2356-9

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

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Theories of ENSO

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THEORIES OF ENSO

1. ELEMENTS THAT A THEORY OF ENSO SHOULD EXPLAIN

2. THE CANE-ZEBIAK MODEL

3. SOME ENSO THEORIES ABSTRACTED FROM HOW INTERMEDIATE MODELS OR CGCMS BEHAVE (BUT THE COMPLEX MODELS ARE NOT NECESSARILY REALISTIC!)

   A. THE DELAYED OSCILLATOR

   B. THE MERIDIONAL MASS EXCHANGE OSCILLATOR

   C NON-NORMAL EVOLUTION: THE ROLE OF ATMOSPHERIC AND OCEANIC NOISE

ELEMENTS THAT A THEORY OF ENSO SHOULD EXPLAIN

A. WHY DOES AN EVENT GROW?

B. WHY DOES AN EVENT DECAY?

C. WHAT SETS THE TIME SCALE?

D. WHAT DETERMINES THE RANGE OF STRUCTURES?

E WHY DO WARM AND COLD EVENTS ALTERNATE IRREGULARLY?

F. AUDIENCE CONTRIBUTIONS WELCOME

A. WHY DOES AN EVENT GROW?

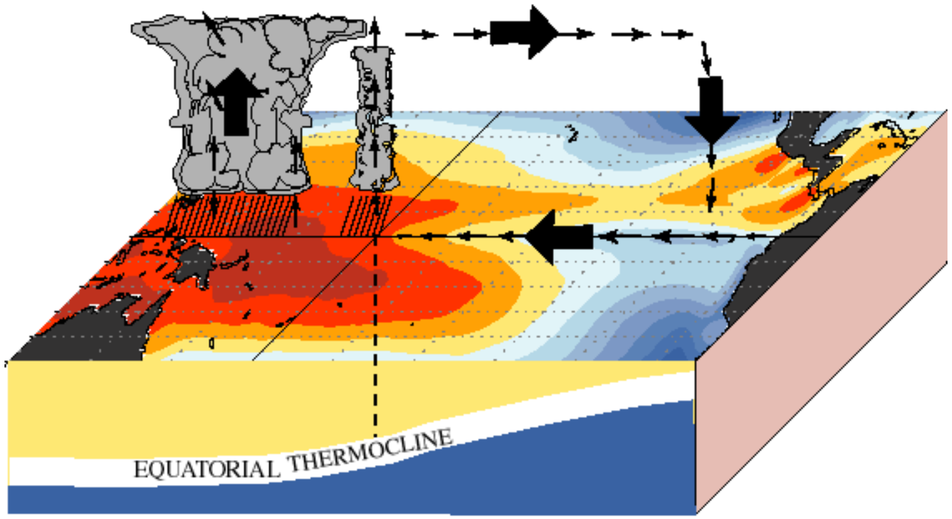
- **A warm anomaly induces westerly (eastward) winds to the west of the warm anomaly.**

- **The westerly winds cause the warm anomaly to grow warmer by reducing the upwelling of cold water. This process works best where the thermocline is shallow.**
  - Homework Problem: Why not warming by heat flux anomaly (WES)? After all, the surface winds are reduced since the mean winds are easterly. Maybe the effect of surface temperature on the saturation specific humidity dominates?

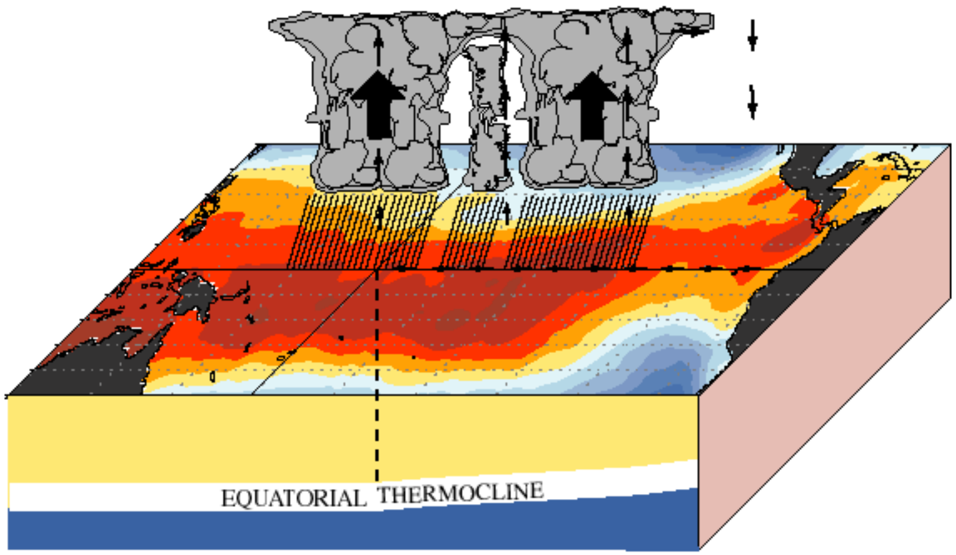
- **The warm anomaly induces heating in the atmosphere that intensifies the westerly wind anomalies.**

- **This is known as the *Bjerknes instability*.**

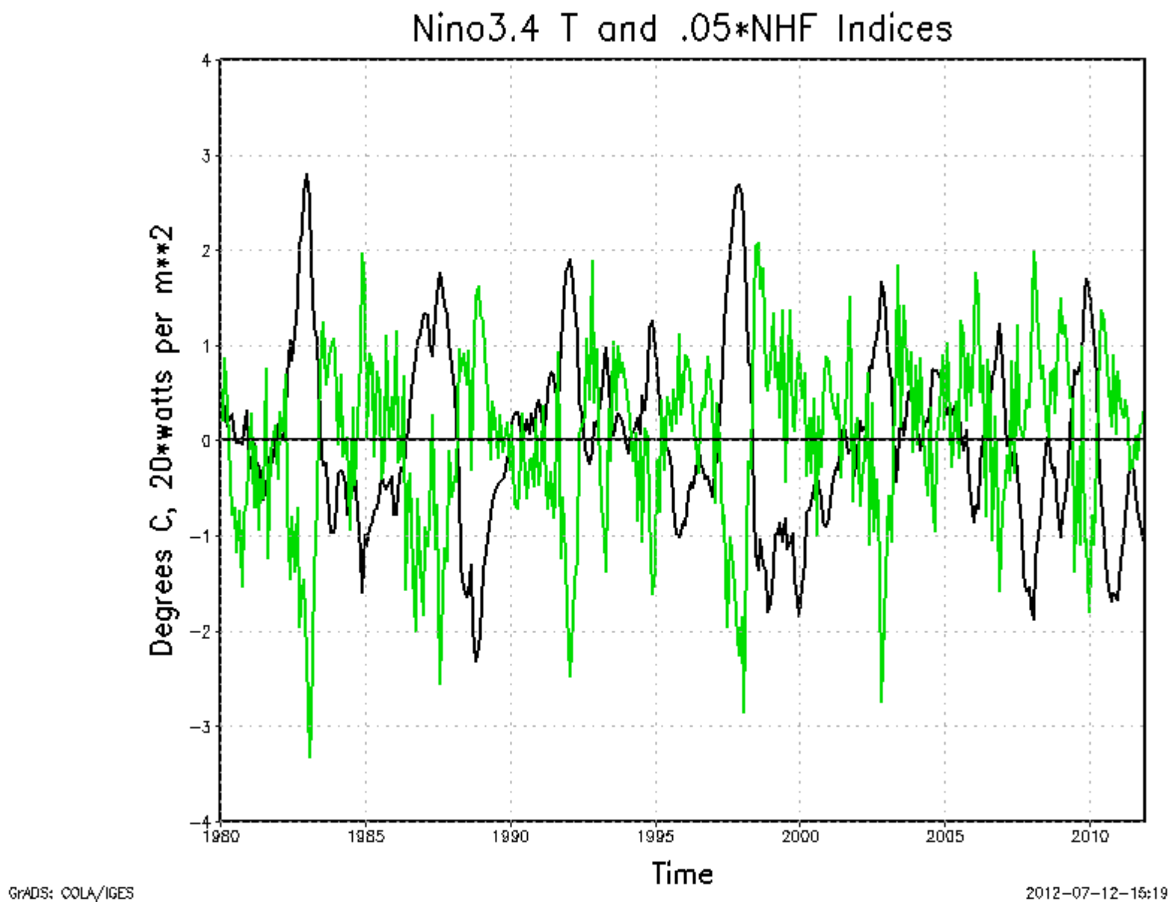
December - February Normal Conditions



December - February El Niño Conditions

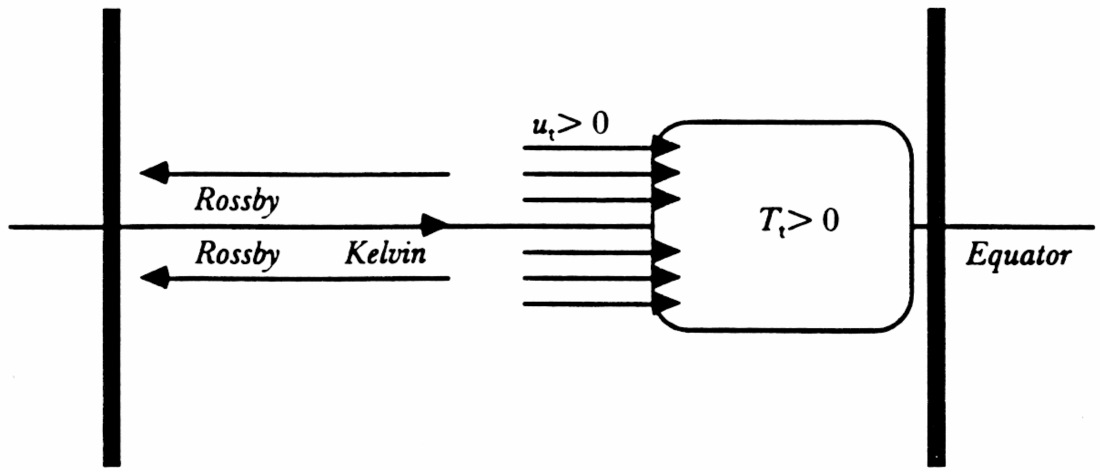


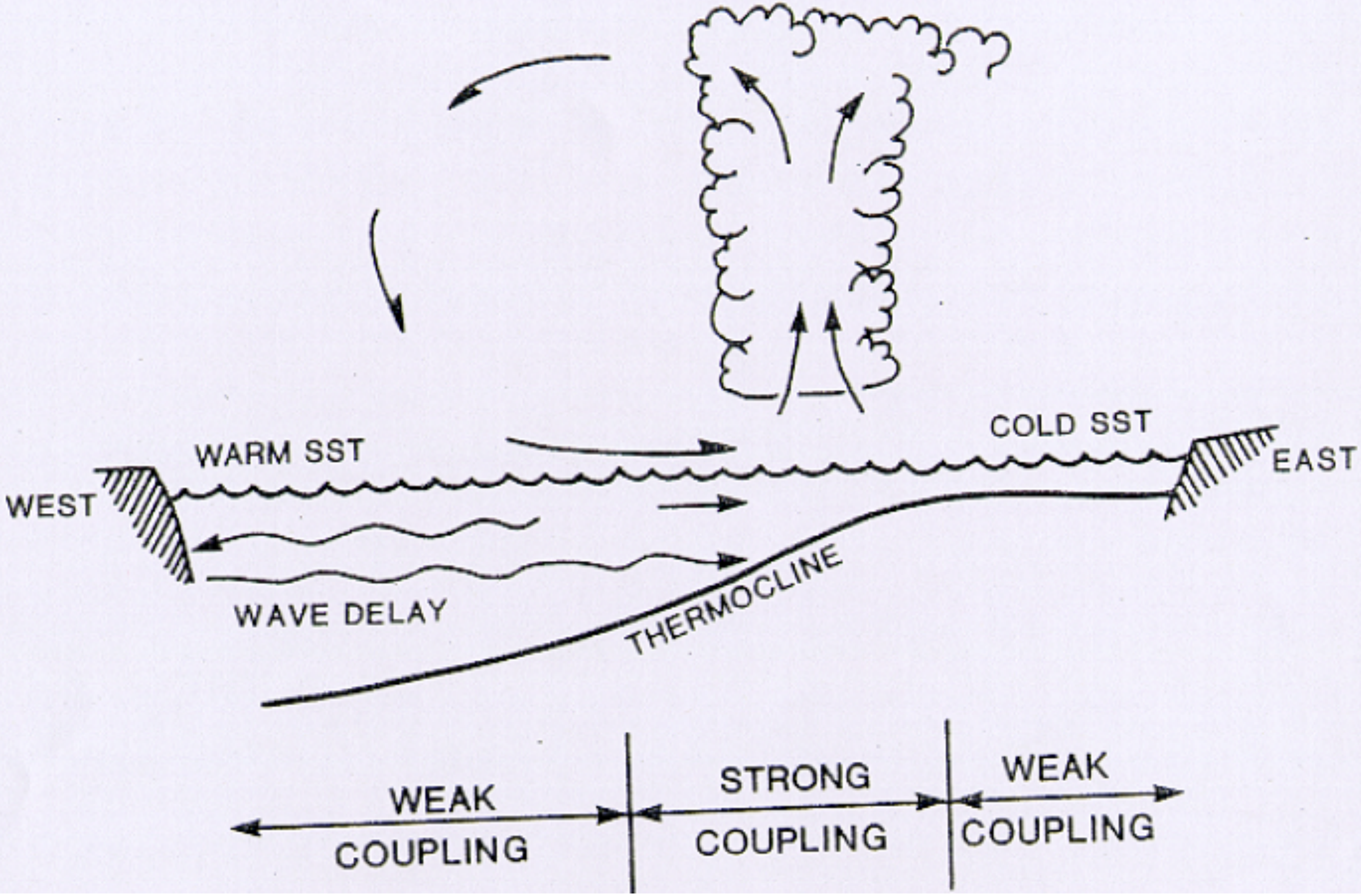
Heat flux forcing of ENSO? Doesn't look important in the NCEP reanalysis – the heat flux primarily damps. Very unusual.



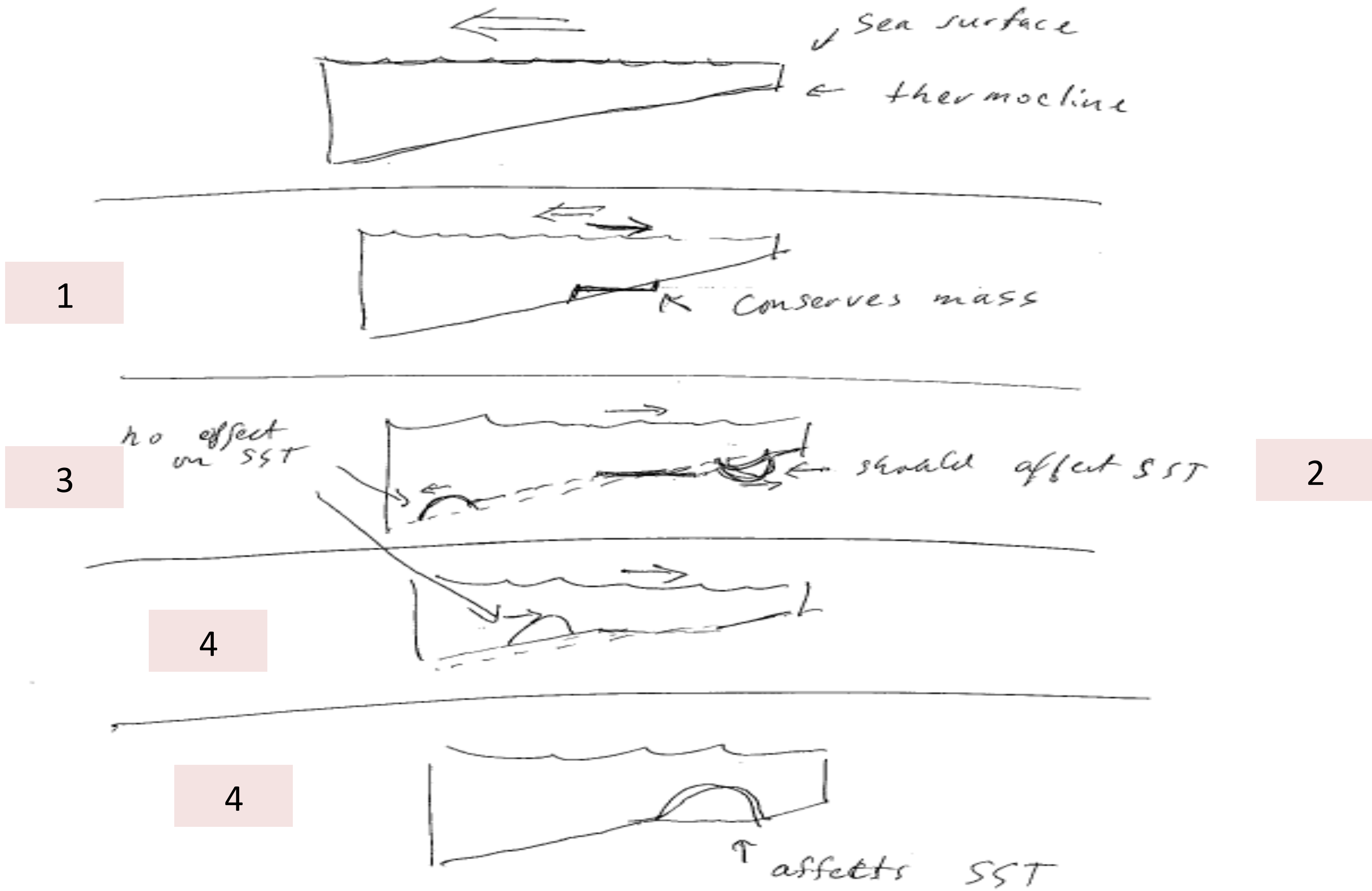
B. WHY DOES AN EVENT DECAY?

1. THE DELAYED OSCILLATOR (SCHOPF AND SUAREZ; BATTISTI)




WARM SST
COLD SST
WEST
EAST
WAVE DELAY
THERMOCLINE
WEAK
COUPLING
STRONG
COUPLING
WEAK
COUPLING

1. **The thermocline adjusts to deep in the eastern part of the wind patch (downwelling) and shallow in the western part (upwelling).**
2. **The downwelling signal is carried eastward by the Kelvin mode and is then dissipated in the mode fronts at the eastern boundary.**
3. **The upwelling signal travels westward as a Rossby mode, reflects as an upwelling Kelvin mode, and travels back to the scene of the growing instability.**
4. **The returning Kelvin wave eventually overcomes the effect of the growth if it is large enough.**

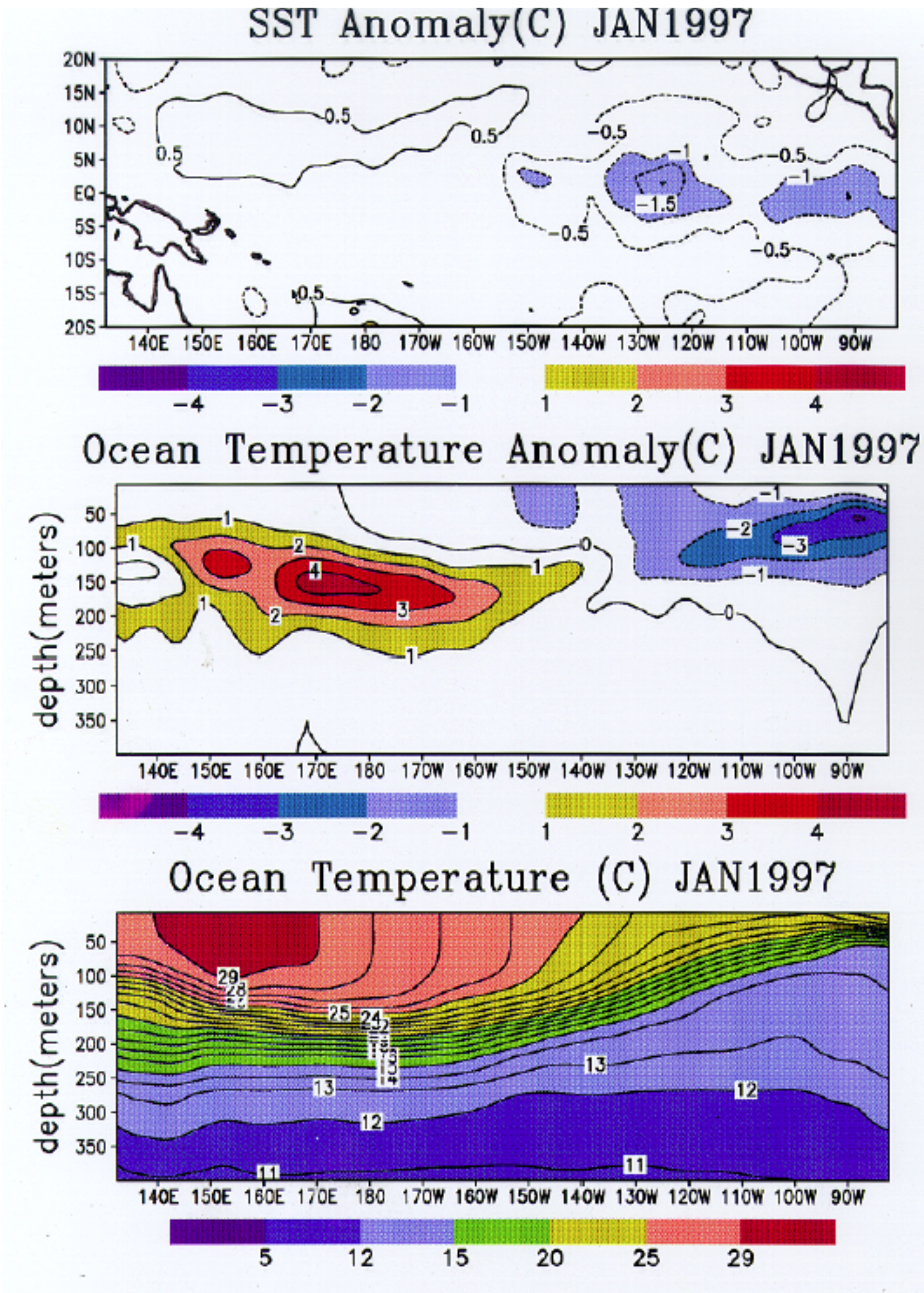


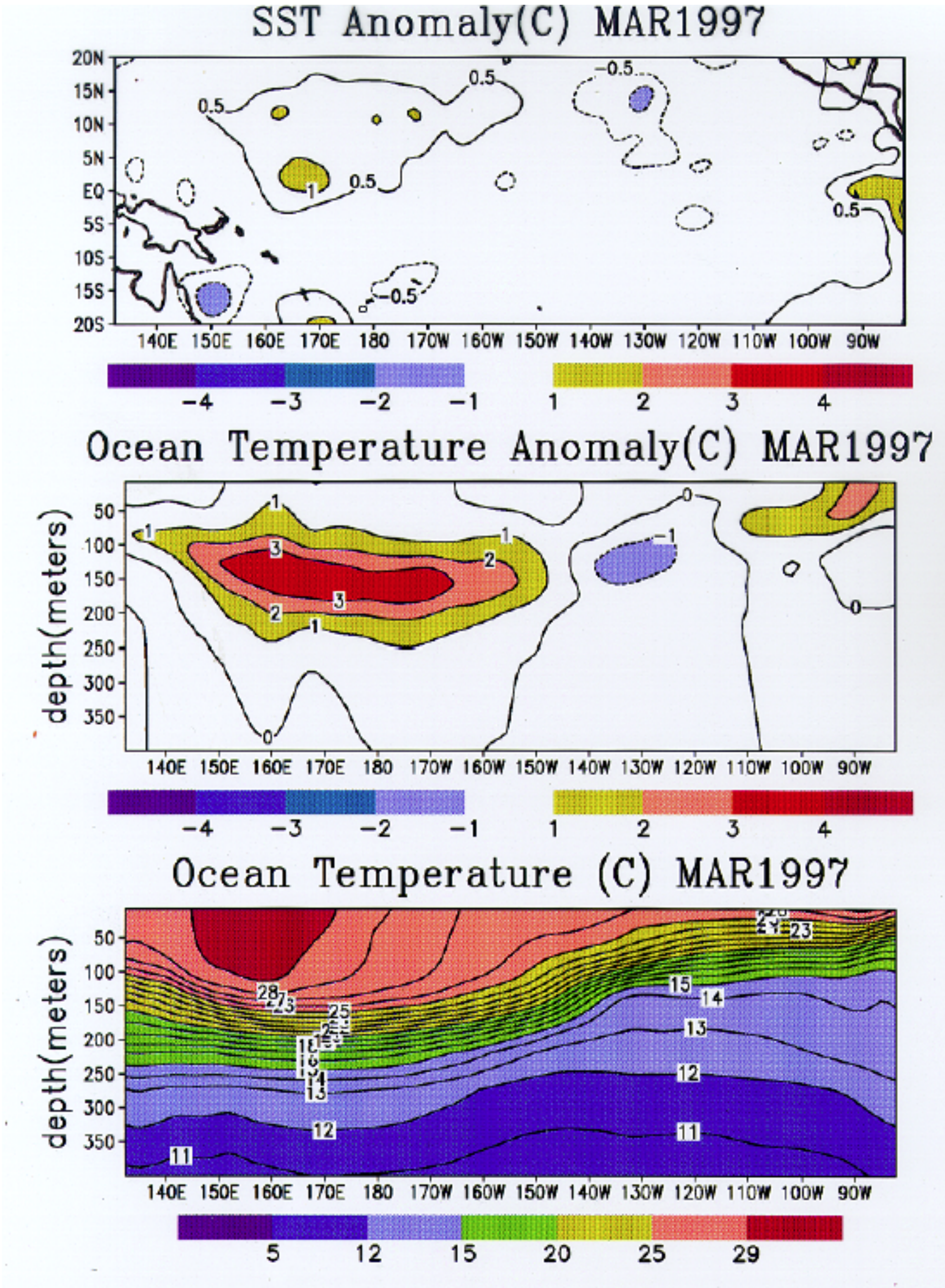
Sea surface
thermocline
1
conserves mass
no effect on SST
3
should affect SST
2
4
4
affects SST

- **The time scale is determined by the competition between the returning Kelvin mode and the growing instability.**
- **The process is reasonably represented by the delayed oscillator equation:**

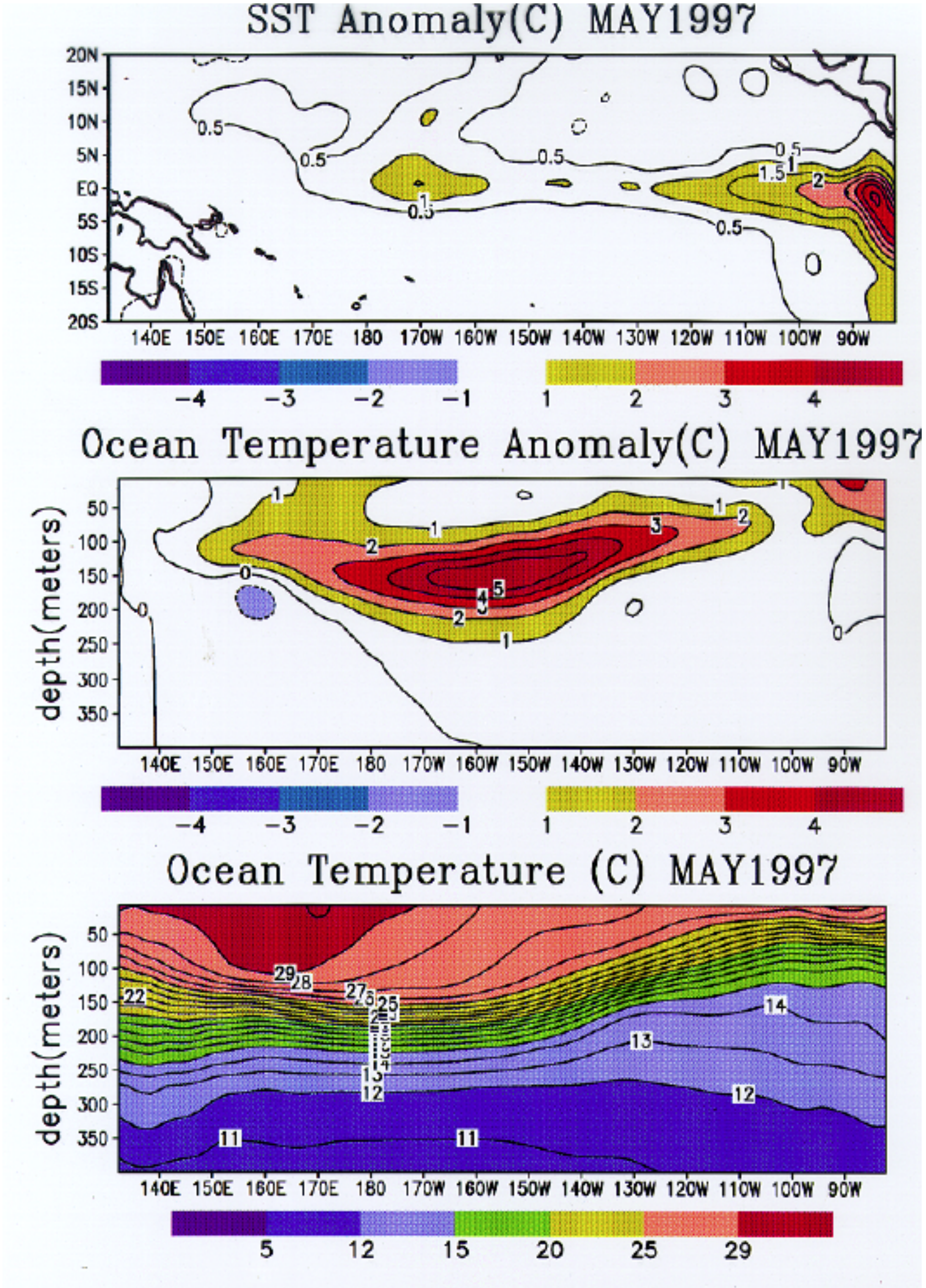
$$\frac{dT}{dt} = aT(t) - bT(t-\tau) - cT^3(t)$$

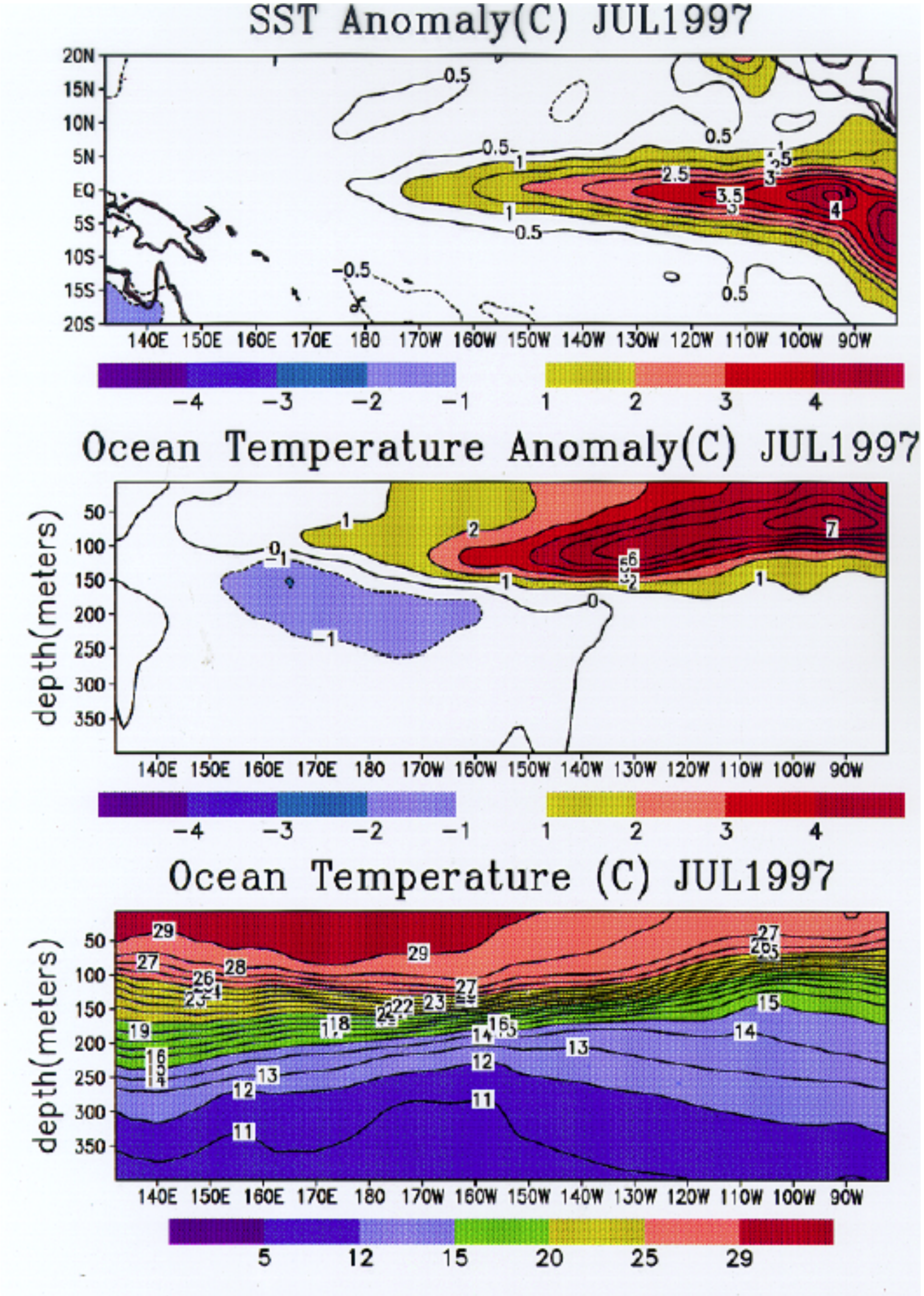
- **The non-linear term is needed in the delayed oscillator to equilibrate the amplitude.**


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



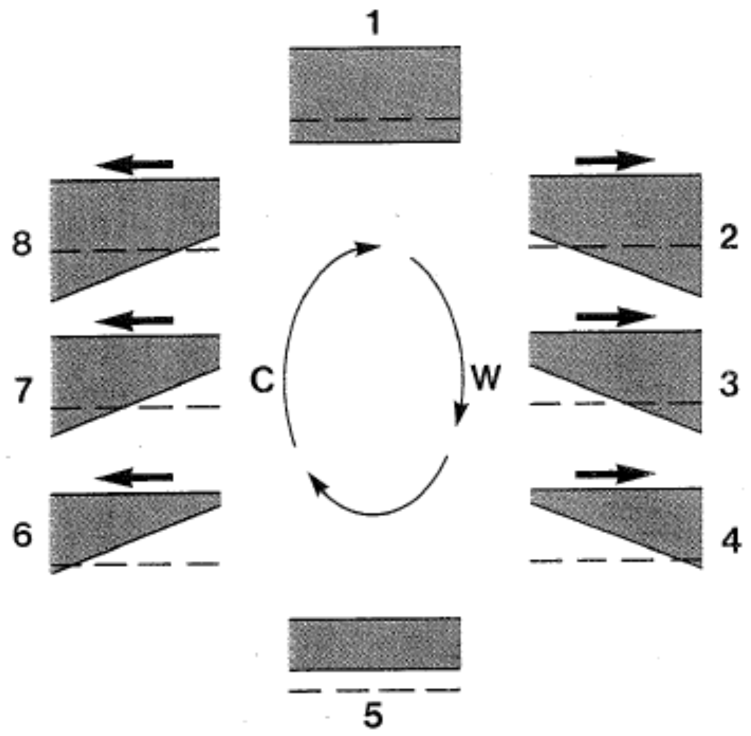
SST Anomaly(C) MAR1997
20N 15N 10N 5N EQ 5S 10S 15S 20S
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
-4 -3 -2 -1 1 2 3 4
Ocean Temperature Anomaly(C) MAR1997
depth(meters)
50 100 150 200 250 300 350
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
-4 -3 -2 -1 1 2 3 4
Ocean Temperature (C) MAR1997
depth(meters)
50 100 150 200 250 300 350
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
5 12 15 20 25 29


SST Anomaly(C) MAY1997
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) MAY1997
depth(meters)
50
100
150
200
250
300
350
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
−4 −3 −2 −1 1 2 3 4
Ocean Temperature (C) MAY1997
depth(meters)
50
100
150
200
250
300
350
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
5 12 15 20 25 29


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) JUL1997
depth(meters)
50 100 150 200 250 300 350
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
−4 −3 −2 −1 1 2 3 4
Ocean Temperature (C) JUL1997
depth(meters)
50 100 150 200 250 300 350
140E 150E 160E 170E 180 170W 160W 150W 140W 130W 120W 110W 100W 90W
5 12 15 20 25 29

B. WHY DOES AN EVENT DECAY?

2. THE MERIDIONAL MASS EXHANGE OSCILLATOR (also has been called the "recharge oscillator")



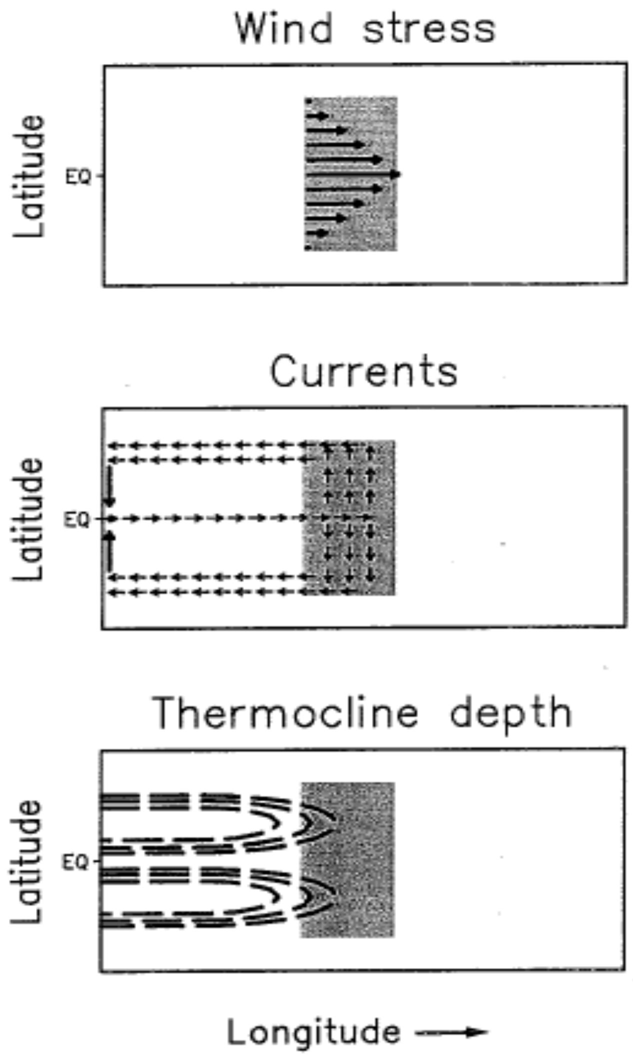
- **Basic fact: the wave propagation time scales are "much" faster than the ENSO time scale.**
- **Therefore, the thermocline slope at the equator is always "in equilibrium" with the wind stress.**
- **However, the mean depth of the thermocline along the equator can and does vary due to mass exchange with neighboring latitudes.**
- **The mass exchange is governed by Sverdrup transport in the interior and boundary currents (a la midlatitude ocean gyres).**

Equilibrium Response to an Equatorial Zonal Wind Stress Anomaly

Mass moves around so that the zonal currents are in geostrophic balance.

Meridional currents in the region of the wind stress anomaly (shaded) are in Sverdrup balance, otherwise 0.

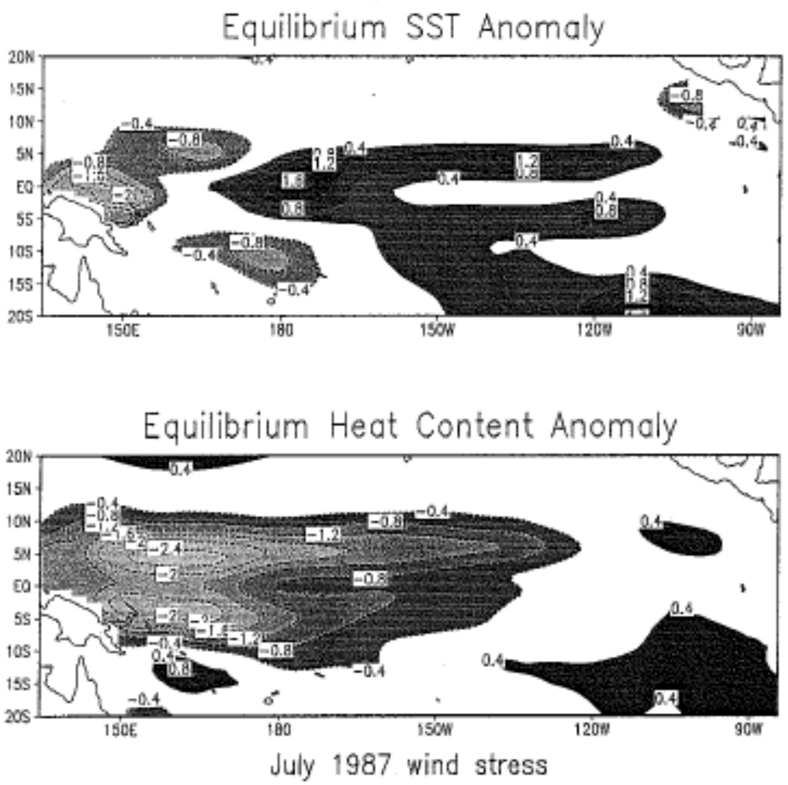
Western boundary currents develop to satisfy mass balance.

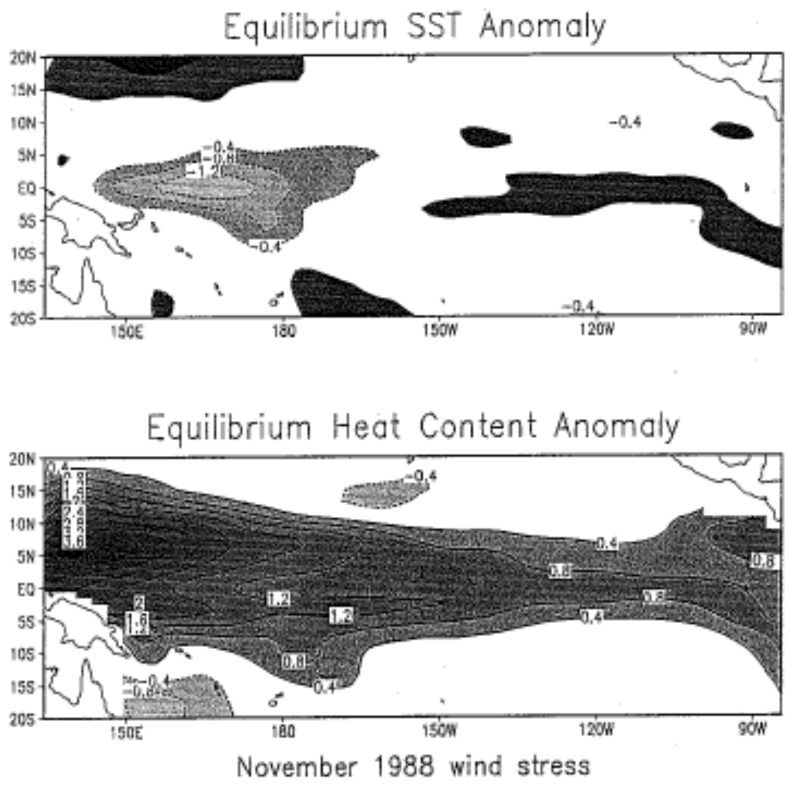


OGCM Simulations

- Force an Tropical Pacific OGCM with observed wind stress 1980-1994 (CONTROL)
- Speed up and slow down the evolution of the wind stress anomalies by a factor of 3 (FAST and SLOW).
- ENSO time scale is related to the time scale of adjustment to equilibrium.

Equilibrium SST and Heat Content Anomalies

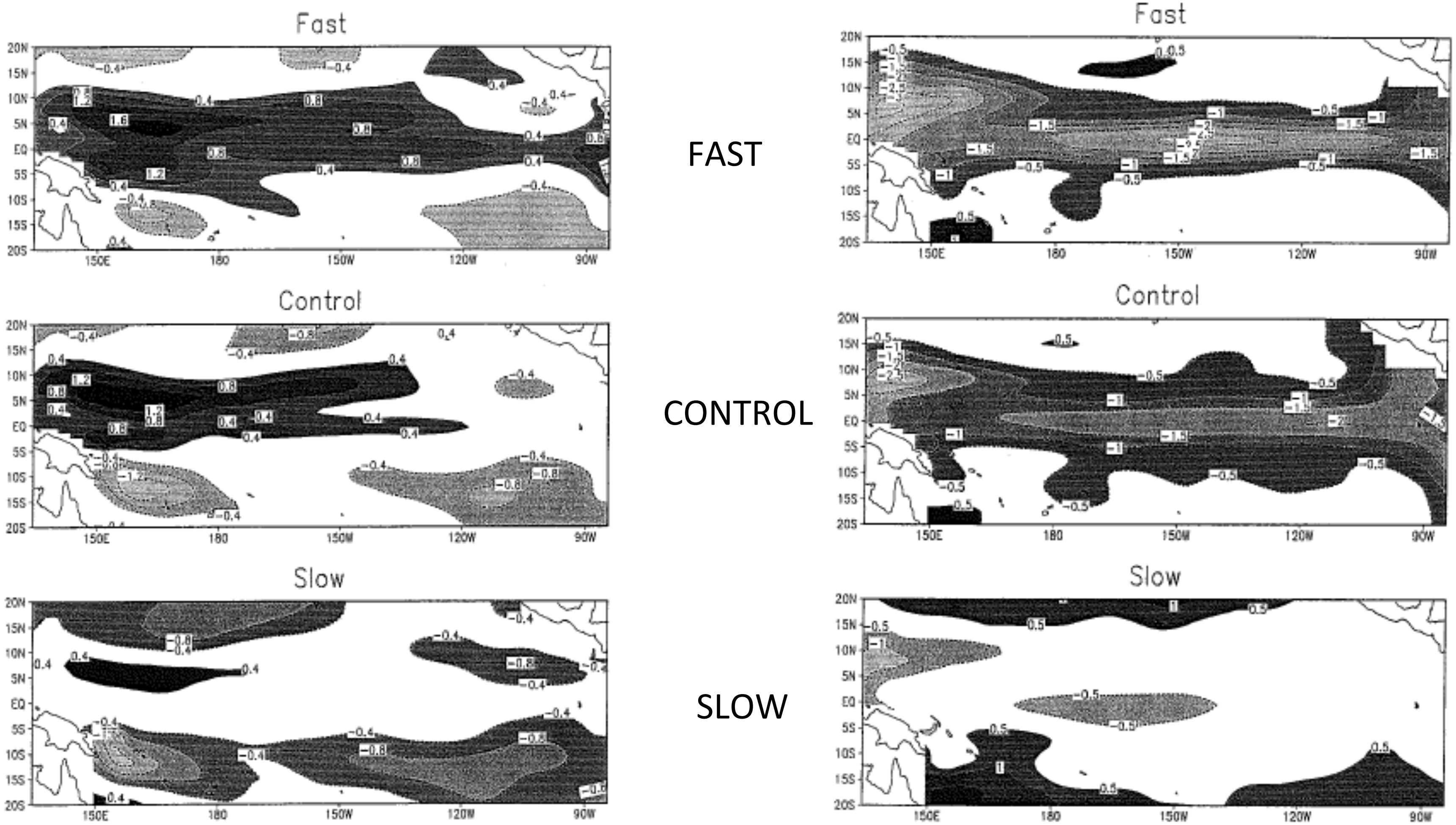




July 1987 wind stress

November 1988 wind stress

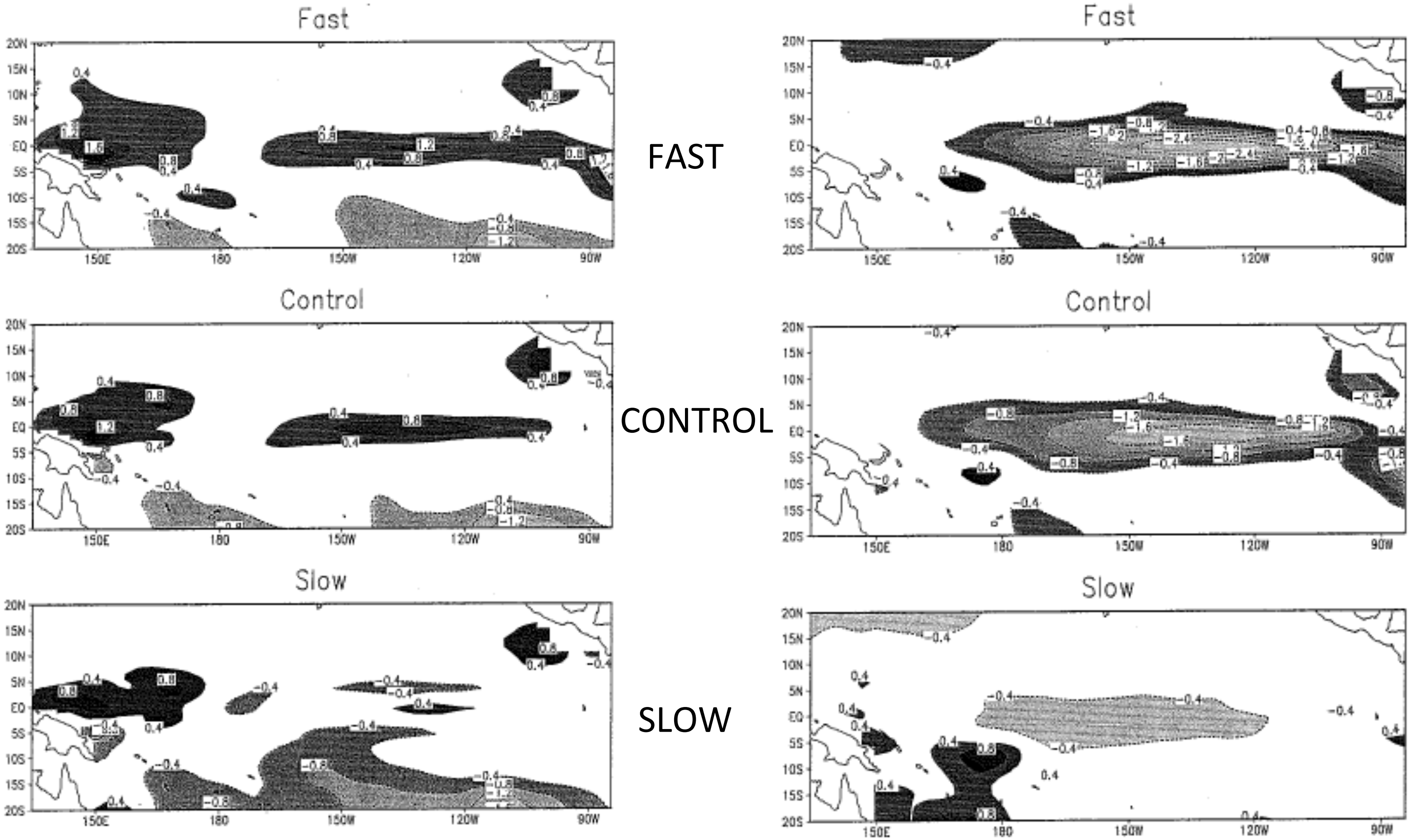
Heat Content of Time Evolving Runs: Deviation from Equilibrium



July 1987

November 1988

SST of Time Evolving Runs: Deviation from Equilibrium



July 1987

November 1988

- The time evolving heat content (thermocline depth) anomalies do not have time to fully adjust to the wind stress anomalies and lag the equilibrium anomalies.
- The time evolving heat content anomalies are opposite in sign to the equilibrium anomalies in regions where the SST is sensitive to thermocline depth.
- The time evolving SST anomalies are opposite in sign to the equilibrium SST anomalies. The adjustment process is responsible both for the decay of the events and the setup for an event of opposite sign.
- The time scale for adjustment to equilibrium appears to be related to the time scale for the setup of the western boundary currents.

The Cane-Zebiak Model

- The CZ model is a simple tropical coupled model that contains the elements of the stable or unstable ENSO mechanism

- It has:
  - A shallow water model in a square basin to calculate the response of the thermocline in response to wind anomalies
  - A fixed 50 m mixed layer to calculate SST anomaly evolution
  - A parameterization of subsurface temperature in terms of the thermocline depth:

$$T_{sub} = [\tanh \{b(h_{mean}+h)\} - \tanh bh_{mean}] \ ; \ b=b_1 \text{ if } h>0,\ b=b_2 \text{ if } h<0$$

  - A slightly modified Gill model slave atmosphere parameterization of the surface wind response to SST anomalies

- The annual cycle is specified and only the anomalies are calculated.

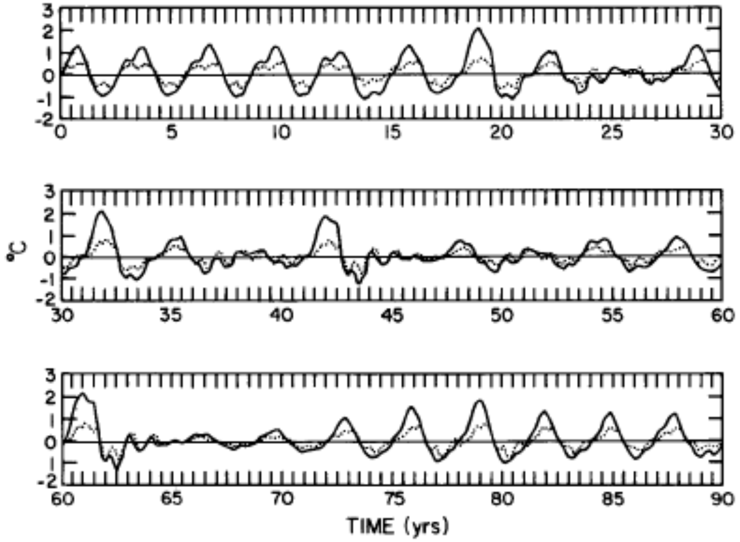


FIG. 1. Area-averaged SST anomalies for the 90-year model simulation. The solid line is NINO3 (5°N–5°S, 90°–150°W), and the dotted line is NINO4 (5°N–5°S, 150°W–160°E).

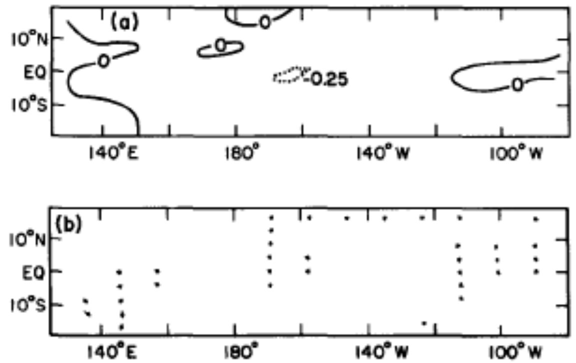


FIG. 4. (a) SST anomalies and (b) wind anomalies in December of year 30 of the model simulation.

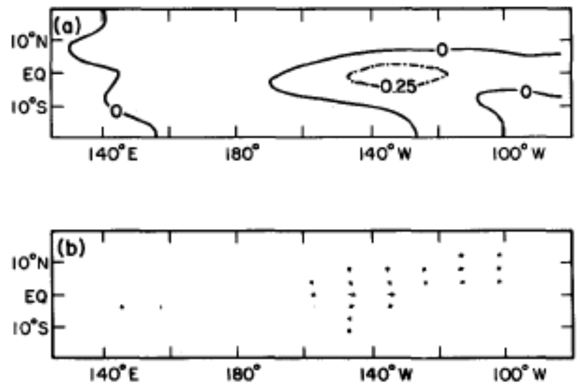


FIG. 5. As in Fig. 4, except for March of year 31.

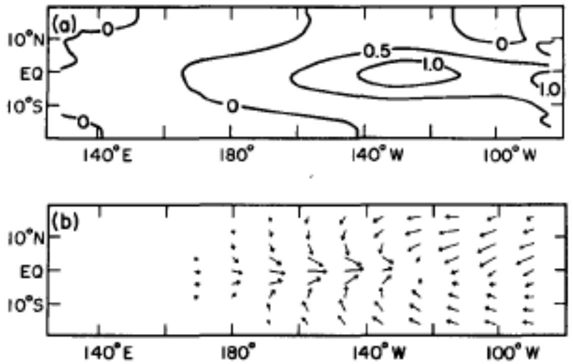


FIG. 6. As in Fig. 4, except for June of year 31.

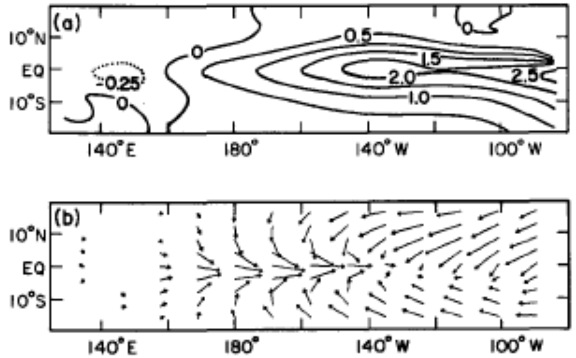


FIG. 7. As in Fig. 4, except for September of year 31.

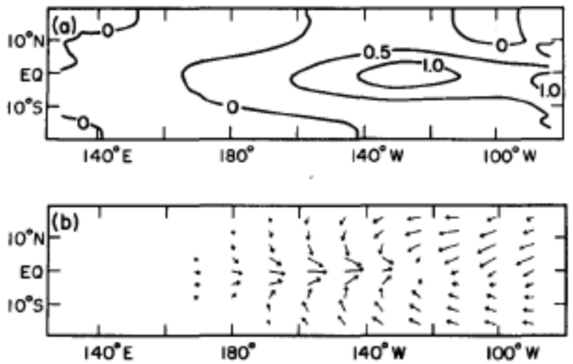


FIG. 6. As in Fig. 4, except for June of year 31.

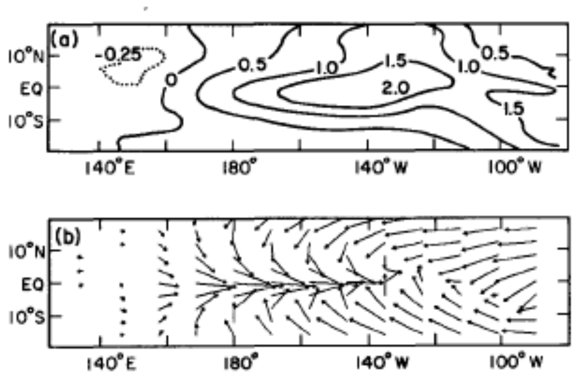


FIG. 9. As in Fig. 4, except for March of year 32.

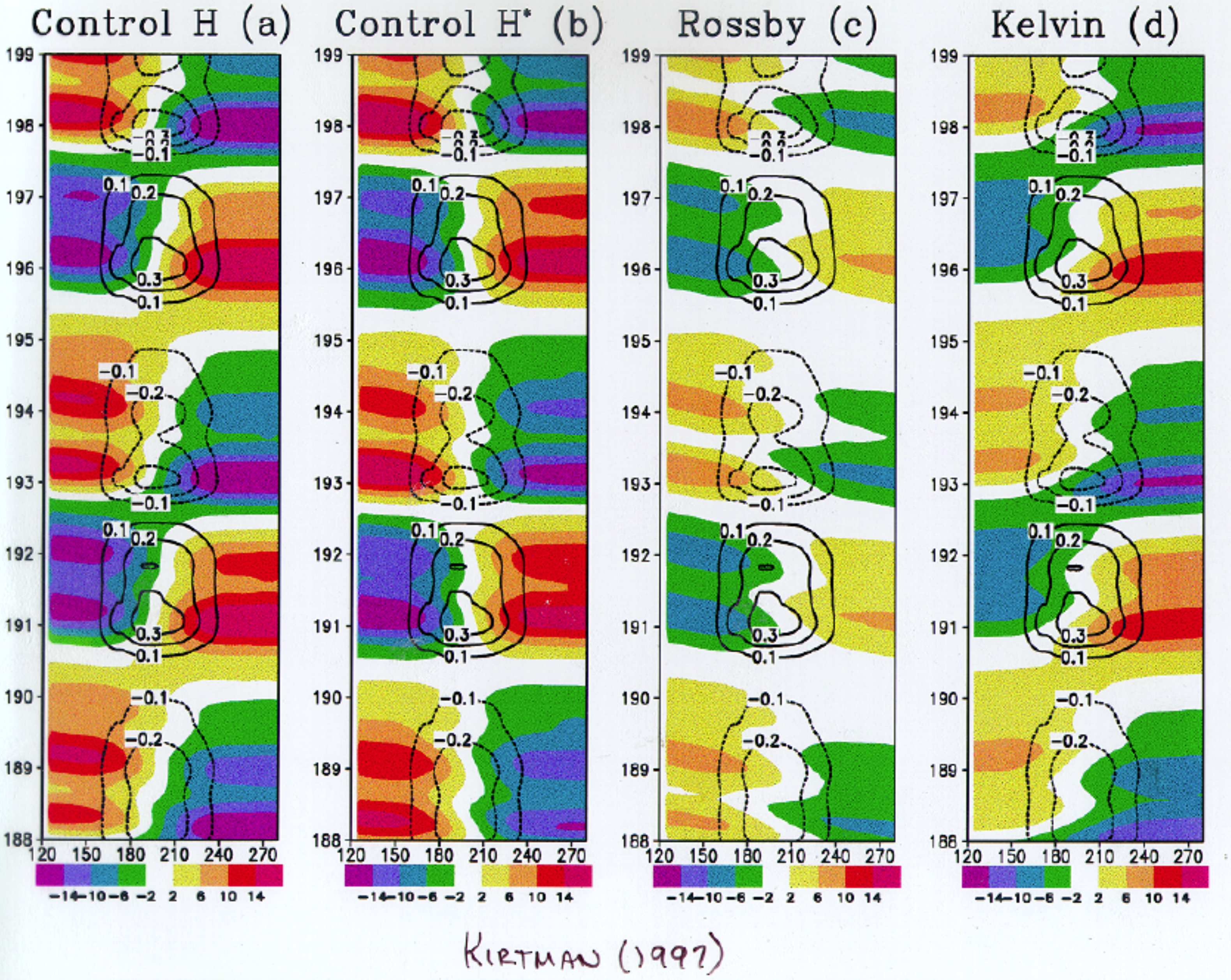
The CZ model is simple enough to be run for very long times and simple and flexible enough to be analyzed for the ENSO mechanisms

C. What Sets the Time Scale?

- The role of reflected Rossby waves in the delayed oscillator view suggests:
  - The farther west the position of the atmospheric heating anomaly, the shorter the time scale
- Other possible sensitivities not covered directly by the DO
  - Meridional structure of the wind stress anomaly?
  - Width of basin (e.g. Pacific vs. Atlantic)?
  - Background state
  - Audience suggestions accepted

Illustration (Kirtman 1997)

- CZ-type ocean model
- Empirical statistical atmosphere: wind stress a function of NINO3 SSTA
  - Vary the zonal position and meridional width of the wind stress
  - OK as long as atmospheric noise is not an important forcing



Control H (a)
Control H* (b)
Rossby (c)
Kelvin (d)
199
198
197
196
195
194
193
192
191
190
189
188
120 150 180 210 240 270
-14 -10 -6 -2 2 6 10 14
0.1
0.2
0.3
-0.1
-0.2
Kirtman (1997)

Close Print

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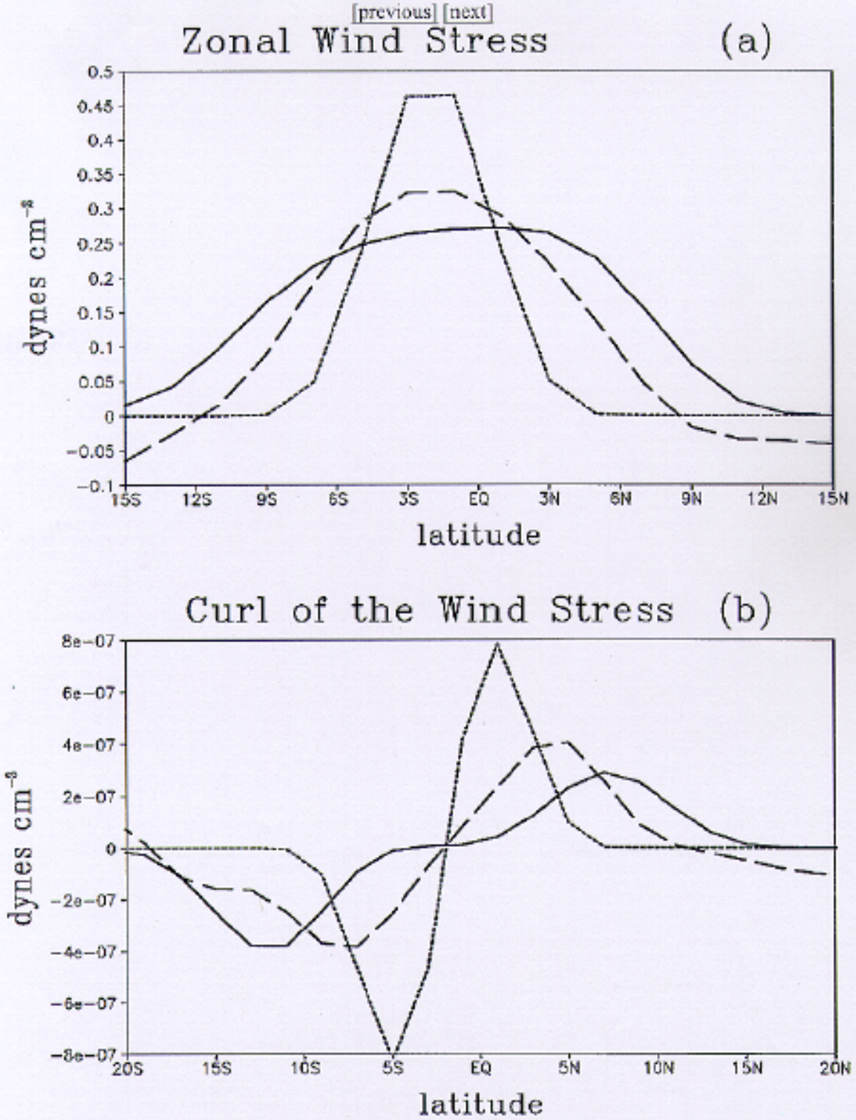
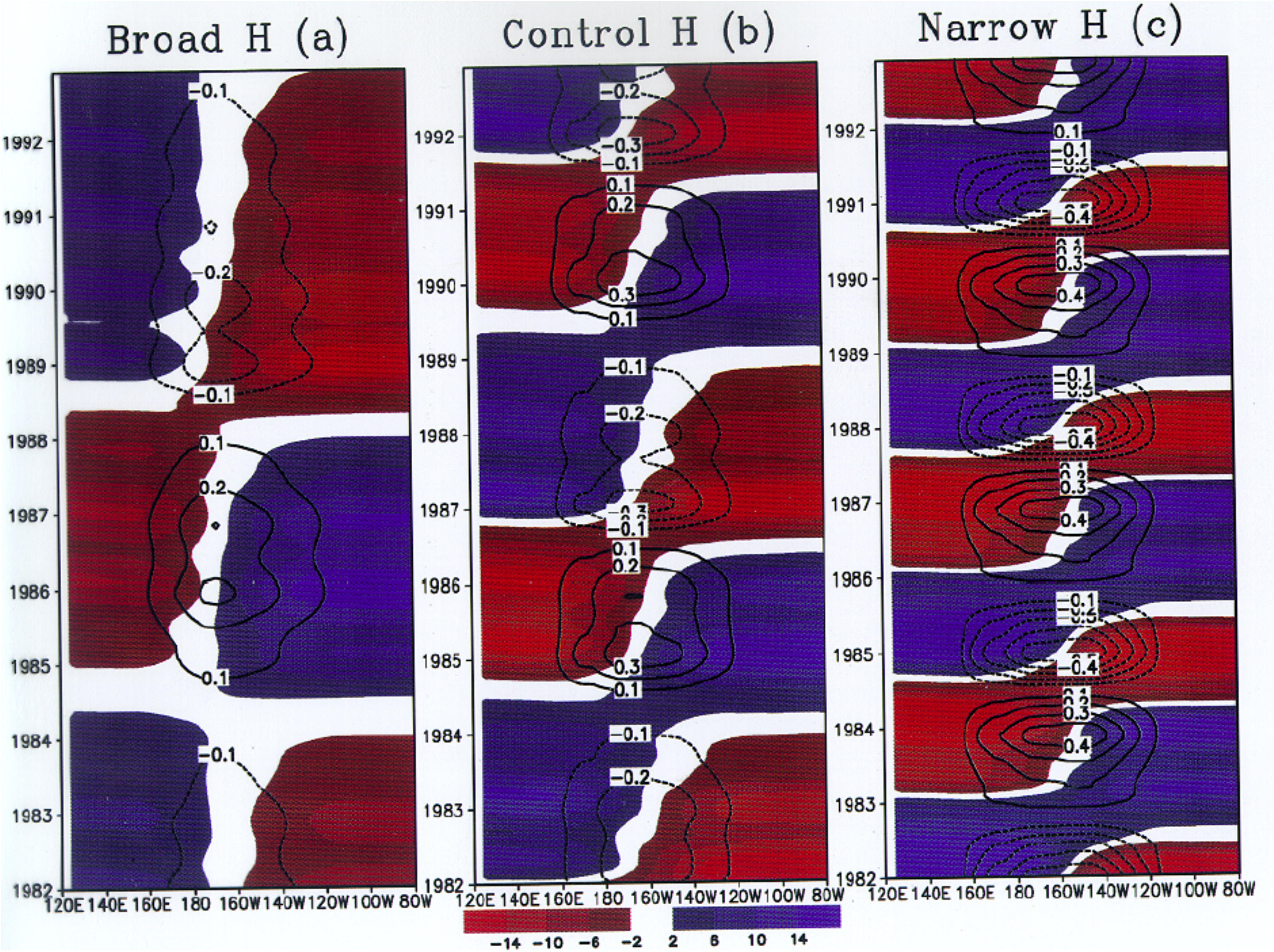
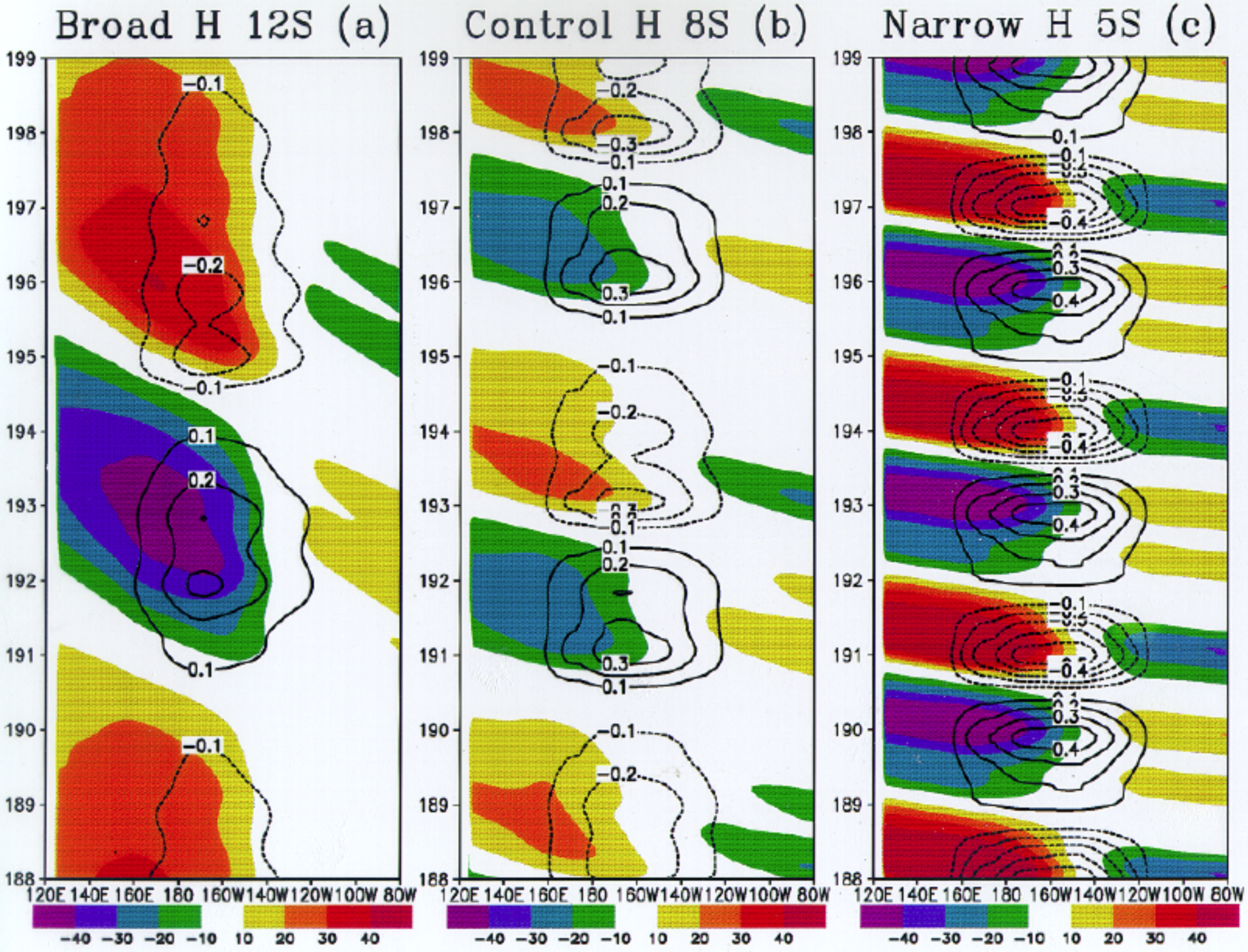
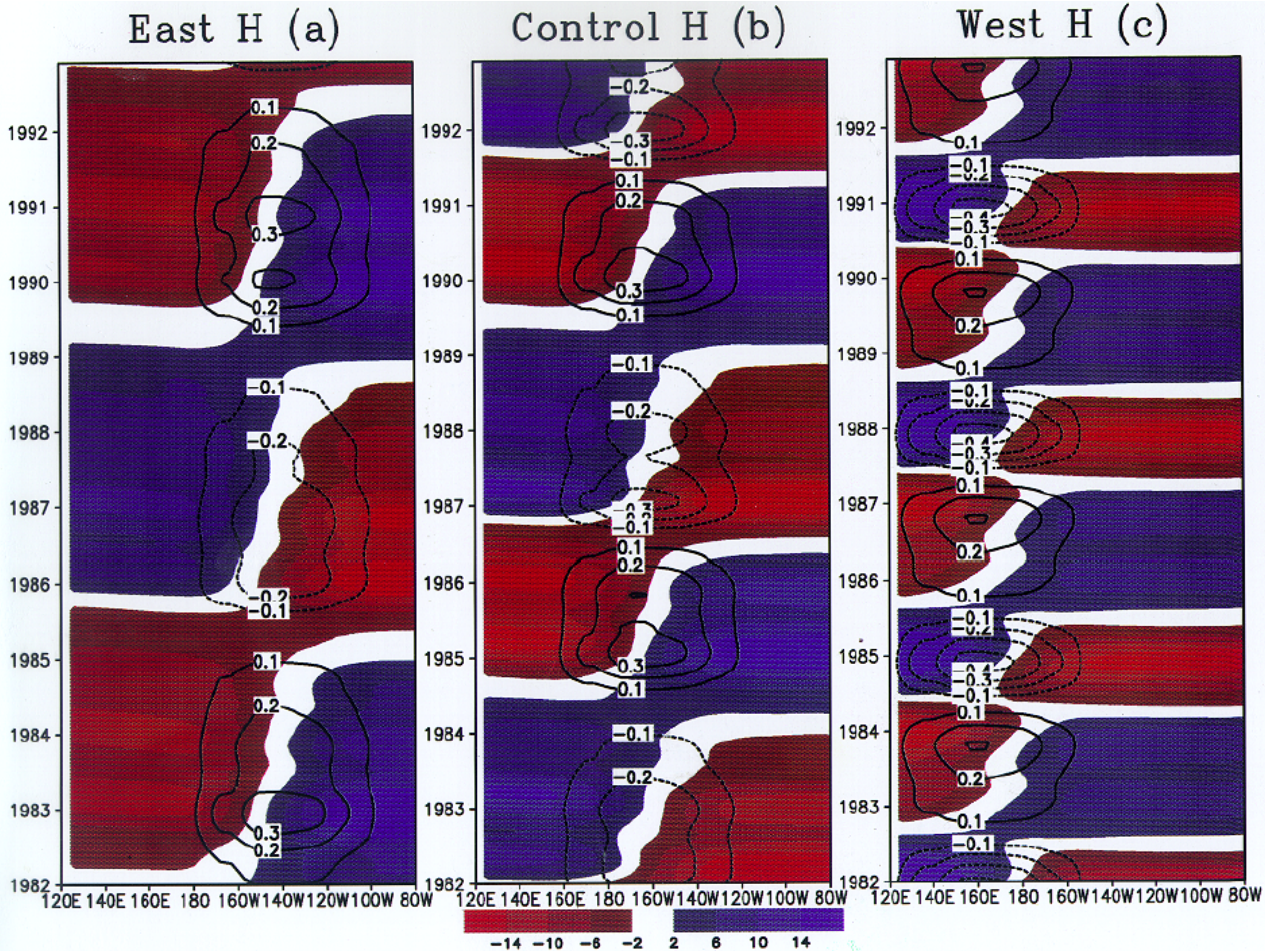




Broad H (a)
Control H (b)
Narrow H (c)
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
120E 140E 160E 180 160W 140W 120W 100W 80W
-14 -10 -6 -2 2 6 10 14



Kirtman (1997)


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
0.1
0.2
0.3
-0.1
-0.2
-0.3
-0.4
-14 -10 -6 -2 2 6 10 14

E. Why Do Warm and Cold Events Alternate Irregularly?

- **Two possibilities (mathematically speaking) in the context of the CZ model**
  1. **Nonlinearity of the ENSO system of equations á la the famous Lorenz butterfly equations leading to chaos**
  2. **Forcing of the ENSO system of equations by external noise. E.g.**
     - **Weather disturbances (atmosphere)**
     - **Tropical Instability Waves (ocean)**
     - **The noise is ultimately due to nonlinearity not represented/ resolved by the ENSO system of equations**
- **Both types can be simulated using the CZ model**

2. NON-NORMAL EVOLUTION: THE ROLE OF ATMOSPHERIC AND OCEANIC NOISE

- The CZ model can be linearized and noise added. The linear matrix formulation is:

$$\frac{dx}{dt} = Ax + Noise$$

where all the eigenvalues of A are negative so there are no unstable normal modes

- How can there be ENSO in a stable system? Answer: there is an external energy source provided by the noise
  - Homework problem: what are the energetics?

The solution of the linear equation is

$$x(t) = R(t)\, x(t=0)$$

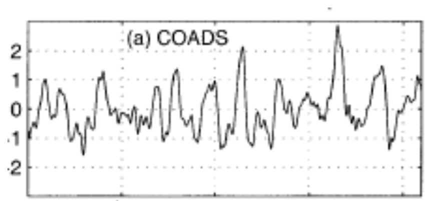
where R(t) = exp [At] is the propagator (which takes the initial solution to the solution at time t).

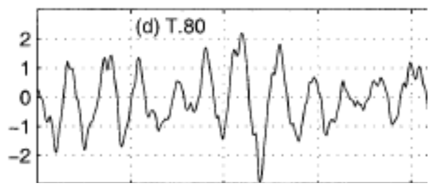
- The propagator R is non-normal [$RR^+ \neq R^+R$] and the eigenvectors are not orthogonal. This allows growing modes for a limited amount of time which then decay.

- A non-normal system can maintain a very much larger variance for a given input of noise than a normal system.

- The growing non-normal disturbances depend on the background flow.

- Thompson and Battisti showed that the linearization of the CZ model driven by random noise has many of the same properties as ENSO





- The growing modes have features of the delayed oscillator but irregularity is inherent and doesn't have to be explained.