- The Delayed Oscillator
- Zebiak and Cane (1987) Model
- Other Theories
- Theory of ENSO teleconnections

Goal: Develop quantitative understanding of ENSO genesis, evolution, and impacts

The delayed oscillator

The leading theoretical model is the delayed oscillator [see Battisti and Hirst, 1989]:

$$\frac{\partial Ts(t)}{\partial t} = bTs(t) - cTs(t-\tau)$$

Here, Ts is the temperature in the East Pacific, b and c are positive constants, and τ is a time-lag determined by equatorial oceanic adjustment.

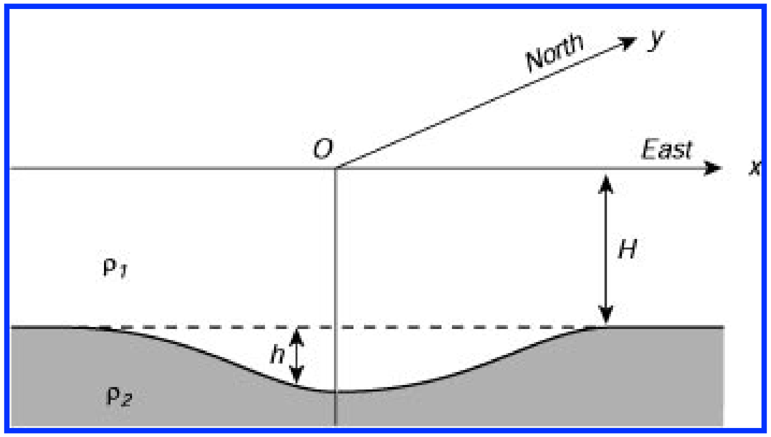
- *The first term on the RHS can be thought of a representing a positive feedback associated with the atmosphere, e.g., the large-scale Darwin-Tahiti pressure difference (the SOI).*

- *The second term represents a negative feedback associated with thermocline adjustment via equatorial waves.*

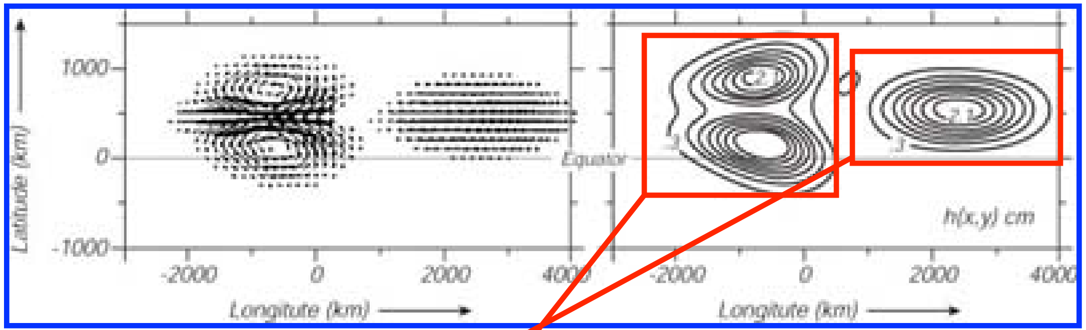
- *The time delay is the time required for Rossby waves to propagate westward, reflect at the boundary, and return to the region of origin.*

Equatorial Kelvin & Rossby Waves

2-layer oceanic SWE model



Surface currents (l) and thermocline displacements (r) for a Gaussian perturbation



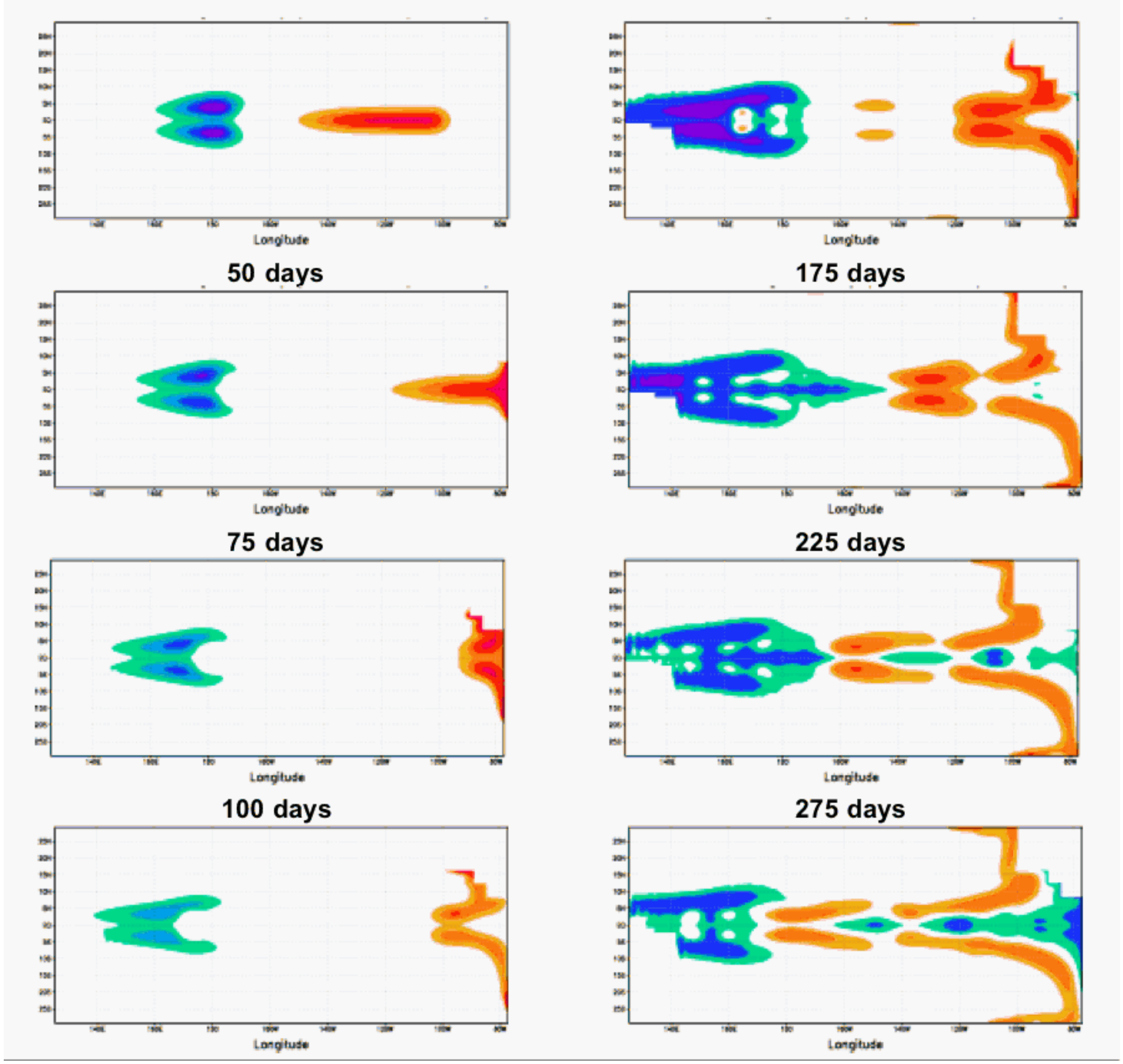
$$c_g[Kelvin] = \sqrt{g'H} \quad ; \quad g' = g(\rho_2/\rho_1 - 1)$$

Kelvin wave: Non-dispersive, eastward propagating (~2 m/s for H = 150 m)

$$c_g[Rossby] = \sqrt{g'H}/(2l+1) \quad ; \quad l = 1,2,\ldots$$

Rossby waves: Dispersive, westward propagating (fastest is 1/3 of Kelvin wave group velocity)

Propagating equatorial waves



http://iri.columbia.edu/climate/ENSO/enso.html

Zebiak and Cane (1987) Model

Oceanic Model: 2 layer (surface=1 & underlying=2)

$$u_t - \beta_0 y v = -g' h_x + \tau^{(x)}/\rho H - r u$$
$$\beta_0 y u = -g' h_y + \tau^{(y)}/\rho H - r v$$
$$h_t + H(u_x + v_y) = -r h,$$
$$\mathbf{u} = H^{-1}(H_1 \mathbf{u}_1 + H_2 \mathbf{u}_2).$$

Shear:
$$r_s u_s - \beta_0 y v_s = \tau^{(x)}/\rho H_1$$
$$r_s v_s + \beta_0 y u_s = \tau^{(y)}/\rho H_1,$$

Entrainment: $w_s = H_1[(u_1)_x + (v_1)_y].$

Surface layer temp:

$$\frac{\partial T}{\partial t} = -\mathbf{u}_1 \cdot \nabla(\bar{T} + T) - \bar{\mathbf{u}}_1 \cdot \nabla T - \{M(\bar{w}_s + w_s) - M(\bar{w})\} \times \bar{T}_z - M(\bar{w}_s + w_s)\frac{T - T_e}{H_1} - \alpha_s T, \quad \text{(A11)}$$

Atmospheric Model: steady state Gill (1980) model on equatorial β-plane; surface pressure dependent on SST and low-level convergence

$$+\epsilon u_a{}^n - \beta_0 y v_a{}^n = -(p^n/\rho_0)_x$$
$$\epsilon v_a{}^n + \beta_0 y u_a{}^n = -(p^n/\rho_0)_y$$

$$\epsilon(p^n/\rho_0) + c_a{}^2[(u_a{}^n)_x + (v_a{}^n)_y] = -\dot{Q}_s - \dot{Q}_1{}^{n-1}$$
$$\dot{Q}_s = (\alpha T)\exp[\bar{T} - 30°\text{C})/16.7°\text{C}]$$
$$\dot{Q}_1{}^n = \beta[M(\bar{c} + c^n) - M(\bar{c})],$$

$$c^n \equiv -(u_a{}^n)_x - (v_a{}^n)_y.$$

$$M(x) = \begin{cases} 0, & x \leqslant 0 \\ x, & x > 0. \end{cases}$$

Zebiak and Cane (ZC, 1987) model

- Steady-state SWE coupled ocean-atmosphere system on an equatorial beta plane
- Physics
  - Inclusion of Rayleigh friction
  - Newtonian cooling
  - Heating: SST and time-dependent low-level moisture convergence
- Model integrations assume:
  - Prescribed mean quantities: model solutions for perturbations
  - Prescribed initial winds: Guassian zonal wind perturbation held fixed for the first 4 months, then removed

ZC model equations

Oceanic Model: 2 layer (surface=1 & underlying=2)

$$u_t - \beta_0 y v = -g' h_x + \tau^{(x)}/\rho H - ru$$
$$\beta_0 y u = -g' h_y + \tau^{(y)}/\rho H - rv$$
$$h_t + H(u_x + v_y) = -rh,$$
$$\mathbf{u} = H^{-1}(H_1 \mathbf{u}_1 + H_2 \mathbf{u}_2).$$

Shear:

$$r_s u_s - \beta_0 y v_s = \tau^{(x)}/\rho H_1$$
$$r_s v_s + \beta_0 y u_s = \tau^{(y)}/\rho H_1,$$

Entrainment: $w_s = H_1[(u_1)_x + (v_1)_y].$

Surface layer temp:

$$\frac{\partial T}{\partial t} = -\mathbf{u}_1 \cdot \nabla(\bar{T} + T) - \bar{\mathbf{u}}_1 \cdot \nabla T - \{M(\bar{w}_s + w_s) - M(\bar{w})\}$$
$$\times \bar{T}_z - M(\bar{w}_s + w_s)\frac{T - T_e}{H_1} - \alpha_s T, \quad \text{(A11)}$$

Atmospheric Model: steady state Gill (1980) model on equatorial β-plane; surface pressure dependent on SST and low-level convergence

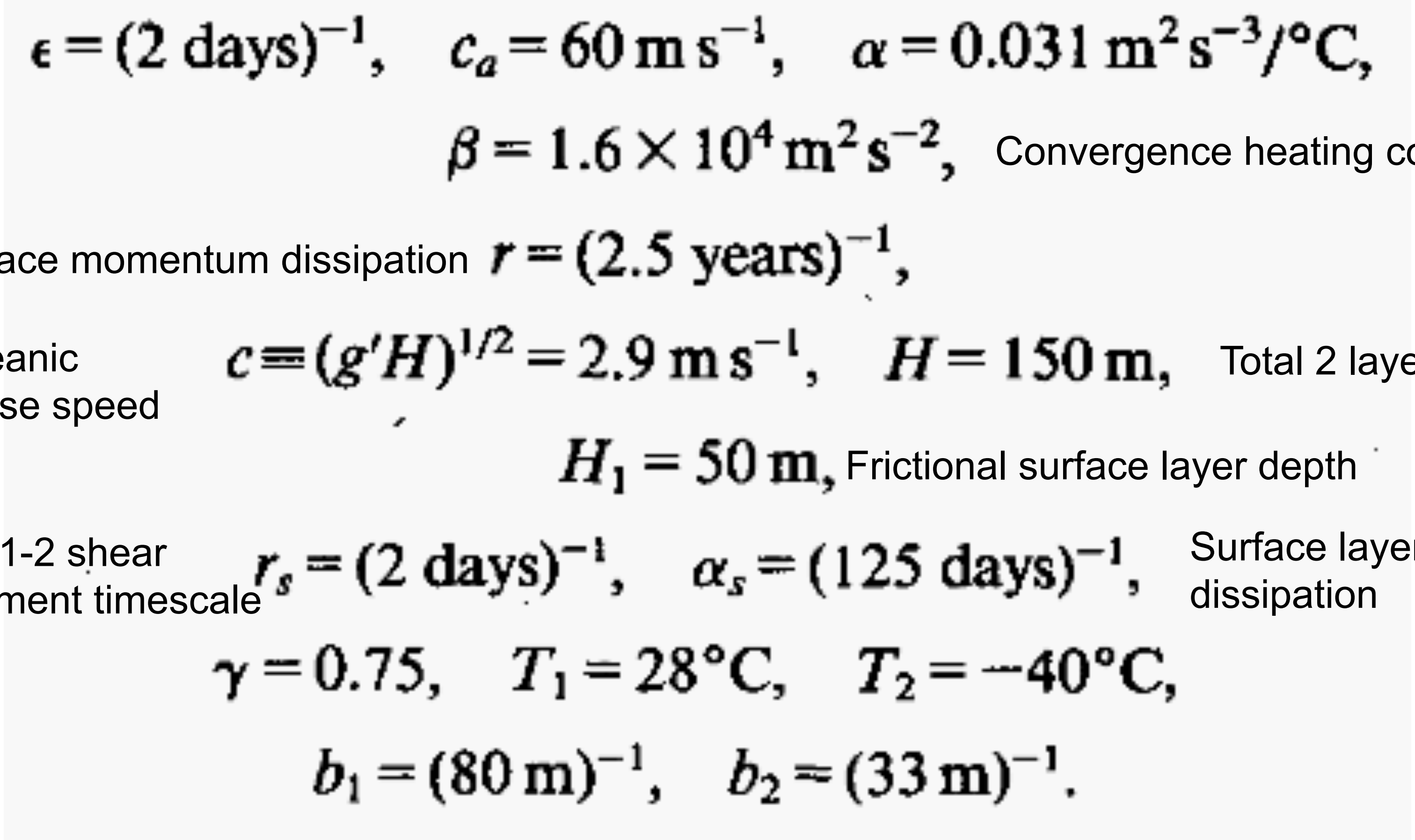
$$+\epsilon u_a{}^n - \beta_0 y v_a{}^n = -(p^n/\rho_0)_x$$
$$\epsilon v_a{}^n + \beta_0 y u_a{}^n = -(p^n/\rho_0)_y$$

$$\epsilon(p^n/\rho_0) + c_a{}^2[(u_a{}^n)_x + (v_a{}^n)_y] = -\dot{Q}_s - \dot{Q}_1{}^{n-1}$$
$$\dot{Q}_s = (\alpha T)\exp[\bar{T} - 30°\text{C})/16.7°\text{C}]$$
$$\dot{Q}_1{}^n = \beta[M(\bar{c} + c^n) - M(\bar{c})],$$

$$c^n \equiv -(u_a{}^n)_x - (v_a{}^n)_y.$$

$$M(x) = \begin{cases} 0, & x \leqslant 0 \\ x, & x > 0. \end{cases}$$

ZC parameters



Atmospheric damping time Atmospheric phase speed SST heating coefficient

$$\epsilon = (2\ \text{days})^{-1}, \quad c_a = 60\ \text{m s}^{-1}, \quad \alpha = 0.031\ \text{m}^2\,\text{s}^{-3}/^\circ\text{C},$$

$$\beta = 1.6 \times 10^4\ \text{m}^2\,\text{s}^{-2},$$ Convergence heating coefficient

Subsurface momentum dissipation $r = (2.5\ \text{years})^{-1},$

Oceanic
phase speed

$$c = (g'H)^{1/2} = 2.9\ \text{m s}^{-1}, \quad H = 150\ \text{m},$$ Total 2 layer depth

$$H_1 = 50\ \text{m},$$ Frictional surface layer depth

Layer 1-2 shear
adjustment timescale

$$r_s = (2\ \text{days})^{-1}, \quad \alpha_s = (125\ \text{days})^{-1},$$

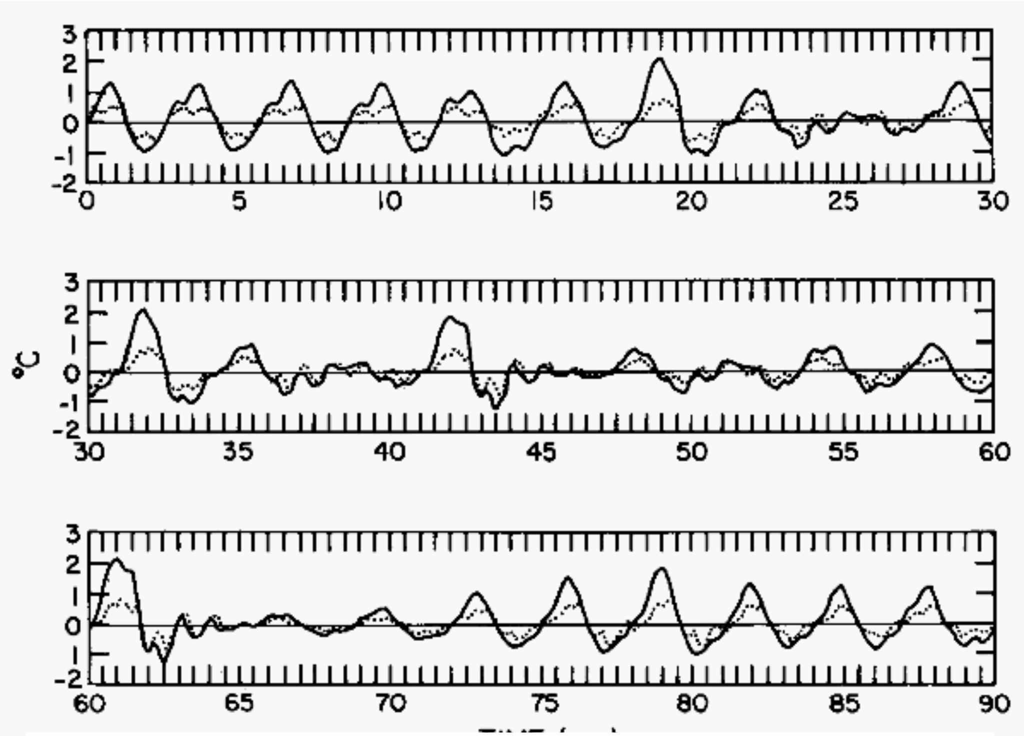
Surface layer thermal
dissipation

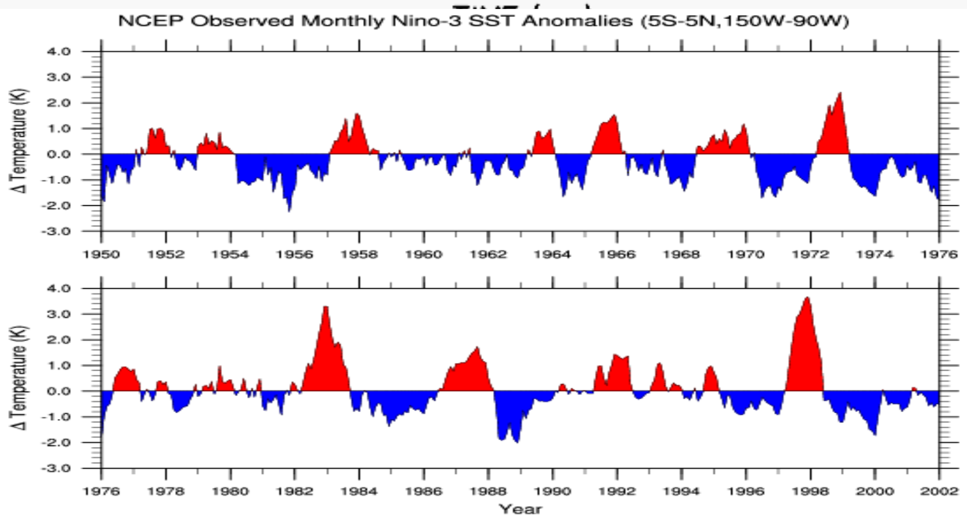
$$\gamma = 0.75, \quad T_1 = 28^\circ\text{C}, \quad T_2 = -40^\circ\text{C},$$

$$b_1 = (80\ \text{m})^{-1}, \quad b_2 = (33\ \text{m})^{-1}.$$

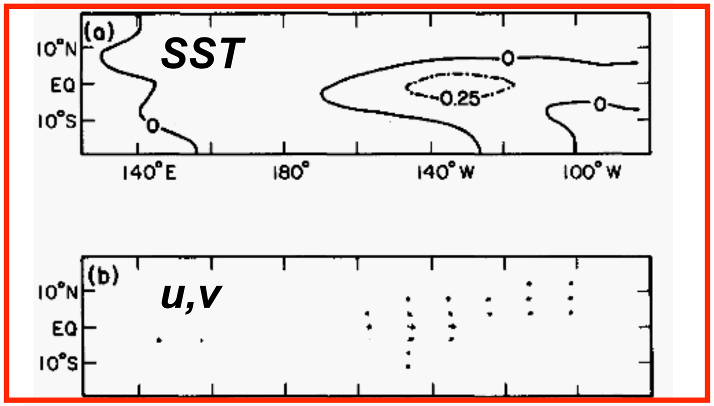
Entrainment parameters

ZC results: NINO3 SSTs





ZC results: Time evolution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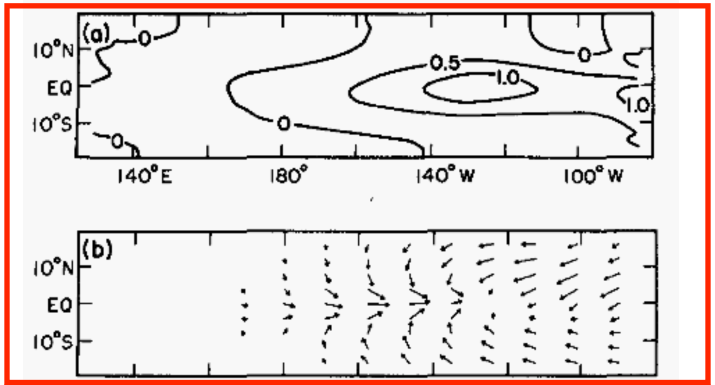
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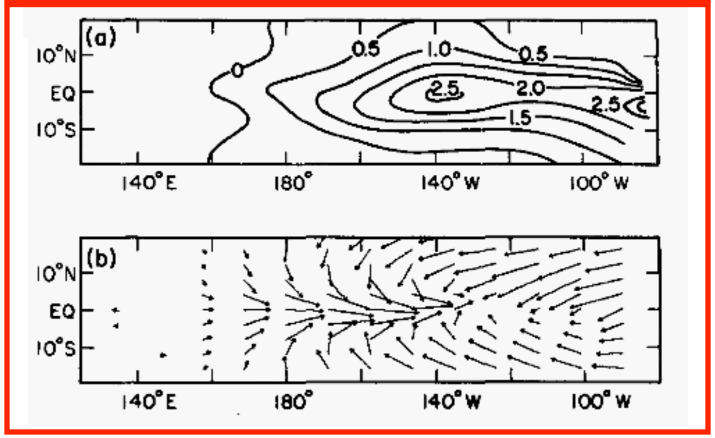
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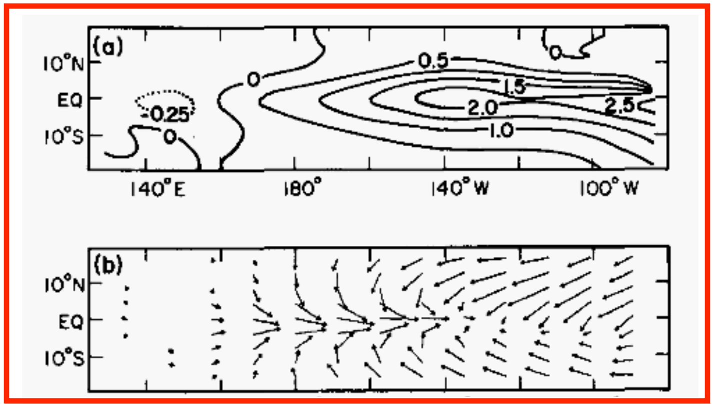
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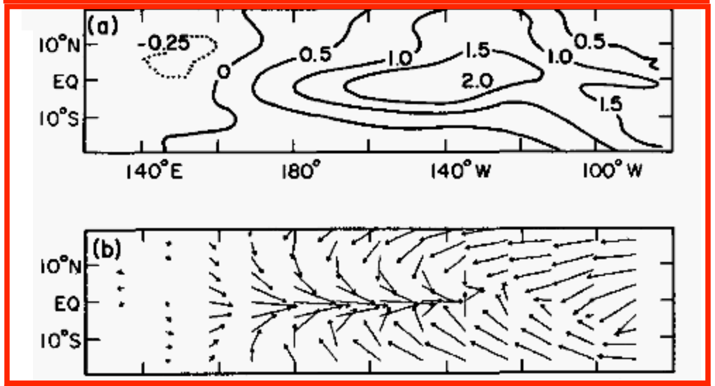
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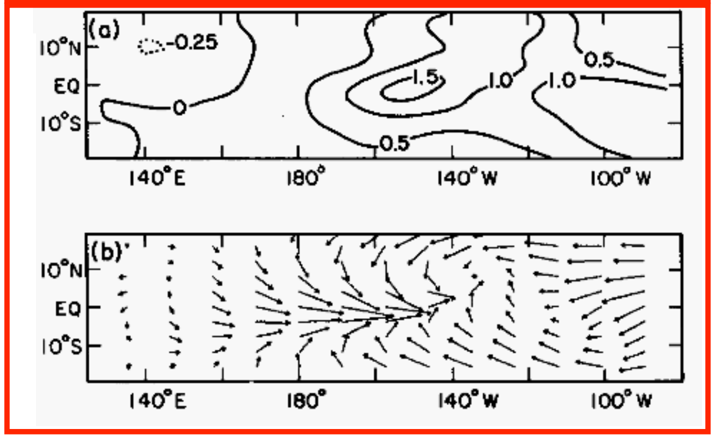
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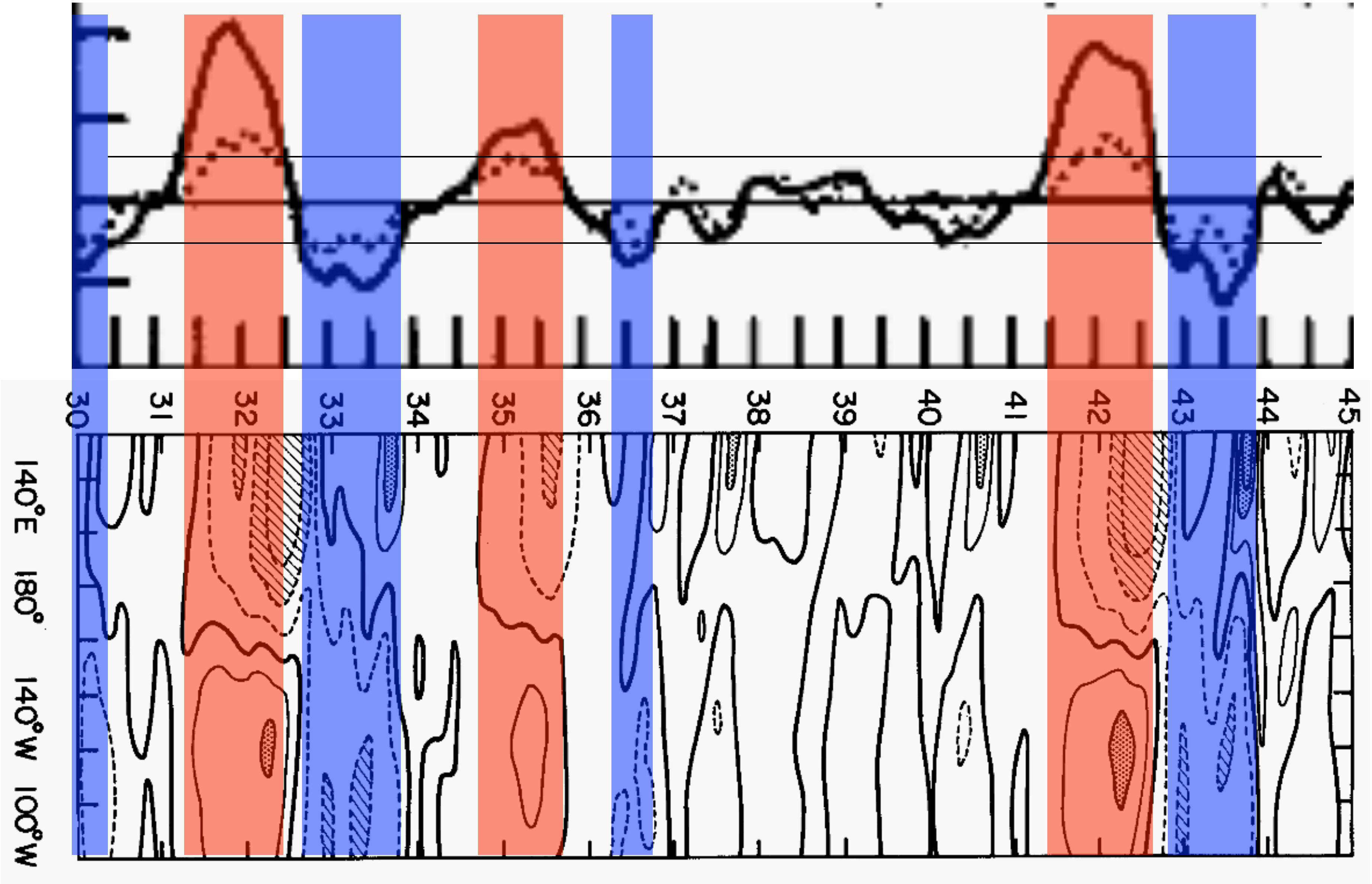
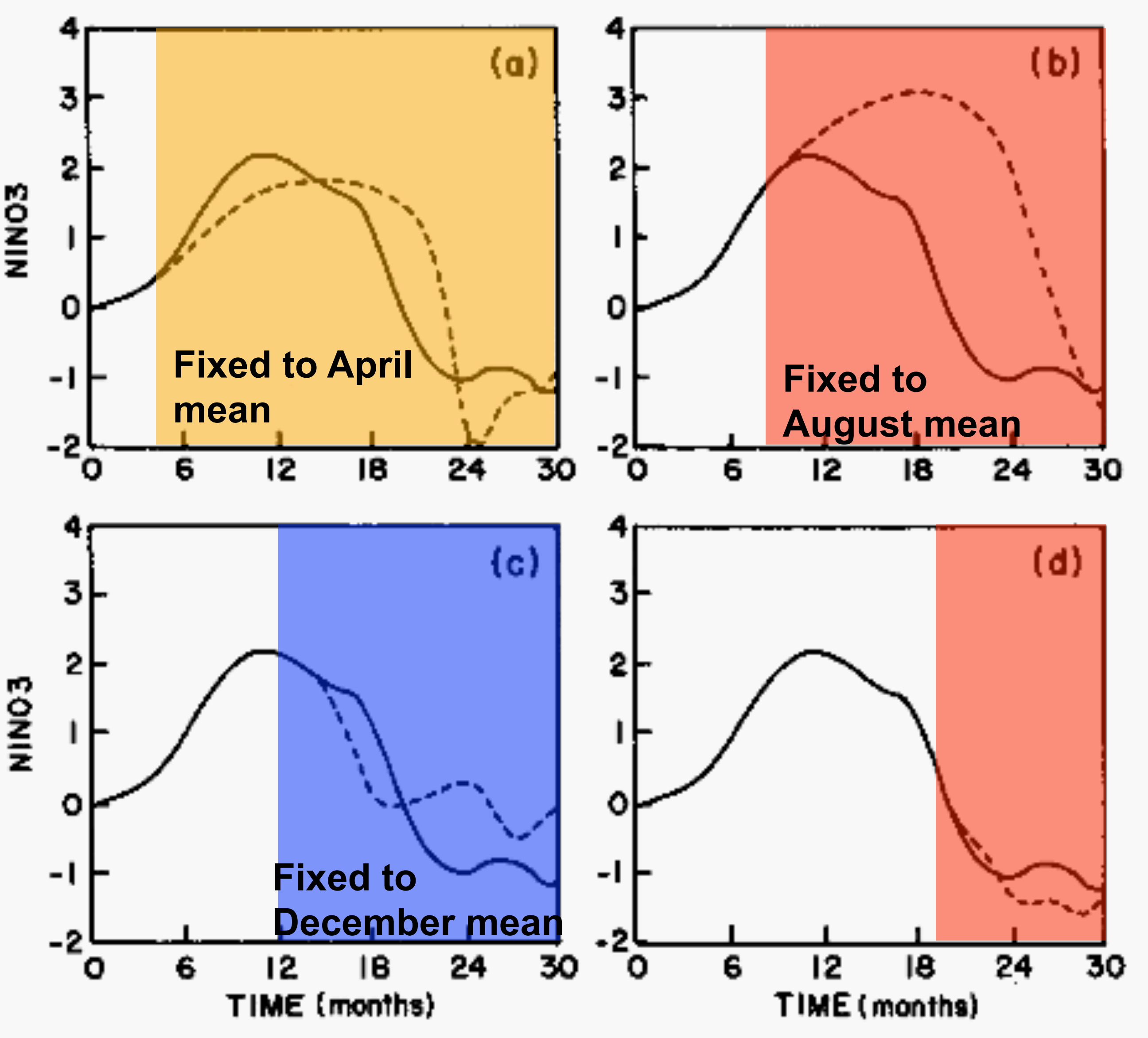
ZC results: Thermocline depth



ZC results: Interaction w/ annual cycle



Fixed to April mean

Fixed to August mean

Fixed to December mean

ZC results: Varying heat content

Insensitivity to areal mean heat content:

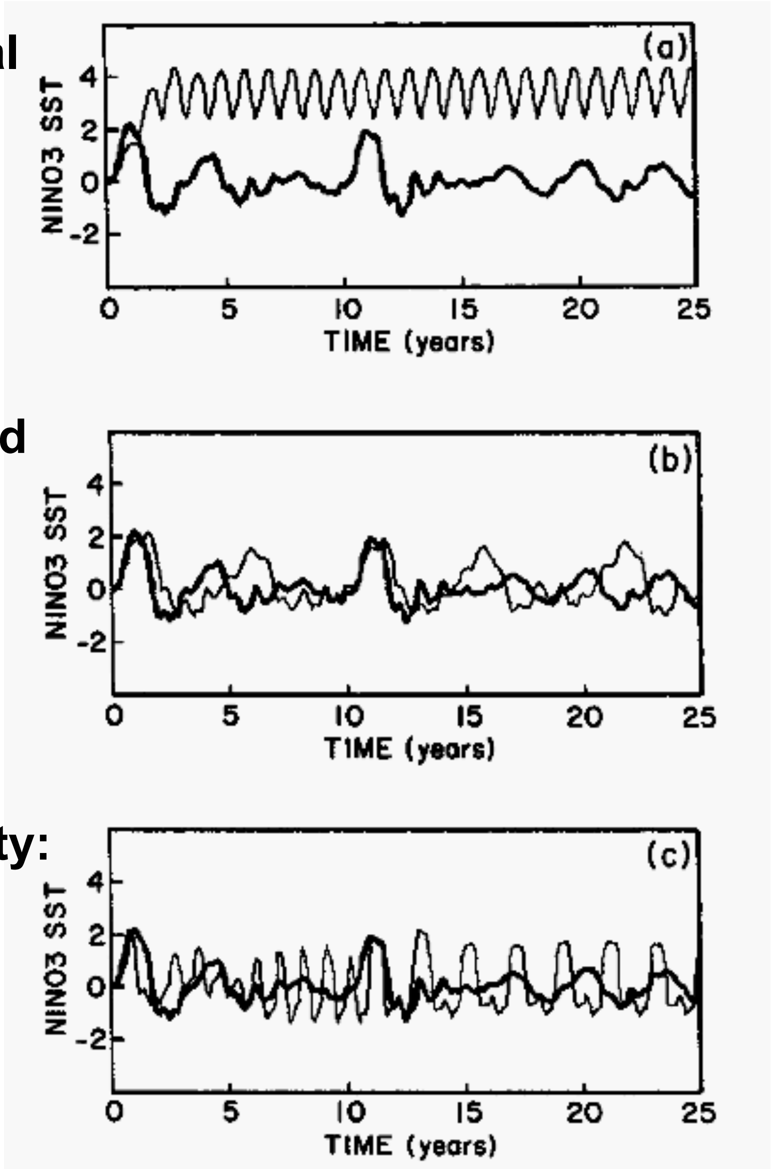
h→h-<h>

Partially suppressed sensitivity:

h→h-0.5<h>

Enhanced sensitivity:

h→h+2<h>



$$T_e = \gamma T_{\text{sub}} + (1-\gamma)T.$$

T_{sub} has the form

$$T_{\text{sub}} = \begin{cases} T_1\{\tanh[b_1(\bar{h}+h)] - \tanh(b_1\bar{h})\}, & h>0 \\ T_2\{\tanh[b_2(\bar{h}-h)] - \tanh(b_2\bar{h})\}, & h<0, \end{cases}$$

ZC model summary (I)

- Similarities to observed ENSO
  - Periodicity
  - Spatial structure: warm SSTs, westerly anomalies
  - Event evolution: onset in spring and intensification through winter of year 0; rapid termination in spring/ summer of year +1
- Differences from observed ENSO
  - During warm events: the model does not show eastward movement of anomalies [attributed to underestimation of temperature anomalies in the west]
  - Between events: easterly anomalies in winds and associated SST anomalies are seen to move westward from the East Pacific [attributed to lack of small scale moisture/temperature advection that would dissipate such anomalies]

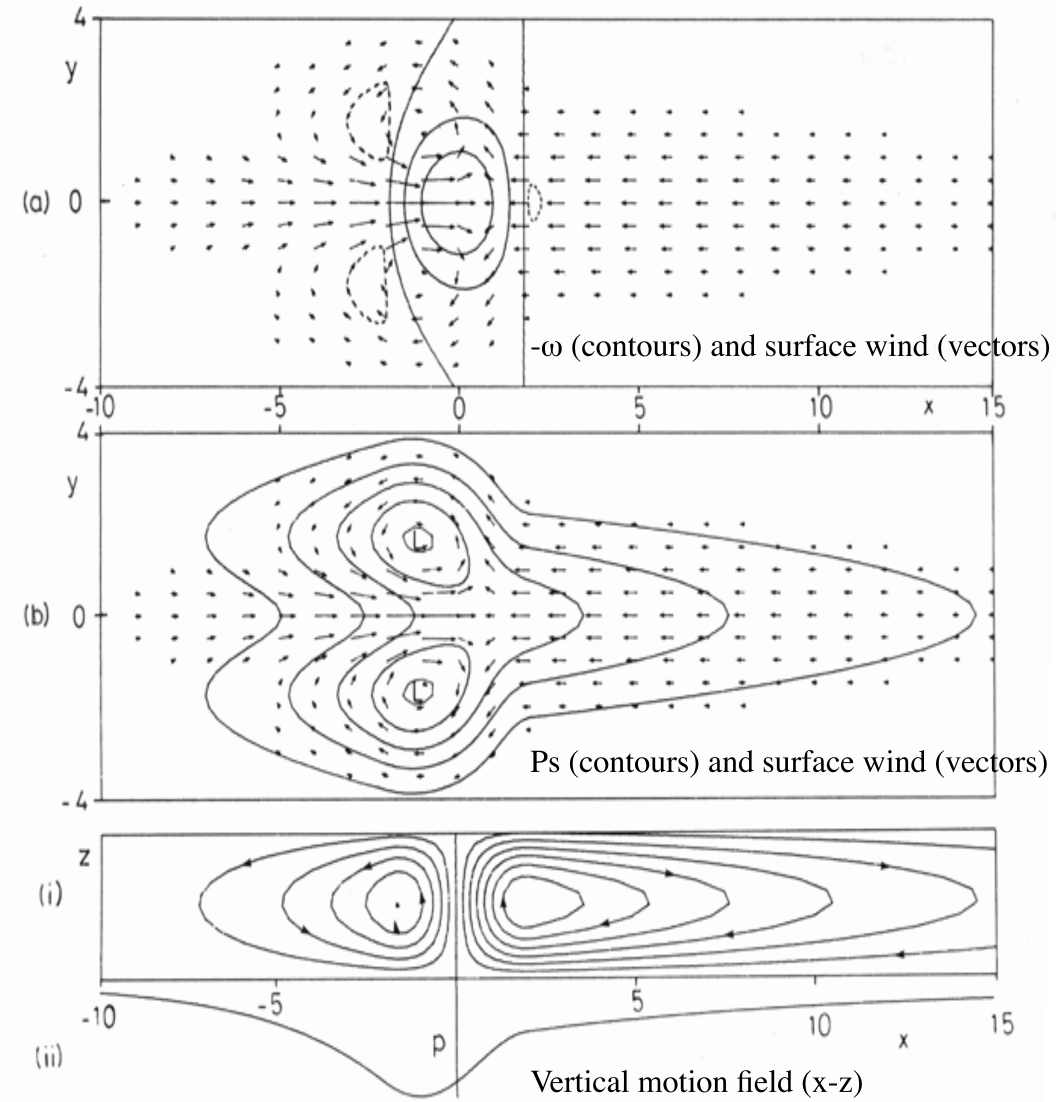
ZC model summary (II)

- Insights:
  - Mean equatorial heat content, i.e., a build-ups before warm events, appears to be important to the oscillation amplitude and period
  - Positive feedback between large-scale atmospheric and oceanic anomalies makes the background state unstable to El Niño-like oscillations [though some sets of background conditions more unstable than others]
  - Mean oceanic thermal structure limits amplitude of anomalies
  - Lag between dynamical changes in the east and fluctuations in wind stress account for transitions between El Niño and non-El Niño states on interannual timescales
- What the model fails to do:
  - Evolution of the mean state
  - Initiation of events [anomalous winds are prescribed]
  - Causal role of heat content variations

Other ENSO theories

- ***Linear Stochastic:*** development and decay of El Niño forced at least in part by higher latitude patterns via moist convection
- ***Advective-Reflective Oscillator:*** westerly wind anomalies induce eastward zonal currents, with El Niño developing as a positive feedback of zonal currents advecting warm western Pacific waters eastward; wave reflections at eastern and western boundaries then drive currents that displace the warm waters back to the west.
- ***Recharge/Discharge:*** heat content builds up in the equatorial region prior to El Niño; with the heat then discharged eastward and poleward during El Niño events.
- ***Western Pacific Oscillator:*** condensational heating in the west-central Pacific creates a pair of Rossby cyclones and westerly wind anomalies to the east, with the latter deepening the thermocline and increasing SST; to the west of the equator, the thermocline is raised, and SST decreases, increasing surface pressure and inducing anomalous easterlies. The cooling propagates eastward, providing a negative feedback.
- ***Unified Oscillator:*** combines interactions of anomalous SST in the east, zonal wind stress in the central and west, and off-equatorial thermocline depth in the west.

Gill (1980) Model



-ω (contours) and surface wind (vectors)

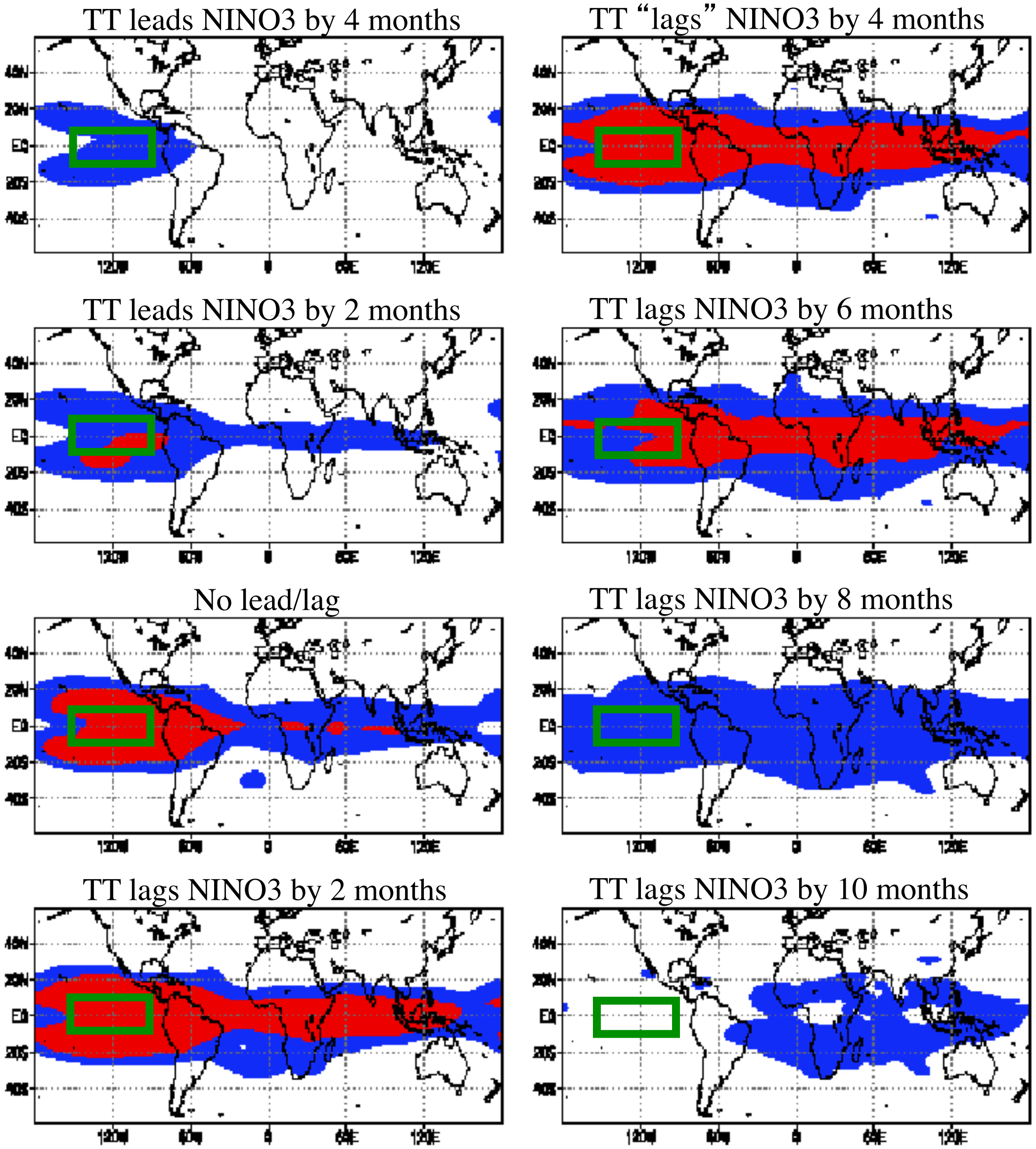
Ps (contours) and surface wind (vectors)

Vertical motion field (x-z)

http://www.asp.ucar.edu/colloquium/2000/Lectures/branstator.html

- Dry atmospheric SWE model forced by imposed atmospheric diabatic heating [the latter is meant to represent a localized increase to convective heating associated with anomalously warm SST]
- Away from the forcing region, the steady-state Gill model produces a pattern of wind and pressure anomalies consisting of a stationary Kelvin wave to the east and Rossby waves to the west.

El Niño and tropical temperatures


TT leads NINO3 by 4 months

TT “lags” NINO3 by 4 months

TT leads NINO3 by 2 months

TT lags NINO3 by 6 months

No lead/lag

TT lags NINO3 by 8 months

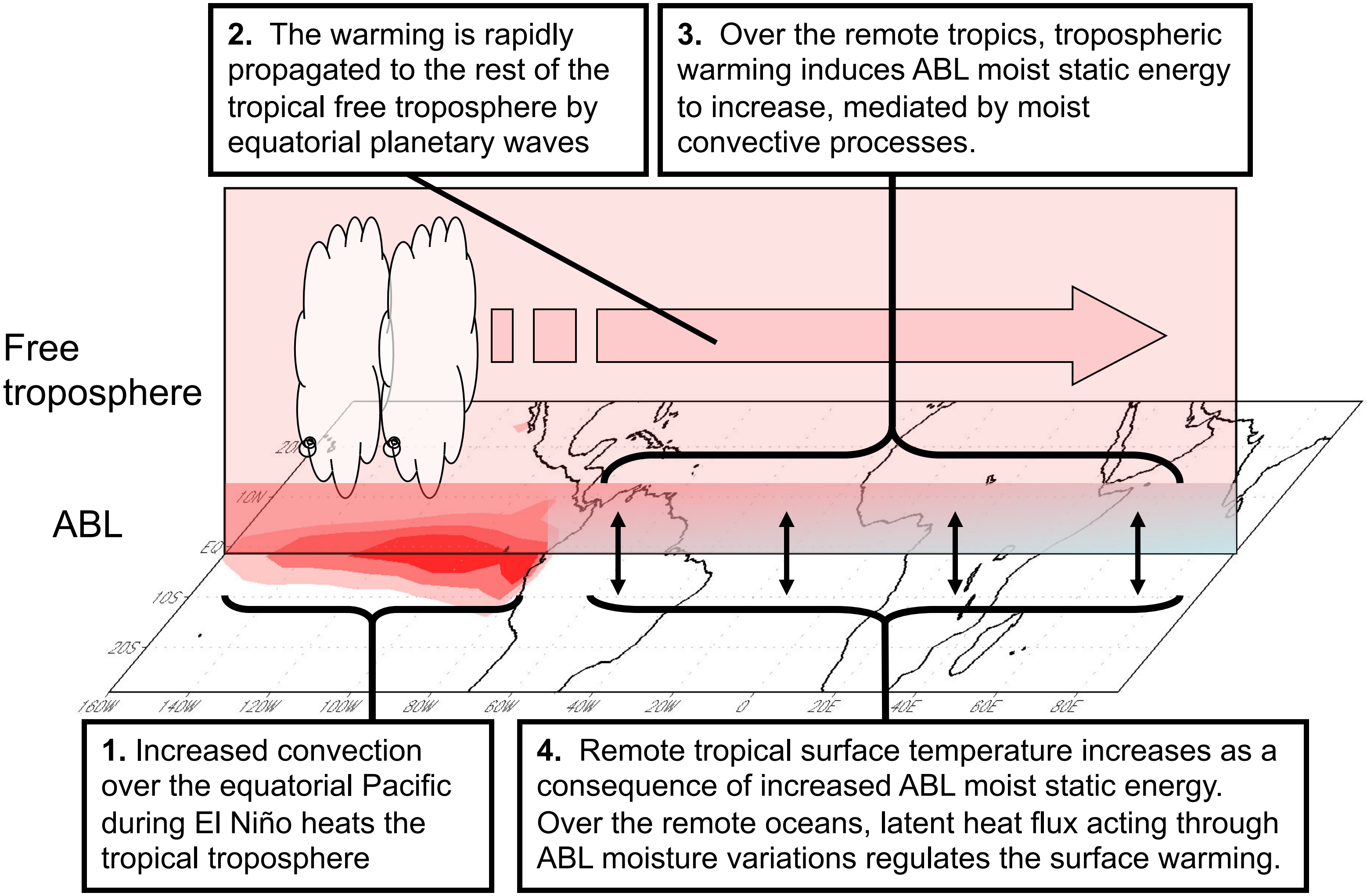
TT lags NINO3 by 2 months

TT lags NINO3 by 10 months

- Lag correlation plot of NINO3 with Microwave Sounding Unit mid-troposphere temperature over 1979-1999. Blue (red) shading denotes correlations with $0.3 < r < 0.6$ ($r \geq 0.6$).
- TT across the tropics between 20S-20N is well correlated with NINO3 region sea surface temperature (SST) anomalies (green box), particularly slightly after the peak of SST anomalies in NINO3 (e.g. bottom left and top right).
- Spreading or communicating of ENSO influence through temperature (“TT mechanism”)

Chiang and Sobel 2002

Schematic of the Chiang and Sobel (2002) TT Mechanism



2. The warming is rapidly propagated to the rest of the tropical free troposphere by equatorial planetary waves

3. Over the remote tropics, tropospheric warming induces ABL moist static energy to increase, mediated by moist convective processes.

1. Increased convection over the equatorial Pacific during El Niño heats the tropical troposphere

4. Remote tropical surface temperature increases as a consequence of increased ABL moist static energy. Over the remote oceans, latent heat flux acting through ABL moisture variations regulates the surface warming.

Courtesy of J.C.H. Chiang