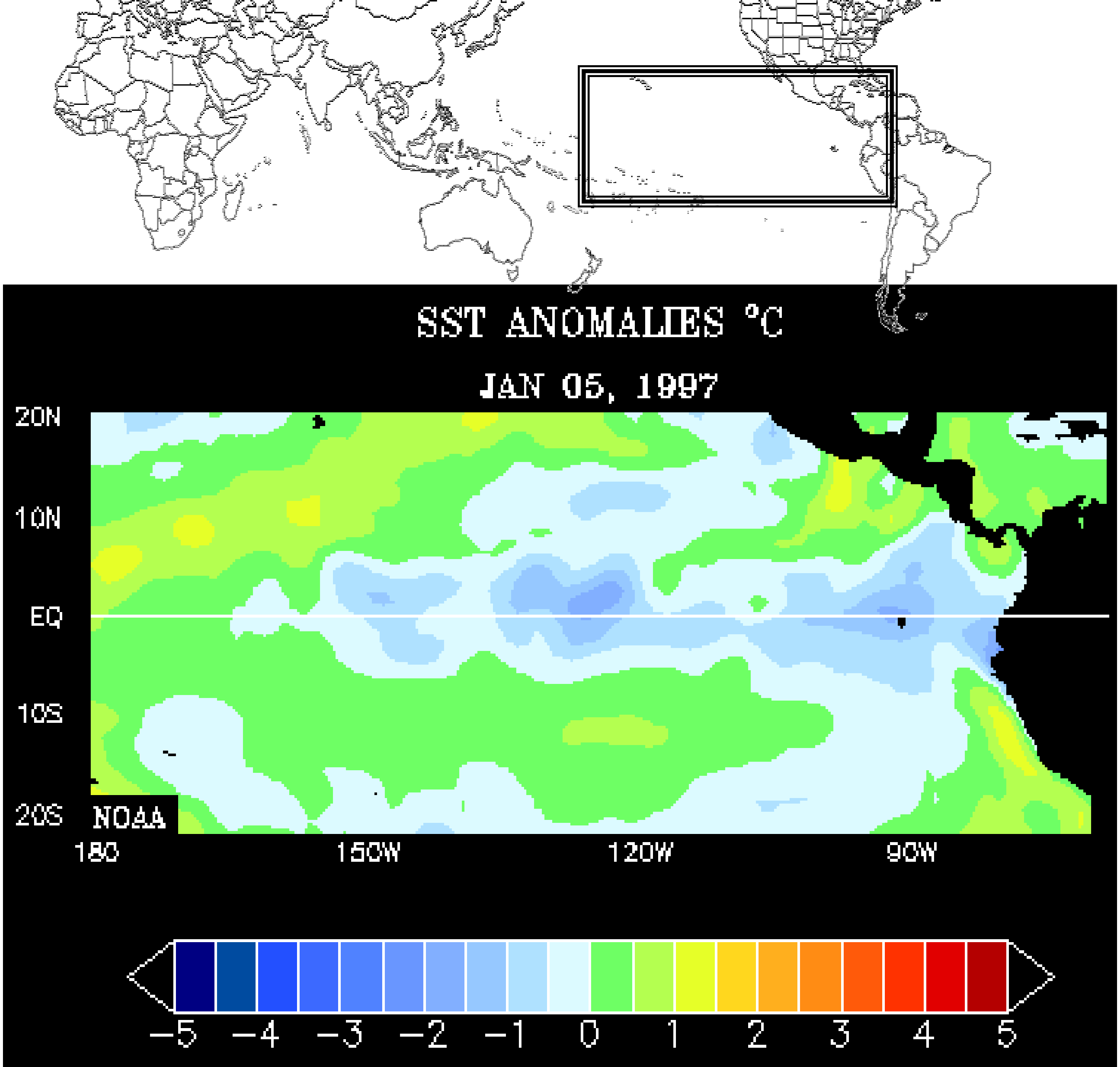
El Nino

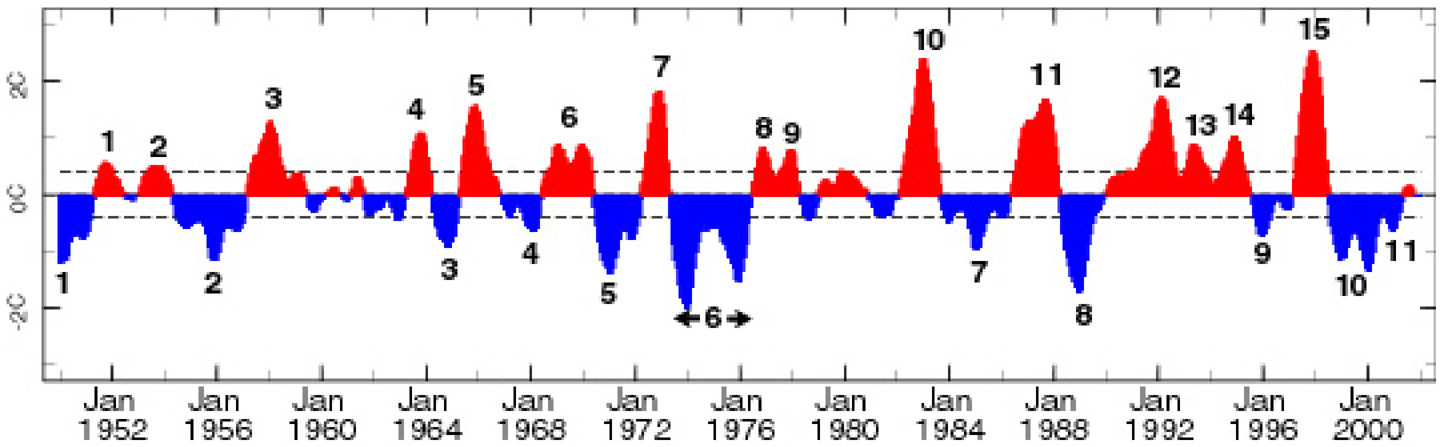
David Romps

December 16, 2008

1997/1998 El Nino

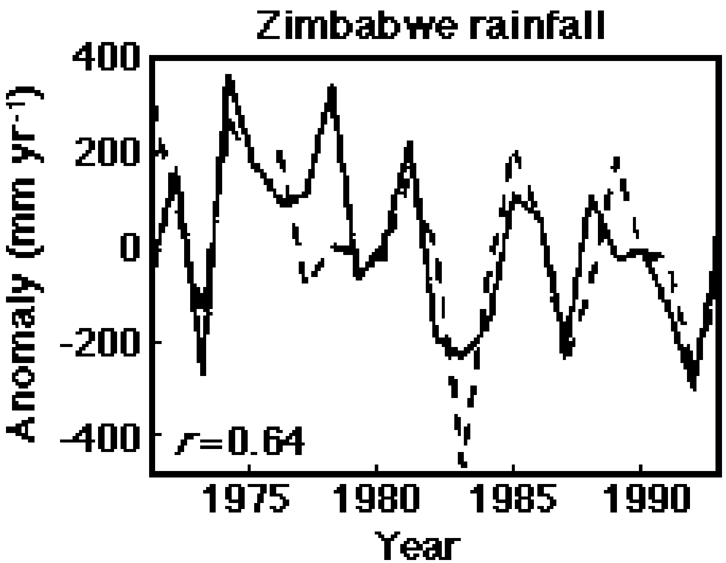


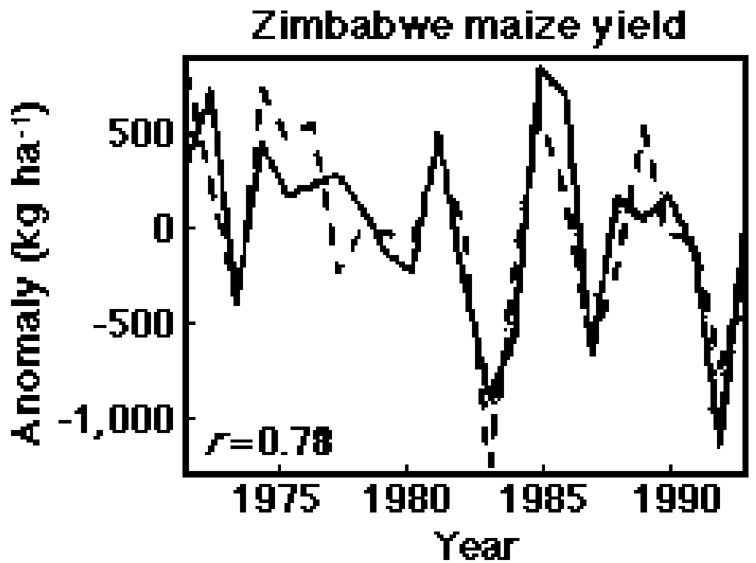
El Niño and La Niña Events 1950- present



Events are defined as periods when temperature in central equatorial Pacific Ocean remained > 0.4 deg. C. from norm for > 6 months

Correlations with El Nino: SST in Eastern Pacific vs Rainfall, Maize in Africa





(Dotted lines are SST anomolies in E equatorial Pacific)

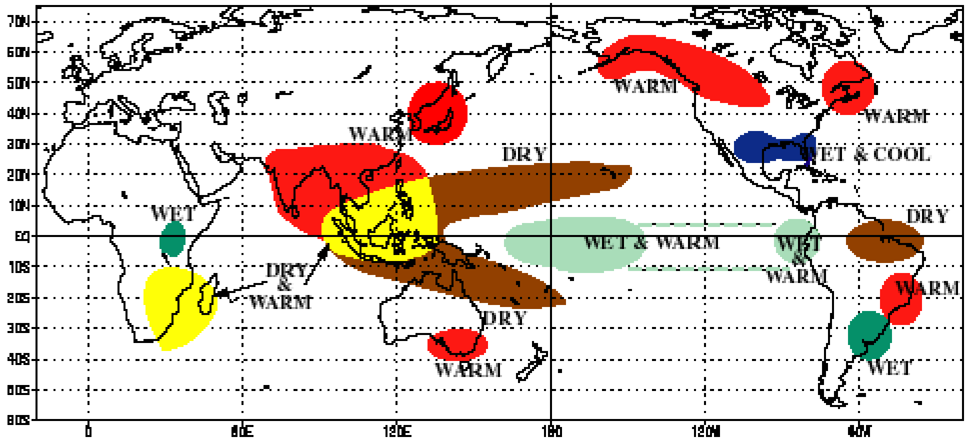
Source: Kane et al., 1994

Other correlations with El Nino

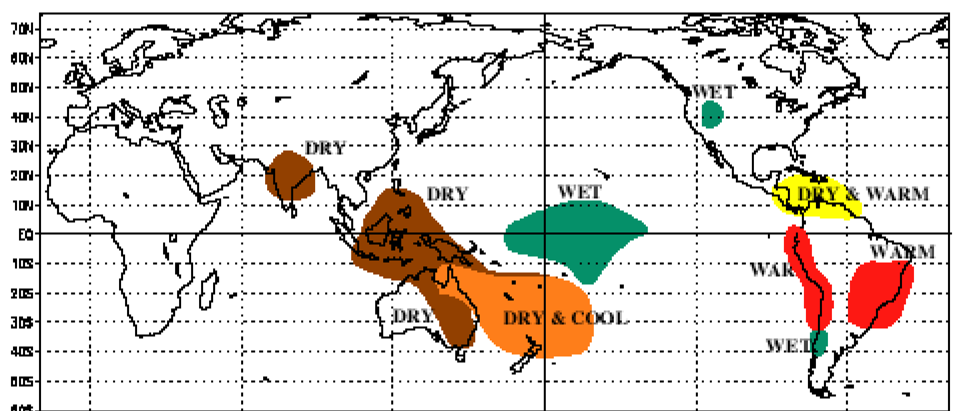
- Crop failures and sometimes famine in southern Africa
- Collapse of the Peruvian anchovetta fisheries
- Damages from floods and landslides caused by very high rainfall in Peru and southern California
- Forest fires in Indonesia and associated serious air pollution problems
- Various disease outbreaks,
- Availability of water resources, disruption to hydropower generation

El Nino Weather

WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



WARM EPISODE RELATIONSHIPS JUNE - AUGUST



Source: NOAA

What is going on?

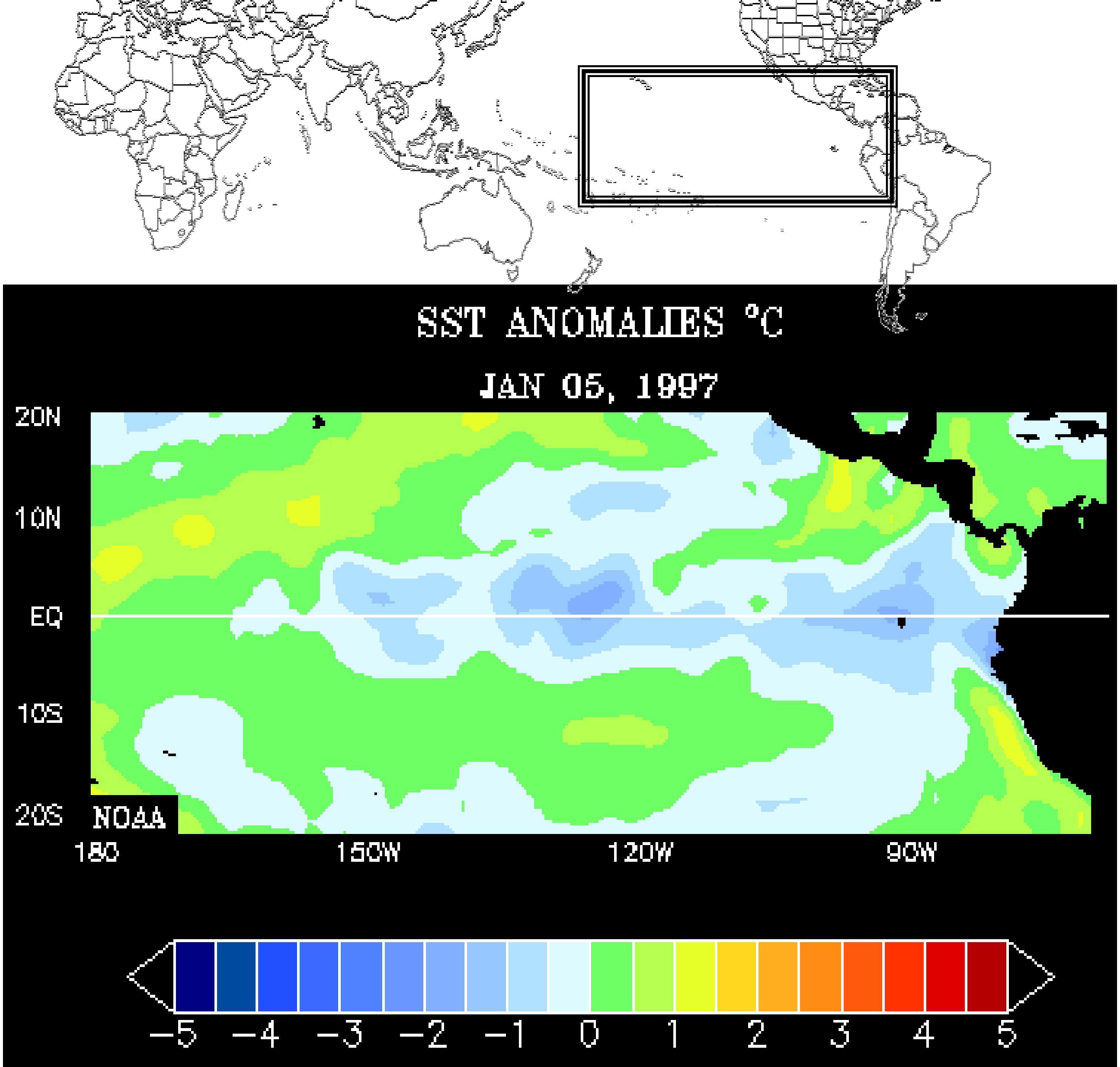
- Semi-regular oscillations in temperature across equatorial Pacific on scales of years to decades
- Patterns of linked cooling and warming across the Pacific
- Apparent connections of Pacific oscillation to weather variations around the planet
- Prospect of predicting impact timing and location…

ENSO is really two different (but related) phenomena

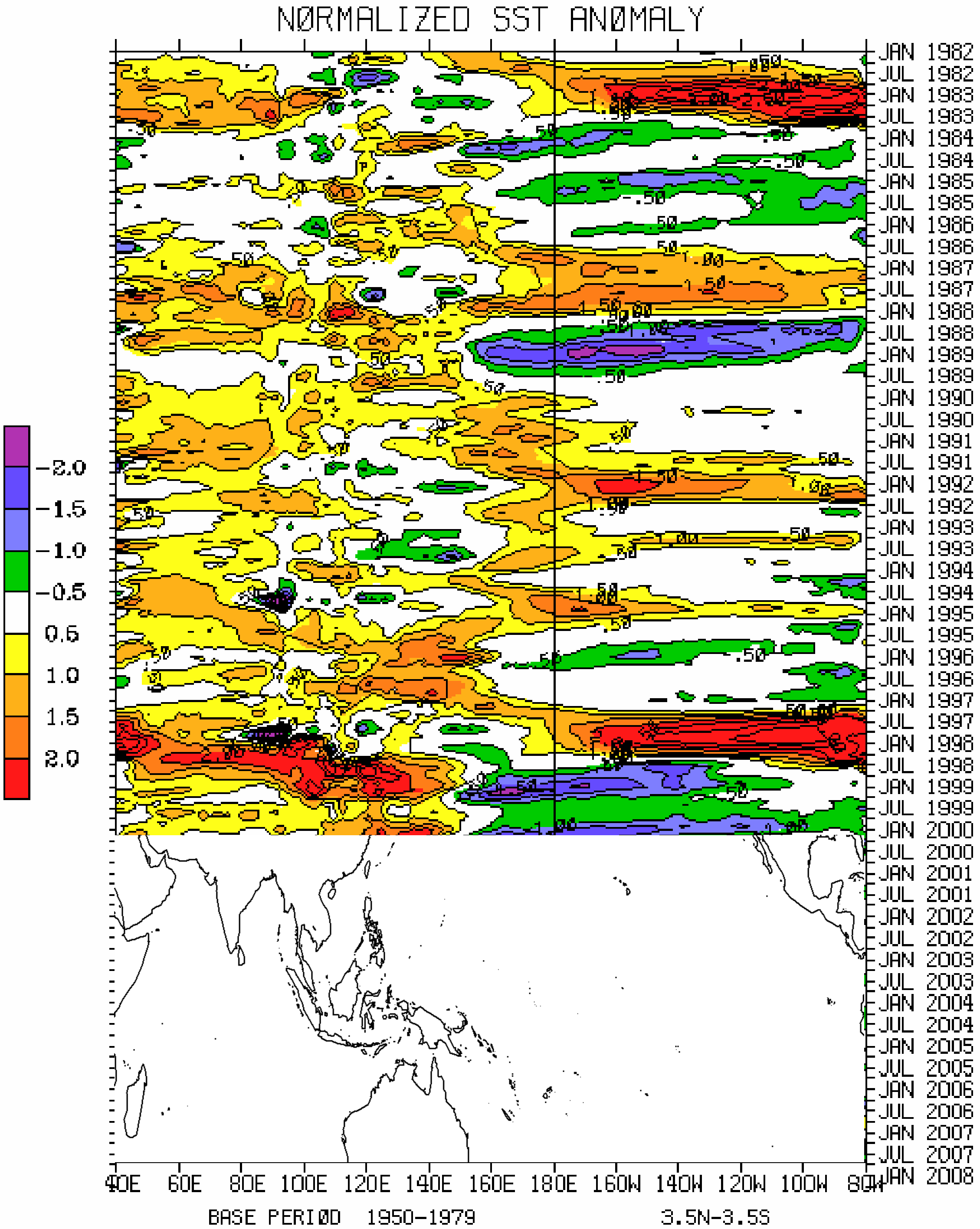
E l
N ino
S outhern
O scillation

First, El Nino….

1997/1998 El Nino

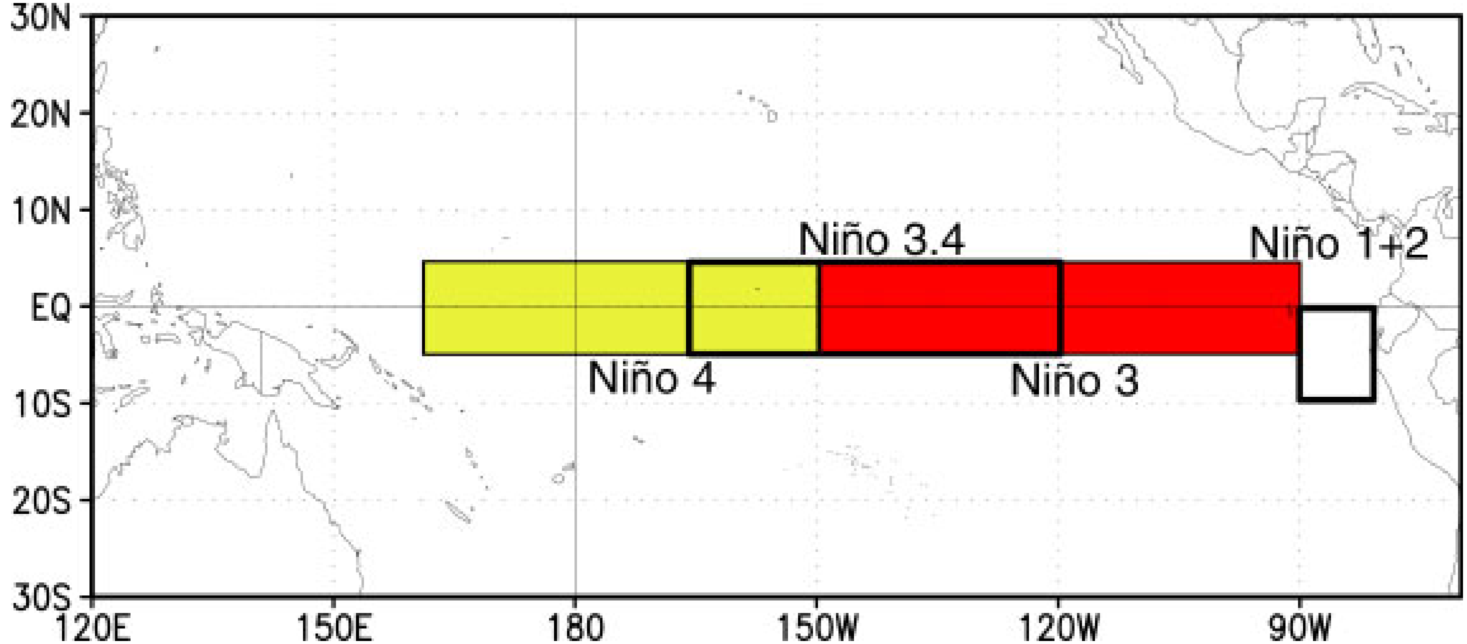


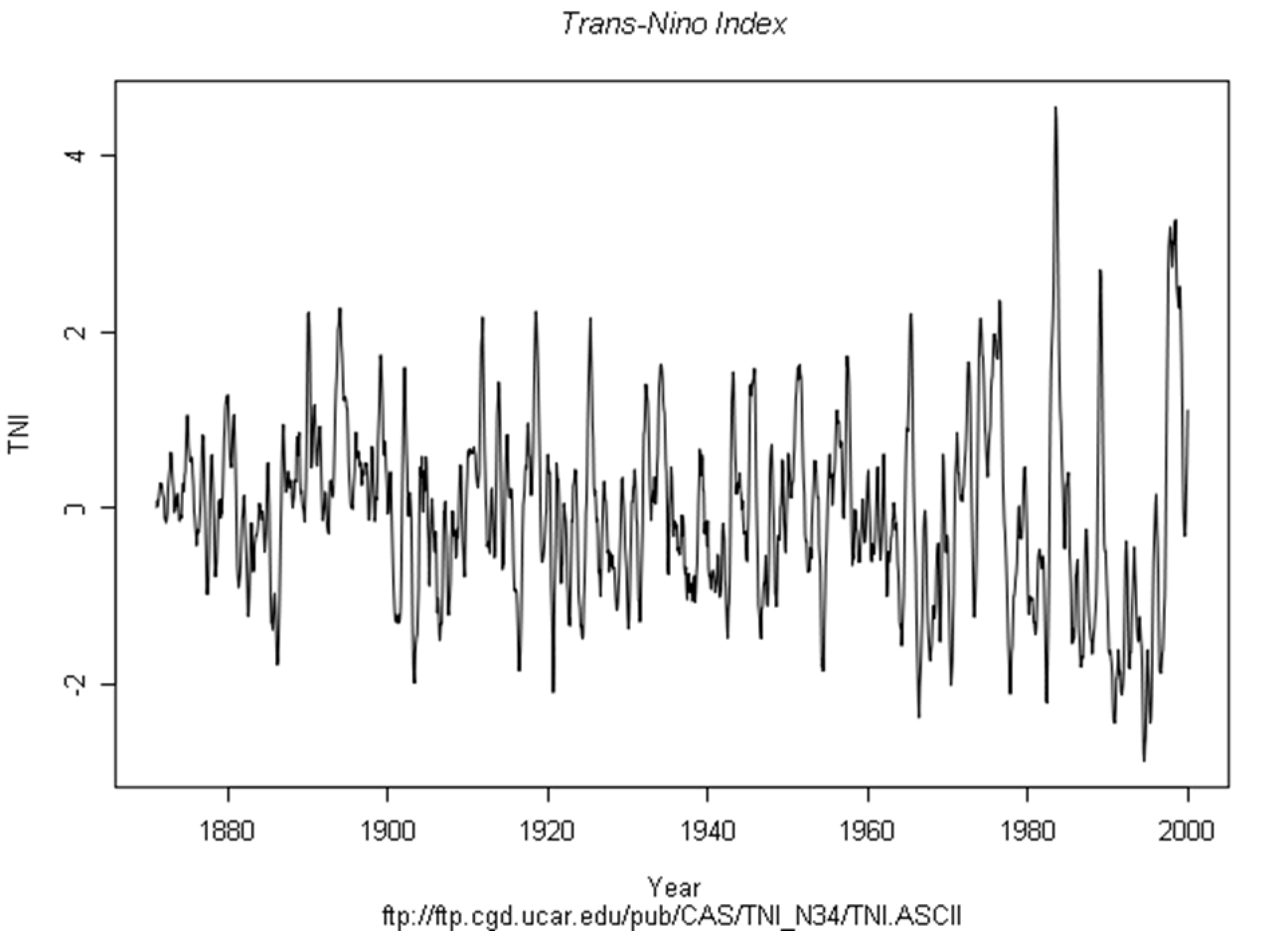
Hovmoller of equatorial SST



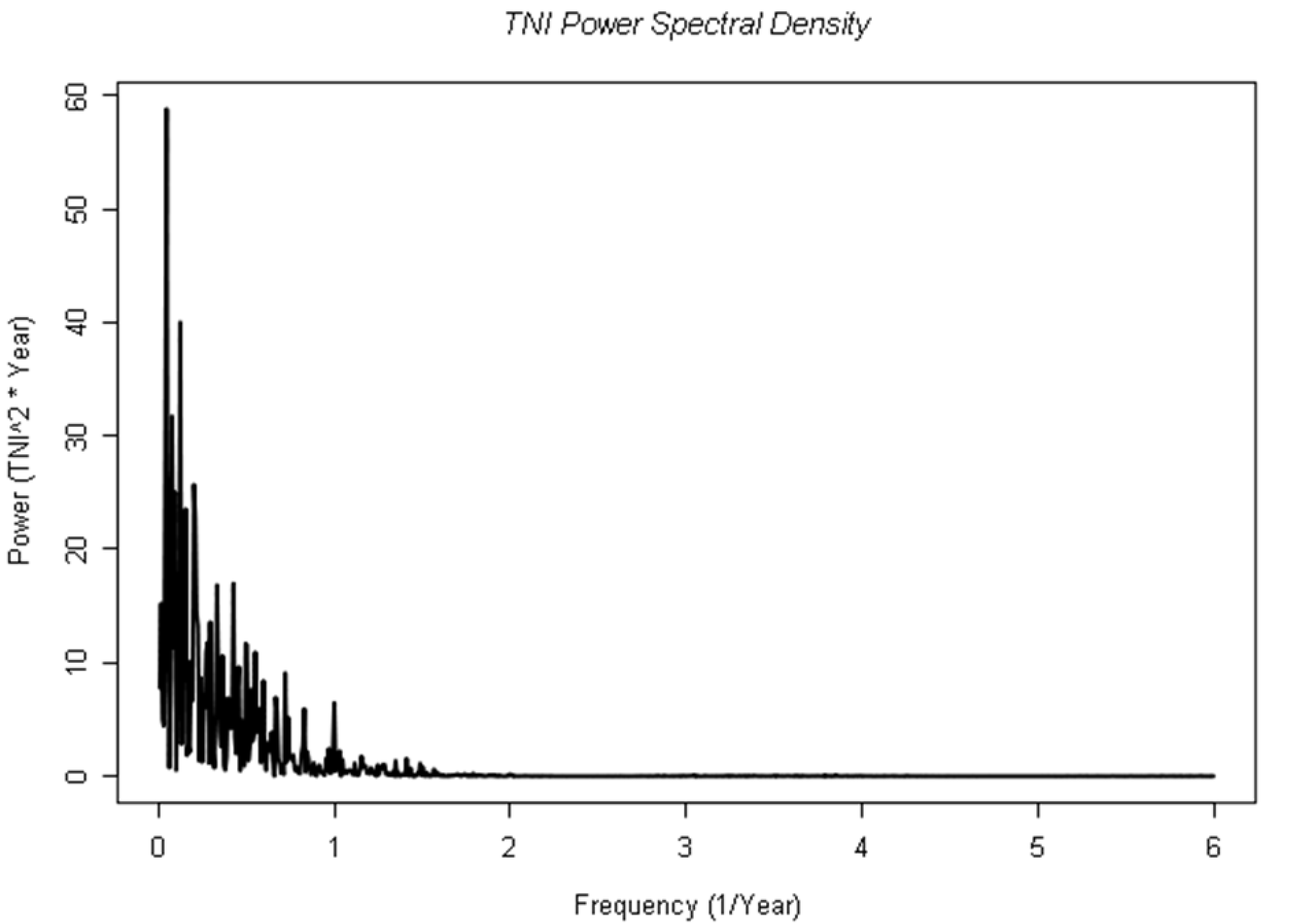
http://www.cdc.noaa.gov/map/clim/sst.shtml

El Niño Regions

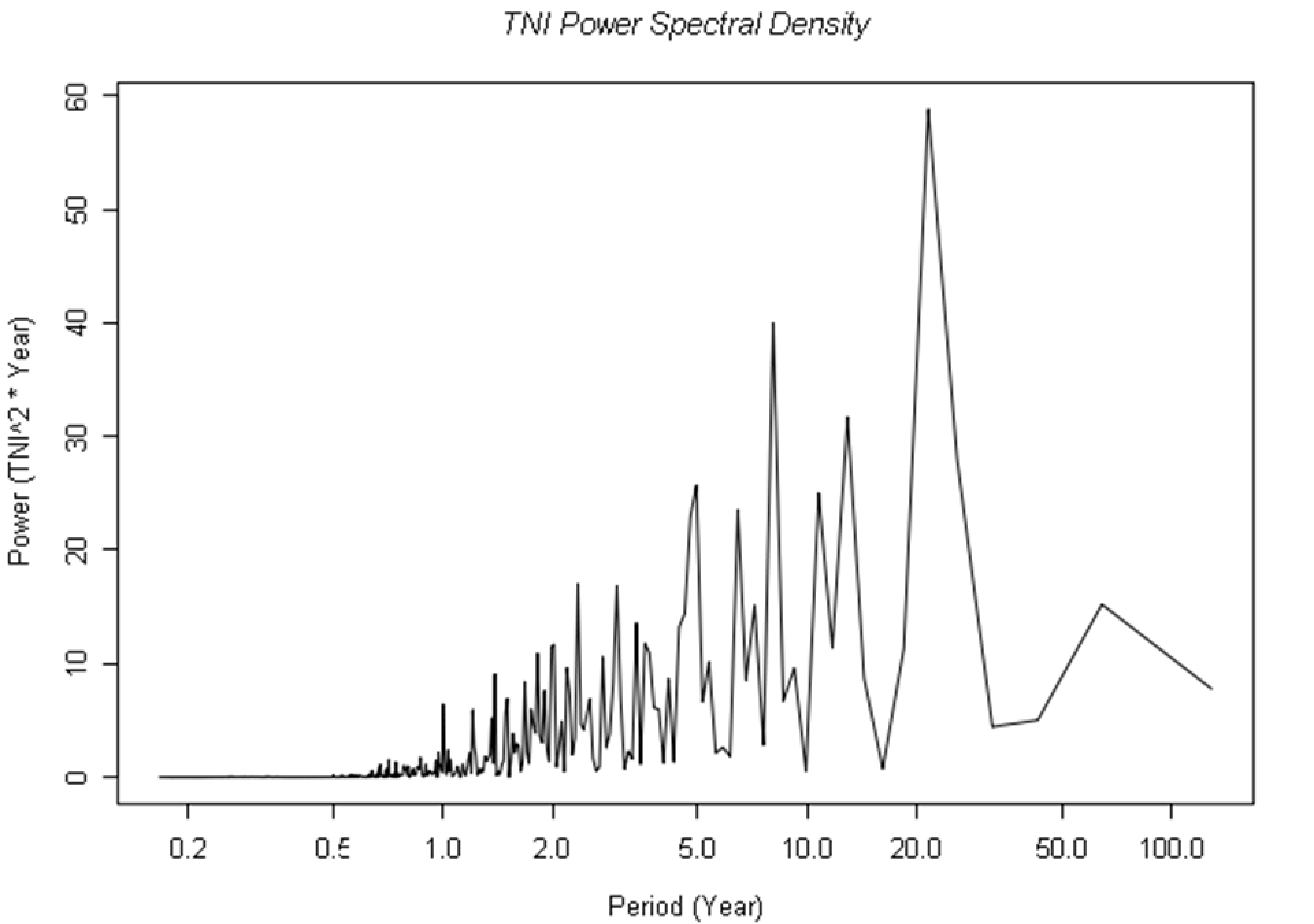




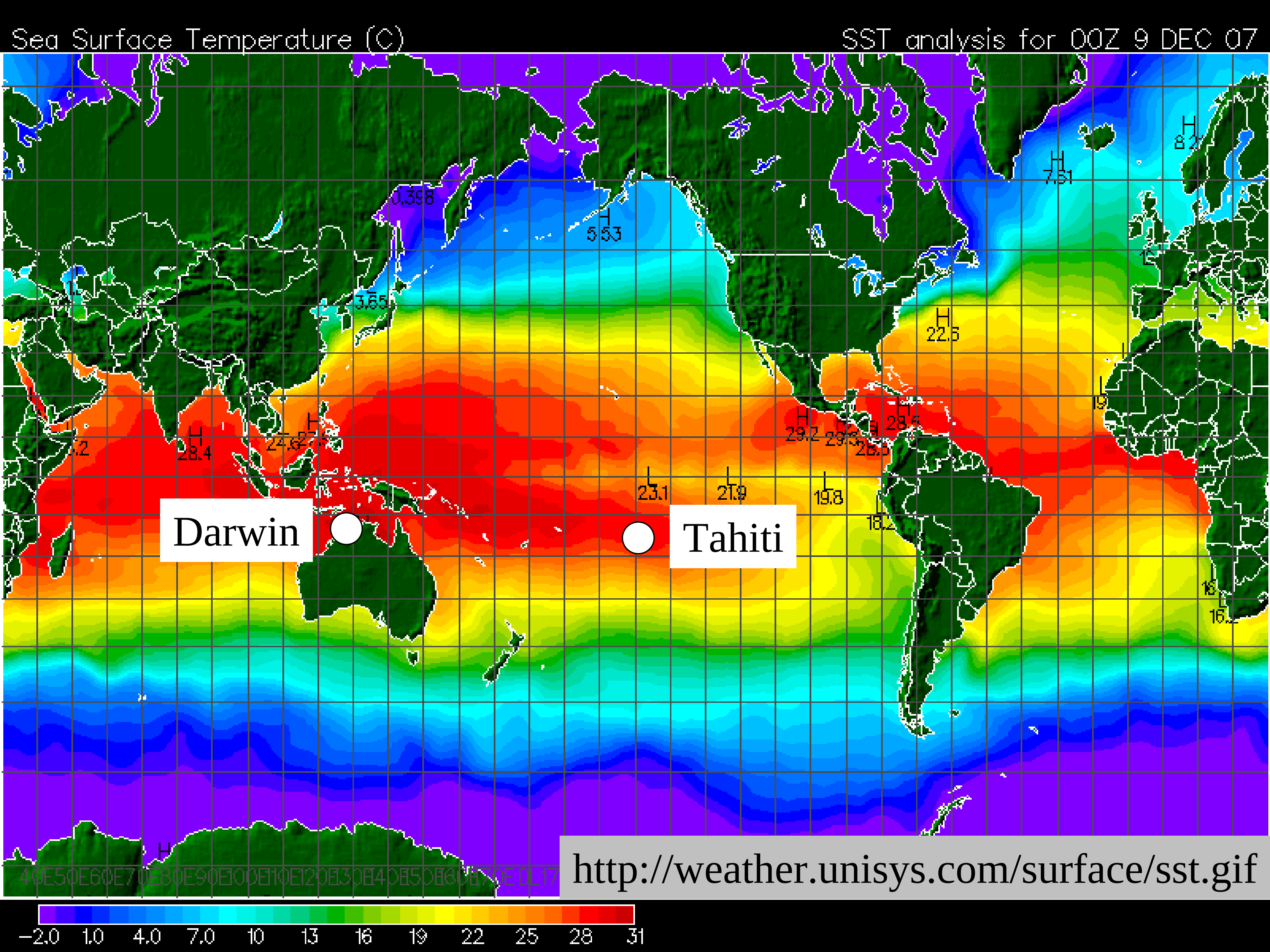
Trans-Nino Index
TNI
4
2
0
-2
1880
1900
1920
1940
1960
1980
2000
Year
ftp://ftp.cgd.ucar.edu/pub/CAS/TNI_N34/TNI.ASCII



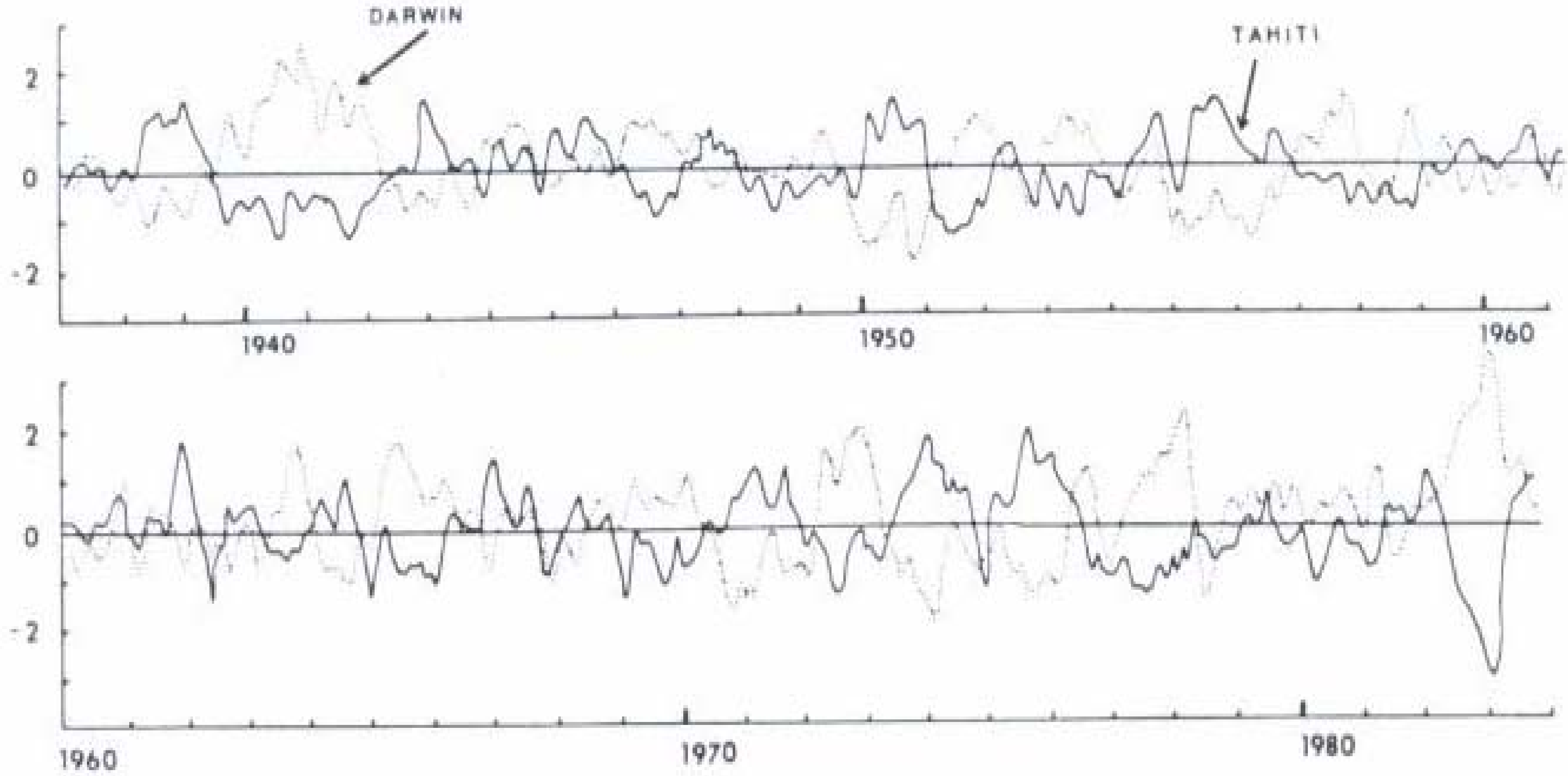
TNI Power Spectral Density
Power (TNI^2 * Year)
60
50
40
30
20
10
0
0
1
2
3
4
5
6
Frequency (1/Year)


TNI Power Spectral Density
Power (TNI^2 * Year)
0
10
20
30
40
50
60
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
100.0
Period (Year)

Now, the Southern Oscillation….

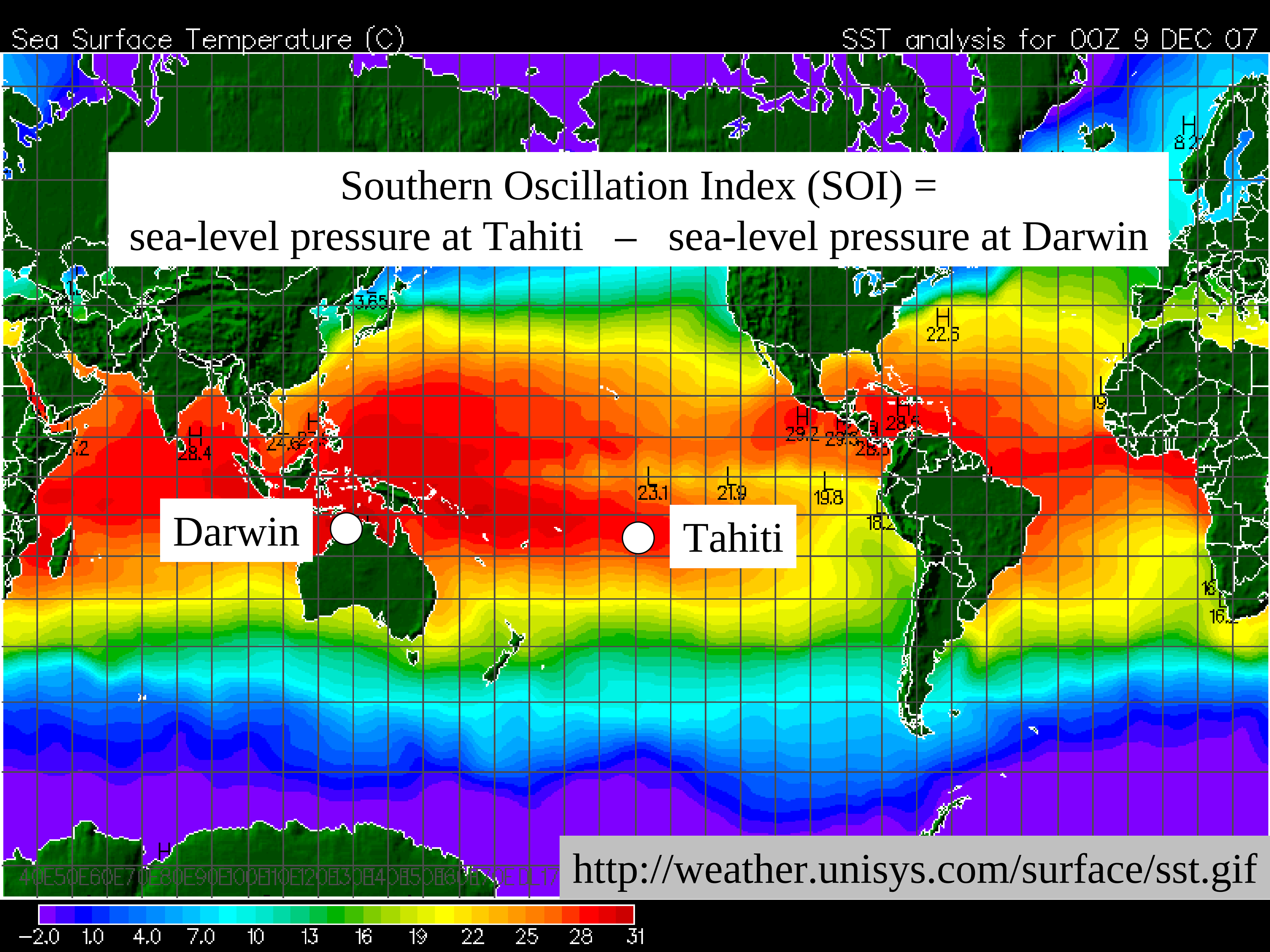

Sea Surface Temperature (C)
SST analysis for 00Z 9 DEC 07
Darwin
Tahiti
http://weather.unisys.com/surface/sst.gif
−2.0 1.0 4.0 7.0 10 13 16 19 22 25 28 31

SLP at Darwin and Tahiti are highly anti-correlated

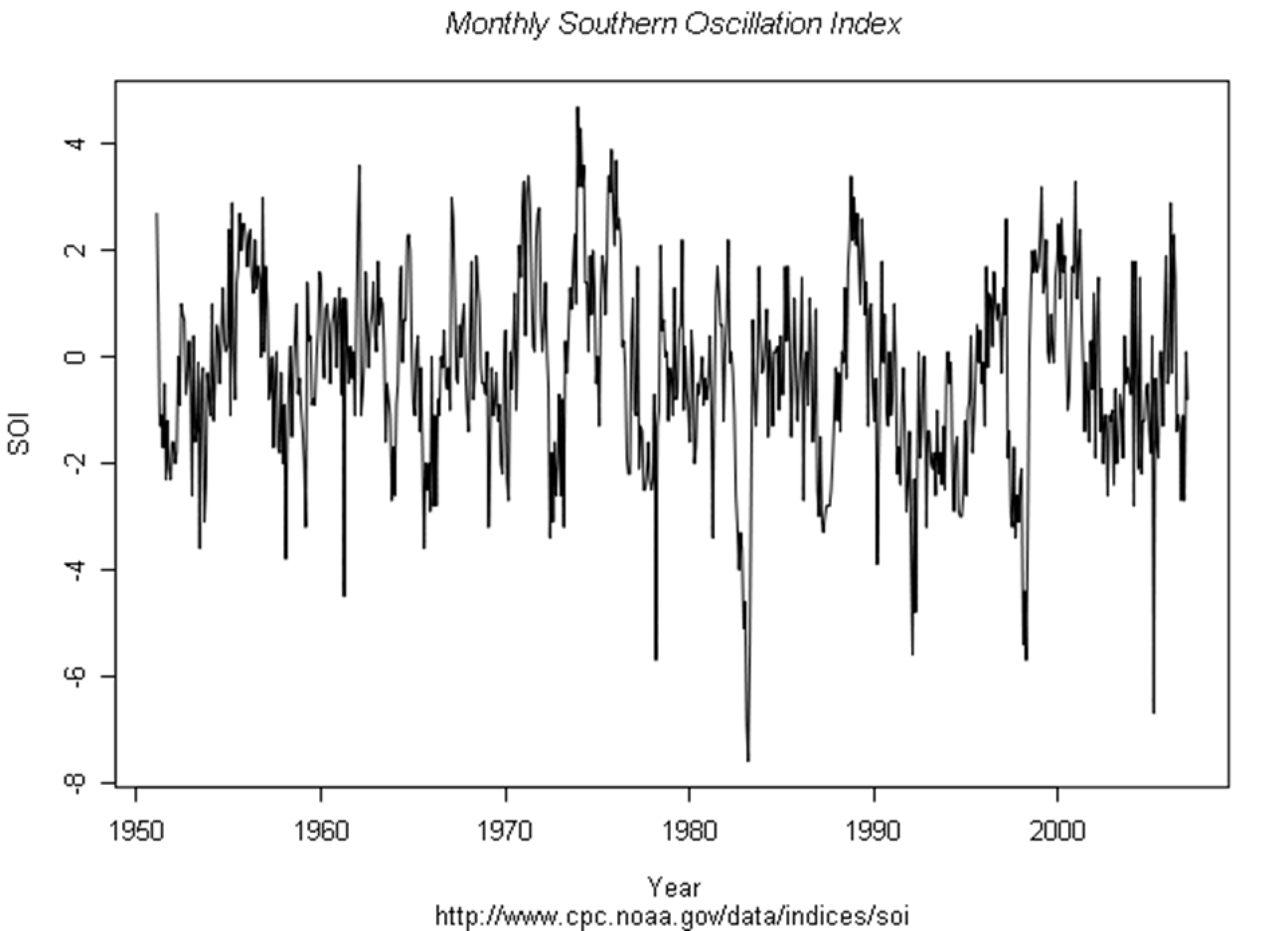


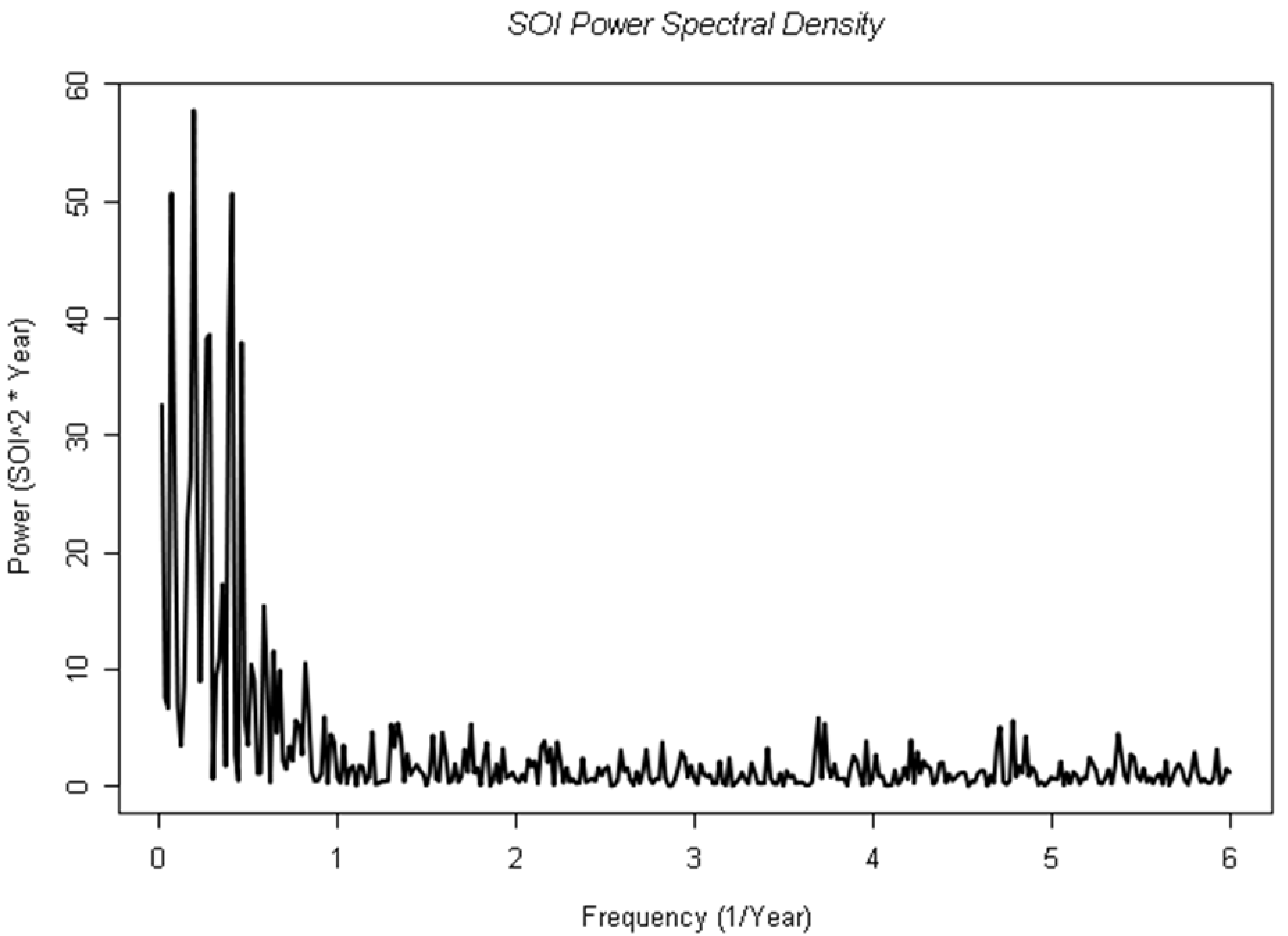
Philander, “El Nino, La Nina, and the Southern Oscillation,” 1990

Southern Oscillation Index (SOI) =
sea-level pressure at Tahiti – sea-level pressure at Darwin

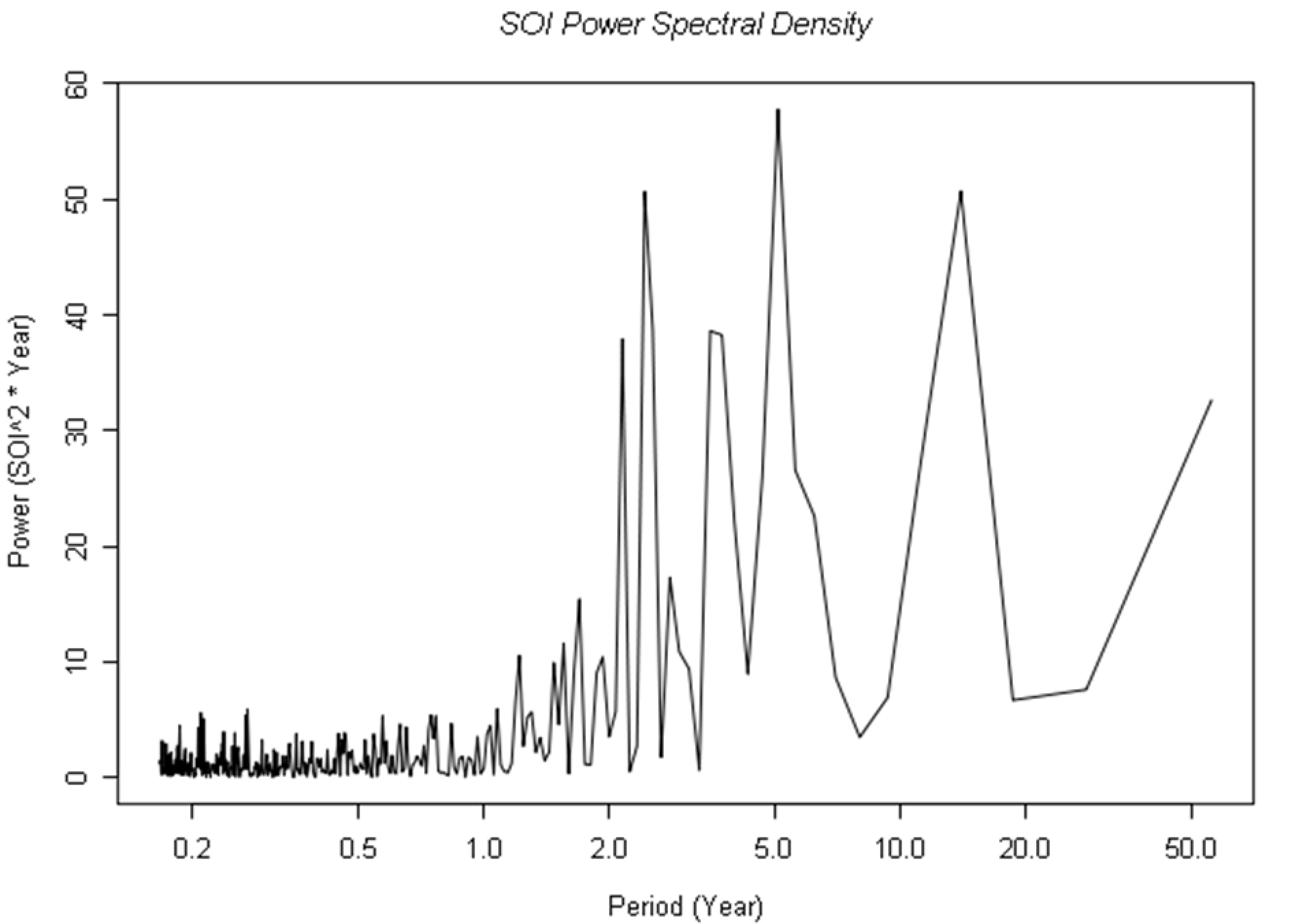


http://weather.unisys.com/surface/sst.gif

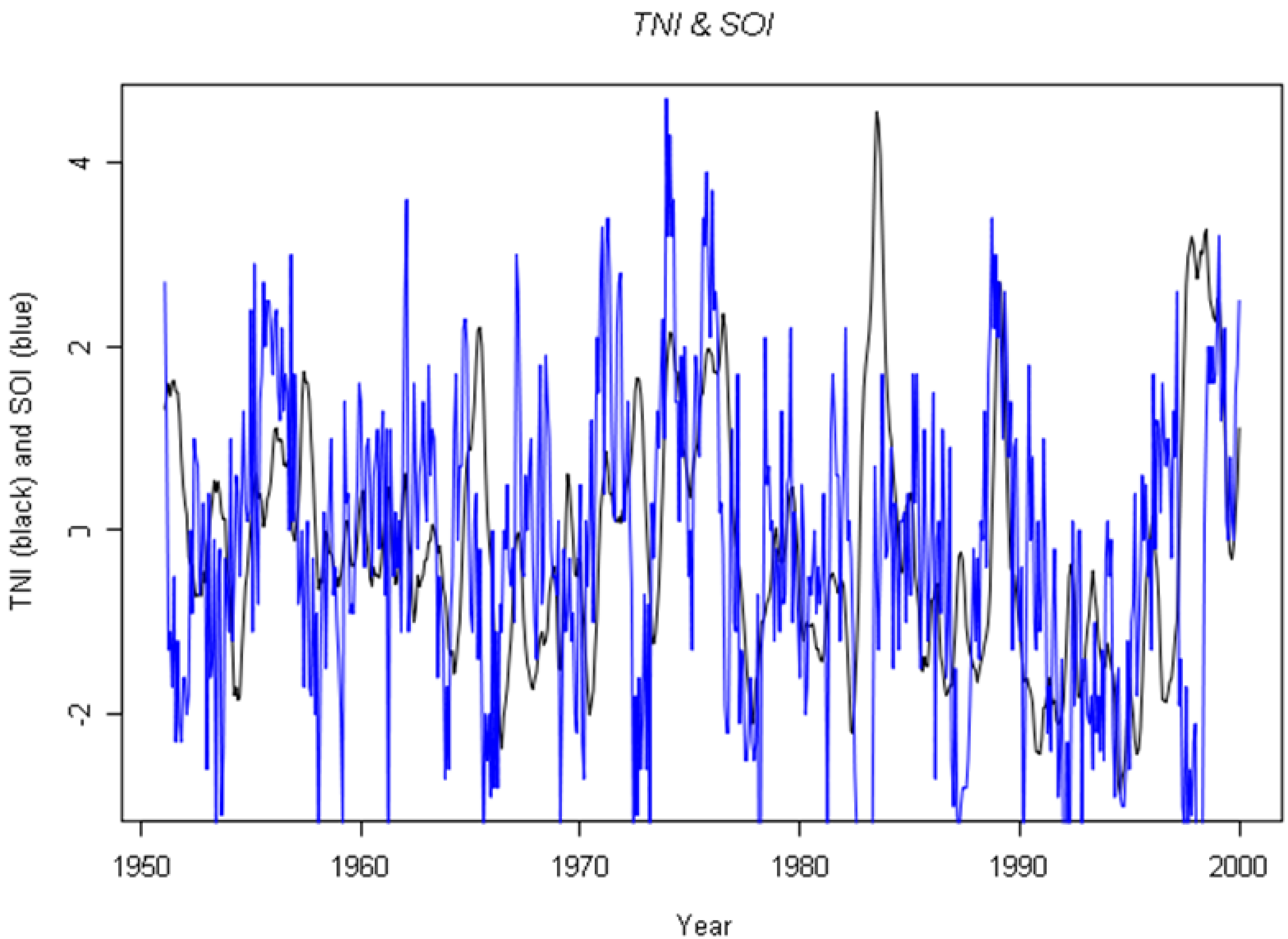

Monthly Southern Oscillation Index
SOI
4
2
0
-2
-4
-6
-8
1950
1960
1970
1980
1990
2000
Year
http://www.cpc.noaa.gov/data/indices/soi



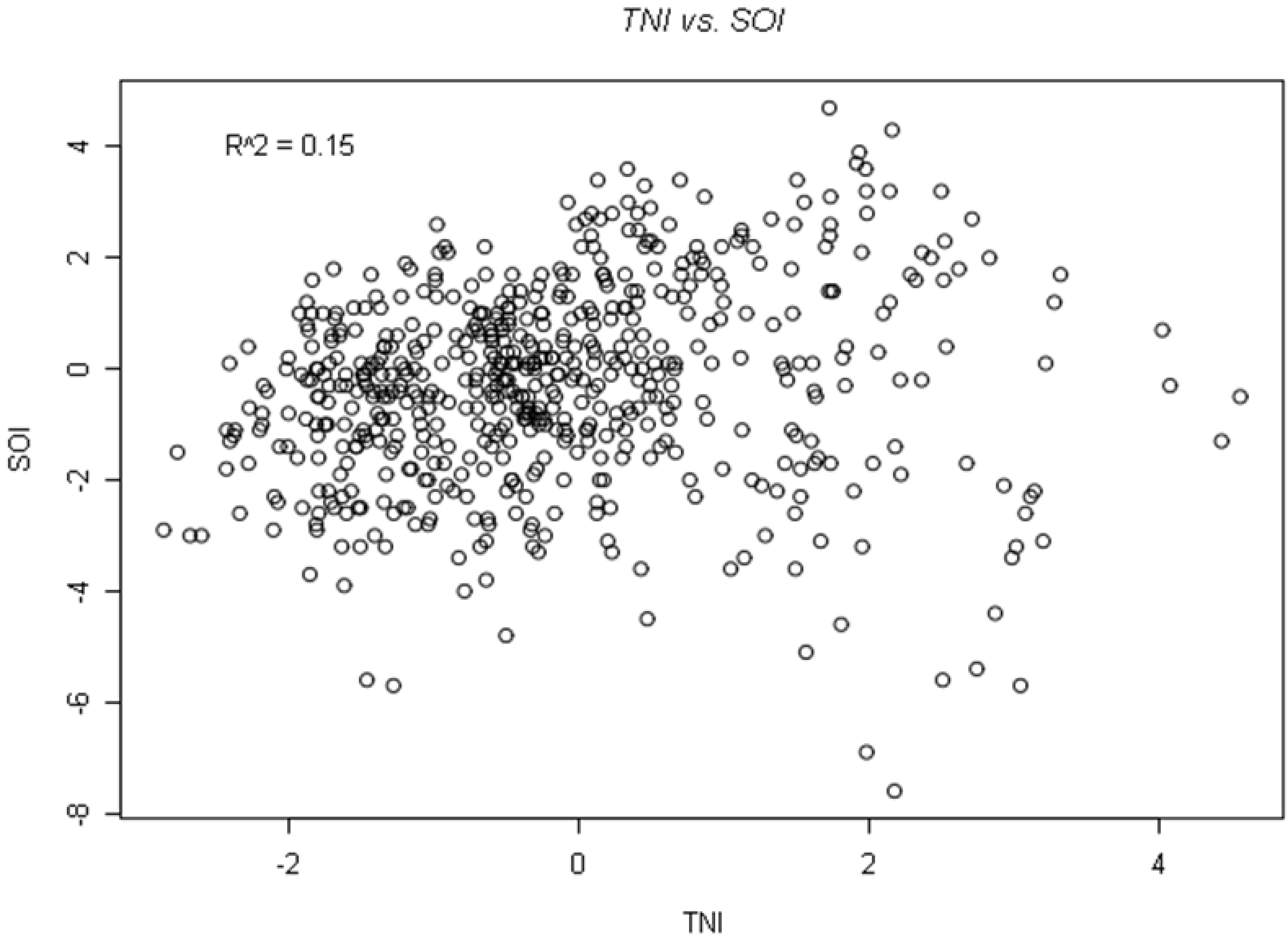
SOI Power Spectral Density
Power (SOI^2 * Year)
Frequency (1/Year)
0
10
20
30
40
50
60
0
1
2
3
4
5
6


SOI Power Spectral Density
Power (SOI^2 * Year)
0
10
20
30
40
50
60
0.2
0.5
1.0
2.0
5.0
10.0
20.0
50.0
Period (Year)

Are El Nino and the Southern Oscillation related?



Are El Nino and the Southern Oscillation related?

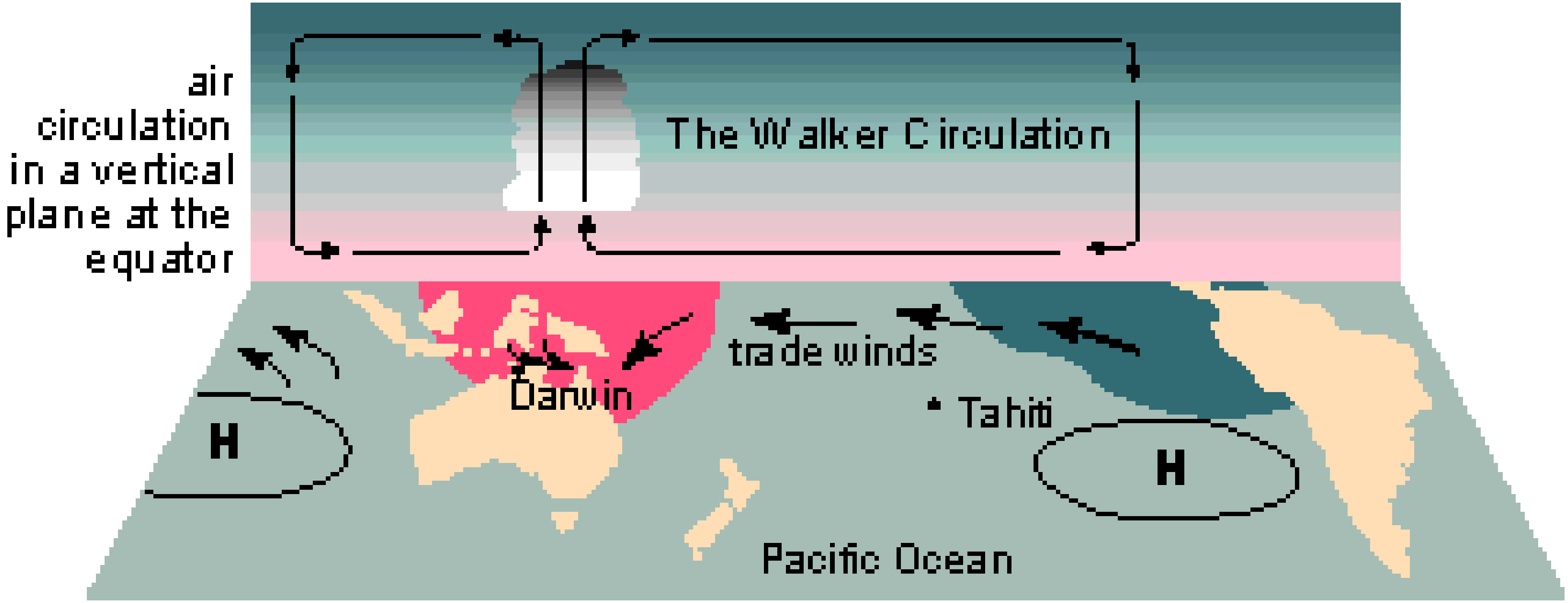


How are EN and SO related physically?

Southern Oscillation: “normal”

- East-to-west winds…
  - …drive currents to the west;
  - …pile up warm water in the west;
  - …induce upwelling of cold water in east;
- Resulting in “normal” Walker circulation:
  - Converging, then rising air in warm west
  - Yielding deep clouds, substantial precipitation

Typical Walker circulation pattern

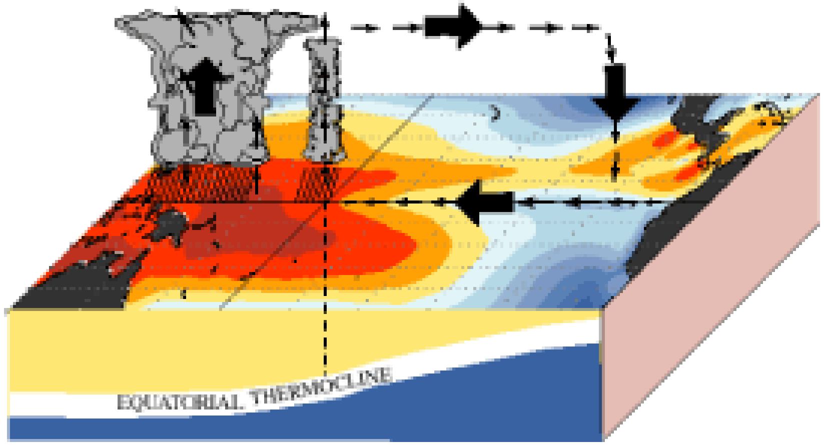


Southern Oscillation: El Nino

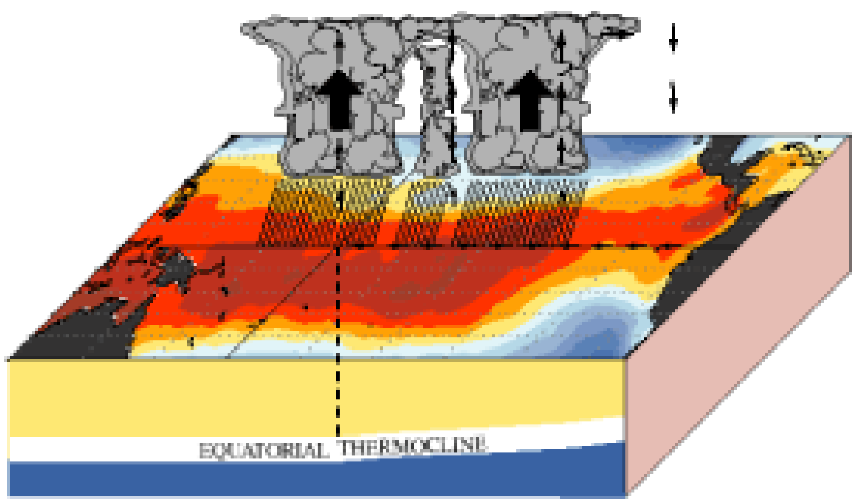
- Weakened or reversed Walker circulation
  - Lower pressure over E. Pacific weakens wind
  - Warm water more evenly distributed, or even accumulates in east
  - E Shift and weakening of areas of precipitation
  - Ocean biota starved of nutrient rich deep water

Sea Surface Temp and Rainfall

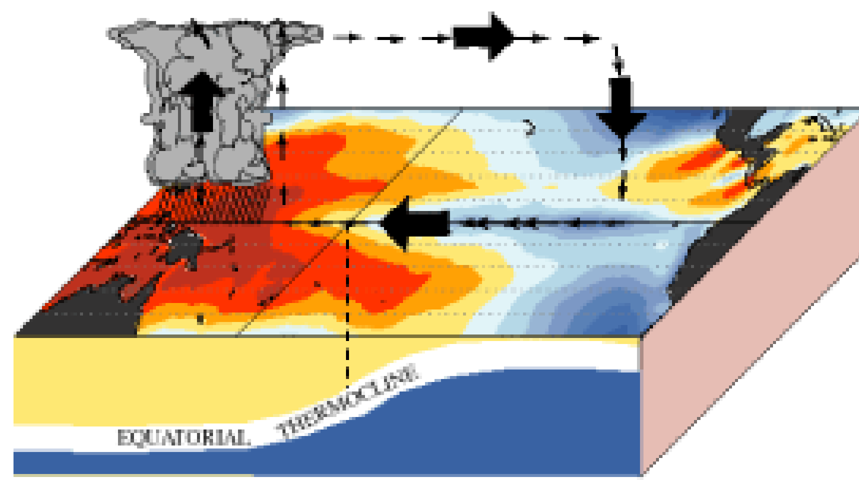
December - February Normal Conditions



December - February El Niño Conditions



December - February La Niña Conditions



Two quasi-stable states:

La Nina

- Easterly winds push westward on the mixed layer
- The warm mixed layer piles up in the west
- The warm SST in the west heats the air
- Low-level atmospheric convergence drives easterly winds

El Nino

- Westerly winds push eastwards on the mixed layer
- The warm mixed layer piles up in the east
- The warm SST in the east heats the air
- Low-level atmospheric convergence drives westerly winds

What sets the time scale for oscillations between these two states?

In other words, what switches the ocean/atmosphere from one state to the other?

Forcings:

- Annual variations in solar radiance
- Stochastic weather

Atmosphere:

- Does not have a memory beyond a few weeks

Ocean:

- Large thermal inertia
- Slow waves

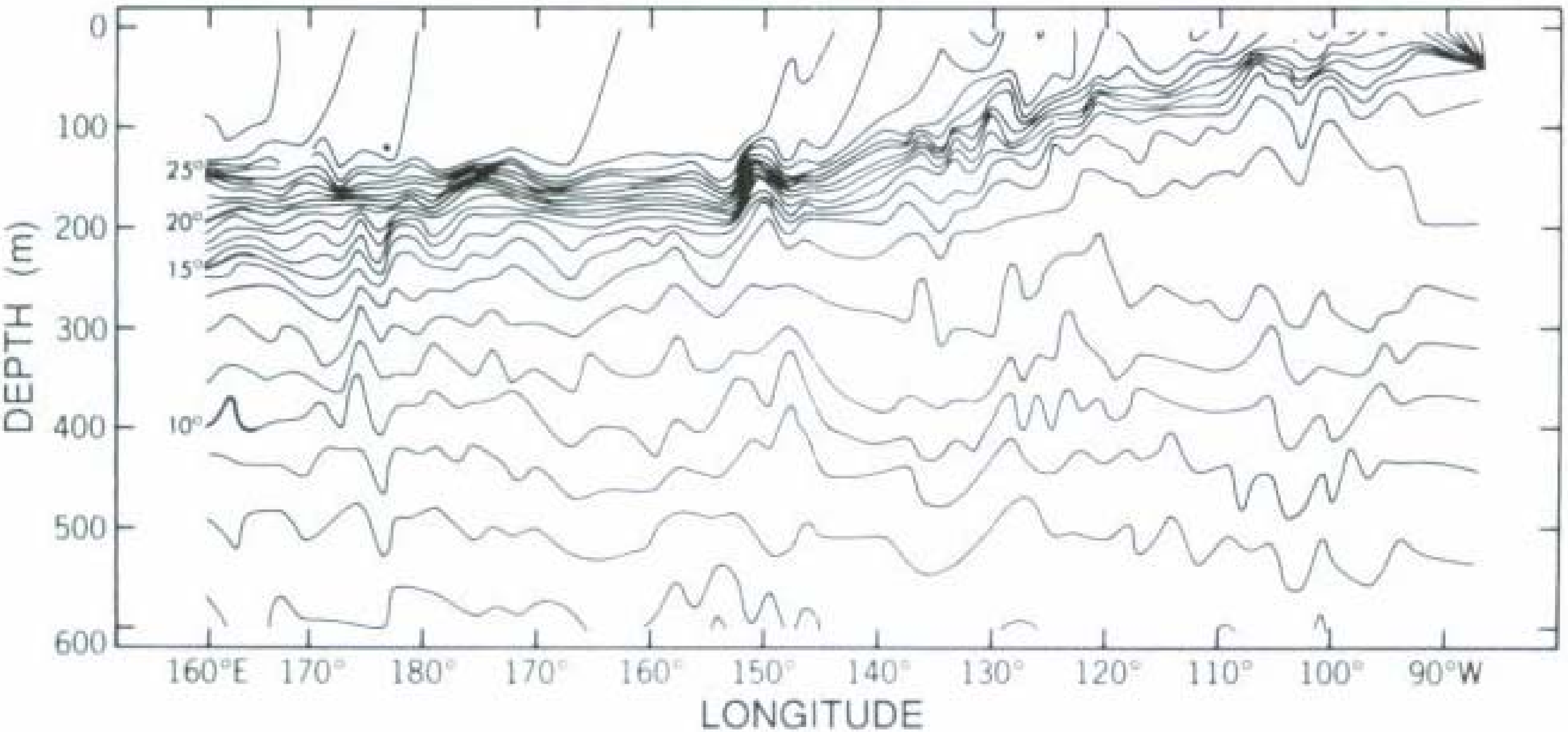
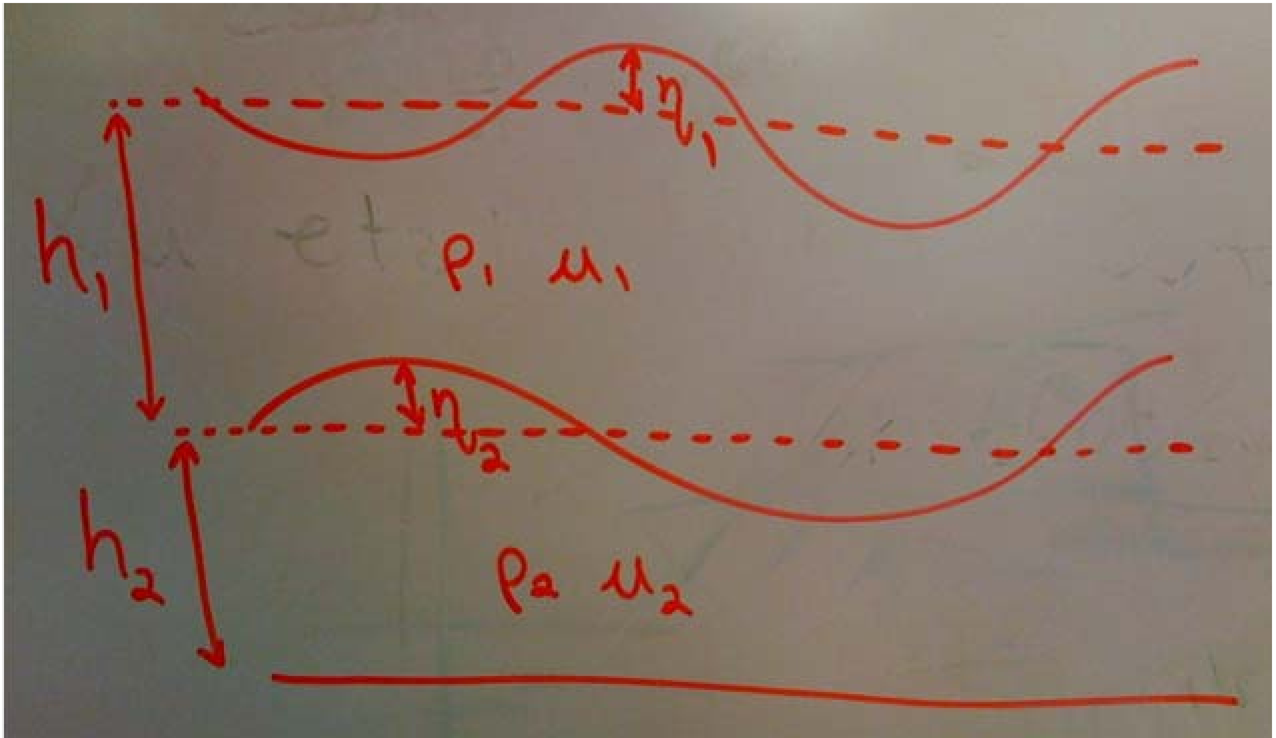


Figure 2.2. Temperature (°C) as a function of depth and longitude along the equator in the Pacific Ocean as measured in 1963 by Colin *et al*. (1971).

Philander, "El Nino, La Nina, and the Southern Oscillation," 1990

2-Layer, Linear, Shallow-Water Model

$$
\begin{aligned}
\rho_1 \partial_t u_1 &= -\rho_1 g \partial_x \eta_1 \\
\rho_2 \partial_t u_2 &= -\rho_1 g \partial_x \eta_1 - (\rho_2 - \rho_1) g \partial_x \eta_2 \\
\partial_t \eta_1 &= -h_1 \partial_x u_1 - h_2 \partial_x u_2 \\
\partial_t \eta_2 &= -h_2 \partial_x u_2
\end{aligned}
$$



Too complicated and not interested in upper surface, so….

Impose “rigid lid” on the upper surface:

$$\eta_1 \equiv 0$$

Recall that

$$\partial_t \eta_1 = -h_1 \partial_x u_1 - h_2 \partial_x u_2$$

So, we get a diagnostic relation

$$h_1 \partial_x u_1 + h_2 \partial_x u_2 = 0$$

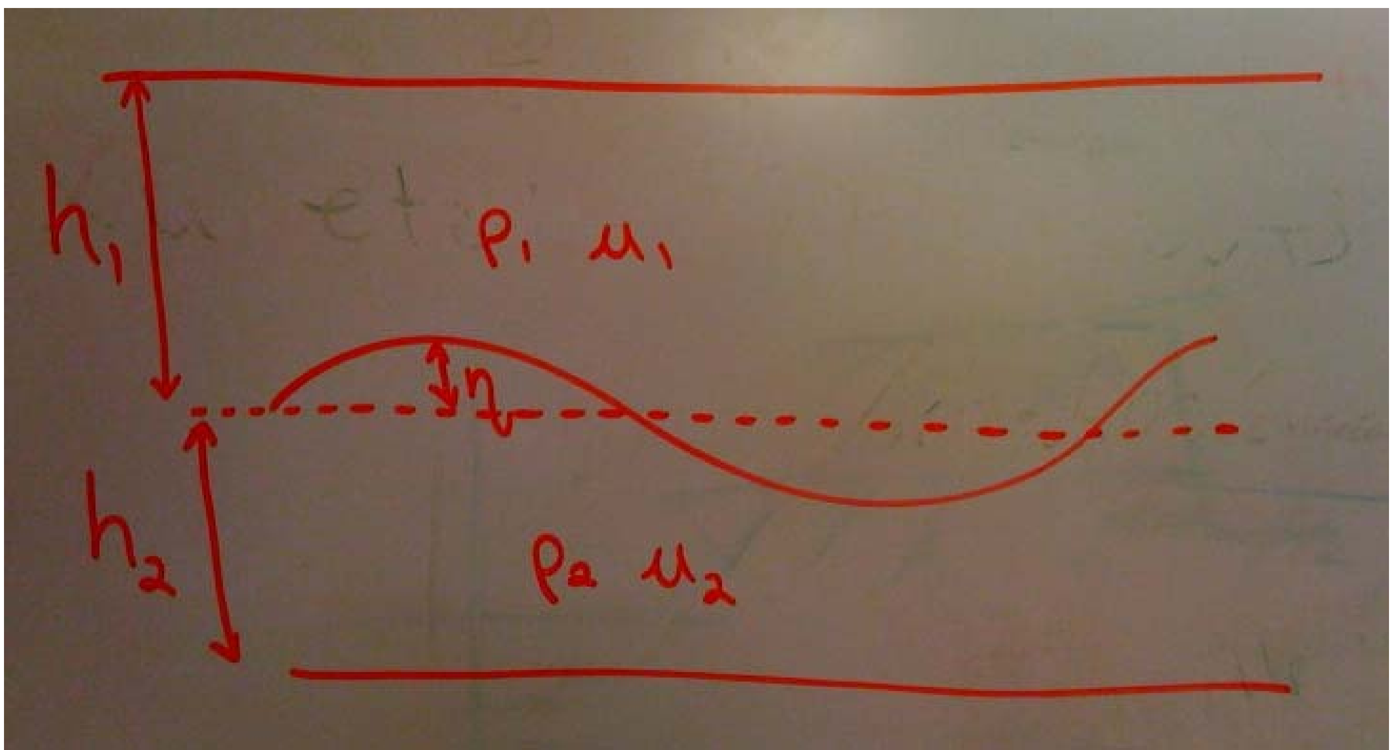
But, now we have

$$\rho_1 \partial_t u_1 = -\partial_x p_1$$

Pressure on the rigid lid

2-Layer, Rigid-Lid, Linear, Shallow-Water Model

$$
\begin{aligned}
\rho_1 \partial_t u_1 &= -\partial_x p_1 \\
\rho_2 \partial_t u_2 &= -\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta \\
0 &= h_1 \partial_x u_1 + h_2 \partial_x u_2 \\
\partial_t \eta &= h_1 \partial_x u_1
\end{aligned}
$$



2-Layer, Rigid-Lid, Linear, Shallow-Water Model

$$
\begin{aligned}
&(1) \qquad & \rho_1 \partial_t u_1 &= -\partial_x p_1 \\
&(2) \qquad & \rho_2 \partial_t u_2 &= -\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta \\
&(3) \qquad & 0 &= h_1 \partial_x u_1 + h_2 \partial_x u_2 \\
&(4) \qquad & \partial_t \eta &= h_1 \partial_x u_1
\end{aligned}
$$

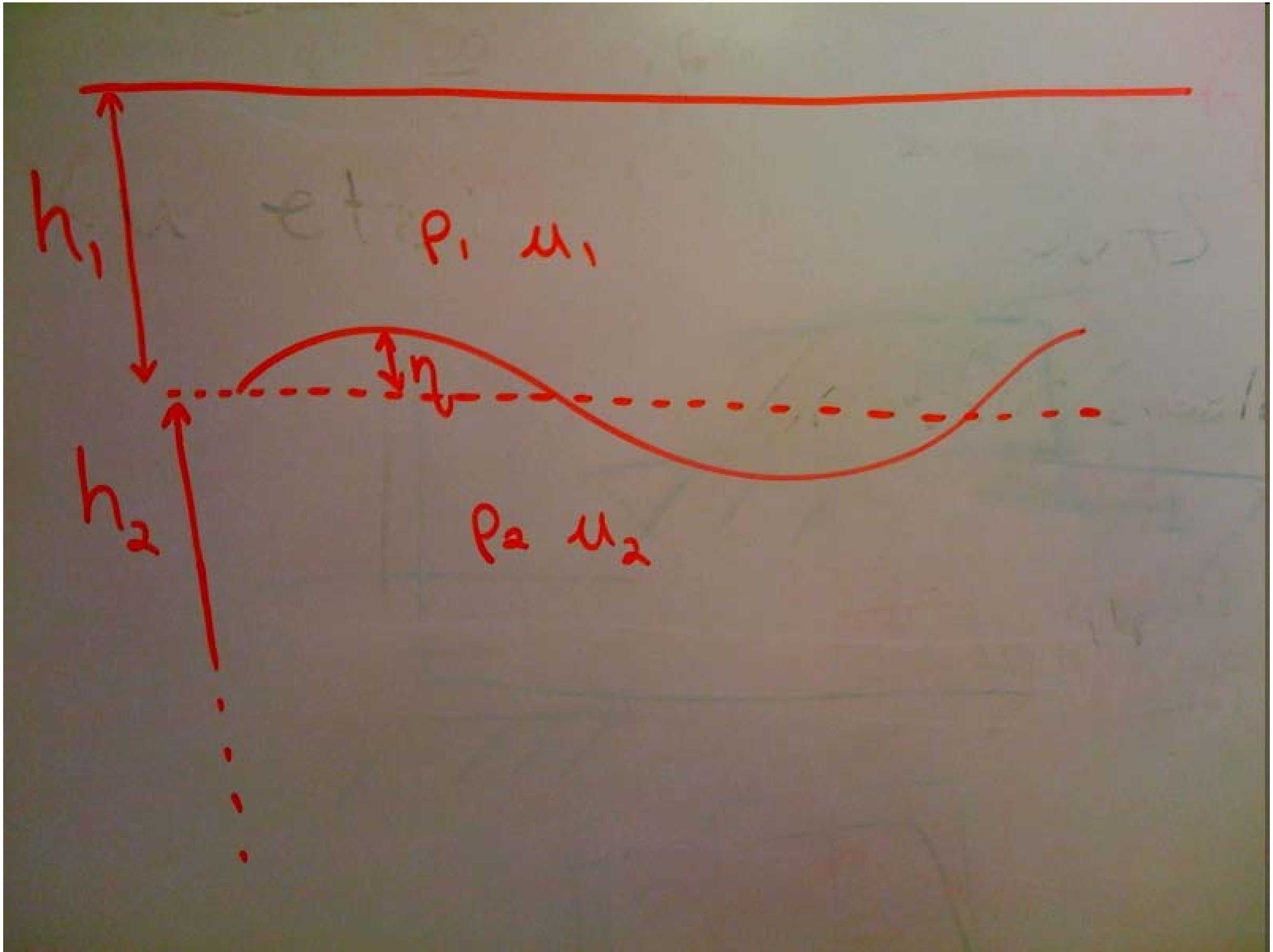
Take d/dt of the (3) and substitute (1) and (2):

$$\partial_x \left[-\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta \right] = \frac{h_1 \rho_2}{h_2 \rho_1} \partial_x^2 p_1$$

If $h_2/h_1 \gg \rho_2/\rho_1$, then the RHS is zero, so

$$-\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta = c(t)$$

2-Layer, Rigid-Lid, Linear, Shallow-Water Model
with a relatively deep lower layer ($h_2 >> h_1$)



2-Layer, Rigid-Lid, Linear, Shallow-Water Model with a relatively deep lower layer ($h_2 >> h_1$)

(1) $$\rho_1 \partial_t u_1 = -\partial_x p_1$$

(2) $$\rho_2 \partial_t u_2 = -\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta$$

(3) $$0 = h_1 \partial_x u_1 + h_2 \partial_x u_2$$

(4) $$\partial_t \eta = h_1 \partial_x u_1$$

Take d/dt of the (3) and substitute (1) and (2):

$$\partial_x \left[-\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta \right] = \frac{h_1 \rho_2}{h_2 \rho_1} \partial_x^2 p_1$$

If $h_2/h_1 \gg \rho_2/\rho_1$, then the RHS is zero, so

$$-\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta = c(t)$$

2-Layer, Rigid-Lid, Linear, Shallow-Water Model with a relatively deep lower layer ($h_2 >> h_1$)

$$
\begin{aligned}
\rho_1 \partial_t u_1 &= -\partial_x p_1 \\
\rho_2 \partial_t u_2 &= -\partial_x p_1 - (\rho_2 - \rho_1) g \partial_x \eta \;=\; c(t) \\
0 &= h_1 \partial_x u_1 + h_2 \partial_x u_2 \\
\partial_t \eta &= h_1 \partial_x u_1
\end{aligned}
$$

We do not care about k = 0 modes of u_2, so:

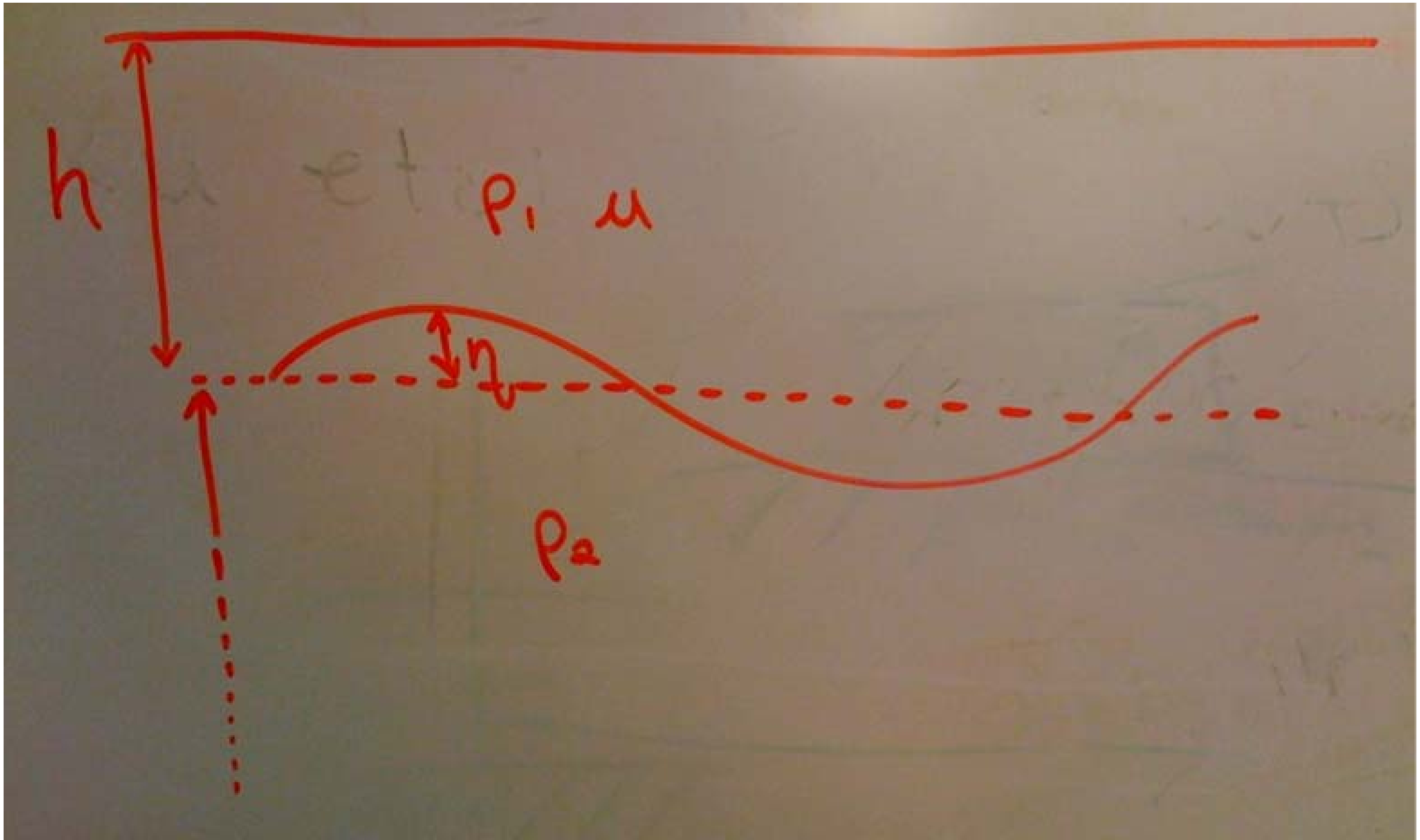
$$c(t) = 0 \qquad u_2 = 0$$

Therefore:

$$-\partial_x p_1 = (\rho_2 - \rho_1) g \partial_x \eta$$

1.5-Layer, Rigid-Lid, Linear, Shallow-Water Model

$$\begin{aligned}\rho_1 \partial_t u &= (\rho_2 - \rho_1) g \partial_x \eta \\ \partial_t \eta &= h \partial_x u\end{aligned}$$



The Shallow Water Model

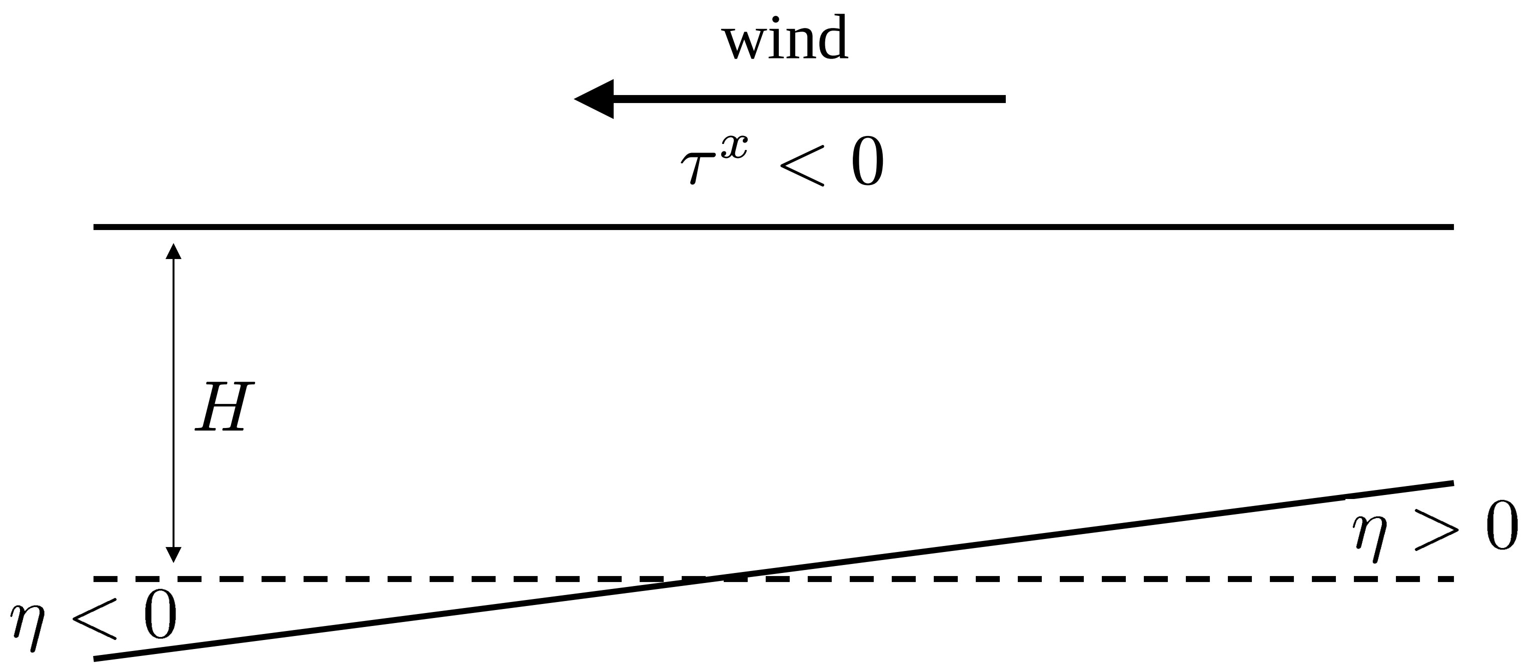
$$
\begin{aligned}
u_t &= g'\eta_x + fv + \tau^x/H \\
v_t &= g'\eta_y - fu + \tau^y/H \\
\eta_t &= -H(u_x + v_y) \\
g' &\equiv \frac{\rho_2 - \rho_1}{\rho_1} g
\end{aligned}
$$

Look for a steady-state solution with constant, westward stress and v = 0

$$
\begin{aligned}
\cancel{u_t} &= g'\eta_x + f\cancel{v} + \tau^x/H \\
\cancel{v_t} &= g'\cancel{\eta_y} - f\cancel{u} + \cancel{\tau^y/H} \\
\cancel{\eta_t} &= -H(u_x + \cancel{v_y}) \\
g' &\equiv \frac{\rho_2 - \rho_1}{\rho_1} g
\end{aligned}
$$

$$
\boxed{
\begin{aligned}
u &= 0 \\
\eta_x &= -\frac{\tau^x}{g'H}
\end{aligned}
}
$$

$$
\boxed{\begin{aligned} u &= 0 \\ \eta_x &= -\frac{\tau^x}{g'H} \end{aligned}}
$$

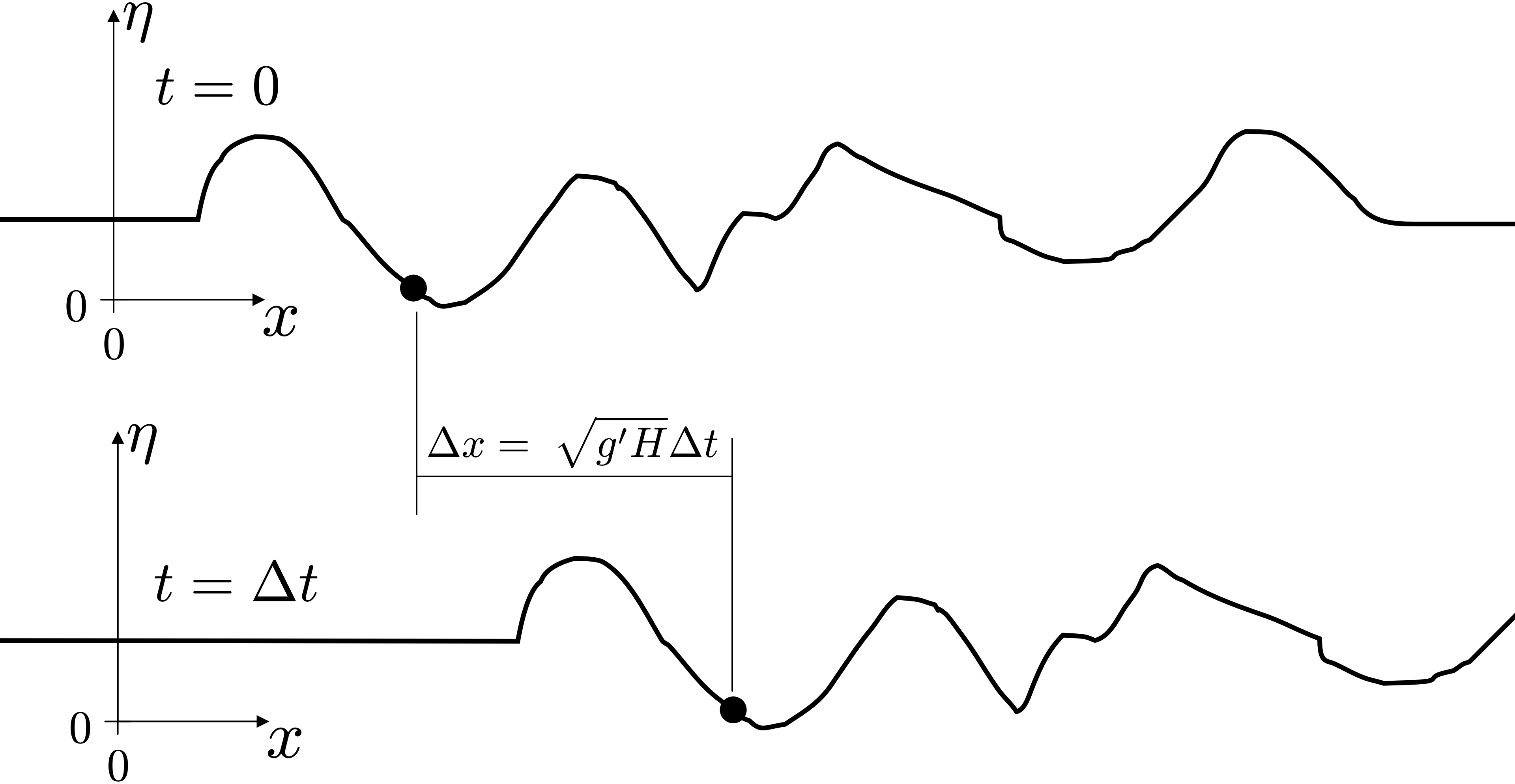


Look for unforced waves
symmetric in y in the case of f = 0

$$
\begin{aligned}
u_t &= g'\eta_x + \cancel{fv} + \cancel{\tau^x/H} \\
\cancel{v_t} &= \cancel{g'\eta_y} - \cancel{fu} + \cancel{\tau^y/H} \\
\eta_t &= -H(u_x + \cancel{v_y}) \\
g' &\equiv \frac{\rho_2 - \rho_1}{\rho_1} g
\end{aligned}
$$

$$
\begin{aligned}
u_{tt} - g'Hu_{xx} &= 0 \\
\eta_{tt} - g'H\eta_{xx} &= 0
\end{aligned}
\quad \Longrightarrow \quad
\boxed{
\begin{aligned}
u &= F(x \pm \sqrt{g'H}t) \\
\eta &= G(x \pm \sqrt{g'H}t)
\end{aligned}
}
$$

$$u = F(x - \sqrt{g'H}t)$$
$$\eta = G(x - \sqrt{g'H}t)$$



$\sqrt{g'H}$ is the wave speed

Shallow water model on a beta plane

$$\begin{aligned} u_t &= g'\eta_x + \beta y v + \tau^x/H \\ v_t &= g'\eta_y - \beta y u + \tau^y/H \\ \eta_t &= -H(u_x + v_y) \\ g' &\equiv \frac{\rho_2 - \rho_1}{\rho_1} g \end{aligned}$$

Reduce to one equation in one variable:

$$(v_{xx} + v_{yy})_t + \beta v_x - \frac{1}{c^2} v_{ttt} - \frac{f^2}{c^2} v_t \; = \; F(\tau)$$

$$(v_{xx} + v_{yy})_t + \beta v_x - \frac{1}{c^2} v_{ttt} - \frac{f^2}{c^2} v_t \;=\; F(\tau)$$

Substitute

$$v = V(y) e^{ikx - i\sigma t}$$

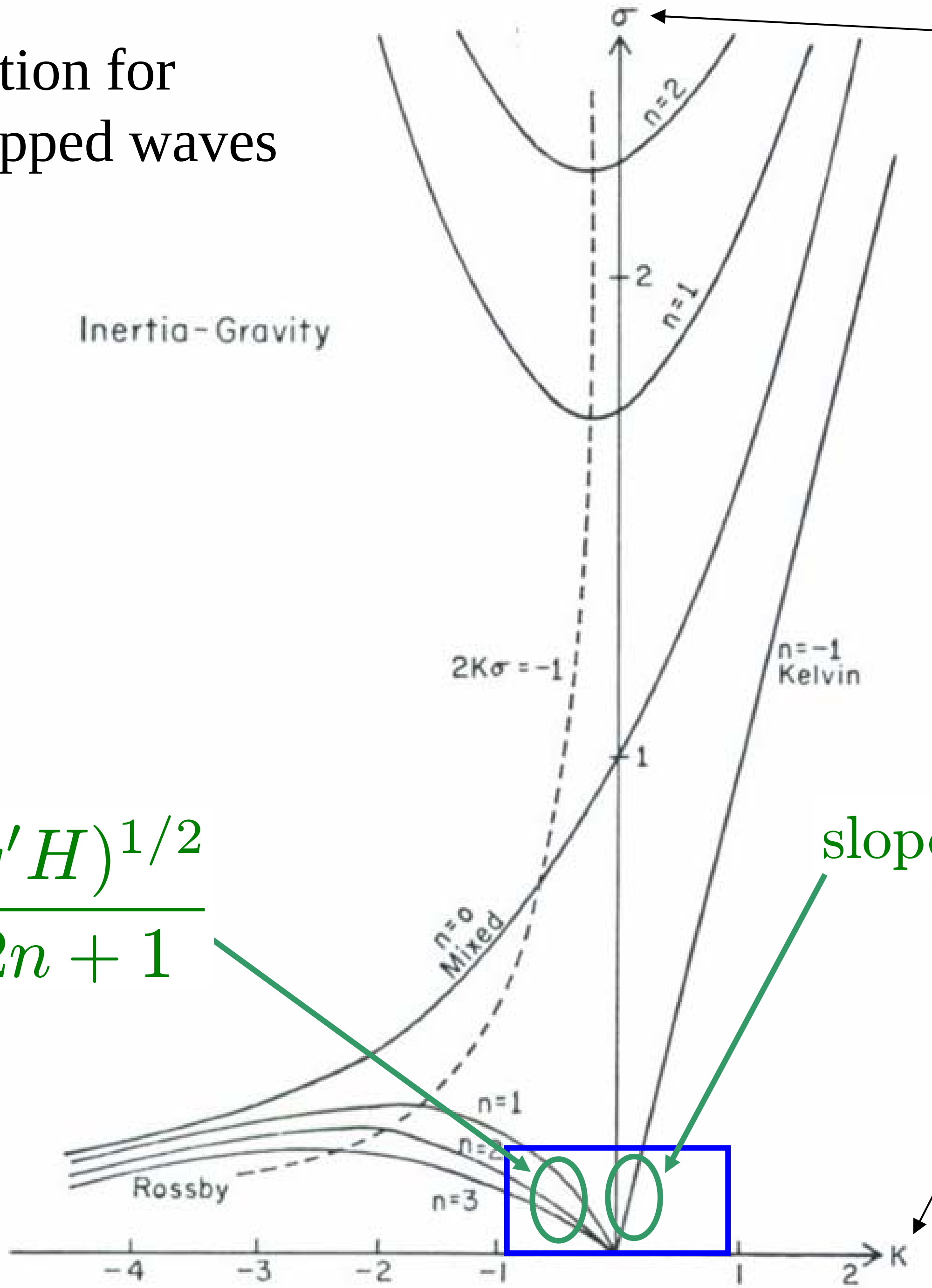
and find that, for V that go to zero as |y| goes to infinity,

$$\boxed{\frac{c}{\beta}\left(\frac{\sigma^2}{c^2} - k^2 - \frac{\beta k}{\sigma}\right) \;=\; 2n+1}$$

Dispersion relation for equatorially trapped waves

Dispersion relation for
equatorially trapped waves

frequency



$$\text{slope} = \frac{(g'H)^{1/2}}{2n+1}$$

$$\text{slope} = (g'H)^{1/2}$$

wavenumber

Philander, “El Nino, La Nina, and the Southern Oscillation,” 1990

Typical values for the ocean mixed layer

$$\begin{aligned} \frac{\rho_2 - \rho_1}{\rho_1} &= 0.002 \\ H &= 100 \text{ meters} \end{aligned}$$

yield

$$\sqrt{g'H} = 1.4 \text{ m/s}$$

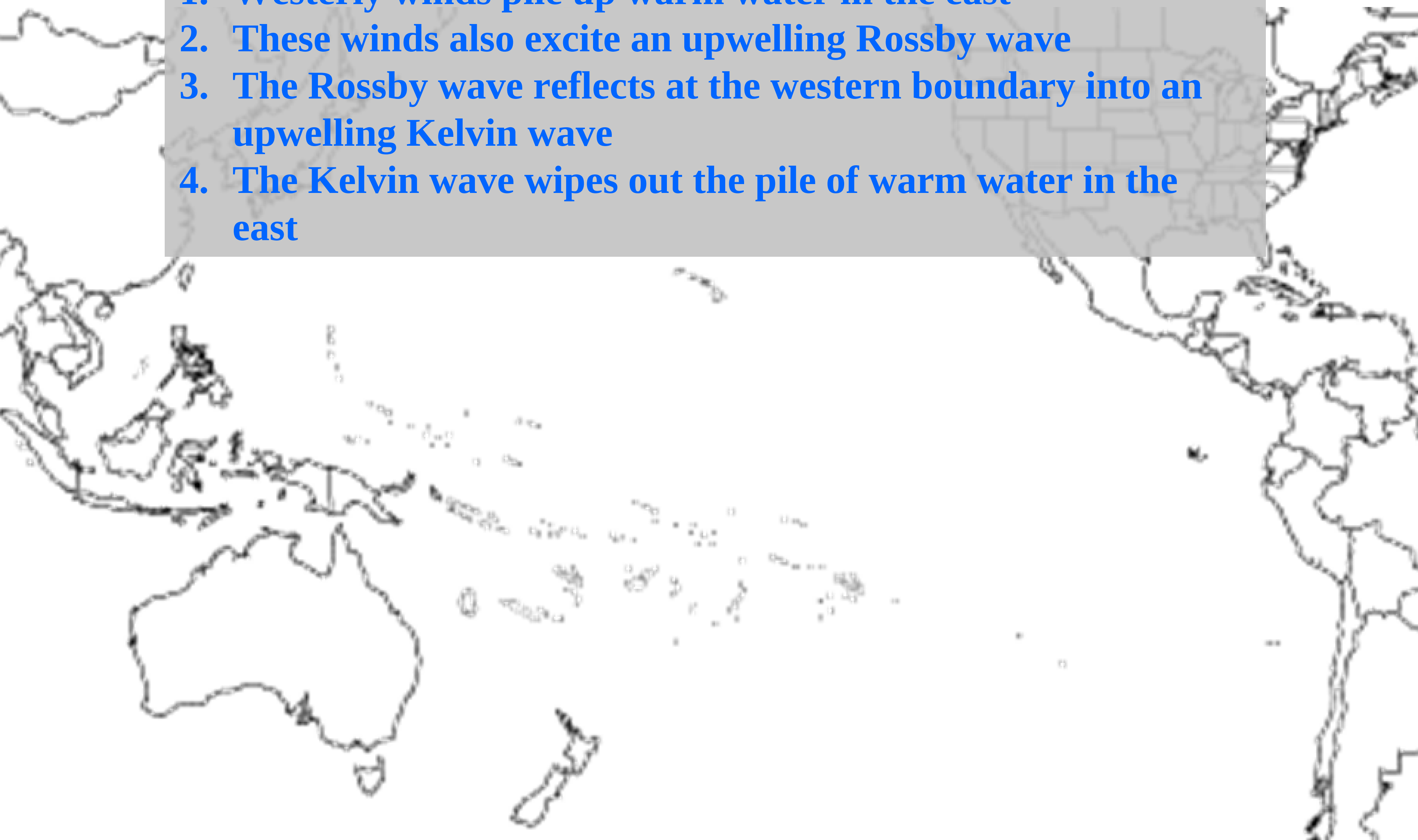
which means it takes

$$\frac{15 \times 10^6}{1.4/3} + \frac{15 \times 10^6}{1.4} = 1.4 \text{ years}$$

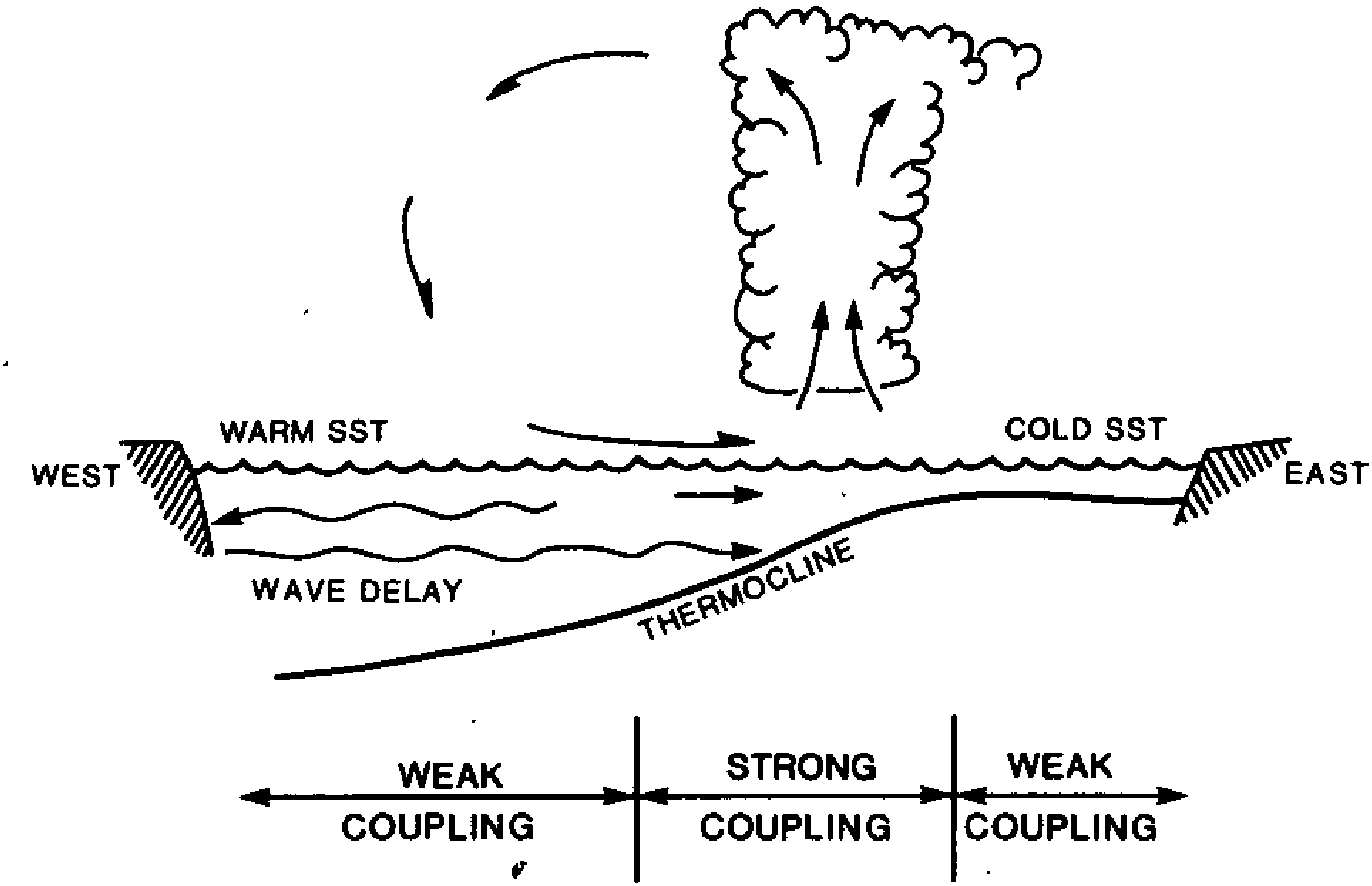
for an n=1 Rossby wave to travel to the western boundary of the Pacific Ocean, reflect off the boundary into a Kelvin wave, and for the Kelvin wave to make it back to the location of the original disturbance.

The “delayed-oscillator” mode (McCreary 1983)

1. **Westerly winds pile up warm water in the east**
2. **These winds also excite an upwelling Rossby wave**
3. **The Rossby wave reflects at the western boundary into an upwelling Kelvin wave**
4. **The Kelvin wave wipes out the pile of warm water in the east**



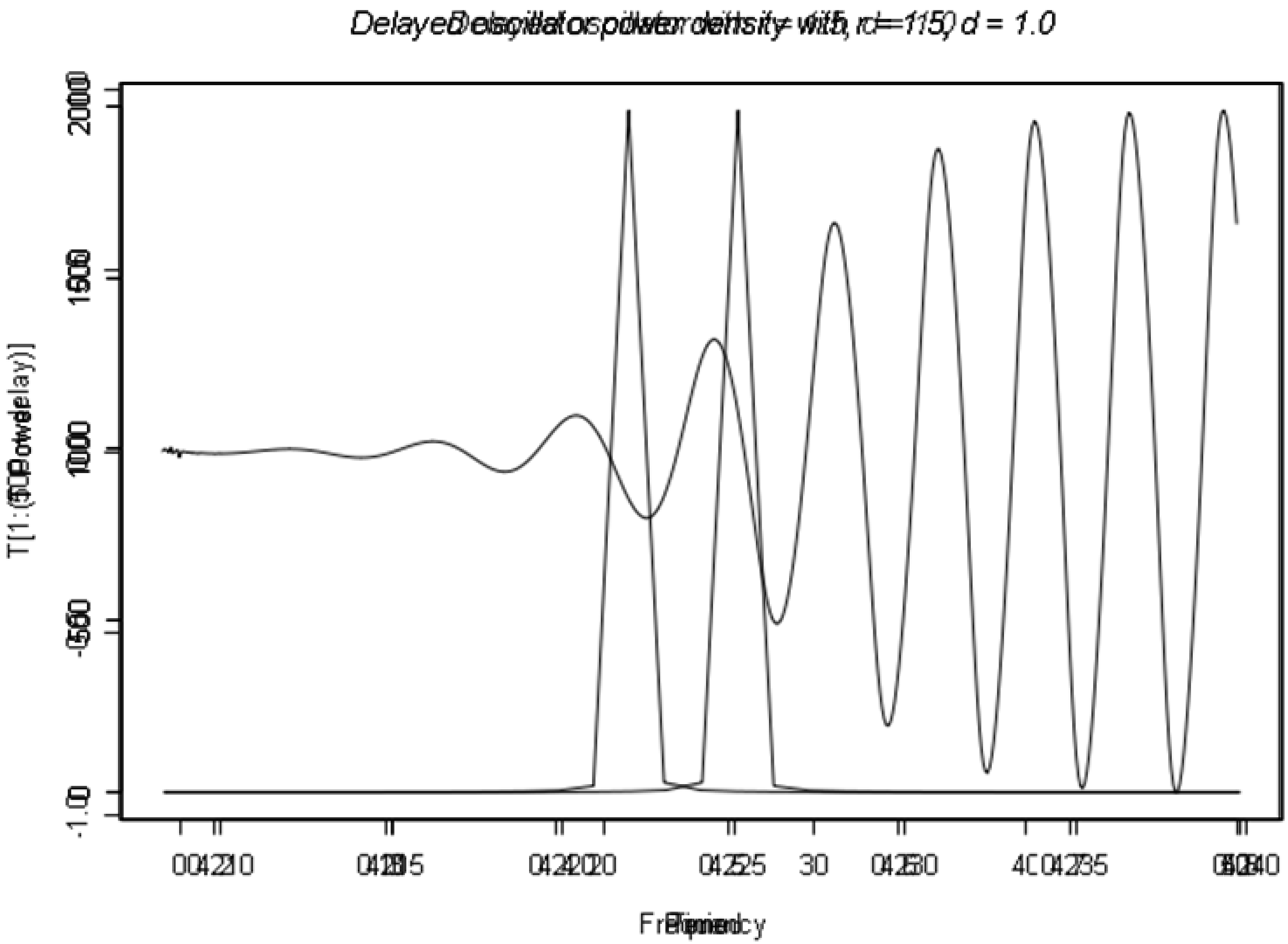
Toy model of a delayed oscillator (Suarez & Schopf, 1988)



$$T_t = T - T^3 - rT(t-d)$$

Toy model of a delayed oscillator

$$T_t = T - T^3 - rT(t-d)$$

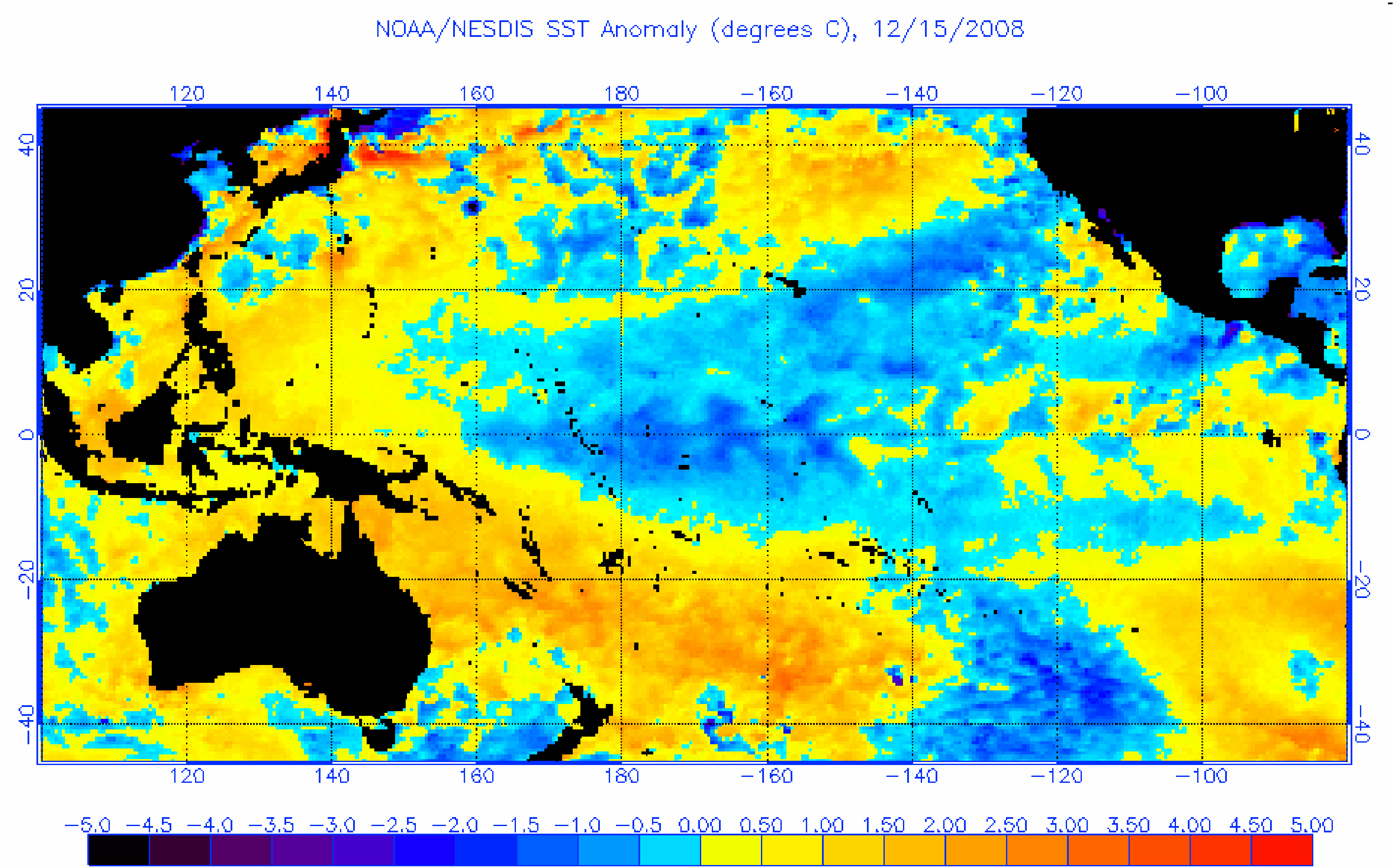


ENSO Forecasts?

“**EL NIÑO/SOUTHERN OSCILLATION (ENSO) DIAGNOSTIC DISCUSSION** issued by

CLIMATE PREDICTION CENTER/NCEP 11 December 2008

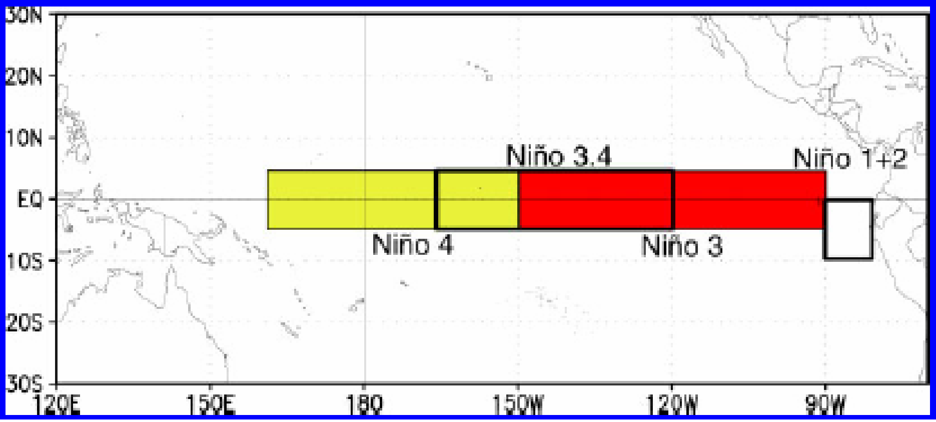
Synopsis: **ENSO-neutral or La Niña conditions are equally likely through early 2009.**

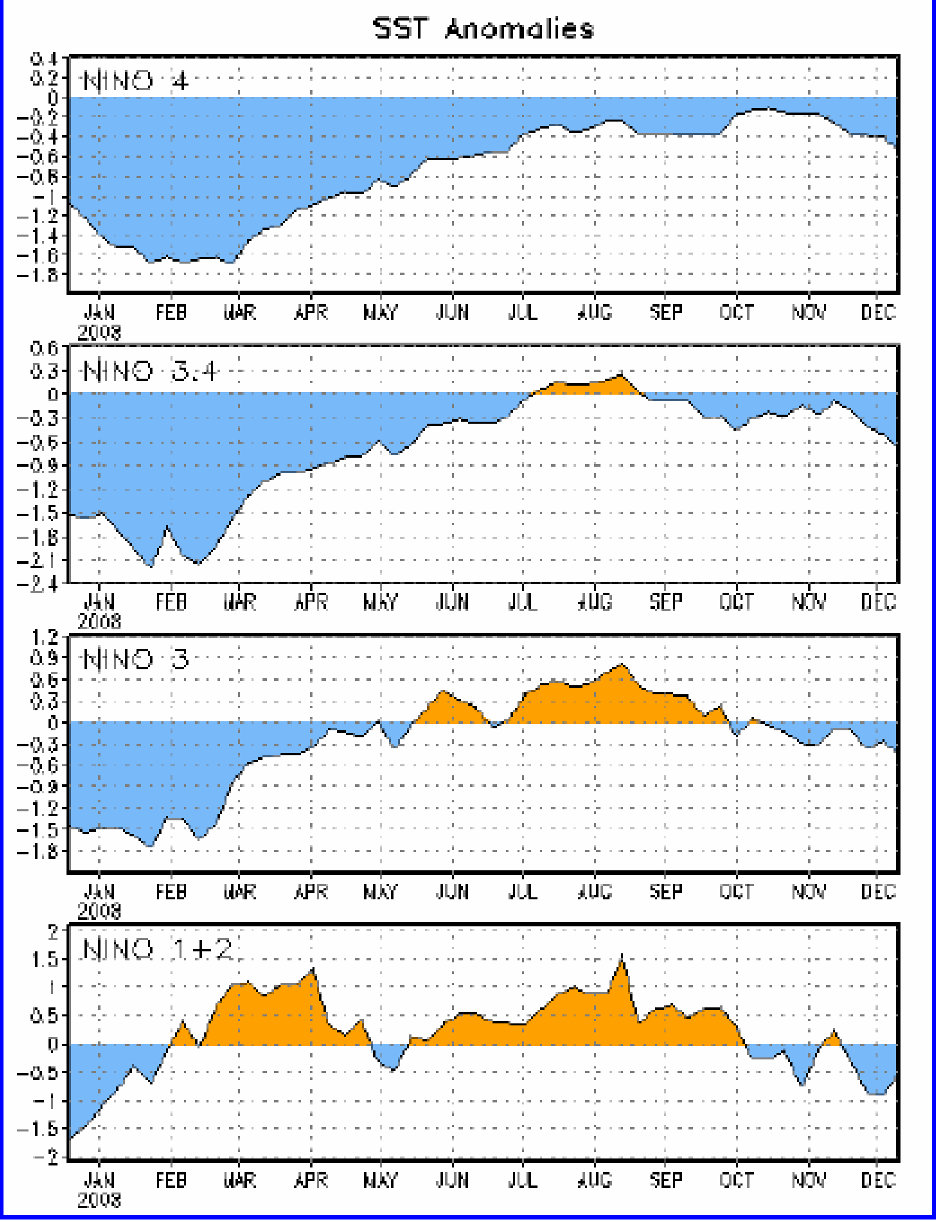


Niño Region SST Departures (ºC) Recent Evolution

The latest weekly SST departures are:

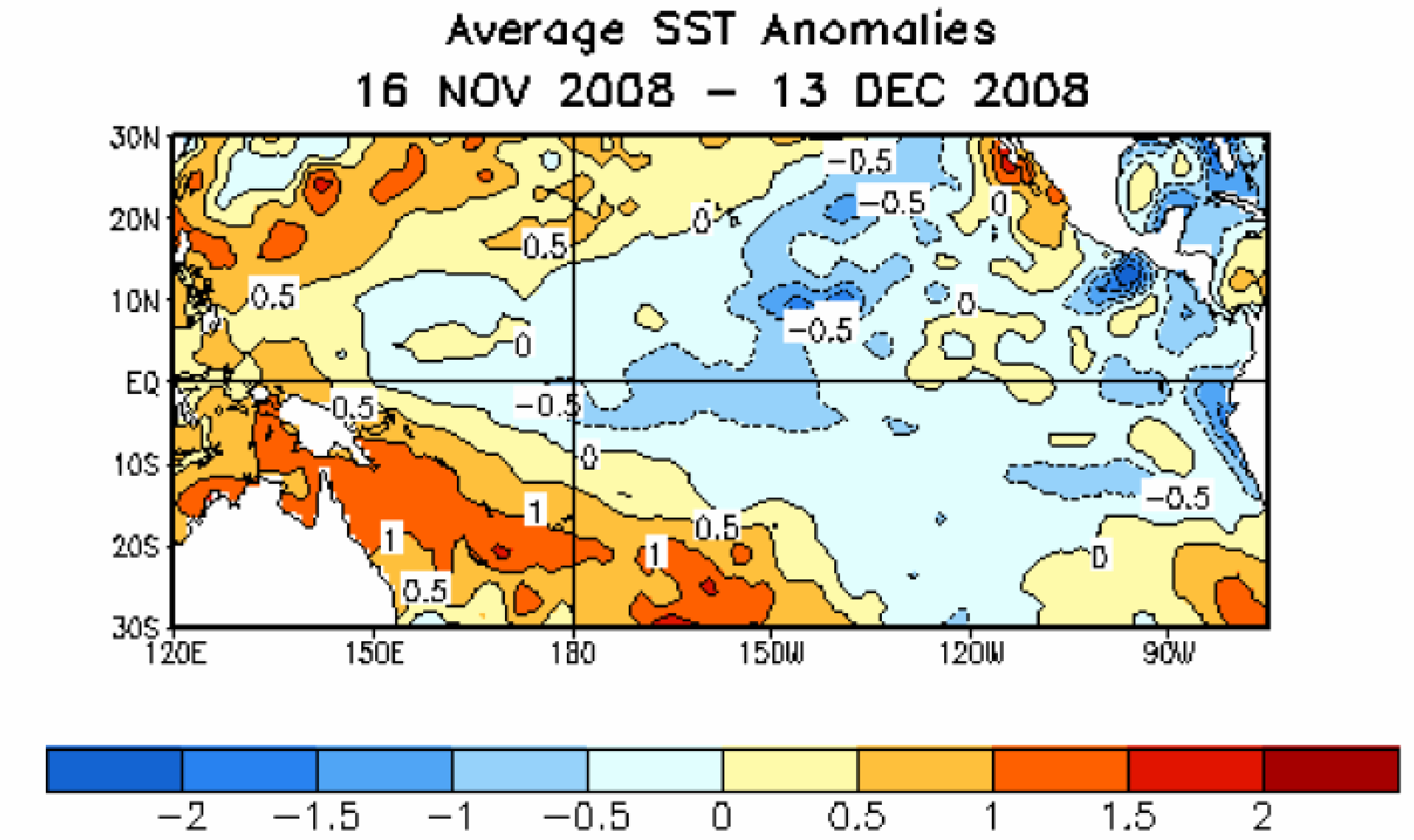
Niño 4	**-0.5ºC**
Niño 3.4	**-0.7ºC**
Niño 3	**-0.4ºC**
Niño 1+2	**-0.4ºC**





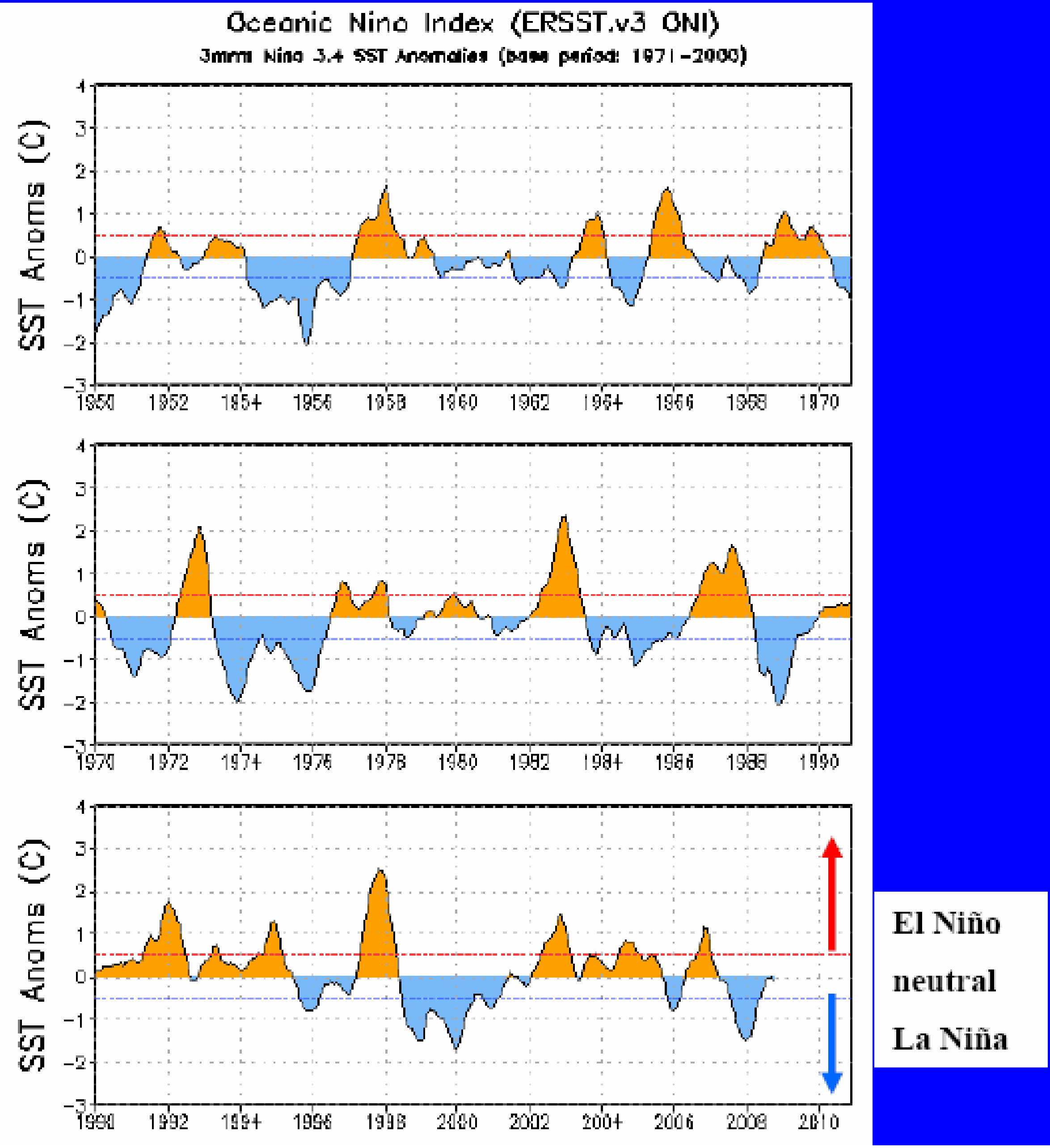
SST Departures (ºC) in the Tropical Pacific During the Last 4 Weeks

During the last 4-weeks, equatorial SSTs were below average (cooler than –0.5°C) in the central Pacific (140°W-180°W) and in parts of the eastern Pacific (80°-100°W).



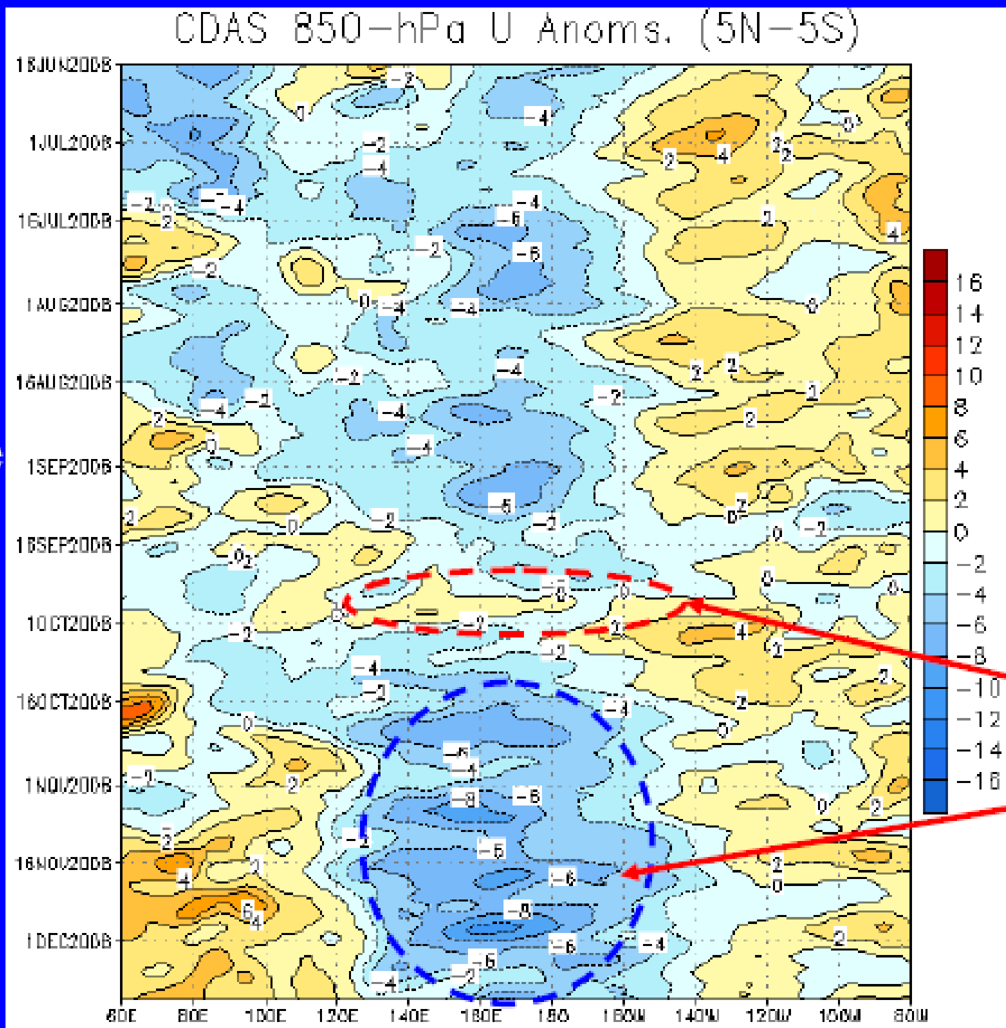
ONI (ºC): Evolution since 1950

The most recent ONI value (September–November 2008) is -0.1ºC.



Low-level (850-hPa) Zonal (east-west) Wind Anomalies (m s^{-1})

Time



Longitude

Westerly wind anomalies (orange/red shading).

Easterly wind anomalies (blue shading).

Low-level (850-hPa) easterly wind anomalies have persisted since January 2007 over the equatorial Pacific between 150°E and 150°W.

However, in late September- early October 2008, intraseasonal (MJO) activity briefly weakened the easterly anomalies across the central equatorial Pacific (dashed red oval in figure).

Since early October, strong easterly anomalies have dominated the central equatorial Pacific.

Pacific Niño 3.4 SST Outlook

A majority of ENSO forecasts indicate slightly below average SSTs in the central equatorial Pacific through Northern Hemisphere Summer 2009. Several models suggest weak La Niña conditions during December 2008-March 2009.

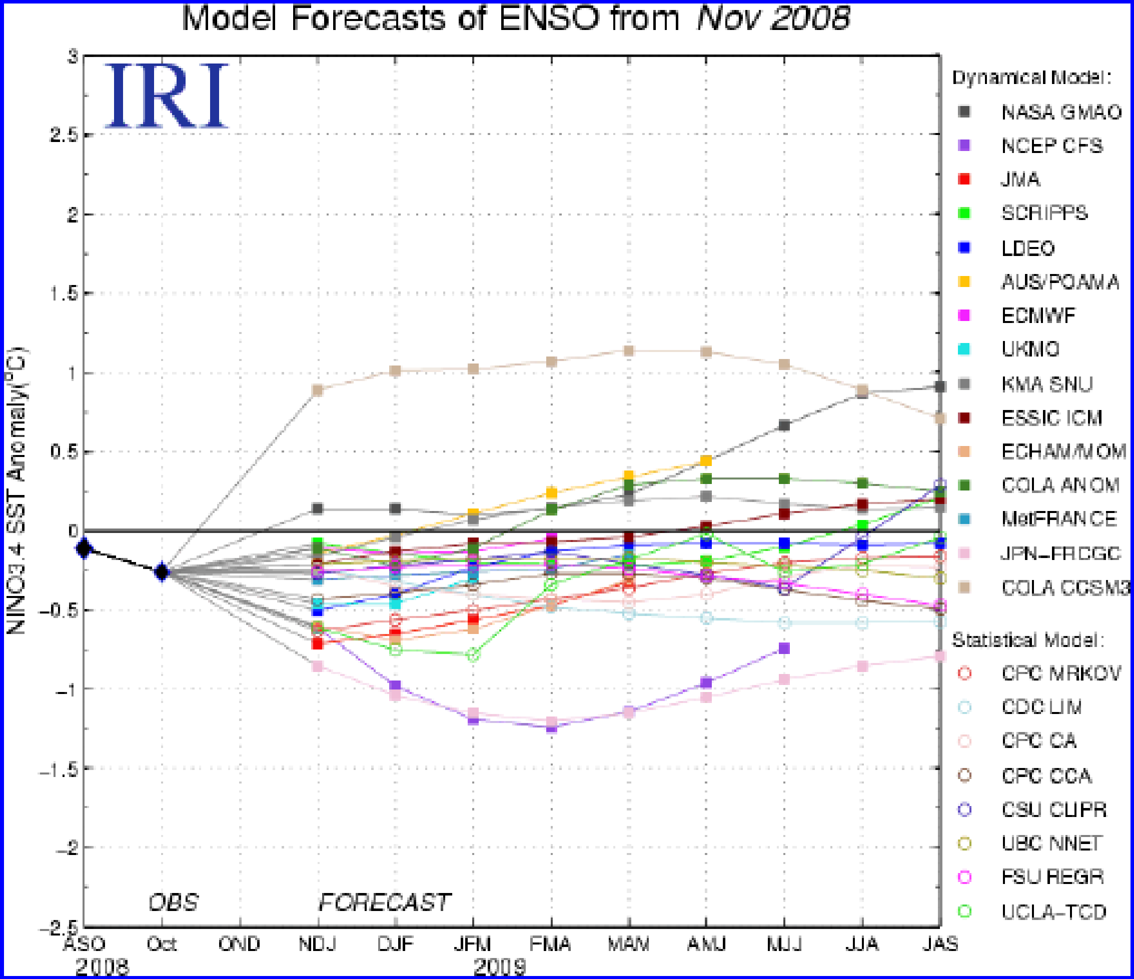


Figure provided by the International Research Institute (IRI) for Climate and Society (updated 20 November 2008).