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

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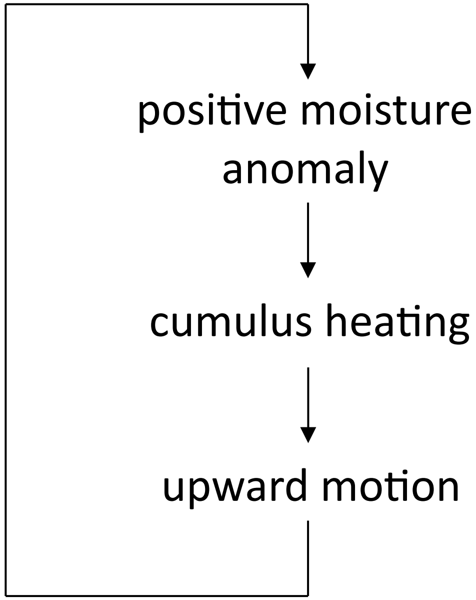
Introduction

- Many theories have been proposed to explain the Madden-Julian Oscillation (MJO).
- Recently, possibility of a new theory called "moisture mode" is under discussion, which seeks more solid physical basis (e.g. Raymond and Fuchs 2009).
- Many observational and modelling studies showed primary importance of free tropospheric moisture for cumulus convection.
- In the theoretical models which gives the moisture mode, cumulus heating depends on free-tropospheric humidity.
- Moisture mode is characterized by "weak temperature gradient balance" (Sobel et al. 2001) where time derivative and horizontal advection terms of temperature are negligible compared to other terms.

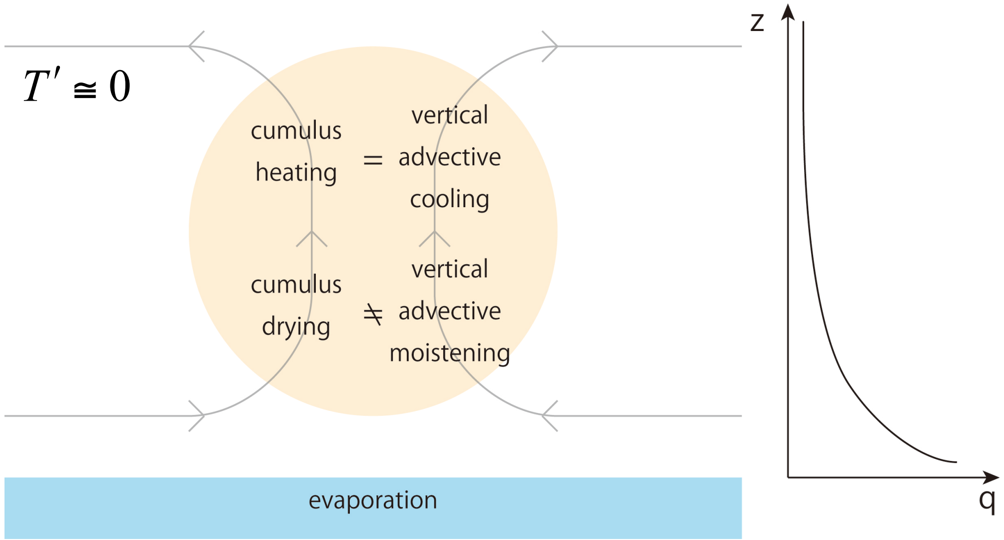
Essence of moisture mode



positive moisture anomaly

cumulus heating

upward motion



if upward advective moistening > cumulus drying, it causes positive feedback

- The moisture mode theory seems to be a good thinking way, but is still an ongoing project in explaining the various observed features of the MJO.
- The formulations for moisture variation in the theoretical models seems to be still crude and need to be improved.
- It is because current meteorology does not have enough knowledge on how free-tropospheric humidity varies.

- This study analyzes MJO-like waves represented by the Chikira-Sugiyama (CS) cumulus scheme (Chikira and Sugiyama 2010) focusing on how free-tropospheric moisture varies.
- The CS scheme is characterized by state-dependent entrainment and can represent the dependence of convection on the free-tropospheric humidity in a relatively physically reasonable way.

Outline of cumulus scheme

(Chikira and Sugiyama 2010)

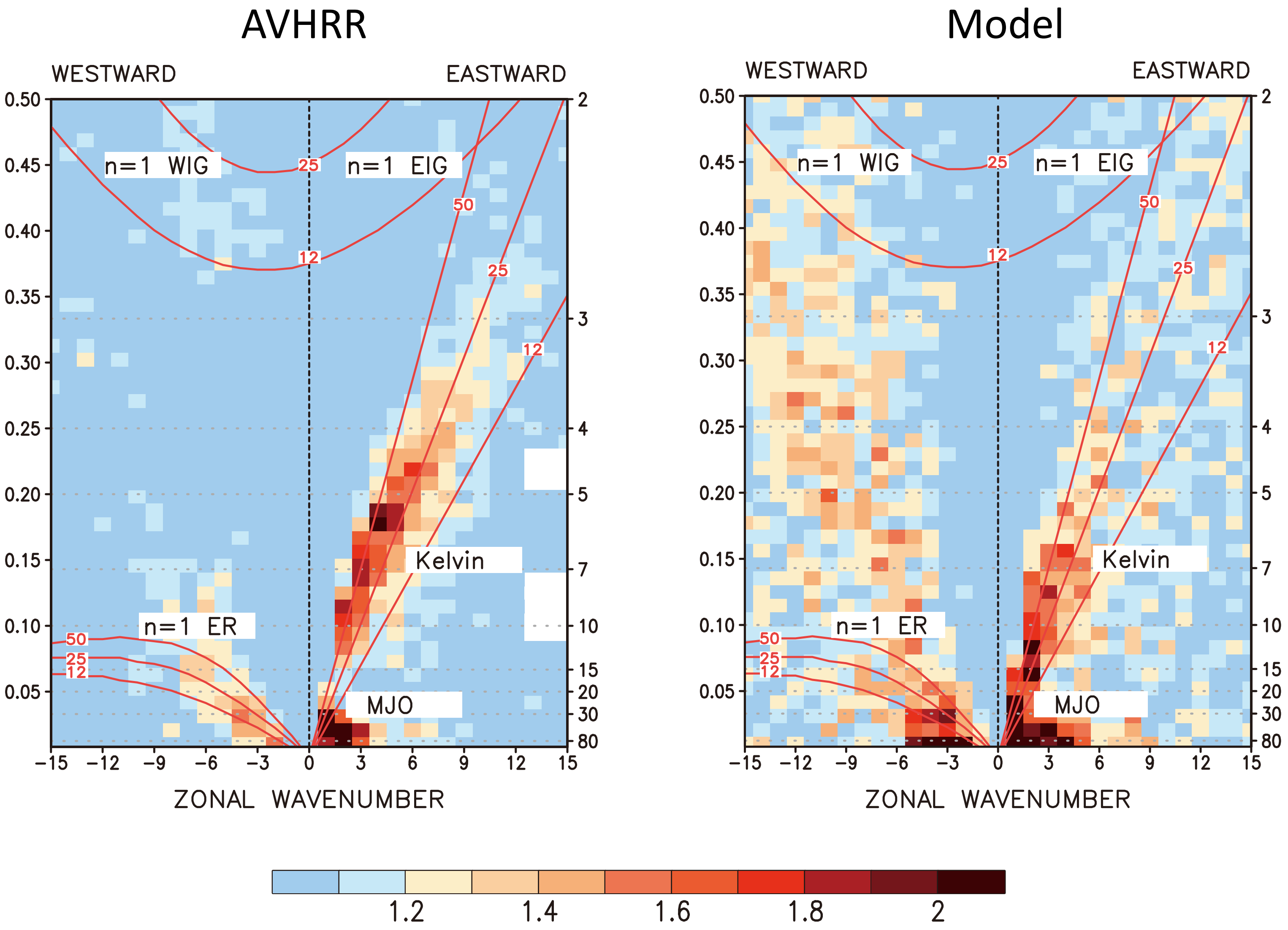
- Based on an entraining-plume model
- Lateral entrainment rate vertically varies depending on buoyancy and updraft velocity following Gregory (2001).
- Updraft ensemble is spectrally represented following the spirit of the Arakawa-Schubert scheme. But cloud types are represented according to updraft 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).
- Implemented in MIROC5. The result was submitted to CMIP5

- A popular method for analyzing the humidity variation is to use the vertically integrated moist static energy and Gross Moist Stability (GMS). (e.g. Peters et al. 2008; Maloney 2009)
- This study proposes another way which gives understanding on how free tropospheric humidity varies at specific levels.

Experimental design

- The atmospheric component of MIROC5 with the horizontal resolution of T42 (approximately 250km) and 56 levels
- Climatological SSTs
- 10 years integration after 5-years spin-up

Wheeler-Kiladis diagram for OLR (Symmetric Component)

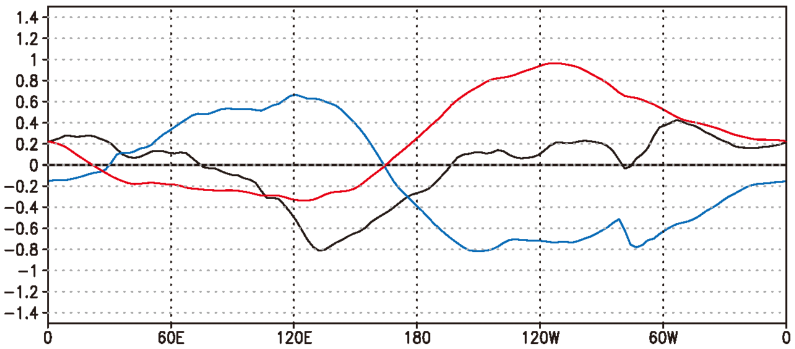


Combined EOF of 20-100day bandpass filtered OLR, U850 and U200 (15S-15N)

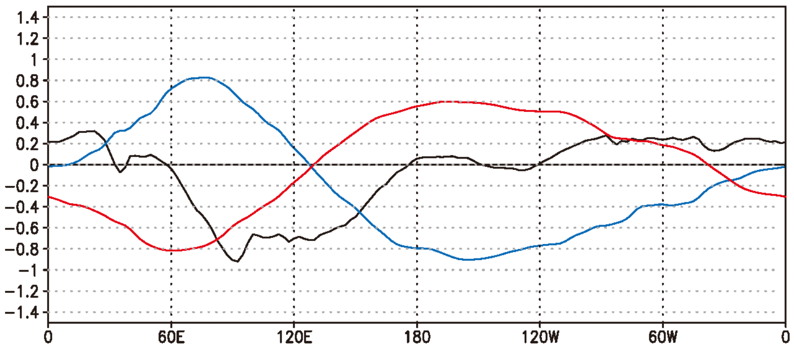
Model

AVHRR+NCEP (1979-2005)

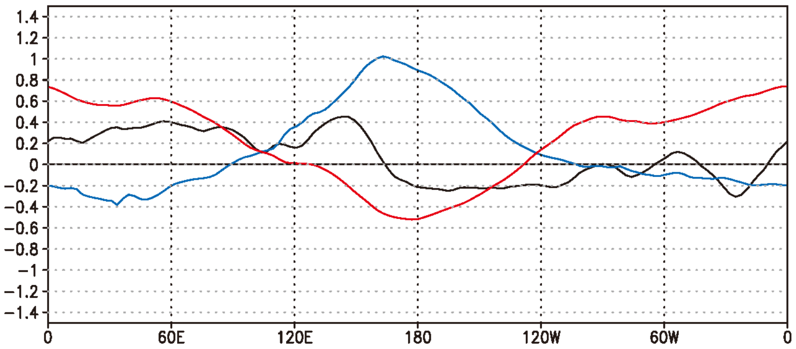
(a)1st mode (19.96%)



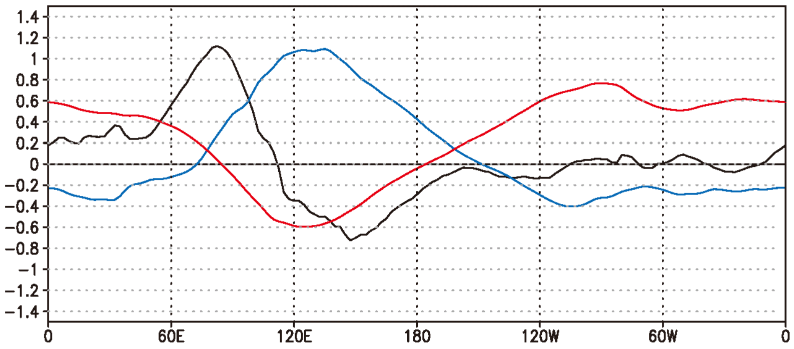
(b)1st mode (22.2%)



(c)2nd mode (14.51%)

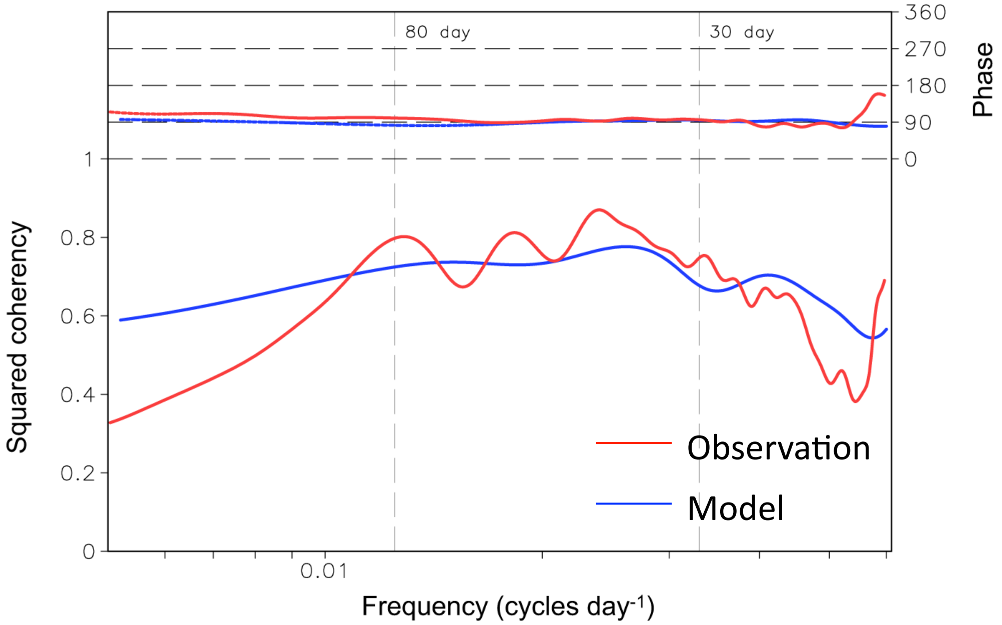


(d)2nd mode (20.9%)

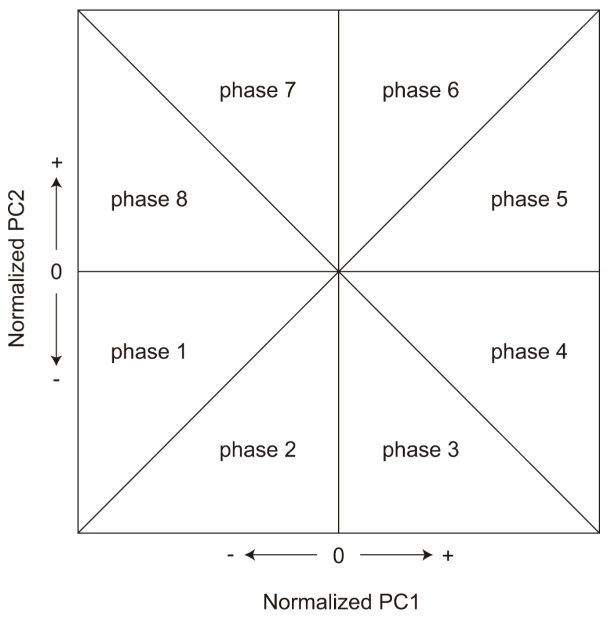


OLR U850 U200

Squared coherency and phase difference of first and second modes

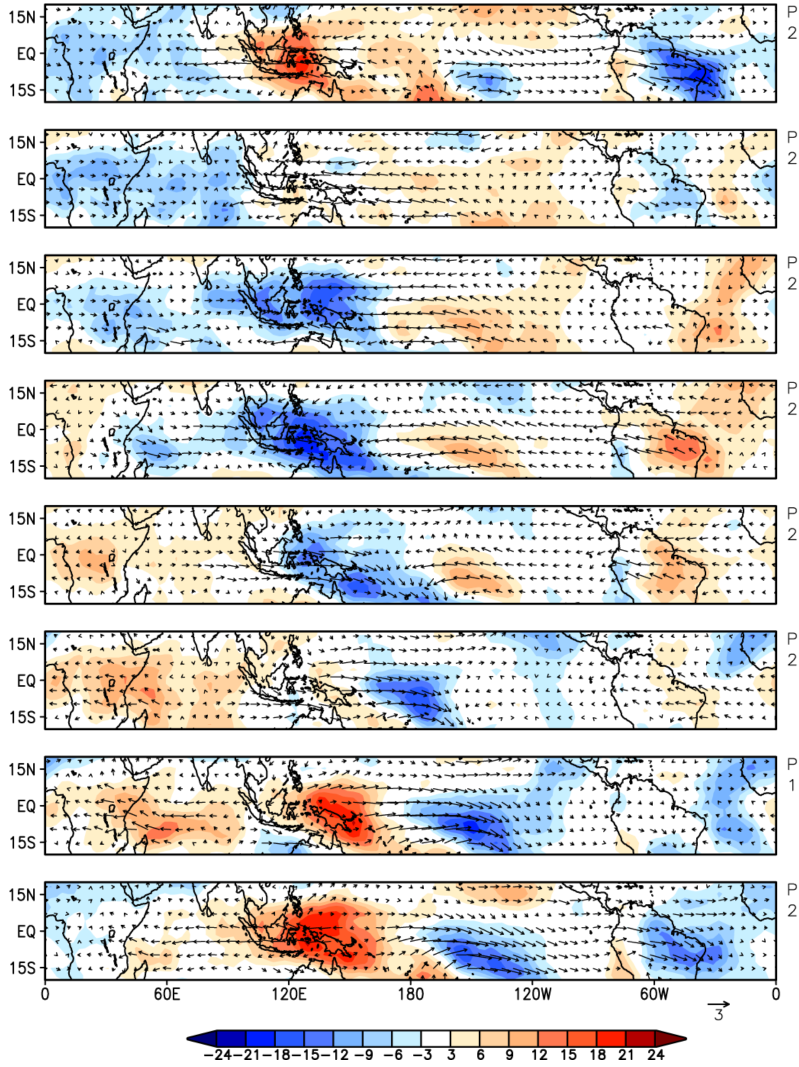


Definition of phase

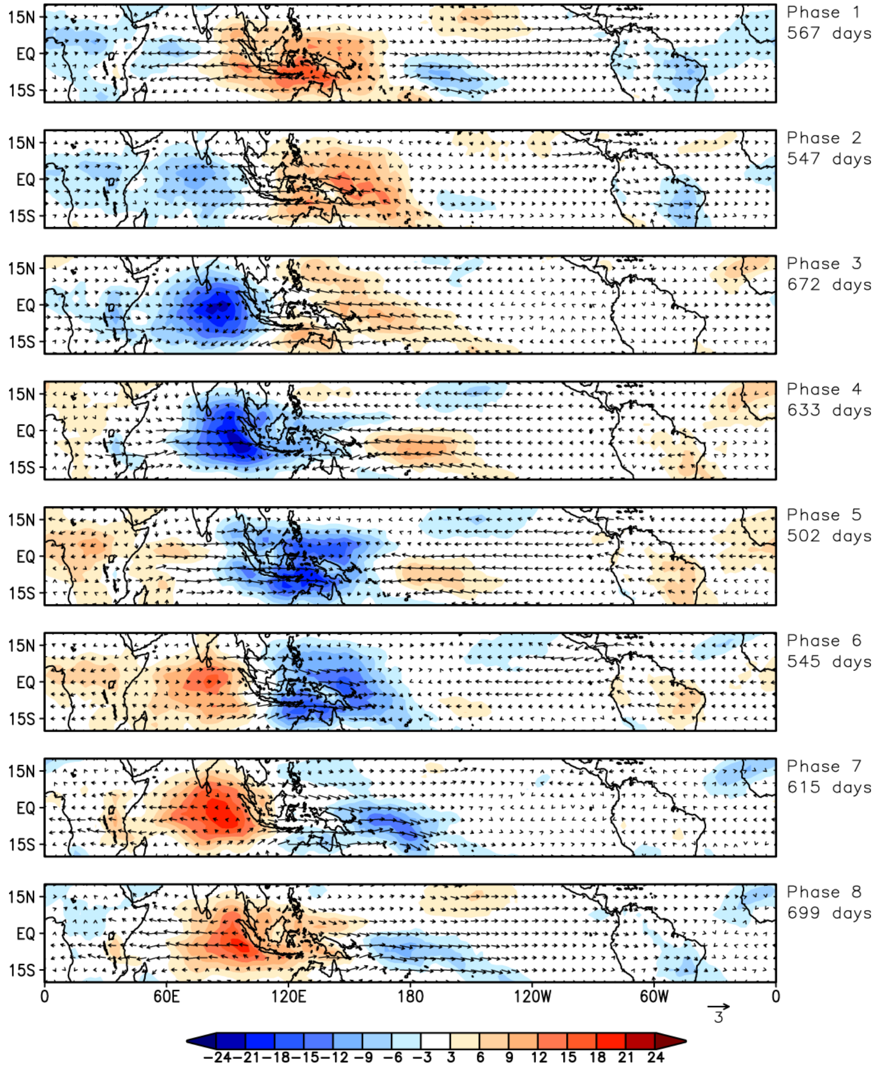


Phase composite of OLR and horizontal velocity at 850hPa

Model



AVHRR+NCEP



Analysis of moisture variation

Data for comparison

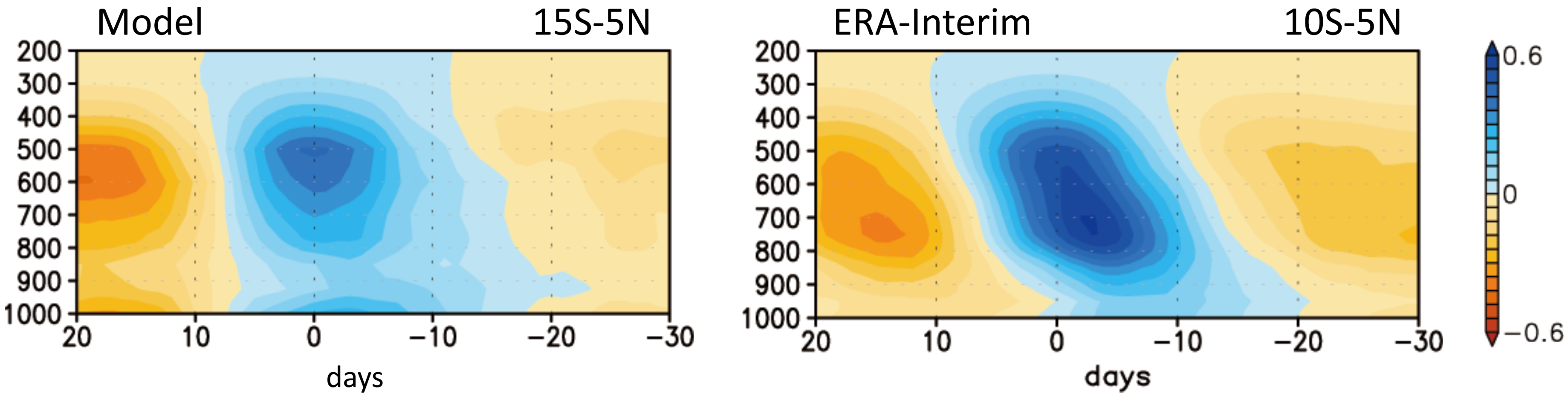
- Outgoing longwave radiation observed by AVHRR (1989-2005)
- ERA-Interim (1989-2005)

Composite method

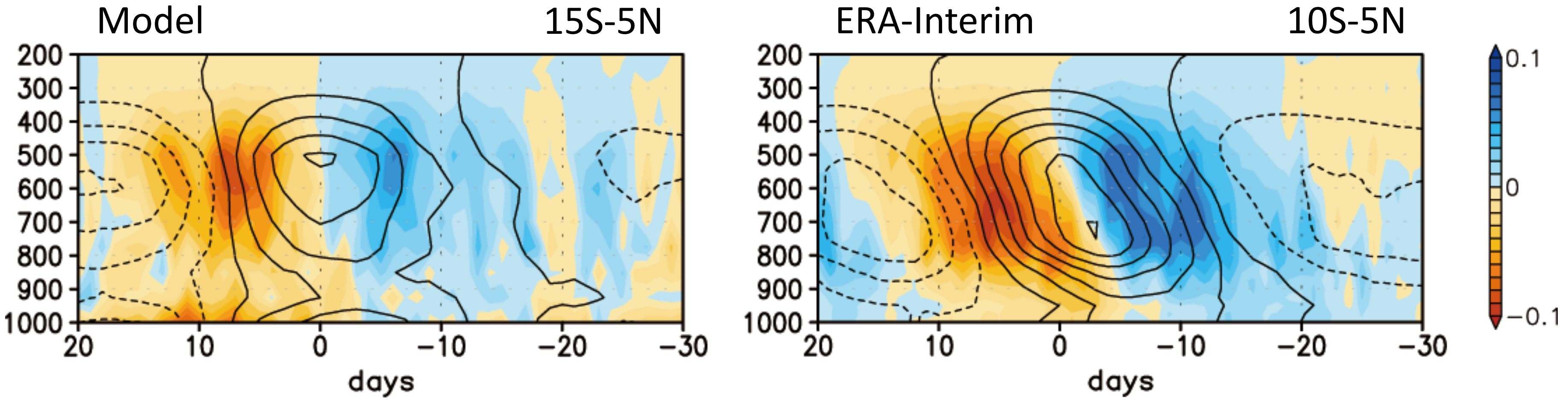
- Base points of the composites are the minimum values of OLR anomaly bandpass-filtered between 20-100days in period and 1-5 in wavenumber.

Results

Total water anomaly (from -30-20days mean) [g/kg]

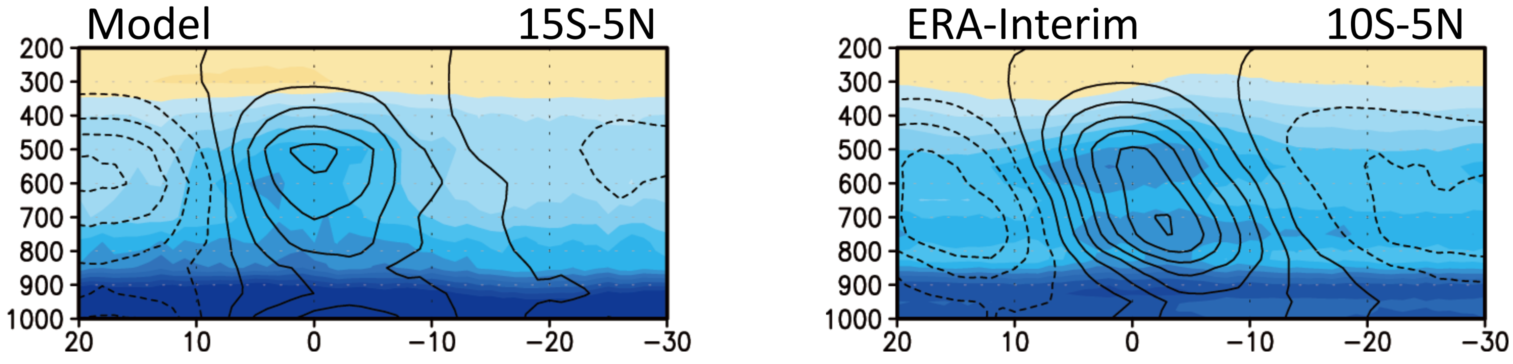


Total water tendency [g/kg/day]

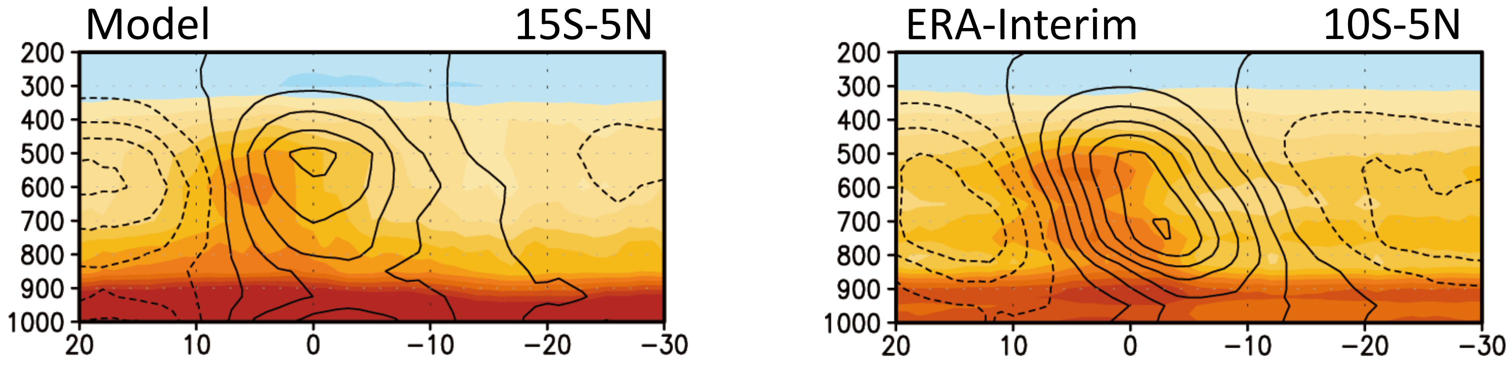


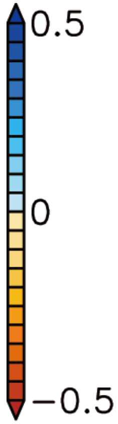
Total water tendency [g/kg/day]

Vertical advection + All physical processes (= Total tendency – Horizontal advection)



Horizontal advection





- Net effect of vertical advection and cloud process moistens the free-troposphere. Especially its tendency is amplified over the convective region, working as a positive feedback for the positive moisture anomaly.
- Horizontal advection dries the free-troposphere. Especially its tendency is enhanced to the west of the convective area, which causes the eastward propagation of the field.

Understanding of the total water variation reduces into two problems

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

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

Analysis of horizontal advection

$$-\mathbf{V}_{\mathbf{h}}\cdot\nabla q_t = -\tilde{\mathbf{V}}_{\mathbf{h}}\cdot\nabla\tilde{q}_t + F$$

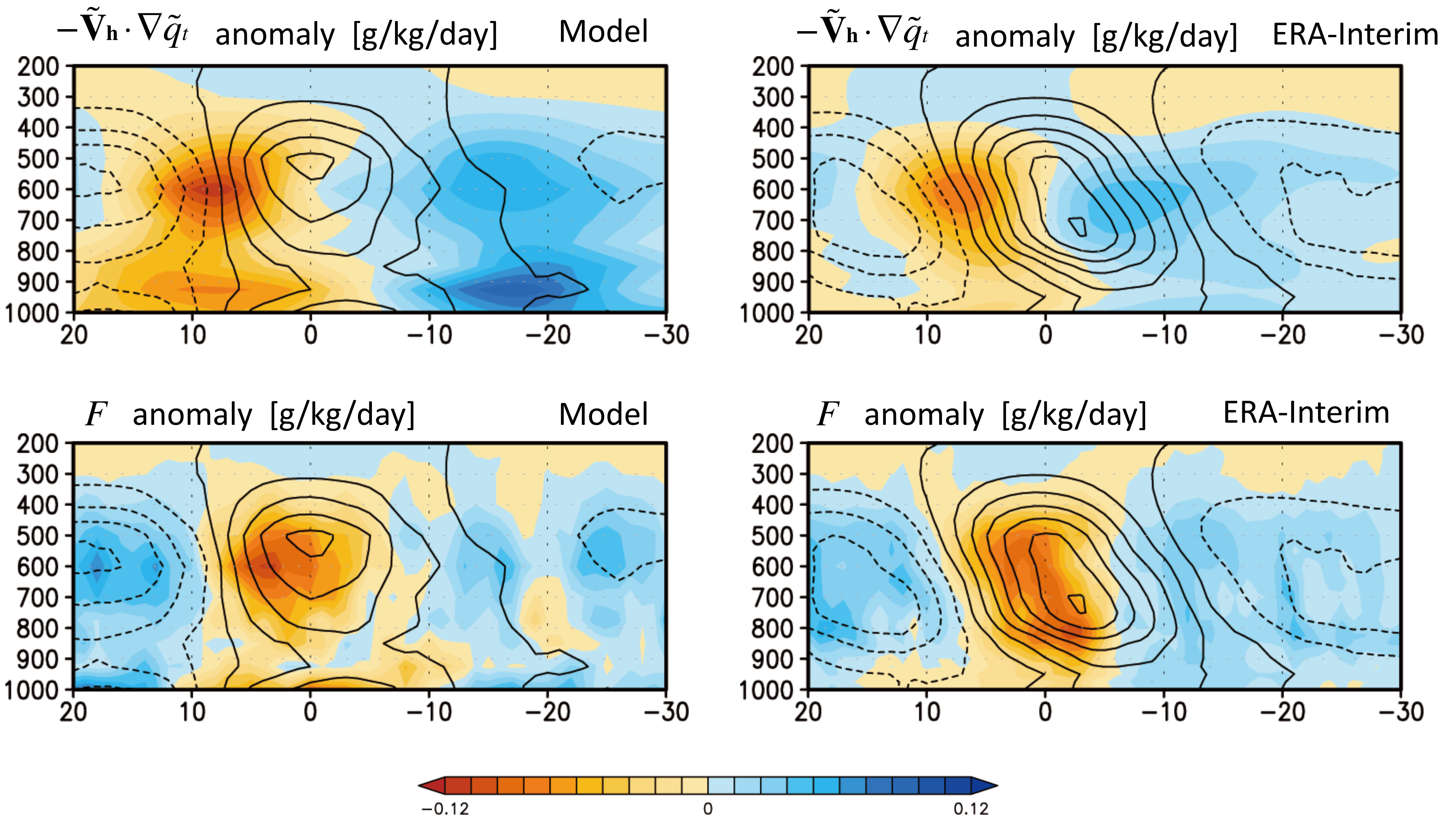
horizontal advection
by slow fields

$$F = -\tilde{\mathbf{V}}_{\mathbf{h}}\cdot\nabla q'_t - \mathbf{V}'_{\mathbf{h}}\cdot\nabla\tilde{q}_t - \mathbf{V}'_{\mathbf{h}}\cdot\nabla q'_t$$

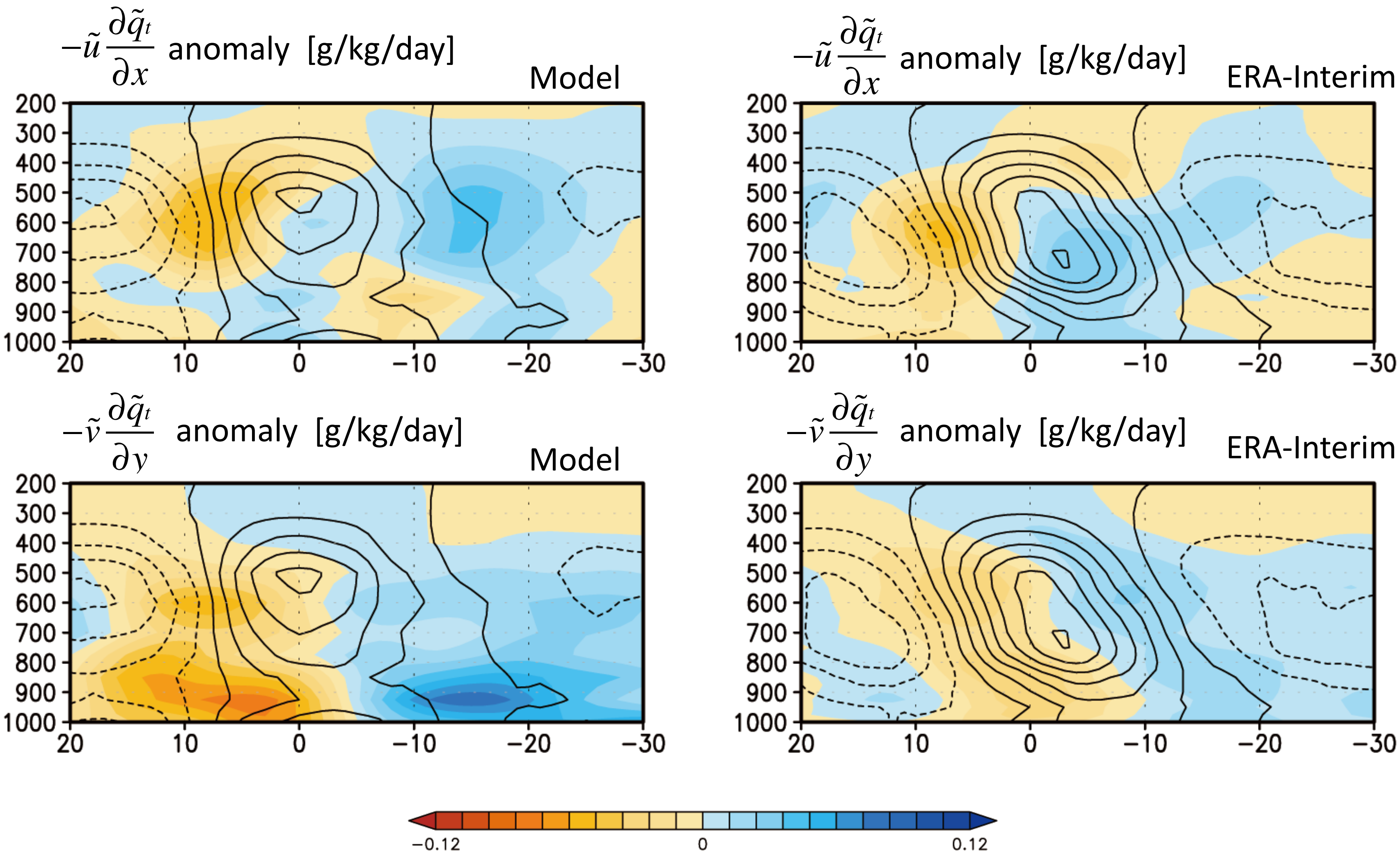
Term generated
by the presence of
fast waves

$\sim$: slow field where Fourier components less than 20 days period are removed out

$'$: Departure from the slow field



- Horizontal advection by slow fields dries the free-troposphere around the western margin of the convective area.
- Fast waves tends to dry the free-troposphere over the interior of the convective area.



$-\tilde{u}\frac{\partial \tilde{q}_t}{\partial x}$ anomaly [g/kg/day] Model

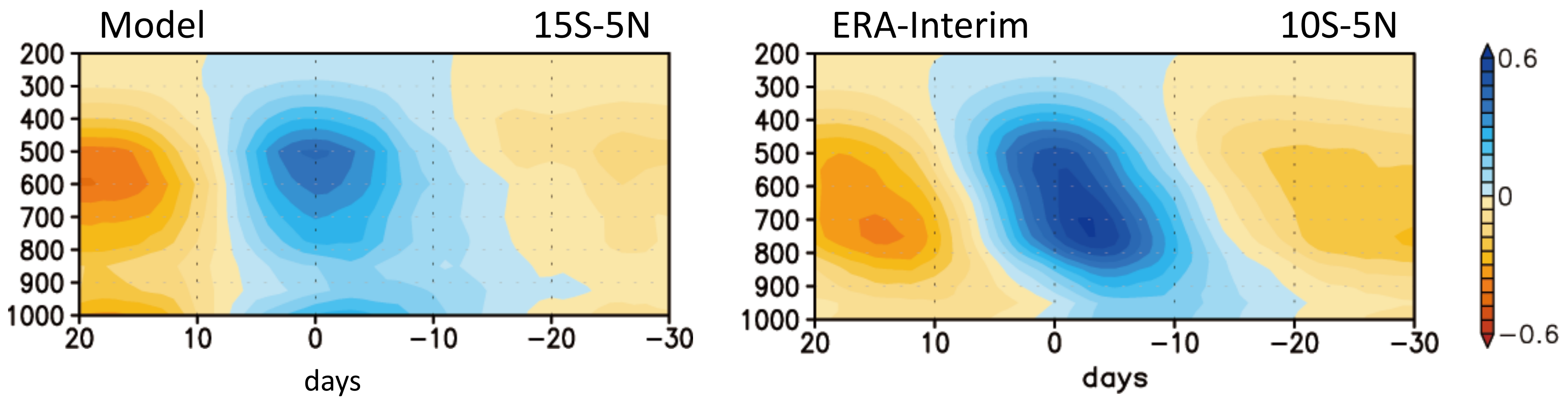
$-\tilde{u}\frac{\partial \tilde{q}_t}{\partial x}$ anomaly [g/kg/day] ERA-Interim

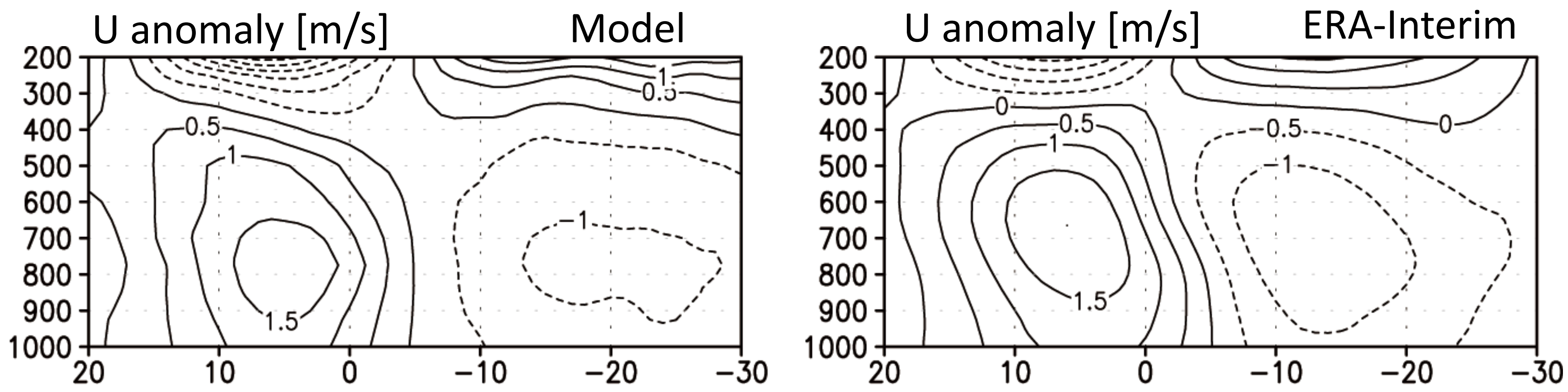
$-\tilde{v}\frac{\partial \tilde{q}_t}{\partial y}$ anomaly [g/kg/day] Model

$-\tilde{v}\frac{\partial \tilde{q}_t}{\partial y}$ anomaly [g/kg/day] ERA-Interim

- The drying around 600hPa is caused by both the U and V advective components.
- That in the lower troposphere is caused by the V advective component.

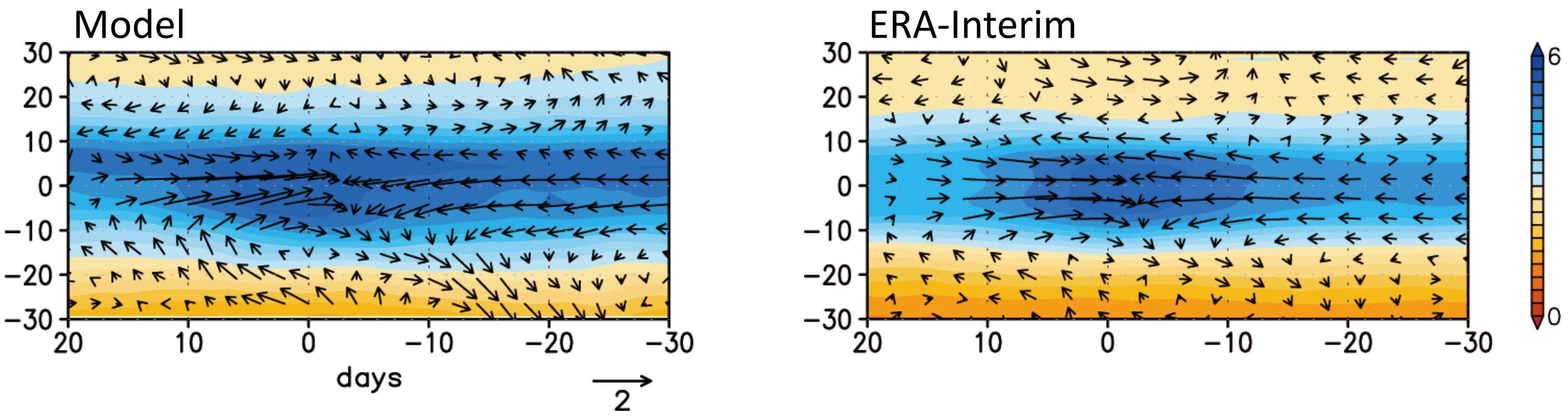
Total water anomaly (from -30-20days mean) [g/kg]





- Larger horizontal gradient of the free tropospheric moisture and larger westerly wind in the western side contribute to the larger drying in the zonal component.

Horizontal wind field anomaly (m/s; vectors) and total water (g/kg; shading) at 600hPa



- Horizontal wind field anomaly is well understood as the Matsuno-Gill pattern as a response to convective heating of the MJO.
- Rossby wave response explains the drying by the meridional wind component in the western side.

Analysis of vertical advection plus cloud process

Prognostic equation of total water

$$\frac{\partial q_t}{\partial t} = \underbrace{-\mathbf{V}_\mathbf{h}\cdot\nabla q_t}_{\text{horizontal advection}} \underbrace{-\,\omega\frac{\partial q_t}{\partial p}}_{\text{vertical advection}} + \underbrace{S_{cum}}_{\text{cumulus}} + \underbrace{S_{fall}}_{\text{fall in/out}} + \underbrace{S_{evap}}_{\text{evaporation}}$$

$$\frac{\partial q_t}{\partial t} = -\mathbf{V}_\mathbf{h}\cdot\nabla q_t \underbrace{-\,\omega\frac{\partial q_t}{\partial p}}_{\text{vertical advection}} + \underbrace{D_{qt}}_{\text{cumulus detrainment}} \underbrace{-\,\omega_{cum}\frac{\partial q_t}{\partial p}}_{\text{cumulus subsidence}} + S_{fall} + S_{evap}$$

$$\frac{\partial q_t}{\partial t} = \underbrace{-\mathbf{V}_\mathbf{h}\cdot\nabla q_t}_{\text{horizontal advection}} \underbrace{-\,\omega_{net}\frac{\partial q_t}{\partial p}}_{\text{net vertical advection}} + \underbrace{D_{qt}}_{\text{cumulus detrainment}} + \underbrace{S_{fall}}_{\text{fall in/out}} + \underbrace{S_{evap}}_{\text{evaporation}}$$

$$\omega_{net} = \omega + \omega_{cum}$$

net vertical velocity
= environmental vertical
velocity outside cumuli

How is the net vertical velocity determined?

Prognostic equation of potential temperature

$$\cancel{\frac{\partial\theta}{\partial t}} + \cancel{\mathbf{V}_{\mathbf{h}}\cdot\nabla}\theta + \omega\frac{\partial\theta}{\partial p} = \frac{1}{C_p\pi}\left[Q_{cum} + L(S_c - S_{evap}) + Q_{rad}\right]$$

weak temperature gradient balance

horizontal advection

vertical advection

cumulus

large scale condensation/ evaporation

radiation

$$\omega\frac{\partial\theta}{\partial p} = D_\theta - \omega_{cum}\frac{\partial\theta}{\partial p} + \frac{1}{C_p\pi}\left[L(S_c - S_{evap}) + Q_{rad}\right]$$

vertical advection

cumulus detrainment

cumulus subsidence

$$\omega_{net}\frac{\partial\theta}{\partial p} = \cancel{D_\theta} + \frac{1}{C_p\pi}\left[L(S_c - S_{evap}) + Q_{rad}\right]$$

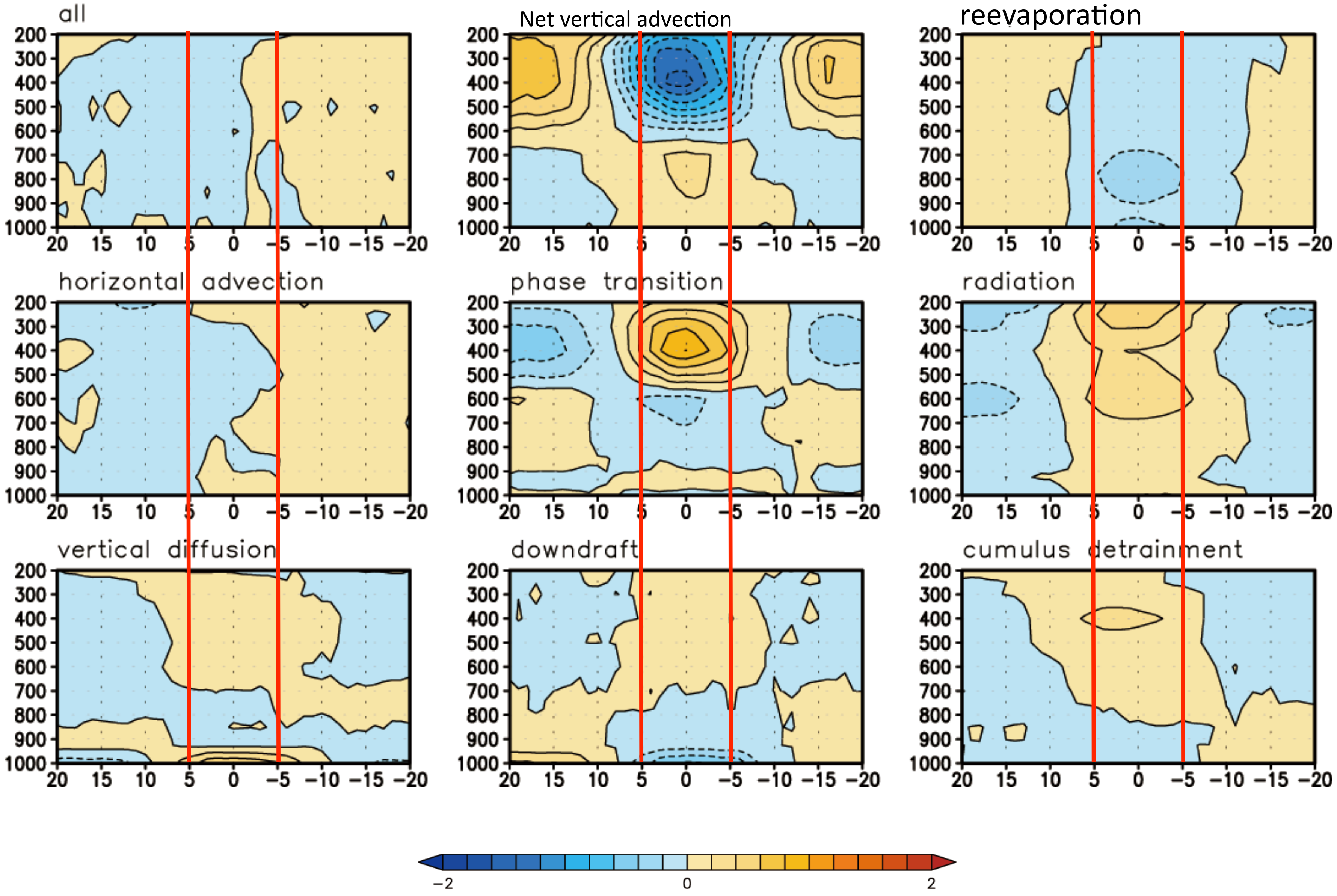
net vertical advection

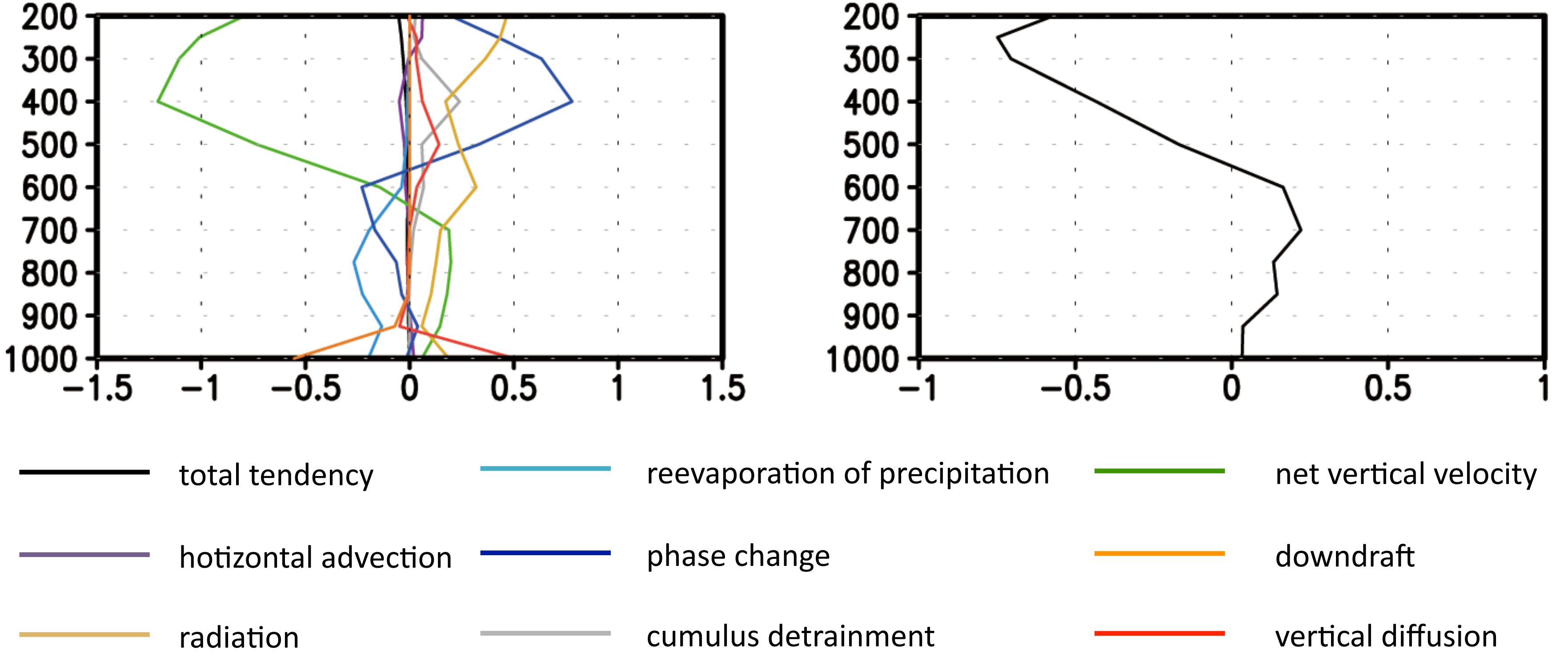
cumulus detrainment

large scale condensation/ evaporation

radiation

Potential temperature tendency anomaly [K/day]
15S-5N




Potential temperature tendency anomaly averaged from -5 to 5 days [K/day]

Net vertical velocity anomaly averaged from -5 to 5 days [hPa/hour]

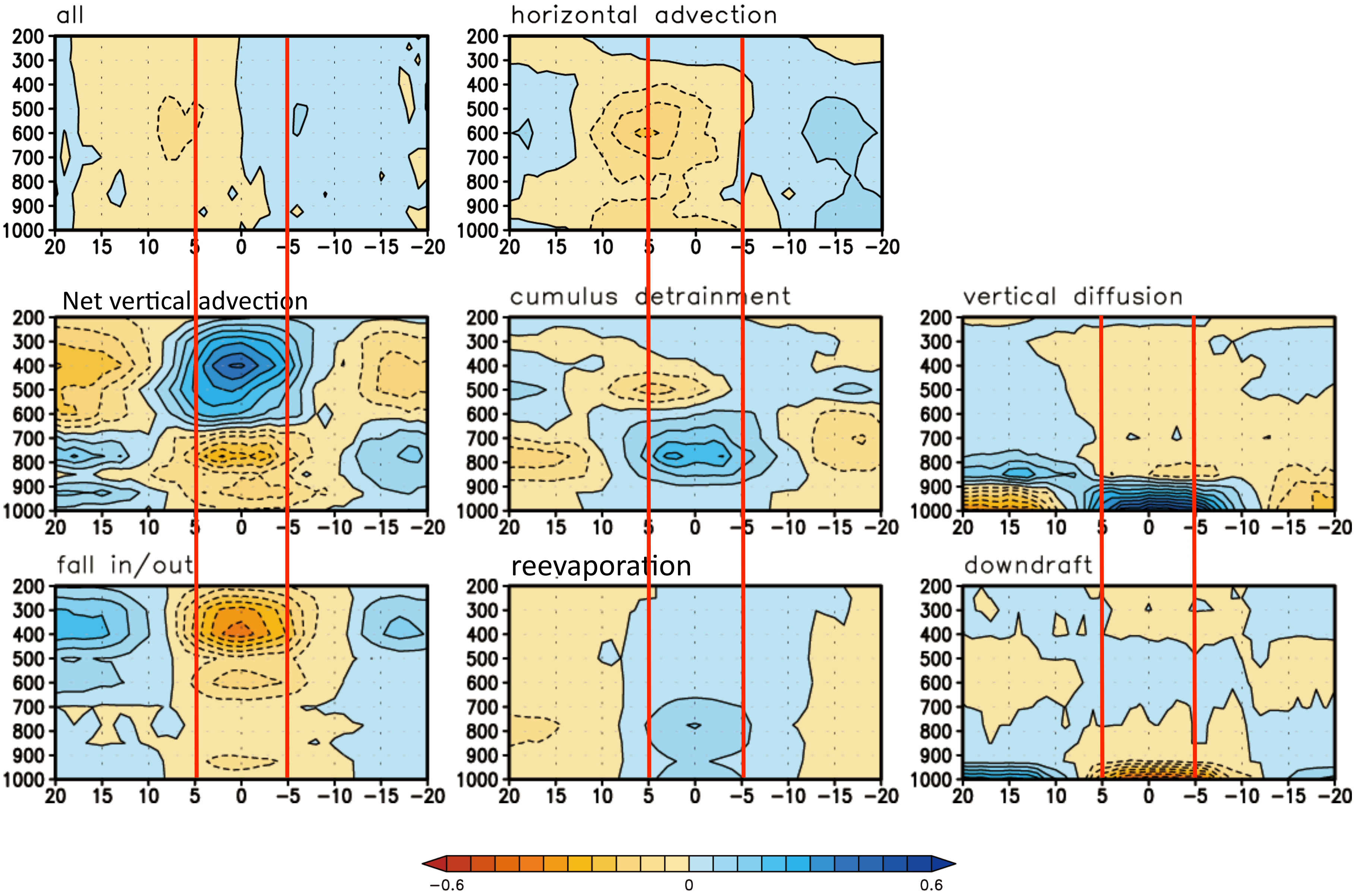
Upper troposphere:

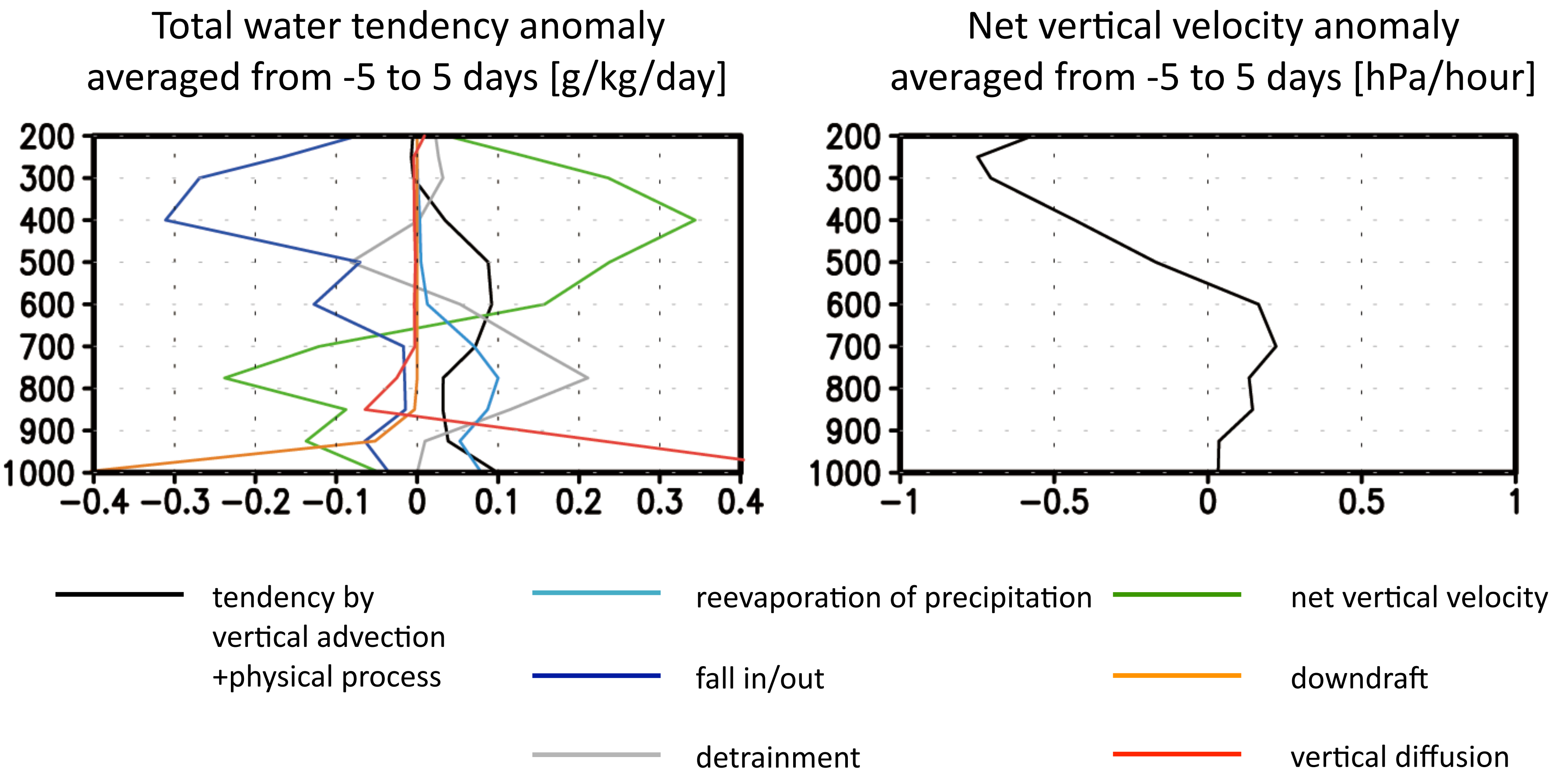
enhanced stratiform condensation + radiative warming anomaly
→ strong upward net vertical velocity anomaly

Lower troposphere:

enhanced evaporative cooling (rain+cloud) > radiative warming anomaly
→ weak downward net vertical velocity anomaly

Total water tendency anomaly [g/kg/day]
15S-5N





Total water tendency anomaly averaged from -5 to 5 days [g/kg/day]

Net vertical velocity anomaly averaged from -5 to 5 days [hPa/hour]

Upper troposphere:

moistening by upward net vertical velocity anomaly > drying by enhanced fall out

→ positive tendency

Lower troposphere:

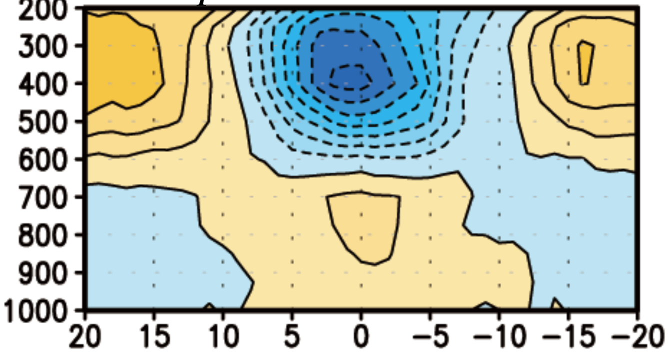
reevaporation + detrainment > drying by downward net vertical velocity anomaly

→ positive tendency

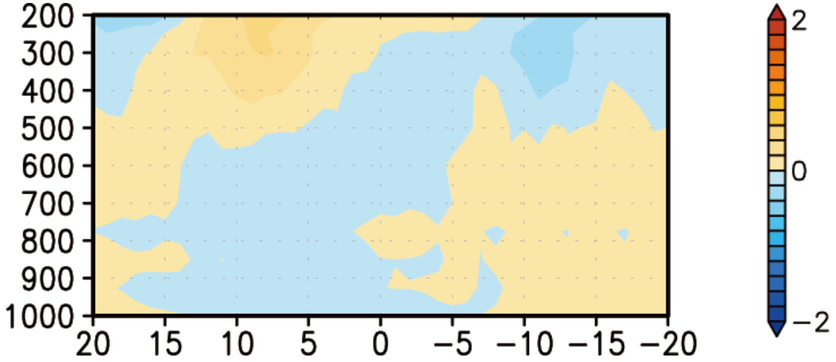
Further interpretation of results

$$-\omega_{net}\frac{\partial\theta}{\partial p} = -\tilde{\omega}_{net}\frac{\partial\tilde{\theta}}{\partial p} + F_\theta \qquad F_\theta = -\tilde{\omega}_{net}\frac{\partial\theta'}{\partial p} - \omega'_{net}\frac{\partial\tilde{\theta}}{\partial p} - \omega'_{net}\frac{\partial\theta'}{\partial p}$$

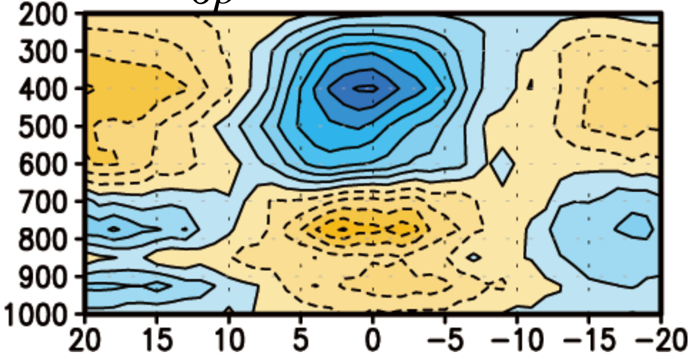
$$-\omega_{net}\frac{\partial q_t}{\partial p} = -\tilde{\omega}_{net}\frac{\partial\tilde{q}_t}{\partial p} + F_{qt} \qquad F_{qt} = -\tilde{\omega}_{net}\frac{\partial q'_t}{\partial p} - \omega'_{net}\frac{\partial\tilde{q}_t}{\partial p} - \omega'_{net}\frac{\partial q'_t}{\partial p}$$



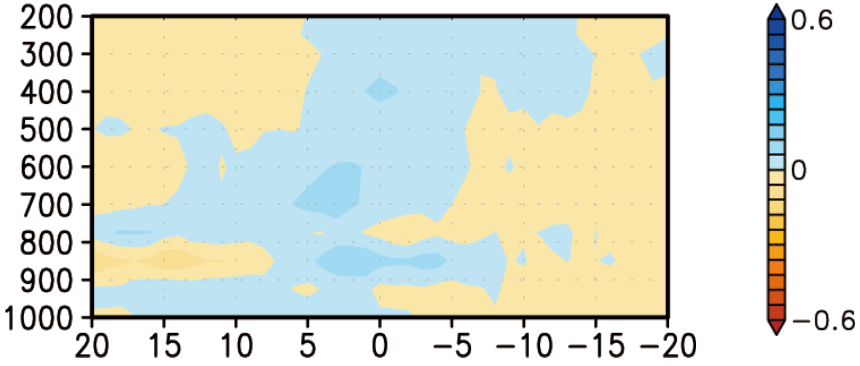
$-\omega_{net}\frac{\partial\theta}{\partial p}$ anomaly



F_θ anomaly



$-\omega_{net}\frac{\partial q_t}{\partial p}$ anomaly



F_{qt} anomaly

In the composite mean,

$$\omega_{net}\frac{\partial\theta}{\partial p} \simeq \tilde{\omega}_{net}\frac{\partial\tilde{\theta}}{\partial p} \qquad \omega_{net}\frac{\partial q_t}{\partial p} \simeq \tilde{\omega}_{net}\frac{\partial\tilde{q}_t}{\partial p}$$

Balance of potential temperature

$$\omega_{net}\frac{\partial\theta}{\partial p} = \frac{1}{C_p\pi}\left[L(S_c - S_{evap}) + Q_{rad}\right]$$

➡ $$\tilde{\omega}_{net}\frac{\partial\tilde{\theta}}{\partial p} \simeq \frac{1}{C_p\pi}\left[L(S_c - S_{evap}) + Q_{rad}\right]$$

Equation for $\tilde{\omega}_{net}$

$$\boxed{\tilde{\omega}_{net} \simeq \frac{1}{C_p\pi}\left[L(S_c - S_{evap}) + Q_{rad}\right]\left(\frac{\partial\tilde{\theta}}{\partial p}\right)^{-1}}$$

S_c : condensation/evaporation of cloud

S_{evap} : evaporation of precipitation

Q_{rad} : radiative cooling

$$\tilde{\omega}_{net} \simeq \frac{1}{C_p\pi}\left[L(S_c - S_{evap}) + Q_{rad}\right]\left(\frac{\partial\tilde{\theta}}{\partial p}\right)^{-1}$$

Prognostic equation of total water

$$\frac{\partial q_t}{\partial t} = -\tilde{\mathbf{V}}_{\mathbf{h}}\cdot\nabla\tilde{q}_t - F - \omega_{net}\frac{\partial q_t}{\partial p} + D_{qt} + S_{fall} + S_{evap}$$

$$\frac{\partial q_t}{\partial t} \simeq -\tilde{\mathbf{V}}_{\mathbf{h}}\cdot\nabla\tilde{q}_t - F - \tilde{\omega}_{net}\frac{\partial\tilde{q}_t}{\partial p} + D_{qt} + S_{fall} + S_{evap}$$

Equation which controls slow variation of total water

$$\frac{\partial q_t}{\partial t} \simeq -\tilde{\mathbf{V}}_{\mathbf{h}}\cdot\nabla\tilde{q}_t - F + D_{qt} + S_{fall} + \alpha\left(S_c + \frac{Q_{rad}}{L}\right) + (1-\alpha)S_{evap}$$

horizontal advection by slow field

horizontal advection by fast wave

cumulus detrainment

fall in/out

condensation/ evaporation of cloud

radiation

reevaporation of precipitation

$$\alpha \equiv -\frac{L}{C_p\pi}\underset{<0}{\left(\frac{\partial\tilde{\theta}}{\partial p}\right)^{-1}}\underset{>0}{\left(\frac{\partial\tilde{q}_t}{\partial p}\right)} \quad > 0$$

$$\frac{\partial q_t}{\partial t} \simeq -\tilde{\mathbf{V}}_{\mathbf{h}} \cdot \nabla \tilde{q}_t - F + D_{qt} + S_{fall} + \alpha\left(S_c + \frac{Q_{rad}}{L} \right) + (1-\alpha) S_{evap}$$

horizontal advection by slow field

horizontal advection by fast wave

cumulus detrainment

fall in/out

condensation/ evaporation of cloud

radiation

reevaporation of precipitation

$$\alpha \equiv -\frac{L}{C_p \pi}\left(\frac{\partial \tilde{\theta}}{\partial p}\right)^{-1}\left(\frac{\partial \tilde{q}_t}{\partial p}\right) \quad > 0$$

Nondimensional parameter which characterizes the efficiency of moistening/drying due to upward/downward net vertical velocity induced by external heating/cooling

Factors affecting development of MJO

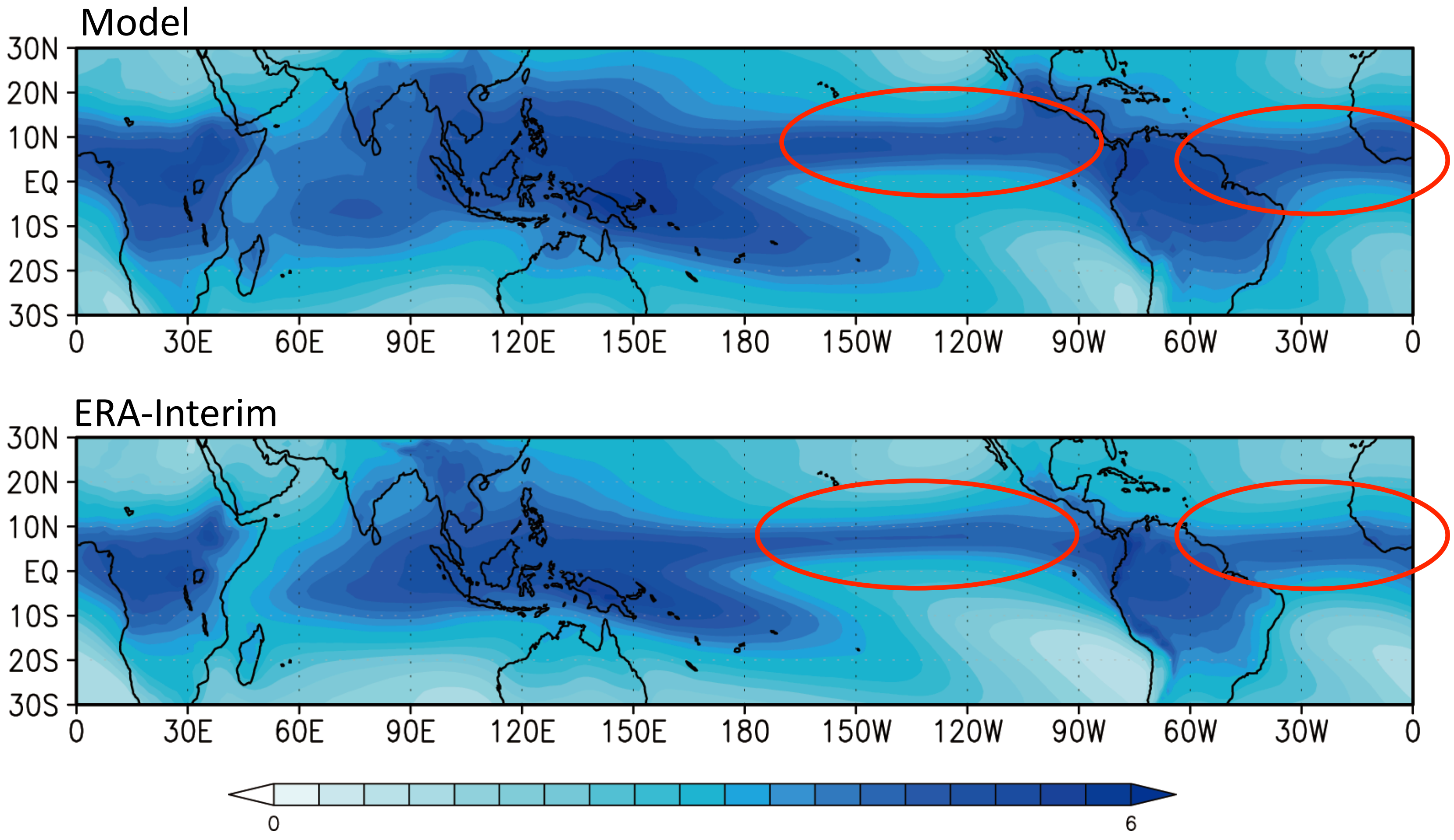
$$\frac{\partial q_t}{\partial t} \simeq \underset{\substack{\text{horizontal}\\ \text{advection}\\ \text{by slow field}}}{-\tilde{\mathbf{V}}_{\mathbf{h}} \cdot \nabla \tilde{q}_t} \underset{\substack{\text{horizontal}\\ \text{advection}\\ \text{by fast wave}}}{- F} + \underset{\substack{\text{cumulus}\\ \text{detrainment}}}{D_{qt}} + \underset{\text{fall in/out}}{S_{fall}} + \alpha \left(\underset{\substack{\text{condensation/}\\ \text{evaporation}\\ \text{of cloud}}}{S_c} + \underset{\text{radiation}}{\frac{Q_{rad}}{L}} \right) + \underset{\substack{\text{reevaporation of}\\ \text{precipitation}}}{(1-\alpha) S_{evap}}$$

$$\alpha \equiv -\frac{L}{C_p \pi} \left(\frac{\partial \tilde{\theta}}{\partial p} \right)^{-1} \left(\frac{\partial \tilde{q}_t}{\partial p} \right) \quad > 0$$

There are at least two factors which affects the development of the MJO.

- Horizontal gradient of moisture in basic field.
- Alpha

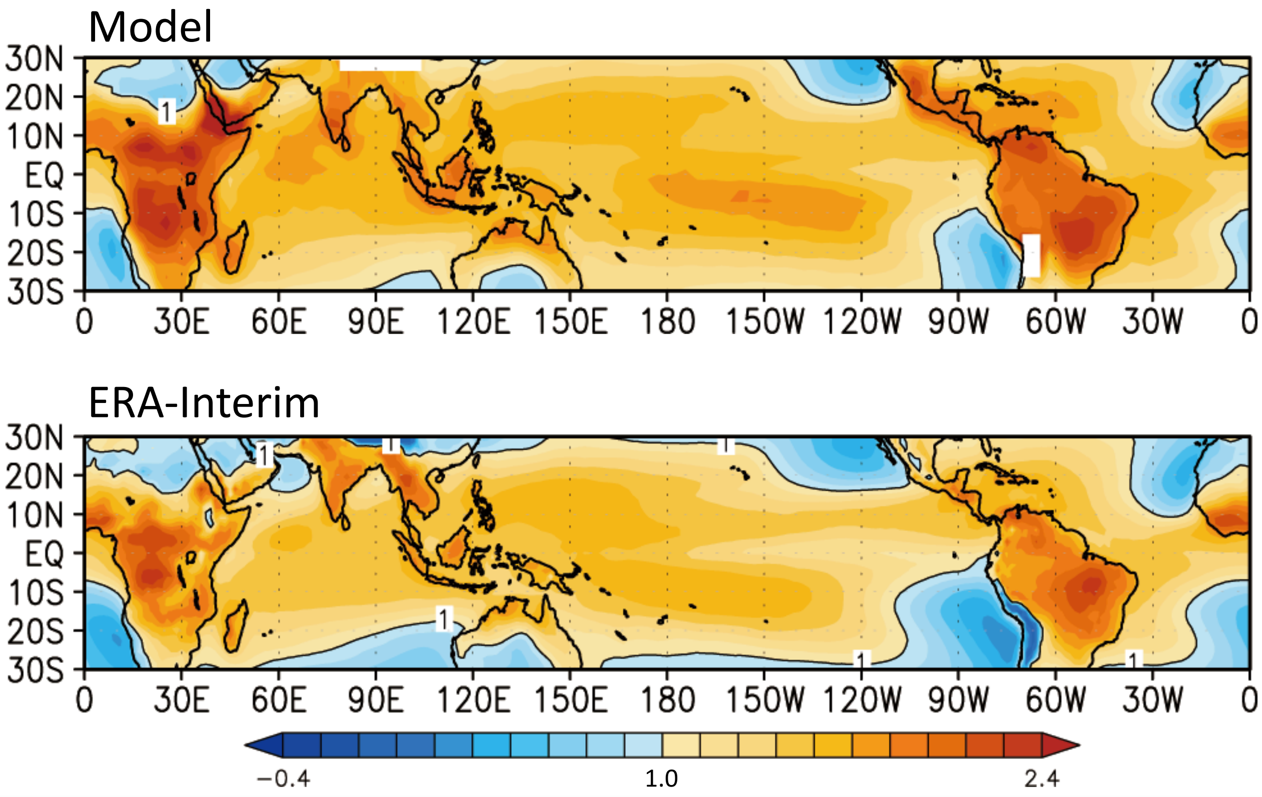
Annual mean total water averaged in the free troposphere (850 to 300hPa) [g/kg]



- Over the eastern Pacific and Atlantic, high values of free-tropospheric humidity is confined in the narrow band where dry air tends to intrude from the south.
- This is unfavorable condition for the development of the MJO and will be one of the reason that the MJO is suppressed over these regions.

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

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



Model

ERA-Interim

- Overall, alpha in the lower troposphere is more than 1 in the tropics. The reevaporation of precipitation works as a drying factor.
- Alpha is large over land. The lower troposphere tends to be effectively dried by downward net vertical velocity over land. This is unfavorable condition for the development of the MJO and consitent with that the MJO is suppressed there.

The effects of each term in the lower troposphere of the convective area

$$\frac{\partial q_t}{\partial t} \simeq -\tilde{\mathbf{V}}_{\mathbf{h}} \cdot \nabla \tilde{q}_t - F + D_{qt} + S_{fall} + \alpha\left(S_c + \frac{Q_{rad}}{L} \right) + (1-\alpha) S_{evap}$$

horizontal advection by slow field	horizontal advection by fast wave	cumulus detrainment	fall in/out	condensation/ evaporation of cloud	radiation	reevaporation of precipitation
eastward propagation	<0	>0	~ 0	<0	>0	$\underbrace{<0 \qquad >0}_{<0}$

- Moistening factors in the lower troposphere over the convective area are positive anomaly of shallow cumulus detrainment and radiative warming anomaly.

$$1-\alpha \simeq \left(\frac{\partial s}{\partial z}\right)^{-1} \left(\frac{\partial h}{\partial z}\right)$$

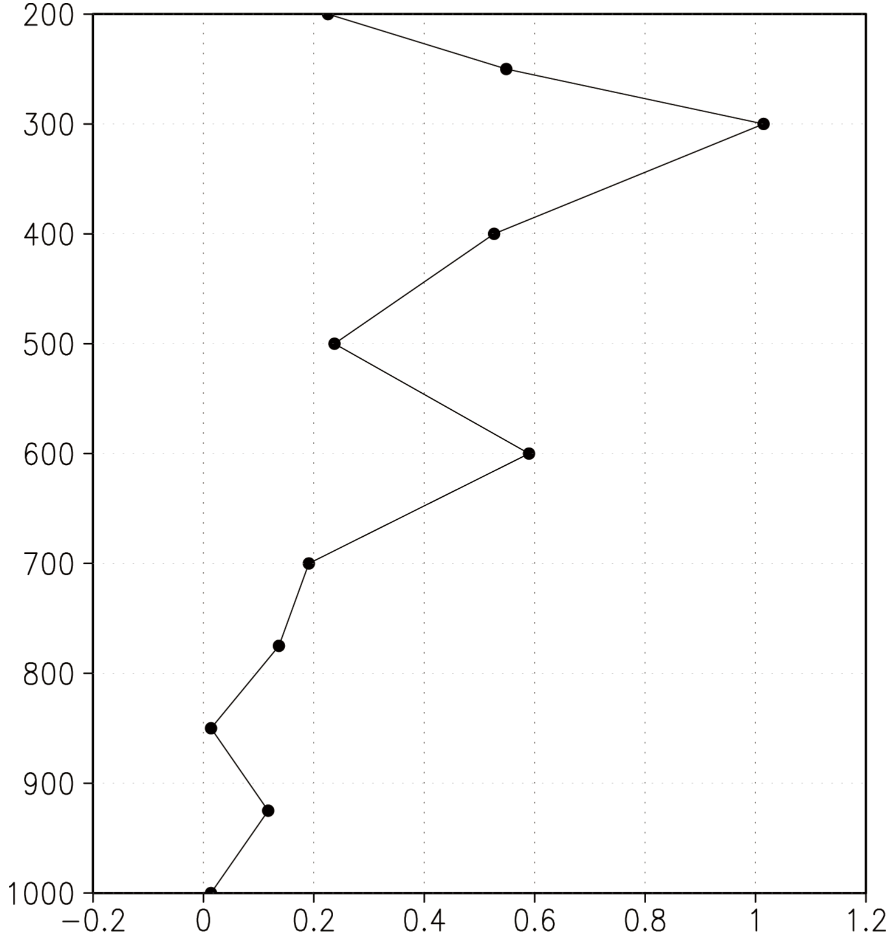
$>0 \qquad <0$

s: dry static energy
h: moist static energy

It depends on the vertical gradient of moist static energy whether the reevaporation of precipitation works as a drying or moistening factor.

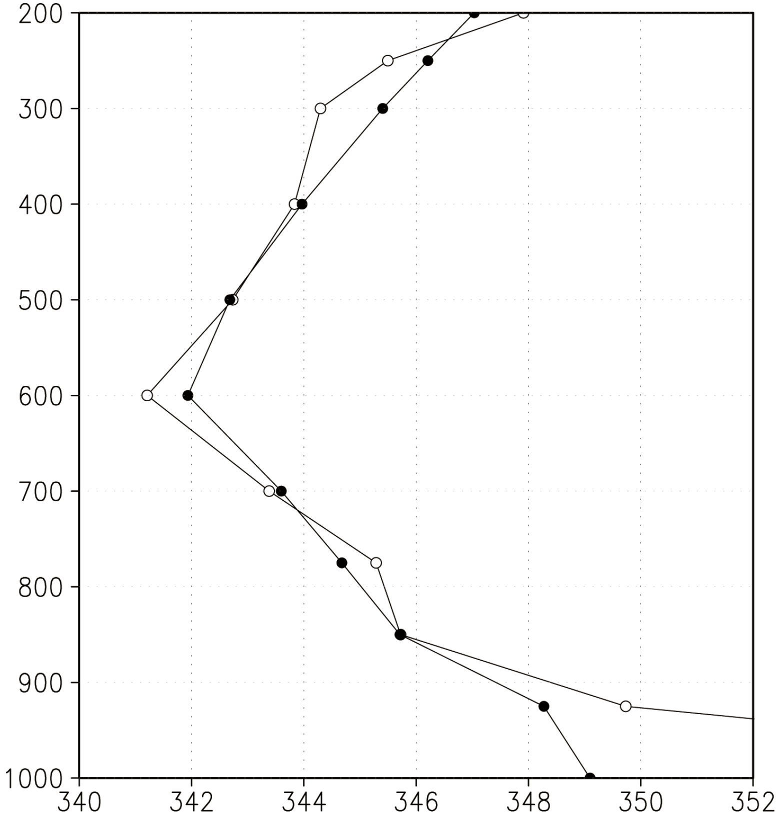
Why does shallow convection occur over the convective area of the MJO together with deep convection?

Correlation of cumulus detrainment with that at 300hPa
over the convective area (-5 to 5 days)



- The correlation is positive at any height, especially high at 600hPa, which means congestus clouds tend to occur in the same timing with deep convection.
- In the lower troposphere, the correlation is small but positive. It is not that shallow convection tends to occur when deep convection is suppressed as is often understood.

Composited large-scale mean θ_e^* (white) and θ_e of the highest cumulus cloud type (black) averaged over the convective area (-5 to 5 days) [K]



Even in the convective area of MJO, the profile of the cumulus θ_e is very close to the large-scale θ_e^*. The atmosphere is marginally unstable against the highest cumulus cloud type.

The other cloud types with larger entrainment rates tend to lose buoyancy earlier and detrain more in the middle and lower troposphere.

Summary

Overall features

- In the composited MJO, the weak temperature gradient balance is well satisfied.
- The net effect of the vertical advection and cloud process moistens the free-troposphere. Especially its tendency is amplified over the convective area, working as a positive feedback for the moisture anomaly.
- Horizontal advection dries the free-troposphere. Especially its tendency is enhanced to the west of the convective area, which causes the eastward propagation of the field.

➡ All these features support the concept of the moisture mode theory

Horizontal advection

- The horizontal advection by slow fields dries the free-troposphere around the western margin of the convective area. The fast waves tend to dry the free-troposphere over the interior of the convective area (similar to damping or horizontal diffusion).
- Contributors to the larger drying to the west include the greater westerly wind in the western side and Rossby wave response.

Net vertical velocity

- Moisture variation is well understood by introducing net vertical velocity defined by the sum of large-scale mean vertical velocity and cumulus subsidence.
- In the upper troposphere over the convective area, the enhanced stratiform condensation and radiative warming anomaly lead to the strong upward net vertical velocity anomaly.
- In the lower troposphere, the enhanced evaporative cooling of the cloud and precipitation is larger than the radiative warming anomaly, resulting in the weak downward net vertical velocity anomaly.

Moisture variation by vertical advection and cloud process

- In the upper troposphere over the convective area, the moistening by the upward net vertical velocity is larger than the enhanced fall out, resulting in the positive tendency.
- In the lower troposphere, the cumulus detrainment and radiative warming anomaly are the factors of moistening. The reevaporation of precipitation works as a drying factor by inducing the downward net vertical velocity.
- Shallow convection plays an important role not only as preconditioning but even in the mature phase. This is consistent with the previous studies that the bottom heavy heating helps moisten the atmosphere (Peters et al. 2008; Kuang 2011).

Factors affecting the development of the MJO

- There are at least two factors which affects the development of the MJO, horizontal gradient of the free tropospheric humidity and alpha represented by the following formula.

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

- Over the eastern Pacific and Atlantic, the high values of the free-tropospheric humidity is confined in the narrow band where the dry air tends to intrude from the south. This is unfavorable condition for the development of the MJO and will be one of the reason that the MJO is suppressed over these regions.
- Since alpha is large over land, the lower troposphere tends to be effectively dried by downward net vertical velocity there. This is unfavorable condition for the development of the MJO and may explain why the MJO is suppressed there.

Why shallow convection occurs over the convective area together with deep convection.

- Even over the convective area, the atmosphere is marginally unstable against the highest cumulus cloud type. This is favorable condition for the shallow convection to occur in the same timing with the deep convection. It enables to increase the lower-tropospheric humidity over the convective area and thereby maintains deep convection.
- This fact suggests that the reason for the success of the CS scheme in producing the better MJO is that the scheme tends to produce shallow convection together with deep convection.