Role of SST structure on convectively coupled Kelvin-Rossby waves and its implication on MJO formation

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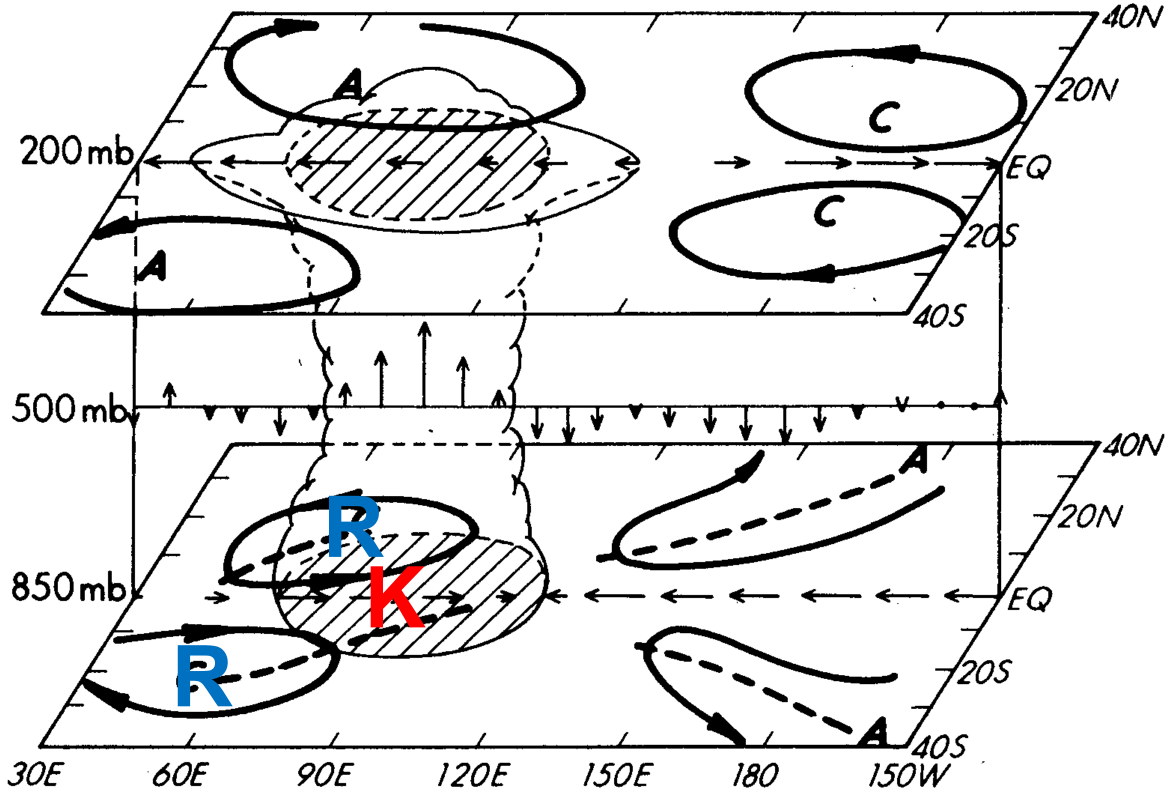
In-Sik Kang, Fei Liu, Min-Seop Ahn and Bin Wang: Role of SST structure on convectively coupled Kelvin-Rossby waves and its implication on MJO formation. Revised, *J. Climate*

Problems

1. What SST structure makes Convectively coupled Kelvin-Rossby waves?

2. Why is it important for the MJO formation?



(From Rui and Wang, 1990)

Working Strategy

1 **AGCM with realistic MJO**

2 **Aqua planet GCM**

Aqua Planet GCM:
GCM without zonal asymmetries due to SST, topography, and land-sea distributions

"For Understanding"

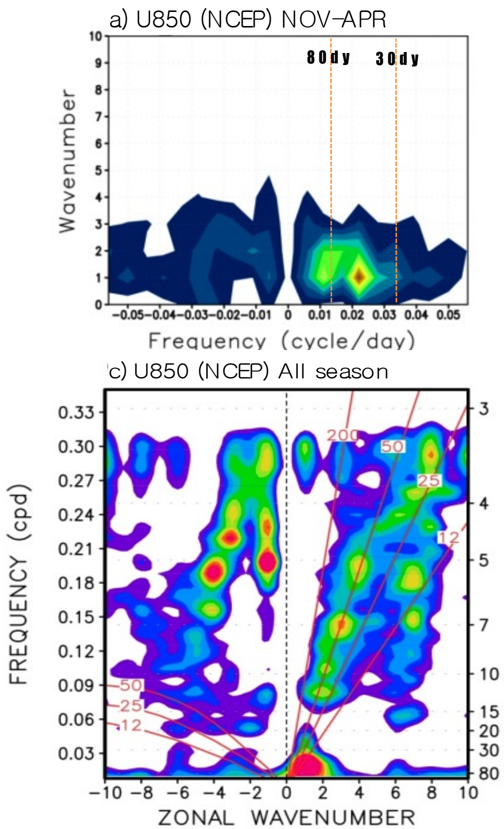
3 **Simple theoretical model**

One and Half layer model: (wang and Rui, 1990)
First baroclinic Troposphere and a barotropic PBL

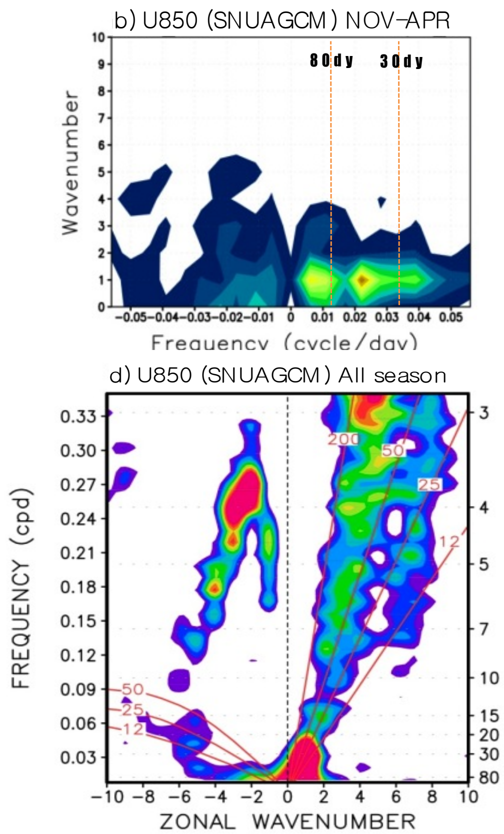
MJO Simulation In The SNUAGCM

Model	SNU FVAGCM.V1
Resolution	128 x 65 x L20 (300 km)
Description	AGCM with seasonally varying observed SST simplified version of relaxed Arakawa-Schubert scheme (SAS, Numaguti et al. 1995) Tokioka constraint: 0.075, Auto-conversion time scale: 2400
Period	Total Running period : 10 years Using period for analysis : last 7 years

OBS



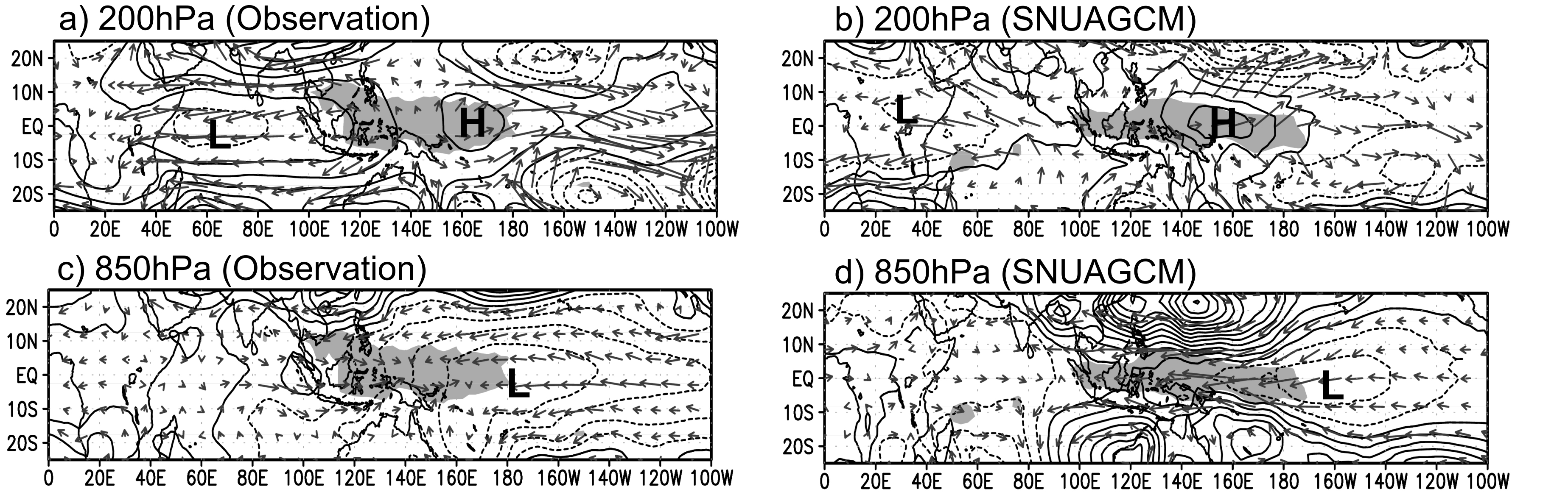
SNUAGCM



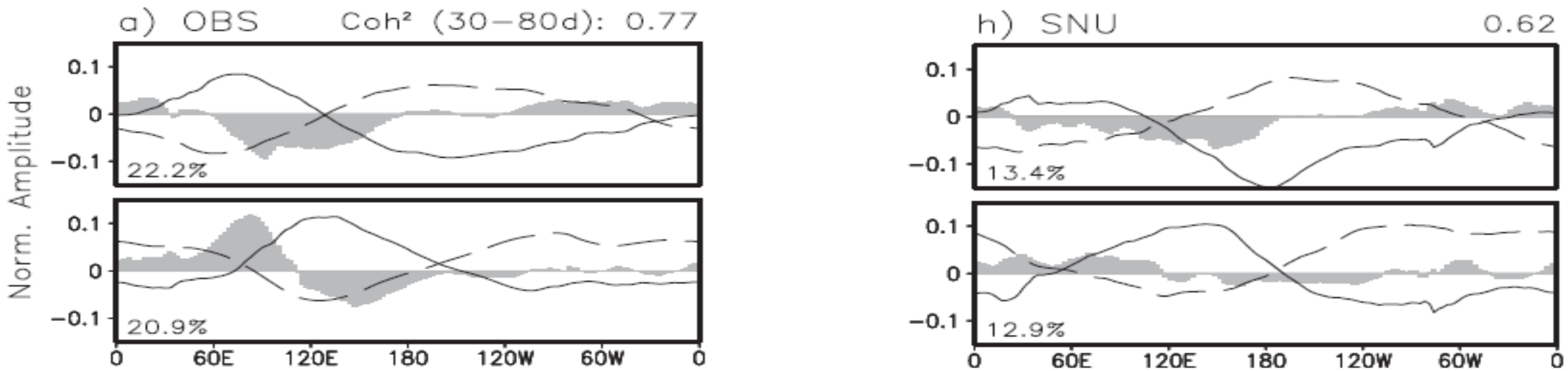
MJO Simulation In The SNUAGCM

MJO spatial patterns

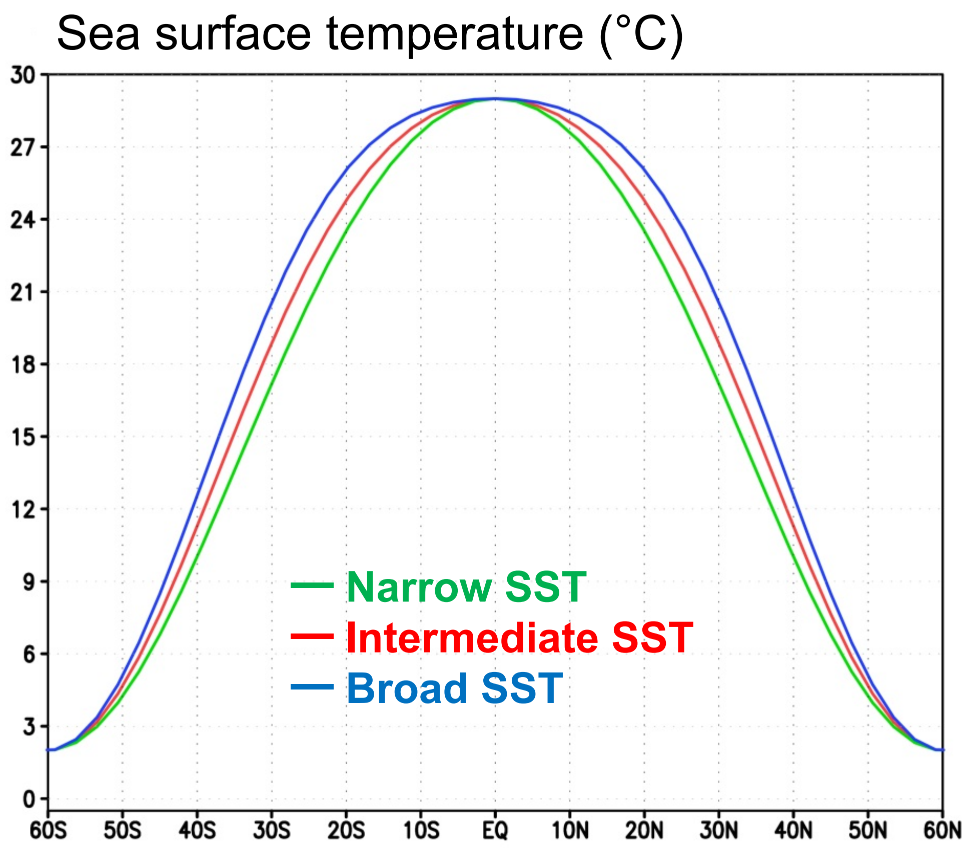
Shading: OLR (negative)
Contour: Geopotential height



Combined EOF patterns (Kim et al. 2009)



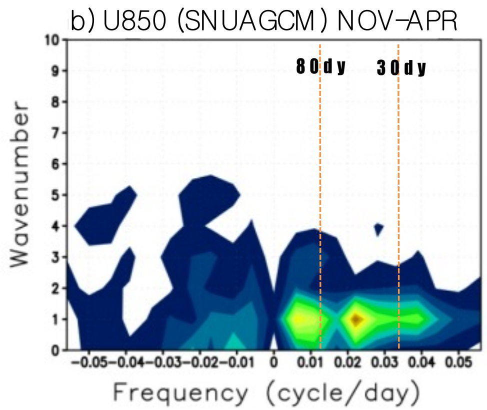
Aqua planet SST profiles

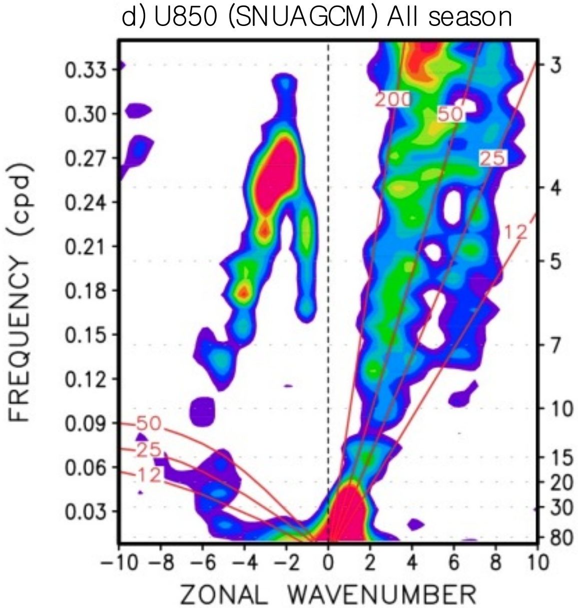


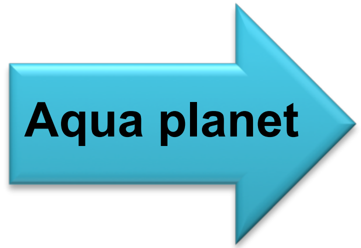
(Neale and Hoskins (2000), except that 2°C was uniformly added)

Aqua Planet SNUAGCM

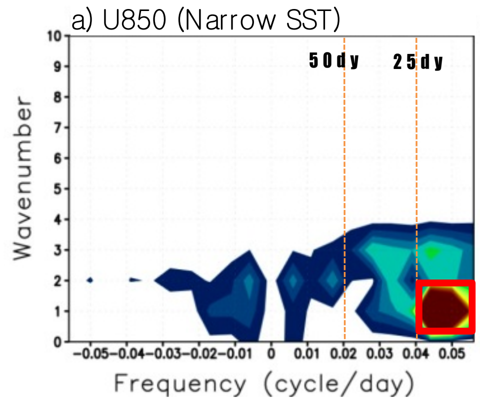
Full GCM

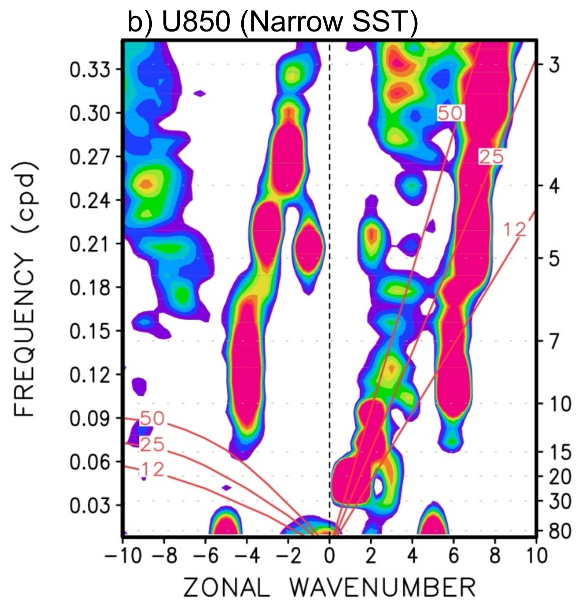






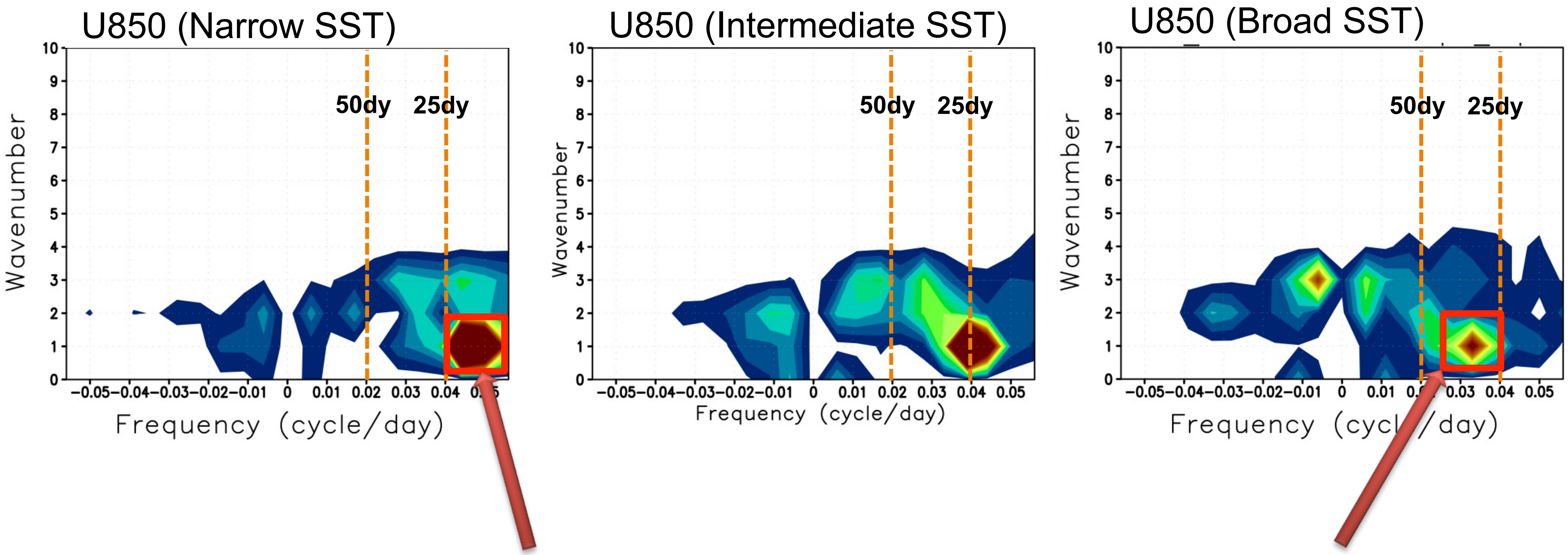
Aqua planet GCM





Impact of Meridional SST Scale

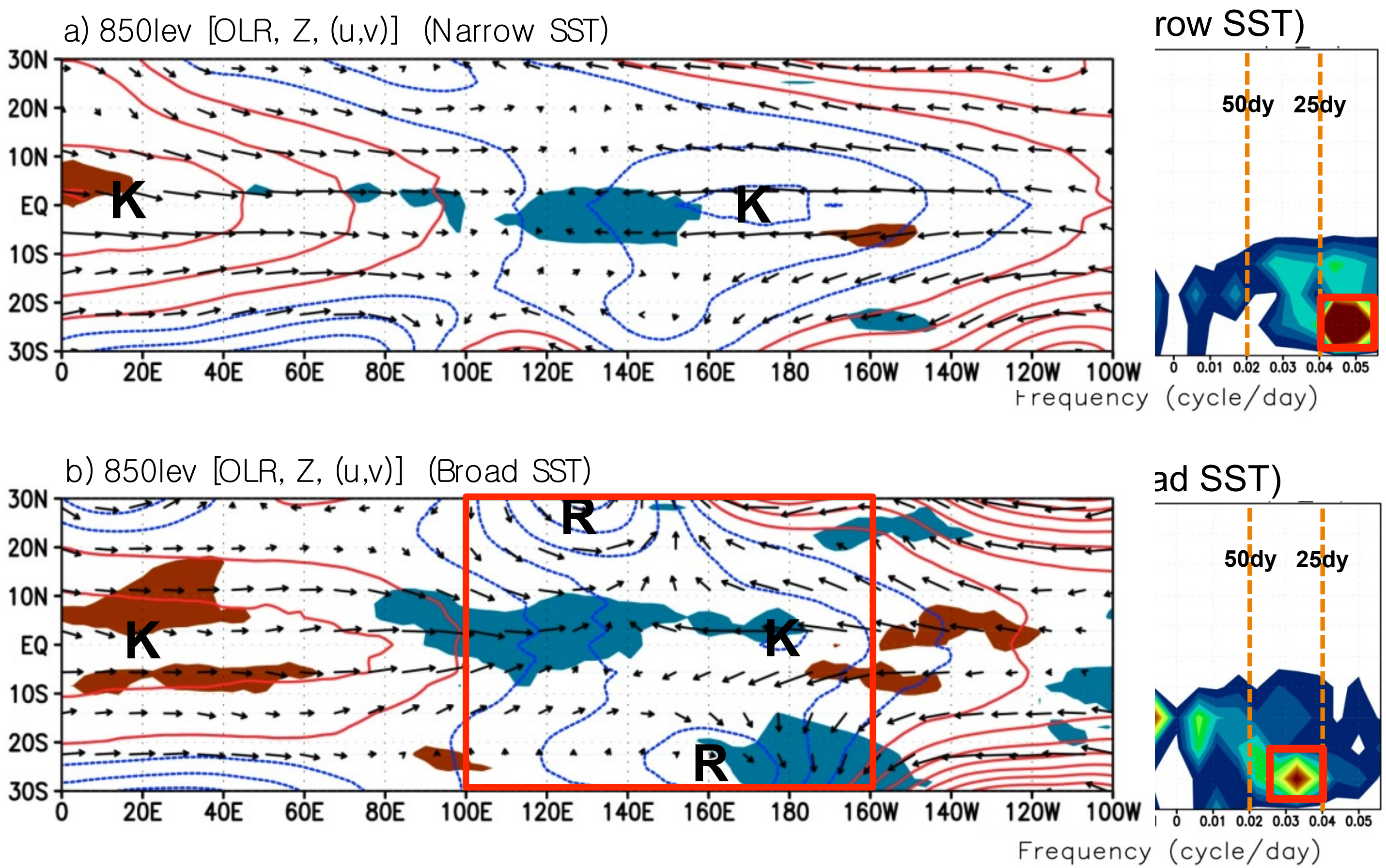
The power spectra of
Narrow, Intermediate, and Broad SST cases



Spatial pattern of these dominant signals shown in the next page!

Impact of Meridional SST Scale

The spatial patterns of Narrow and Broad SSTs



Contour: **850hPa Φ**, Shading: **OLR**(negative: blue), Vector: **850hPa wind**

Theoretical Model Equations

First Baroclinic Troposphere

$$u_t - \beta y v + \phi_x = -\kappa \nabla^2 u$$

$$\beta y u + \phi_y = 0$$

$$\phi_t + C_0^{\,2}(u_x + v_y) = \boxed{Q} - N\phi$$

$$\boxed{Q = \frac{bL}{\Delta p}\left(-\frac{1}{g}\int_{p_M}^{p_B} \nabla \cdot (\boxed{q(p)}V)\,dp + \frac{q_B - q_L}{g}\, b\boxed{W_b}\right)}$$

PBL

$$-\beta y v_b = -\phi_{bx} - \varepsilon u_b$$

$$\beta y u_b = -\phi_{by} - \varepsilon v_b$$

$$\boxed{W_b = -\Delta p_b (d_1 \phi_{yy} + d_2 \phi_y)}$$

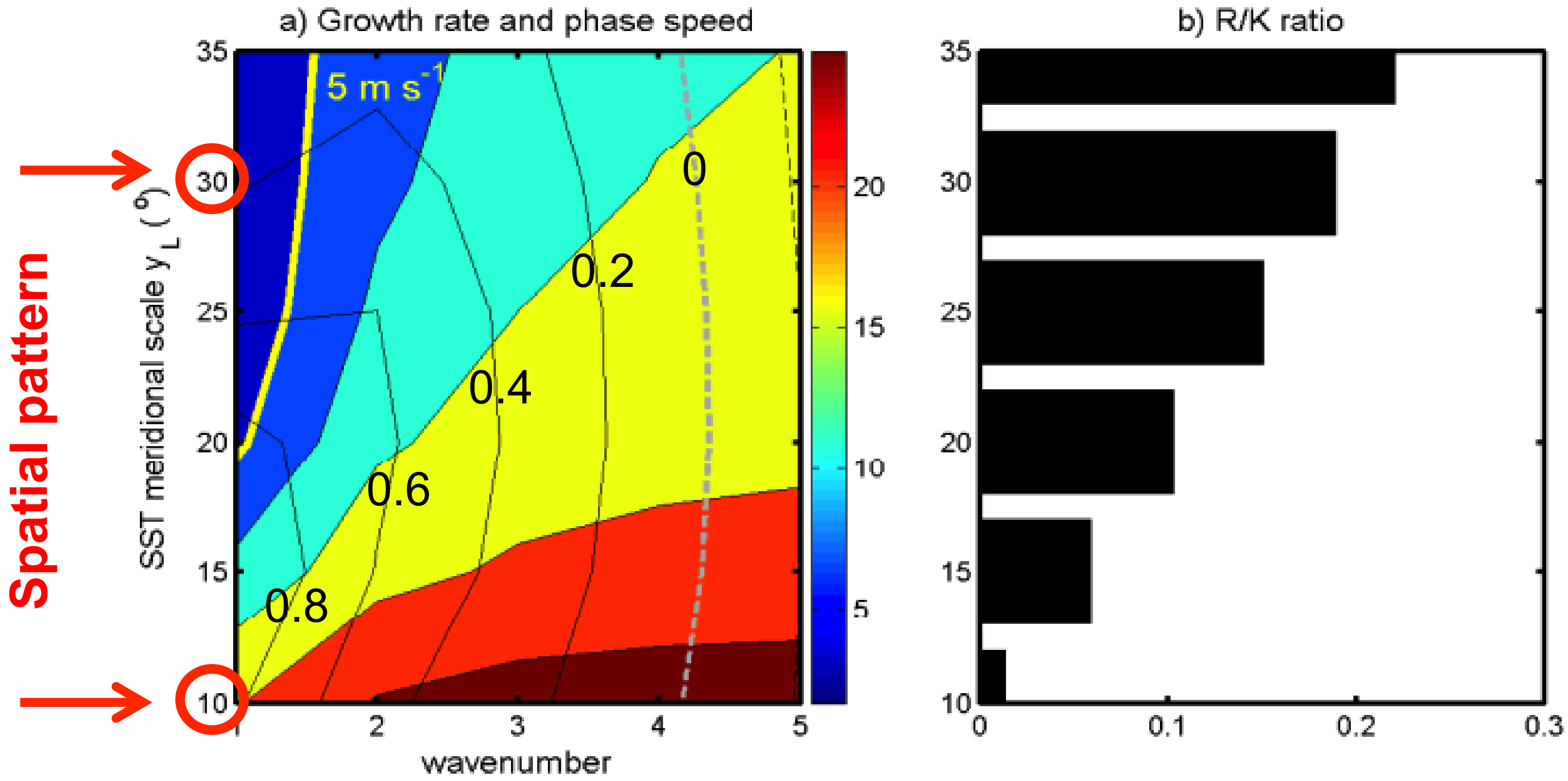
SST

$$\boxed{q(p) = [(0.972 \times SST - 8.92) \times 10^{-3}](p/p_s)^{7.6/2.2-1}}$$

Impact of Meridional SST Scale

SST center is specified at the equator, $y_0 = 0$

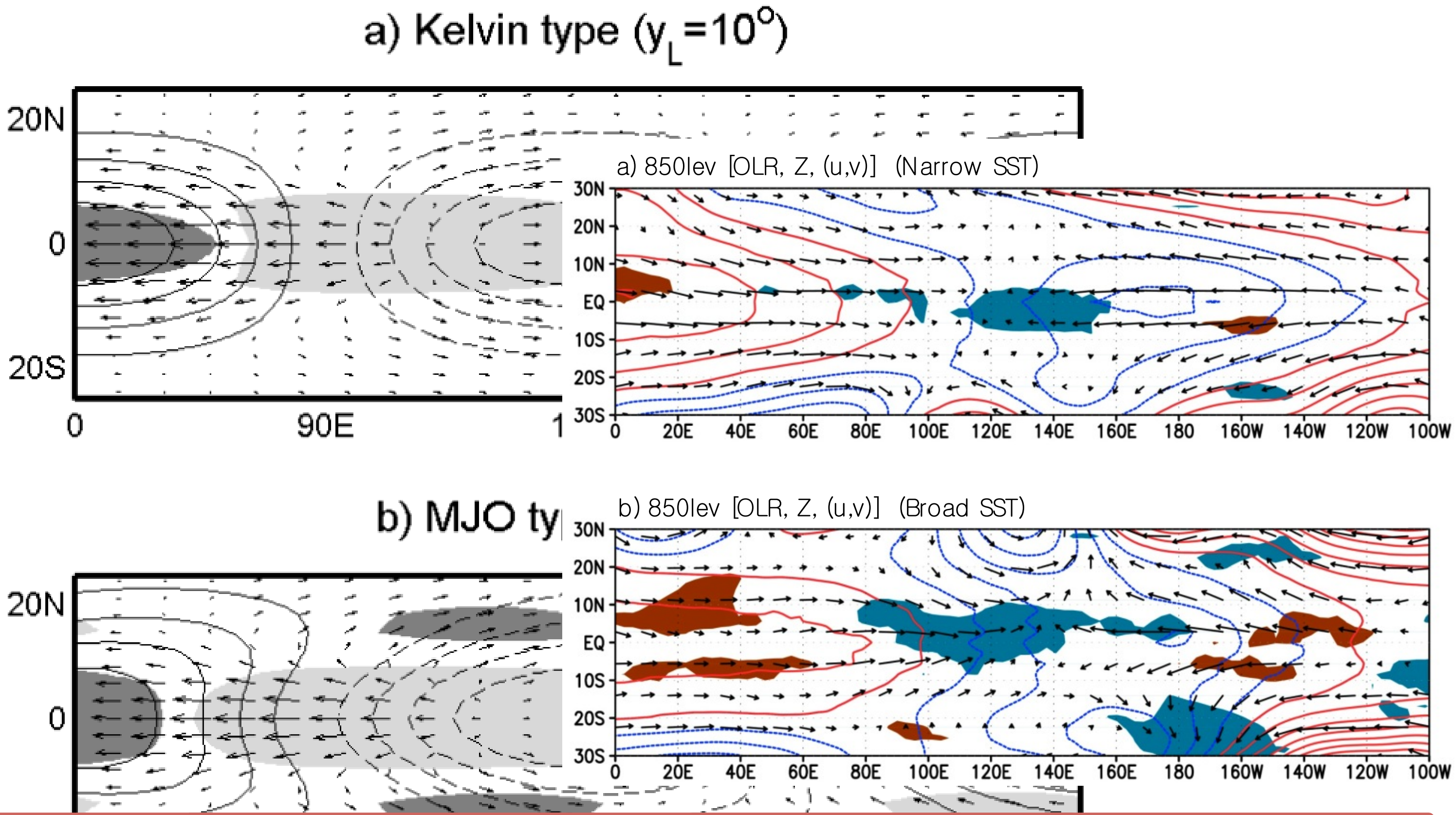
Meridional SST scale, y_L, is changed



Shading: **Phase speed ,** Contour: **Growth rate**

Impact of Meridional SST Scale

The spatial patterns of Kelvin and MJO type waves



Questions

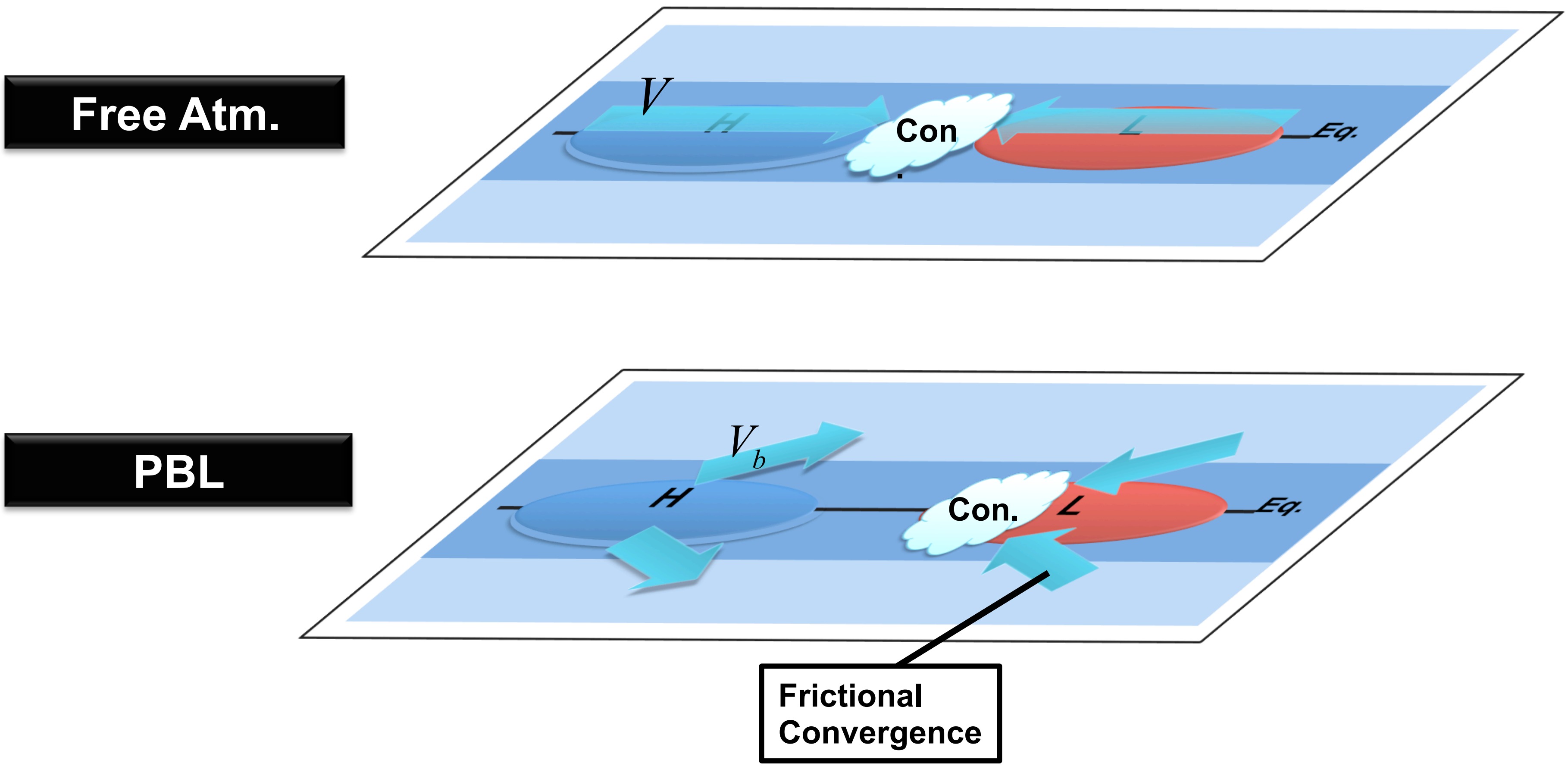
1. Why does the coupled Rossby wave only occur in the broad SST ?
2. How does the coupled Rossby wave modulate the phase speed of eastward propagating wave ?

Interpretation Ⅰ

Why does the coupled Rossby wave only occur in the broad SST ?

Narrow SST case

Low Moisture on the off-equator



Interpretation Ⅰ

Why does the coupled Rossby wave only occur in the broad SST ?

Broad SST case

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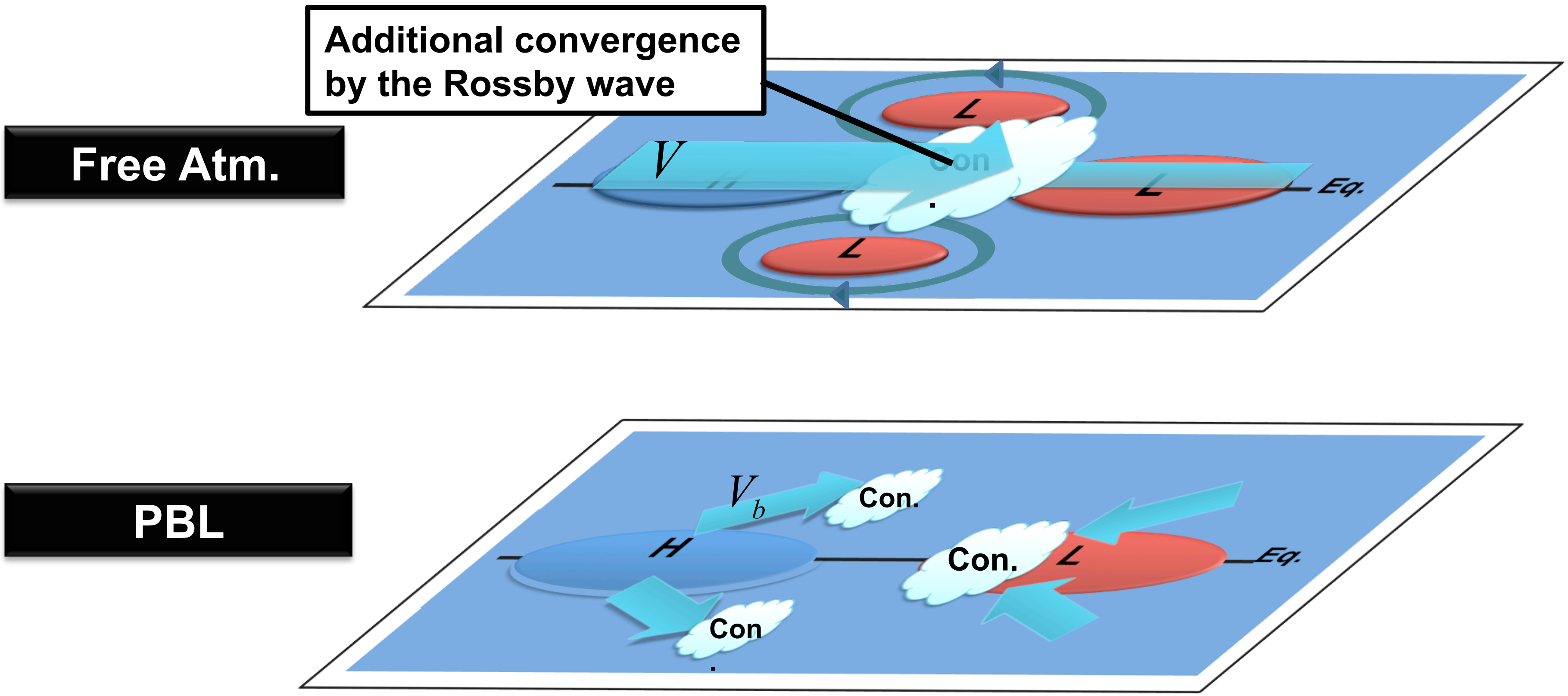


Interpretation II

Theoretical Model Equations

$$u_t - \beta y v + \phi_x = -\kappa \nabla^2 u$$

First Baroclinic Troposphere

$$\beta y u + \phi_y = 0$$

$$\phi_t + C_0^{\,2}(u_x + v_y) = \boxed{Q} - N\phi$$

Phase speed of propagating wave mainly determined by Φ_t

$$Q = \frac{bL}{\Delta p}\frac{1}{g}\int_{p_M}^{p_B} \nabla\cdot(\boxed{q(p)}\,\mathbf{V})\,dp + \frac{q_B - q_L}{g}\,\boxed{W_b}$$

PBL

$$\boxed{W_b = -\Delta p_b (d_1 \phi_{yy} + d_2 \phi_y)}$$

SST

$$\boxed{q(p) = [(0.972 \times SST - 8.92)\times 10^{-3}](p/p_s)^{7.6/2.2-1}}$$

Interpretation II

Geopotential height tendency equation

(Considering the Heating term and nondimensionalized form)

$$\frac{\partial \varphi}{\partial t} = -\boxed{M}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) - \boxed{B}\left(d_1 \frac{\partial^2 \varphi}{\partial y^2} + d_2 \frac{\partial \varphi}{\partial y}\right) - N\varphi$$

$\underline{M} = [1 - \boxed{\alpha}(SST - 9.2)]$: Free Atm. moisture convergence effect

$\underline{B} = \boxed{\gamma}(SST - 9.2)$: PBL frictional convergence effect

(0 < *M*, *B* <1)

$$\underline{\alpha} = \frac{b\Delta A}{p_M}\boxed{q_c}\frac{LR}{C_0^{\,2} C_p} \qquad \underline{\gamma} = \frac{1}{\varepsilon}\frac{b\Delta A_b}{p_M}(q_b - \boxed{q_c})\frac{LR}{C_0^{\,2} C_p}$$

Additional convergence by the Rossby wave

(q_c : Moisture in free atmosphere)

$\therefore\ q_c\uparrow \Rightarrow \alpha\uparrow, \gamma\downarrow \Rightarrow M\downarrow, B\downarrow \Rightarrow$ **small tendency**

(Slow propagation)

Conclusion

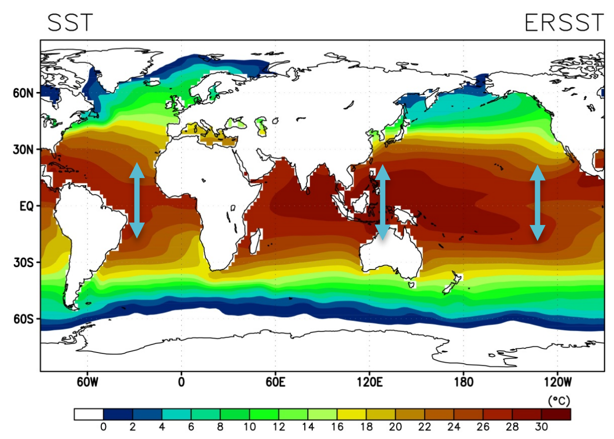
▶ **Aqua planet GCM and Theoretical model show that**

- Convectively coupled Kelvin-Rossby wave is essential structure of the MJO

- Meridional SST scale controls couple of K-R waves

→ Changes Moisture Availability on the off-equator

▶ **A Region from the Indian Ocean to the Western Pacific shows meridionally broad SST scale because of the warm pool**



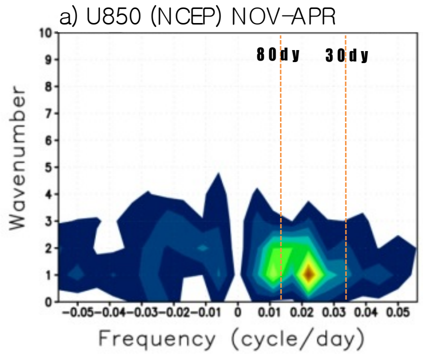
Thank you

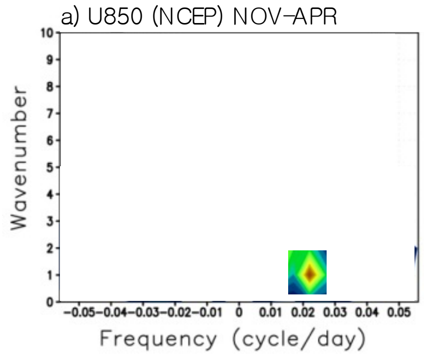
Questions and Comments
slowly please

(Wheeler et al. 2000)

Raw data

Fourier transform





Spectral power makes to “0”
, except the wanted signal

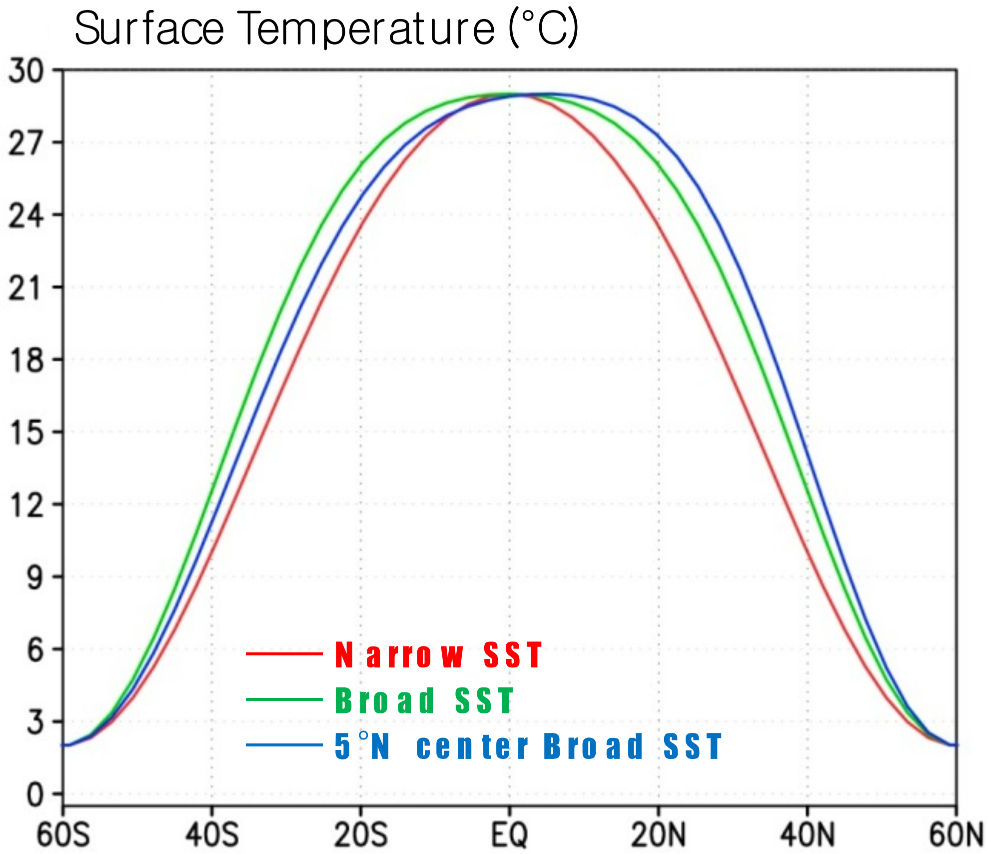
Inverse Fourier transform

Wave signal data

Regressed to other variables

Wave Spatial pattern

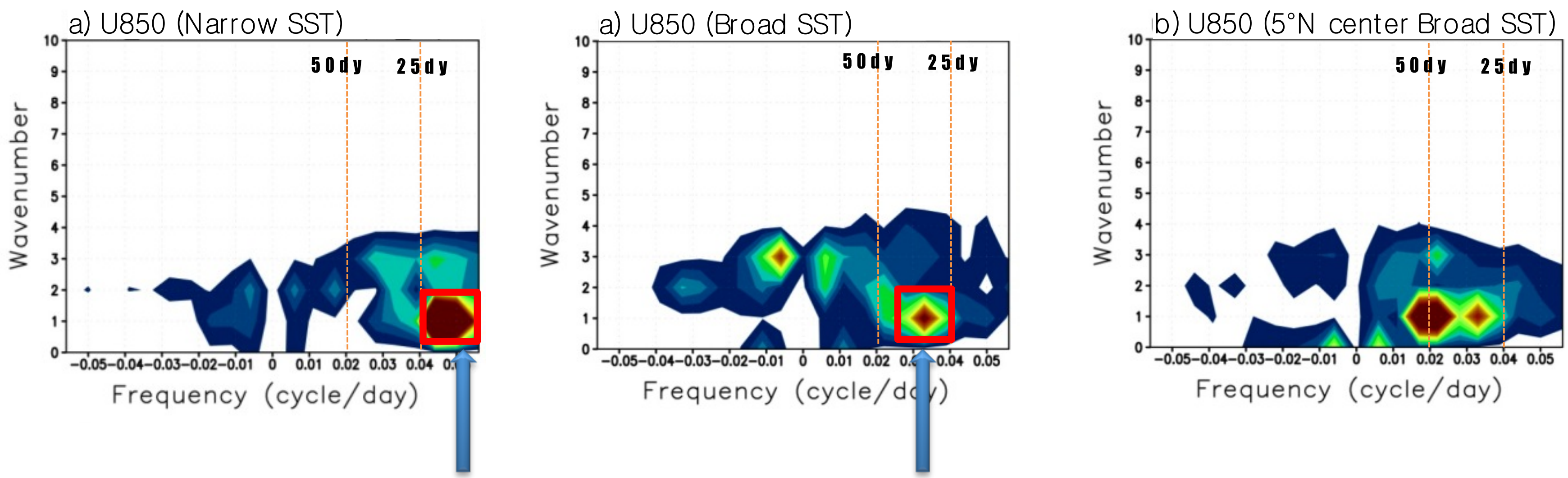
Aqua planet SST profiles



(Neale and Hoskins (2000), except that 2°C was uniformly added)

Impact of SST

The power spectra of
Narrow, Broad, and 5°N centered Broad SSTs



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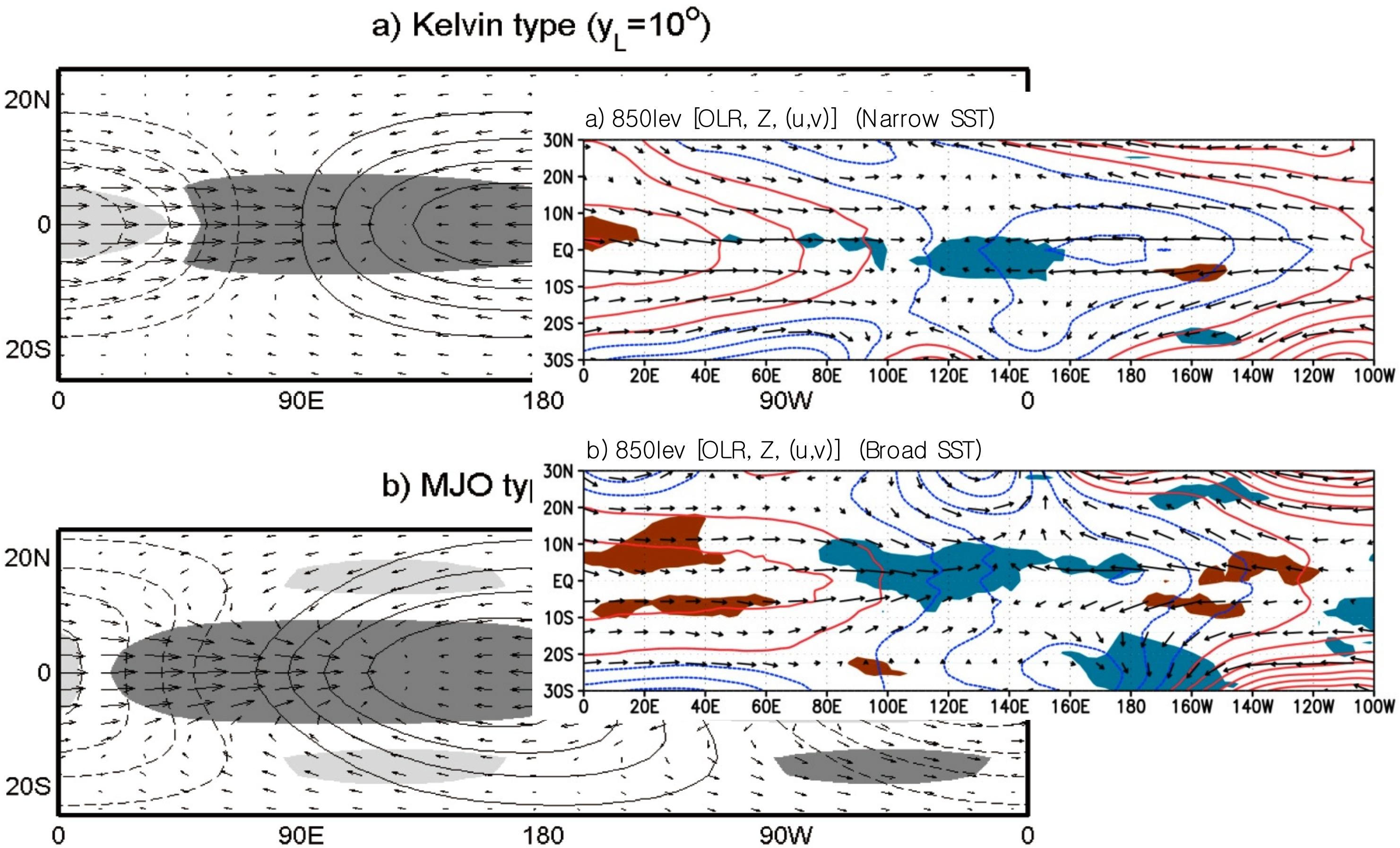
The spatial patterns of Kelvin and MJO type waves



Contour: **Temperature**, Shading: **Precipitation**(positive: dark), Vector: **wind**

First Baroclinic free atmosphere equations

based on the long-wave approximation

$$u_t - \beta y v + \phi_x = -\kappa \nabla^2 u$$

$$\beta y u + \phi_y = 0$$

$$\phi_t + C_0^2 (u_x + v_y) = Q - N\phi$$

Where, $$Q = \frac{bL}{\Delta p}\Big(\underbrace{-\frac{1}{g}\int_{p_M}^{p_B} \nabla \cdot (q(p)V)\,dp}_{①} + \underbrace{\frac{q_B - q_L}{g} b \boxed{W_b}}_{②}\Big)$$

① Free tropospheric moisture convergence ($\sim q\nabla \cdot V$)

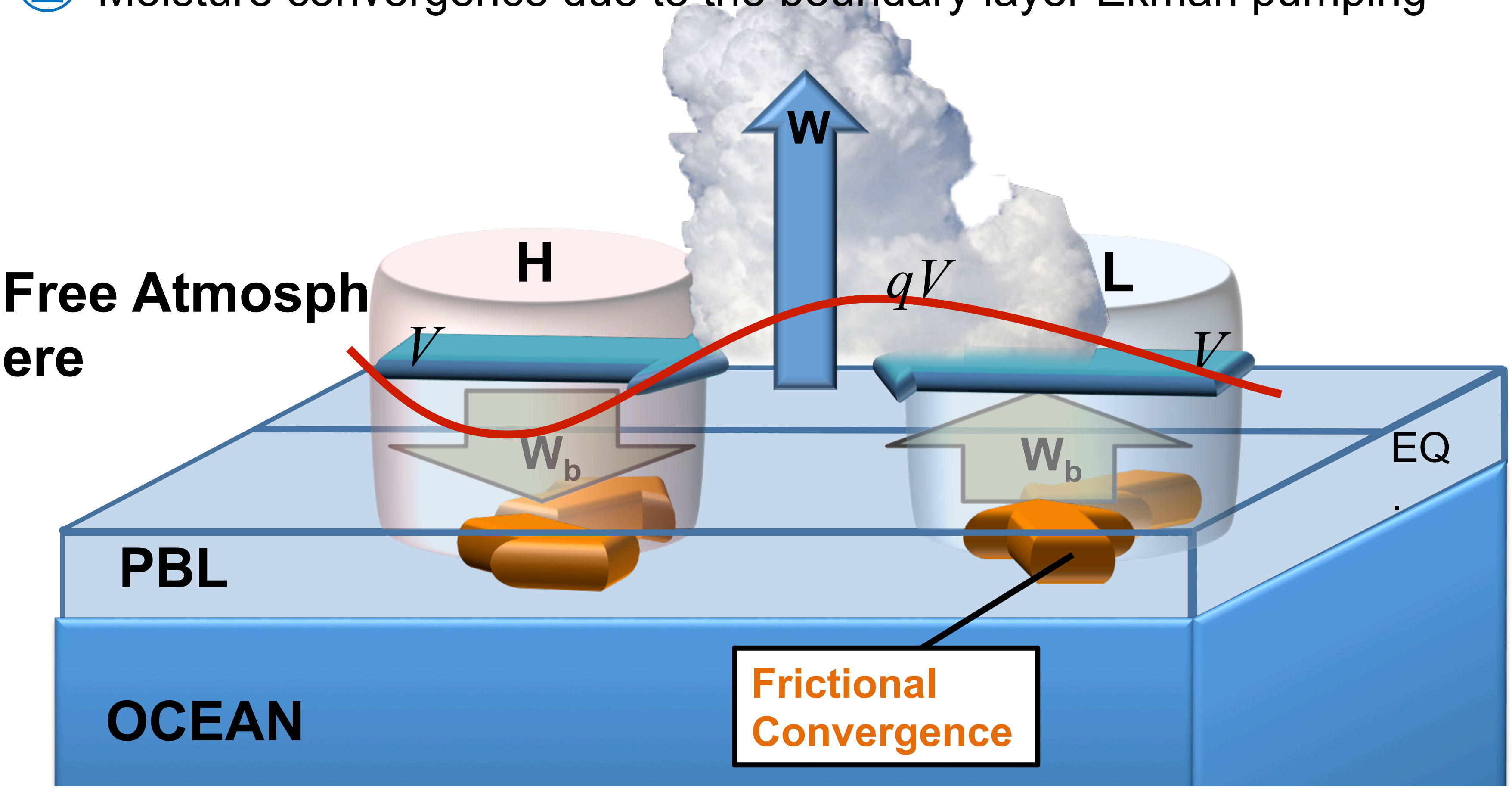
② Moisture convergence due to the boundary layer Ekman pumping W_b

Forcing Term

$$Q = \frac{bL}{\Delta p}\Big(\underbrace{-\frac{1}{g}\int_{p_M}^{p_B} \nabla\cdot(q(p)V)\,dp}_{①} + \underbrace{\frac{q_B - q_L}{g} bW_b}_{②}\Big)$$

① Free tropospheric moisture convergence

② Moisture convergence due to the boundary layer Ekman pumping W_b



PBL Equations

Steady boundary layer momentum equation
for low frequency motion (Wang and Li 1994)

$$-\beta y v_b = -\phi_{bx} - \varepsilon u_b$$

$$\beta y u_b = -\phi_{by} - \varepsilon v_b$$

Ekman pumping at the top of the PBL

$$\boxed{W_b = -\Delta p_b (d_1 \phi_{yy} + d_2 \phi_y)}$$

Where,
$$\left(\begin{aligned} d_1 &= \varepsilon / (\varepsilon^2 + \beta^2 y^2) \\ d_2 &= -2\varepsilon\beta^2 y / (\varepsilon^2 + \beta \ \ y^2)^2 \end{aligned} \right)$$

Non-dimensionalized Equations

After assuming, $q(p) = [(0.972 \times SST - 8.92) \times 10^{-3}](p / p_s)^{7.6/2.2-1}$

Nondimensional equations become

$$u_t - yv + \phi_x =$$

$$yu + \phi_y =$$

$$\phi_t + (u_x + v_y) = (SST - 9.2)[\boxed{\alpha}(u_x + v_y) - \boxed{\gamma}(\boxed{d_1}\phi_{yy} + \boxed{d_2}\phi_y)] - N\phi$$

$$\phi_t + M(u_x + v_y) + C(d_1\phi_{yy} + d_2\phi_y) = -N\phi$$

$$\begin{pmatrix} M = [1 - \alpha(SST - 9.2)] \\ C = \gamma(SST - 9.2) \end{pmatrix}$$

Considering only 3 meridional modes

$$\phi(y) = \hat{\phi}(e^{-y^2/2} + ye^{-y^2/2} + (2y^2 - 1)e^{-y^2/2})$$

The equation governing the Kelvin wave ($v = 0$) near the equator ($y)\approx 0$

without the diffusion term becomes

$$\boxed{\phi_{tt} - M\phi_{xx} - B\phi_t = 0}$$

Where, $\left(\begin{array}{l} M = 1 - \alpha(SST - 9.2) \\ B = 2\gamma(SST - 9.2)/\varepsilon \end{array} \right)$

→ wave solution, $\phi = \hat{\phi} \cdot e^{i(kx - \sigma t)}$

$$\sigma = iB/2 + \sqrt{Mk^2 - B^2/4}$$

Phase speed $\mathrm{Re}(\sigma)/k = \sqrt{M - B^2/4k^2}$

,

M : Free Atm. moisture convergence

B : PBL frictional convergence

Phase speed of equatorial wave

$$\mathrm{Re}(\sigma)/k = \sqrt{\boxed{M} - \boxed{B^2}/4k^2}$$

$$\left[\begin{array}{ll} M = 1 - \alpha(SST - 9.2) & \text{: Free Atm. moisture convergence effect} \\ B = 2\gamma(SST - 9.2)/\varepsilon & \text{: PBL frictional convergence effect} \end{array}\right.$$

SST↑ ⇒ M↓, B↑ ⇒ phase speed slow down

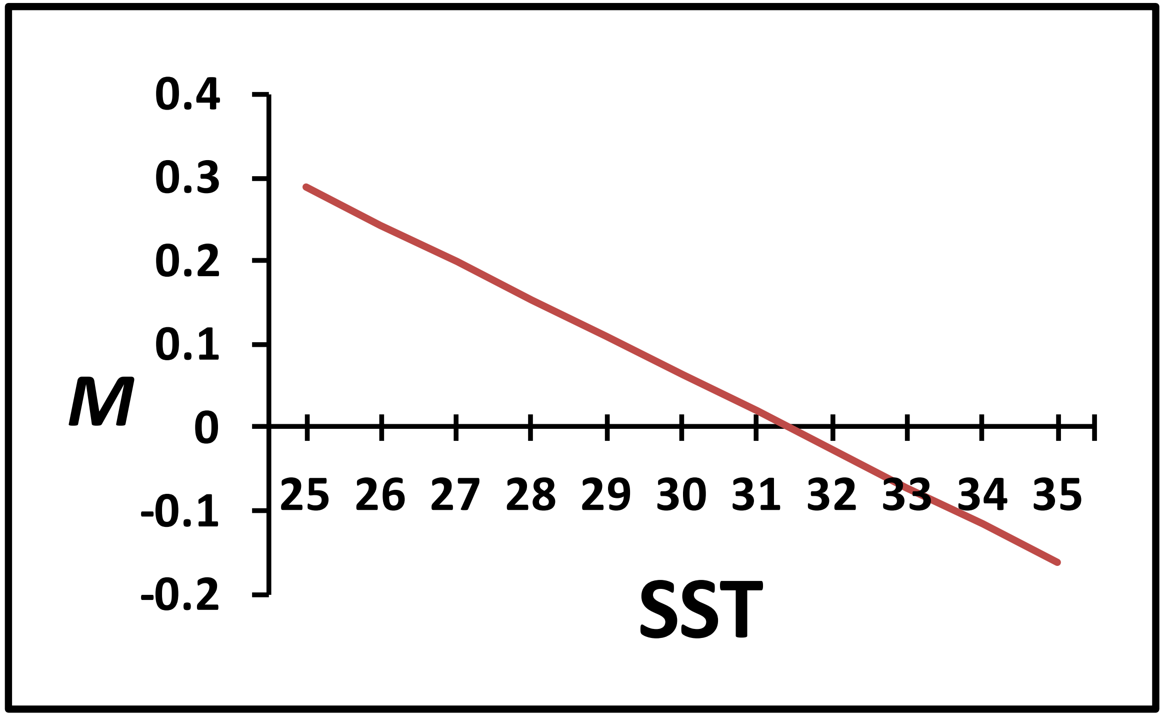
$$\alpha = \frac{b\Delta p}{p_M} q_c \frac{LR}{C_0{}^2 C_p} \approx 0.045 \qquad \gamma = \frac{1}{\varepsilon} \frac{b\Delta p_b}{p_M} (q_b - q_c) \frac{LR}{C_0{}^2 C_p} \approx 0.04$$

Phase speed

$$\mathrm{Re}(\sigma)/k = \sqrt{\boxed{M} - B^2/4k^2}$$

For $B = 0$, Gross moist stability($)M$ **(Phase speed)**

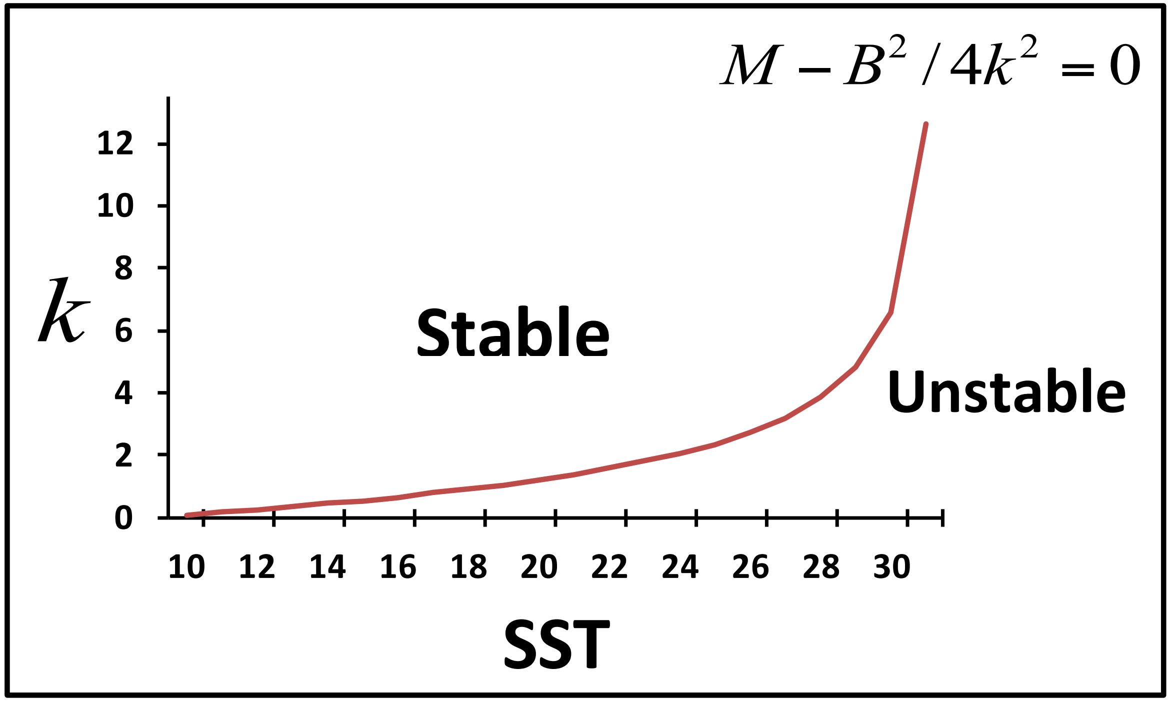
$$M = [1 - \alpha(SST - 9.2)]$$



Wave Number Dependency

$$\mathrm{Re}(\sigma)/k = \sqrt{\boxed{M - B^2/4k^2}}$$

If $M < (B^2/4k^2)$, **Unstable**



∴ longest waves are more amplified

Simplified Governing Equations

$$u_t - yv + \phi_x = -\kappa \nabla^2 u$$

$$yu + \phi_y = 0$$

$$\phi_t + (u_x + v_y) = (SST - 9.2)[\alpha(u_x + v_y) - \gamma(d_1\phi_{yy} + d_2\phi_y)] - N\phi$$

$$SST = SST_0 \exp[-((y - y_0)/y_L)^2/2]$$

$SST_0 = 29.5^o C$

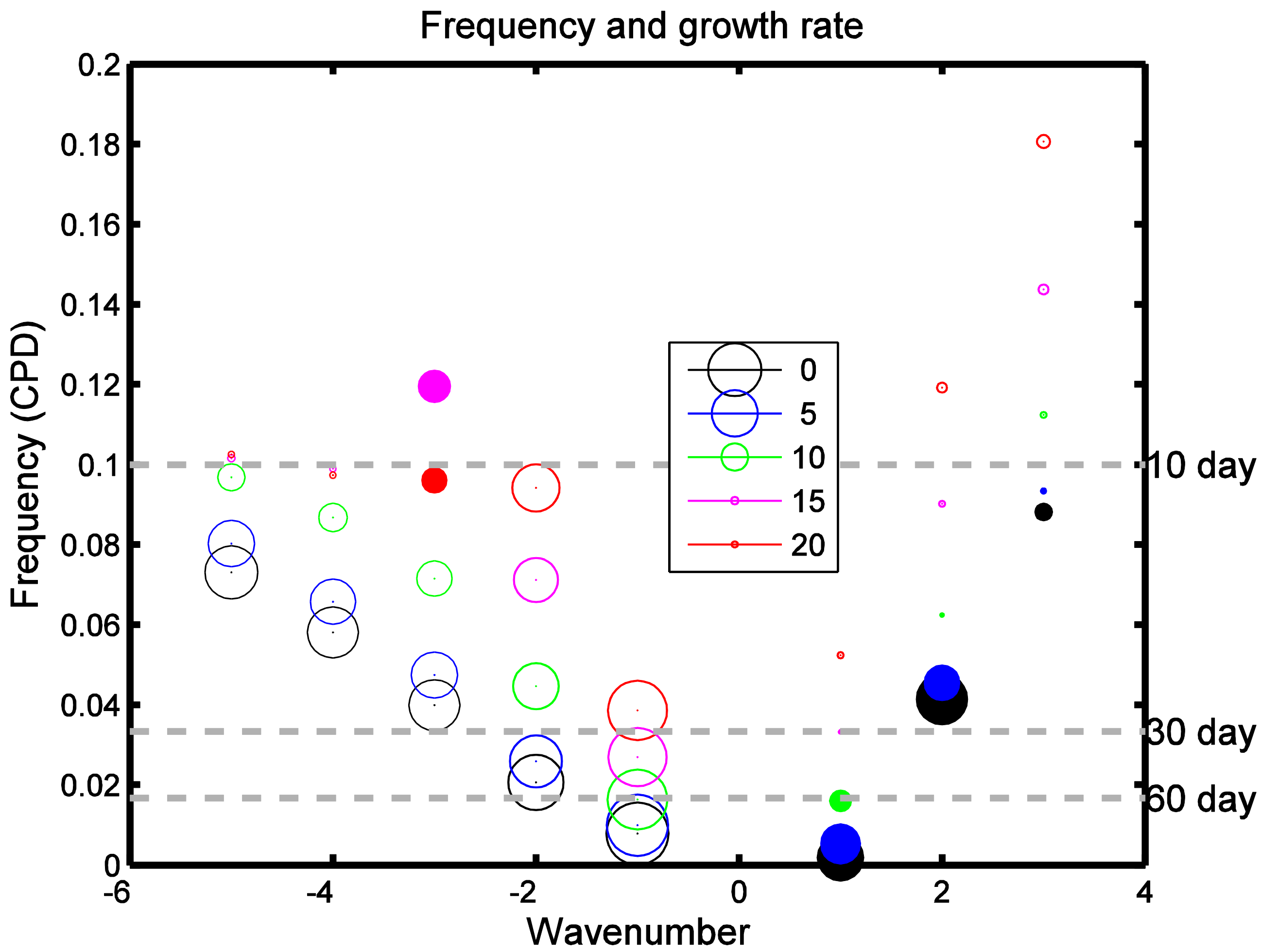
y_0 : SST center latitude

y_L : meridional e-folding scale of the SST

Impact of SST Center

Meridional SST scale is specified at $y_L = 25$

SST center, y_0 , is changed from 0 to 20°N



Color : **SST center**

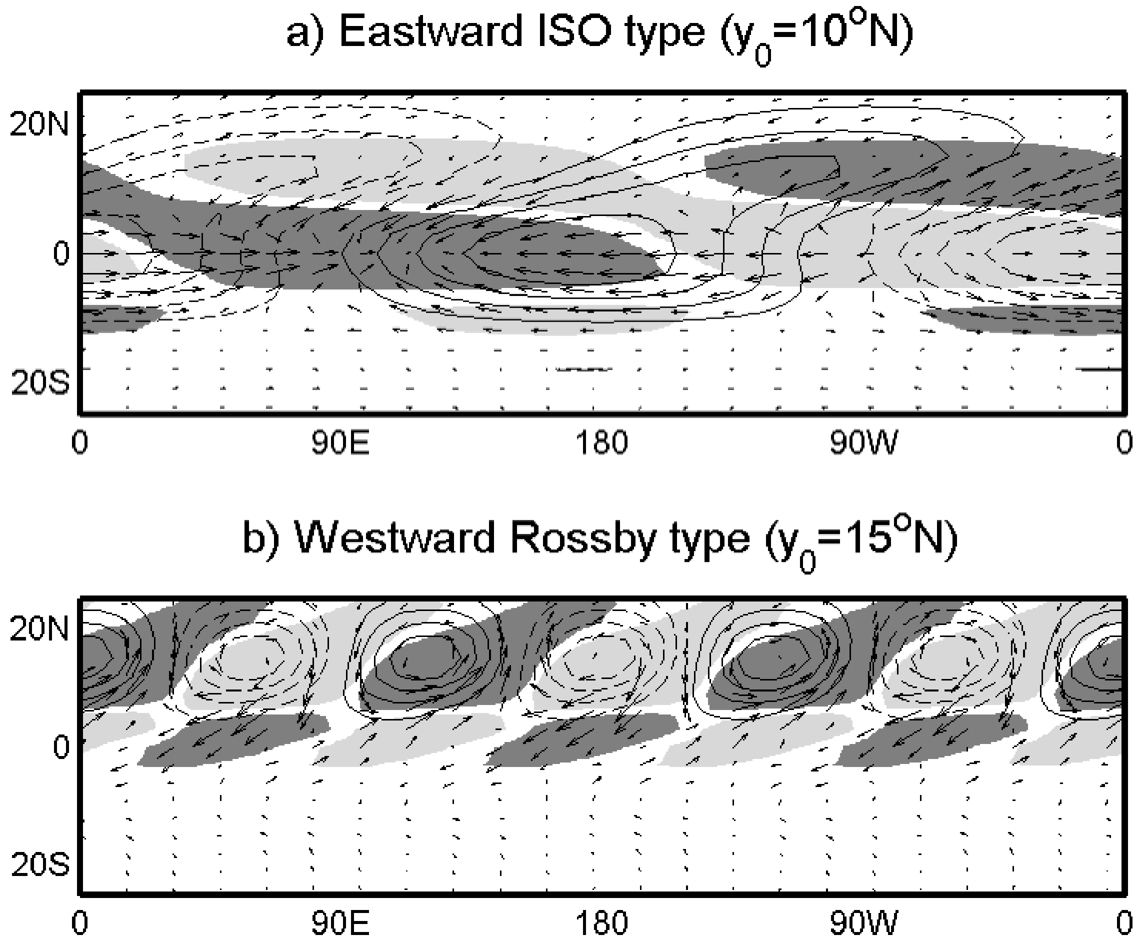
Dots : **unstable mode**

Circles: **damped mode**

Diameter : **growth rate**

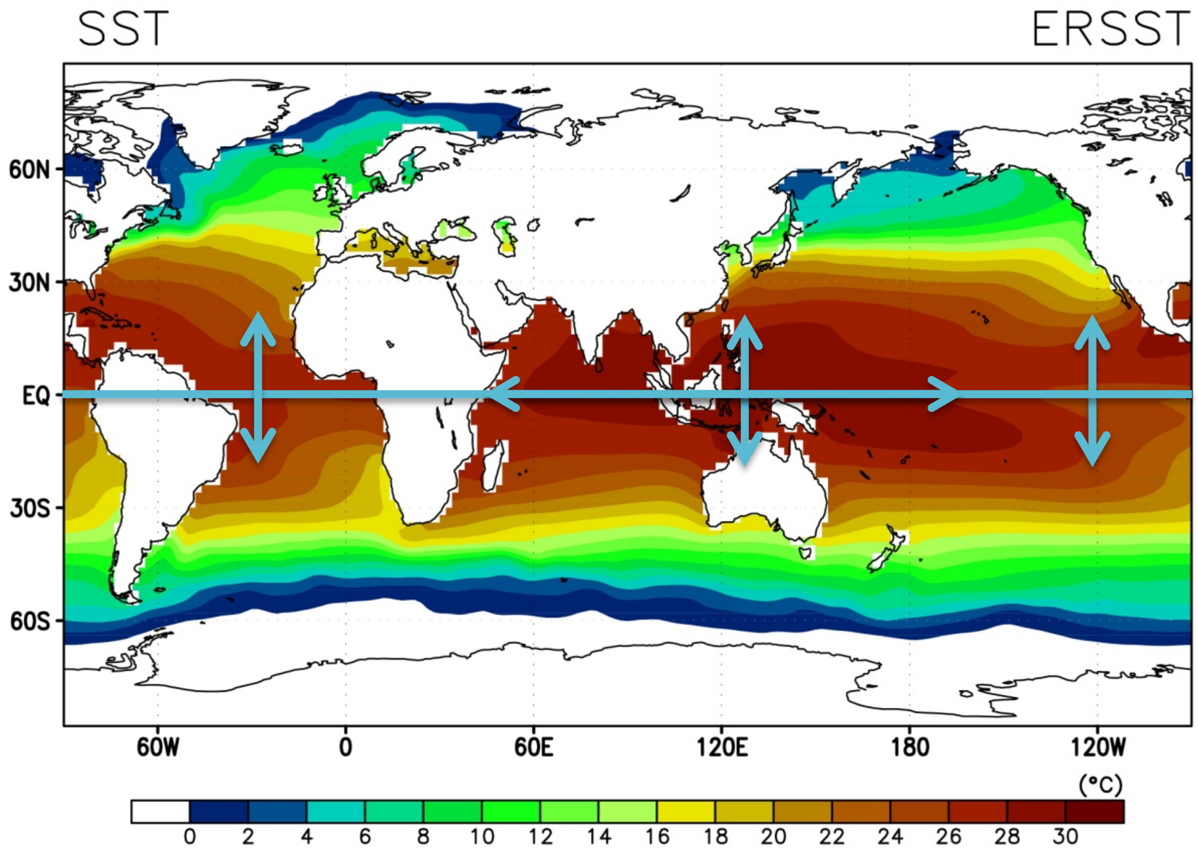
Impact of SST Center

The spatial patterns of
eastward ISO and westward Rossby type waves. ($y_L = 25^o$)



Contour: **Temperature**, Shading: **Precipitation**(positive: dark), Vector: **wind**

Characteristics of Observed SST



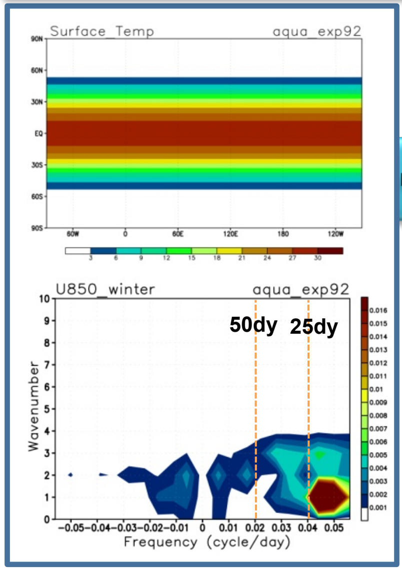
From **I.O** to the **W.Pacific**

- **Meridional Scale**
  - Broad
- **Maximum Center**
  - Shifted to north
- **Warm pool**
  - Background wind: Westerly
- **Maximum value**
  - High

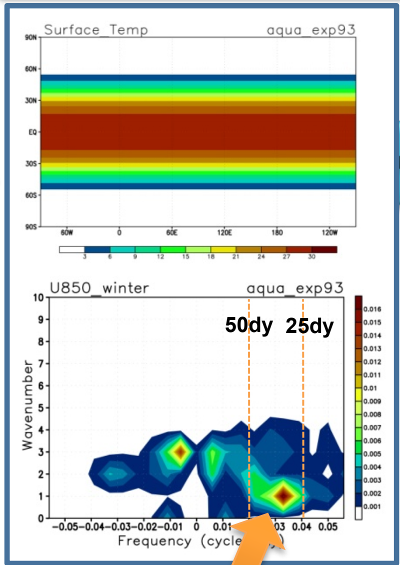
Impact of SST In The Aqua Planet GCM

SST structures are obtained by Neale and Hoskins (2000)

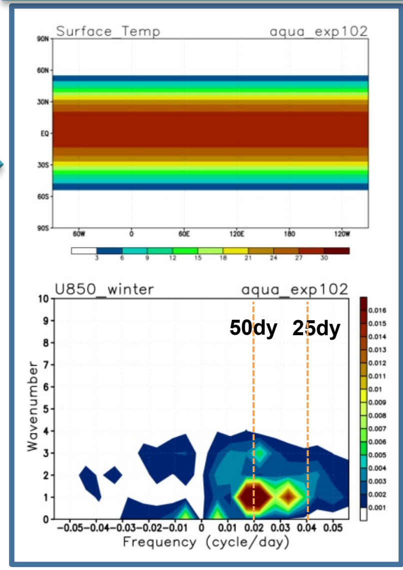
Narrow SST



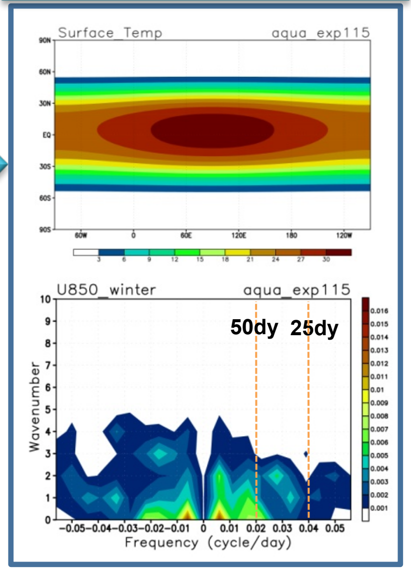
Broad SST



5°N center



Idealized W arm pool

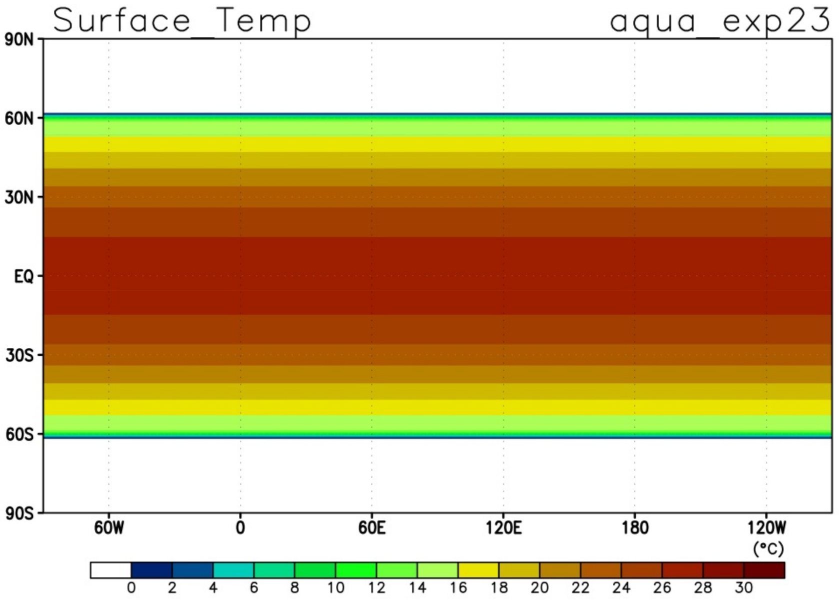


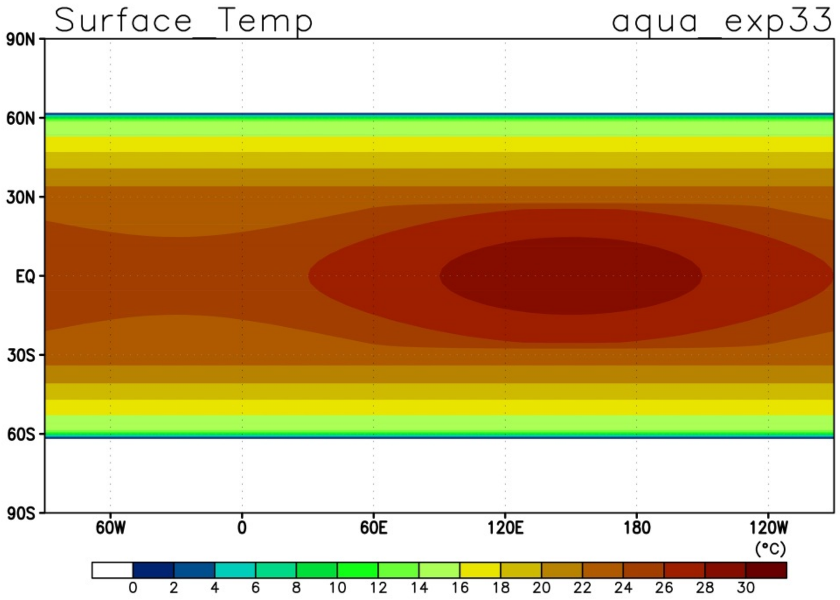
Eastward propagation slows down

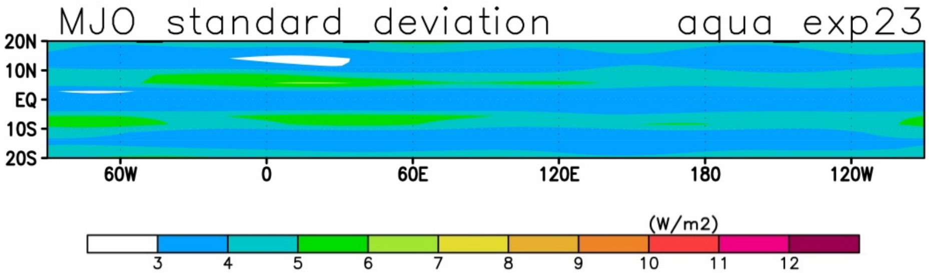
NCAR/CAM3 shows that meridional SST gradient is important factor for MJO (Maloney et al. 2010)

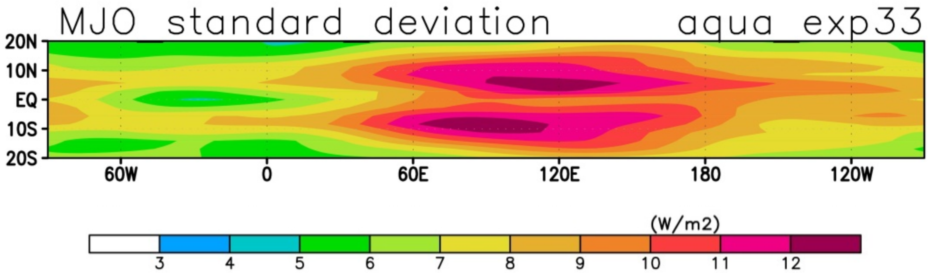
Zonally symmetric SST

Idealized Warm pool SST

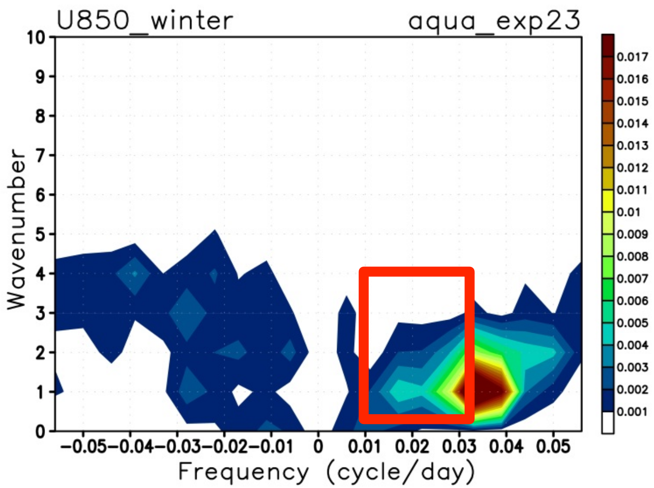




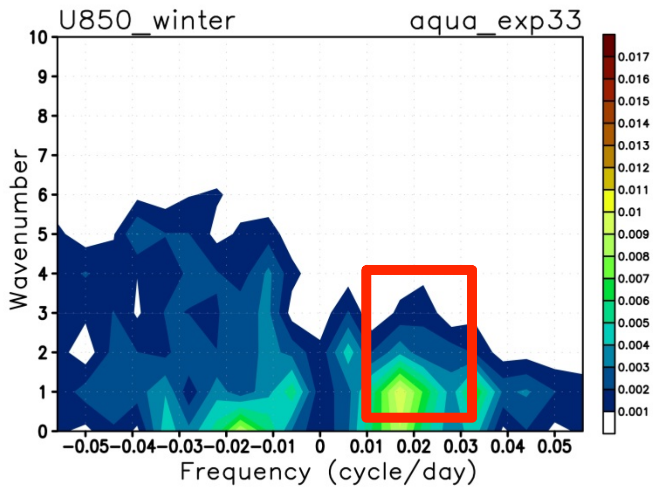




Zonally symmetric SST



Idealized Warm pool SST



Filter signal
Period: 30~100 days
Wave number: 0.3~5

MJO Theories

1. frictionally coupled moist Kelvin-Rossby wavepacket
   (Wang and Rui 1990)

2. wind-evaporation feedback
   (Emanuel 1987; Neelin et al. 1987)

3. air-sea interaction
   (Flatau et al. 1997; Wang and Xie 1998; Waliser et al. 1999; Hendon 2000)

Interaction between large-scale moisture dynamics and convection seems to b
e one of the key dynamical processes of the MJO

Interpretation II

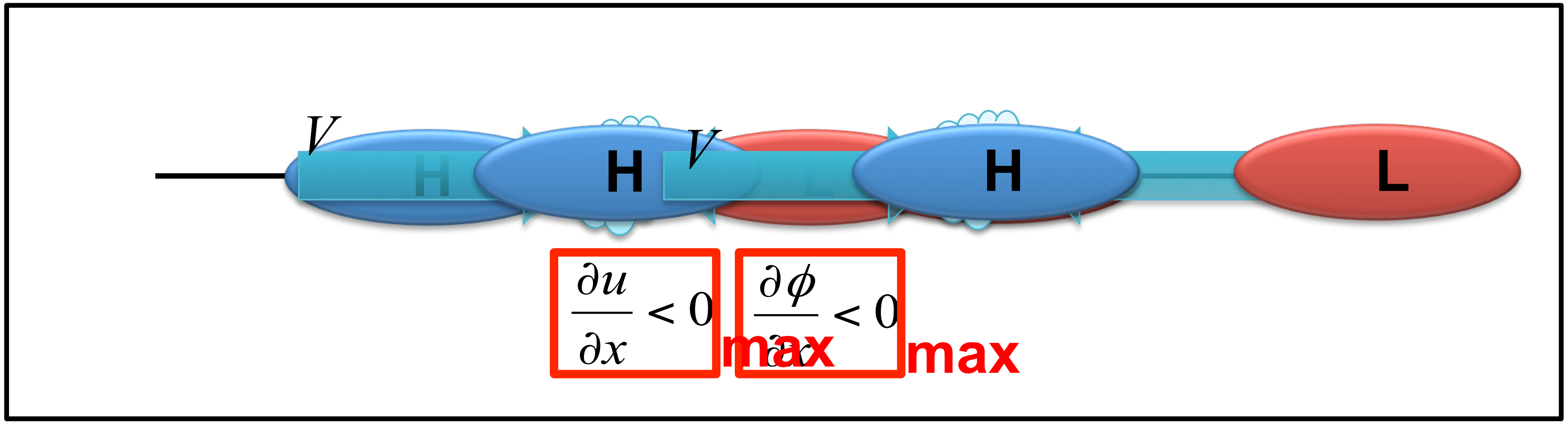
How does the coupled Rossby wave modulate the phase speed of eastward propagating wave?

Kelvin wave equation

$$\frac{\partial u}{\partial t} = -\boxed{\frac{\partial \phi}{\partial x}}$$

$$\frac{\partial \phi}{\partial t} = -M\boxed{\frac{\partial u}{\partial x}}$$

Eastward propagation of Kelvin wave



Interpretation II

How does the coupled Rossby wave modulate the phase speed of eastward propagating wave?

Kelvin wave equation

$$\frac{\partial u}{\partial t} = -\boxed{\frac{\partial \phi}{\partial x}}$$

Rossby wave makes Additional Heating

T↑ ⇒ ***M***↓ (0<M<1)

Smaller tendency

$$\boxed{\frac{\partial \phi}{\partial t}} = -\boxed{M}\frac{\partial u}{\partial x}$$

(M ~ Gross moist stability)

Eastward propagation of Coupled wave