A theory for TISO: Equatorial Coupled Moist Waves by Frictional feedback (ECMWF)

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Outline

1. What a theory should explain

2. Review of theories

3. A unified theoretical model

4. A theory for MJO

5. A model for boreal summer ISO

6. Mechanism of northward propagation

7. Roles of air-sea interaction

8. Summary

Observed features

What a theory should explain

1. Zonal circulation shows preferred planetary scale but convection and meridional winds show a trapped scale of Rossby radius of deformation (Madden-Julian 1972)
2. Horizontal structure: Kelvin-Rossby wave couplet (Rui and Wang 1990, Hendon and Salby 1994)
3. Vertical structure: Baroclinic motion with an upward and westward tilt of vertical motion (Sperber and Slingo 2003)
4. Amplification over the equatorial Indian Ocean and Western Pacific; decay over the maritime continent and eastern Pacific
5. Remarkable seasonal variations of propagation and intensity. Northward propagation in boreal summer.
6. SST anomalies leads convection anomalies by a quarter cycle.

Review of Mechanisms for MJO

1. **Equatorial wave-Convection feedback (Wave-CISK):, Lau and Peng 87**, Hayashi and Miyahara 87, Yamagata 87, Miyahara 87, Takahashi 87, Chang and Lim 88, Hendon 88, Lau and Shen 88,Itoh 1989, Sui and Lau 89, Lim et al. 90, Dunkerton and Crum 91, Yoshizaki 91, Wang and Xue 92, Chao 95, Cho '00
2. **Evaporation-wind feedback (WISHE): Emanuel 87, Neelin et al. 87**, **Wang 88**, Yano and Emanuel 92, Emannuel 93, Xie et al. 93, Neelin and Yu 94, Yu and Neelin 94, Hayashi and Gold 97, Raymond and Torres 98, Matthew et al. 99, Lin and Neelin '00,
3. **Boundary layer feedback: Wang 88**, Wang and Chen 89, Xie and Kubakawa 90, Wang and Rui 90, **Blade and Hartmann 93**, Gaswami and Rao 94, Wang and Li 94, Salby et al.94, Hendon and Salby 94, Jones and Weare 96, Ohuchi and Yamasaki 97, Li and Cho 97, Maloney and Hartmann 98, Moskowitz and Bretherton 2000, Matthews '00, Kemball-Cook and Weare '01, Lee et al. '03
4. **Other atmospheric feedback Processes**

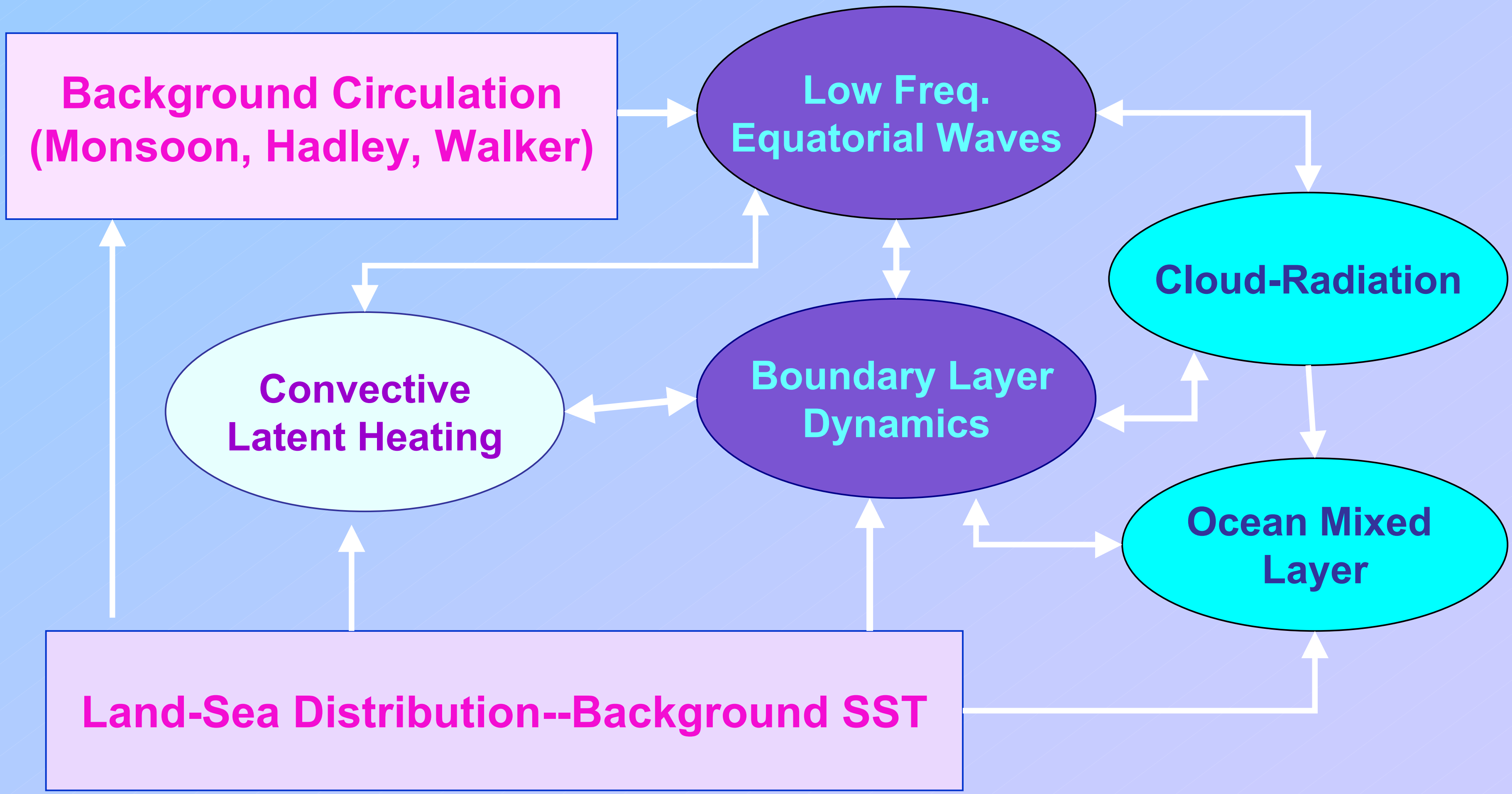
   Cloud-radiation: Chang 77, **Hu and Randal 94a,b**, Slingo and Madden 91, Raymond '01, Lee et al. '01;

   Cumulus parameterization: **Itoh 89**, Kuma 90, Cho et al. 94, Chao and Lin 94, Hayashi and Golder 97, Cho ans Pendlebury 97,Chao and Dong 98, Grabowski '03,

   Resolution: Crum and Dunkerton 92,
5. **Air-sea interaction**

   Hirst and Lau 90, **Wang and Xie 98**, Flateau et al. 98, Waliser 99, Gualdi et al. 99, Kemball-Cook and Wang '01, '02; Woolnough et al. '00, '01; Wu et al. '02, Fu et al. '03

What Essential Physics are needed in a Theoretical Model?



Model Equations on equatorial beta-plane

$$\frac{\partial u}{\partial t} - \beta y u = \frac{\partial \phi}{\partial x} + M(u) - \varepsilon u \qquad (1)$$

$$\frac{\partial v}{\partial x} + \beta y u = -\frac{\partial \phi}{\partial y} + M(v) - \varepsilon v \qquad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \qquad (3)$$

$$\frac{\partial}{\partial t}\frac{\partial \phi}{\partial p} + \overline{S}(p)\omega = -\frac{R}{C_p p} Q_c(p) + M\left(\frac{\partial \phi}{\partial p}\right) - \mu \frac{\partial \phi}{\partial p} \qquad (4)$$

$$\frac{\partial}{\partial t}\int_{p_u}^{p_s} q \frac{dp}{g} + \int_{p_u}^{p_s}\left(u\frac{\partial \overline{q}}{\partial x} + v\frac{\partial \overline{q}}{\partial y}\right)\frac{dp}{g} = -\frac{1}{L_c}\int_{p_u}^{p_s} Q_c \frac{dp}{g} + E_v + M(q) \qquad (5)$$

$$\overline{q}(p) = q_s\left(\frac{p}{p_s}\right)^{\frac{H}{H_1}-1}$$

$$q_s = q_s(SST) = (0.940 \times SST(^oC) - 7.64) \times 10^{-3}$$

Mean flow effects

$$M(u) = \left(-\overline{u}\frac{\partial u'}{\partial x} - u'\frac{\partial \overline{u}}{\partial x} - \overline{v}\frac{\partial u'}{\partial y} - v'\frac{\partial \overline{u}}{\partial y} - \overline{\omega}\frac{\partial u'}{\partial p} - \omega'\frac{\partial \overline{u}}{\partial p} \right)$$

$$M(v) = \left(-\overline{u}\frac{\partial v'}{\partial x} - u'\frac{\partial \overline{v}}{\partial x} - \overline{v}\frac{\partial v'}{\partial y} - v'\frac{\partial \overline{v}}{\partial y} - \overline{\omega}\frac{\partial v'}{\partial p} - \omega'\frac{\partial \overline{v}}{\partial p} \right)$$

$$M\left(\frac{\partial \phi}{\partial p}\right) = -\overline{u}\frac{\partial^2 \phi}{\partial x \partial p} - u'\frac{\partial^2 \overline{\phi}}{\partial x \partial p} - \overline{v}\frac{\partial^2 \phi}{\partial y \partial p} - v'\frac{\partial^2 \phi}{\partial y \partial p}$$

$$M(q) = -\int_{p_u}^{p_s} \left(\overline{u}\frac{\partial q}{\partial x} + \overline{v}\frac{\partial q}{\partial y} \right) \frac{dp}{g}$$

A Theory for MJO

Equatorial Coupled Moist Waves by Frictionally moisture convergence (ECMWF)

Model:

Two-layer free troposphere plus a well-mixed PBL

Specified SST and basic state specific humidity and static stability Distribution

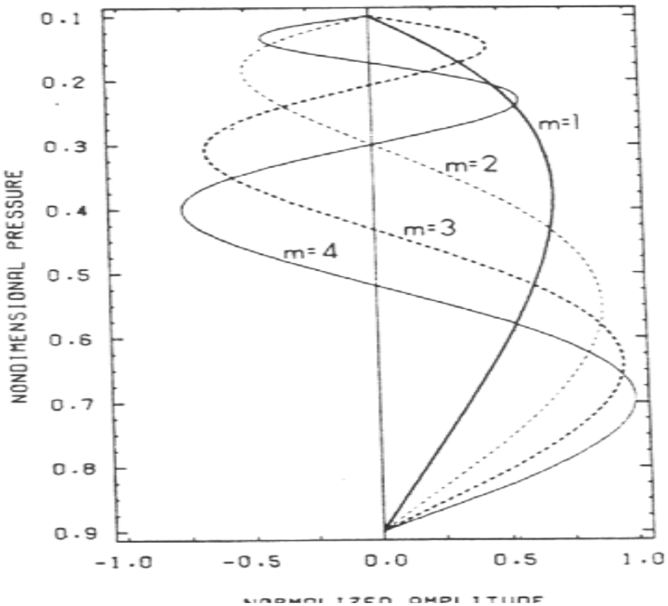
No mean flows

Dynamical processes:

- Equatorial Kelvin and Rossby waves
- PBL dynamics
- Interactive convective (nonlinear or linear) heating (No wave-CISK)
- Evaporation-wind feedback

Vertical structure (in a vertical continuous model)

Dry vertical modes Wang and Chen 1989

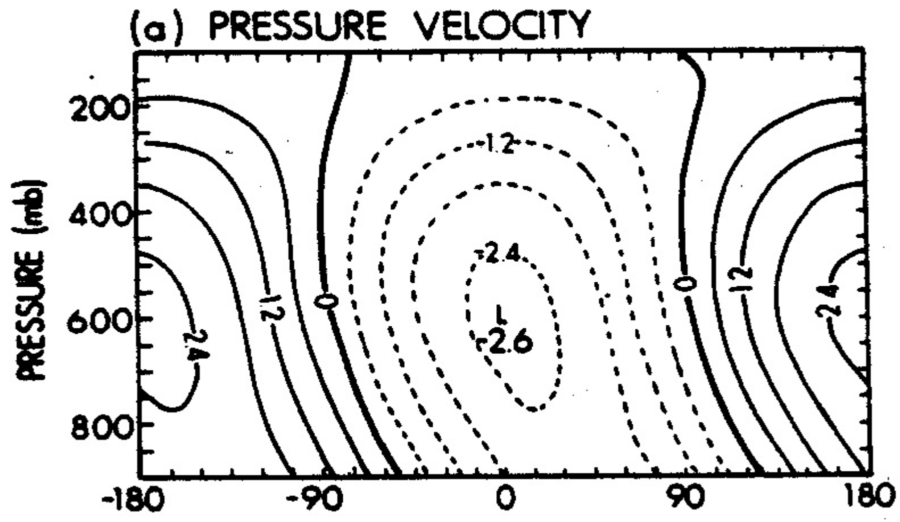


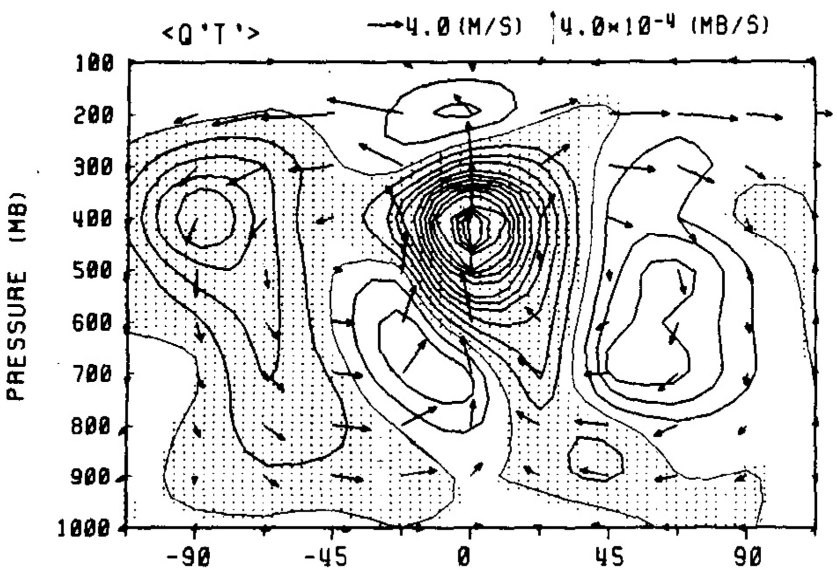
Propagation Speed

m=1: 50 m/s
m=2: 24 m/s
m=3: 15 m/s
m=4: 8 m/s

$$S(p)=S_0/S^2$$

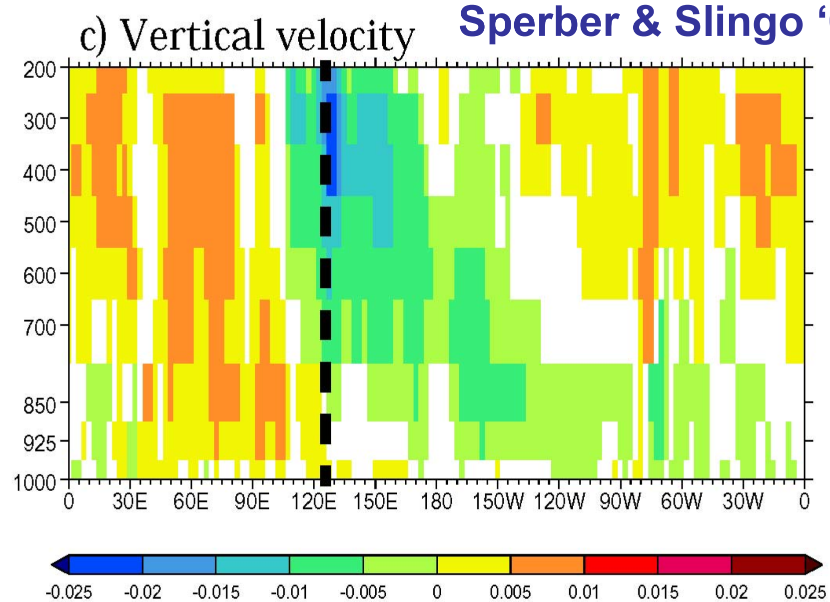
Most Unstable Moist Kelvin wave



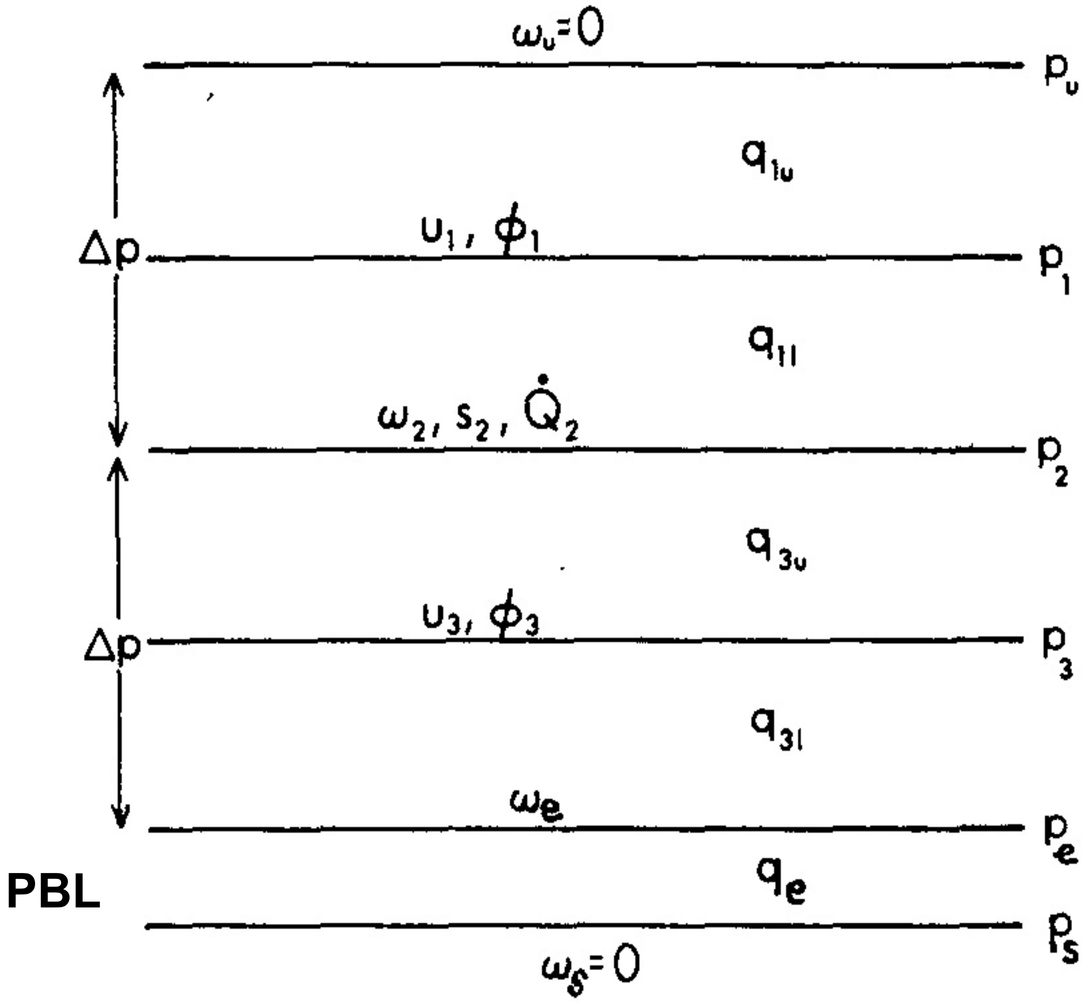


Lau et al. 1988

Sperber & Slingo '03



Structure of three-layer model



Governing Equations in the 2-1/2 layer model

$$\partial u / \partial t - \beta y v = -\partial \phi / \partial x + r \nabla^2 u \qquad (1)$$

$$\partial v / \partial t - \beta y u = -\partial \phi / \partial y + r \nabla^2 v \qquad (2)$$

$$C_0^{-2} \partial \phi / \partial t + (1 - \delta I) \nabla \cdot V = d(\delta B - 1) \nabla \cdot V_B - \delta F C_E |V_B| / h \qquad (3)$$

$$\partial u_B / \partial t - \beta y v_B = -\partial \phi / \partial x - E u_B \qquad (4)$$

$$\partial v_B / \partial t - \beta y u_B = -\partial \phi / \partial y - E v_B \qquad (5)$$

$I = q_3 / q_c$ heating coefficient due to wave convergence

$B = qe / q_c$ heating coefficient due to frictional convergence

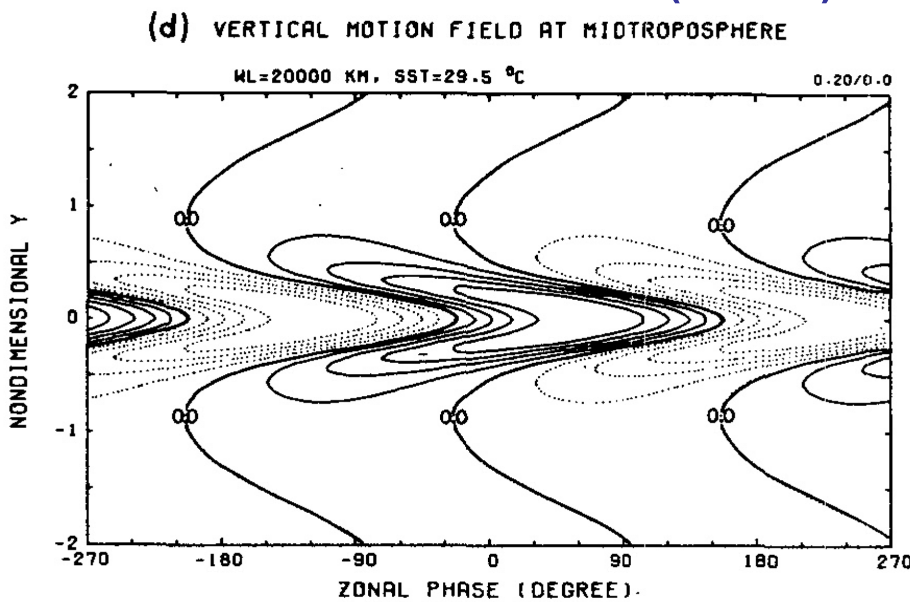
$I = (q_s - q_0) / q_c$ heating coefficient due to evaporation

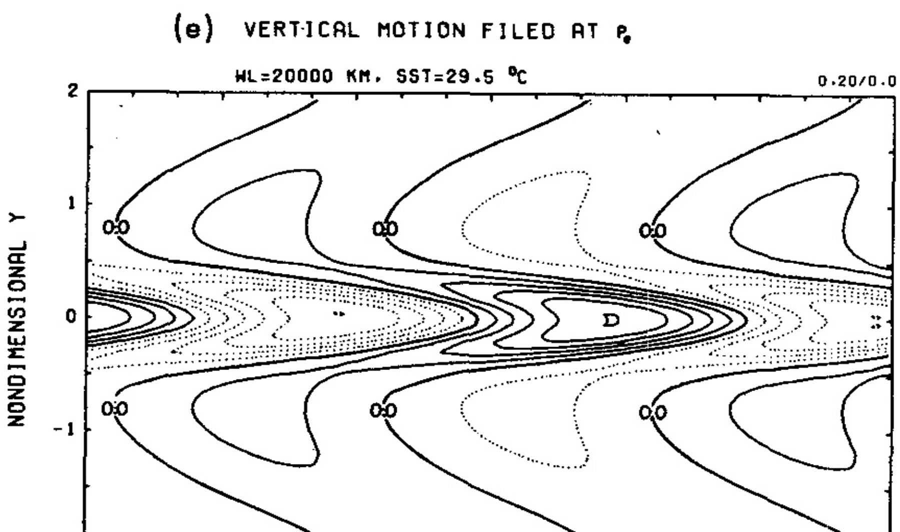
For a steady BL: $$\nabla \cdot \vec{V}_B = D_1 \nabla^2 \phi + D_2 \frac{\partial \phi}{\partial x} + D_3 \frac{\partial \phi}{\partial y}$$

$$D_1 = -\frac{E}{E^2 + \beta^2 y^2}, \quad D_2 = \beta \frac{(E^2 - \beta^2 y^2)}{(E^2 + \beta^2 y^2)^2}, \quad D_3 = \frac{2 \beta^2 E y}{(E^2 + \beta^2 y^2)^2}$$

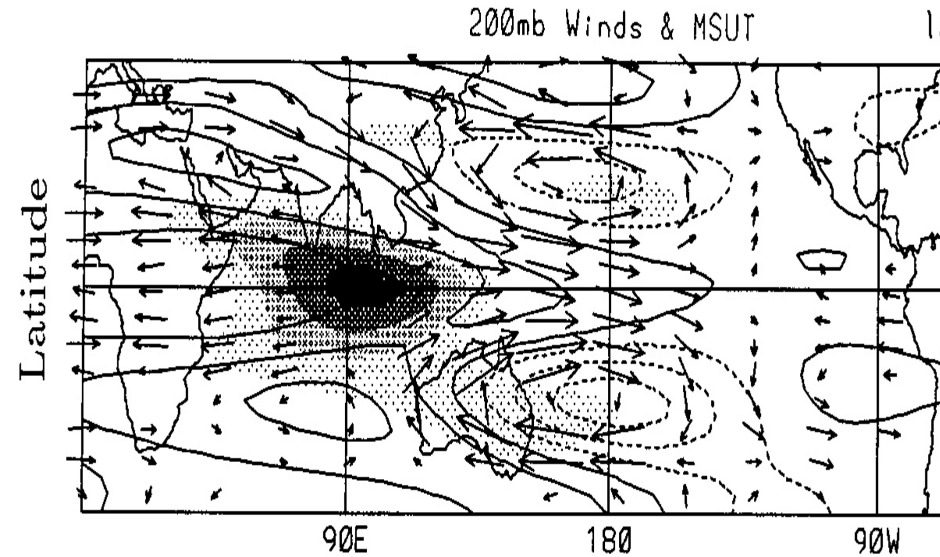
Linear analysis (1):
Horizontal structure of frictionally coupled Kelvin-Rossby mode

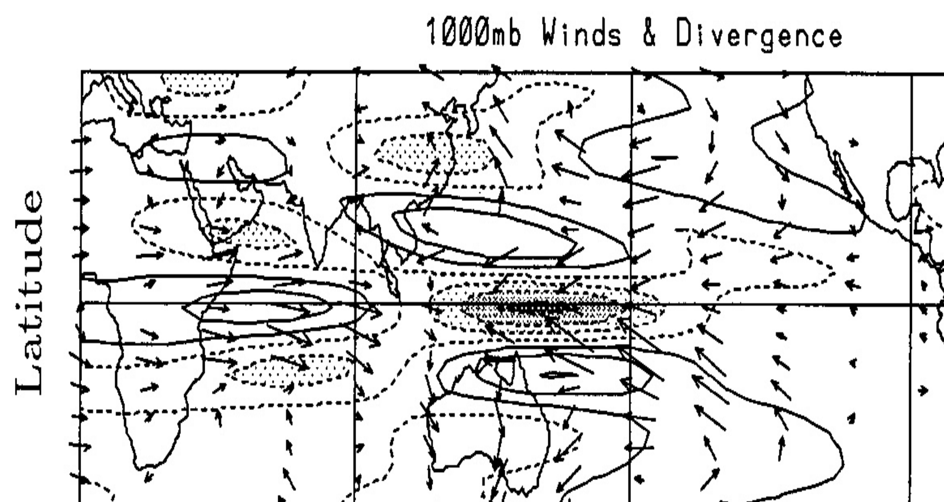
Unstable Normal mode (Model)



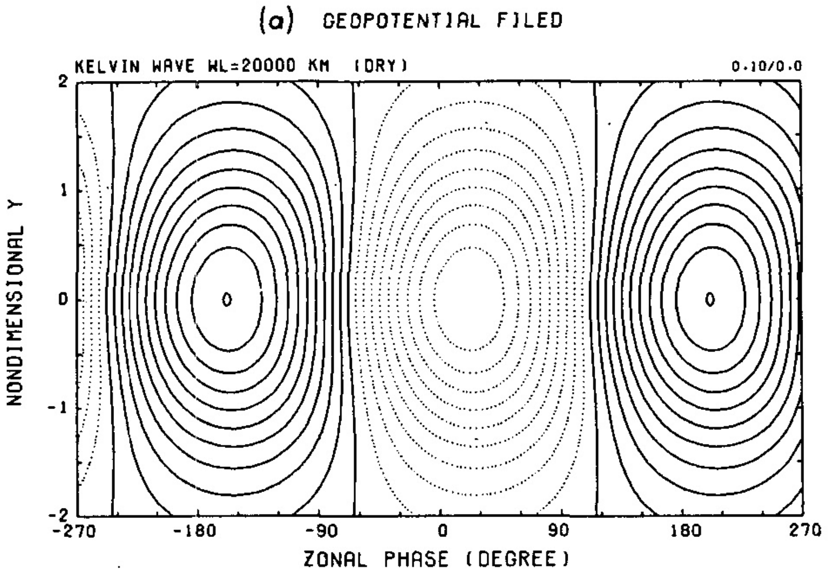


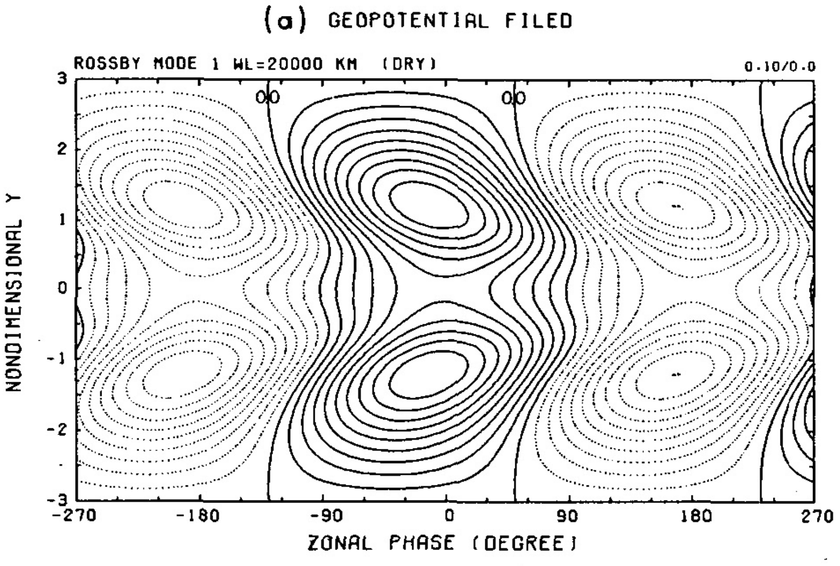
Hendon and Salby 1994 (OBS)

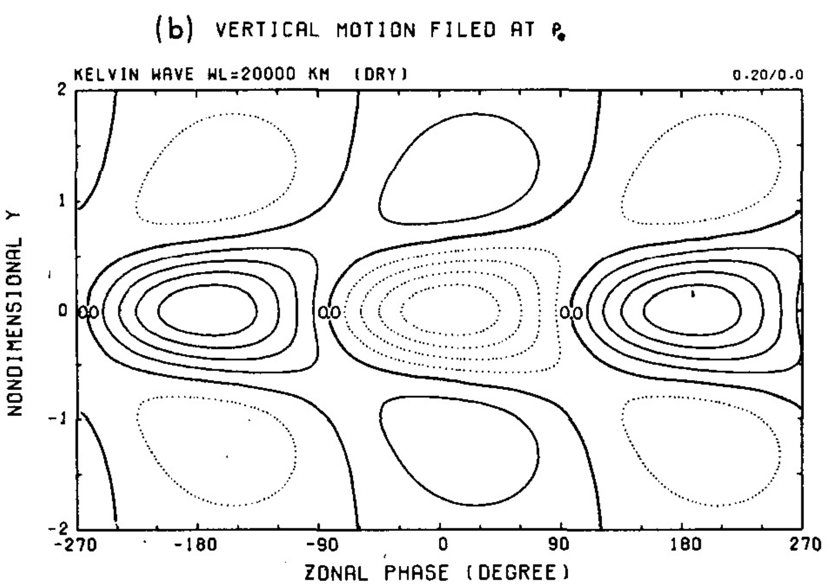


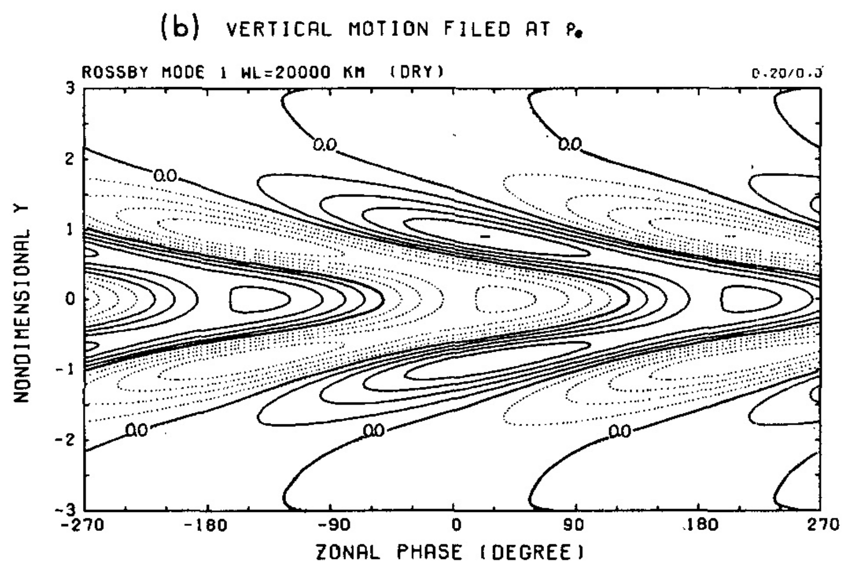


Linear analysis (2): Why eastward propagating mode is selected

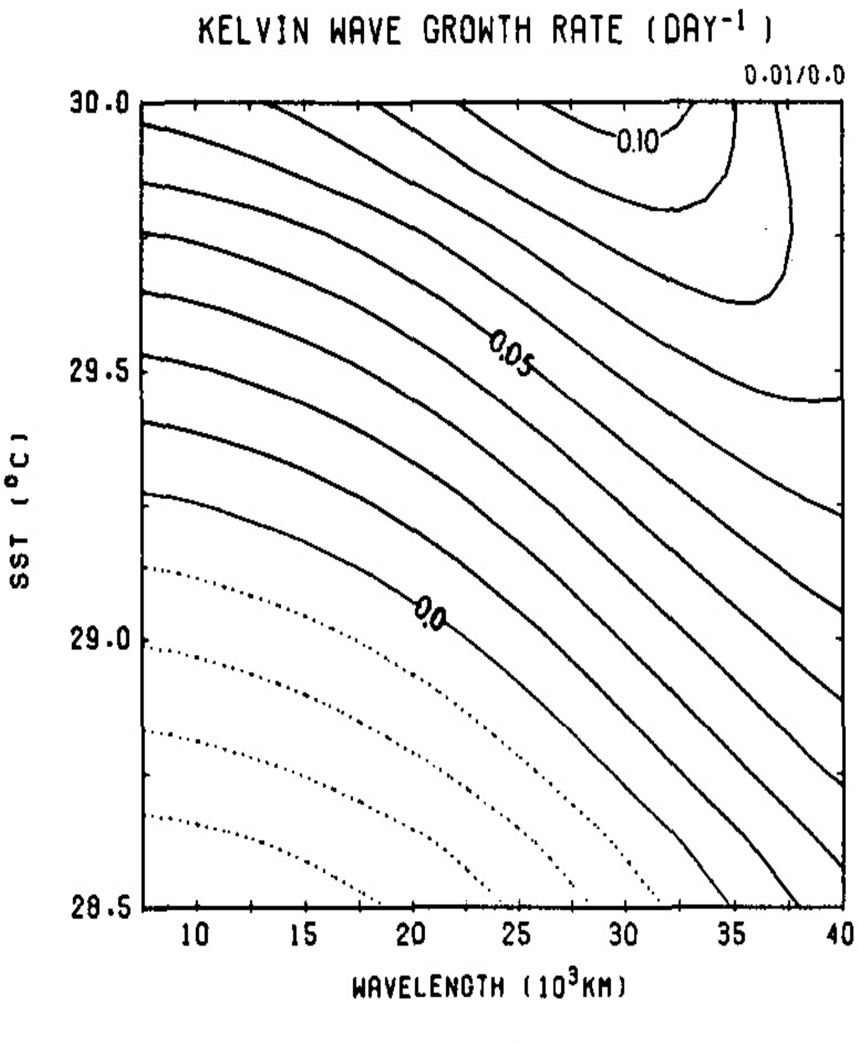




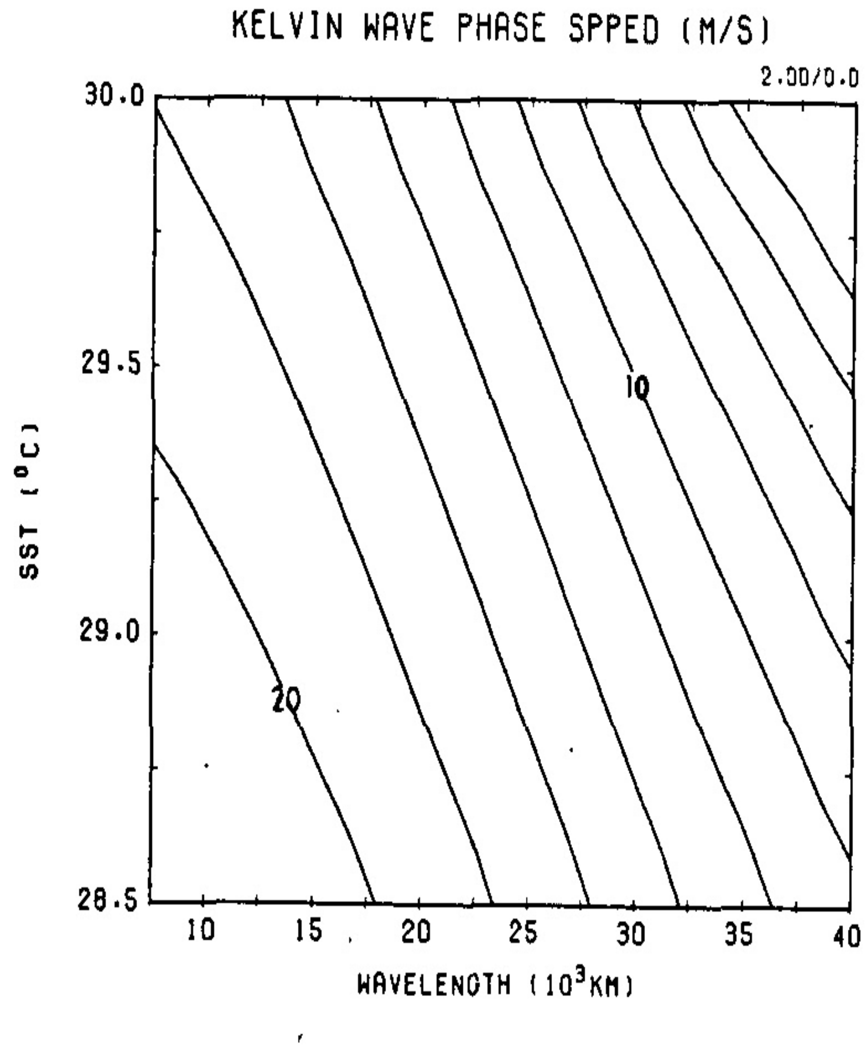




Linear analysis(3): Growth rate and slow propagation of frictional coupled Kelvin-Rossby mode

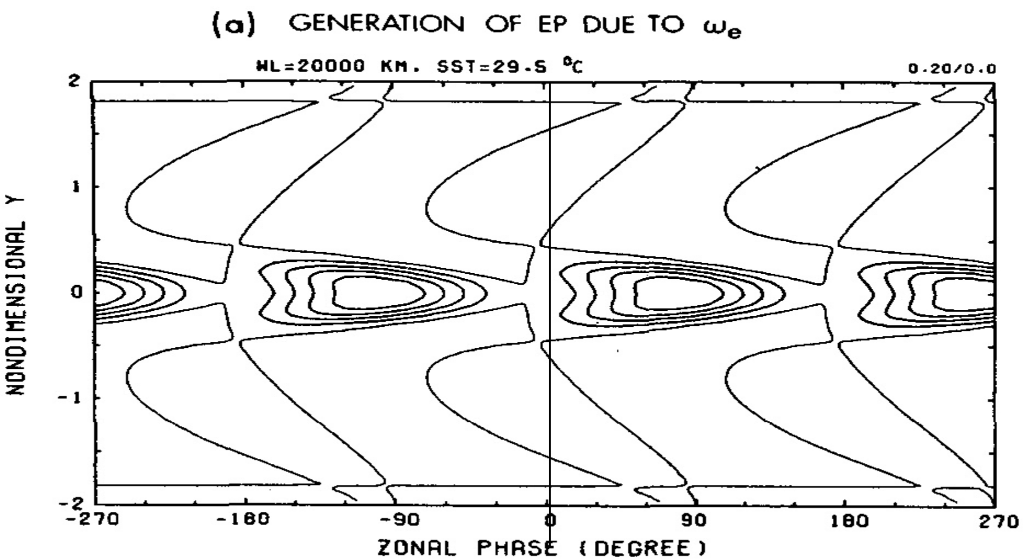


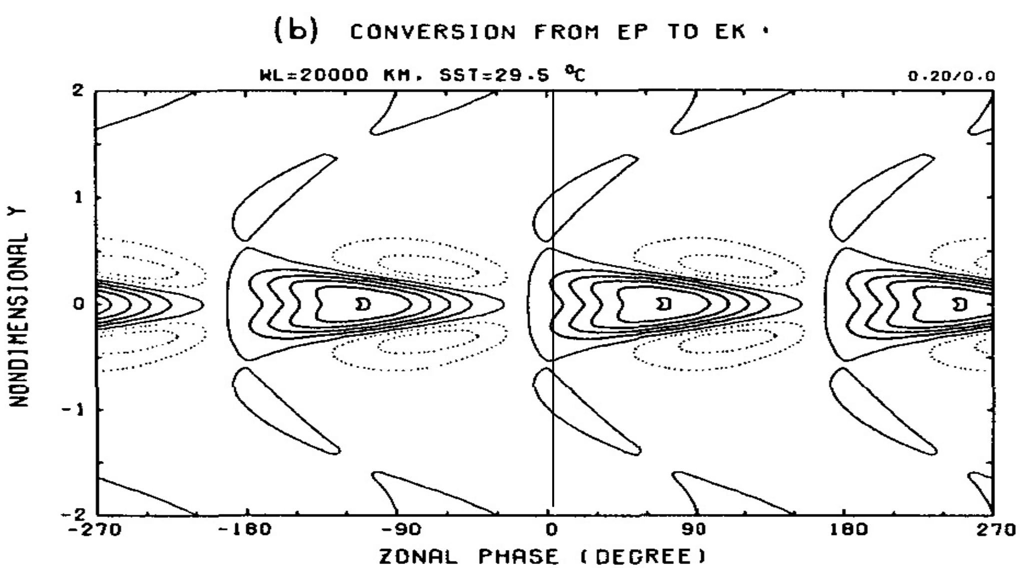
Wavenumber selection



Slow eastward propagation

Linear analysis (4): Energy source and wavelength selection





Frictional Convergence Feedback

provides a planetary wave selection mechanism

Wang 1988

Conceptual model

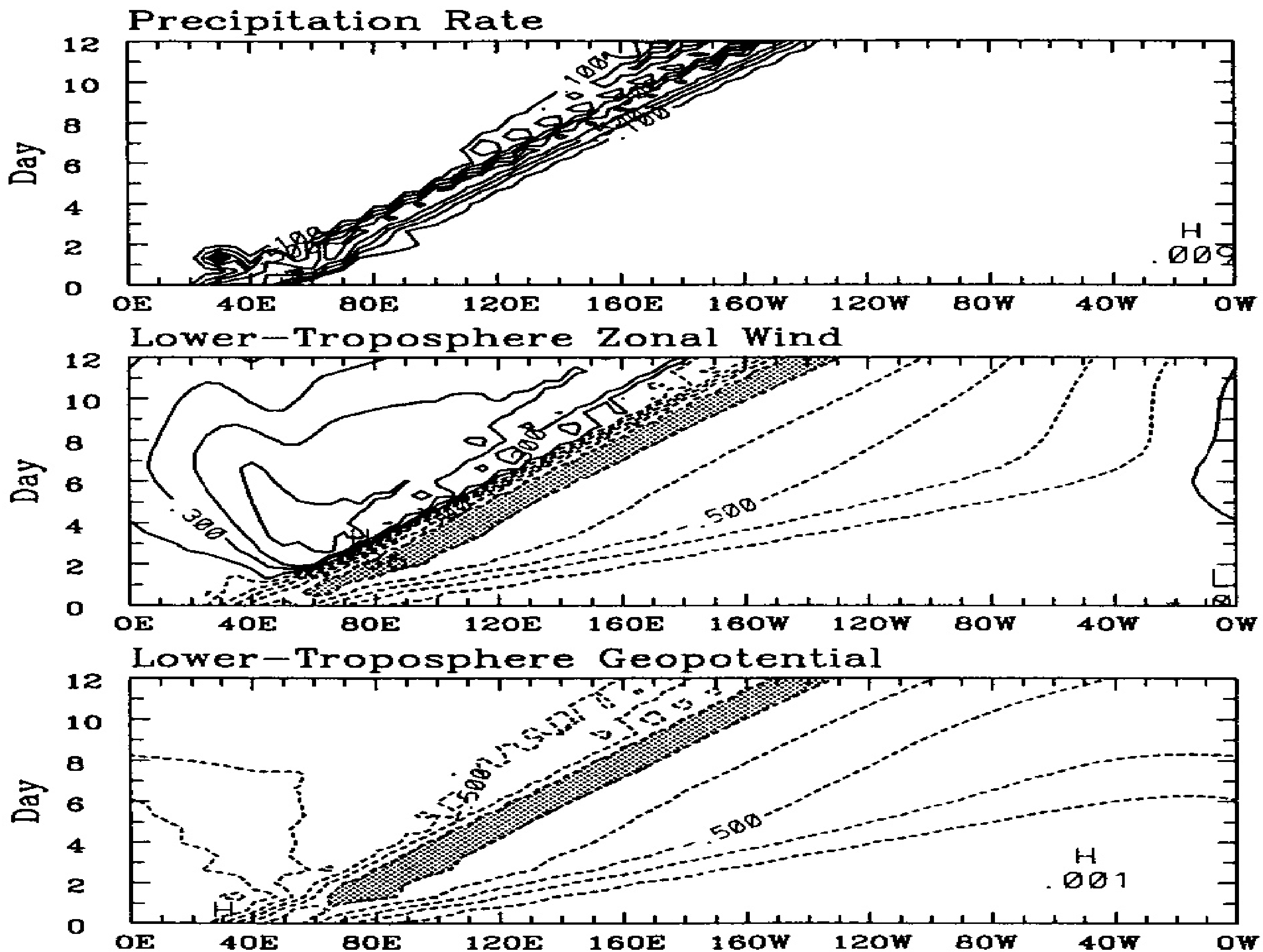
Planetary wave selection

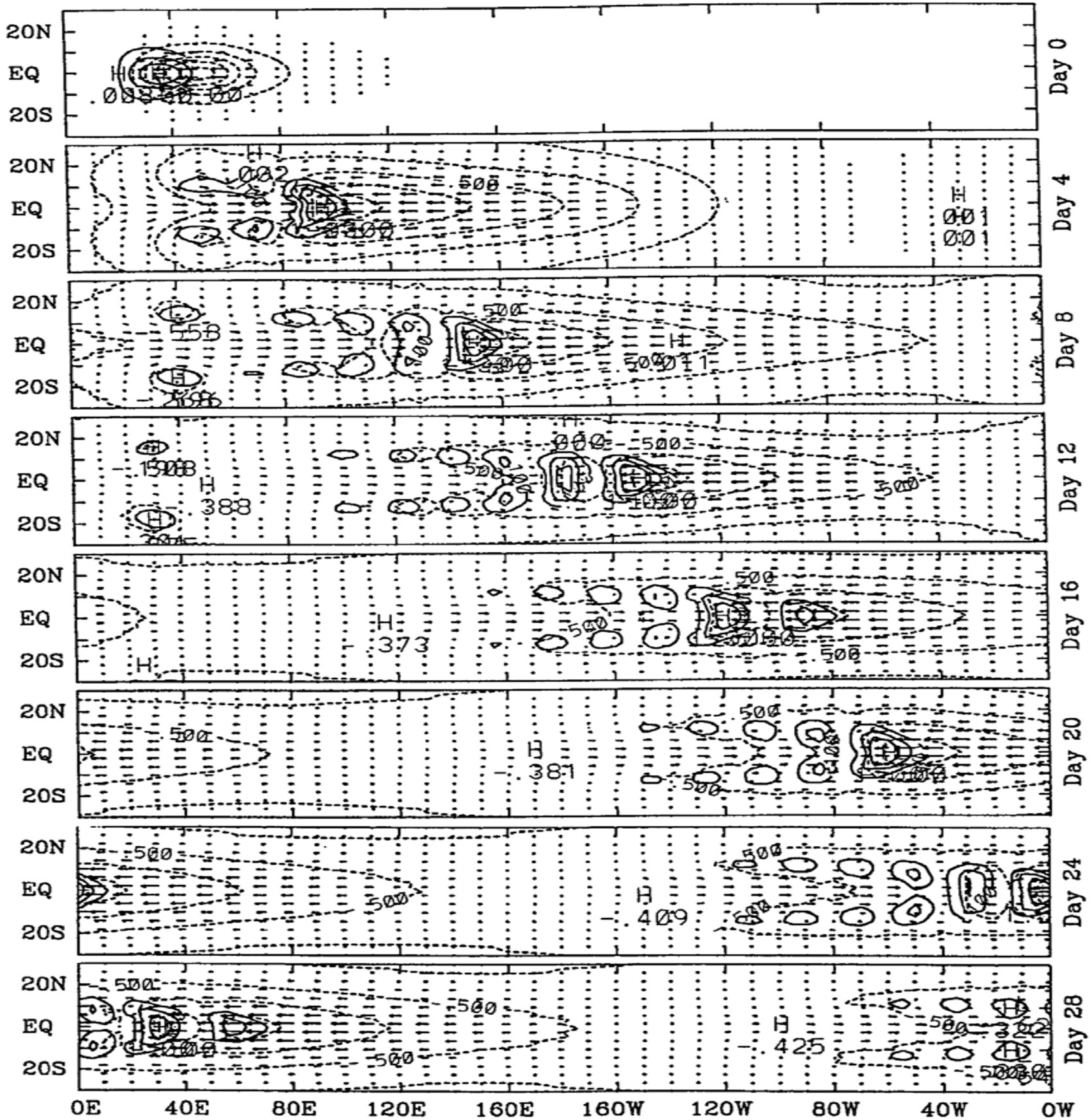
<Q'T'> = <Q'T'> (k)

Increases with decreasing k

Nonlinear Heating (1) : Propagation along the equator

a concentrated precipitation and a broad subsidence area





Nonlinear Heating (2): Propagation of Kelvin-Rossby wave packet in uniform SST

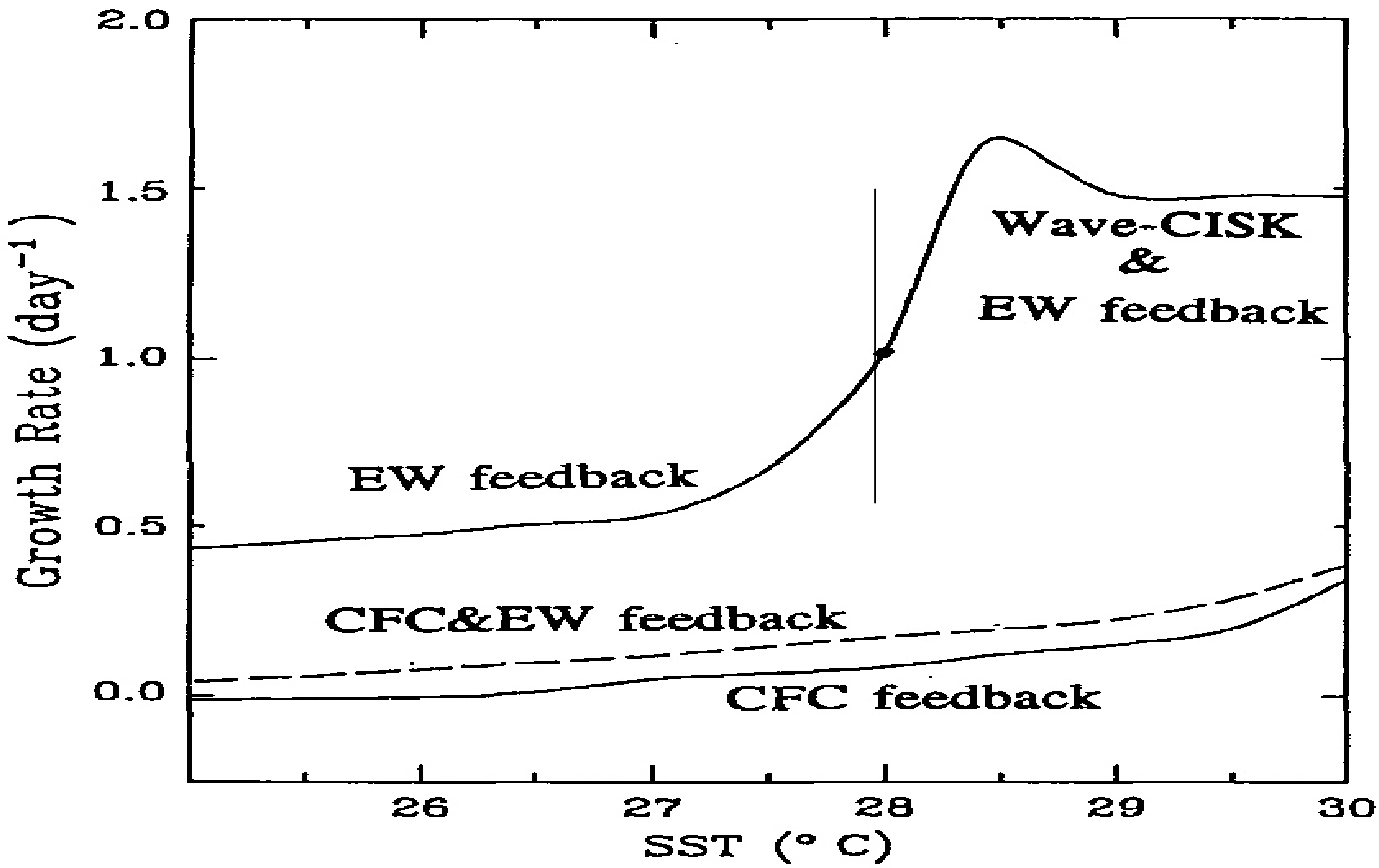
Precipitation/ Low-level winds

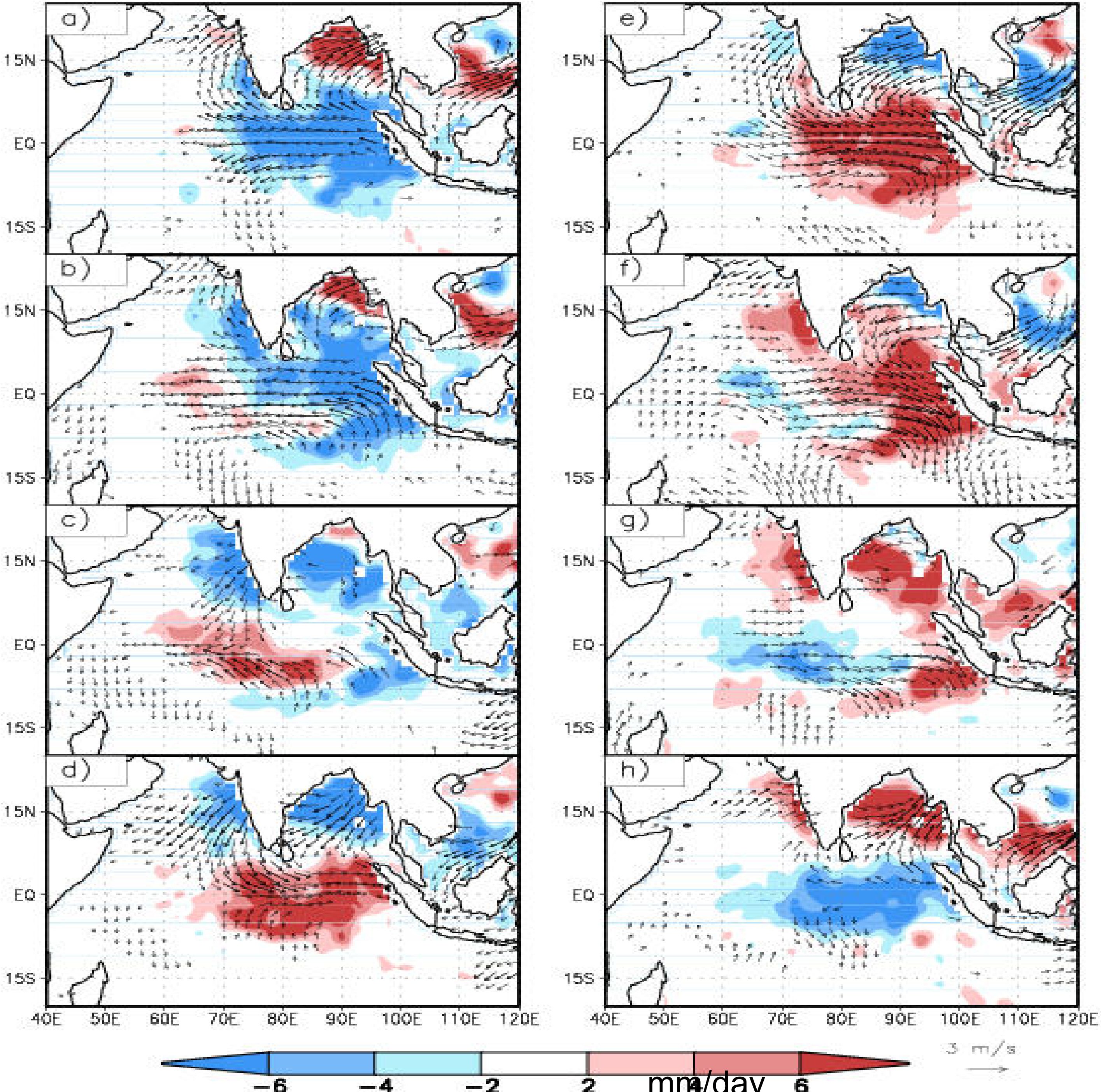
(Every four days)

Wang and Li 1994

Nonlinear heating (3)

Comparison of Frictional Feedback, Wave-CISK, and Wind-Evaporation Feedback (Under nonlinear heating)





Life Cycle of the ISO in the Indian Ocean

TMI rainfall & QuikSCAT wind (90% confidence level)

12 cases in May-Sept, 2000-2002

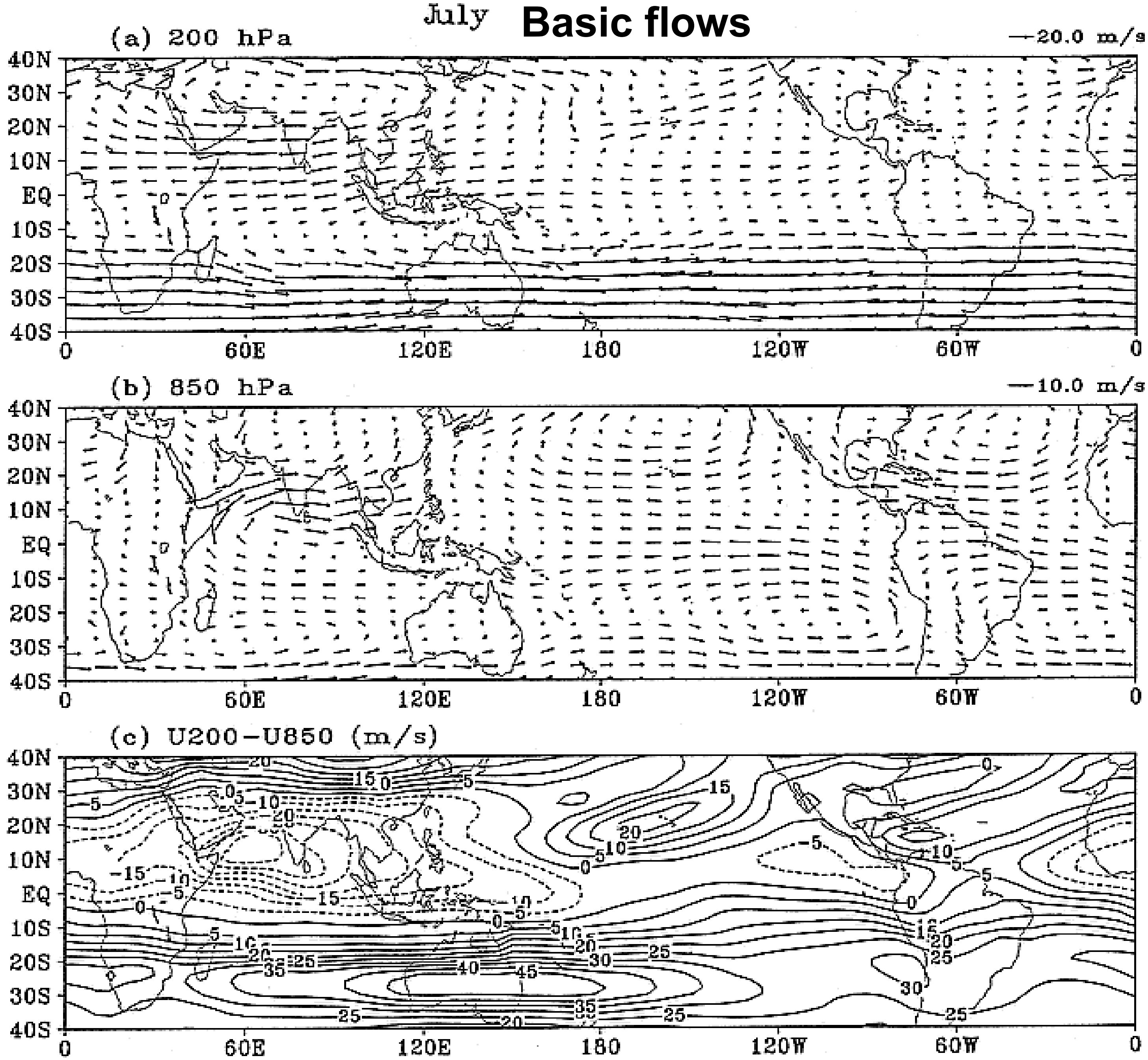
A model for Boreal Summer ISO

Equatorial Coupled Moist Wave Packets Modified by background flows and SST distribution

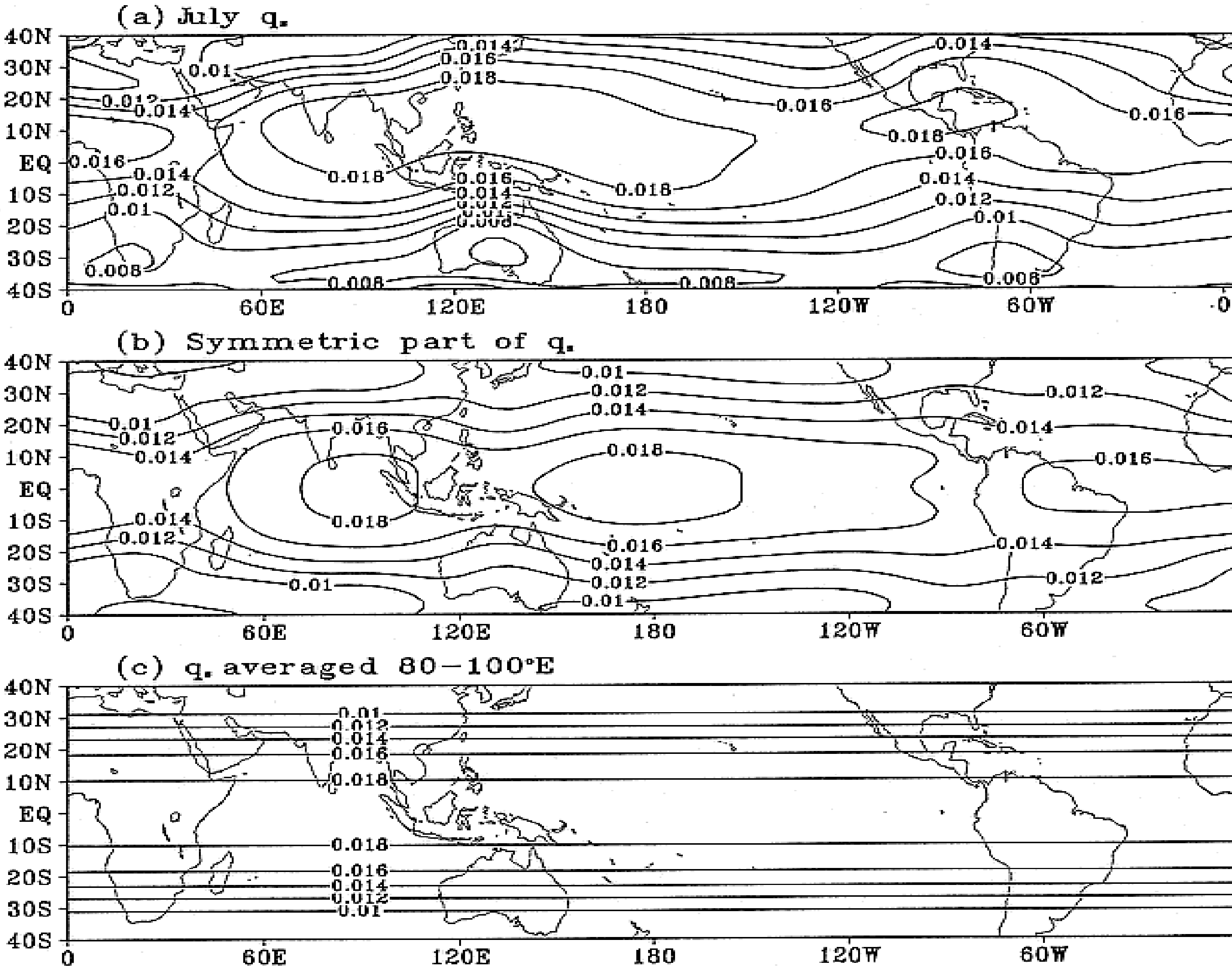
Model: The same as the model for MJO but include

- Observed Mean flows (U,V,W,T)
- Realistic q_s or SST
- Nonlinear heating
- Initial value problem

Basic flows

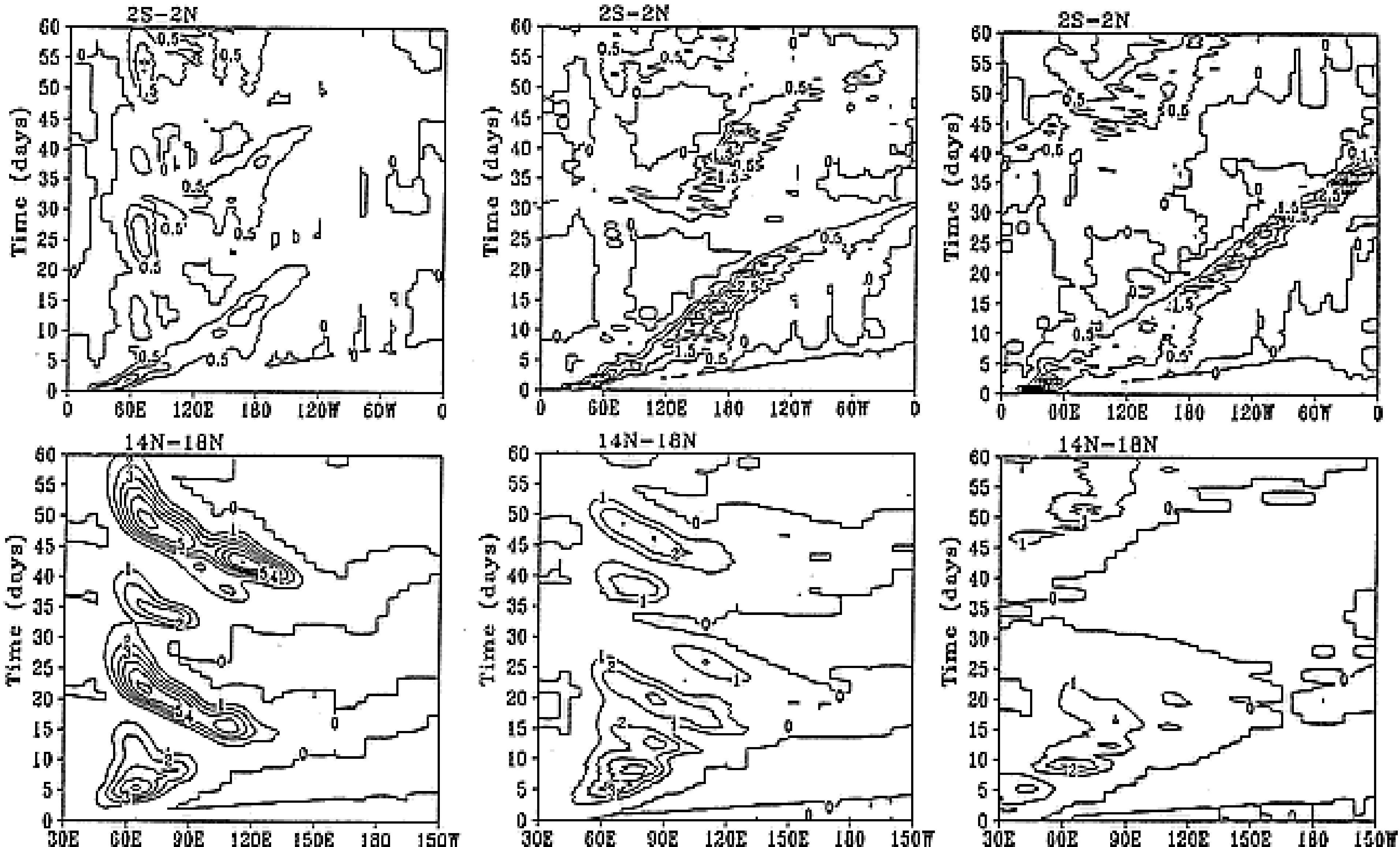

July
(a) 200 hPa
20.0 m/s
40N
30N
20N
10N
EQ
10S
20S
30S
40S
0
60E
120E
180
120W
60W
0
(b) 850 hPa
10.0 m/s
(c) U200-U850 (m/s)

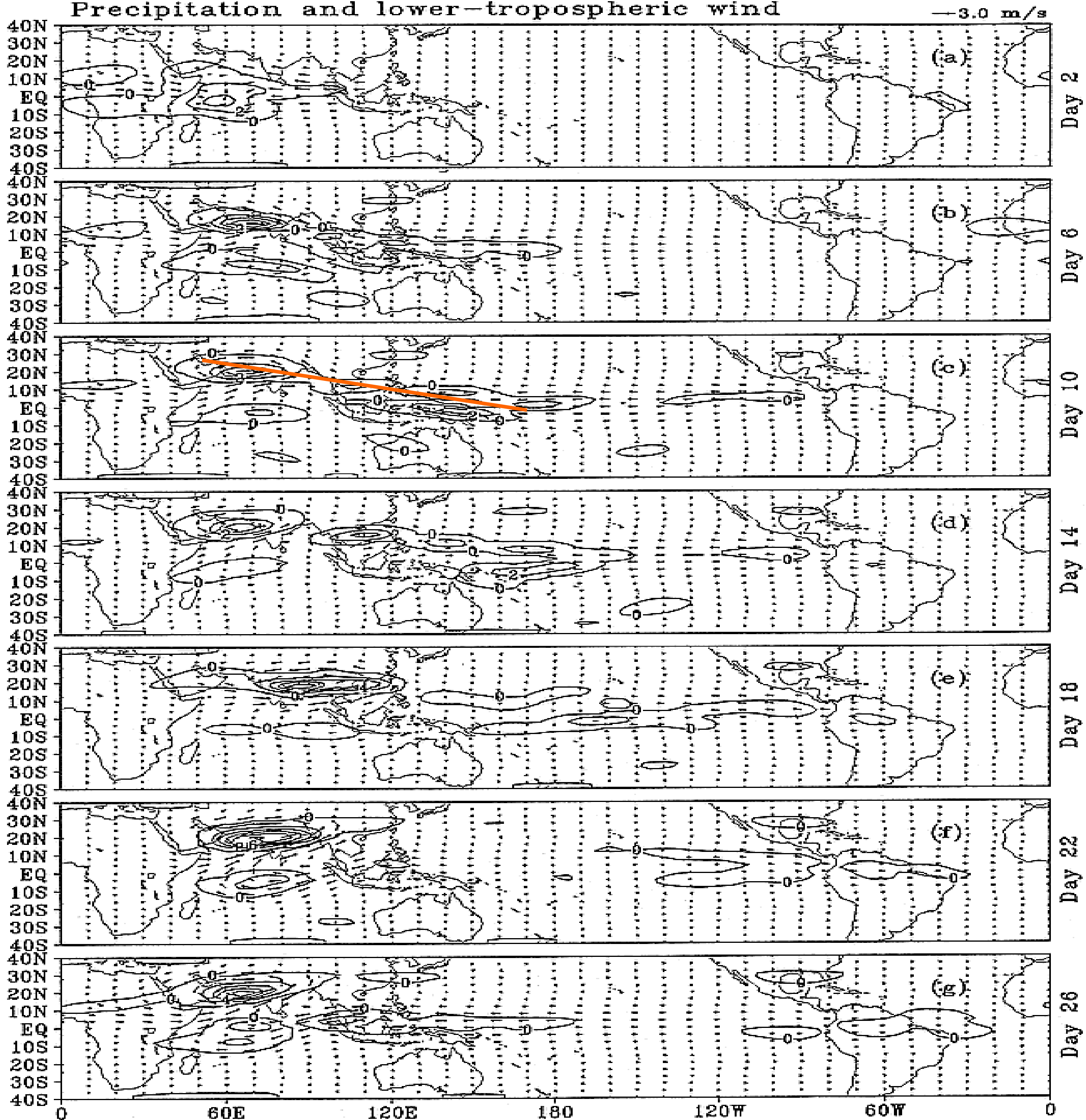
Basic state specific humidity



Precipitation along the equator)upper) and 15N (lower)

Control: observed July mean Qs	Zonally symmetric, Longitudinal varying Qs	Zonally symmetric, No longitudinal variation
(a) Exp. 1	(b) Exp. 5	(c)Exp. 6

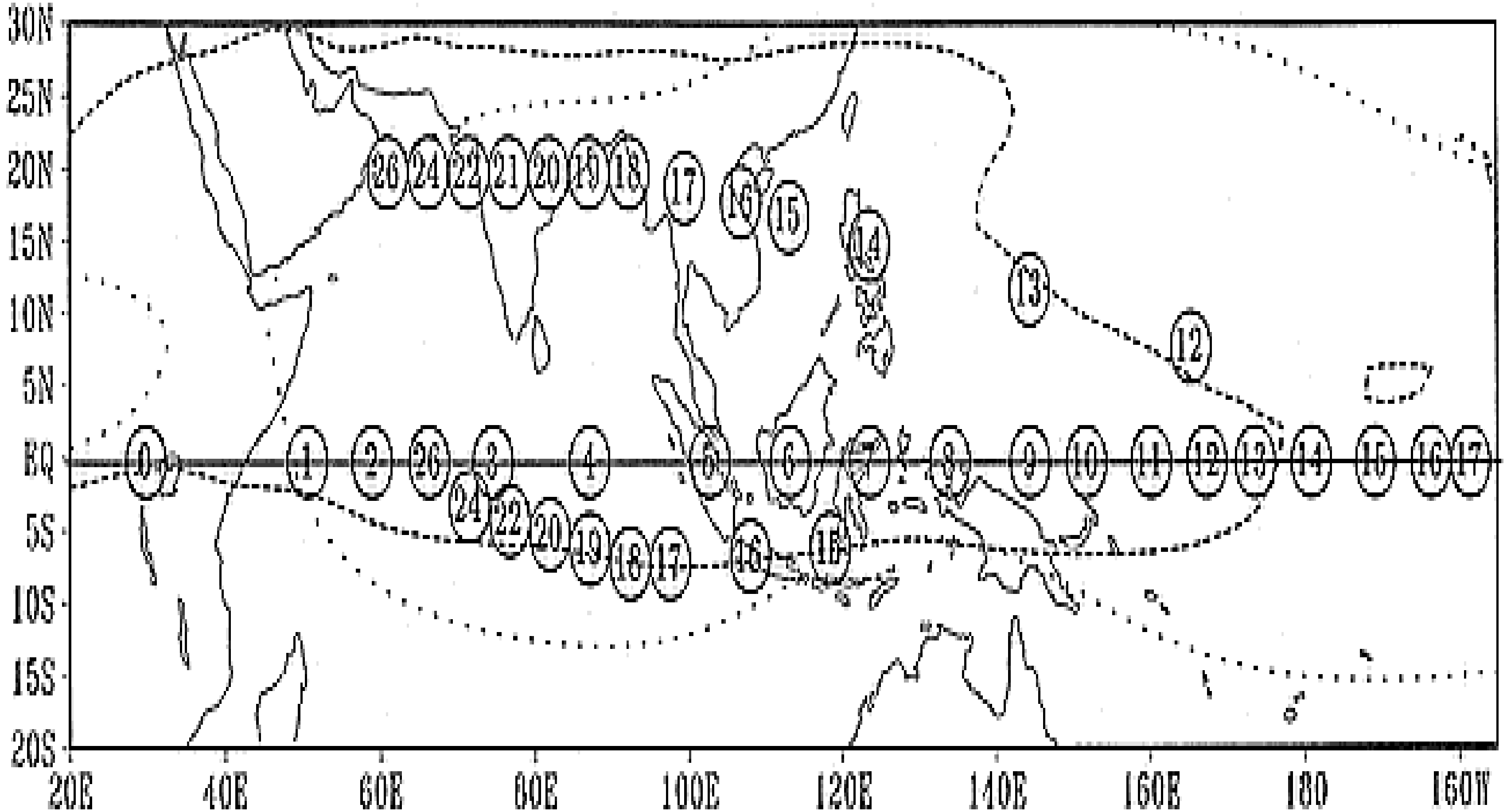




Propagation of Frictional Kelvin-Rossby wave Packet in July mean basic state

Precipitation and low-level winds (every 4 days)

Wang and Xie 97



The trajectory of the major precipitation centers in the control experiment with the encircled numbers denoting the day of the model integration. The dashed and dotted curves outline the contour lines of 4 m s of July mean $U_{200} - U_{850}$ and 0.016 of July mean surface specific humidity, respectively.

Northward propagation

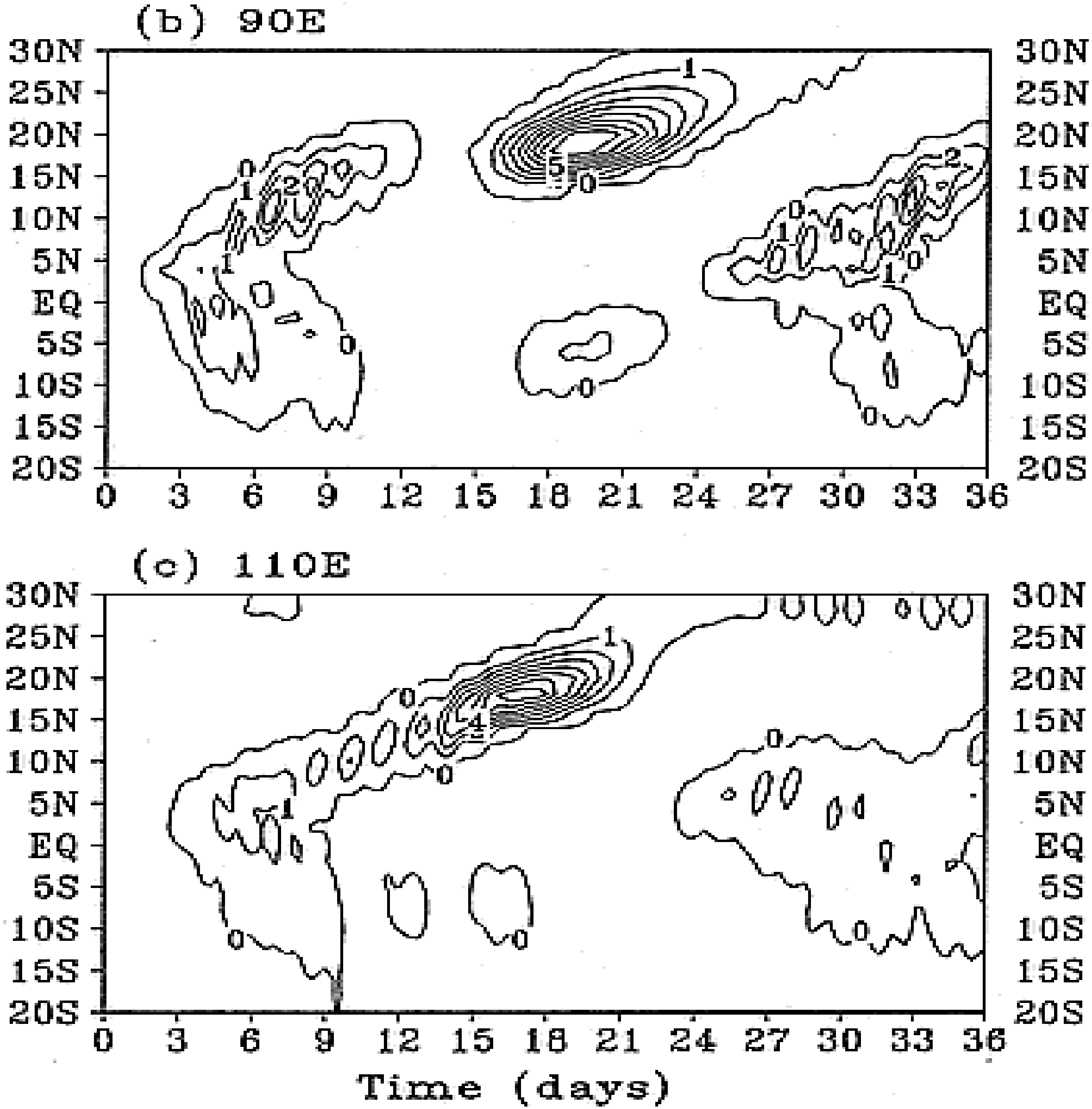
Hypotheses

Hydrological cycle feedback:
Webster 1983, Goswami and Shukla 1984,

Baroclinic unstable waves: Lau and Peng 1990,

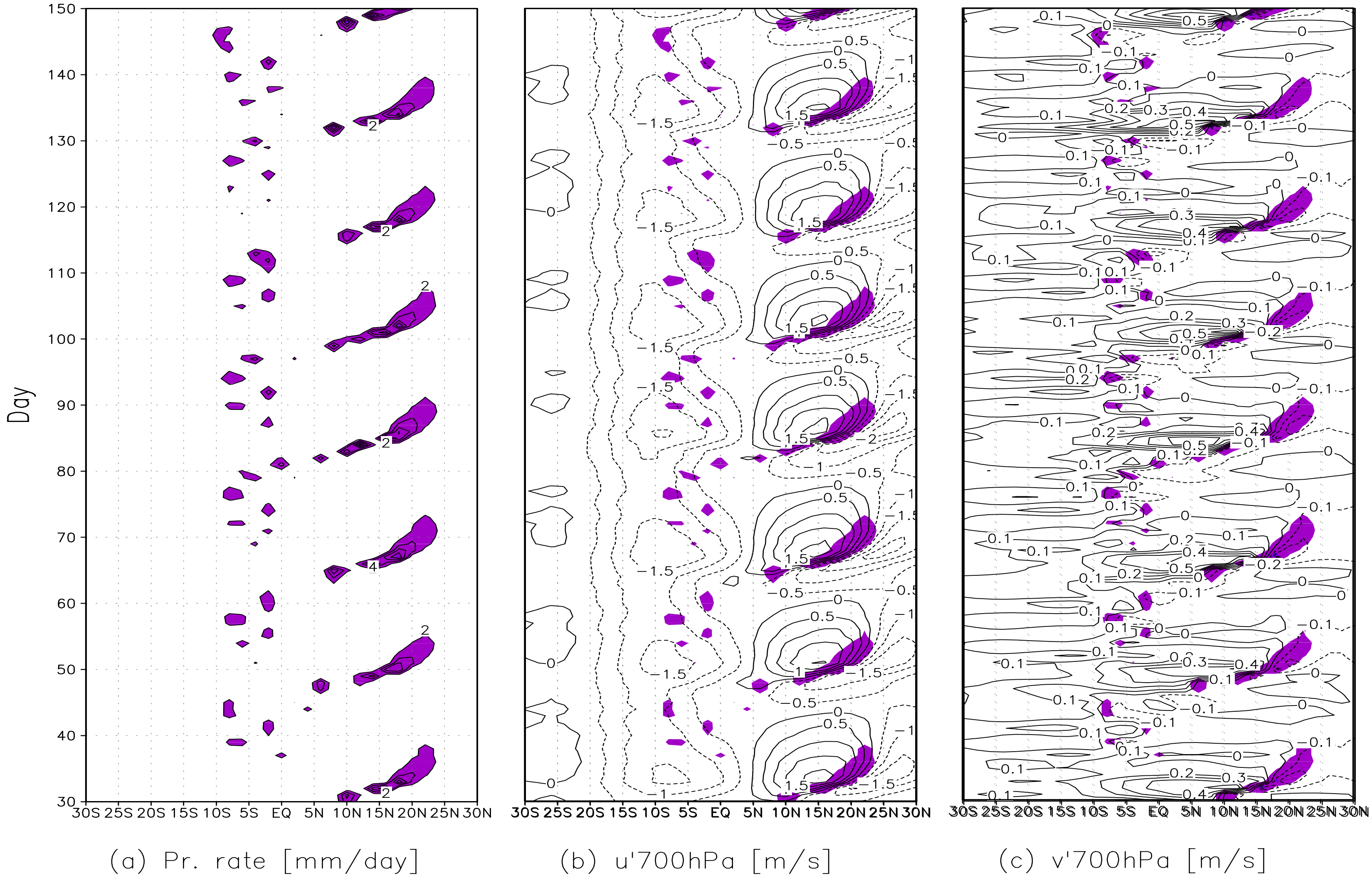
Rossby wave emanation and vertical shear:
Wang and Xie 1997, Kemball-Cook and Wang 2001, Lawrenec and Webster 2002, Hsu 2002,

Vertical shear effects: Jiang et al. 2003,
Drbolav and Wang 2003



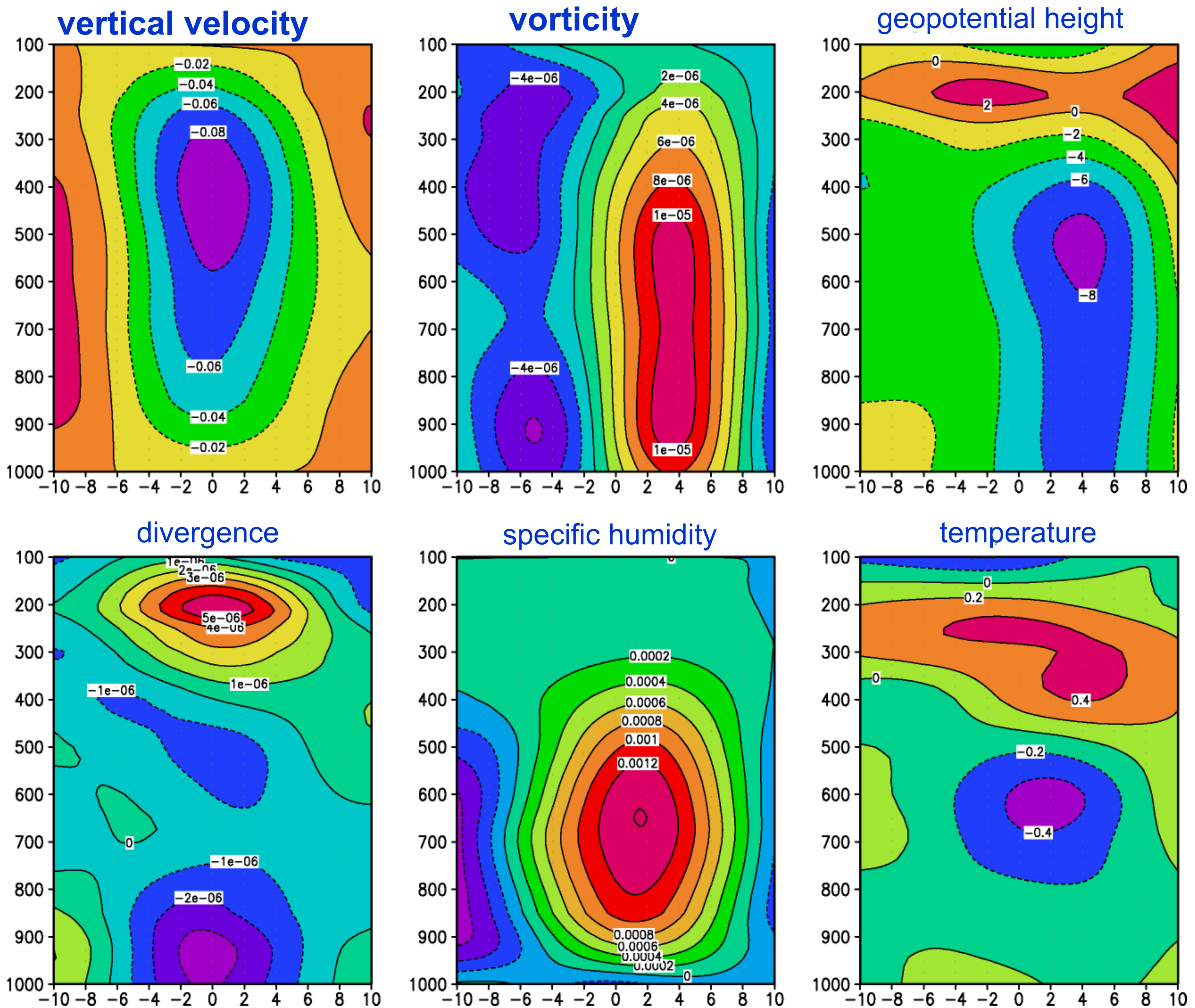
Simulated Northward propagation associated Rossby wave Emanation Over the Indian ocean (90E) and maritime continent (110E)

Northward propagation in a 2-D model
An Independent mechanism for northward propagation

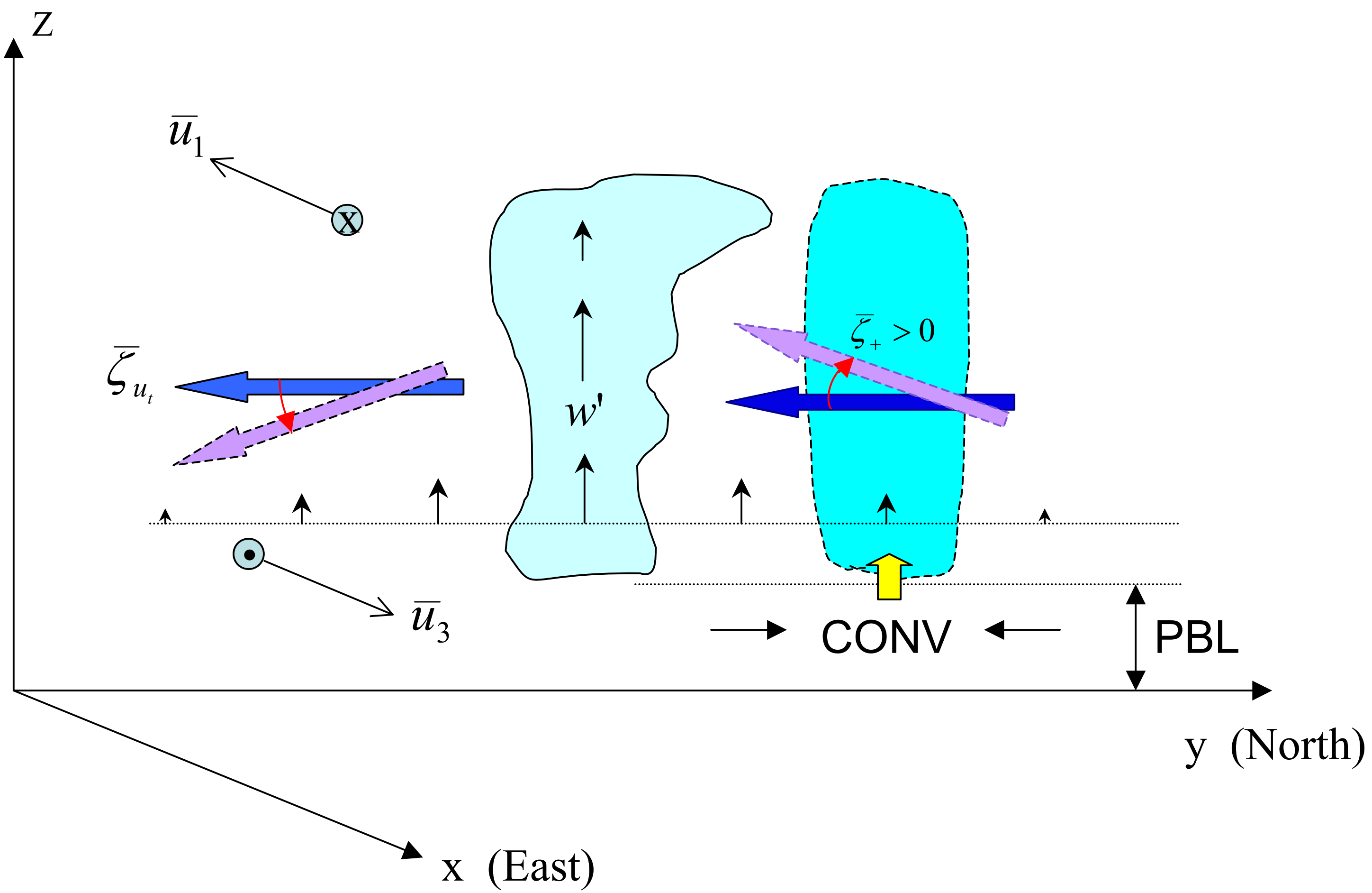


Drbohlav and Wang 2003

ECHAM Model: Vorticity leads convection anomalies



Mechanism for northward propagation



Barotropic vorticity generation by tilting of basic-state horizontal vorticity vector (Wang 2003)

$$\frac{\partial \zeta_+}{\partial t} + f_o D_+ + \beta v_+ = 2\bar{u}_T \frac{\partial}{\partial y}(2D_+ + D_-) \quad \Rightarrow \quad \frac{\partial \zeta_+}{\partial t} \propto 2\bar{u}_T \frac{\partial D_-}{\partial y}$$

$$\frac{\partial D_+}{\partial t} - f_o \zeta_+ + \beta u_+ + \nabla^2 \phi_+ = 0 \quad \Rightarrow \quad \frac{\partial D_+}{\partial t} \propto f_o \zeta_+$$

Roles of ISO-Warm ocean coupling

MJO:

Theoretical analysis:
Hirst and Lau 90,
Wang and Xie 98,

Numerical modeling:
Flateu et al. 97, Waliser et al. 99, Gualdi et al. 99, Hendon 2000, Woolnouhg et al. ’00, ’01; Kemball-cook et al. ‘01, ’02; Wu et al. ’02

Northward propagation of Monsoon ISO:
Fu et al. ’03, Fu and Wang ‘03

Air-sea thermodynamically coupled anomaly model

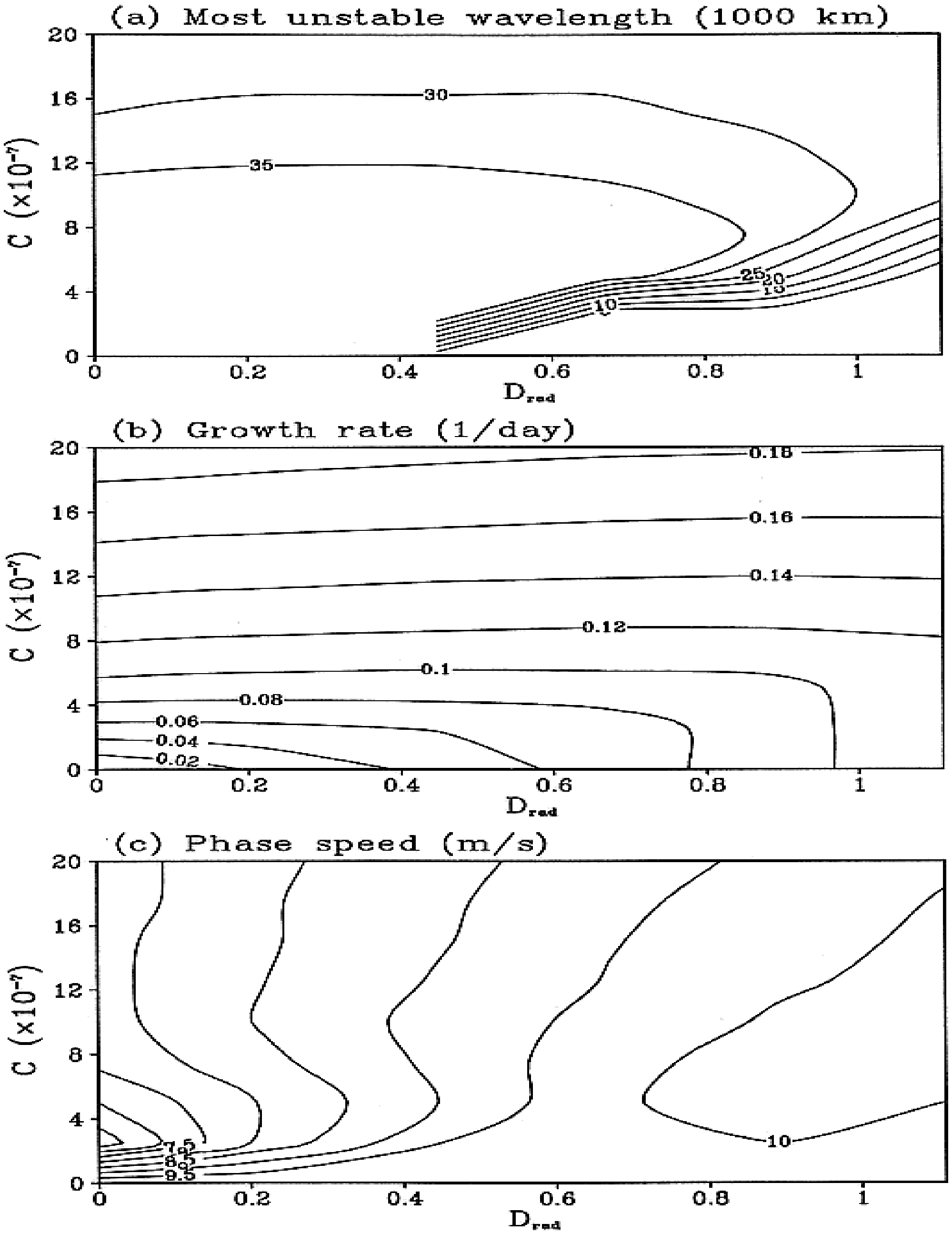
(Wang and Xie 1998)

Model feature

Resting atmosphere except surface wind
Uniform background SST
Single vertical mode-Gill (atmosphere)
Linear mixed layer dynamics
Linear upper ocean dynamics

Air-sea coupling processes:

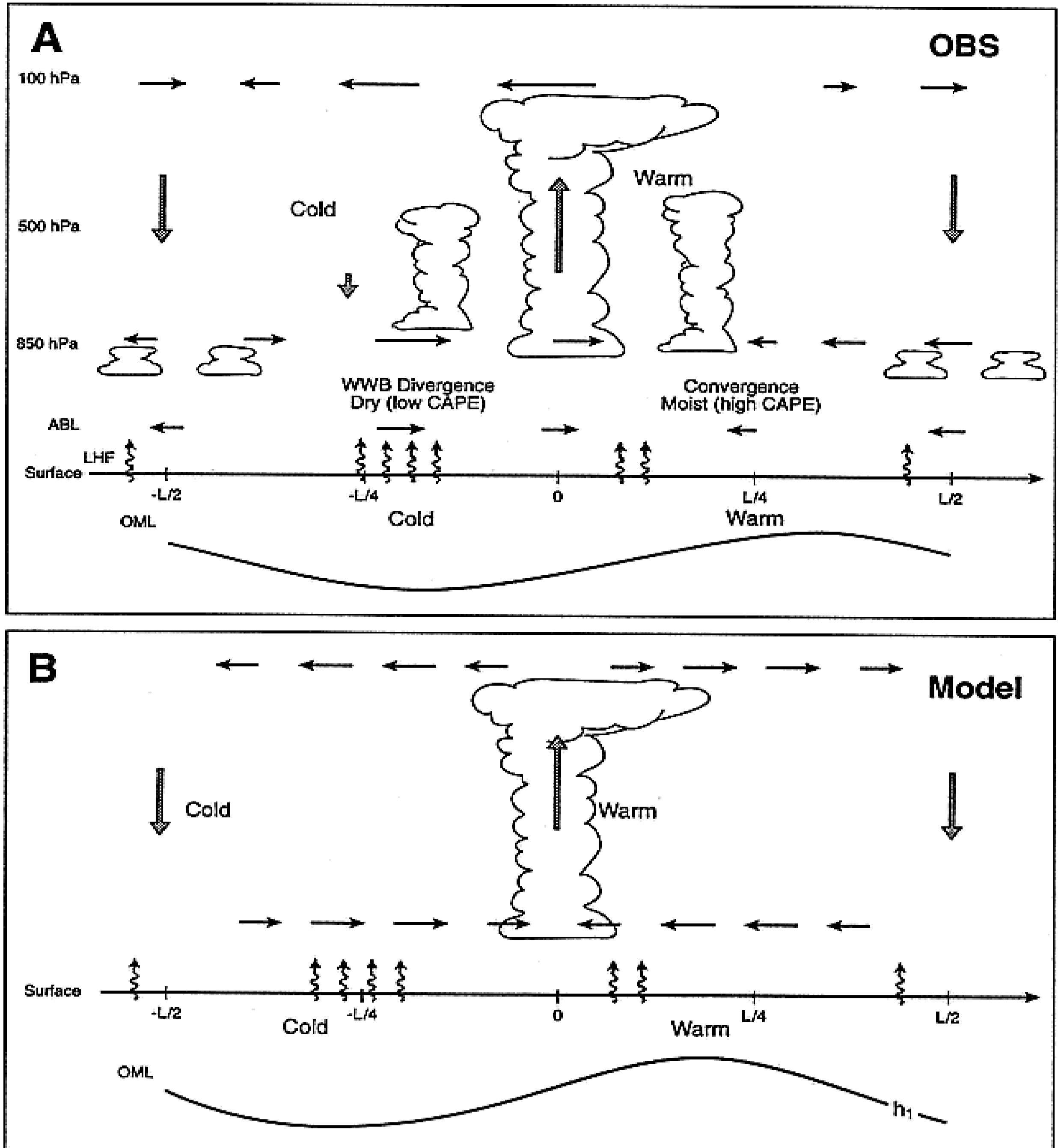
Wind-evaporation/entrainment-SST feedback
Cloud-radiation-SST feedback



Most Unstable coupled mode

(a) Wavelength
(b) Growth rate
(c) Phase speed

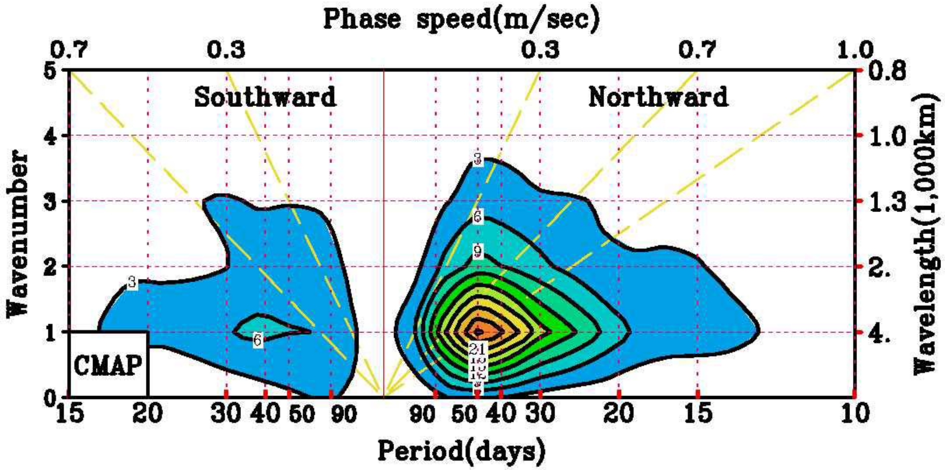
as functions of the
(1) **cloud-radiation feedback** coefficient D_{rad} (K) and
(2) **wind-evaporation /entrainment feedback** coefficient C (K s ^{1})



Schematic diagram illustrating the equatorial vertical structure of the Madden–Julian Oscillation observed in (a) TOGA COARE and (b) the most unstable mode in the coupled atmosphere-mixed layer ocean model of Wang and Xie (1997)

The observations are based on Chen et al. (1991), Sui et al. (1996), Zhang (1996) , Lin and Johnson (1996) , Jones and Weare (1991), Fasullo and Webster (1995) , and

Roles of air-sea coupling in northward propagation

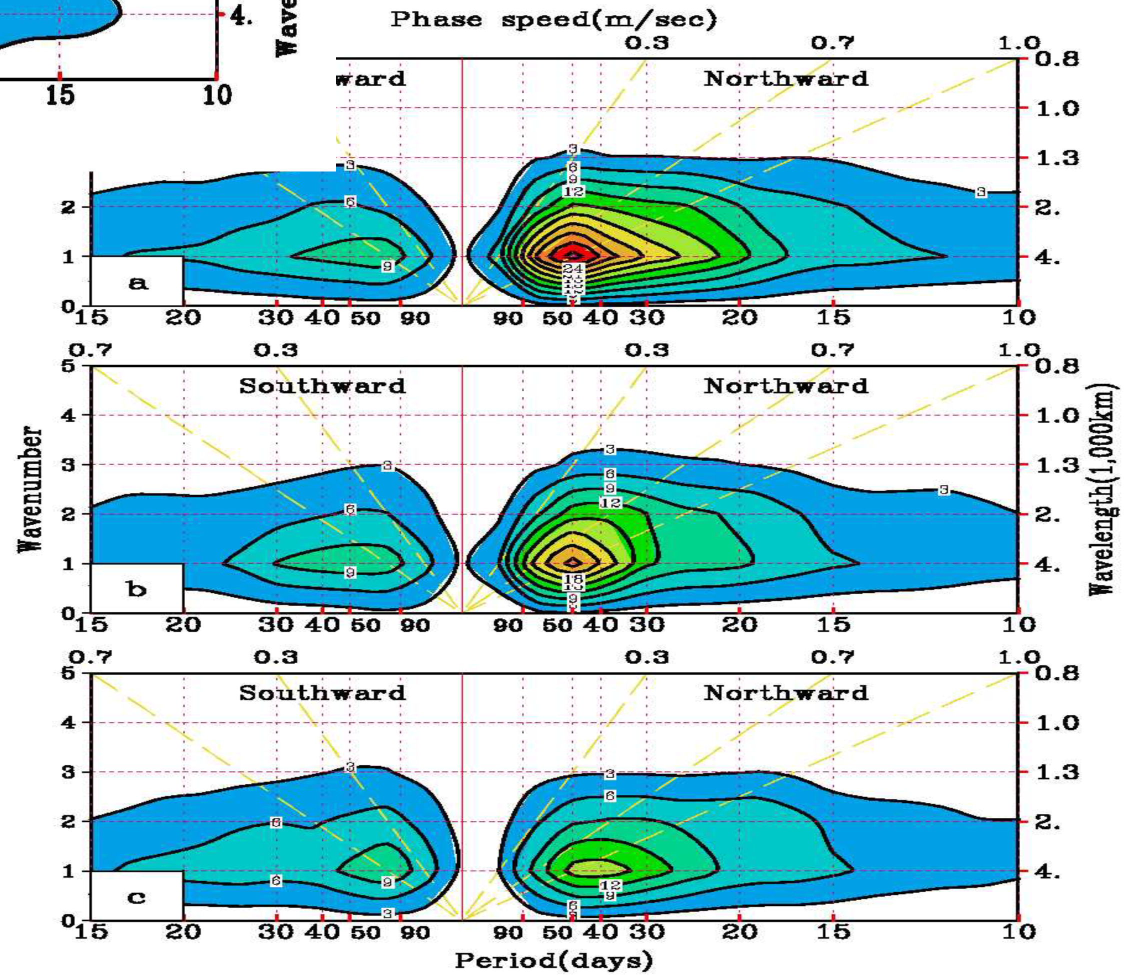


CMAP Rainfall

Coupled

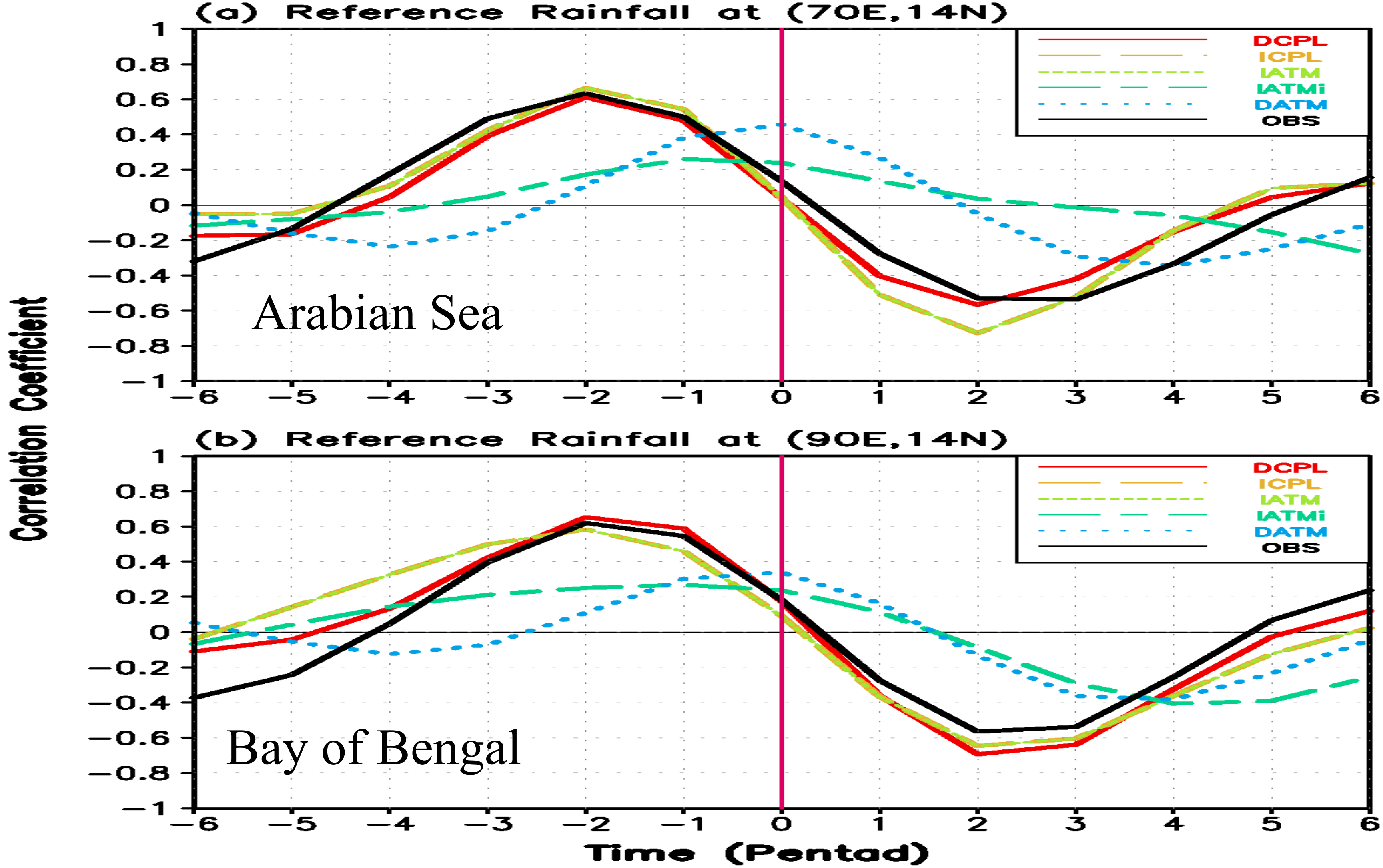
Daily Forced

Mean Forced



Fu and Wang 2003

Lag Corr. of Rainfall with SST in Northern Indian Ocean

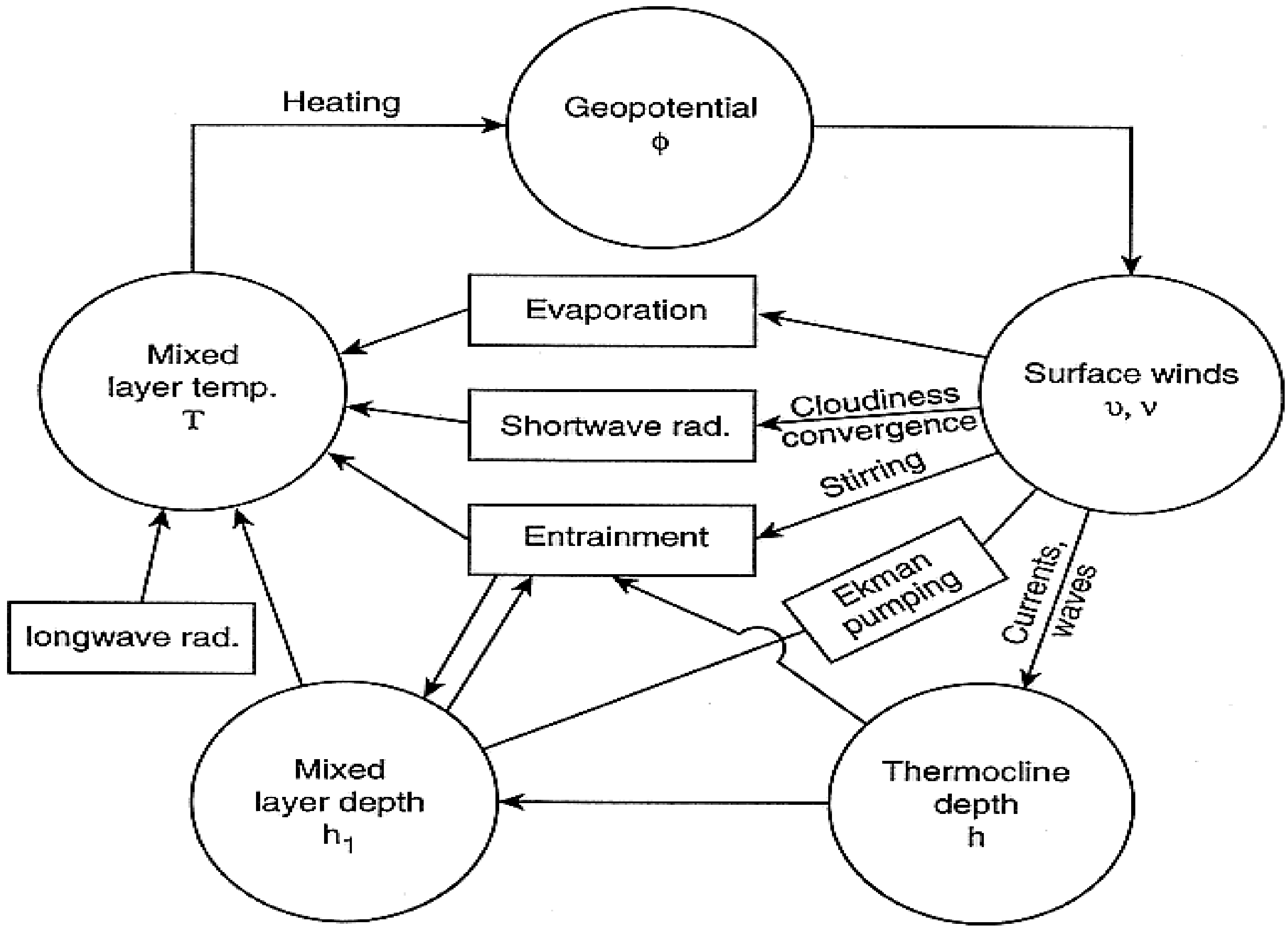


Phase Relationships between Rainfall and SST

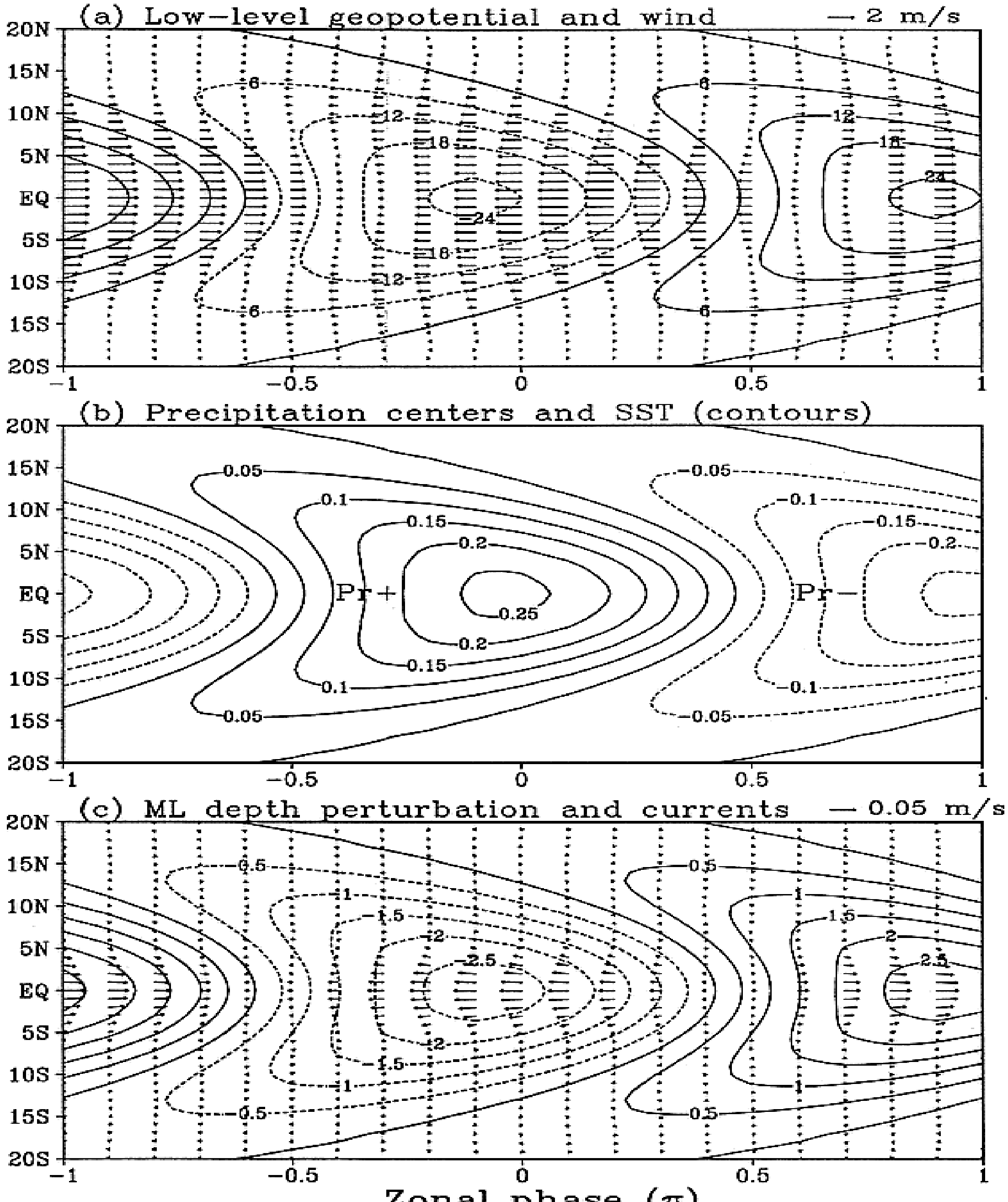
Conclusions

1. MJO and boreal summer ISO can be explained by a unified prototype model: Equatorial Coupled Moist Waves by Friction (ECMWF) regulated by seasonal mean circulation and moist static energy (SST) distribution.
2. BL Frictional moisture convergence feedback Linking convection and PBL thermodynamics (moist entropy) and allow instability in a stable regime to wave convergence-convection interaction. In a linear dynamic framework, Frictional feedback provides mechanisms for (a) selecting eastward propagating planetary scale waves, (b) upward and westward tilt of vertical motion, (c) horizontal structure of coupled Kelvin-Rossby wave packet, and (4) low-frequency amplification.
3. Monsoon easterly vertical shears (easterly increases with height) provides an northward propagation mechanism through **barotropic vorticity generation by tilting of basic-state horizontal vorticity vector**. The reduction of basic state moist static energy over the maritime continent and central Pacific cause northwestward emanation of moist Rossby waves over Indian monsoon and WNP monsoon regions.
4. Air-sea interaction over warm pool ocean can enhance coupled instability MJO through wind-evaporation/entrainment feedback and cloud-radiation feedback. Both feedbacks tend to slow down eastward propagation.

Thank you



Heating
Geopotential
ϕ
Evaporation
Mixed
layer temp.
T
Surface winds
υ, v
Shortwave rad.
Cloudiness
convergence
Stirring
Entrainment
Ekman
pumping
Currents,
waves
longwave rad.
Mixed
layer depth
h1
Thermocline
depth
h



Horizontal structure of the coupled unstable Kelvin mode:

(a) low-level geopotential (contour interval 6 m^2 s ^{2}) and winds;

(b) SST (°C) anomaly and anomalous precipitation centers denoted by P_{r+} and P_{r} ;

(c) mixed layer depth (m) and current anomalies.

Roles of PBL in MJO

- Linking convection and PBL thermodynamics (moist entropy) and allow stable interaction between wave dynamics and convection (No wave-CISK).

- BL convergence favors moist Kelvin wave response dominating (selection of eastward propagation mode)

- Generate eddy available potential energy by creating vertical tilt of heating against propagation.

- Favor planetary zonal circulation scales.

- More realistic vertical structures (tilt of secondary circulation) and horizontal structure (Coupled Kelvin and Rossby waves).