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COURSE ON "OCEAN-ATMOSPHERE INTERACTIONS IN THE TROPICS"
26 May - 6 June 1997

"5A) Intermediate Coupled Models Support ENSO-Like Variability"

presented by

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Please note: These are preliminary notes intended for internal distribution only.

5A) Intermediate Coupled Models Support ENSO-like Variability

- **Cane and Zebiak (1985); Zebiak and Cane (1987)**
- **Shopf and Suarez (1988)**

  Intermediate coupled models yield interannual variability that is temporal and spatially similar to the observed ENSO phenomenon.

  Inhomogeneous basic state and surface mixed layer physics are crucial;

  Upper ocean thermodynamic processes are rich and varying during the simulated ENSO cycle.

- **Many other intermecdiate coupled models later shown to support ENSO-like interannual variability (e.g., Chang et al.),**

1B) Inhomogeneous Basic State + ENSO

Schopf + Suarez's (1988) coupled Model

Ocean active here only →

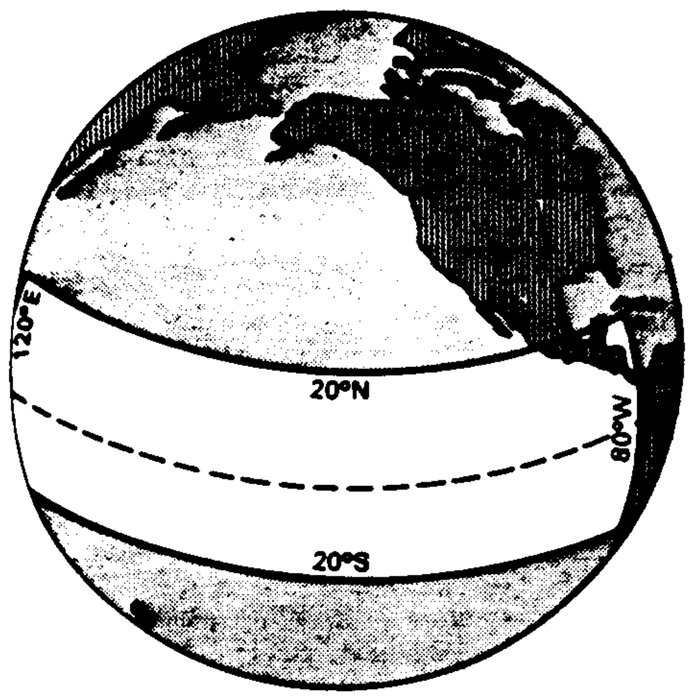


FIG. 1. Coupled ocean–atmosphere model geometry. The ocean basin extends from 20°S to 20°N, 120°E to 80°W.

Held/Suarez atmosphere

2-layer primitive eqn. ocean model

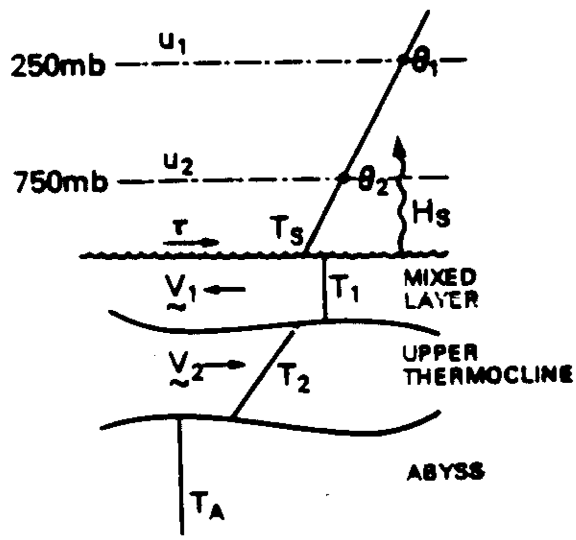
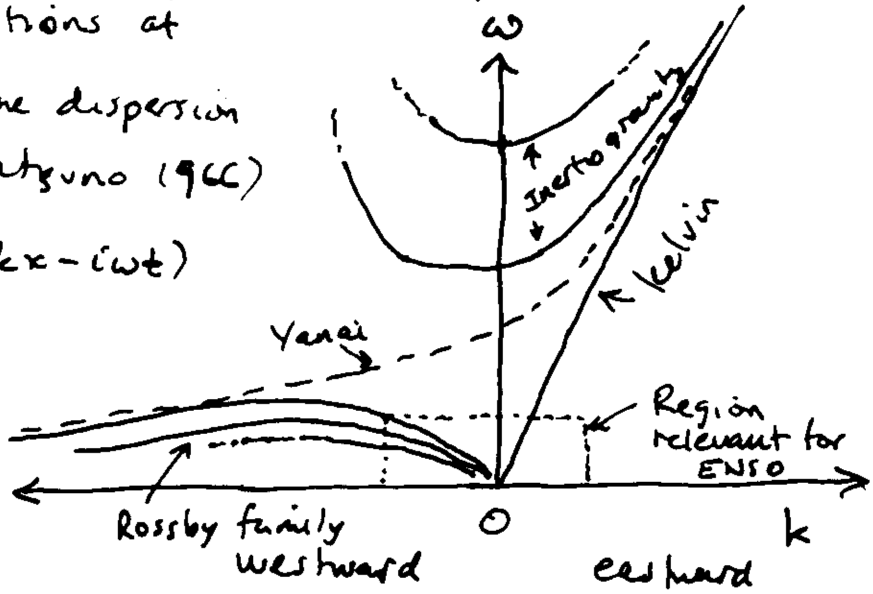


FIG. 2. Model vertical structure.

- heating of atmosphere $\propto (T_s - T_1)$
- forcing of ocean: $-u$ and $\tau = a\, u_2$

Highlights of linear adiabatic tropical dynamics theory

- Assuming an equatorial β-plane ($f = \beta y$; $y=0$ at equator) and bounded motions at $y = \pm\infty$ yields the dispersion relationship (Matsuno 1966) solutions $\exp(ikx - i\omega t)$

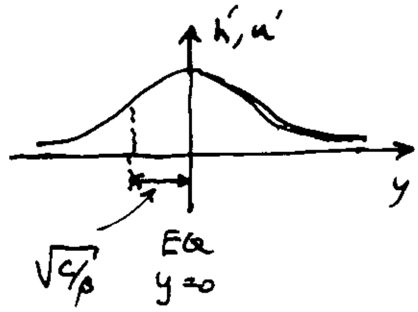


- Solutions fundamental for ENSO include

<u>Kelvin signal</u>

$$\frac{\omega}{k} \simeq c_k = \sqrt{g^* h} \quad ; \quad g^* = g\,\frac{(\rho_s - \rho_0)}{\rho_0}$$

eastward



<u>Long Rossby Waves</u> ($n = 1, 2 \ldots \infty$)

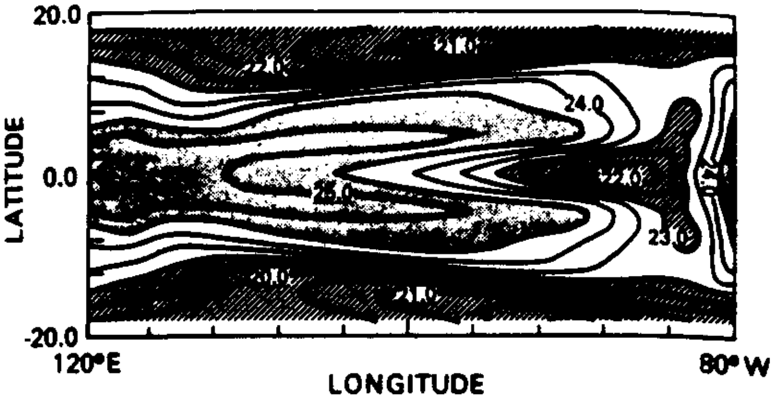
$$c_n = \frac{-c_k}{2n+1}$$ westward

- Typical Scales

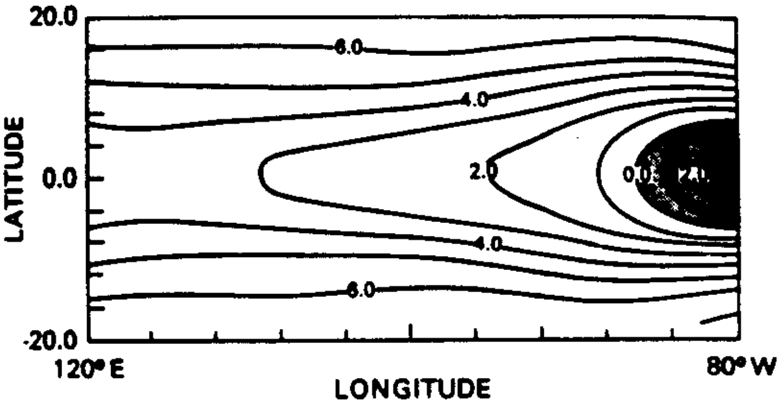
	Phase/Group Kelvin	Phase/Group n=1 Rossby	Basin Crossing Time (Pacific) Kelvin	Basin Crossing Time (Pacific) Rossby (n=1)
Atmosphere	30-60 m/s	10-20 m/s	~ 6 days	18 days
Ocean	2.5-3 m/s	~ 1 m/s	~3 months	8 months

Climatology of the Schopf and Suarez (1988)
model

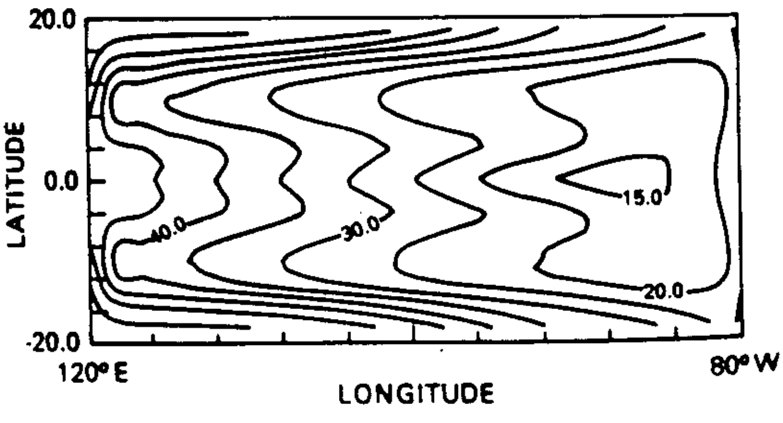
SEA SURFACE TEMPERATURE (°C)



ZONAL SURFACE WIND (m/s)



SURFACE HEIGHT (cm)



SVD mode 1 for SST and windstress fields

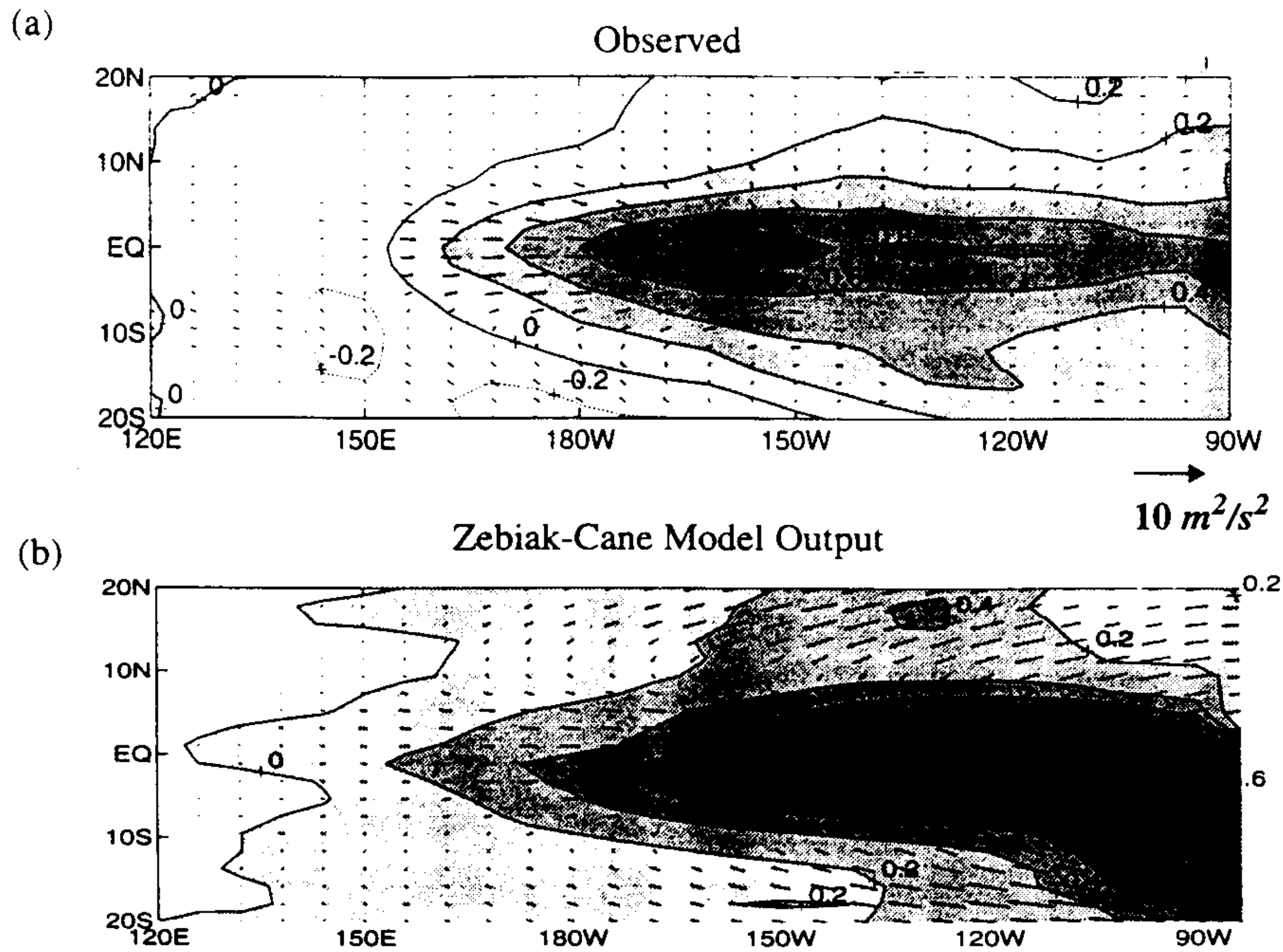
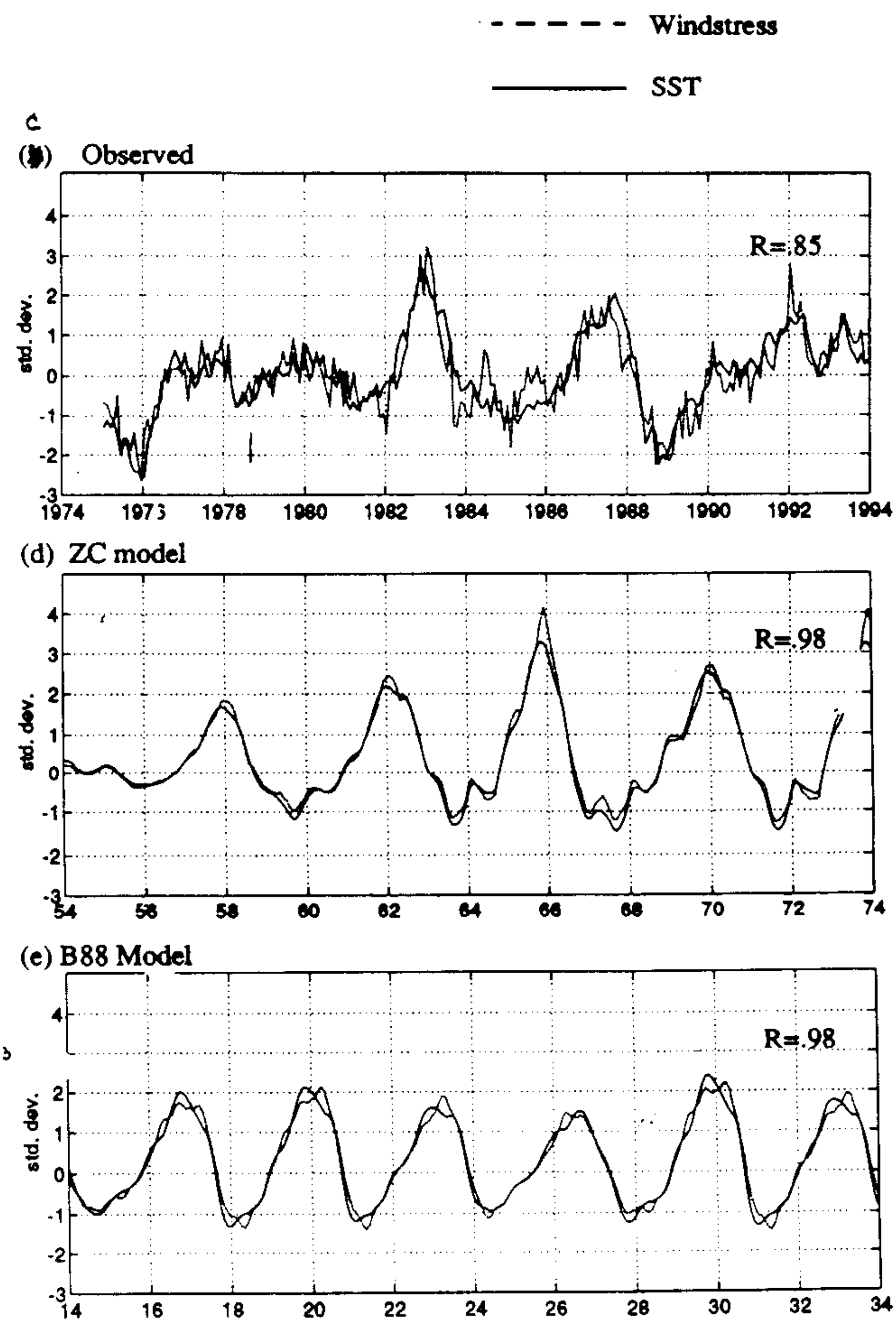


FIGURE 5. Results from the SVD analysis of tropical SST and windstress fields: leading eigenvectors (SVD1), in the form of heterogeneous regression maps (see text for interpretation) for the (a) observed, and (b) ZC model; SST fields are contoured at 0.2 °C intervals and positive values are shaded; windstress fields are given with vectors, and a sample 10 *(m/s)*^{2} vector is included for scale. Normalized expansion coefficients for the leading SST (solid lines) and windstress (dashed lines) eigenvectors are plotted for (c) the observed, (d) the ZC model, and (e) the B88 model. The correlation coefficients (r) between the time-series pairs are listed in the lower right corner of panels (c), (d) and (e).

Expansion Coefficients for the leading SVD eigenvector pairs:



The model ENSO events are consistent with those observed in nature....

* SST and wind perturbations are consistent with observations in magnitude and pattern.

* Regular oscillations with period of 3 or 4 years

* Model ENSO's are locked to the seasonal cycle al a observations.

—//—

The model allows us to examine the important thermodynamic + dynamic processes that act to produce a model ENSO.

Thermodynamic Anatomy of the 388/CZ model ENSO

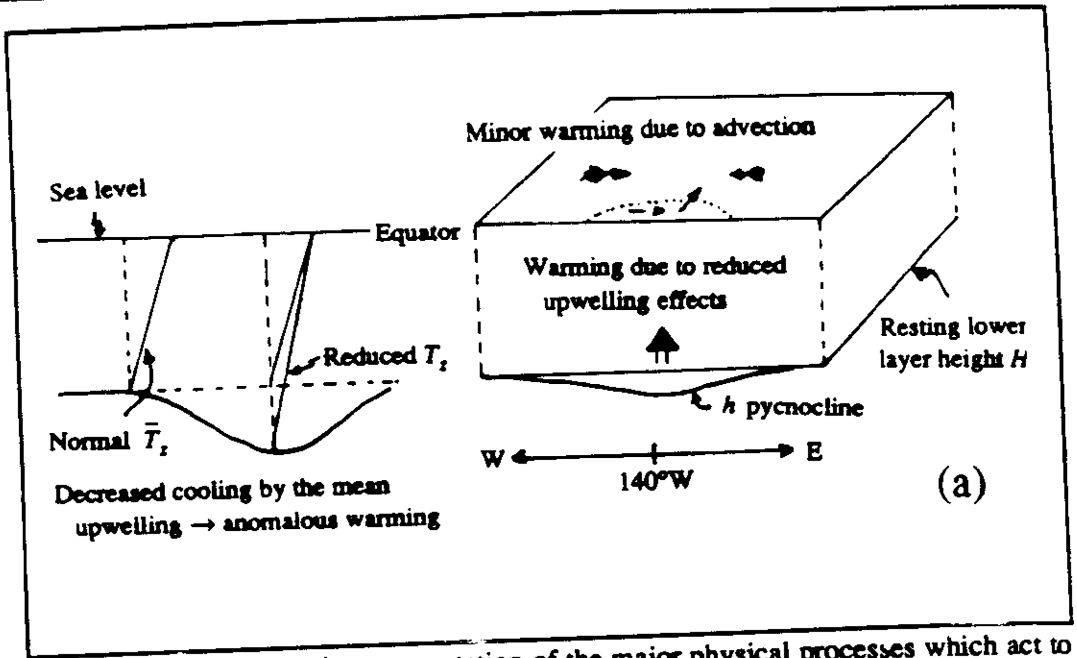


Figure 2a. A schematic representation of the major physical processes which act to produce a model ENSO event, based on the analysis presented in Battisti (1988a,b). Cut-away views on the equator are given for the main stages of development: Thick arrows point to regions of major heating/cooling, with the primary heating and cooling sources and mechanisms noted. Thin arrows denote upper-layer ocean current anomalies and direction of advective heating. Arrows with tails denote wind stress direction. The size of the arrows does not reflect relative amplitude (from Battisti 1988a). Spring (prior to a warm event maximum) when the event is triggered;

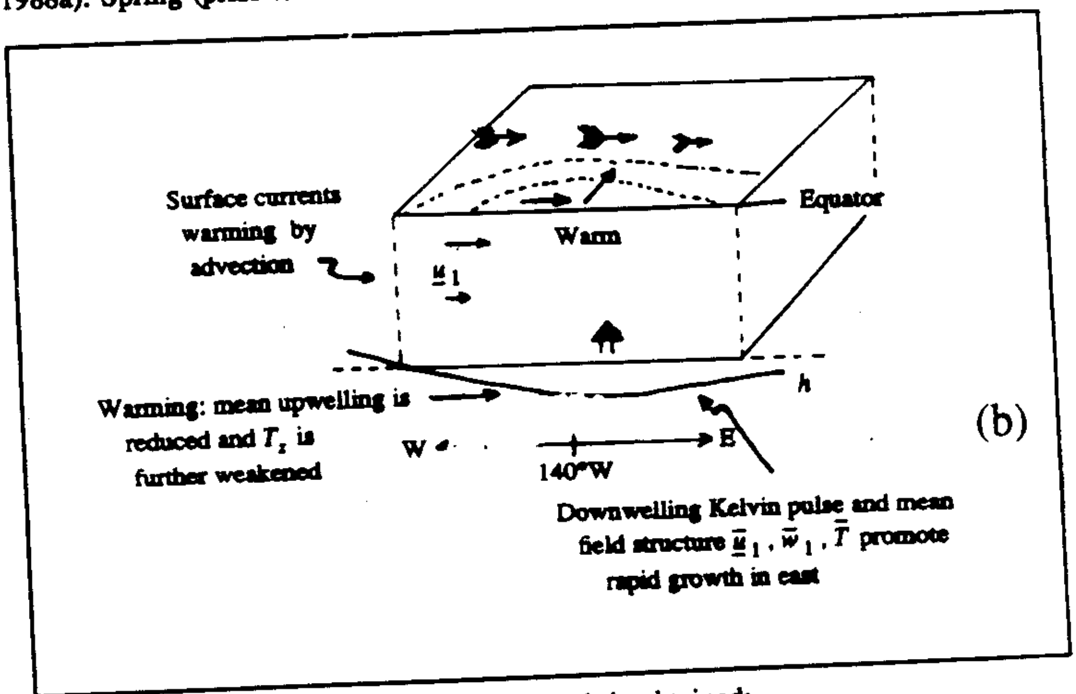


Figure 2b. fall, in which maximum growth is obtained;

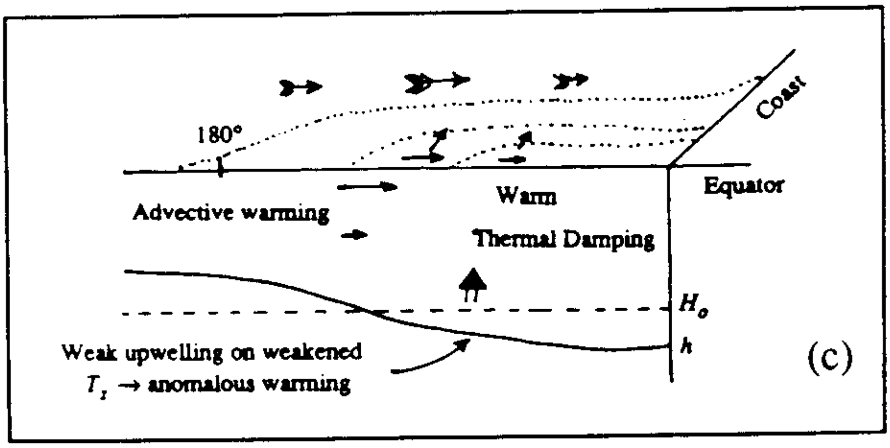


Figure 2c. peak event, winter;

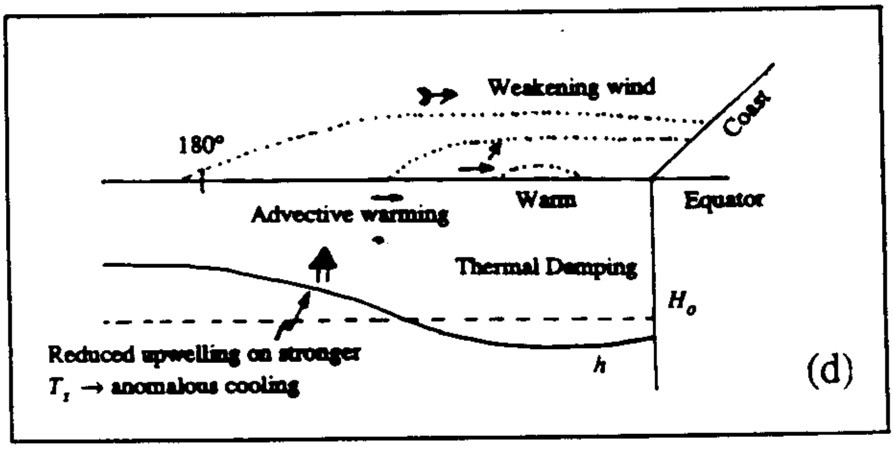


Figure 2d. decay, in the following (early) summer;

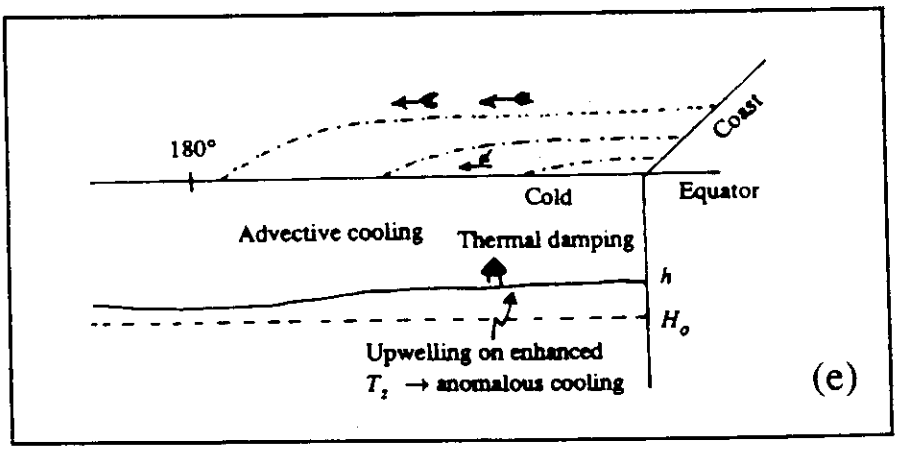


Figure 2e. peak cold state, the winter following a warm event.

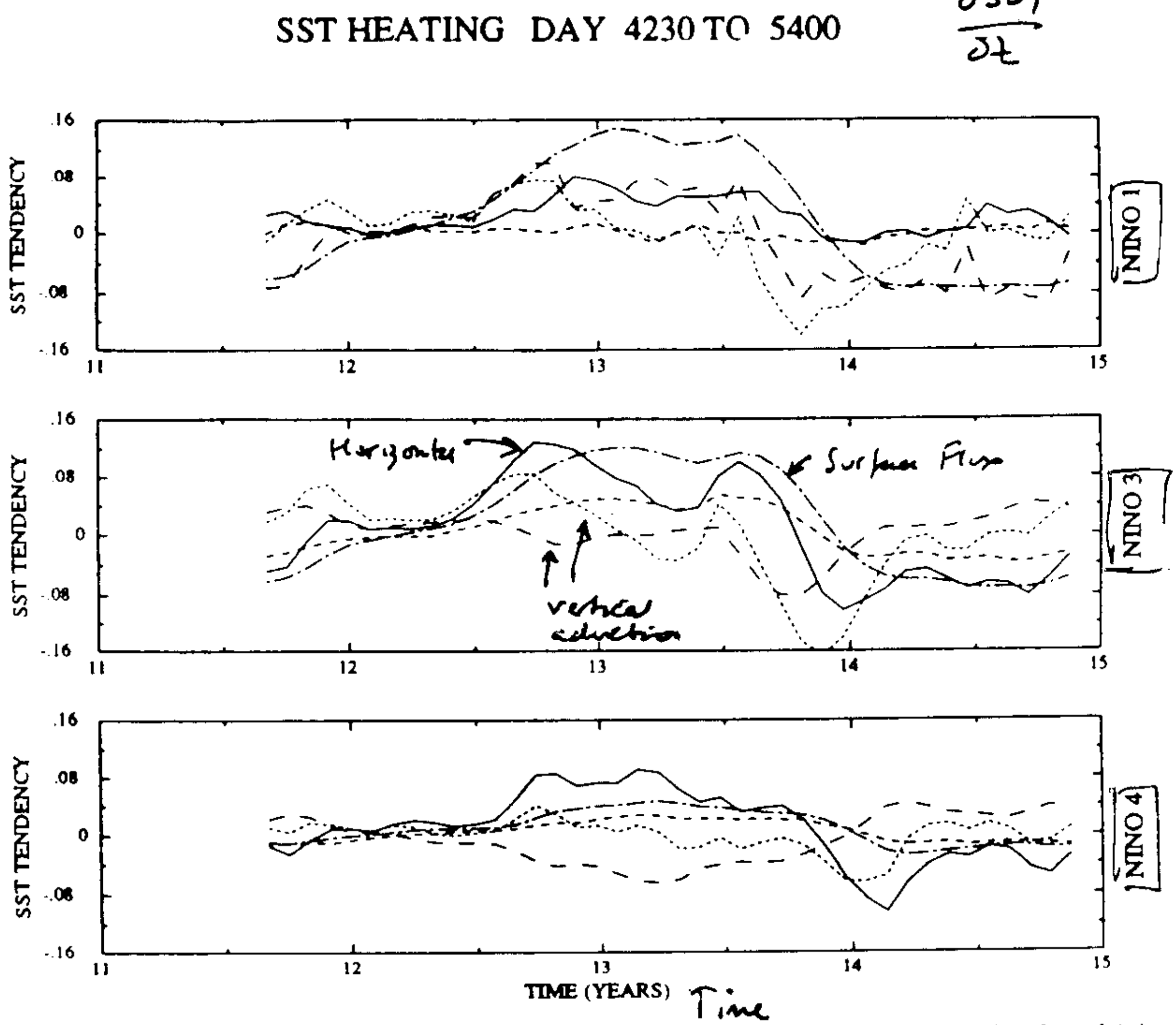


FIG. 4. The balance of terms in the SST tendency equation (3.1) for (a) Niño 1, (b) Niño 3, and (c) Niño 4. Horizontal advection $-\mathbf{u}_1 \cdot \nabla(\bar{T} + T) - \bar{\mathbf{u}}_1 \cdot \nabla T$ (solid line), anomalous upwelling on the mean vertical temperature gradient $-\delta[\Delta(\bar{w}_1 + w_1) - \Delta(\bar{w}_1)]\partial\bar{T}/\partial z$ (short dashed line), upwelling on the anomalous vertical temperature gradient $-\delta\Delta(\bar{w}_1 + w_1)\partial T/\partial z$ (long dashed line), total SST tendency $\partial T/\partial t$ (dotted line) and thermal damping $\alpha_s T$ (dash-dot line) are plotted vs time. Units are in °C/10 days.

SENSITIVITY STUDIES

TABLE 1

Case	Description	Comments
1	Standard physics (SPC)	3 or 4 year period; quasi-regular events
2	No western boundary	uncontrolled growth
3	No seasonal cycle (NSC)	periodic 3.47 year events
4	$\nabla \bar{T} = 0$	no interannual variability
5	SPC and $\partial \bar{T}/\partial x = 0$ for $t >$ Jan(12)	warmer, longer event
6	SPC and $\partial \bar{T}/\partial y = 0$ for $t >$ Jan(12)	smaller amplitude event than SPC
7	SPC and $\bar{v}_1 = 0$ for $t \geqslant 0$	no interannual variability
8	SPC and $\bar{v}_1 = 0$ for $t >$ Jan(12)	no interannual variability
9	NSC and $\bar{u}_1 = 0$ for $t >$ Jan(12)	as in case 3
10	Filtered off-equatorial winds	3–4 year period; regular events
11	Meridional boundary Kelvin waves included	periodic 4 year oscillation

Inhomogeneous mean state sensitivity (cases 3–9)

Battisti (1988)

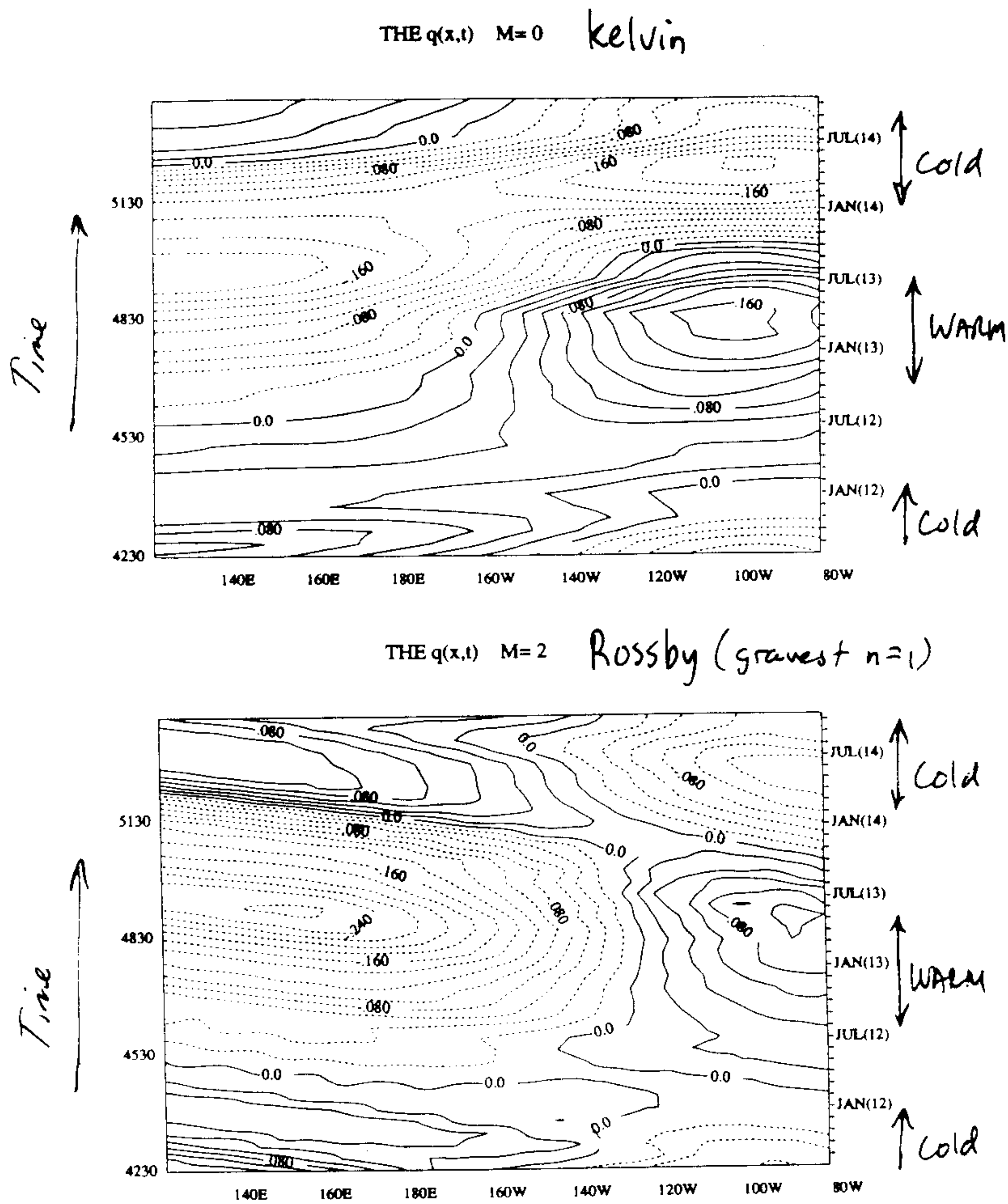
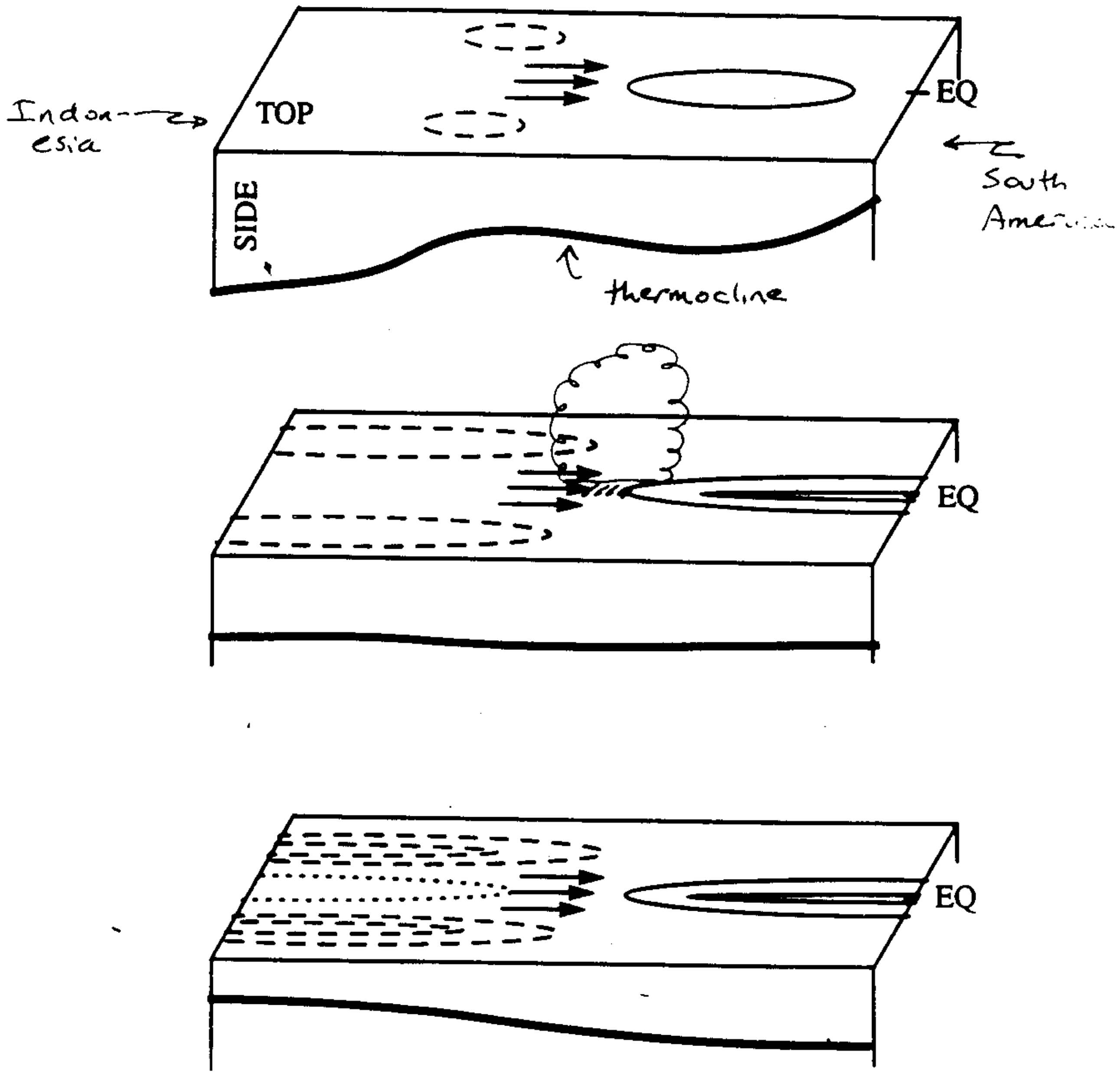


FIG. 9. Time vs longitude plot of the nondimensional amplitude (a) Kelvin $q_{m=0}$ and (b) gravest mode symmetric Rossby $q_{m=2}$ mode.

free propagation

Delayed Oscillator Physics

Diagnosis of coupled atmosphere/ocean models of intermediate complexity (e.g., the model of Cane and Zebiak) led to the delayed oscillator paradigm for ENSO. Schematically, it goes like this ...



5B) The Delayed Oscillator Theory (DOT) of ENSO

- **Overview of the Delayed Oscillator Theory for ENSO**

  In this theory for ENSO, the ocean memory and the dynamical adjustment time of the oceans is crucial to the evolving ENSO event, including the event onset, peak, demise, and the ensuing cold event.

  Why "Delayed Oscillator"?

  DOT of ENSO is a statement that a growing ENSO event contains the seeds of it's own destruction. This is due to the nature of equatorial dynamics, the long time scales associated with the adjustment of the tropical Pacific Ocean and the close relationship between wind and SST anomalies in the tropics.

- **Implications of DOT for long-range climate forecasting**

  If delayed oscillator physics is relevant to Nature's ENSO events, then (i) ENSO events should be predictable at least nine months in advance; and (ii) The Atlantic Ocean should not support an unstable ENSO-like mode.

- **Uncertainties concerning DOT and nature *circa* 1990**

No observational evidence verifying the crucial subsurface variability.

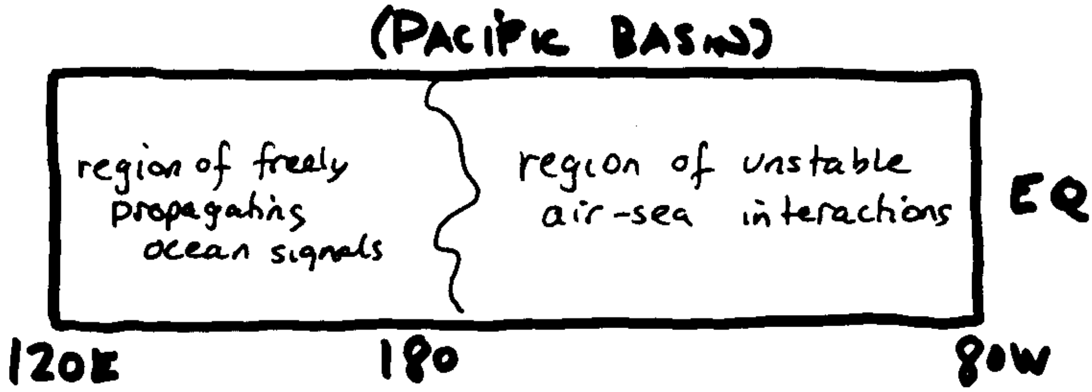
Can you get sufficient reflection of ocean signals off Indonesia?

The delayed oscillator physics explains how ENSO works in a "simple" numerical atmosphere/ocean model. What do the coupled GCMs say? No coupled A/O GCMs available.

What is the cause of irregularity in the ENSO cycle?

What is the limit of predictability of the state of the tropical system?

A simple model for the numerical coupled atmosphere/ocean model

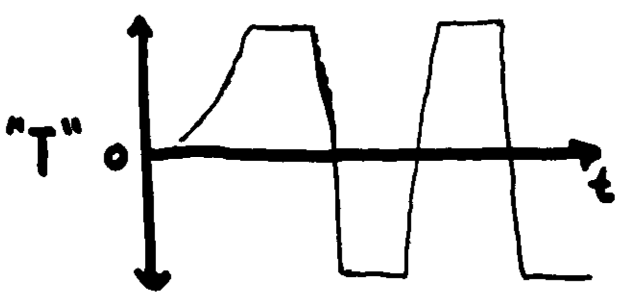


$$\frac{\partial T}{\partial t} = cT - bT(t-\tau) - \varepsilon T^3$$

- **"T" is the eastern basin temperature anomaly**
- **Local coupled instability (c) in the central and eastern Pacific generates a delayed, opposing forcing (b) that eventually reverses the sign of the local anomaly.**
- **A key assumption is that the western Pacific is passive.**

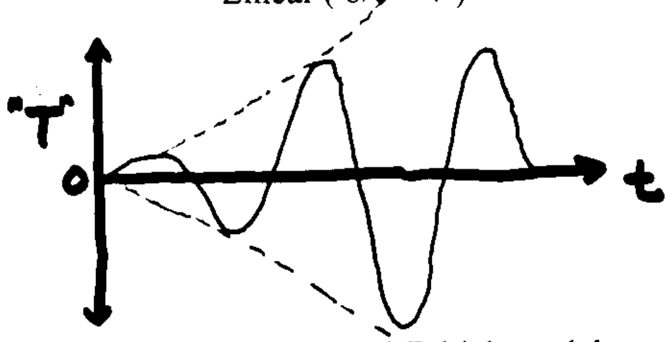
Postulated by Suarez and Shopf (1988), and derived by Battisti and Hirst (1988).

Suarez and Schopf
Nonlinear ($b/c < 1$, $\varepsilon \neq 0$)



Relevant to McCreary (1983)

Battisti and Hirst
Linear ($b/c > 1$)



Relevant to Cane and Zebiak model,
Relevant to some coupled A/O GCMs

INFLUENCE OF BASIC STATE / OCEAN GEOMETRY

or Comparison of Analog Model with Full Model

* Three experiments
(with full model)

1. Change Local
   Instability rate in full model
   (thermal damping)

Today

2. Change 'remote wave' strength (imperfect reflections, mechanical damping)
   (change b)

3. Widen Ocean western (inert) basin
   (change τ)

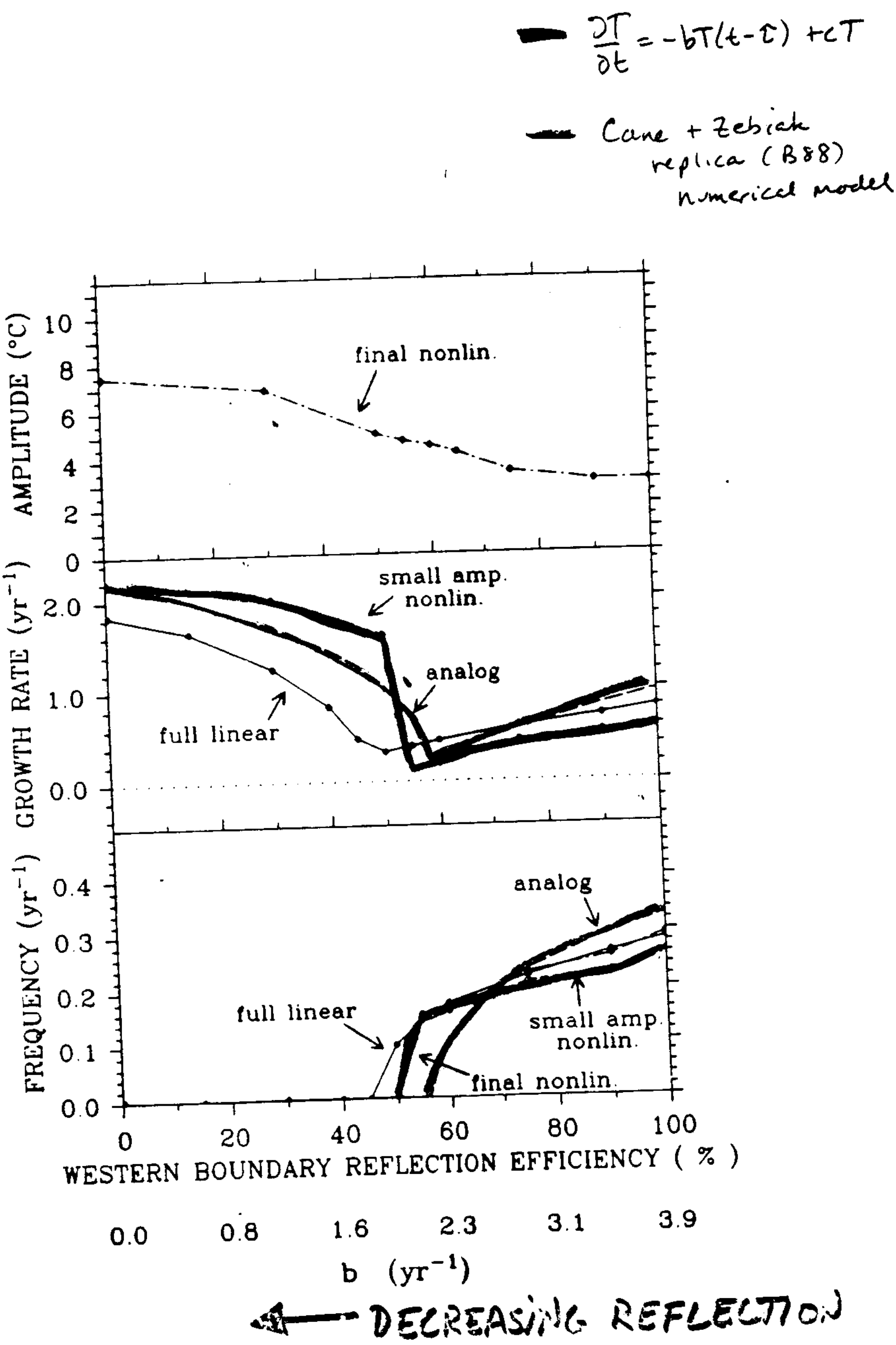
Models

1. Analog

$$\frac{\partial T}{\partial t} = \underline{c}T - \underline{b}T(t-\tau)$$

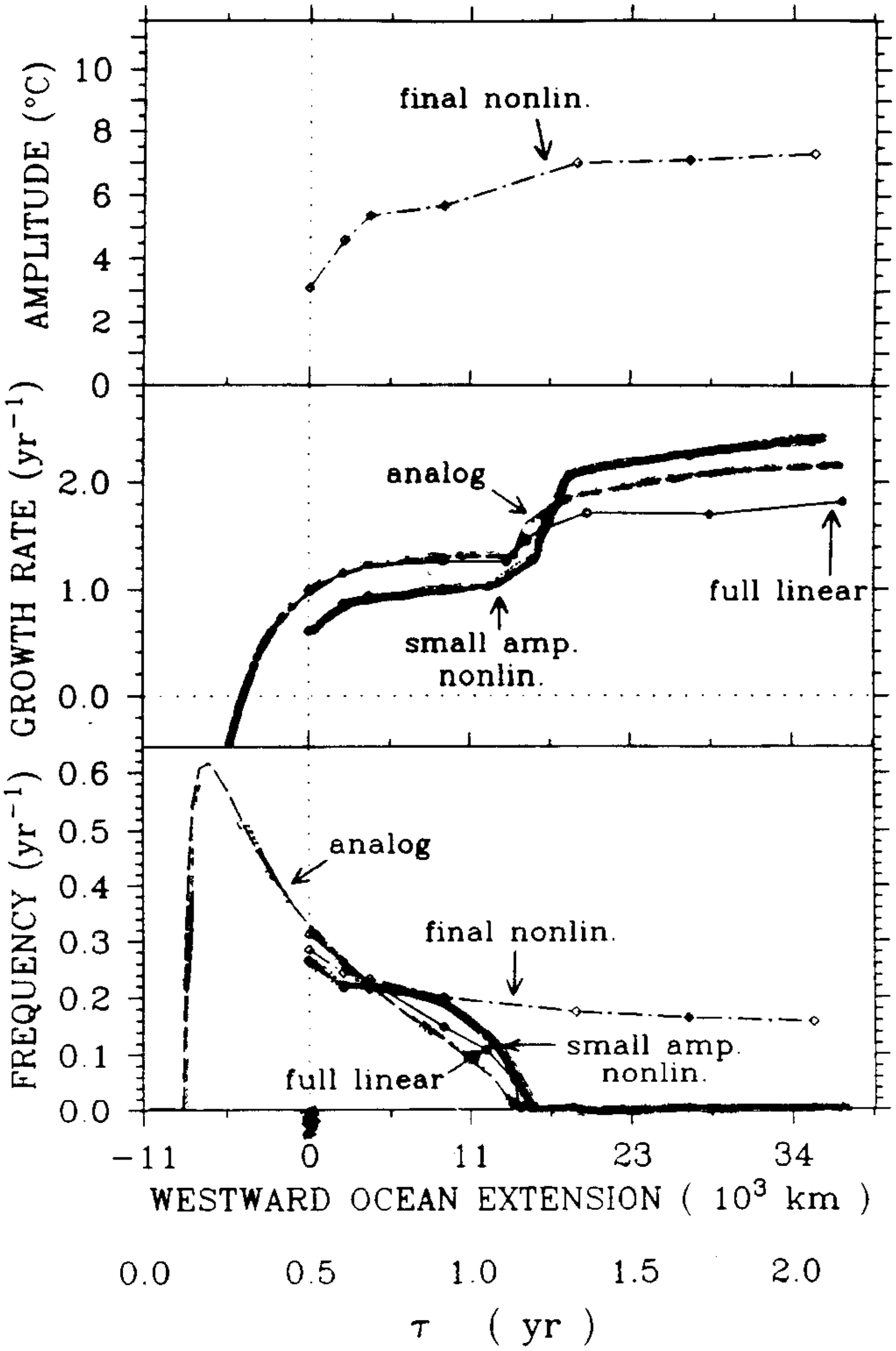
2. Linearized Full Numerical Model

3. Nonlinear Full Numerical Model



$\frac{\partial T}{\partial t} = -bT(t-\tau) + cT$
Cane + Zebiak replica (B88) numerical model
AMPLITUDE (°C)
final nonlin.
GROWTH RATE (yr^{-1})
small amp. nonlin.
analog
full linear
FREQUENCY (yr^{-1})
analog
full linear
small amp. nonlin.
final nonlin.
WESTERN BOUNDARY REFLECTION EFFICIENCY (%)
0.0 0.8 1.6 2.3 3.1 3.9
b (yr^{-1})
DECREASING REFLECTION

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



INCREASE BASIN SIZE →

Summary of Delayed Oscillator Physics

- **The character of the model coupled atmosphere/ocean ENSO seems to be critically dependent on the inter-play of:**

  (1) Local (eastern basin) instability characteristics;

  (2) Delayed ocean wave effects on a localized, growing instability

(1) Depends on a delicate balance in the ocean thermodynamics.

(2) Depends on oceanic wave speed and the reflective and dissipative properties of the oceanic waves.

- **A simple linear analog model (the delayed oscillator) based on these processes qualitatively explains the behaviour of the interannual variability in full numerical coupled atmosphere/ocean model (Battisti and Hirst 1989).**

5C) Verification of DOT from Observations

- **The Ocean Subsurface Thermal Structure**

Is the ocean subsurface thermal structure consistent with DOT? Essentially, yes.

Observations: Kessler 1990; Bigg and Blundell 1992; Mantua and Battisti 1994.

Ocean model hindcasts: Wakata and Sarachik 1991; Chao and Philander 1993; Rosati et al. 1995; Schneider et al. 1995.

- **Western Boundary Refection Efficiency**

Is there enough signal reflected off Indonesia to shut down a growing ENSO event? Yes.

Numerical estimate of minimum (critical) value for DOT to operate is 55% efficiency (BH); Back of the envelope gives 60 - 80% with geometry of Indonesia.

Detailed theoretical calculations by DuPenhoat and Cane (1991) and Clarke (1991) indicate that 81% and 83%, respectively.

Observational evidence indicates 84% of the incoming energy is reflected back (Mantua and Battisti 1994).

- **Coupled Atmosphere/Ocean GCMS and DOT**

Does delayed oscillator physics act in full physics models? Yes.

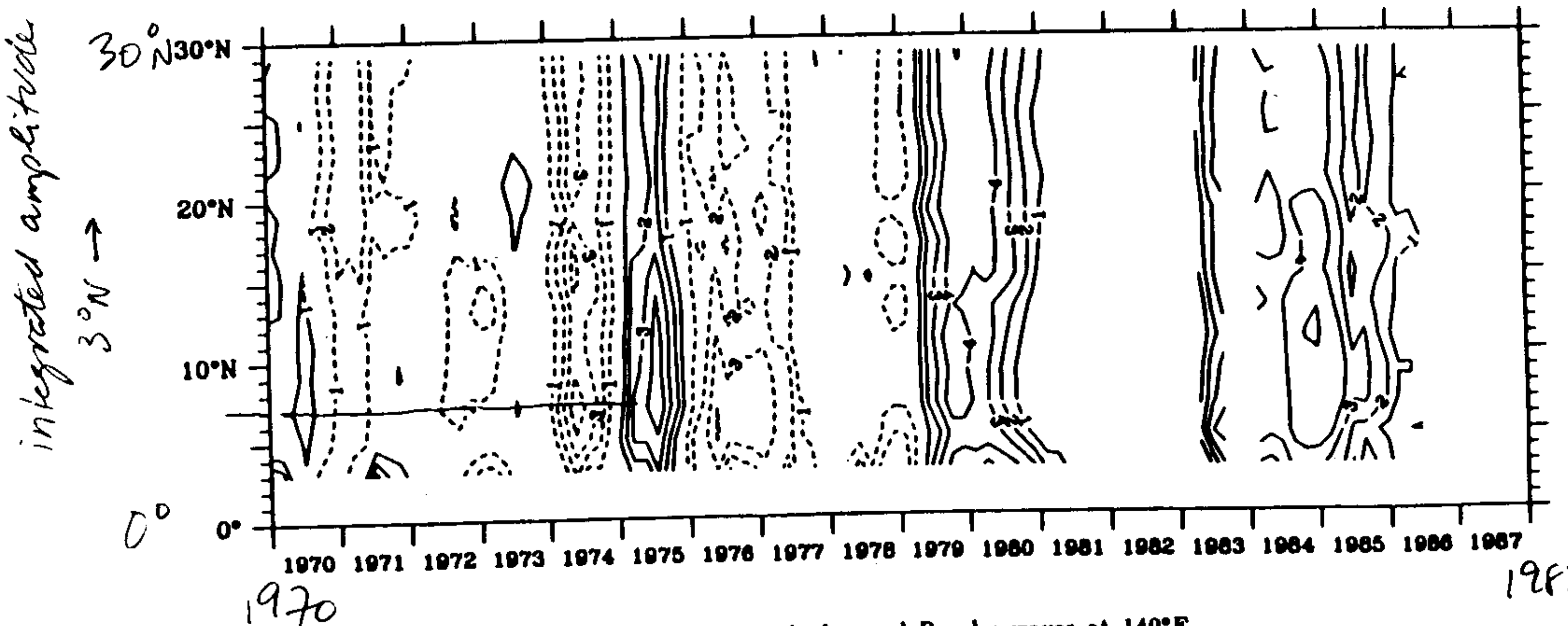
DOT has been shown to be consistent with the interannual variability in the models of Philander et al. 1992, Nagai et al. 1992, Latif et al. 1993, Chao and Philander 1993, Barnett et al. 1993 (hybrid model), Schneider et al. (1995) and Davey et al. 1994.

First Coupled Atmosphere/Ocean General Circulation models used for ENSO Prediction (Latif et al. 1993); predicted ENSO events evolve consistent with the DOT.

KELVIN WAVE ULT AMPLITUDE (m) DUE TO REFLECTED ROSSBY WAVES

$$\text{Amplitude} = \left(\beta/2c^3\pi\right)^{1/2} \int_{3^\circ N}^{y}\int_{0}^{H} u_{g140^\circ E}\, dz\, dy$$

AVERAGE ANNUAL CYCLE REMOVED

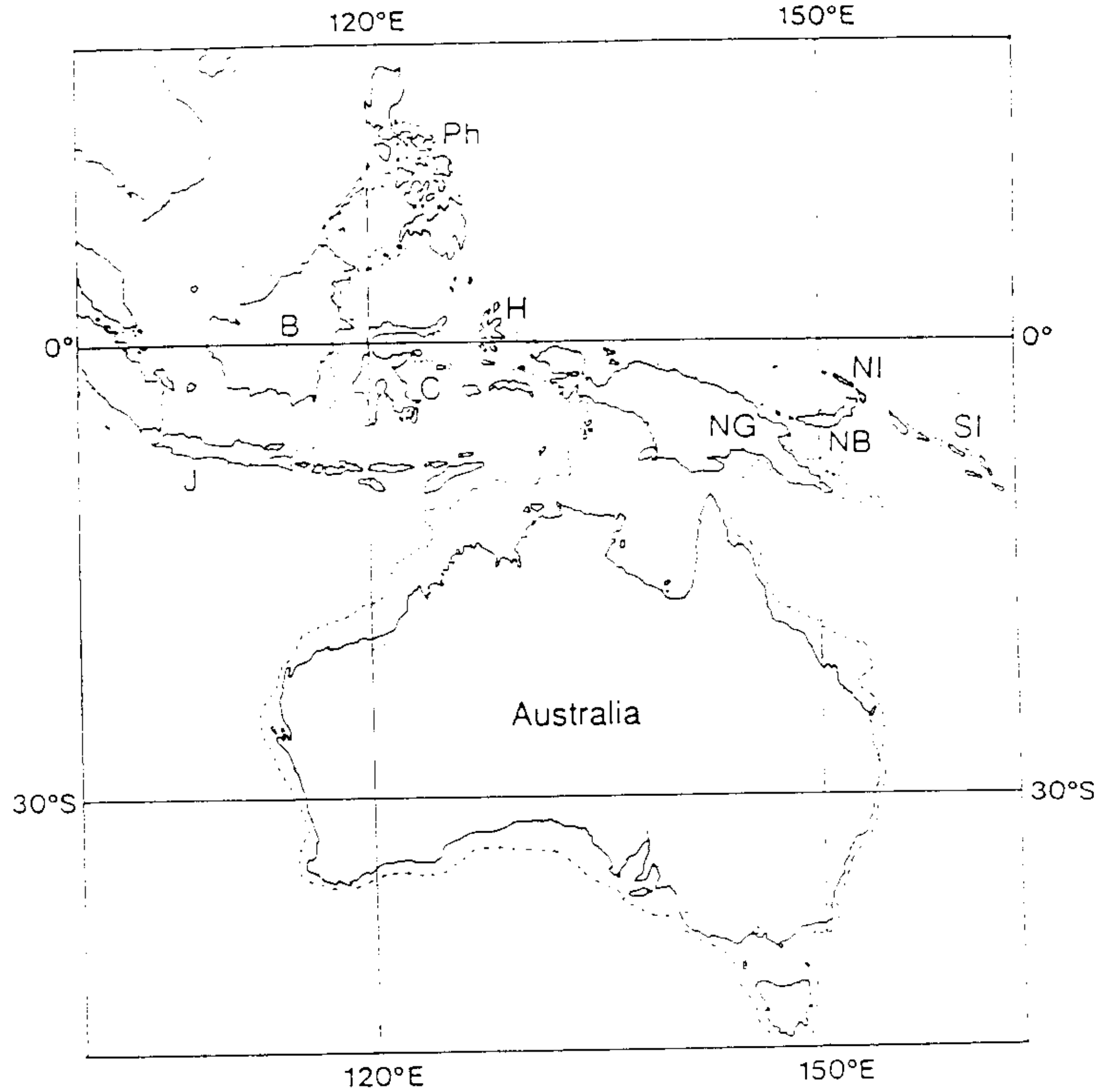


6. Kelvin wave amplitude (m) due to reflected observed Rossby waves at 140°E, shown as a running integral over latitude, calculated according to equation (4). The average annual cycle has been removed. Blank regions occur where data was missing. Solid contours indicate deep and dashed contours shallow anomalies.

from XBT data

Kessler (1990).

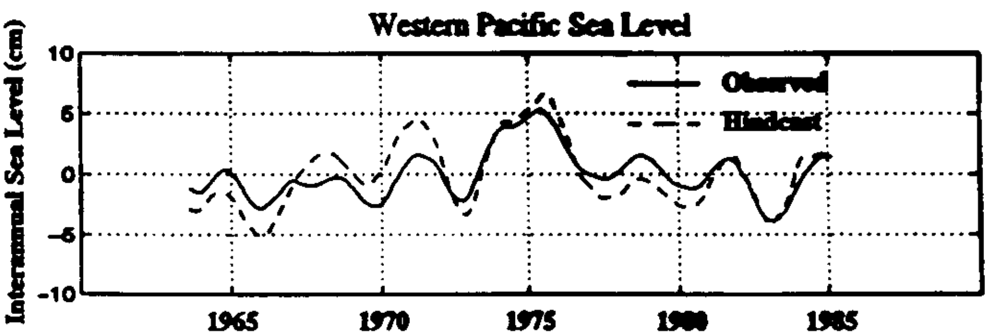
∴ Beyond 7°, only 1 m contribution (sig ~ 20–40 m).


120°E
150°E
Ph
H
B
0°
0°
NI
C
NG
NB
SI
J
Australia
30°S
30°S
120°E
150°E

Strategy: analyze the output from a hindcast of ocean variability

- reduced-gravity ocean model for the tropical Pacific basin forced with the observed surface wind stress from 1961-1992;

Results: the interannual variability from the model reproduces most of that from the observations . . .

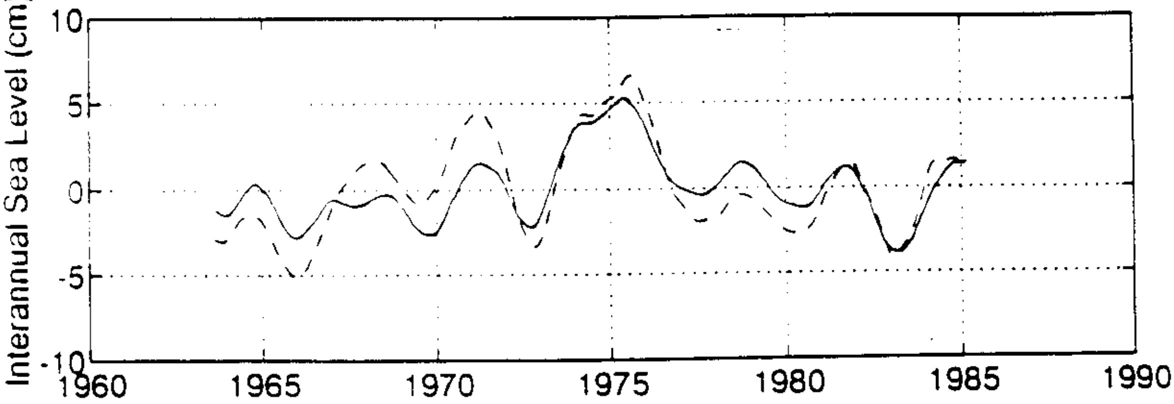


. . . and the evolution of INDIVIDUAL (warm and cold) ENSO events follows the delayed oscillator scenario.

- Delayed oscillator theory cannot explain the aperiodic nature of the observed ENSO cycle.

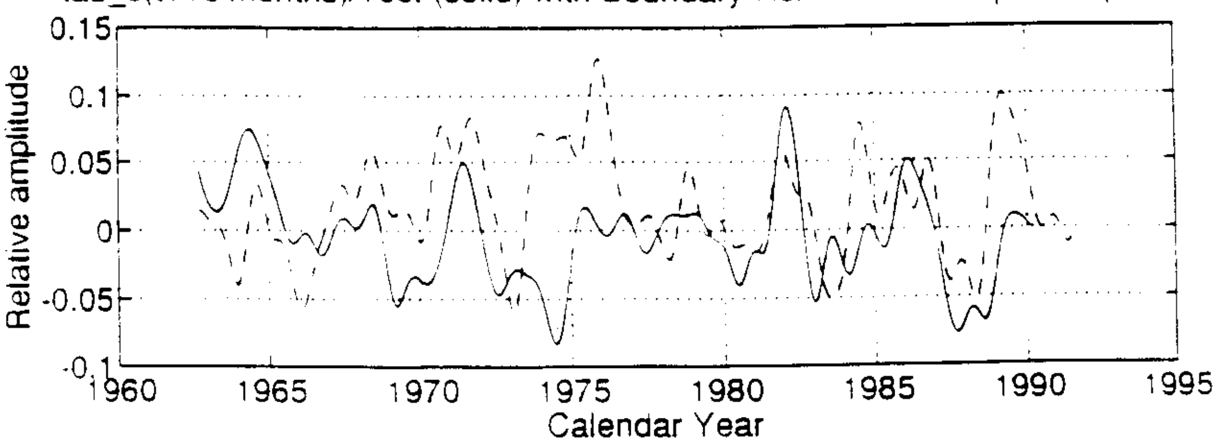
(Mantua and Battisti, '94)

Filtered Kelvin Wave Sea Level: Observed (solid) vs. Hindcast (dashed)



7c

tau_b(t+16 months)/100. (solid) with Boundary Kelvin mode amplitude (dashed)



- ## Coupled Atmosphere/Ocean GCMS and DOT

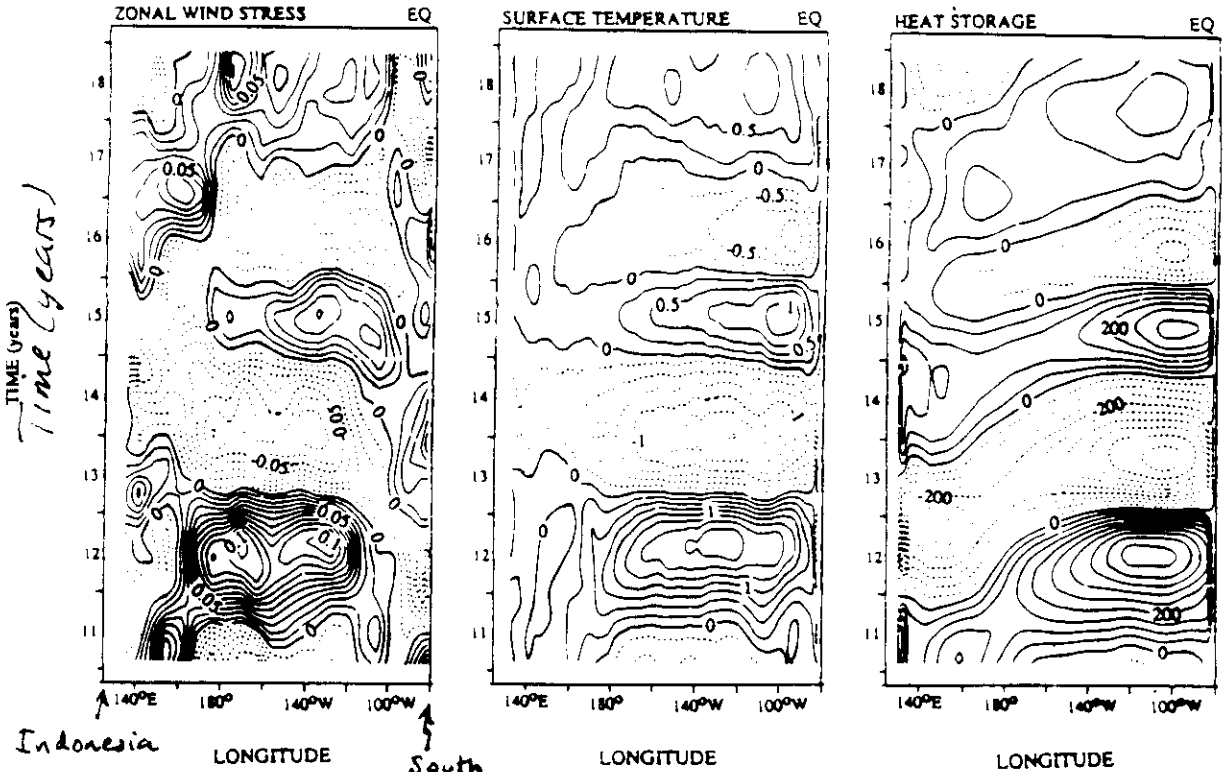
Does delayed oscillator physics act in full physics models? Yes.

Philander et al. 1992, Nagai et al. 1992, Latif et al. 1993, Chao and Philander 1993, Barnett et al. 1993 (hybrid model), Schneider et al. (1995) and Davey et al. 1994. Coupled Atmosphere/Ocean General Circulation models used for ENSO Prediction (Latif et al. 1993): ENSO events evolve consistent with the DOT.

- ## Verification of DOT from observations

Is the ocean subsurface thermal structure consistent with DOT? Essentially, yes.

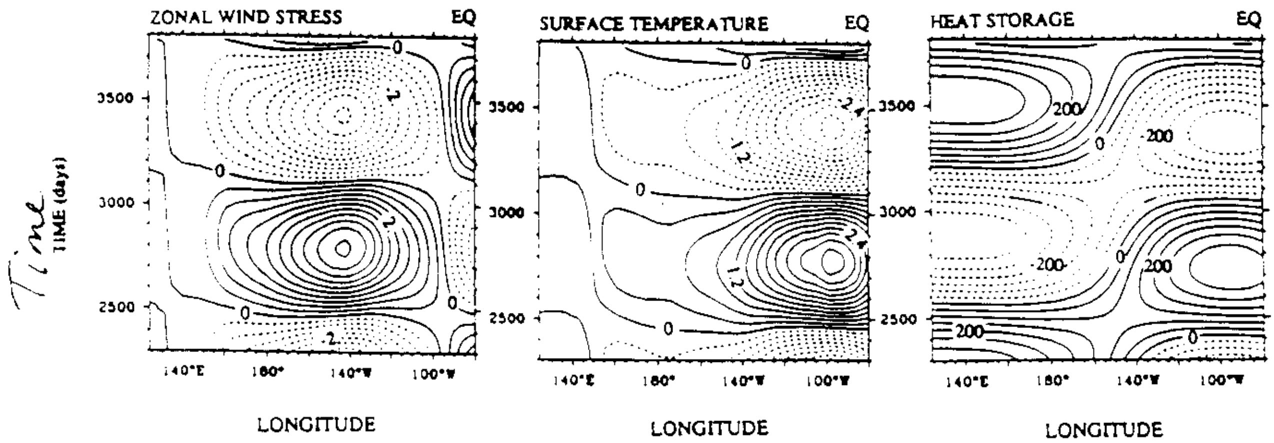
Observations: Kessler 1990; Bigg and Blundell 1992; Mantua and Battisti 1994. Ocean model hindcasts: Wakata and Sarachik 1991; Chao and Philander 1993; Rosati et al. 1995; Schneider et al. 1995.



Time (years)
Indonesia
South America
Coupled A/O GCMs
(Chao + Philander 1993)

FIG. 18. Time-longitude plots along the equator of zonal wind stress (dyn cm^{-2}), sea surface temperature (°C), and heat storage (°C m) in the coupled ocean-atmosphere GCMs of Philander et al. (1992). Solid (dashed) lines indicate westerly (easterly) winds, warm (cold) waters, and deepening (shoaling) of the thermocline.

Zonal Wind Stress
Sea Surface Temperature
Heat Storage Upper Ocean



Time
Cane/Zebiak replica (BH)

FIG. 19. Time-longitude plots along the equator of zonal wind stress (in nondimensional unit), sea surface temperature (°C), and thermocline depth (in unit of 5×10^{-2} m) in the coupled ocean-atmosphere model of Battisti and Hirst (1989). Solid (dashed) lines indicate westerly (easterly) winds, warm (cold) waters, and deepening (shoaling) of the thermocline.

5D) ENSO-like Variability in the Atlantic Basin

- **ENSO-like variability in the Atlantic Basin Exists**

  Zebiak 1994; Chang et al. 1996.

- **Assuming DOT, however, ...**

  The geometry of the basin excludes the possibility of unstable coupled modes in the Atlantic Basin (Zebiak 1994; Battisti 1988; Chang et al. 1996).

  Indian Ocean: the "homogeneous" basic state.

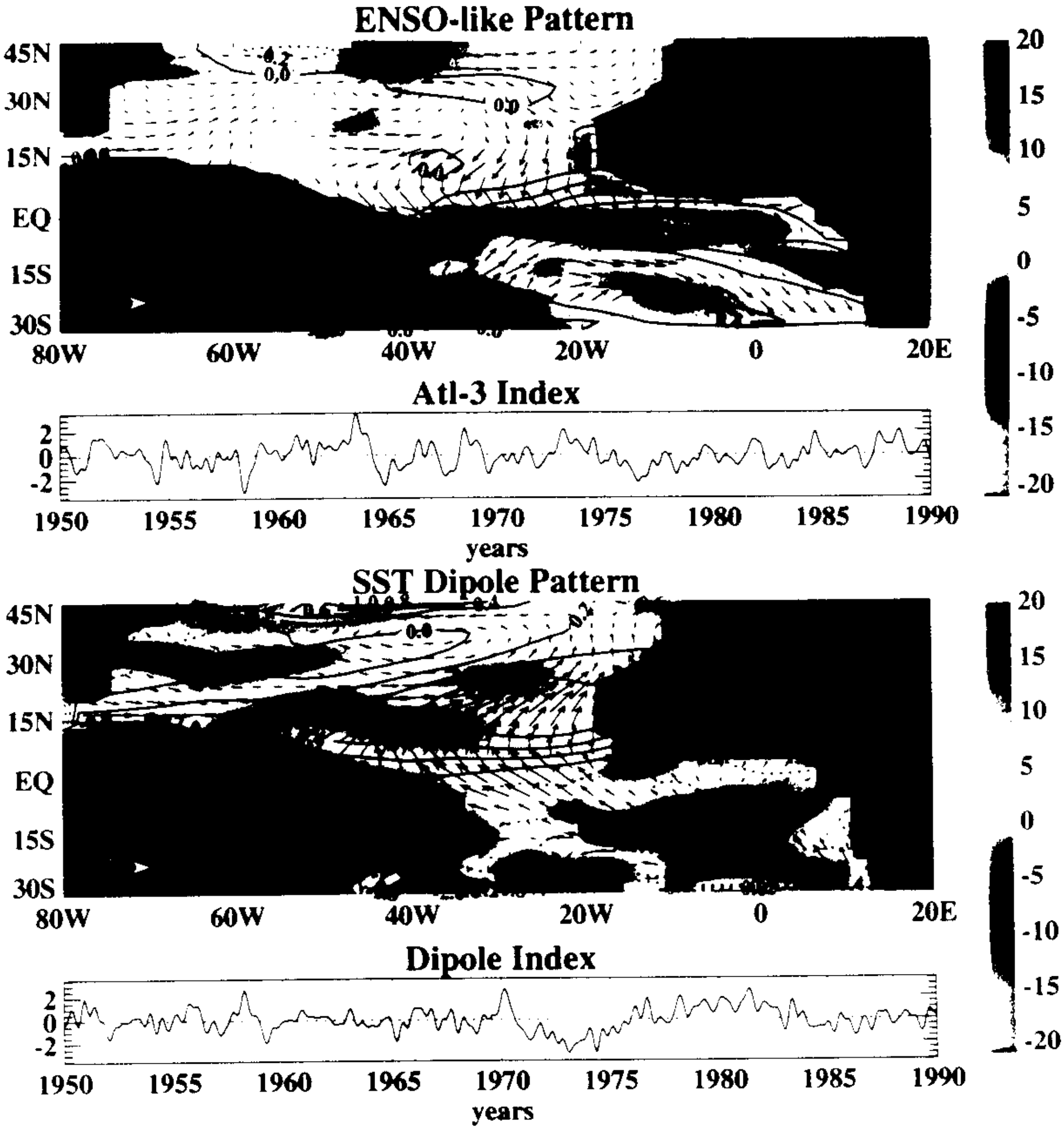


Figure 1. The Atlantic ENSO-like and SST dipole patterns revealed by a regression analysis of COADS (see text) for January,1950 to December,1989. The ENSO-like pattern was obtained by regressing surface variables including SSTA, wind and heat flux anomalies upon an Atl-3 index defined by averaging SSTA in a 20°x8° region centered at 10°W and the equator. The SST dipole pattern was obtained by regressing the surface vairables upon a dipole index generated by differencing area-averaged SSTAs in the Northern and Southern Hemispheres. The area-averages were taken over 18°-wide, cross-basin, longitudinal bands centered at 15°S and 15°N. Both indexes were normalized by their own standard deviations whose values are 0.41°C for the Atl-3 index and 0.46°C for the dipole. Contours represent SSTAs and are in units of 0.2°C per standard deviation of the reference time series. Vectors depict wind-stress anomalies. The unit vector in the lower-left conner represents an easterly wind-stress anomaly of 0.1 dyncm^{-2} per standard deviation of the reference time series. Colors imdicate the strength of surface heat flux anomalies in Wm^{-2} per standard deviation of the reference time series.

5. One Year in Advance, ENSO is Predictable.

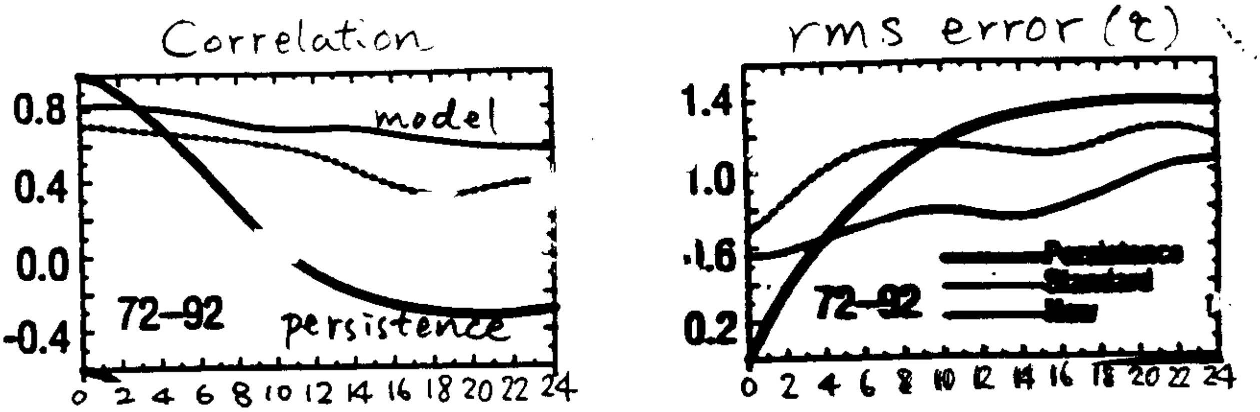
- **Implications for long-range climate forecasting**

  If the ENSO physics in the models (the delayed oscillator physics) is relevant to Nature's ENSO events, then ENSO events should be predictable at least nine months in advance

- **Predictions of ENSO using dynamical climate (atmosphere/ocean/land/ice) models**

  Successful predictions have, and are, being made by about one dozen research groups.

Zebiak-Cane Model Skill in NINO3



lead Time in months

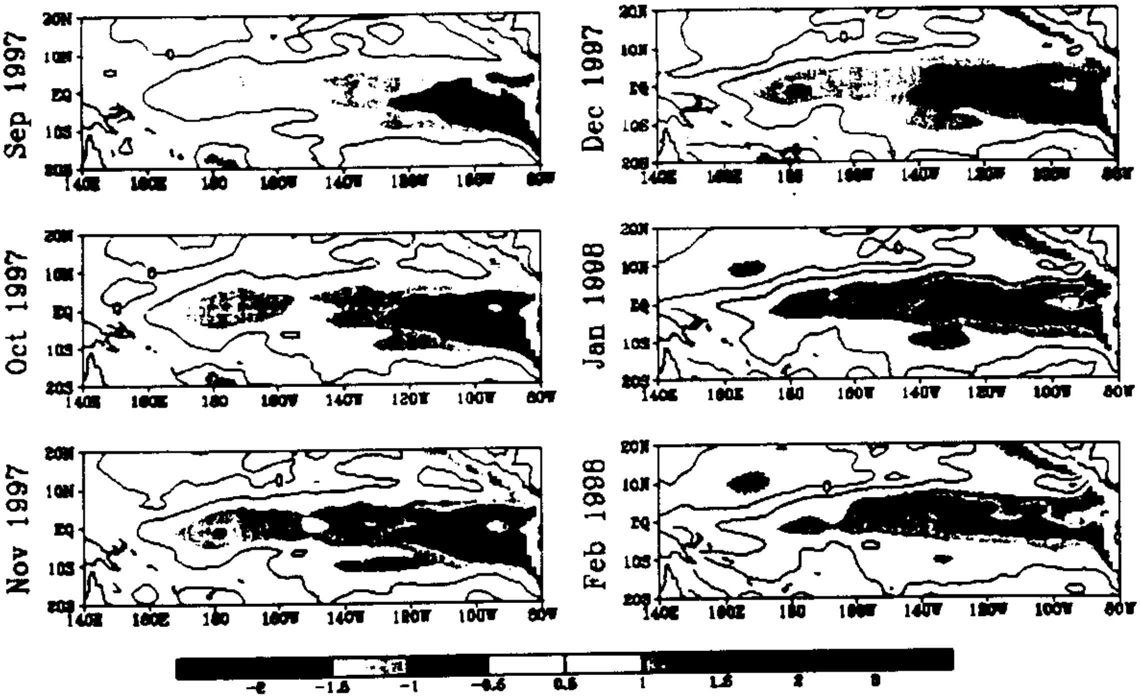
(D. Chen et al. 1995 Science)

- Useful skill up to 1-2-year-lead time
  - much better than persistence
  - correlation > 0.5

FORECAST FOR NEXT WINTER (DEC 97 – FEB 98)

NOAA/NCEP

FORECAST SST Anomaly



Last Update: Thu Apr 10 1997

Summary

- Coupling the atmosphere and ocean may lead to *locally* unstable modes. The structure of these instabilities depends crucially on the mix of processes that affect SST. However, inhomogenieties in the basic state of the ocean and atmosphere lead to fundamentally different (basin) coupled modes: the "delayed oscillator."
- The key processes for the delayed oscillator mechanism are localized atmosphere/ocean instabilities and equatorial ocean adjustment; they have comparable time-scales. These basin modes have much in common with the observed ENSO events (e.g., the structure of the quasi-stationary SST anomalies confined to the central/eastern Pacific).
- Analyses of the subsurface thermal structure (a.k.a the ocean memory) from the observations (XBT data) and the forced ocean models of the Pacific indicate these data are largely consistent with the delayed oscillator theory for individual ENSO events.
- The delayed oscillator theory for ENSO appears to explain the interannual variability in the tropical Pacific of several coupled atmosphere/ocean general circulation models, and in many of the intermediate level coupled models.

- The DOT (more generally, the ocean memory) provides the foundation for the extraordinary skill in the long-lead (one year) forecasts of ENSO that is demonstrated by several coupled atmosphere/ocean models and is providing clues to the seasonal structure in the forecast skill.
- Robust interannual variability *vis a vis* the delayed oscillator physics is unique to the Pacific Basin.