ENSO Coupled Ocean-Atmosphere Dynamics and its Representation in Coupled Climate Models

Antonietta Capotondi

NOAA/ Physical Science Division

University of Colorado/Cires/CDC

Outline

- Review coupled ocean-atmosphere interactions associated with ENSO events

- Introduce simple dynamical models used to explain the oscillatory nature of ENSO (delayed and recharge oscillators)

- Examine how ENSO is represented in state-of-the-art climate models, with focus on the temporal structure of ENSO.

El Niño-Southern Oscillation (ENSO)

- Originally detected as an unusual warming (El Niño) or cooling (La Niña) of the ocean along the coast of Peru, occurring every 3-6 years during boreal winter.

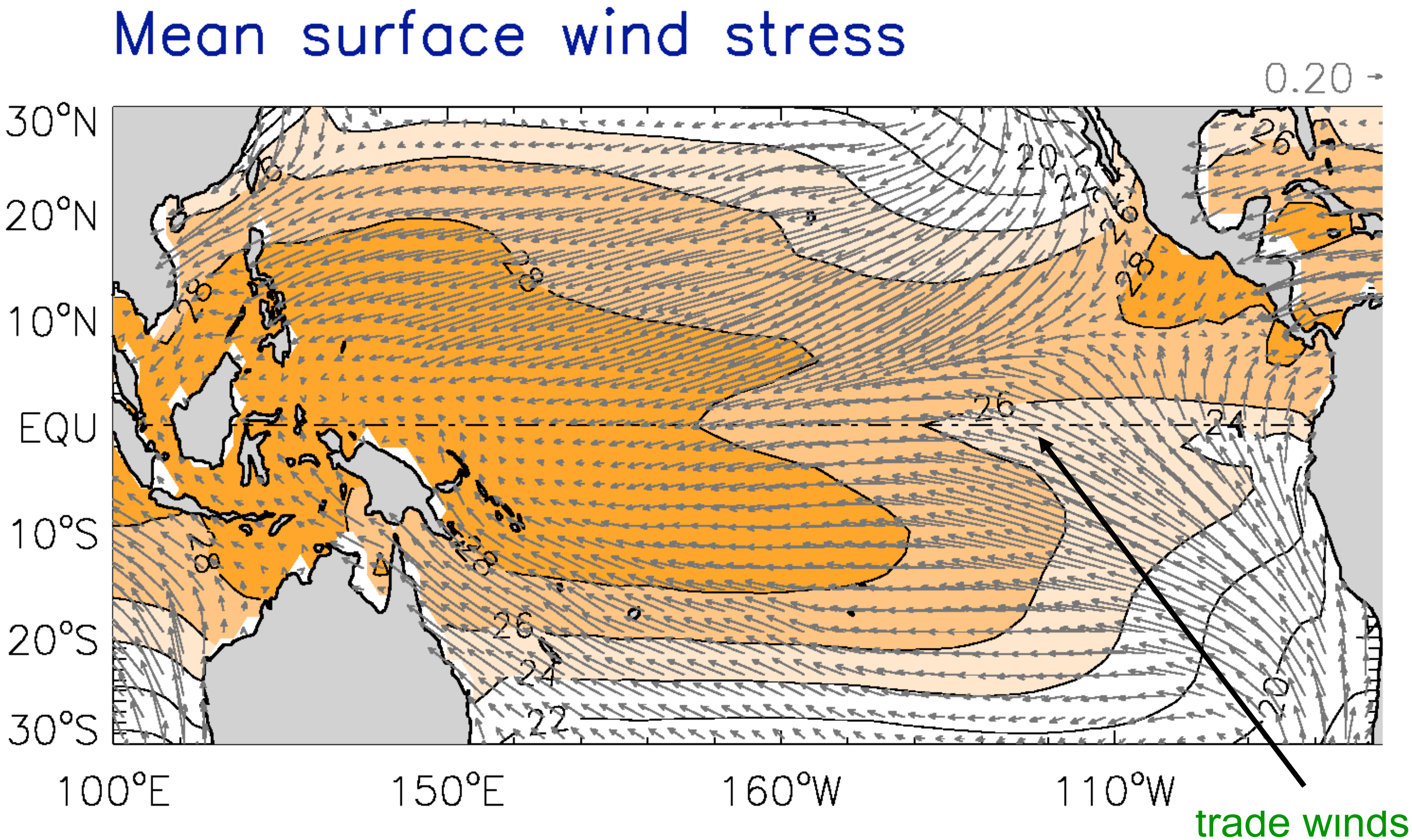
- Natural phenomenon in which the system oscillates between warmer-than-average to colder-than-average conditions.

El Niño-Southern Oscillation (ENSO)

- Warming of the surface water is associated with variations in precipitation, surface winds, and sea level pressure. The Southern Oscillation is the pressure difference (see-saw) between Tahiti and Darwin (central-western tropical Pacific) which varies during El Niño/La Niña events.

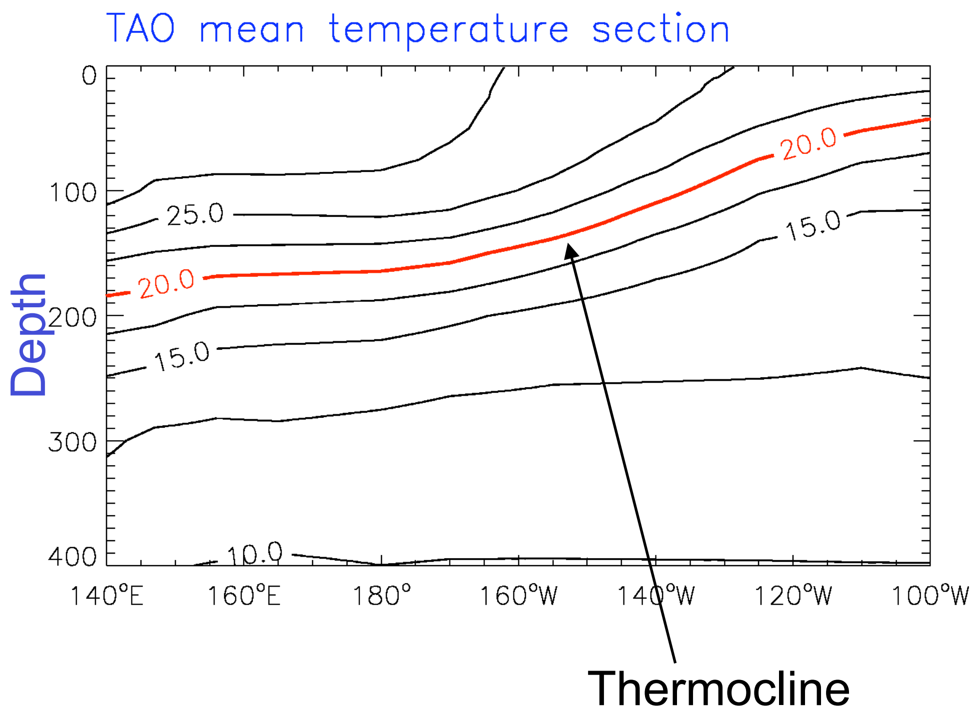
- ENSO is an ocean-atmosphere coupled phenomenon: changes in the ocean induce changes in the atmosphere, and the latter feed back to the ocean.

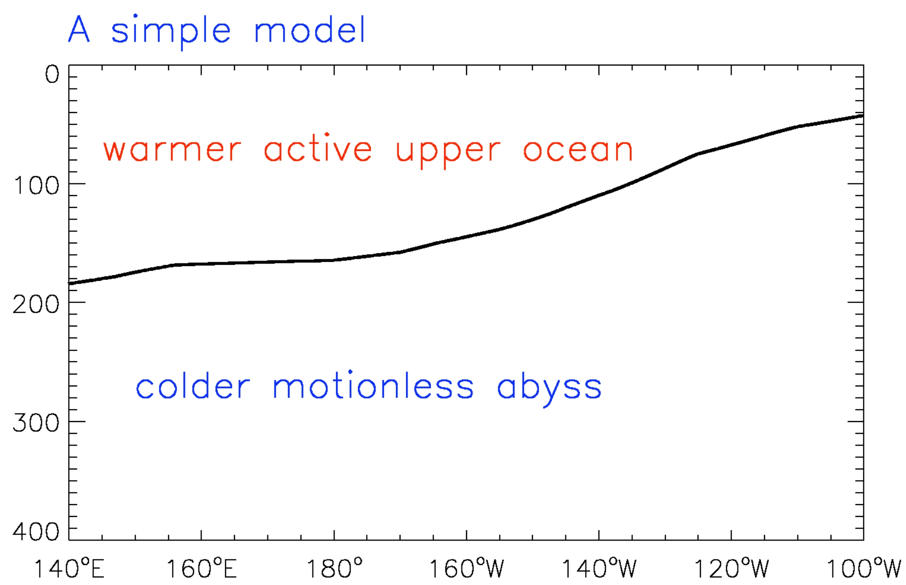
Tropical Pacific mean conditions



Vertical temperature section along the Equator

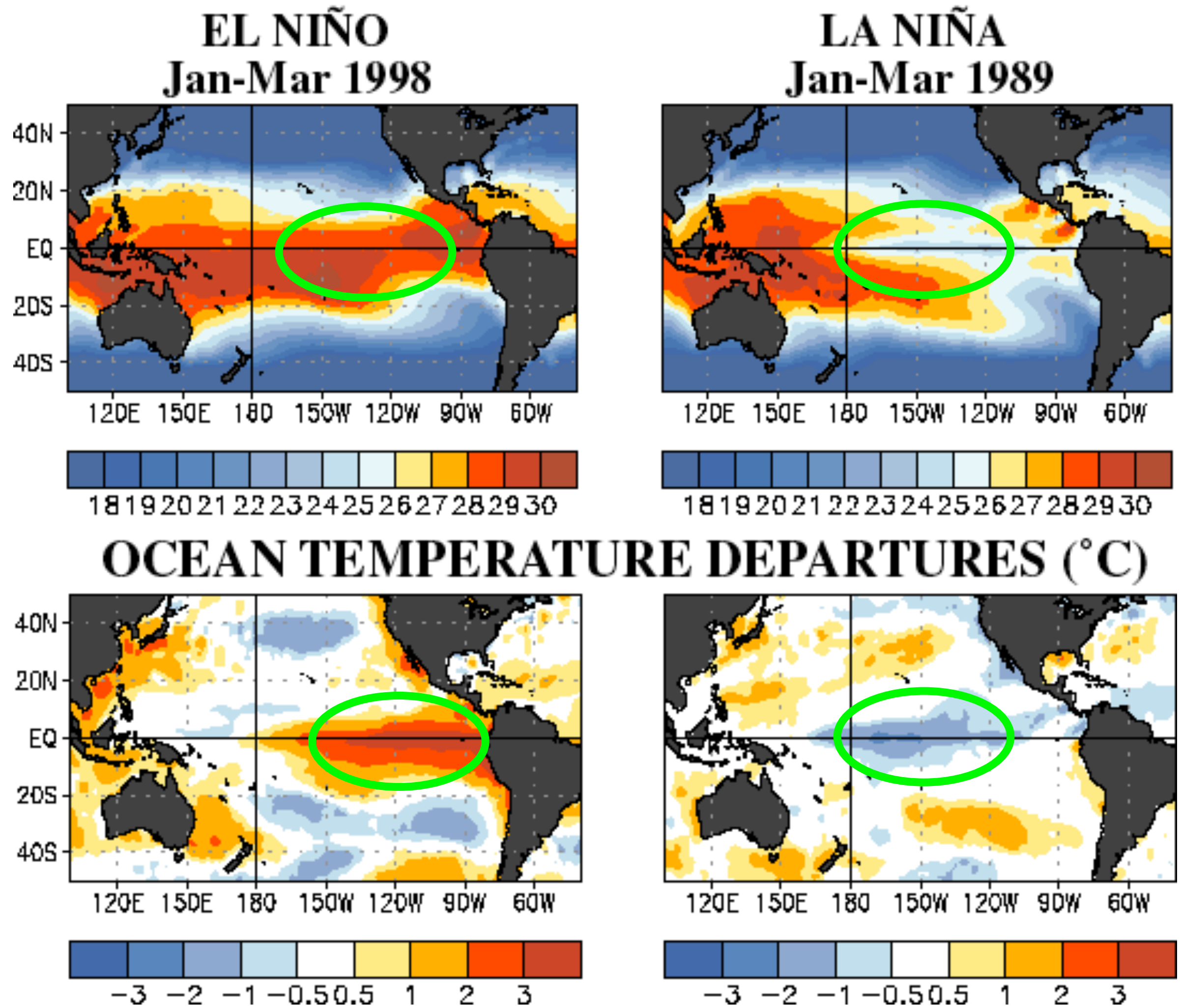
Tropical Atmosphere Ocean (TAO) data (1980-2000)





Sea Surface Temperatures

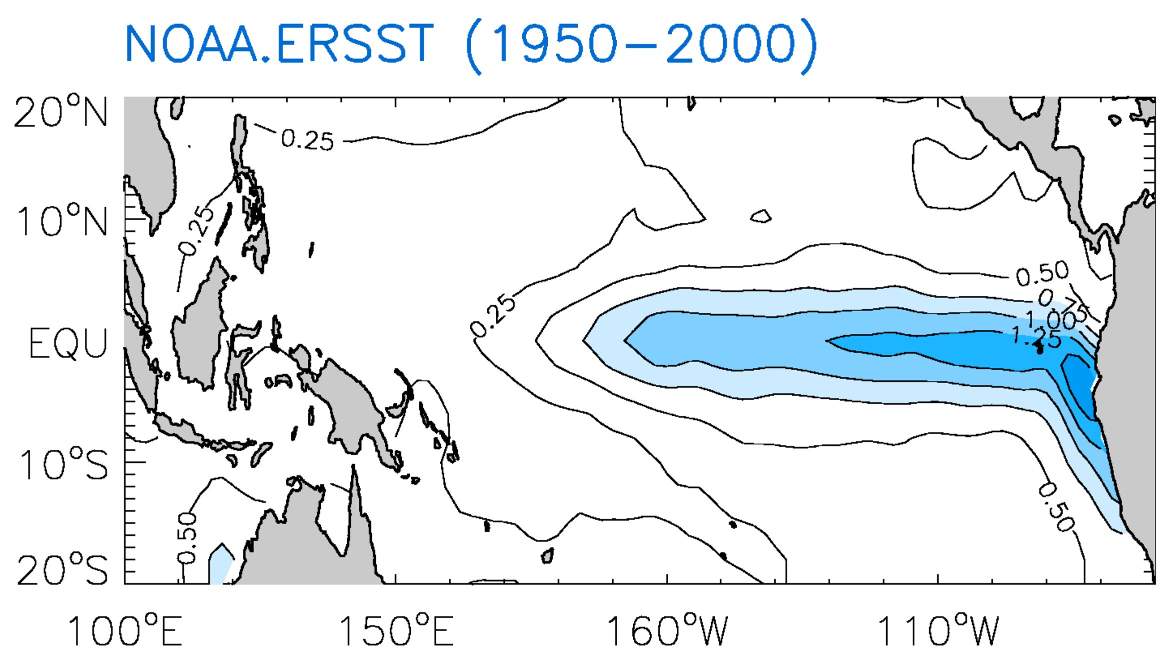
Equatorial cold tongue is weaker than average or absent during El Niño, resulting in positive SST anomalies



Equatorial cold tongue is stronger than average during La Niña, resulting in negative SST anomalies

Standard deviation of interannual SST anomalies

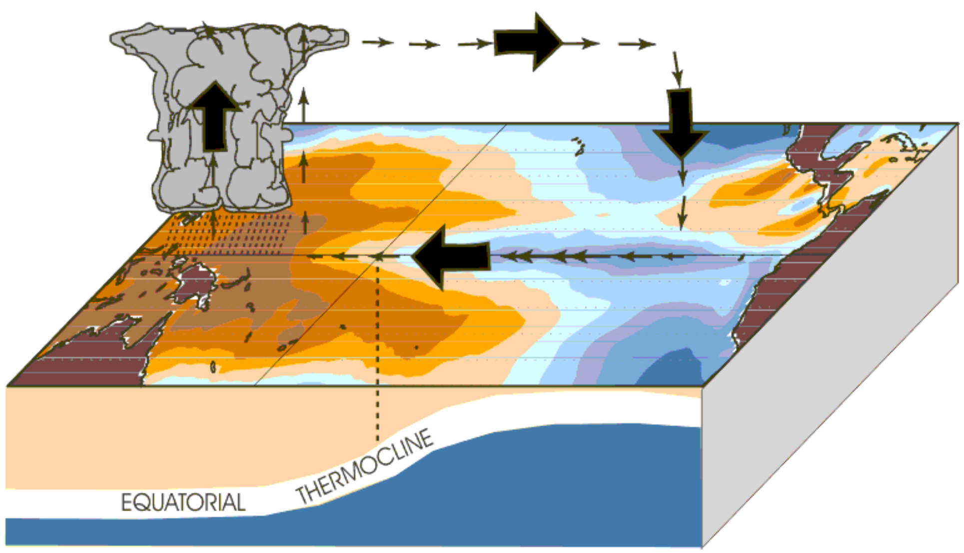
Standard deviation of x(t)= $\sqrt{\dfrac{\sum_{n=1}^{n=N}(x_i - \bar{x})^2}{N-1}}$



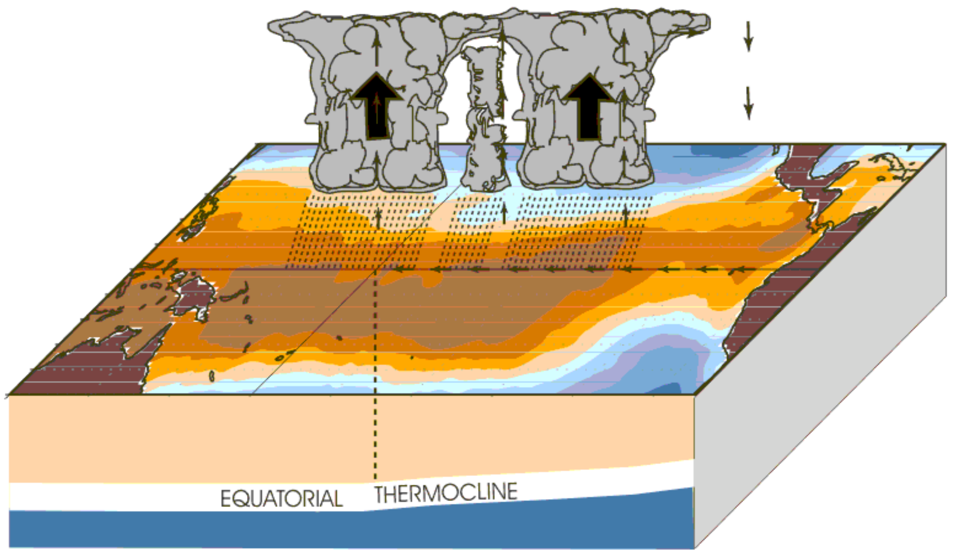
El Niño cycle

The changes in SST affect the distribution of tropical rainfall and atmospheric circulation features

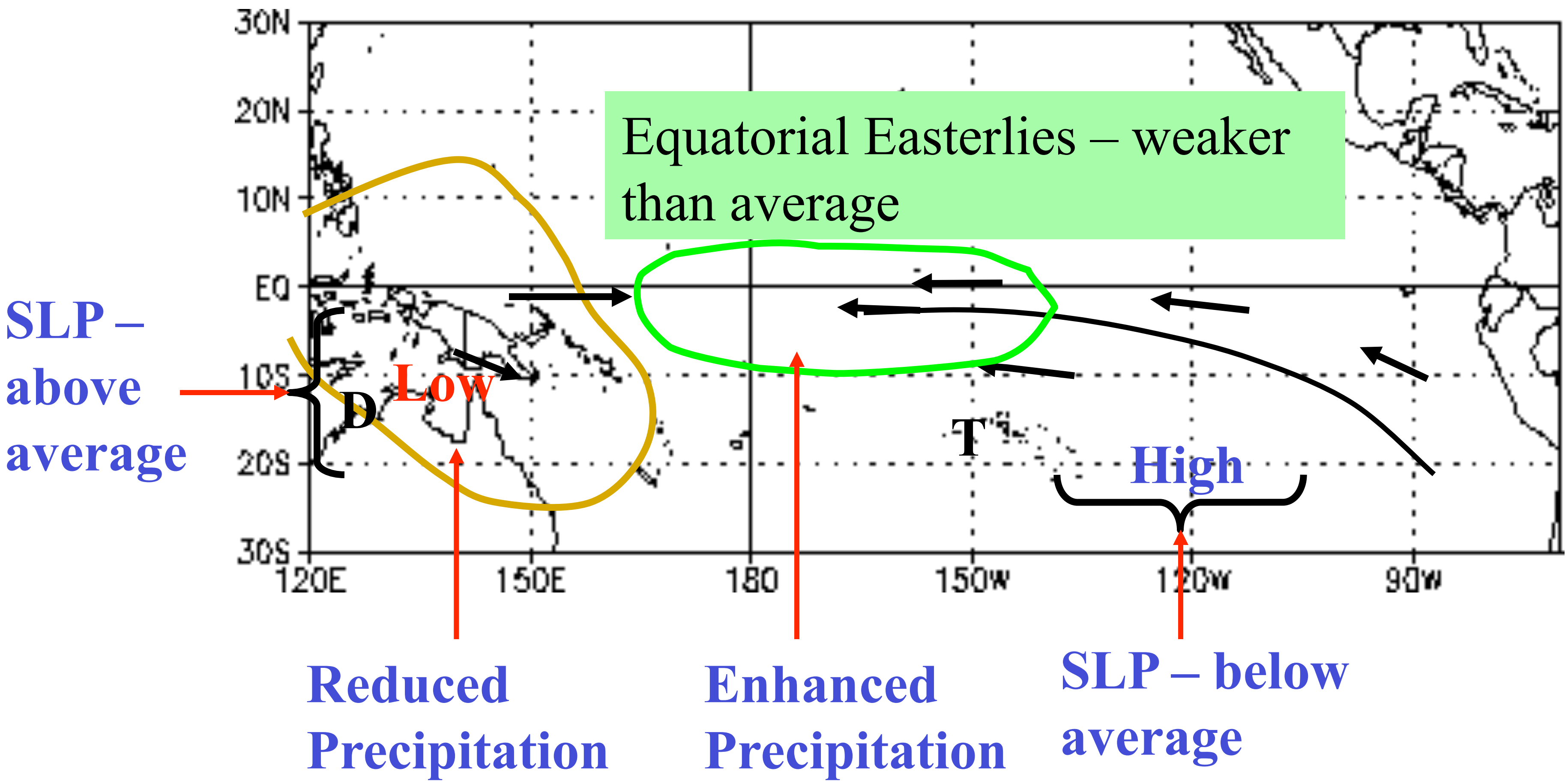
December - February La Niña Conditions



December - February El Niño Conditions



Southern Oscillation – Low Index Phase (El Niño)



Ocean adjustment to wind changes

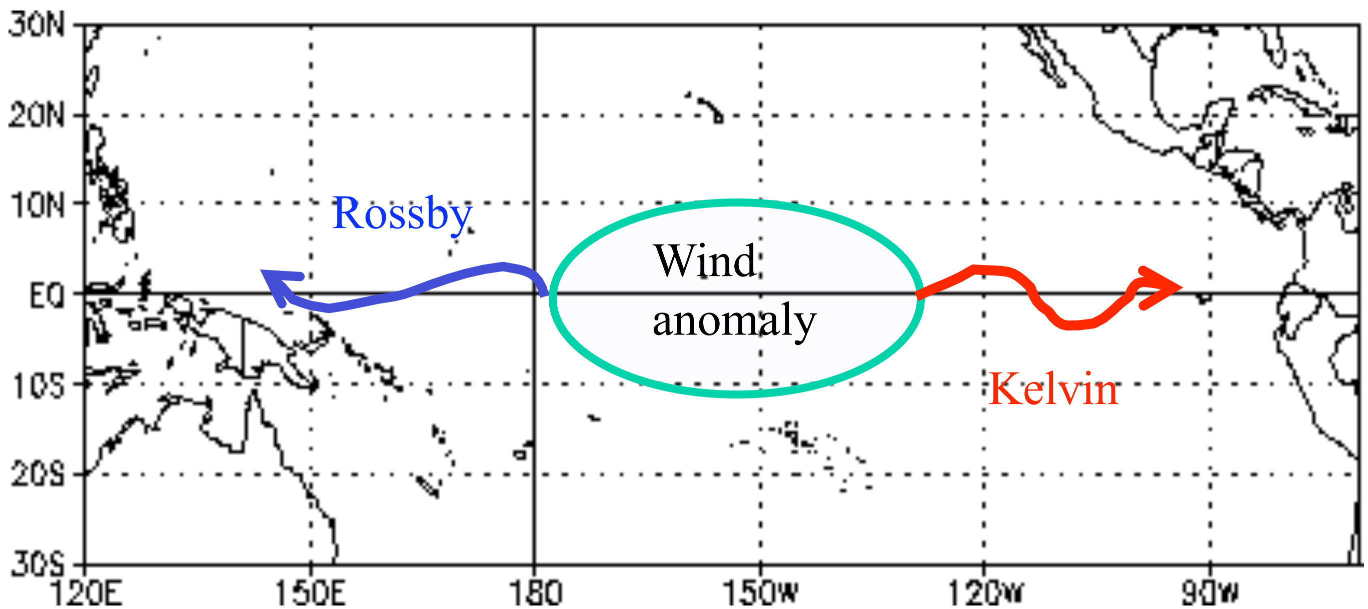
The ocean adjusts to wind changes through wave propagation: equatorial and extraequatorial (Rossby) waves.

Equatorial waves include:

•Kelvin waves. They propagate eastward along the equator

•Rossby waves. They propagate westward

Ocean adjustment

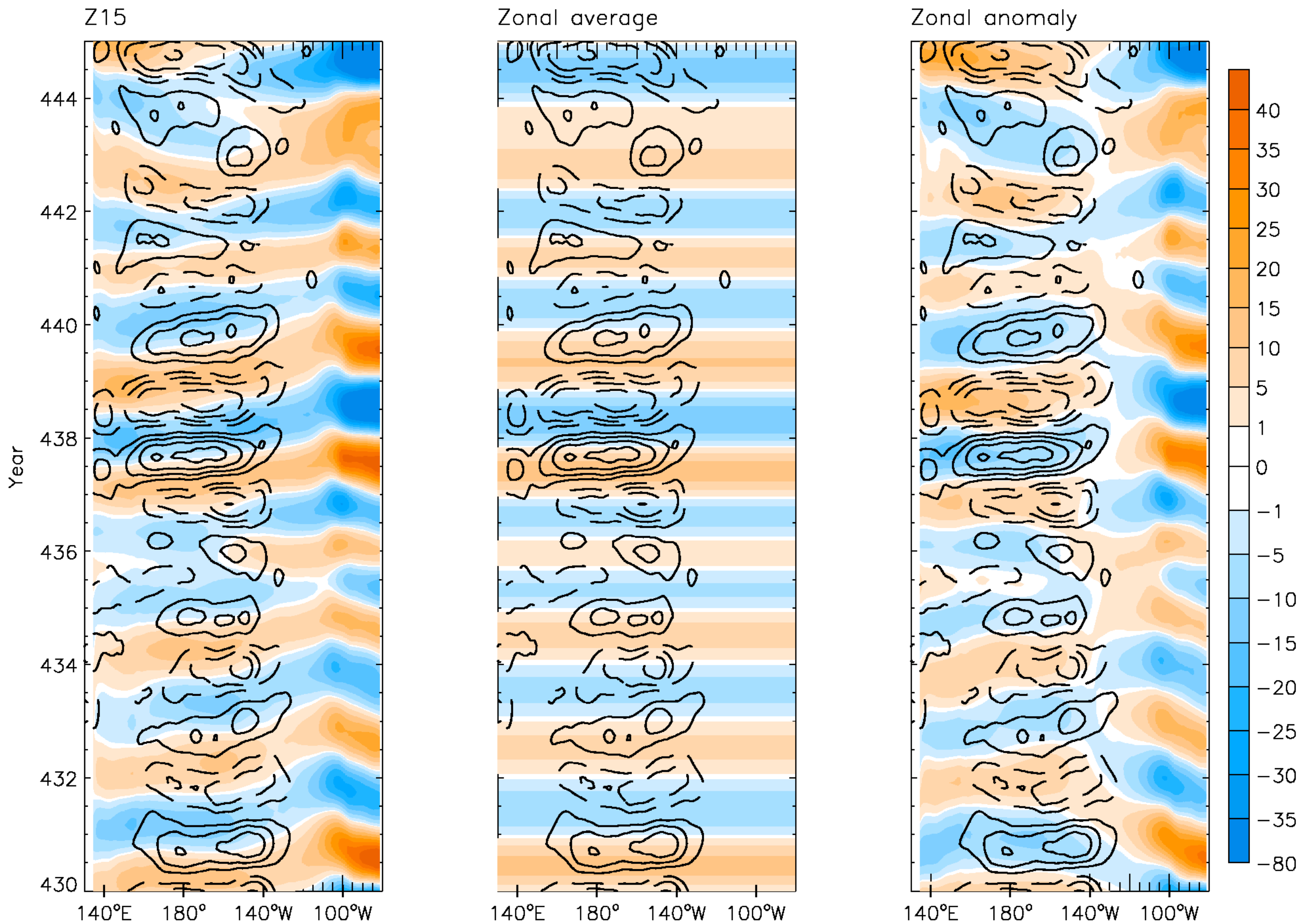


Kelvin waves propagate eastward from the area of wind anomalies and make the thermocline become deeper in the east. This is a positive feedback known as Bijerknes feedback.

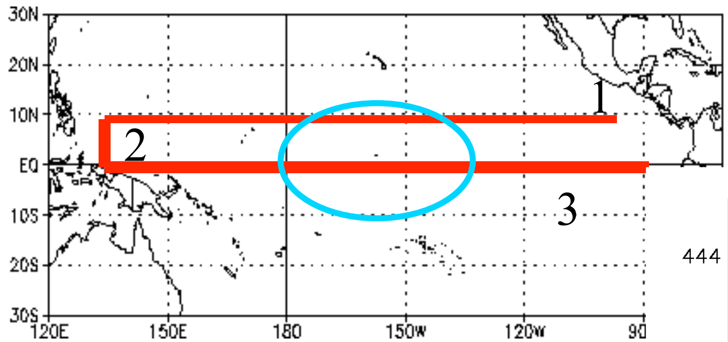
Rossby waves propagate westward, and reflect at the coast as eastward propagating Kelvin waves, providing a negative feedback.

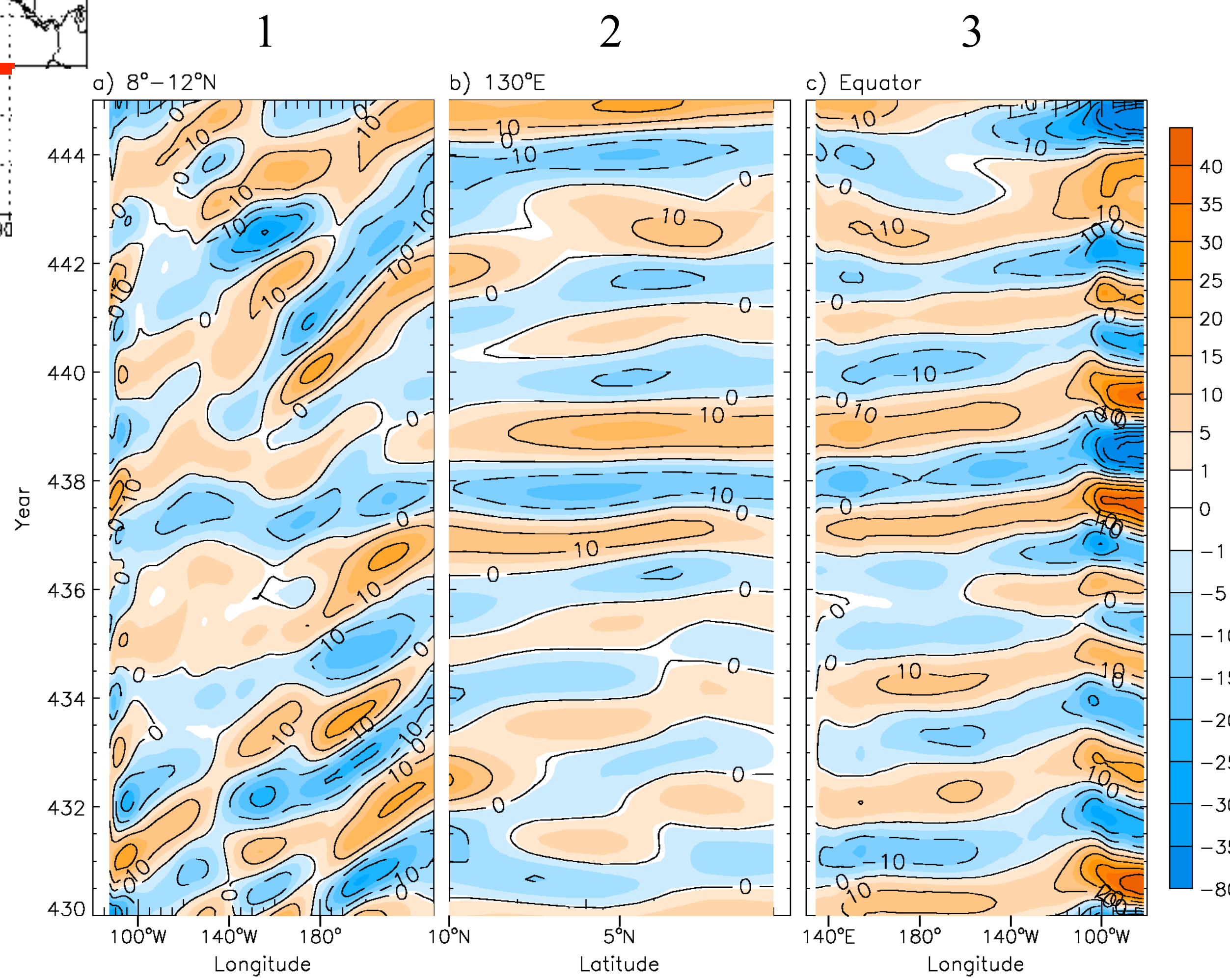
Ocean adjustment through wave propagation
The "delayed oscillator" paradigm

Evolution of thermocline depth along the equator

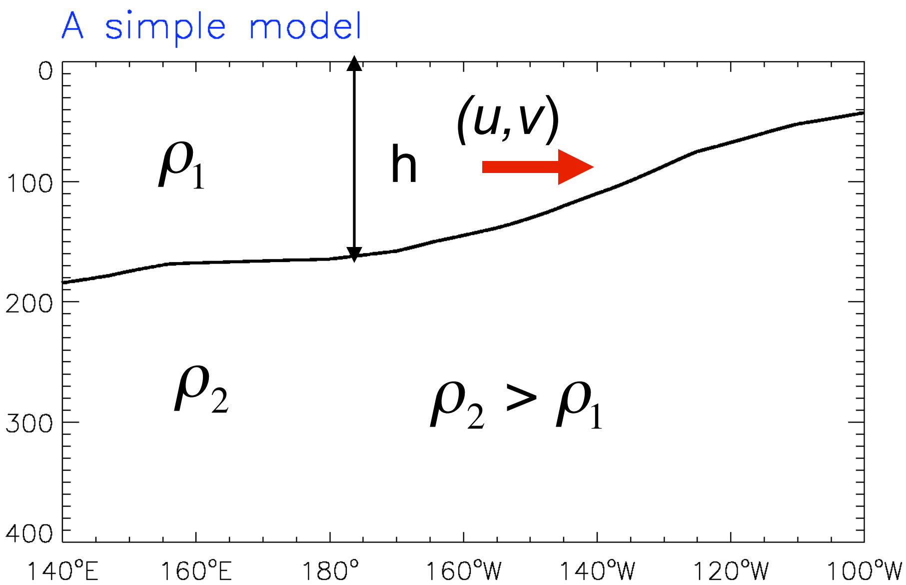


The "delayed oscillator" paradigm
The role of off-equatorial waves





The “reduced-gravity” model



Momentum equations:

$$\frac{\partial u}{\partial t} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} + F_x + D_x$$

$$\frac{\partial v}{\partial t} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} + F_y + D_y$$

p = pressure, F=forcing,D=dissipation
ρ=mean density, f=Coriolis paarameter

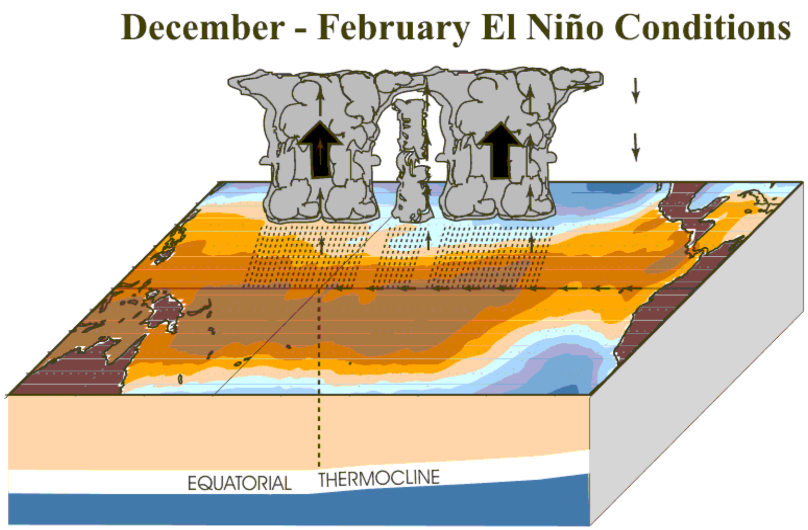
$$p = \frac{g'}{\rho}h \qquad g' = \frac{\rho_2 - \rho_1}{\rho}g$$

$$v = \frac{g'}{f}\frac{\partial h}{\partial x}$$

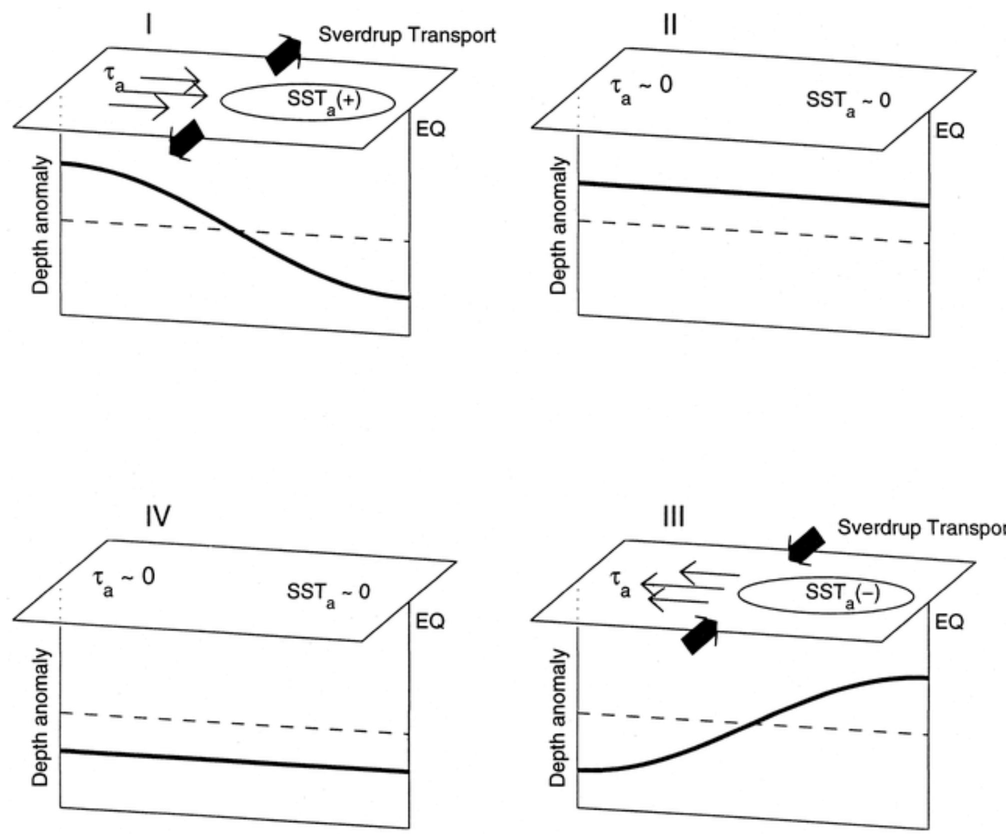
Continuity equation:

$$\frac{\partial h}{\partial t} = -\bar{h}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)$$

The "recharge oscillator": A simple paradigm for the El Niño cycle

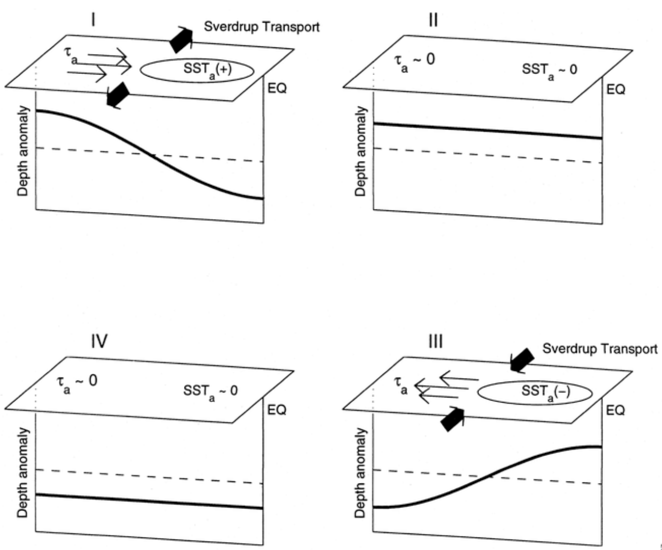


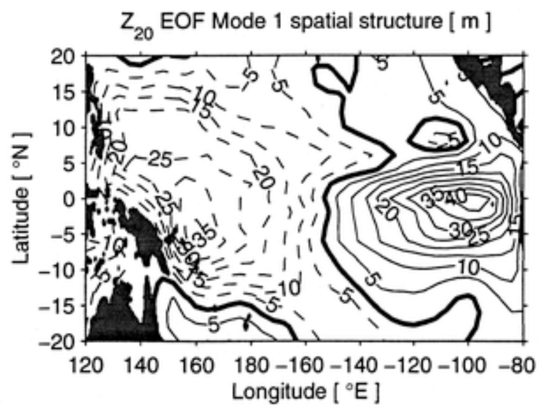
$$v = \frac{g'}{f} \frac{\partial h}{\partial x}$$

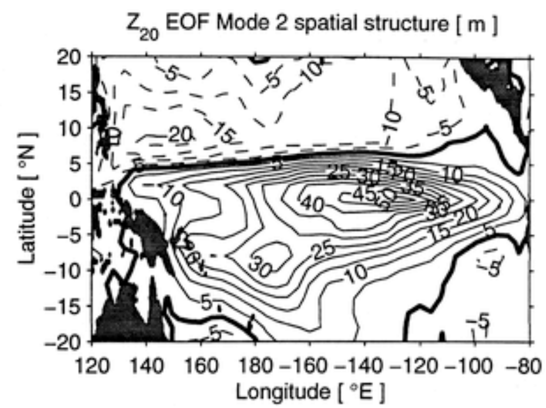


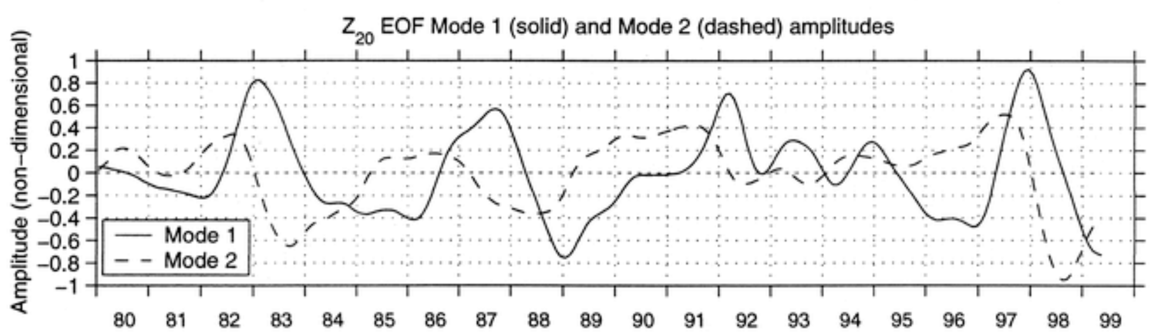
Does the real ocean behave as a “recharge oscillator”?

Empirical orthogonal function analysis of subsurface temperature data (Meinen and McPhaden 2000)









Models

- CCSM3 (USA)
- GFDL-CM2.0 (USA)
- GISS-EH (USA)
- PCM (USA)
- IPSL-CM4 (France)
- CNRM-CM3 (France)
- UKMO-HadCM3 (UK)
- MRI-CGCM2.3.2 (Japan)
- CSIRO-CM3 (Australia)

Models have different grids and resolutions for both oceanic and atmospheric components.

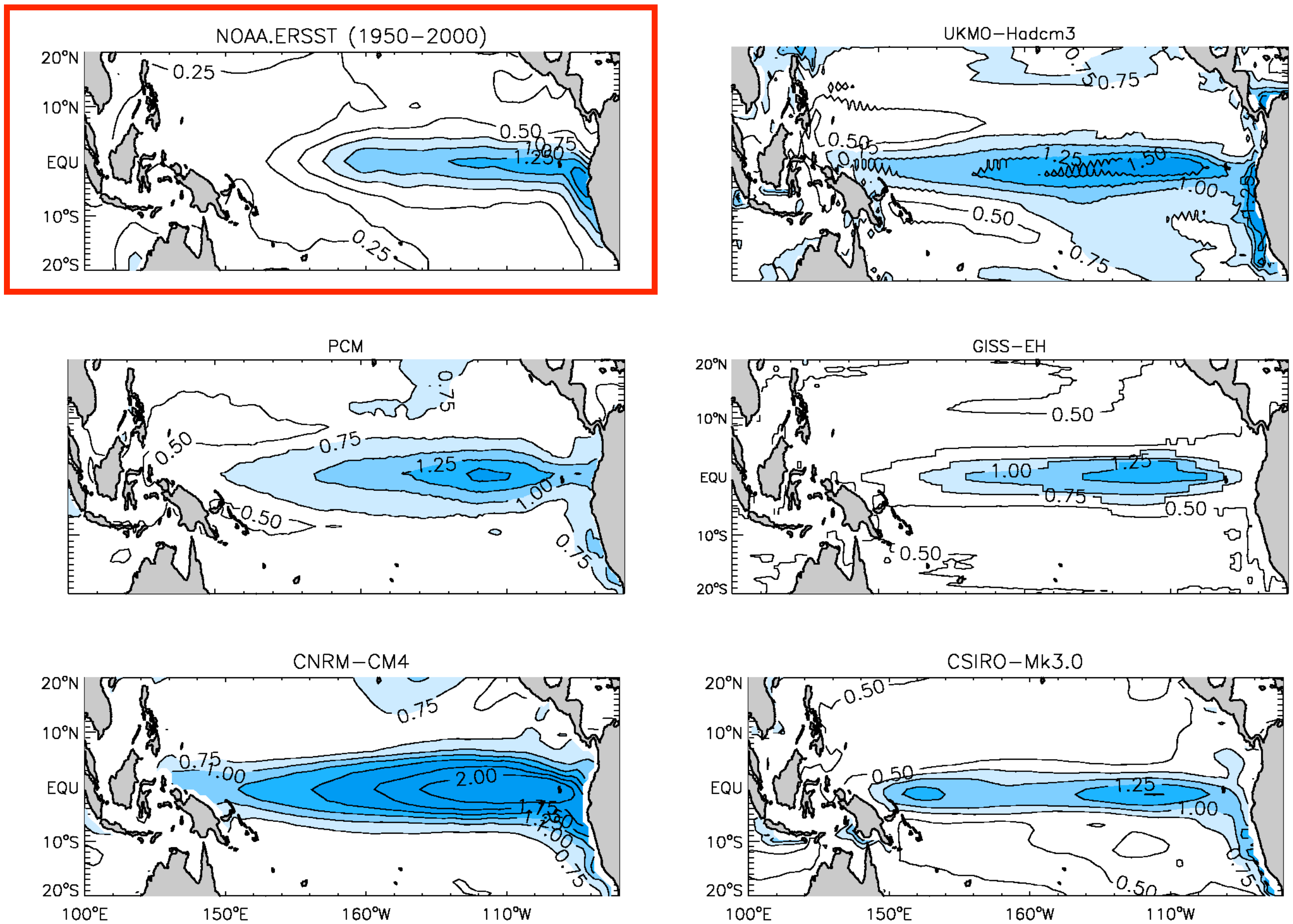
Ocean analyses:

- GFDL/ARCs (1980-2000)
- INGV (1958-2000)

ENSO in coupled climate models

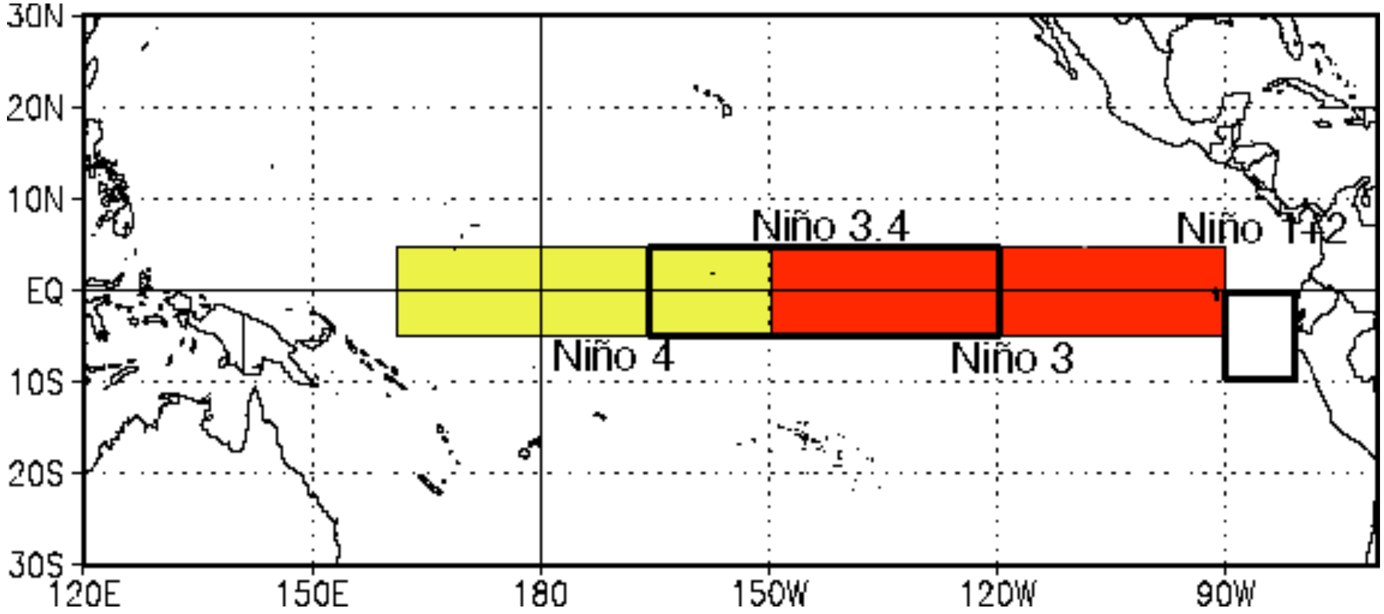
SST standard deviations

Observations



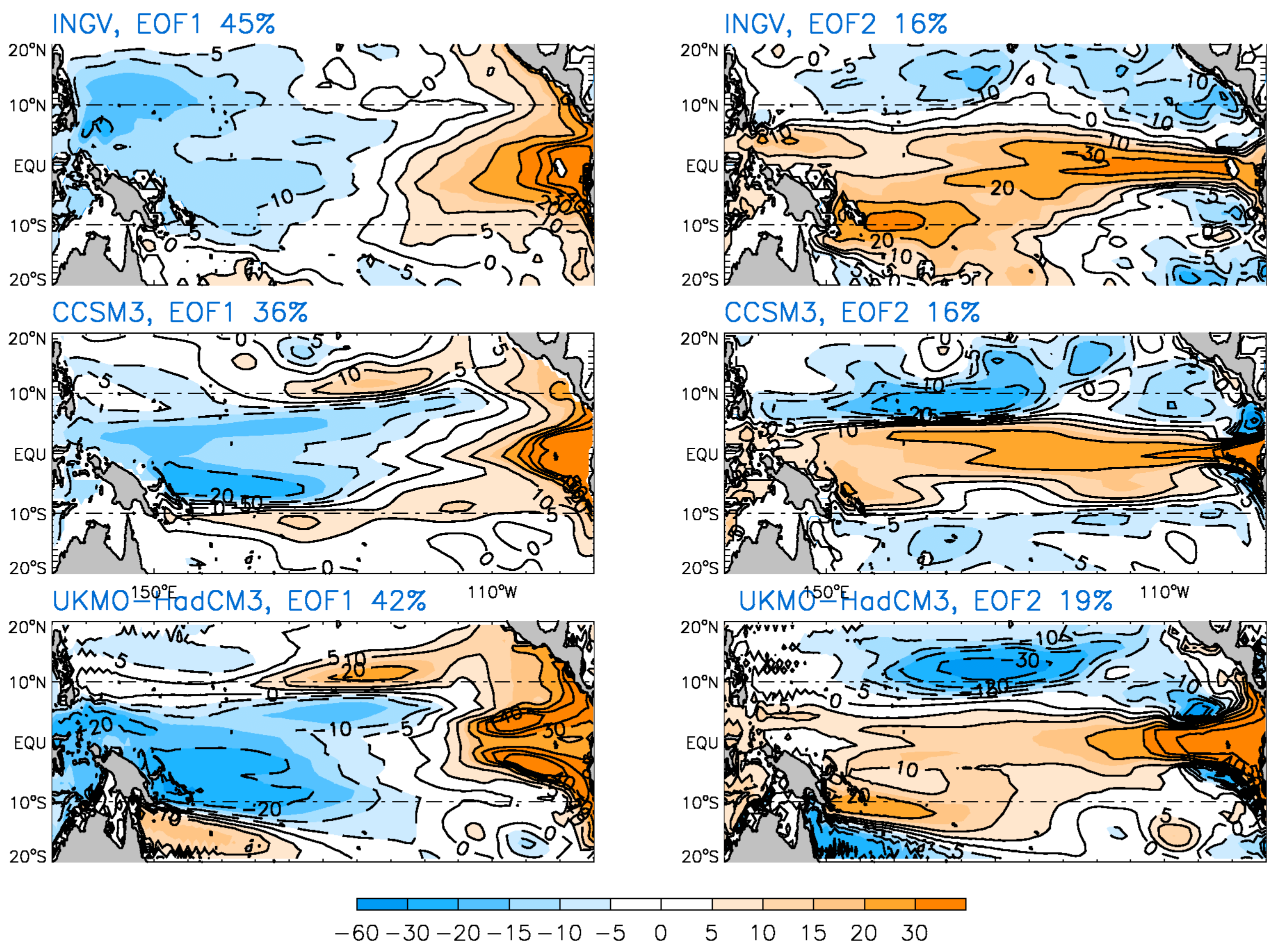
All the models have SST variations which are displaced too further west. Some models have very little variations along the eastern coast.

Niño Regions



Are the models "recharge oscillators"?

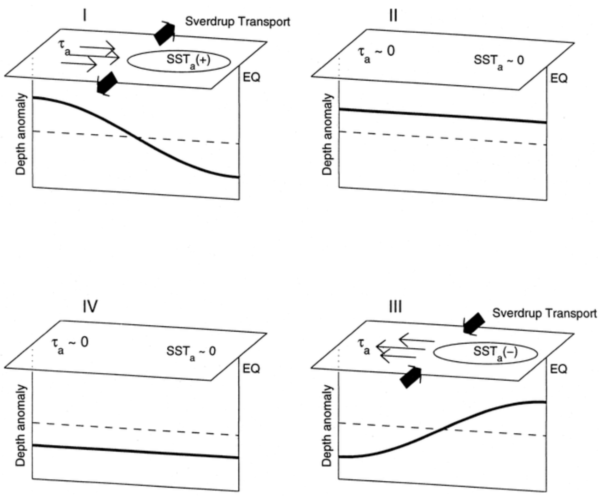
EOFs of thermocline depth



Ocean analysis

1958-2000

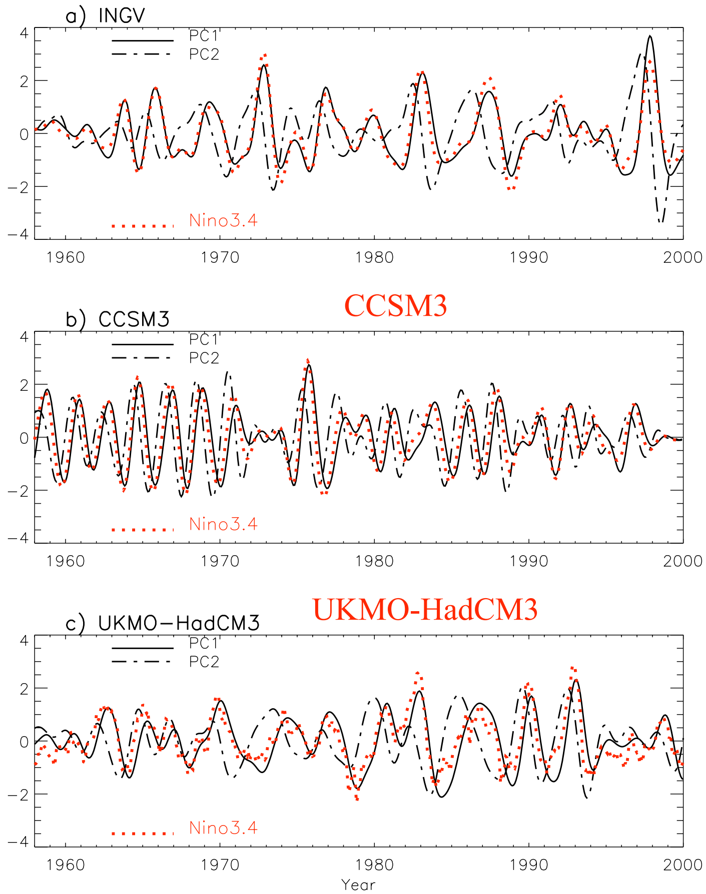
Phase relationship between the Z15 modes



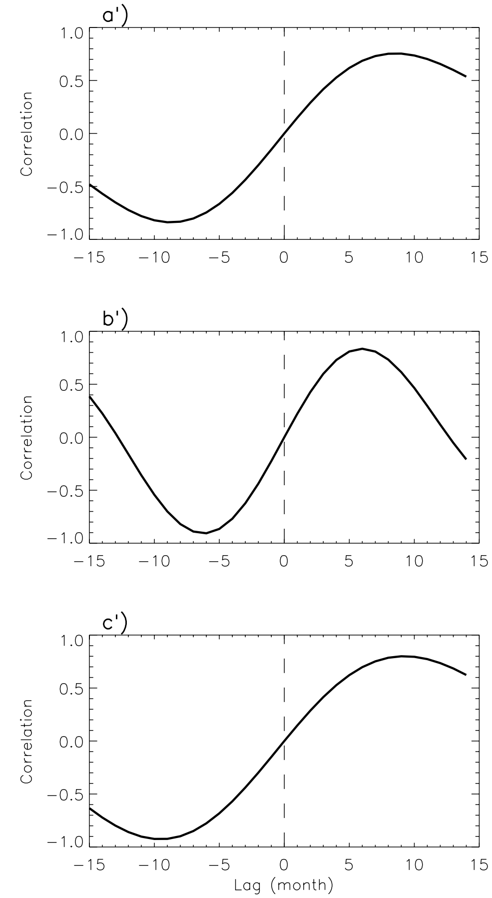
INGV

CCSM3

UKMO-HadCM3



PC2-PC1 lag-correlation

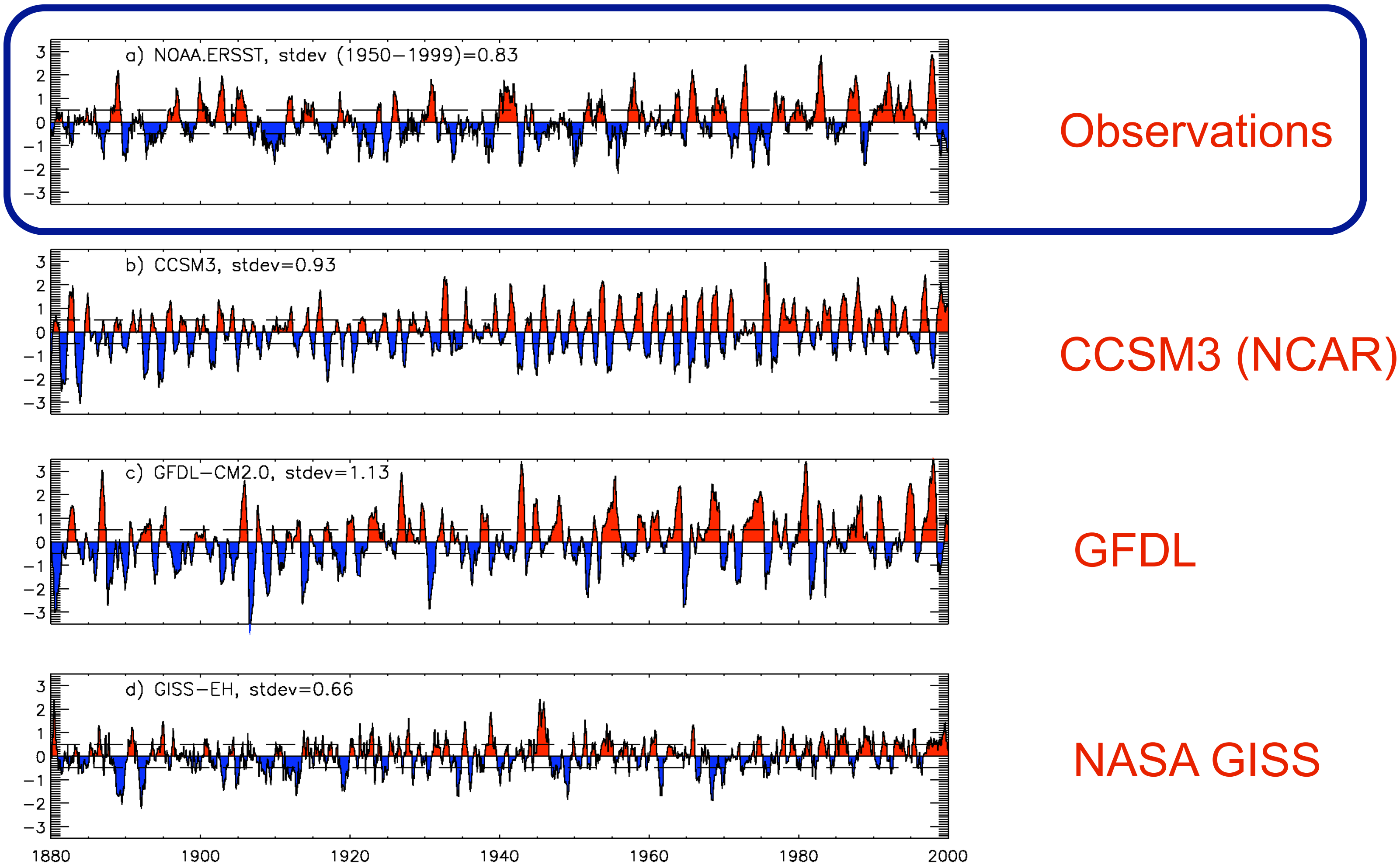


PC1 leads PC2

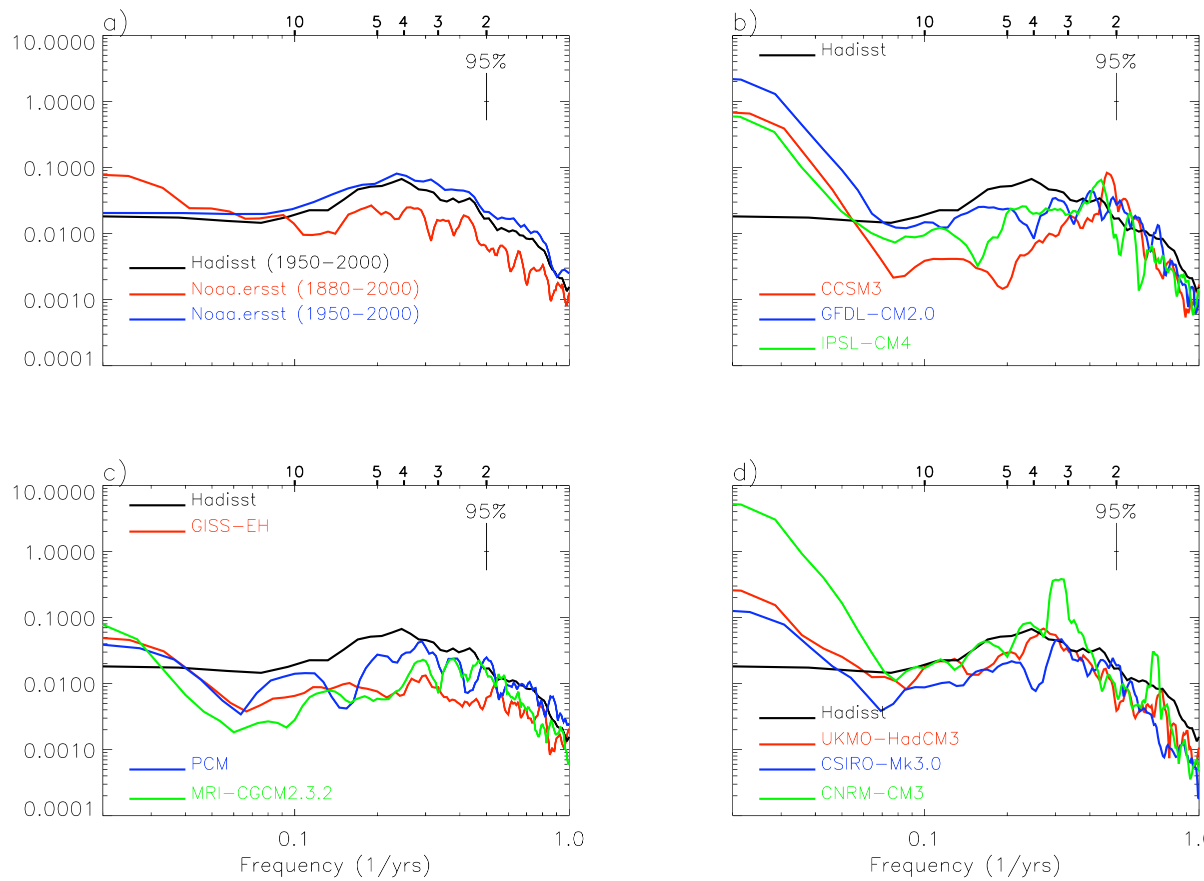
PC1 lags PC2

ENSO in coupled climate models 2

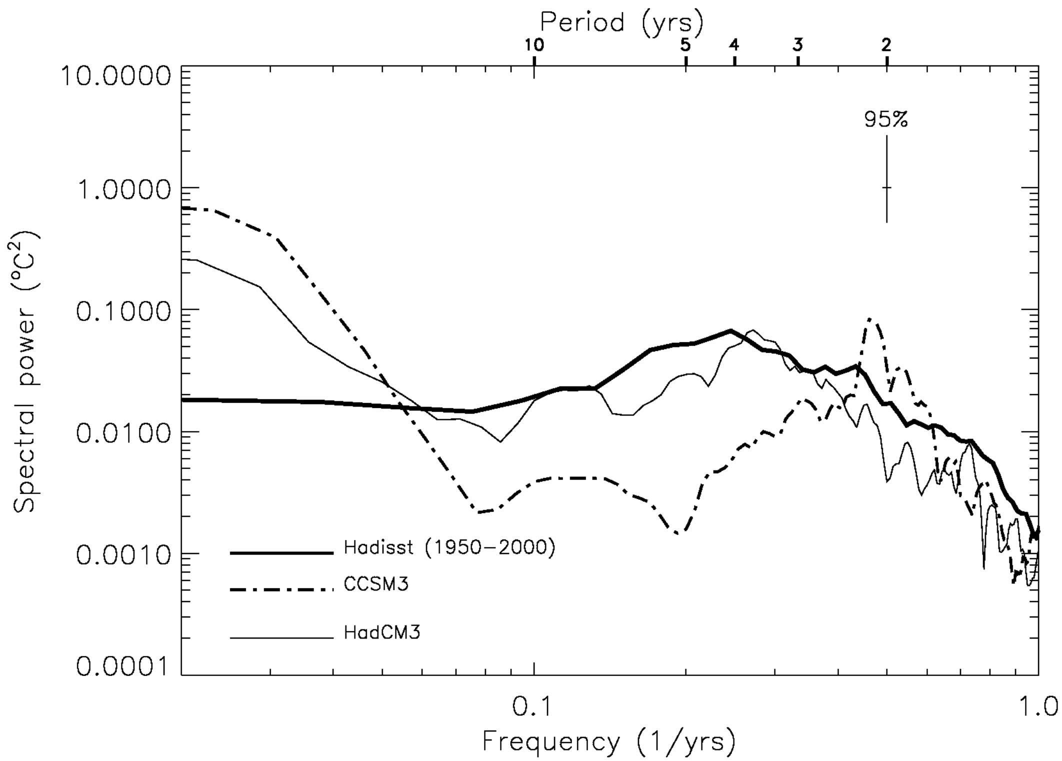
Evolution of the Niño3.4 index



Spectral characteristics
Nino3.4 index (5°S-5°N, 170°W-120°W)



Comparison of CCSM3 and HadCM3



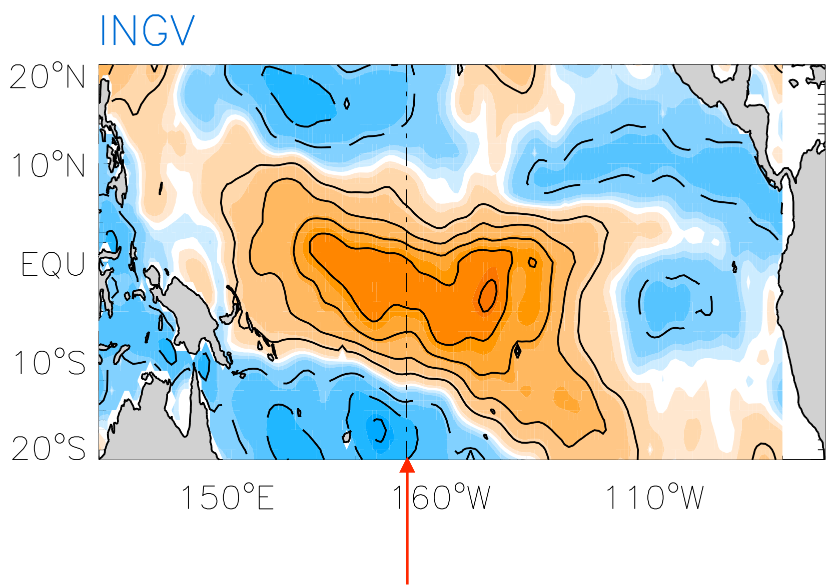
Wind forcing

Studies performed with intermediate coupled models (Kirtman et al. 1997, An and Wang 2000) have shown that the spatial structure of the wind stress anomalies can influence the ENSO timescale (see also Wittenberg et al. 2005, Deser et al. 2005).

- Meridional width of the wind stress anomalies: if the wind stress extends over a broader range of latitudes the adjustment timescale of the equatorial ocean increases.

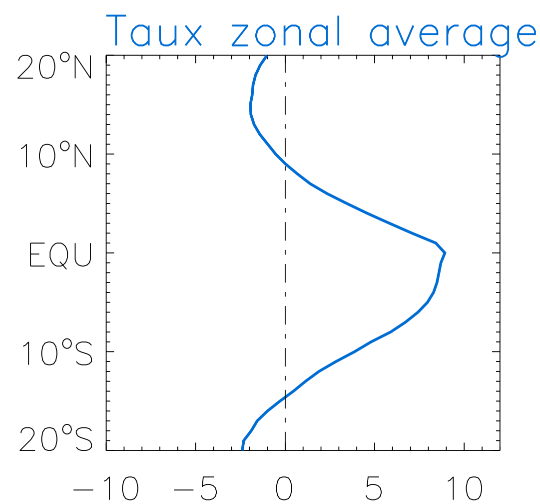
- Longitudinal position of the wind stress anomalies: it influences the zonal advective feedback. Eastward displacement of the wind stress anomalies favors ENSO growth and longer duration.

Regression of τ^x upon the Niño3.4 index
NCEP/NCAR Reanalyses

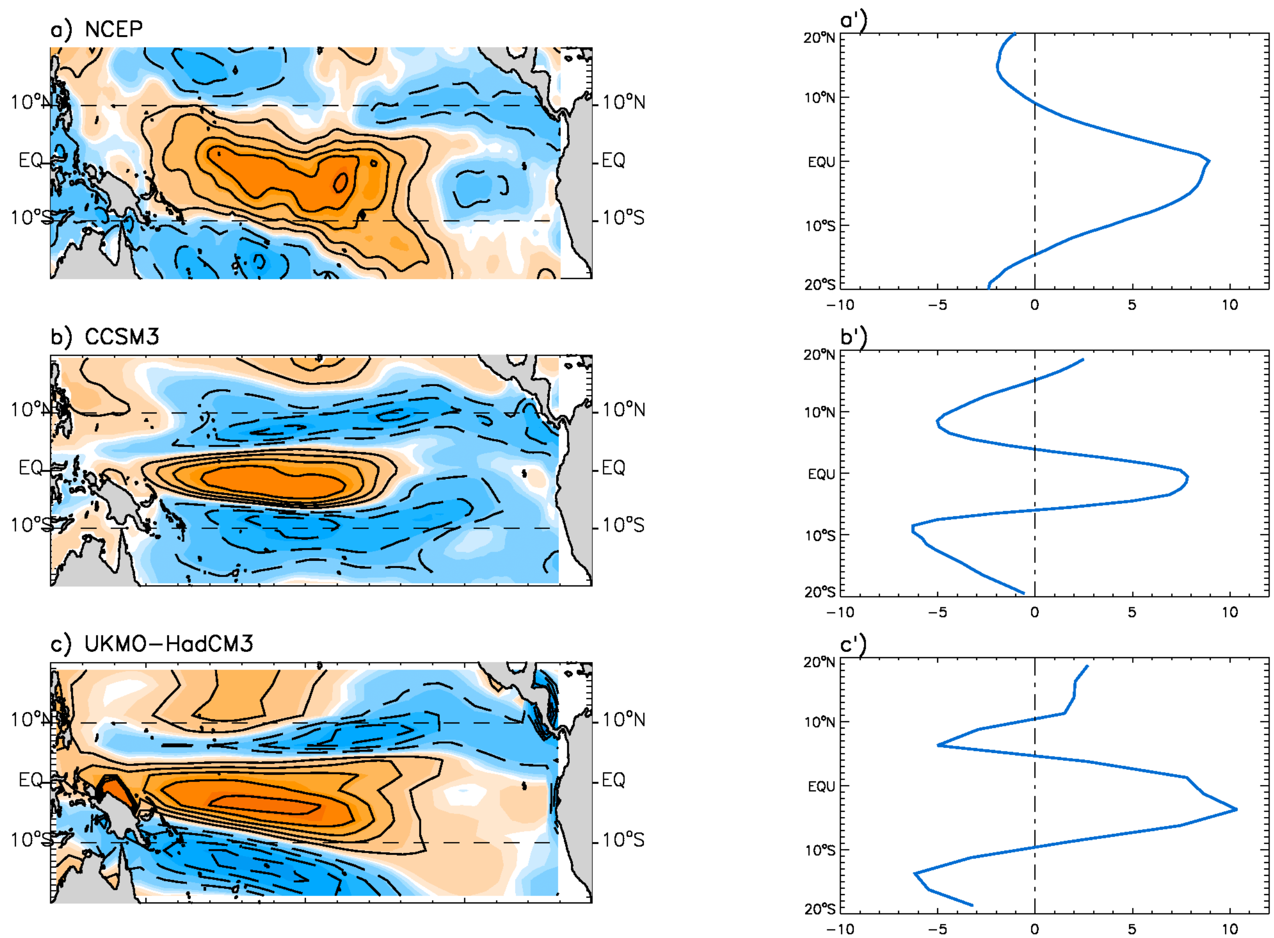


‘Center of mass’ of τ'_x

168°W

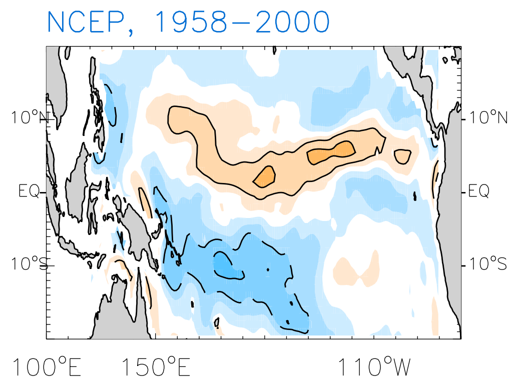


Regression of zonal wind stress

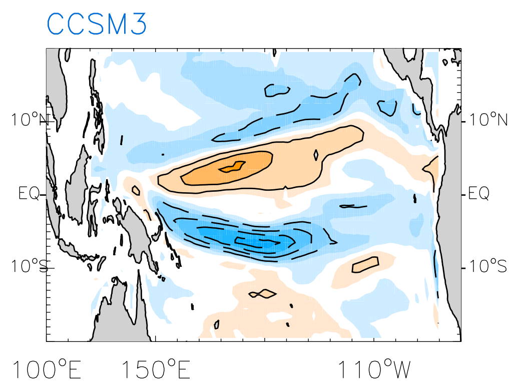


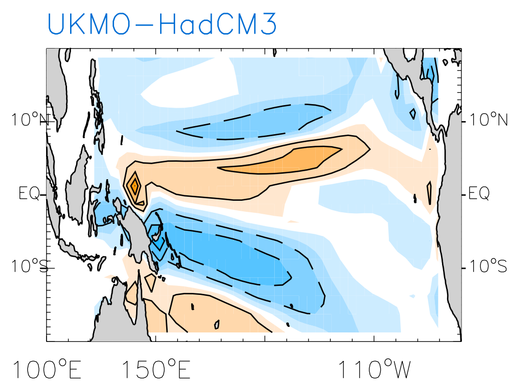
Influence of meridional width of τ_x

Regression of the curl(τ) upon the Nino3.4 index

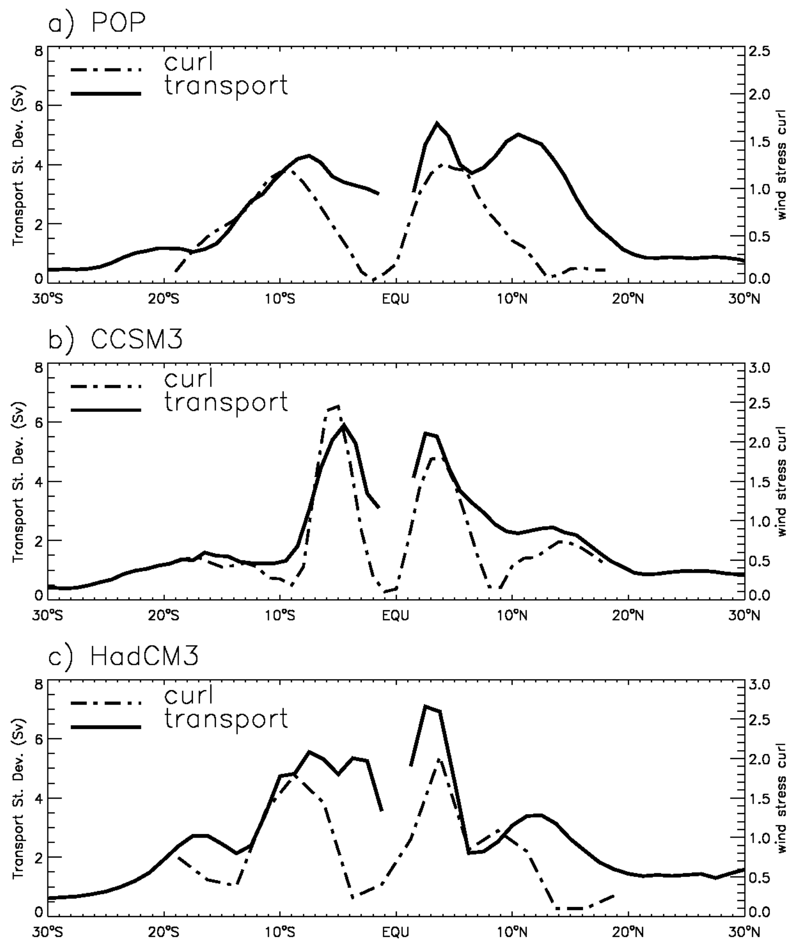


$$curl(\tau) = \frac{\partial \tau_x}{\partial y} - \frac{\partial \tau_y}{\partial x}$$





Relationship between thermocline transport and wave dynamics



Conclusions

- The representation of ENSO in the coupled climate models has considerably improved in the last generation of models.
- Inaccuracies in the representation of ENSO include spatial structure of the variability, as well as its temporal evolution. In the models, ENSO events tend to occur too frequently and too regularly than in nature.
- Wind stress forcing in the CGCMs has a narrower meridional scale and is displaced westward compared to observations. Both factors can lead to a shorter timescale for ENSO.

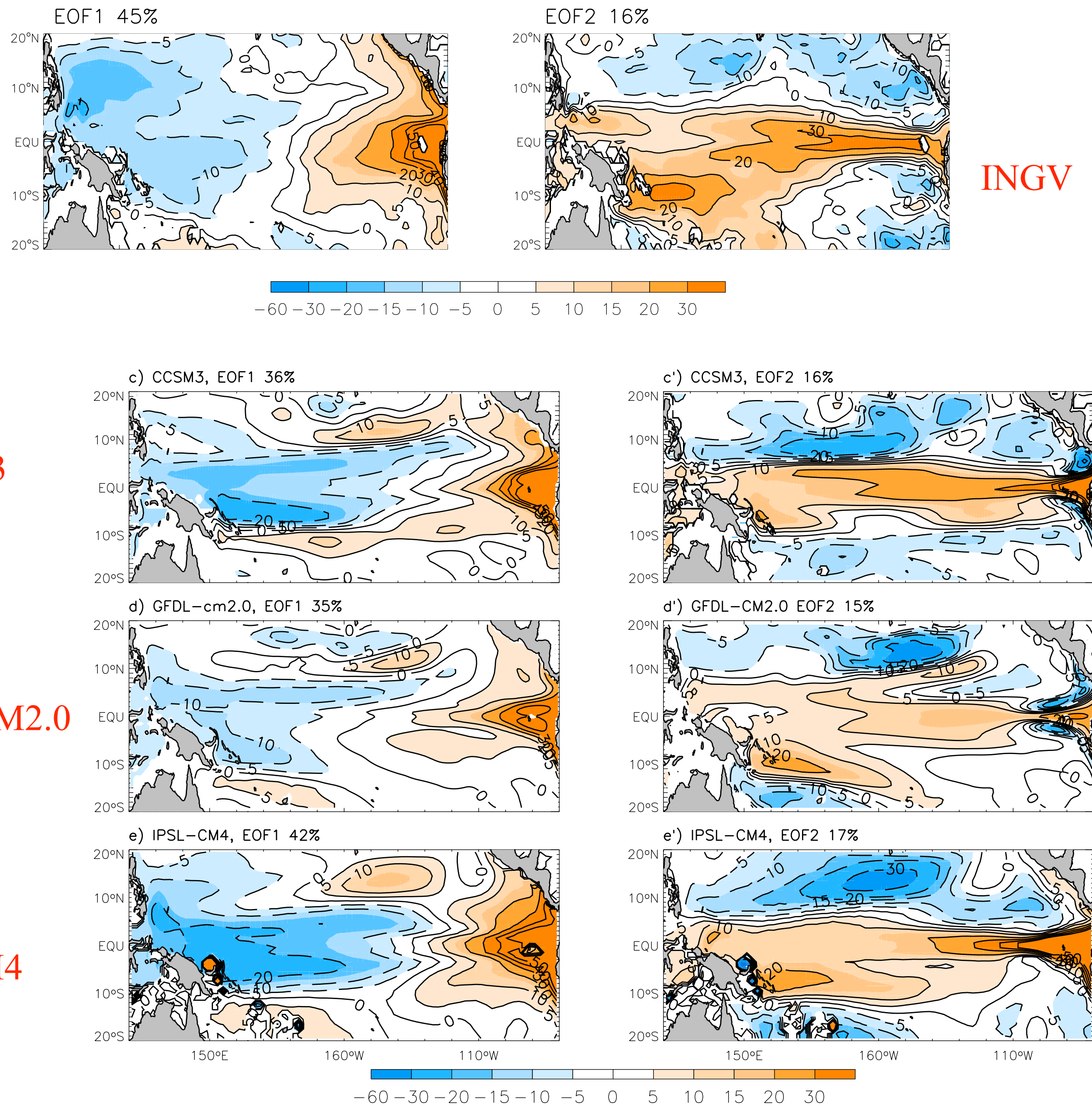
EOFs of Z15

INGV

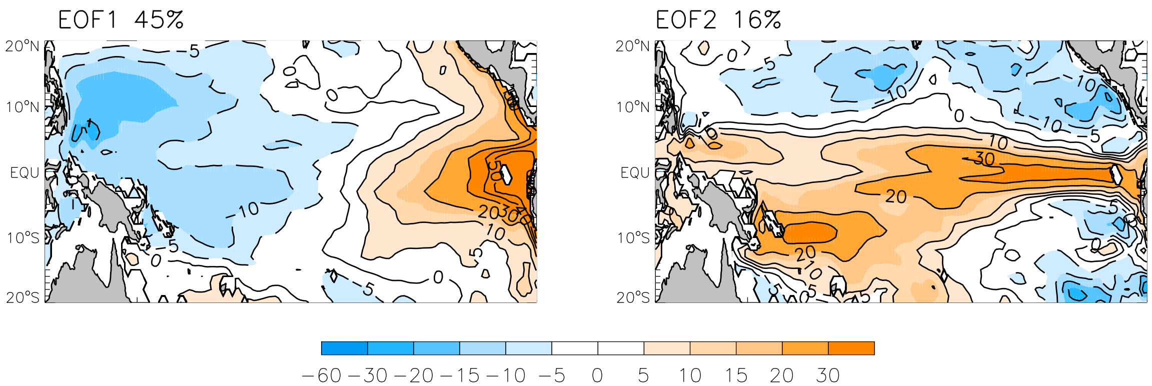
CCSM3

GFDL-CM2.0

IPSL-CM4



EOFs of Z15

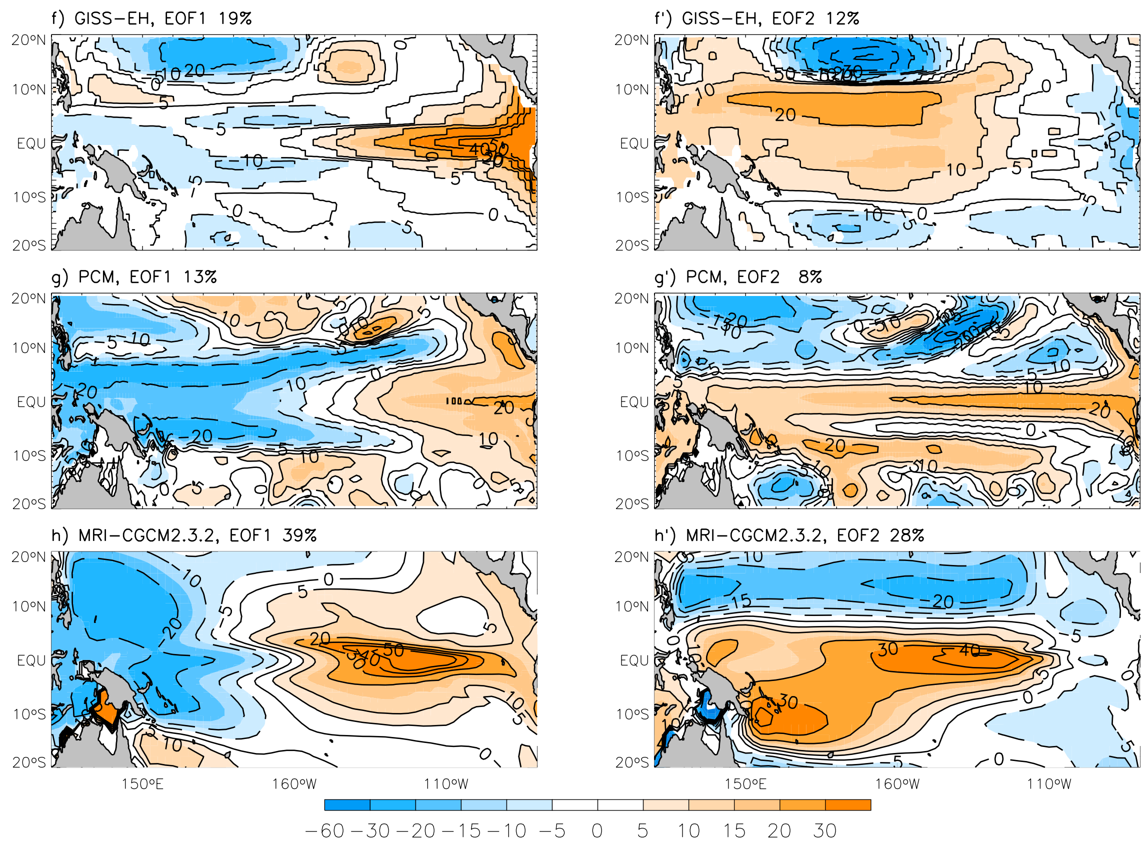


INGV

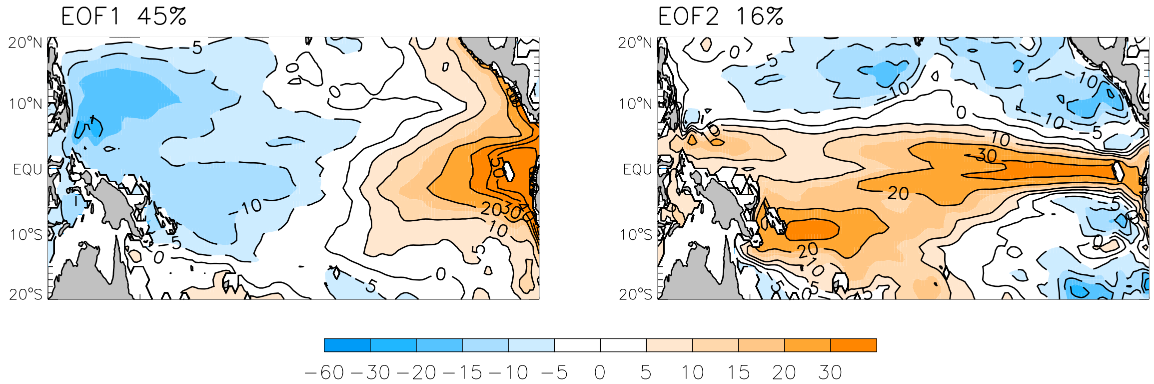
GISS-EH

PCM

MRI



EOFs of Z15

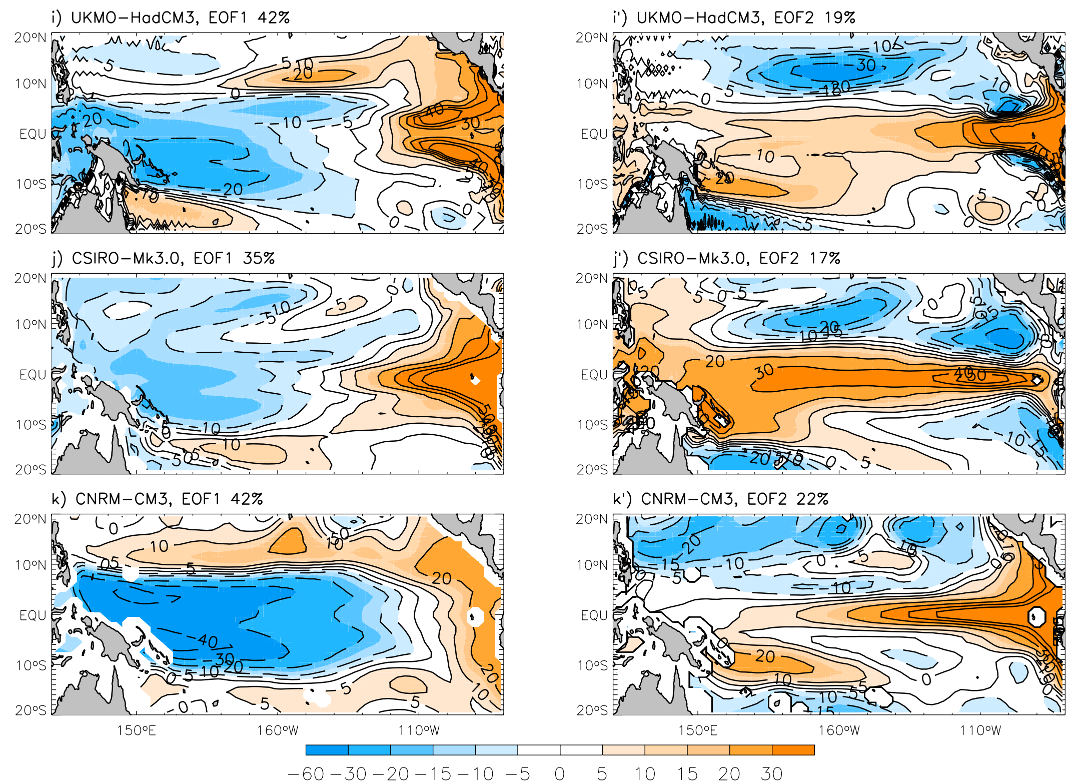


INGV

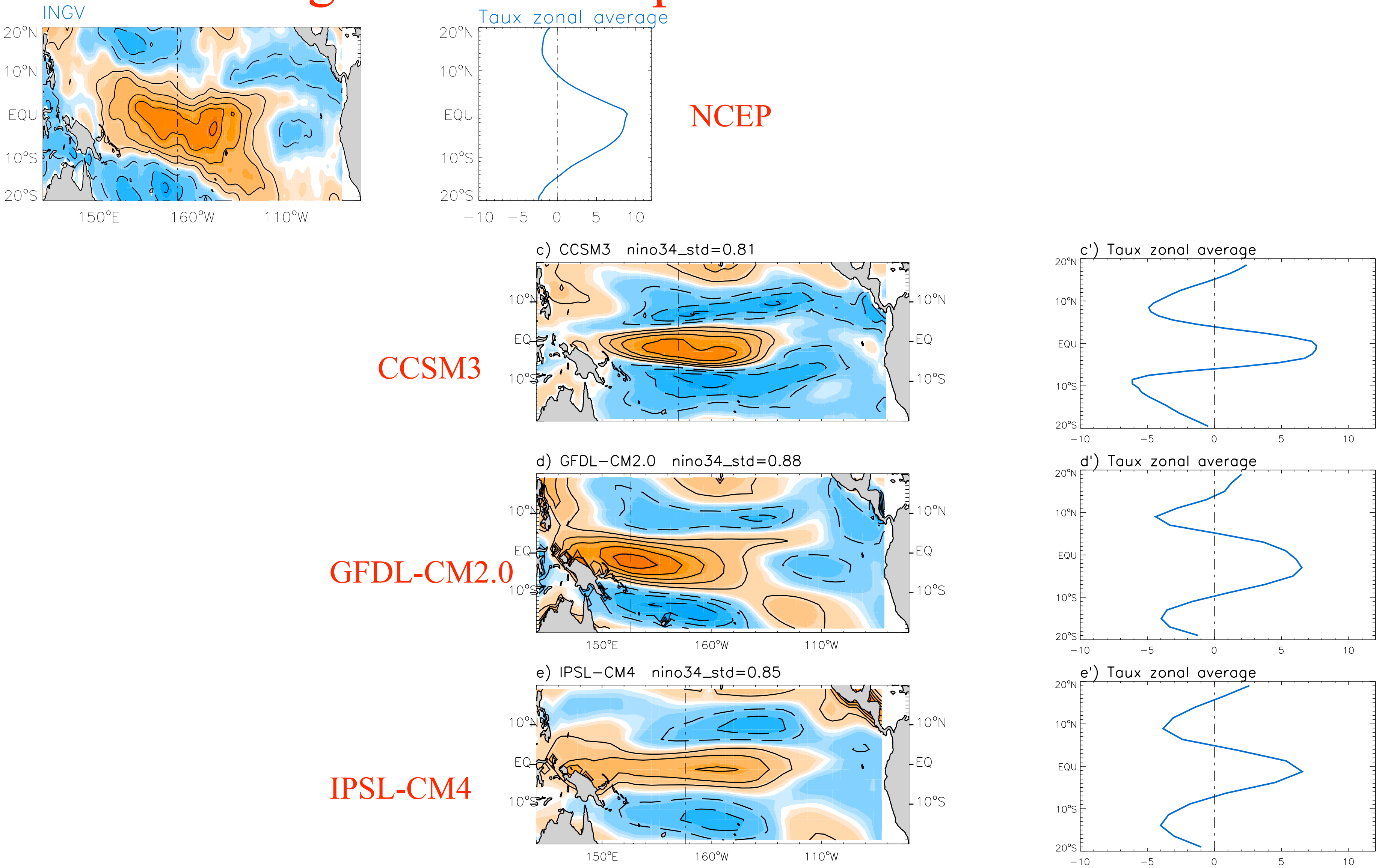
UKMO-HadCM3

CSIRO

CNRM



Regression of τ^x upon the Niño3.4 index



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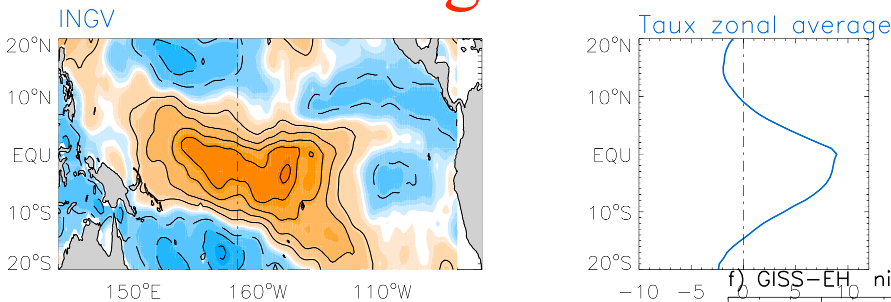
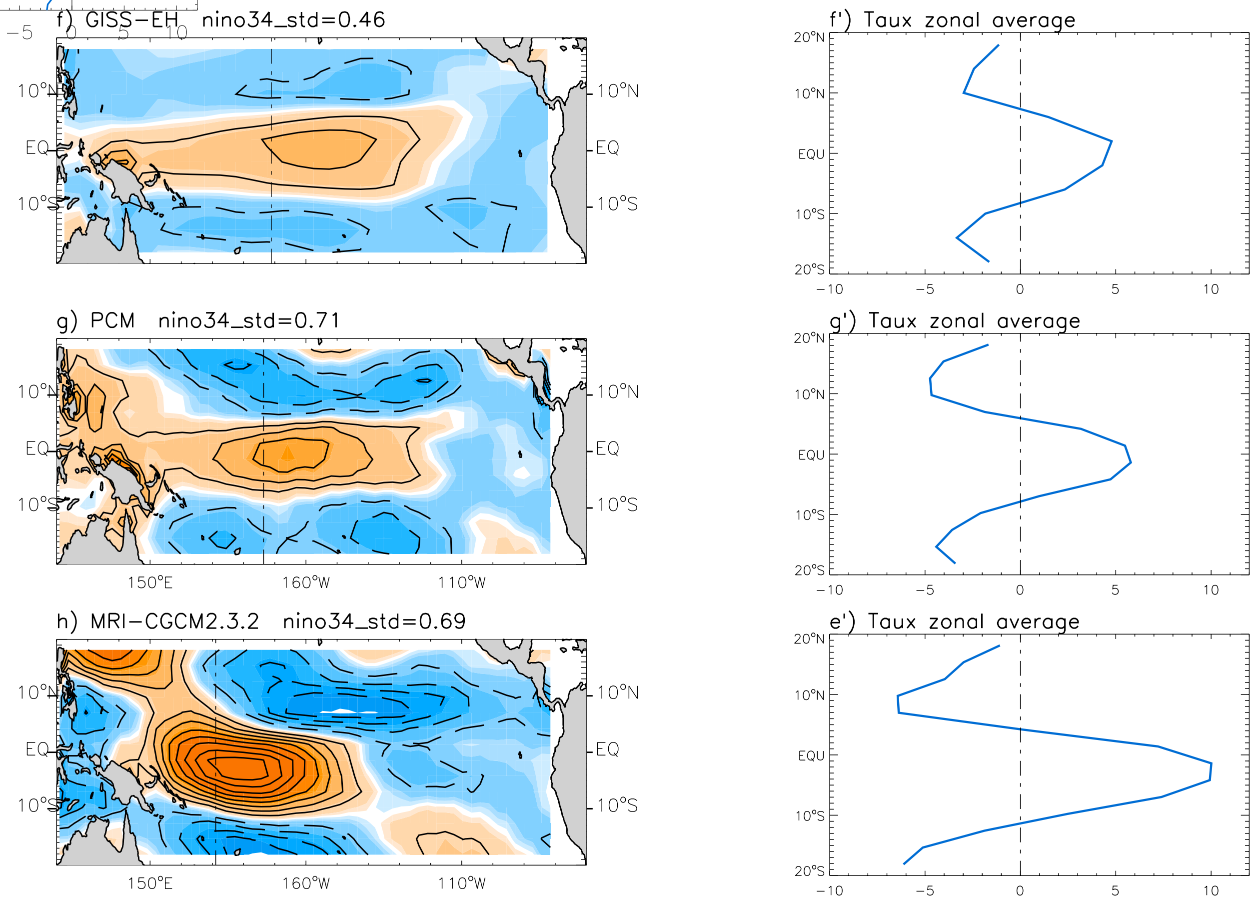


GISS-EH

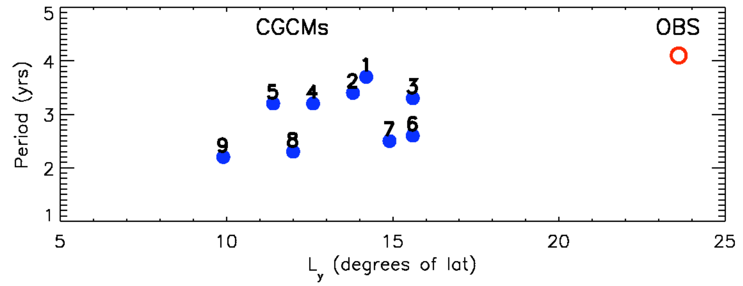
PCM

MRI



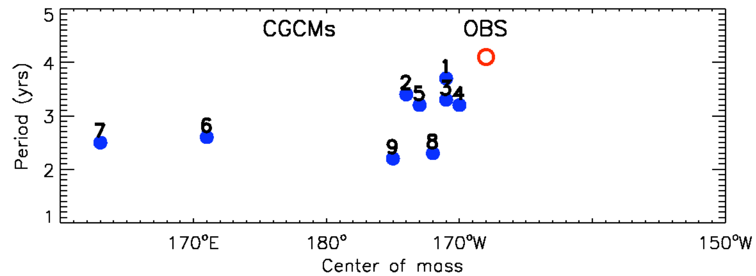
Dependency of period upon structure of anomalous wind stress

T_p vs. L_y

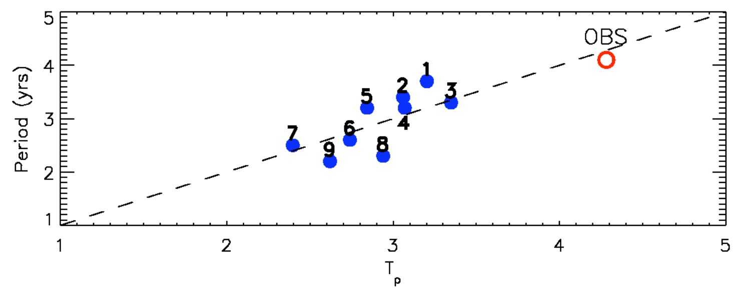


1 =UKMO−HadCM3
2 =PCM
3 =GISS−EH
4 =CNRM−CM3
5 =CSIRO−Mk3.0
6 =MRI−CGCM2.3.2
7 =GFDL−CM2.0
8 =IPSL−CM4
9 =CCSM3

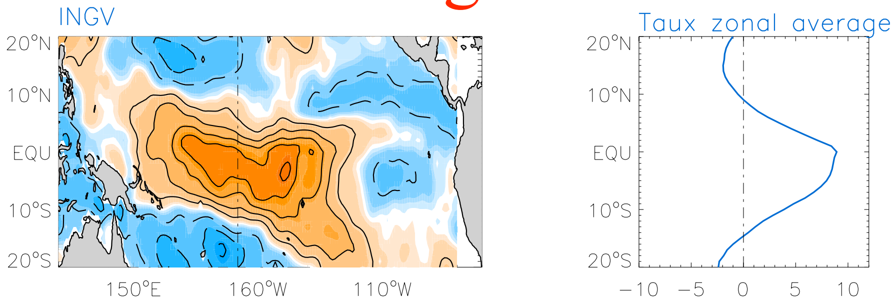
T_p vs. C



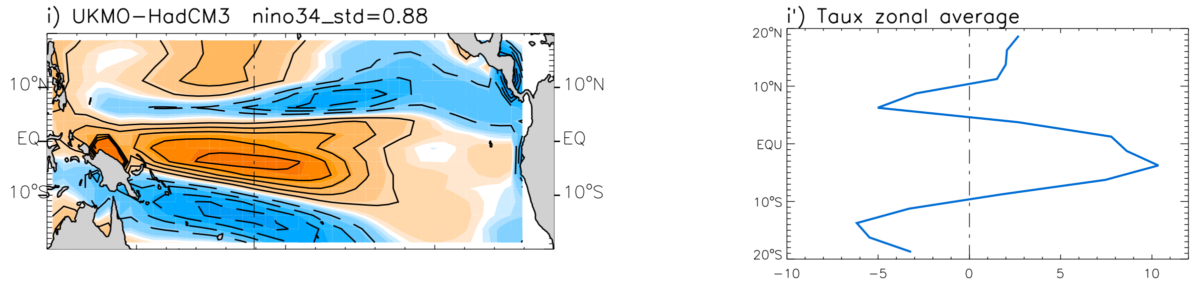
T_p vs. $T(L_y,C)$



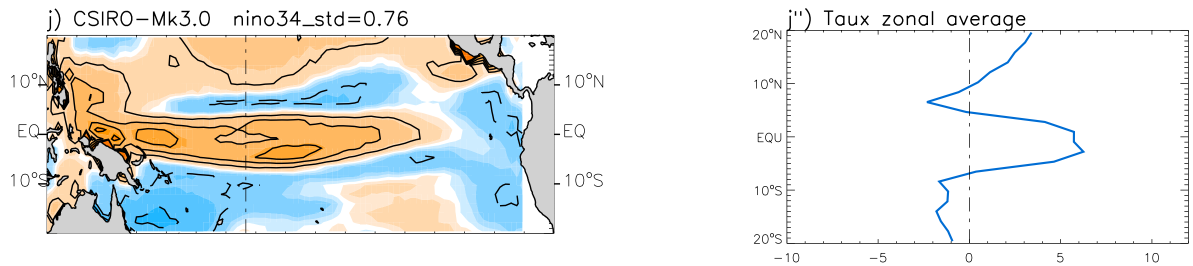
Regression of τ^x upon the Niño3.4 index



UKMO-HadCM3



CSIRO



CNRM