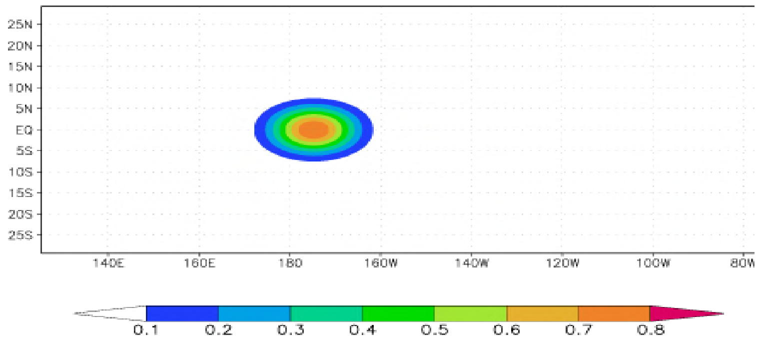
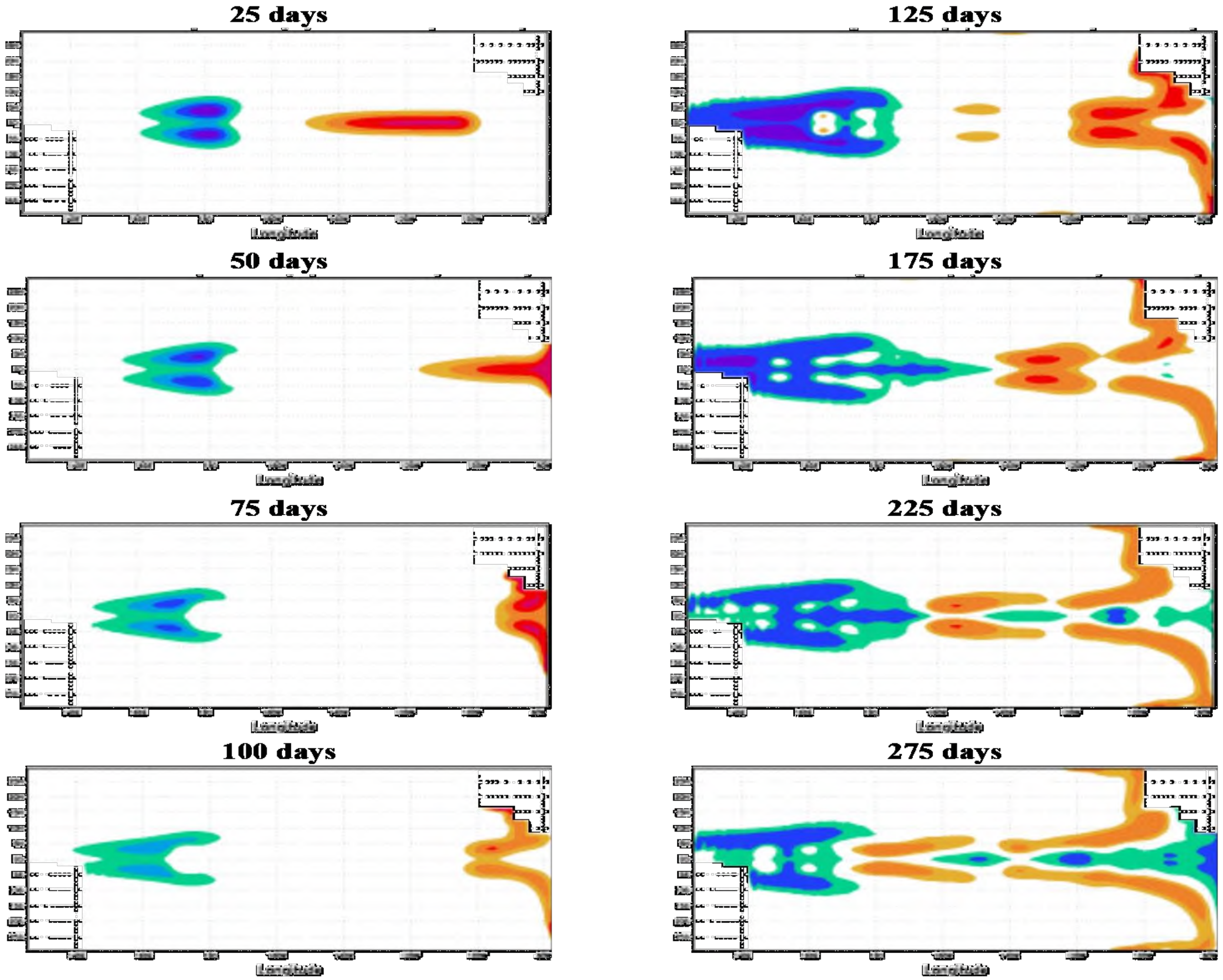
Applying Equatorial Wave Dynamics and Gill Model Solutions to Real Phenomena

1. ENSO phase transition dynamics

A growing El Nino contains the seeds of its own destruction.

1. Force the ocean with a westerly wind stress pulse



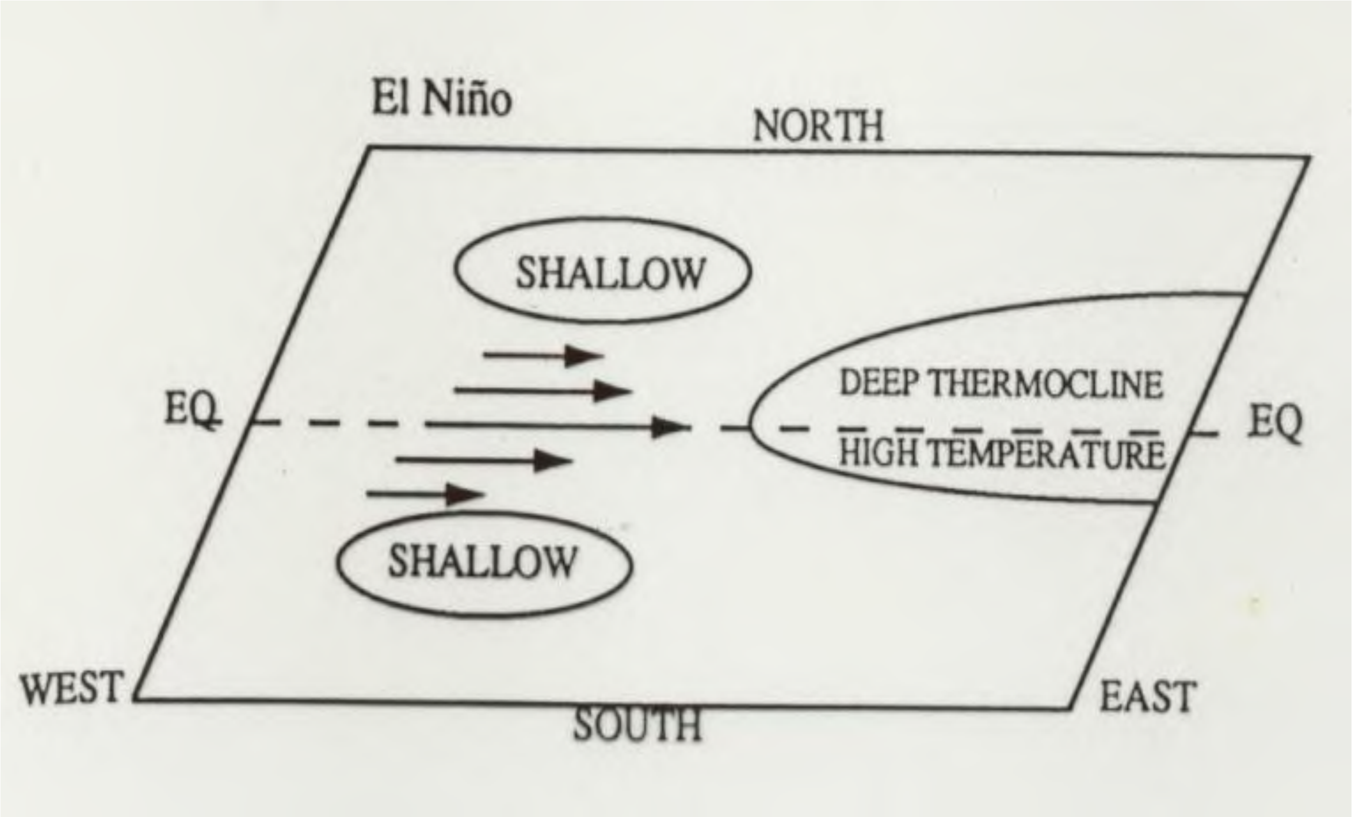


2. Warm Kelvin waves propagate east along equator

➔ Event starts!

3. Cold Rossby waves propagate westward off the equator and reflect back eastward as Kelvin waves ➔ Event ends

Delayed Oscillator Theory:



$$\frac{\partial T}{\partial t} = -bT(t-\tau) + cT$$

Battisti and Hirst 1989

Key process: delayed negative feedback of ocean waves

Simulations from a simple coupled model (Schopf and Sureaz 1988)

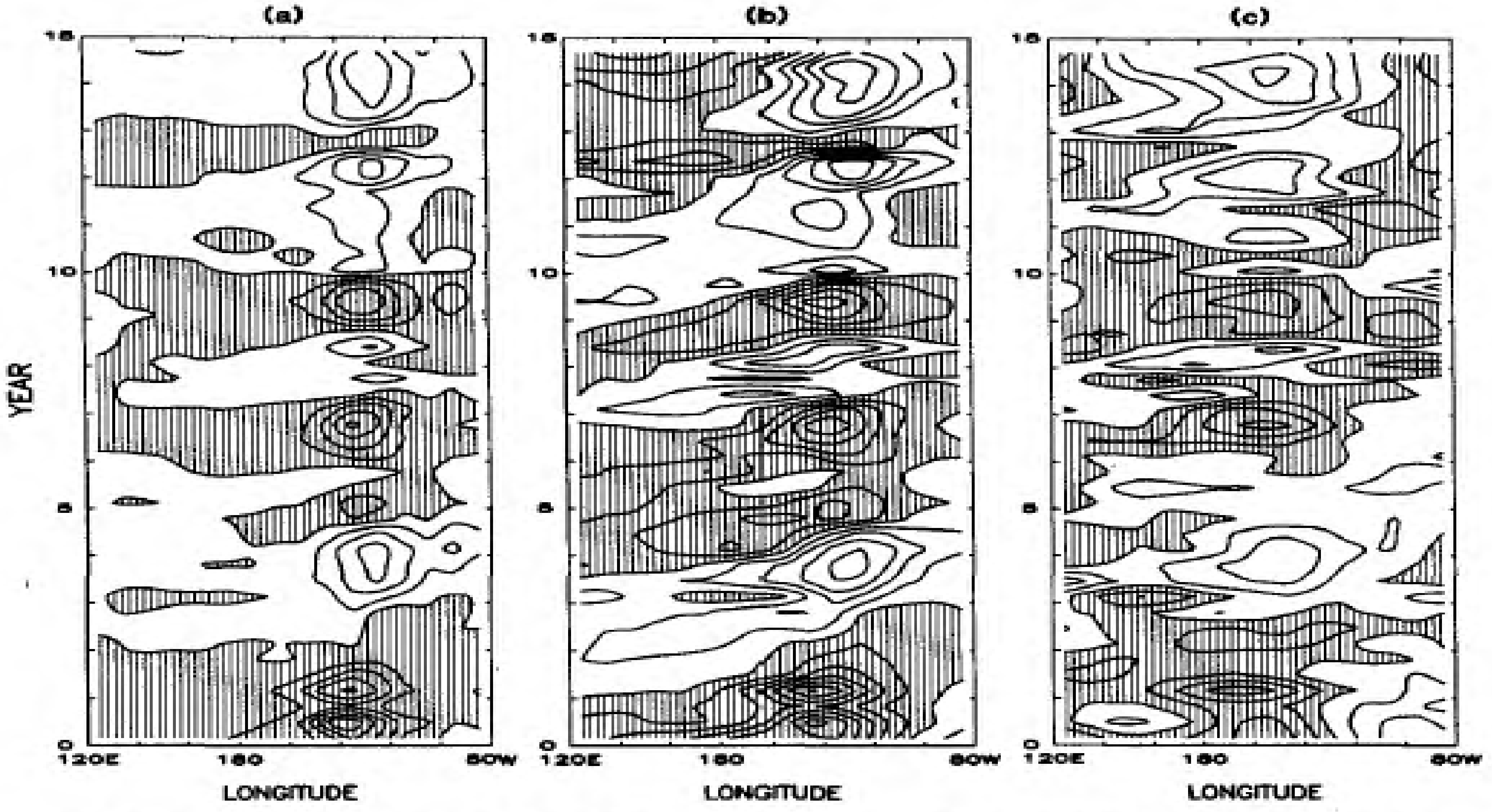


FIG. 4. Time–longitude history of model anomalies averaged between 2°S and 2°N for the first 15 years of the run: (a) SST. Contour interval = 0.5°C. (b) Ocean surface height (η_K). Contour interval = 1 cm. (c) lower-level zonal wind. Contour interval = 0.2 m s^{-1}. Negative anomalies are hachured.

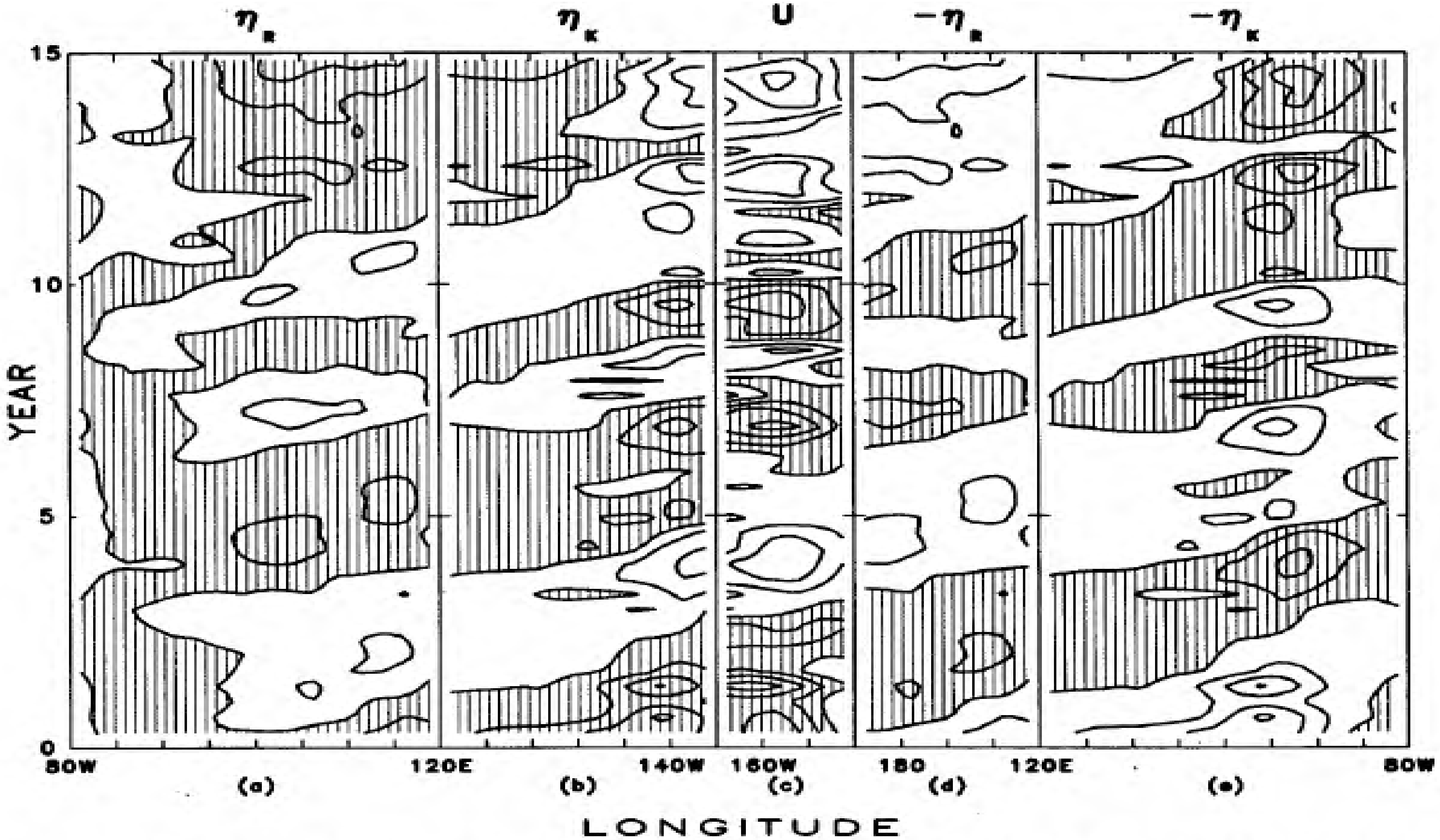
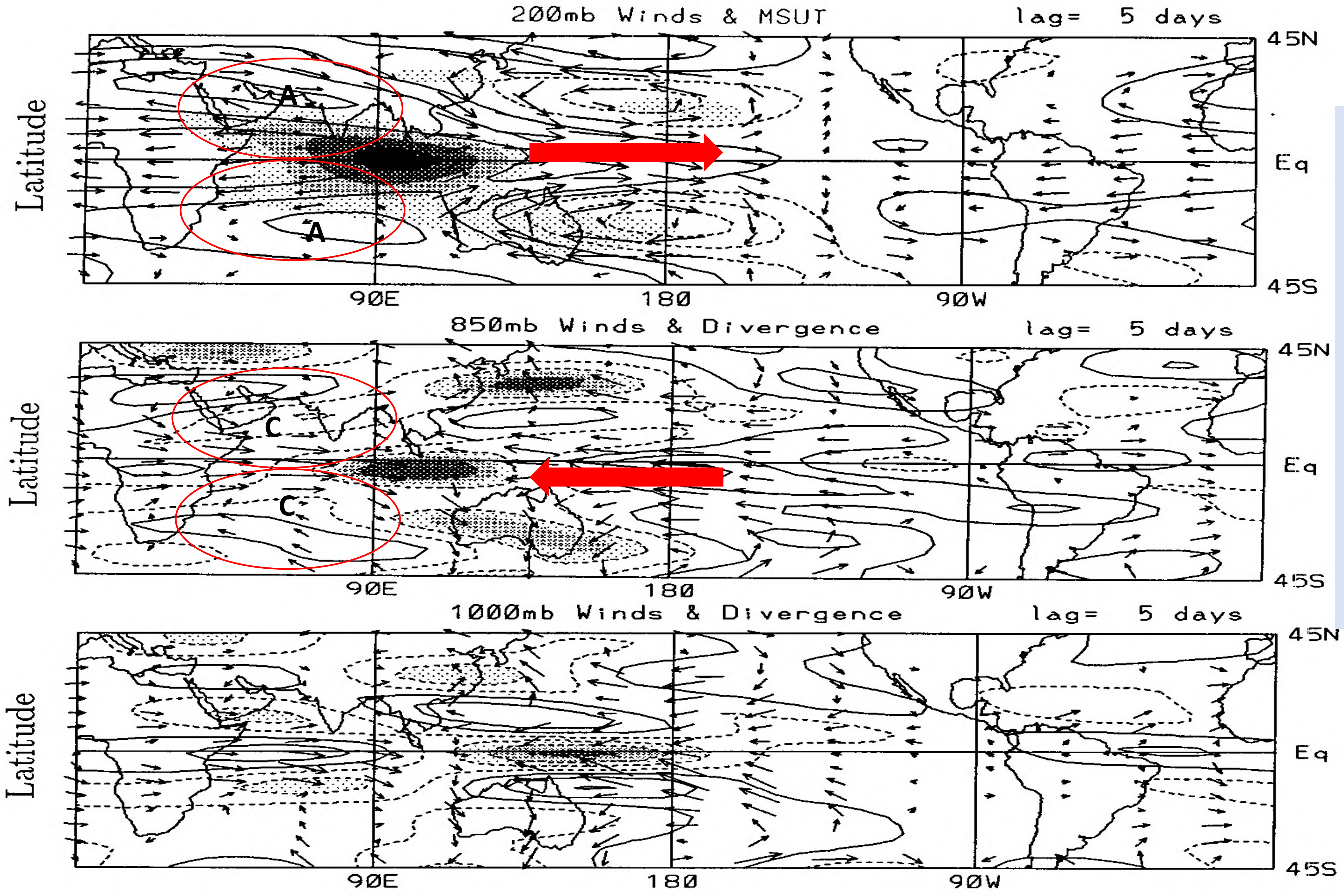


FIG. 10. Time–longitude behavior of the coupled model oscillator. (a) η_R from 80°W (on left) to 120°E (on right). (b) η_K from 120°E to 120°W. (c) Zonal surface wind on equator from 180°W to 125°W. (d) η_R from 160°W (on left) to 120°E. (e) η_K from 120°E to 80°W. In (a)–(c) Positive anomalies are hachured. In (d) and (e) negative anomalies are hachured.

2. MJO Kelvin – Rossby Wave Couplet Structure and Eastward-Propagation Dynamics



Observed Horizontal Structure of MJO:

Kelvin-Rossby wave couplet with BL friction leading convection

Hendon and Salby 1994

Atmospheric Response to a Symmetric Heating (Gill model)

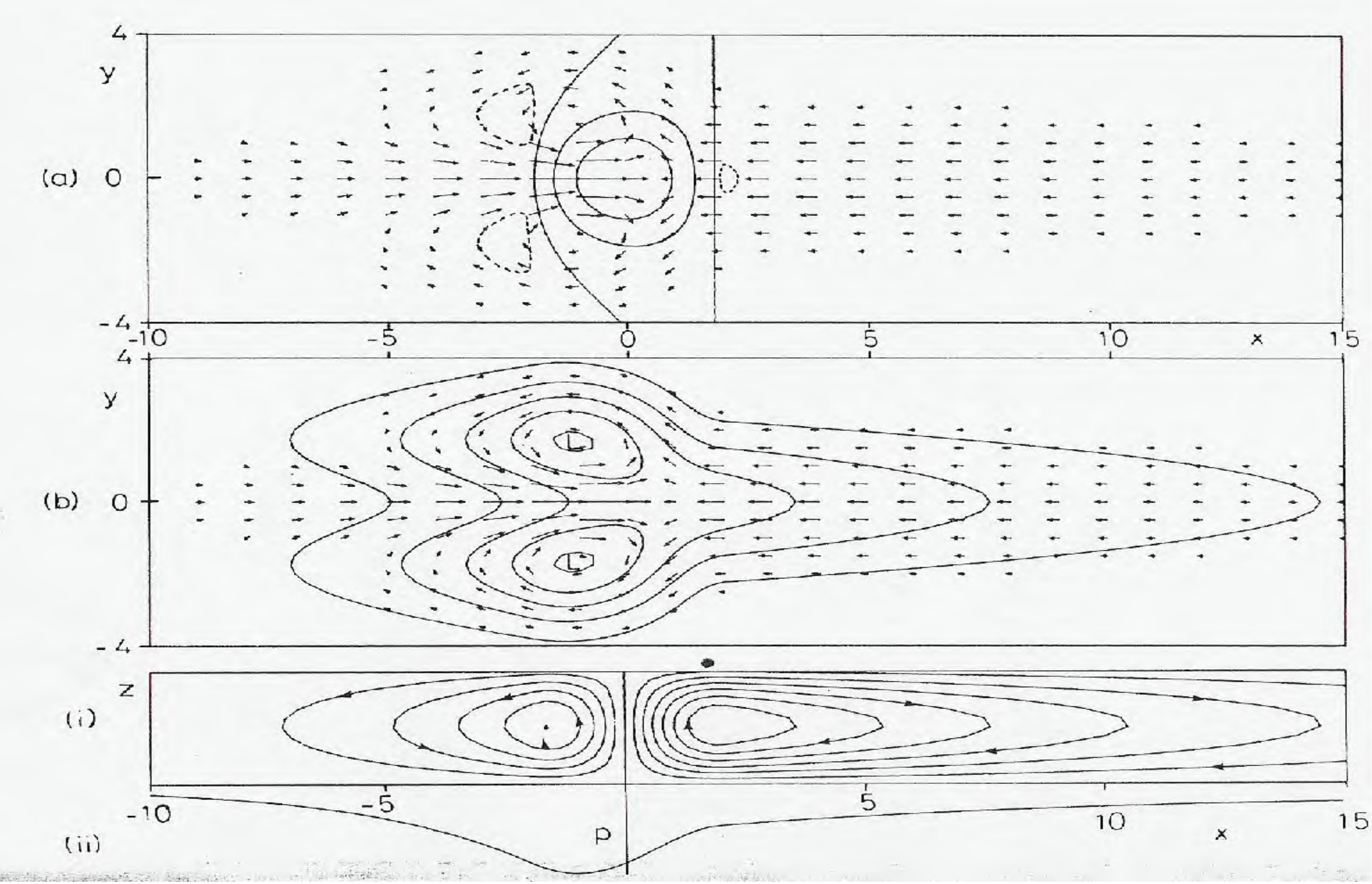


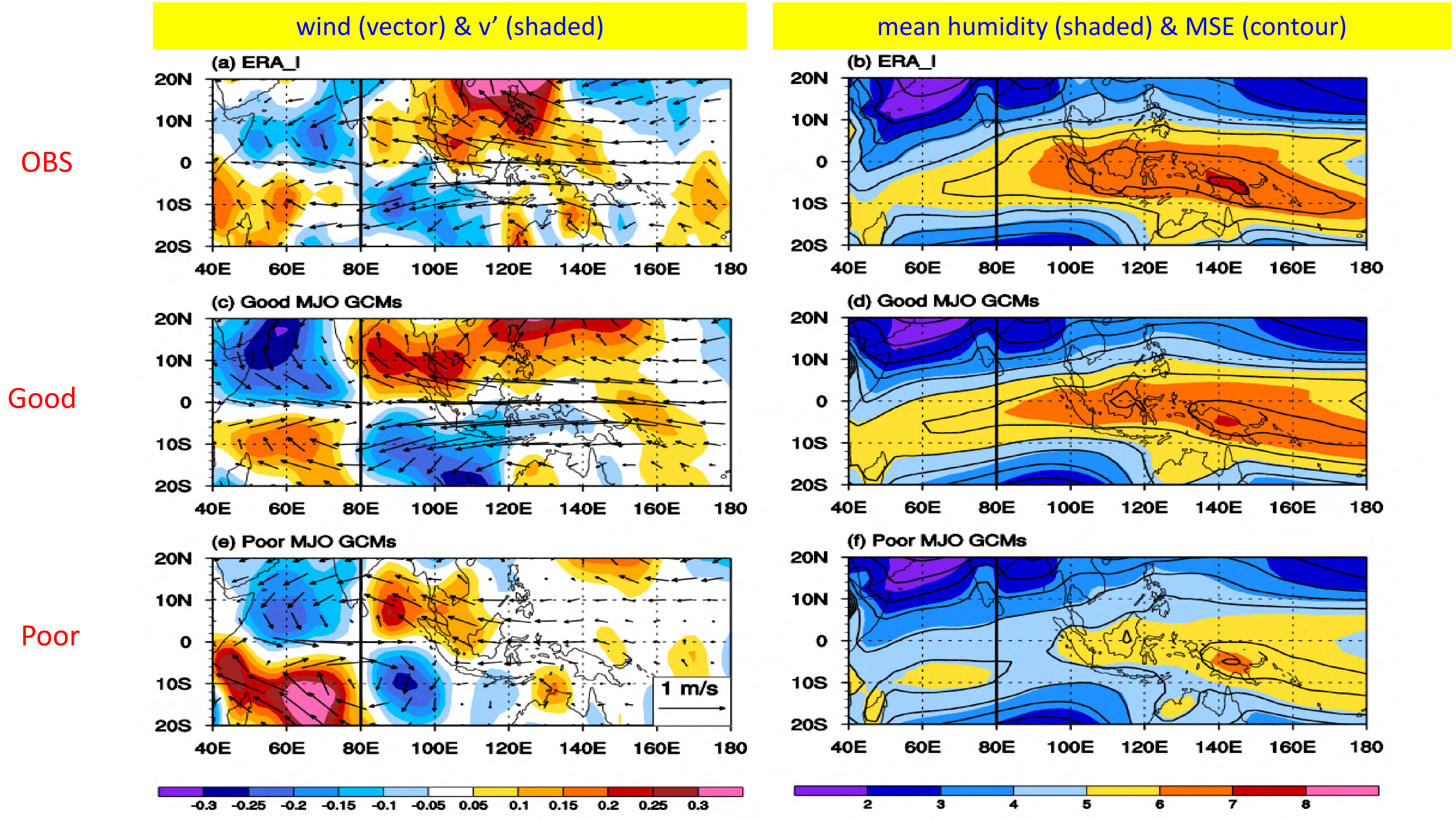
Fig. 1 Solutions for heating symmetric about the equator in the region $|x|<2$ for decay factor $\varepsilon=0.1$

(a) Contours of vertical velocity *w* (solid contours are 0, 0.3, 0.6, broken contour is -0.1) superimposed on the velocity field for the lower layer. The field is dominated by the upward motion in the heating region where it has approximately the same shape as the heating function. Elsewhere there is subsidence with the same pattern as the pressure field.

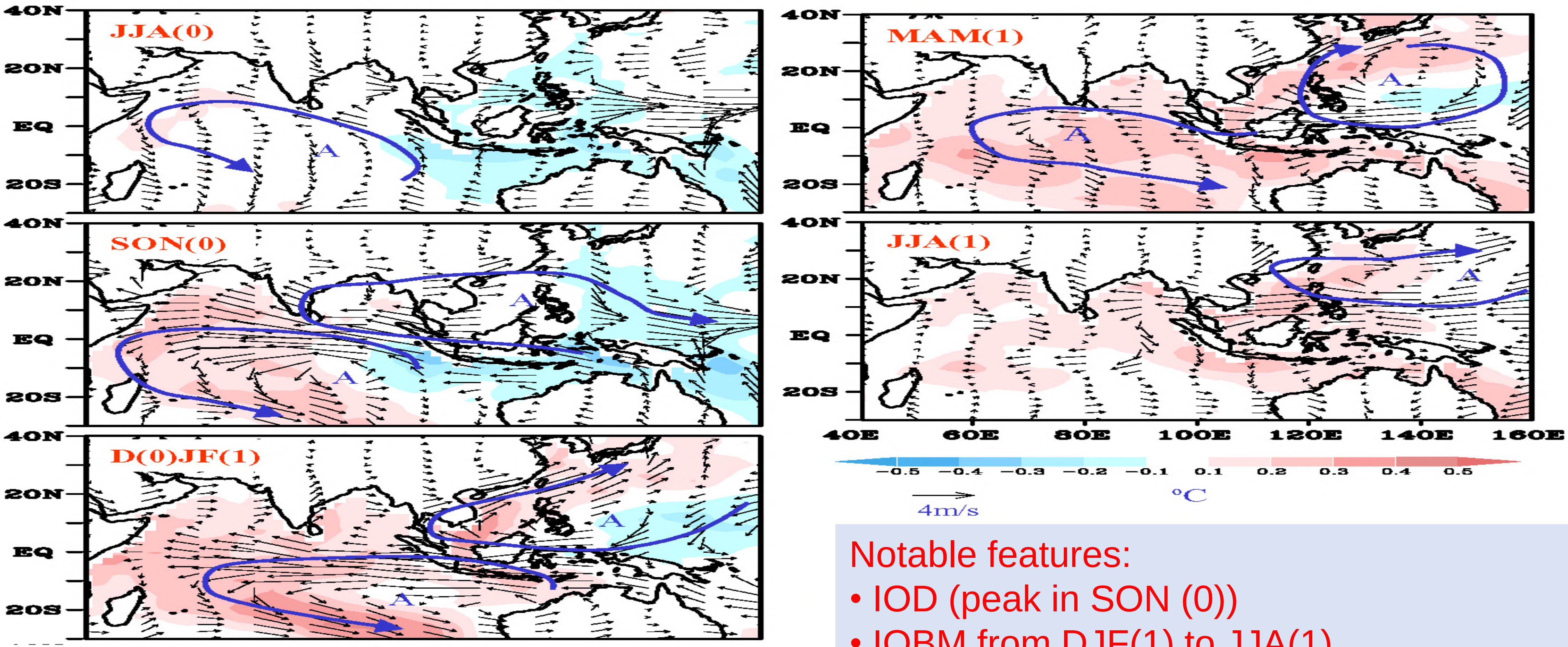
(b) Contours of perturbation pressure *p* (contour interval 0.3) which is everywhere negative. There is a trough at the equator in the easterly regime to the east of the forcing region. On the other hand, the pressure in the westerlies to the west of the forcing region, though depressed, is high relative to its value off the equator. Two cyclones are found on the north-west and south-west flanks of the forcing region.

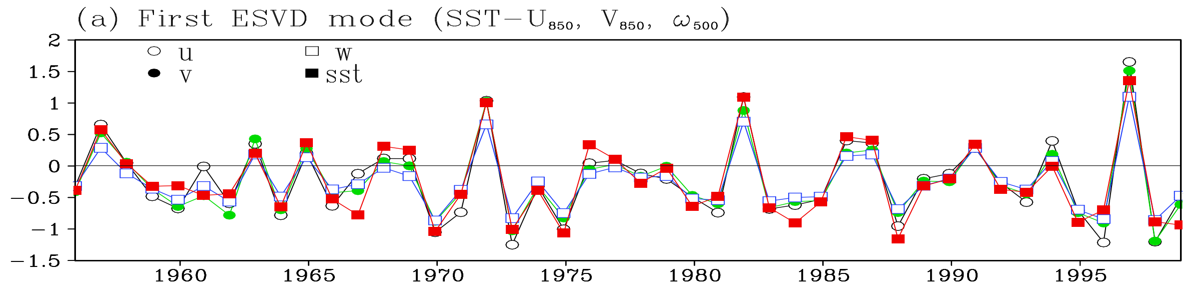
(c) The meridionally integrated flow showing (i) stream function contours, and (ii) perturbation pressure. Note the rising motion in the heating region (where there is a trough) and subsidence elsewhere. The circulation in the right-hand (Walker) cell is five times that in each of the Hadley cells shown in (c).

MJO Flow (left) and Background Mean MSE (right) at 600-800hPa



3. WNPAC formation mechanism



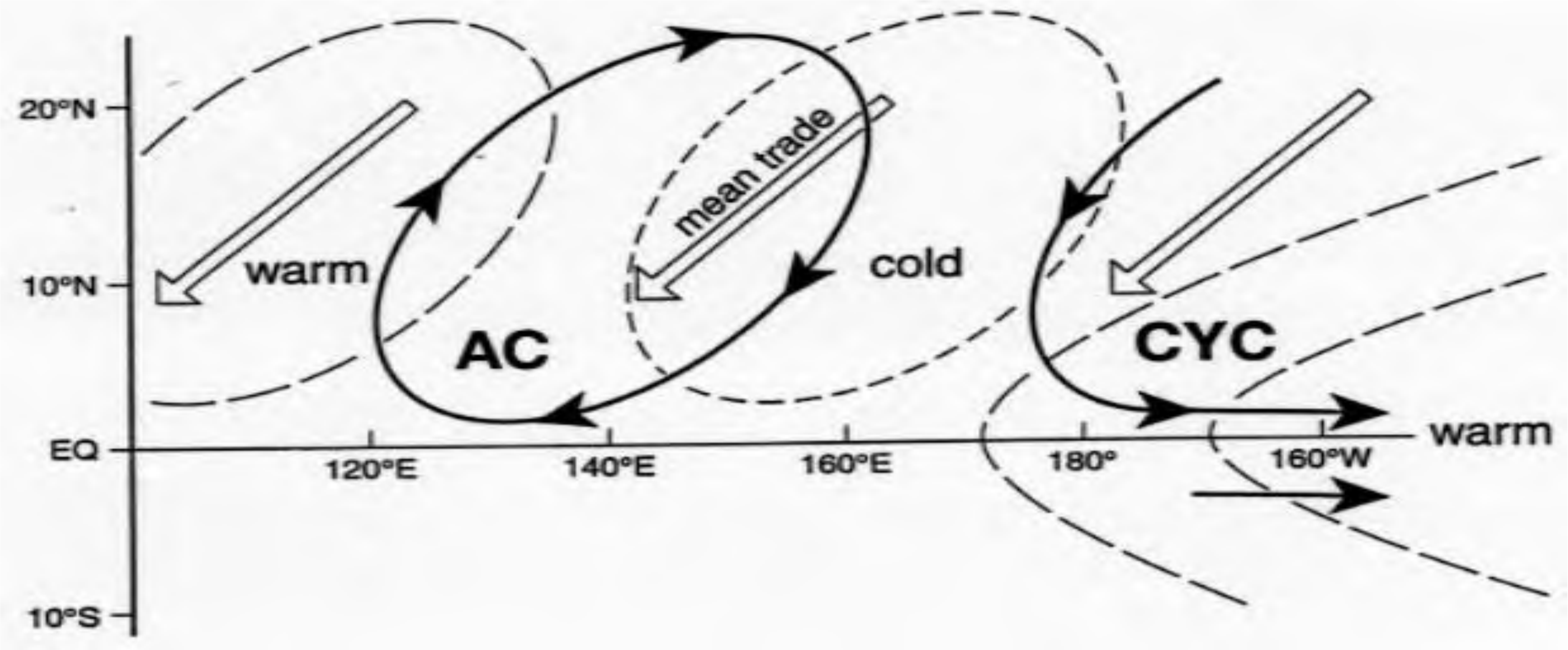


Notable features:

- IOD (peak in SON (0))
- IOBM from DJF(1) to JJA(1)
- WNPAC – cold SSTA pattern persists from DJF(1) to MAM(1) and local SSTA decays in JJA(1)

Wang, Wu, Li 2003, J. Climate

3.1 Local Air-Sea Interaction Mechanism (Wang et al. 2000)



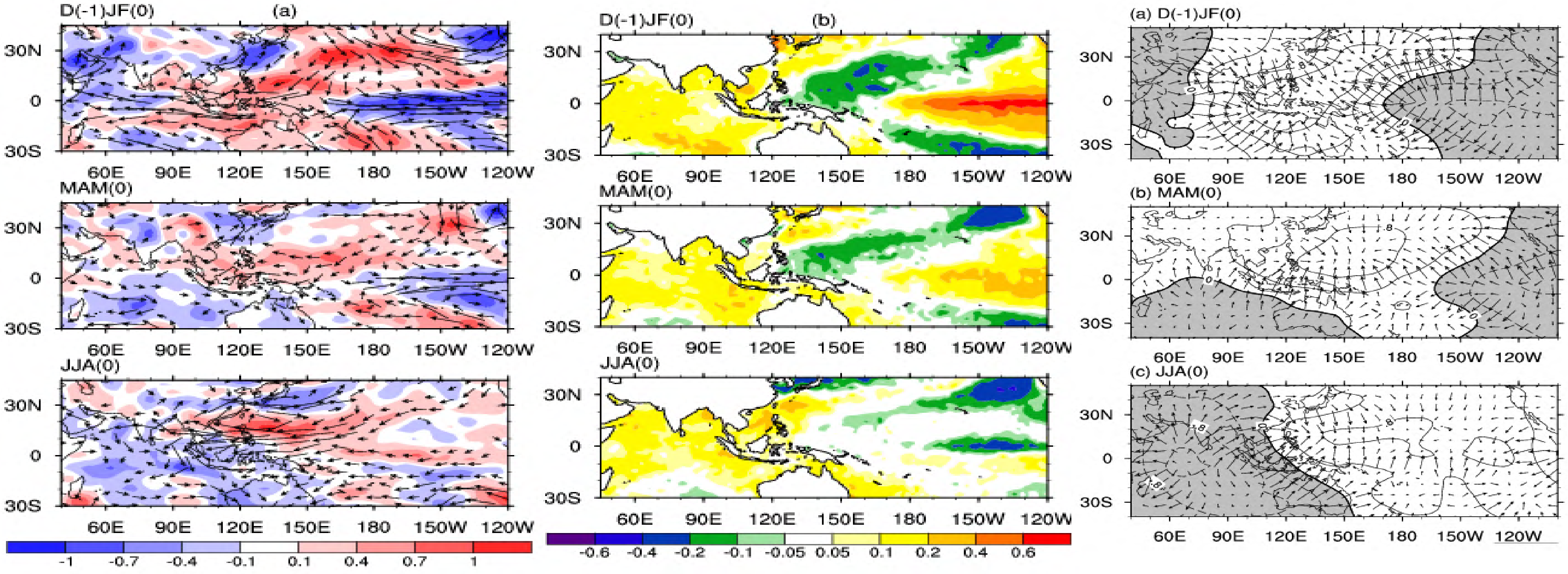
El Nino heating in CP → atmospheric Rossby wave response → cold SSTA/negative heating in WNP → anomalous AC

3.2 Indian Ocean Capacitor Mechanism (Xie et al. 2009, Wu et al. 2009)

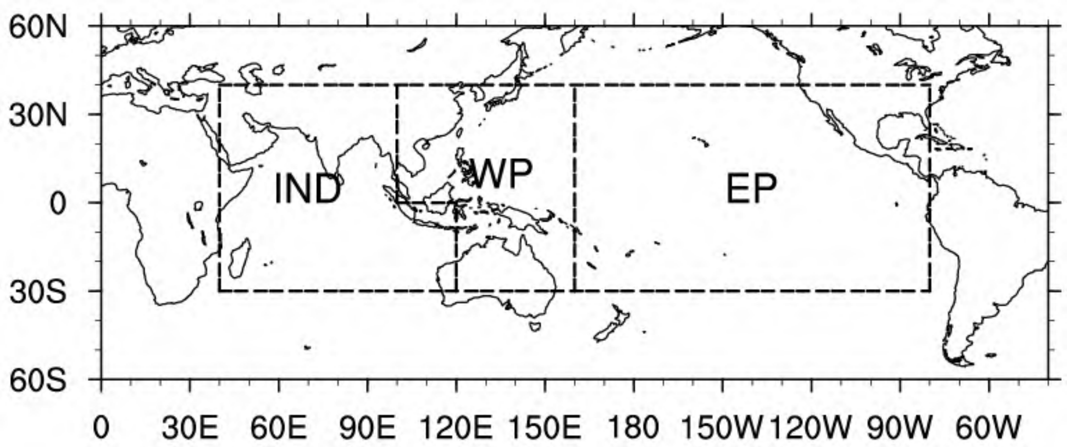
UV850，OMEGA500

SST

200hPa velocity potential

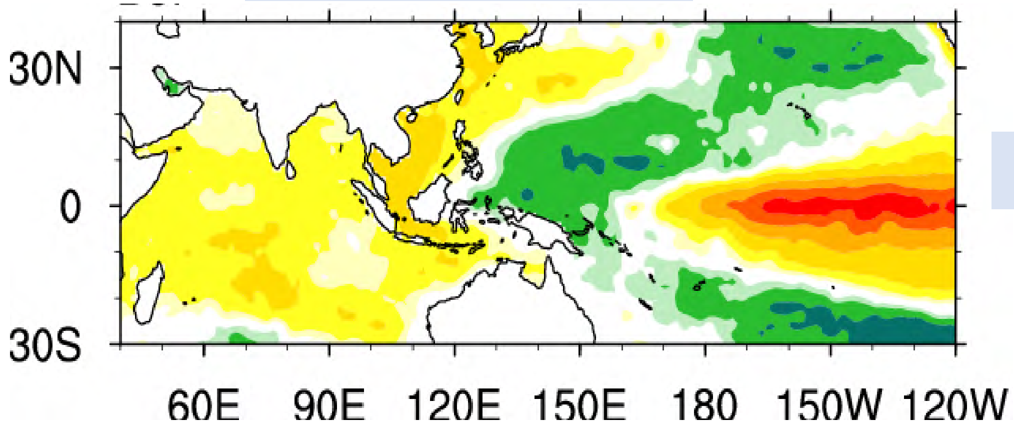


- IO basin warming has little effect on WNPAC formation in DJF.
- IO warming becomes effective only in El Nino decaying summer.

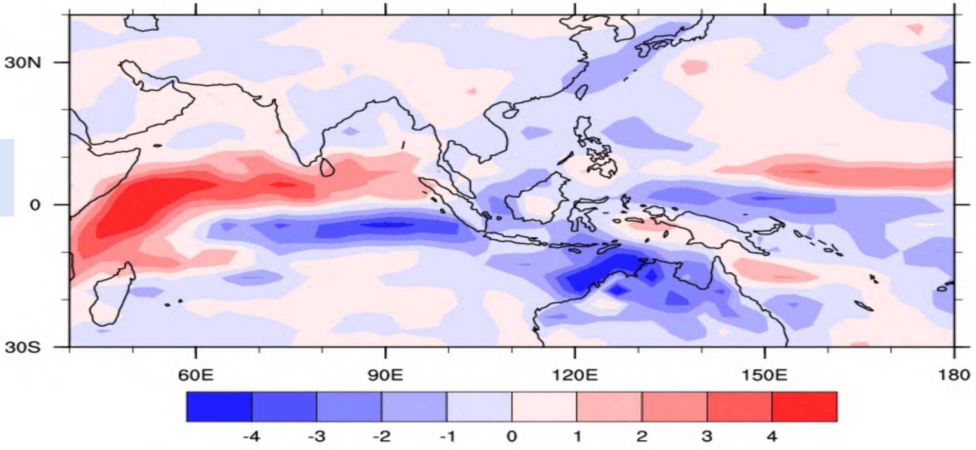


The season-dependent IO forcing mechanism **challenges** our conventional AGCM modeling strategy with specified SSTA forcing experiments !

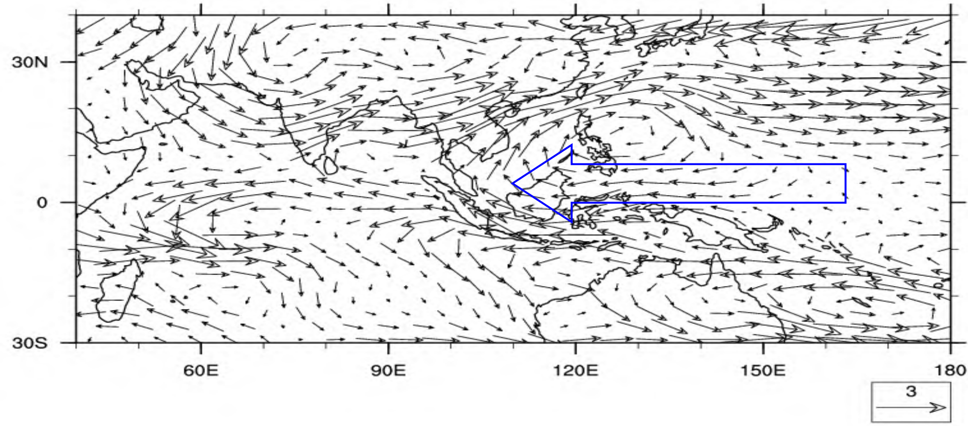
DJF SSTA



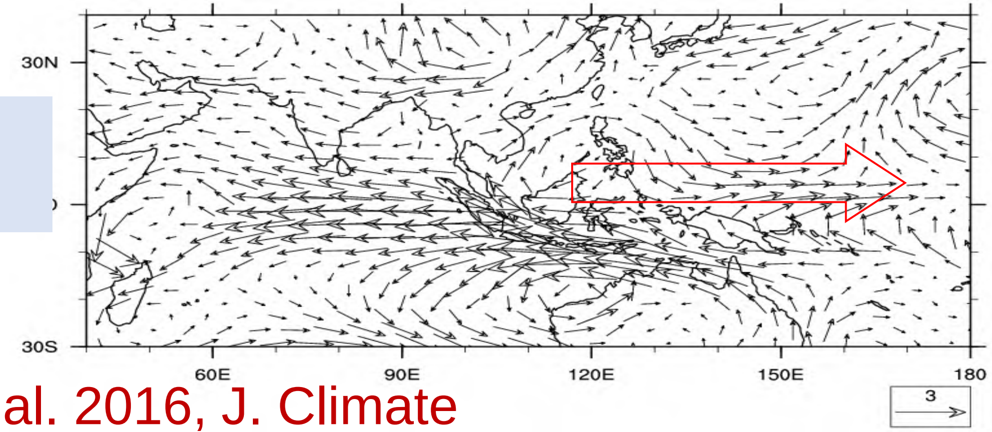
DJF precipitation anomaly



Forcing



850-hPa wind response

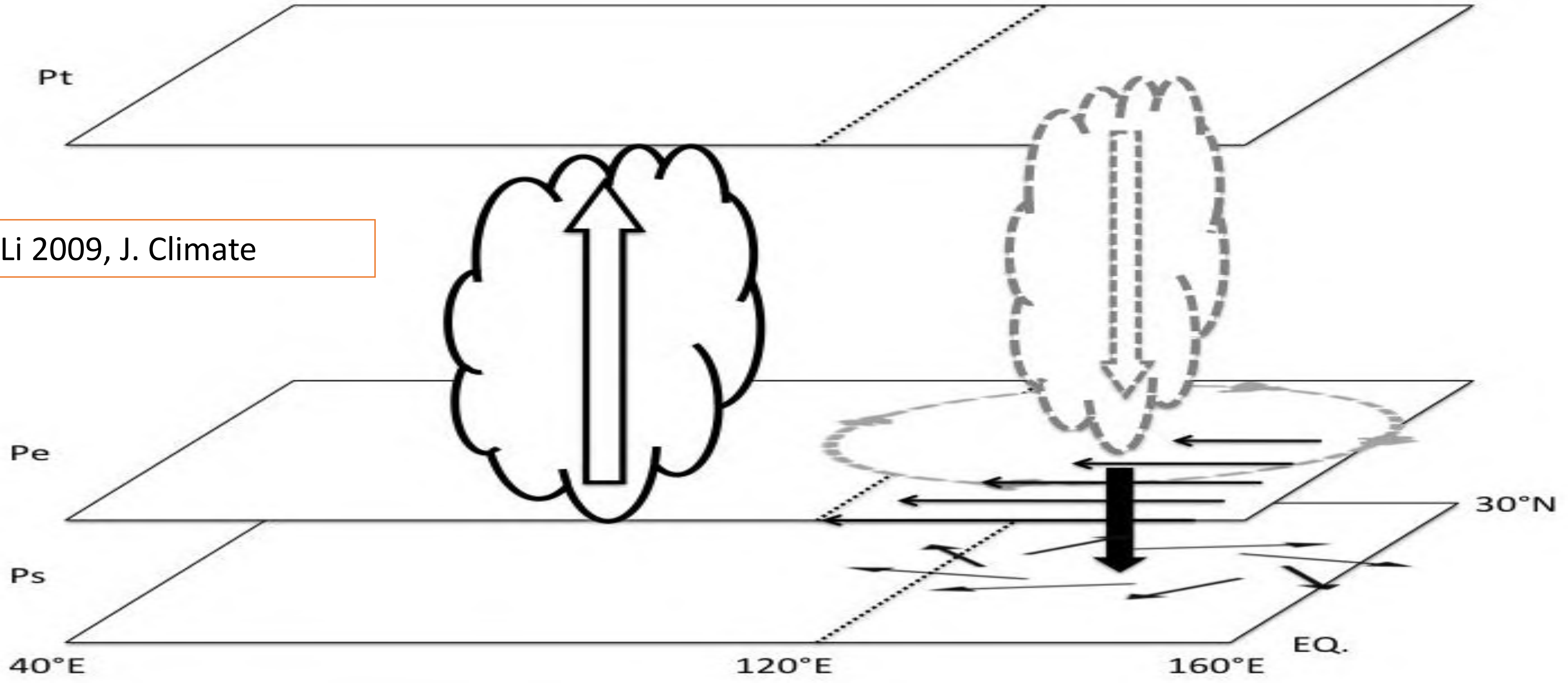


Chen, Li et al. 2016, J. Climate

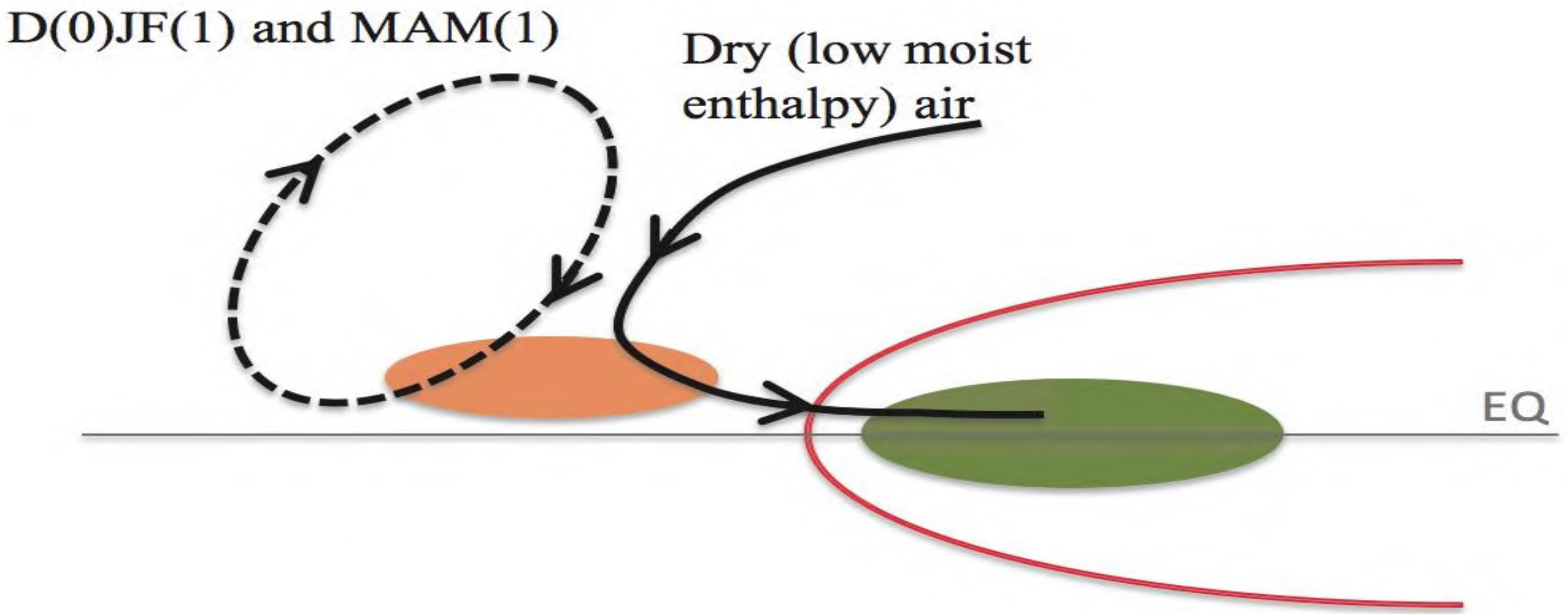
How does IO basin warming in JJA (1) affect the WNPAC?

IOB heating → Kelvin wave response → Anticyclonic shear of Kelvin wave easterly → Ekman pumping induced PBL divergence → suppressed WNPM heating → Anomalous anticyclone

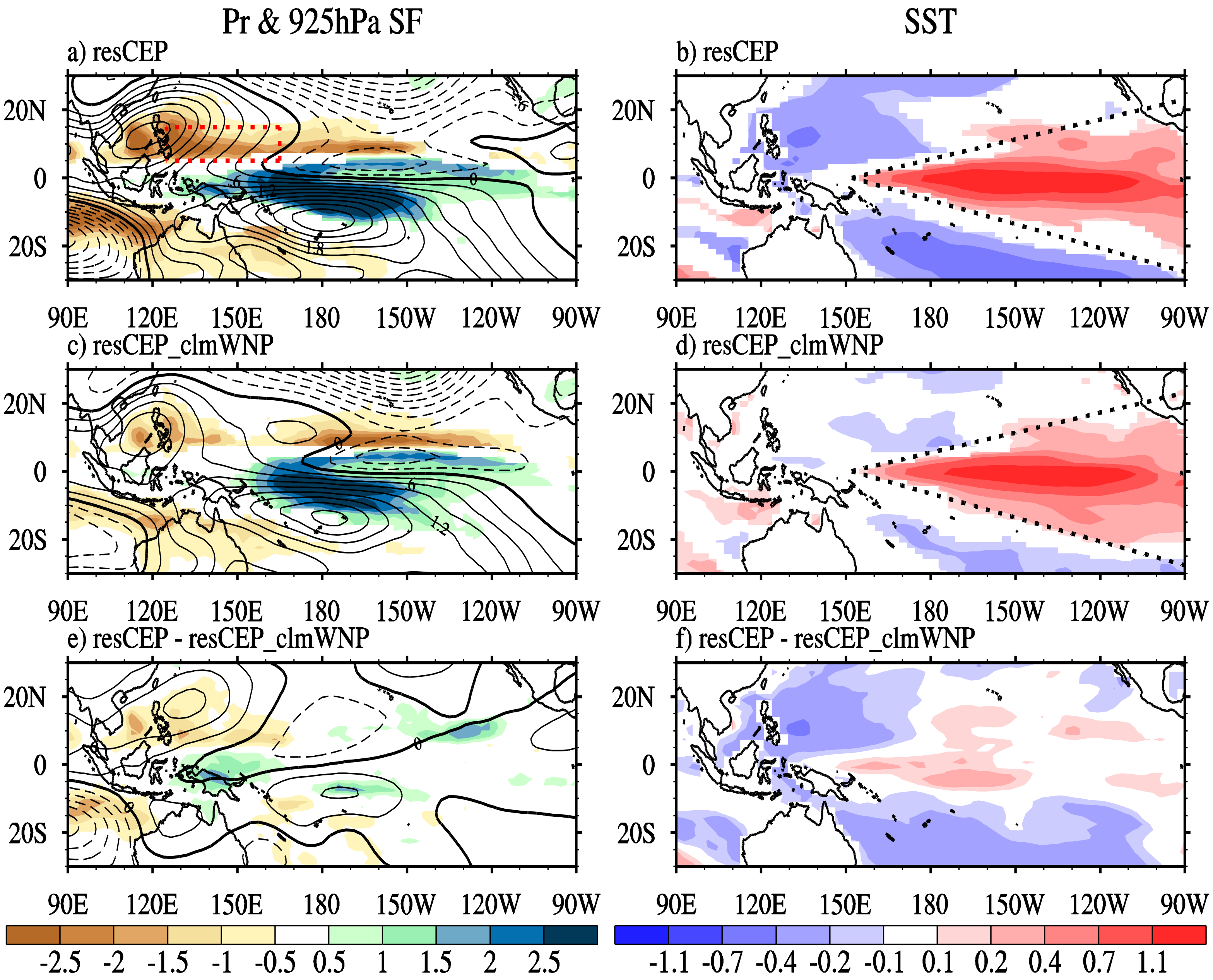
Wu, Zhou and Li 2009, J. Climate



3.3 Moist Enthalpy Advection Mechanism (Wu, Zhou and Li 2017)



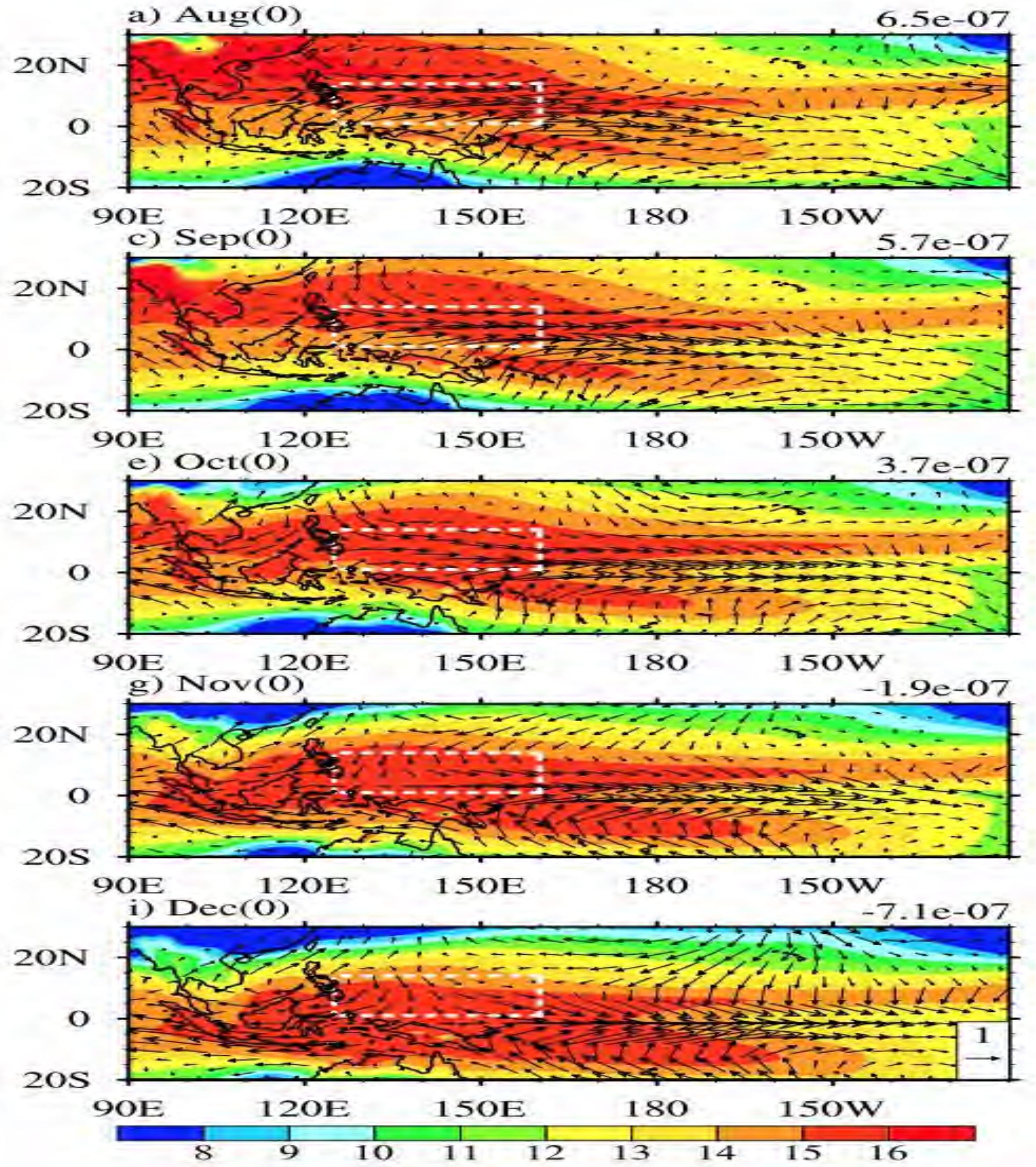
Relative role of local air-sea interaction and remote El Nino forcing



WNPAC and associated precipitation and SST anomalies during El Nino mature winter [D(0)JF(1)] simulated by the FGOALS-s2

➔ Roughly **50%** is attributed to El Nino remote forcing and another **50%** to local SSTA effect.

WNPAC onset timing: Role of Mean Meridional Moisture Gradient Change

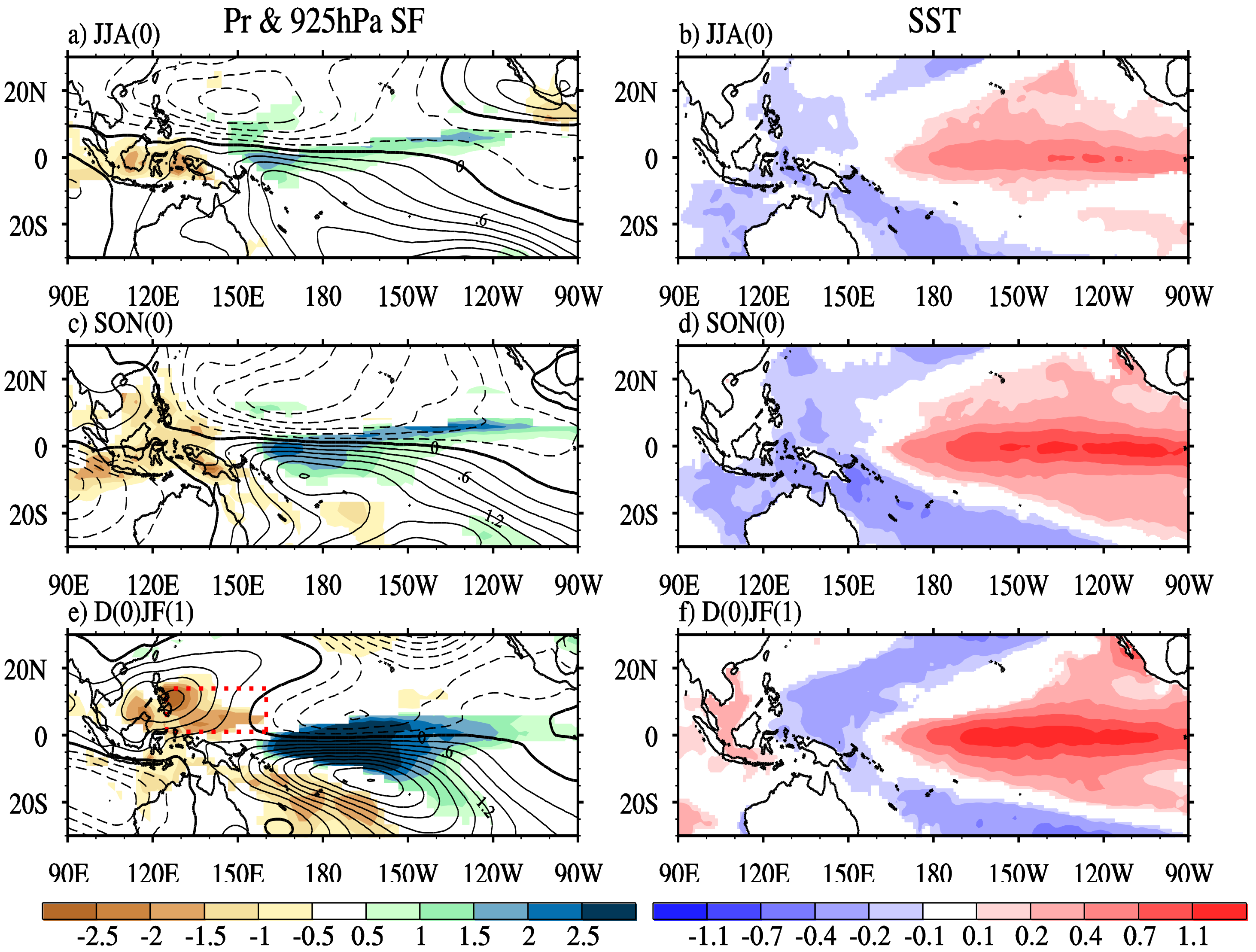


Vector: wind anomaly at 925hPa

Shaded: mean specific humidity at 925hPa

Wu, Zhou and Li 2017, JC

Distinctive Circulation Responses to El Nino between Summer and Winter

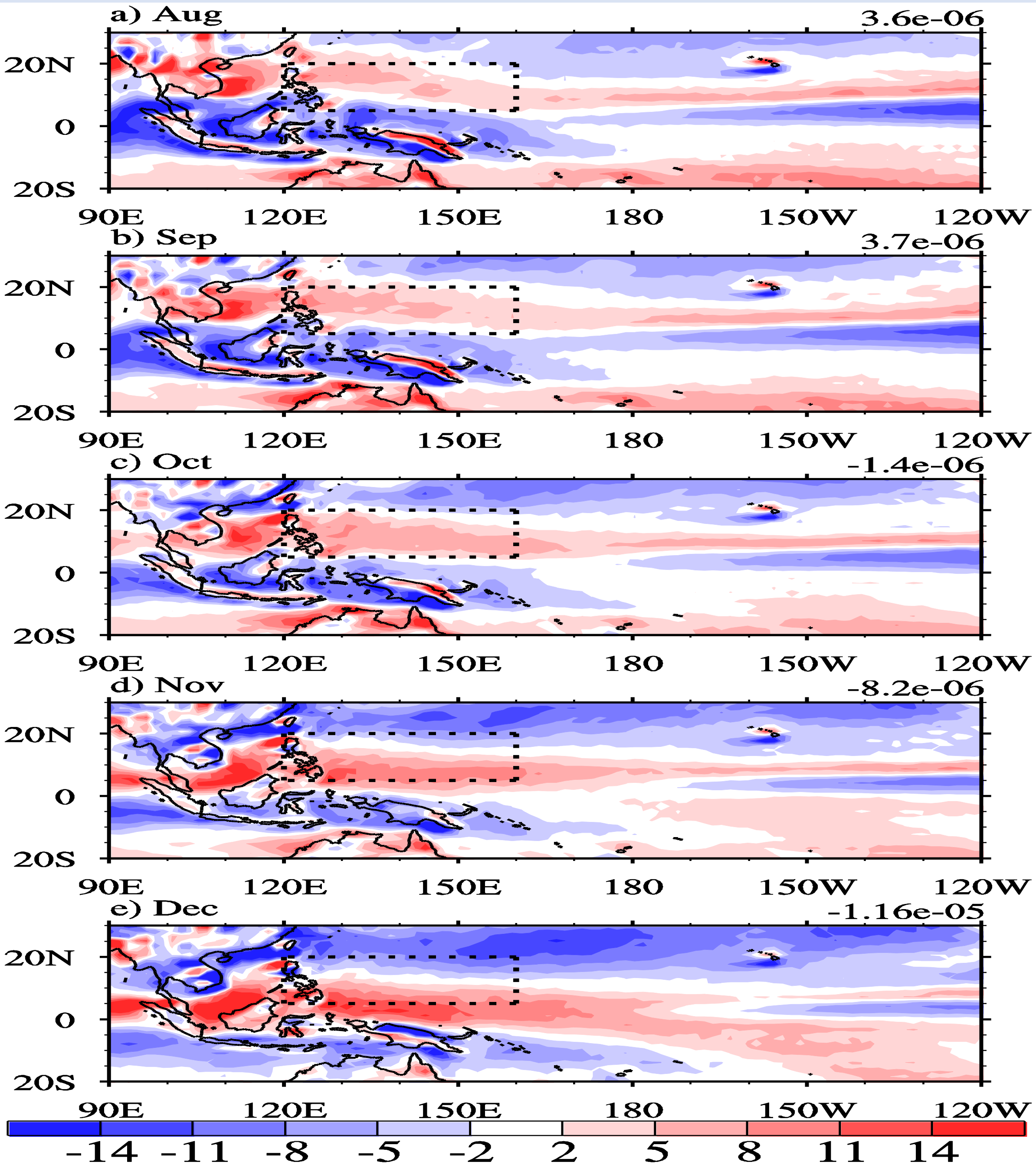


Left panels: Precipitation (shading, mm d^{-1}) and 925 hPa stream function anomalies (contours) regressed against the DJF Nino-3.4 index

Right panels: Regressed SST anomalies (K).

➔ Given a similar SSTA pattern during El Nino developing summer and mature winter, why does the circulation response in the WNP differ greatly?

Background Meridional Vorticity Gradient Change

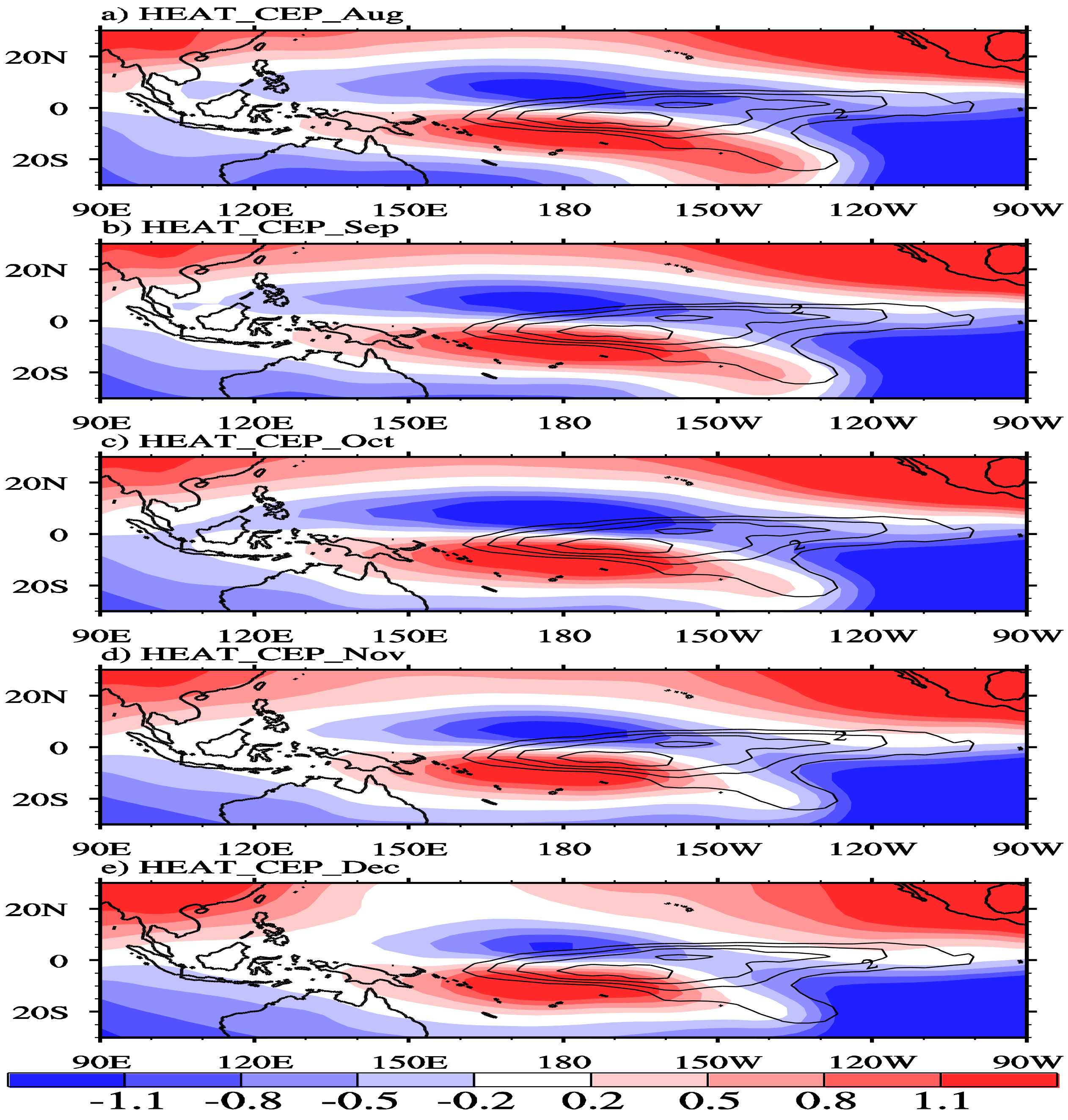


Shaded: Climatological 850hPa **relative vorticity** field from August to December (from ERA-I)

Equivalent beta effect

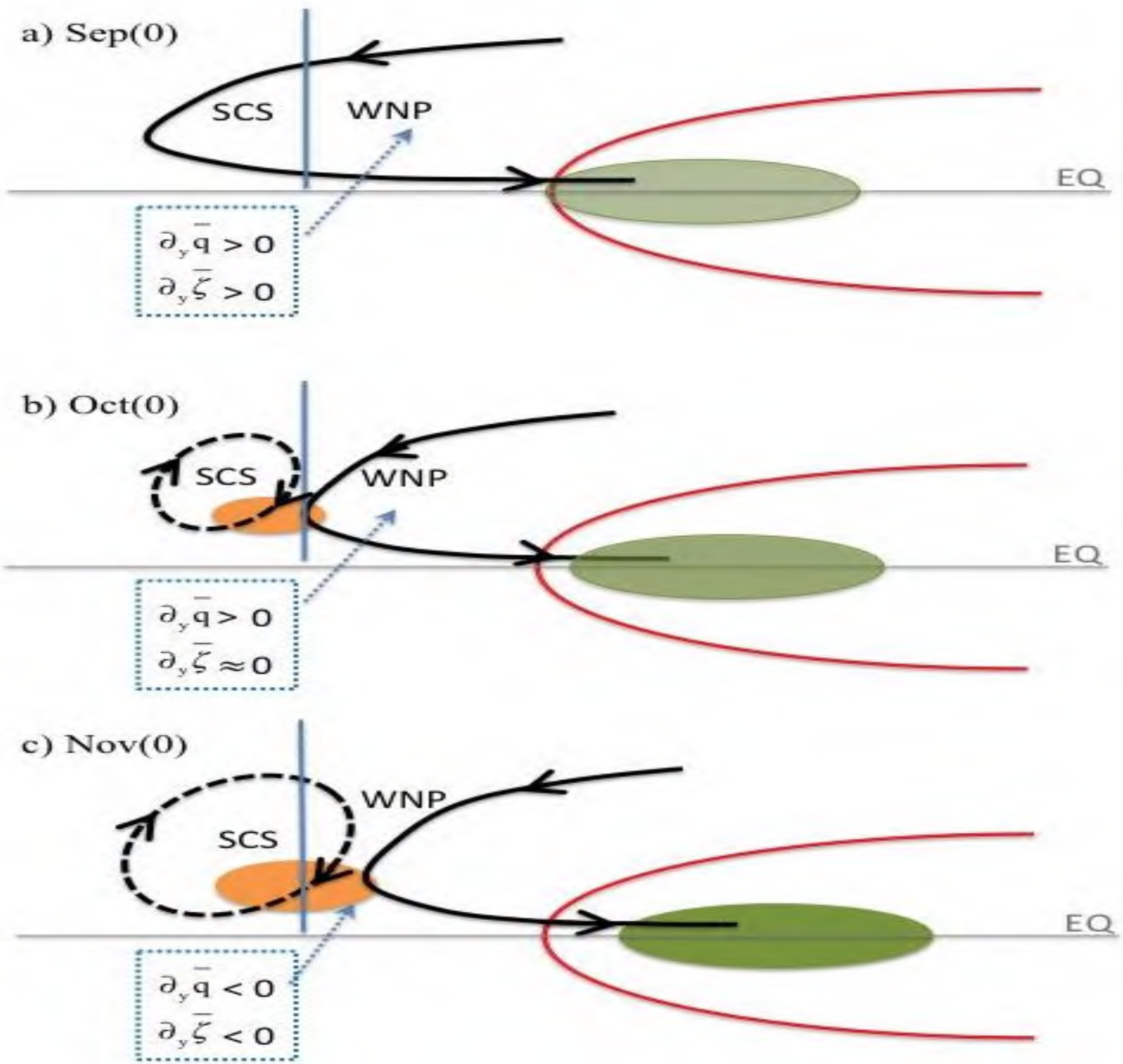
$$\beta_* = \beta + \partial_y \overline{\zeta}$$

Atmospheric Responses to a Specified El Nino-like Heating



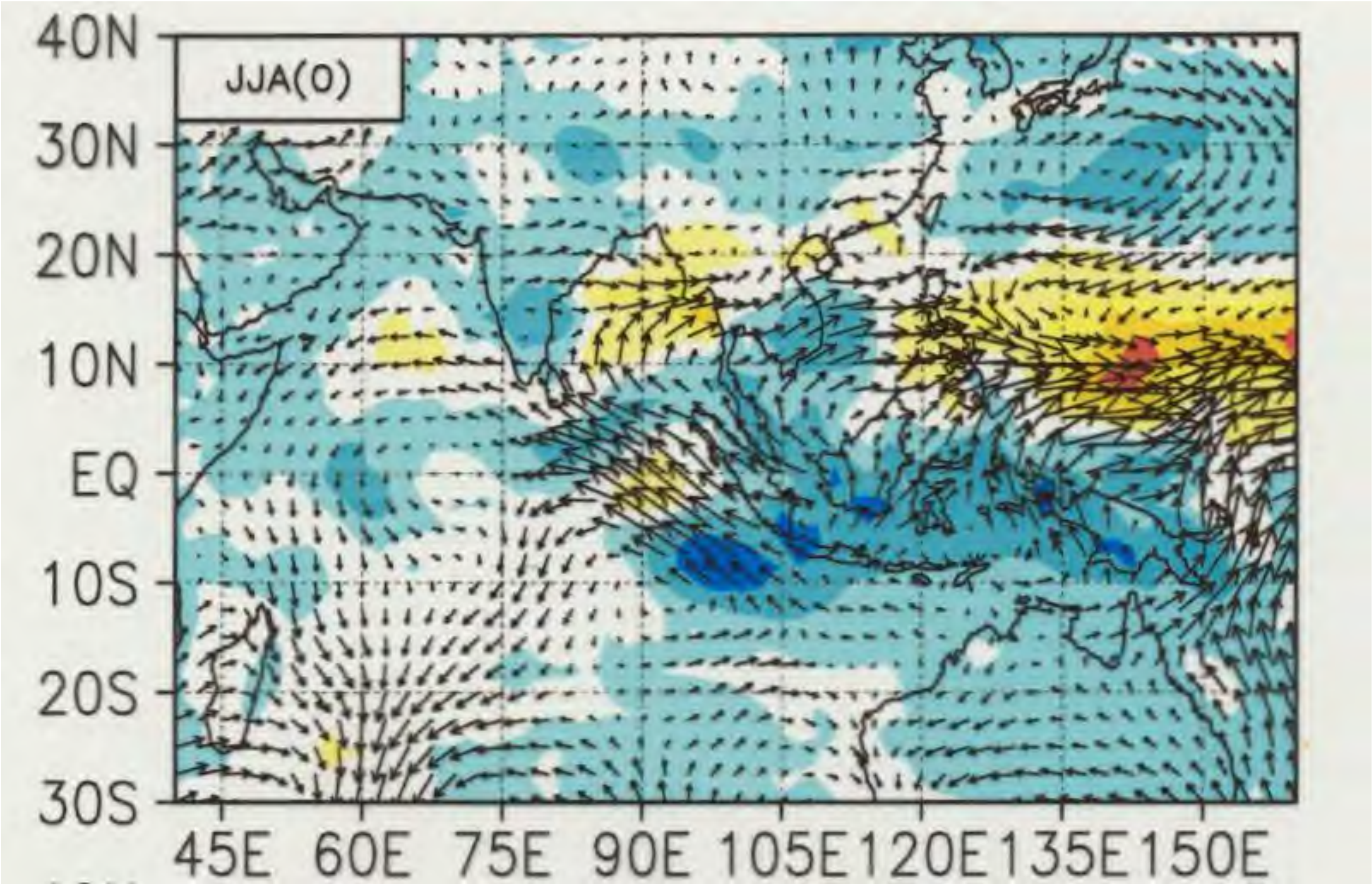
850hPa **stream function** anomalies (shading, 10^6 m^2 s^{-1}) simulated by an **anomaly AGCM** with a fixed heating structure

Schematic for Moist Enthalpy Advection – Rossby Wave Modulation Mechanism



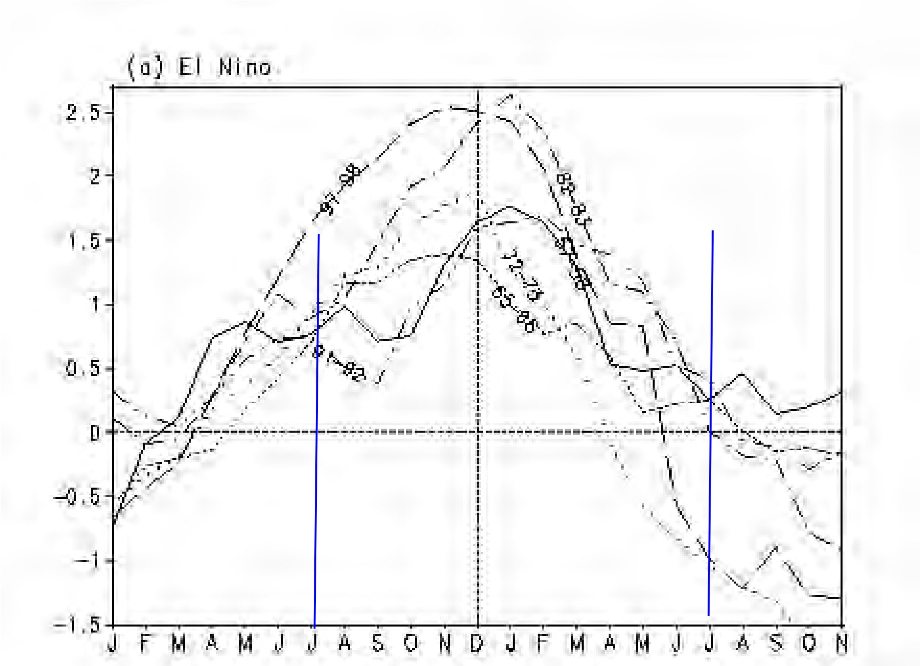
4. How does El Nino impact Asian monsoon?

Walker Circulation ?   Rossby wave response to negative heating ?



El Nino composite JJA(0) during 1950-2006

Rainfall (shaded) and 925-hPa wind (vector) anomaly



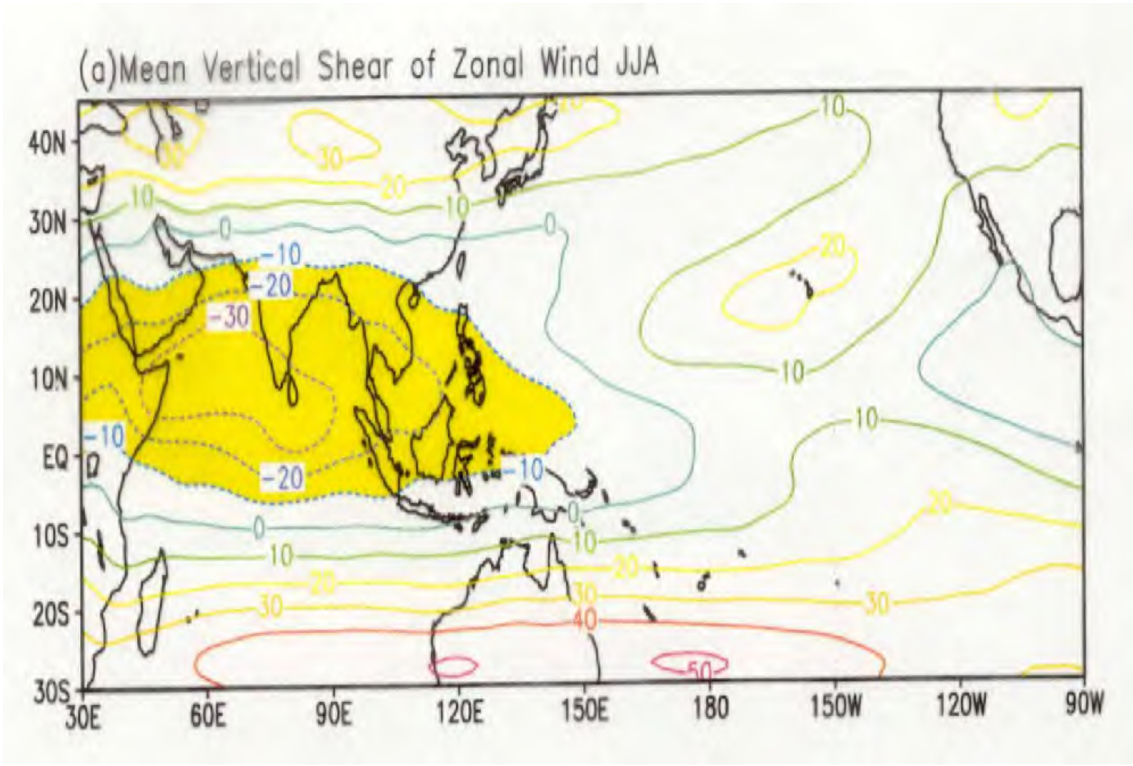
El Nino developin g year

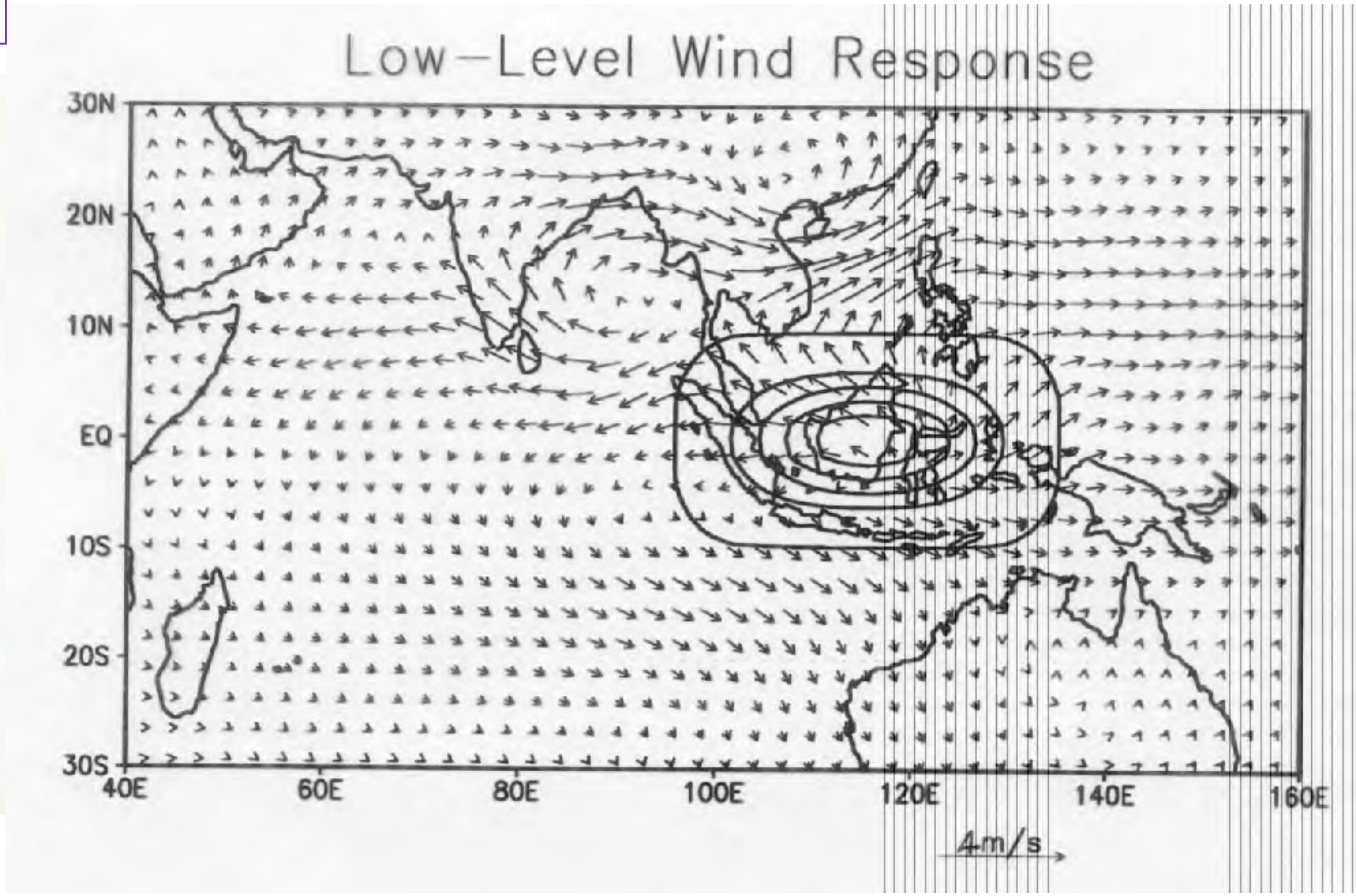
El Nino decay year

Modulation of the Mean Flow on El Nino Response

Why do we observe an equatorial asymmetric response in the Indian monsoon region to a symmetric El Nino forcing?

Anomaly dry AGCM with specified 3D summer mean flow and diabatic heating

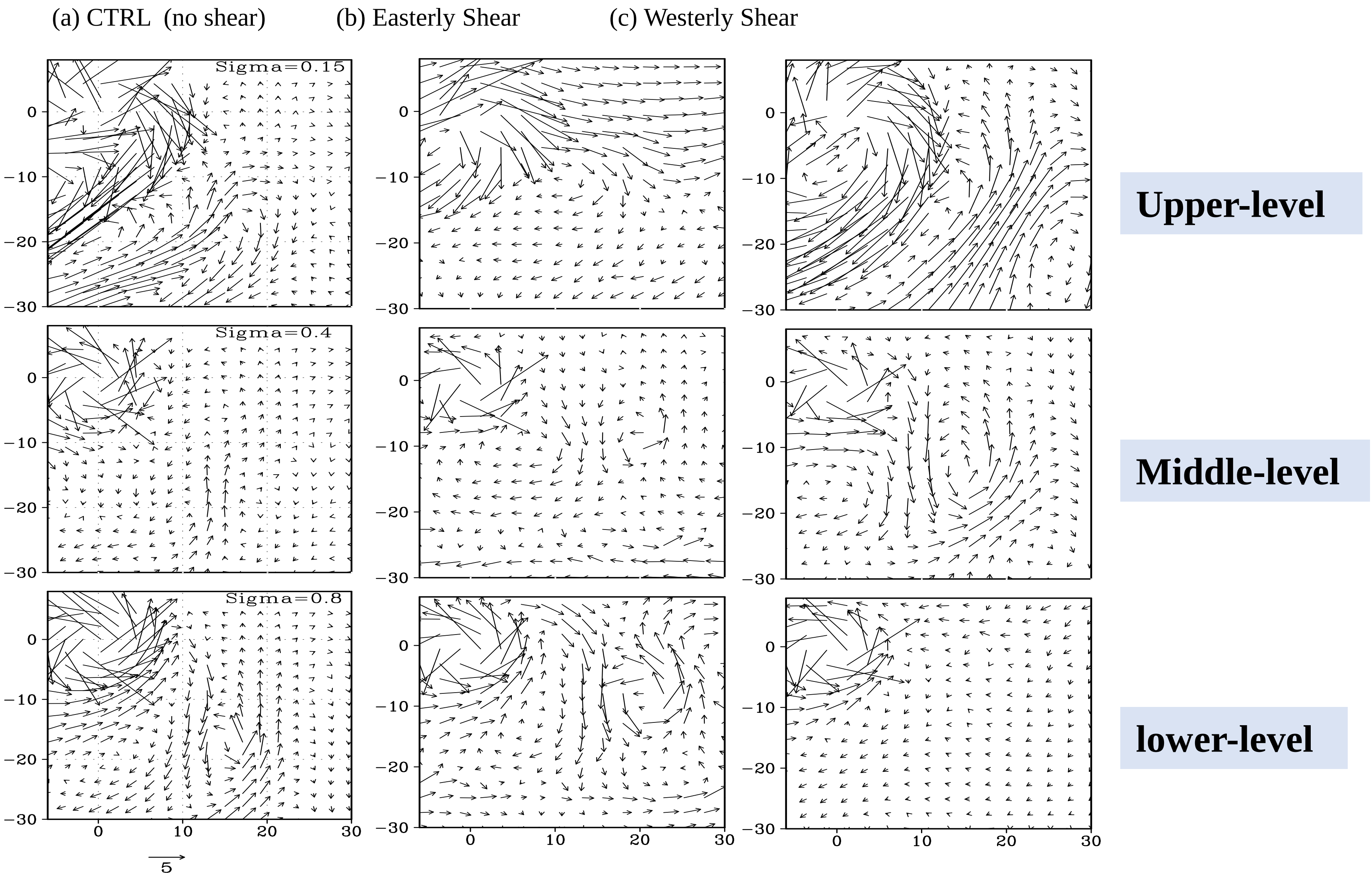




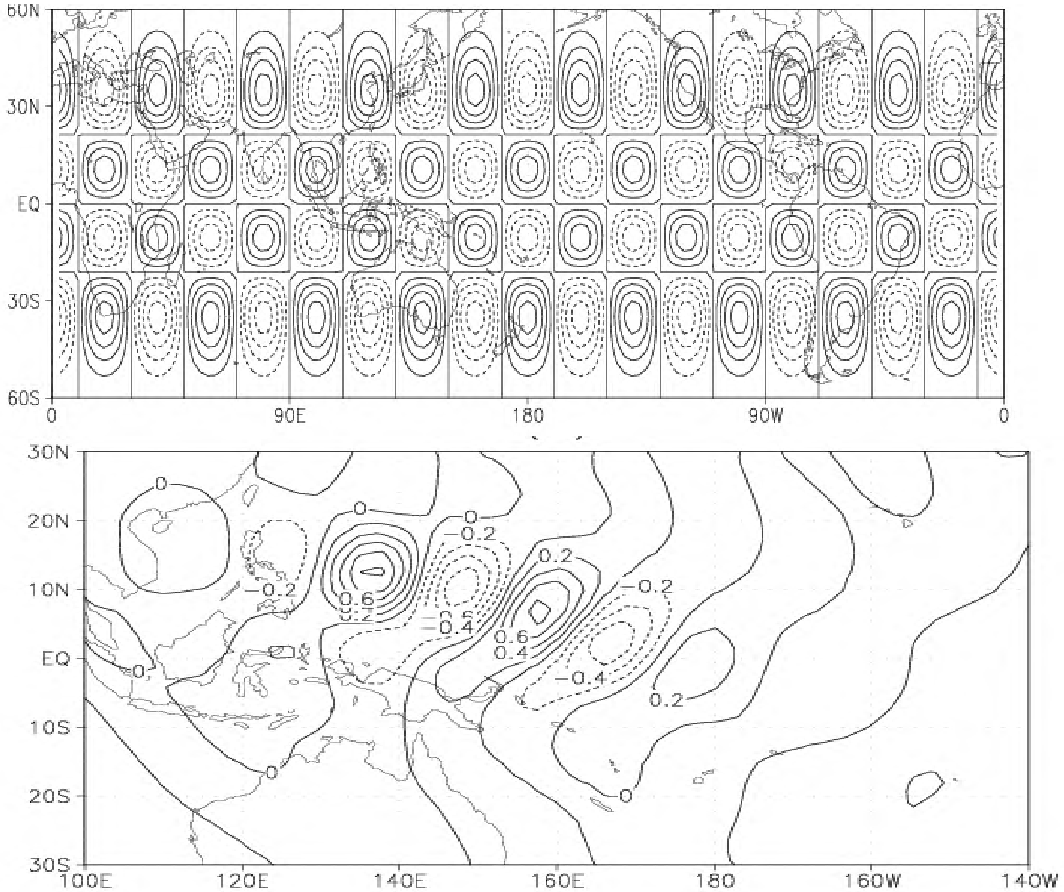
Wang, Wu and Li 2003, J. Climate

Effect of Mean-state Vertical Shear on TCED-induced Rossby Wave Train

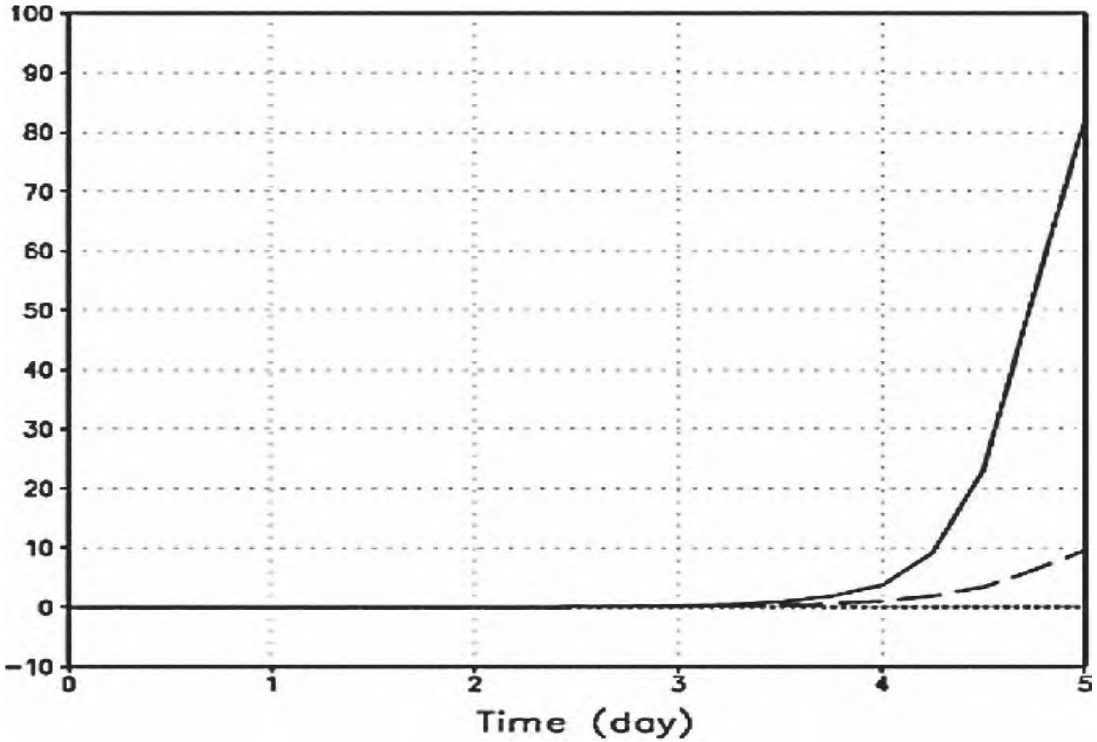
(Ge, Li, et al. 2007, GRL)



Effect of vertical shear on growth of synoptic wave train in WNP



Left: Anomaly AGCM simulation with specified 3D summer (JJA) mean flows and SST and surface moisture condition

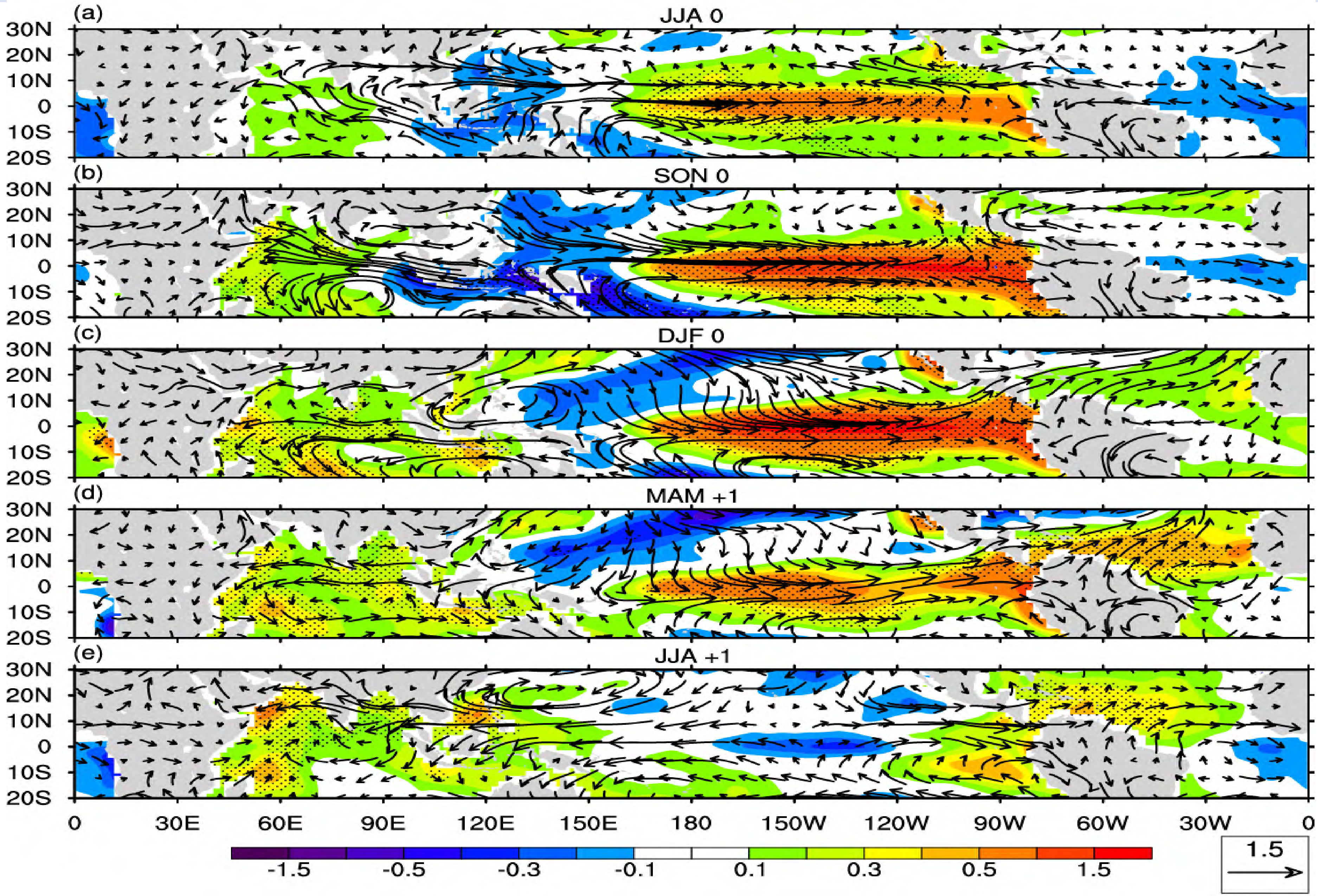


Right: Evolution of maximum perturbation kinetic energy under a constant easterly shear (solid line) and a constant westerly shear (dashed line).

Li 2006, JAS

6. NTA feedback to the Pacific

Regressed SSTA and 850hPa Wind Fields to Nino3.4 Index (Li et al. 2017, JMR)



SST (shading)

850hPa wind (vector)

El Nino ➔ NTA warming

NTA warming ➔ La Nina

Atlantic Capacitor Effect

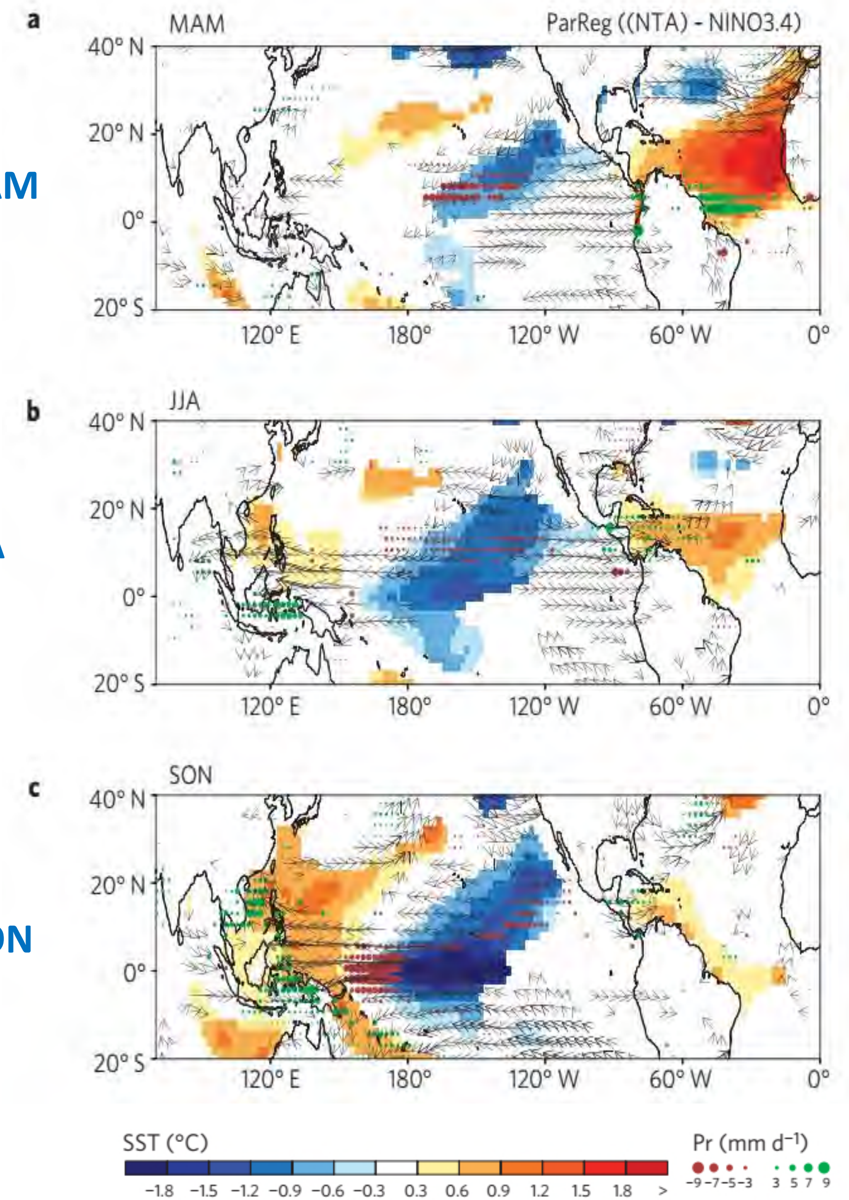
Question: How does NTA warming feed back to ENSO?

Mechanism 1: Rossby wave effect (Ham et al. 2013)

MAM

JJA

SON

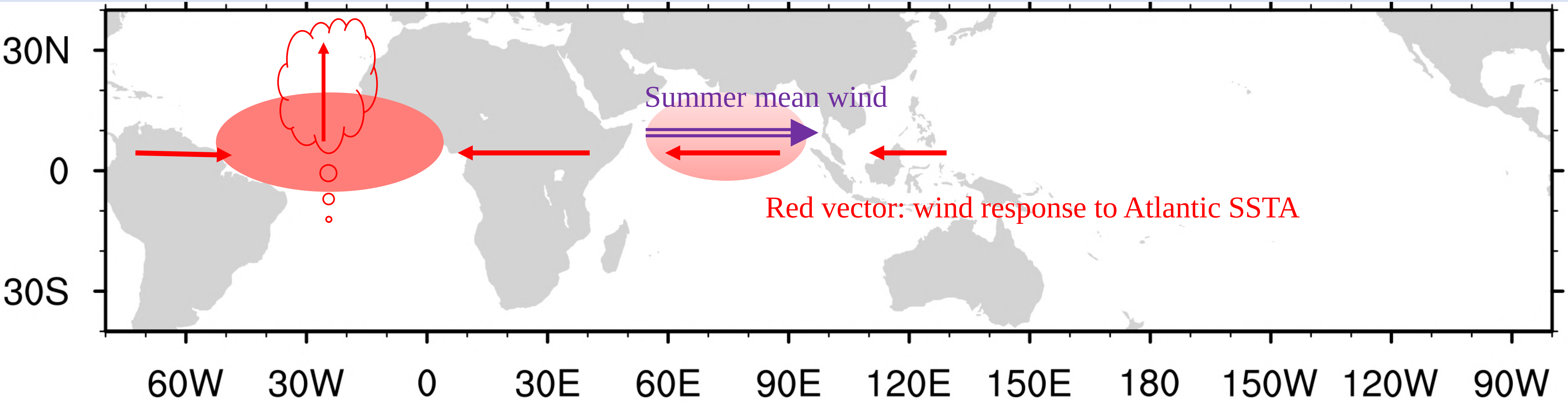


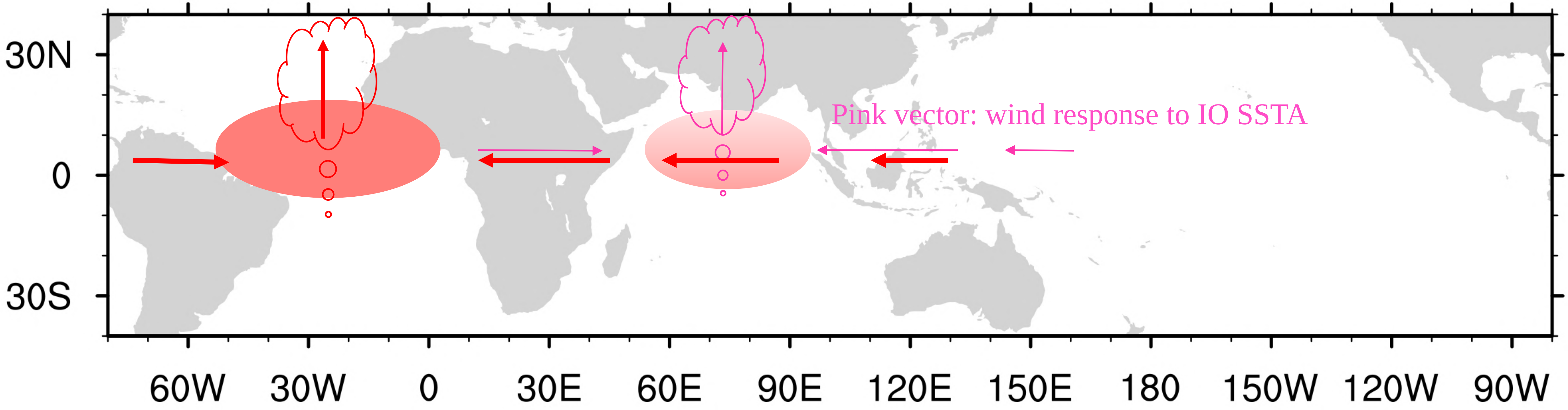
Ham et al. (2013)

Lagged regression between **Feb-Apr NTA SST (90°W-20°E, 0-15°N)** and **SST (shading),** **V850 (vectors)** and **pr (dots)** after removing the impact of DJF Niño-3.4 SST.

Boreal spring TNA warming → enhanced convection over Atlantic ITCZ → low-level cyclonic flow over subtropical eastern Pacific (Rossby wave response) → **northerly flow in west flank enhances trade wind and causes cold SSTA** → suppressed convection in situ → **anomalous anticyclonic (AC) response to the west of the cold SSTA** → positive air-sea feedback maintains the AC → **easterlies anomalies** in the western equatorial Pacific → occurrence of a **La Nina** over equatorial Pacific

Mechanism 2: Kelvin wave effect: Indian Ocean Relaying process (Yu, Li, et al. 2016)





Thank you!