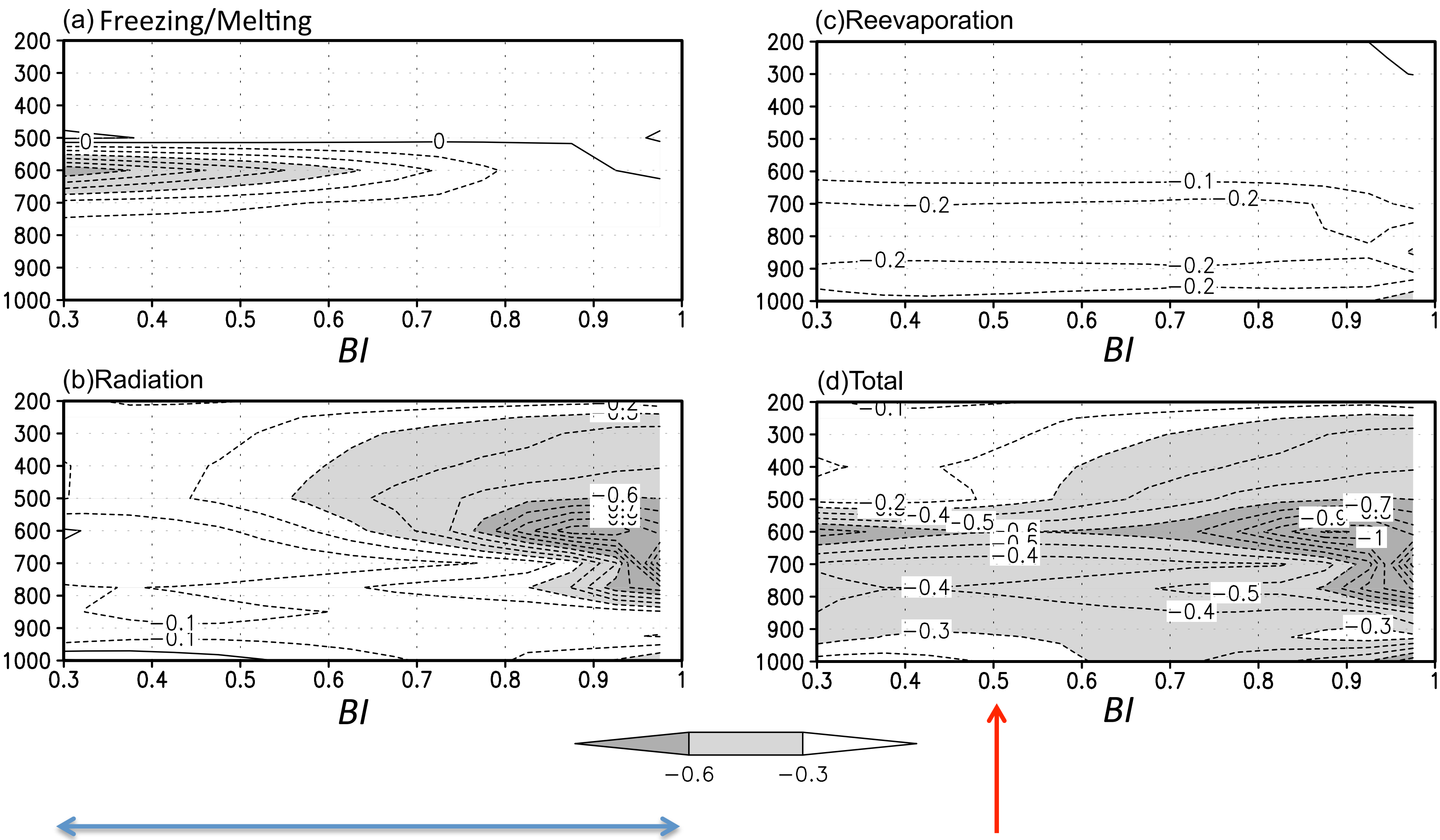
(2) Smaller snow melting and reevaporation (by shallower clouds)

Bottom-heavy heating Index (*BI*) was defined.

$$BI = \int_{600hPa}^{850hPa} Q_{cu} dp \Big/ \int_{100hPa}^{850hPa} Q_{cu} dp.$$

Q_{cu} : Heating by cumulus scheme

Then radiative cooling, freezing/melting and reevaporation were binned against *BI* in the tropics (10S-10N).



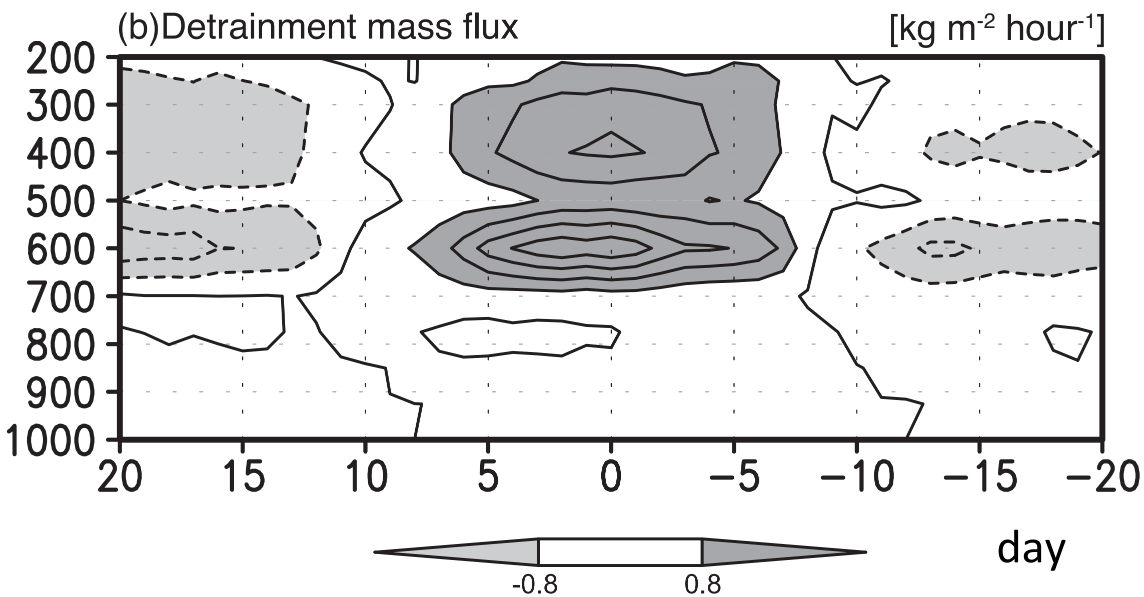
Top-heavy

Bottom-heavy

Cooling is minimized
(=Moistening is maximized)
when *BI* is around 0.5

BI over the mature phase of the model MJO is 0.51.

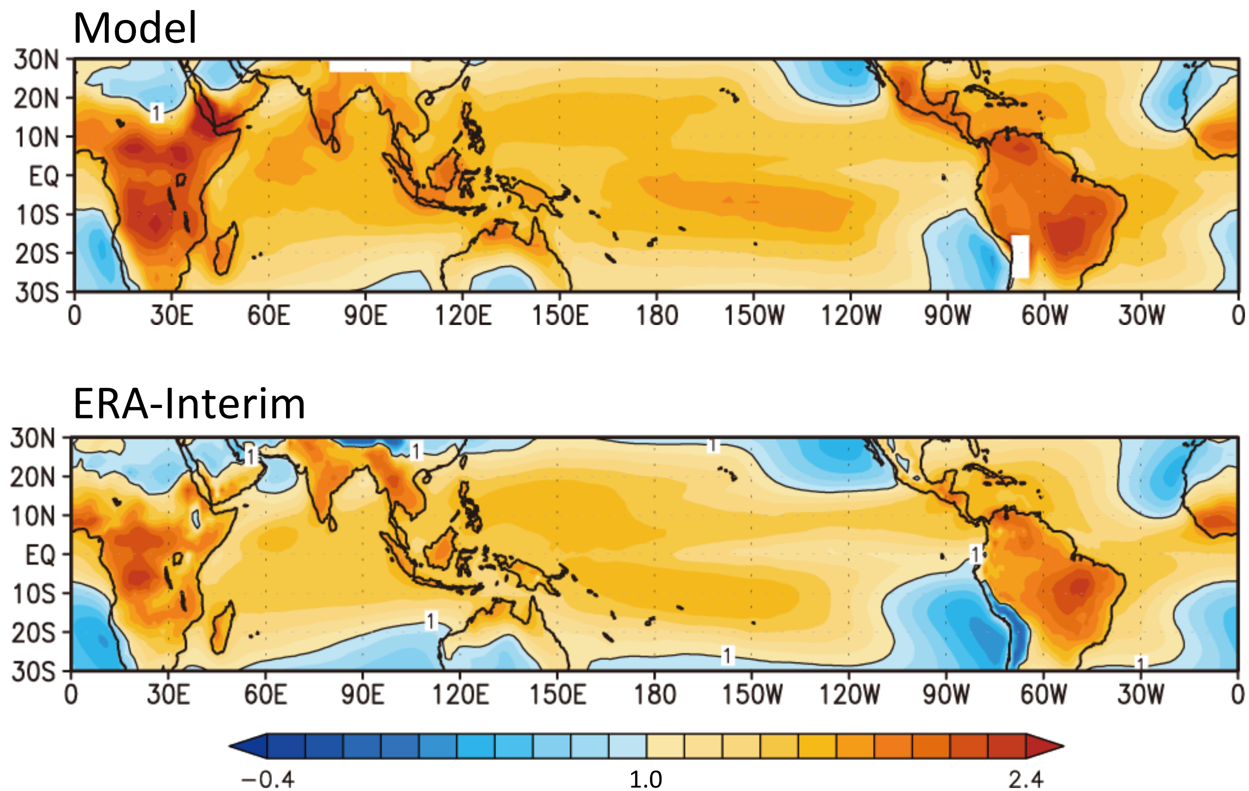
Vertical heating profile which maximizes the moistening of the free-troposphere is selected.



Over the mature phase, the population of congestus clouds are enhanced, which is consistent with some observation.

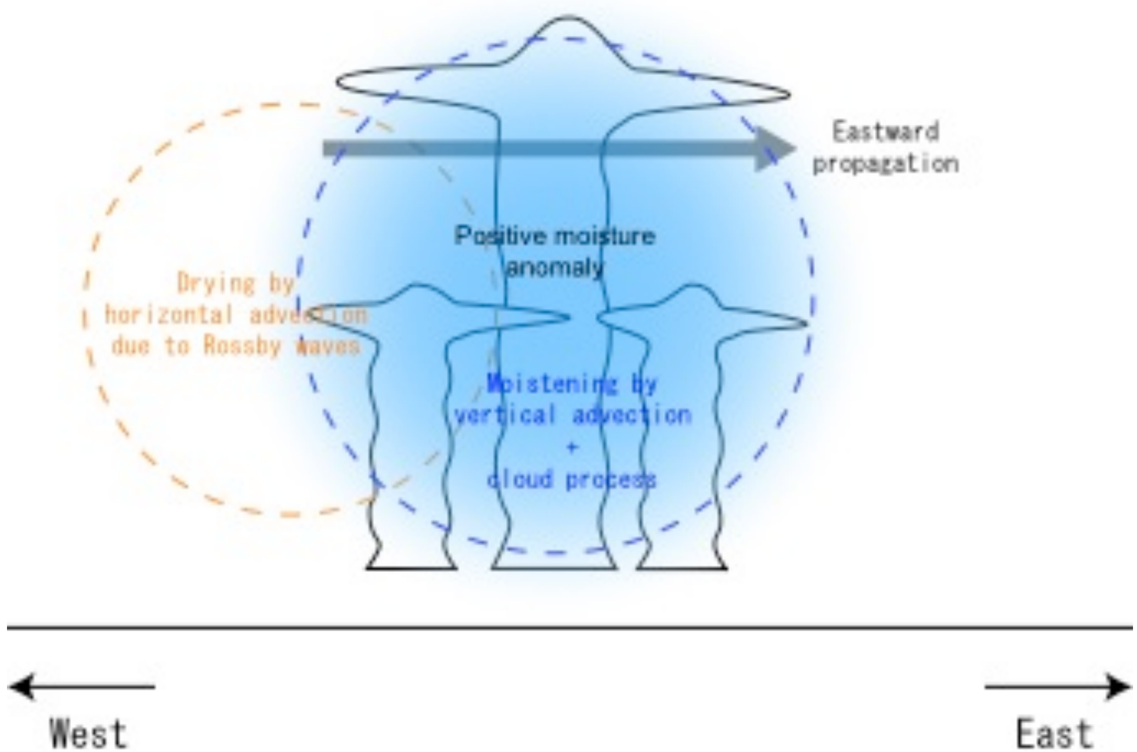
$$\alpha \equiv -\frac{L_v}{C_p \pi}\left(\frac{\partial q}{\partial p}\right)\left(\frac{\partial \theta}{\partial p}\right)^{-1}$$

annually averaged in the lower troposphere (850-700hPa)



- Alpha is large over land. The lower troposphere tends to be effectively dried by downward environmental vertical velocity over land. This is unfavorable condition for the development of the MJO
- This is consitent with the observed fact of suppressed MJO variability over land.

Summary



- Positive moisture anomaly is amplified by vertical advection and cloud process.
- Horizontal advection mainly due to Rossby waves greatly dries the western side of the convective area.
- These two processes in total propagate the moisture anomaly eastward.
- The role of preconditioning by shallow convection is not definitive in this model.

- By focusing on environmental vertical velocity outside cumuli and applying the WTG balance, we obtain an equation where vertical velocity is eliminated.

$$\frac{\partial q}{\partial t} \simeq -\mathbf{v}_h \cdot \nabla q$$

$$(\alpha - 1)(\tilde{C} - \tilde{R}_v) + \frac{\alpha}{L_v}(Q_r + \tilde{Q}_i + Q_{df}) + D_q + S_{df} + S_{hf}$$

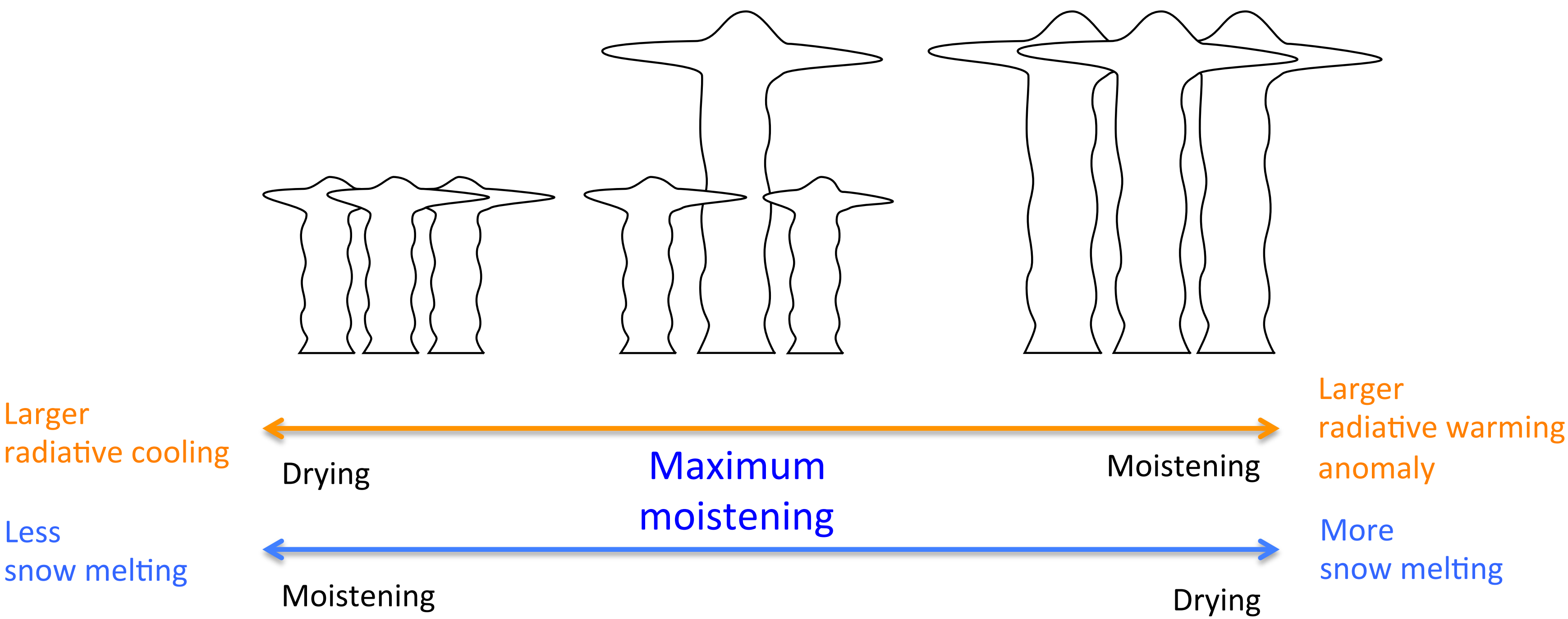
Large-scale condensation/evaporation; Reevaporation of precipitation; Radiation; Freezing/Melting; Heating by vertical diffusion; Detrainment; Vertical diffusion; High-frequency waves

- A new nondimensional parameter alpha appears as a controlling factor.

$$\alpha \equiv -\frac{L_v}{C_p \pi}\left(\frac{\partial\langle q\rangle}{\partial p}\right)\left(\frac{\partial\langle\theta\rangle}{\partial p}\right)^{-1} = -L_v\left(\frac{\partial\langle q\rangle}{\partial z}\right)\left(\frac{\partial\langle s\rangle}{\partial z}\right)^{-1} > 0$$

- The use of this equation enables to avoid ambiguity coming from the mutual cancellation of large-scale vertical advection and cumulus effects.

- The primary factor for the amplification of the moisture based on this equation is radiative warming anomaly.
- Snow melting and reevaporation of precipitation significantly dries the middle and lower-troposphere.



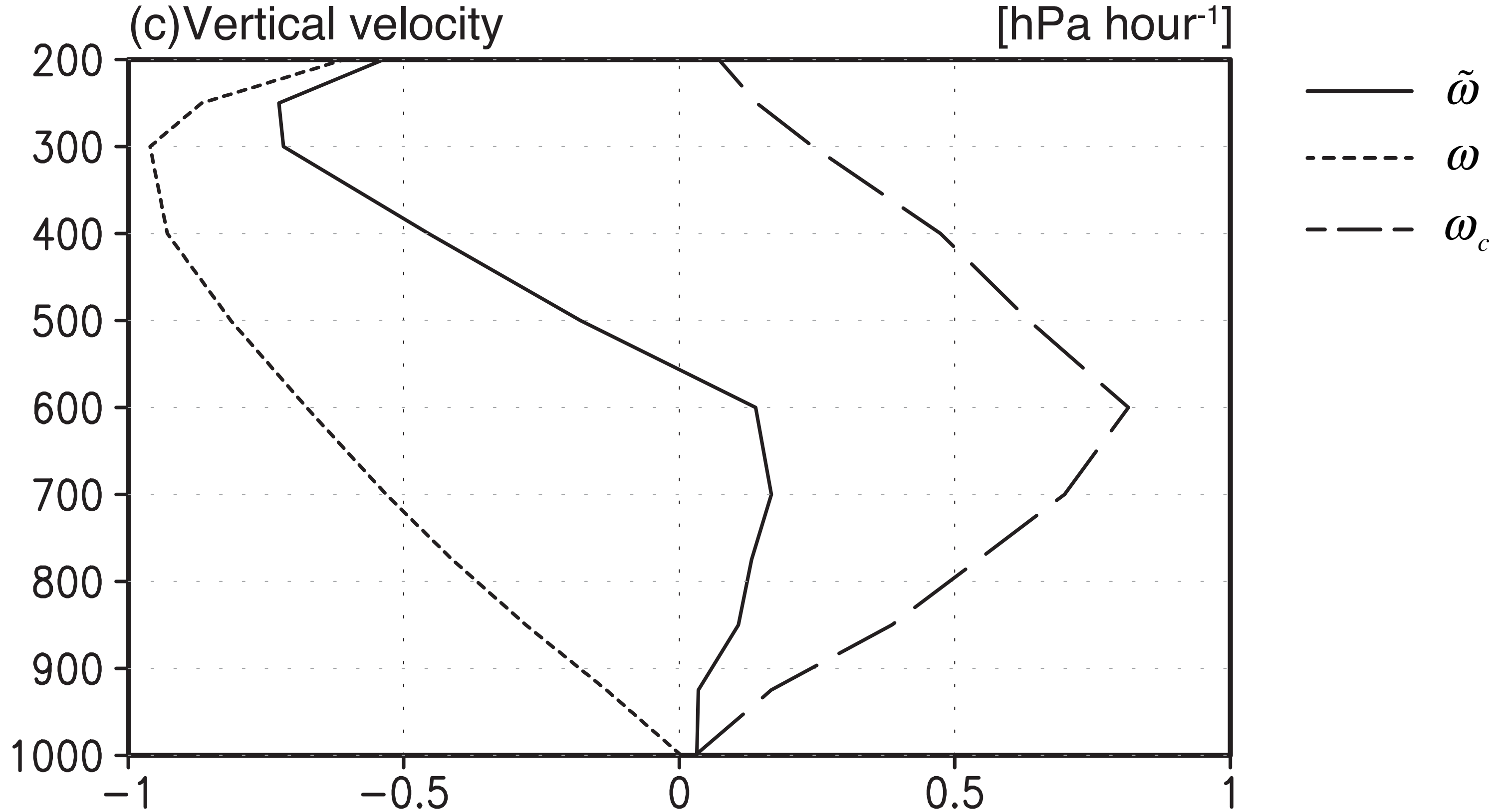
- Moistening is maximized when larger population of congestus clouds coexist with deep convection.
- A heating profile which maximizes moistening is selected.
- The representation of congestus clouds is crucial for reproducing MJO.

Back up

Outline of cumulus scheme

(Chikira and Sugiyama 2010)

- Based on an entraining-plume model
- Lateral entrainment rate vertically varies depending on buoyancy and updraft velocity following Gregory (2001).
- Updraft ensemble is spectrally represented following the spirit of the Arakawa-Schubert scheme. But cloud types are represented according to updraft velocity at cloud base.
- Cloud base mass flux is determined by a method identical to the prognostic Arakawa-Schubert scheme (originally proposed by Xu 1993).
- Never uses empirical triggering schemes
- Implemented in MIROC5. The result was submitted to CMIP5



(c)Vertical velocity
[hPa hour-1]
200
300
400
500
600
700
800
900
1000
−1
−0.5
0
0.5
1
ω̃
ω
ωc

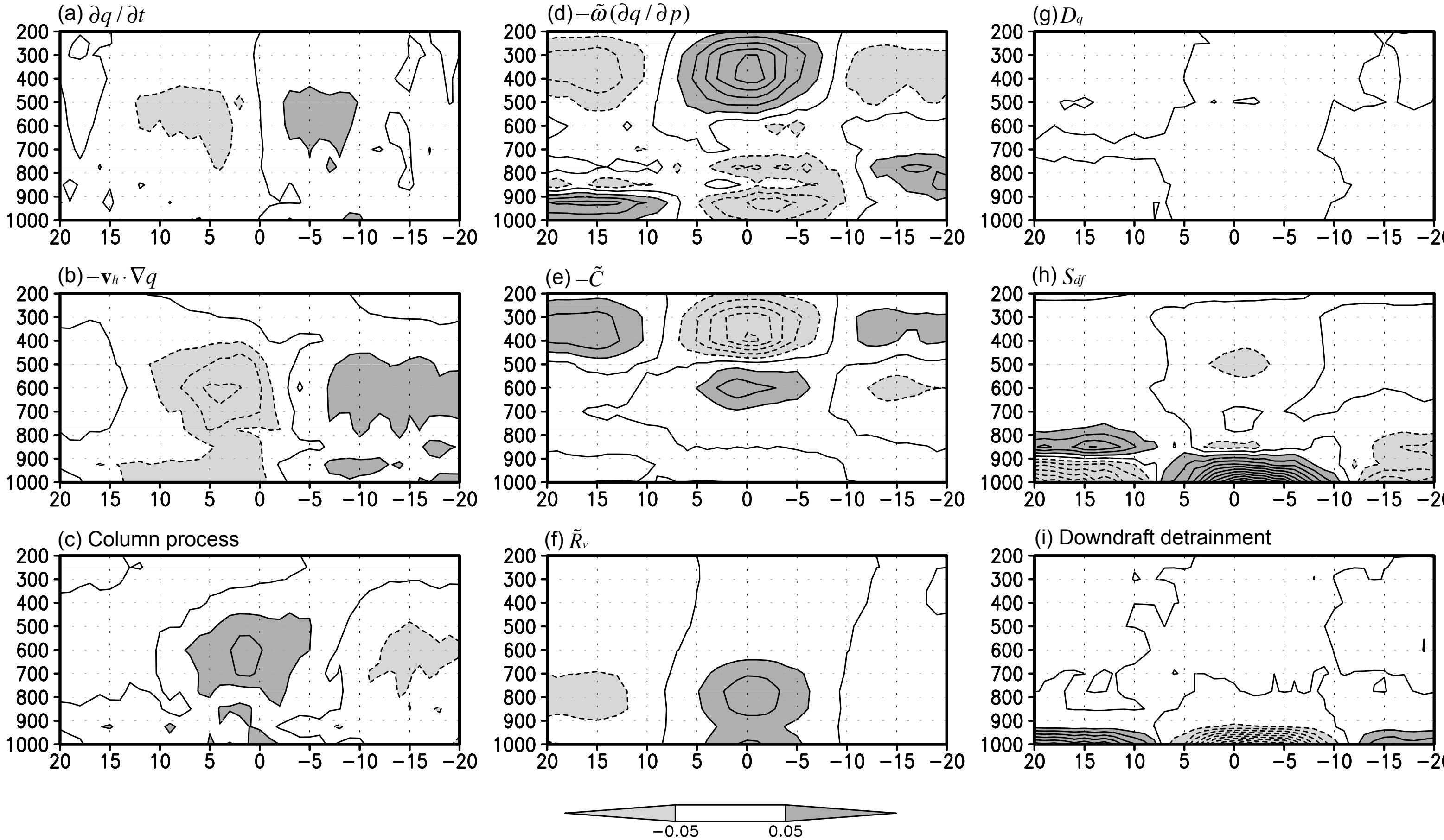


FIG. 9. Composited specific humidity tendency anomalies ($g\,kg^{-1}\,day^{-1}$) by each of the terms in (4). Contour intervals are $0.06\,g\,kg^{-1}\,day^{-1}$.

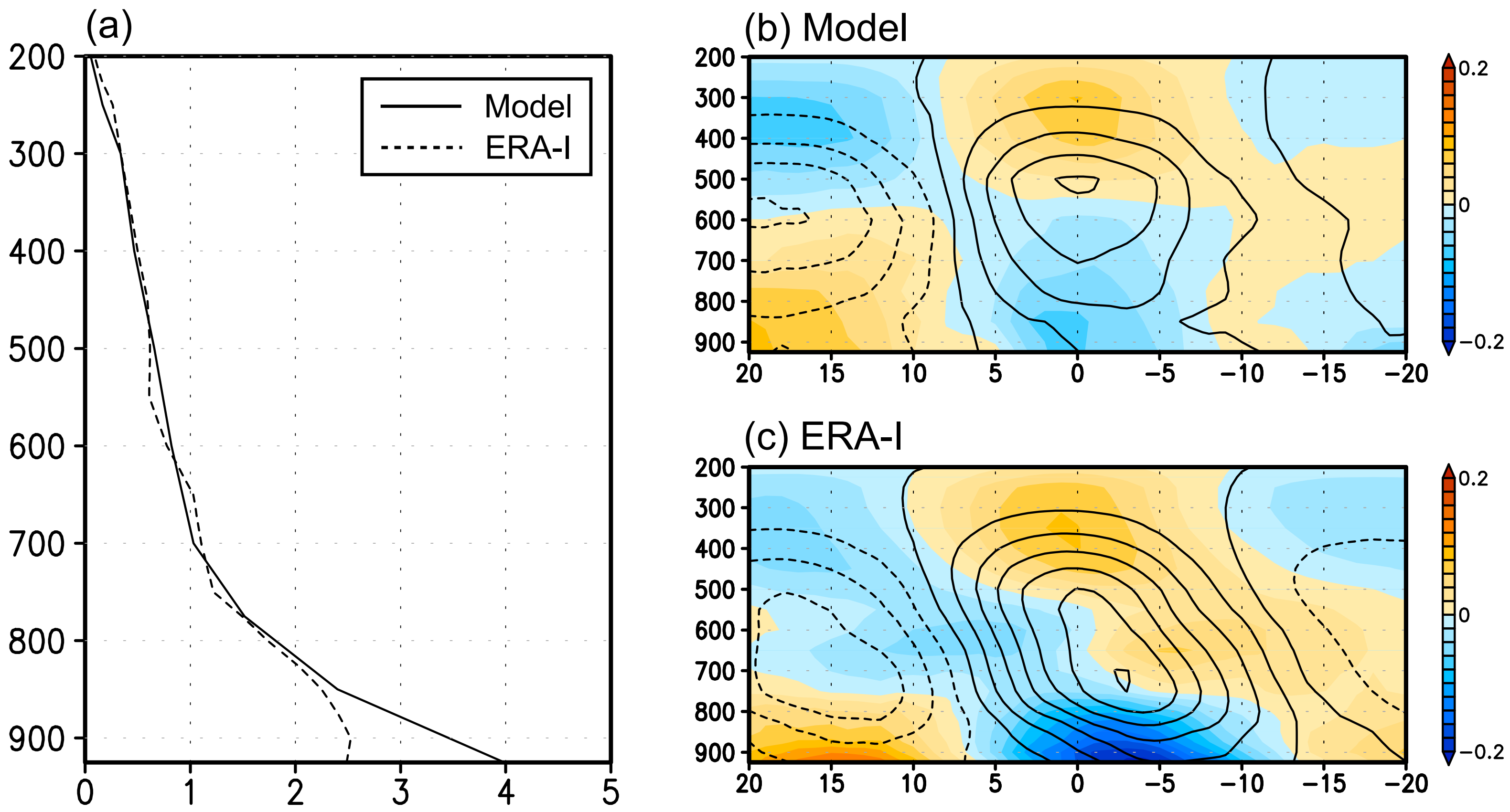
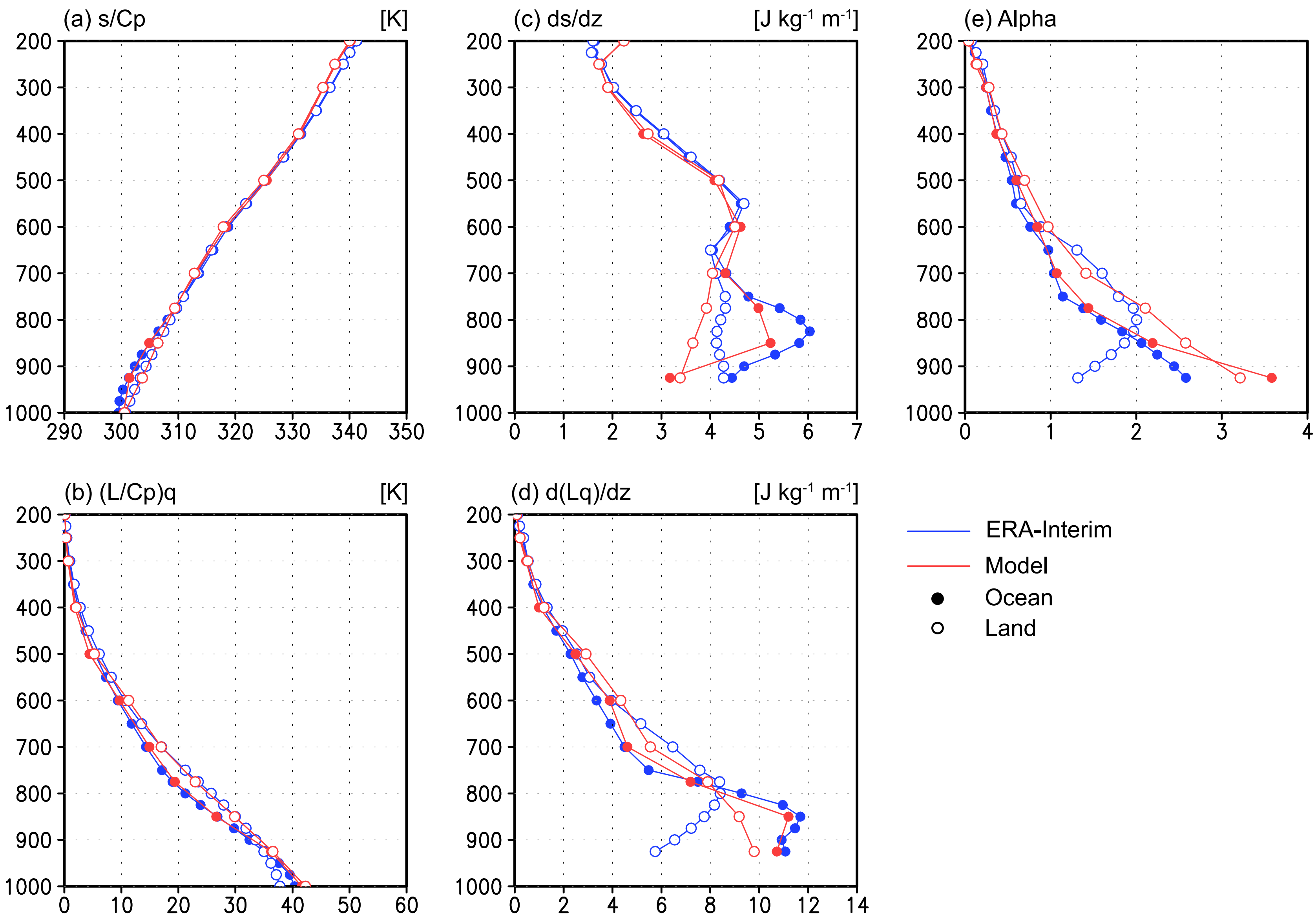


FIG. 12. (a): α averaged between day -30 and 20 in the model (solid line) and ERA-Interim (dashed line). (b-c): Time-height sections of α anomalies in the (b)model and (c)ERA-Interim. Contours in (b) and (c) indicate the specific humidity anomalies and the intervals are $0.1\, g\, kg^{-1}$. α is calculated using the composited $\tilde{q}$ and $\tilde{\theta}$.



(a) s/Cp
[K]
(b) (L/Cp)q
[K]
(c) ds/dz
[J kg-1 m-1]
(d) d(Lq)/dz
[J kg-1 m-1]
(e) Alpha
ERA-Interim
Model
Ocean
Land
200
300
400
500
600
700
800
900
1000
290 300 310 320 330 340 350
0 10 20 30 40 50 60
0 1 2 3 4 5 6 7
0 2 4 6 8 10 12 14
0 1 2 3 4