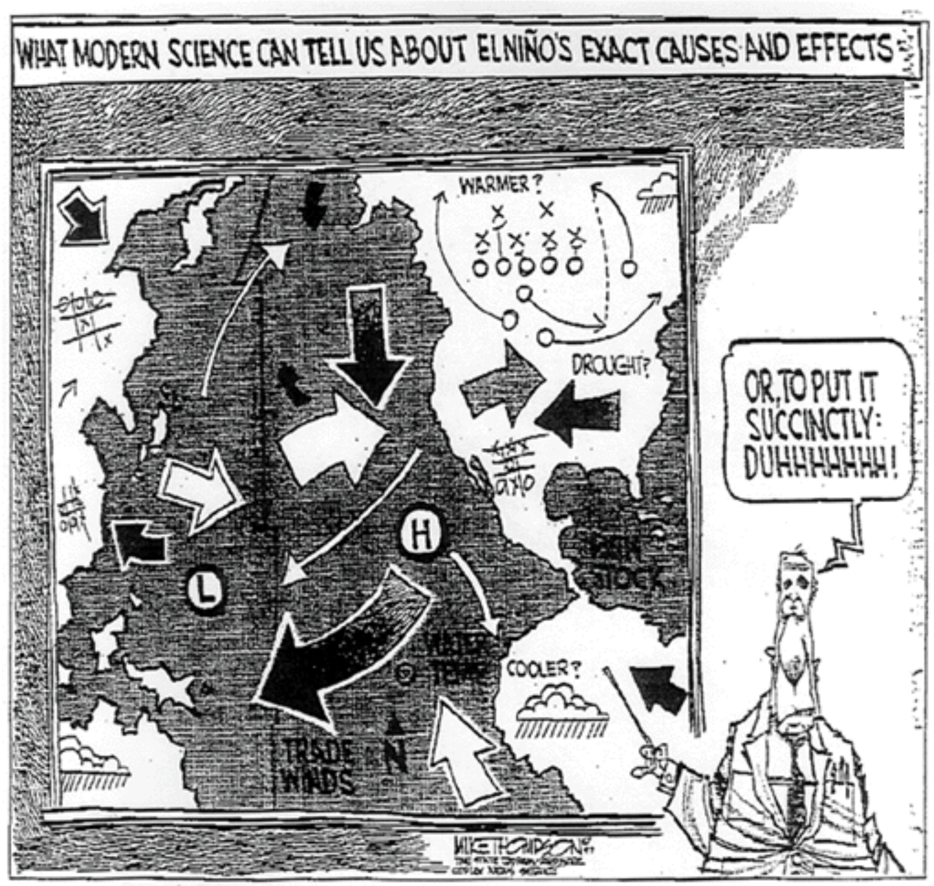
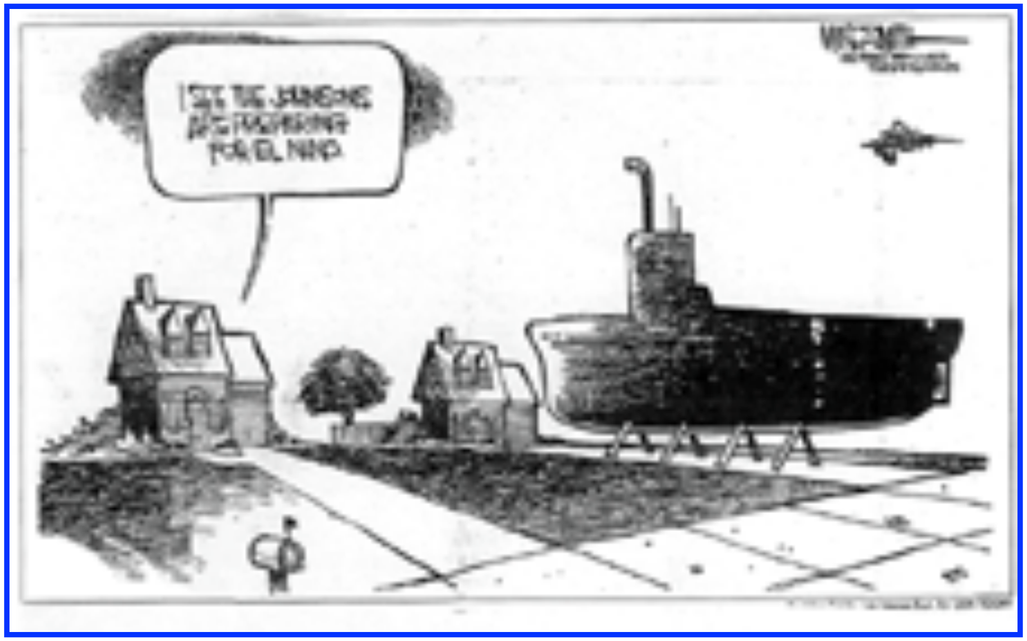
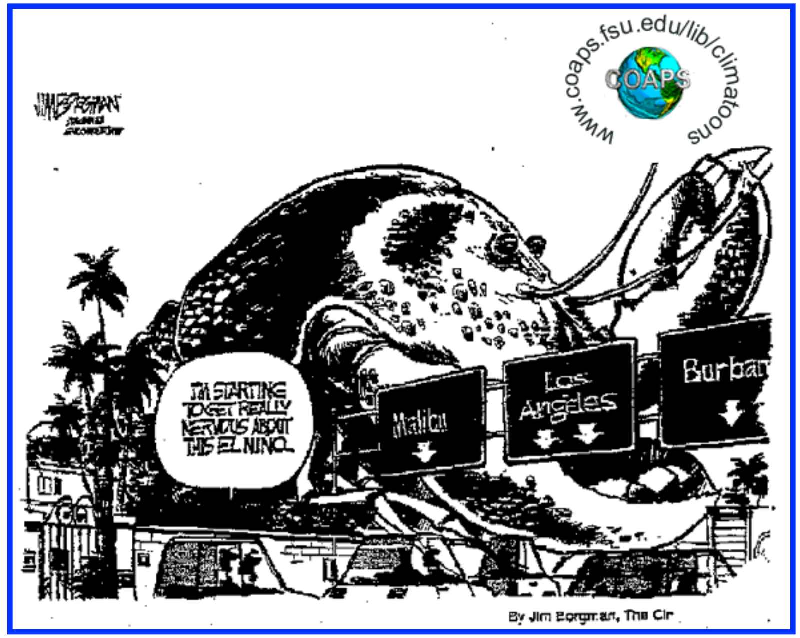
Goal: Describe the principal features and characteristics of the El Niño/ Southern Oscillation (ENSO)

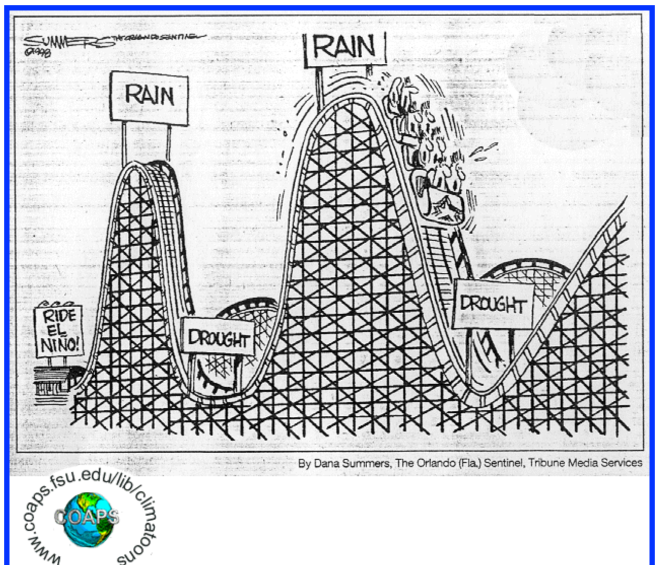


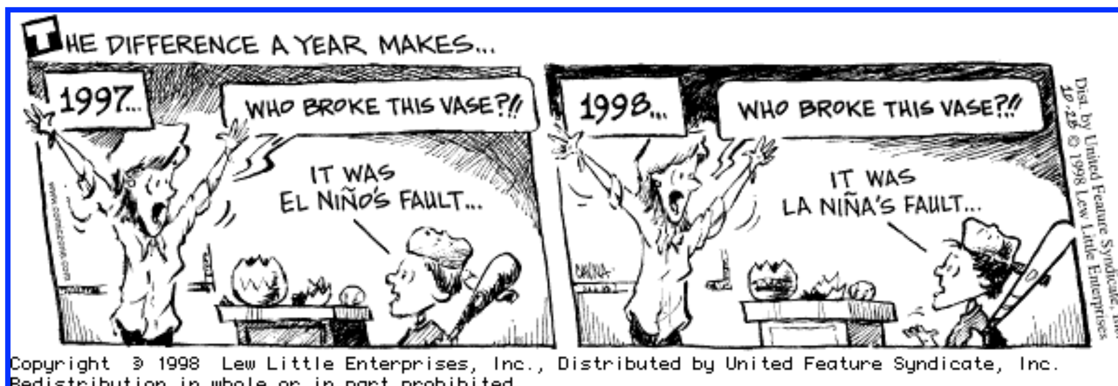
www.coaps.fsu.edu/lib/climatoons

Here Comes El Niño (or La Niña)!

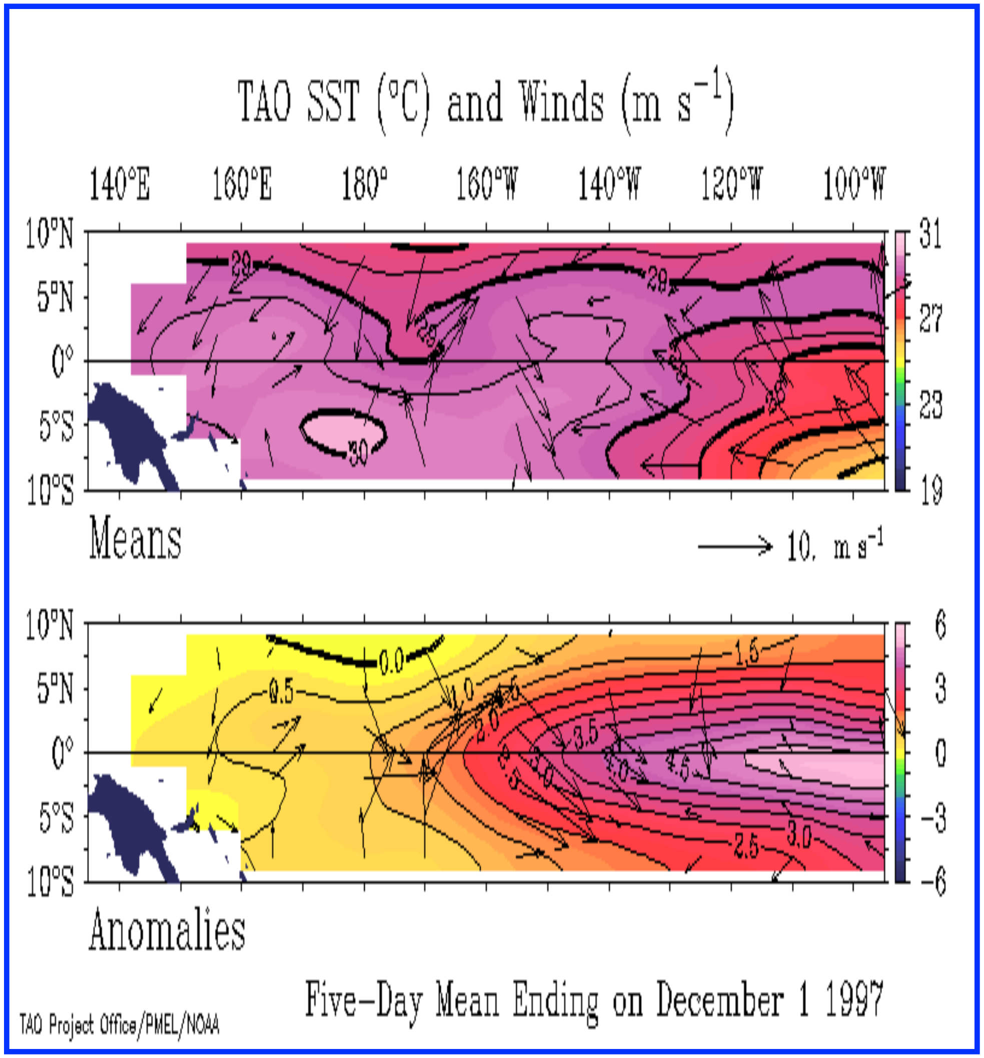








What is ENSO?

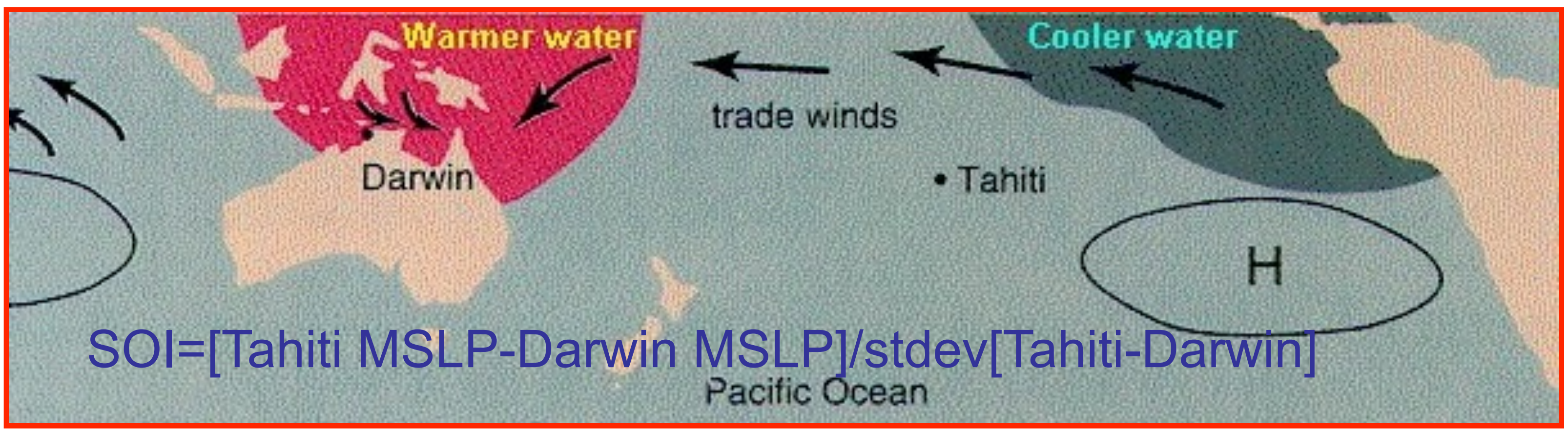


- ENSO is a coupled ocean (El Niño)-atmosphere (Southern Oscillation) phenomenon affecting global climate on characteristic timescales of 2-7 years.
- *Wytrki (1975):*

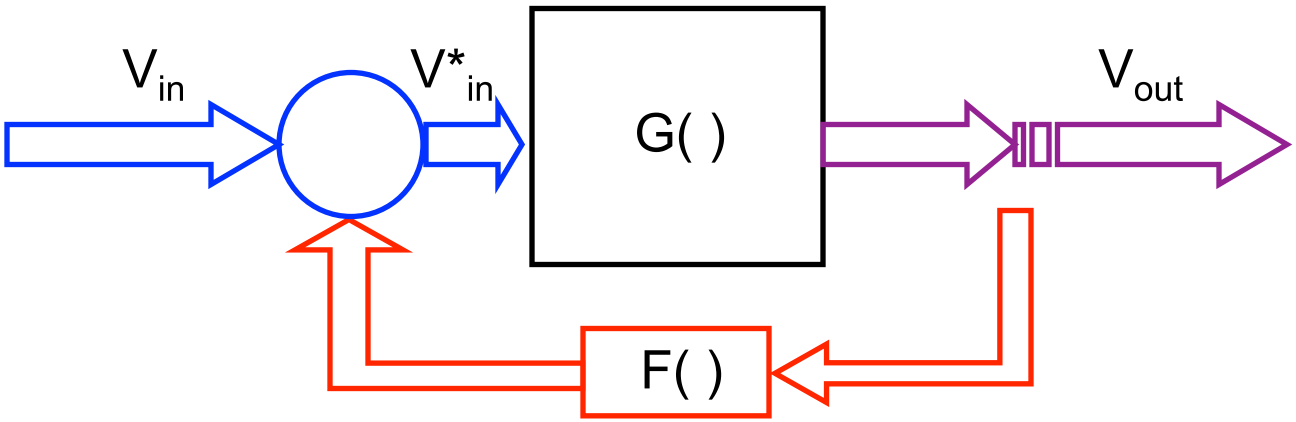
  During the two years preceding El Niño, excessively strong southeast trades are present in the central Pacific. These strong southeast trades intensify the subtropical gyre of the South Pacific, strengthen the South Equatorial Current, and increase the east-west slope of sea level by building up water in the western equatorial Pacific. As soon as the wind stress in the central Pacific relaxes, the accumulated water flows eastward, probably in the form of an equatorial Kelvin wave. This wave leads to the accumulation of warm water off Ecuador and Peru and to a depression of the usually shallow thermo cline. In total, El Niño is the result of the response of the equatorial Pacific to atmospheric forcing by the trade-winds.

A Little ENSO History

- Peruvian fishermen [16th century]: periodic warming of SSTs (dubbed *El Niño* because of its appearance in December) caused considerable reductions of anchovy fishery and seabird populations
- Sir Gilbert Walker [early 20th century]: identification of the pressure pattern known as the Southern Oscillation based on the pressure difference between Tahiti and Darwin, Australia [now called the Southern Oscillation Index]
- Bjerknes [1960s]: an east-west circulation in the Pacific (Walker circulation) explains the east-west temperature gradient in the Pacific
- Satellite Observations [1960s-present]: improved observations of El Niño anomalies and their widespread spatial extent
- George Philander, Mark Cane, Steve Zebiak, David Battisti, and others [1980s]: theoretical advances and modeling of ENSO as a coupled ocean-atmosphere phenomenon



Schematic feedback process



Consider *G(x)* = *G x* and *F(x)* =*F x*. In the absence of a feedback process (i.e., *F ( )* = 0), we would simply have: $V_{out} = GV_{in}$ (no feedback)

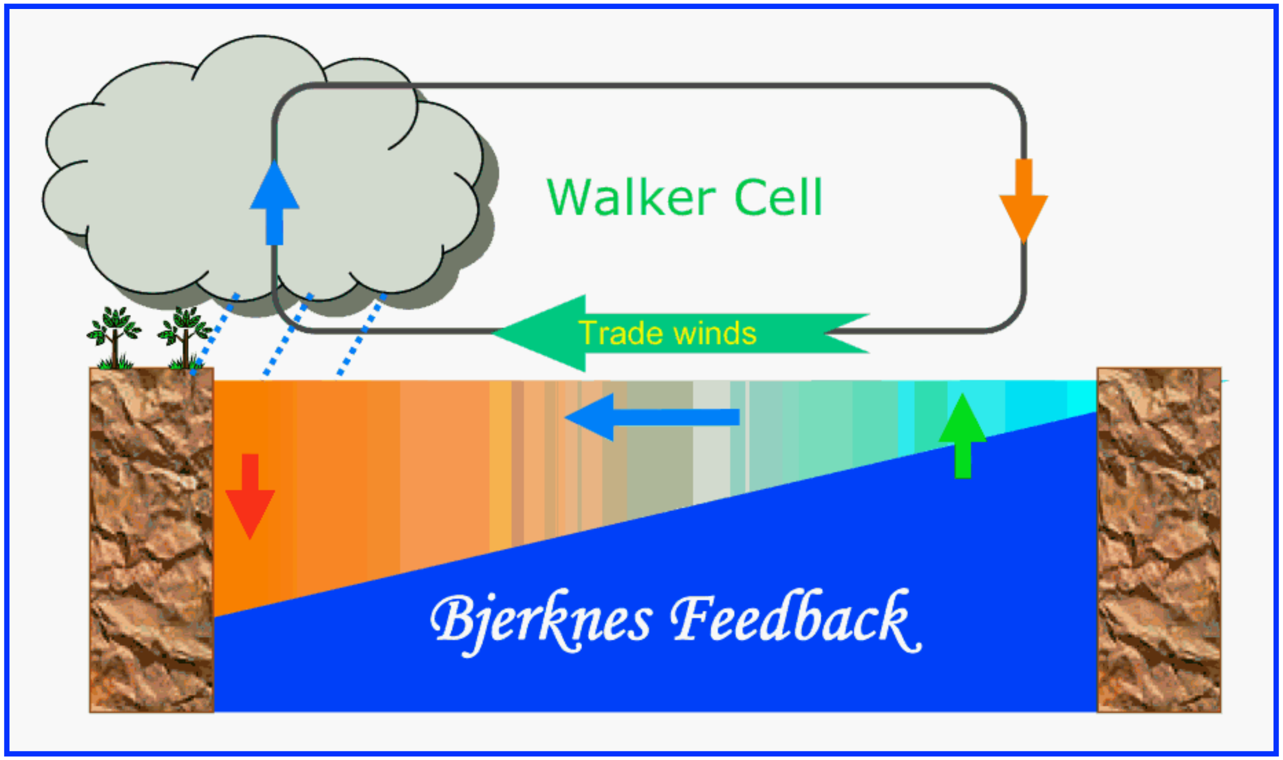
With a feedback process, the input signal V_{in} is altered by the output signal V_{out}, by an amount FV_{out}; thus:

$$V_{out} = GV^*_{in} = G(V_{in} + FV_{out}) \Rightarrow V_{out} = \frac{GV_{in}}{(1 - GF)}$$

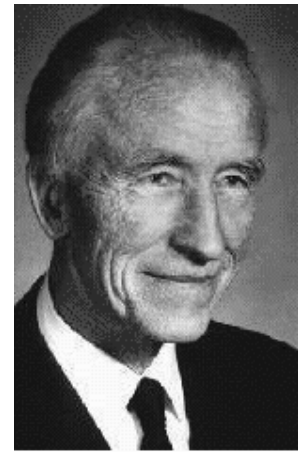
The **feedback**, *f*, of the system is defined as: $f = GF$ and the **gain**, *g*, is defined as: $g = \frac{G}{1 - f}$ Note that independent feedbacks are simply summed.

For a negative feedback ($f < 0$), $0 < g < G$. For a positive feedback, with $0 < f < 1$, $g > G$, but note that $f > 1$ is unphysical.

Bjerknes Feedback



From S.-P. Xie (U. Hawaii)



Jacob Bjerknes (1897-1975)

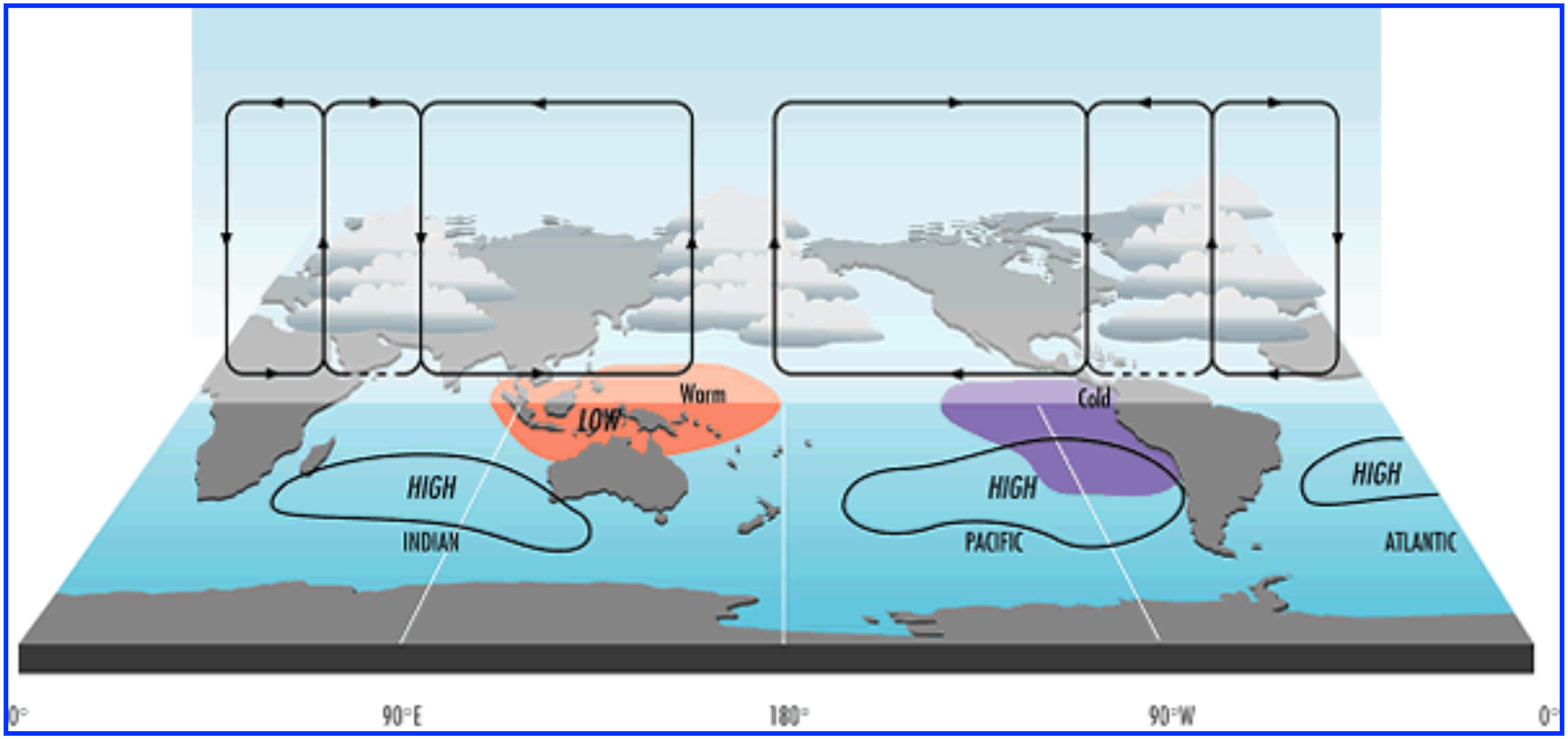
- Norwegian meteorologist
- Son of meteorlogist Vilhelm Bjerknes (1862-1951)
- Founded UCLA's Department of Meteorology

Two views of the Bjerknes feedback

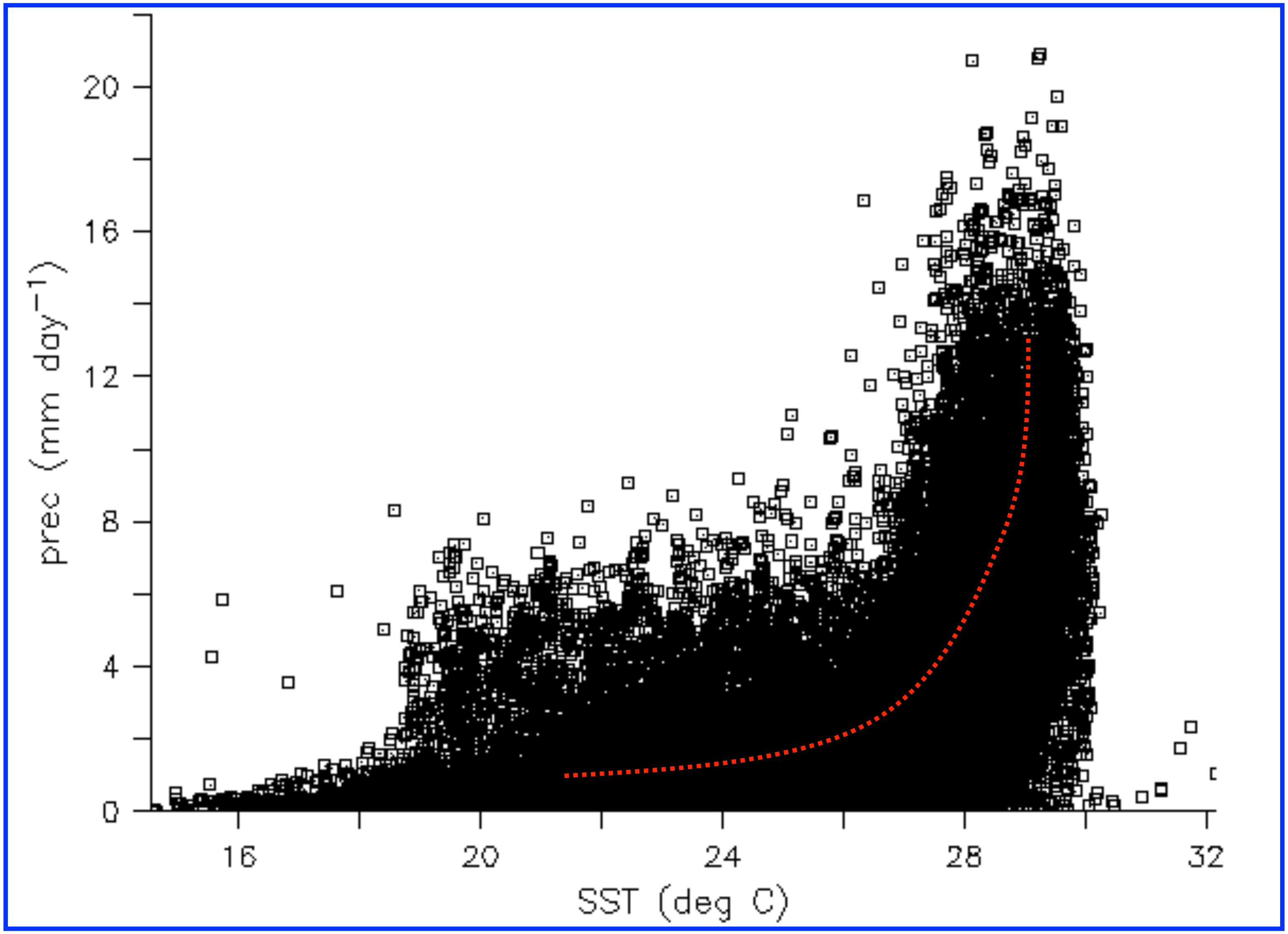
- *Atmospheric view*: strong convection (precipitation) confined to the (warm) western Pacific and is associated with an east-west sea level pressure gradient that drives equatorial easterlies.
- *Oceanic view*: easterly winds shoal the equatorial thermocline and induce upwelling in the eastern Pacific, keeping the east cool.
- The circularity implies full understanding only possible by considering the fully coupled system.

Let’s now examine the essential components of the Bjerknes feedback…

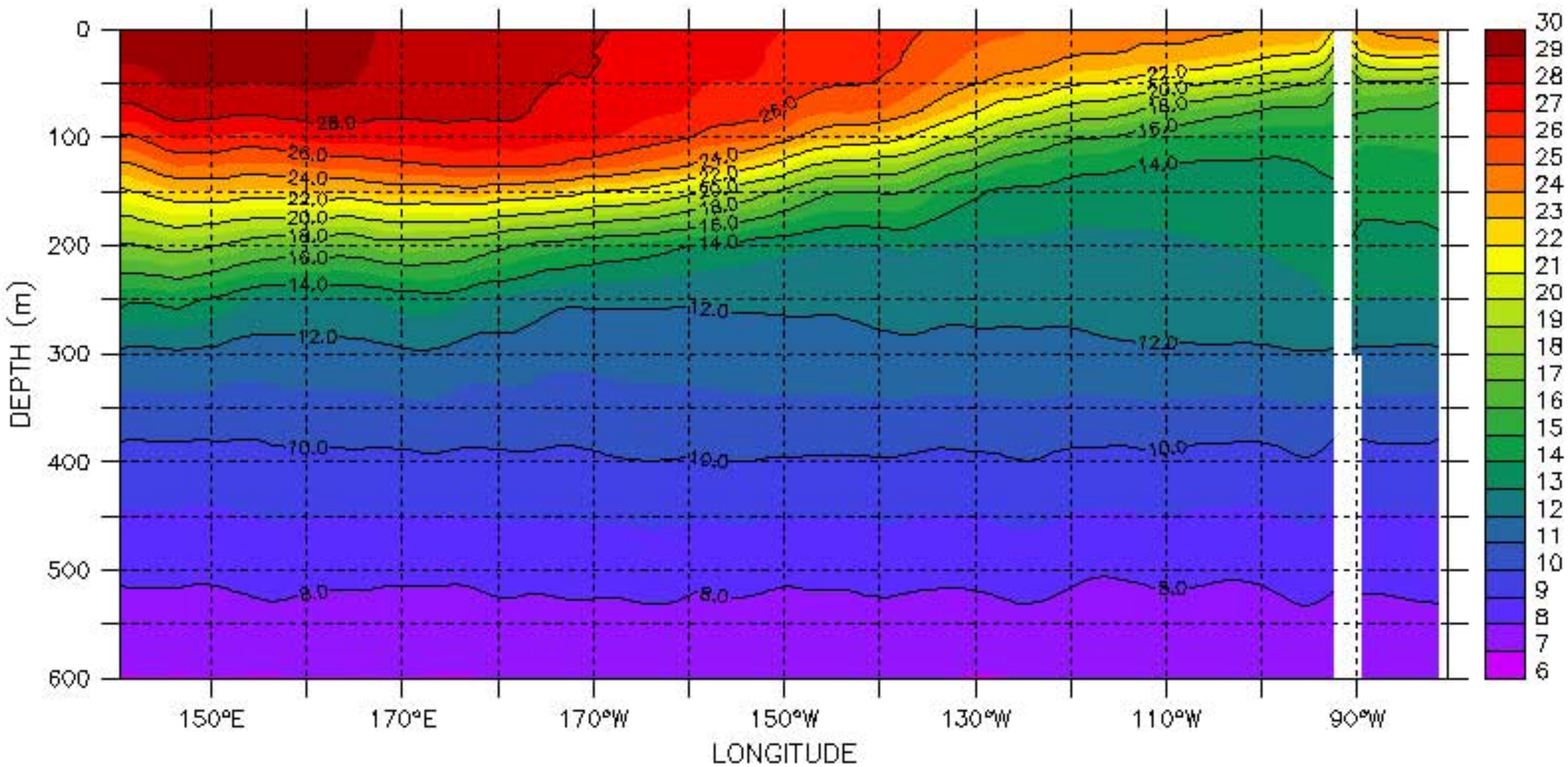
Walker circulation



Precipitation vs. SST



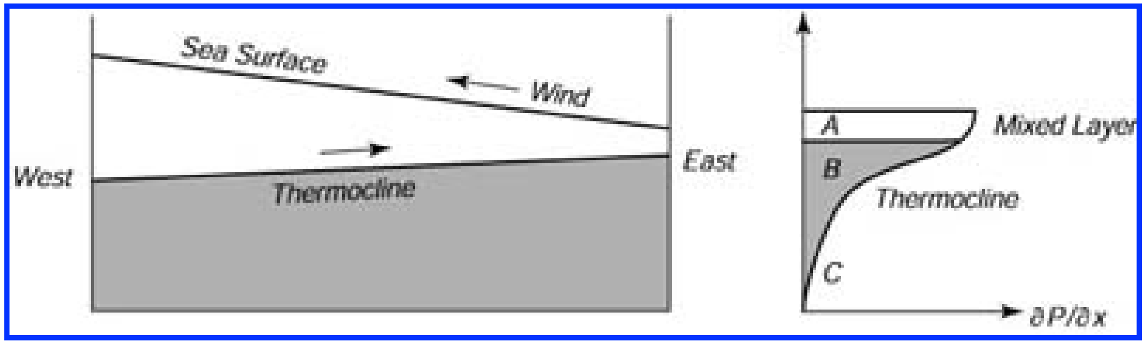
Equatorial upper ocean

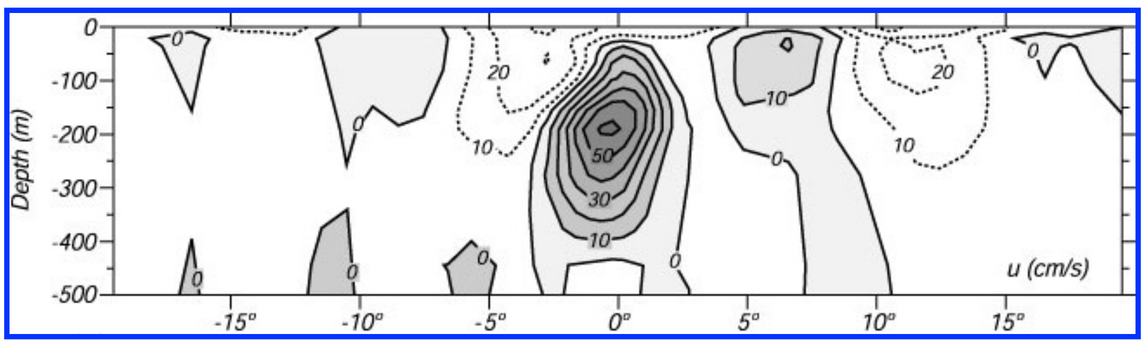


Temperature (Celsius)

Figure 14-2, *Introduction to Physical Oceanography*, R. H. Stewart

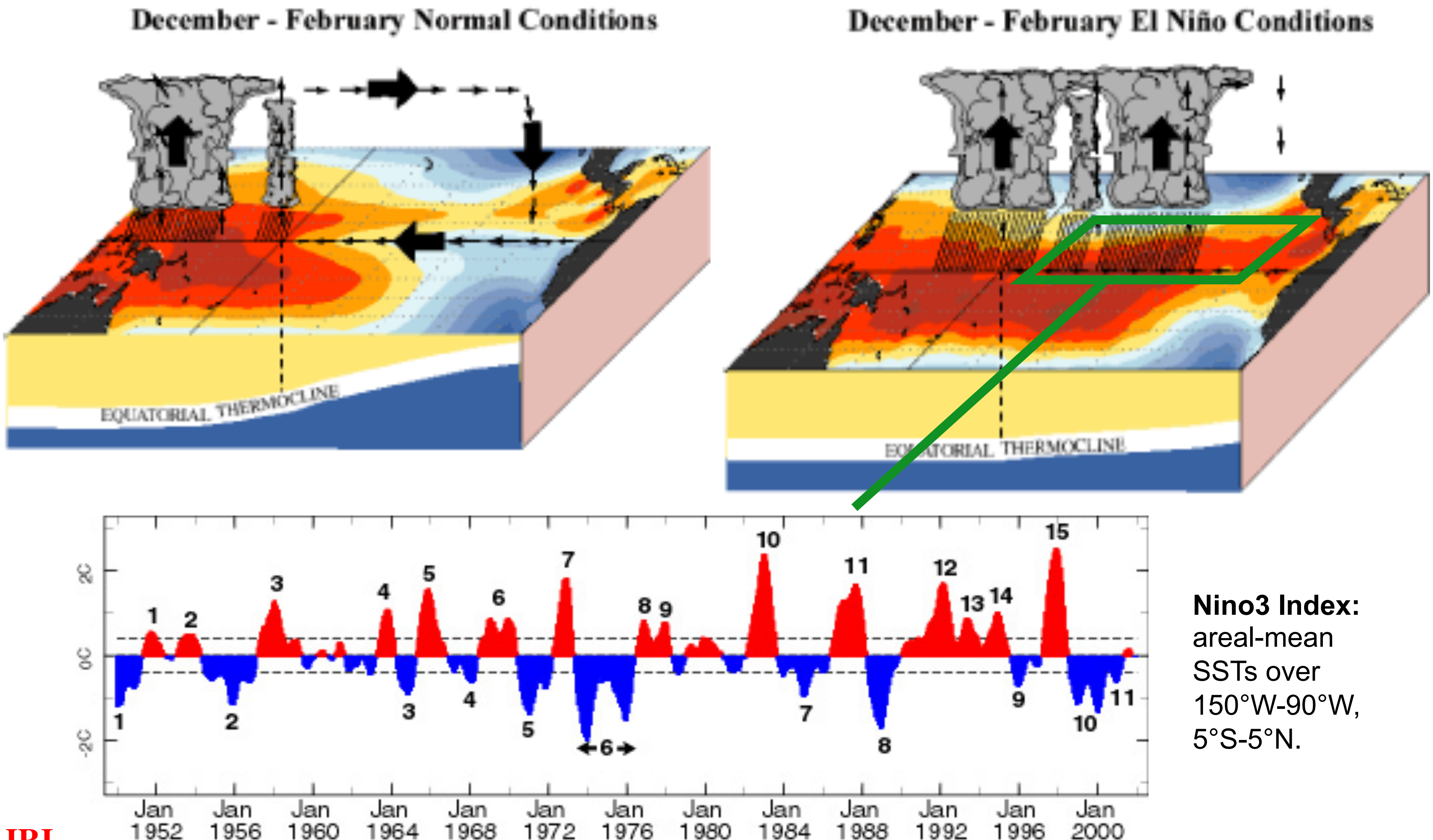
Upper oceanic momentum balance





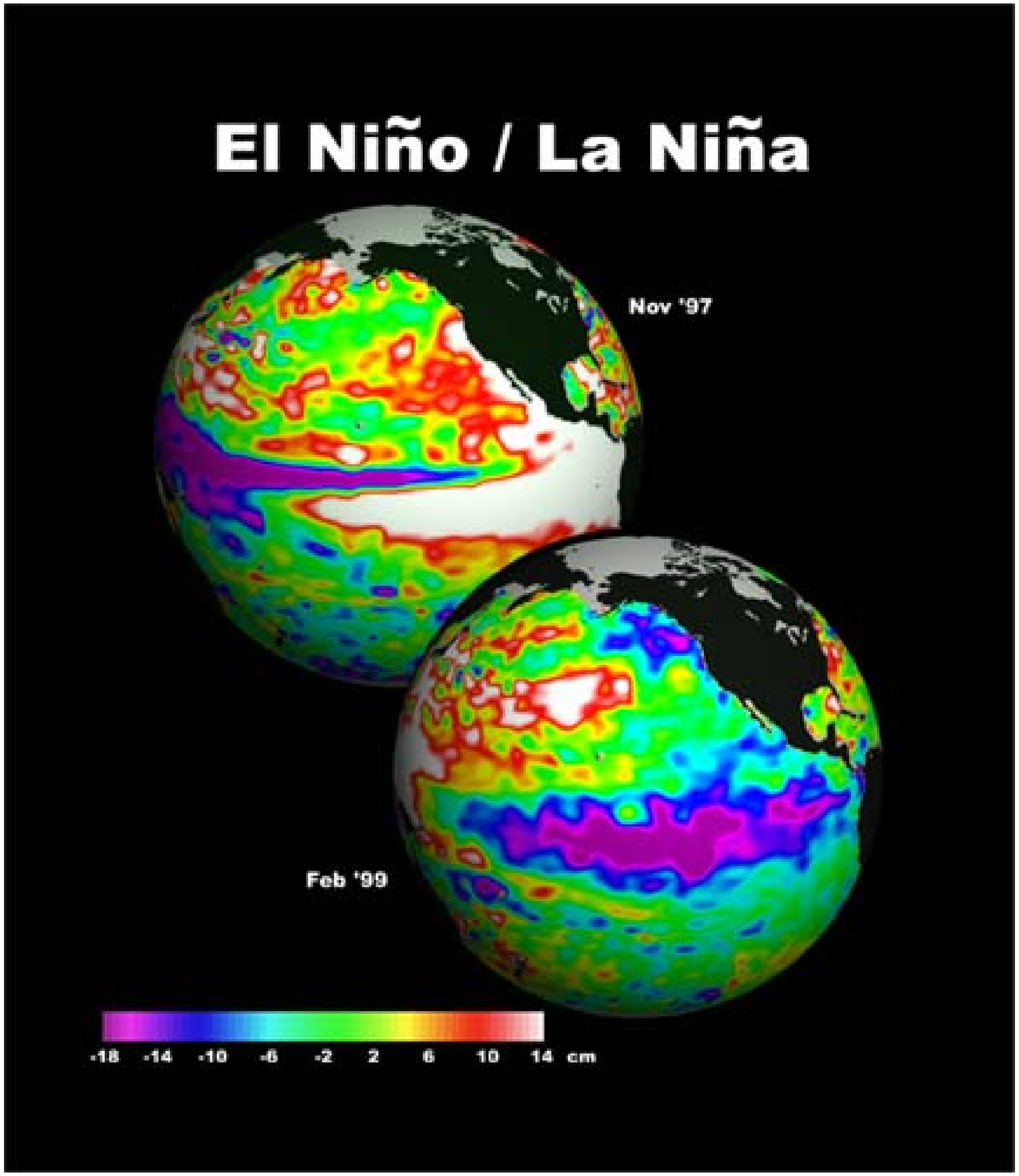
- In near surface layer (A), windstress (τ_x) balances zonal pressure gradient [$-\partial p/\partial x$]
- In layer C, $-\partial p/\partial x \approx 0$
- In layer B, effect of τ_x is small, so $\partial p/\partial x$ is balanced by friction. This balance leads to the development of the so-called equatorial undercurrent.

Characteristics of ENSO



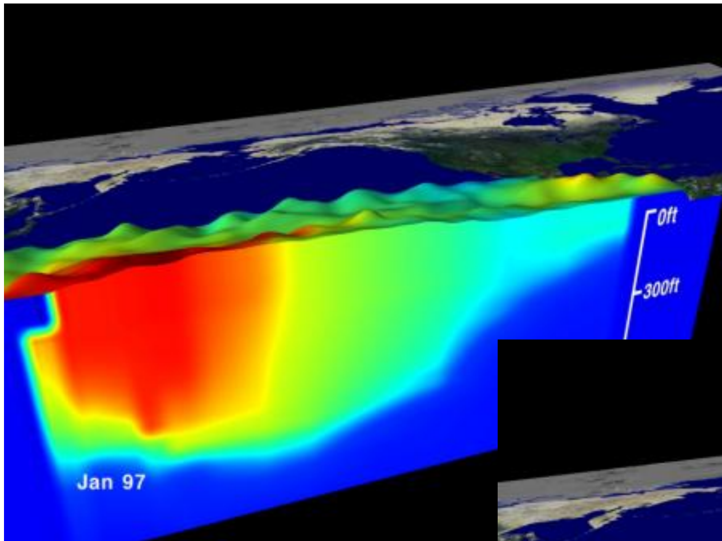
Nino3 Index: areal-mean SSTs over 150°W-90°W, 5°S-5°N.

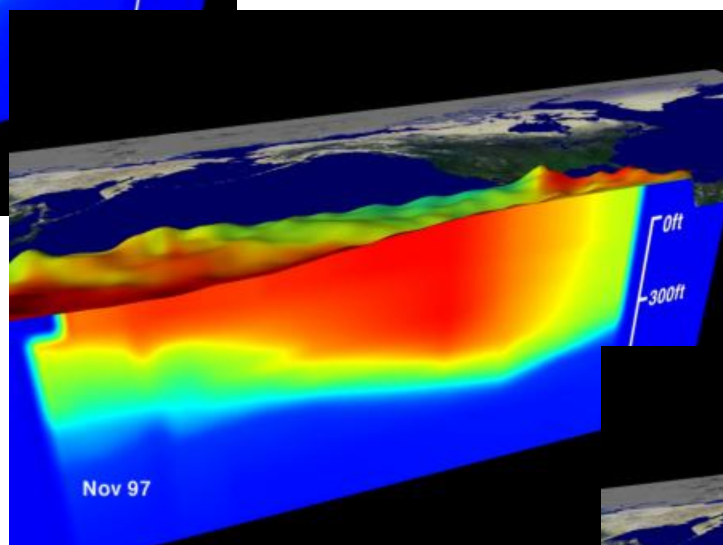
El Niño/La Niña Sea Surface Height

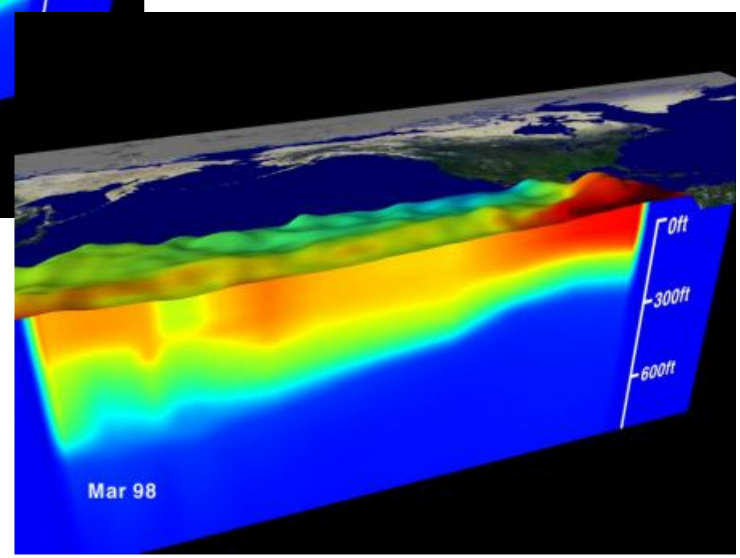


From Topex-Poseidon satellite

Subsurface Structure

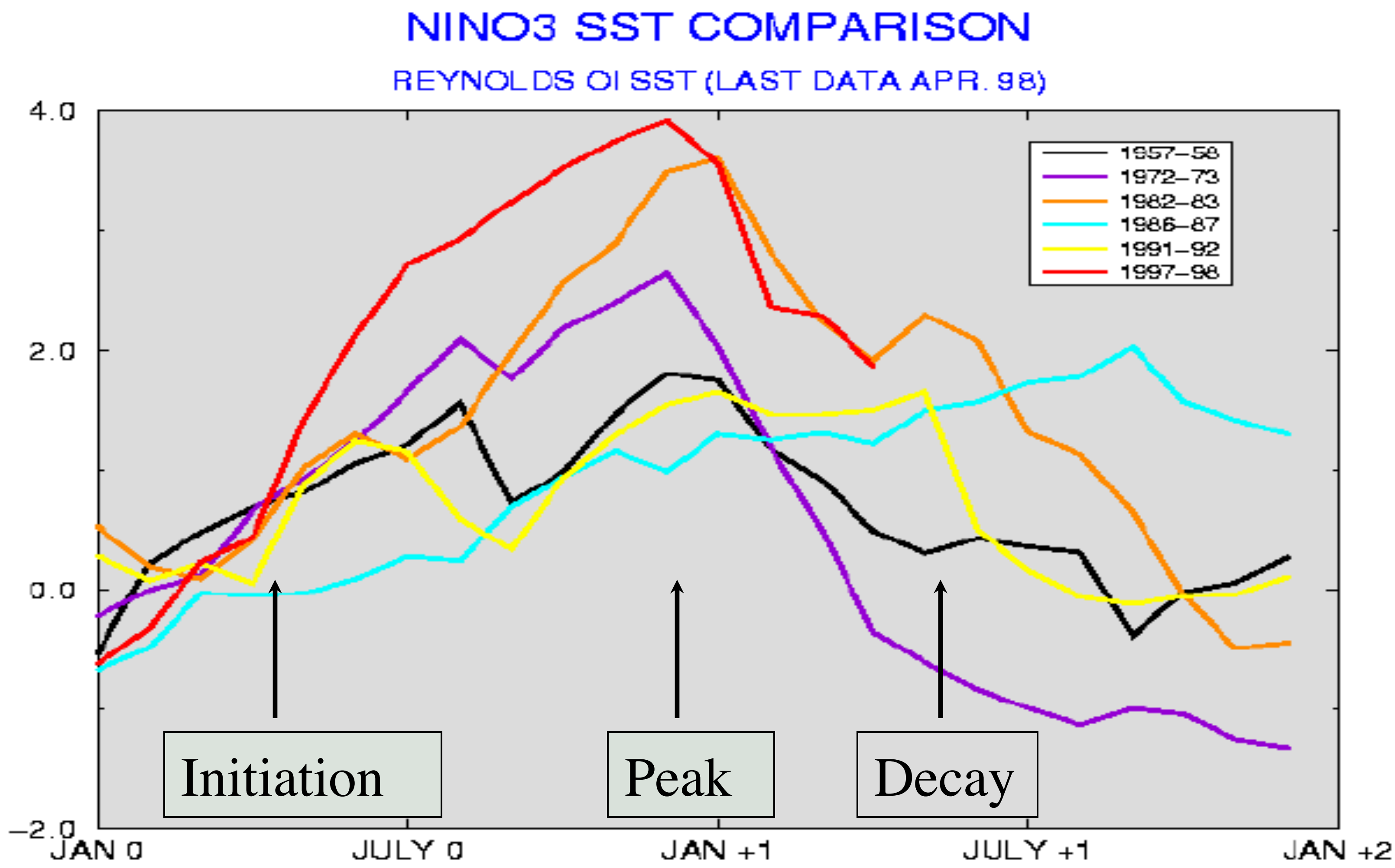






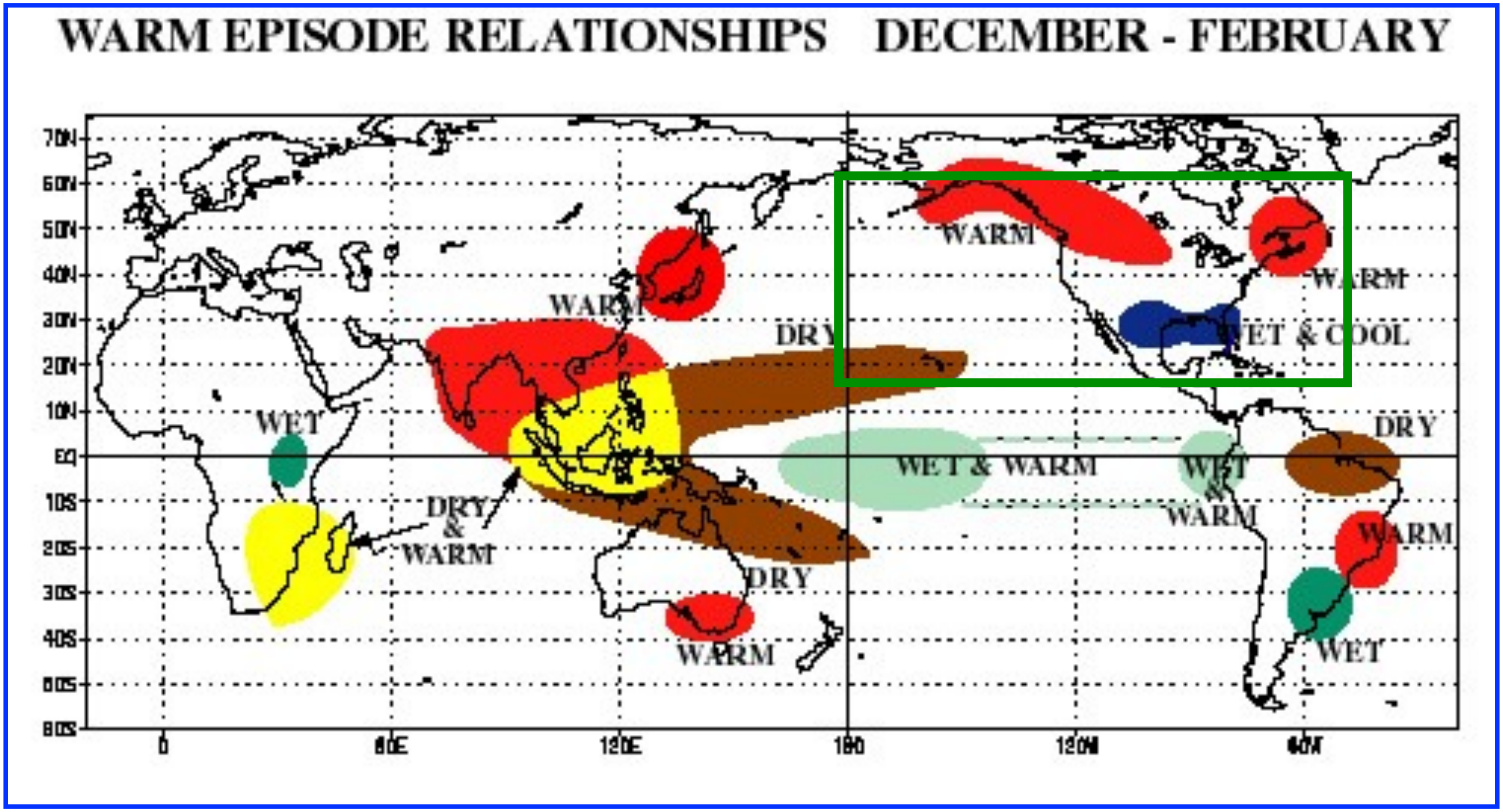
Source: NASA Goddard Space Flight Center

El Niño's Life Cycle



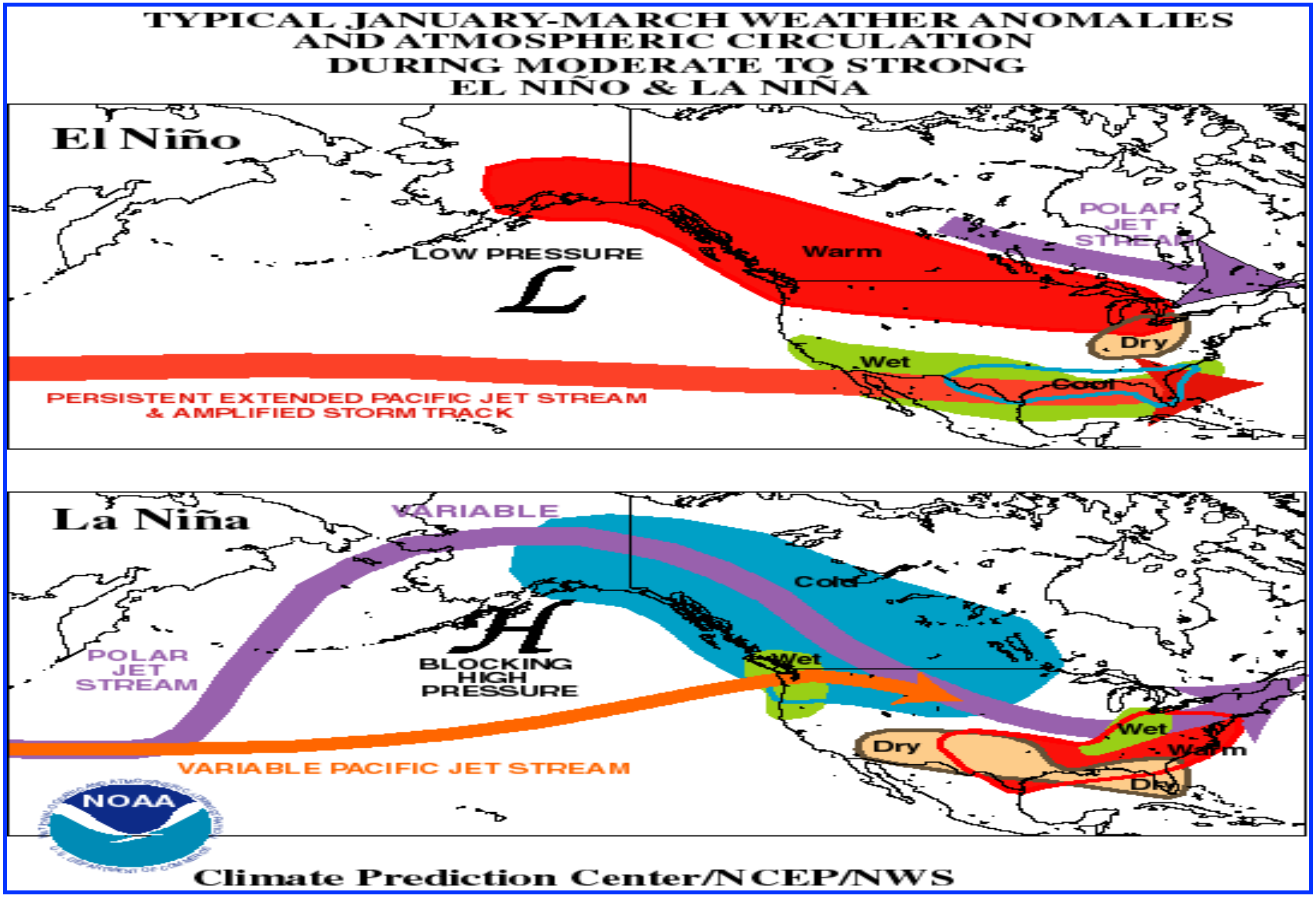
Source: IRI

El Niño Impacts: Prec & T

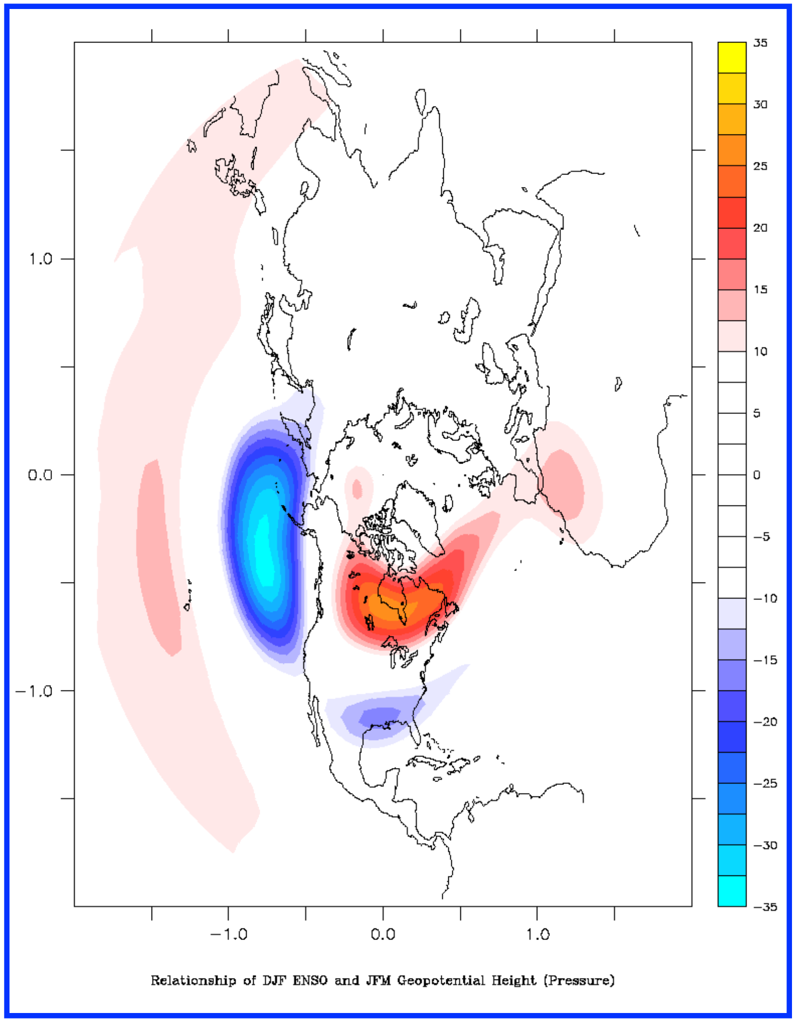


Source: NOAA CPC

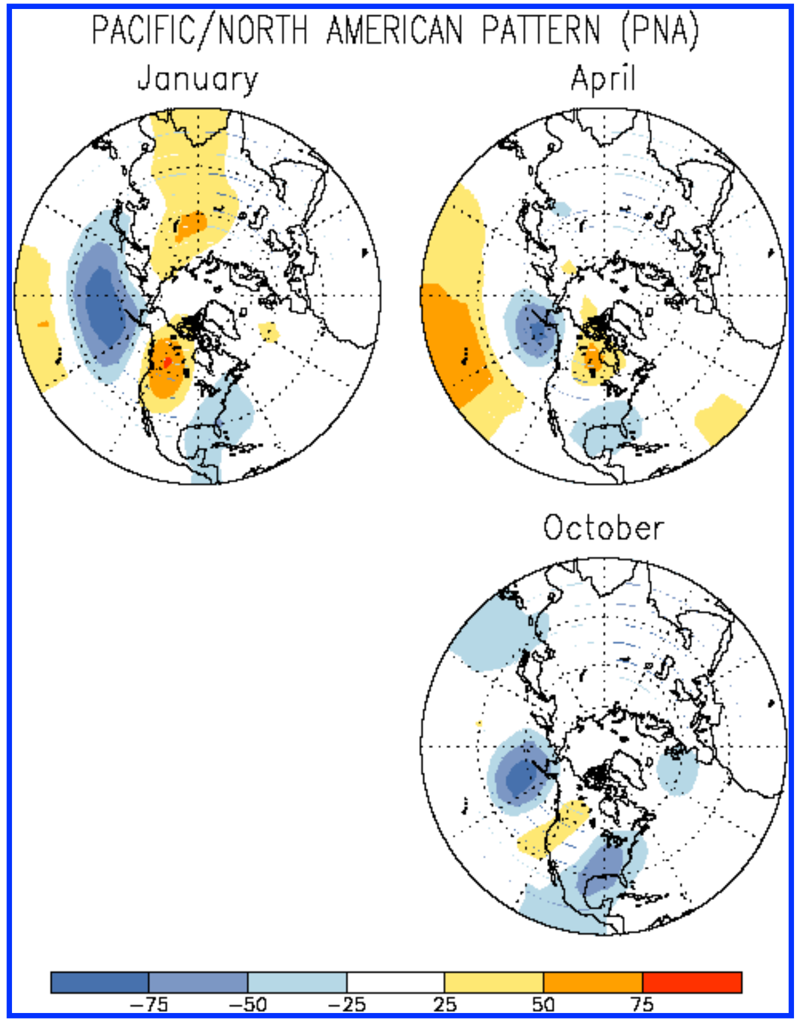
ENSO Teleconnections: N. America



ENSO Teleconnections

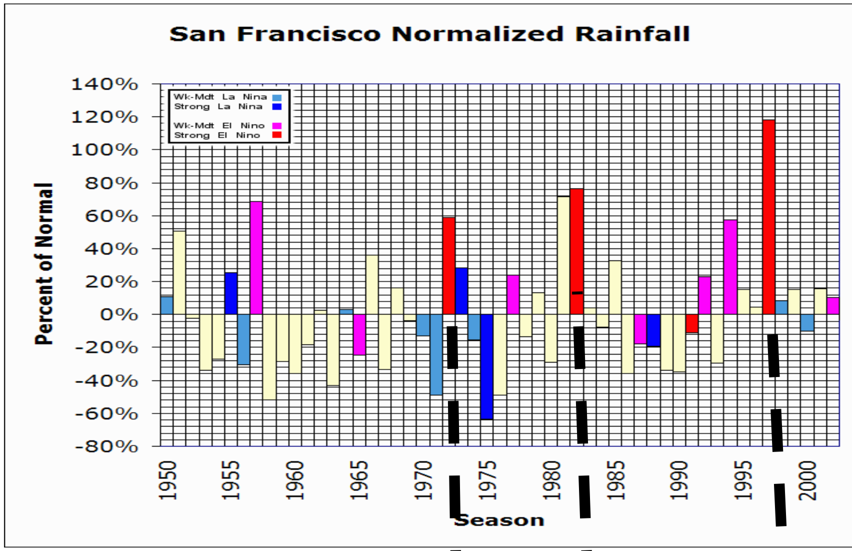


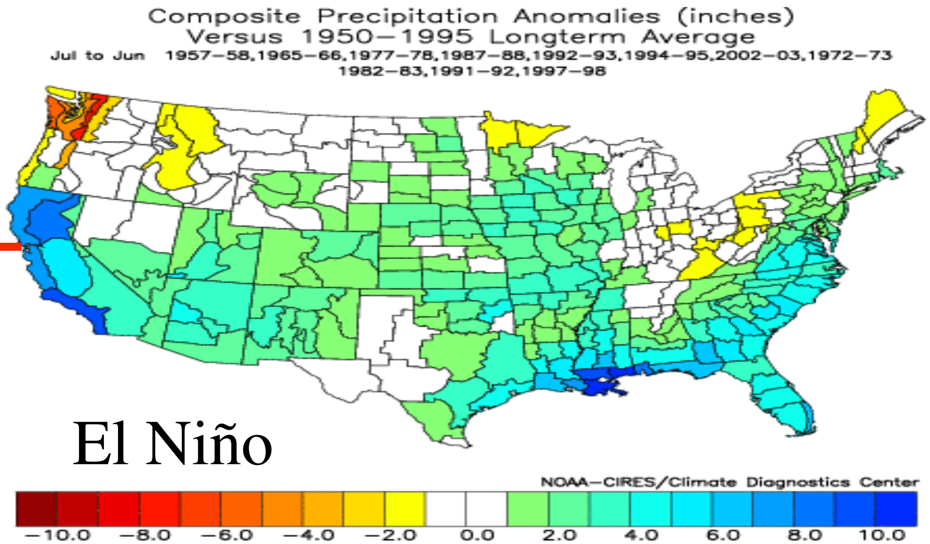
ENSO 500mb Geopotential Pattern

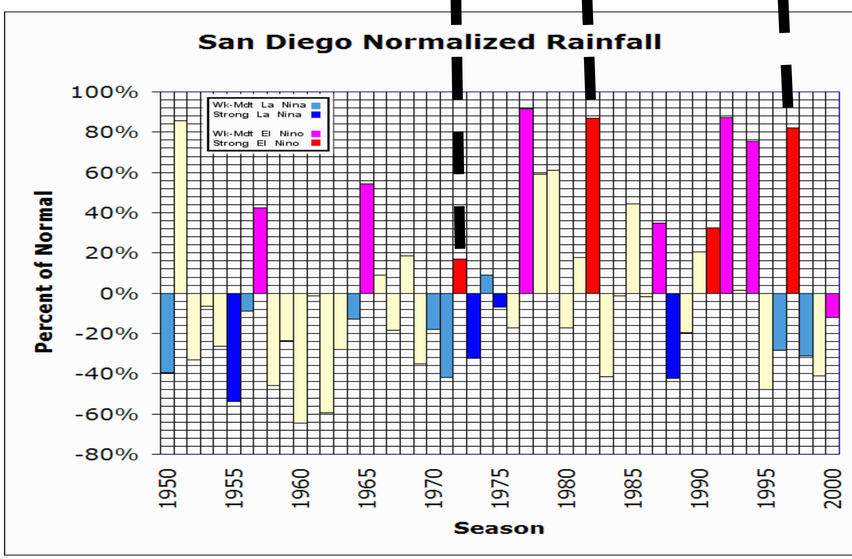


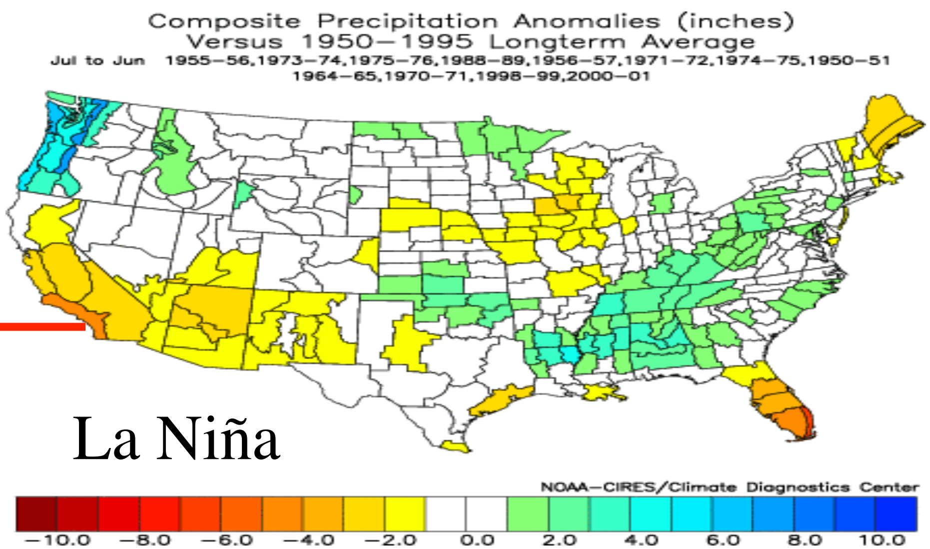
PNA 300mb Geopotential Pattern

ENSO and Precipitation in the US



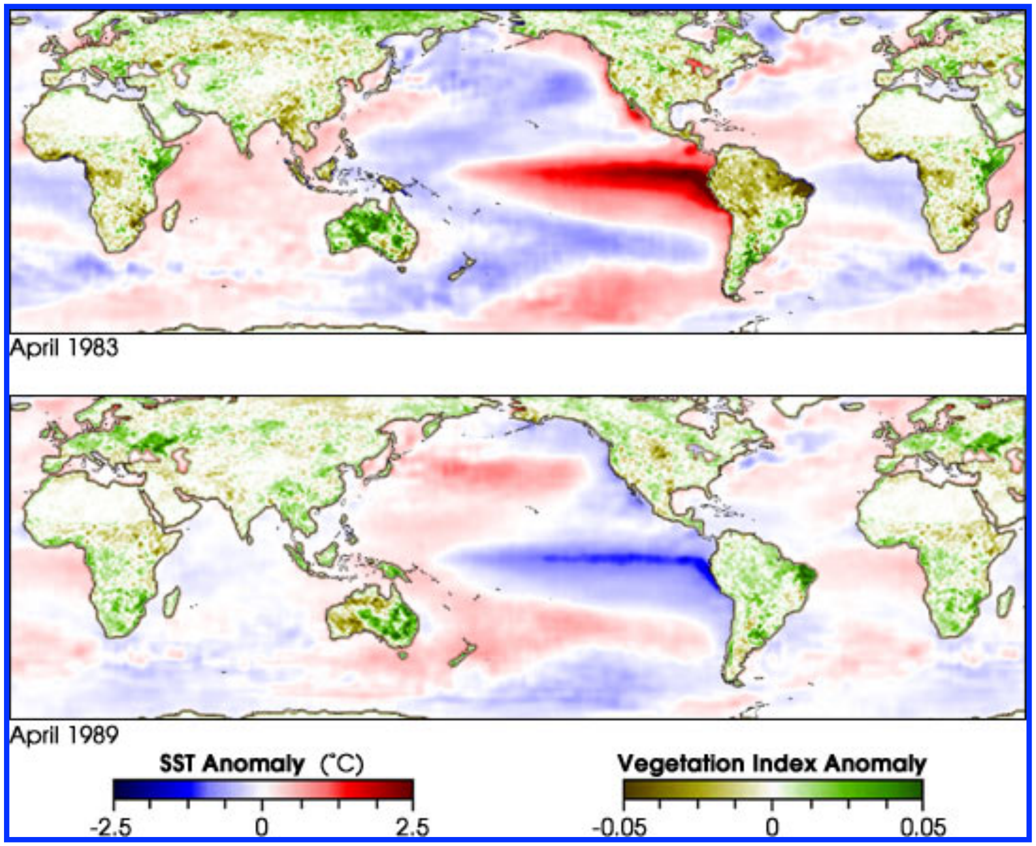


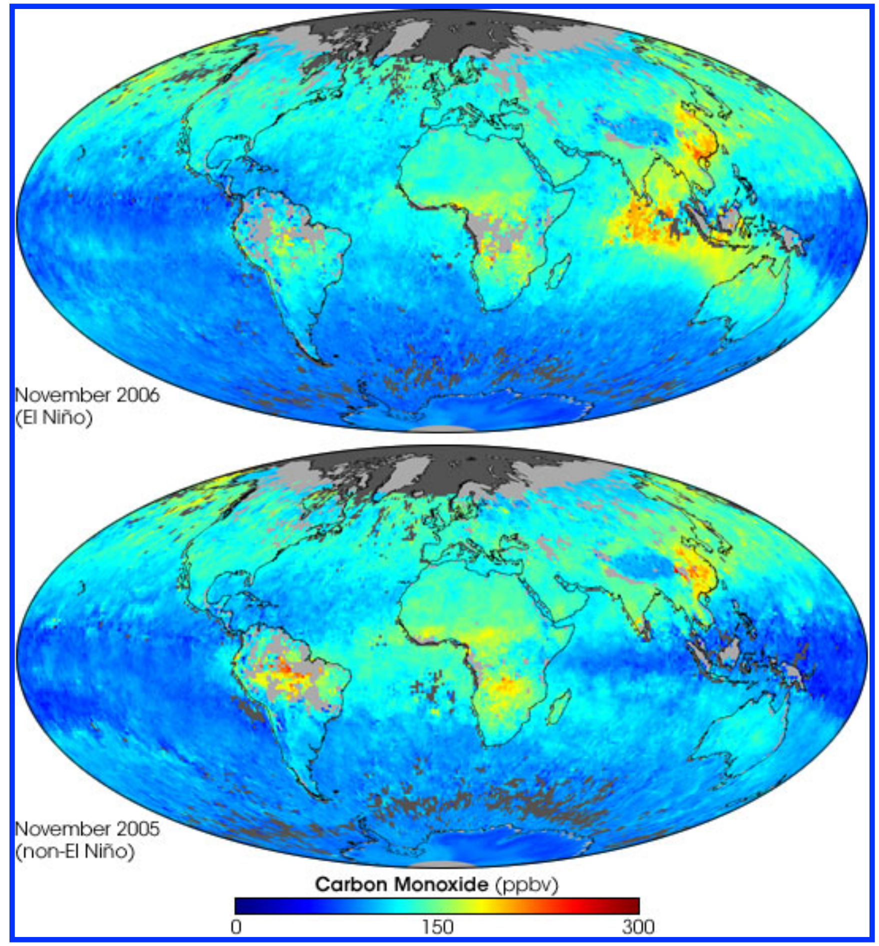




Golden Gate Weather Services

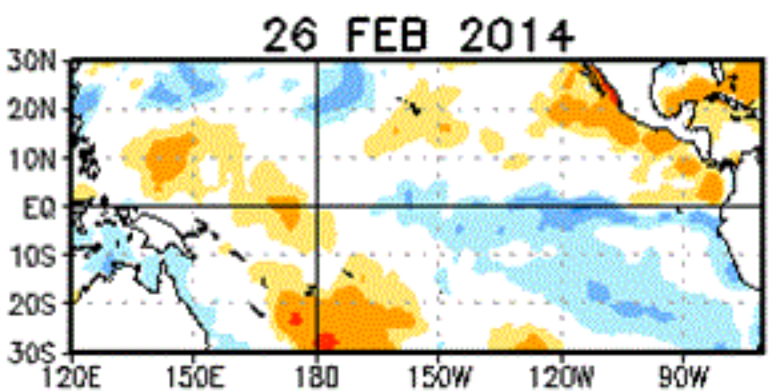
Other El Niño impacts

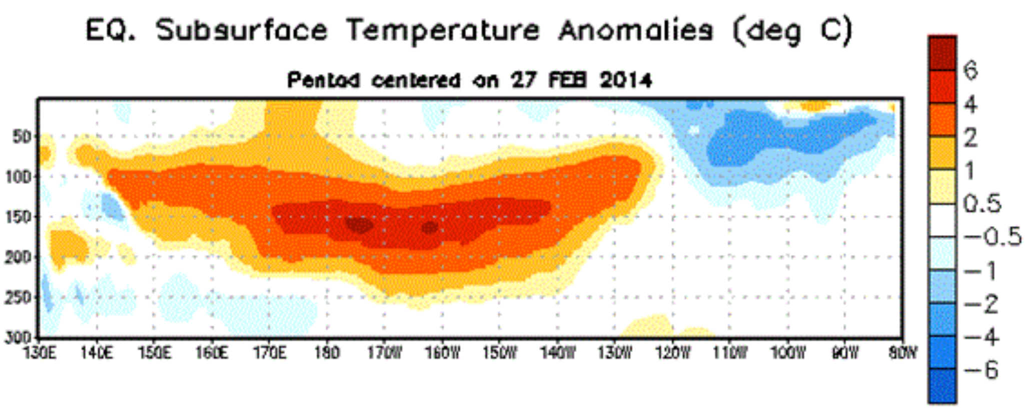




Current conditions and forecast

Synopsis: ENSO-neutral is expected to continue through the Northern Hemisphere spring 2014, with about a 50% chance of El Niño developing during the summer or fall.





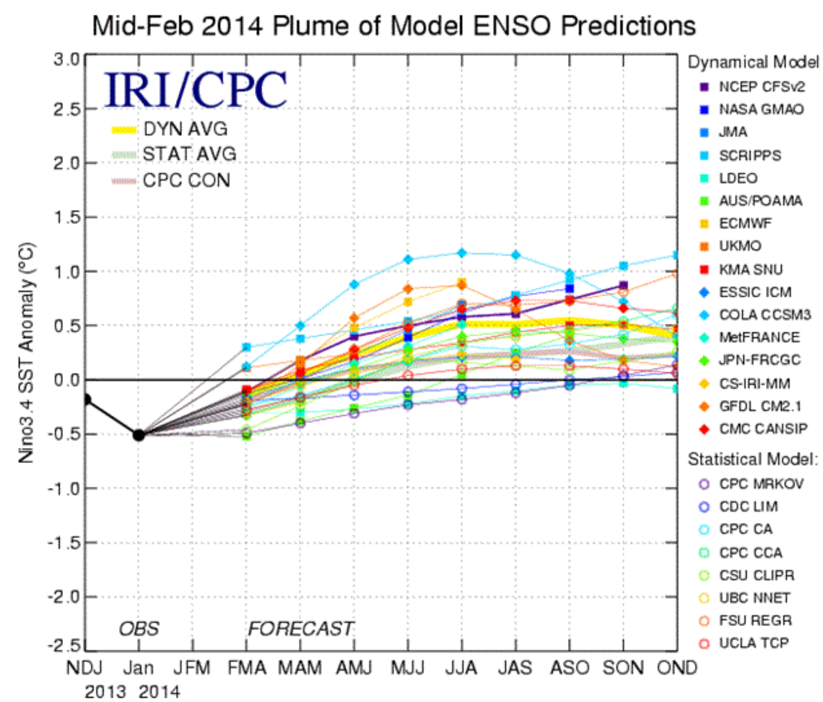


Figure 6. Forecasts of sea surface temperature (SST) anomalies for the Niño 3.4 region (5°N-5°S, 120°W-170°W). Figure updated 18 February 2014.

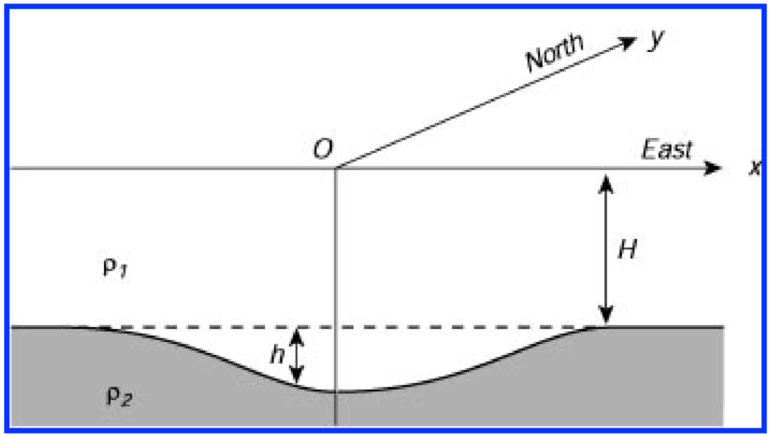
See: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/index.shtml

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

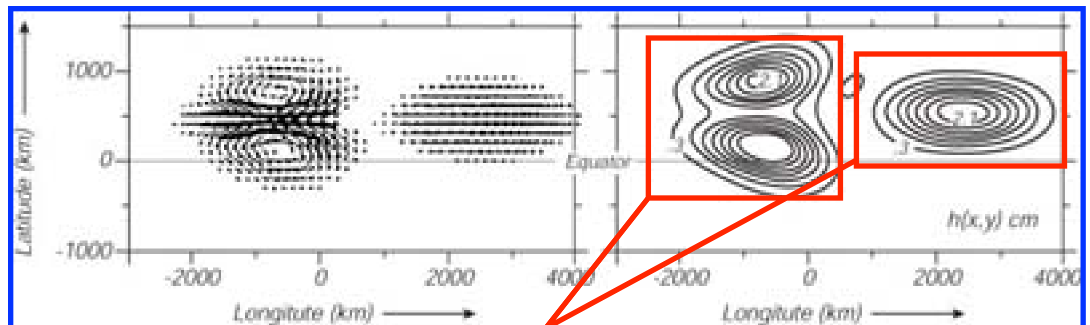
Goal: Develop quantitative understanding of ENSO genesis, evolution, and impacts

Equatorial Kelvin & Rossby Waves

2-layer oceanic SWE model



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



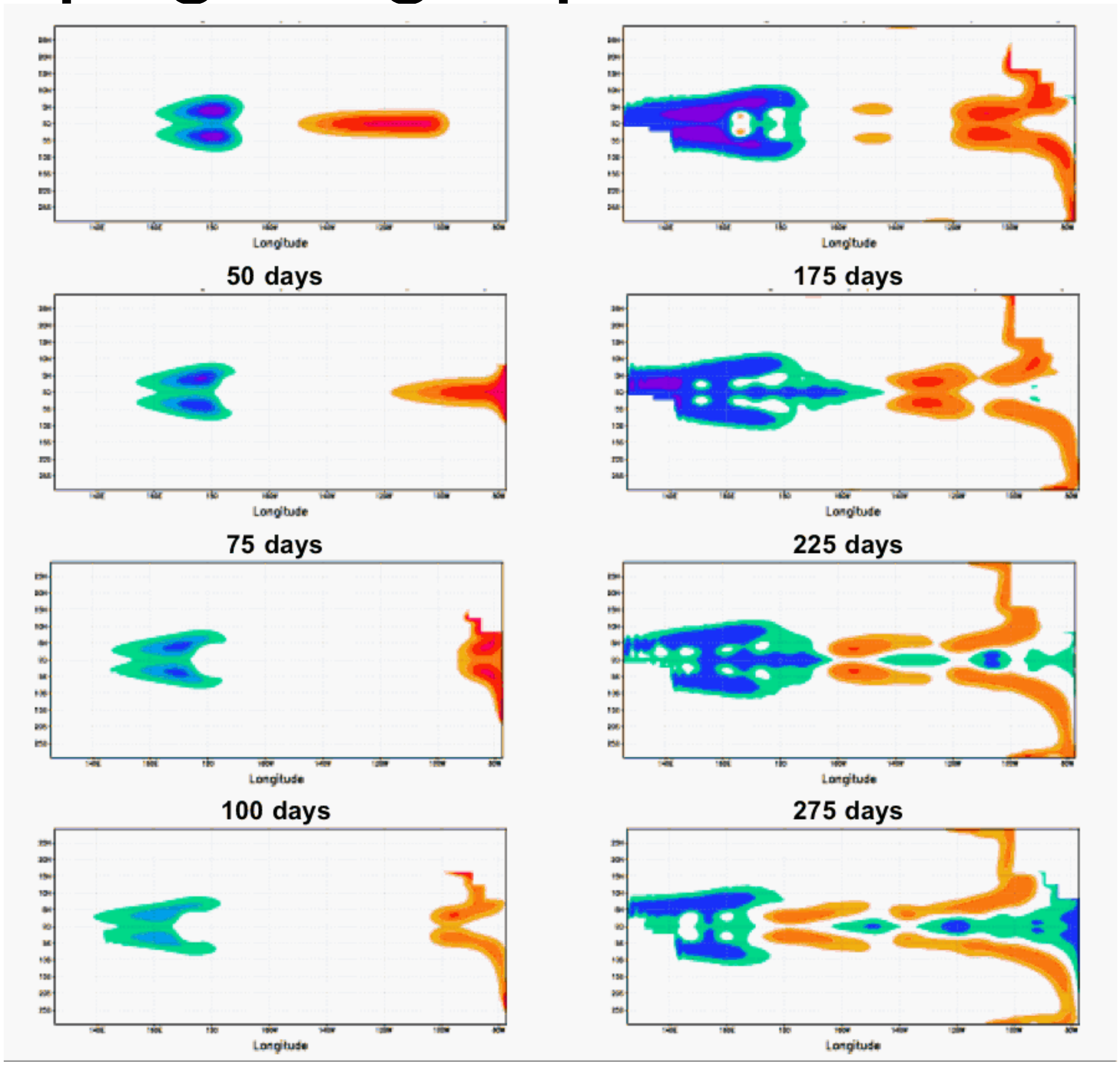
$$c_g[Kelvin] = \sqrt{g'H} \quad ; \quad g' = g(\rho_2/\rho_1 - 1)$$

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

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 represented in terms of, say, 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.*

Zebiak and Cane (1987) Model

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

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

Shear:

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

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

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

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

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

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

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)

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

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

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

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

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

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

ZC parameters

Atmospheric damping time — Atmospheric phase speed — SST heating coefficient

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

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

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

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

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

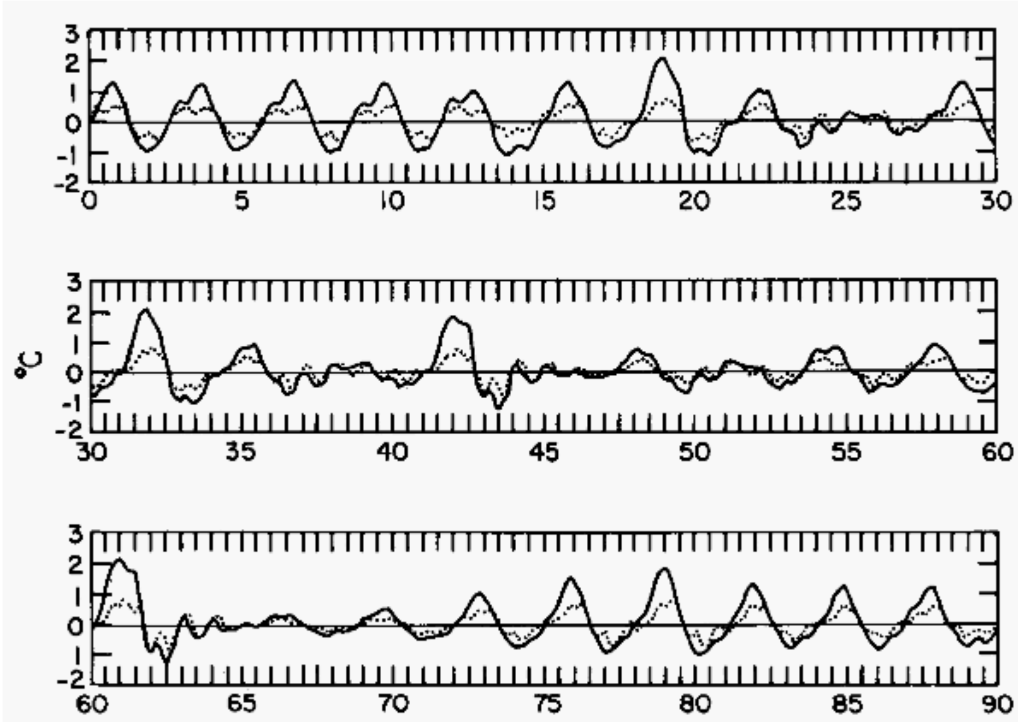
Layer 1-2 shear adjustment timescale $r_s = (2\ \text{days})^{-1}$, $\alpha_s = (125\ \text{days})^{-1}$, Surface layer thermal dissipation

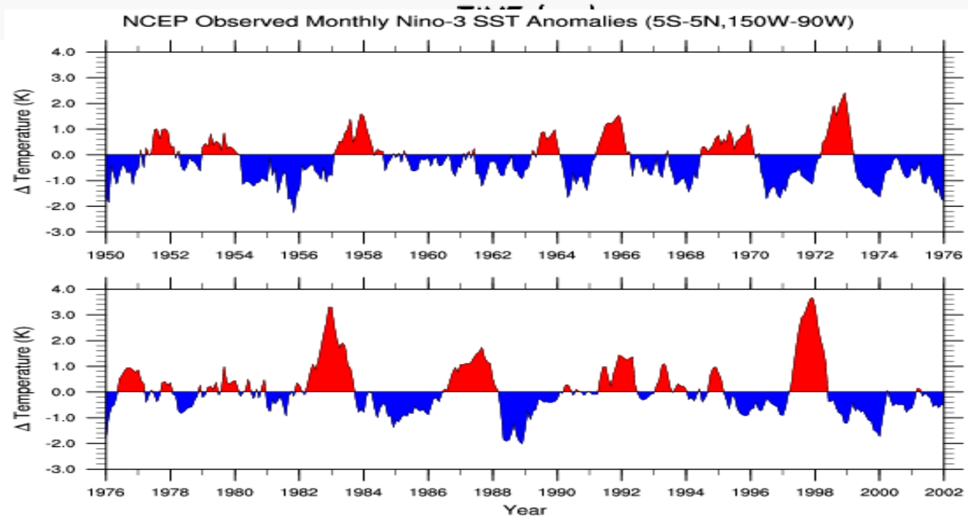
$$\gamma = 0.75, \quad T_1 = 28°\text{C}, \quad T_2 = -40°\text{C},$$

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

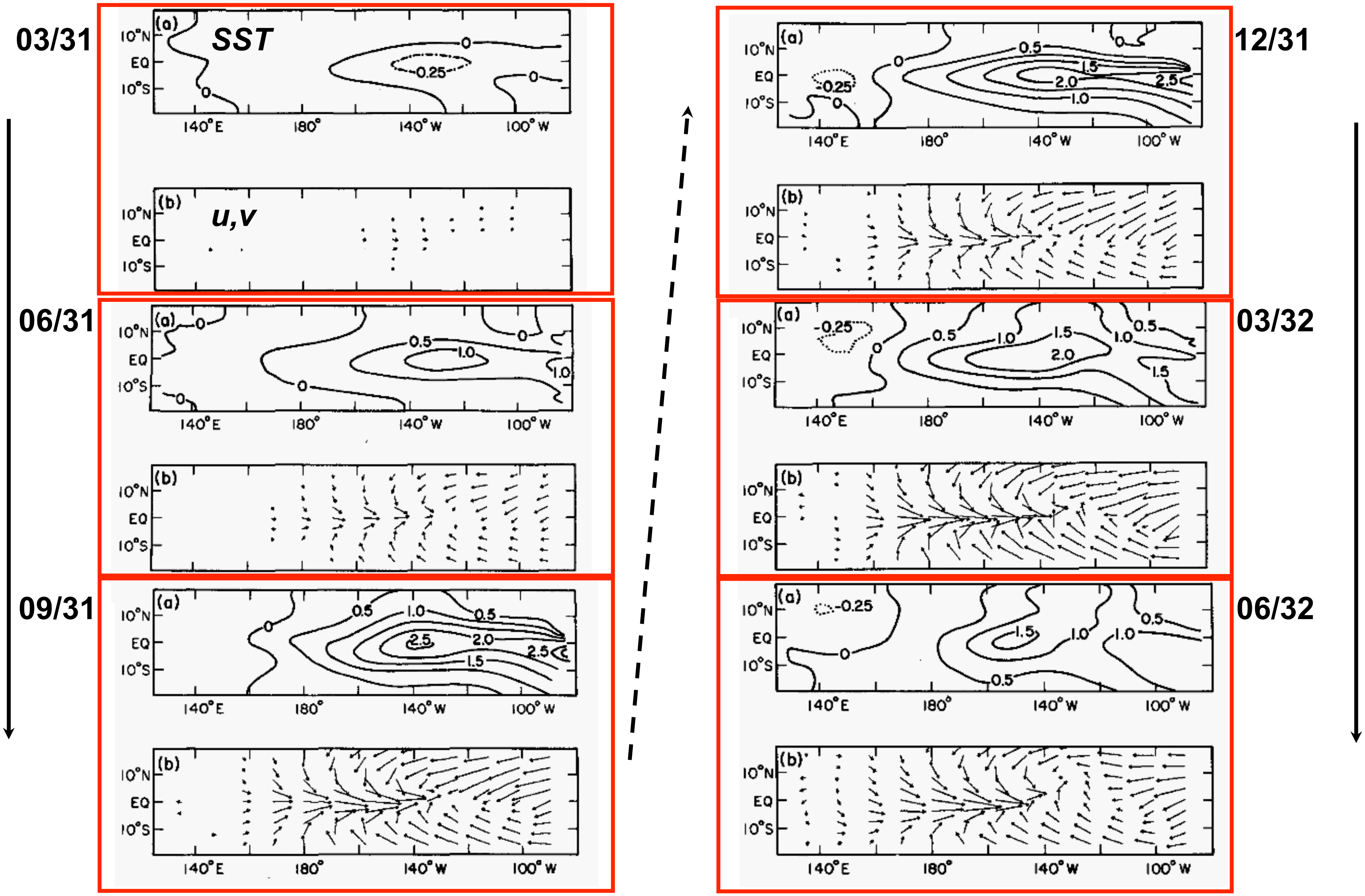
Entrainment parameters

ZC results: NINO3 SSTs

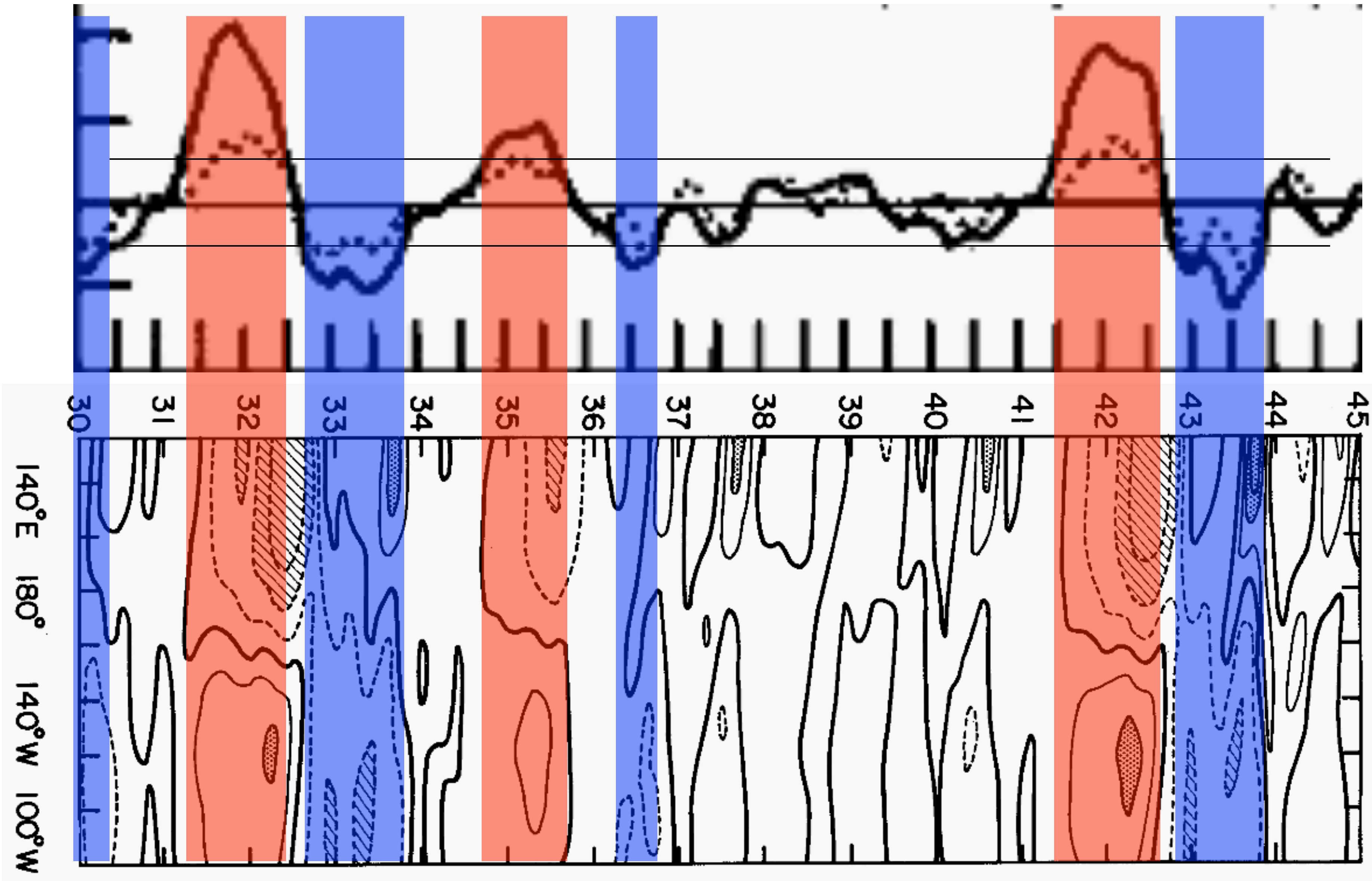




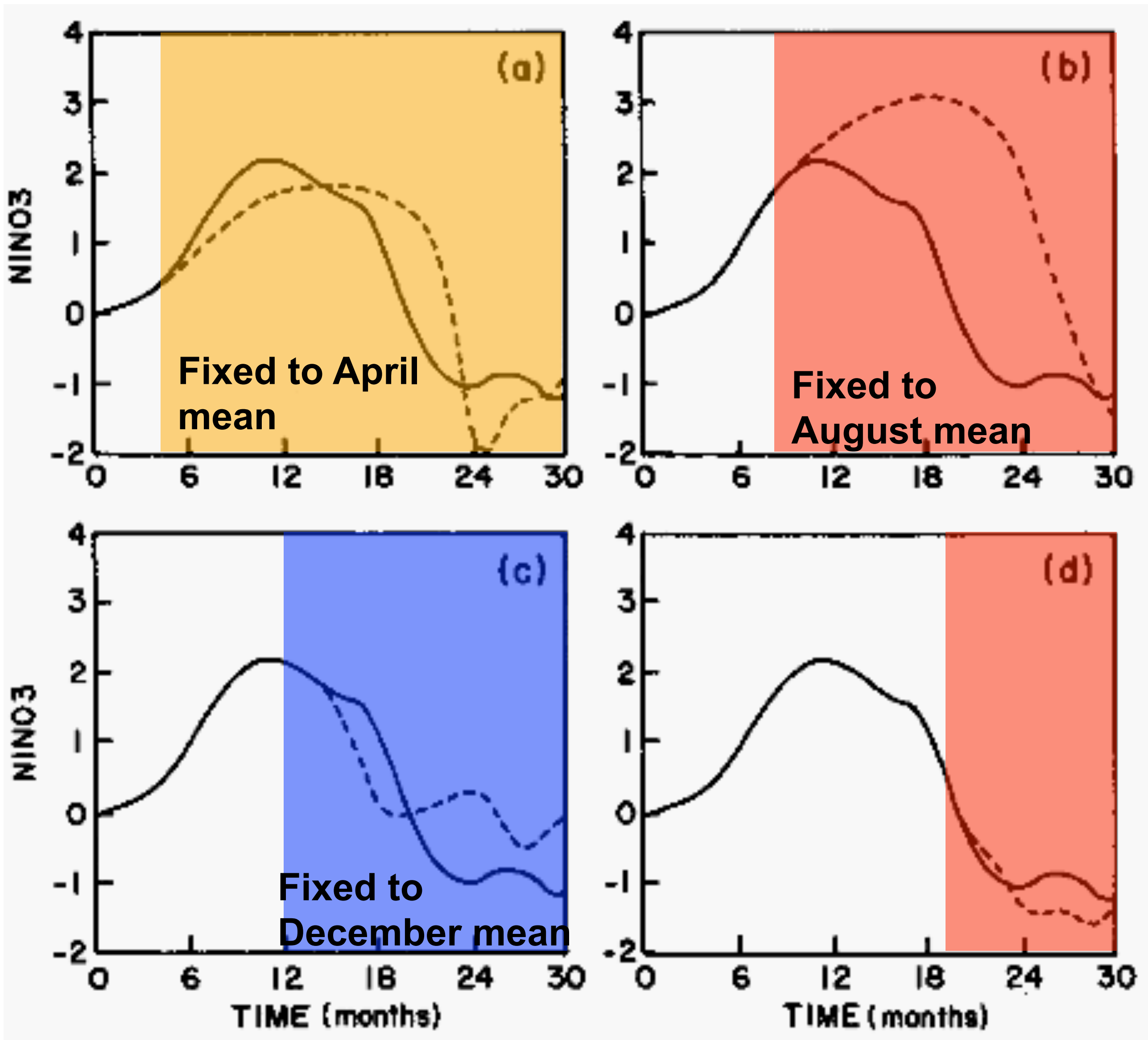
ZC results: Time evolution



ZC results: Thermocline depth



ZC results: Interaction w/ annual cycle



ZC results: Varying heat content

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

T_{sub} has the form

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

Insensitivity to areal mean heat content:

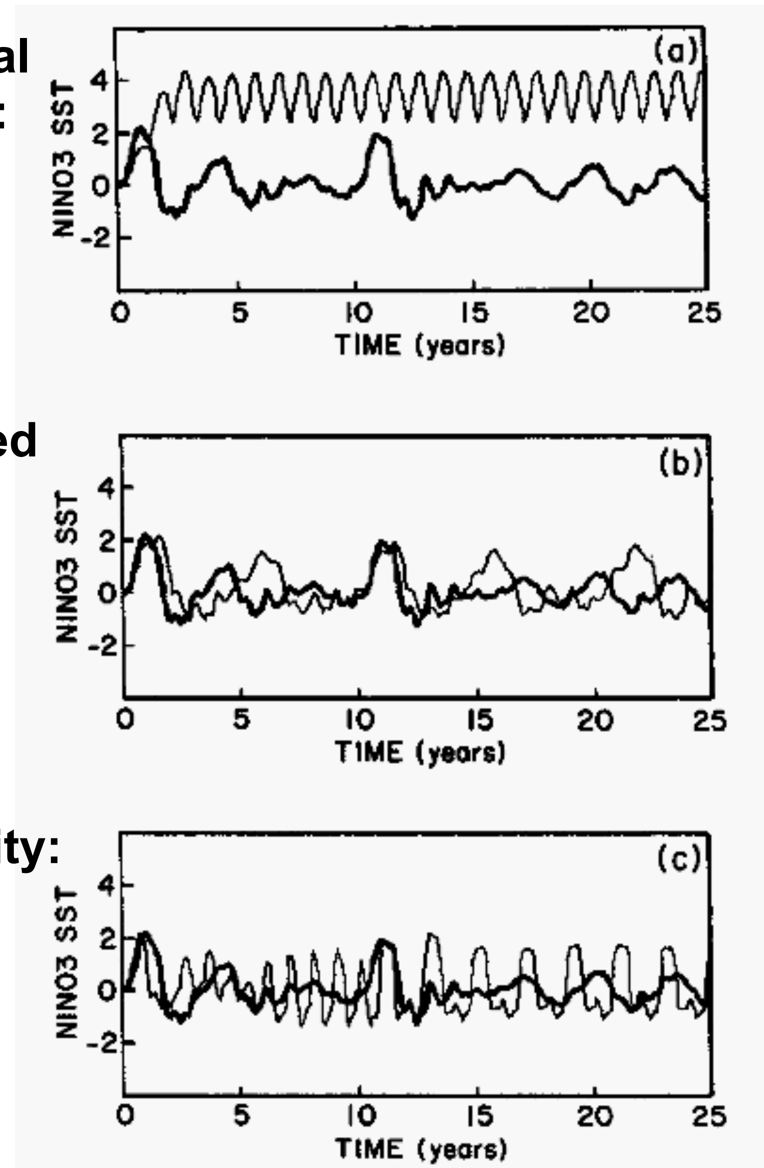
$h \to h - \langle h \rangle$

Partially suppressed sensitivity:

$h \to h - 0.5\langle h \rangle$

Enhanced sensitivity:

$h \to h + 2\langle h \rangle$



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]

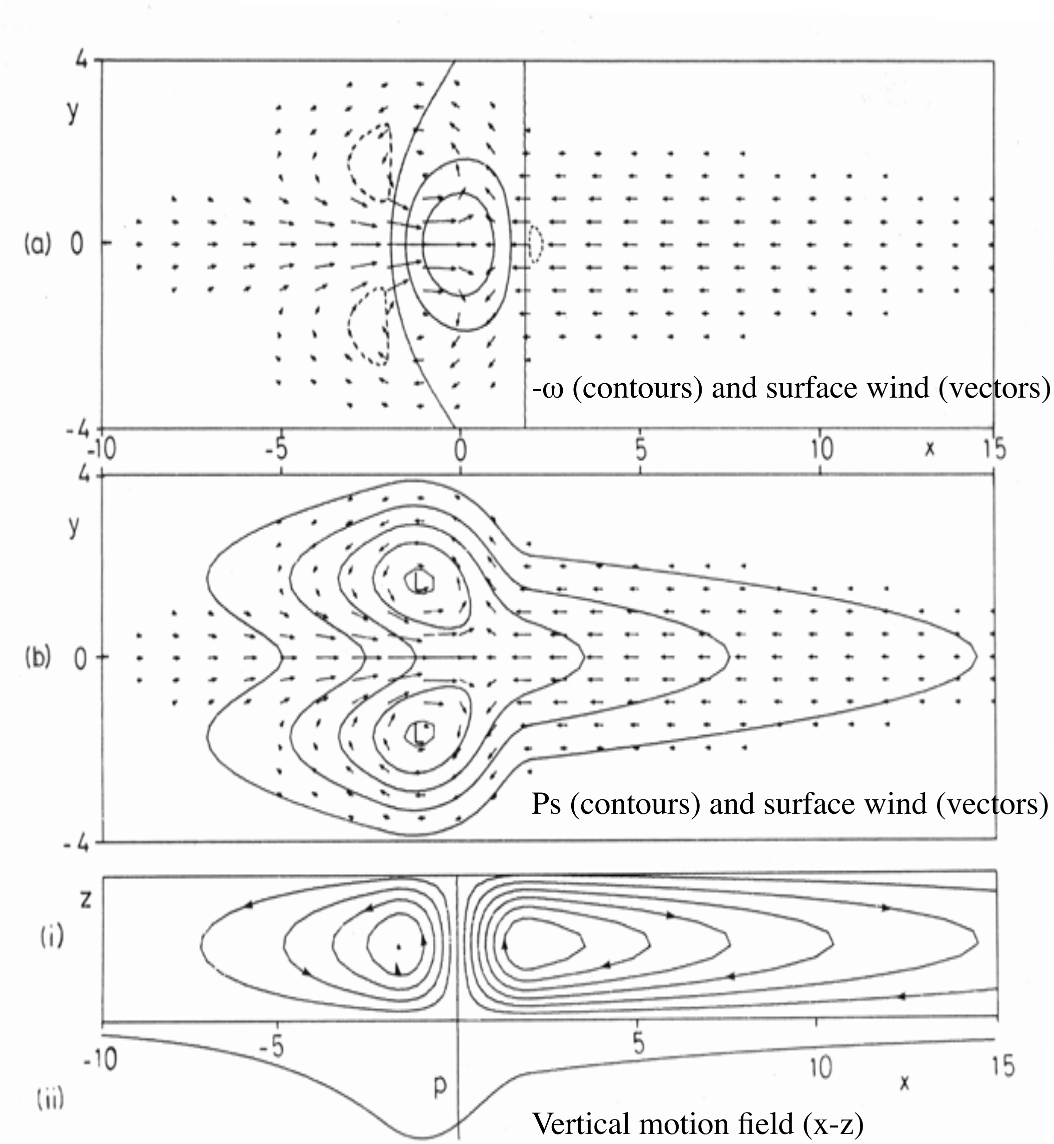
ZC model summary (II)

- 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.

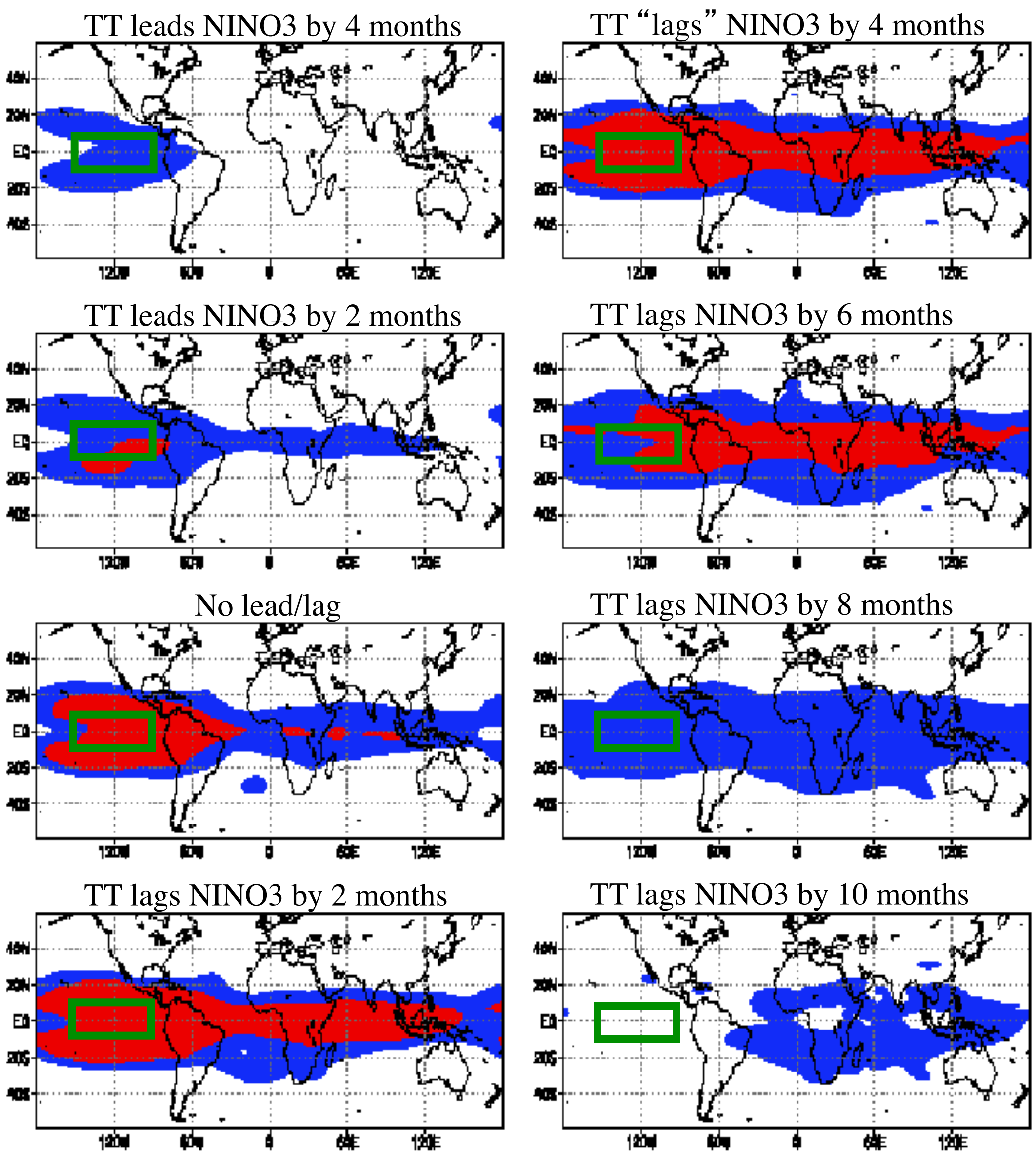
Gill (1980) Model



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.

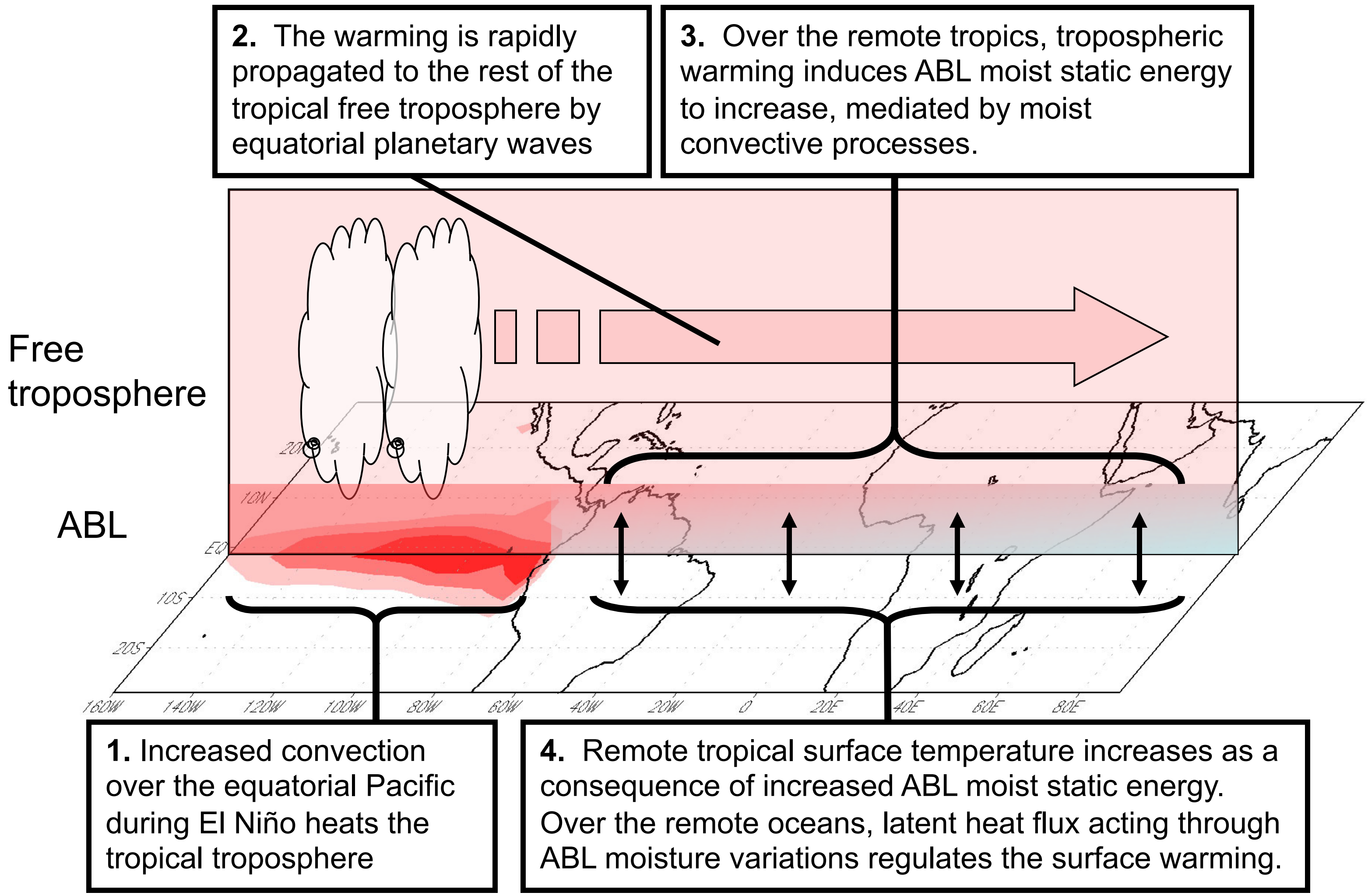
El Niño and tropical temperatures



- 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 ≥ 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



Courtesy of J.C.H. Chiang