El Niño and global warming:

a short-term perspective

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Thanks to:

George Philander
Andrew Wittenberg
Scott Harper
Barbara Winter

Major hypotheses:

I. Global warming/ decadal trends can affect the mean state of the tropical Pacific, leading to changes in El Niño characteristics.

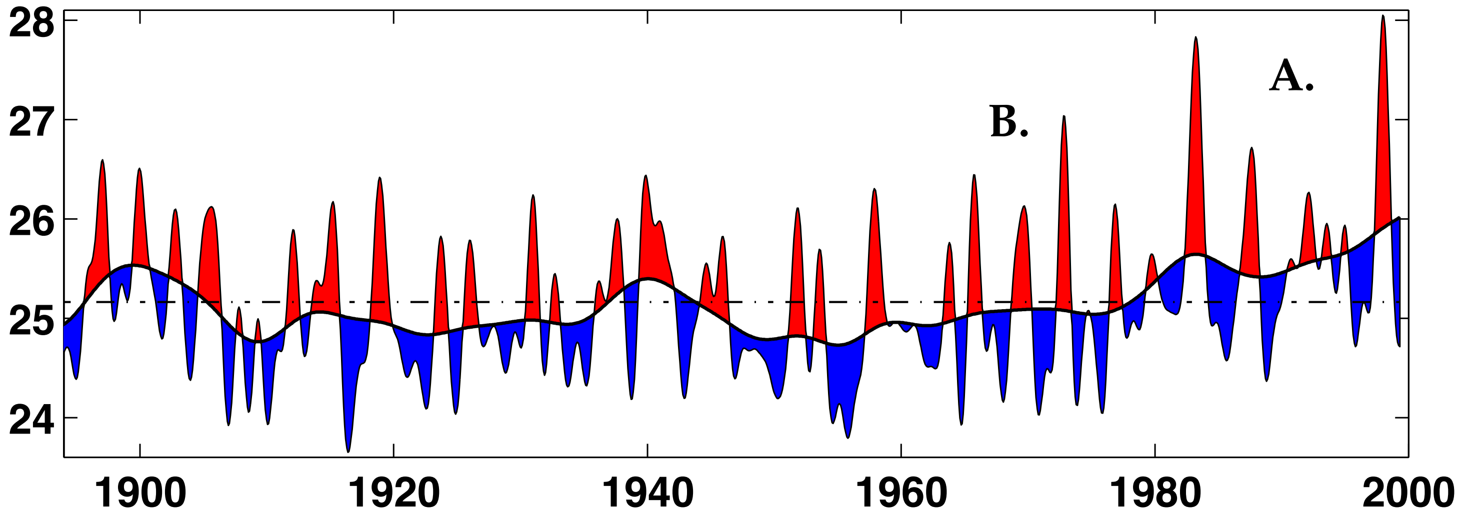
II. Differences between El Niño events can be accounted for by the effect of the atmospheric noise (e.g. westerly wind bursts). Global warming can influence El Niño by affecting the noise.

III. The effect of global warming on El Niño is currently negligible. Differences between El Niño events are explained by the chaotic (deterministic) dynamics of the coupled ocean-atmosphere in the tropics. The decadal trends can be generated solely by those dynamics.

Hypothesis I:

I. Global warming/ decadal trends can affect the mean state of the tropical Pacific, leading to changes in El Niño characteristics.

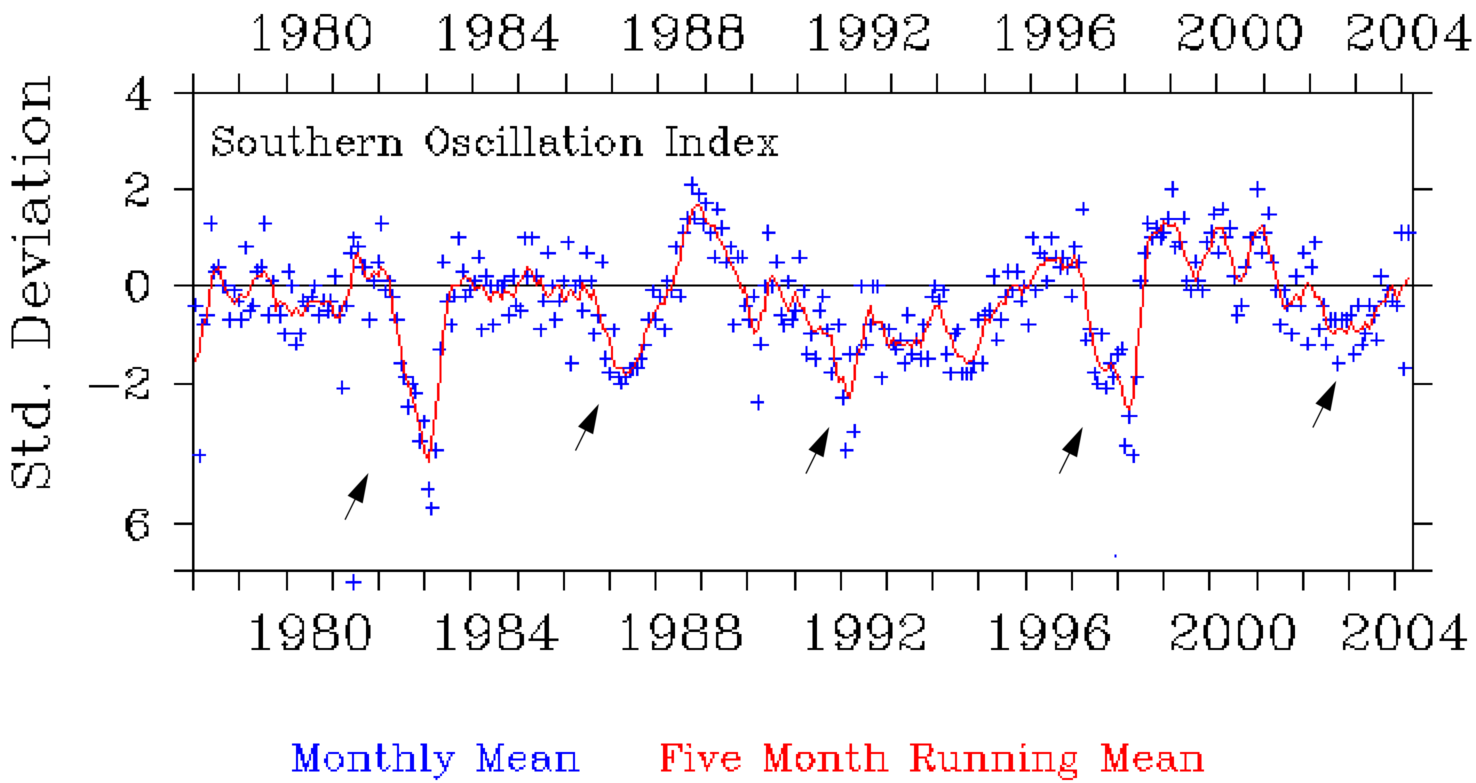
SST in the Eastern equatorial Pacific

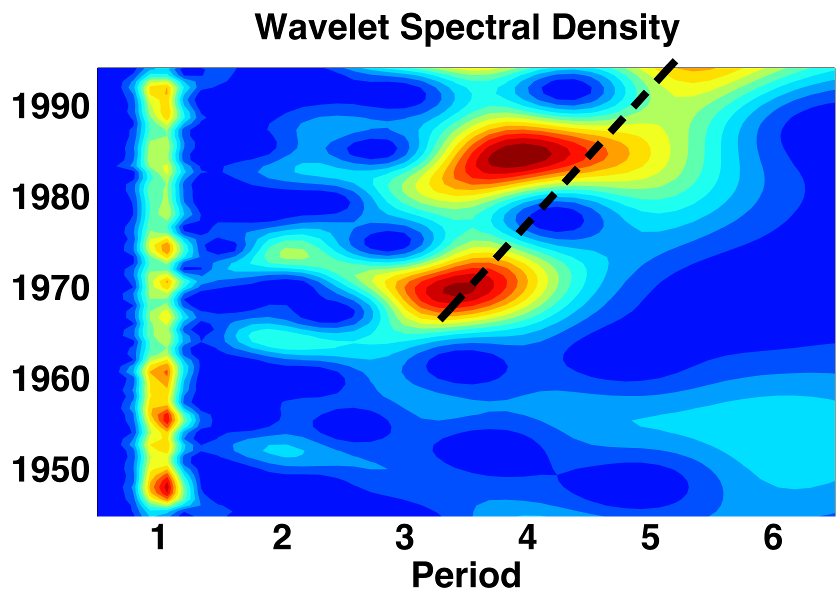


B - the 1960s and 1970s

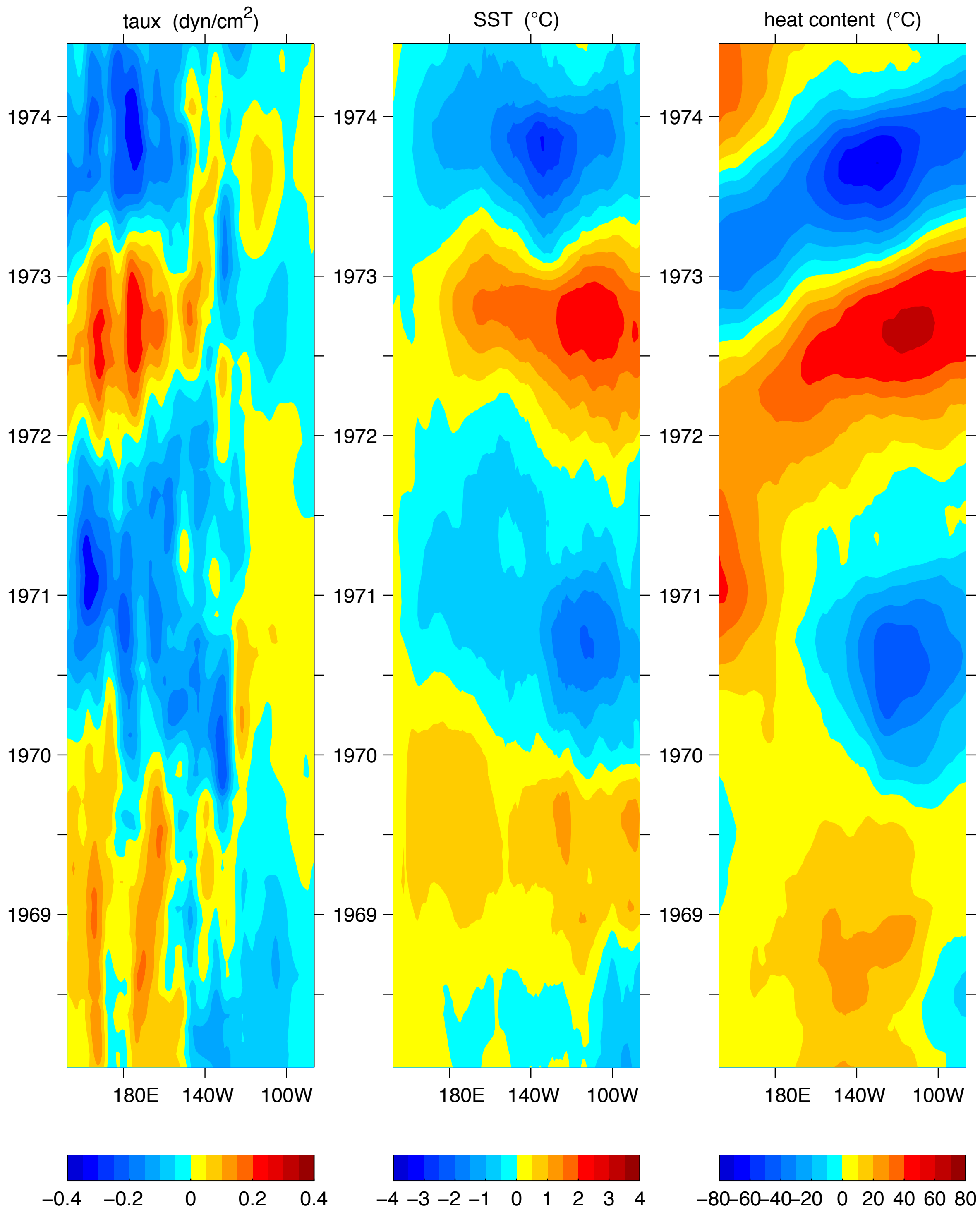
A - the 1980s and 1990s

Southern Oscillation Index

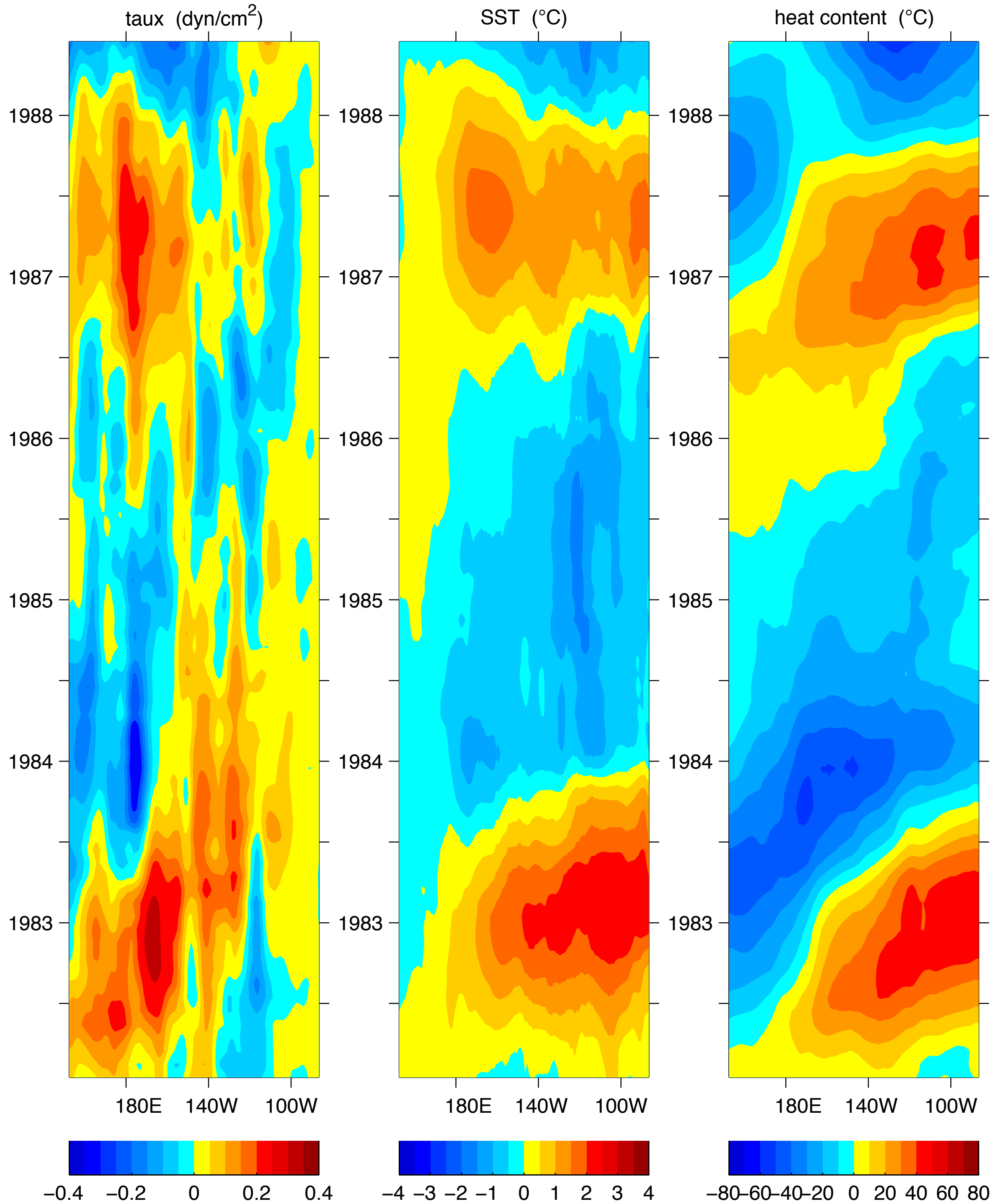




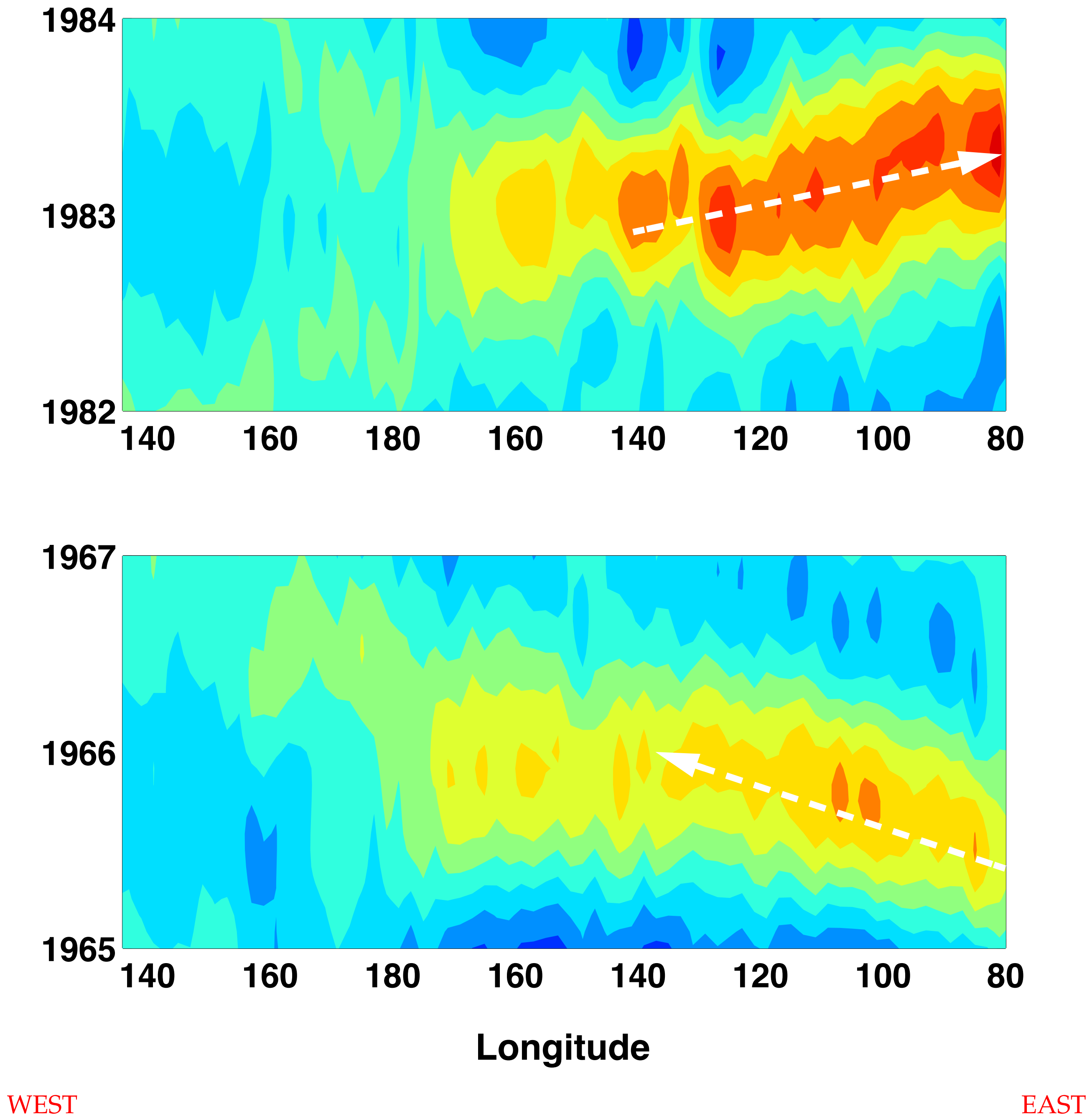
The wavelet spectral density for the SST fluctuations in the eastern Pacific. Dark red /blue correspond to high /low values, respectively. Notice the apparent shift in El Niño frequency.



taux (dyn/cm²)
SST (°C)
heat content (°C)
1974
1973
1972
1971
1970
1969
180E
140W
100W
−0.4
−0.2
0
0.2
0.4
−4
−3
−2
−1
0
1
2
3
4
−80
−60
−40
−20
0
20
40
60
80

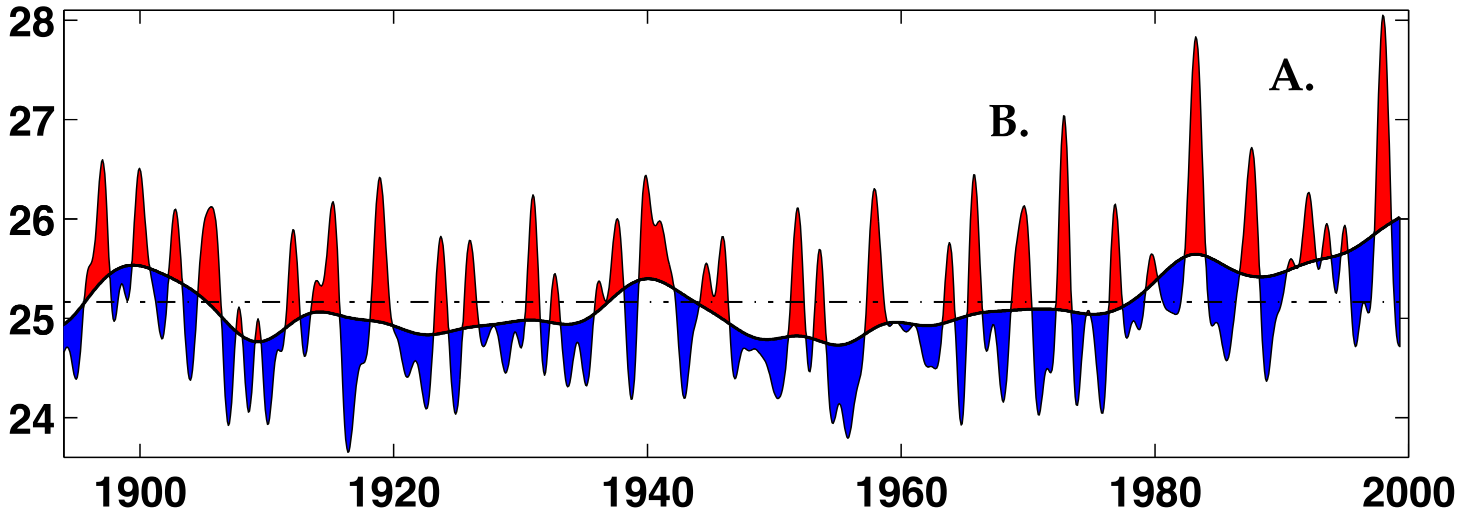


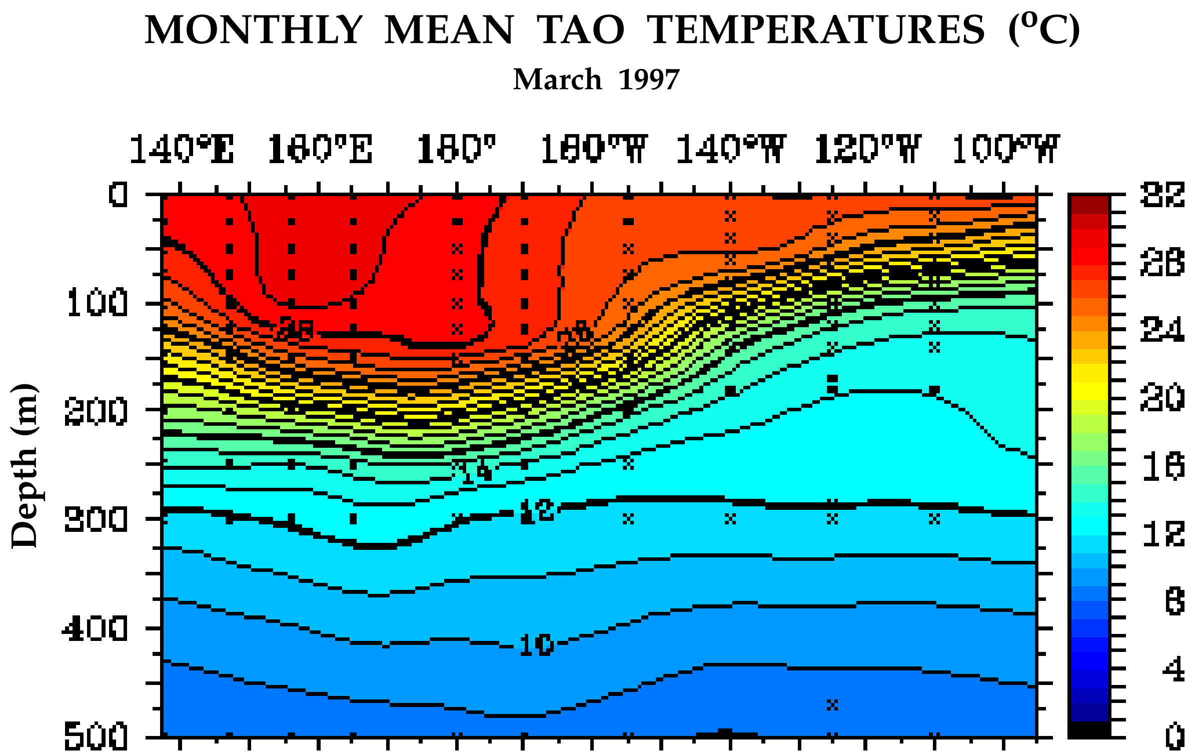
taux (dyn/cm^2)
SST (°C)
heat content (°C)
1988
1987
1986
1985
1984
1983
180E 140W 100W
−0.4 −0.2 0 0.2 0.4
−4 −3 −2 −1 0 1 2 3 4
−80 −60 −40 −20 0 20 40 60 80



El Niño of 1982/1983 and 1965/1966 as revealed in the anomalous SST along the equator. Dark red /blue correspond to high /low temperatures.

SST in the Eastern equatorial Pacific



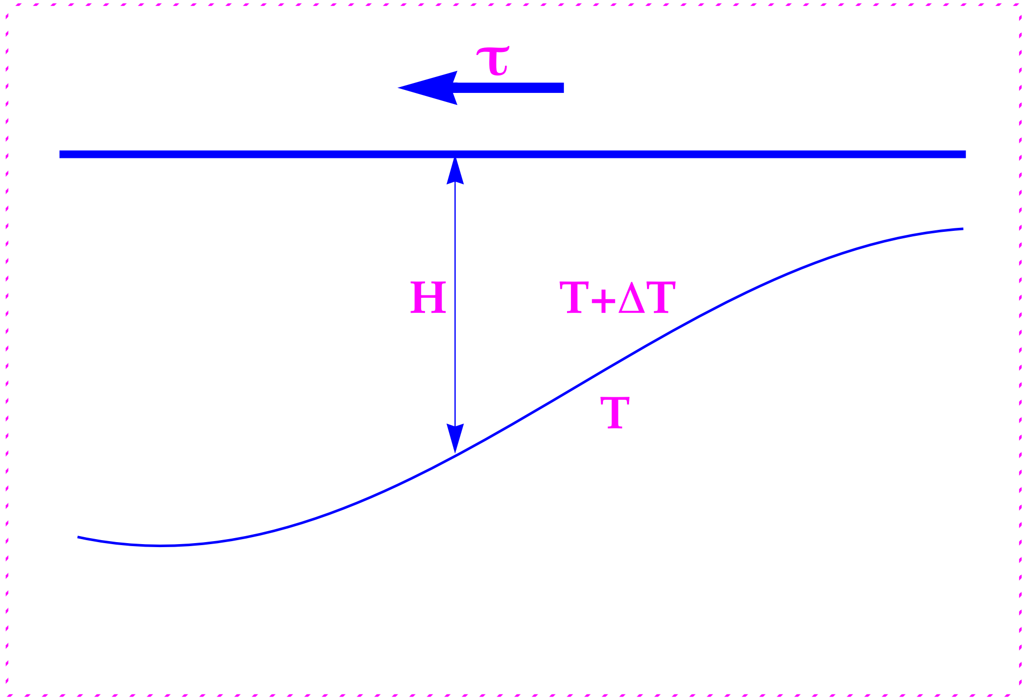


The thermal structure of the upper ocean in the Pacific along the equator. The thermocline corresponds to about 20°.

τ – mean wind intensity

H - mean depth of the thermocline

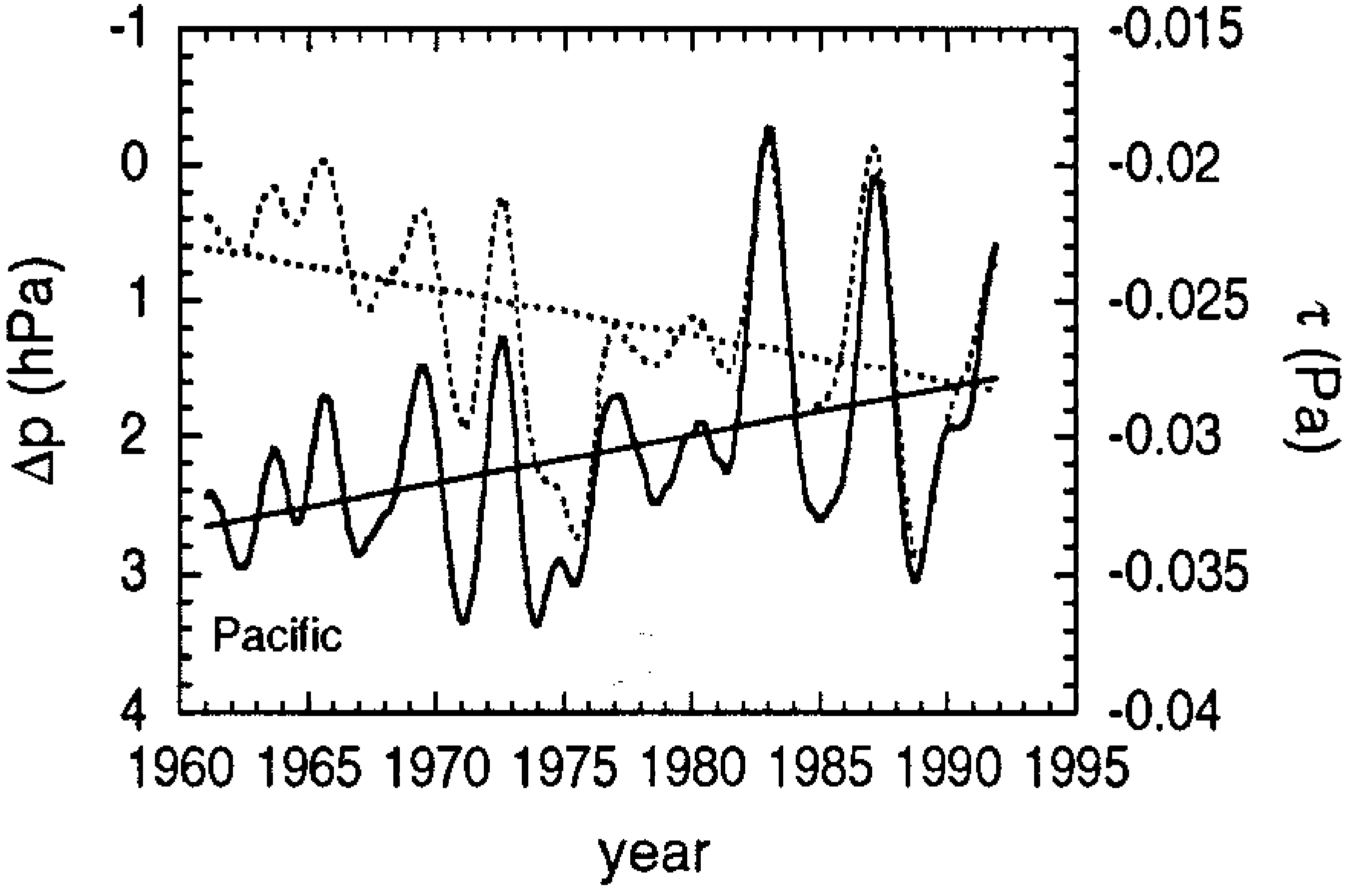
ΔT - temperature difference across the thermocline



τ – mean wind intensity
H - mean depth of the thermocline
ΔT - temperature difference across the thermocline

The zonal wind stress τ

(the 1960s versus the 1990s)



(After Lebedev and Clark 1996)

Changes in the tropical Pacific since the late 1970s.

ENSO:

- A longer period between El Niño events
  (the period has increased from 3-4 years to 5 years).
- Larger amplitudes of El Niño (e.g. El Niño of 1982 and 1997).
- The direction of propagation of the SST anomalies
  (has changed from westward to slightly eastward or stationary).

Background conditions:

- Warming of the eastern Pacific (by 0.5 - 1.0 ^{o}C).
- Weakening of the zonally-averaged trade winds (decrease in τ by 10-20%).
- Deepening of the thermocline (increase in H by ~5 m?)
- ΔT - ? (has not changed significantly).

THE MODEL.

inspired by Cane and Zebiak (1987); Battisti and Hirst (1988); Jin and Neelin (1993)

Domain.

- **30^oS- 30^oN; 130^oE-80^oW**

Ocean.

- **Shallow-water dynamics; Embedded mixed layer**

Atmosphere.

- **Shallow-water dynamics**

SST.

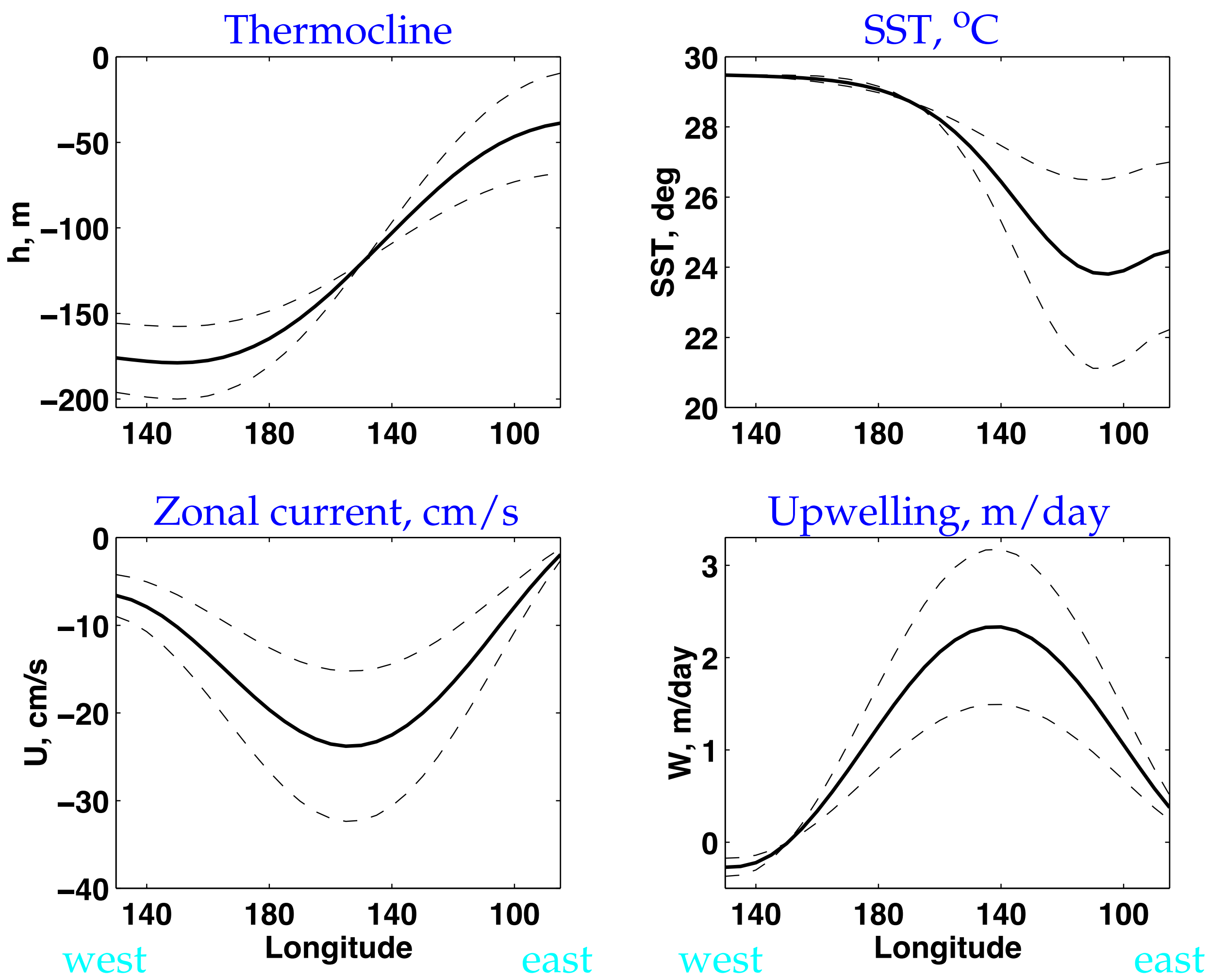
- **Temperature (advection-diffusion) equation for the equatorial strip**

$$T_t + UT_x + WT_z = \mu T_{xx} - q(T - 29^0)$$

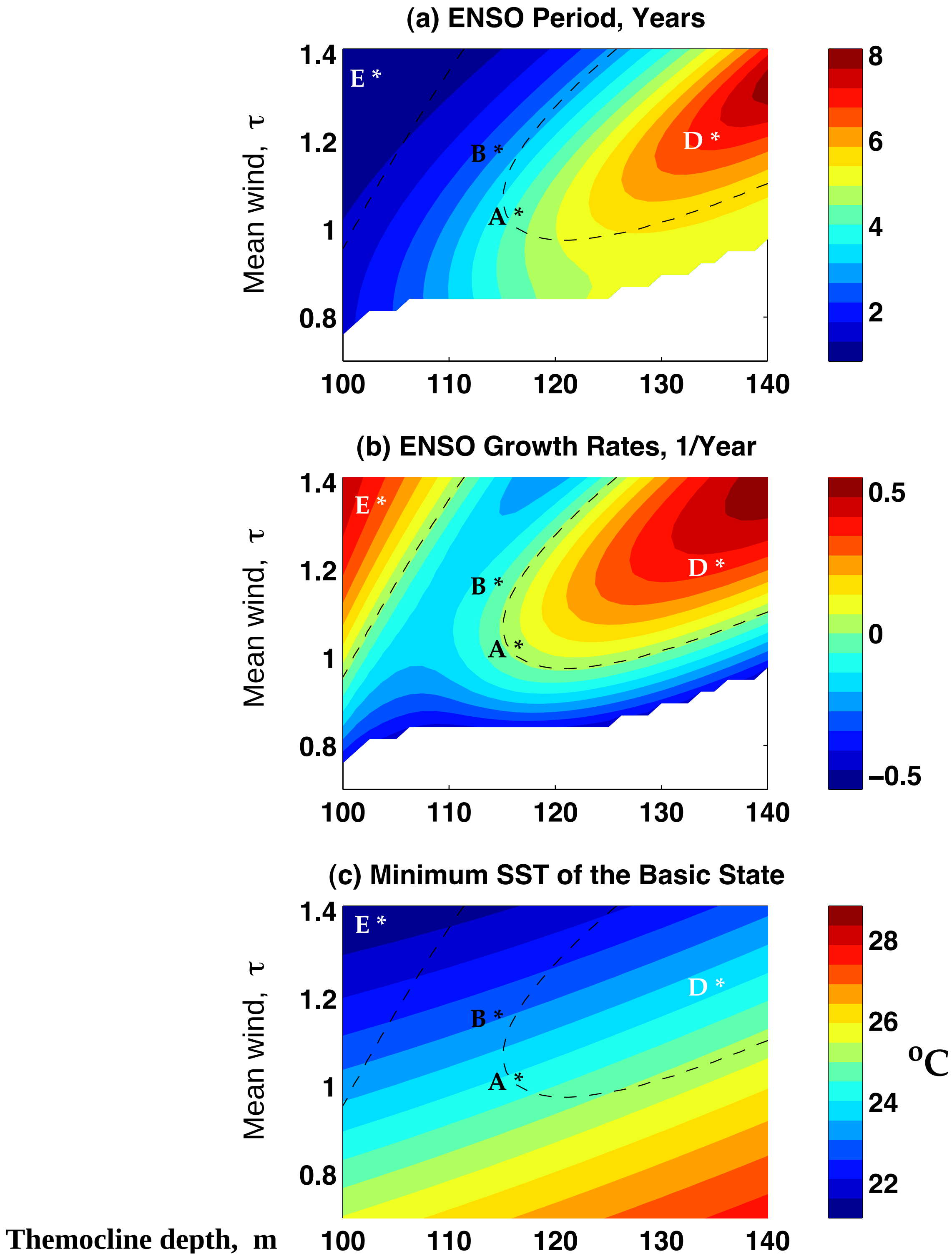
with $WT_z \propto W \frac{T - T^e}{h^m}$**;**

T^e **- entrainment temperature;** h^m **- depth of the mixed layer**

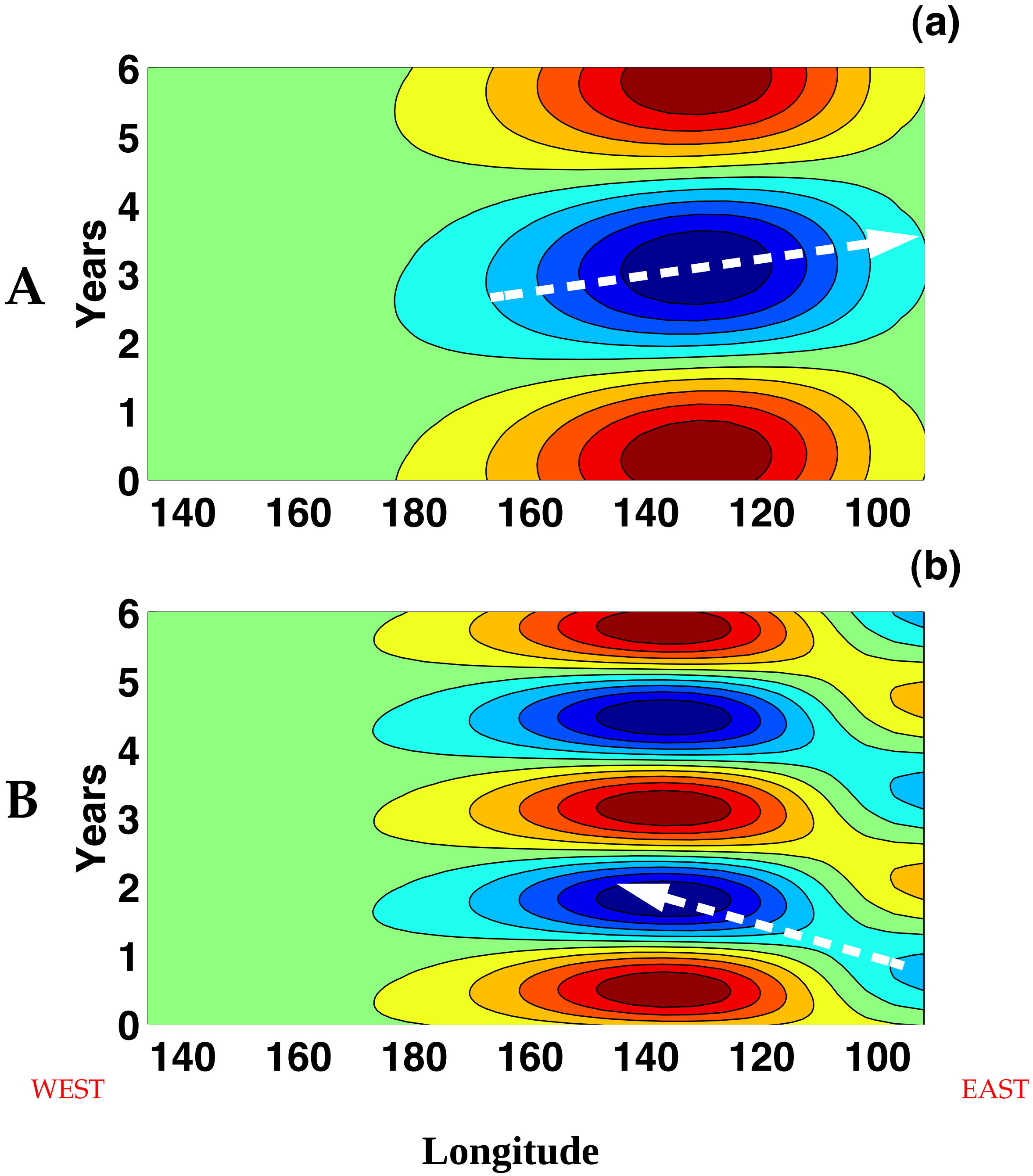
Free parameters: **H, ΔT and τ.**



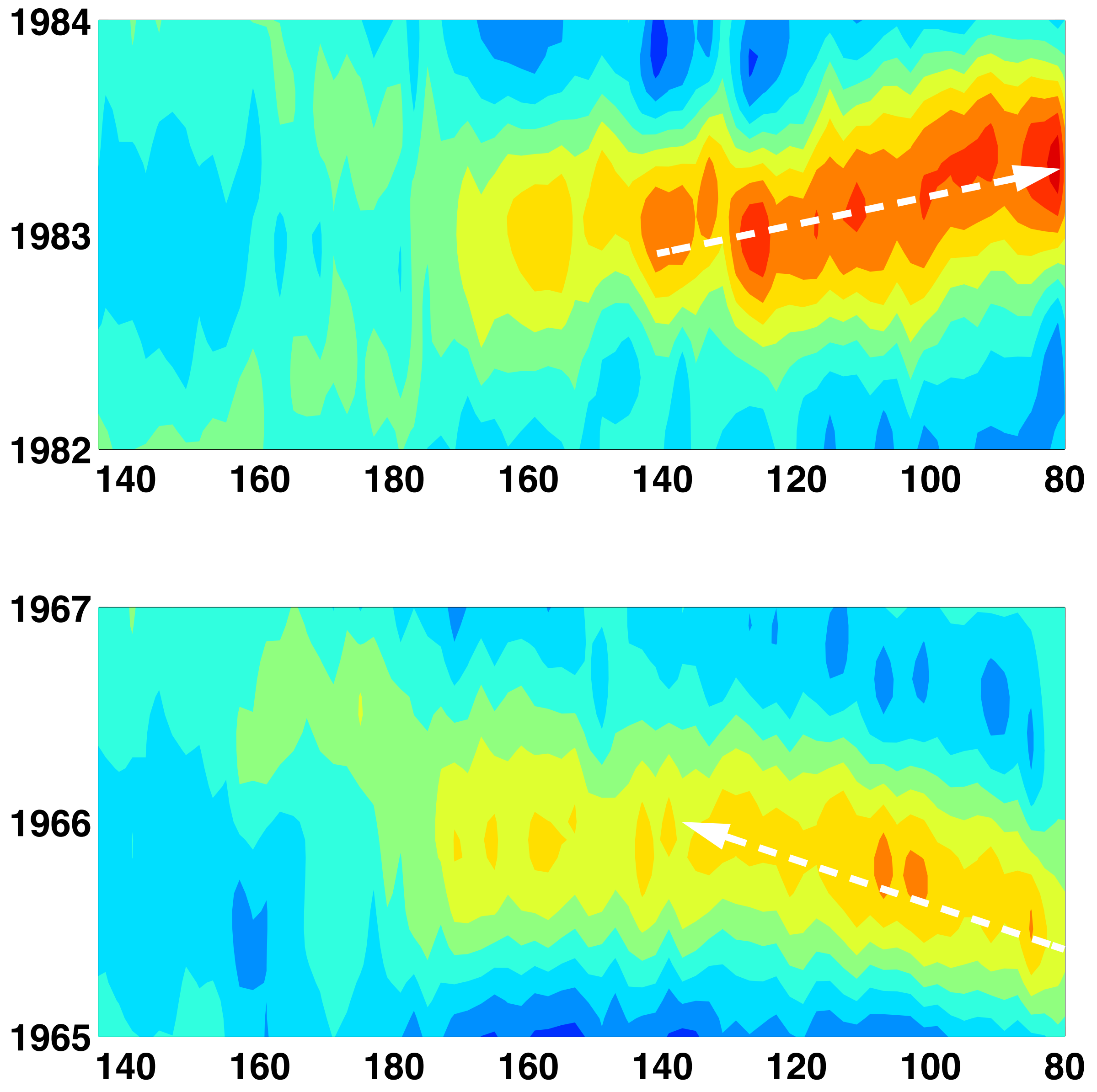
A typical background state as calculated from the model, and its variations for different τ



(a) ENSO Period, Years
(b) ENSO Growth Rates, 1/Year
(c) Minimum SST of the Basic State
Mean wind, τ
Themocline depth, m
1.4
1.2
1
0.8
100
110
120
130
140
8
6
4
2
0.5
0
−0.5
28
26
24
22
°C
A *
B *
D *
E *



The structure of the modes at points A and B, as seen in the anomalous SST as a function of longitude and time.



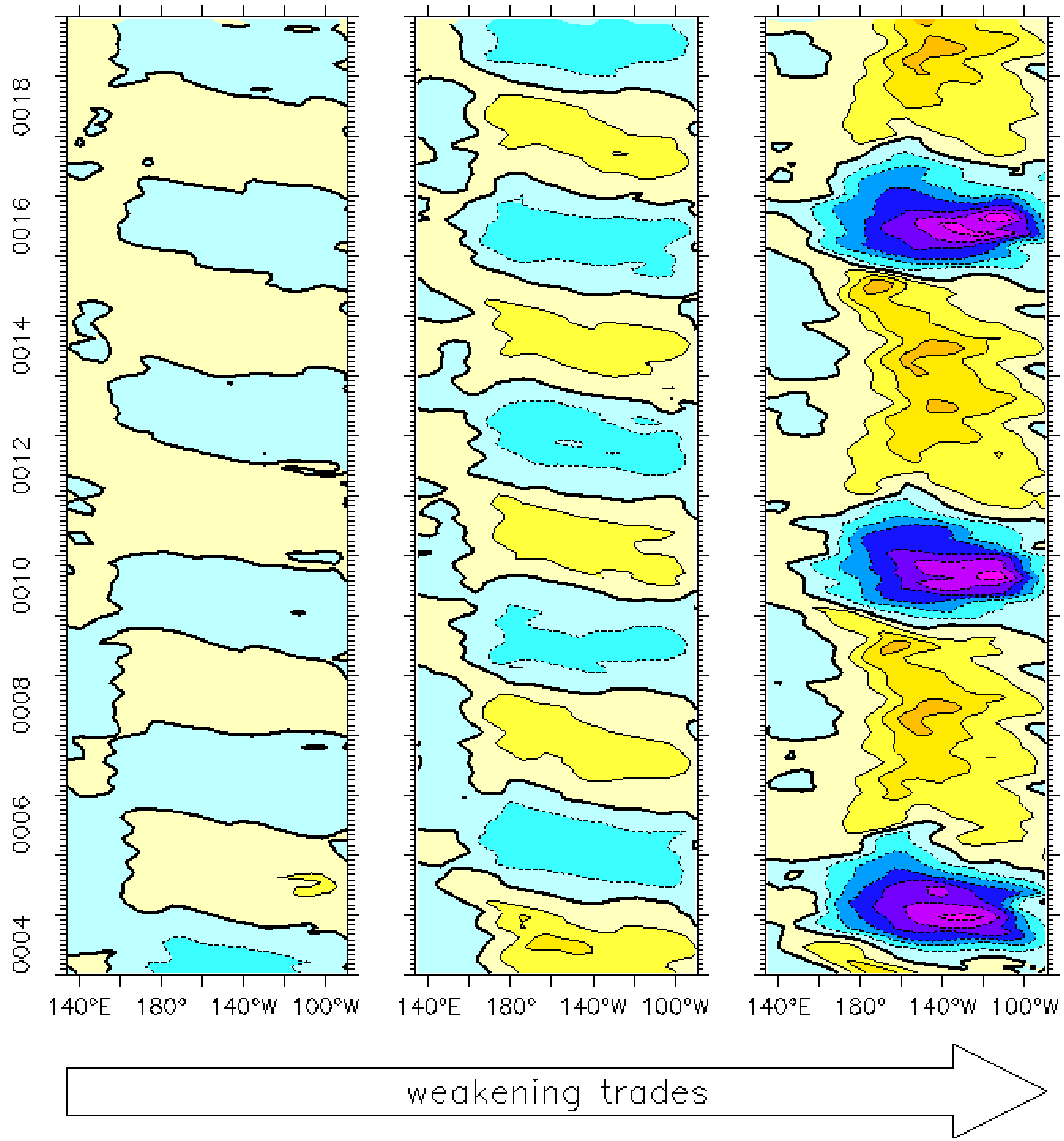
Longitude

WEST EAST

El Niño of 1982/1983 and 1965/1966 as revealed in the anomalous SST along the equator. Dark red /blue correspond to high /low temperatures.

The effect of weakening trade winds in a hybrid GCM:

τ (+10%)	τ (standard)	τ (-10%)
Period (2.8 years)	Period (3.2 years)	Period (5.5 years)



Hypothesis II:

II. Differences between El Niño events can be accounted for by the effect of the atmospheric noise (e.g. westerly wind bursts).

Global warming can influence El Niño by affecting the noise.

$$\frac{d\boldsymbol{x}}{dt} = A\boldsymbol{x} + \boldsymbol{f}$$

$$\boldsymbol{x}\big|_{t=0} = \boldsymbol{x}_0$$

$\boldsymbol{x}$ - a vector describing the state of the coupled ocean-atmosphere in the tropical Pacific

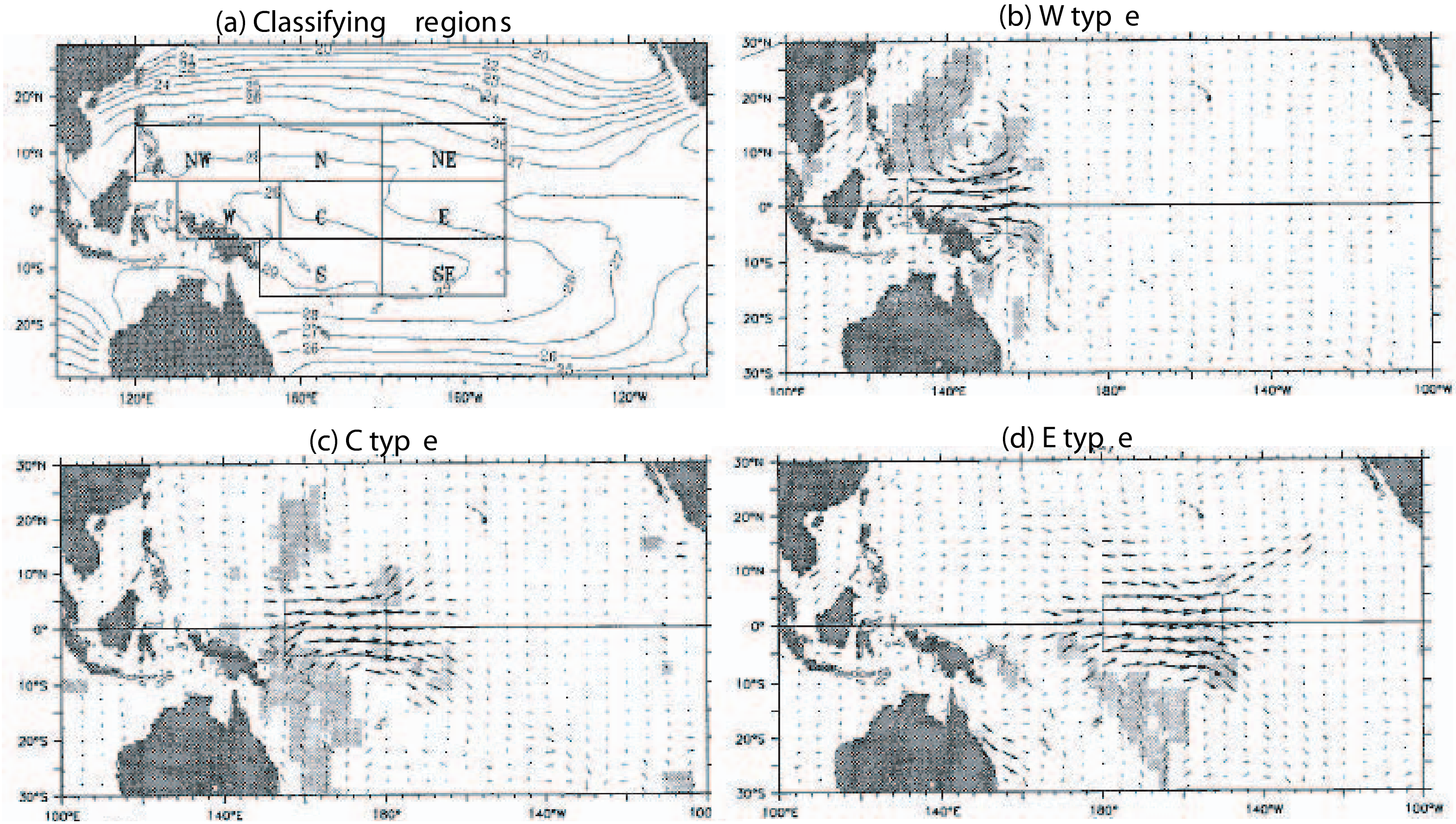
and

A - the dynamic operator, or matrix

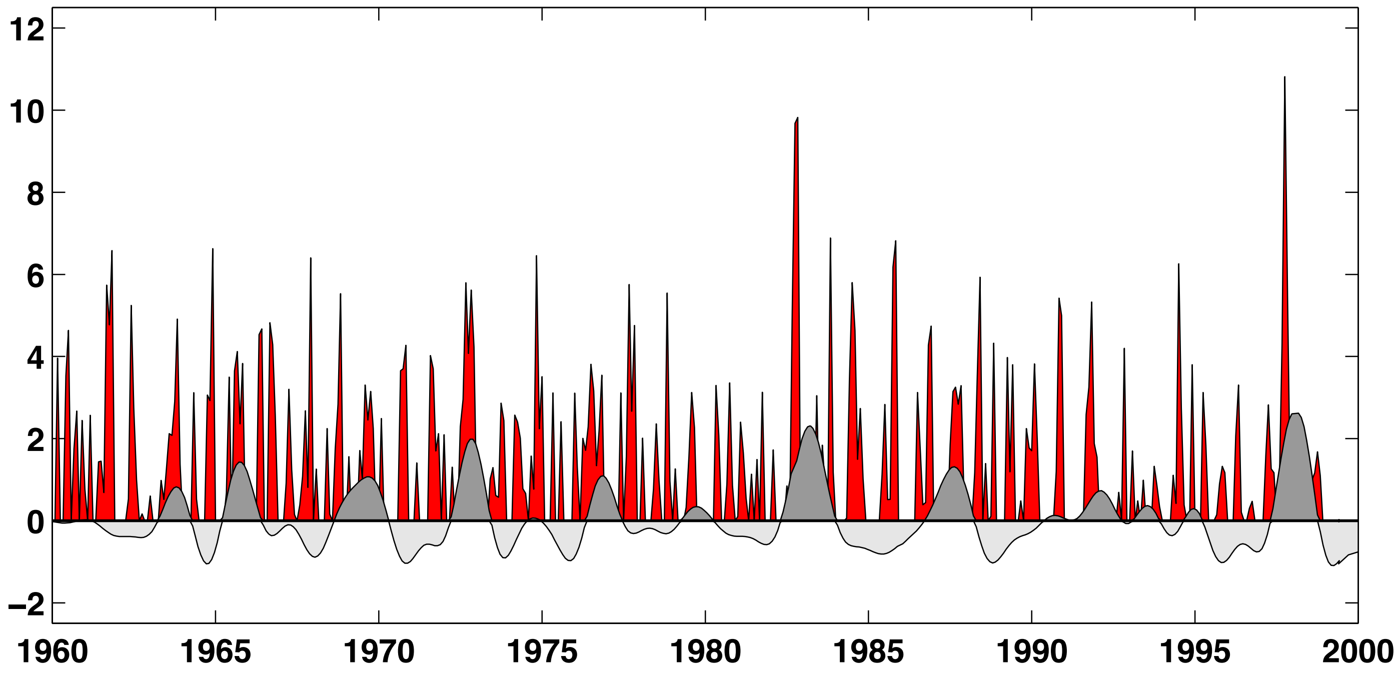
$\boldsymbol{f}$ - the noise (atmospheric)

$\boldsymbol{x}_0$ - initial conditions

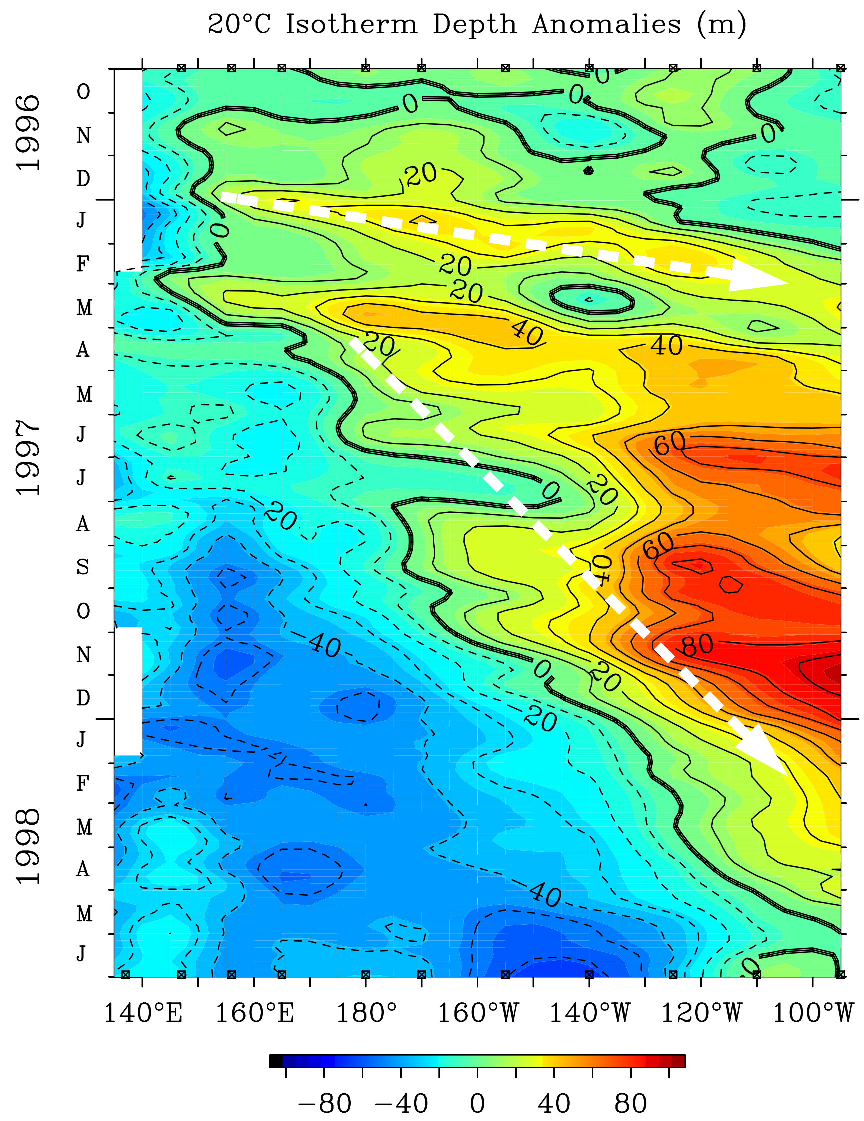
The noise:



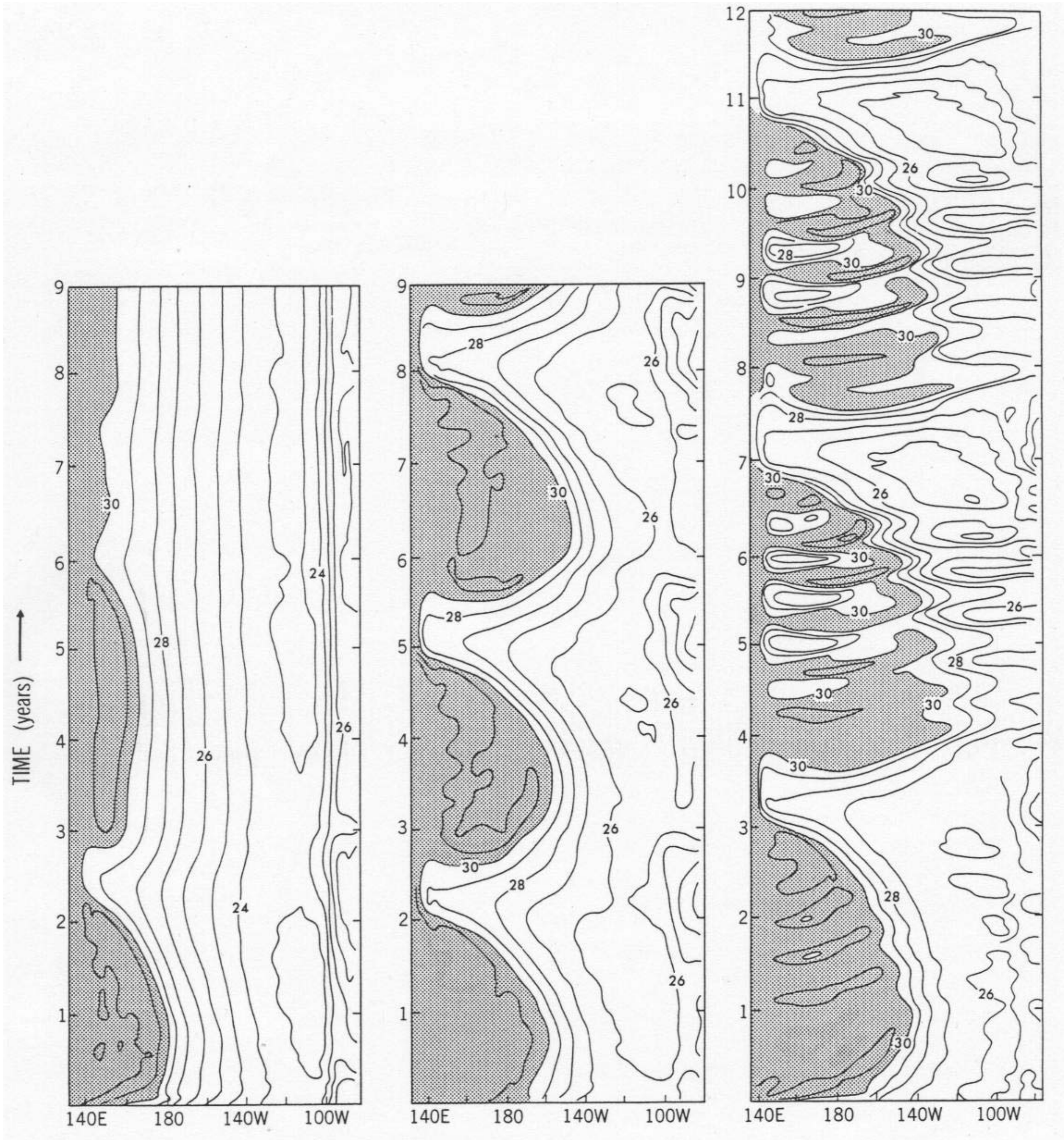
(After Harrison and Vecchi 1997, J. Climate)



Westerly wind bursts as seen in the higher-frequency variations of the zonal wind stress averaged in the domain 140^{o}E-210^{o}E, 5^{o}S-5^{o}N (in the units of 0.02 dyn cm^{-2}). Only positive values are shown. The underlying plot shows the interannual signal in the Niño-3 SST (in ^{o}C).



The displacement of the 20 ^{O}C isotherm, in meters, along the equator in the Pacific during El Niño of 1997. The upper dashed line corresponds to a rapid Kelvin wave. The lower dashed line shows the slower eastward progression of warm water.



(a) (b) (c)

Evolution of the SST along the equator in the coupled model of Neelin (1990). The strength of the ocean-atmosphere coupling increases from (a) to (b) to (c).

Energy balance for the tropical ocean-atmosphere system

$$\frac{d}{dt}E = W + (\dots)$$

W = Wind Work per unit time

E = APE = perturbation Available Potential Energy

(...) = Dissipation, nonlinear terms, fluxes in and out of the tropical domain

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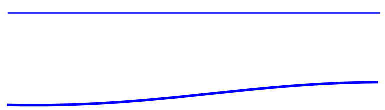
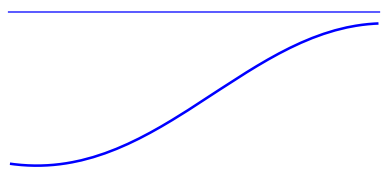
E is anti-correlated with the Niño-3 SST

1) $E<0$: Flat thermocline - El Niño



1) $E>0$: Large thermocline slope - La Niña



W, E can be used as phase coordinates

$$W = \iint U\tau \, dx\, dy$$

$$E = APE \propto \frac{g'}{2}\iint (h - H)^2 \, dx\, dy$$

(for Shallow-water models)

$$E = APE \propto -\frac{g}{2}\iiint \frac{(\rho - \hat{\rho})^2}{\hat{\rho}_z} \, dx\, dy\, dz$$

(for GCMs, or observations)

$U=U(x,y,t)$ - zonal current

$\tau=\tau(x,y,t)$ - zonal wind stress

$h=h(x,y,t)$ - local thermocline depth

H - mean thermocline depth

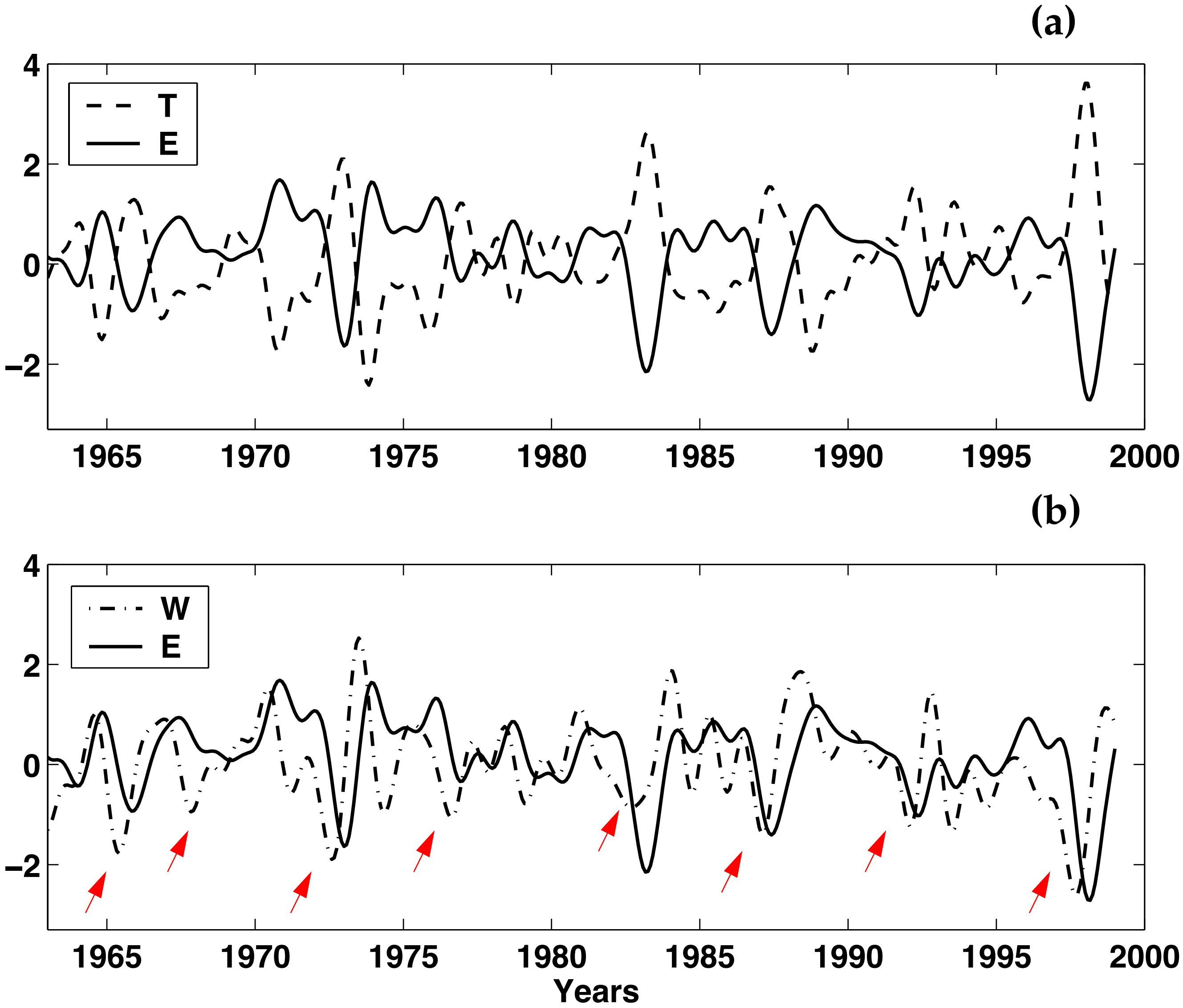
$\rho=\rho(x,y,z,t)$ - local density

$\hat{\rho} = \hat{\rho}(z)$ - hydrostatically-balanced density

The integration is conducted over

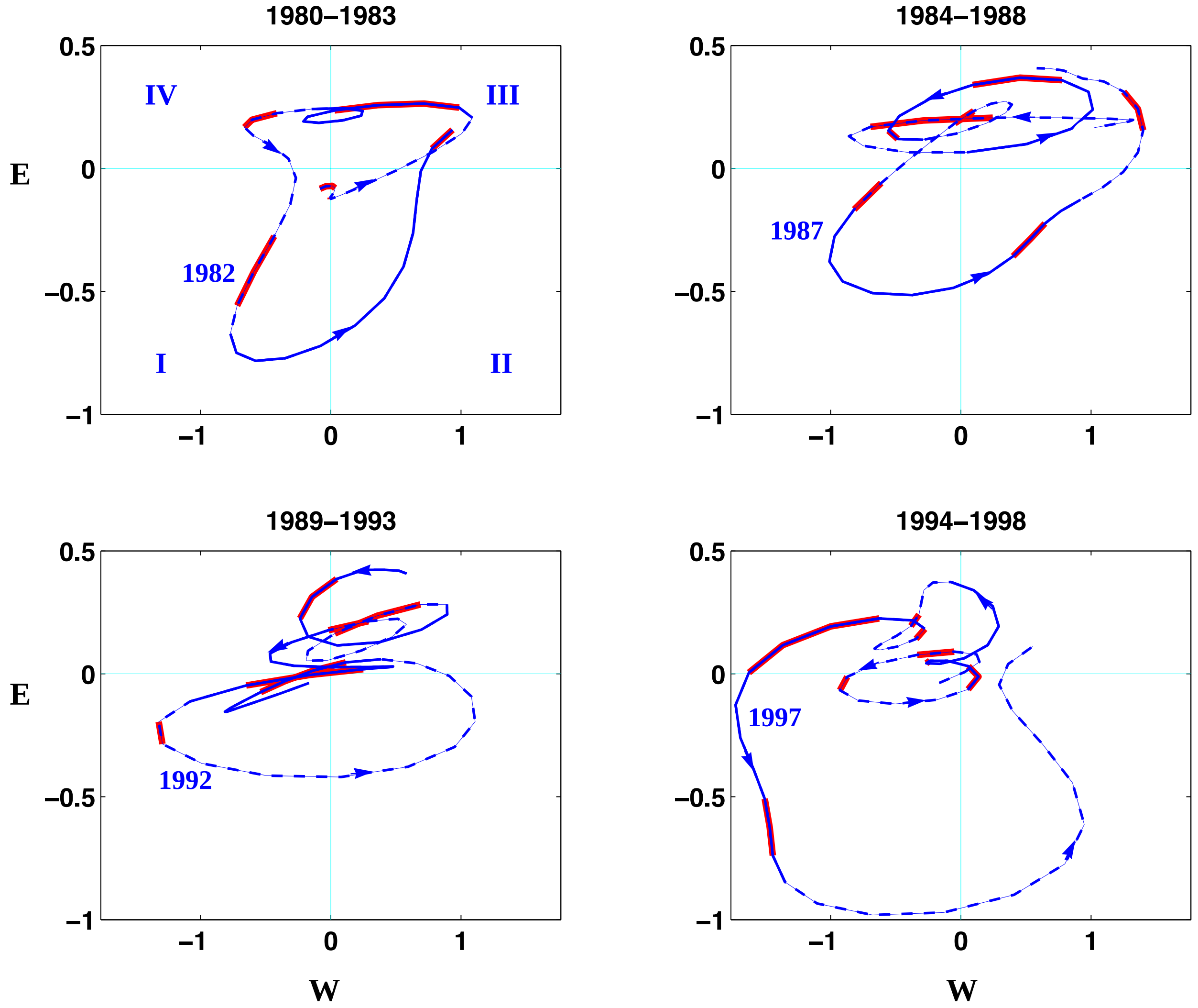
the tropical Pacific domain

(e.g. 15^{o}N-15^{o}S, 130^{o}E - 85^{o}W).



(a) Variations in the sea surface temperature (T) of the eastern equatorial Pacific (^{o}C), and in the available potential energy (E) of the tropical ocean, for the period 1963-2000. Correlation is ~0.9

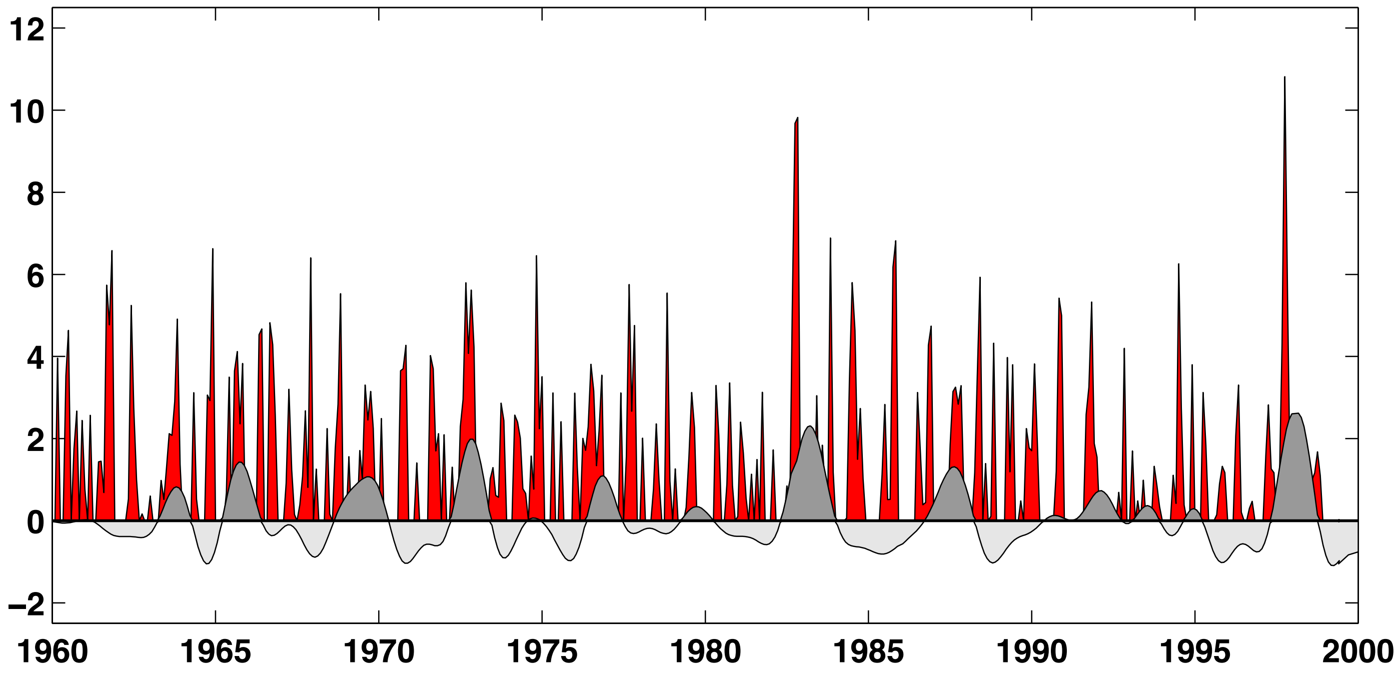
(b) Variations in the wind power (W), and in the available potential energy (E) of the tropical ocean. W leads E by approximately 8 months.



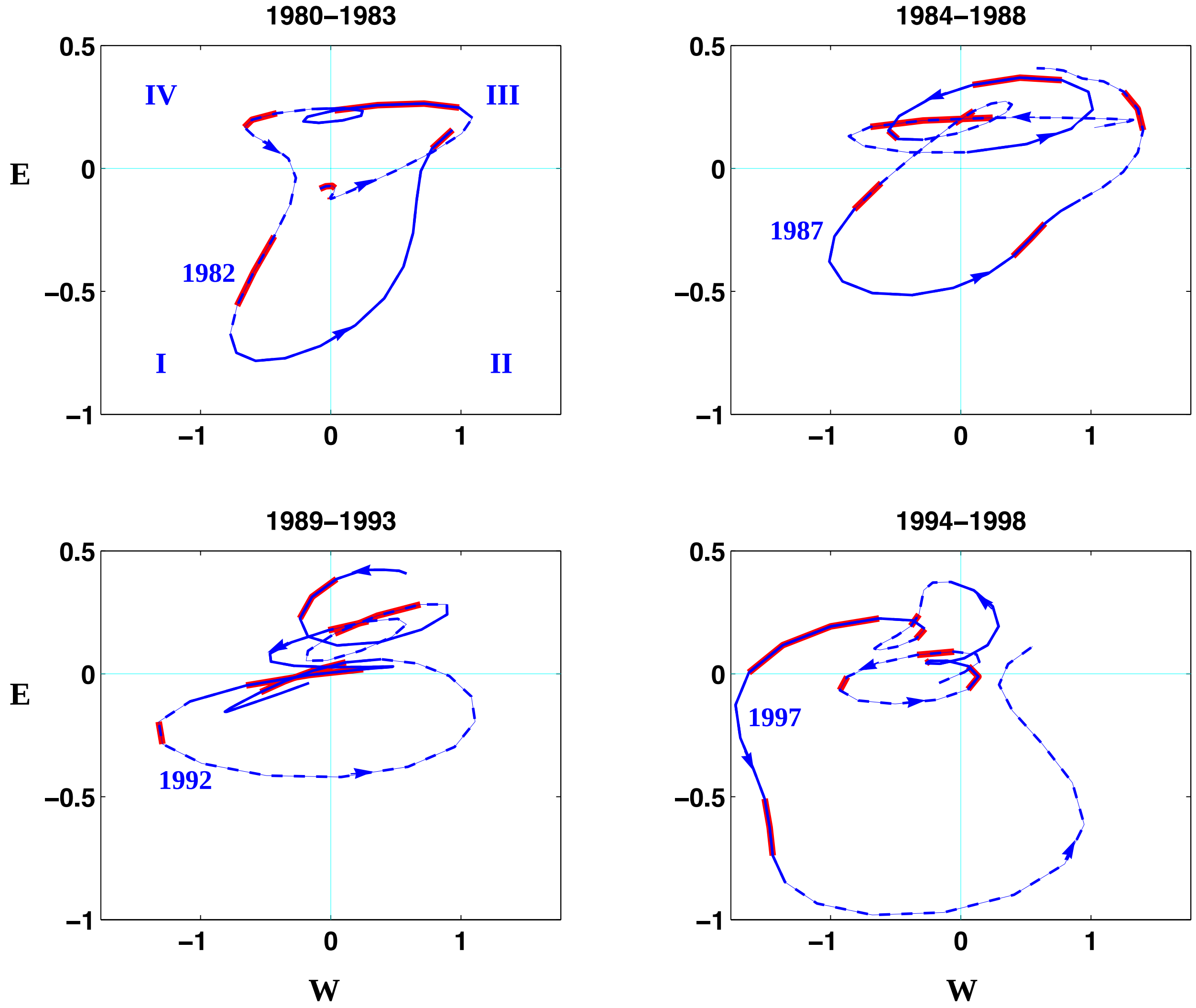
The E-W phase diagrams for the period 1979-1998.The red portions of the plot indicate the occurrence of westerly wind bursts. The intensities of bursts vary considerably. I, II, III, IV indicate different quadrants.

W **= Wind Work per unit time**

E **= APE = perturbation Available Potential Energy**



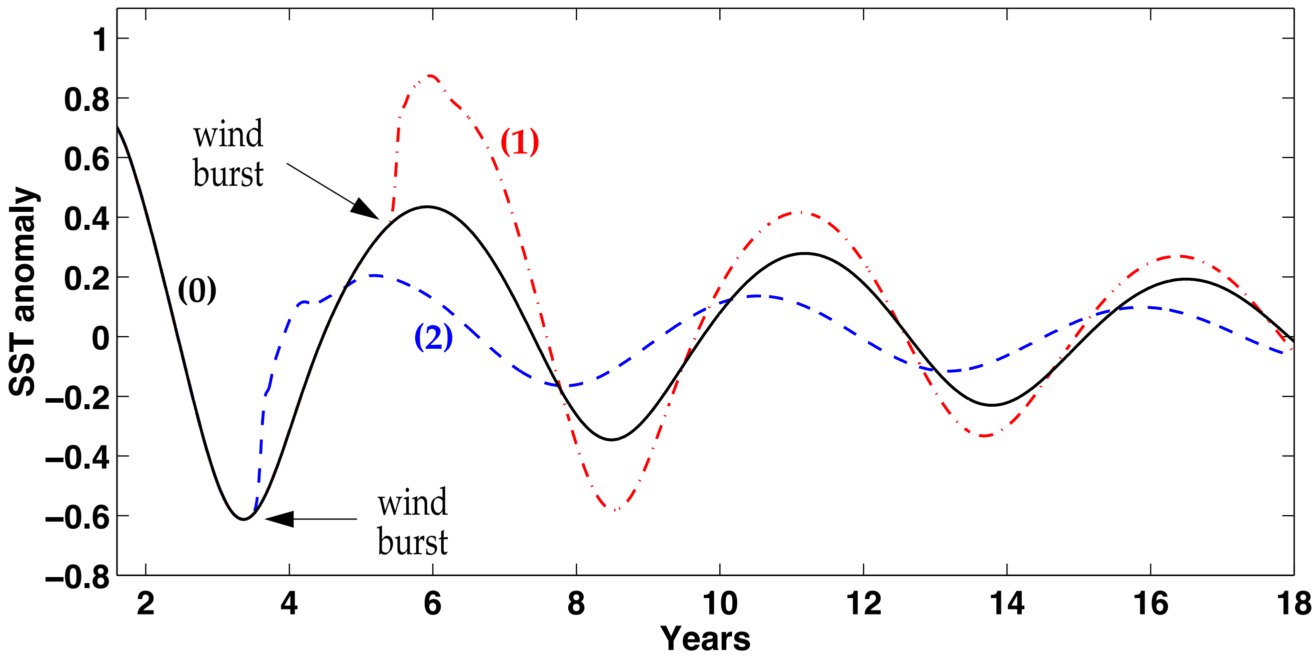
Westerly wind bursts as seen in the higher-frequency variations of the zonal wind stress averaged in the domain 140^{o}E-210^{o}E, 5^{o}S-5^{o}N (in the units of 0.02 dyn cm^{-2}). Only positive values are shown. The underlying plot shows the interannual signal in the Niño-3 SST (in ^{o}C).



The E-W phase diagrams for the period 1979-1998.The red portions of the plot indicate the occurrence of westerly wind bursts. The intensities of bursts vary considerably. I, II, III, IV indicate different quadrants.

W **= Wind Work per unit time**
E **= APE = perturbation Available Potential Energy**

The system is weakly-damped or close to neutral stability.

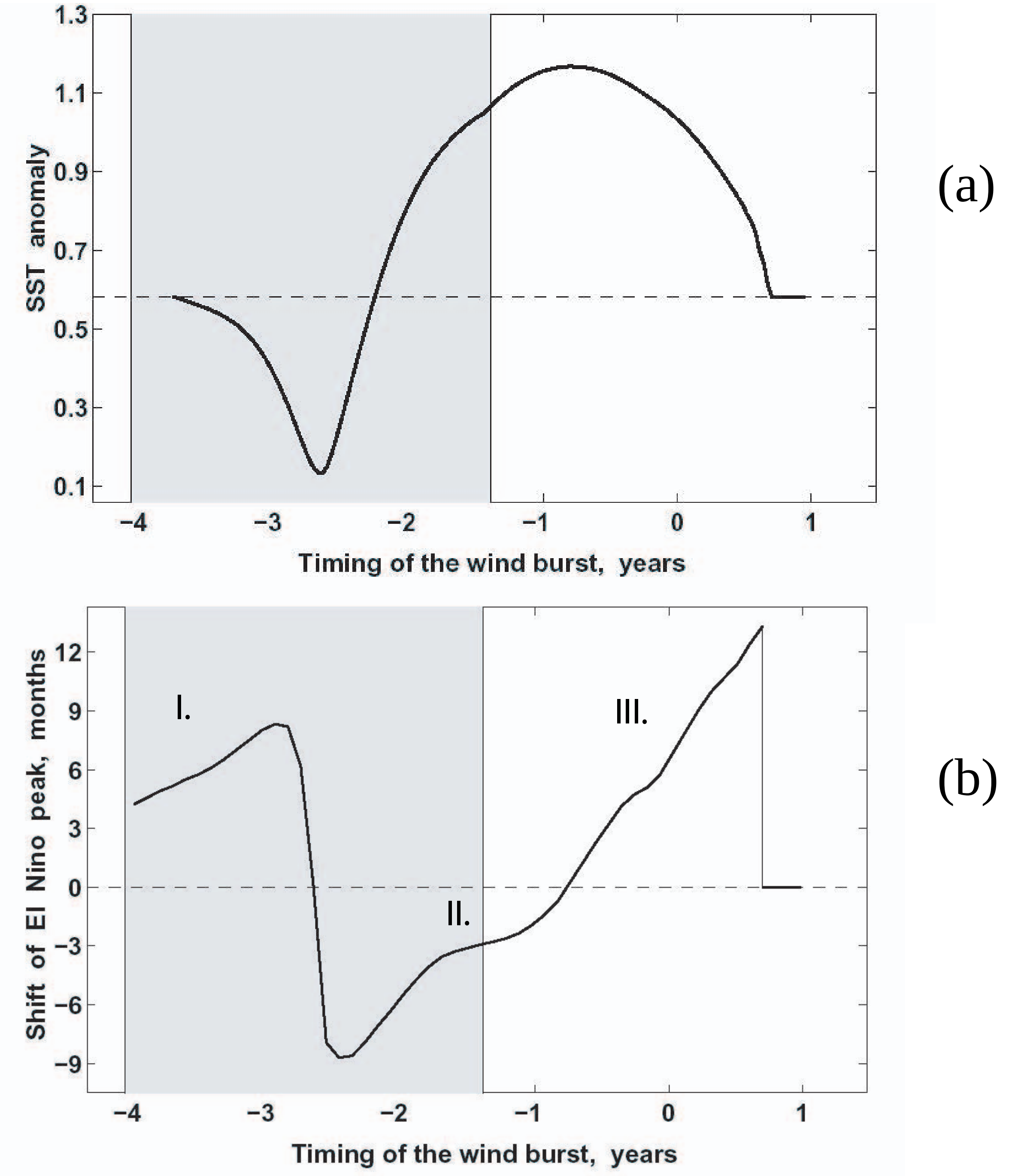


The response of the coupled ocean-atmosphere, with a slowly attenuating Southern Oscillation, to a WWB, as seen in the evolution of the anomalous SST of the eastern Pacific (in ^{o}C).

(0)No westerly wind bursts; black line.

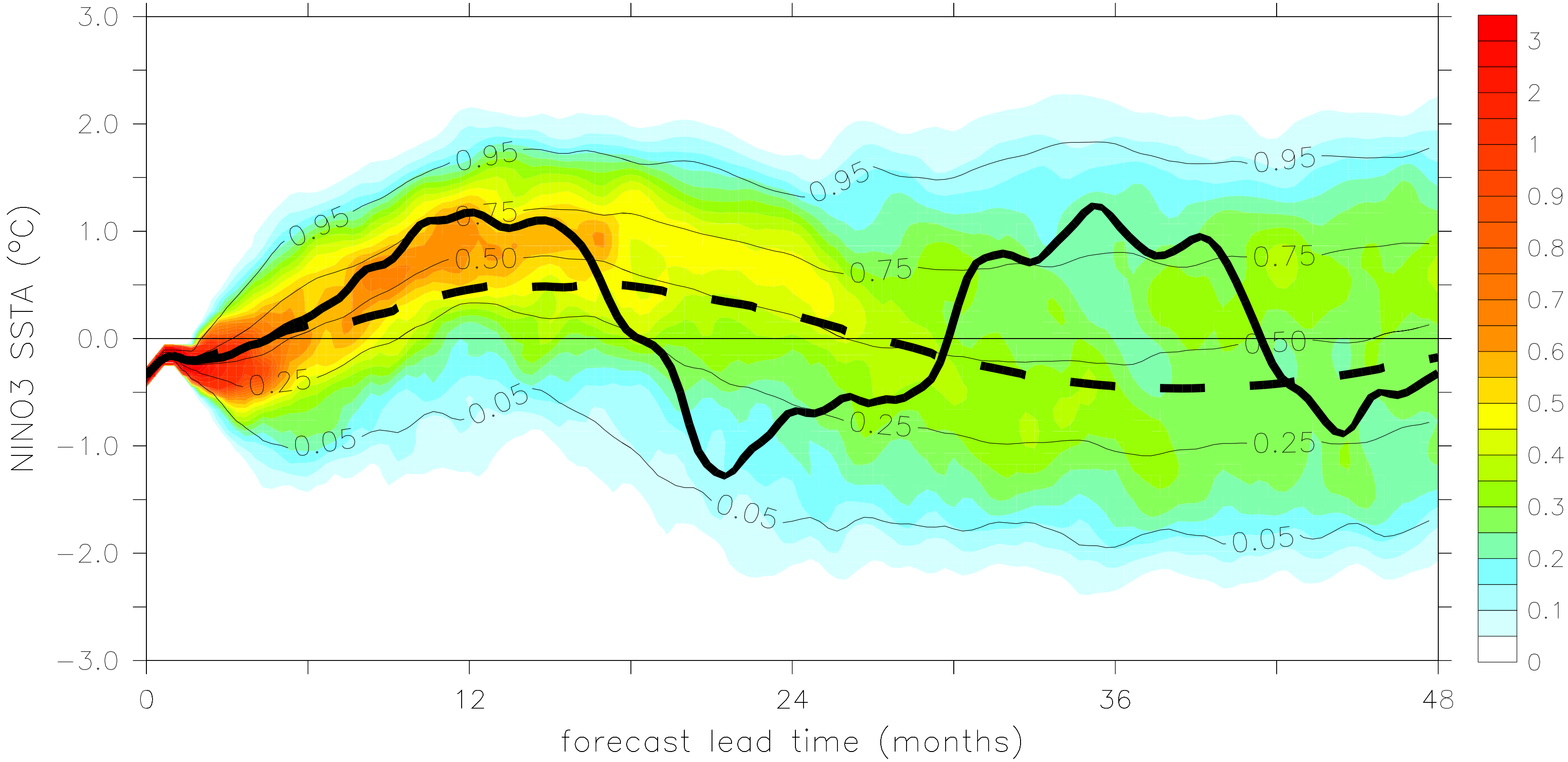
(1) A burst occurs 6 months before El Niño; red line.

(2) A burst occurs 3 months after the peak of La Niña; blue line.



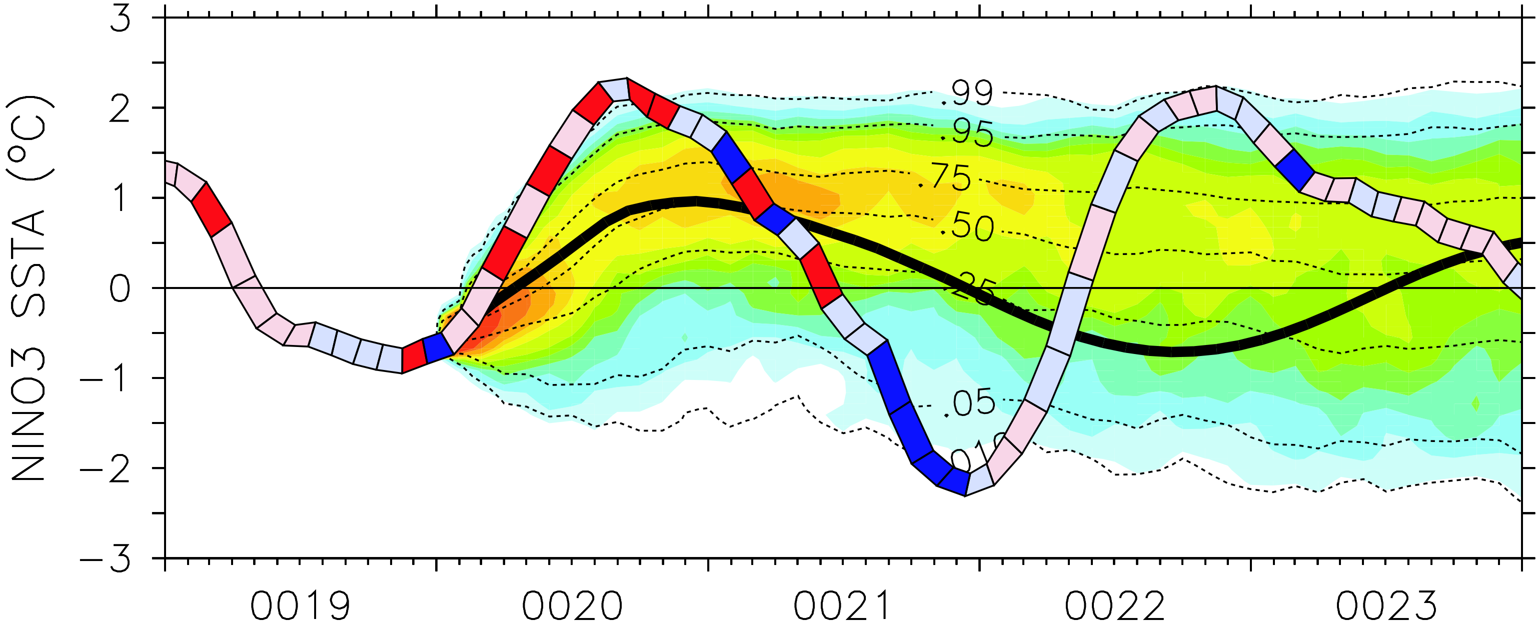
The impact of westerly wind bursts that happen at different times of an ENSO cycle on the magnitude (a) and timing (b) of El Niño.

An example of the probabilistic "forecast" of the SSTanomalies (^oC) in the eastern Pacific Ocean.

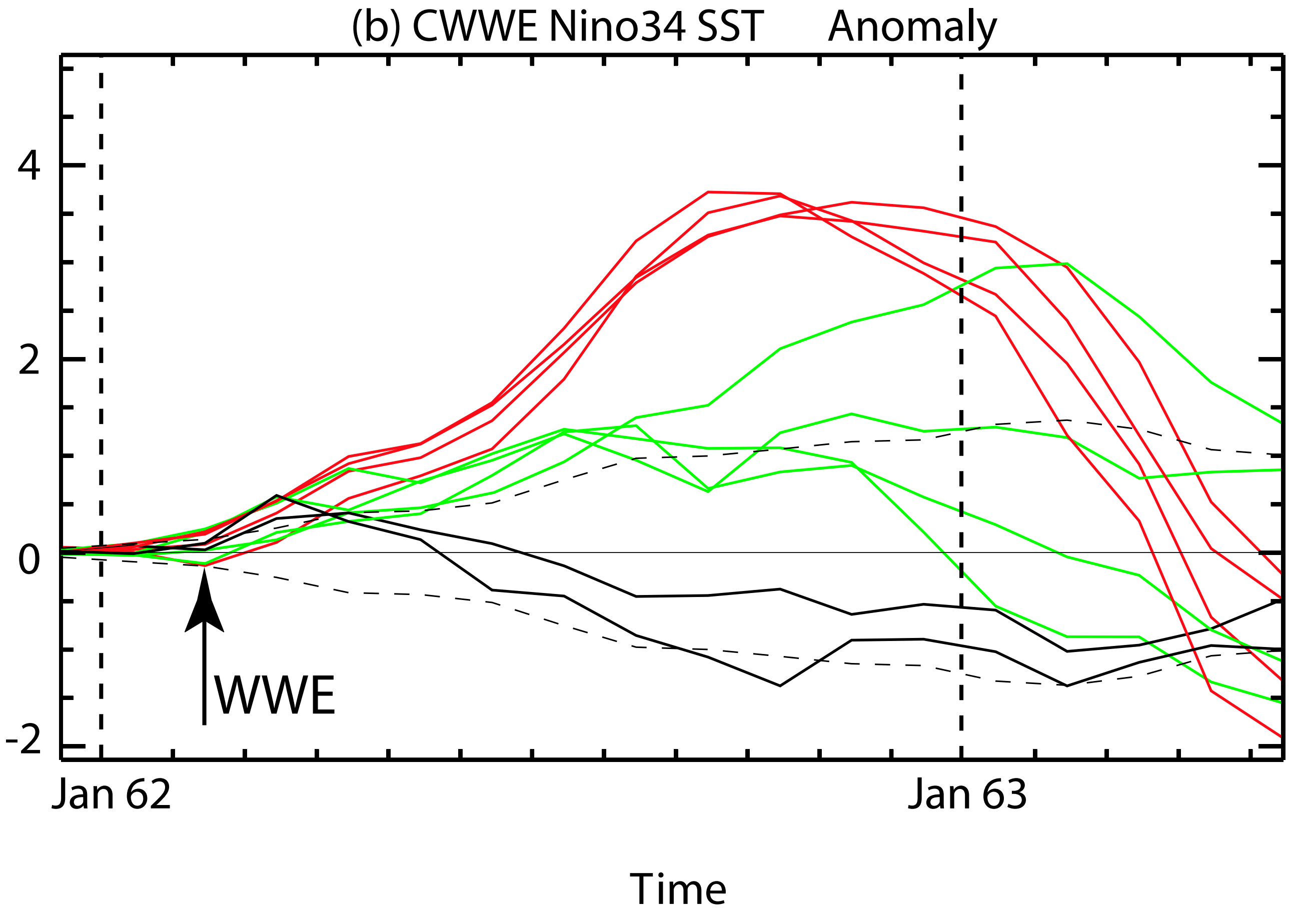


The dashed line shows a deterministic forecast in the absence of any noise.
The heavy solid line is an example of the effect of noise on the development of El Niño.

The colors illustrate how the forecasts are distributed - the red regions have the highest concentration of forecasts - and show how the probability density function (in units of 1/ ^oC) changes with time.



The solid line shows a deterministic forecast in the absence of any noise. The patchy red-blue line is an example of the effect of wind bursts on the development of El Niño.



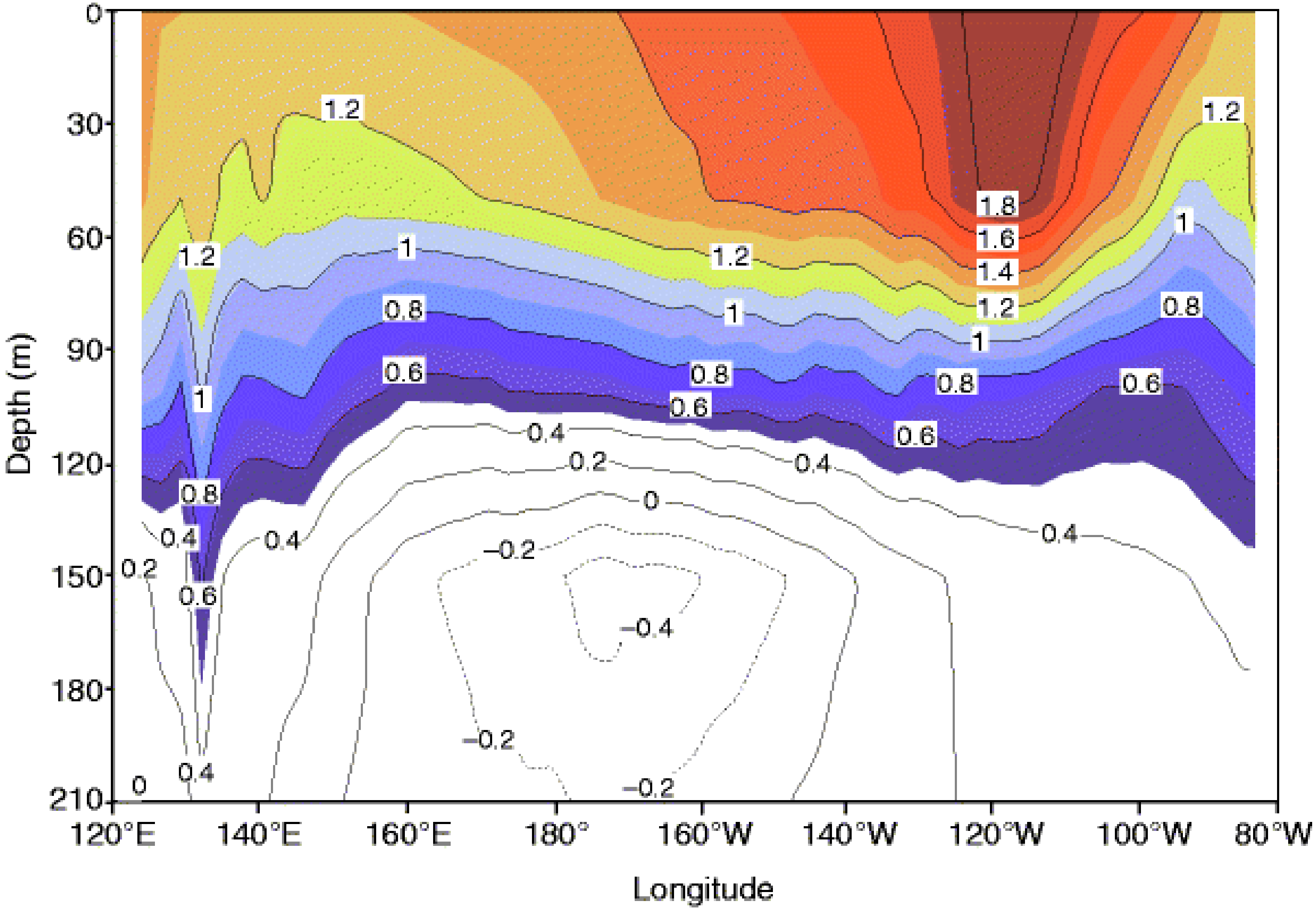
An ensemble of calculations with a coupled GCM with an externally imposed Westerly Wind Event

(After Lengaigne *et al* 2004, Clim. Dyn., in press)

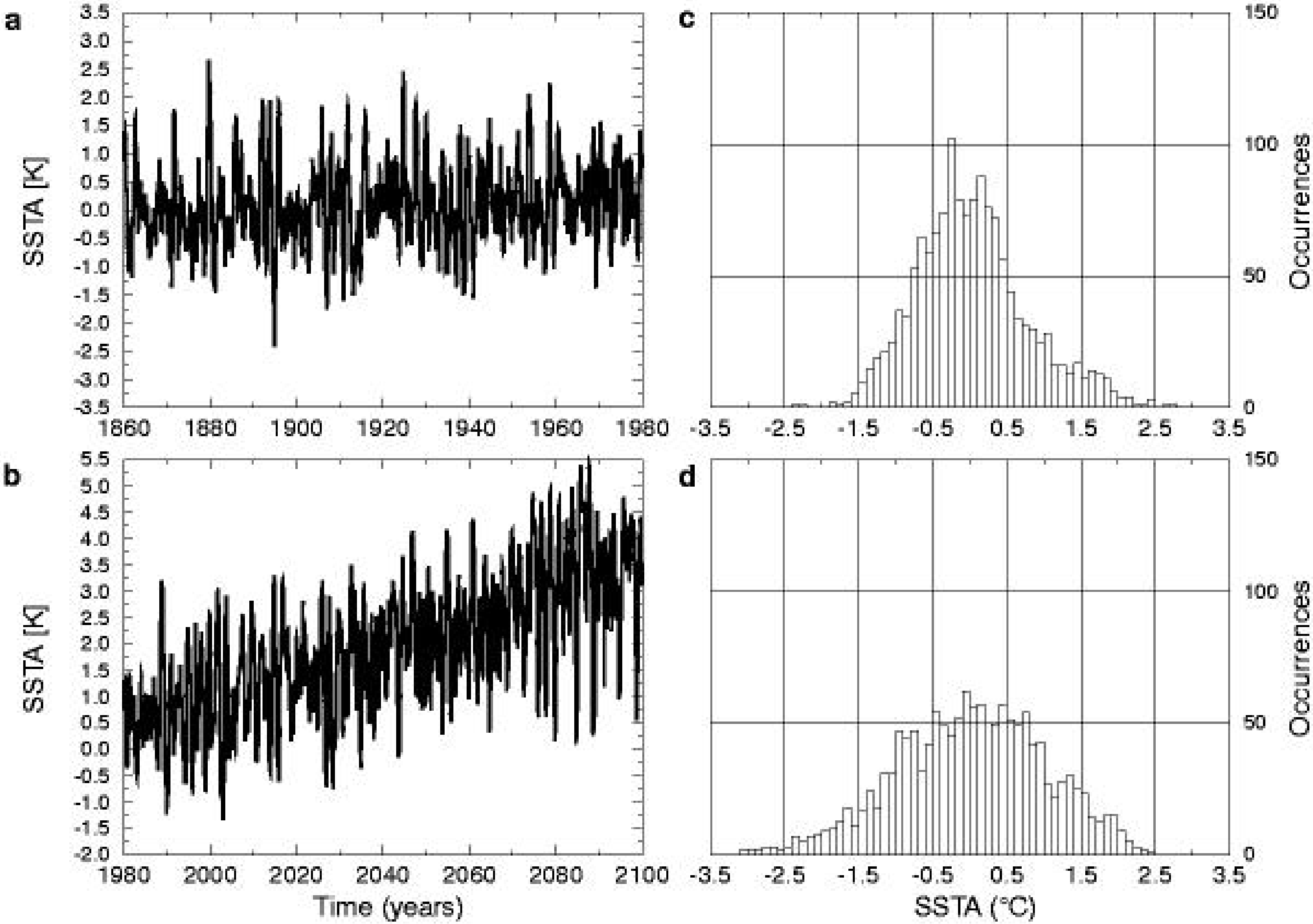
Conclusions:

- At the current state of knowledge we cannot exclude either of the two hypotheses - both are likely to contribute to changes in El Niño. Different coupled models may emphasize one or the other.

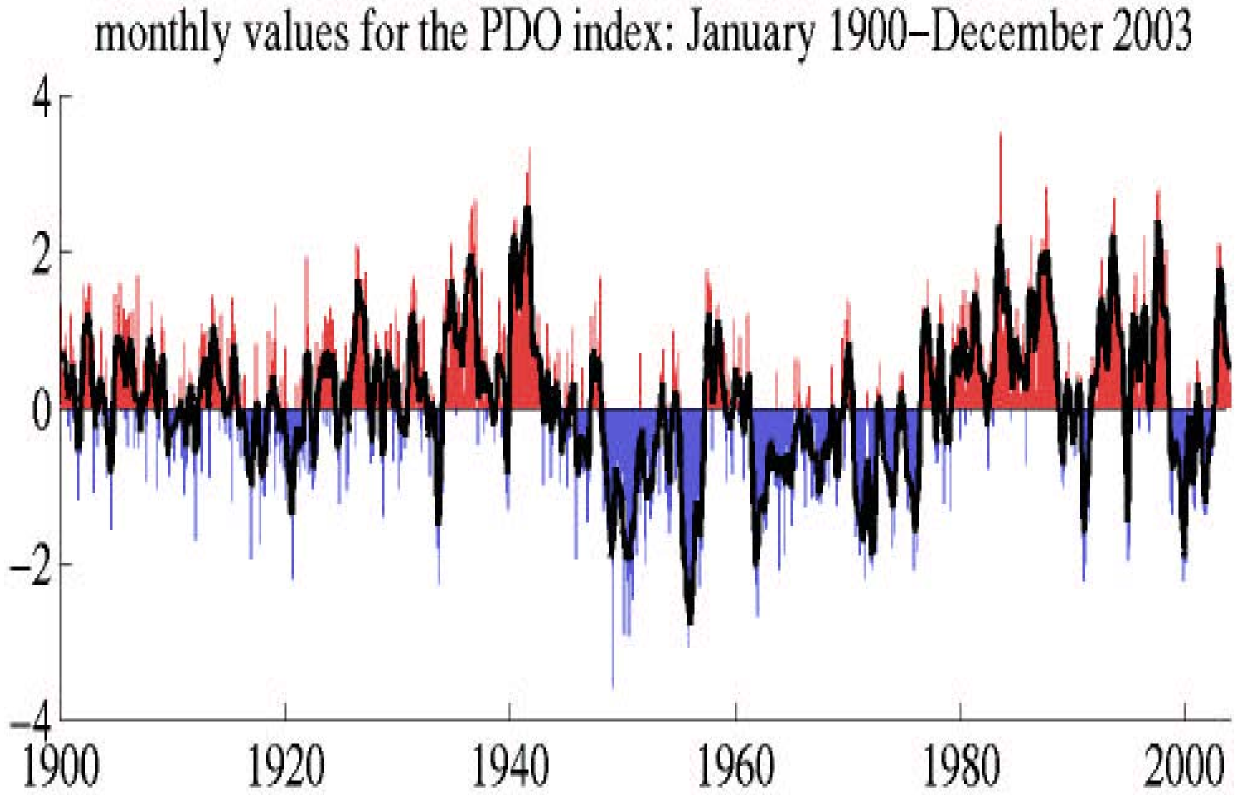
- There are indications that we can expect stronger El Niño events (from time to time) in a warmer climate, even though the periods between warm events may become longer.



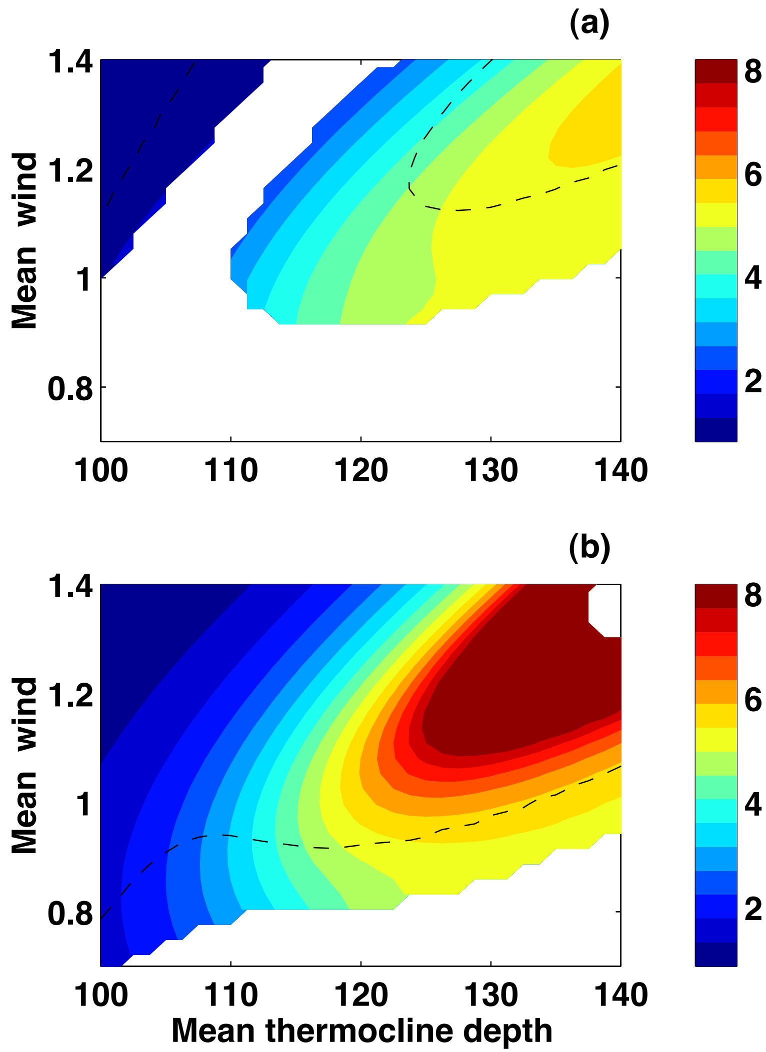
Simulated temperature trends in equatorial waters. The linear trends in the temperatures (°C rise per 100 years) are derived from a 240-year-long transient greenhouse warming simulation. The trends at the surface resemble the anomalous conditions observed during present-day El Niño. (after TIMMERMANN et al 1999)



Simulated sea-surface-temperature anomalies.
(after TIMMERMANN et al 1999)



Pacific Decadal Oscillation.



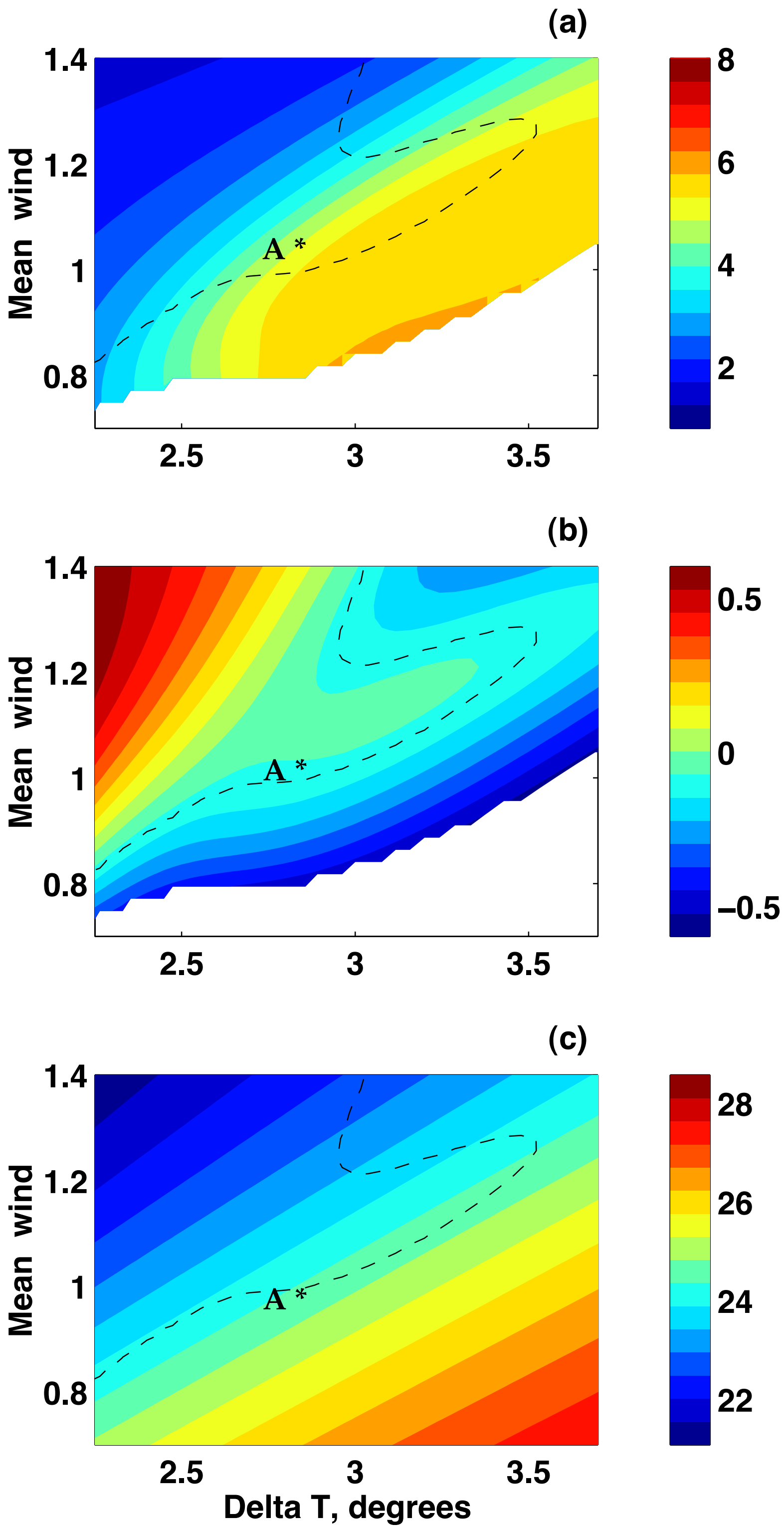
(a)
1.4
1.2
1
0.8
Mean wind
100
110
120
130
140
8
6
4
2
(b)
1.4
1.2
1
0.8
Mean wind
100
110
120
130
140
Mean thermocline depth
8
6
4
2

Hypothesis III:

III. The effect of global warming on El Niño is currently negligible.

Differences between El Niño events are explained by the chaotic (deterministic) dynamics of the coupled ocean-atmosphere in the tropics.

The decadal trends can be generated solely by these dynamics.


(a)
(b)
(c)
Mean wind
1.4
1.2
1
0.8
2.5
3
3.5
A *
8
6
4
2
0.5
0
−0.5
28
26
24
22
Delta T, degrees