

The Global Circulation Response to Diabatic Heating Associated with the MJO

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(1) To investigate the detailed dynamical mechanisms of the global circulation response to MJO convective forcing.

- forced response in a simple dynamical core model

- roles of equatorial Rossby-Kelvin waves and meridionally propagating Rossby wave train

- Rossby wave source

(2) Does an improved simulation of the MJO improve the global circulation response pattern in the NCEP CFS model?

- (1) GFDL Dynamical Core GCM: R30L20 (output grids: 96* 80)
- Initial State: 3-D DJF mean basic state (T, q, winds, & Psfc)
 - Initial Forcing: Diabatic Heating Profile
with a Peak at 400hPa
 - Integration : 30 days
 - Integration time step: ~15 min
 - 8th order horizontal diffusion coefficient: $8.0 \cdot 10^{37}$

- (2) NCEP Coupled high resolution run: **CFS T126 SAS**
(=GFS T126 +GFDL MOM3)
(64 Vertical Levels)

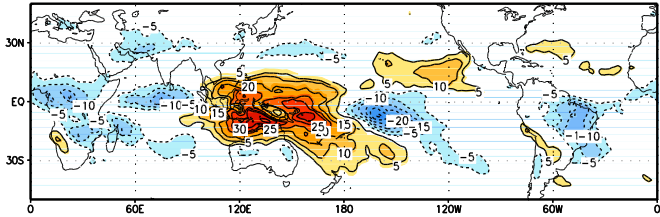
NCEP Coupled high resolution run with Relaxed Arakawa-Schubert
cumulus parameterization scheme: **CFS T126 RAS**
Simulation Period: 14 years

Horizontal structure of MJO convection/forcing for phases 1-4

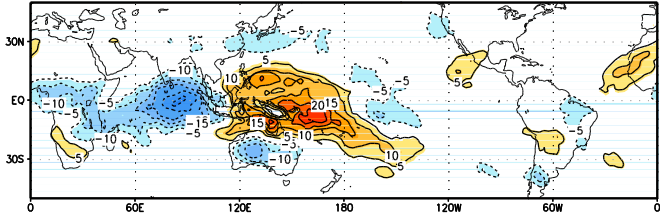
OLR

Diabatic Heating

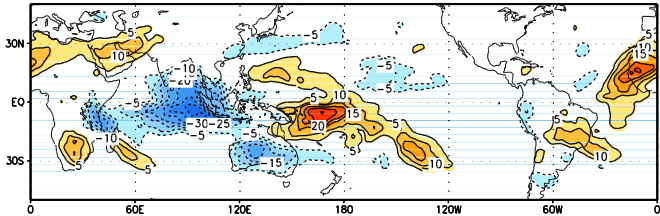
(a) phase 1



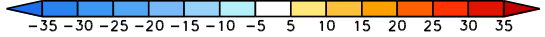
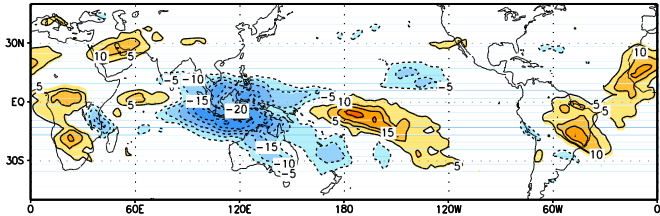
(b) phase 2



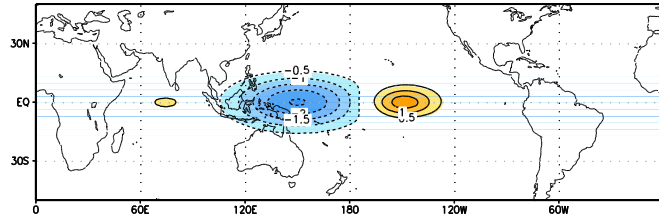
(c) phase 3



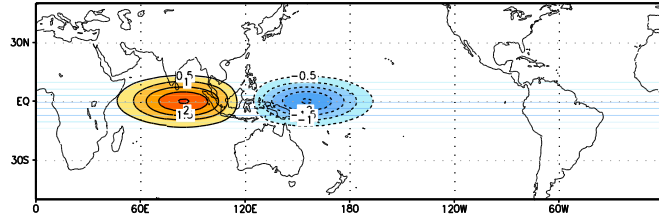
(d) phase 4



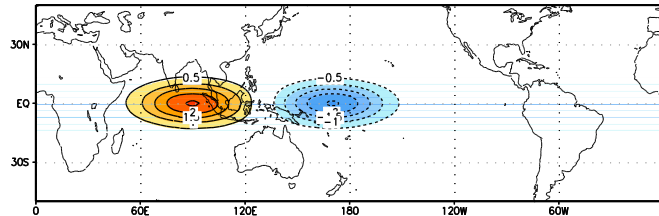
(a) phase 1



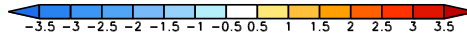
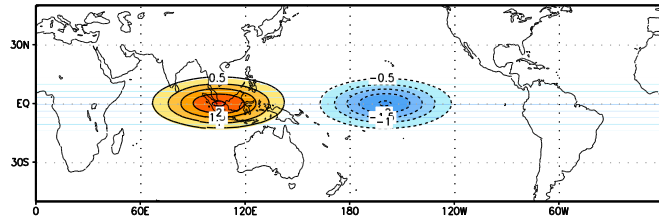
(b) phase 2



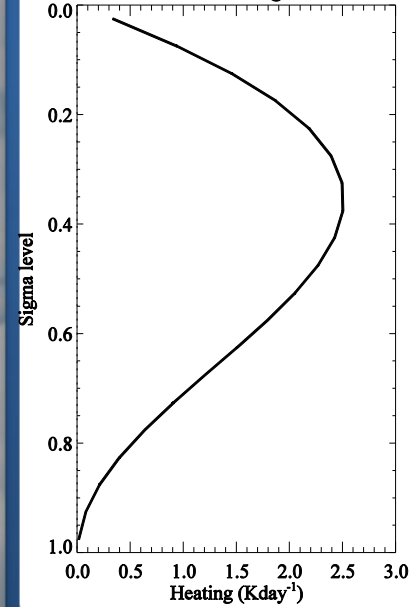
(c) phase 3



(d) phase 4



Vertical Heating Profile



Vertical Heating Profile

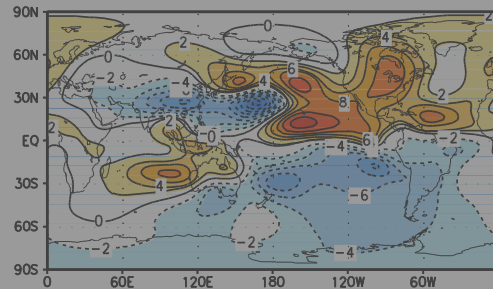
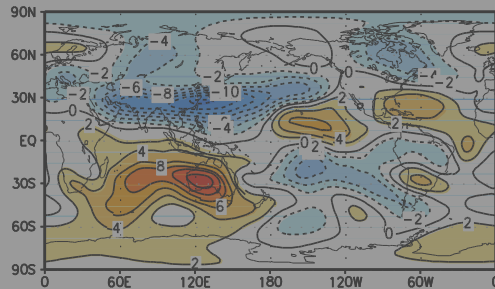
Heating anomaly forced to derive model fields

Streamfunction at 200hPa OBS

Streamfunction at sigma=0.225

(a) phase 1

(e) phase 1

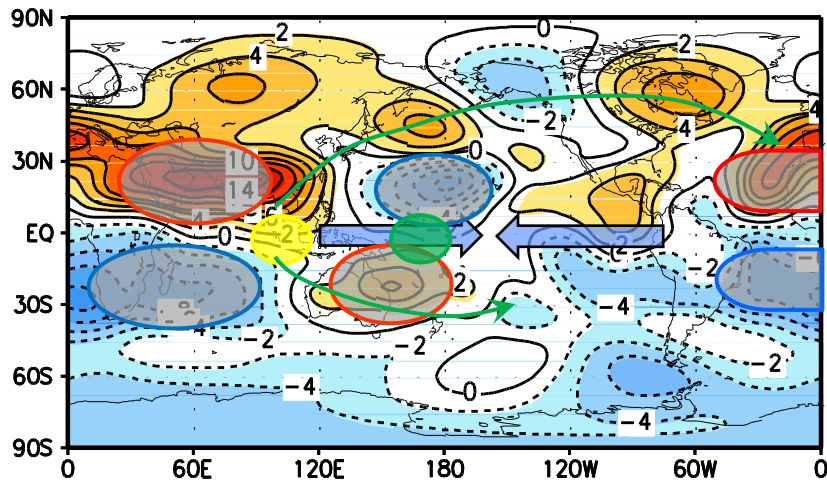


(b) phase 2

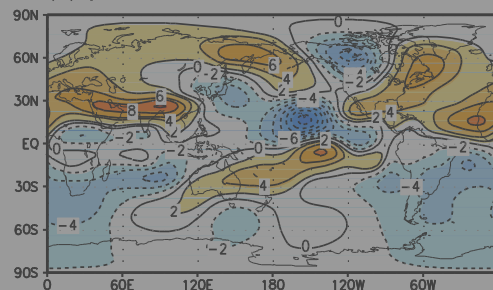
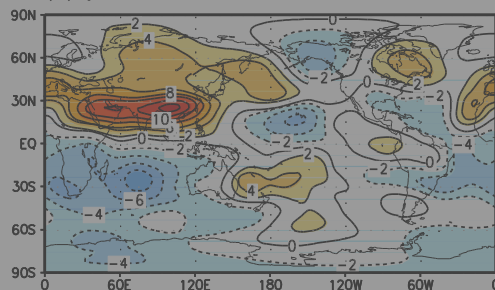
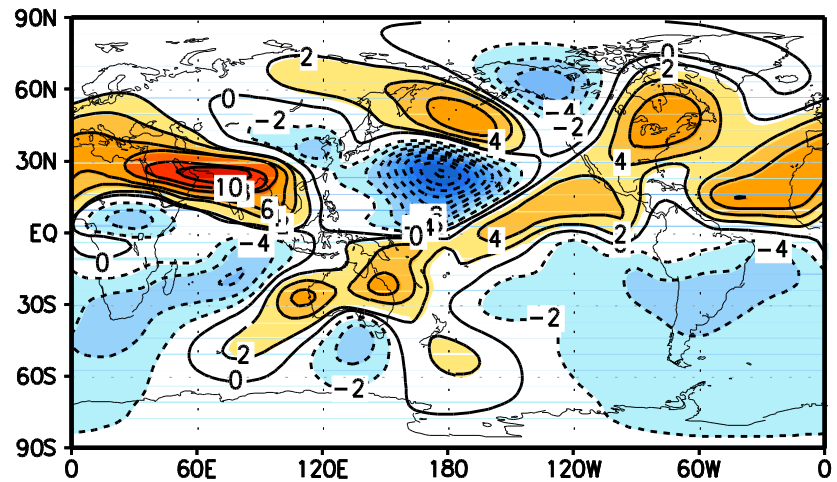
(f) phase 2



(c) phase 3



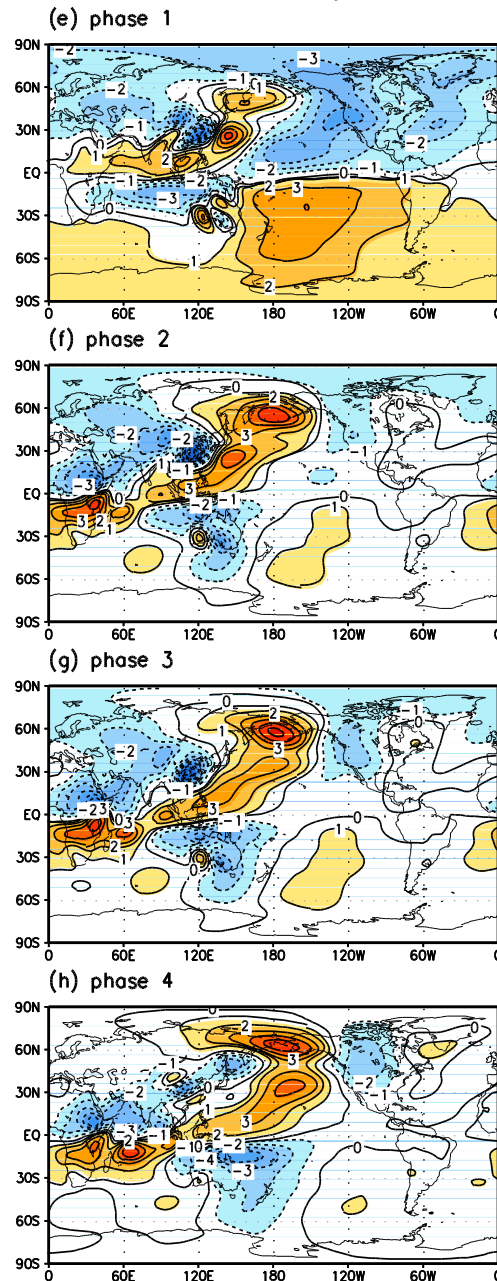
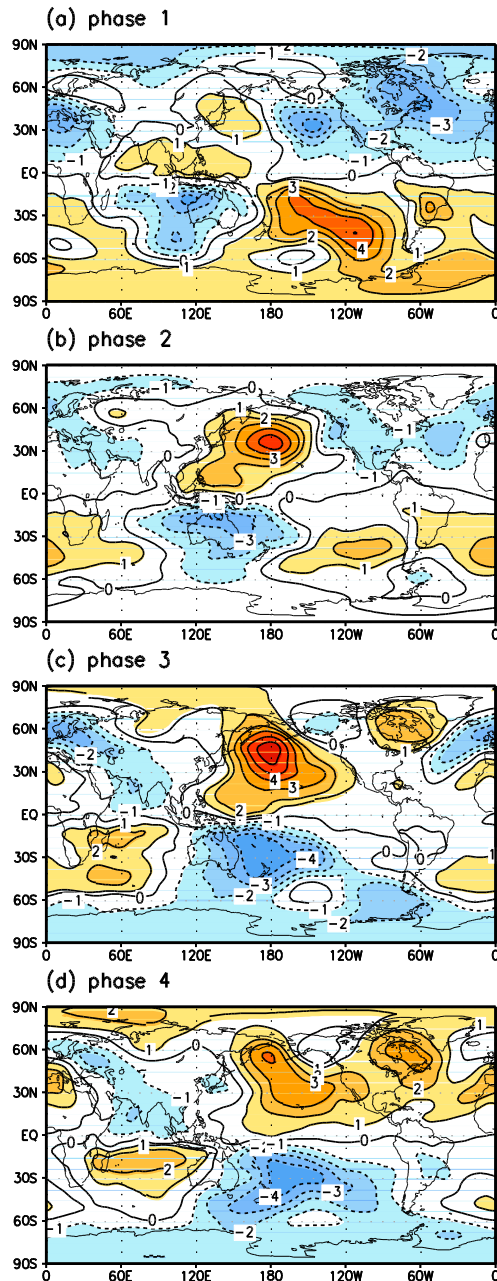
(g) phase 3



**Global (Upper-Level)
Streamfunction
Anomalies for Obs (left)
and Model (right) at day
15**

Streamfunction at 850hPa OBS

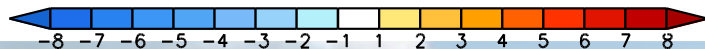
Streamfunction at sigma=0.875



Small-scale features due to the growth of unstable baroclinic waves in the lower-troposphere earlier in the model integrations.

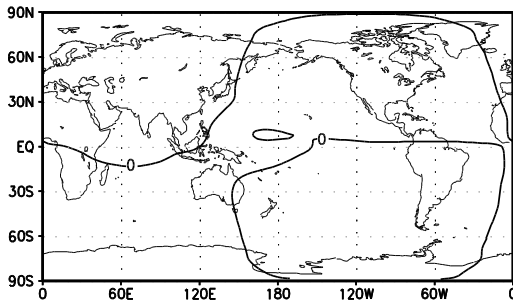
Tropical response: vertically baroclinic structure
Extratropical response: equivalent barotropic

Global (Lower-Level) Streamfunction Anomalies for Obs (left) and Model (right) at day 13

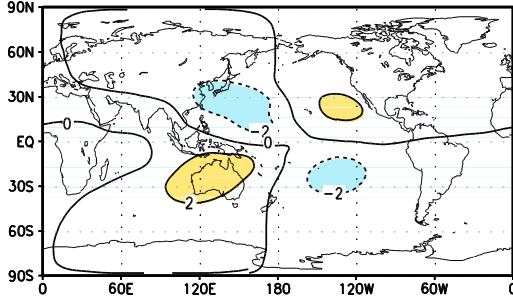


Streamfunction at sigma=0.225 (Phase 3)

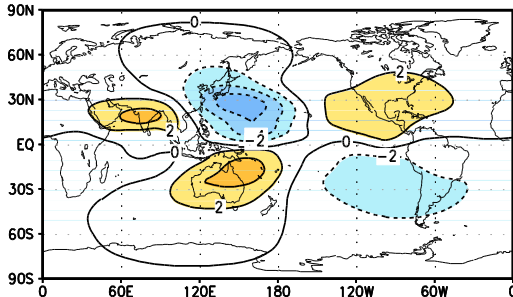
(a) t=1



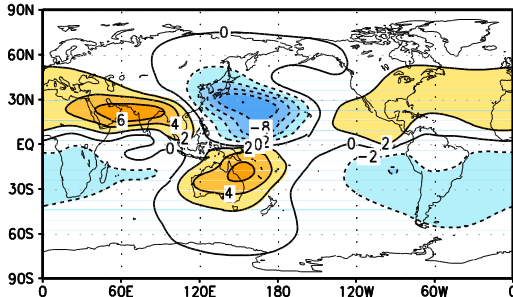
(b) t=3



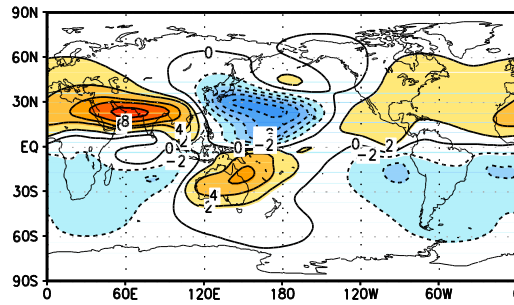
(c) t=5



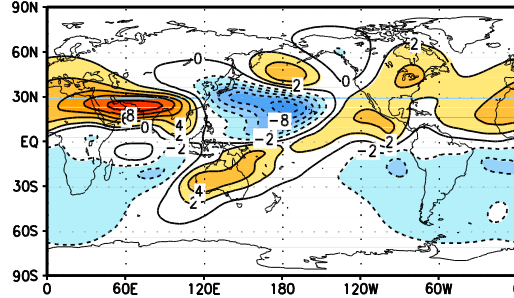
(d) t=7



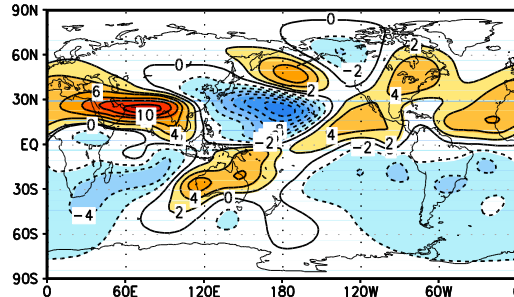
(e) t=9



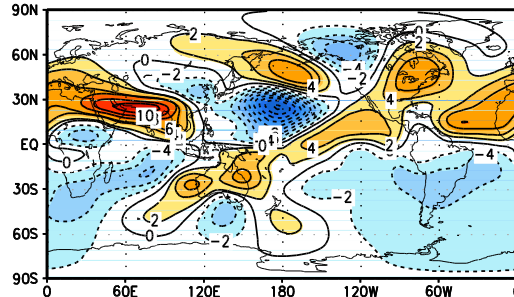
(f) t=11



(g) t=13



(h) t=15



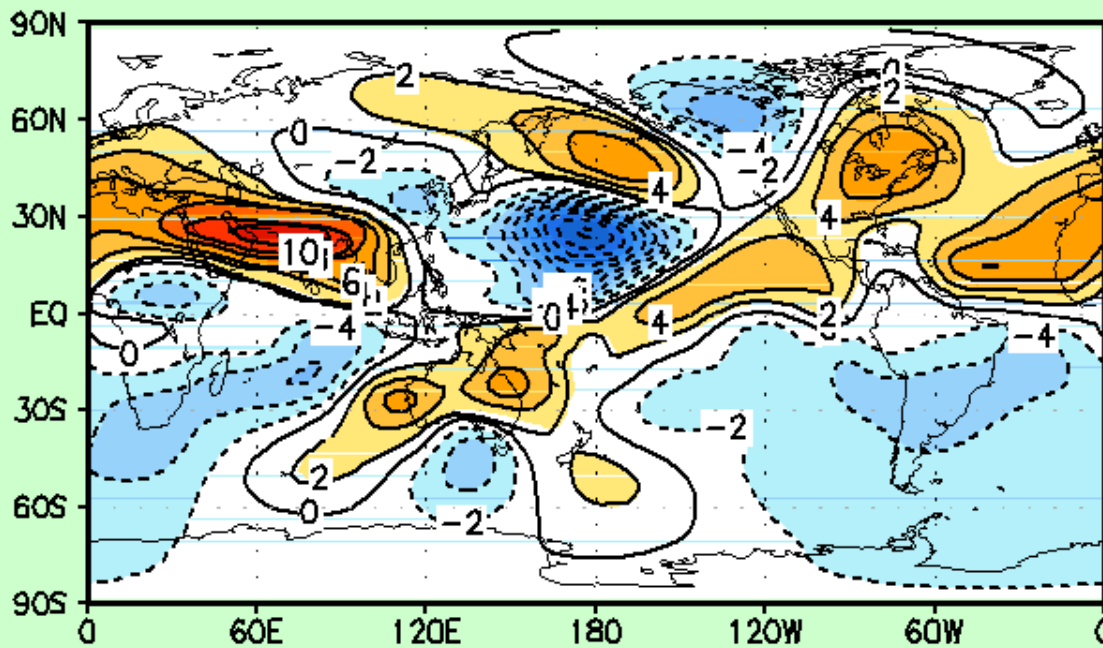
Time Evolution of Streamfunction Anomalies at sigma=0.225 for phase 3 from day 1 to 15.

*the subtropical circulation anomalies induced by Kelvin waves in the WH propagate eastward and meet the westward propagating Rossby waves over Africa and the Atlantic.

*Rossby wave propagation in the NH and SH is seen in midlatitudes

Ray Tracing using nondivergent barotropic Rossby wave theory

(g) phase 3



Rossby wave dispersion relationship

$$\omega = \bar{U}k - \frac{\beta k}{K^2}, \quad \text{where } K^2 = k^2 + l^2$$

$$\beta = \frac{\partial f}{\partial y} - \frac{\partial^2 \bar{U}}{\partial y^2}$$

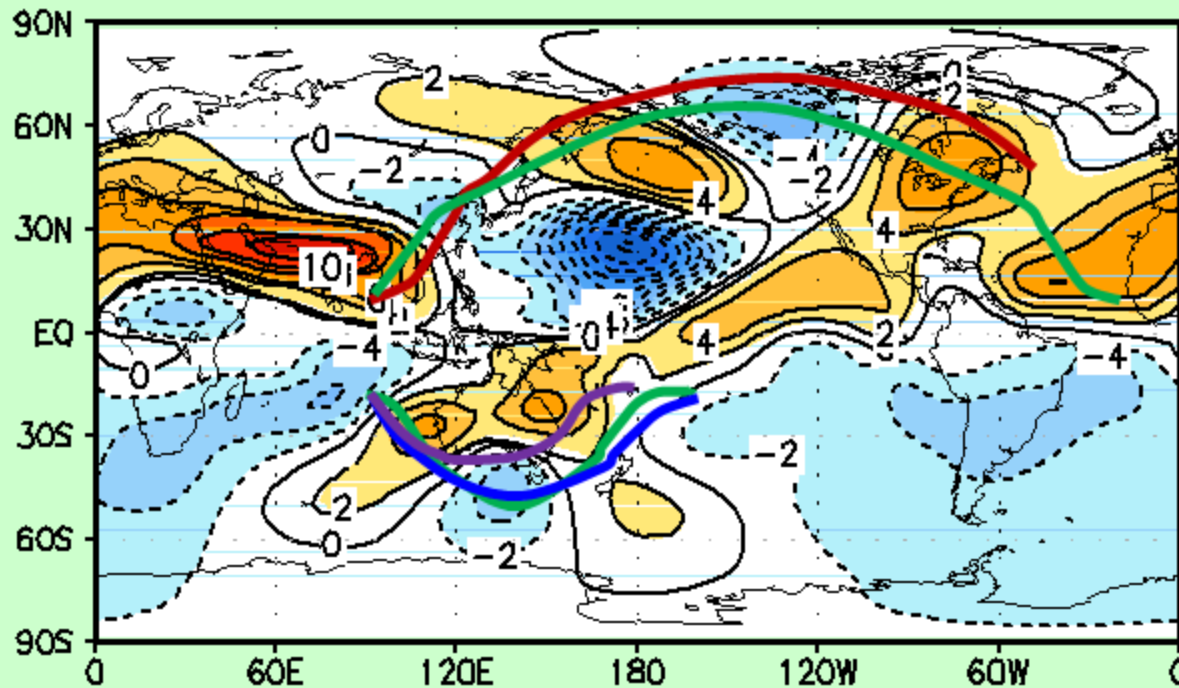
$$u_g = \frac{\partial \omega}{\partial k} = c + \frac{2\beta k^2}{K^4}$$

$$v_g = \frac{\partial \omega}{\partial l} = \frac{2\beta kl}{K^4}$$

$$\frac{dx}{dt} = u_g, \quad \frac{dy}{dt} = v_g$$

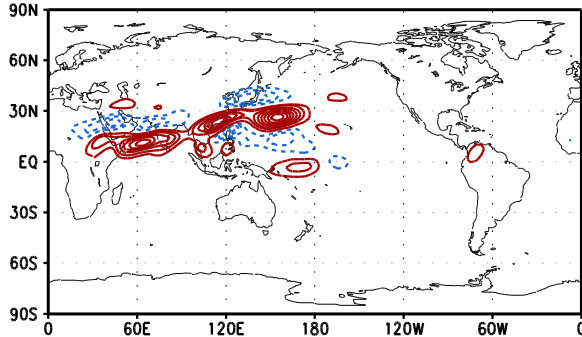
Ray Tracing by Nondivergent Barotropic Rossby Wave Theory

(g) phase 3

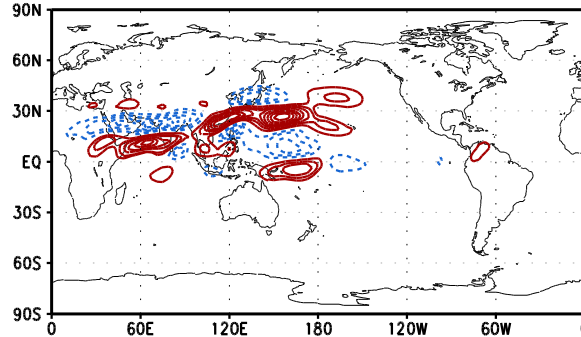


Rossby Wave Source at day 7

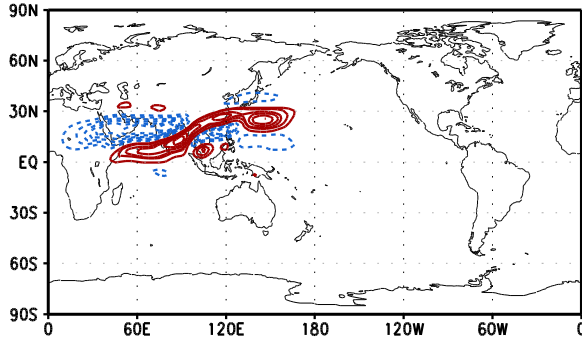
(a) RWS term 1 (phase 3, t=7)



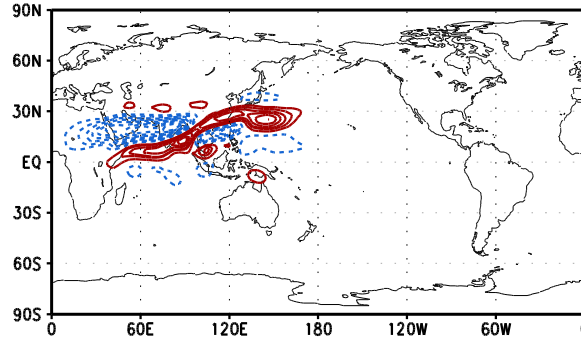
(b) RWS total (phase 3, t=7)



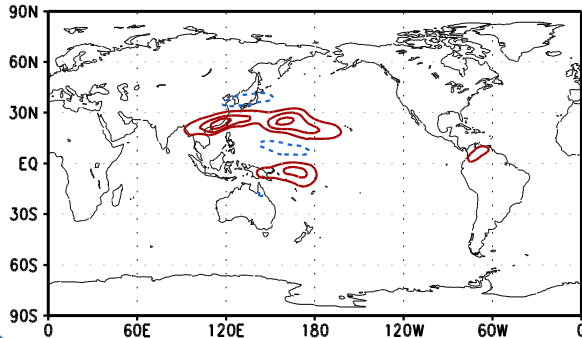
(c) RWS term 1 (positive heating 90E, t=7)



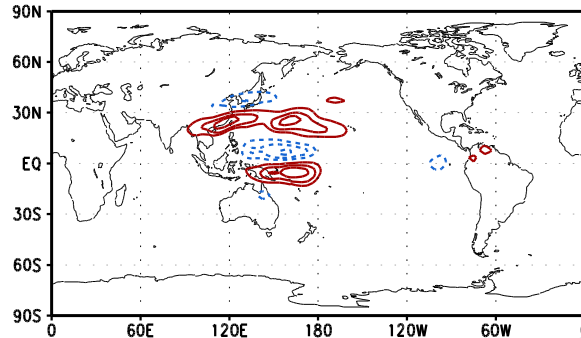
(d) RWS total (positive heating 90E, t=7)



(e) RWS term 1 (negative heating 170E, t=7)



(f) RWS total (negative heating 170E, t=7)



Rossby Wave Source at Phase 3

*The first term (the generation of wave vorticity by anomalous divergence) is dominant.

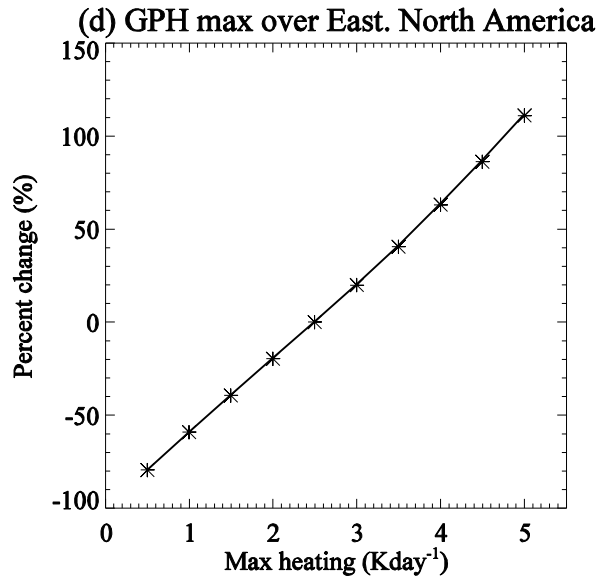
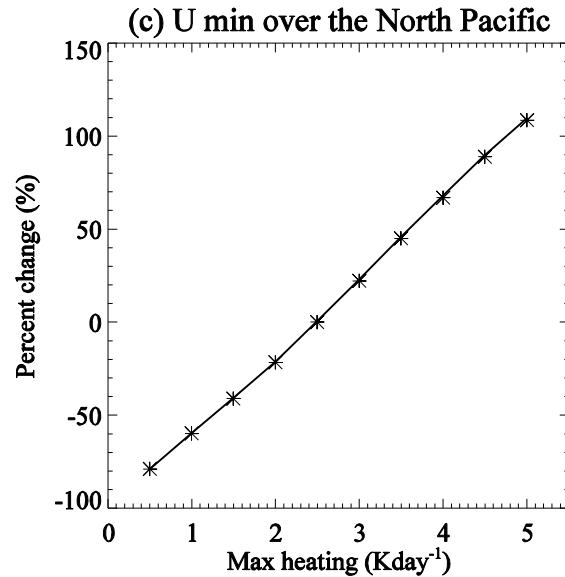
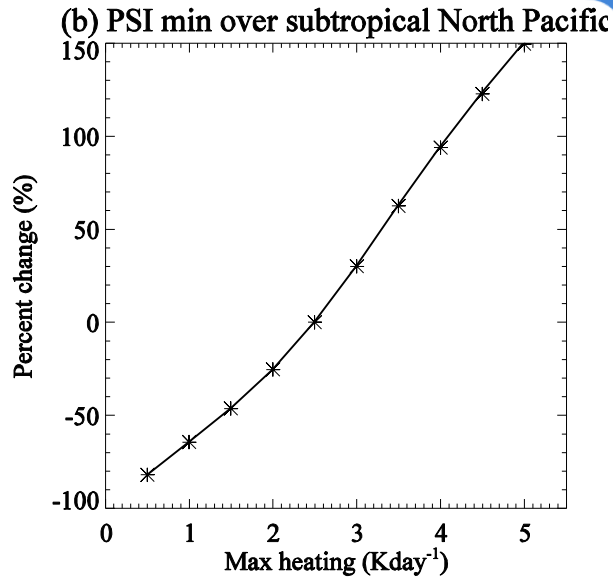
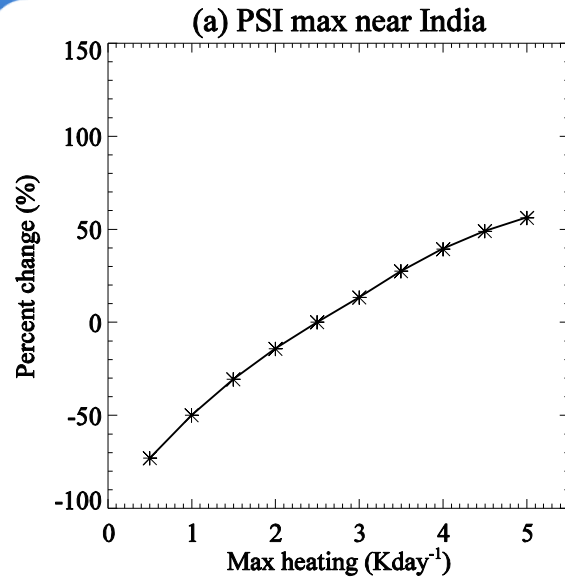
The RWS perturbations by the positive heating at 90°E are as much as twice greater than those by the negative forcing at 170°E

Linearized forced barotropic vorticity equation and perturbation Rossby Wave Source

$$\frac{\partial \zeta'}{\partial t} + \bar{V}_\psi \cdot \nabla \zeta' + V'_\psi \cdot \nabla \bar{\zeta} = S' + F'$$

$$S' = -\bar{\zeta} \nabla \cdot V'_x - V'_x \cdot \nabla \bar{\zeta} - \zeta' \nabla \cdot \bar{V}_x - \bar{V}_x \cdot \nabla \zeta'$$

Sensitivity Test



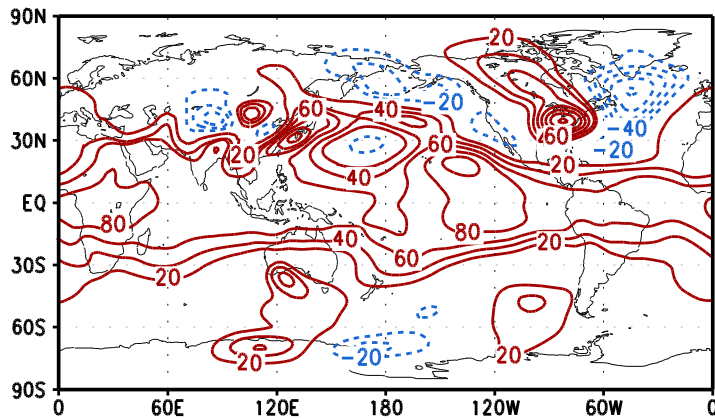
Sensitivity Test

*Quasi-linear relationship between the circulation response and imposed diabatic heating strength

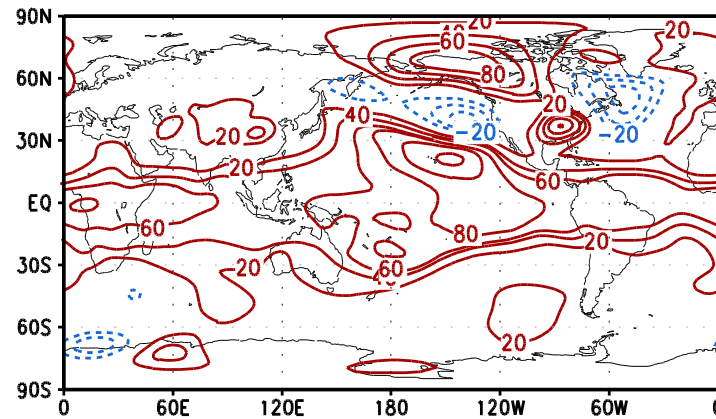
The model circulation response is almost linear.

MJO-ENSO Interaction

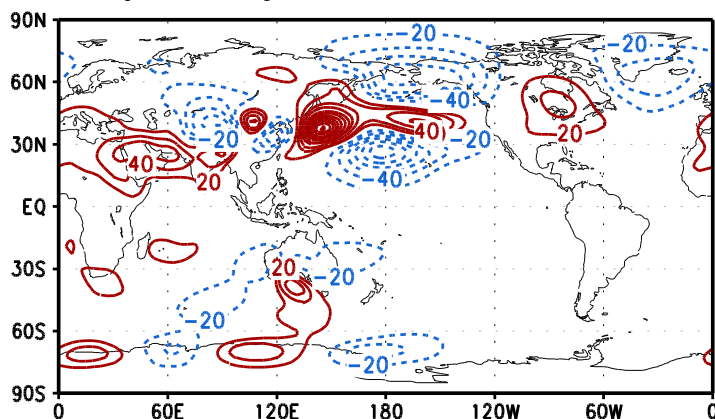
(a) gph at sigma=0.225 (El Nino+Phase 3)



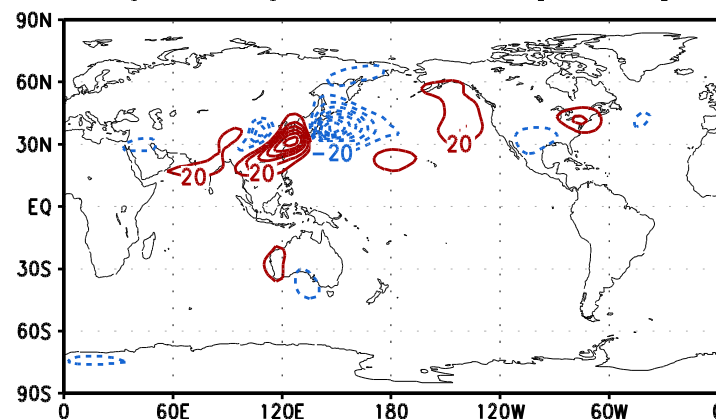
(b) gph at sigma=0.225 (El Nino only)



(c) gph at sigma=0.225 (Phase 3)



(d) gph at sigma=0.225 ((a)-[(b)+(c)])



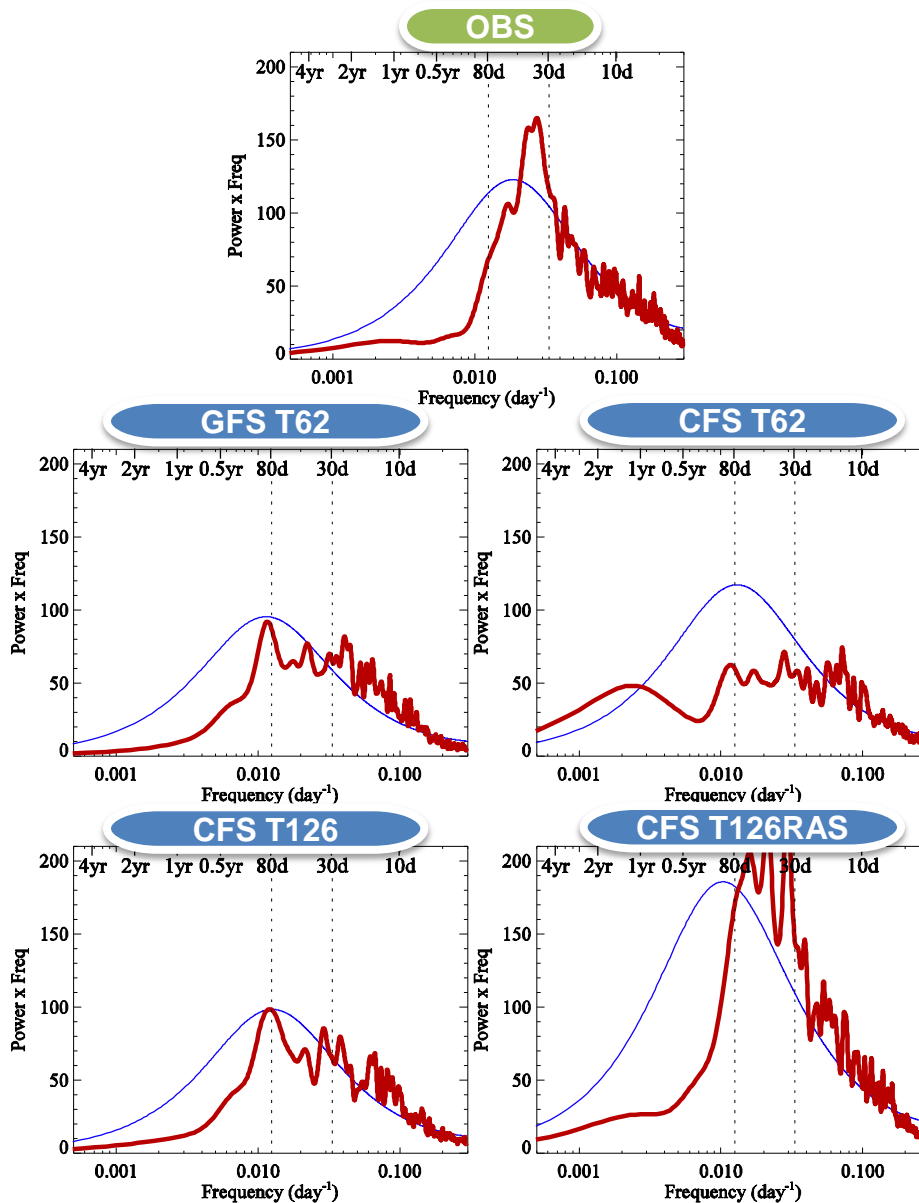
$$TOT_{MJO} \approx LN_{MJO} \text{ \& } TOT_{ENSO} \approx LN_{ENSO}$$

$$TOT_{MJO+ENSO} = LN_{MJO+ENSO} + NON_{MJO+ENSO} \approx LN_{MJO} + LN_{ENSO} + NON_{MJO+ENSO}$$

MJO-ENSO Interaction (at Phase 3)

The nonlinear interaction between the MJO and ENSO takes place primarily in the northern extratropics along the jets, and mostly occurs along the Asian-Pacific jet

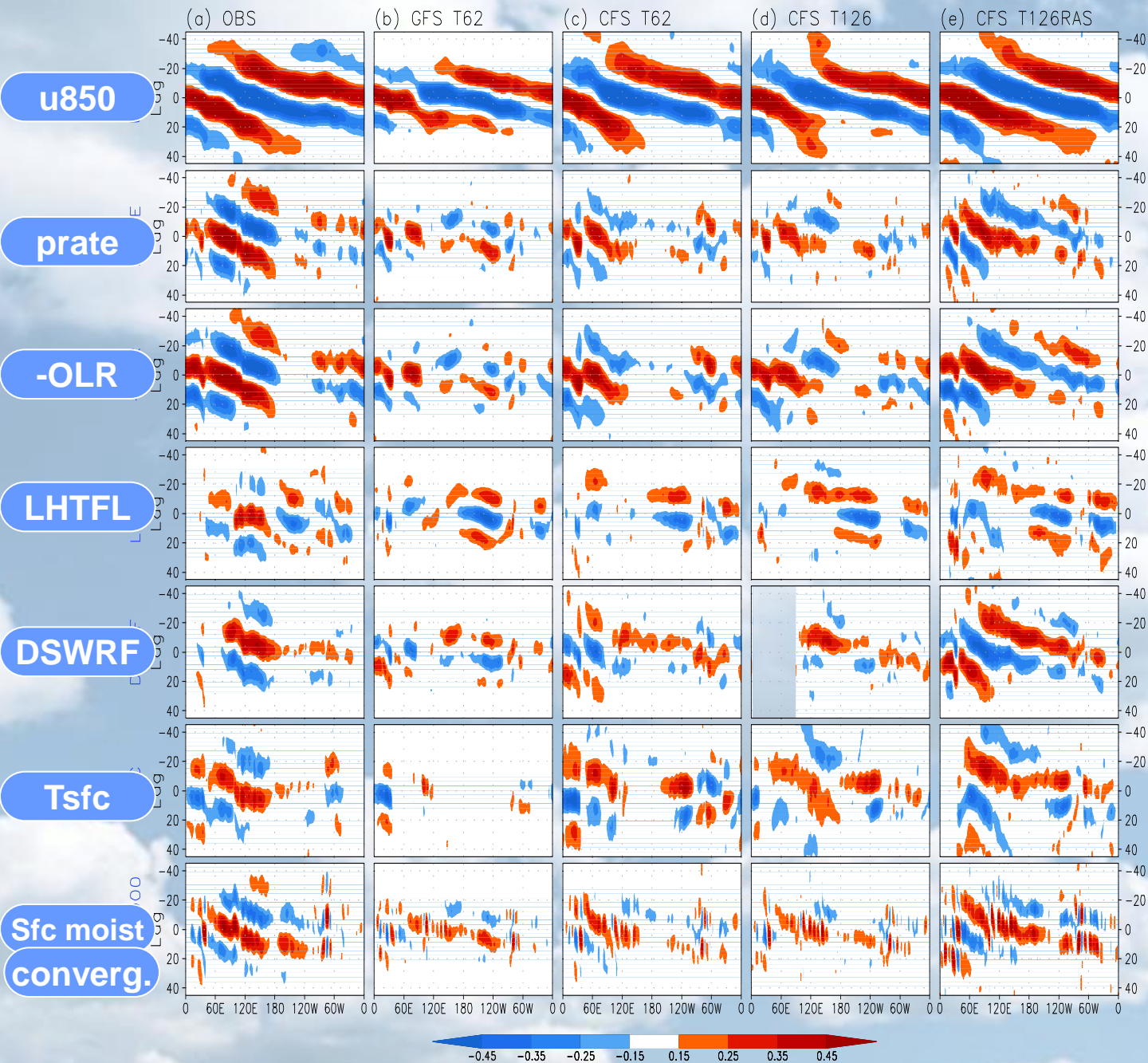
Power Spectra over equatorial Indian Ocean



Power Spectra over the equatorial Indian Ocean

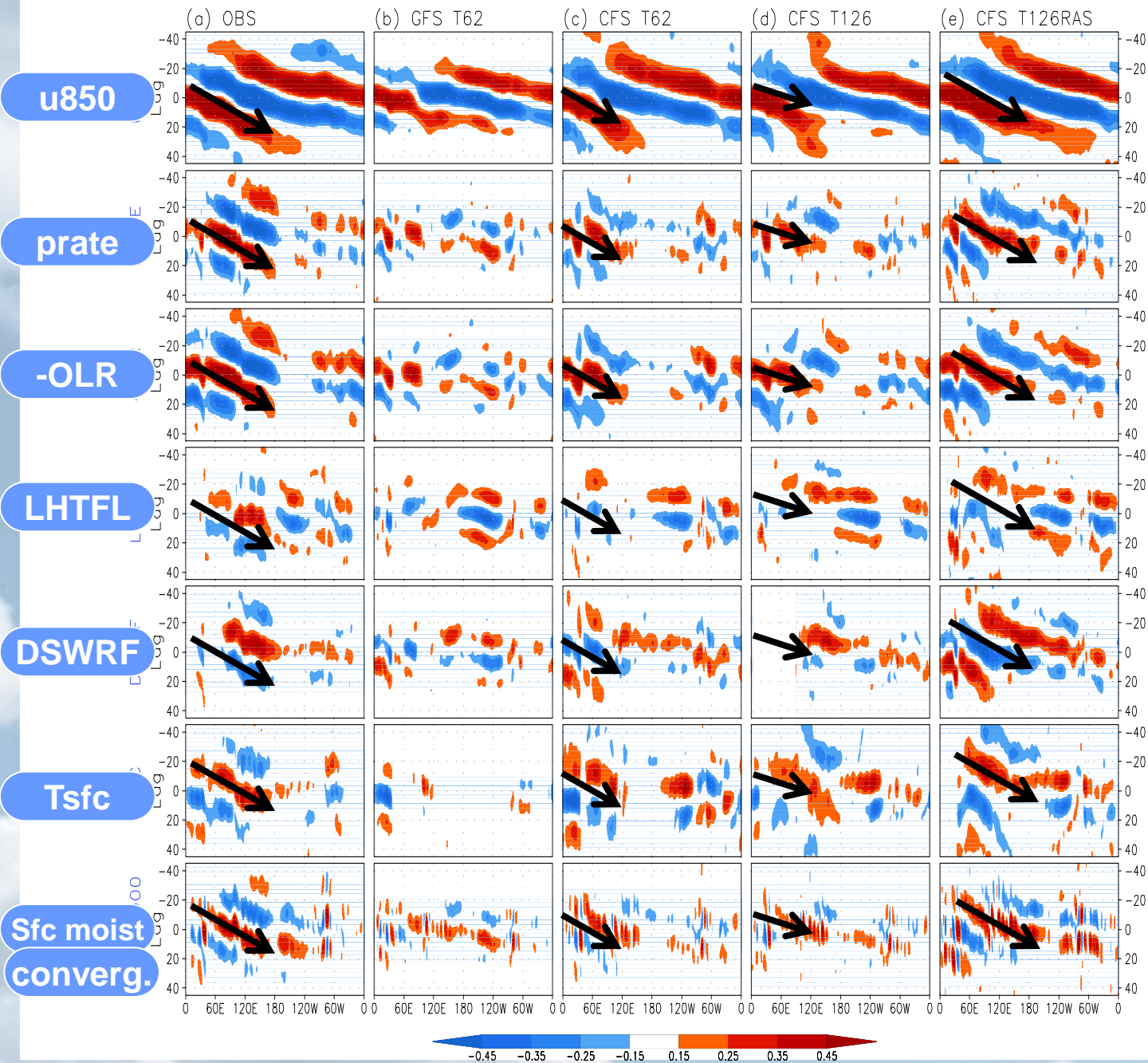
- Red line: calculated power spectrum
- Blue line: background red spectrum

- OBS: pronounced 30-80 day signal
- GFS T62, CFS T62, CFS T126: less significant
- CFS T126RAS: significant, vigorous power in 30-80 day range



Regression against PC2

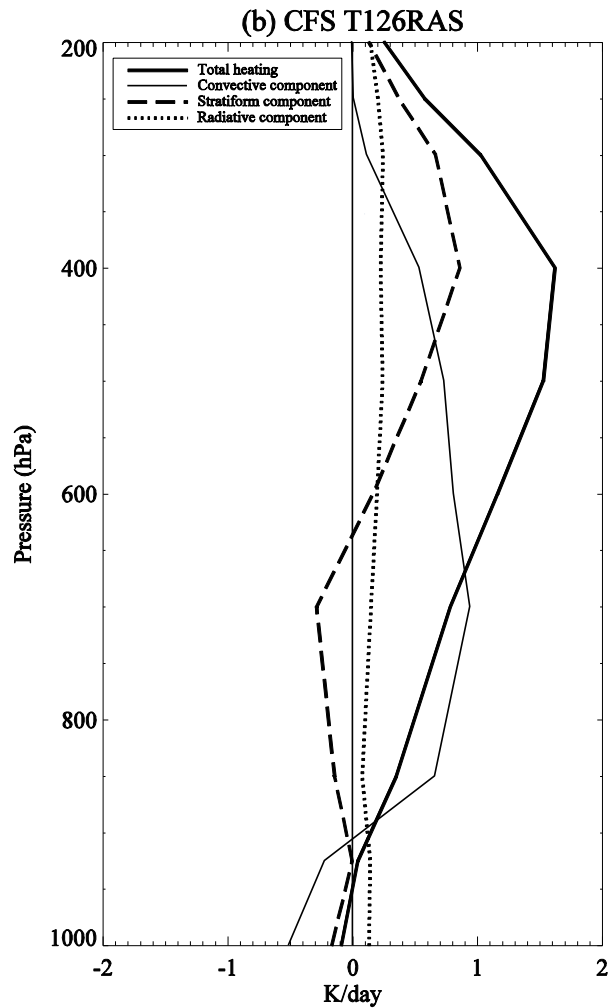
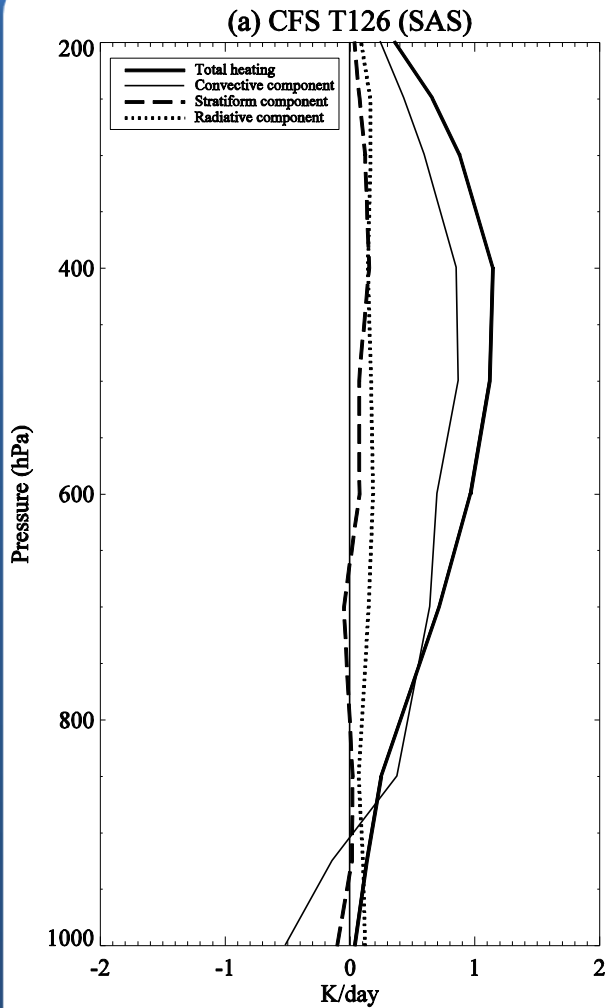
- GFS, CFST62, CFS T126: propagation barrier problem over the Maritime continent
- Coherence in CFST62 is improved compared to GFST62
- CFS T126RAS: shows a successful propagation across the Maritime continent & Regressed dynamical variables are consistent with the observations



Regression against PC2

- GFS, CFST62, CFS T126: propagation barrier problem over the Maritime continent
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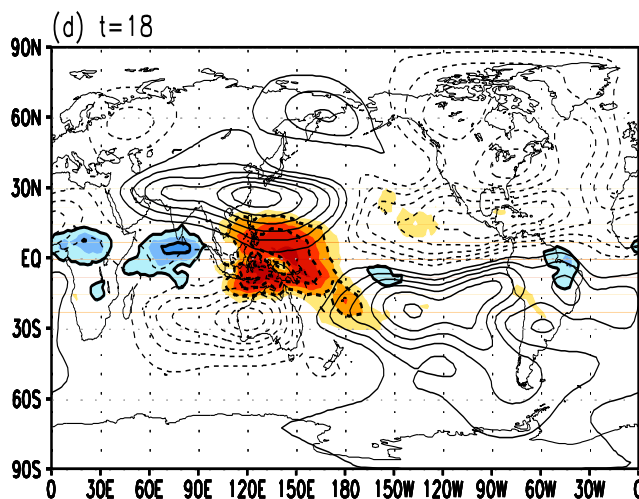
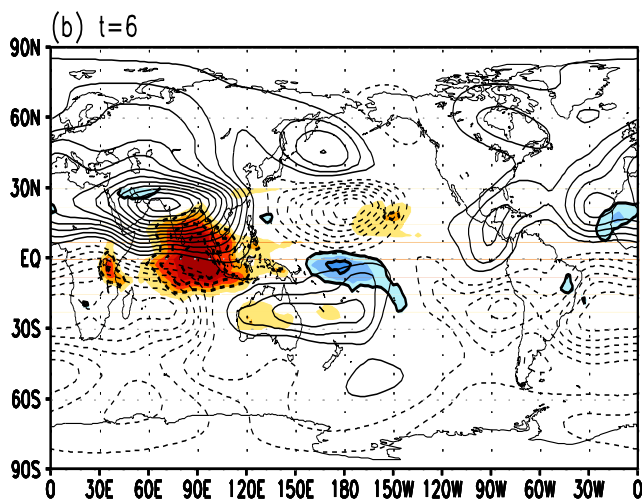
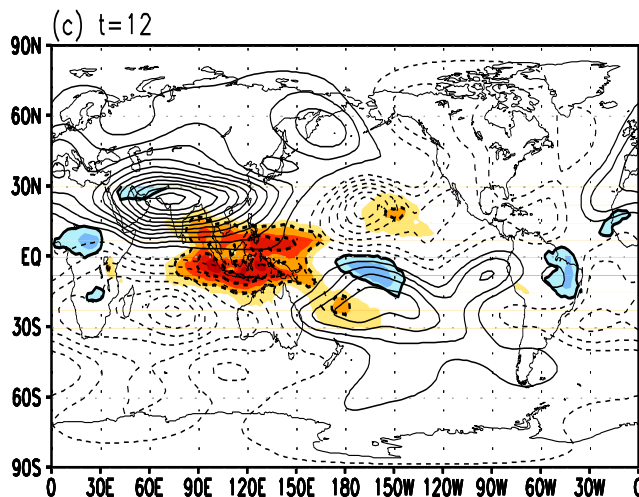
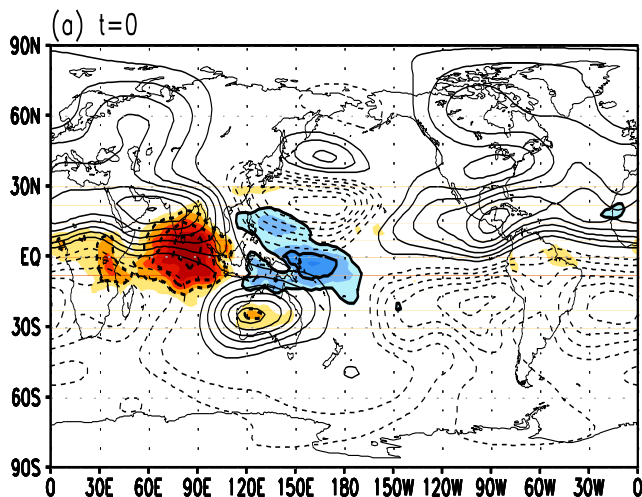
Vertical heating profile



The partition of the total vertical heating profile (thick solid line) into the convective component (thin solid line), the stratiform component (dashed line), and the radiative component (dotted line) for (a) CFS T126SAS and (b) CFS T126RAS.

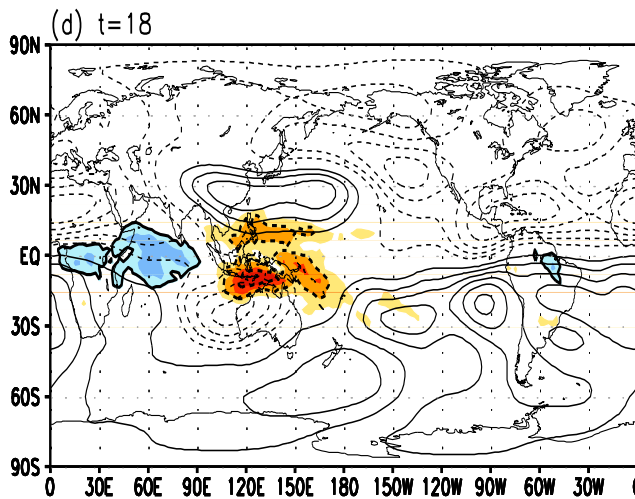
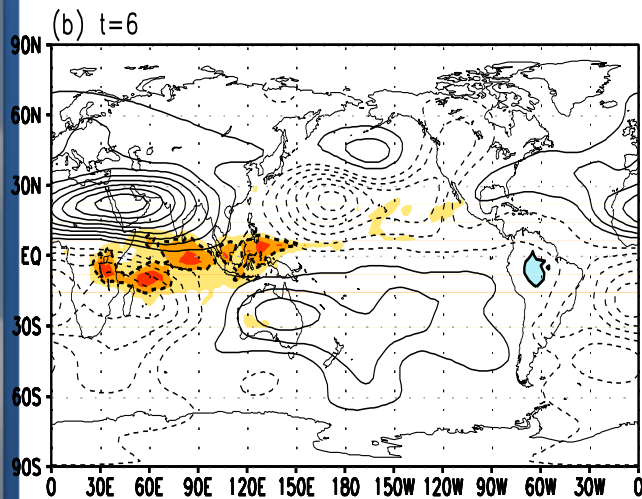
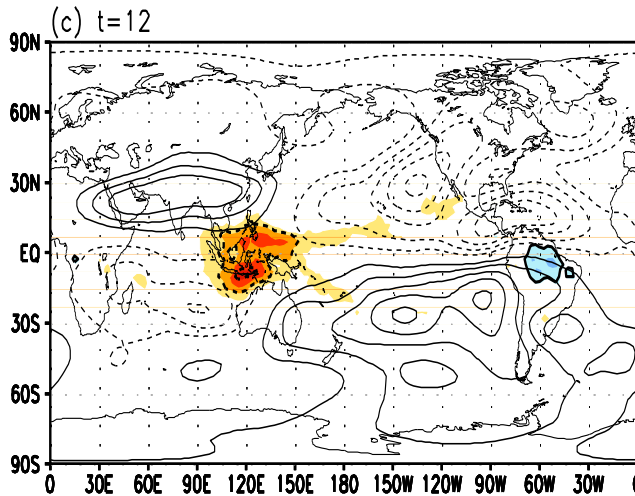
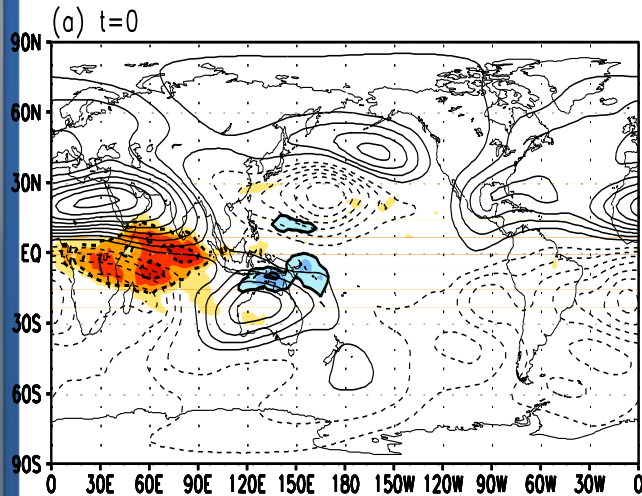
Seo and Wang,
J. of Climate (2010)

Global Circulation Response to the MJO Convection: OBS



- 200hPa Streamfunction regressed onto PC1 and PC2
- Half life cycle
- Red: enhanced MJO convection
- Blue: suppressed convection
- Tropics: anticyclonic couplet at or west of enhanced convection + tropical westerly anom east of enhanced convection: Rossby-Kelvin wave response
- PNA-like response
- Continued influence to the Americas

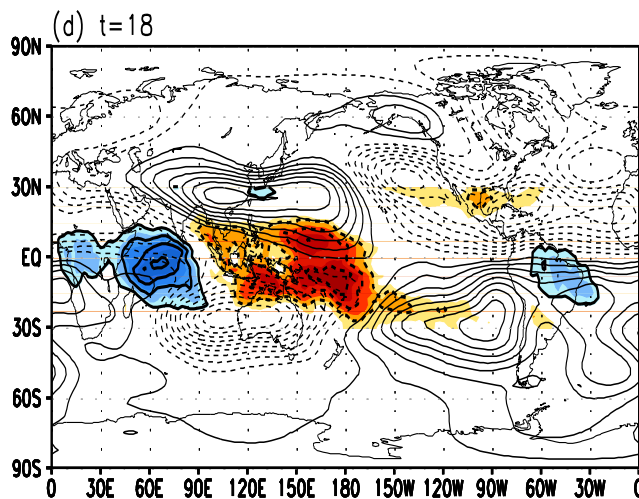
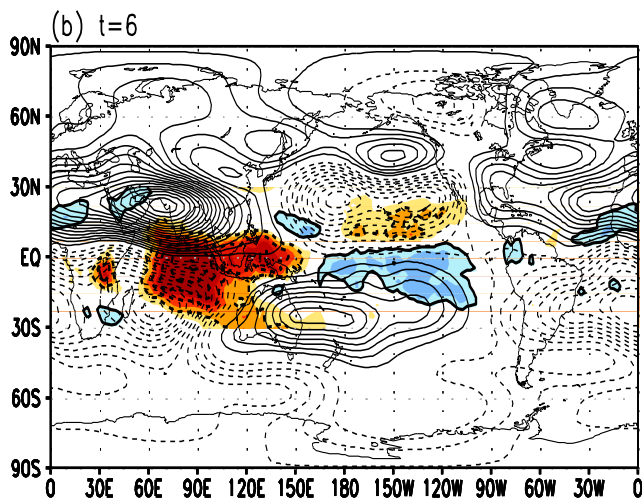
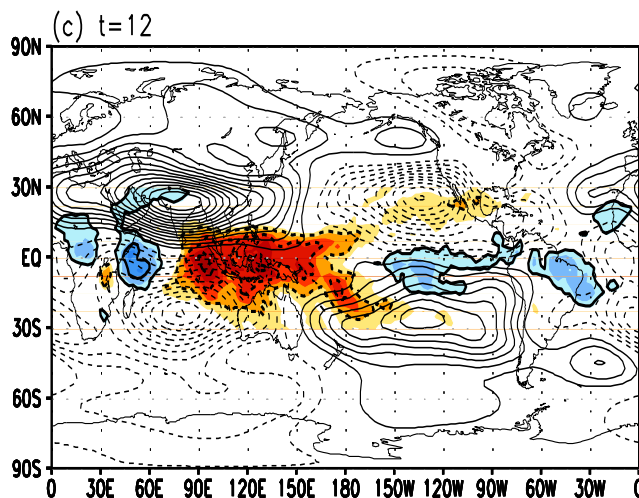
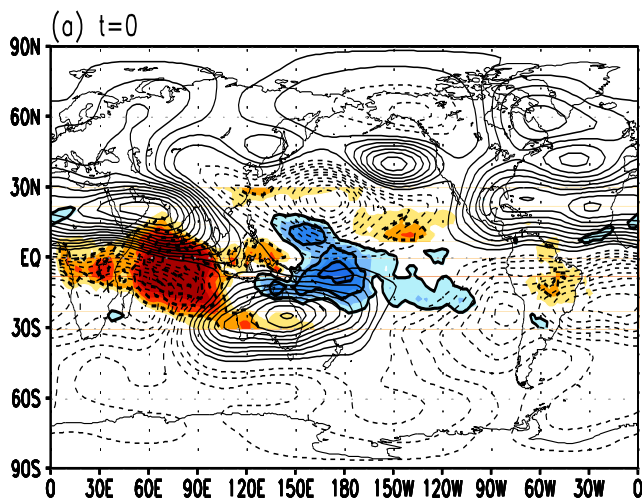
Global Circulation Response to the MJO: CFS T126SAS



-Red: enhanced MJO convection
-Blue: suppressed convection

-CFS T126SAS: convection and streamfunction anomalies are weak
-No significant suppressed convection over the western Pacific at t=6 & t=12 → weaker circulation response

Global Circulation Response to the MJO: CFS T126RAS



-Red: enhanced MJO convection

-Blue: suppressed convection

-CFS T126RAS: stronger circulation response

-Similar pattern to the observation → pattern correlation 0.84-0.91 (vs 0.47-0.78 in CFS T126)



Summary and Conclusions

(1) The global circulation response to the MJO is largely determined by the wintertime large-scale background mean flow and the location of the enhanced and suppressed heating anomalies in the MJO development region.

**(1a) “Extratropical circulation is almost entirely from tropical heating anomalies”:
Barotropic Rossby wave trains with zonal wavenumbers 2-4 in the NH and 3-5 in the SH are dominant.**

(1b) Tropical circulations are formed from cooperation between negative and positive circulation anomalies due to eastward propagating Kelvin and westward propagating Rossby waves, plus the meridionally propagating Rossby wave activity.

(2) The nonlinear interaction between the MJO response and El Niño response takes place preferentially along the NH midlatitude jets when the enhanced convection is located over the Indian Ocean.

(3) The improved MJO simulation in CFS T126RAS improves the simulation of the extratropical circulation anomalies

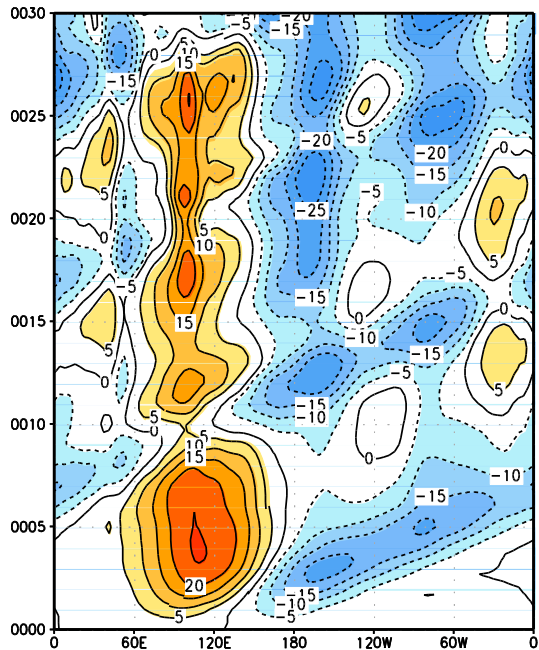
Seo, K.-H., and W. Wang, 2010: The Madden-Julian oscillation simulated in the NCEP CFS model: The importance of stratiform heating. *J. Climate*, in print.

Seo, K.-H., 2010: The Global Atmospheric Circulation Response to Tropical Diabatic Heating Associated with the Madden-Julian Oscillation during Northern Winter., *J. Atmos. Sci.*, in prep.

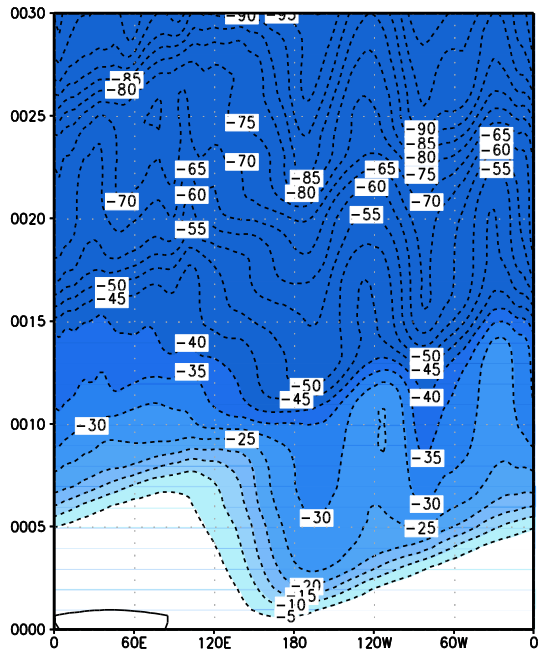
Thank you

Geopotential height anomaly at sigma=0.225

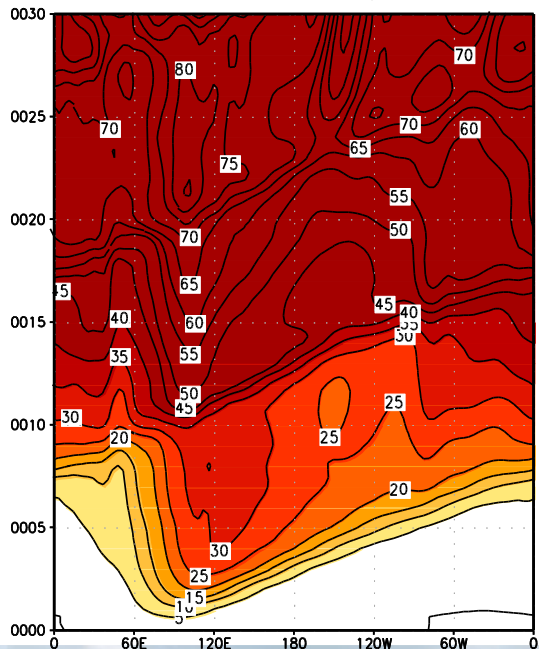
(a) GPH Phase 3 (90E, 170E)



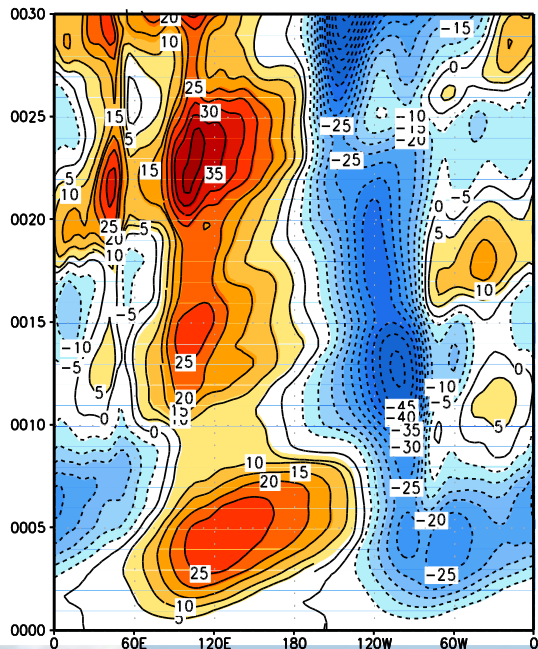
(c) GPH 170E negative heating



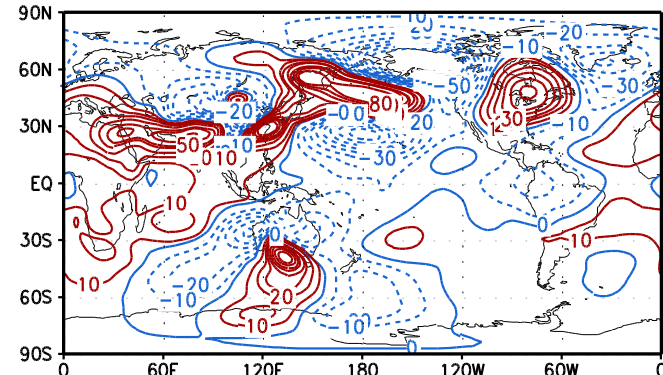
(b) GPH 90E positive heating



(d) GPH 90E, 90+180E



(e) gph at sigma=0.225

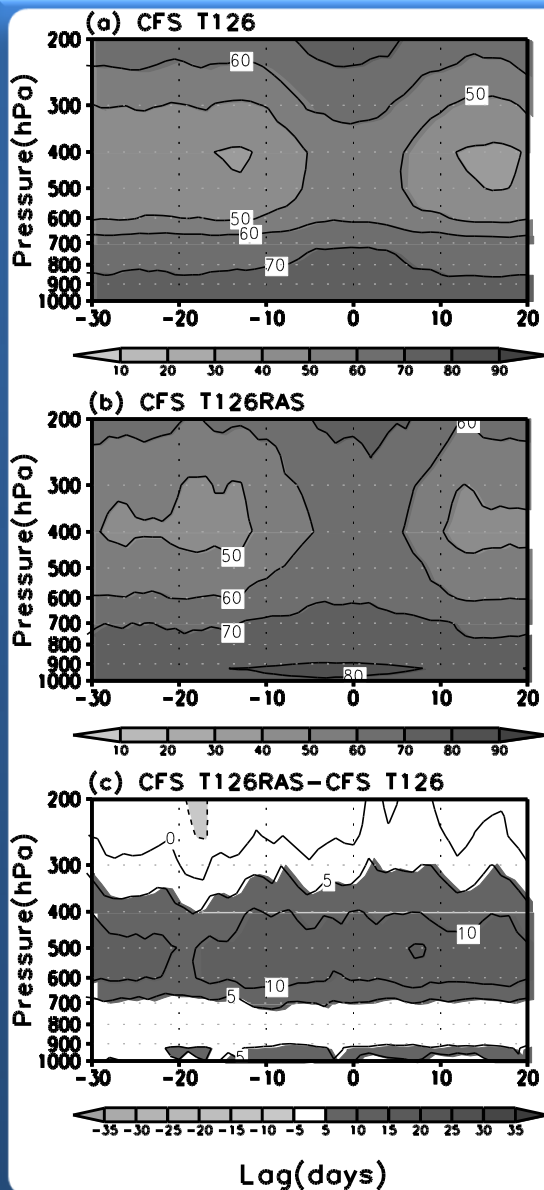


Equatorial Rossby and Kelvin Waves due to Dipole Convective Forcing Along the Equator

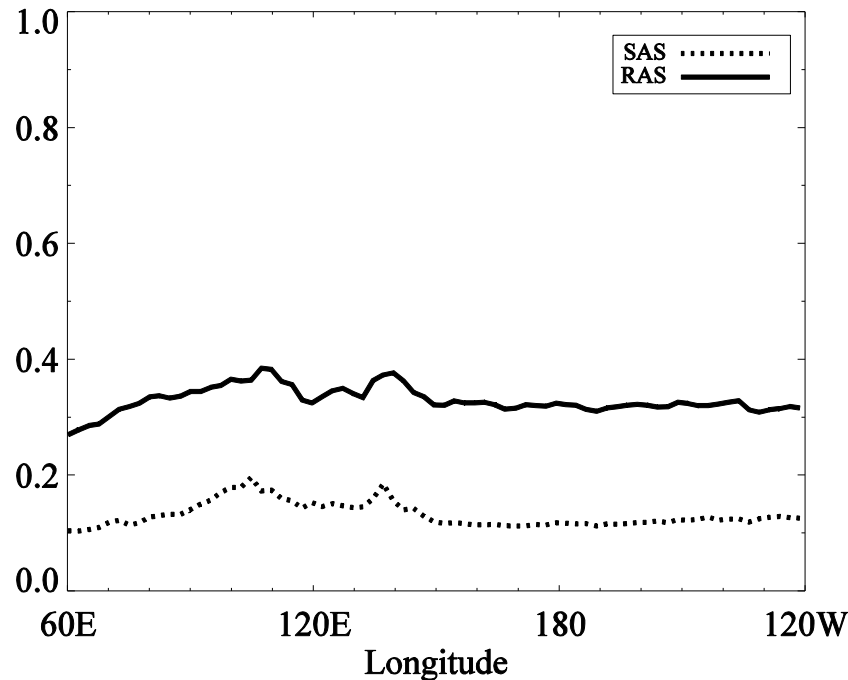
*Formation of circulation anomalies by equatorial Rossby and Kelvin Waves

*Competition between the Rossby and Kelvin Waves of positive and negative signs

Global Circulation Response to the MJO: CFS T126RAS

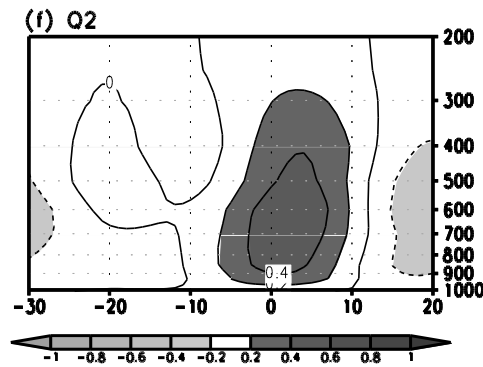
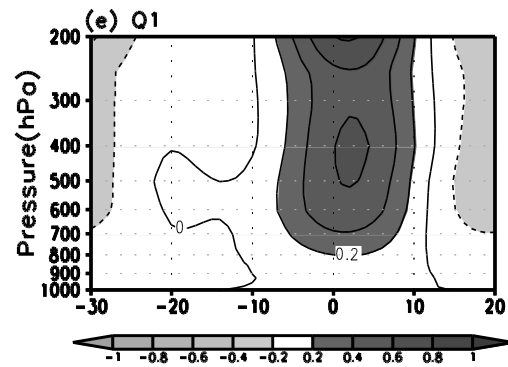
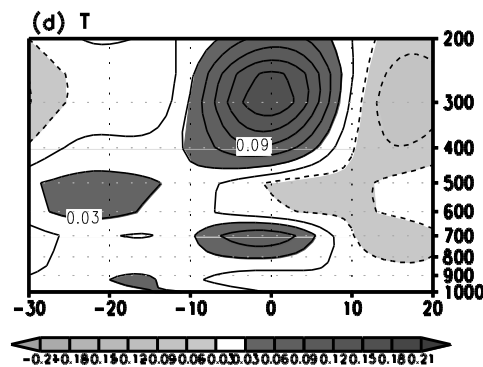
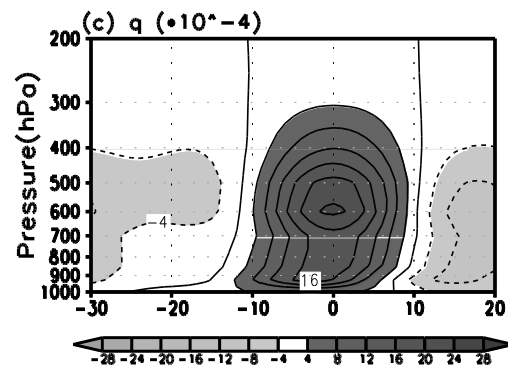
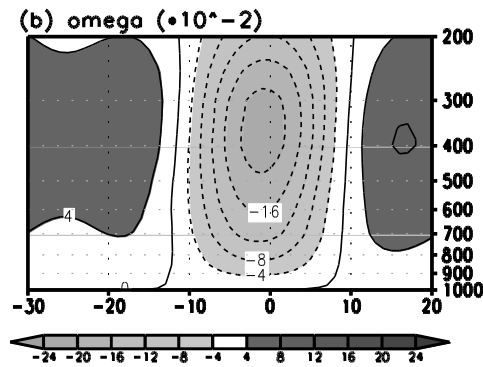
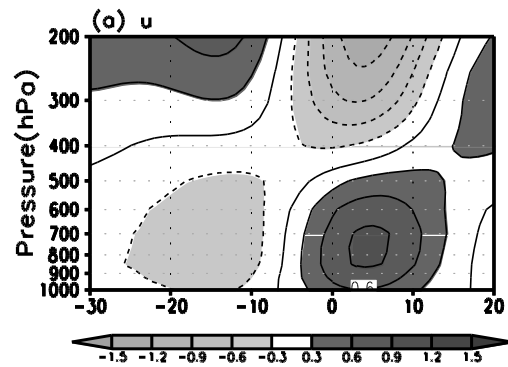


Stratiform Rainfall Fraction



The fraction of the stratiform rainfall to the total rainfall. Dotted line denotes CFS T126 and solid line CFS T126RAS.

The composite relative humidity (%) field as a function of lag days for (a) CFS T126, (b) CFS T126RAS, and (c) their difference (CFS T126RAS - CFS T126). The composite is formed only for the cases where the normalized OLR index is less than 1.0 standard deviation (i.e., for the strong convection events).

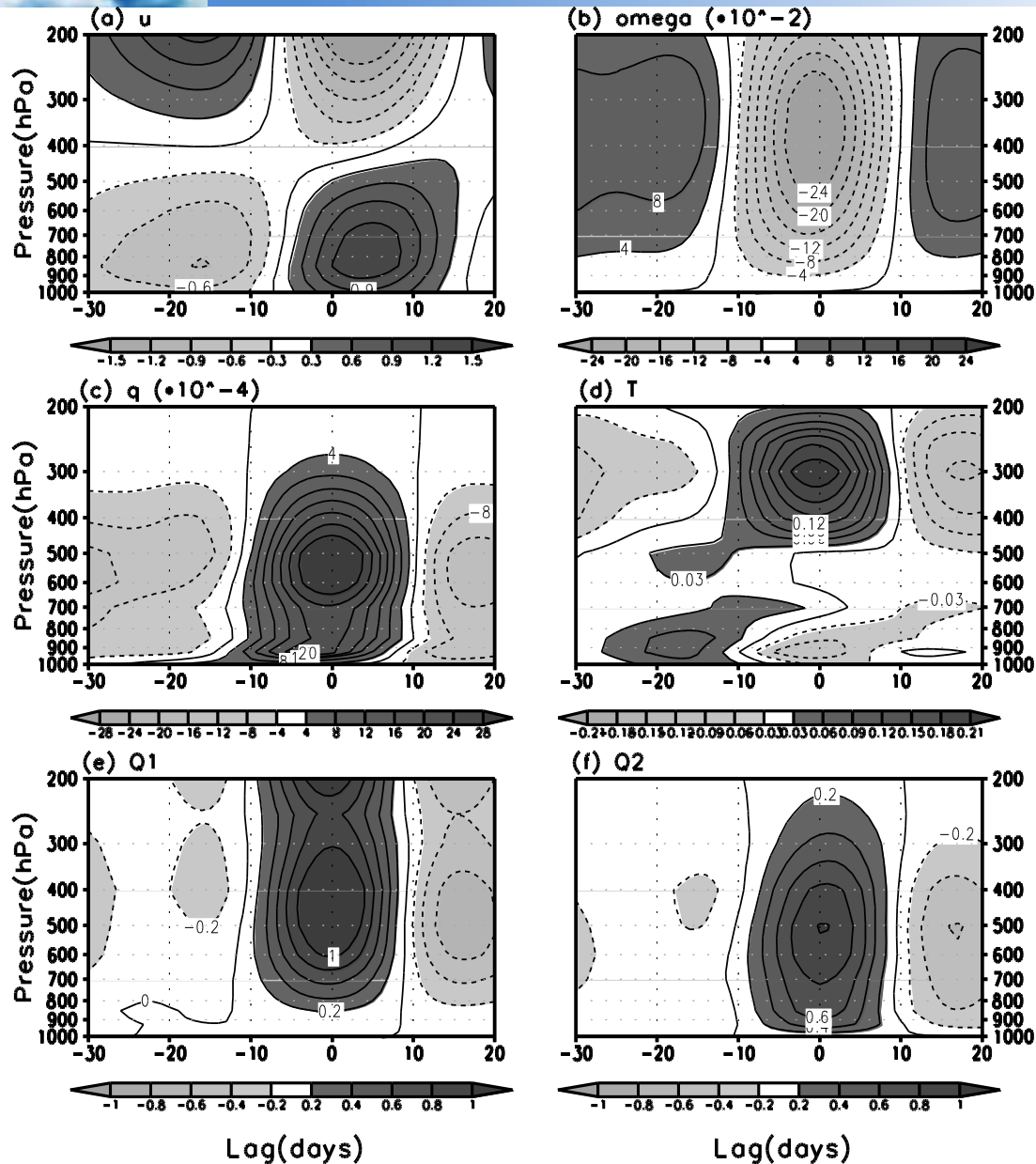


Lag(days)

Lag(days)

Lag-height plots of (a) zonal wind, (b) pressure velocity, (c), specific humidity, (d) temperature, (e) apparent heat source ($Q1$), and (f) apparent moisture sink ($Q2$) anomalies regressed onto OLR anomalies averaged over $[110^{\circ}-130^{\circ}E$ and $10^{\circ}S-10^{\circ}N]$ for CFS T126.

CFS T126 RAS



Lag-height plots of (a) zonal wind, (b) pressure velocity, (c), specific humidity, (d) temperature, (e) apparent heat source ($Q1$), and (f) apparent moisture sink ($Q2$) anomalies regressed onto OLR anomalies averaged over $[110^{\circ}-130^{\circ}\text{E}$ and $10^{\circ}\text{S}-10^{\circ}\text{N}]$ for CFS T126 RAS.