CMMAP Summer 2015 Team Meeting
August 4, 2015, Fort Collins, Colorado

A Weak Temperature Gradient Framework for MJO Diagnosis

Minoru Chikira

Colorado State University

Introduction

- Initiation and propagation of MJO came to be viewed from a viewpoint of moisture variation (Discharge-recharge mechanism and moisture mode theory).
- A popular method for understanding the moisture variation is to use vertically integrated moist static energy and Gross Moist Stability (GMS).
- We want to understand the moisture variation at specific levels such as the lower free-troposphere which is known to be particularly important for cumulus convection.
- Chikira (2014) proposed a new approach which enables to understand the variation of moisture profile.

Experimental design

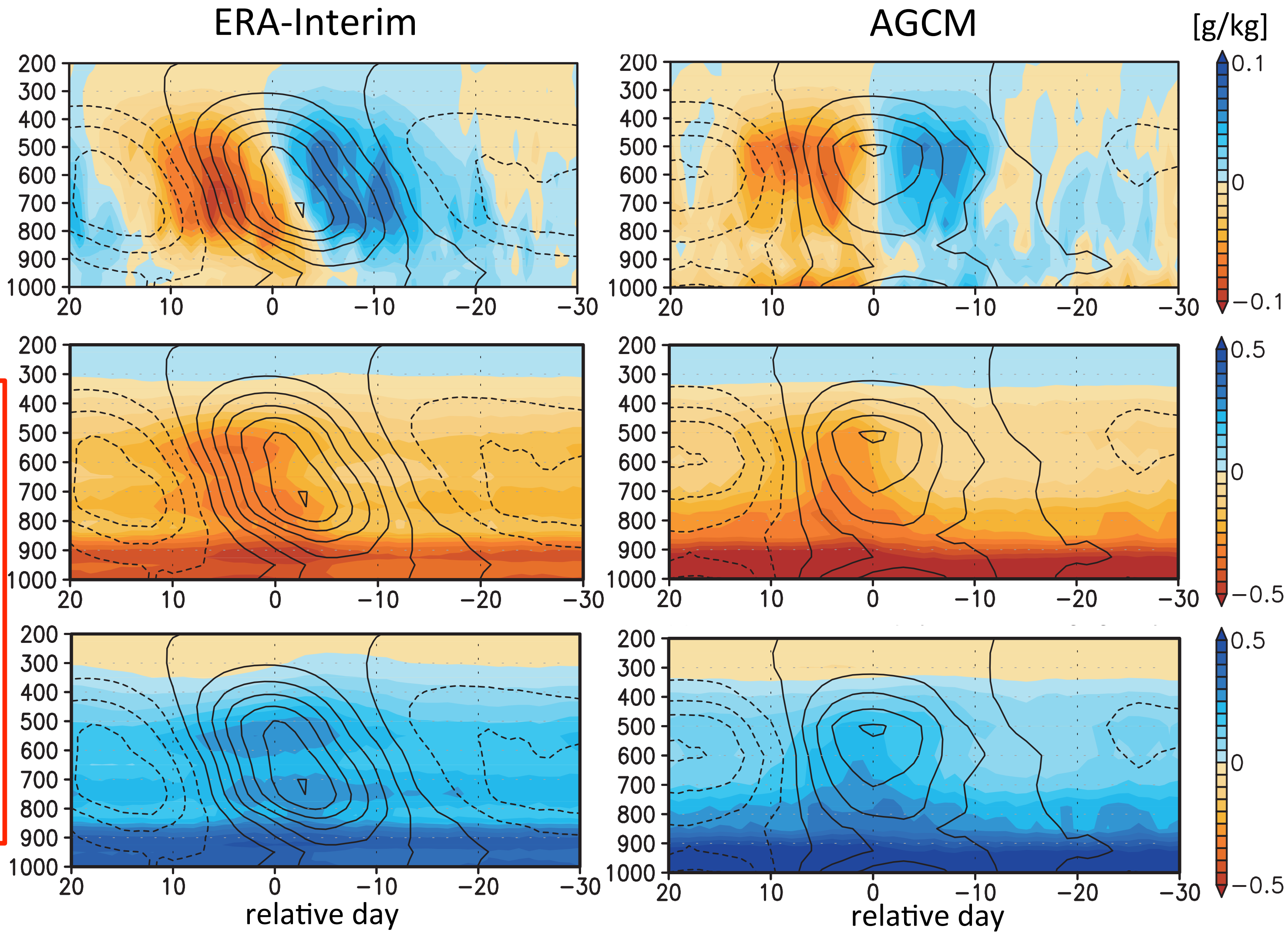
- MIROC5
- Horizontal resolution: 250km.
- Cumulus scheme: Chikira and Sugiyama (2010).
- Climatological SSTs

Moisture tendency
of composited MJO

Horizontal
advection

+

Vertical advection
+ physical process



*Moisture anomaly is indicated by contours

- Horizontal advection preferentially dries the western side of the convective area.
- The net effect of the vertical advection and physical 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 physical process amplify the positive moisture anomaly?

Method

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

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

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

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

Effect of high-frequency waves

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

Prognostic equation of potential temperature

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

weak temperature gradient balance

Horizontal advection

Vertical advection

Cumulus

Large scale condensation/ evaporation

Re-evaporation

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

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

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

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

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

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

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

Large-scale condensation/ evaporation

Reevaporation of precipitation

Radiation

Freezing/ Melting

Heating by vertical diffusion

Detrainment

Vertical diffusion

High-frequency waves

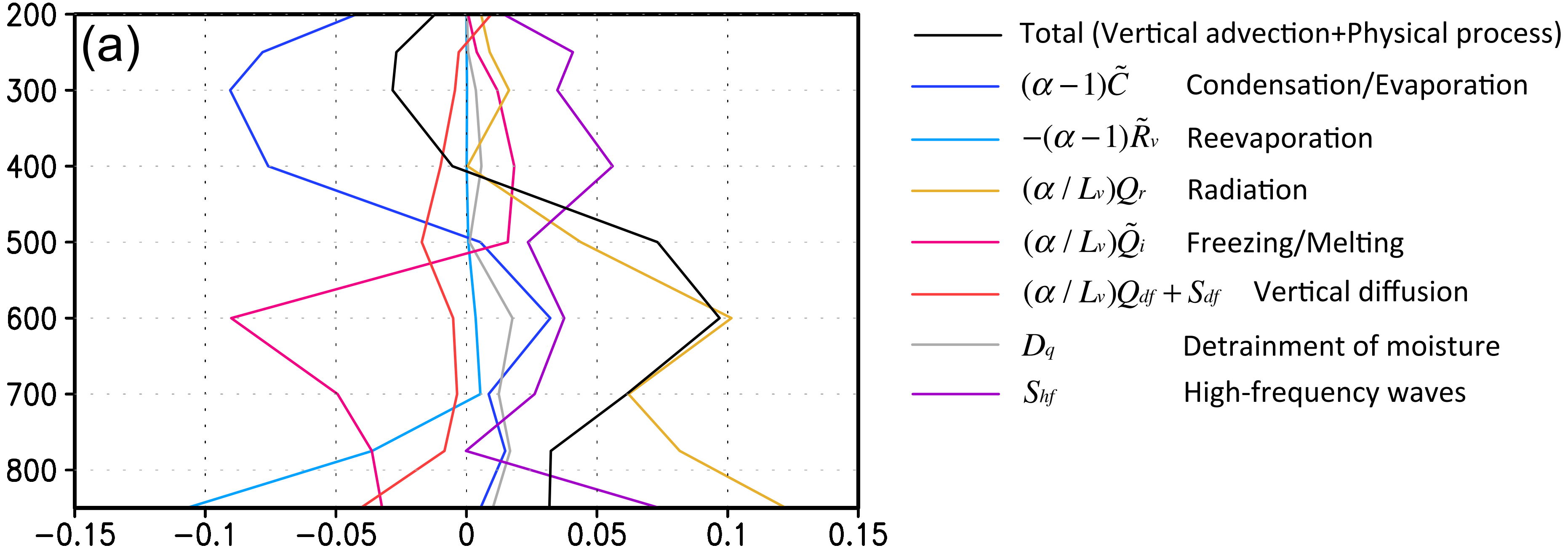
Nondimensional parameter

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

s: dry static energy

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

Composited anomalous moisture tendency by each term over the mature phase (-5～5days）



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

Moistening in the middle and lower troposphere is enhanced with ...

(1) Larger radiative warming anomaly (by higher clouds)

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

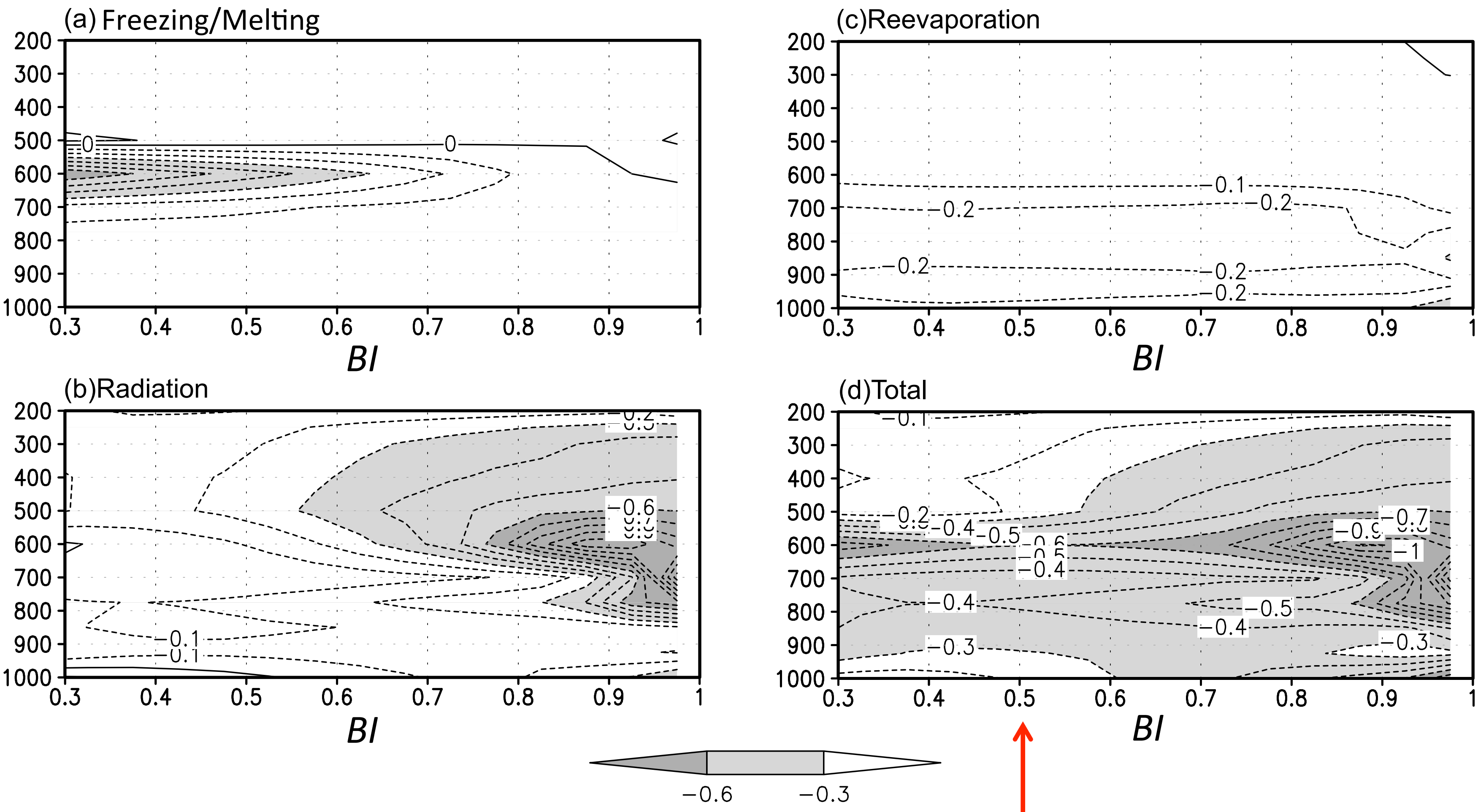
What type of clouds has the largest moistening effect?

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).



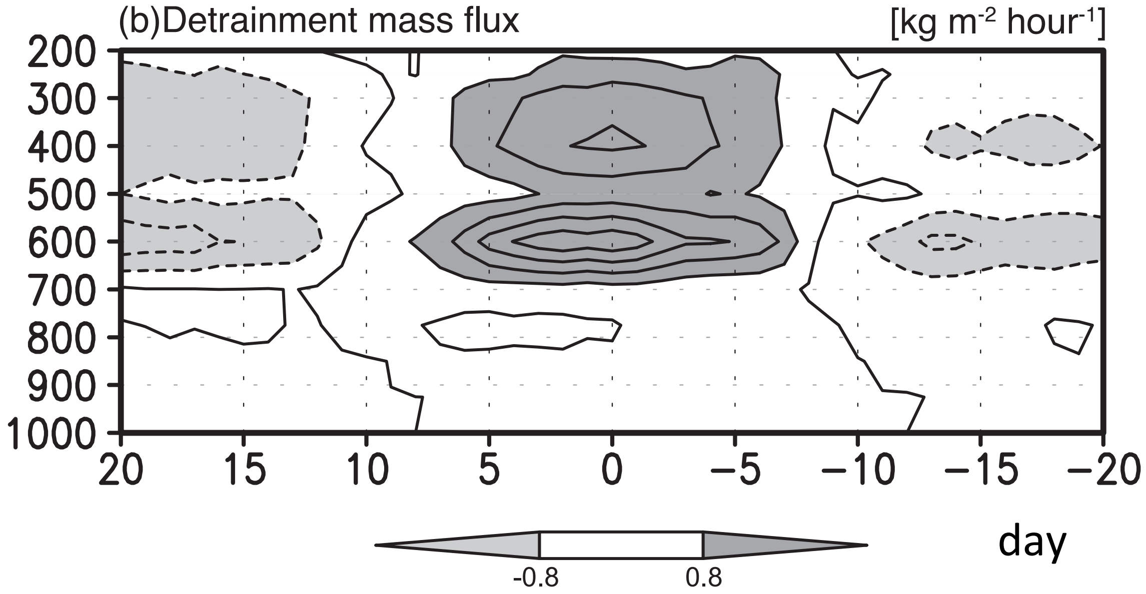
Top-heavy

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.

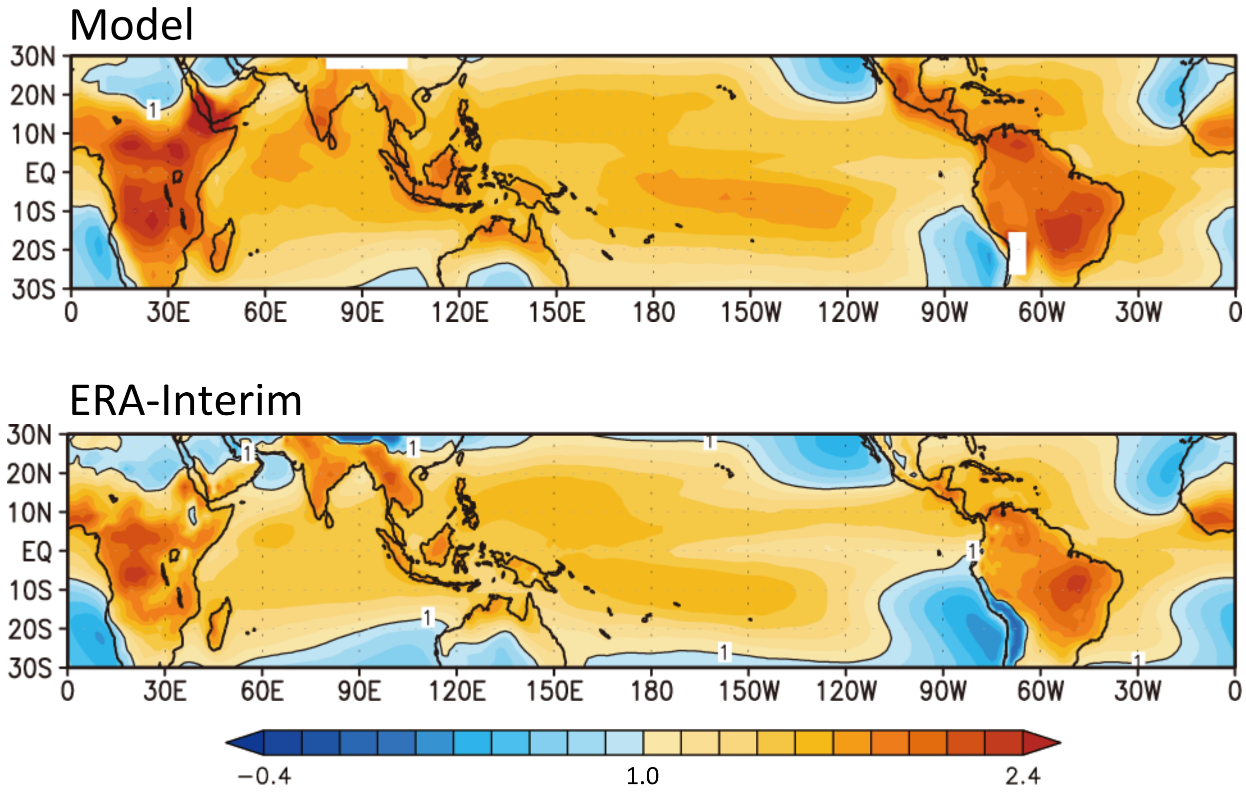
Vertical heating profile which maximizes the moistening of the free-troposphere is selected.


(b)Detrainment mass flux

Over the mature phase, a large population of congestus clouds coexist with deep convection, which is consistent with observed facts.

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

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



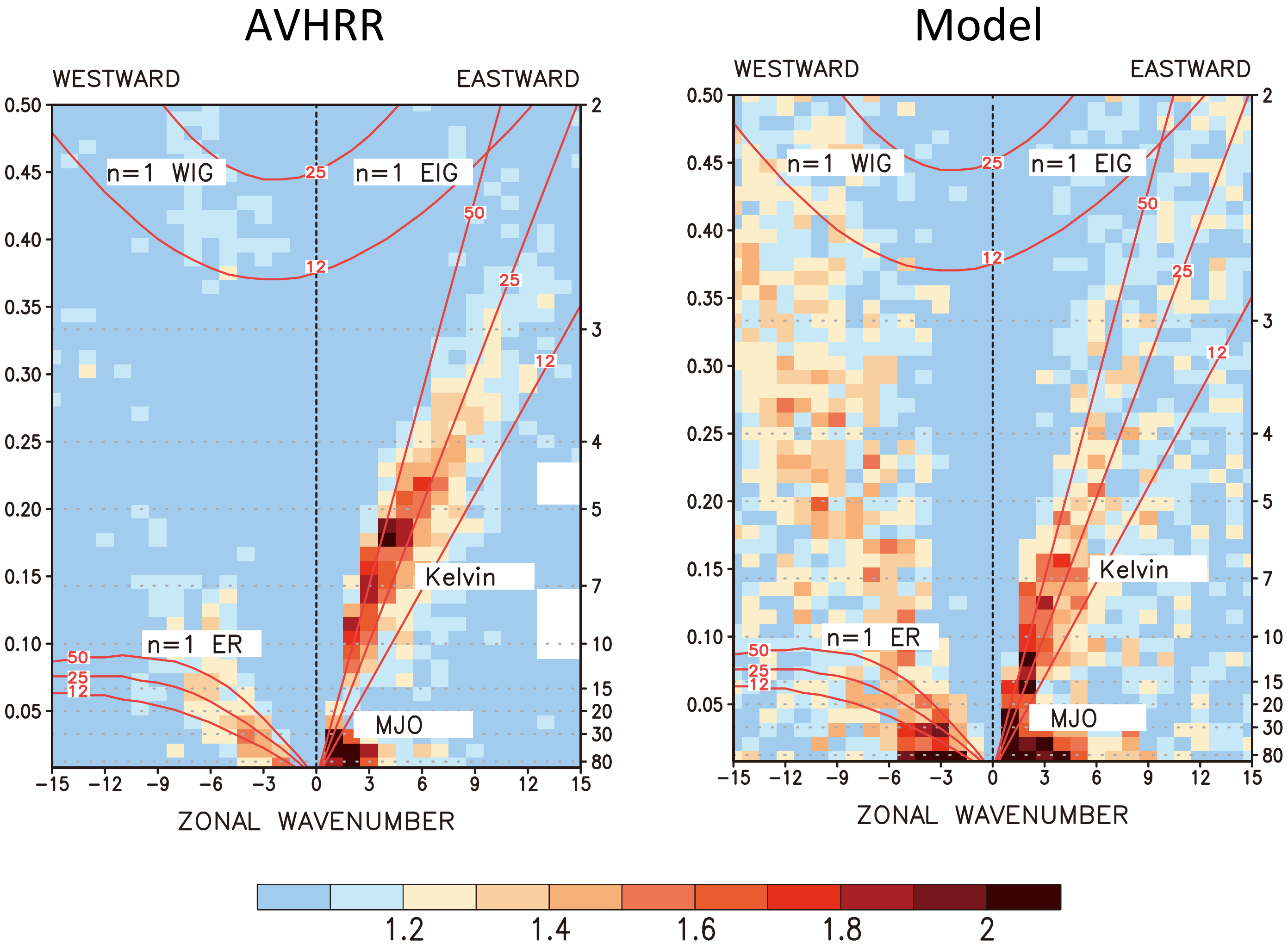
- Alpha is large over land. The lower troposphere tends to be effectively dried by convection over land. This is unfavorable condition for the development of the MJO.
- This is consitent with the observed fact that MJO tends to be suppressed over land.

Summary

- Positive moisture anomaly is amplified by vertical advection and physical process, which is consistent with the moisture mode theory.
- Horizontal advection mainly due to Rossby waves preferentially dries the western side of the convective area.
- These two processes in total propagate the moisture anomaly eastward.
- By focusing on environmental vertical velocity outside cumuli and applying the WTG balance, we obtain an equation where vertical velocity is eliminated.
- A new nondimensional parameter alpha appears as a controlling factor.
- The primary factor in moistening based on this equation is radiative warming anomaly.
- Snow melting and reevaporation significantly dries the middle and lower-troposphere.
- Moistening is maximized when a large population of congestus clouds coexists with deep convection.
- A heating profile which maximizes moistening is selected.

Back 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.

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

How to understand the effect of vertical advection plus physical process

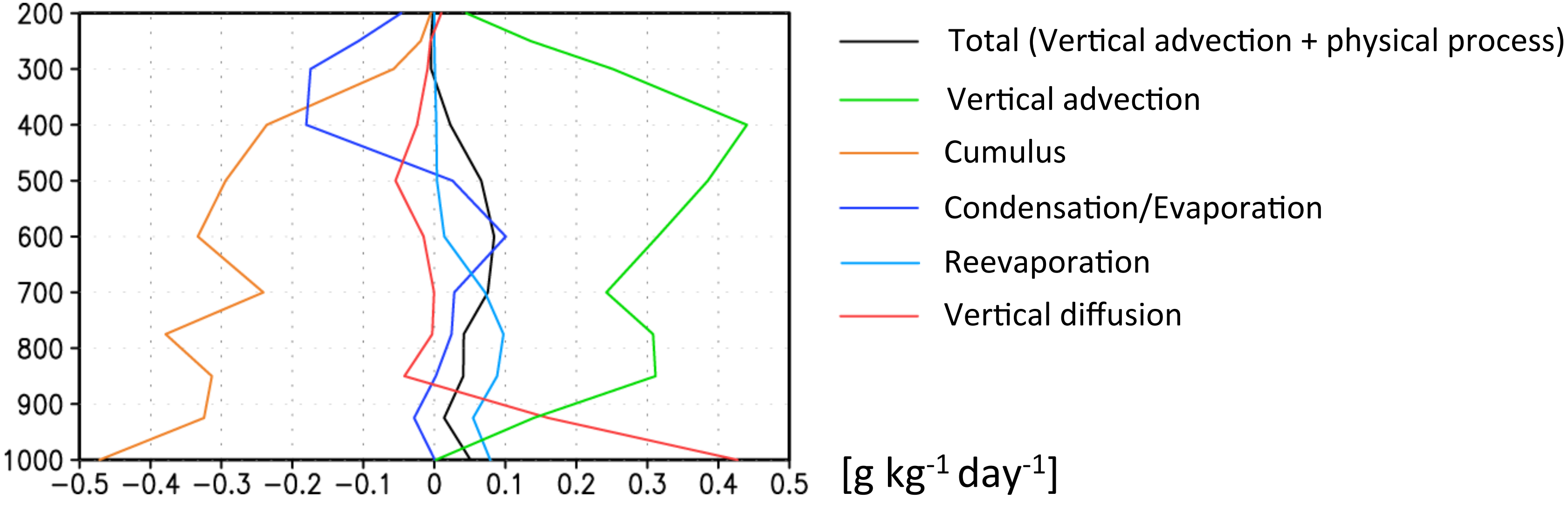
Prognostic equation of moisture (omitting horizontal advection)

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

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

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

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



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

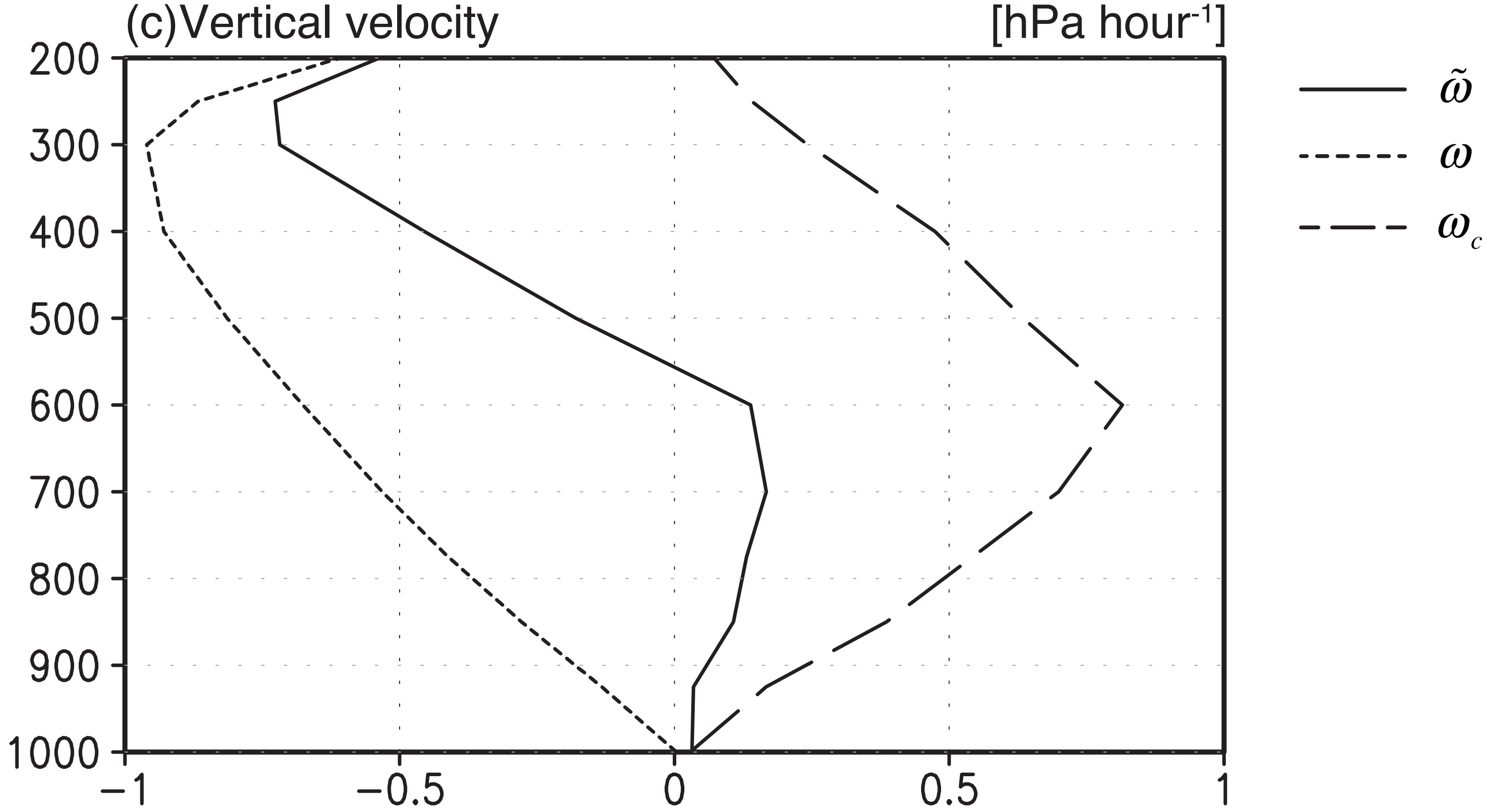
Large-scale condensation/ evaporation	Reevaporation of precipitation	Radiation	Freezing/ Melting	Heating by vertical diffusion	Detrainment	Vertical diffusion	High-frequency waves

- 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.


(c)Vertical velocity
[hPa hour⁻¹]
200
300
400
500
600
700
800
900
1000
−1
−0.5
0
0.5
1
$\tilde{\omega}$
ω
ω_c

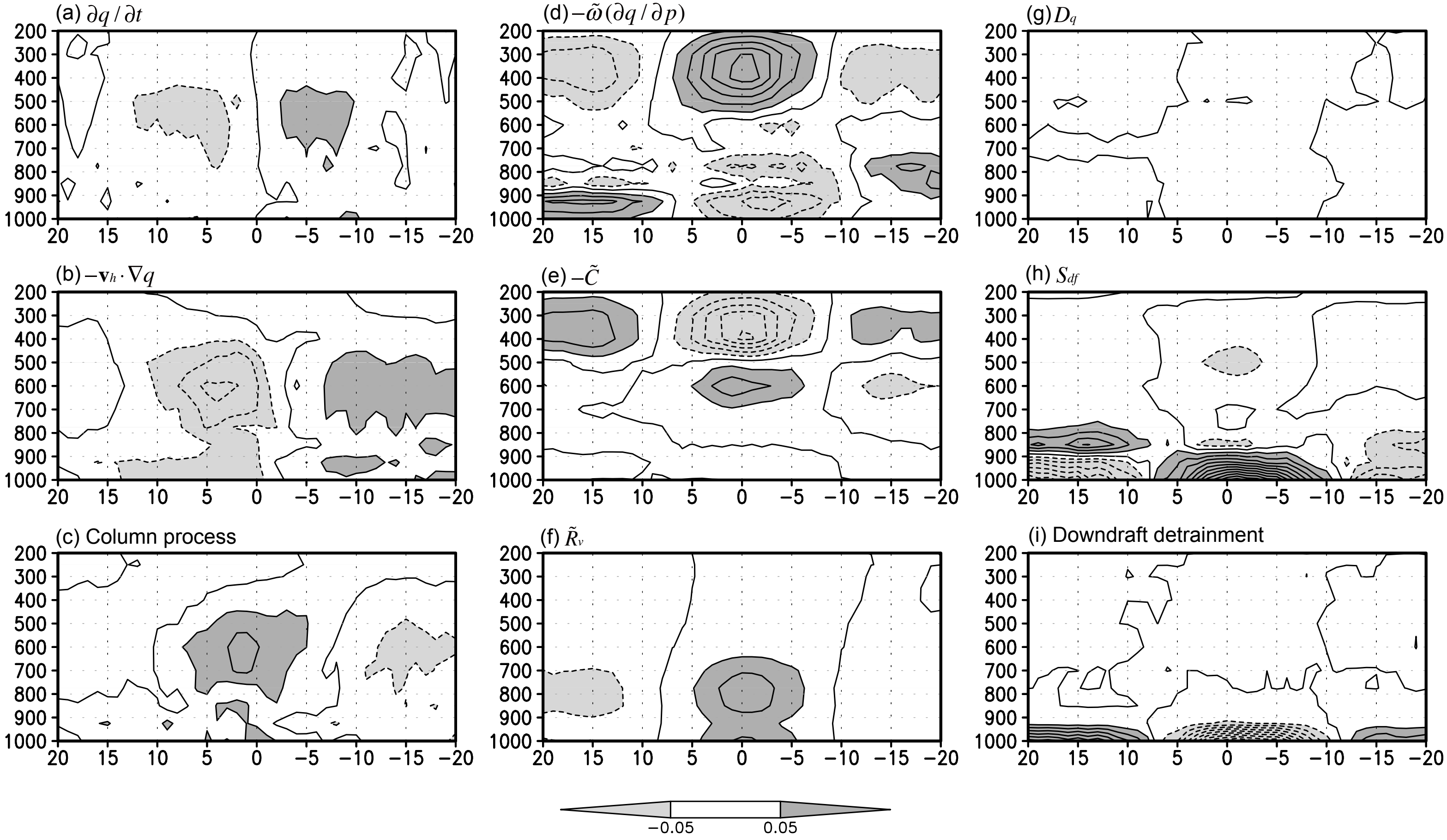


FIG. 9. Composited specific humidity tendency anomalies ($g\,kg^{-1}\,day^{-1}$) by each of the terms in (4). Contour intervals are $0.06\,g\,kg^{-1}\,day^{-1}$.

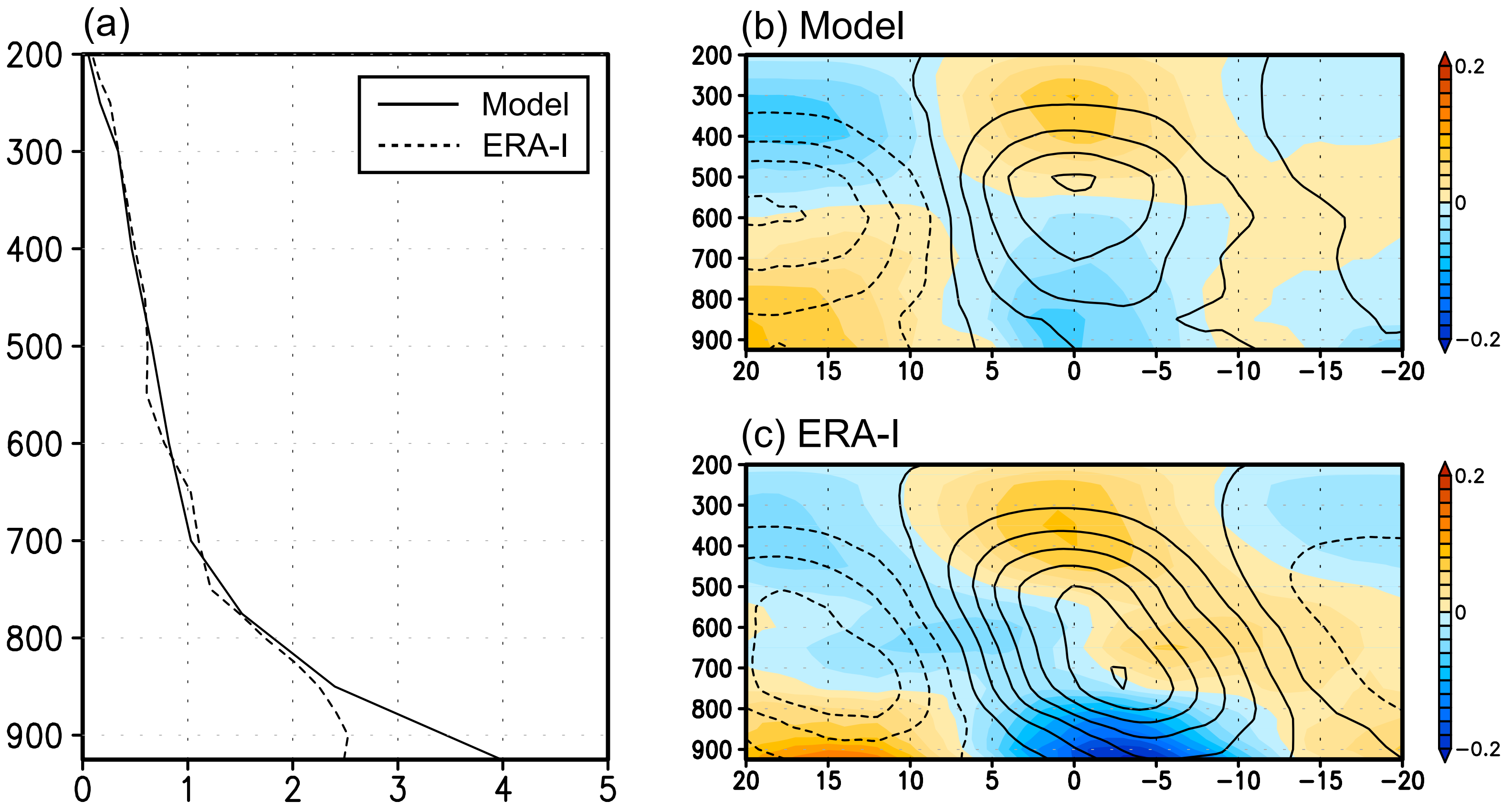
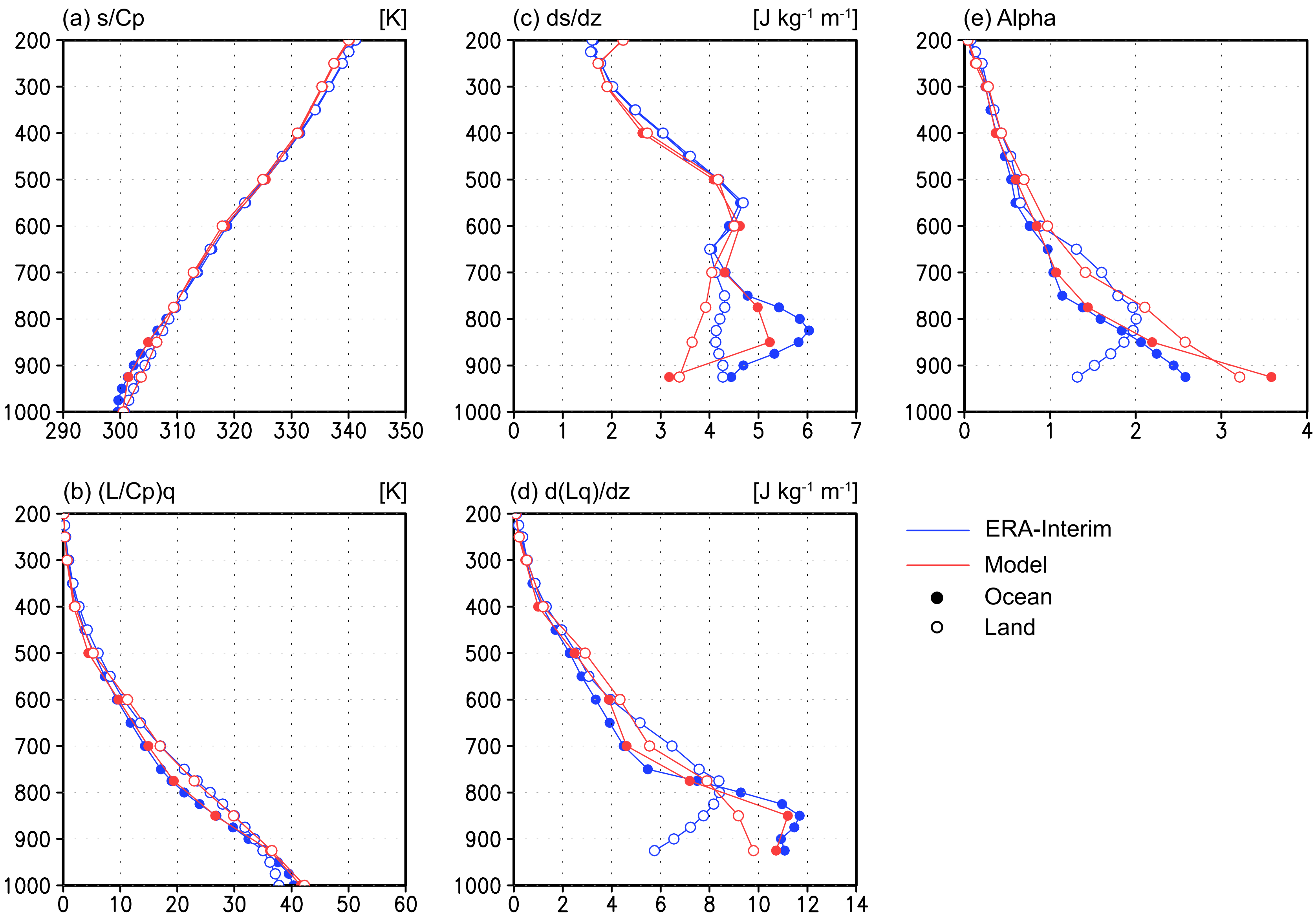
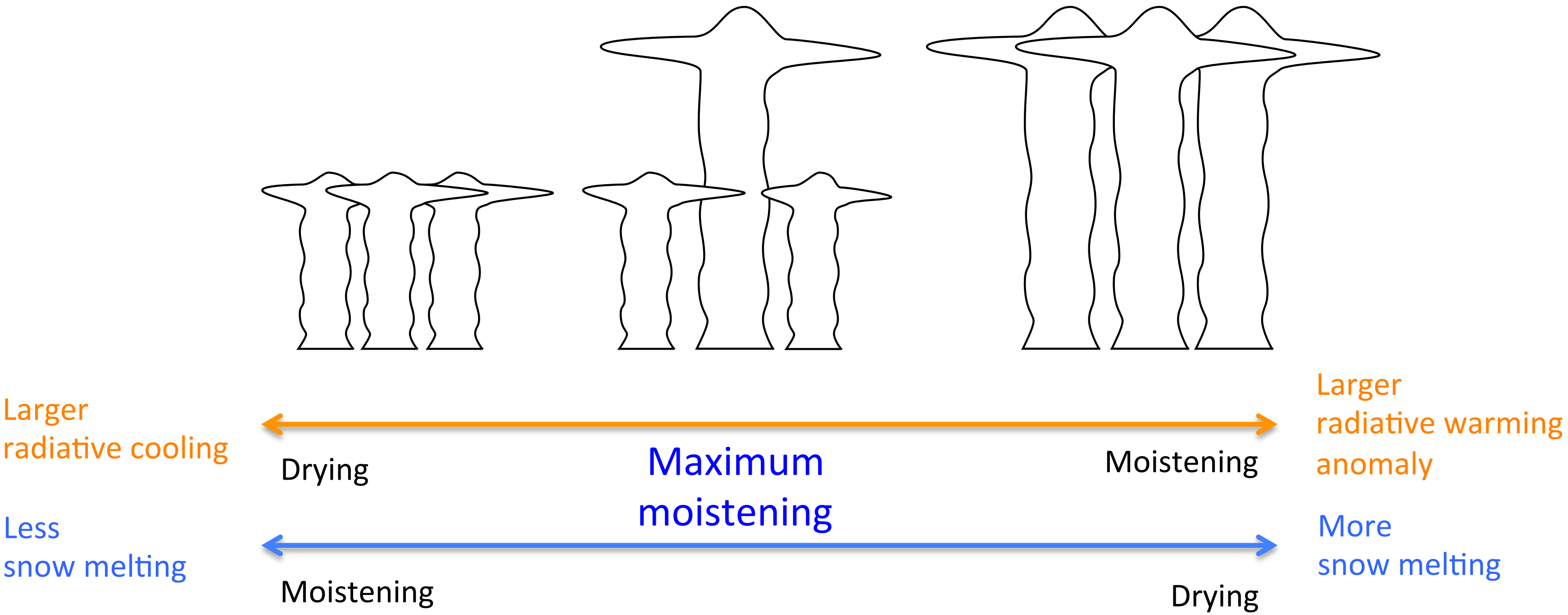


FIG. 12. (a): α averaged between day -30 and 20 in the model (solid line) and ERA-Interim (dashed line). (b-c): Time-height sections of α anomalies in the (b)model and (c)ERA-Interim. Contours in (b) and (c) indicate the specific humidity anomalies and the intervals are $0.1\,g\,kg^{-1}$. α is calculated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


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



Larger
radiative cooling

Drying

Maximum
moistening

Moistening

Larger
radiative warming
anomaly

Less
snow melting

Moistening

Drying

More
snow melting