The Abdus Salam
International Centre
for Theoretical Physics

2356-16

Targeted Training Activity: ENSO-Monsoon in the Current and Future Climate

30 July - 10 August, 2012

ENSO: Role of the Ocean

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ROSENSTIEL
SCHOOL of MARINE &
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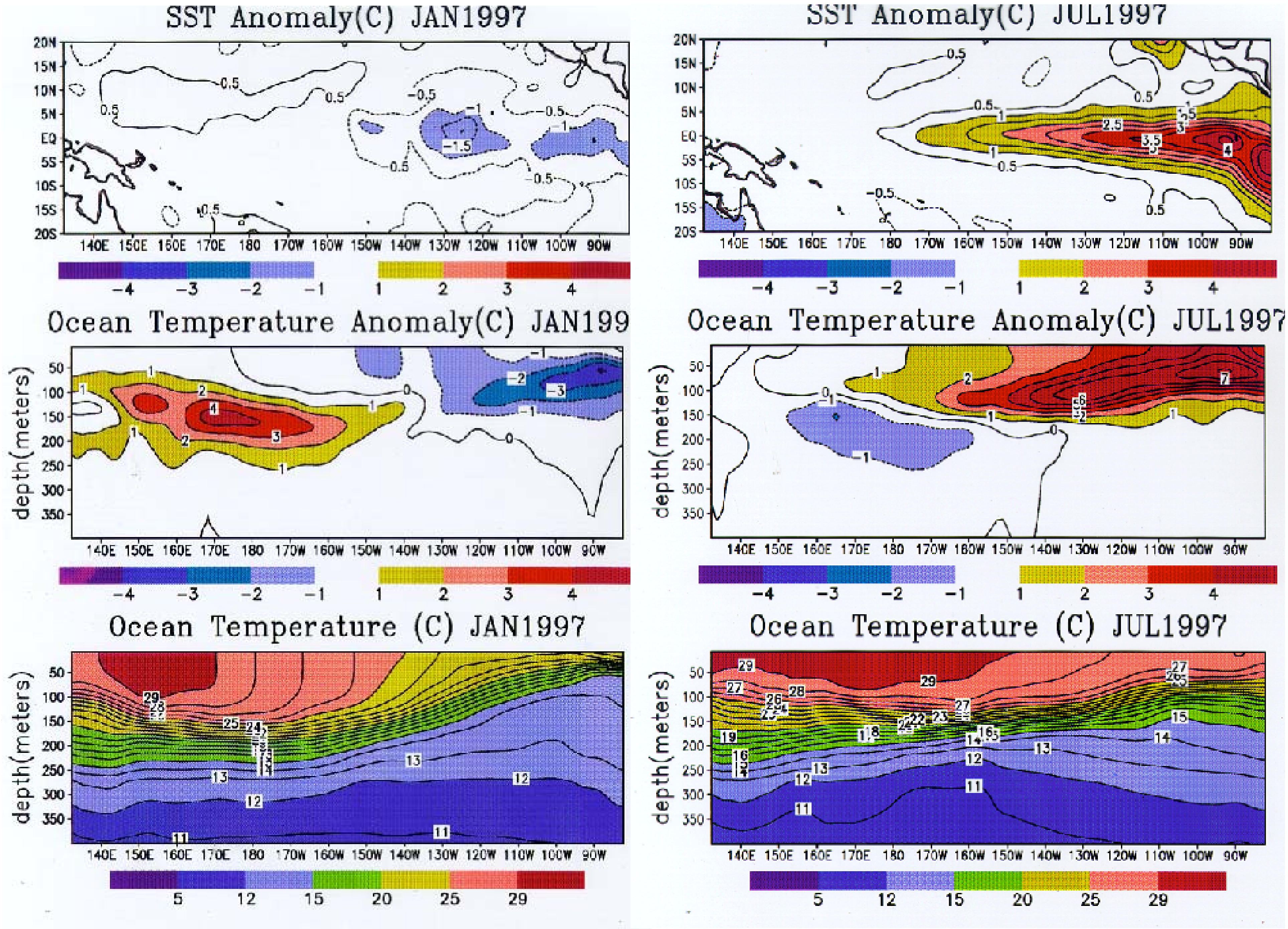
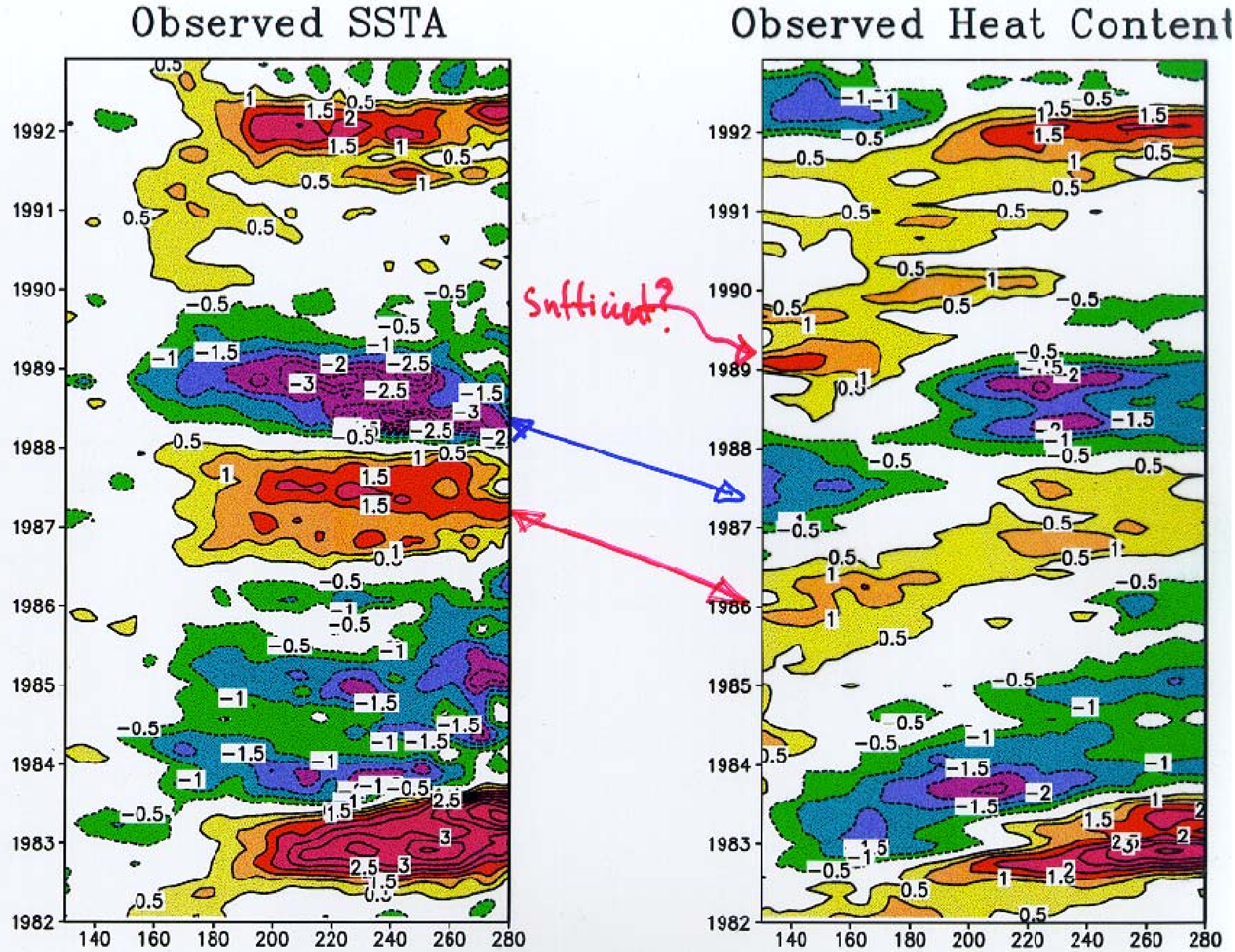
ENSO: Role of the Ocean

Ben Kirtman
University of Miami – Rosenstiel School

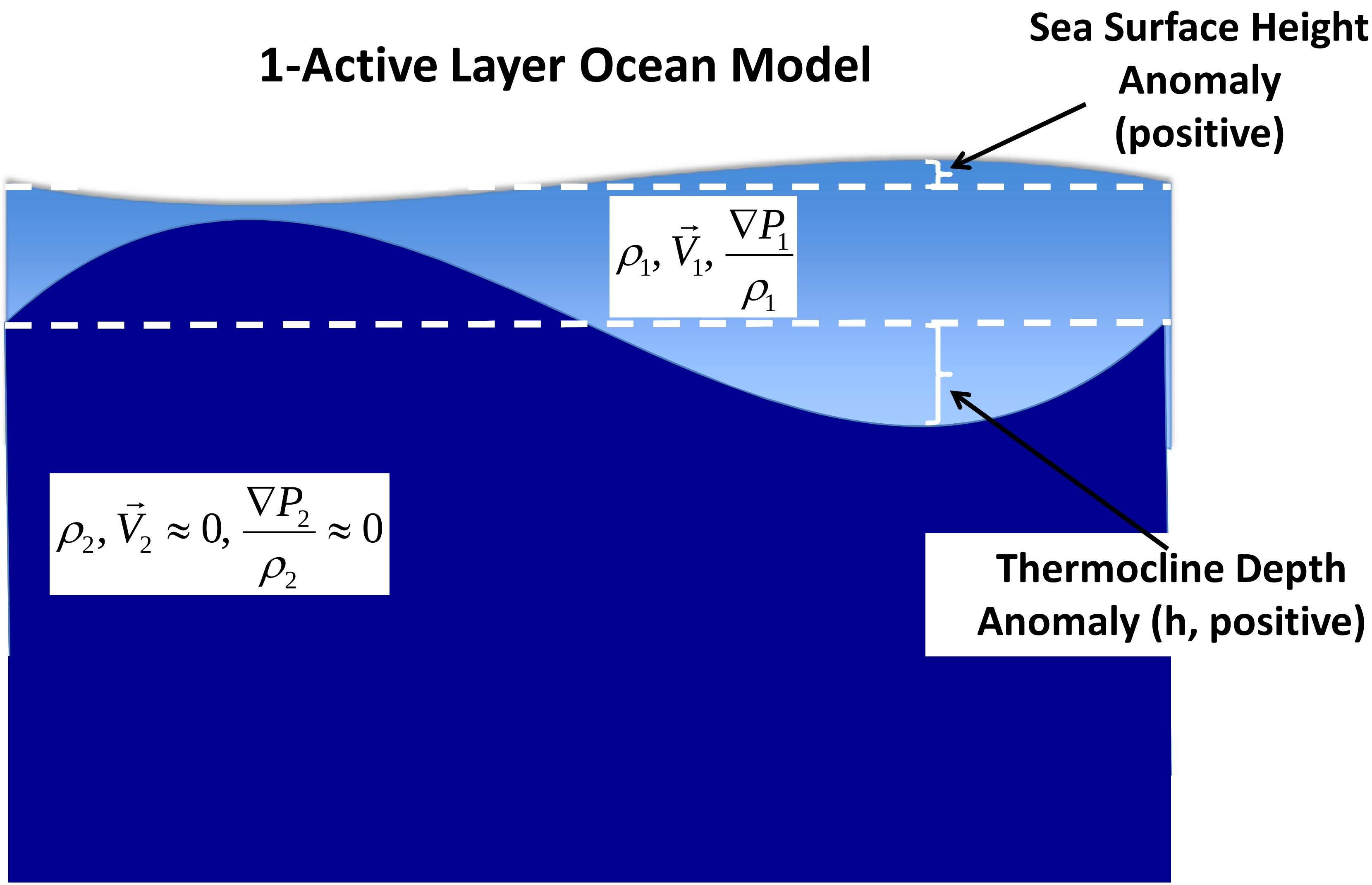

SST Anomaly(C) JAN1997
SST Anomaly(C) JUL1997
20N 15N 10N 5N EQ 5S 10S 15S 20S
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
-4 -3 -2 -1 1 2 3 4
Ocean Temperature Anomaly(C) JAN199
Ocean Temperature Anomaly(C) JUL1997
depth(meters)
50 100 150 200 250 300 350
Ocean Temperature (C) JAN1997
Ocean Temperature (C) JUL1997
5 12 15 20 25 29


Observed SSTA
Observed Heat Content
1992
1991
1990
1989
1988
1987
1986
1985
1984
1983
1982
140
160
180
200
220
240
260
280
Sufficient?

Outline

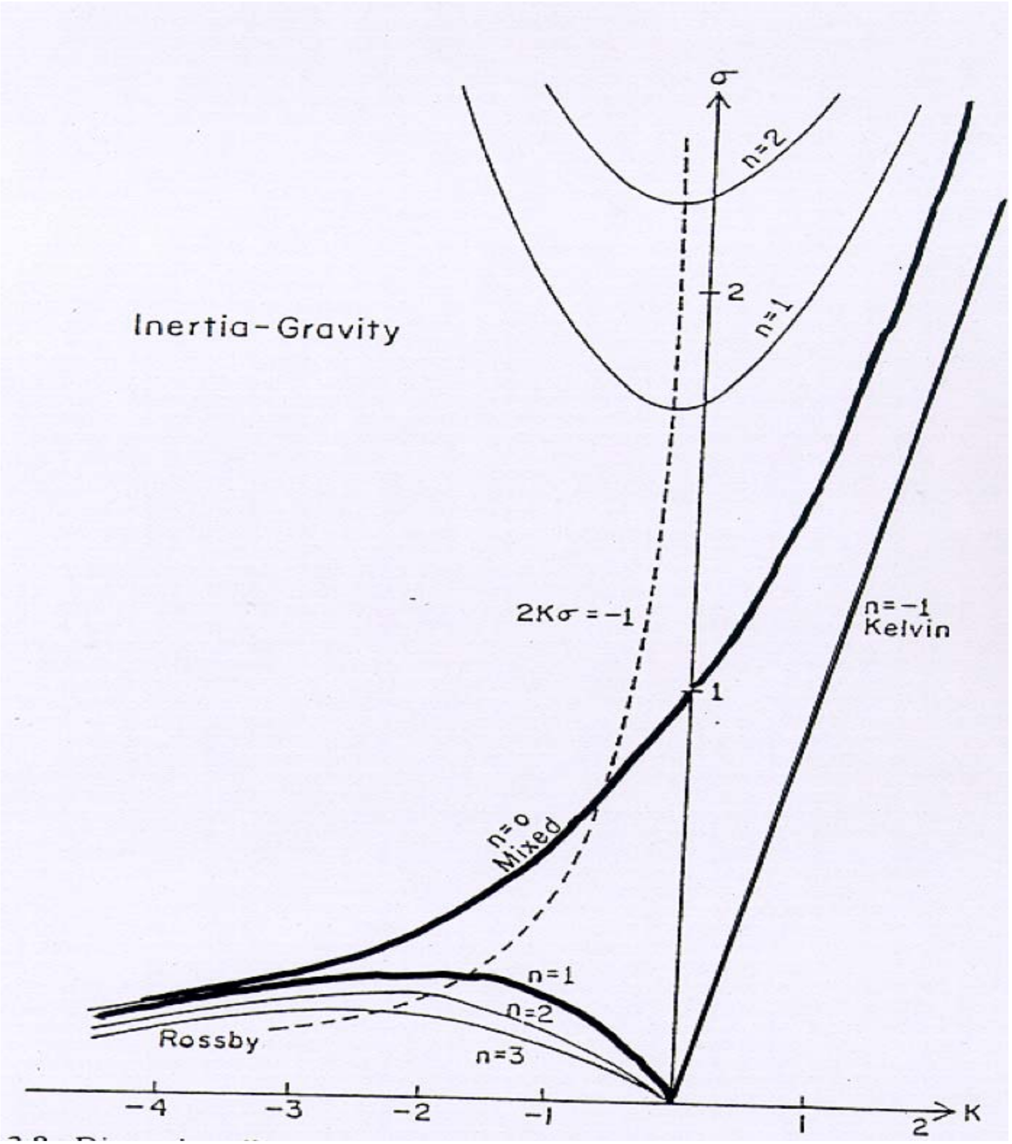
- Free Equatorial Waves
  - Rossby and Kelvin Wave
- Forced Equatorial Waves
  - Equatorial Sverdrup Balance
- Coupled Problem
  - Delayed Oscillator, Recharge Oscillator, Fast Wave – Slow SST

1-Active Layer Ocean Model



$$\rho_2 > \rho_1 ; \frac{1}{\rho_2} \nabla P_2 \approx 0 ; \vec{V}_2 \approx 0 \quad \Longrightarrow \quad h = \frac{\Delta\rho}{\rho} (SSH\ Anomaly)$$

Equatorial Ocean Wave Dynamics



$$\frac{\partial u}{\partial t} - \beta y v = -g' \frac{\partial h}{\partial x}$$

$$\frac{\partial v}{\partial t} + \beta y u = -g' \frac{\partial h}{\partial y}$$

$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0$$

$$g' = \frac{\Delta \rho}{\rho} g$$

Frequency vs Wave Number Diagram – Dispersion Relation

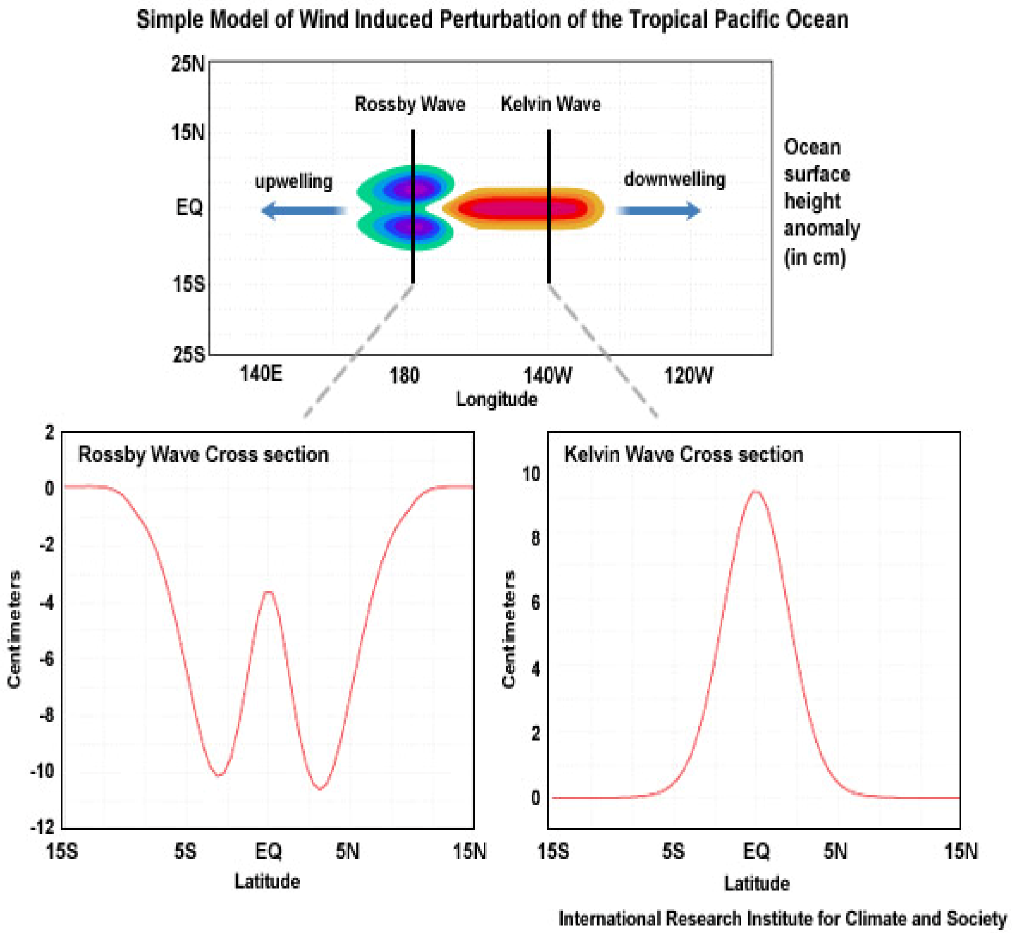
Equatorial Ocean Wave Dynamics

$$\frac{\partial u}{\partial t} - \beta y v = -g' \frac{\partial h}{\partial x}$$

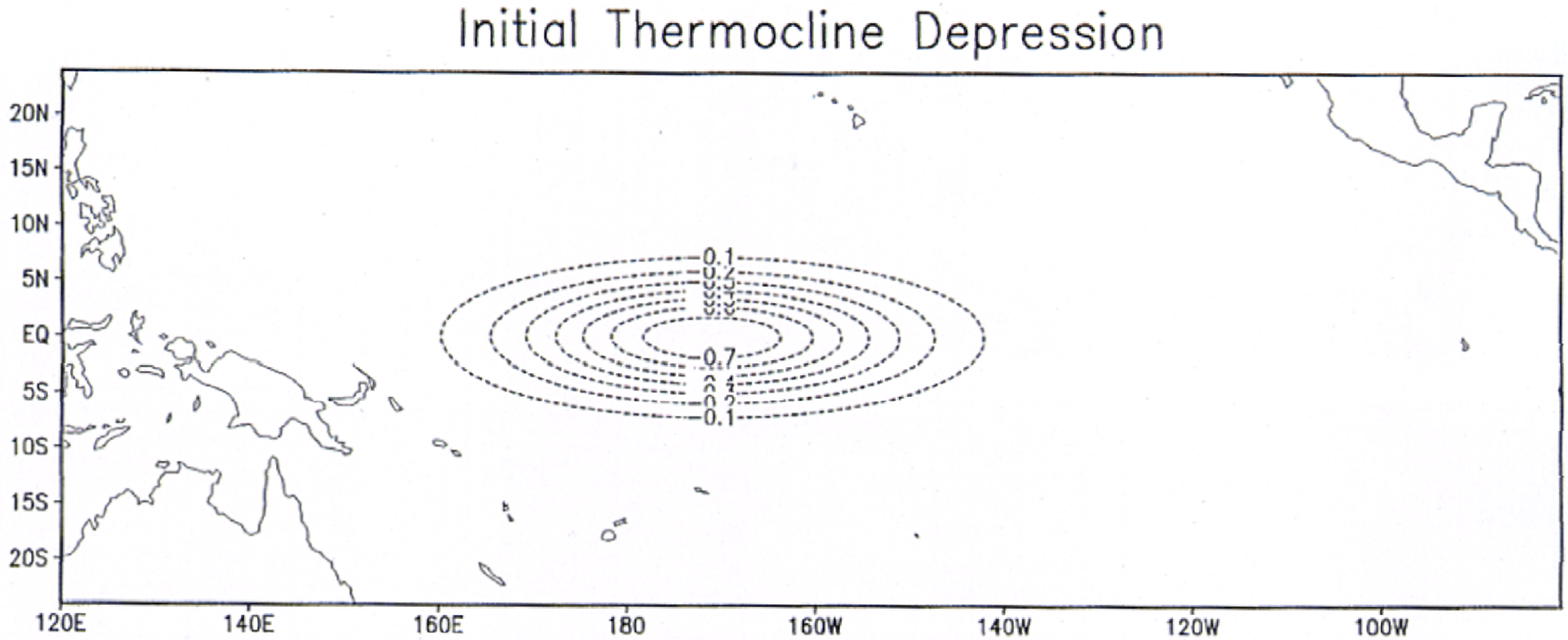
$$\frac{\partial v}{\partial t} + \beta y u = -g' \frac{\partial h}{\partial y}$$

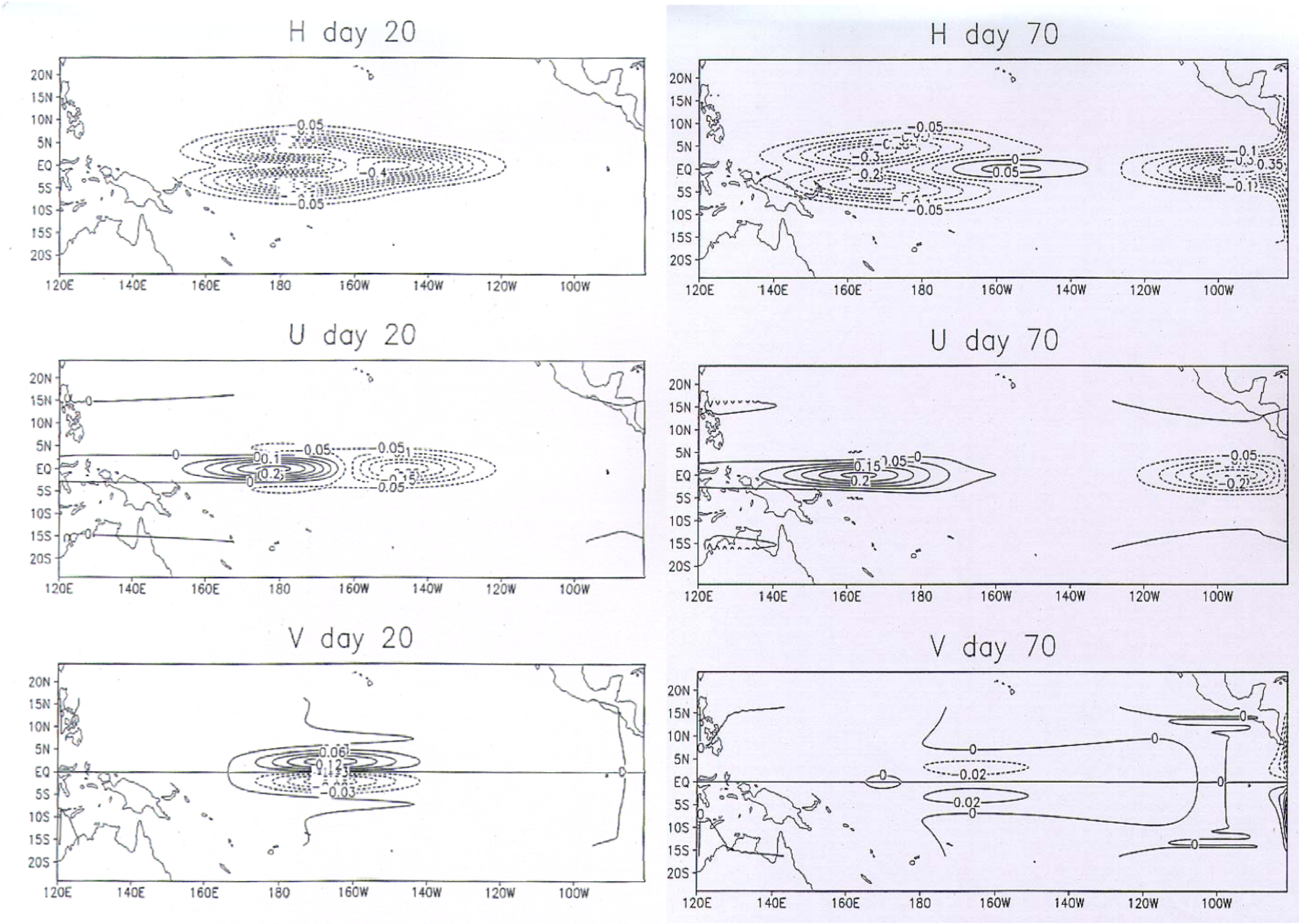
$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0$$

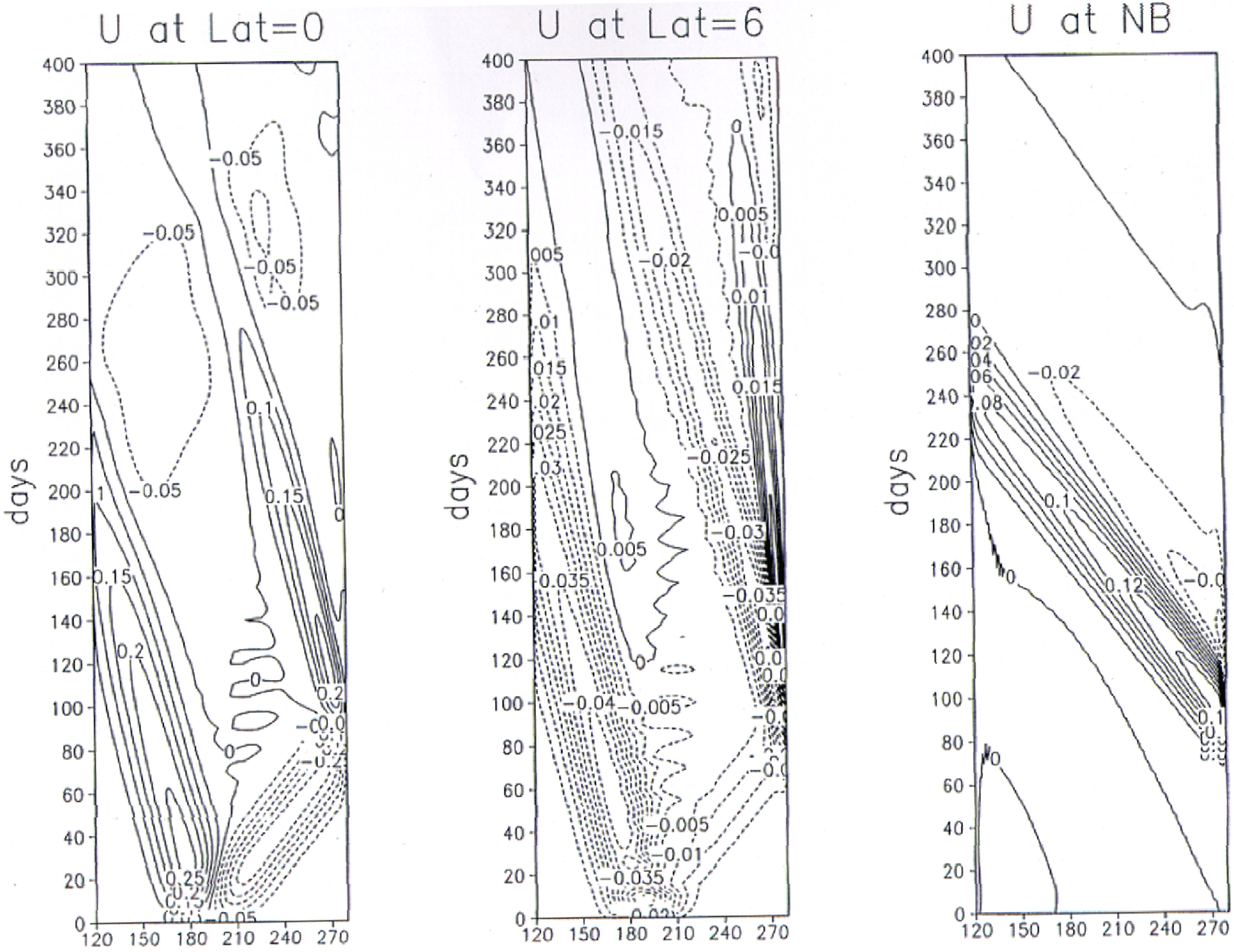
$$g' = \frac{\Delta\rho}{\rho} g$$



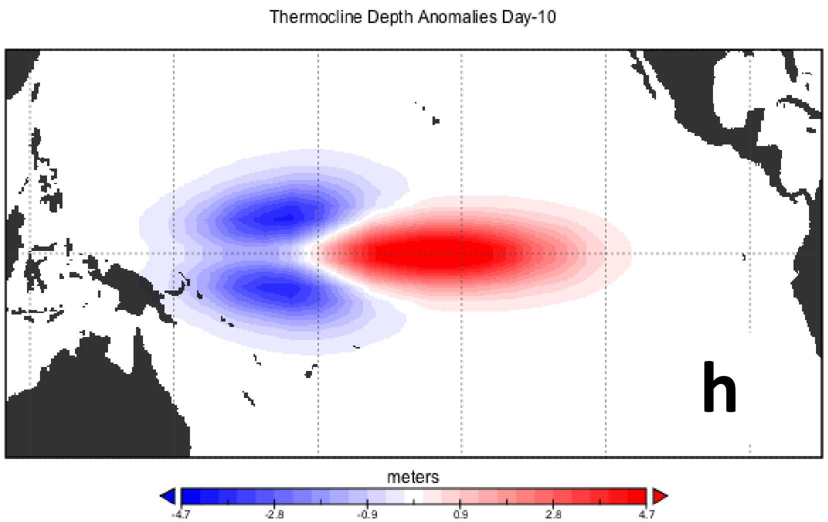
A Simple Numerical Example

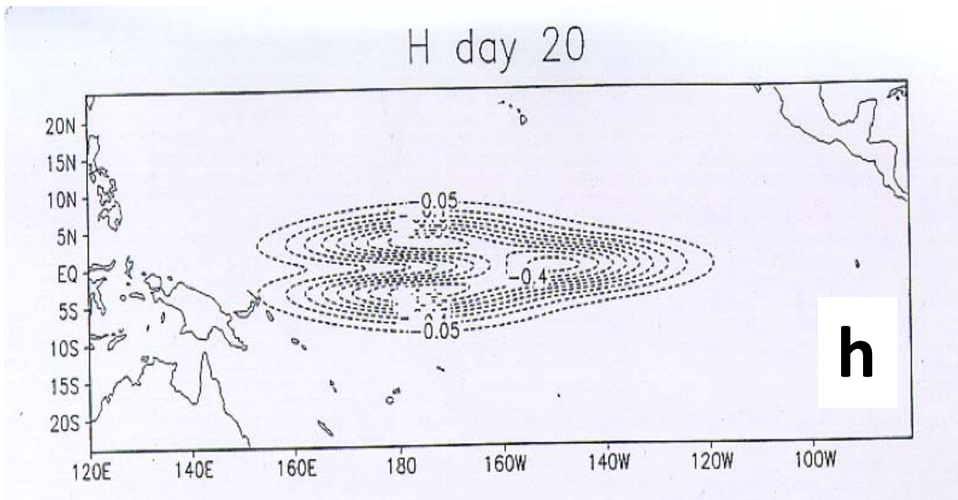



H day 20
U day 20
V day 20
H day 70
U day 70
V day 70
20N
15N
10N
5N
EQ
5S
10S
15S
20S
120E
140E
160E
180
160W
140W
120W
100W
-0.05
-0.4
0
-0.1
-0.2
0.1
0.2
-0.15
0.06
0.12
-0.03
-0.3
0.05
0.35
0.15
0.02
-0.02


U at Lat=0
U at Lat=6
U at NB
days
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0
120 150 180 210 240 270
−0.05
0.1
0.15
0.2
0.25
−0.015
−0.02
−0.025
−0.03
−0.035
−0.04
−0.005
0.005
−0.01
−0.02
0.12
0

Equatorial Ocean Wave Dynamics





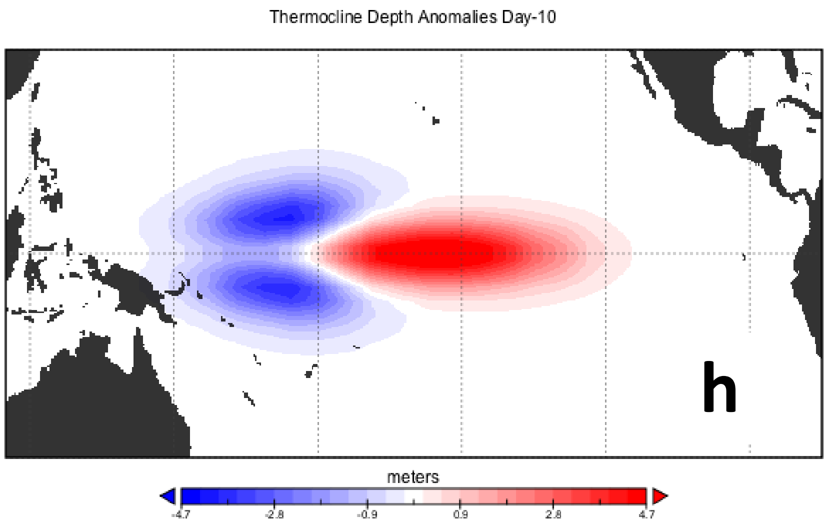
$$\frac{\partial u}{\partial t} - \beta y v = -g' \frac{\partial h}{\partial x} + \frac{\tau_x}{\rho_1 H} - \varepsilon u$$

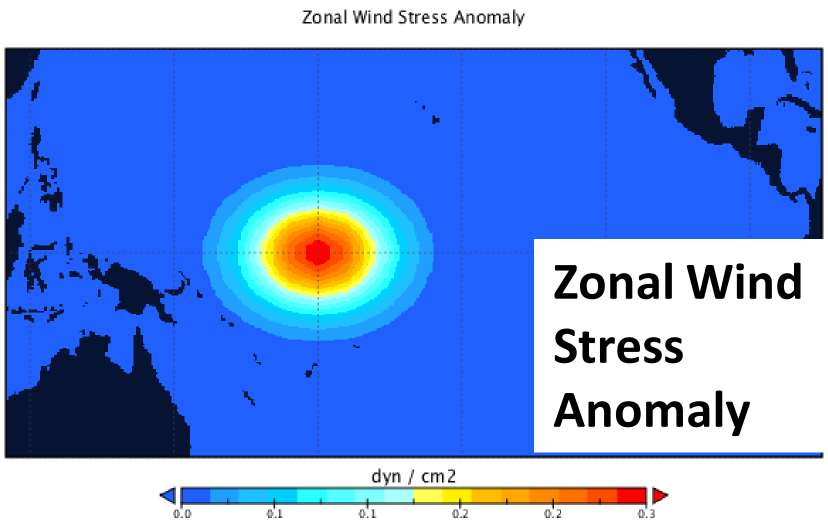
$$\frac{\partial v}{\partial t} + \beta y u = -g' \frac{\partial h}{\partial y} + \frac{\tau_y}{\rho_1 H} - \varepsilon v$$

$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = -\alpha h$$

Free vs. Steady Response

Equatorial Ocean Wave Dynamics



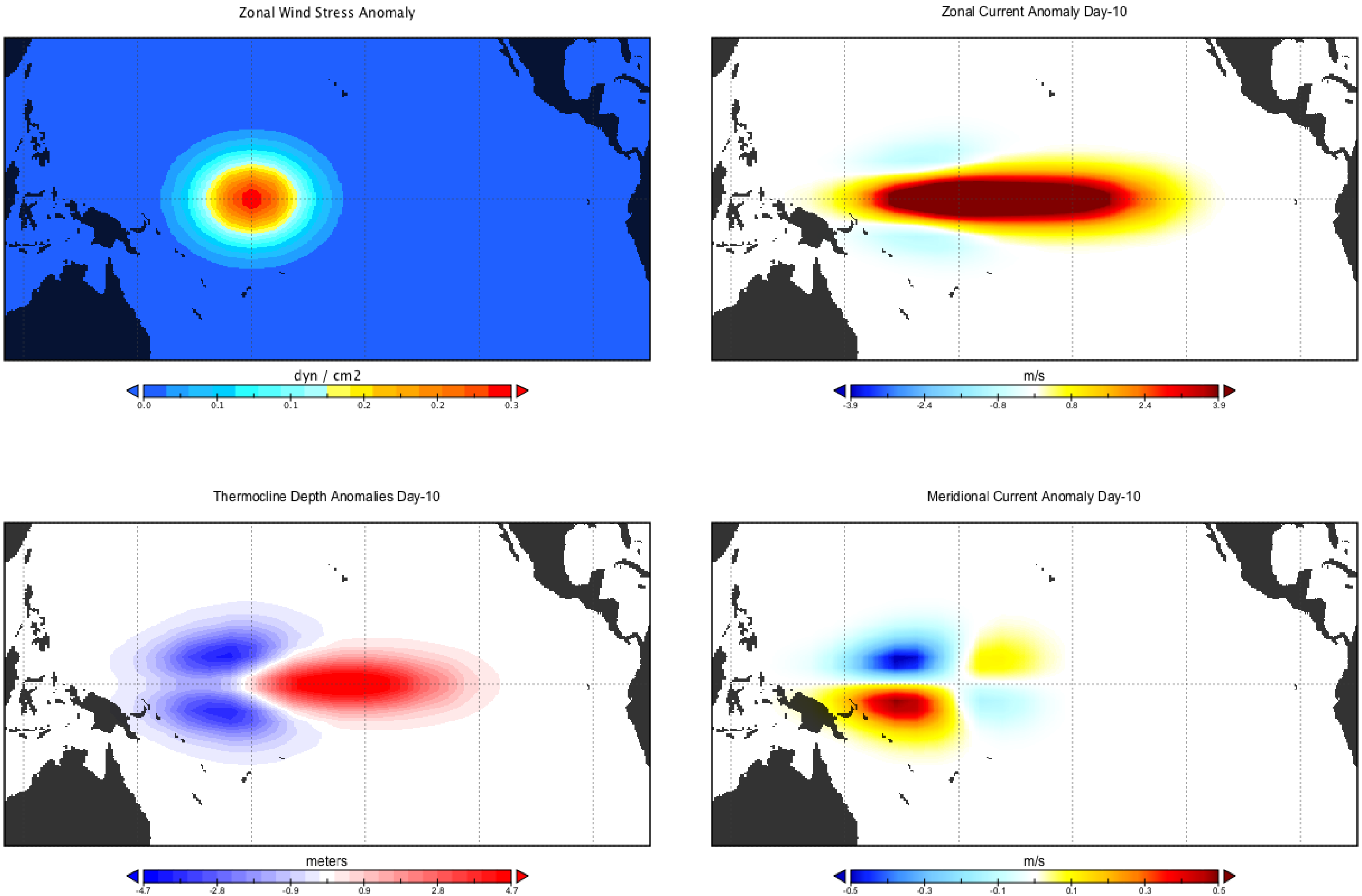


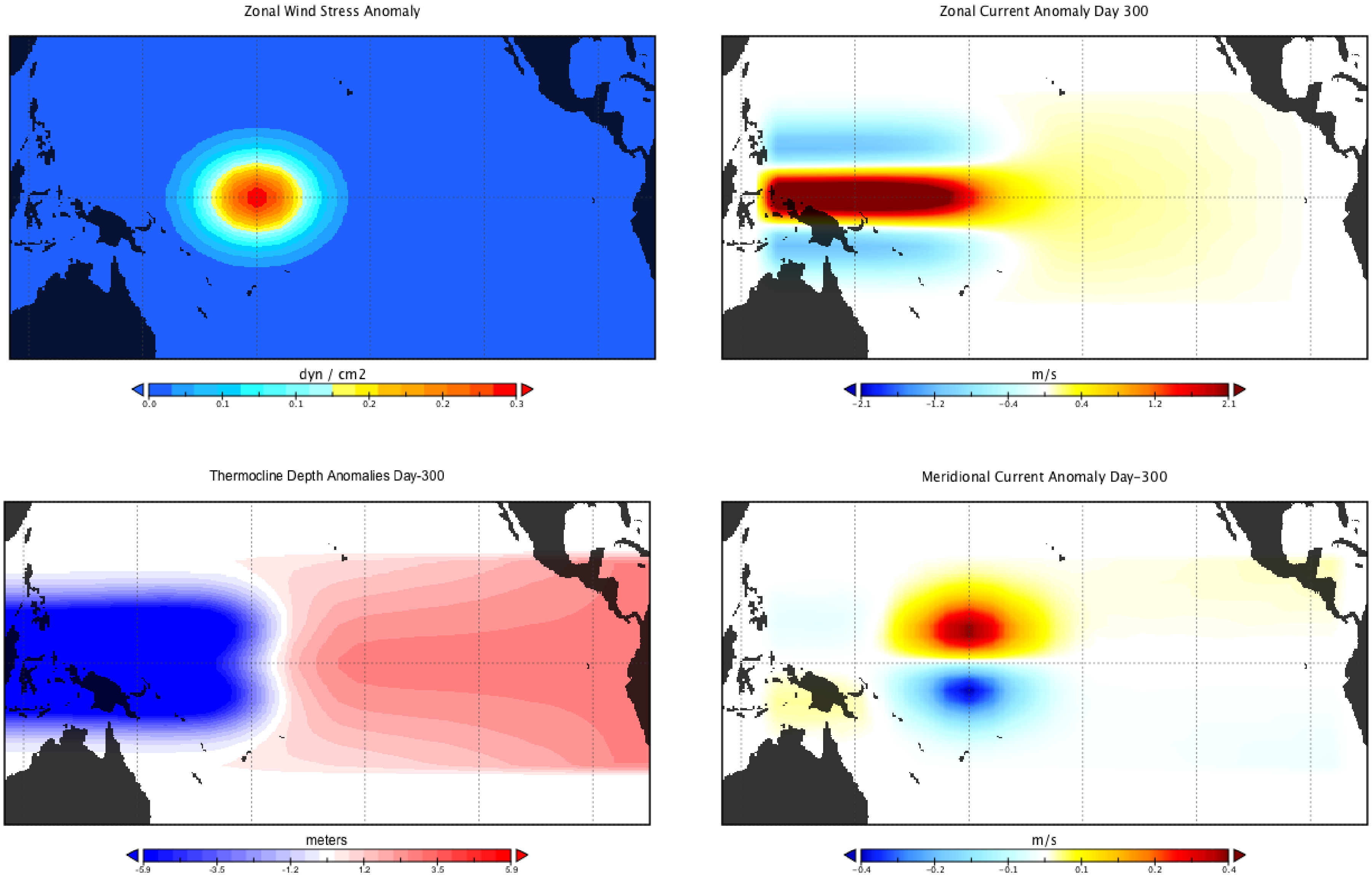
$$\frac{\partial u}{\partial t} - \beta y v = -g' \frac{\partial h}{\partial x} + \frac{\tau_x}{\rho_1 H} - \varepsilon u$$

$$\frac{\partial v}{\partial t} + \beta y u = -g' \frac{\partial h}{\partial y} + \frac{\tau_y}{\rho_1 H} - \varepsilon v$$

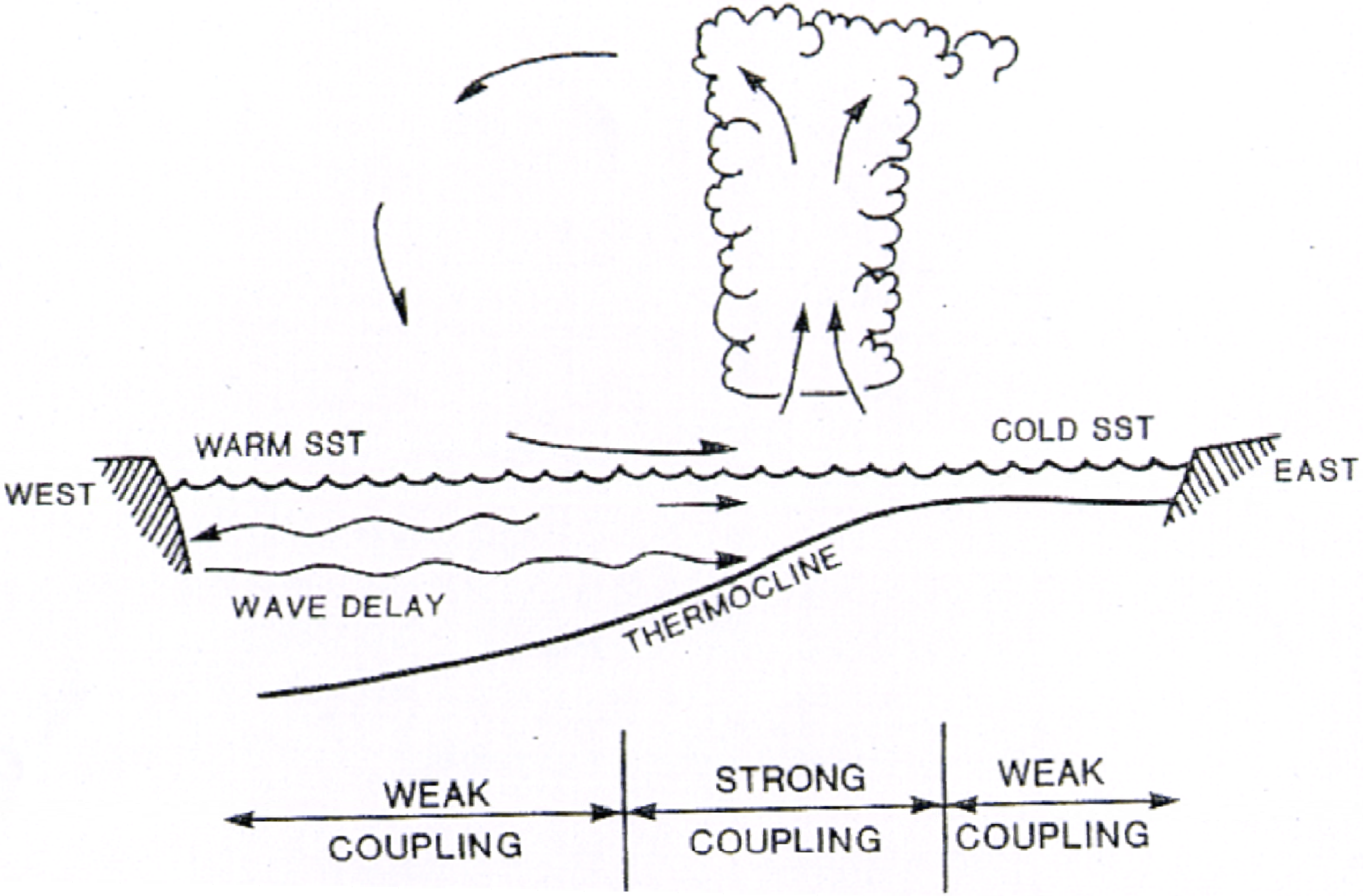
$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = -\alpha h$$

Free vs. Steady Response


Zonal Wind Stress Anomaly
dyn / cm2
0.0 0.1 0.1 0.2 0.2 0.3
Zonal Current Anomaly Day-10
m/s
-3.9 -2.4 -0.8 0.8 2.4 3.9
Thermocline Depth Anomalies Day-10
meters
-4.7 -2.8 -0.9 0.9 2.8 4.7
Meridional Current Anomaly Day-10
m/s
-0.5 -0.3 -0.1 0.1 0.3 0.5


Zonal Wind Stress Anomaly
dyn / cm2
0.0 0.1 0.1 0.2 0.2 0.3
Zonal Current Anomaly Day 300
m/s
-2.1 -1.2 -0.4 0.4 1.2 2.1
Thermocline Depth Anomalies Day-300
meters
-5.9 -3.5 -1.2 1.2 3.5 5.9
Meridional Current Anomaly Day-300
m/s
-0.4 -0.2 -0.1 0.1 0.2 0.4

Role of the Ocean in the Delayed Oscillator Theory for ENSO



A Very Simple Coupled Model
Delayed Oscillator – Rossby Waves

$$\frac{\partial u}{\partial t} - \beta y v = -g' \frac{\partial h}{\partial x} + \frac{\tau_x}{\rho_1 H} - \varepsilon u$$

$$\frac{\partial v}{\partial t} + \beta y u = -g' \frac{\partial h}{\partial y} + \frac{\tau_y}{\rho_1 H} - \varepsilon v$$

Atmosphere

$$\frac{\partial h}{\partial t} + H\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = -\alpha h$$

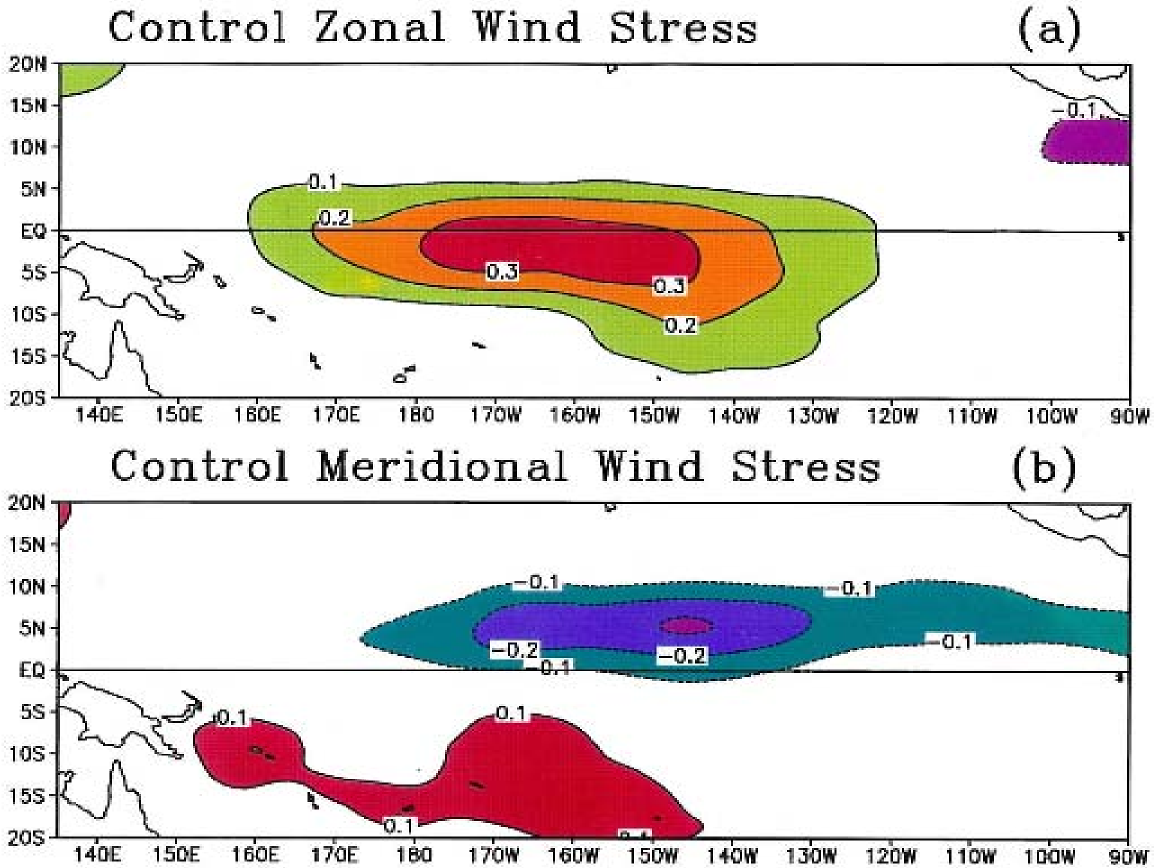
$$\frac{\partial (SST)}{\partial t} = -\vec{V} \cdot \nabla (SST) + upwelling + disipation$$

Source of Non-linearity

An Empirical Atmospheric Component Model

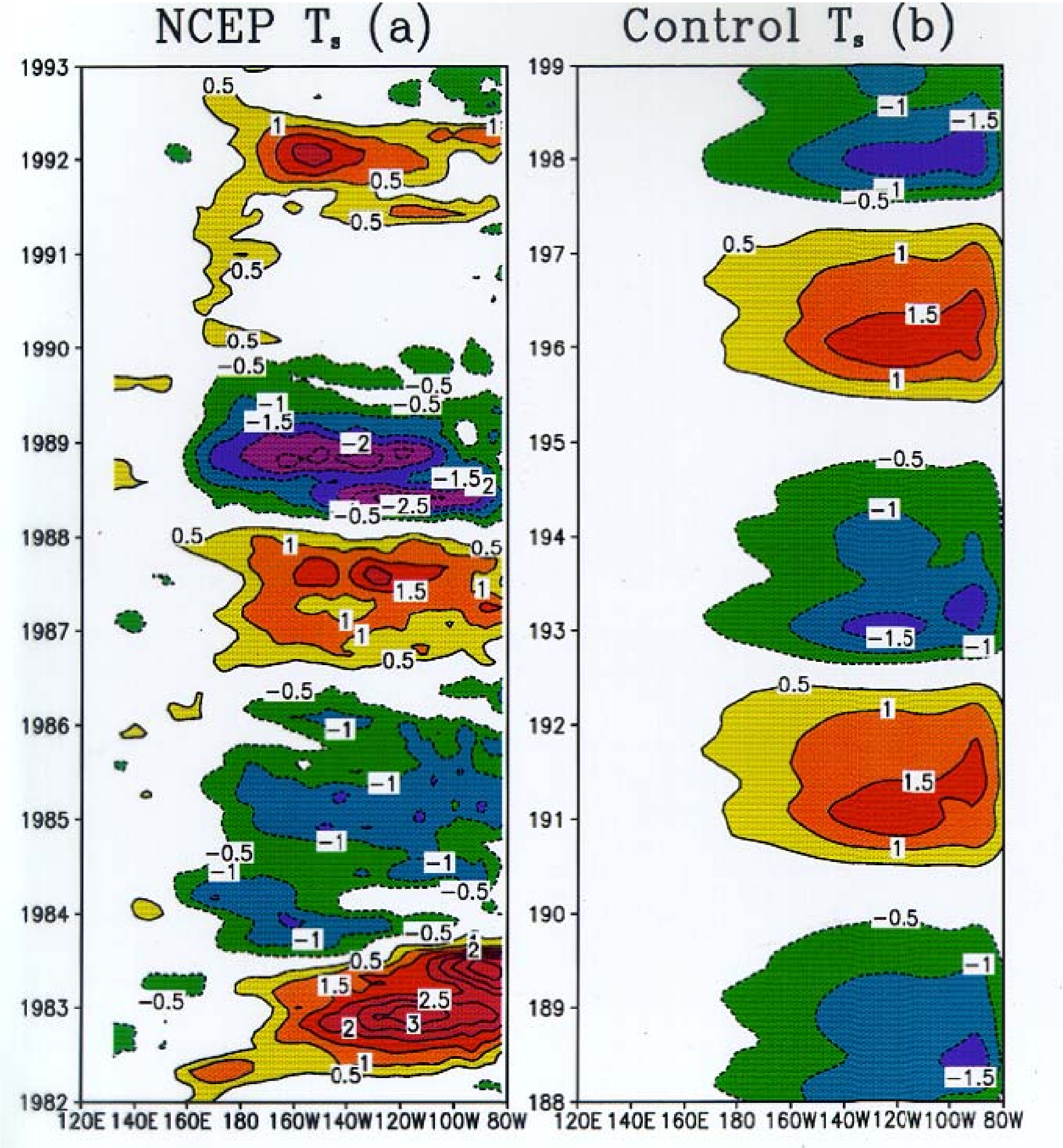
$\alpha(x,y)$

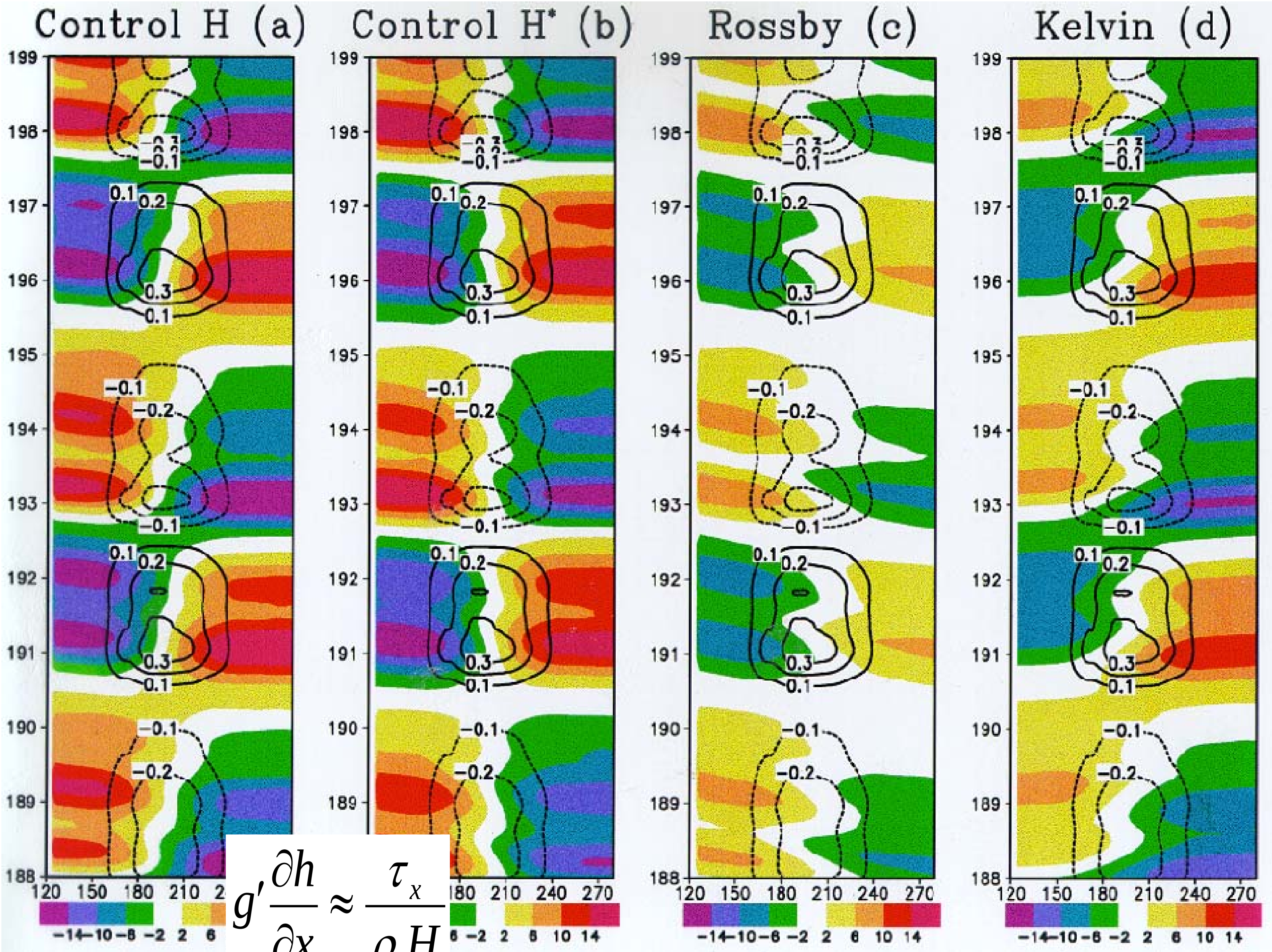
$\beta(x,y)$



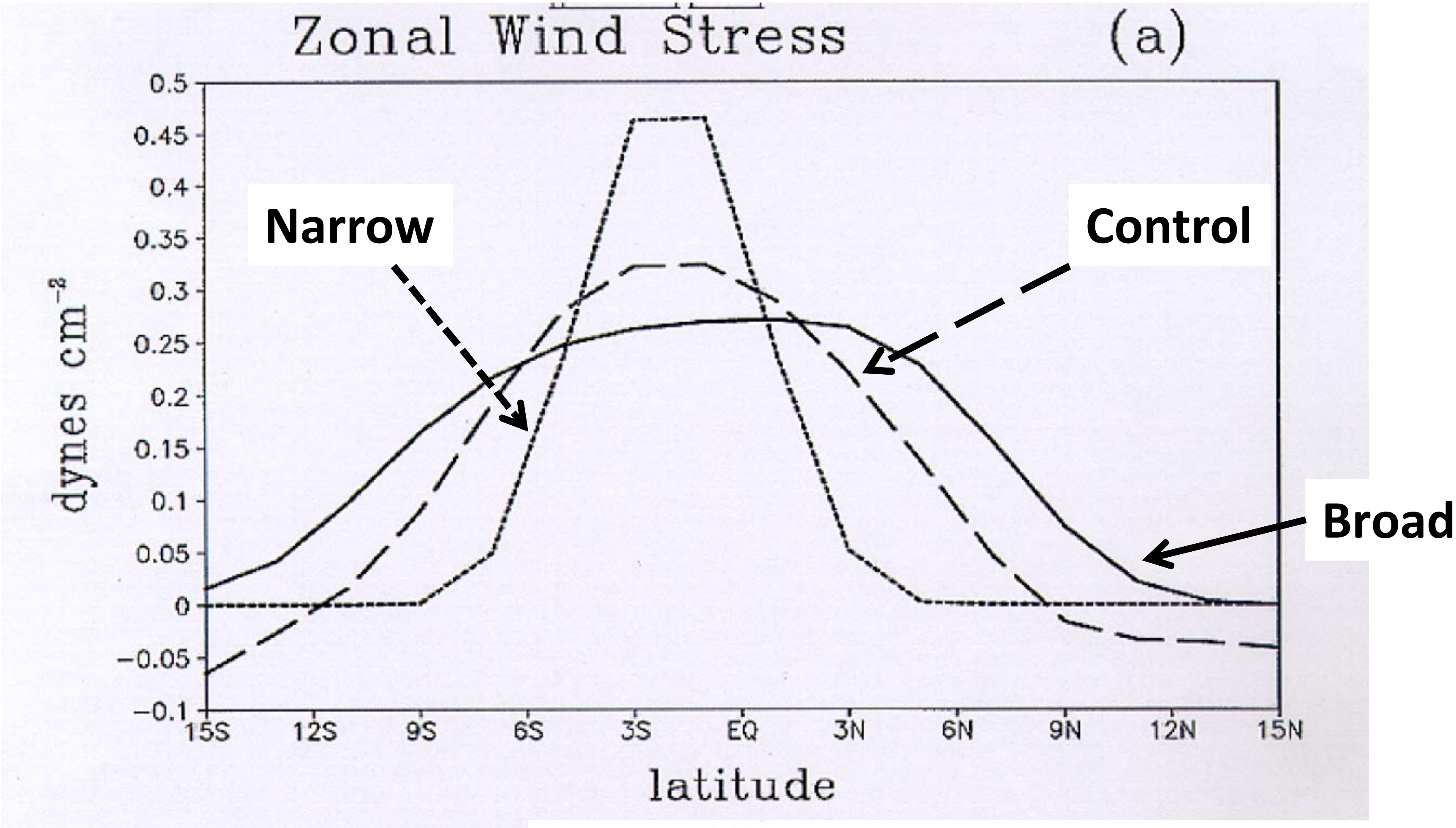
$$\tau_x(x,y) = \alpha(x,y) * NINO3$$

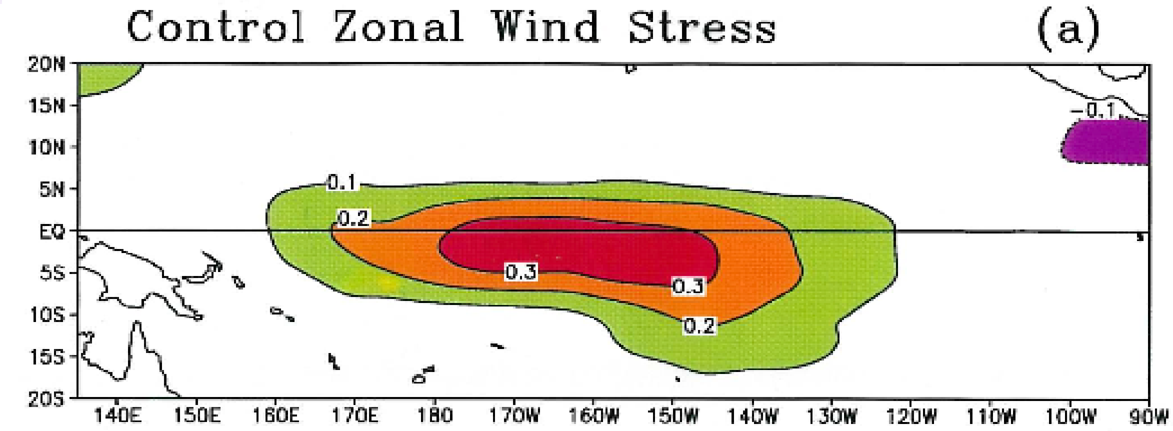
$$\tau_y(x,y) = \beta(x,y) * NINO3$$

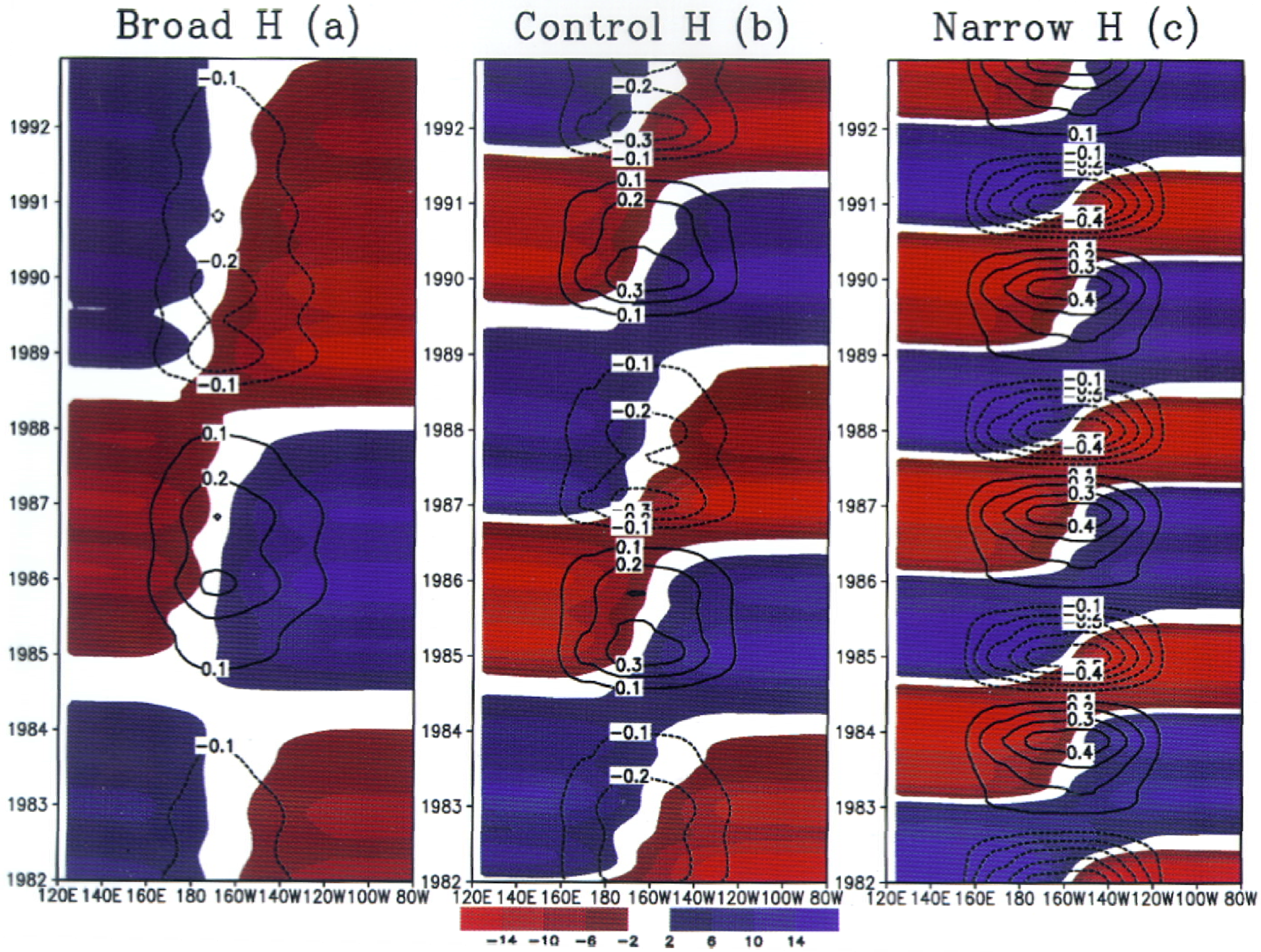

NCEP T$_s$ (a)
Control T$_s$ (b)
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
188
189
190
191
192
193
194
195
196
197
198
199
120E 140E 160E 180 160W 140W 120W 100W 80W



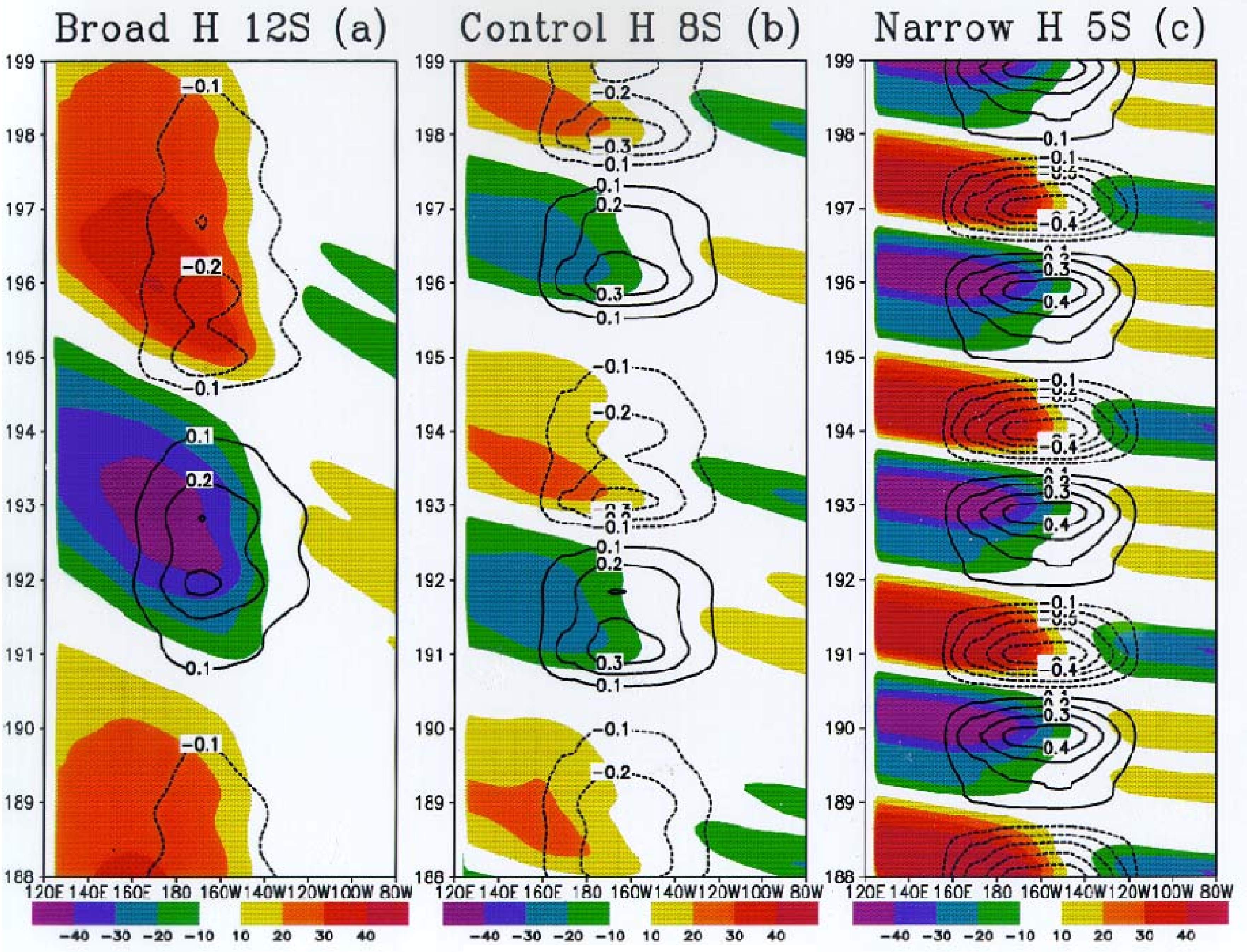
$$g'\frac{\partial h}{\partial x} \approx \frac{\tau_x}{\rho_1 H}$$


Zonal Wind Stress
(a)
dynes cm^{-2}
latitude
Narrow
Control
Broad
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
−0.05
−0.1
15S
12S
9S
6S
3S
EQ
3N
6N
9N
12N
15N

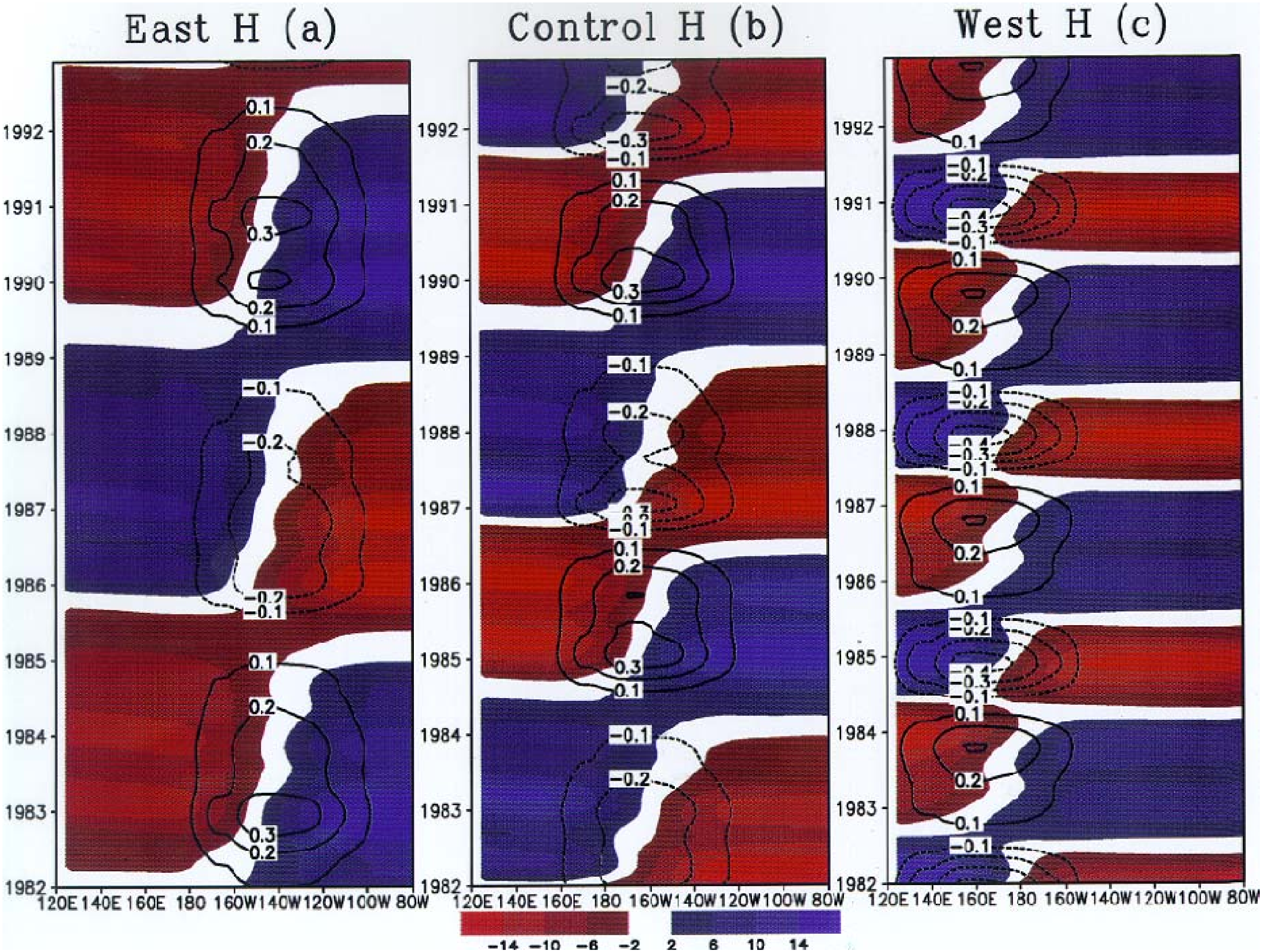

Control Zonal Wind Stress
(a)
20N
15N
10N
5N
EQ
5S
10S
15S
20S
140E
150E
160E
170E
180
170W
160W
150W
140W
130W
120W
110W
100W
90W
0.1
0.2
0.3
-0.1



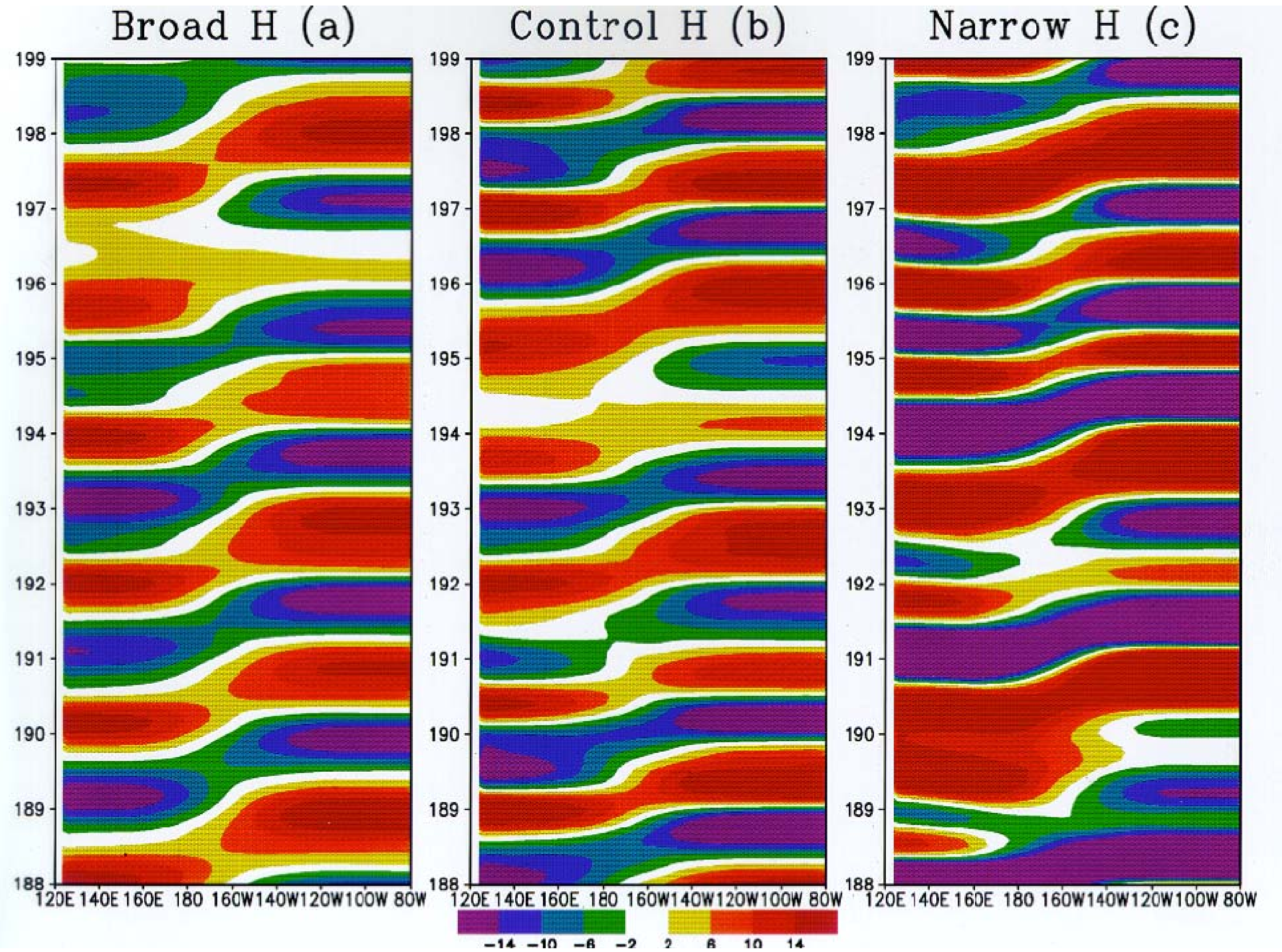
Broad H (a)
Control H (b)
Narrow H (c)
1992
1991
1990
1989
1988
1987
1986
1985
1984
1983
1982
120E 140E 160E 180 160W 140W 120W 100W 80W
−14 −10 −6 −2 2 6 10 14

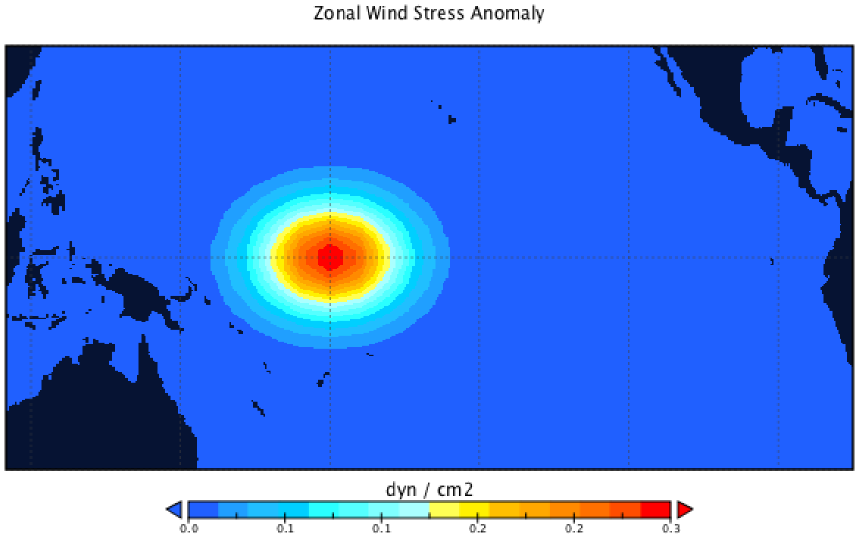


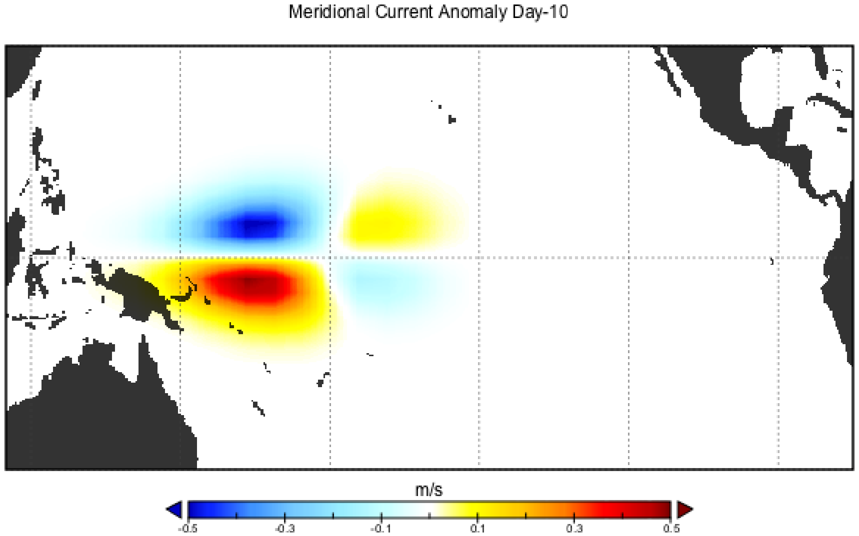
Broad H 12S (a)
Control H 8S (b)
Narrow H 5S (c)
199
198
197
196
195
194
193
192
191
190
189
188
120E 140E 160E 180 160W 140W 120W 100W 80W
-40 -30 -20 -10 10 20 30 40
-0.1
-0.2
0.1
0.2
-0.3
0.3
0.4
-0.4



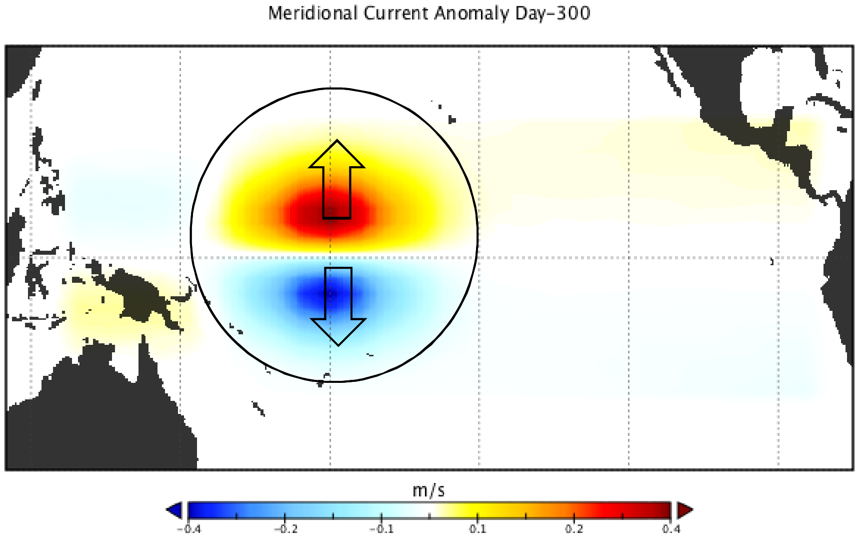
East H (a)
Control H (b)
West H (c)
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
120E 140E 160E 180 160W 140W 120W 100W 80W
-14 -10 -6 -2 2 6 10 14


Broad H (a)
Control H (b)
Narrow H (c)
199
198
197
196
195
194
193
192
191
190
189
188
120E 140E 160E 180 160W 140W 120W 100W 80W
−14 −10 −6 −2 2 6 10 14

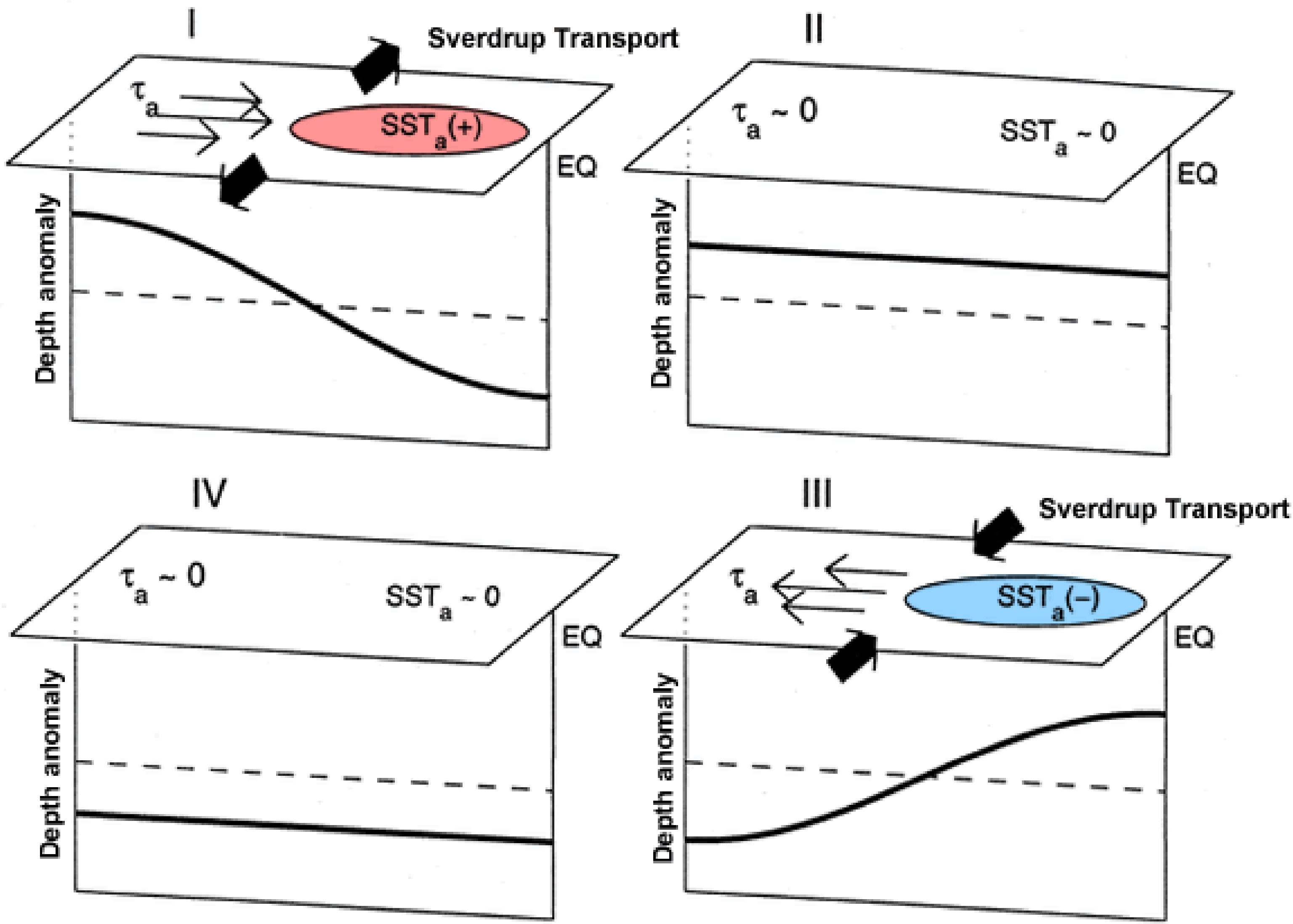




Recharge Oscillator Model:
"Steady State" – Sverdrup Response
Warm Phase – Equatorial Discharge

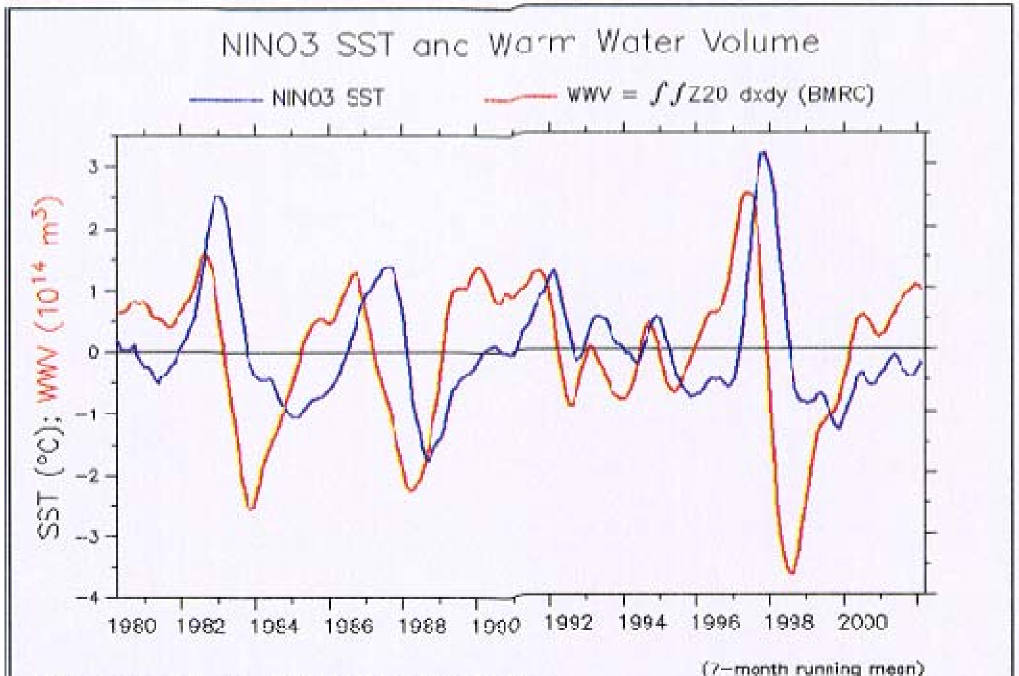


Schematic of the Recharge/Discharge Theory of ENSO

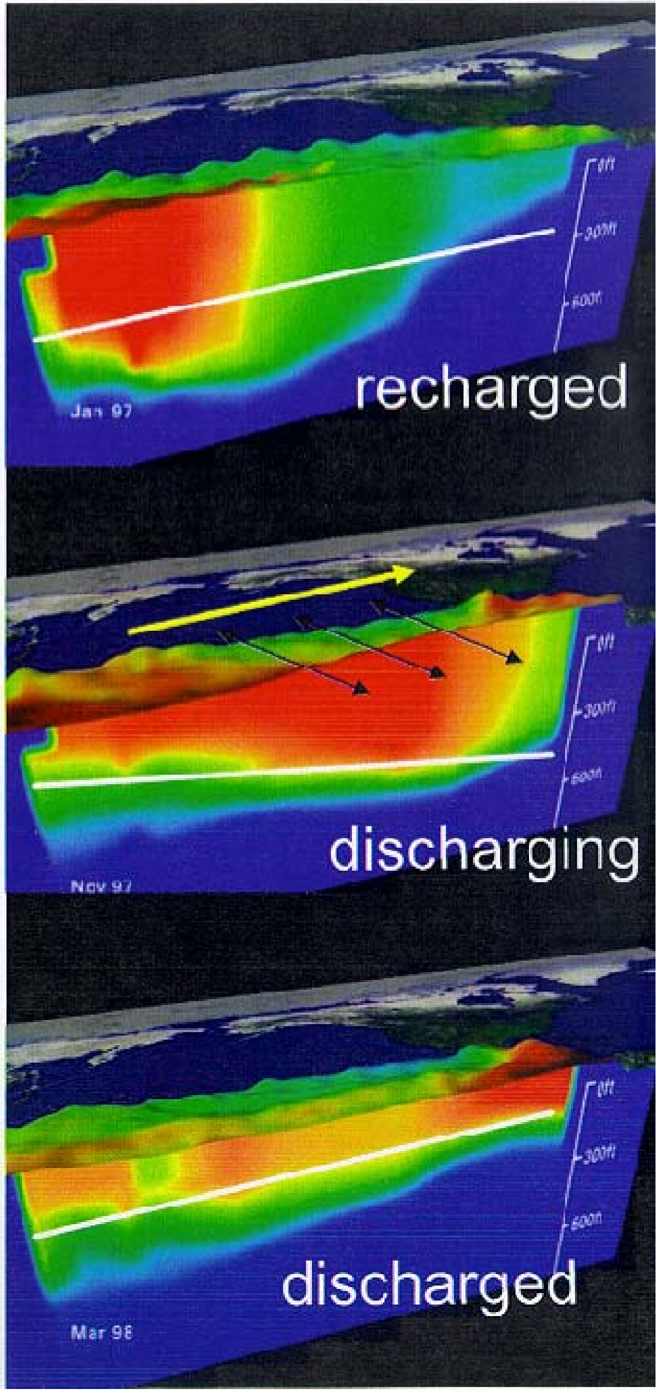


Meinen and McPhaden 2002

Recharge/Discharge theory (Jin, 1997)



Source: A. Timmermann



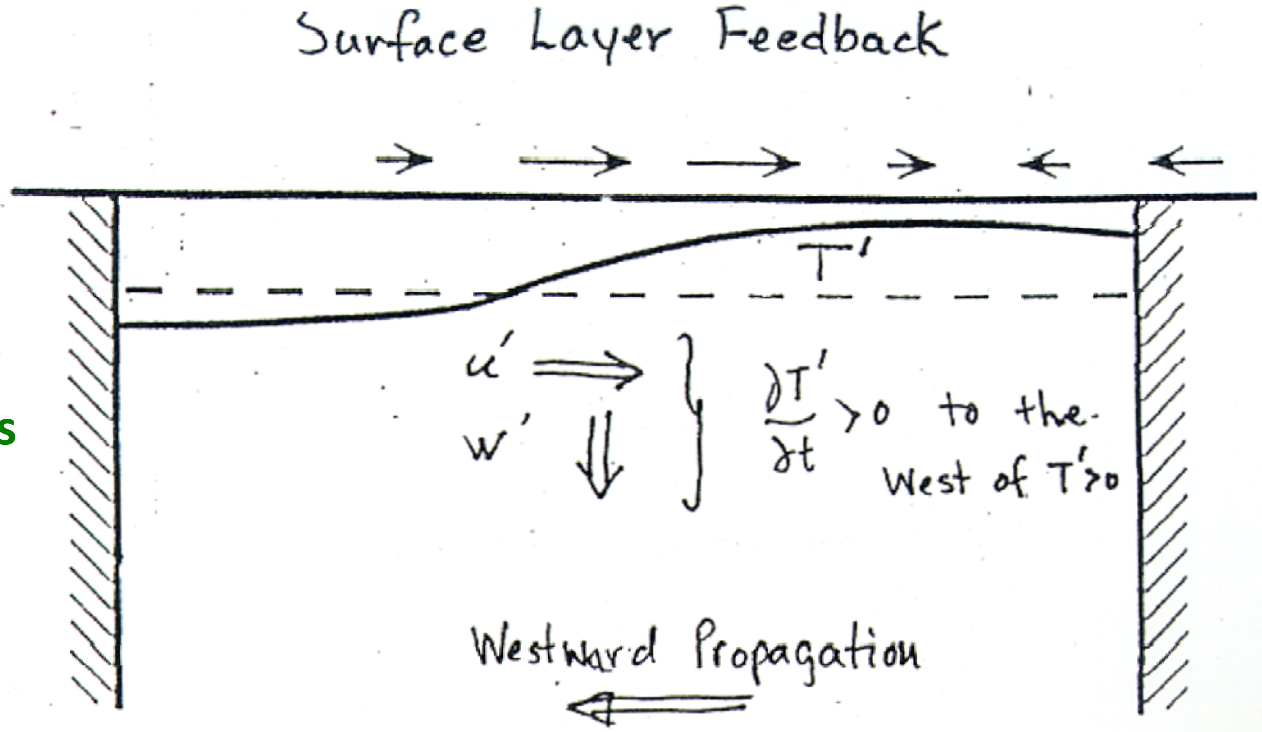
- Prior to El Nino heat content in equatorial region builds up
- During El Nino heat is “discharged” eastward and polewards

Surface Layer Feedback Mechanism
(Slow SST – Fast Wave Limit)

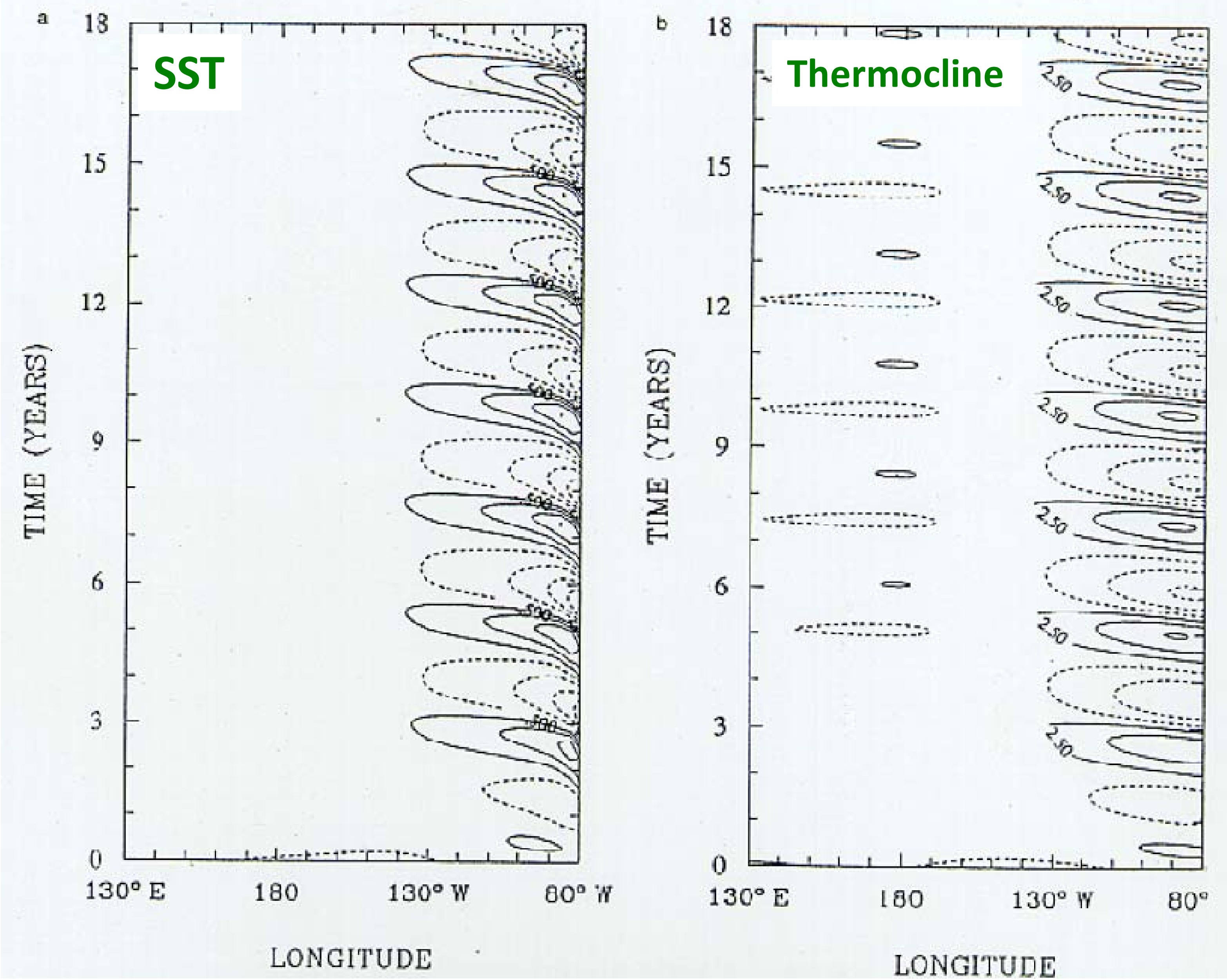
$$\frac{\partial u}{\partial t}, \frac{\partial v}{\partial t}, \frac{\partial h}{\partial t} \approx 0$$ - No Transient Wave Propagation

$$u'\frac{\partial(\overline{SST})}{\partial t}, w'\frac{\partial \overline{T}}{\partial z}$$ - Surface Feedback Amplify to the West SSTA

Thermocline Perturbations Unimportant



Surface Layer Feedback Mechanism

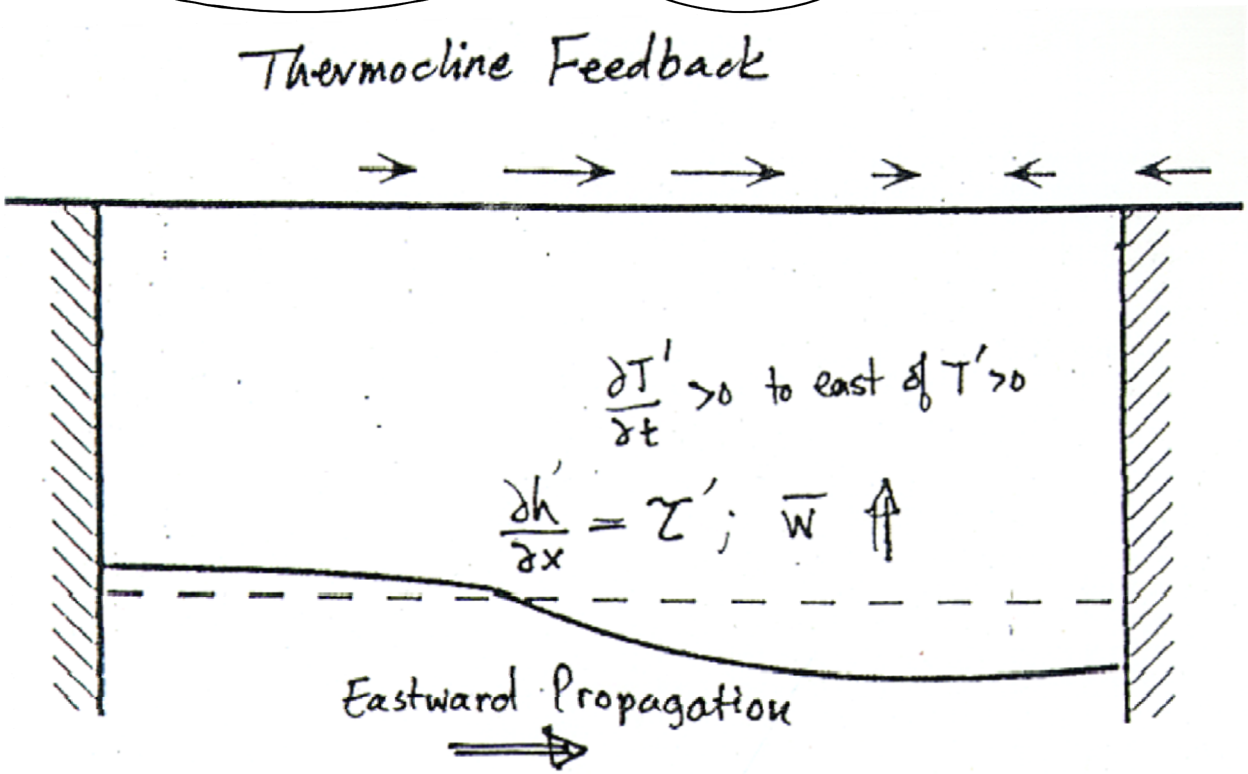


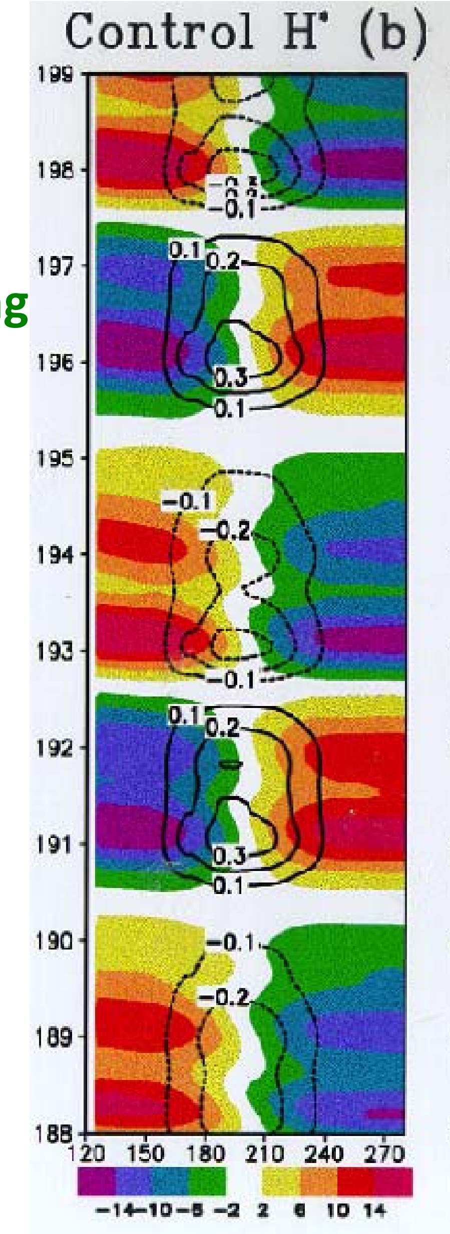
Thermocline Feedback Mechanism
(Slow SST – Fast Wave Limit)

$$\frac{\partial u}{\partial t} - \beta y v = -g' \frac{\partial h}{\partial x} + \frac{\tau_x}{\rho_1 H} - \varepsilon u$$

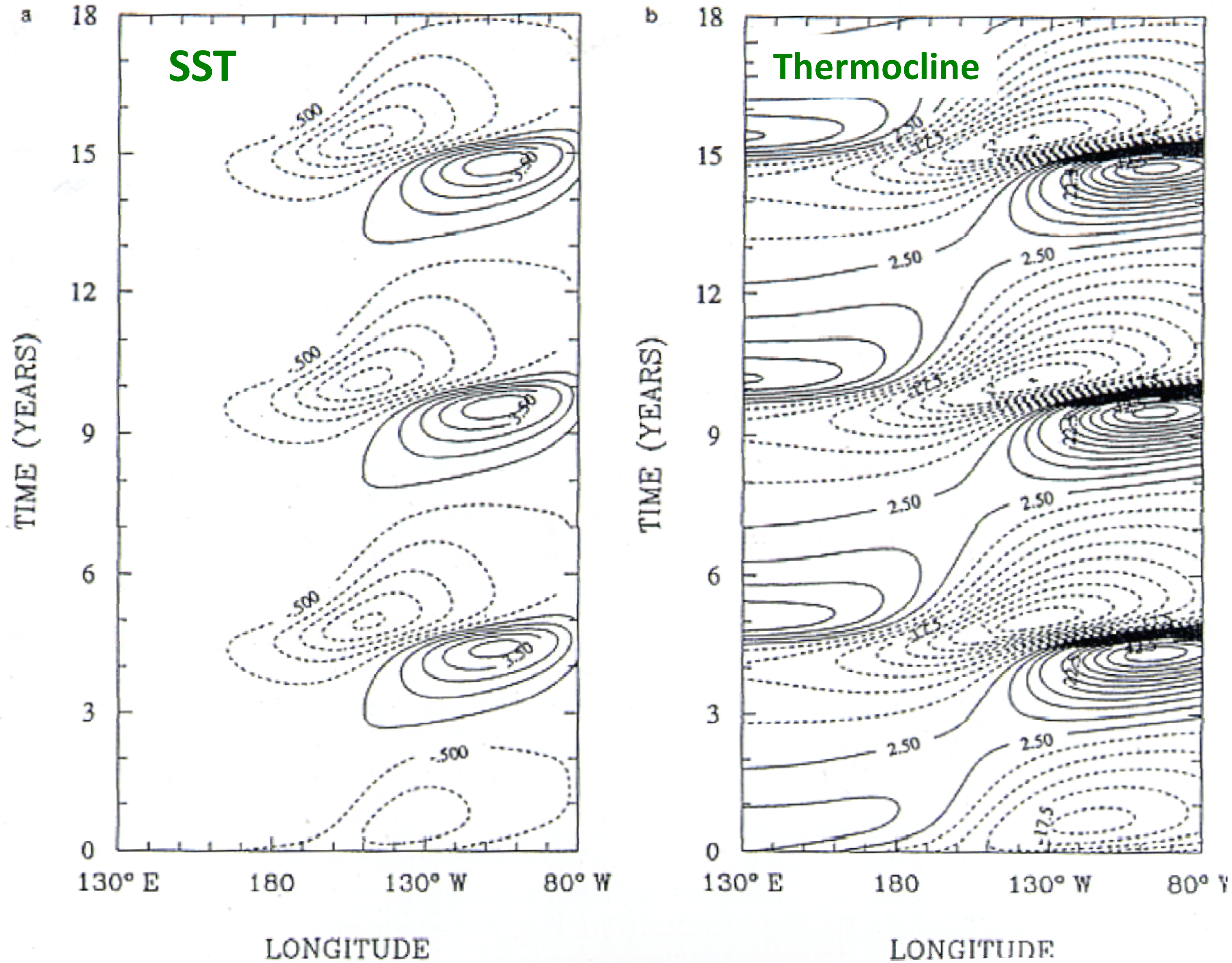
$$g' \frac{\partial h}{\partial x} \approx \frac{\tau_x}{\rho_1 H} \qquad \bar{w} \frac{\partial T'}{\partial z}$$

- Anomalous Upwelling by Mean Important

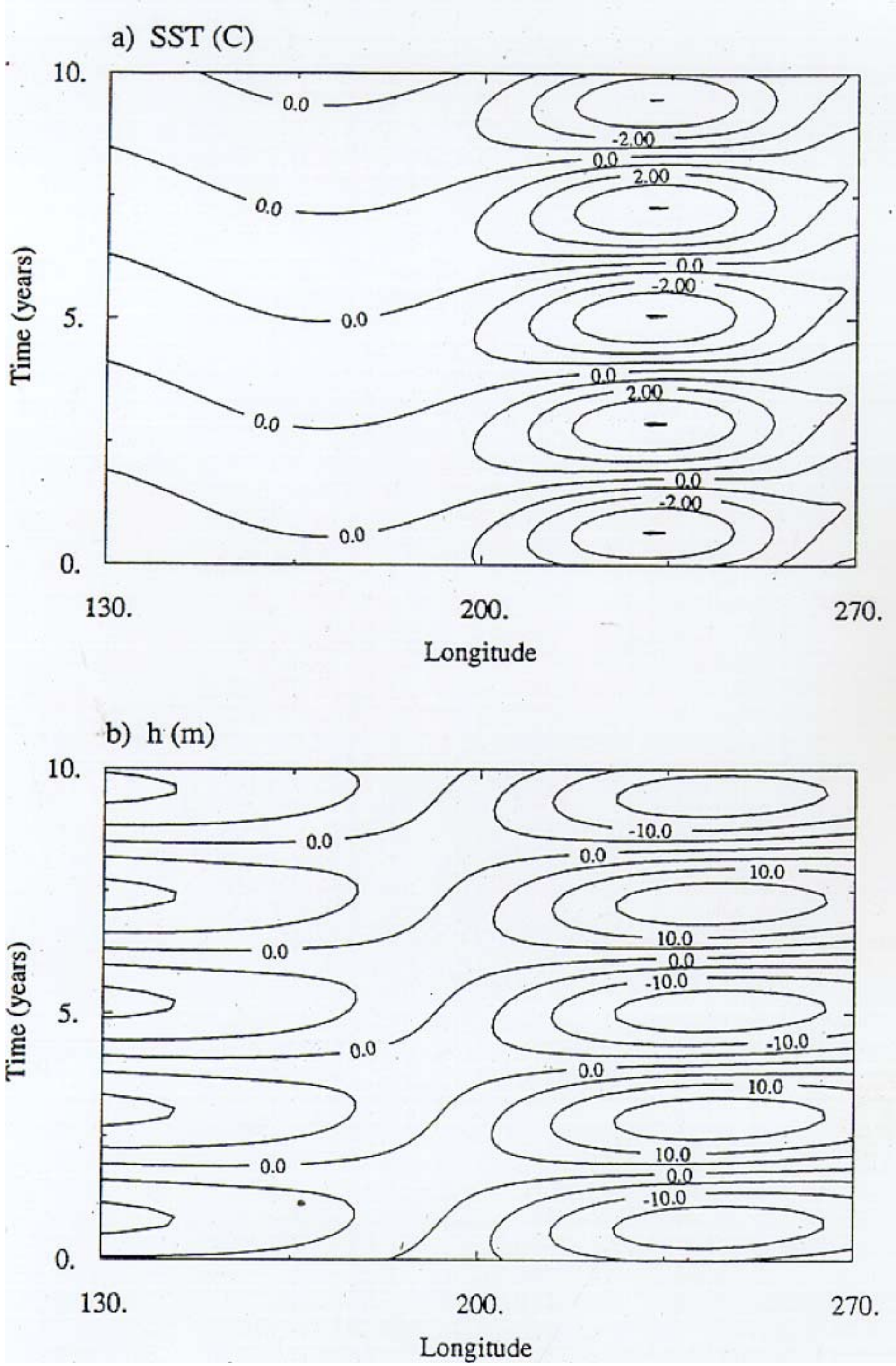




Thermocline Feedback Mechanism



Mixing Both Mechanisms



Outline

- **Free Equatorial Waves**
  - **Rossby and Kelvin Wave**
- **Forced Equatorial Waves**
  - **Equatorial Sverdrup Balance**
- **Coupled Problem**
  - **Delayed Oscillator, Recharge Oscillator, Fast Wave – Slow SST**