Atmospheric Response to the El-Niño Southern Oscillation Phenomenon (ENSO)
(A winter and summer example)

*(or: **The single largest predictable signal on sesaonal time scales**)*

Northern Winter (DJM)

-- ENSO produces tropical SST anomalies: Why are they significant?
-- Changes in convection and tropical divergence
-- Forces changes in both the seasonal mean flow and storm tracks
-- Changes in low frequency flow

Northern Summer (JJAS)

-- ENSO / Indian Monsoon relationship
-- A well-noted recent exception
-- A mechanistic study using an atmospheric GCM

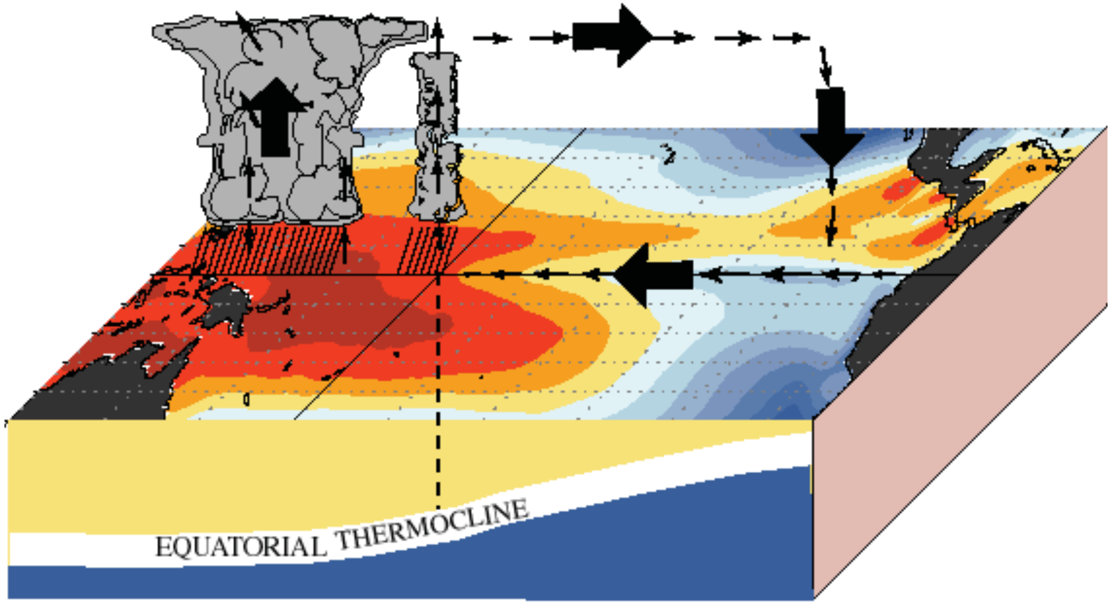
Normal Northern Winter Conditions, Equatorial Pacific

“Walker Circulation” driven by sea surface temperature gradient

Rainy west

Dry east

in West, “warm pool” of surface water



in East, “cold tongue” of water upwells from below

Thermocline tilt/upwelling driven by westward wind stress

www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm_impacts.html

Overturning Circulation in the Zonal / Pressure Plane
The Walker Circulation??

July 5, 2011

1 Continuity Equation

The mass continuity equation in pressure coordinates is a diagnostic equation:

$$\vec{\nabla} \cdot \vec{v} + \frac{\partial \omega}{\partial p} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial \omega}{\partial p} = 0 \tag{1}$$

in Cartesian coordinates. (u, v) are the components of the horizontal wind $\vec{v}$, $\omega = \frac{dp}{dt}$ gives the Lagrangian rate of change of pressure of a parcel.

In spherical coordinates, this becomes:

$$\frac{1}{a \cos \phi} \frac{\partial u}{\partial \lambda} + \frac{1}{a \cos \phi} \frac{\partial}{\partial \phi} (v \cos \phi) + \frac{\partial \omega}{\partial p} = 0 \tag{2}$$

where λ is longitude, ϕ is latitude, and a is the earth's radius.

2 Streamfunction in the zonal / pressure plane

Averaging over latitude from pole to pole (denoted by angular brackets): we obtain:

$$\frac{1}{a\cos\phi}\frac{\partial\langle u\rangle}{\partial\lambda}+\frac{\partial\langle\omega\rangle}{\partial p}=0 \tag{3}$$

from which we could define the *mass streamfunction* that would represent mass flow in the zonal / pressure plane.

3 Why not the Walker Circulation?

If we average the continuity equation from latitude - ϕ_0 to + ϕ_0

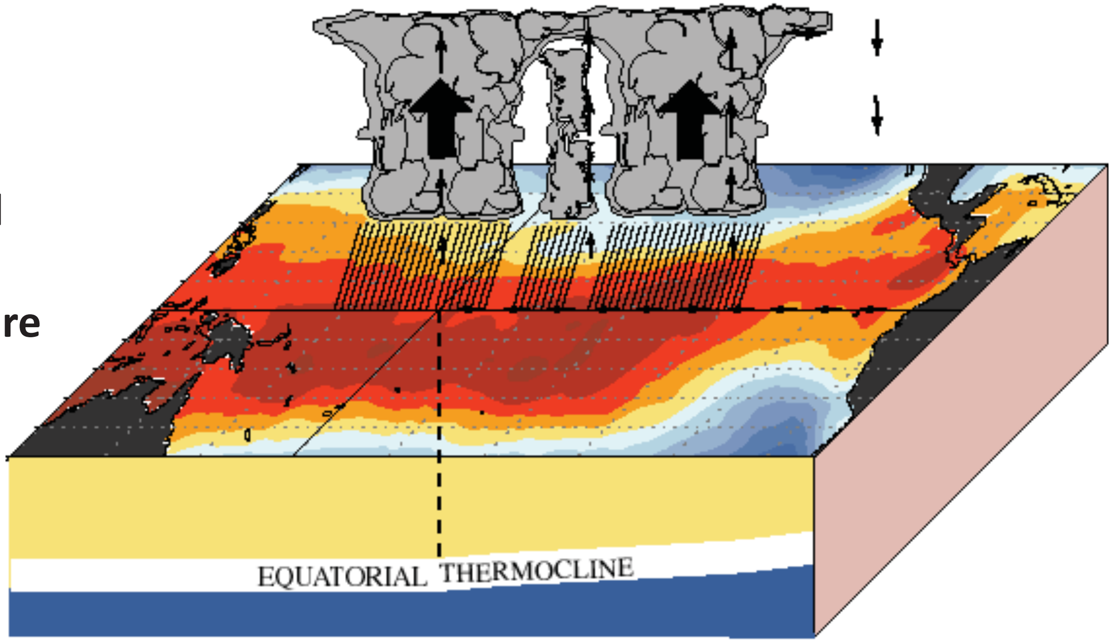
$$\frac{1}{a\cos\phi}\frac{\partial\langle u\rangle}{\partial\lambda}+\frac{\partial\langle\omega\rangle}{\partial p}=-\frac{1}{\cos\phi_0}\left(v(\phi_0)-v(-\phi_0)\right)\cos\phi_0 \tag{4}$$

Hence the circulation depends on meridional inflow / outflow. This is not represented in all schematic diagrams of the so-called Walker Circulation.

El Nino Winter Conditions, Equatorial Pacific

Warm SSTs in the Eastern Pacific -->Increased evaporation in the Eastern Tropical Pacific, increased deep convection and rainfall, increased rising motion, and finally increased tropical divergence near the top of the troposphere

warm pool extends across entire Pacific



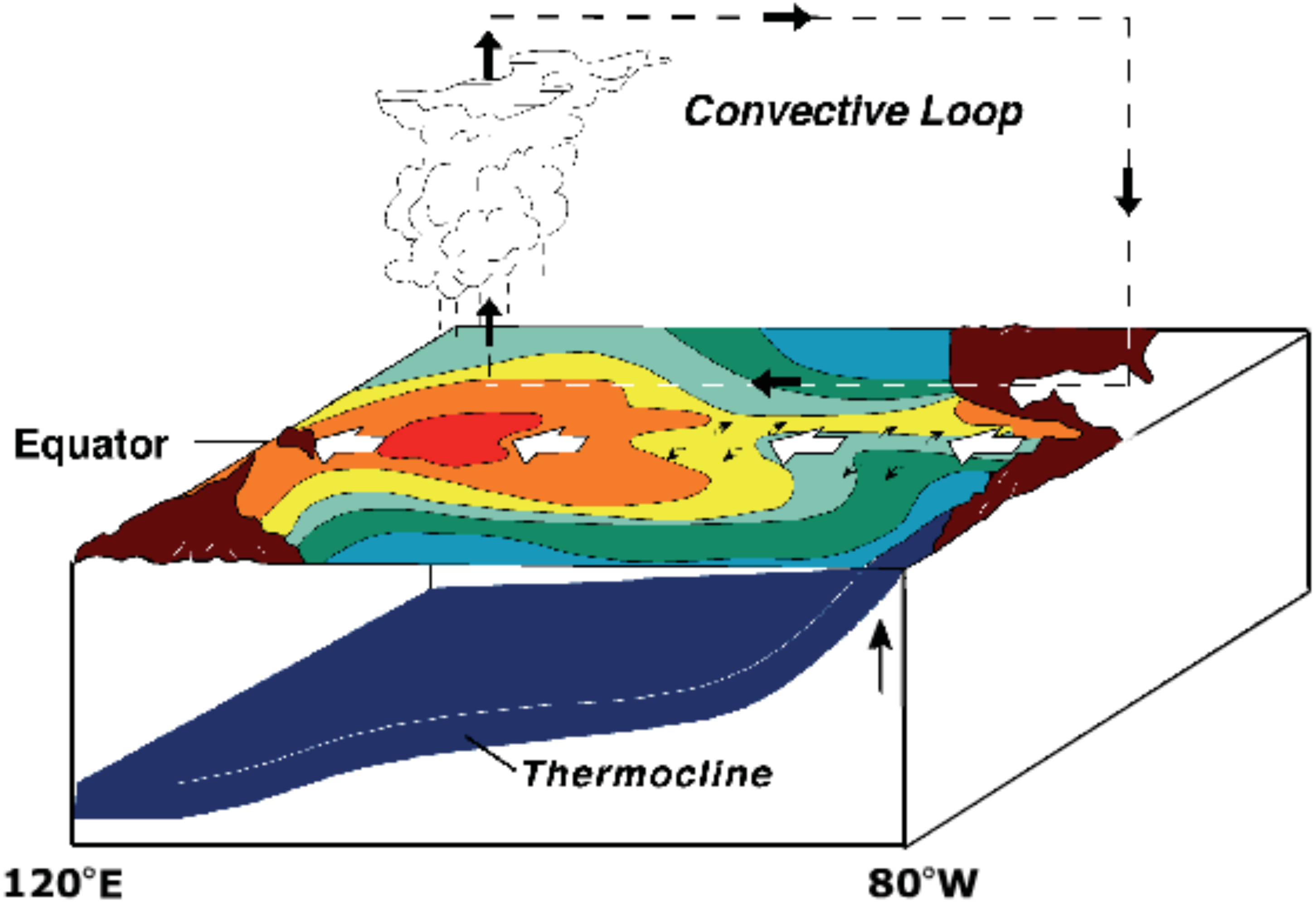
cold tongue disappears

weakening of easterlies allows flattens thermocline, weakens upwelling

Consistency of surface winds, zonal circulation, and upper ocean: Bjerknes Mechanism

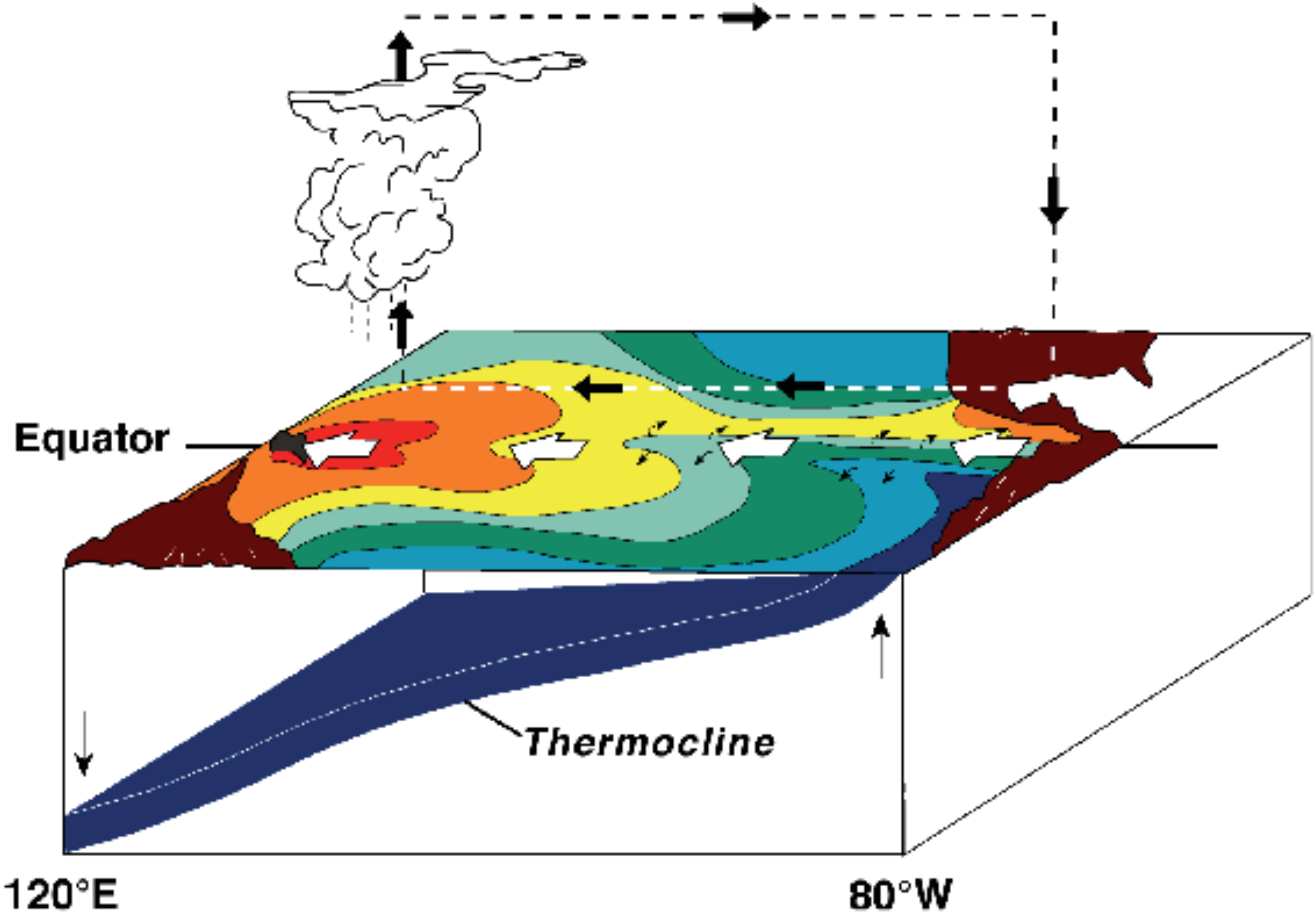
www.cpc.ncep.noaa.gov/products/analysis_monitoring/impacts/warm_impacts.html

Normal Conditions



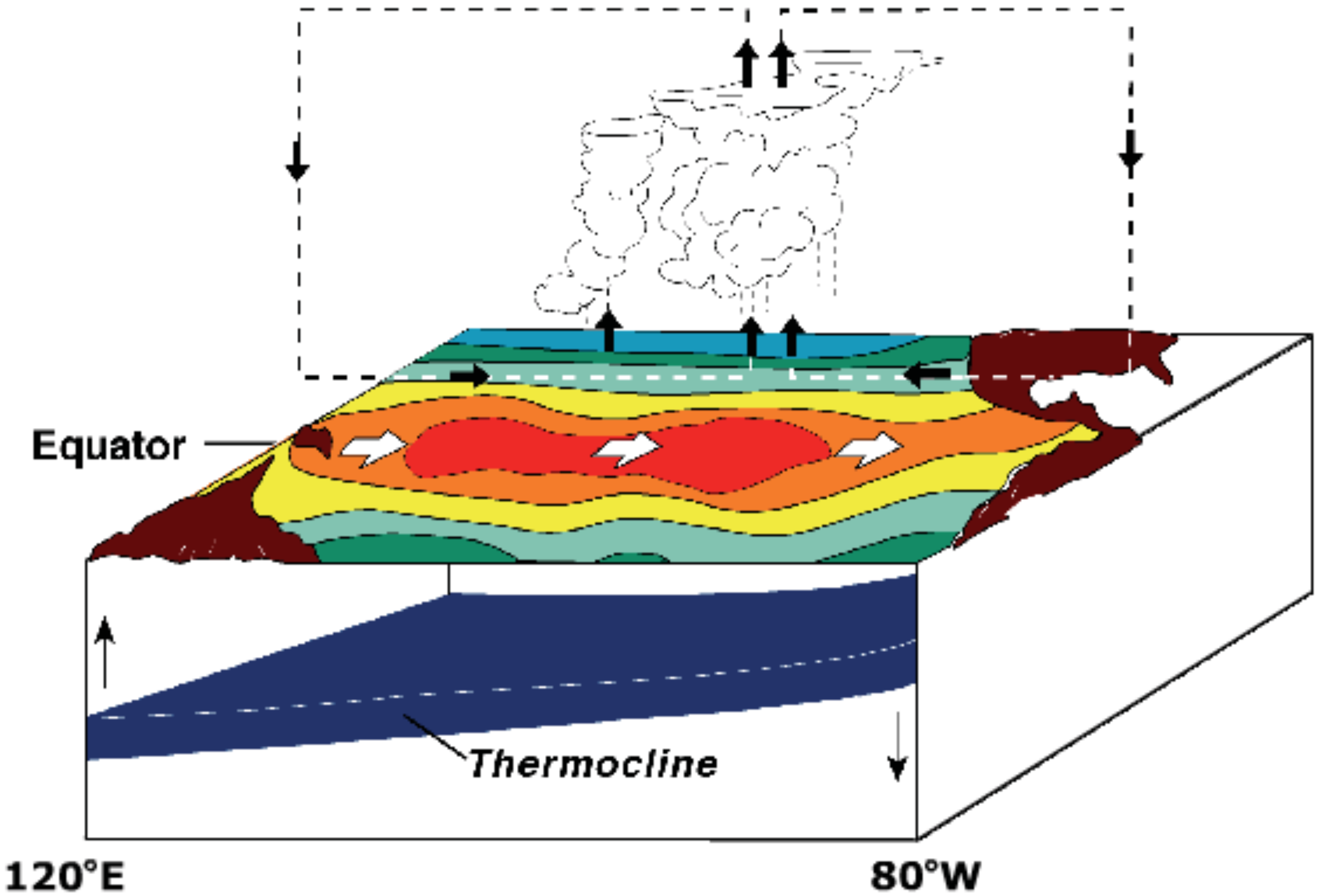
http://en.wikipedia.org/wiki/File:Enso_Normal.png
Derived from NOAA / PMEL / TAO diagrams. http://www.pmel.noaa.gov/tao/proj_over/diagrams/index.html

“La Nina” Cold Conditions



http://en.wikipedia.org/wiki/File:Enso_lanina.png
Derived from NOAA / PMEL / TAO diagrams. http://www.pmel.noaa.gov/tao/proj_over/diagrams/index.html

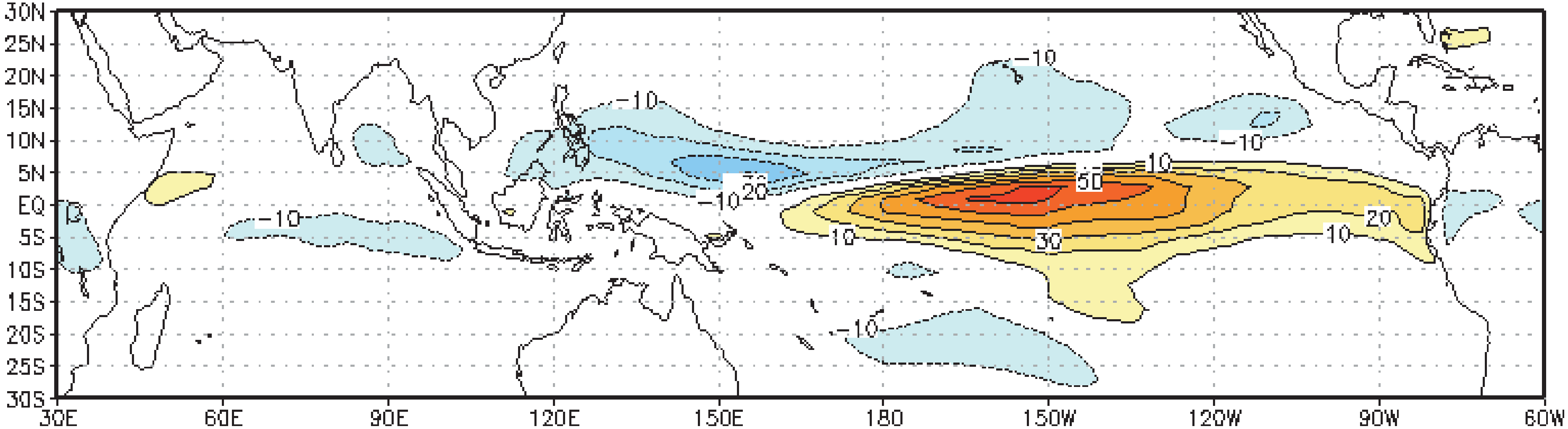
“El Nino” Warm Conditions



http://en.wikipedia.org/wiki/File:Enso_elnino.png
Derived from NOAA / PMEL / TAO diagrams. http://www.pmel.noaa.gov/tao/proj_over/diagrams/index.html

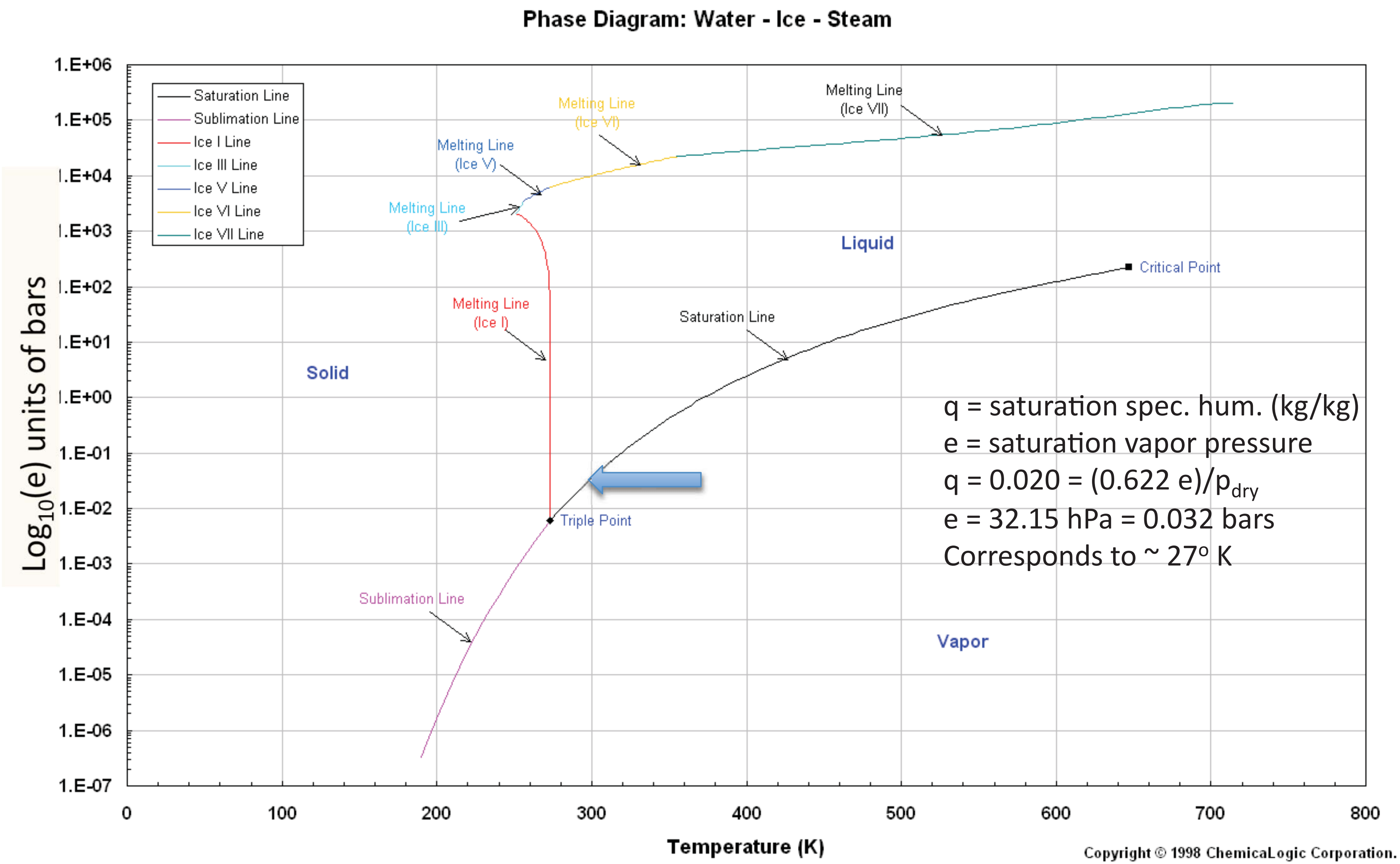
Ensemble Mean Heating Anomaly from SST-forced atmospheric model:

Average of three Model (CAM4) runs with three observed El Nino SSTs specified:
DJF 1982/83, 1991/92, 1997/98



Vertically integrated heating (Watts / m^2)
Model climatology is subtracted

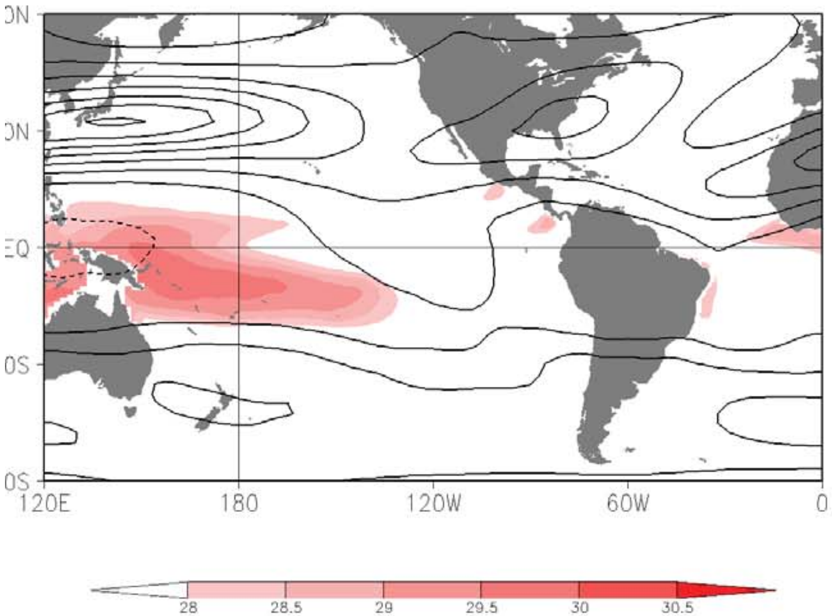
http://www.chemicalogic.com/images/phase_diagram.gif



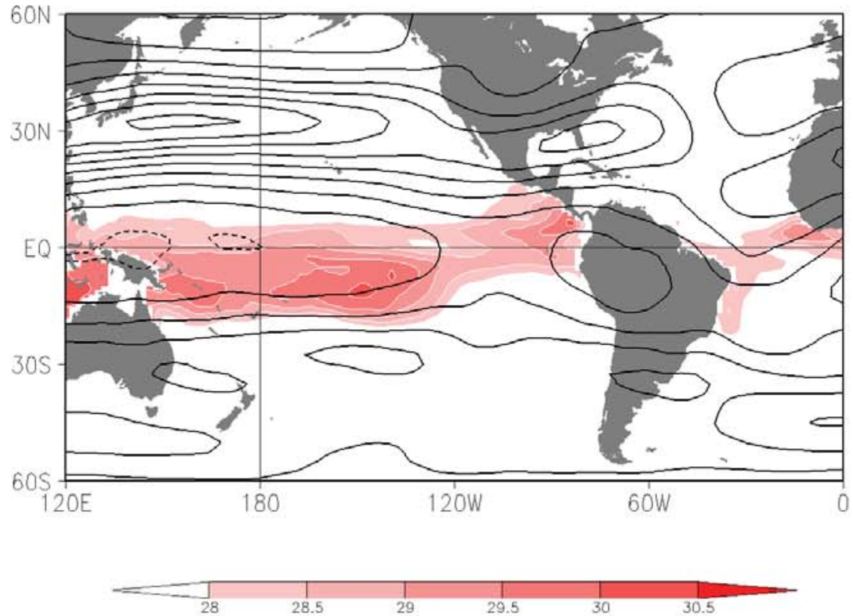
Part of interest in ENSO warm event is what it does to midlatitudes:

Extension of Pacific Jet

Normal Conditions:



ENSO Warm event (avg of obs)



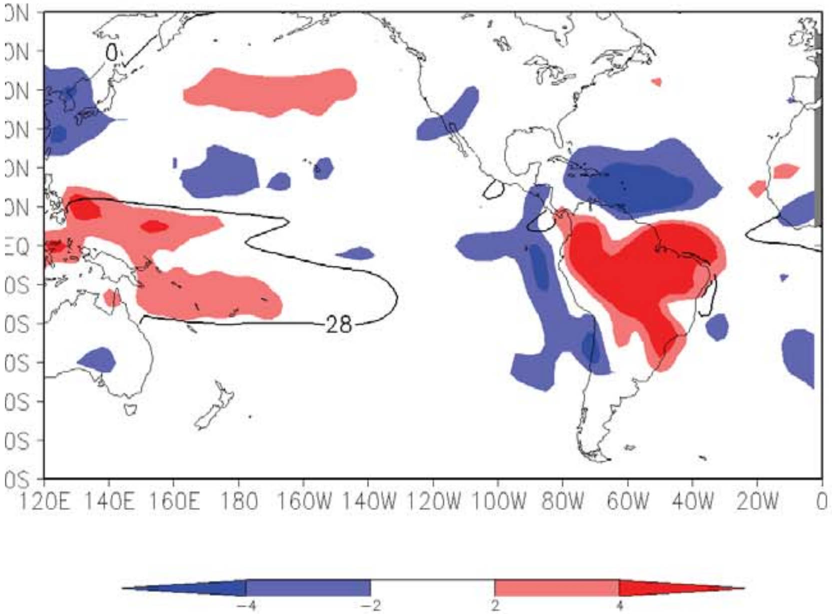
Contours are jets: Winter mean 200 hPa zonal wind (CI=10 m/s)

Shading is SST in degrees C (28°C seems to be threshold for convection to occur)

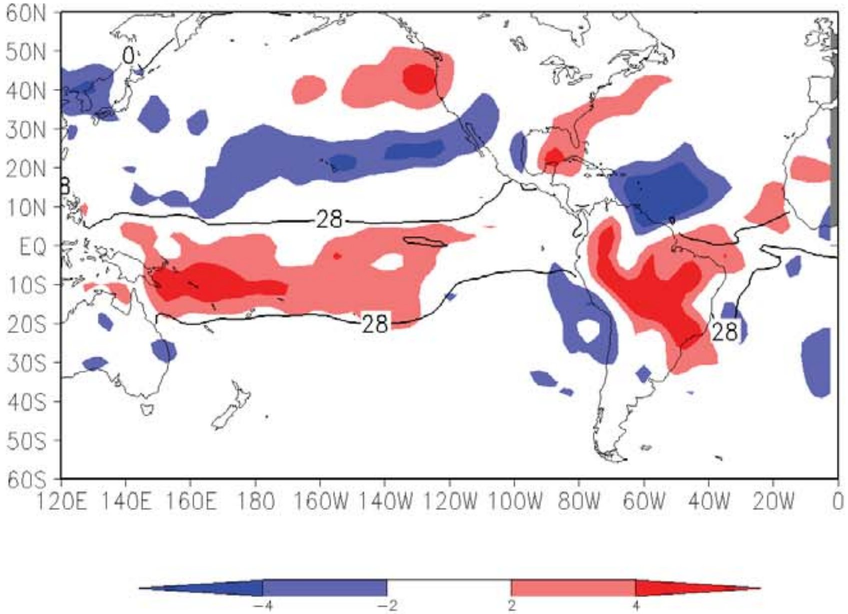
Increased Rising Motion in the Tropical Eastern Pacific Leads to increased upper-level divergence of flow.

This leads to mid-latitude effects!!

Normal Conditions *for winter*



Warm Event (avg. of obs)



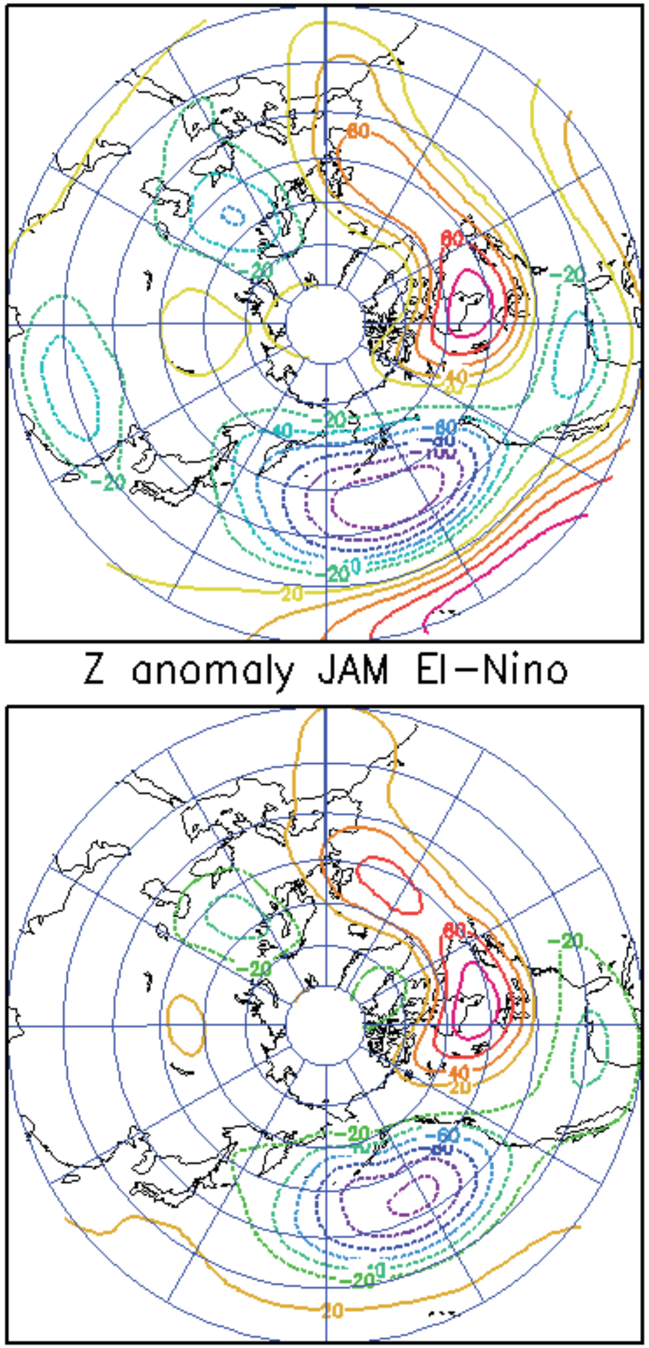
Shading: Winter Mean upper level divergence (CI=2.0 x 10^{-6} 1/s)

SST Isotherm of 28 C is shown (warmer water allows convection)

Equivalent barotropic ‘far field’ response to ENSO Heating.

Panels show geopt. ht. field anomaly averaged over 3 El-Ninos for Jan-March: 1983, 1987, 1998

(ERA 40)



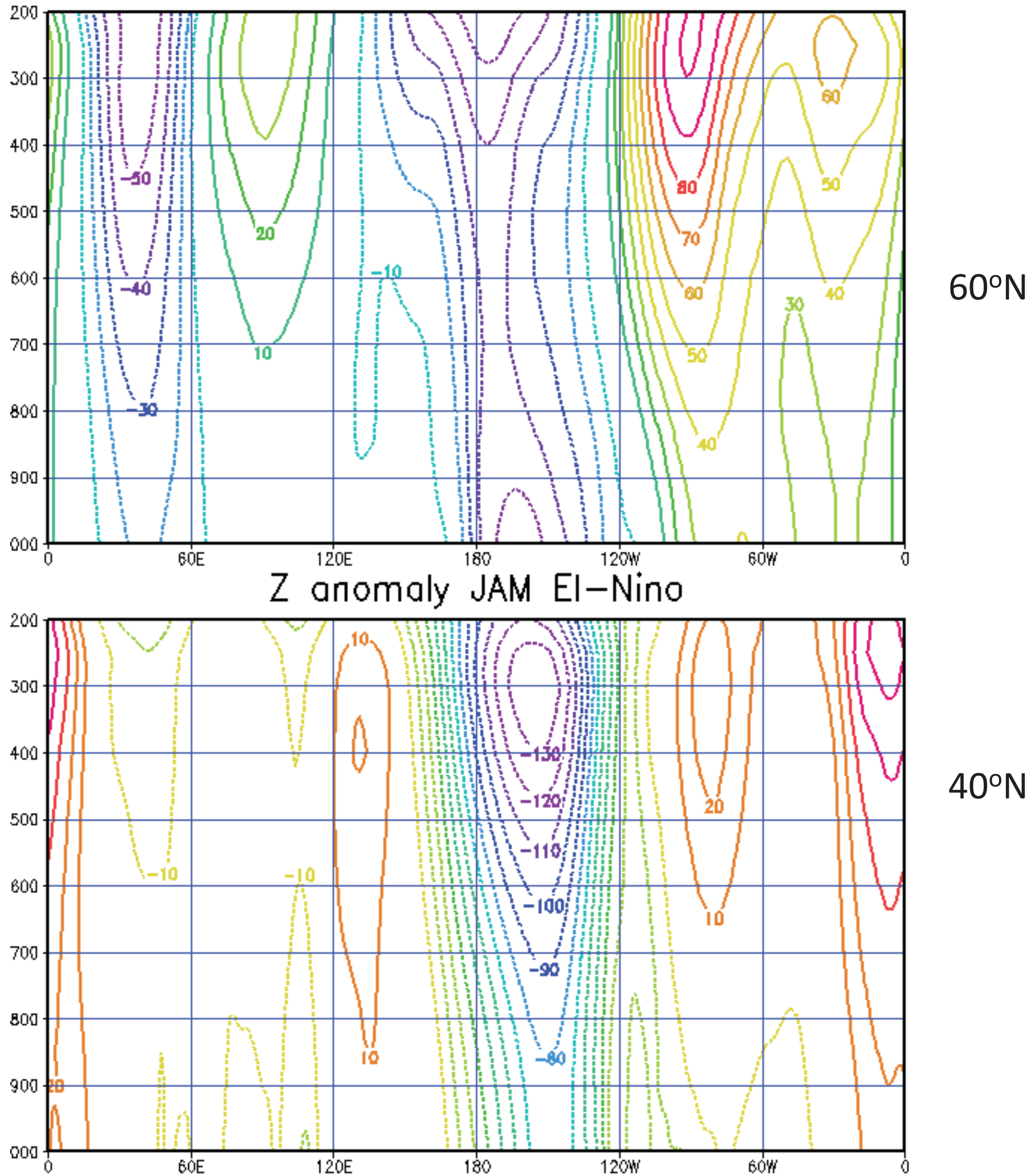
200 hPa

500 hPa

Equivalent barotropic 'far field' response to ENSO Heating.

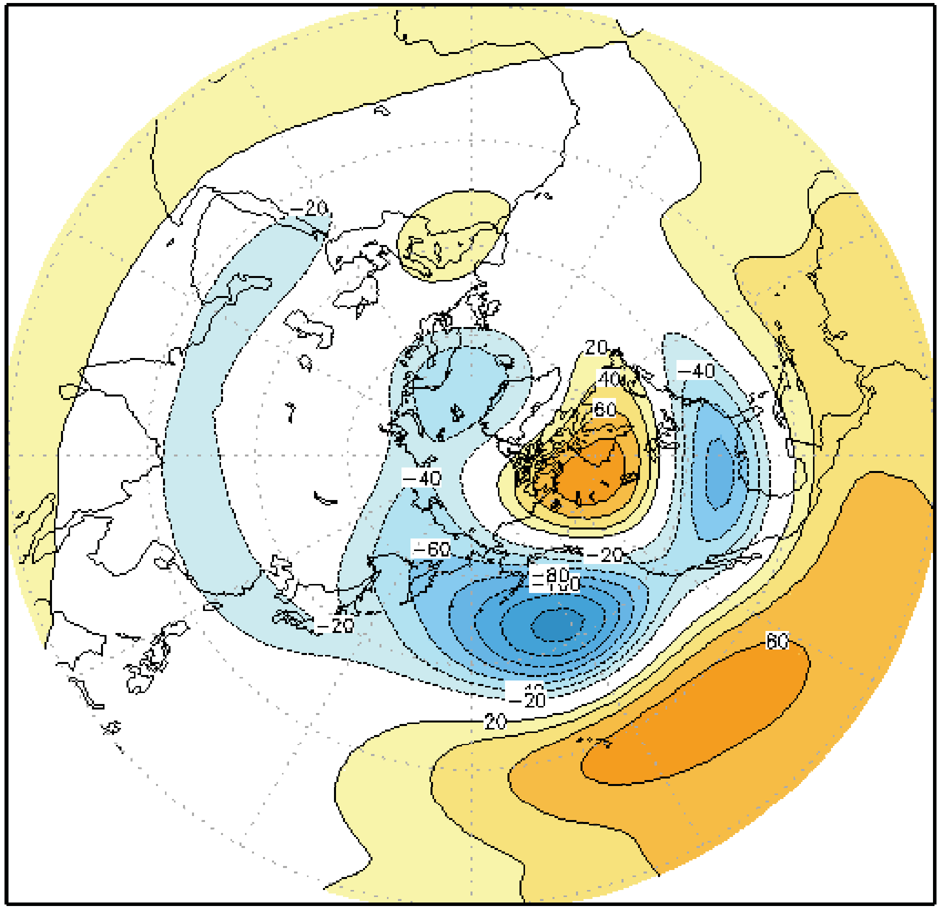
Panels show geopt. ht. field anomaly averaged over 3 El-Ninos for Jan-March: 1983, 1987, 1998

(ERA 40)



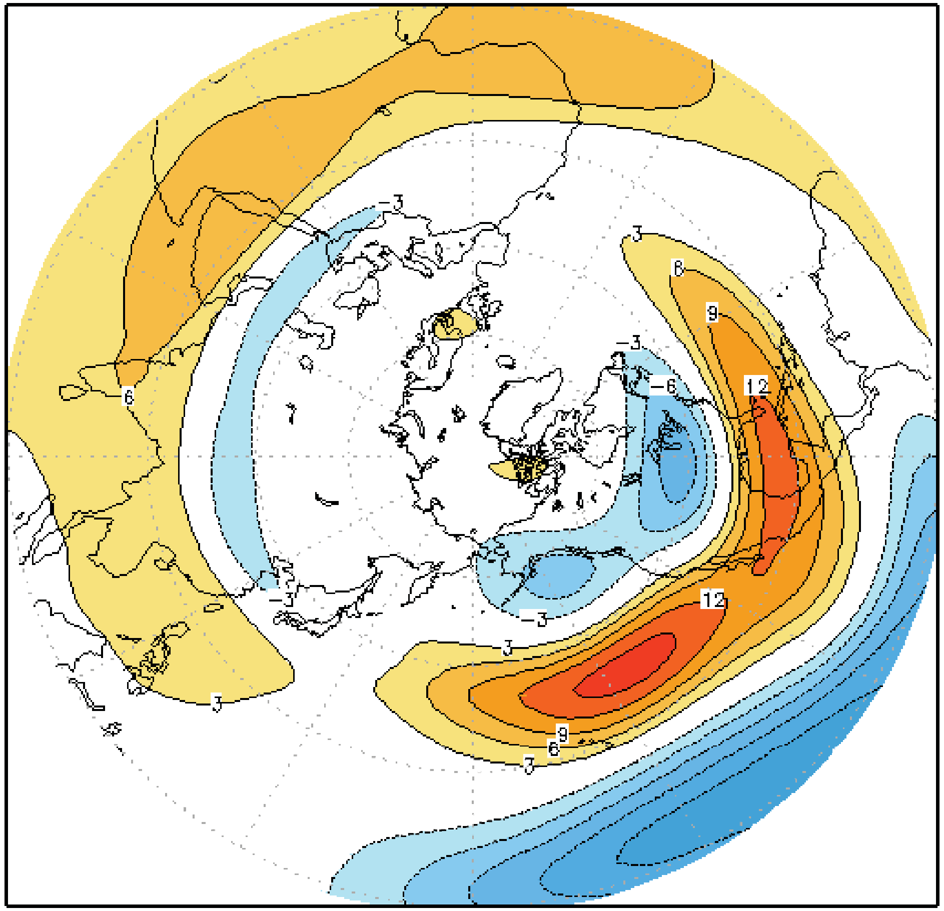
Ensemble Mean 200 hPa height anomaly from SST-forced atmospheric model:

Average of three Model (CAM4) runs with three observed El Nino SSTs specified:
DJF 1982/83, 1991/92, 1997/98



Ensemble Mean 200 hPa u-wind anomaly from SST-forced atmospheric model:

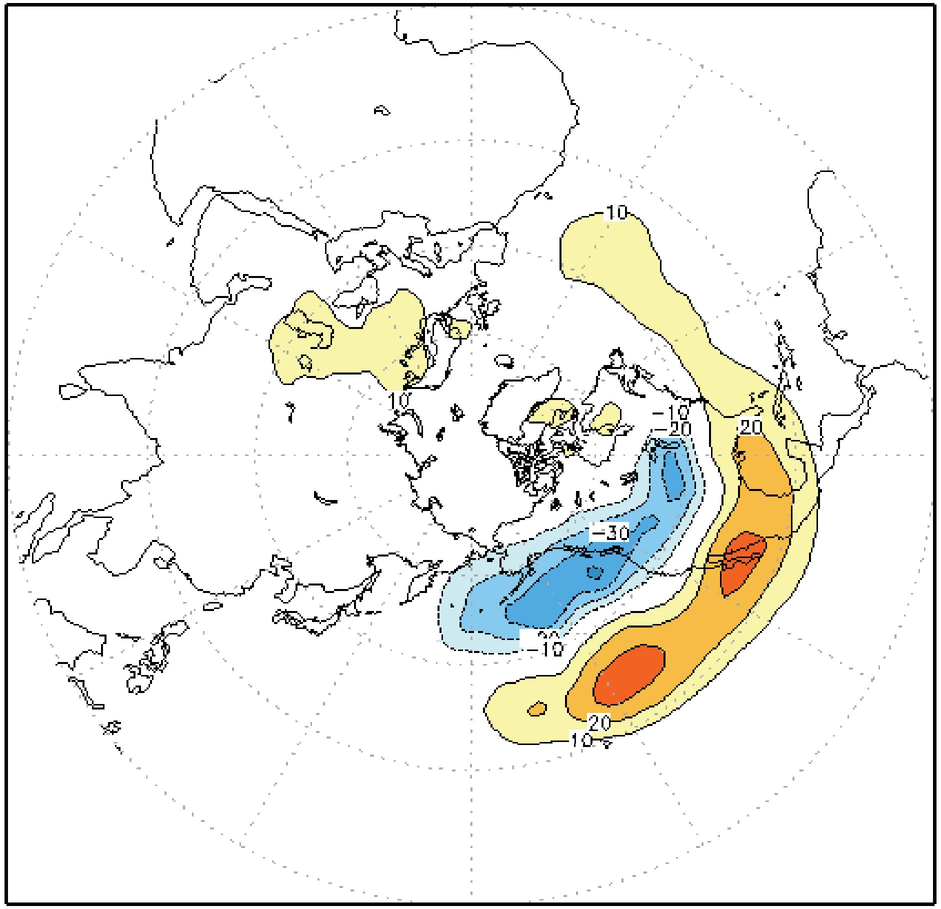
Average of three Model (CAM4) runs with three observed El Nino SSTs specified:
DJF 1982/83, 1991/92, 1997/98



Pacific jet stream extended towards east and moved equatorward

Ensemble Mean 200 hPa storm track anomaly from SST-forced atmospheric model:

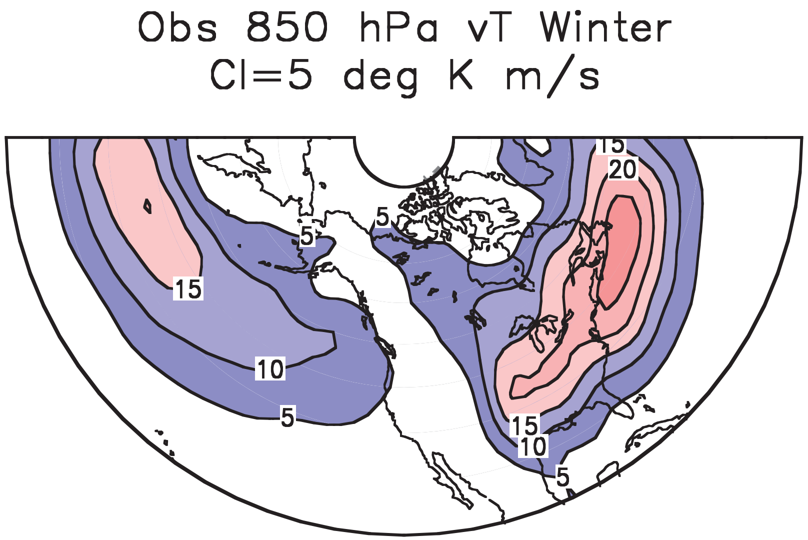
Average of three Model (CAM4) runs with three observed El Nino SSTs specified:
DJF 1982/83, 1991/92, 1997/98

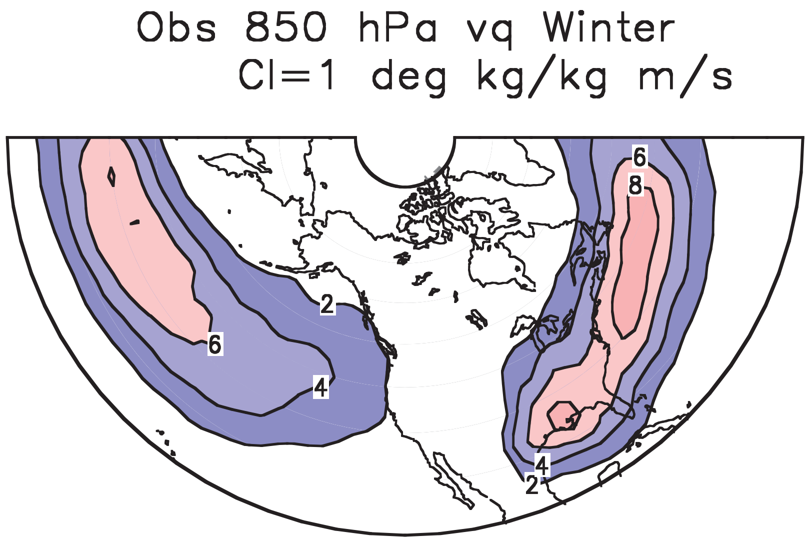


Storm track measured by variance of 2-10 day filtered v wind

Change in jets means a change in storm - tracks.

One very good measure of storms and storm tracks is given by the poleward transport of heat and moisture by motions with time scales of 2-10 days





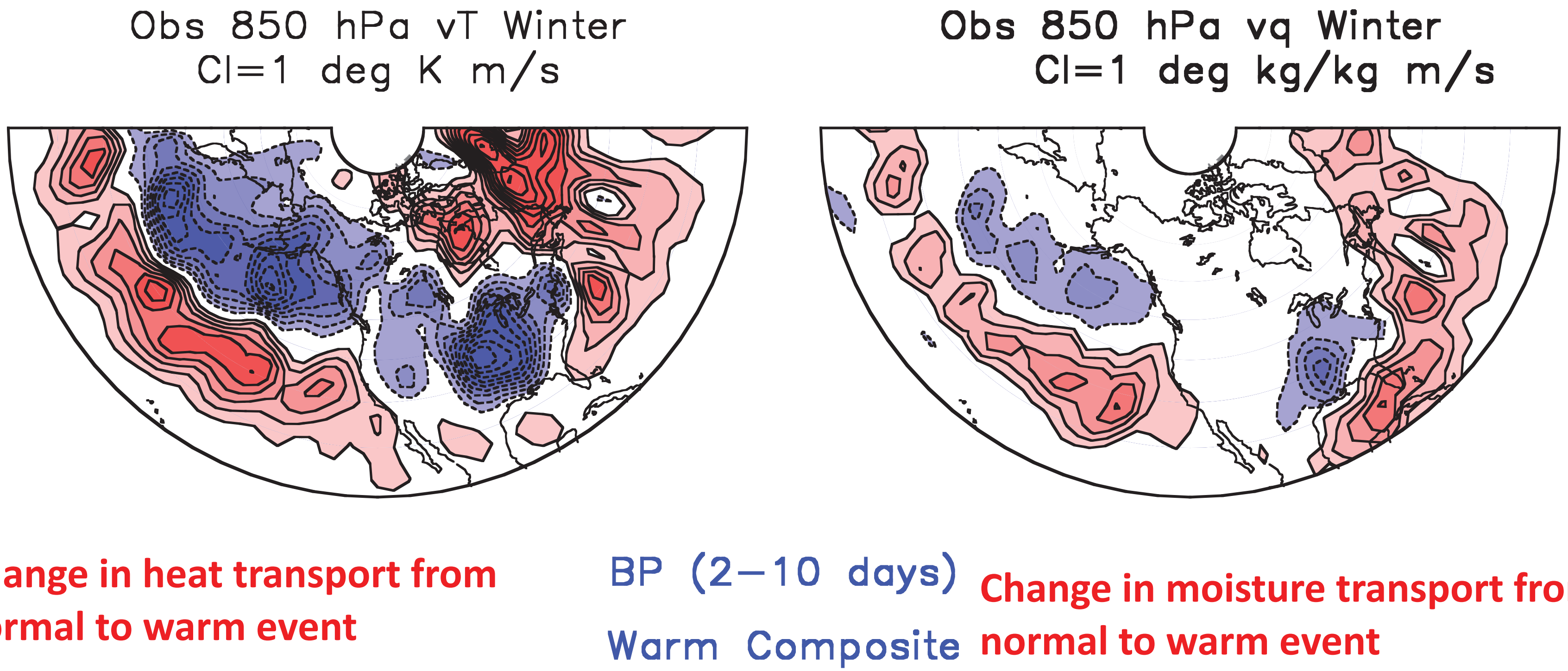
Heat Transport

BP (2–10 days)
climate

Moisture Transport

Normal Conditions

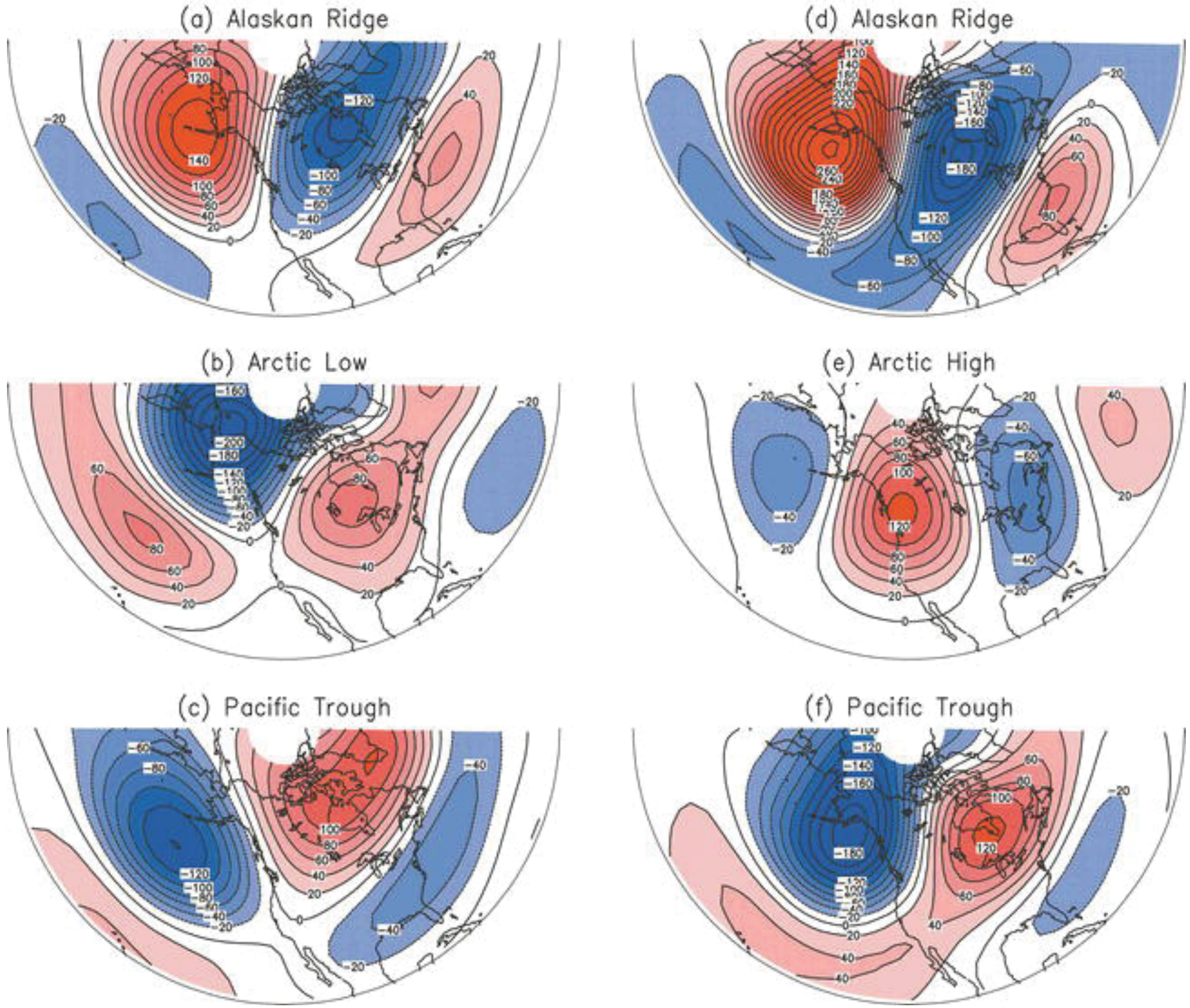
The equatorward and eastward extension of the jets during El-Nino pulls the storm tracks along!

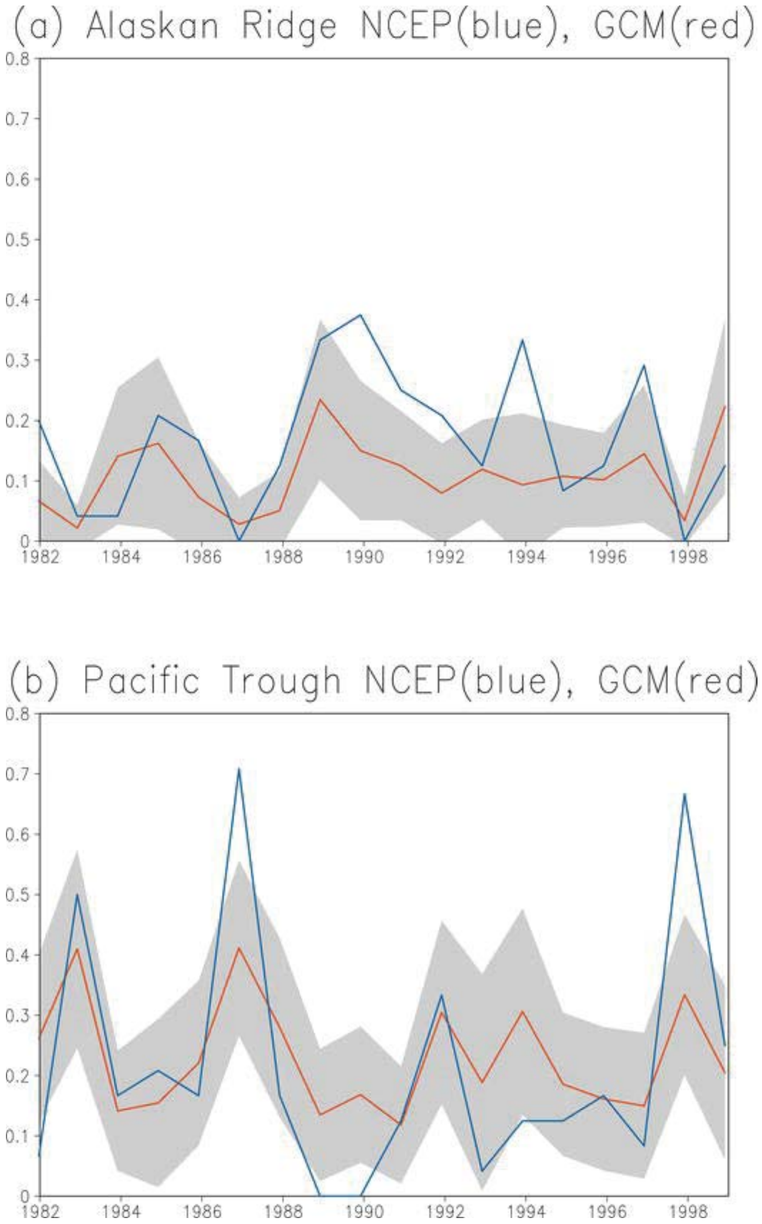


Change in heat transport from normal to warm event

Change in moisture transport from normal to warm event

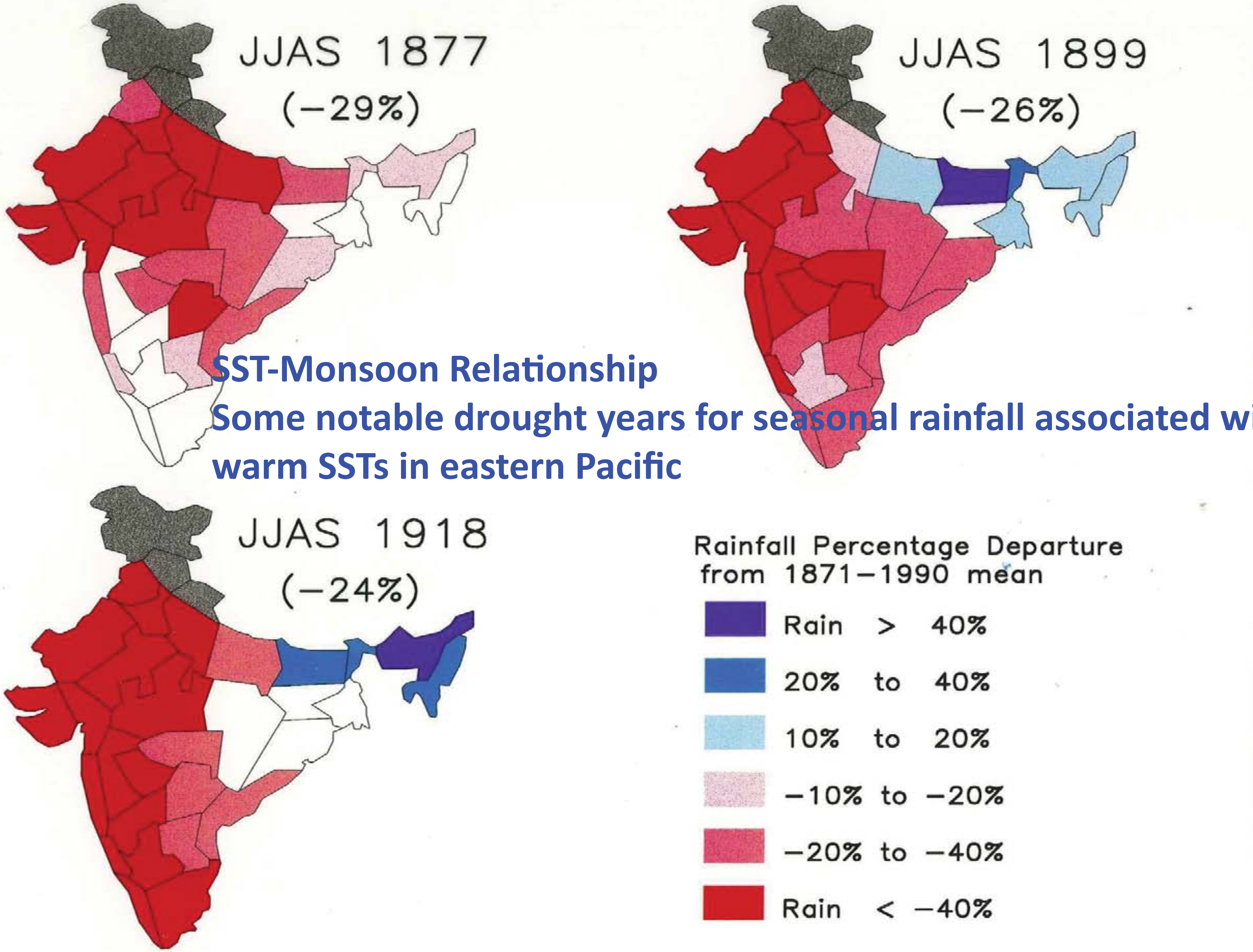
Straus, D.M., S. Corti and F. Molteni, 2007: Regimes: Chaotic Variability versus SST-Forced Predictability, J. Clim., 2007

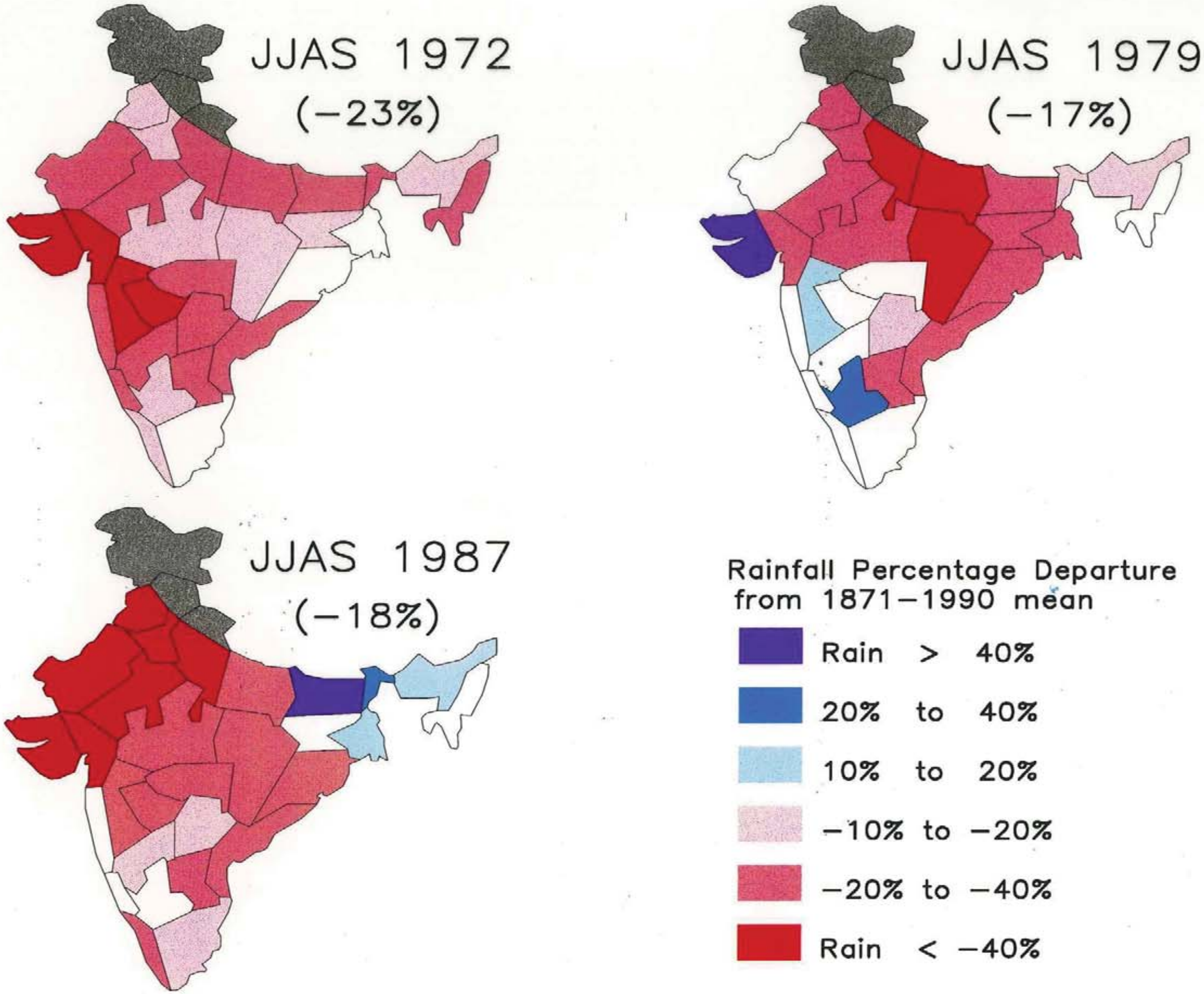


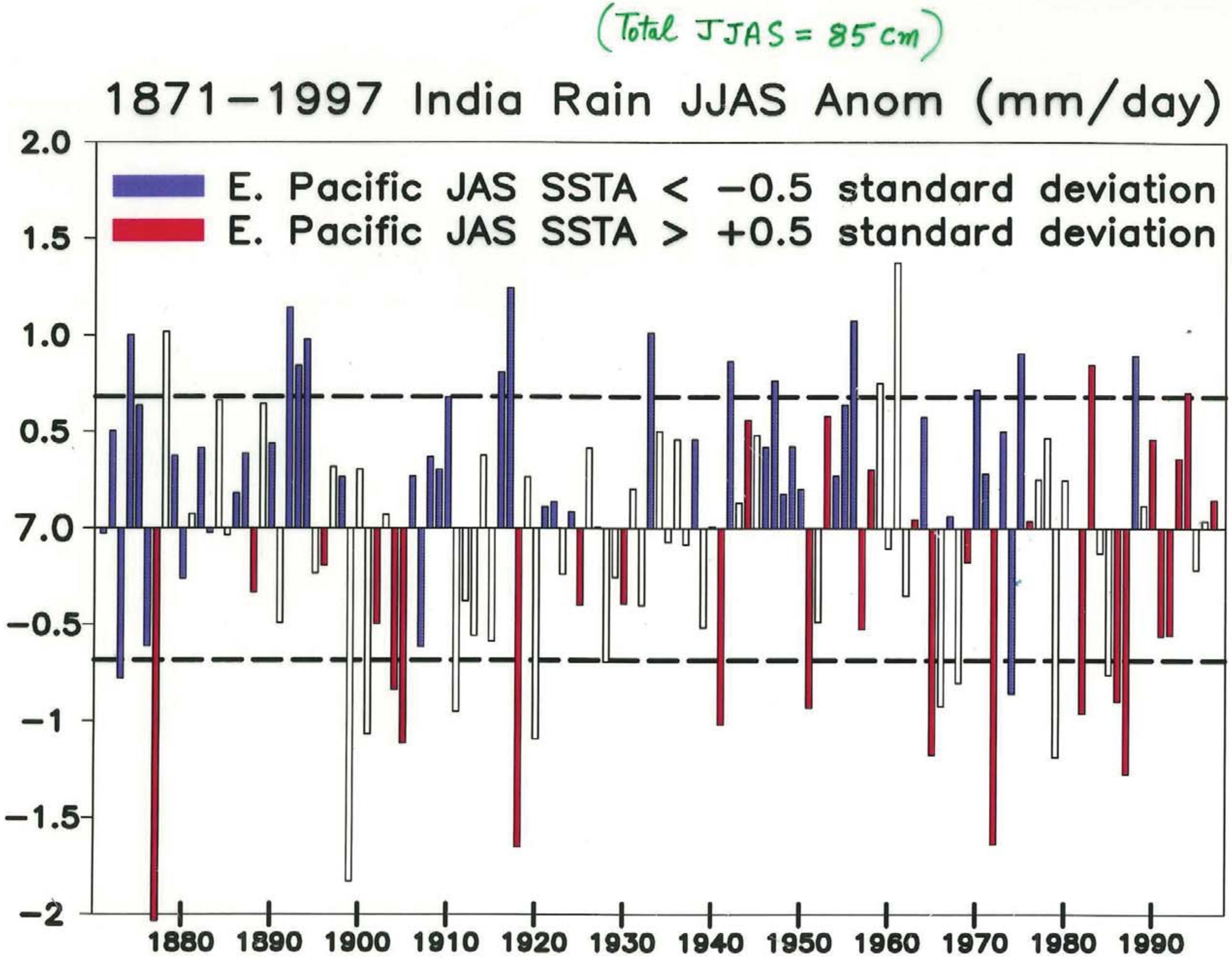

(a) Alaskan Ridge NCEP(blue), GCM(red)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1982
1984
1986
1988
1990
1992
1994
1996
1998
(b) Pacific Trough NCEP(blue), GCM(red)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1982
1984
1986
1988
1990
1992
1994
1996
1998

SST-Monsoon Relationship

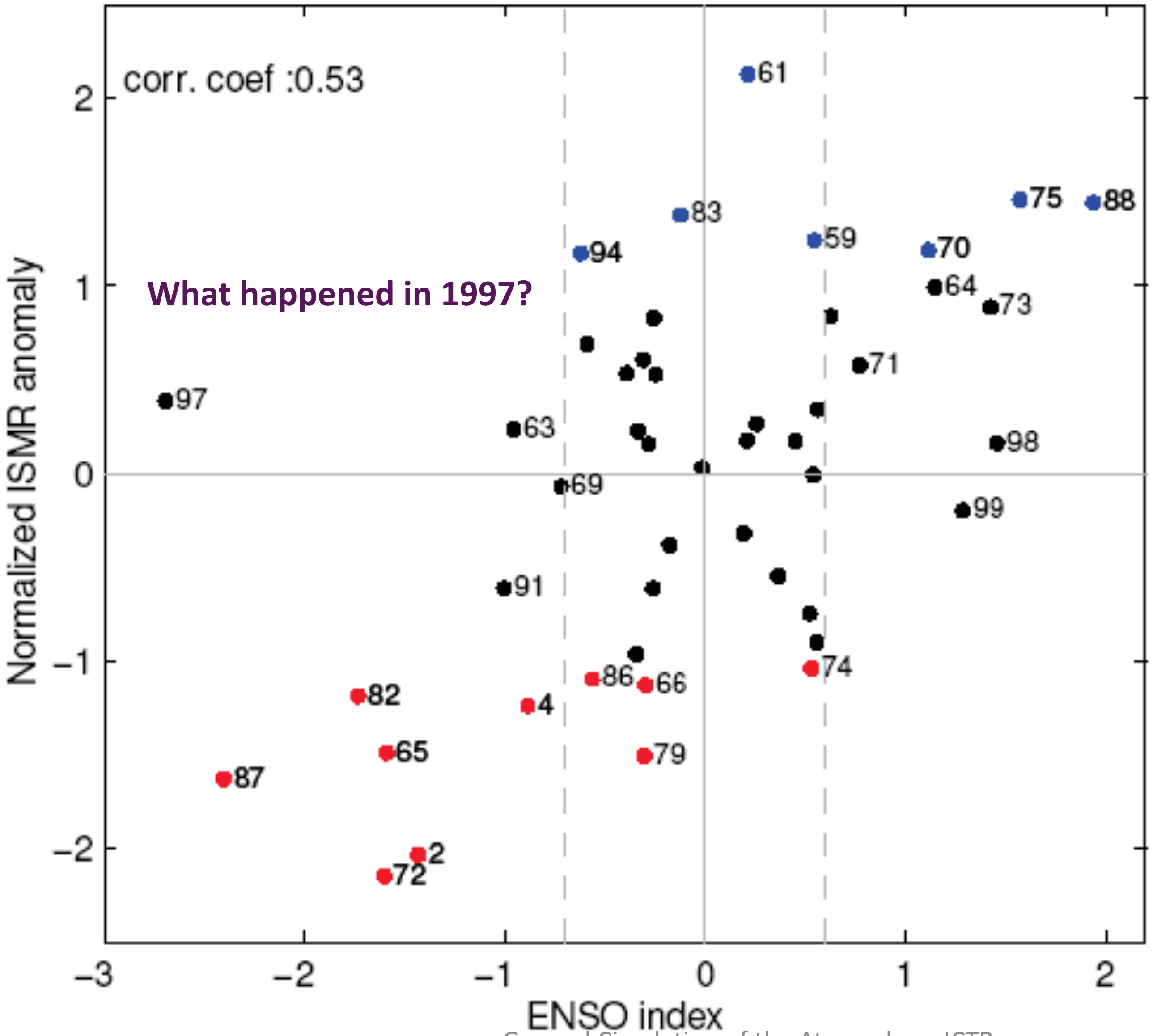
Some notable drought years for seasonal rainfall associated with warm SSTs in eastern Pacific




JJAS 1972
(−23%)
JJAS 1979
(−17%)
JJAS 1987
(−18%)
Rainfall Percentage Departure
from 1871−1990 mean
Rain > 40%
20% to 40%
10% to 20%
−10% to −20%
−20% to −40%
Rain < −40%


(Total JJAS = 85 cm)
1871–1997 India Rain JJAS Anom (mm/day)
E. Pacific JAS SSTA < −0.5 standard deviation
E. Pacific JAS SSTA > +0.5 standard deviation
2.0
1.5
1.0
0.5
7.0
−0.5
−1
−1.5
−2
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990

ENSO and Monsoon rainfall over India



No droughts

when ENSO index >1

No excess rainfall

when ENSO index < -1

But several extremes
when -1< ENSO Index < 1

Negative ENSO index
means warm E. Pac. SST

The Atmospheric Influence of Tropical Diabatic Heating Associated with Developing ENSO on Indian Monsoon

Youkyoung Jang (Ph D Thesis)
Department of Atmospheric, Oceanic and Earth Science
George Mason University
Spring 2011

Committee
Dr. David M. Straus (Chair)
Dr. Timothy DelSole
Dr. Ben P. Kirtman
Dr. Timothy Sauer
Dr. J. Shukla

Method

Change in tropical circulation associated with tropical SST anomalies assessed by adding localized idealized heating directly to a full atmospheric model in order to understand remote effects

Control Runs (20 years)

- non-SOM : climatological SST
- SOM: slab ocean model over the western Pacific and Indian Ocean other basins with climatological SST

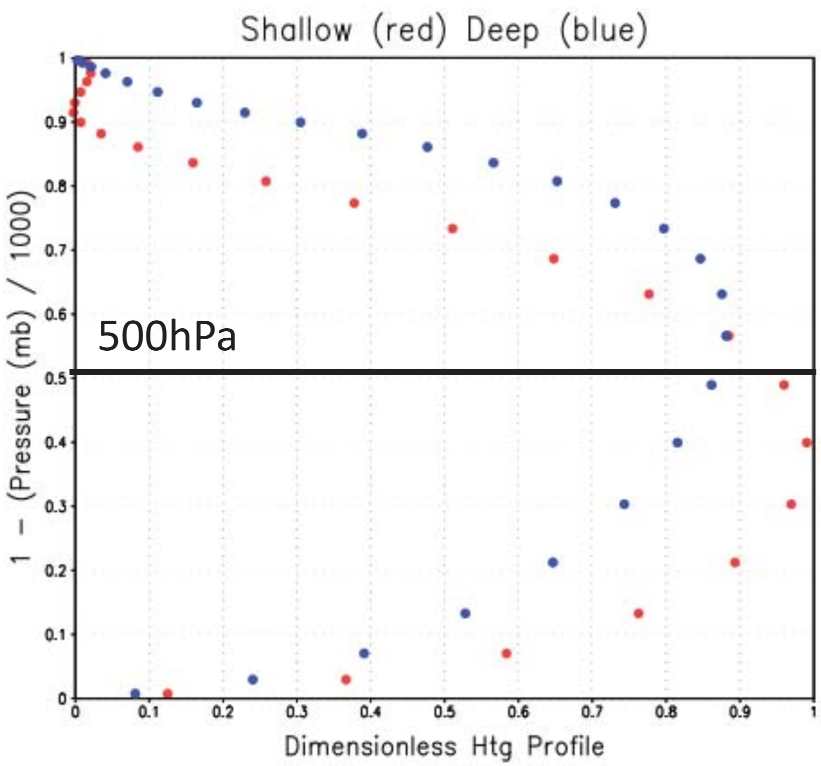
Forced Runs

Q (total heating rate) = Q (AGCM) + Q (Added heating)

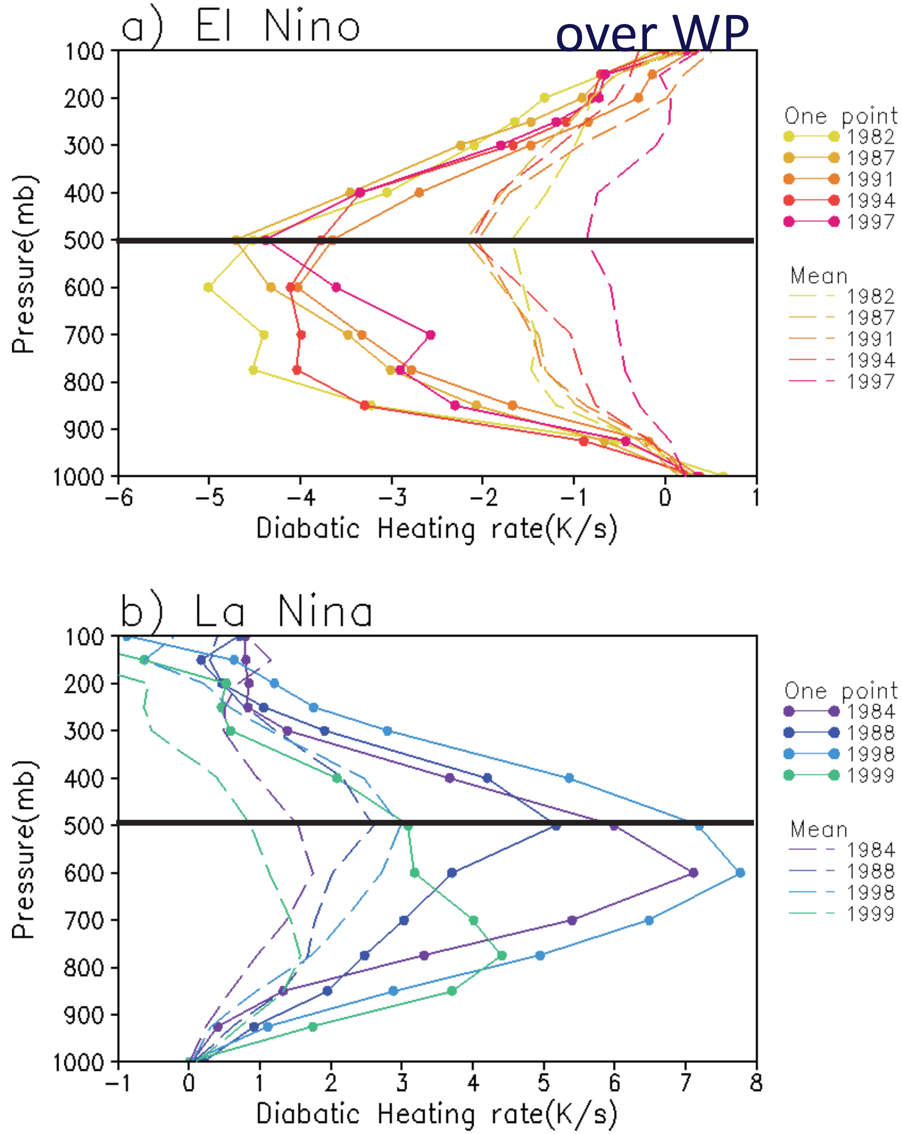
- Q (AGCM): feedback from dynamics on heating
- Responses defined as Forced Exp - Control Run
- Forced experiments with SOM and non-SOM
- **Focused on Seasonal Mean (MJJA)**

Vertical structure (K/day)

➢ Model



➢ Observation

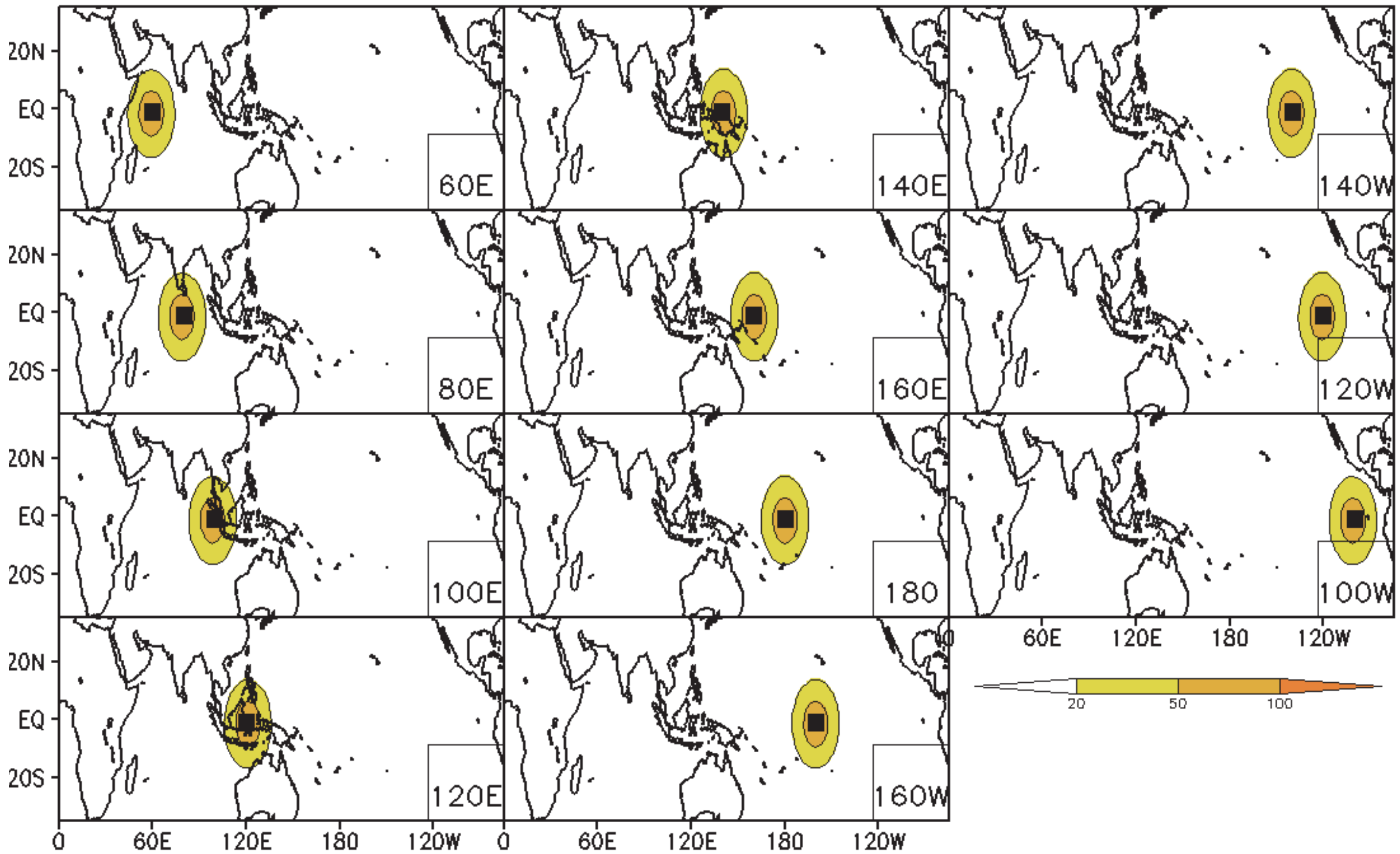


Three types of Forcing

1) Idealized heating and cooling

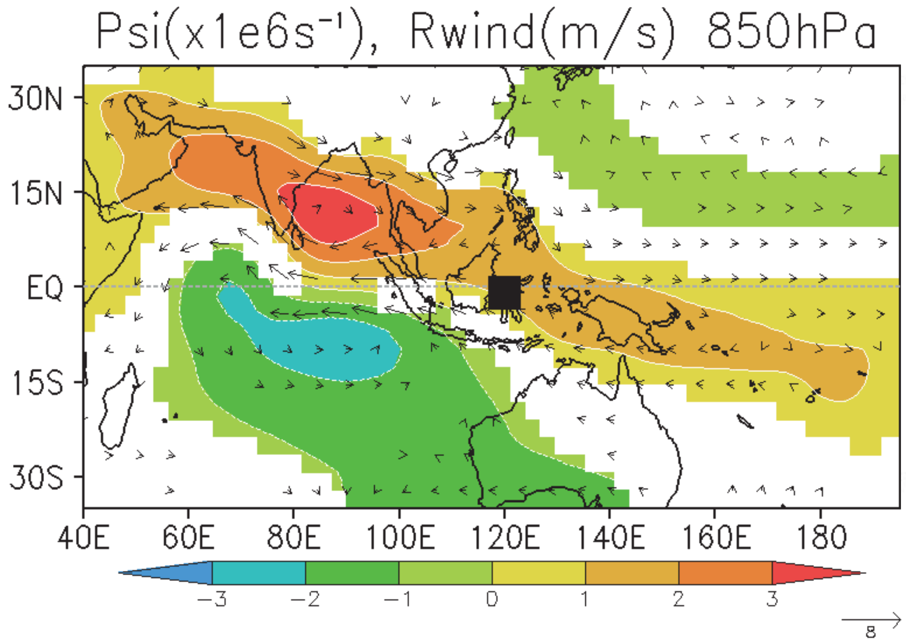
: vertically integrated Wm^{-2}

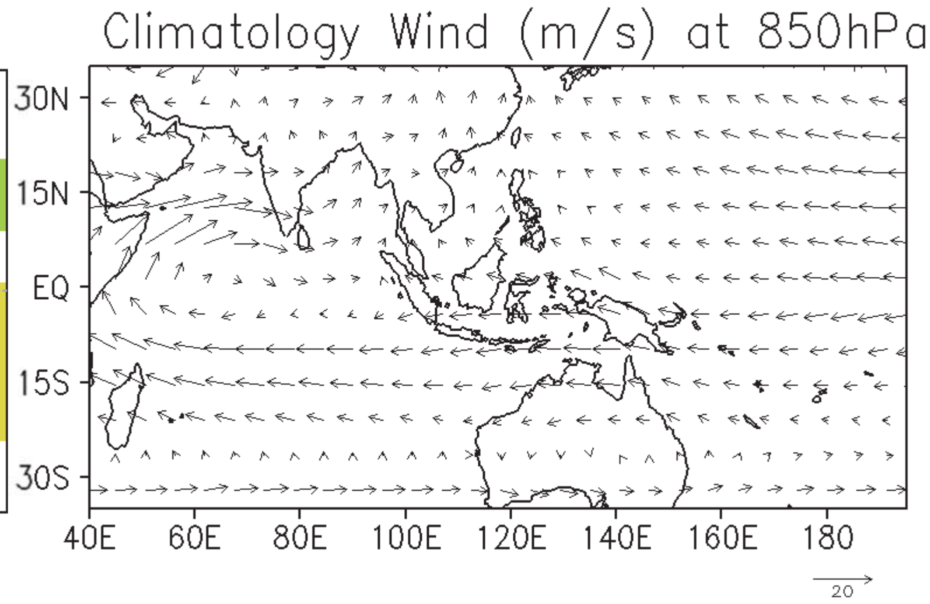
- longitude: 11 locations
- latitude: equator, 7S, 7N



Cooling Exp: GCM effect 1

- WP Cooling ~ opposed to monsoon flow





Compare to very simple Gill theory
for negative heating

Simple theory of steady state response to heating in tropics (no mean flow)
Westward propagating Rossby waves and Eastward propagating Kelvin waves participate

Gill (1980) response to heating Q_c

Pressure field

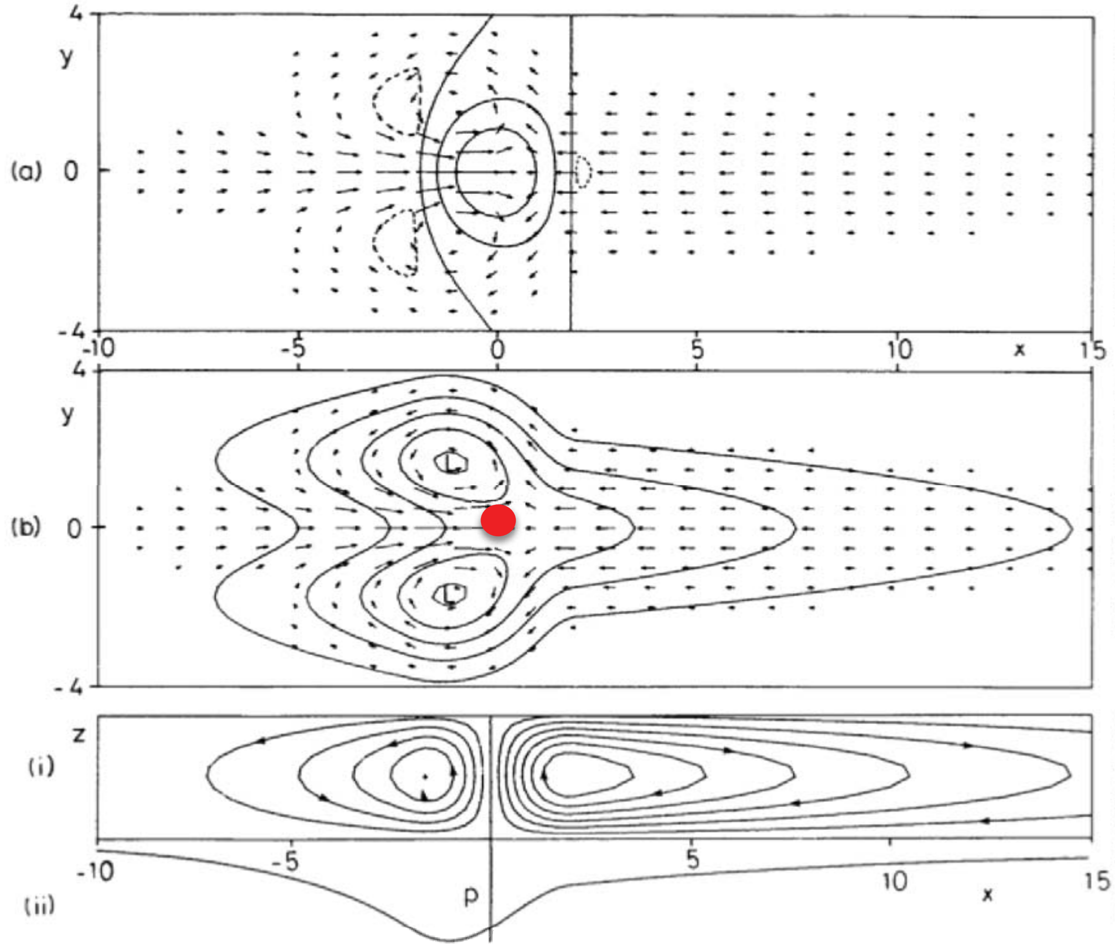
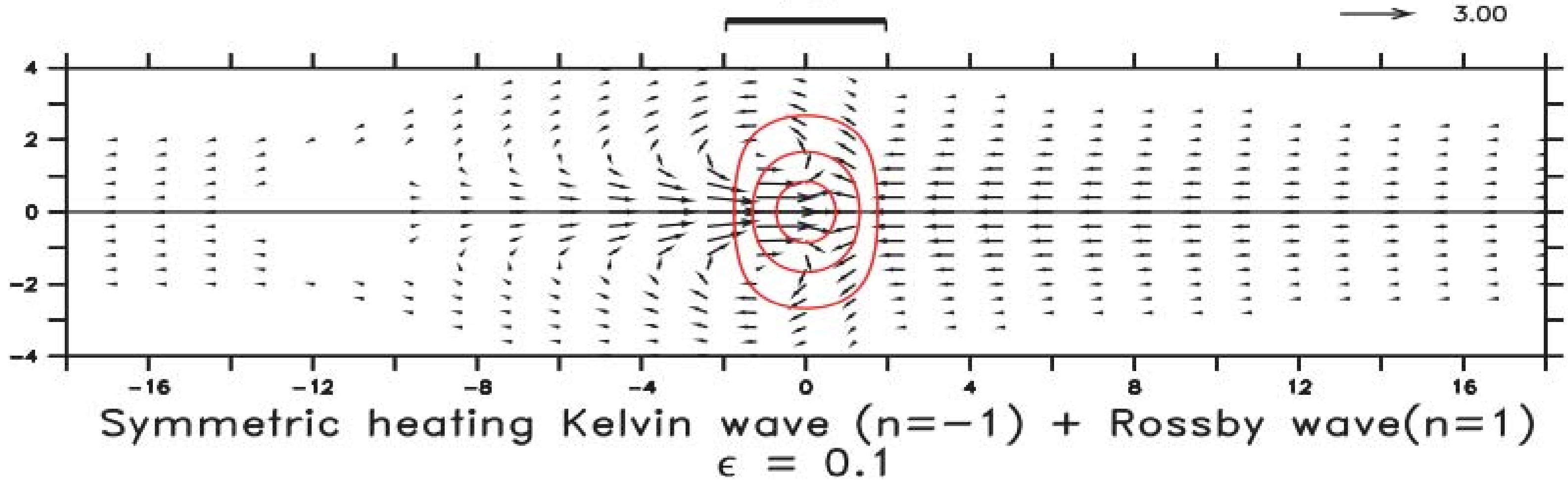


Figure 1. Solution for heating symmetric about the equator in the region $|x| < 2$ for decay factor $\varepsilon = 0{\cdot}1$.
(a) Contours of vertical velocity w (solid contours are 0, 0·3, 0·6, broken contour is −0·1) superimposed on the velocity field for the lower layer. The field is dominated by 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 régime 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).

(a)

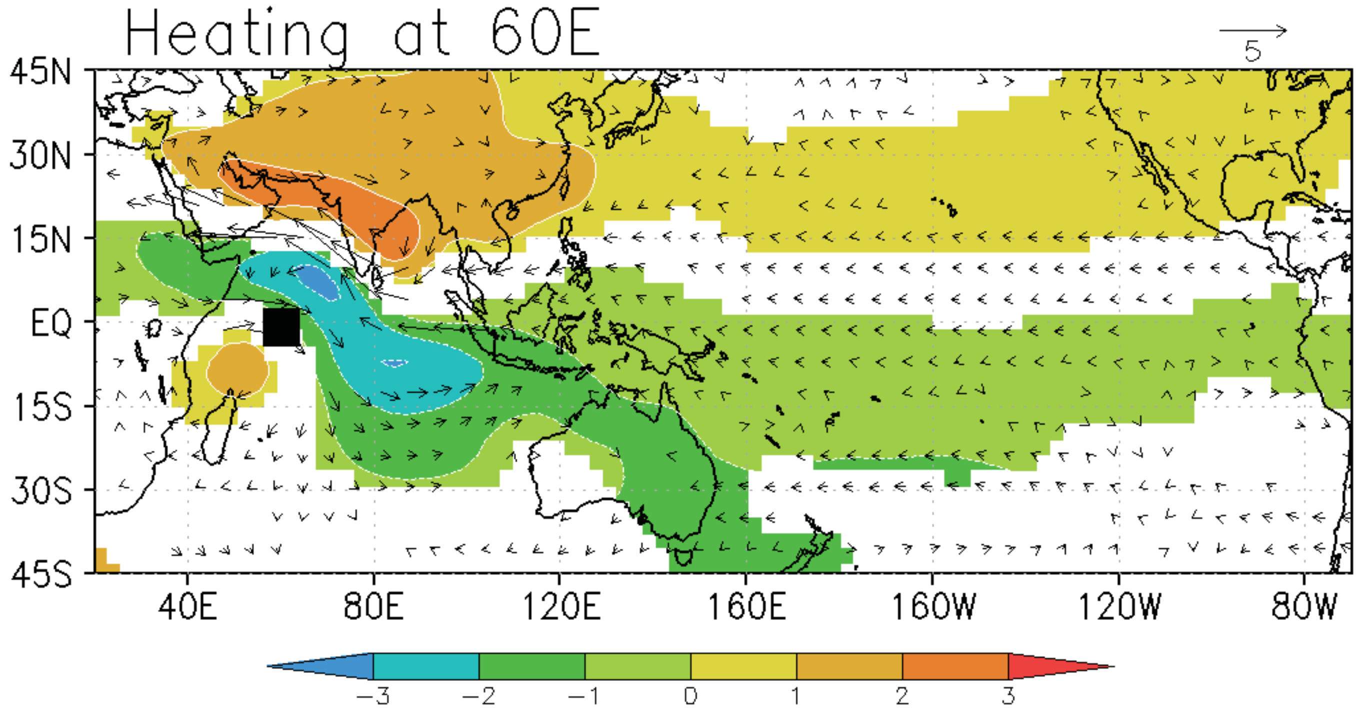


(b)

“THE GLOBAL TROPICAL CIRCULATION AND THE MONSOONS FROM THE PERSPECTIVE OF FOUR PLANETARY WAVES” by Mark Williams

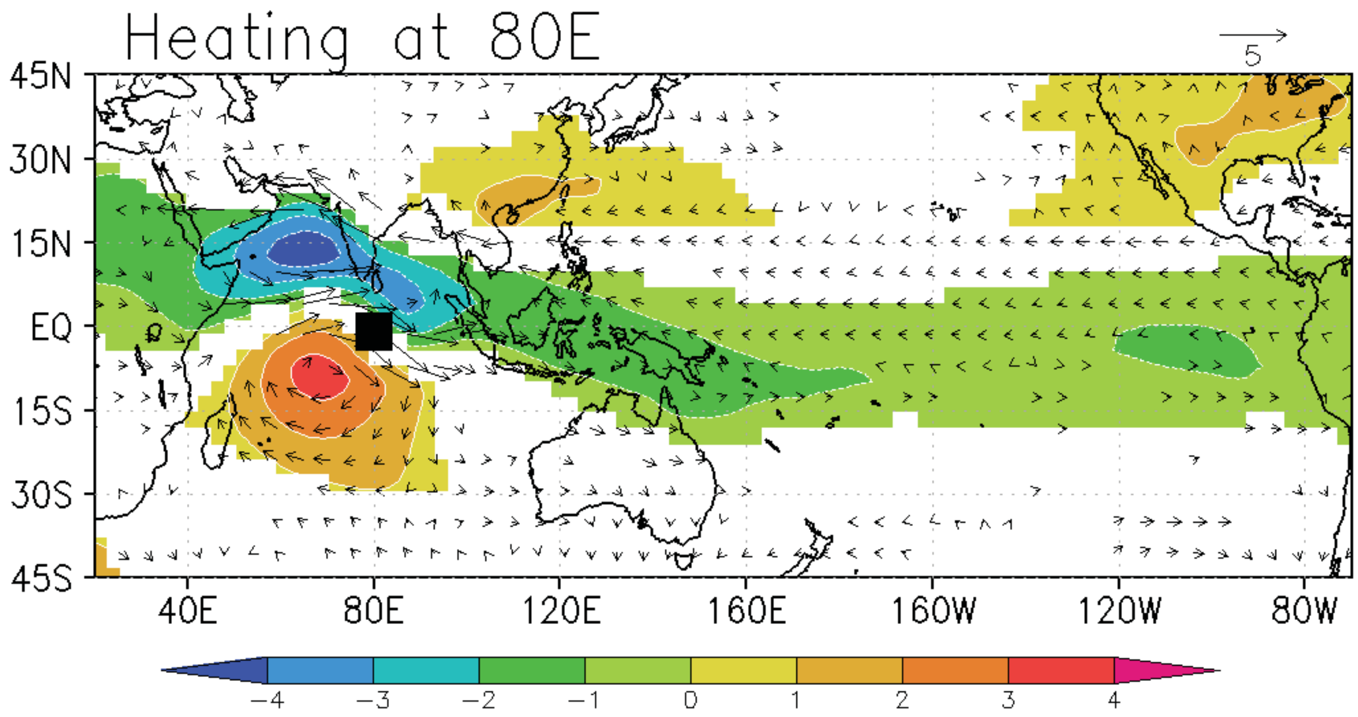
Sensitivity to Longitude: 60E ~ 100W

Streamfunction, Rotational Wind at 850hPa



Sensitivity to Longitude: 60E ~ 100W

Streamfunction, Rotational Wind at 850hPa



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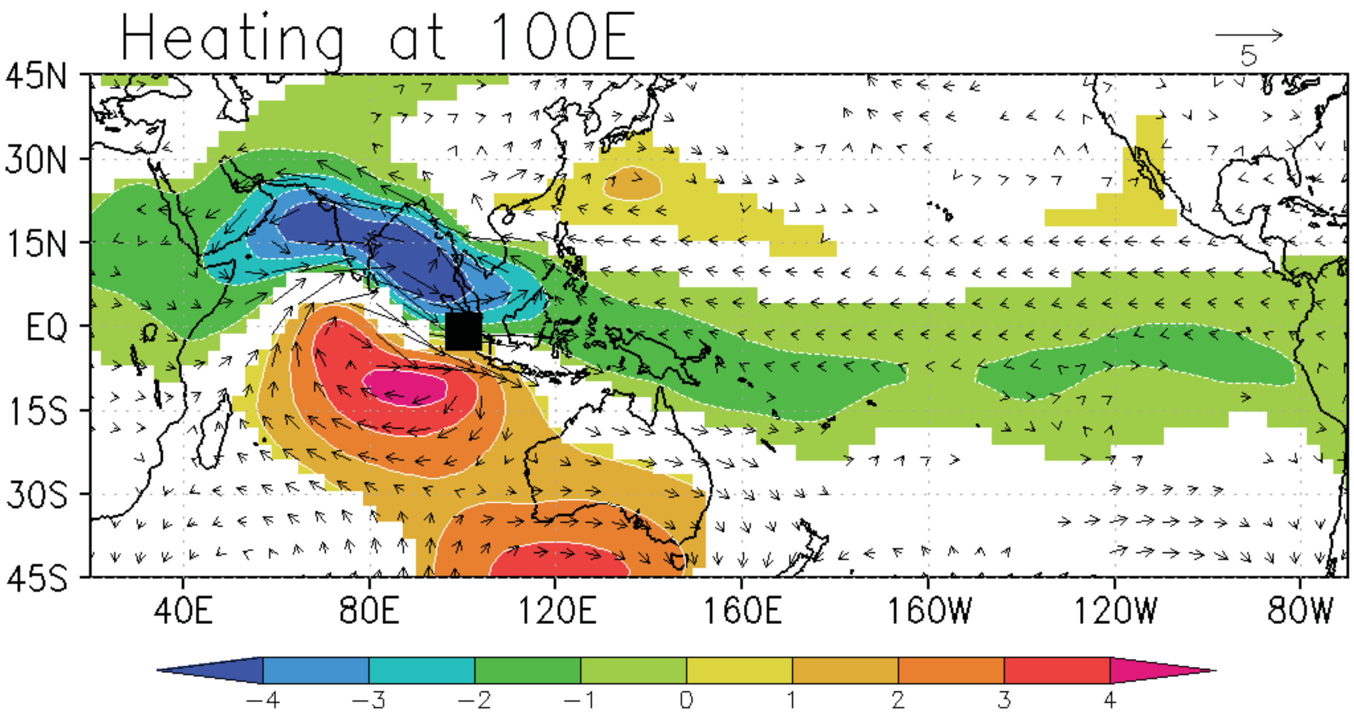
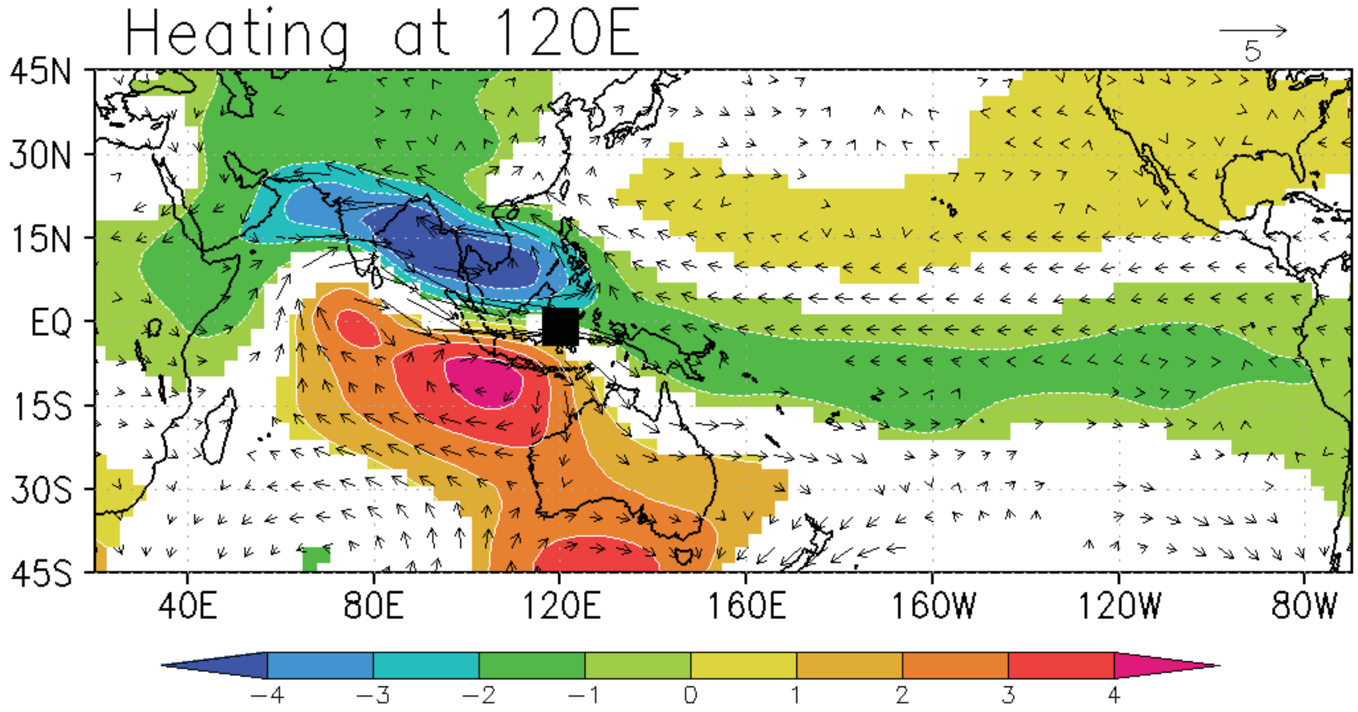
Streamfunction, Rotational Wind at 850hPa



Sensitivity to Longitude: 60E ~ 100W

Streamfunction, Rotational Wind at 850hPa



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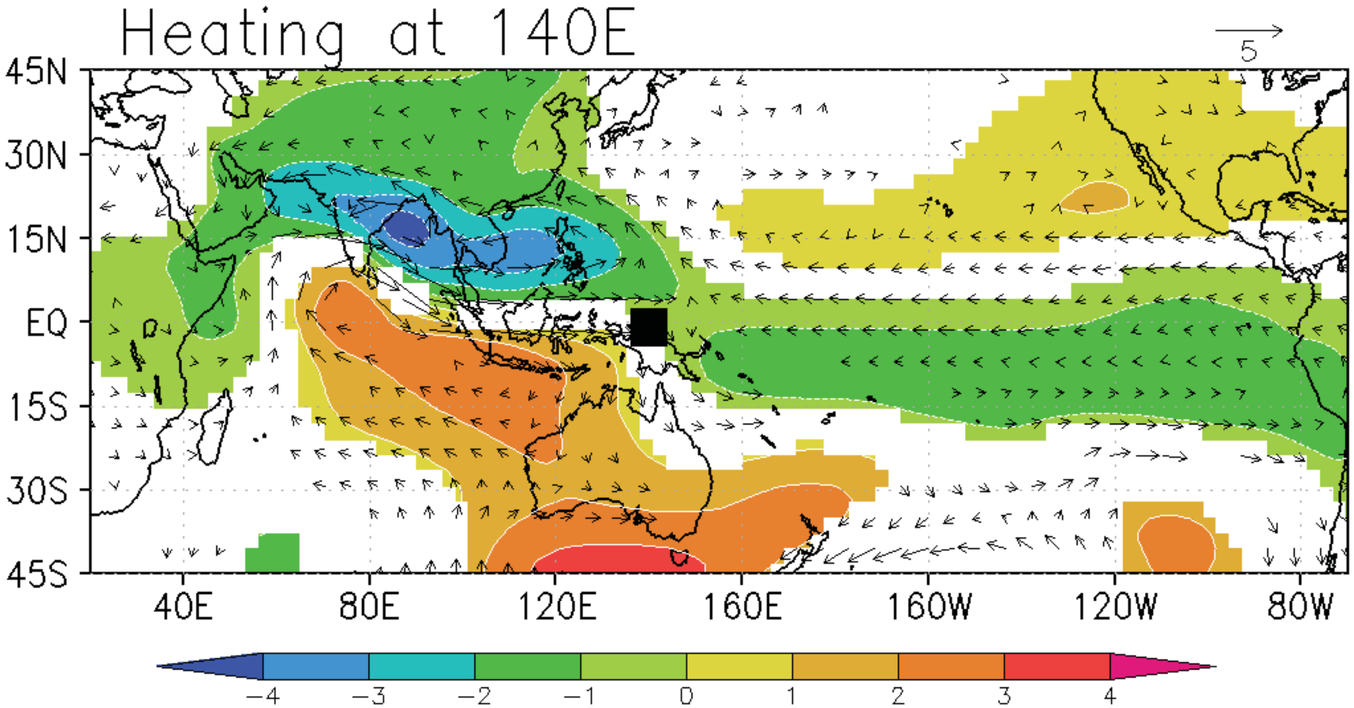

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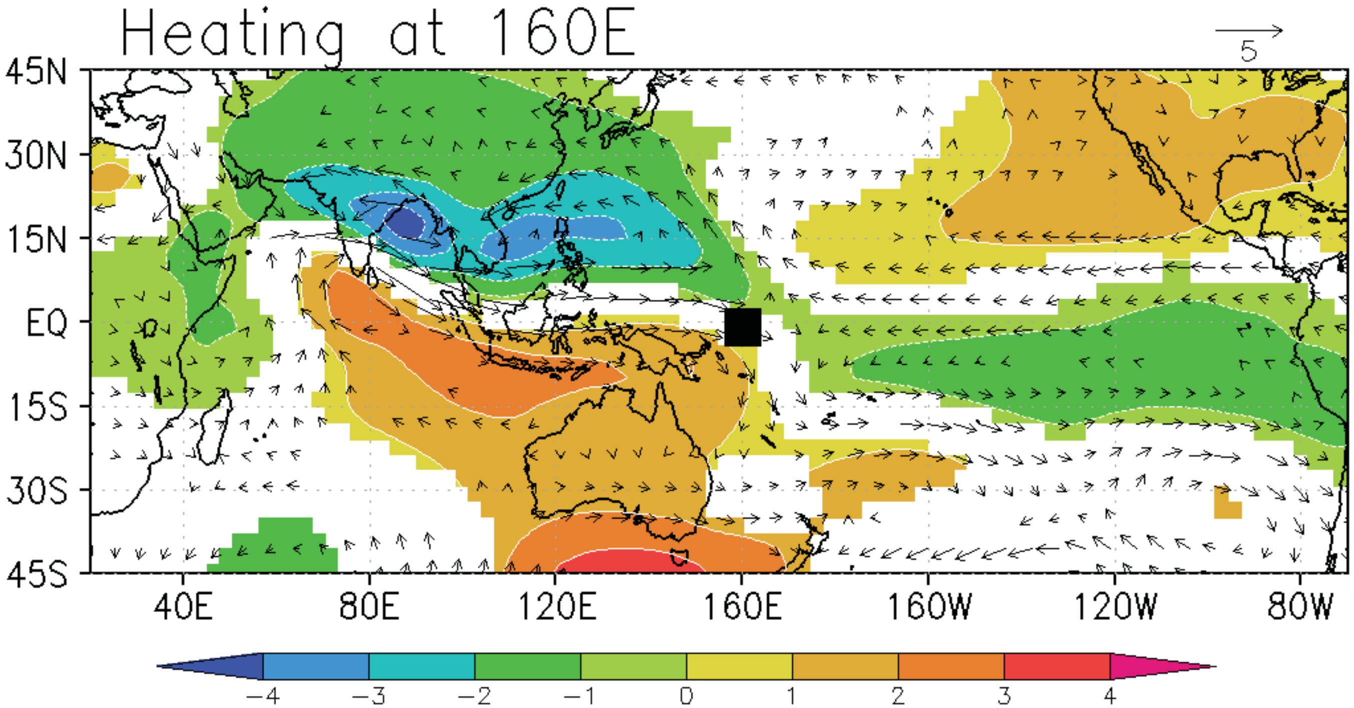
Streamfunction, Rotational Wind at 850hPa



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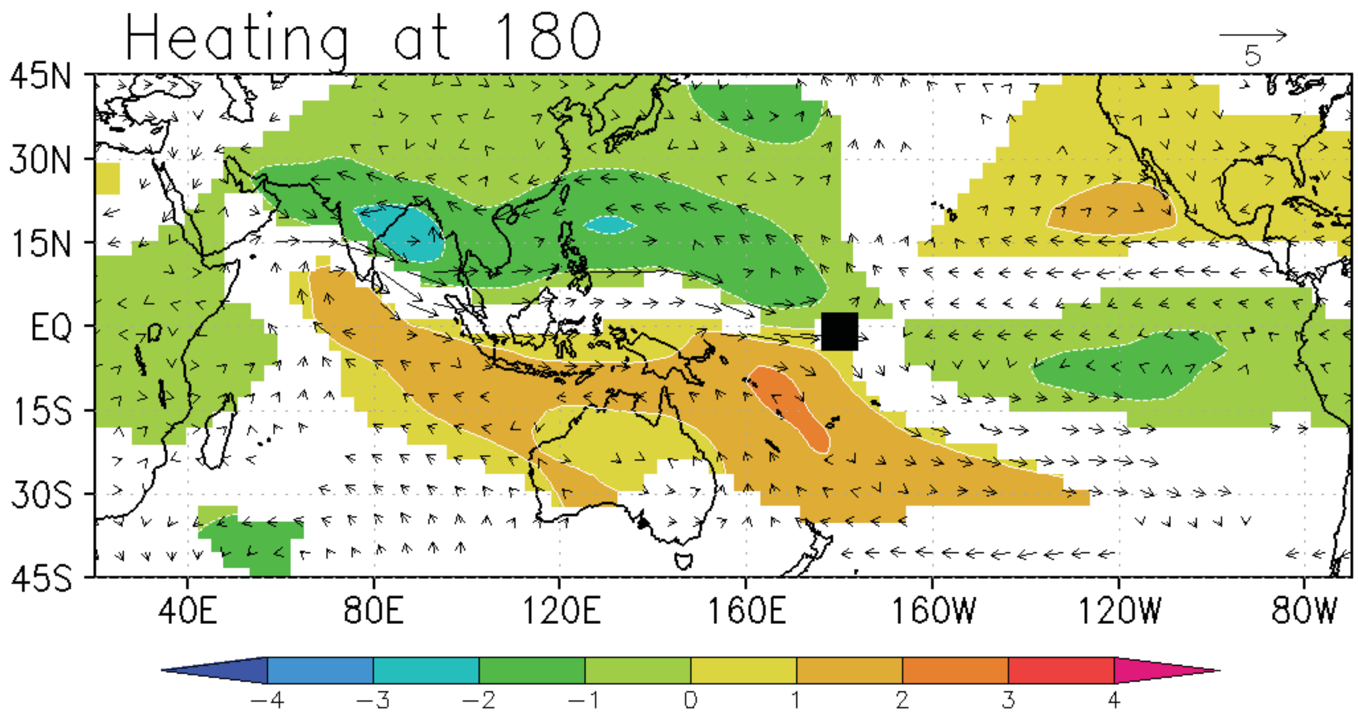
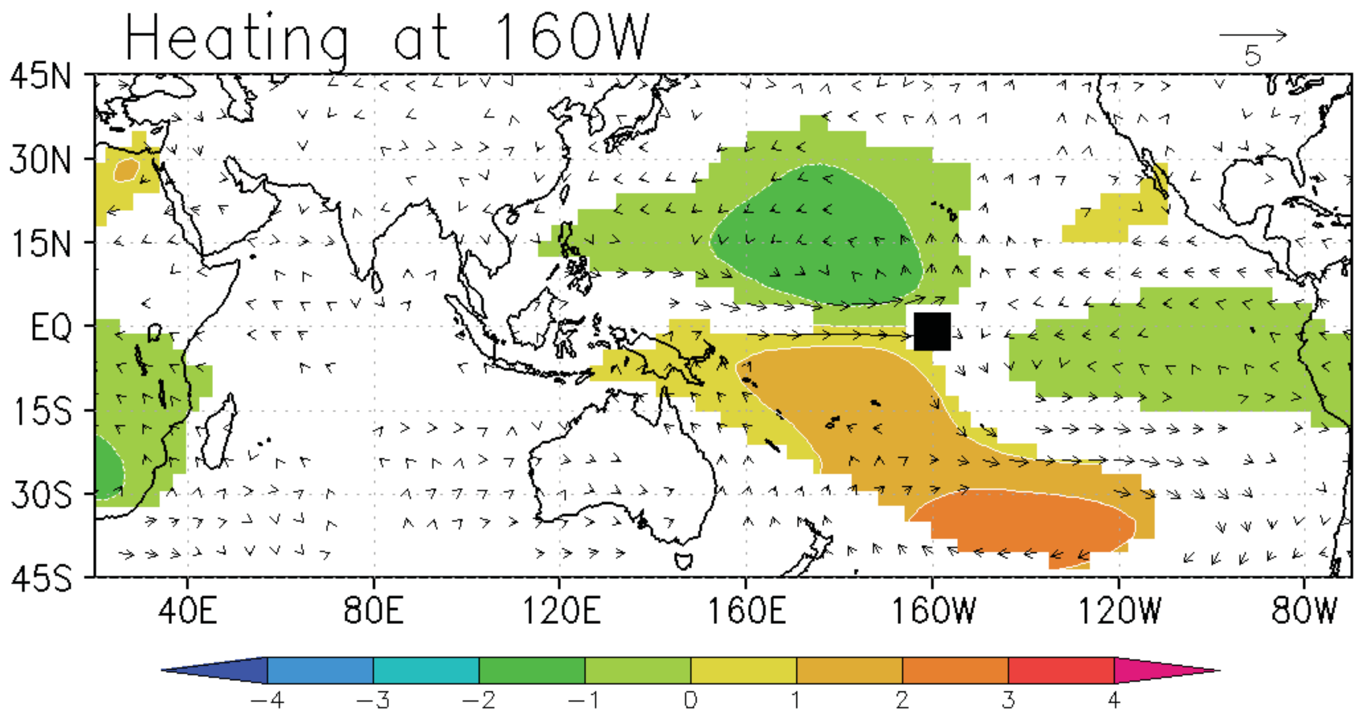
Streamfunction, Rotational Wind at 850hPa



Sensitivity to Longitude: 60E ~ 100W

Streamfunction, Rotational Wind at 850hPa



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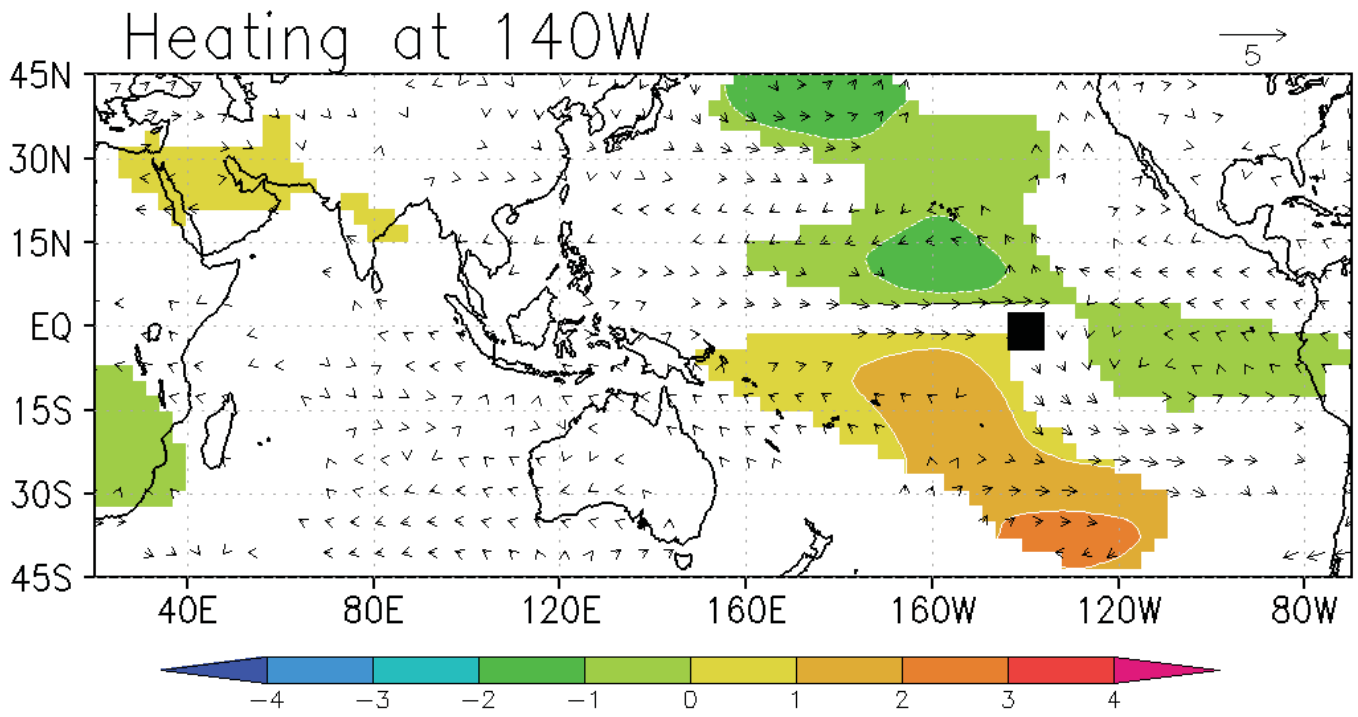
Streamfunction, Rotational Wind at 850hPa



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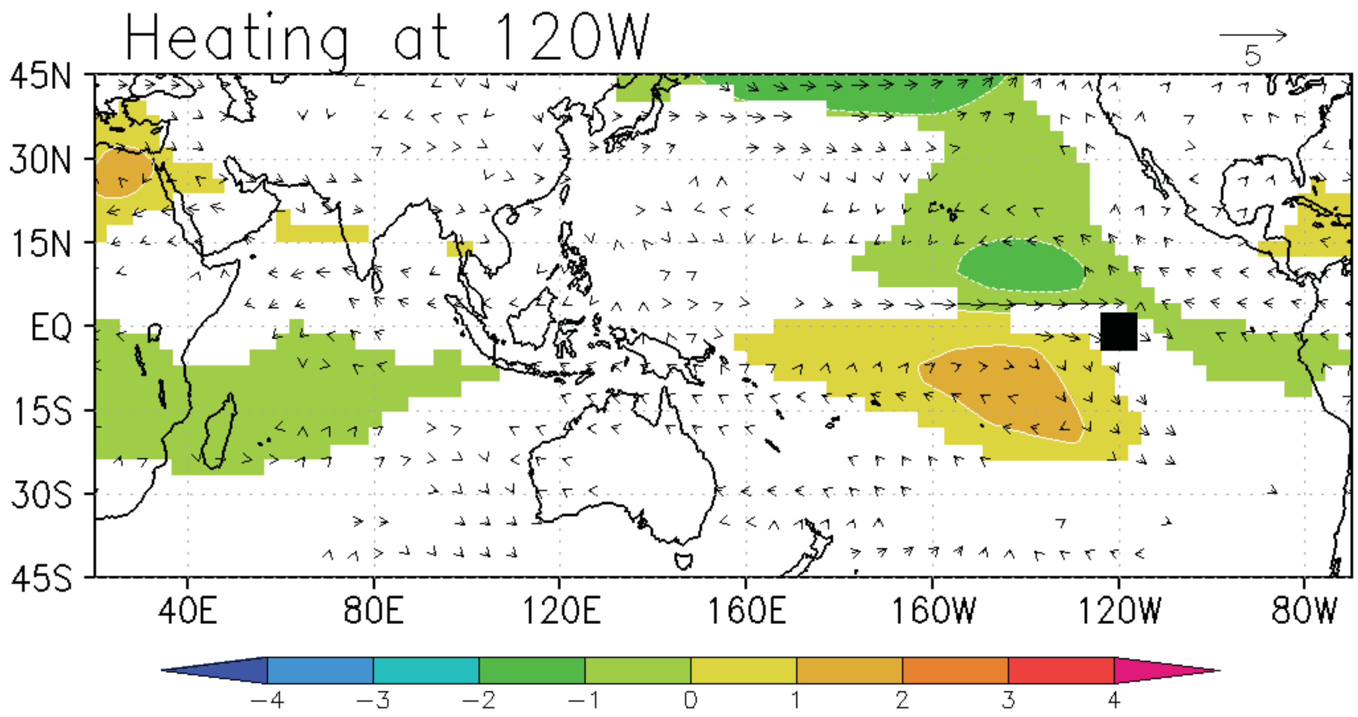

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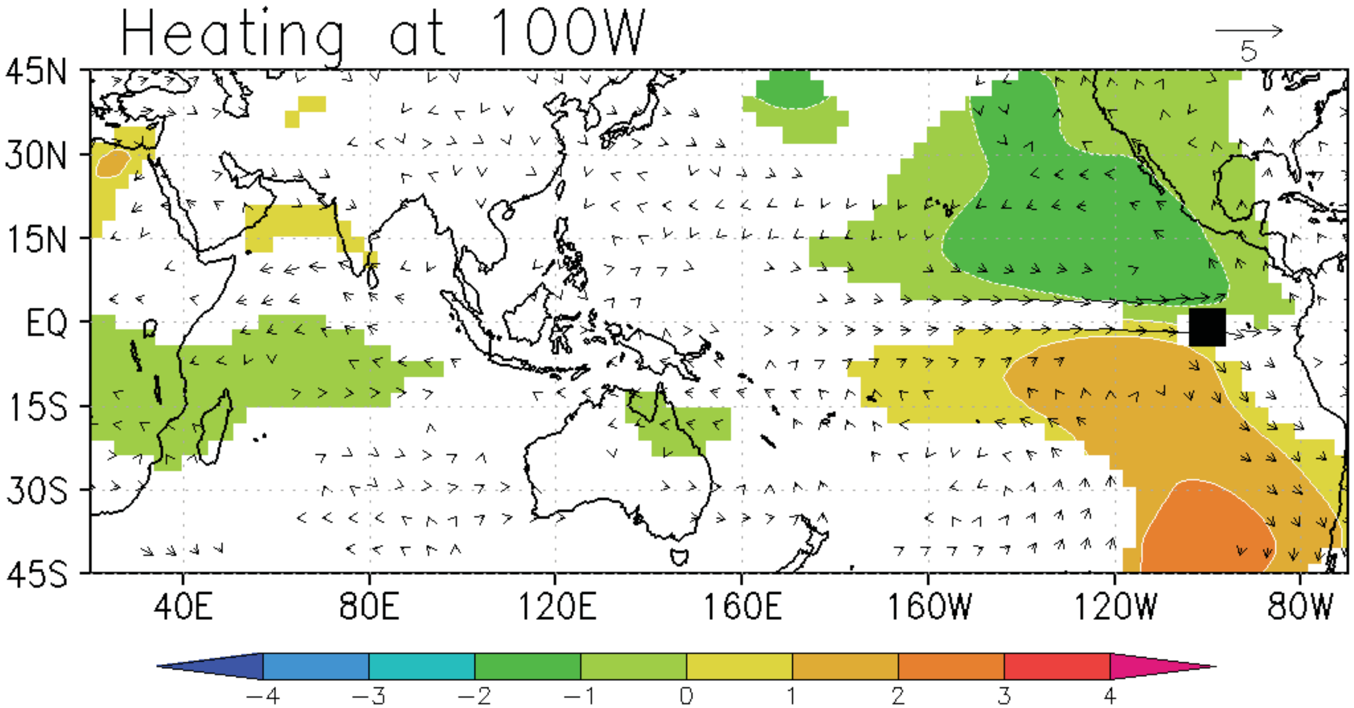
Streamfunction, Rotational Wind at 850hPa



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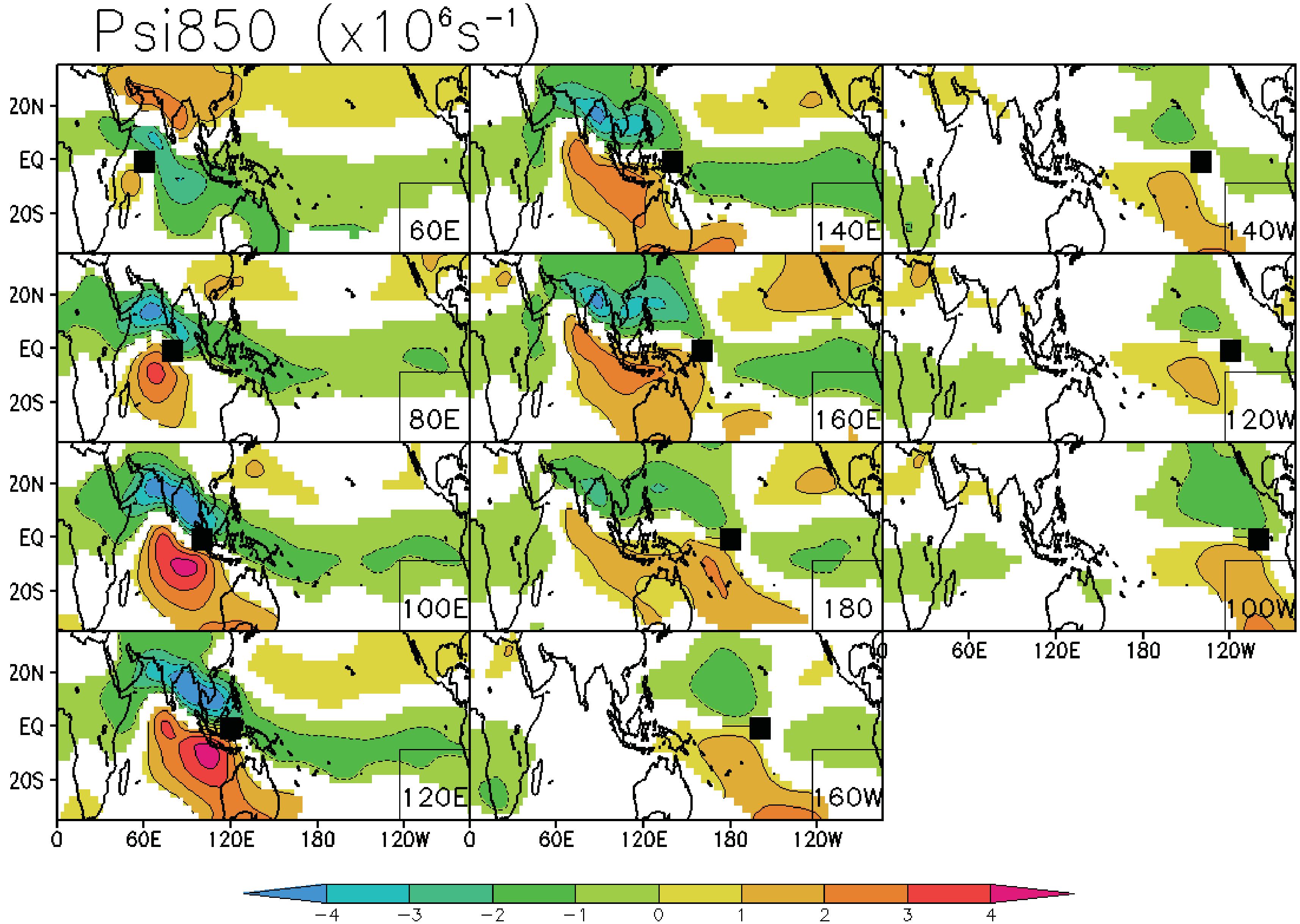
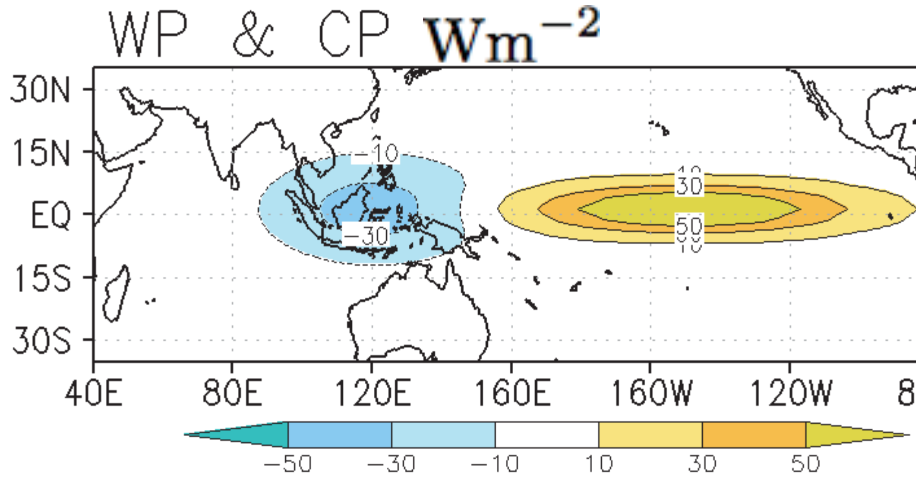


Three types of Forcing

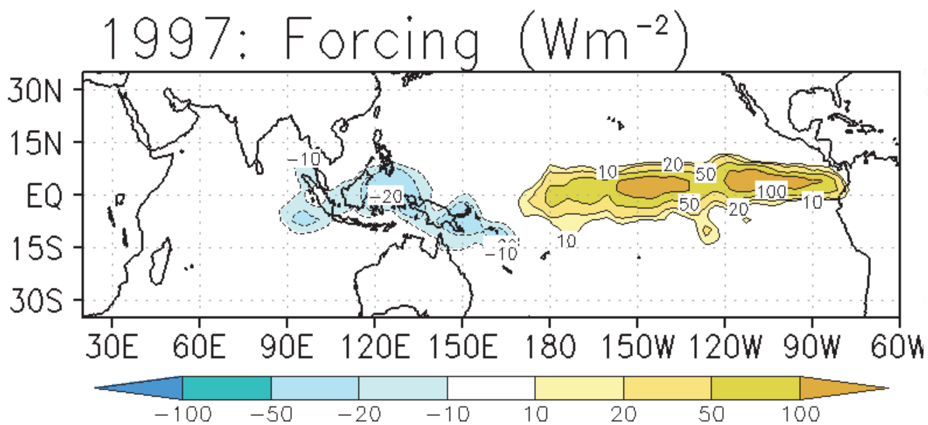
Chan, S. C. and S. Nigam, 2009: Residual diagnosis of diabatic heating from ERA-40 and NCEP reanalyses: Intercomparisons with TRMM. J. Climate, 22, 414{428.

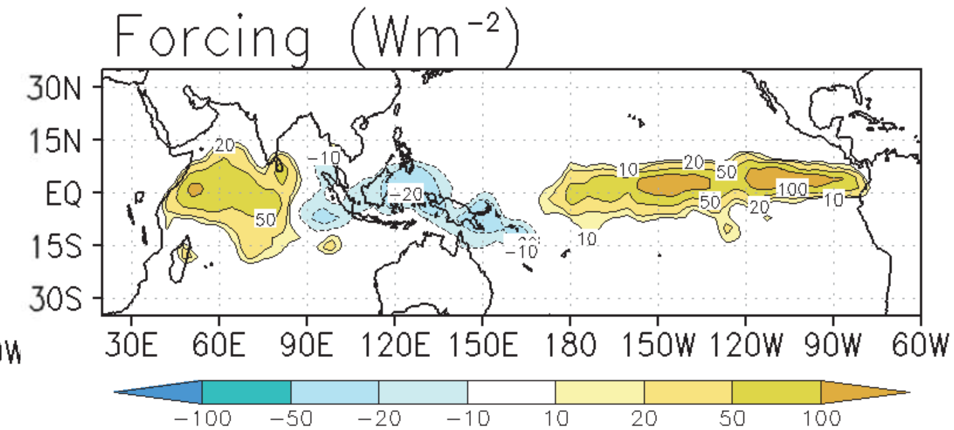
2) Realistic Forcing



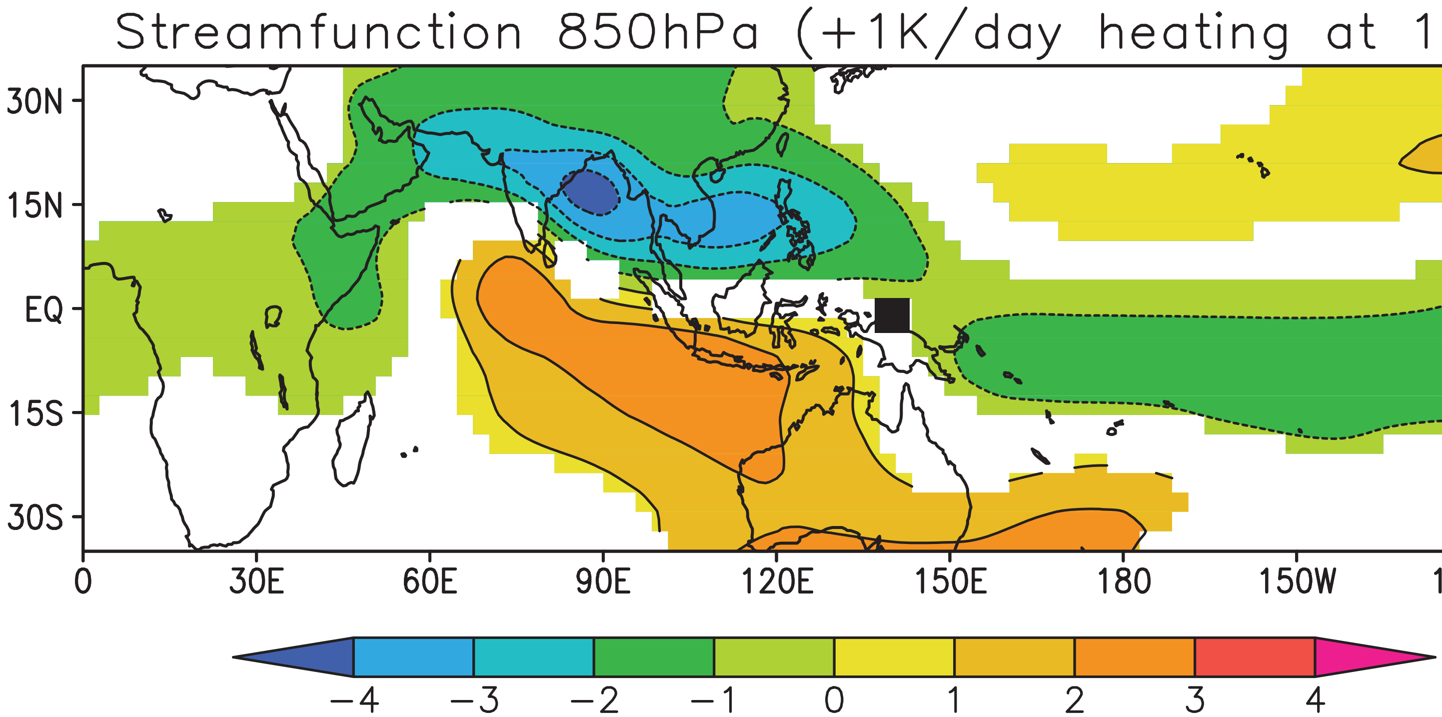
3) Observed Forcing

diagnosed diabatic heating with SOM



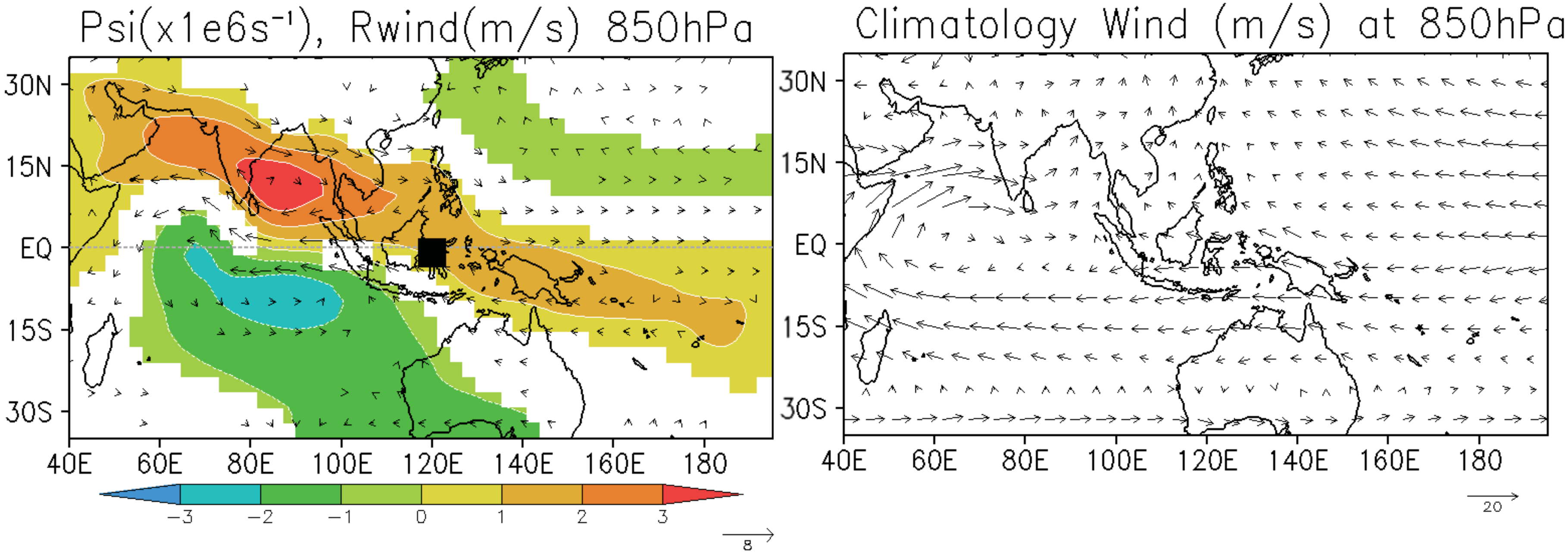


Idealized Western Pacific Heating: Relevant for La Nina



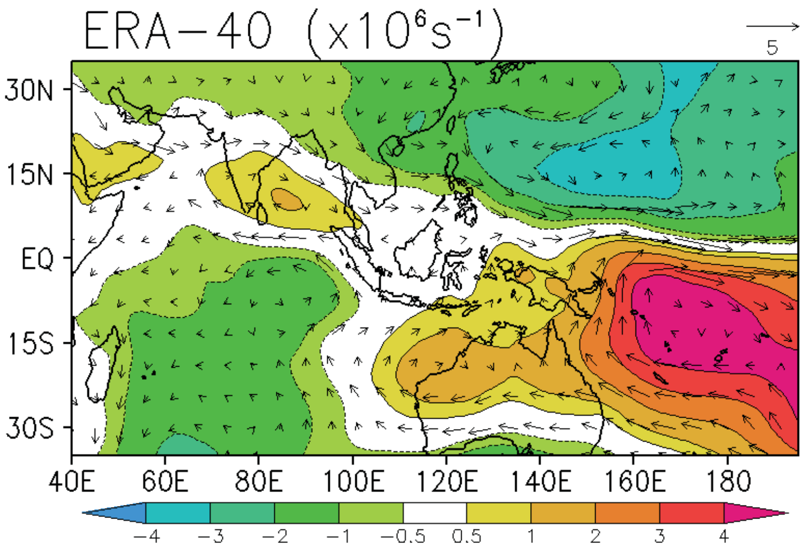
Idealized Western Pacific Cooling: Relevant for El Nino

- WP Cooling ~ Weakens the monsoon flow



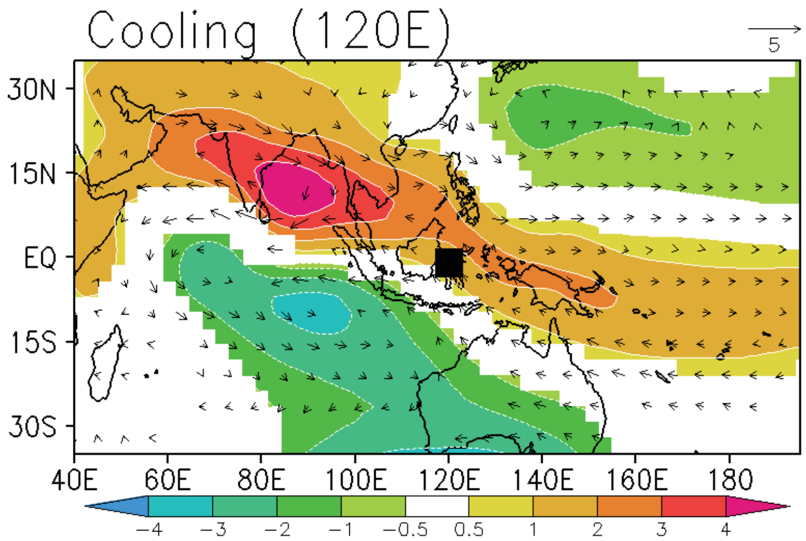
Idealized Experiments vs. 1997 observations

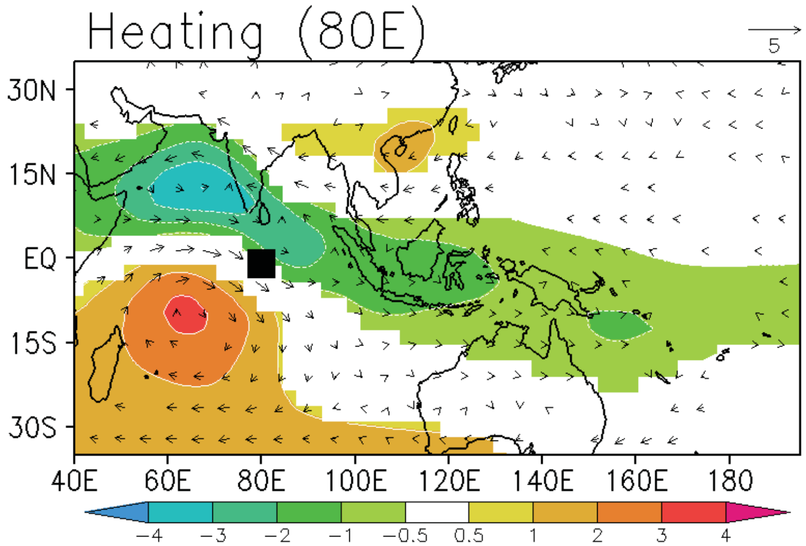
➢ Observation



- **Streamfunction (x1e6s⁻¹) at 850hPa**
- **Wind (m/s) at 850hPa**

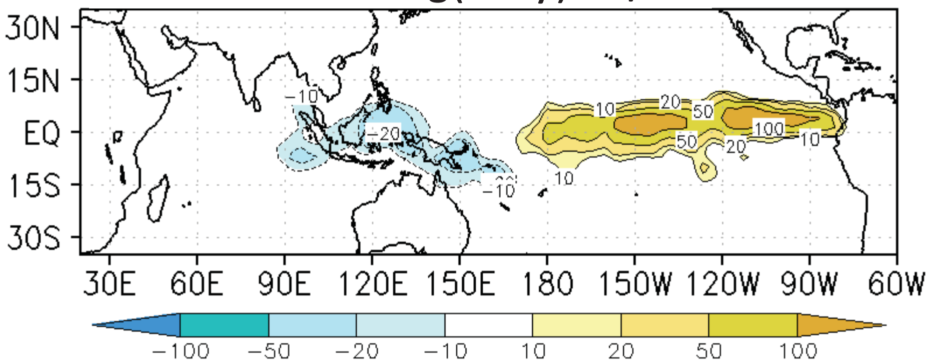
➢ Two Idealized forcing Exps



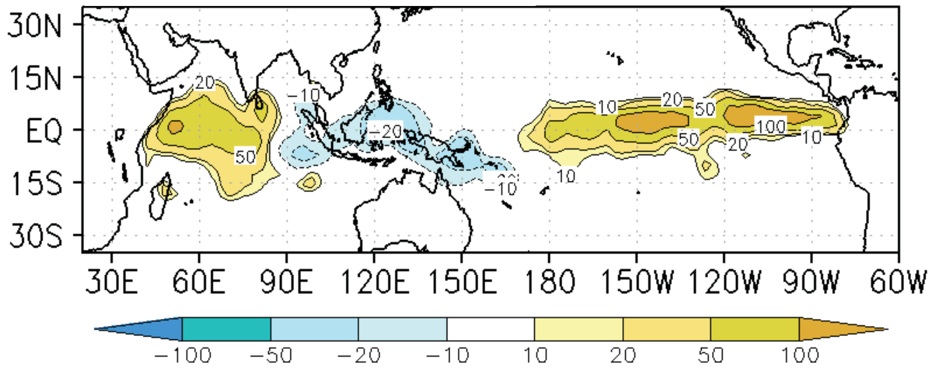


1997 Response using “Observed” Heating: Role of Indian Ocean heating

- 1997 Pacific forcing(only) W/m²

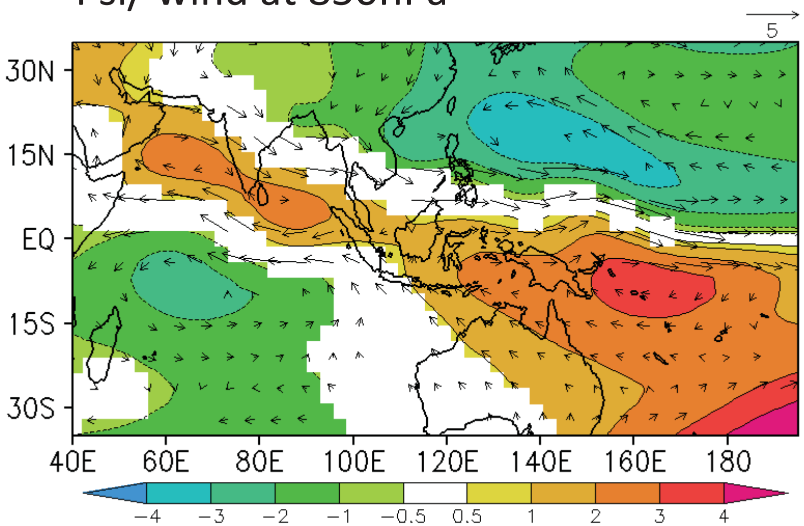


- 1997 Pacific + IO forcing W/m²



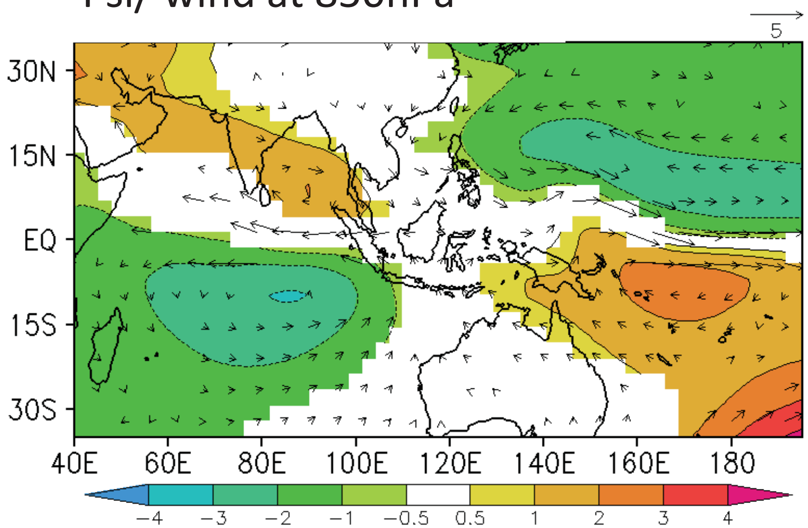
- Response:

  Psi/ wind at 850hPa



- Response:

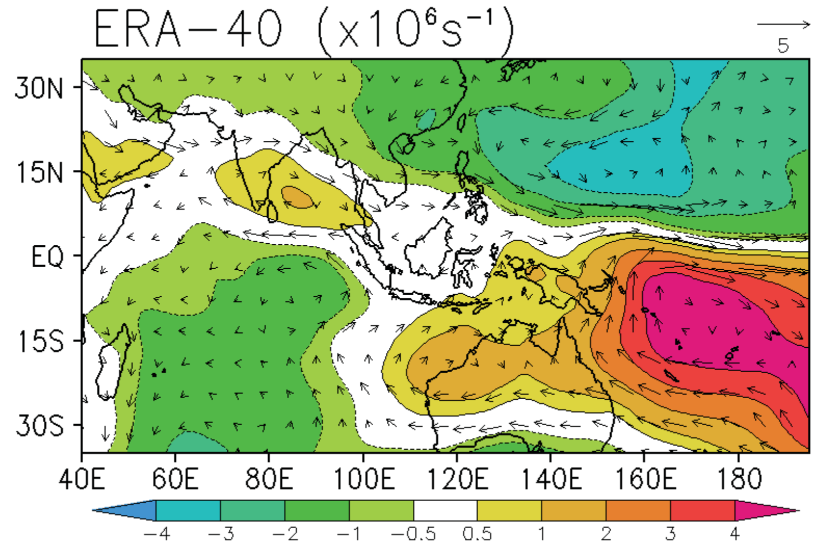
  Psi/ wind at 850hPa



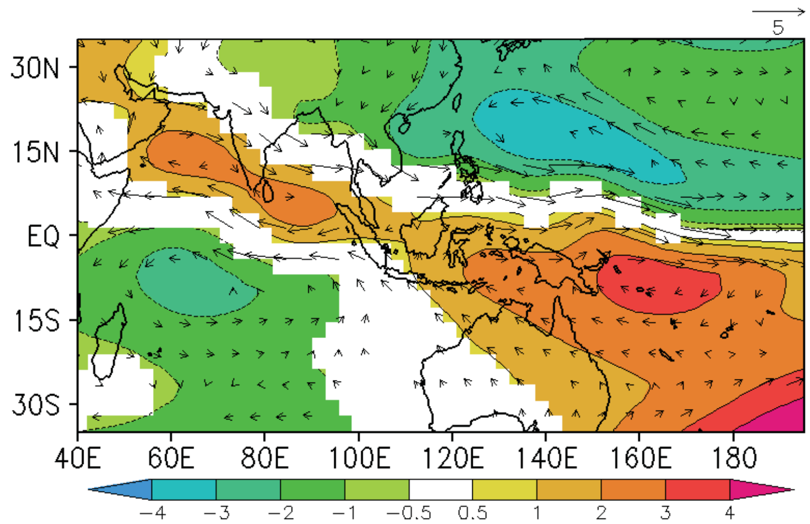
Pacific Only vs. Pacific + Indian Ocean

- Streamfunction (x1e6s^{-1}) at 850hPa
- Wind (m/s) at 850hPa

➢ **Observation**



➢ **1997 Pacific forcing only**



➢ **1997 Pacific + IO forcing**