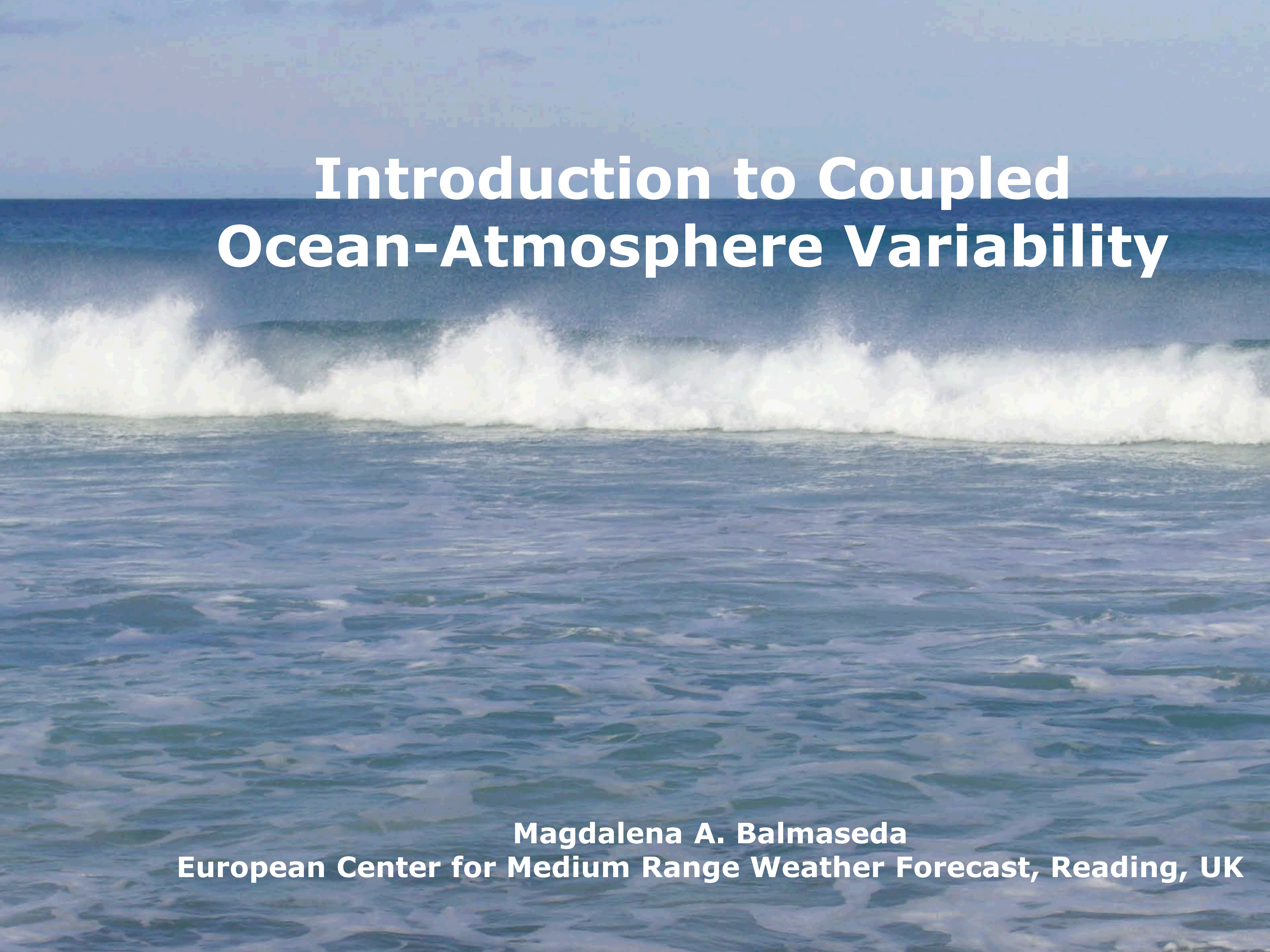

Introduction to Coupled Ocean-Atmosphere Variability

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Ocean Atmosphere Interaction

Why does it matter?

- **Predictability:** How far into the future can we predict the weather/climate?
  - How does the atmosphere respond to the ocean?
  - How predictable is the ocean?

- **Modelling:** Which air-sea processes need to be represented to predict the weather/climate at different time scales?

  Momentum flux (wind-wave-currents…) and mixing, diurnal cycle, baroclinic instability over sharp SST fronts, SST and tropical convection (MJO, ENSO) …

This talk will cover

- **Implications for Predictability**
  - Basis for extended range prediction
  - Simple conceptual models to understand predictability

- **Some examples of Ocean-Atmosphere Intercation**
  - Some facts
  - Different time scales and modes of variability
    - From diurnal to decadal
    - Known modes
    - Ocean heat uptake
  - **ENSO**

- **The Rebel El Nino 2014**

Ocean and Predictability

- **Ocean** is responsible for the slow time scales

  The ocean has a **large heat capacity** and **slow adjustment times** relative to the atmosphere.

- **Atmospheric response to ocean forcing**: very sensitive to the structure, location, and amplitude of the ocean forcing.

  i. **Response to large-scale spatial SST gradients**

  ii. **Response high SST to trigger deep atmospheric convection**

     Example: warm pool, tropical cyclones

  iii. **Response to sharp SST fronts**

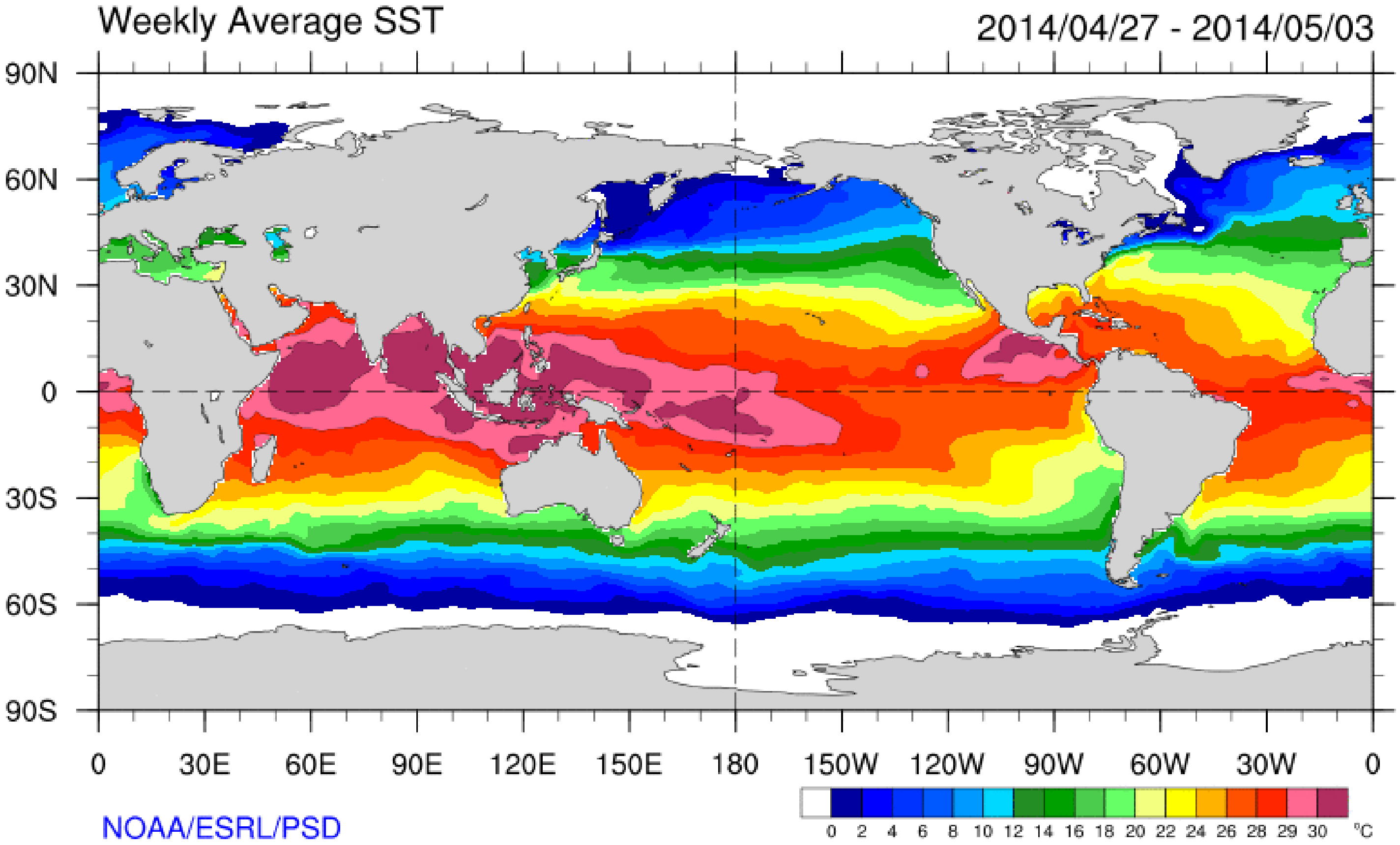
     example: mid latitude storm tracks over western boundary currents

Without any atmospheric response to boundary forcing, there can not be interannual-decadal atmospheric "predictability"

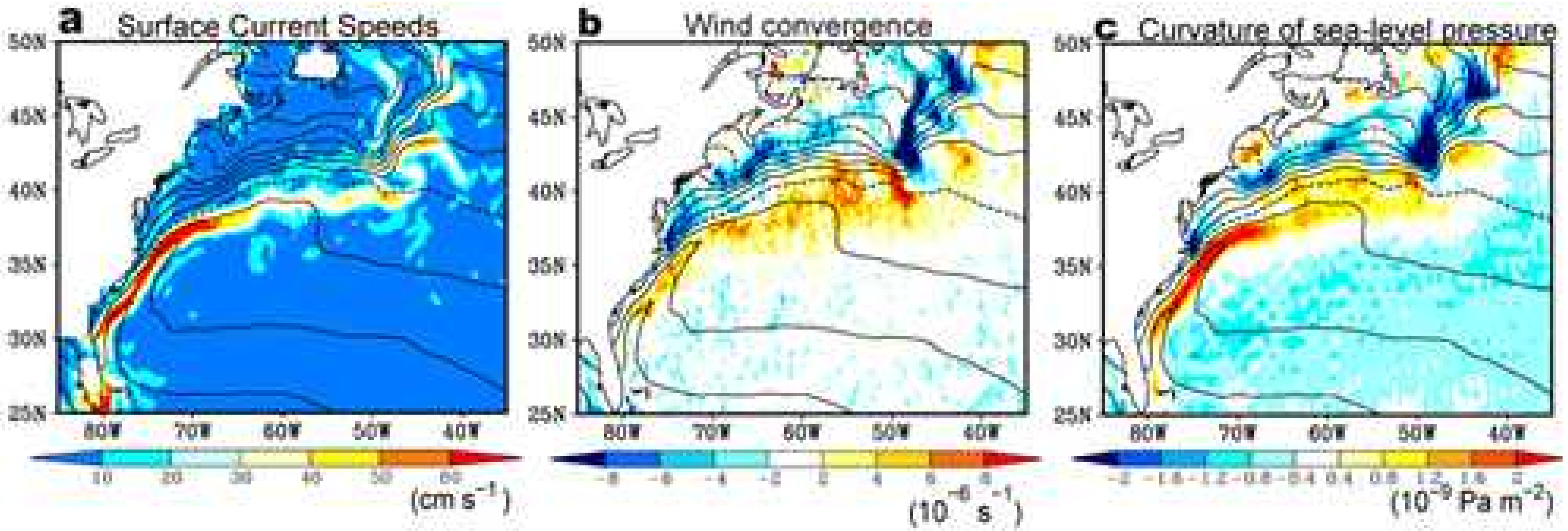
Hasselmann 1976

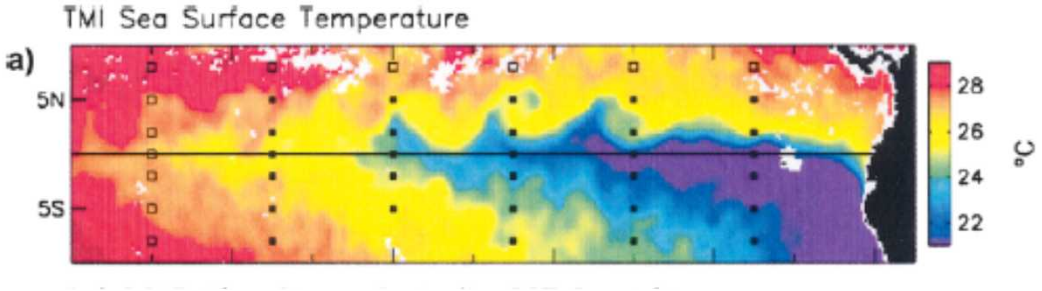
Latif et al 2002, Timmermann 2005…

Atmosphere responds to SST



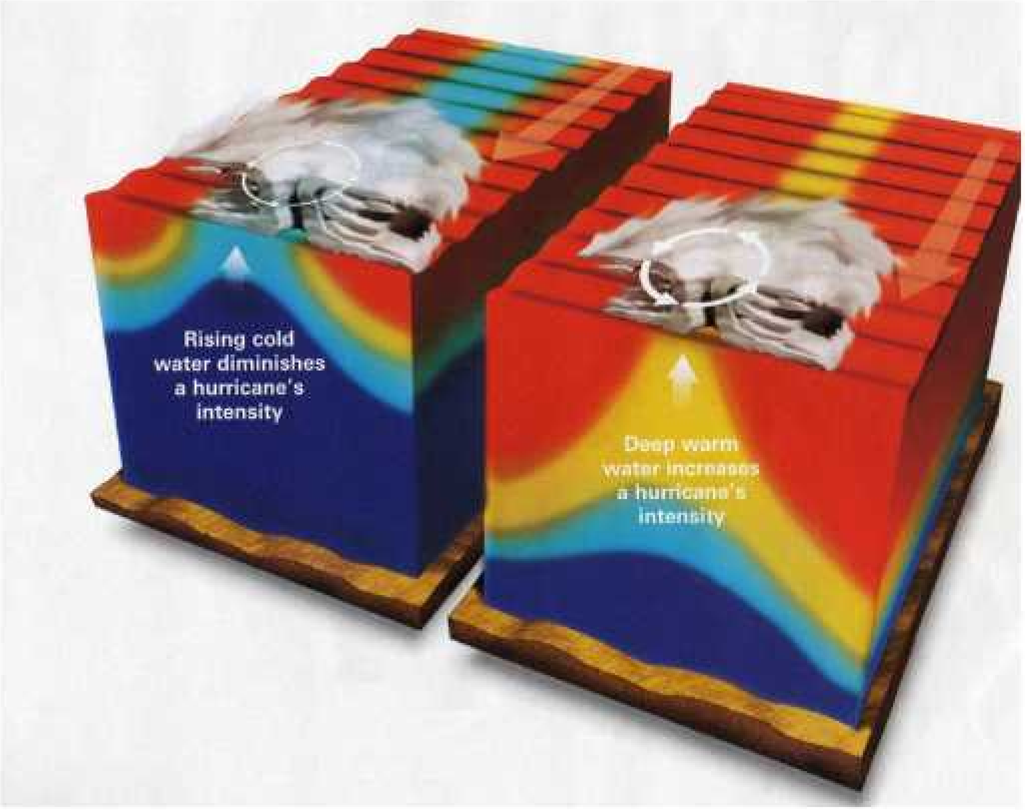
O-A interaction over SST fronts





Air-Sea Interaction also occurs at small scales, such as that of the Western Boundary currents (above) and Tropical Instability Waves TIW (left).

Air-Sea Interaction in Tropical Cyclones



Two U.S. operational hurricane prediction models are coupled with ocean models: GFDL (since 2001) and HWRF (since 2007)

From Ginis 2008

Paradigms to understand the predictability of atmosphere and ocean System with 2 time scales

- **Linear Stochastic, AutoRegressive (AR) models** (Hasselmann 1976)

  Modal decomposition

- **Non linear modulation of a chaotic system** (Lorenz 1969)

  Slow component as a boundary condition problem changing the PDF or the fast component.

  This is the “loaded dice” paradigm

2-timescales systems as an AR1

2-time scale ocean atmospheric system:

$$\mathbf{x}^T(t) = \left(\mathbf{x}_1(t), \mathbf{x}_2(t)\right)$$

With time evolution as a multivariate AR1 process

$$\mathbf{x}_{t+1} = \mathbf{A}\mathbf{x}_t + \varepsilon_t \ ; \ \varepsilon_t \equiv \text{white gaussian noise N}(0, \sigma_\varepsilon{}^2)$$

Matrix **A** has complex eigenmodes
occurring in complex conjugate pairs

$$\mathbf{A}\mathbf{v} = \Lambda\mathbf{v}; \qquad \Lambda = \lambda_R \pm i\lambda_I = \lambda e^{\pm i\omega_0}$$

If *X(ω)* is the Fourier transform of **x**(t), the spectral density of each eigenmode is

$$G(\omega) = X(\omega) X^*(\omega)$$

$$G(\omega) = \frac{1}{2\pi} \frac{\sigma_\varepsilon{}^2}{1 + \lambda^2 - 2\lambda\cos(\omega - \omega_0)}$$

λ is the damping term (or memory term)
ω0 is the characteristic frequency

1) Red noise ocean, white noise atmosphere

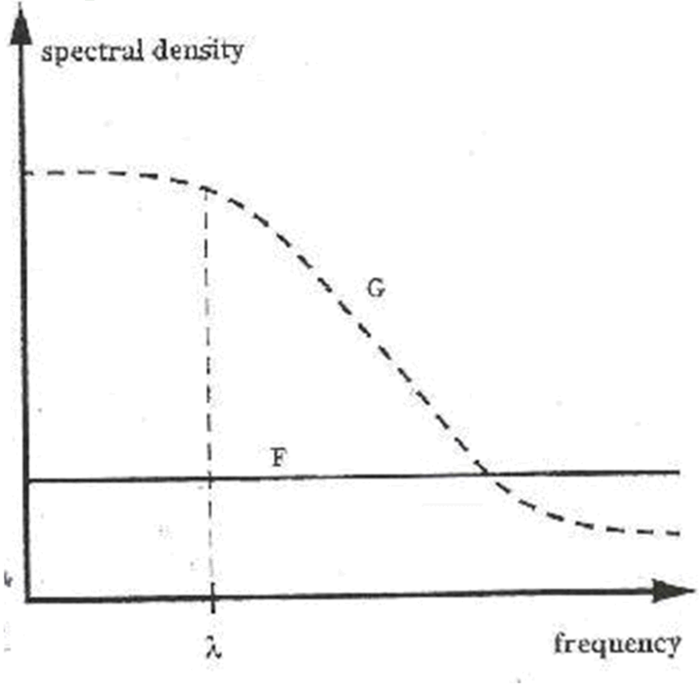
$$\mathbf{A} = \begin{pmatrix} \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \lambda \end{pmatrix}; \quad a=c=d=0\ ;\ b=\lambda$$

$$\mathbf{v}_1 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \mathbf{v}_2 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

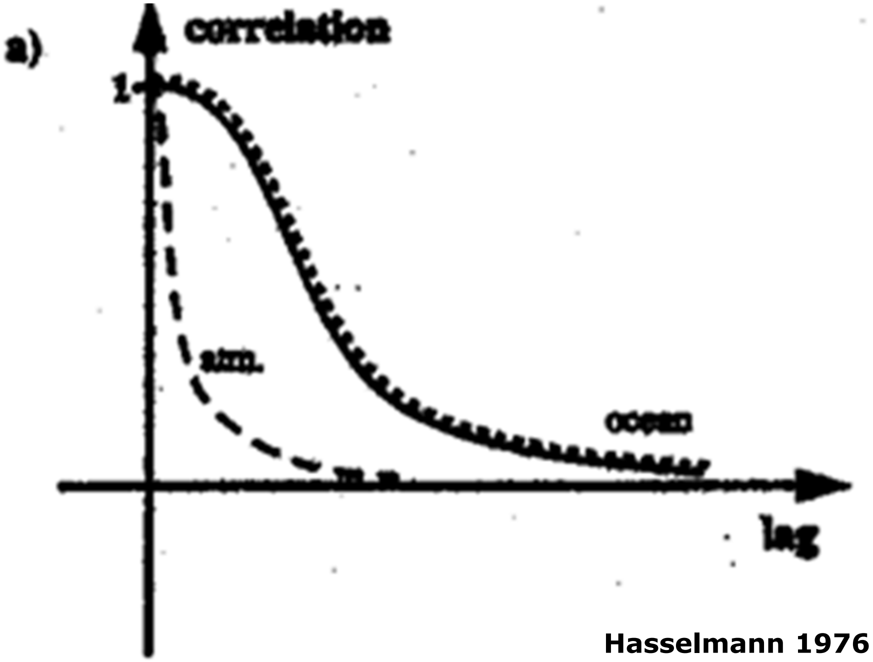
$$G(\omega) = \frac{1}{2\pi} \frac{\sigma_\xi^2}{(1+\lambda^2 - 2\lambda Cos\omega)} \qquad \text{; Ocean spectra}$$

$$F(\omega) = \frac{1}{2\pi} \sigma_\xi^2 \qquad \text{; Atmosphere spectra}$$

Spectra



Lag-correlation and skill



Hasselmann 1976

2) Ocean resonance, white noise atmos

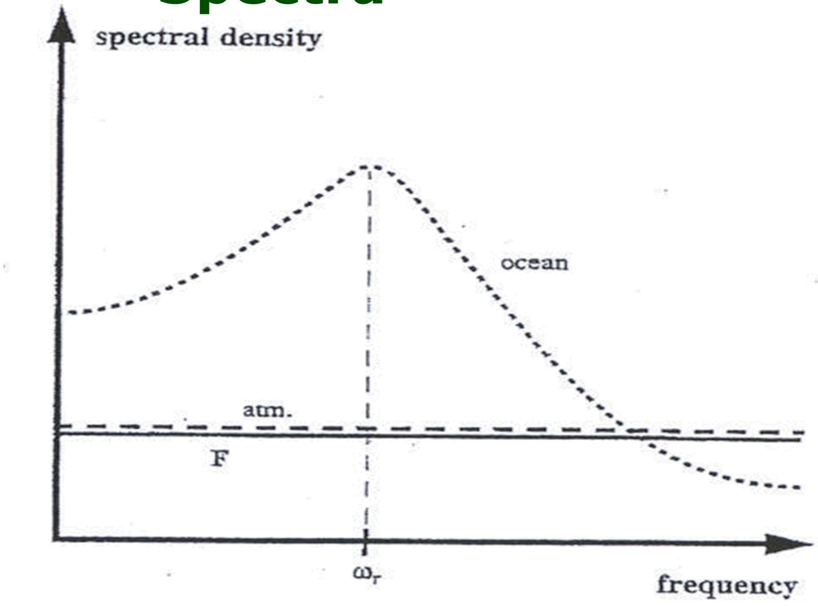
$$x_2 = \begin{pmatrix} x_t \\ x_{t-\delta} \end{pmatrix}; \delta \equiv \text{ time delay}$$

$$A = \begin{pmatrix} 0 & 0 \\ c & D \end{pmatrix} \quad ; \mathrm{D} = \begin{pmatrix} a & b \\ 0 & 1 \end{pmatrix}$$

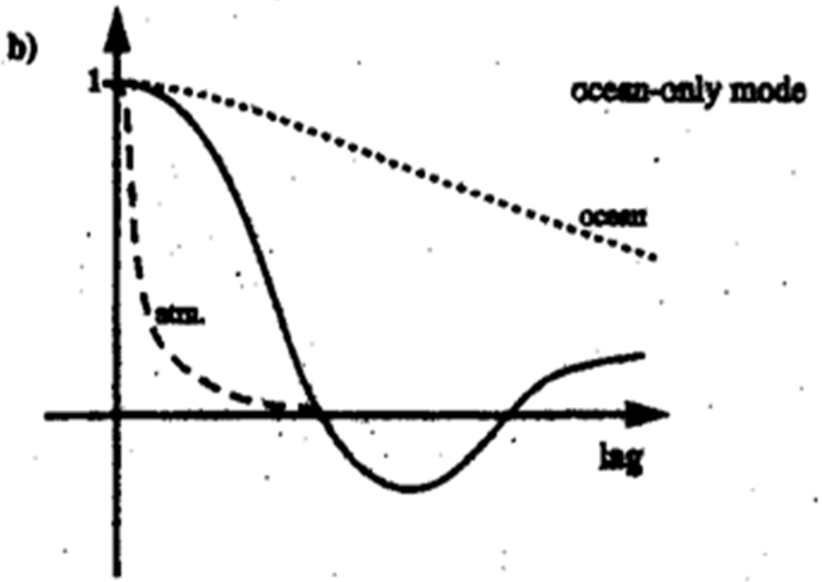
$$G(\omega) = \frac{1}{2\pi} \frac{\sigma_\xi^2}{(1 + \lambda^2 - 2\lambda Cos(\omega_0 - \omega))}$$

$$F(\omega) = \frac{1}{2\pi} \sigma_\xi^2$$

Spectra



Lag-correlation and skill



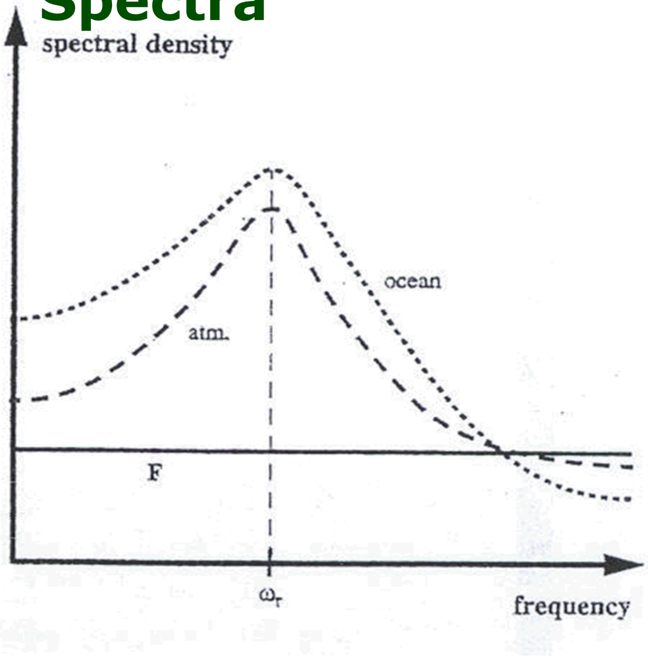
3) Coupled ocean-atmosphere modes

$$A = \begin{pmatrix} a & c \\ d & b \end{pmatrix}; \; 4dc < -(a-b)^2;$$

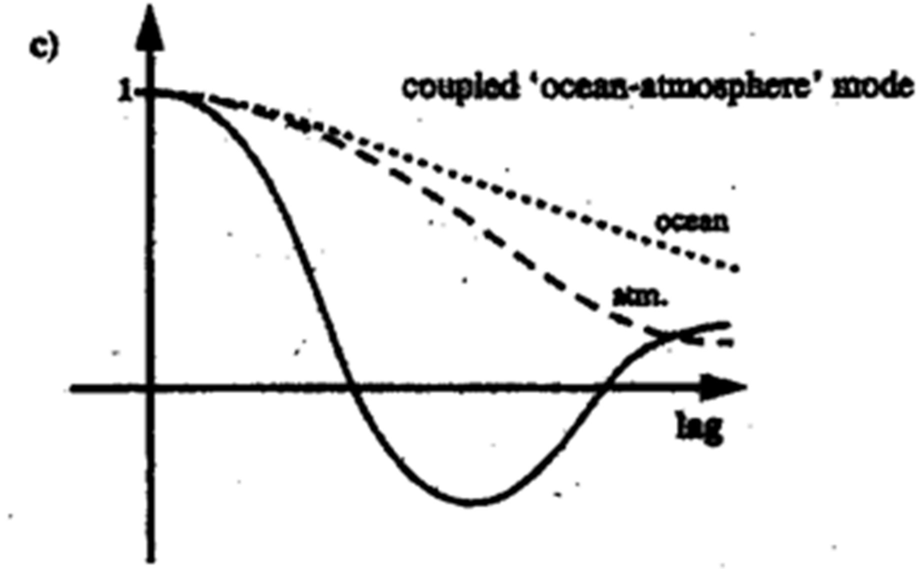
$$\mathbf{v}^k = \begin{pmatrix} a^k_1 \\ a^k_2 \end{pmatrix} \quad ; \Lambda^k = \lambda^k e^{i\omega_0^k}$$

$$G^k(\omega) = \frac{1}{2\pi} \frac{\sigma_\xi^2}{1 + \lambda^{k2} - 2\lambda^k Cos(\omega^k_0 - \omega)}$$

Spectra

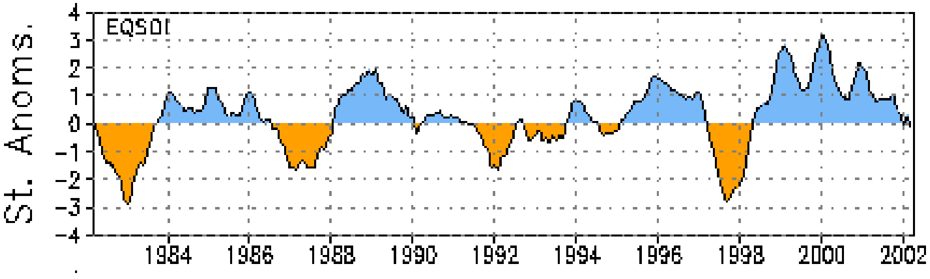


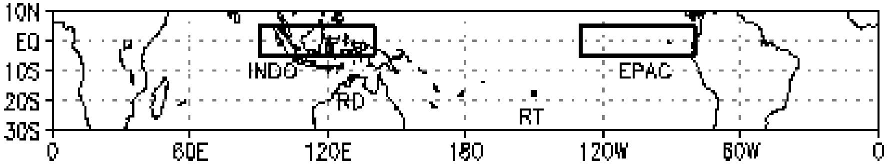
Lag-correlation and skill



Example: ENSO

Sea Level Pressure (SOI)

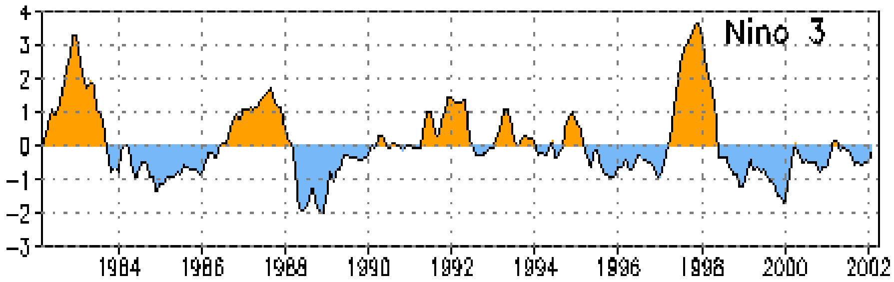


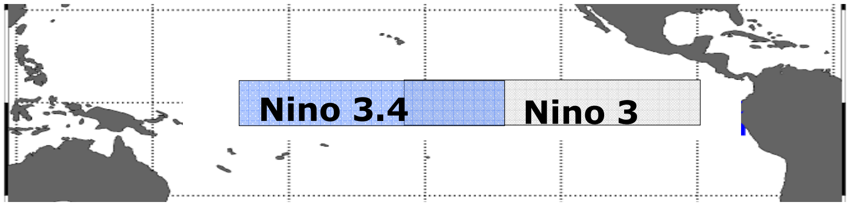


- In the equatorial Pacific, there is considerable interannual variability.

- Note 1983, 87, 88, 97, 98
- Note the skewness of the distribution .

Sea Surface Temperature (Nino 3)





- SST variability is linked to the atmospheric variability (SOI, Darwin-Tahiti), suggesting a strongly coupled process.

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  - **ENSO**

- **Ocean-Atmosphere Coupled Prediction Systems**

- **The Rebel El Nino 2014**

Some facts

- **Spatial/time scales** The radius of deformation in the ocean is small (~30km) compared to the atmosphere (~3000km).

  Radius of deformation =c/f where c= speed of gravity waves. In the ocean c~<3m/s for baroclinic processes. Smaller spatial scales and Longer time scales

- **The heat capacity** of the ocean is vastly greater than that of the atmosphere (1000 times).

  The total atmospheric heat content ~ the ocean heat content of 3.5m layer

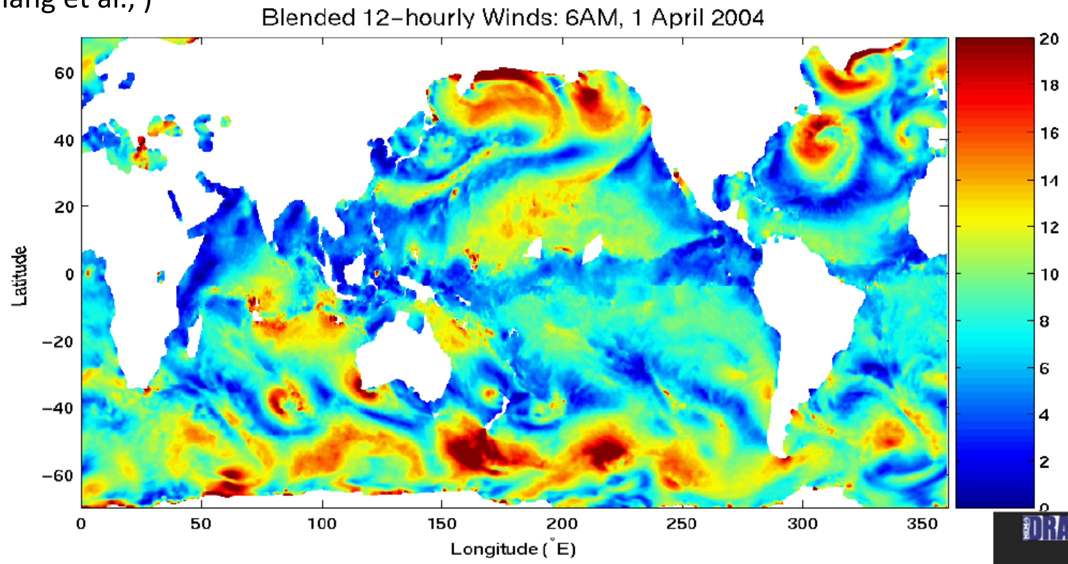
- **The ocean is strongly stratified in the vertical,** although deep convection also occurs

  Density is determined by Temperature and Salinity

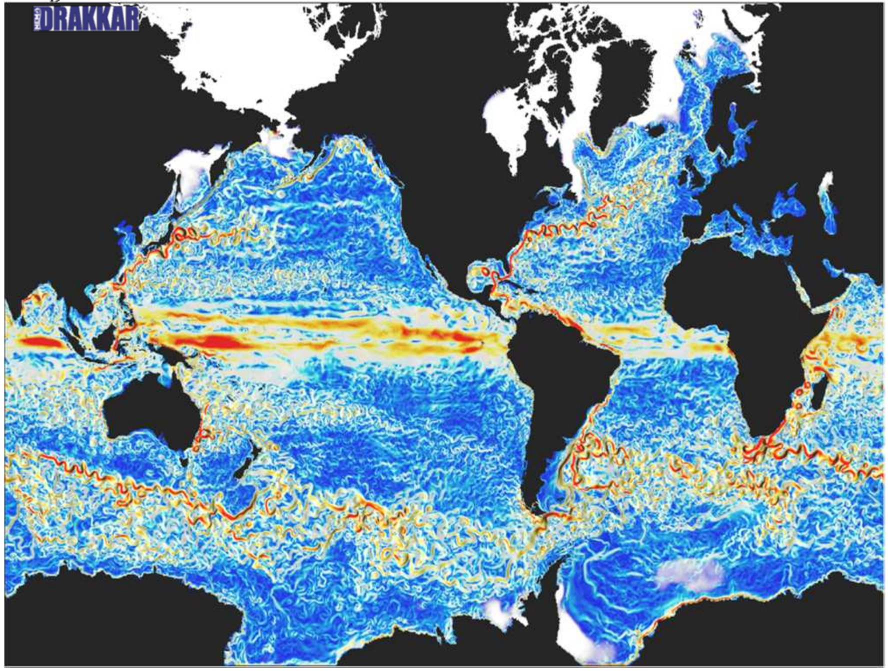
- **The ocean is forced at the surface** by the wind/waves, by heating/cooling, and by fresh-water fluxes.

- **Role of the ocean in meridional heat transports**
  - Why is it different in the different basins? Why is the Atlantic heat transport always northward?
  - Presence of bifurcations?

(Zhang et al.,)



Atmospheric wind speed (12h)



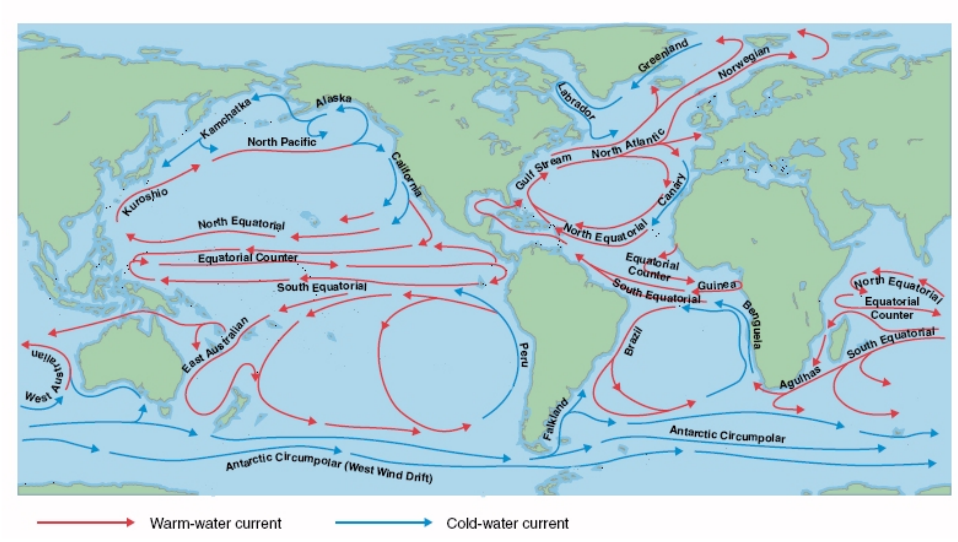
Ocean current speed (model simulation, 5 day mean)

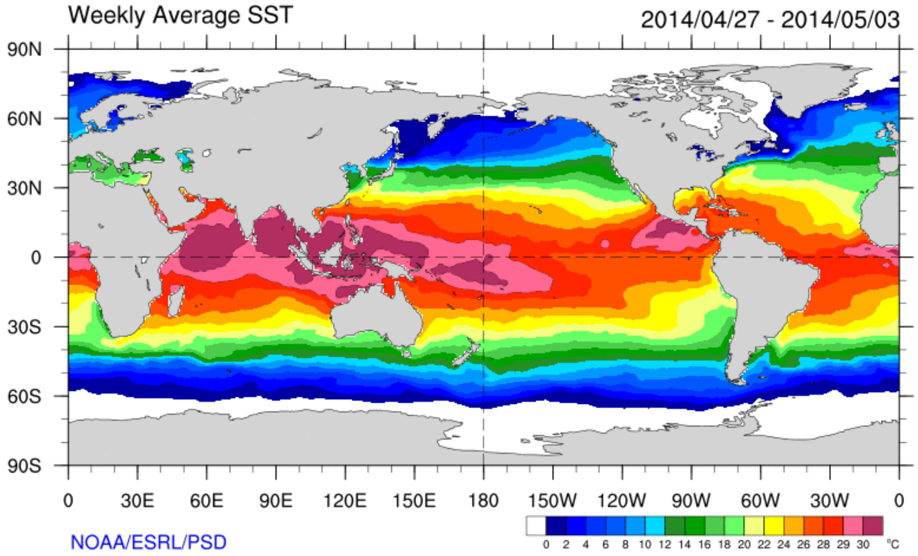
Ocean Circulation

- Wind Driven:
  - Gyres
  - Western Boundary Currents
  - Ekman Pumping: upwelling regions (coastal, equatorial) and subduction
- Bouyancy Driven: Thermohaline Circulation
  - Ubiquitous upwelling maintaining the stratification
  - Deep circulation concentrated in the western boundary
  - Sinking of water in localized areas and wind/tide mixing
  - Multiple equilibria
- Adjustment processes
  - Equatorial Kelvin waves (c ~2-3m/s) (months)
  - Planetary Rossby waves (months to decades)

Wind driven circulation

Sverdrup (1947), Stommel (1948), Munk (1950)

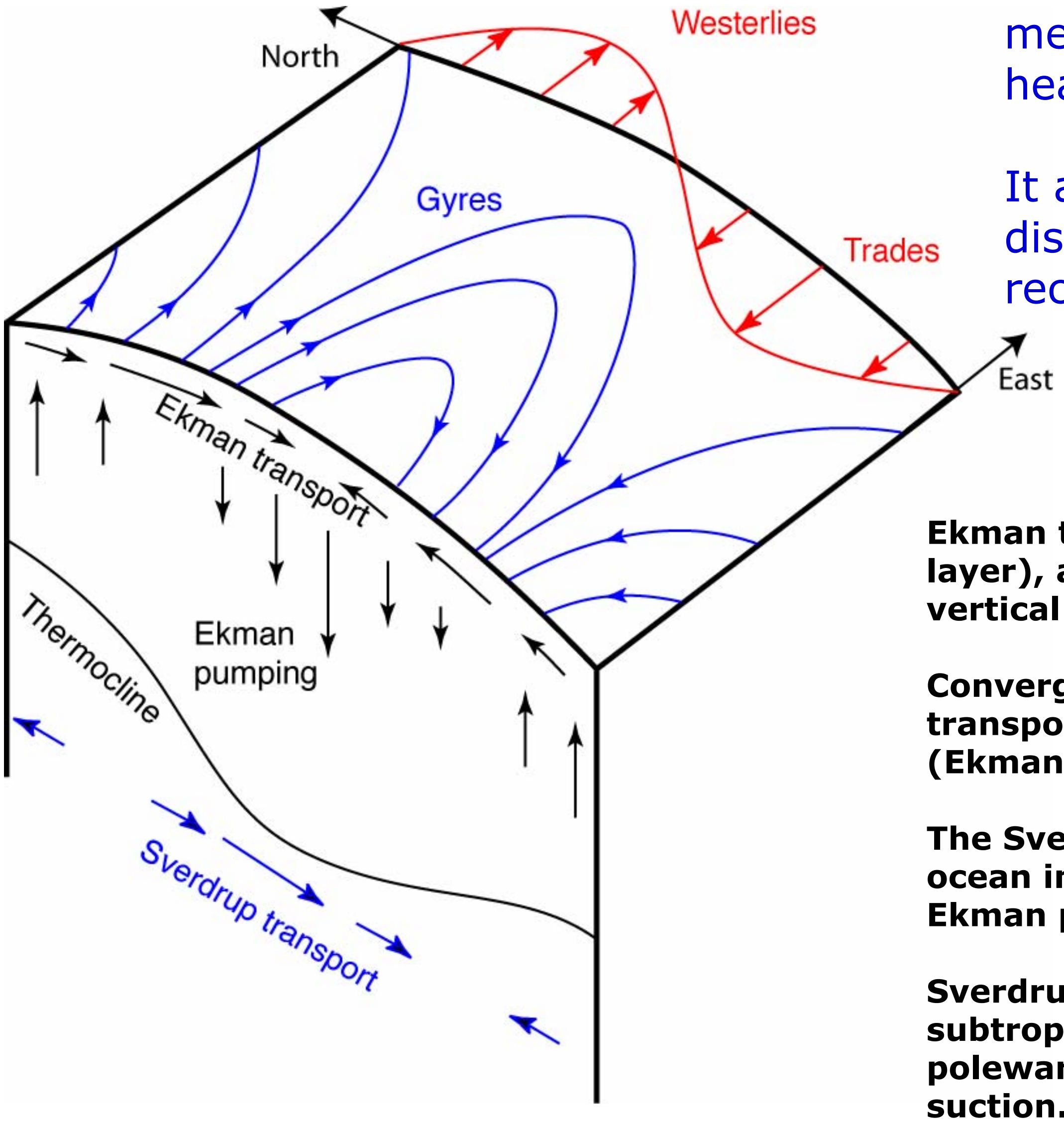




The surface circulation of the ocean is largely wind driven: sub-tropical gyres, western boundary currents, coastal upwelling. Note also the countercurrents which flow against the wind and the vigorous Antarctic circumpolar current

The wind driven circulation is responsible for important SST patterns, meridional heat transports, ocean heat absorption**.**

Ekman and Sverdrup Transports



The wind driven circulation results in meridional transports of mass and heat.

It also influences the vertical distribution of heat (hurricanes, recent hiatus in surface warming)

Ekman transport in the upper ocean (Ekman layer), a balance between wind stress, vertical mixing and rotation.

Convergence and divergence of Ekman transports create subduction/upwelling (Ekman pumping).

The Sverdrup transport is a transport in the ocean interior that feeds the large scale Ekman pumping.

Sverdrup transport is equatorward in subtropical regions of Ekman pumping and poleward in subpolar regions of Ekman suction.

Wind driven circulation profile

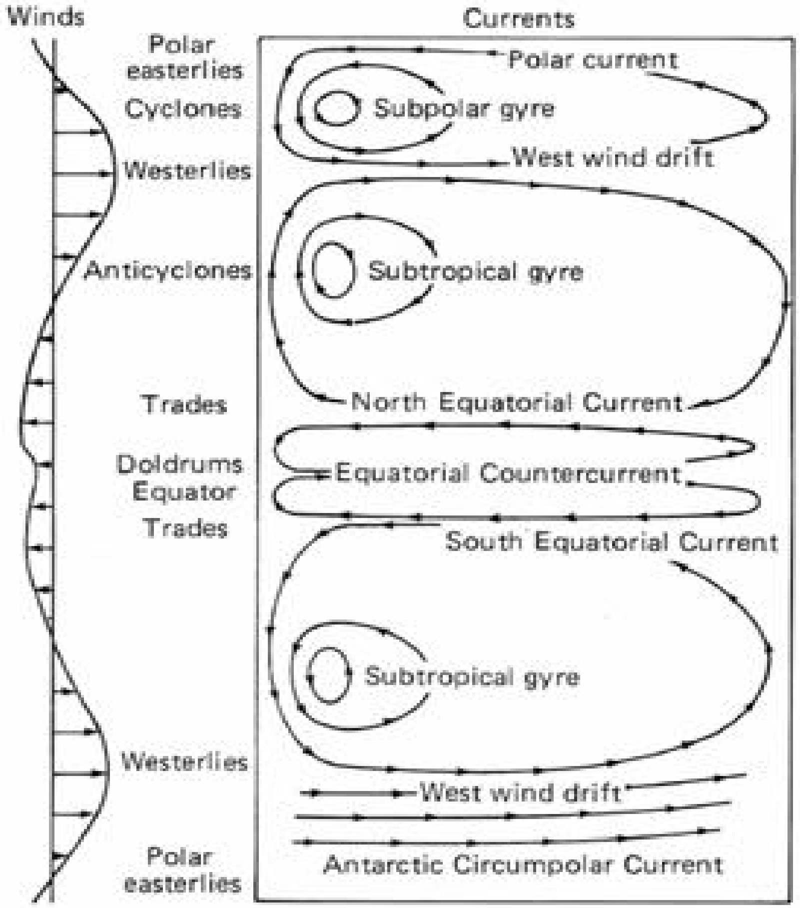


Fig. 6.36 Schematic configuration of current gyres in the Pacific as driven by wind stress curl.

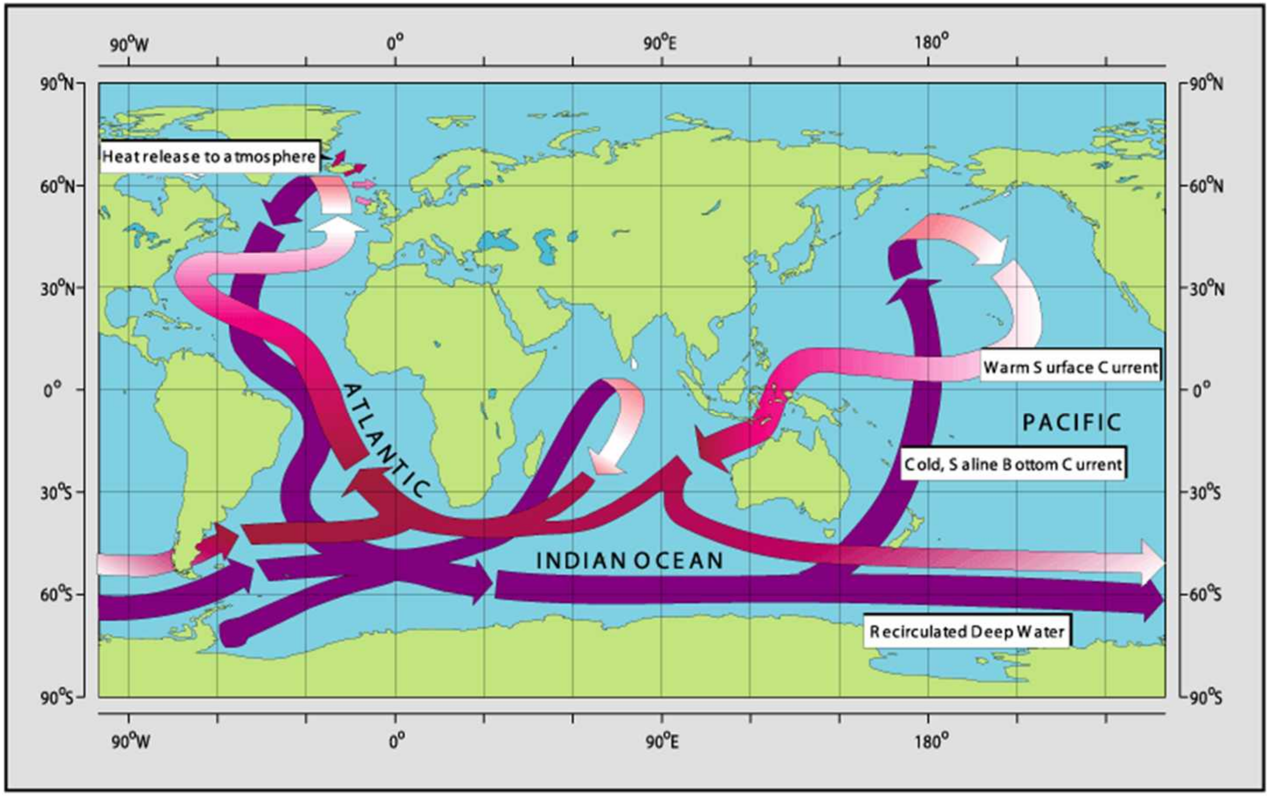
Western Boundary Currents (WBC)

- Narrow Currents flowing poleward on the western part of the basins.
  - Concieved as part of the Gyre Circulation.
  - Gulf stream:Narrow boundary current off North American coast (Florida)
  - Pacific has counterpart (Kuro-shio)
  - Gulf Stream cannot collapse, as long as winds blow, continents exist, and the Earth rotates
- The existence of WBC can be anticipated from the existence of Rossby Waves (see later), which travel to the west with group velocity:

$$\beta c^2 / f^2$$

- This means energy is carried to the western boundary where it is concentrated so generating western boundary currents such as the Gulf stream or the Kuroshio.
- This westward energy propagation may also be important in ENSO through the delay-oscillator mechanism. (see later)

Thermohaline Circulation

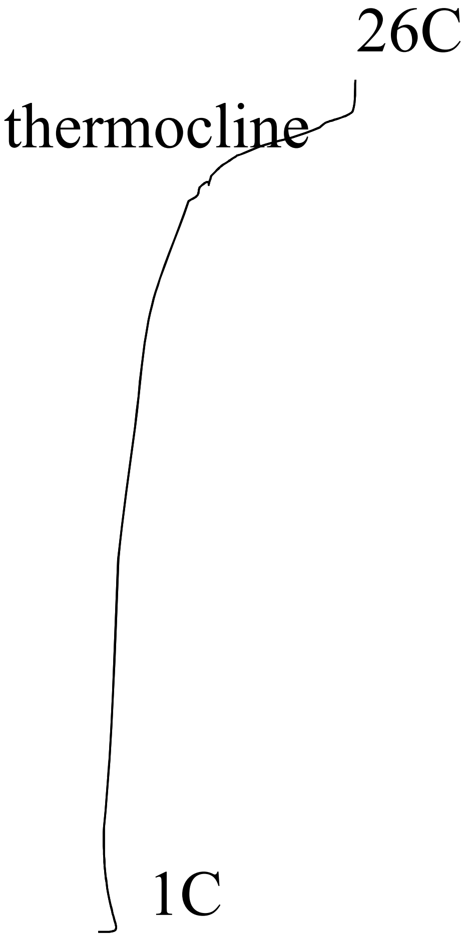


Thermo+Haline= Circulation driven by density differences.

Related to localized deep water formation areas.

Important for meridional heat transports and ocean stratification.

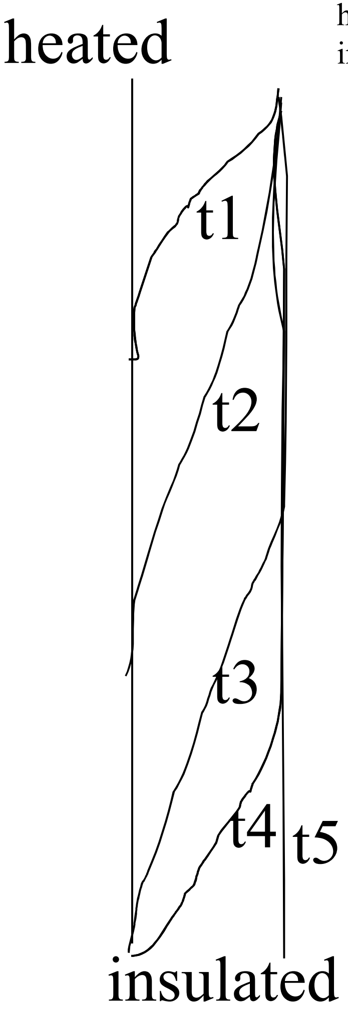
What maintains the ocean stratification?



Temperature profile from the surface to the deep ocean (4000m)

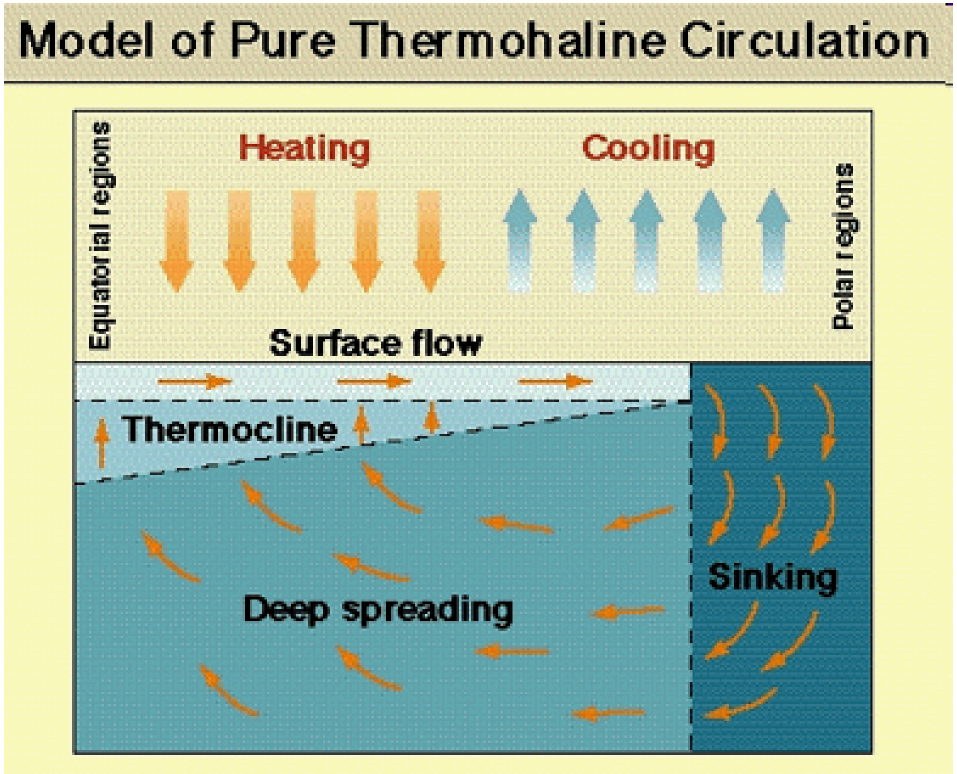
Thought experiment:

The temperature profile becomes homogeneous (well mixed) with increasing time t1, t2, t3 …



- **<u>Ellis 1751</u>**: The temperature of the ocean at the equator is warm (heated by the atmosphere) at the surface, but is cold at depth: i.e. the ocean is not in thermal equilibrium.

Thermohaline circulation



- The circulation is driven by density differences.
- Density differences forced to heat and fresh water fluxes, which in some areas act in different directions.
- In the current climate, sinking at high latitudes appears localized in small regions
- Upwelling is more widespread.
- Stommel box model can present bifurcations. Different solutions depending on the balance between heat and fresh water fluxes.

Stommel model

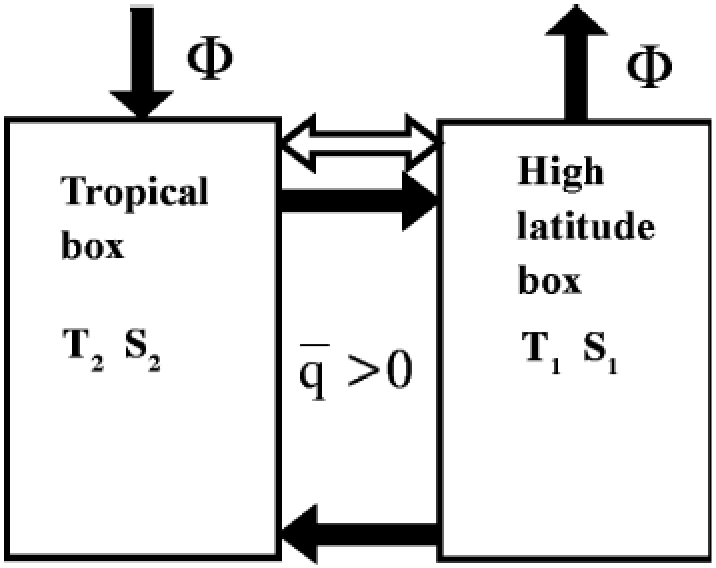
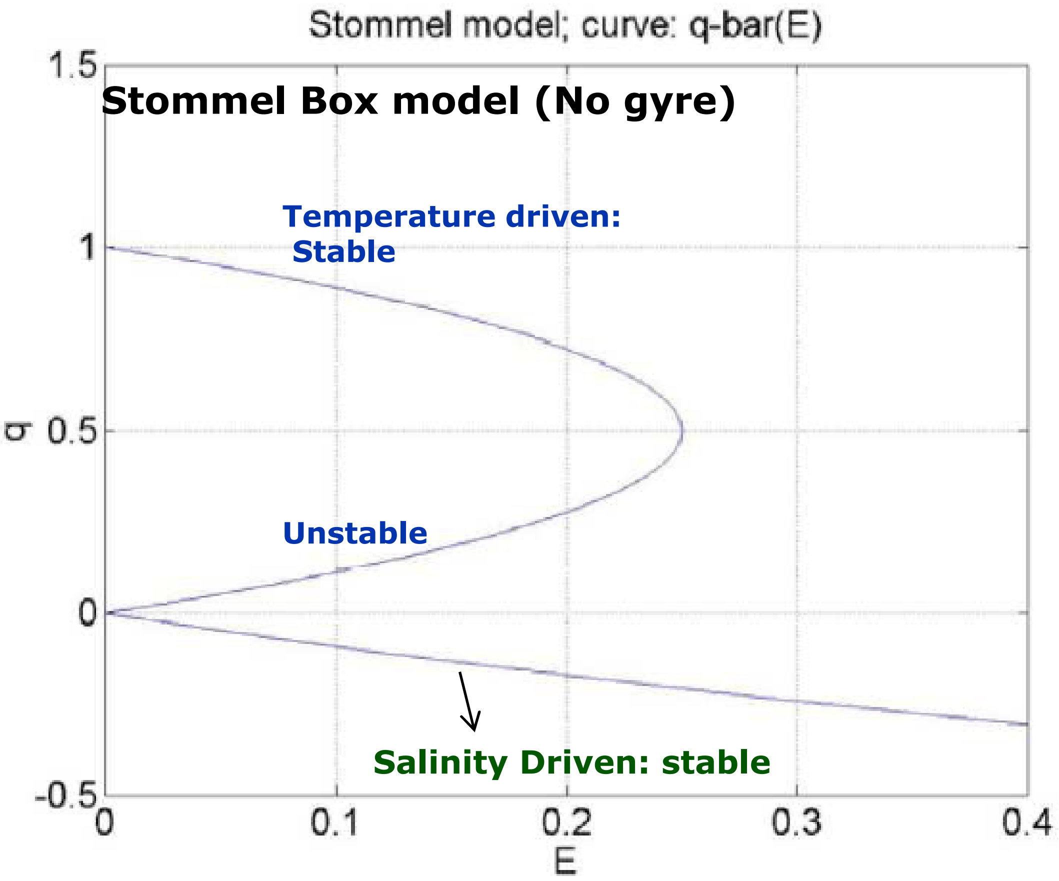


FIG. 1. The Stommel model with diffusion. Filled and unfi arrows are the advective and diffusive flow components, res tively. Advective arrows reverse under flow reversal but diffu arrows are unchanged.



Stommel Box model (No gyre)

Temperature driven: Stable

Unstable

Salinity Driven: stable

$$\Phi = S_0 E / H$$

E=evaporation

Longworth, Marotzke, and Stocker, 2005

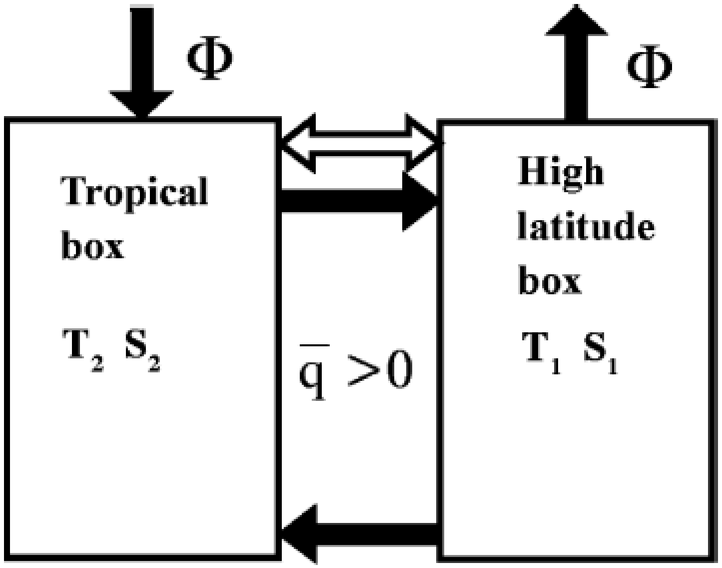


FIG. 1. The Stommel model with diffusion. Filled and unfilled arrows are the advective and diffusive flow components, respectively. Advective arrows reverse under flow reversal but diffusive arrows are unchanged.

$$\Phi = S_0 E / H$$

E=evaporation

$$\Phi = -S_0 P/H,$$

$$q = k(\rho_1 - \rho_2)/\rho_0 = k[\alpha(T_2 - T_1) - \beta(S_2 - S_1)],$$

$$\dot{S}_1 = -\Phi + |q|(S_2 - S_1) + k_d(S_2 - S_1),$$

$$\dot{S}_2 = \Phi - |q|(S_2 - S_1) - k_d(S_2 - S_1).$$

Reducing the number of variables, taking time derivative of q using the time derivatives of S

$$T \equiv T_2 - T_1; \quad S \equiv S_2 - S_1,$$

$$\dot{q} = -2k\beta\Phi - 2(|q| + k_d)(q - k\alpha T).$$

Equilibrium Solutions (time derivative=0. barred values)

$$\bar{q} > 0, \quad \alpha T > \beta\bar{S},$$

$$\bar{q}_{A/B} = \frac{1}{2}\left\{(k\alpha T - k_d) \pm \sqrt{(k\alpha T + k_d)^2 - 4k\beta\Phi}\right\},$$

Equilibrium Solutions

1) Temperature dominated: 2 solutions

$$\overline{q} > 0, \quad \alpha T > \beta \overline{S},$$

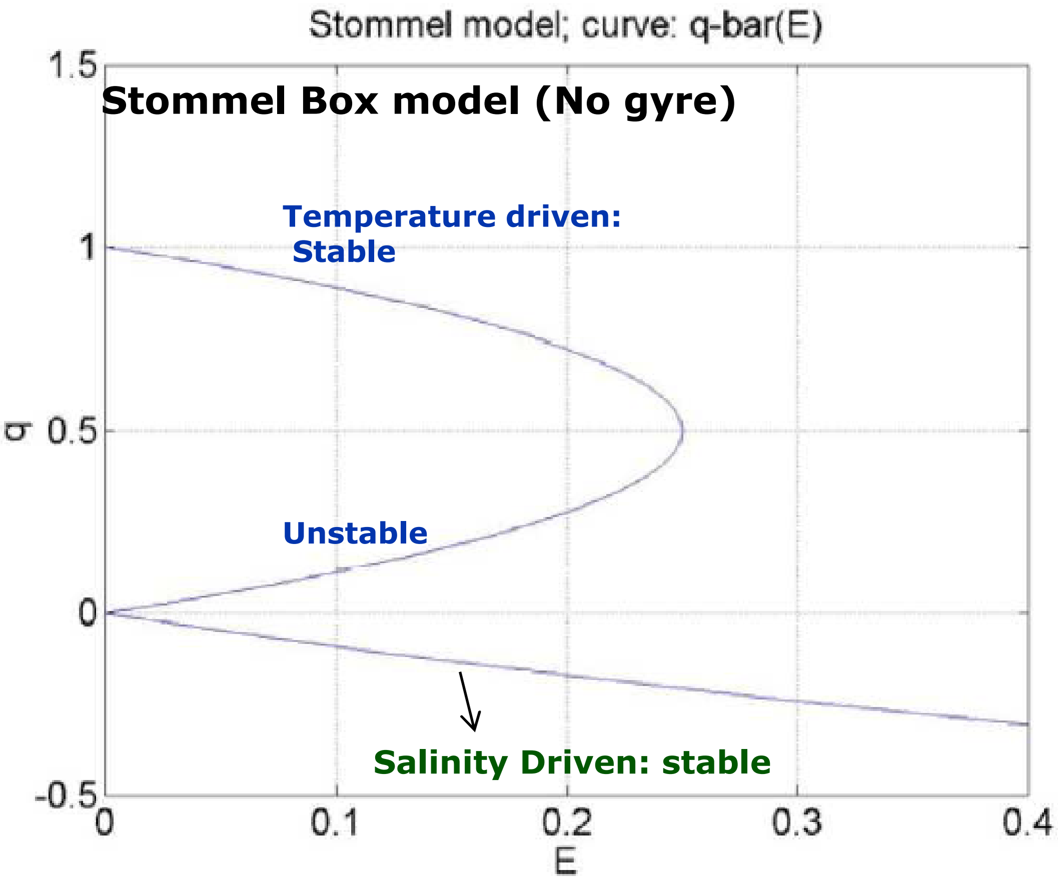
$$\overline{q}_{A/B} = \frac{1}{2}\left\{(k\alpha T - k_d) \pm \sqrt{(k\alpha T + k_d)^2 - 4k\beta\Phi}\right\},$$

$$\frac{k\beta\Phi}{(k\alpha T + k_d)^2} < \frac{1}{4},$$

2) Salinity dominated (only negative values of q)

$$\overline{q} < 0, \quad \alpha T < \beta \overline{S},$$

$$\overline{q}_C = \frac{1}{2}\left\{(k\alpha T + k_d) - \sqrt{(k\alpha T - k_d)^2 + 4k\beta\Phi}\right\}$$



Stommel Box model (No gyre)

Temperature driven: Stable

Unstable

Salinity Driven: stable

Stability and bifurcations

Meridional Heat transport: MOC x Stratification

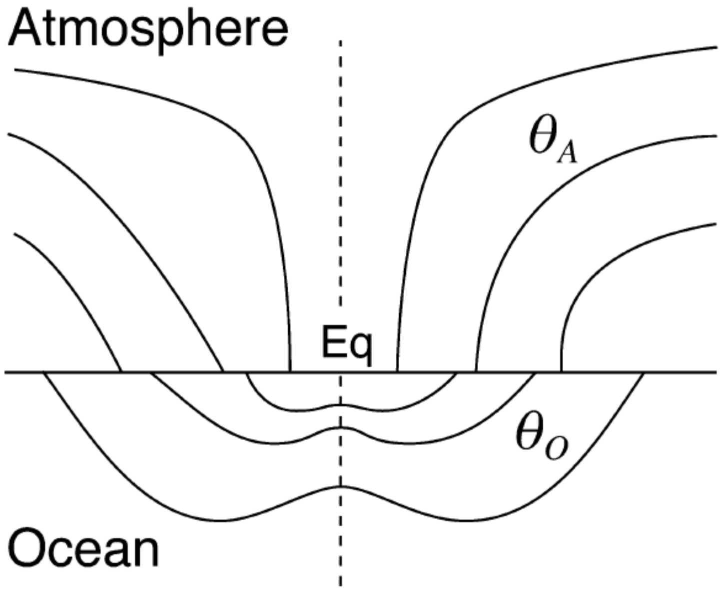
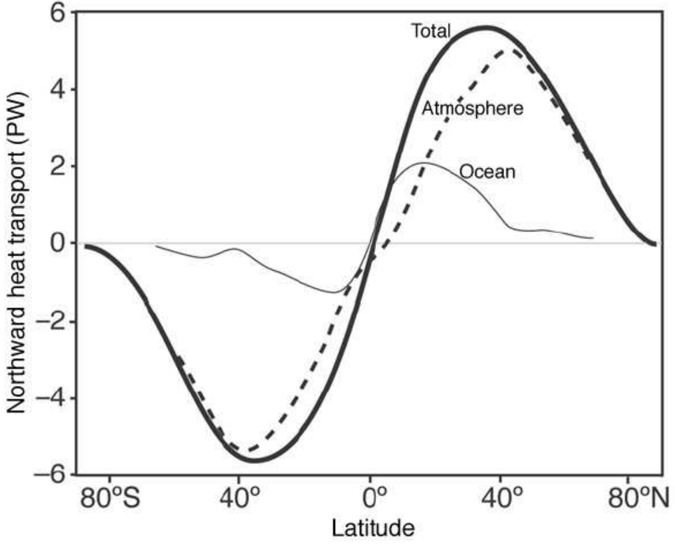


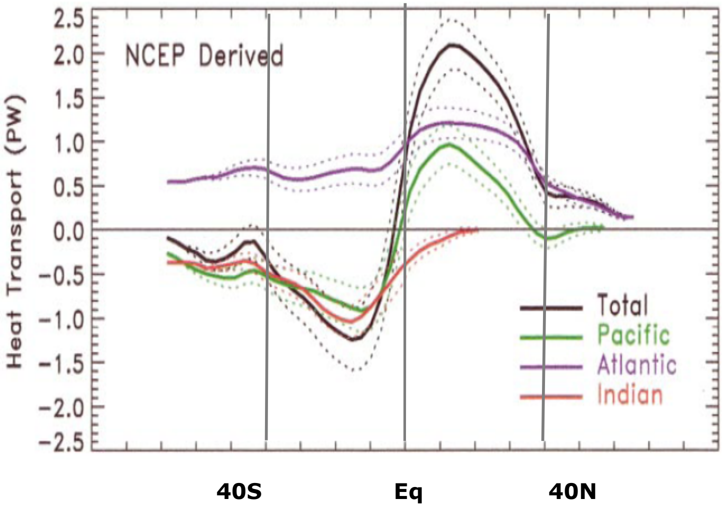
FIG. 2. Schematic of the distribution of atmospheric moist potential temperature (θ_A, i.e., moist static energy) and oceanic potential temperature (θ_O) as a function of latitude and height (black contours). The equator is indicated as a vertical dashed line.

Stratification of Ocean/Atmosphere
From Czaja and Marshall 2006.

Ocean and atmosphere heat transport

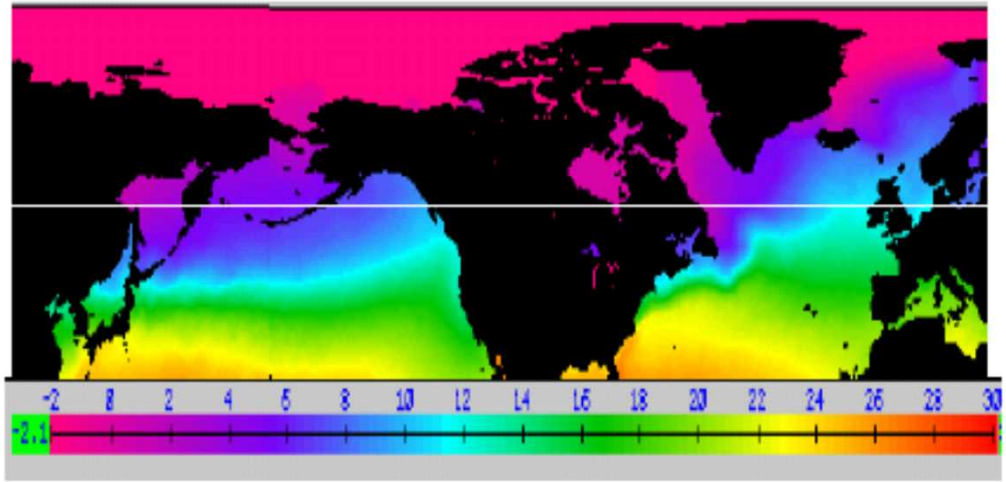


Oceanic heat transport by basins



Trenberth and Caron 2001

Meridional SST gradients



- **What determines the sharp frontal areas and their latitudinal position?**

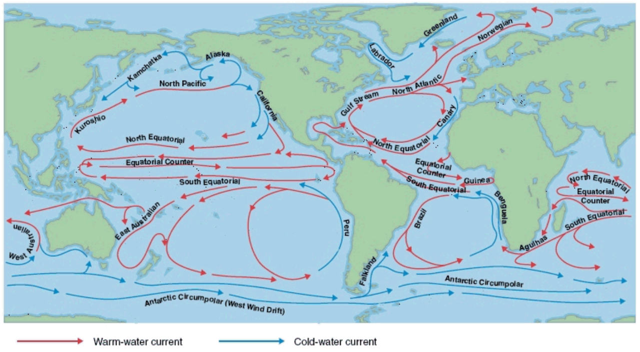
- **What determines the zonal structure of SST (Atlantic versus Pacific, for instance)? (Does the Gulf Stream tilt because of the Rockies, because of bathimetry, because of AMOC)?.**

- **What is the impact on the atmosphere of the SST structure? (storm tracks)**

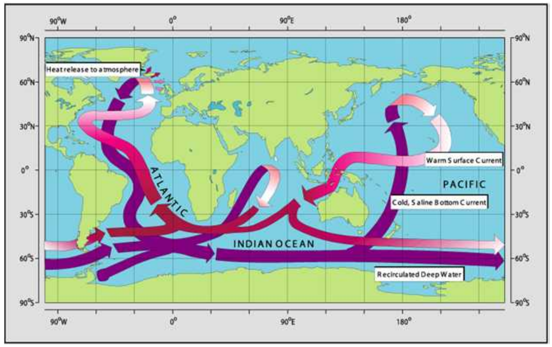
See Seager, American Scientist 2006 for a good (popular) discussion of these topics.
Brayshaw et al, 2011, JAS, for more recent findings

Ocean Circulation in the Equilibrium

Wind Driven



Buoyancy Driven



What about the transient behaviour?

- Response to external forcing: diurnal, seasonal, …
- Response to a perturbation: Adjustment processes?
- Modes of variability and bifurcations?

Dynamical Adjustment
Vertically stratified fluid and rotation

- **Kelvin waves**: equatorially confined, eastward propagating and non dispersive.

$$c = \sqrt{Hg'} \sim 0.5 - 3m/s$$

$$g' = g\delta\rho / \rho_0$$

$$a = \sqrt{c/2\beta} \sim 100 - 200Km$$ Equatorial Radius of Deformation

It takes about 2 months for a the first baroclinic Kelvin wave to cross the Equatorial Pacific

- **Rossby waves**: westward propagating and dispersive
  - Lower frequencies for shorter waves
  - Speed decreases with latitude

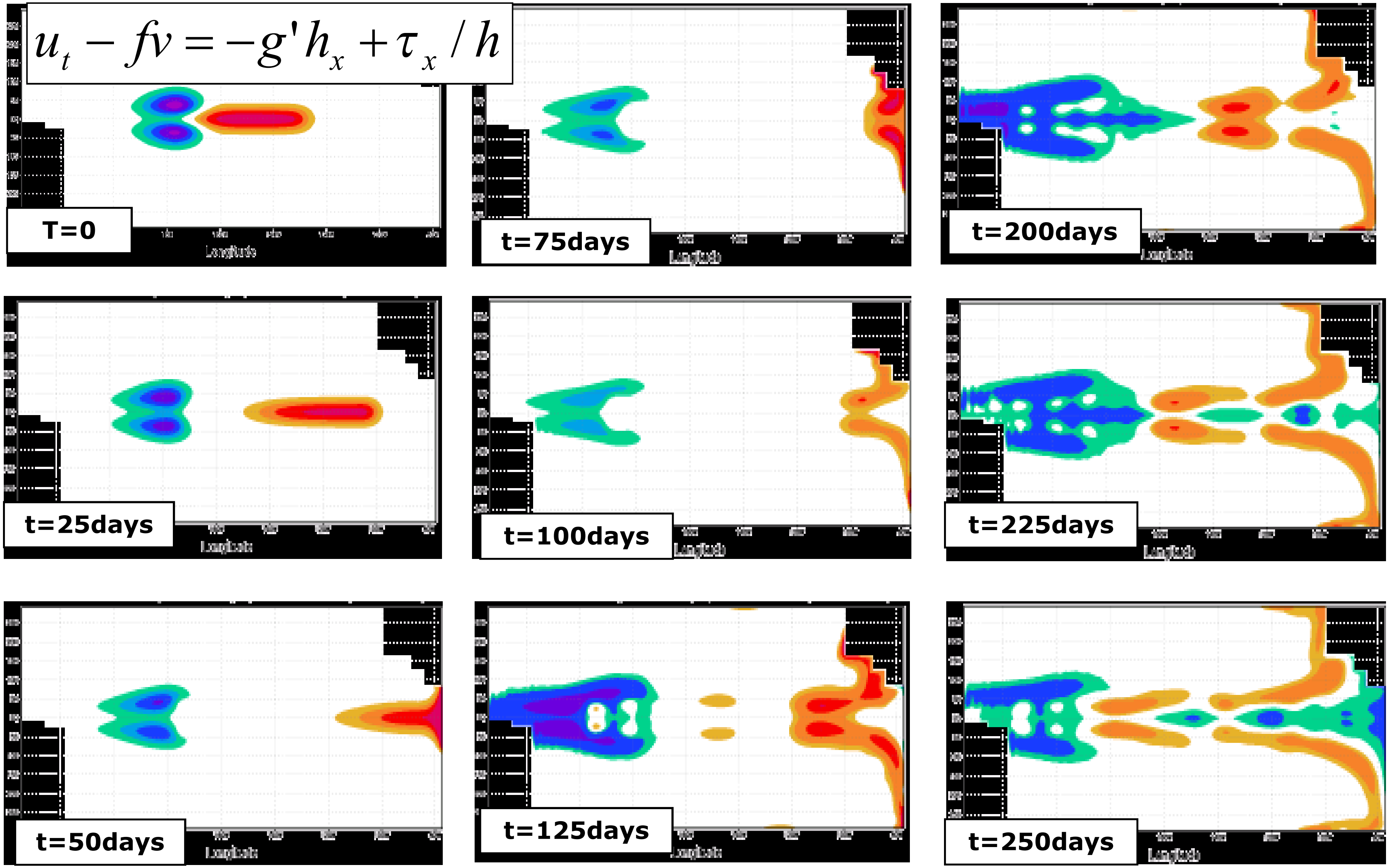
$$\omega = -\beta k / (k^2 + l^2 + f^2 / c^2)$$

$a = c / f$; Rossby Radius of deformation

a~40Km at mid latitudes (H~800m,g'~0.02,f~$10^4 s^{-1}$)

It takes 10 years for the first baroclinic Rossby mode to cross the Atlantic at 40N

Kelvin & Rossby waves and Delayed Oscillator



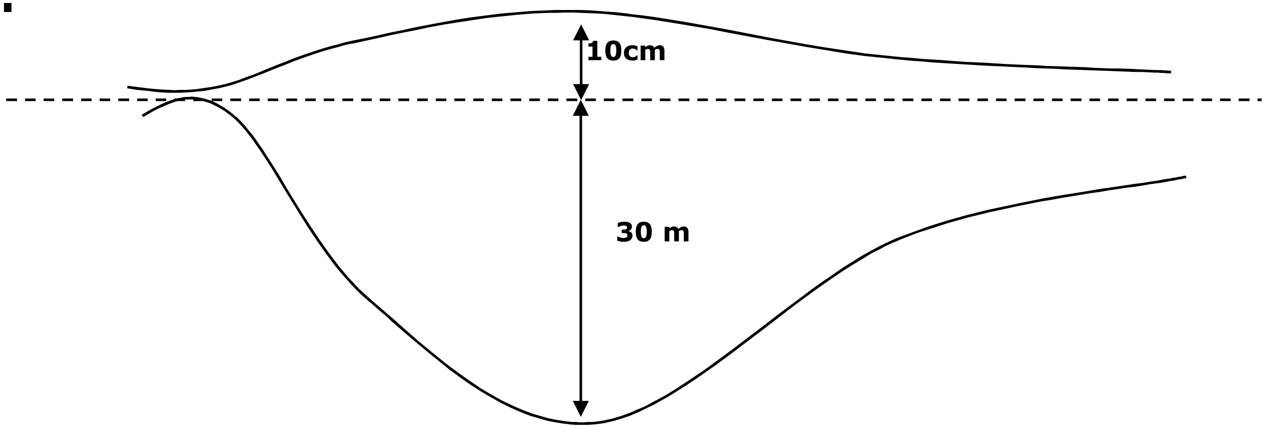
$$u_t - fv = -g' h_x + \tau_x / h$$

Vertical Stratification and Satellite altimetry

- The density of the second layer is only a little greater than that of the upper layer.

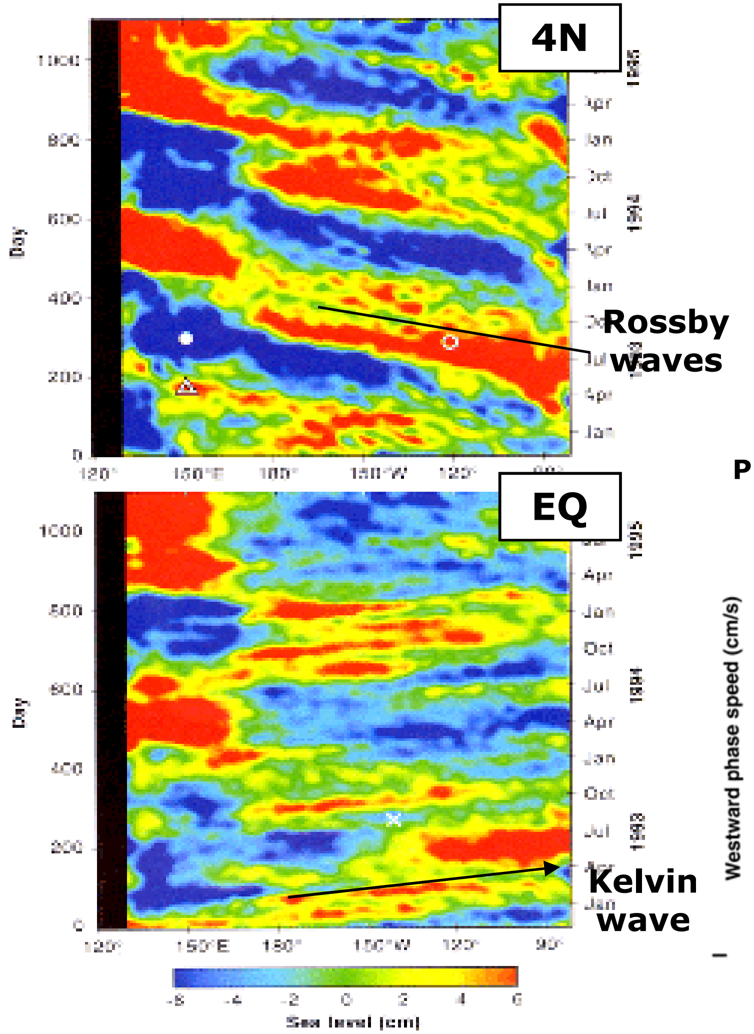
Typically g’~g/300

- A 10cm displacement of the top surface is associated with a 30m displacement of the interface (the thermocline).



If we observe sea level, one can infer information on the vertical density structure

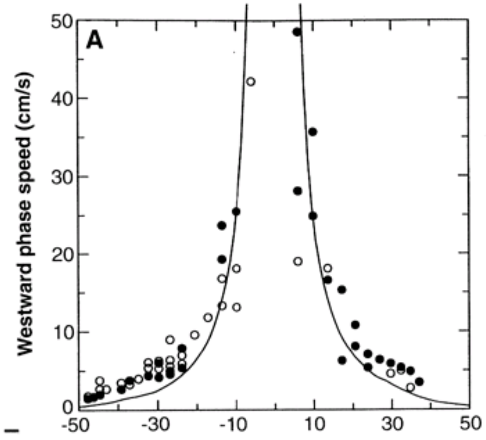
Rossby/Kelvin Waves from Space

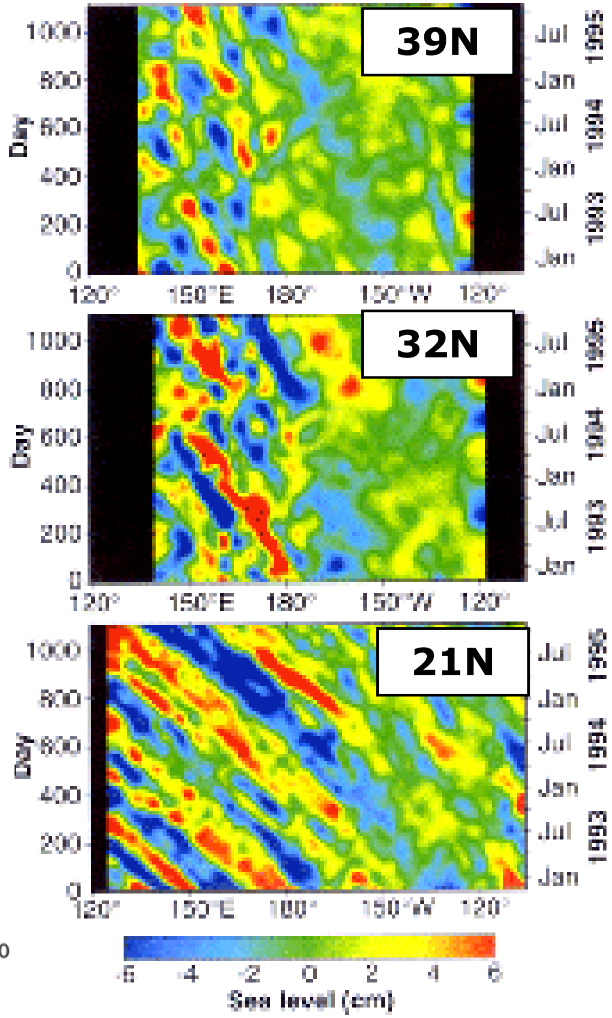


Rossby waves

Kelvin wave

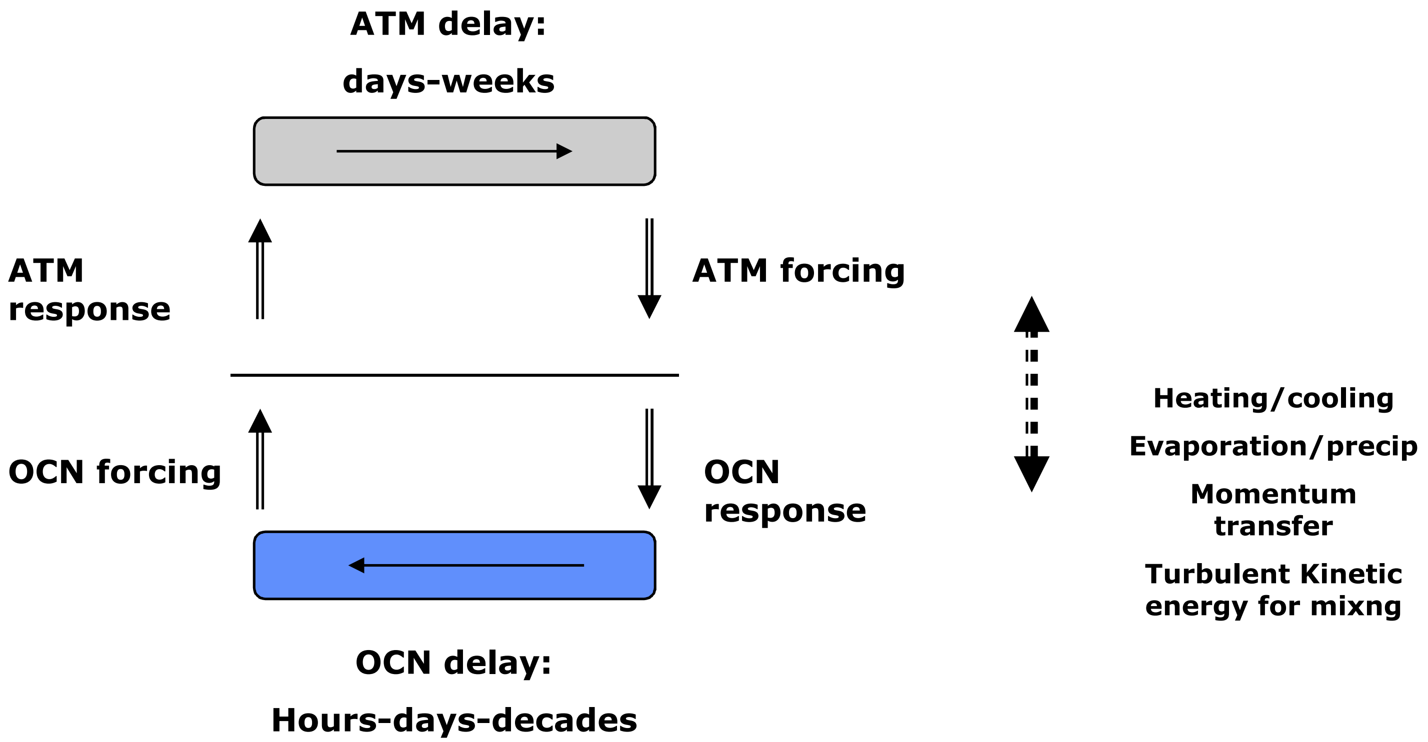
Phase speed as a function of latitude





Chelton et al 1996

Time scales for ocean-atmosphere interaction



ATM delay:

days-weeks

ATM response

ATM forcing

OCN forcing

OCN response

OCN delay:

Hours-days-decades

Heating/cooling

Evaporation/precip

Momentum transfer

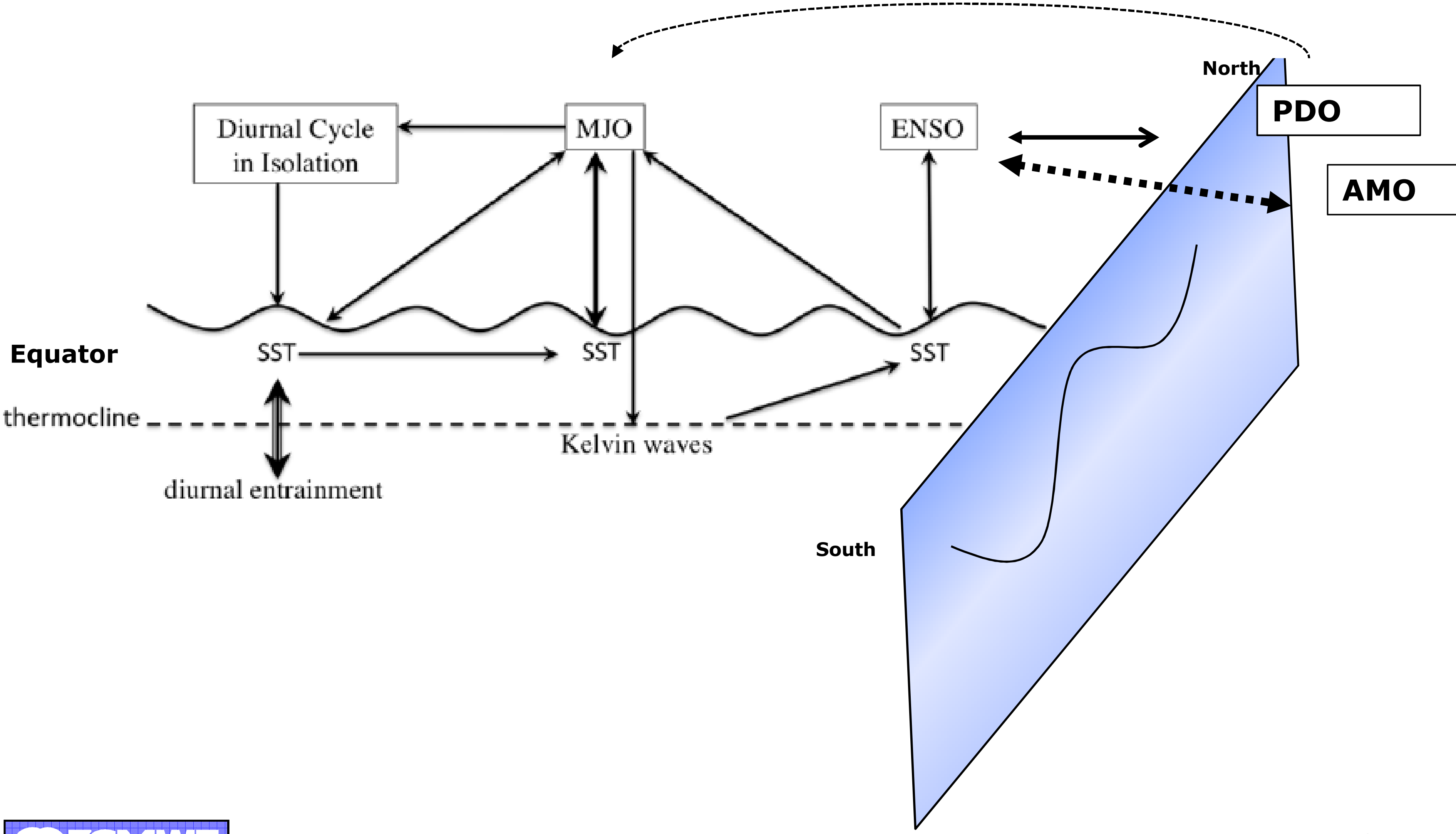
Turbulent Kinetic energy for mixng

days	weeks	Months/years	Decades and beyond
Boundary layer processes		**Equatorial Ocean Dynamics:**	**Subtropical Gyre, Rossby Waves, THC, MOC**
Tropical cyclones	**Madden-Julian Oscillation**	**ENSO, IOD**	**Pacific/ Atlantic Decadal Variability**
Surface waves	**Tropical Instability Waves**	**Seasonal ML variations: NAO?**	
Diurnal Cycle			

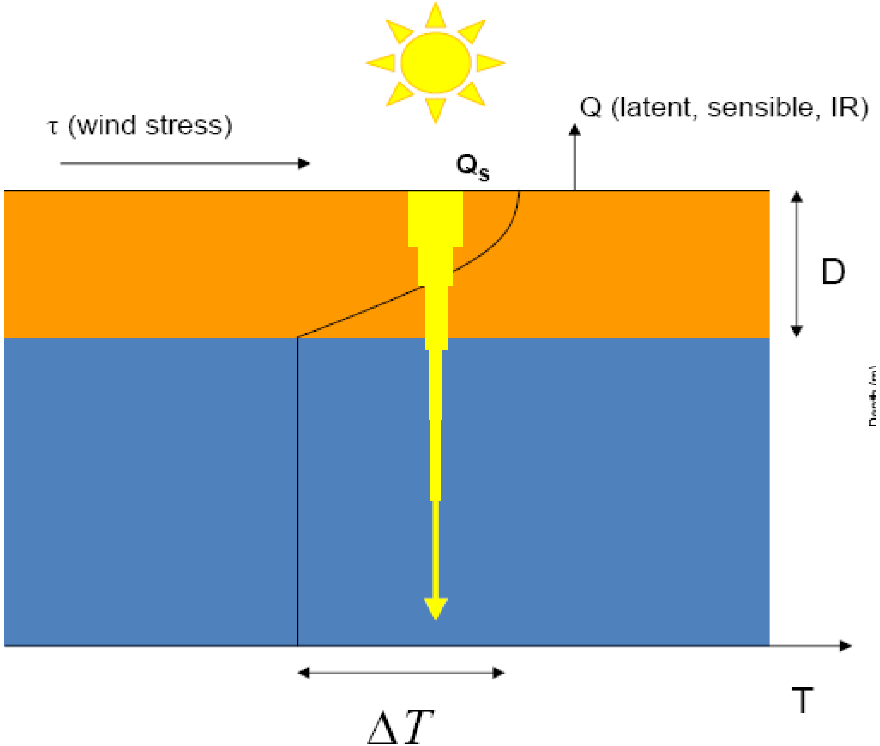
Air-Sea coupled modes and time scales

- **ENSO: Interannual**
  - Tropical — Dynamic/thermodynamic
  - Essential for Seasonal Prediction
- **MJO: Intraseasonal**
  - Tropical — Ocean mixed layer
  - Essential for Monthly Prediction
- **Seasonal Cycle**
  - Forced by the sun.
- **PDO, AMO: Decadal**
  - Tropical/midlatitudes — Deeper ocean dynamics
  - Decadal predictions
- **Diurnal:**
  - Tropical, summer — Ocean diurnal layer
- **Others: Tropical cyclones, SST fronts**

Air-Sea coupling: **Scale interaction**



Diurnal Warm Layers

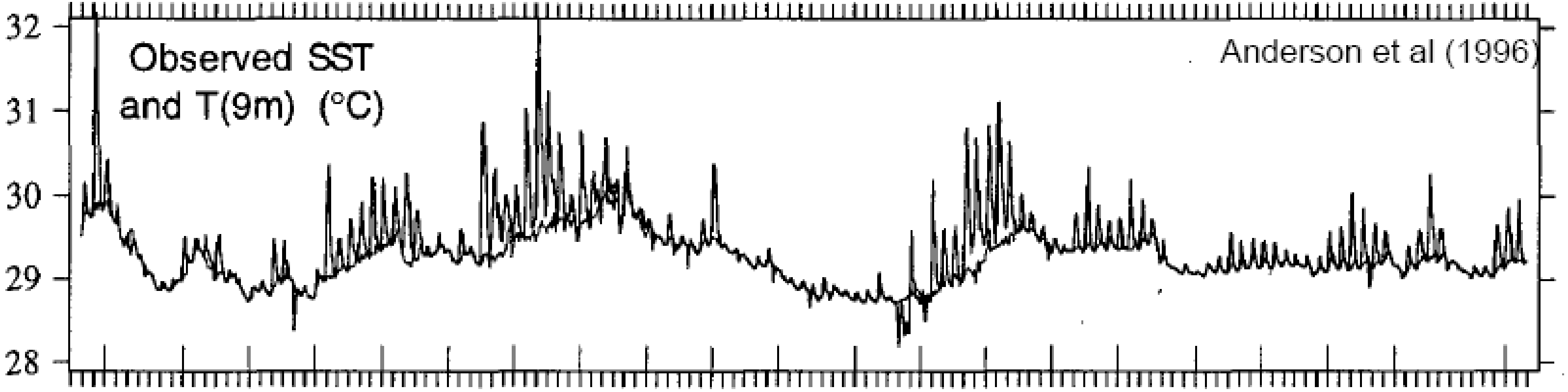


Stably stratified (warm) thin layers form during the day.

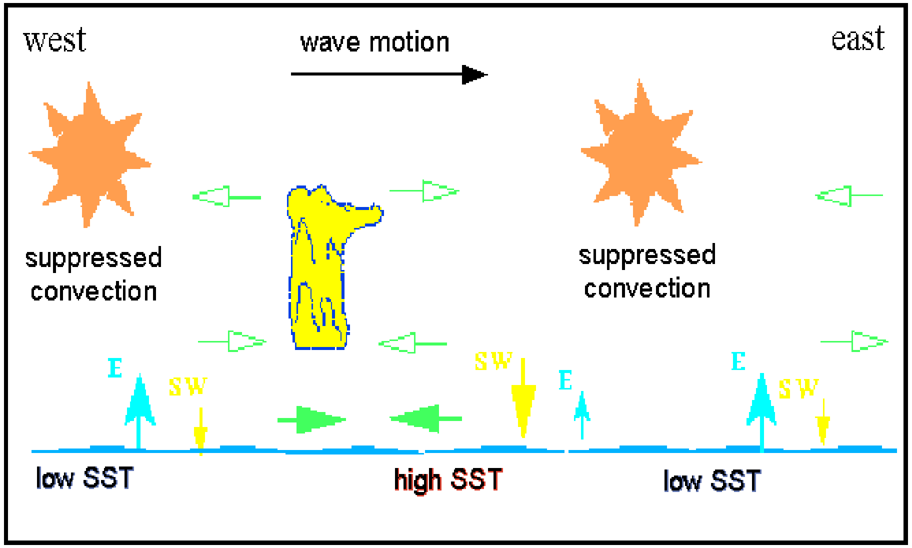
They isolate the deeper ocean by reducing vertical mixing.

The increase the value of peak temperature.

They trigger convection events, which can rectify in MJO



Madden-Julian Oscillation (MJO):30-60 days



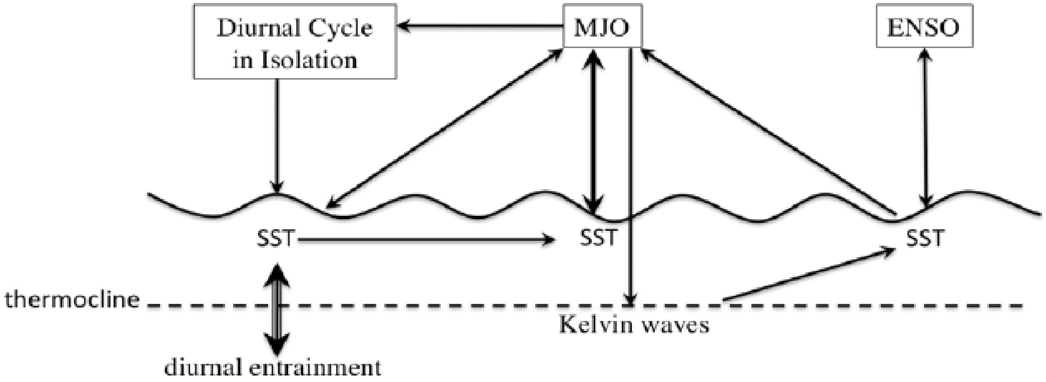
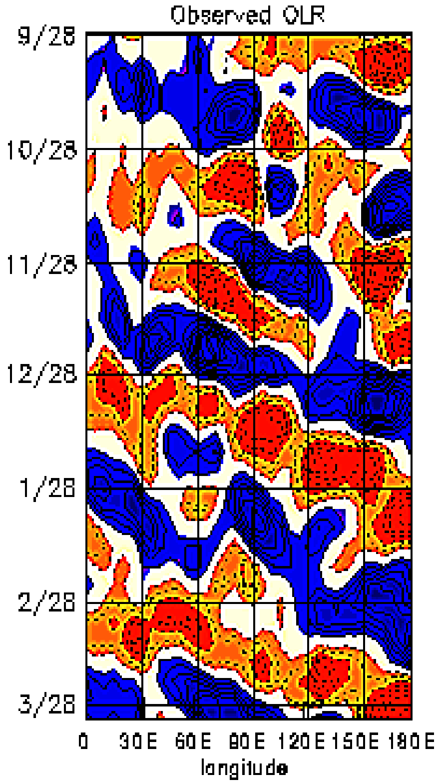
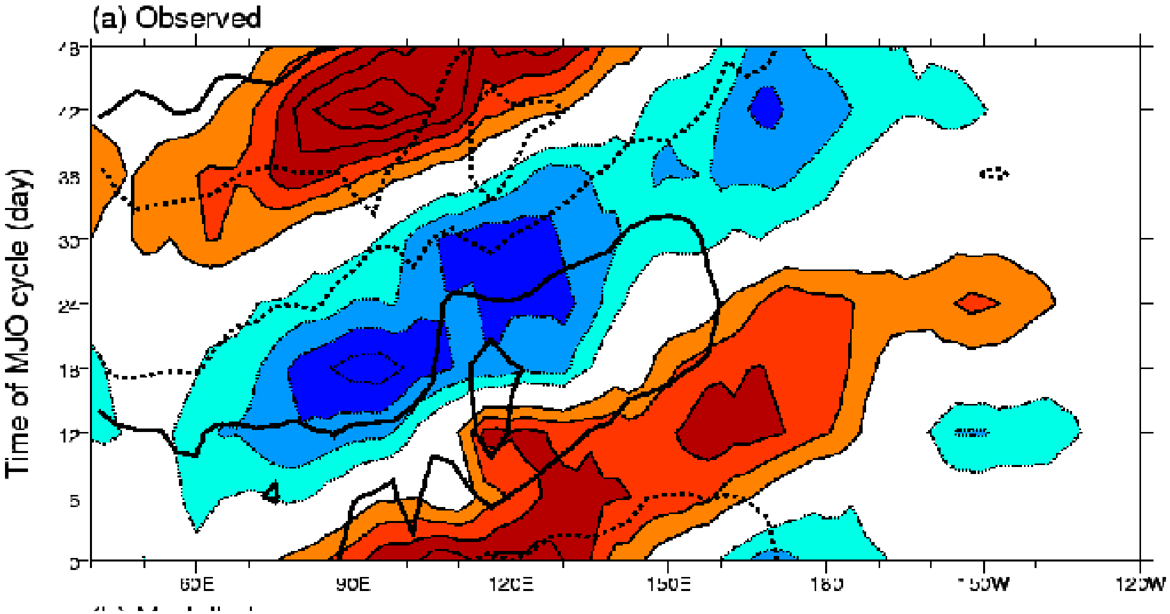


Figure 1: Schematic diagram of cross-scale air-sea interactions between the MJO and diurnal cycle and between the MJO and ENSO. Arrows denote directions of influences.



- Eastward propagating atmospheric disturbances associated to deep convection (see OLR above).
- Bridge connecting diurnal and interannual variability. They can trigger ENSO.
- Backbone of Monthly forecasts. Impacts NAO regimes

MJO: Coupled Mode

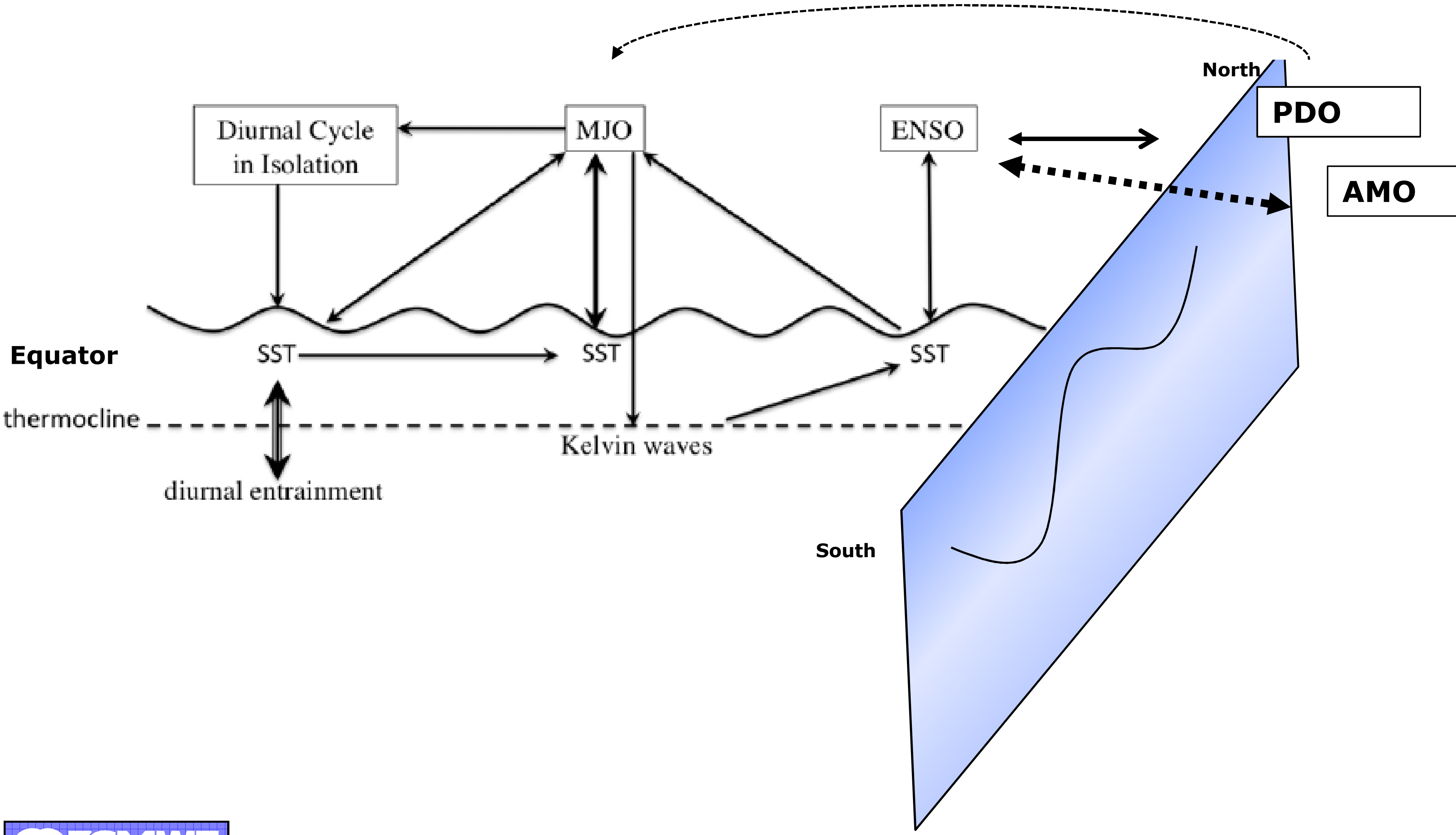

(a) Observed

Composites of SST anomalies (contours) and OLR (colours) of MJO events. SST and convection are in quadrature.

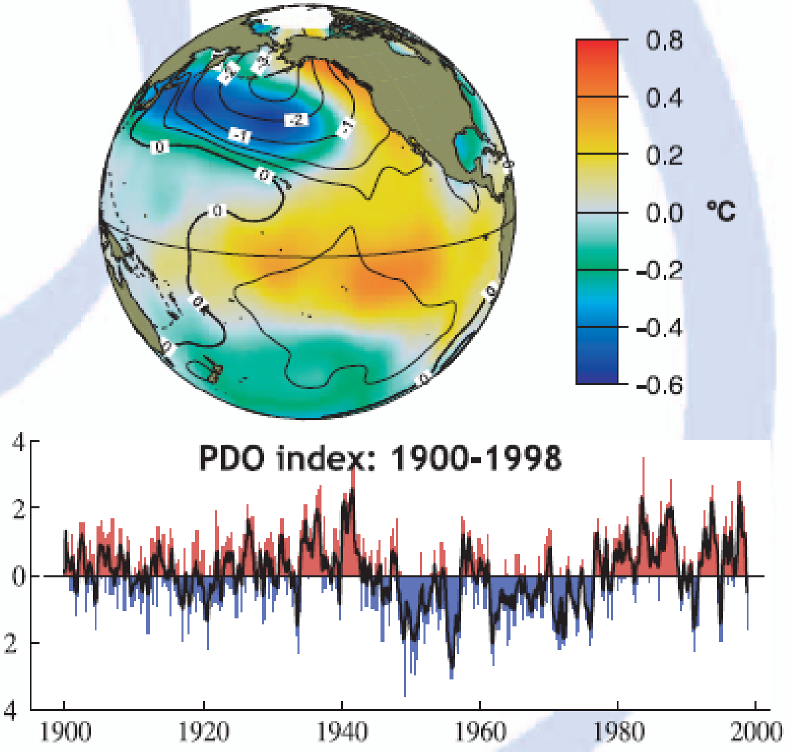
The lead-lag relationship between SST and deep convection seems instrumental for setting the propagation speed of the MJO.

A two way coupling is required. Thin ocean layers are needed to represent this phase relationship.

Air-Sea coupling: **Scale interaction**



Decadal: Pacific Decadal Oscillation



Structure of the PDO, and the PDO Time series.

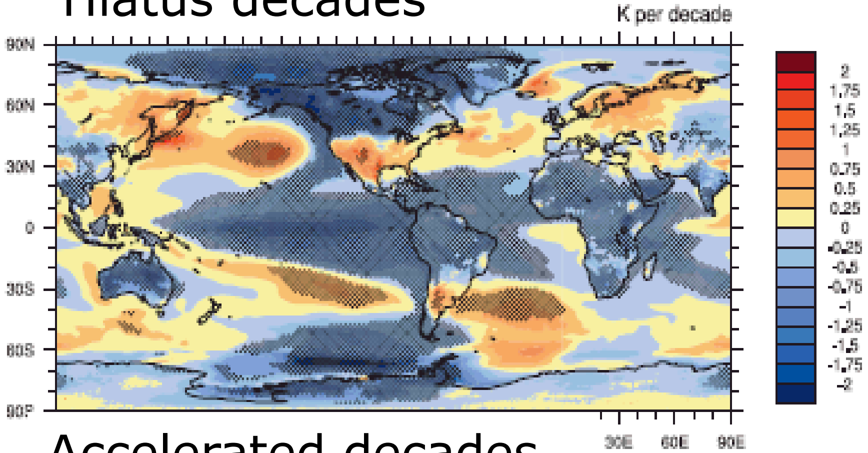
Considerable debate: Is it integrated red noise? Or a truly coupled mode?

- Influences marine ecosystems (Mantua et al 1997), North American rainfall (Latif and Barnet 1994,1996, Waliser 2008)
- Latif et al, using results from a coupled model, hypotesized there is a coupled feedback (meridional SST gradients and gyre circulation).
- Latif et al: there is no need of a coupled mode nor ocean dynamics to produce decadal variability.
- Link with ENSO decadal variability.
- More recently, link with heat absorption
- y

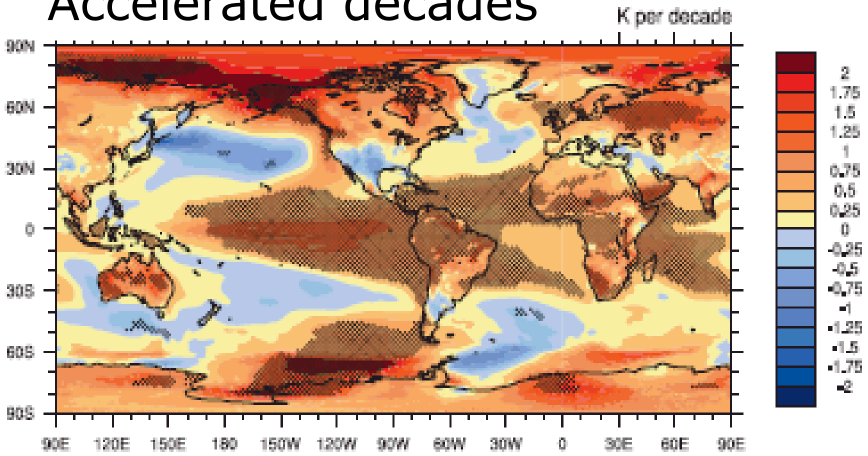
PDO, Hiatus decades and deep ocean warming

SST trends

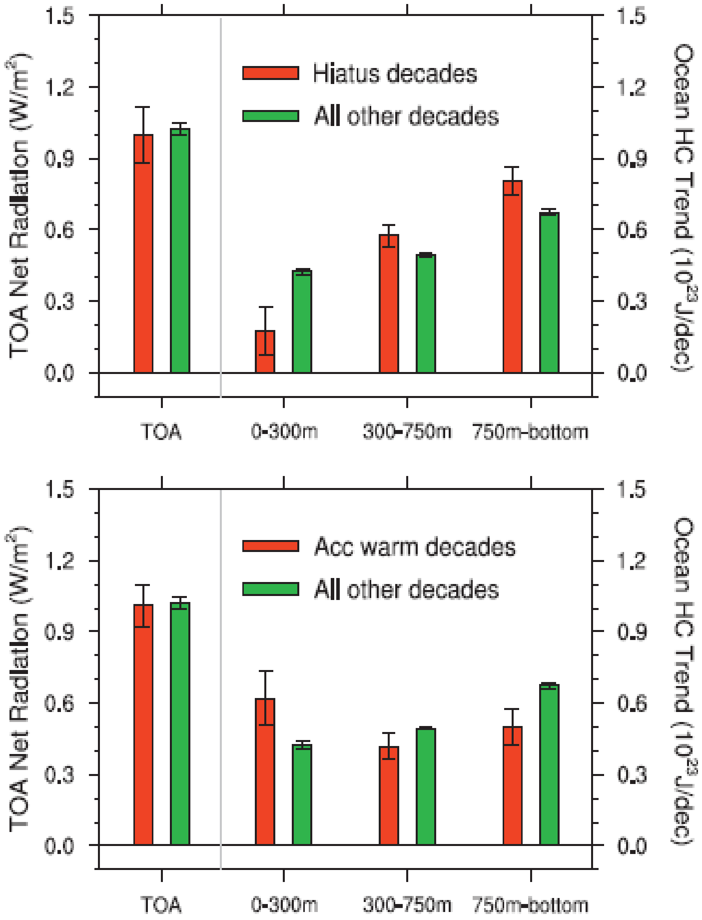
Hiatus decades



Accelerated decades



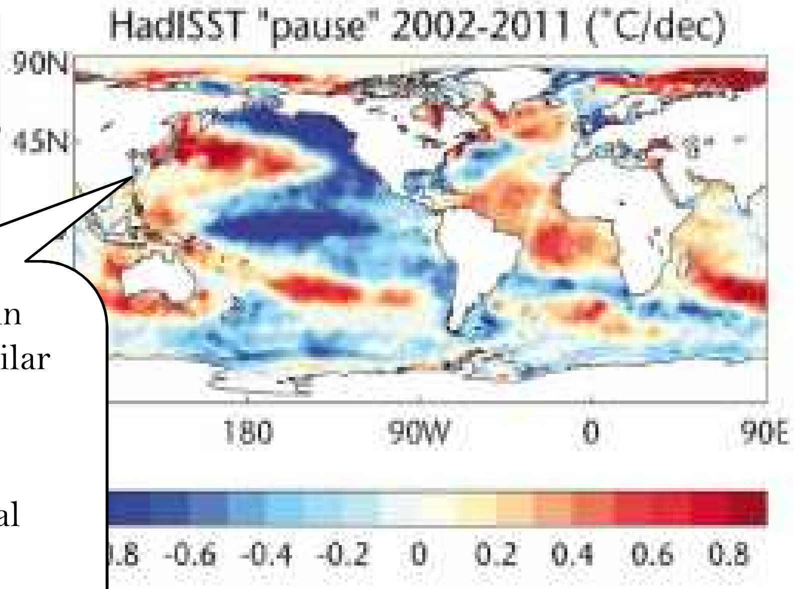
Warming Rates



Meehl et al 2011, NG, Meehl et al 2013, JClim

The warming penetrates deeper during the hiatus decades, with less surface warming (weaker stratification).
Stronger surface warming and stratification in accelerated decades.

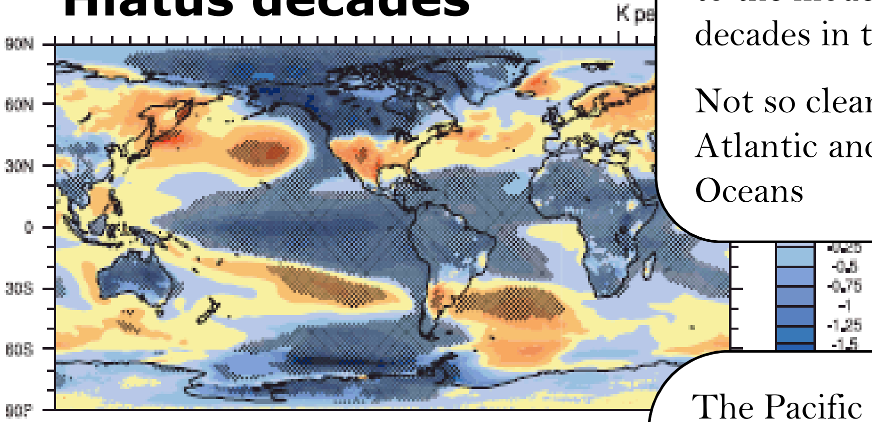
Hiatus from observations of SS



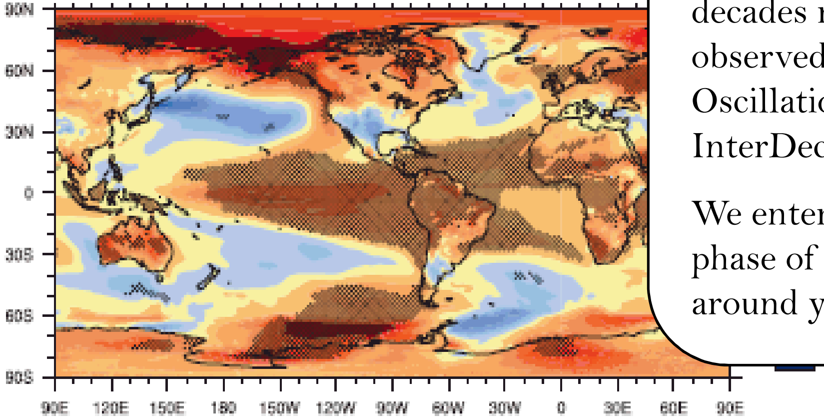
HadISST "pause" 2002-2011 (°C/dec)

Observed SST trends in the last decade are similar to the model hiatus decades in the Pacific.

Not so clear in Tropical Atlantic and Indian Oceans



Hiatus decades

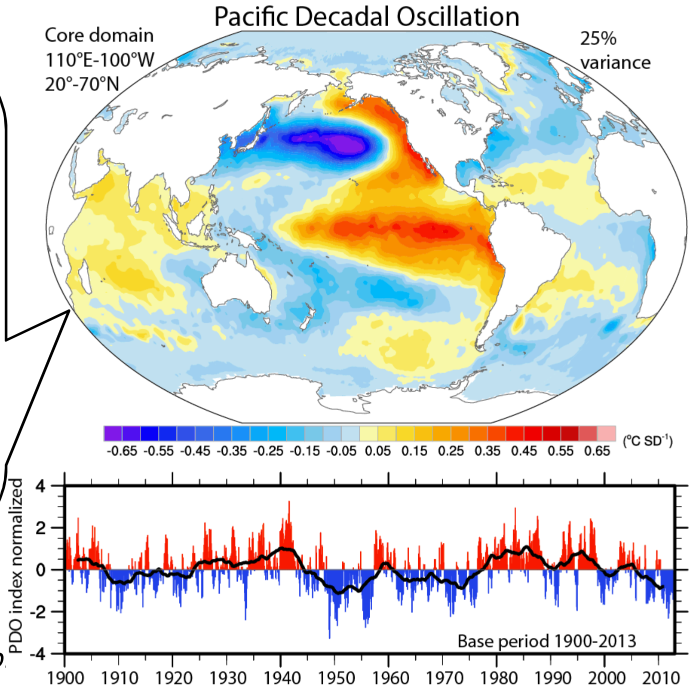


Accelerated decades

The Pacific SST structure of the accelerated decades resembles the observed Pacific Decadal Oscillation (or Pacific InterDecadal Oscillation)

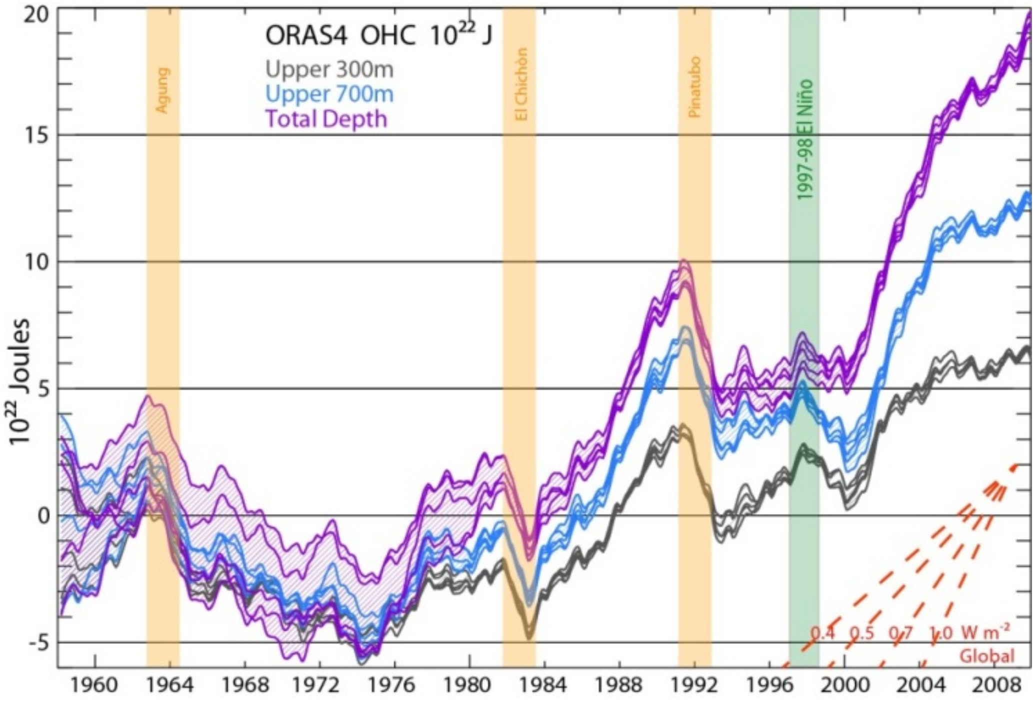
We entered the negative phase of the PDO/IPO around year 2000.

The PDO/IPO



Pacific Decadal Oscillation

Changes in ocean stratification?



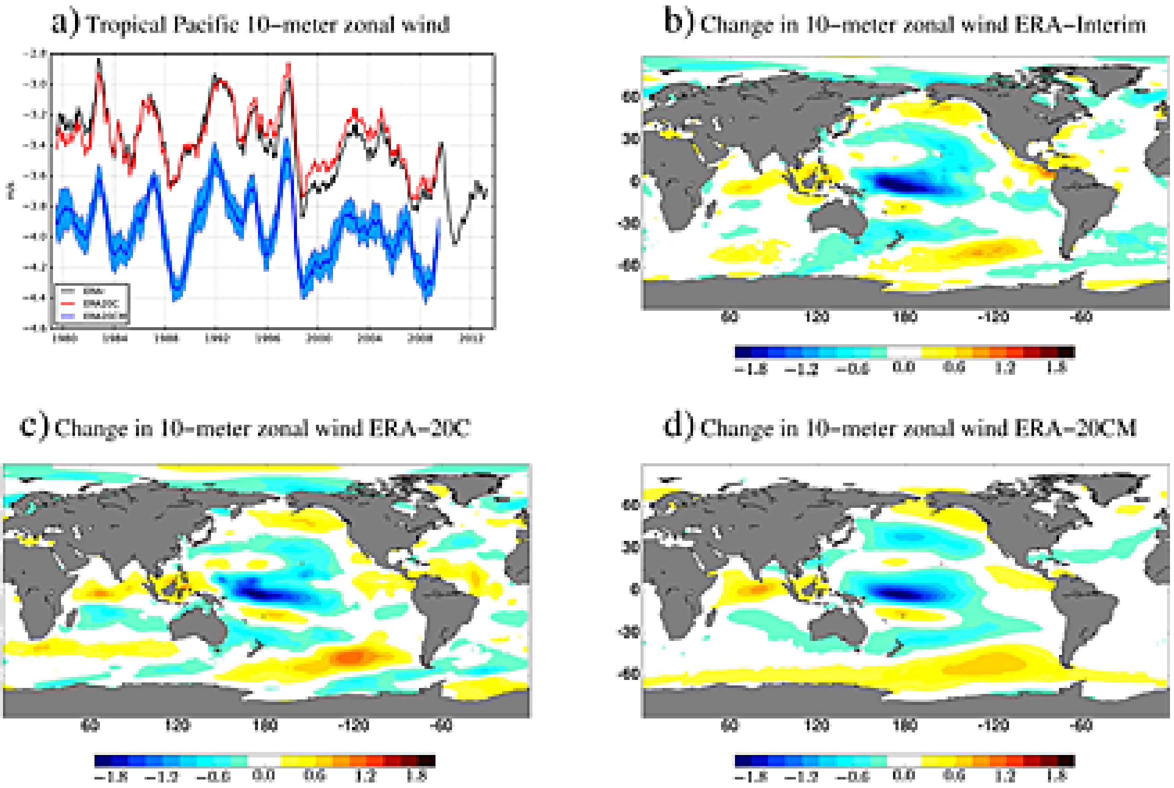
Recent hiatus in surface warming

Deep ocean heat uptake important for energy budget.

Which processes are involved in the increased ocean heat uptake?

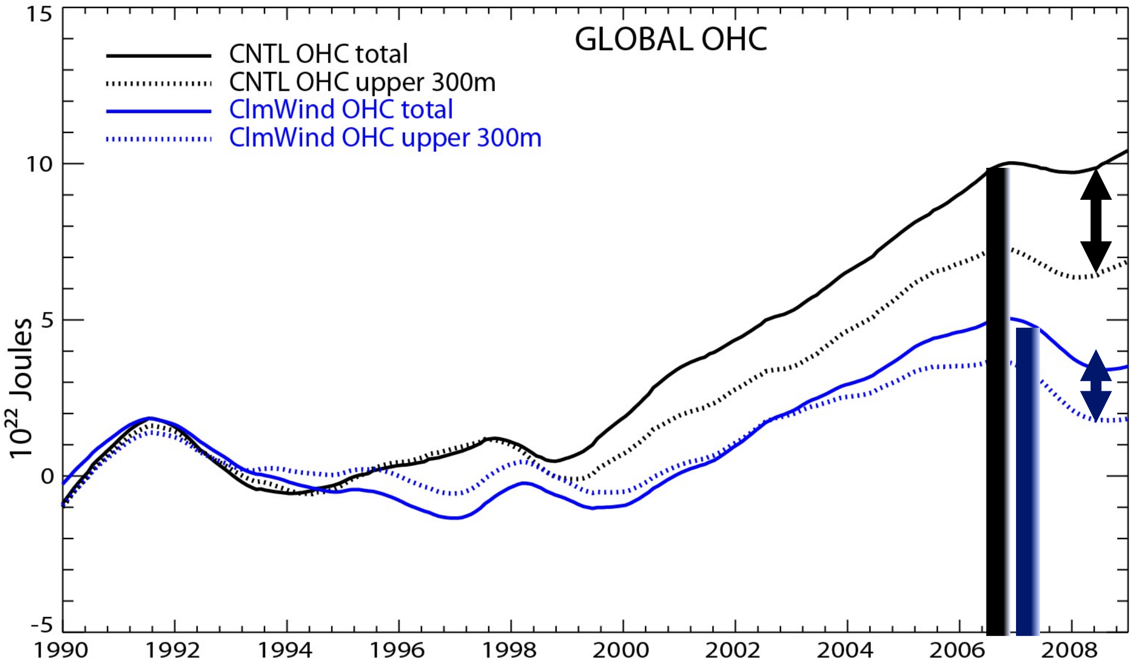
Balmaseda et al , GRL 2013,

How robust is the recent strengthening of the Tropical Pacific trade winds?



Geophysical Research Letters
Volume 41, Issue 12, pages 4398-4405, 26 JUN 2014 DOI: 10.1002/2014GL060257
http://onlinelibrary.wiley.com/doi/10.1002/2014GL060257/full#grl51808-fig-0001

Model Result: wind variability instrumental in ocean heat uptake.



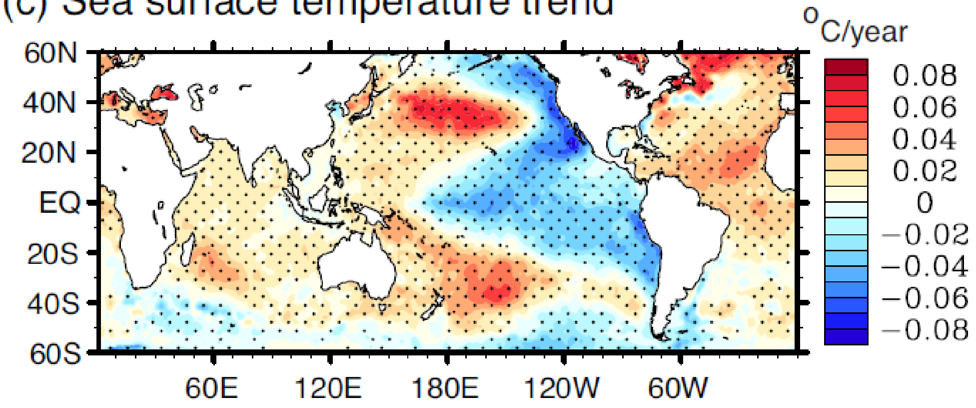
The total heat uptake by the ocean depends on the wind variability (stronger when variable winds)

% of heat stored in the deep ocean also increases with the wind variability. (The ocean stratification decreases)

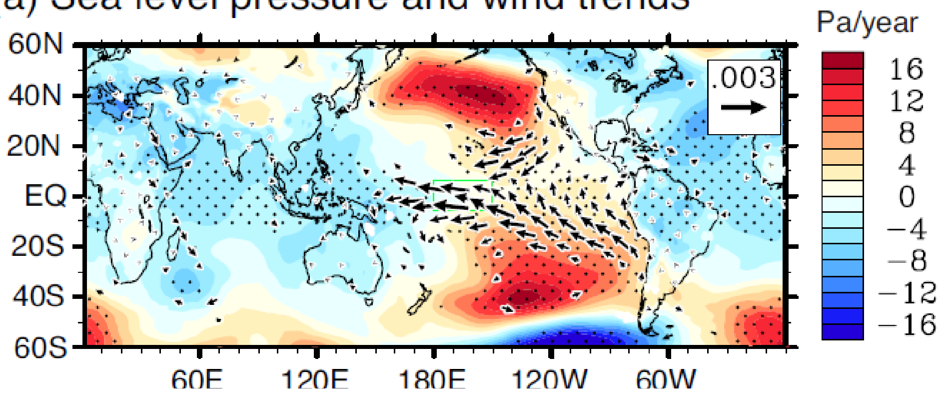
In both experiments the OHC increases around year 2000. Something else going on?... The AMOC decreases around that time in both experiments (not shown)

PDO and wind driven circulation

(c) Sea surface temperature trend



(a) Sea level pressure and wind trends



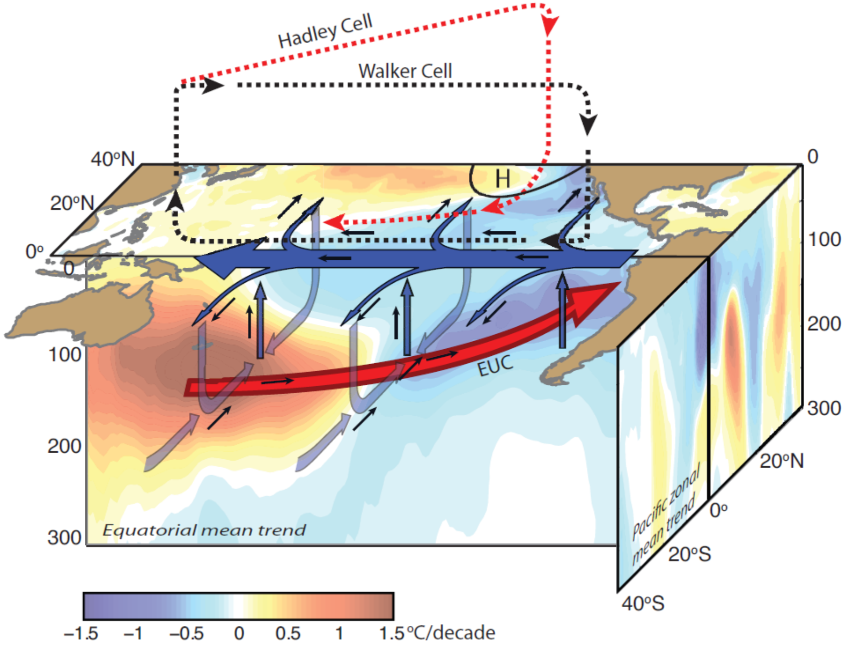
From England et al 2014

Intensified Walker circulation steepens the Equatorial Thermocline.

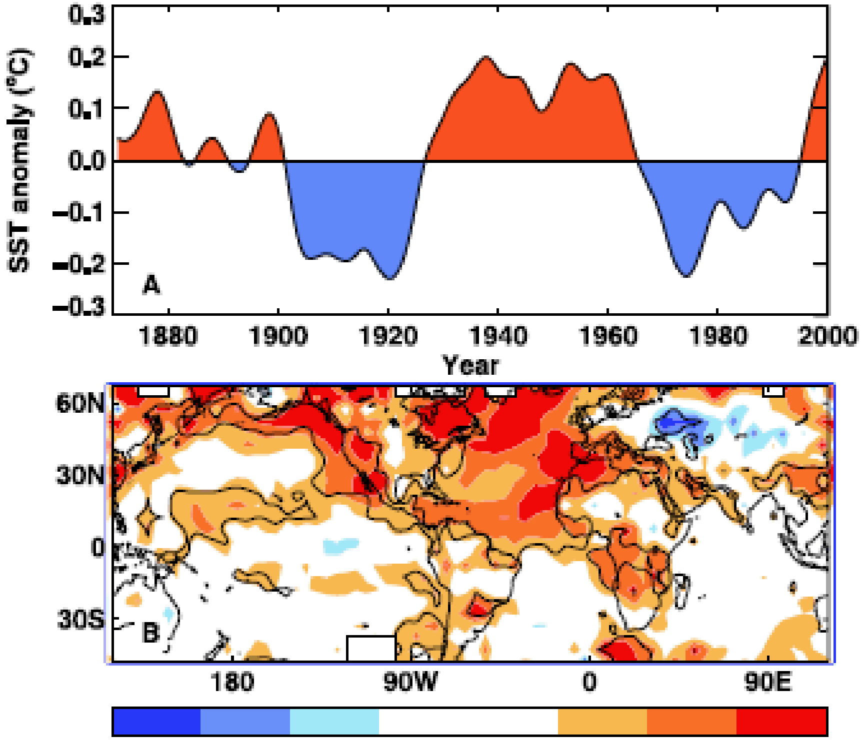
Intensified Hadley circulation, stronger gyres.

Stronger-deeper Ekman pumping and subduction.

Stronger Poleward heat transport.



Atlantic Multidecadal Oscillation: AMO



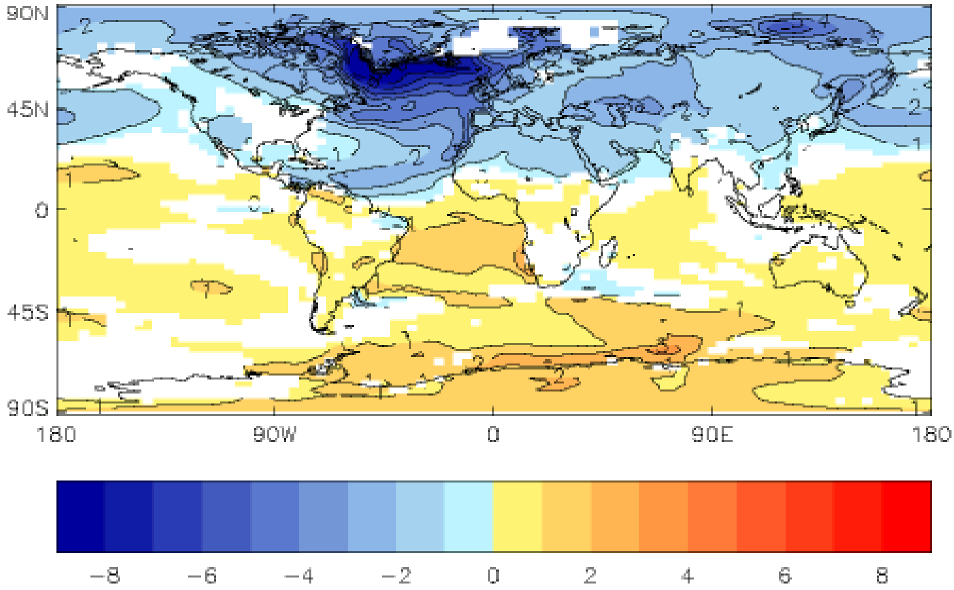
From King et al 2005

- Changes in the AMO linked to NE Brazil and Sahel rainfall, North Atlantic hurricane frequency, European and North American climate
    - Warm AMO phase during the 40-50’s associated to decreased NE Brazil rainfall, increased Sahel rainfall, increased hurricane frequency

- Evidence from observations and model studies.

- It appears connected to the AMOC (Atlantic Meridional Overturning circulation)

Sensitive to the Stability of the THC



Vellinga and Wood 2002:

Surface Air Temperature change 20-30 years after the THC slowdown by large fresh water input. The THC recovers after 120 years

Bryden et al 2005 suggested the slowing down of the AMOC based on 5 snapshots But large uncertainty due to possible aliasing

RAPID program is monitoring the AMOC at 26N since 2004.

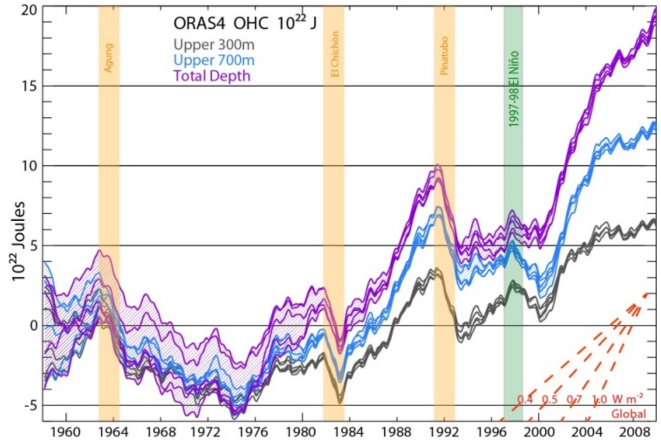
But this is not long enough. It needs to be sustained.

Estimation of the AMOC using models and data assimilation is a big challenge

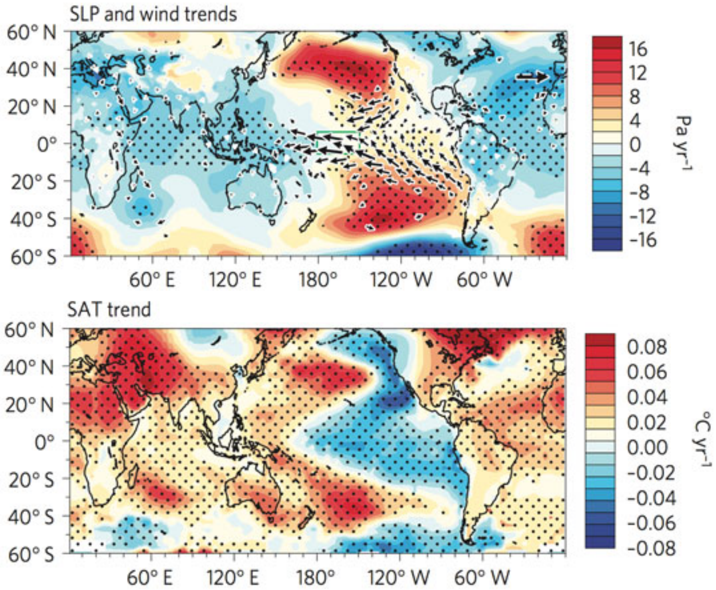
Recent work advocating for the acceleration of the AMOC?

Changes in ocean stratification?

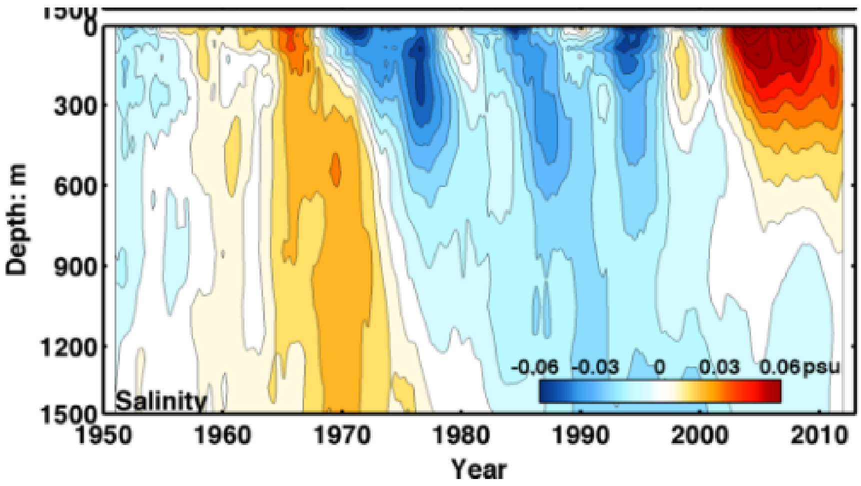
- Deep ocean heat uptake important for energy budget.
- Ocean circulation determines the heat uptake (Wind driven? THC?)
- Atlantic versus Pacific Ocean



Pacific, Wind driven (England et al 2014)



Atlantic, Salinity driven (Tung and Chen 2014)



Interannual Time scales: ENSO

ENSO: El Nino -Southern Oscillation

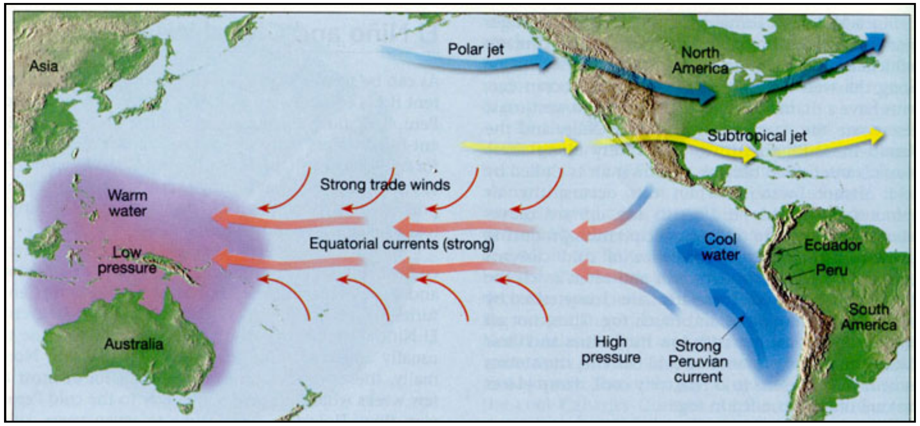
Largest mode of O-A interannual variability

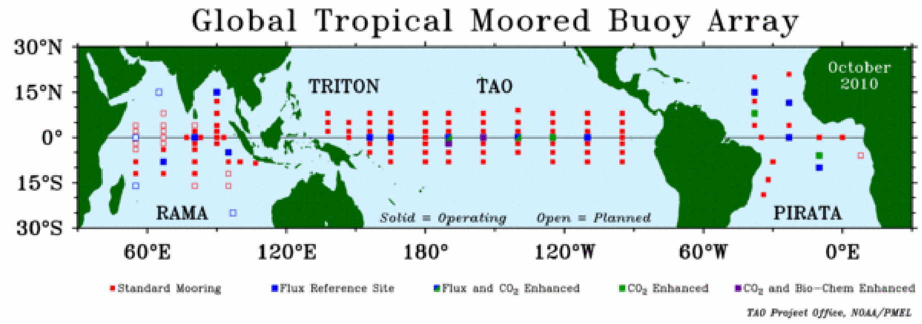
Best known source of predictability at seasonal time scales

It affects global patterns of atmospheric circulation, with changes in rainfall, temperature, hurricans, extrem events

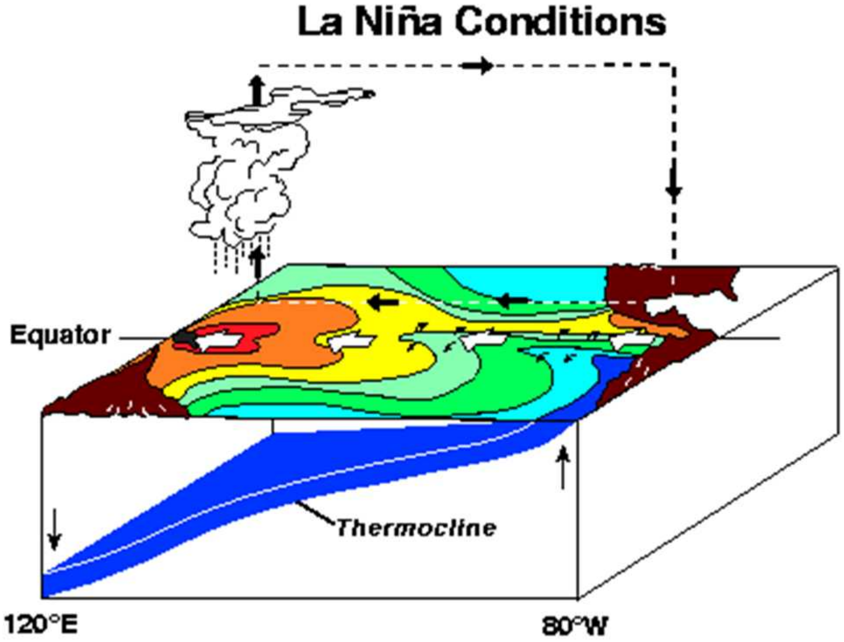
Main Characters:

- **Walker 1924, 1928** : Southern Oscillation Darwin-Tahiti
- **Peruvian fishermen:** El Nino current interannual variability
- **Bjerkness 1966, 1969:** EN-SO Coupled Ocean Atmosphere interaction and positive feedback
- **Wirtky 1975:** Western Pacific Sea level as a predictor of El Nino (Kelvin wave propagation)
- **Conceptual models of ENSO 80's.** (Anderson and McCreary, Schopf and Sarez, Cane and Zebiak, Battisti and Hirst). Encompassed by Jin, JAS,1997
- **90's Development of coupled GCMs**
- **90'sTAO array:** Back-bone of the ENSO observing system

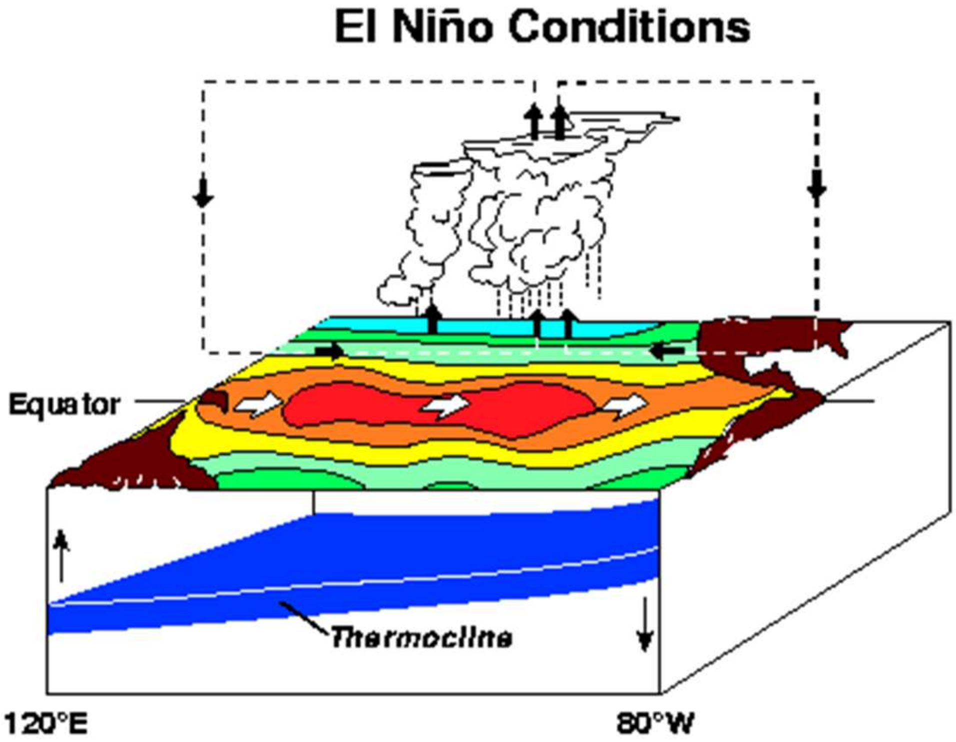




EL Nino (warm) and La Nina (cold)



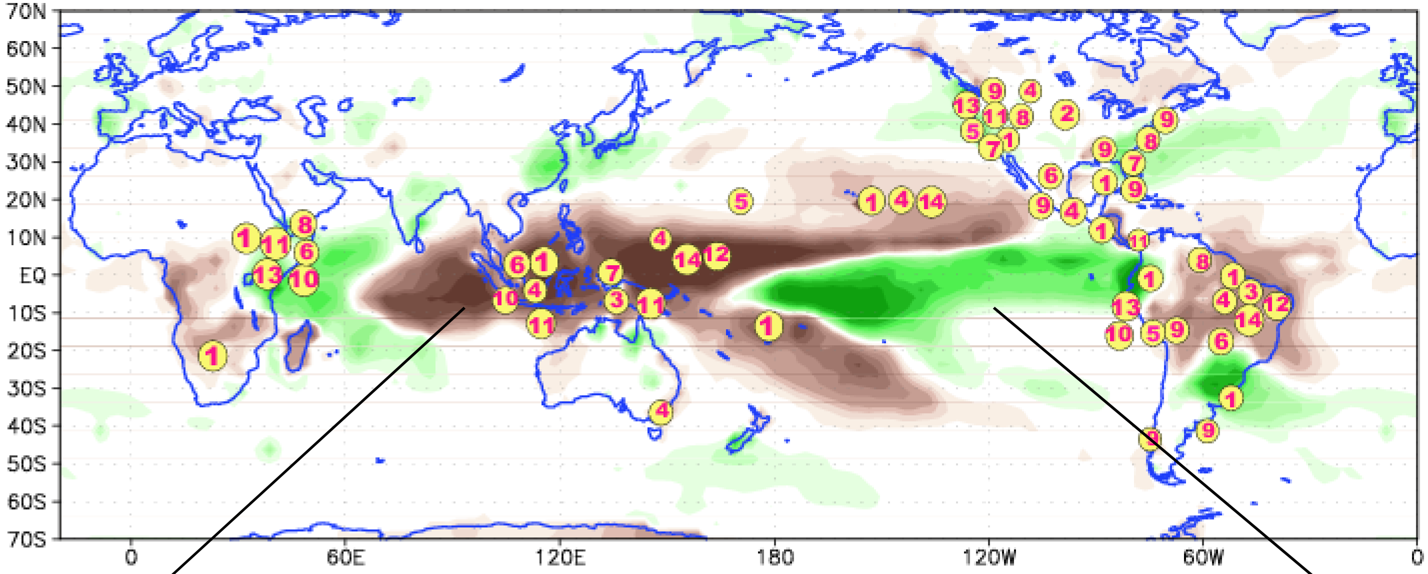
El Nino is associated with reduced easterly (maybe even westerly) winds at the surface, a reduced thermocline slope and warm water in the east.



Normal/La Nina is associated with strong(er) easterly winds at the surface, a stronger thermocline tilt and cold water in the east.

El Niño and Large Scale Precipitation

Societal Impacts from 1997/98 El Niño



1. Crop/Stock Damage
2. Energy Savings
3. Famine
4. Fires
5. Fisheries Disruption
6. Health Risks
7. Human Fatalities
8. Pests Increased
9. Property Damage
10. Tourism Decreased
11. Transportation Problems
12. Social Disruptions
13. Wildlife Fatalities
14. Water Rationing

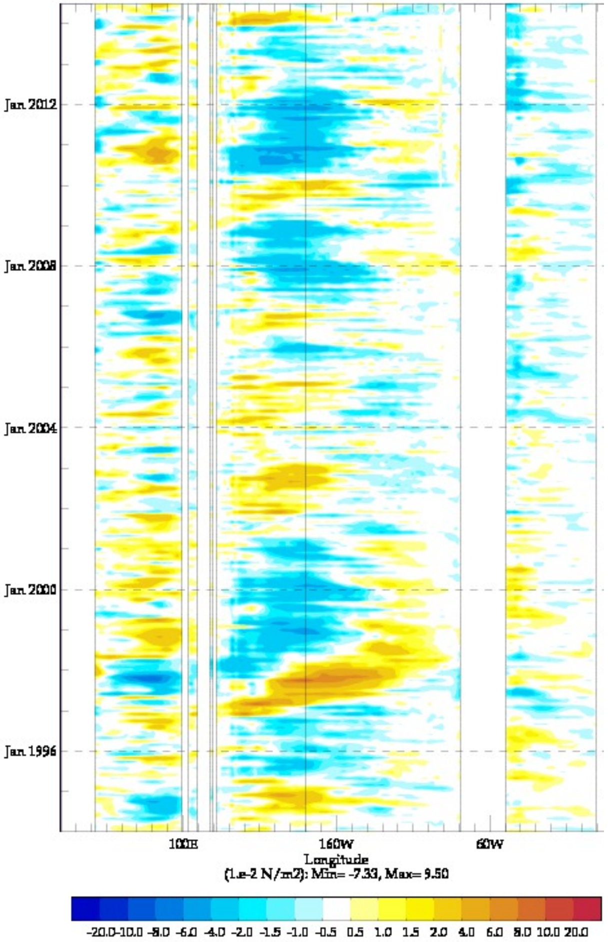
Decreased
Precipitation

Increased
Precipitation

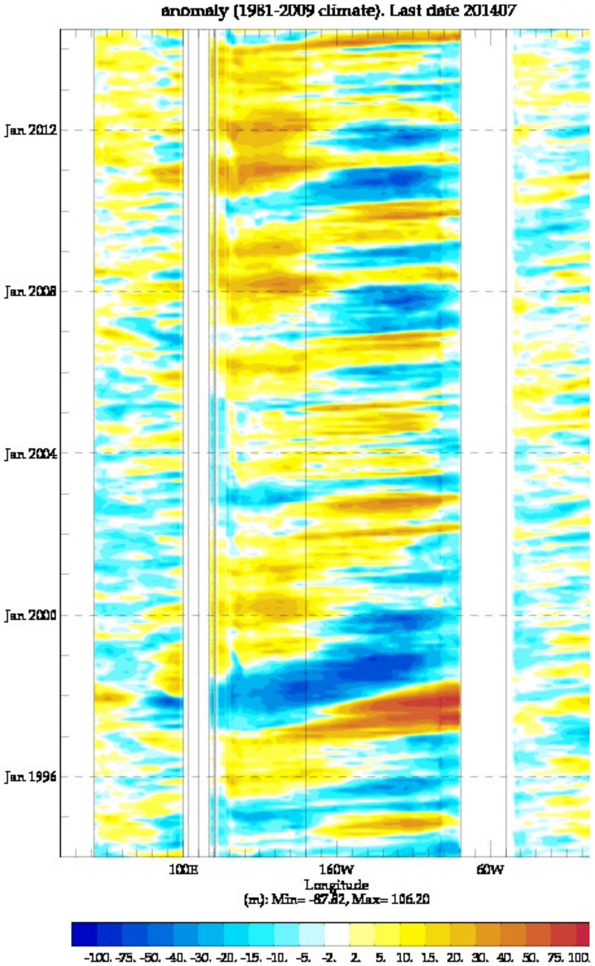
Climate Prediction Center

Last 20 years of Equatorial Anomalies

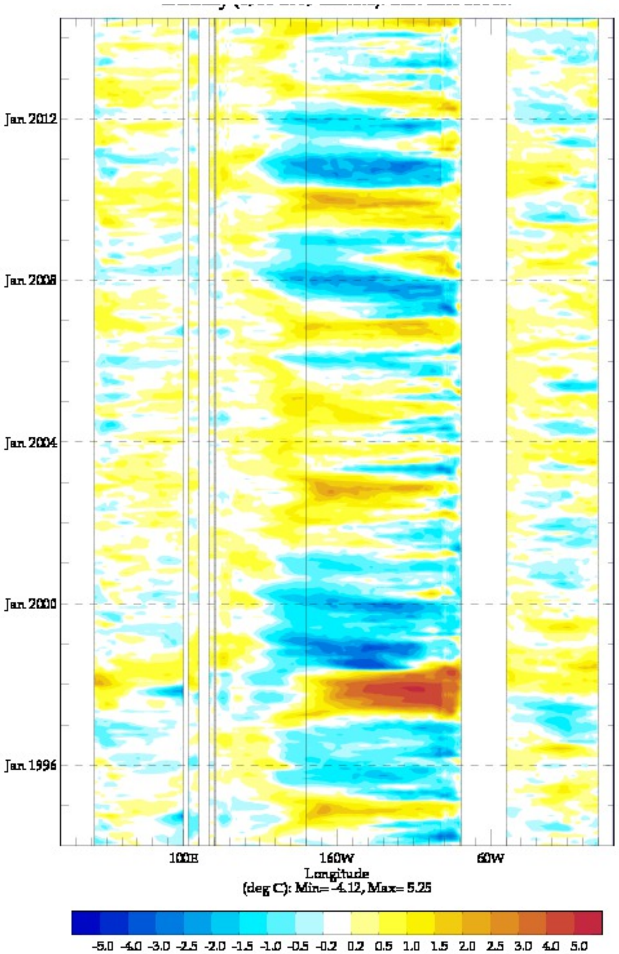
Taux Anomalies



D20 Anomalies



SST Anomalies



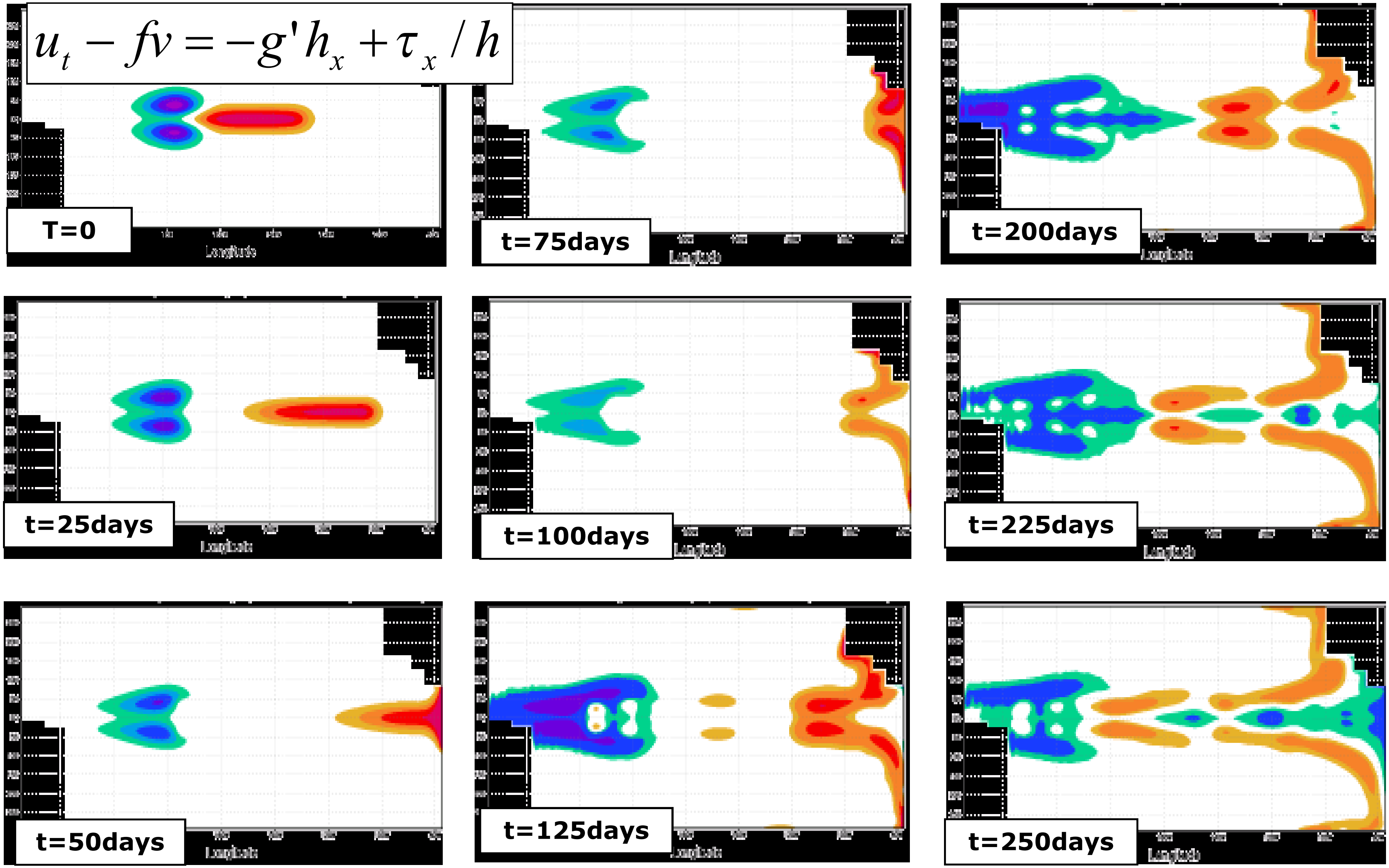
Note the strong 1997-8 El Nino and 1998-9 La Nina in Taux, D20 and SST

After them, ENSO has shown short-cycles of Central Pacific anomalies (no reaching the East Coast)

Until 2014, when a strong Kelvin wave was generated….

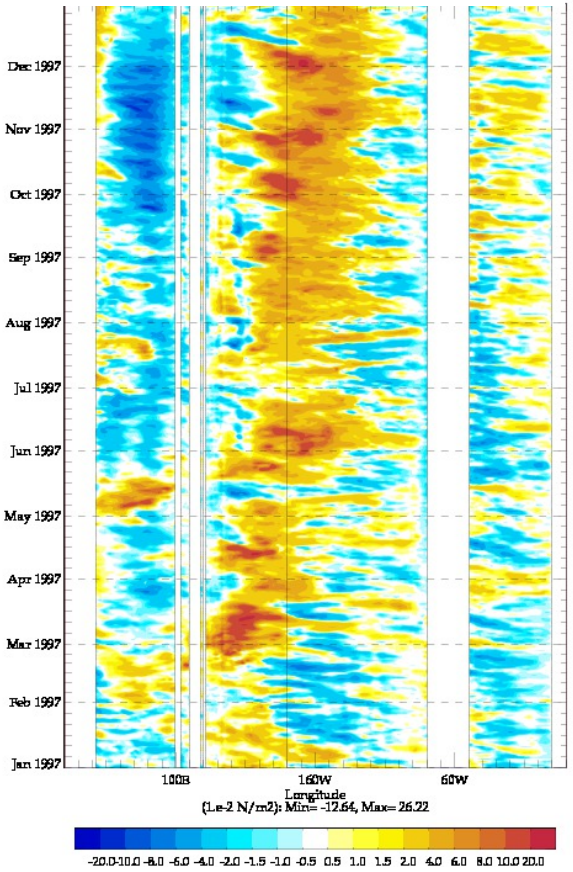
Kelvin & Rossby waves and Delayed Oscillator

$$u_t - fv = -g' h_x + \tau_x / h$$

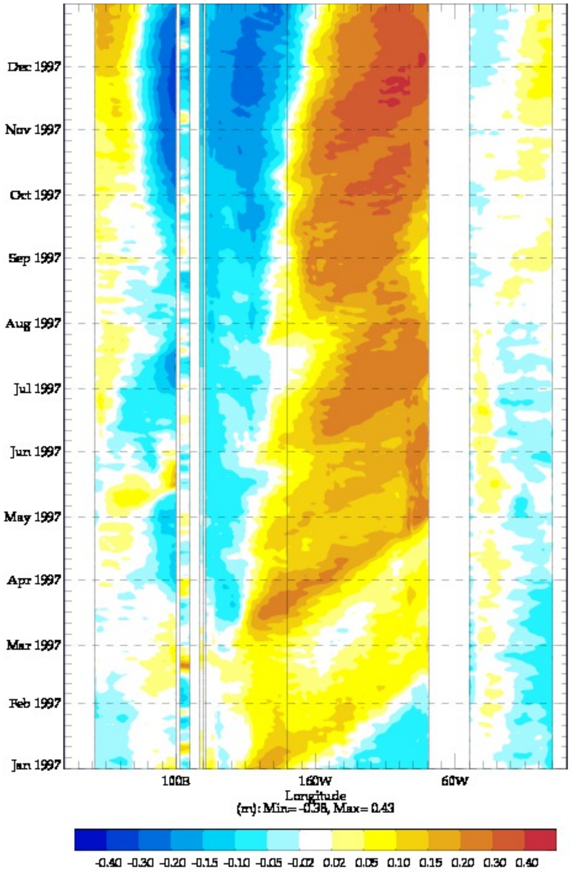


Daily Equatorial Anomalies: Jan 1997-Jan 1998

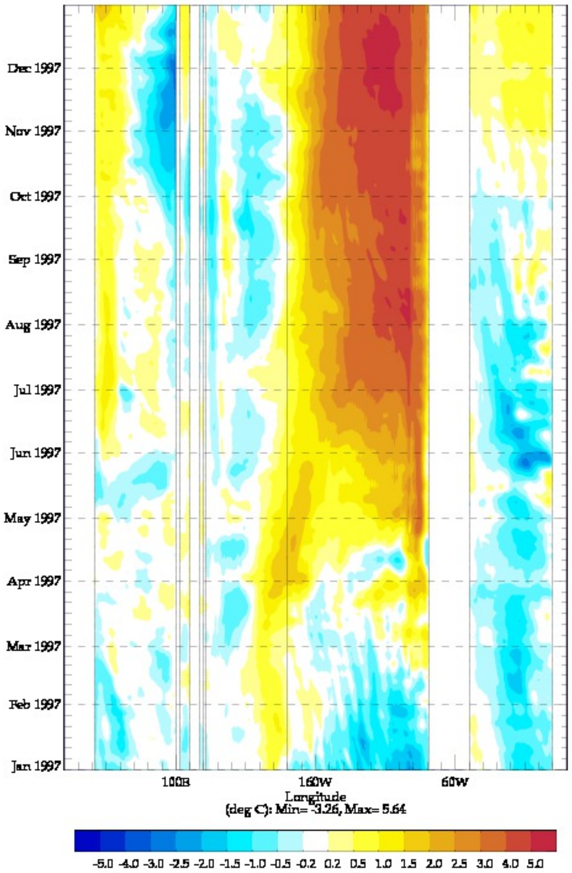
Taux Anomalies



SL Anomalies



SST Anomalies



March 1997@ Strong Westerly Wind bursts (WWB) in the West Pacific.

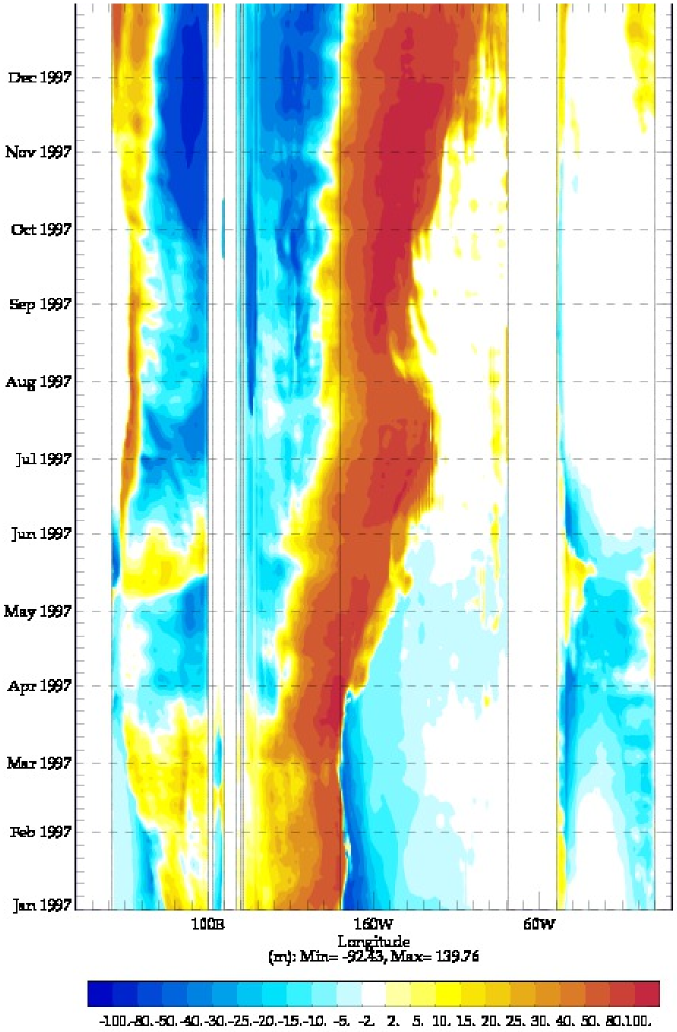
Associated eastward propagating groups of Kelvin waves. The latest reaching the Eastern Coast

SST anomalies develop in the West (as a displacement off the warm pool), and in the East, when the Kelvin waves arrive and depress the thermocline

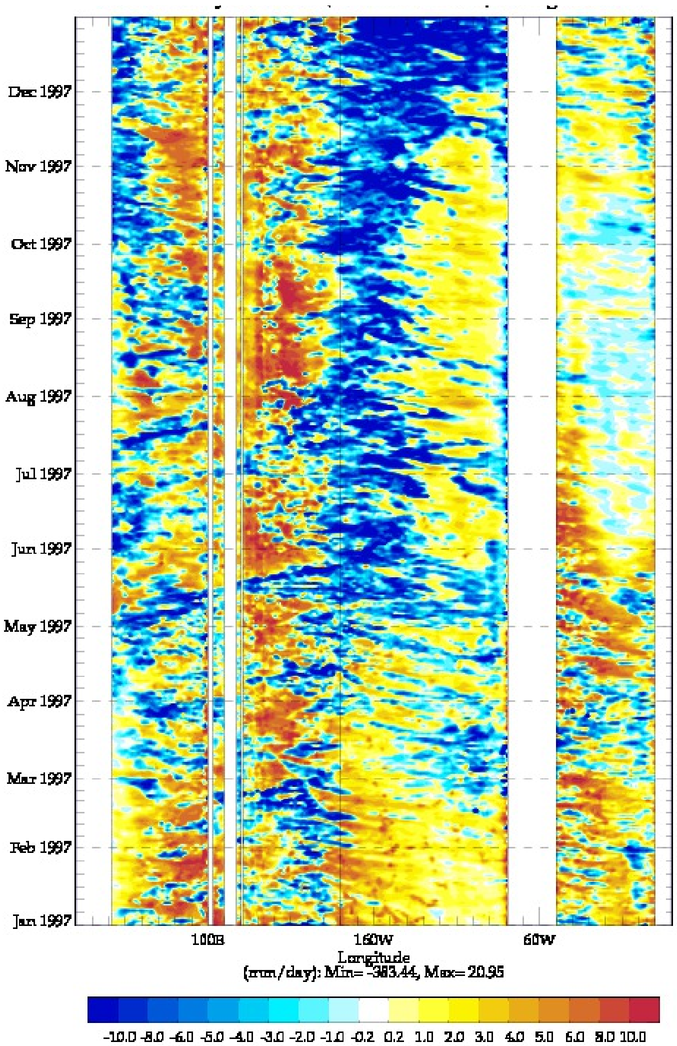
May/June 1997: More WWB . Or is this already ENSO? Bjerknes feedback in action.

Daily Equatorial Anomalies: Jan 1997-Jan 1998

D28 Anomalies
“Warm Pool”

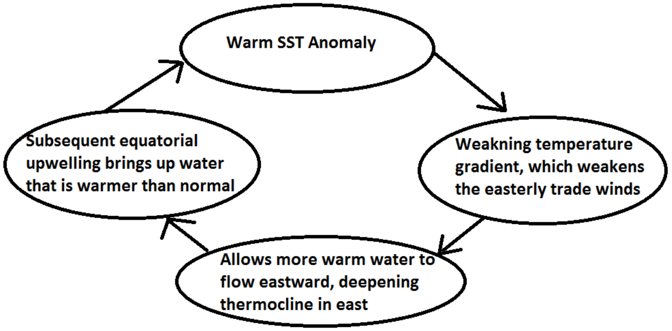


Fresh Water Flux Anomalies
Blue is into the ocean



Warm pool moves to the Central Pacific, taking with it the Atmospheric Deep Convection and Rainfall

Flora and Fauna for conceptual models for EL Nino

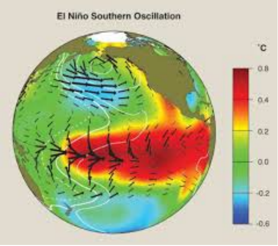

Warm SST Anomaly

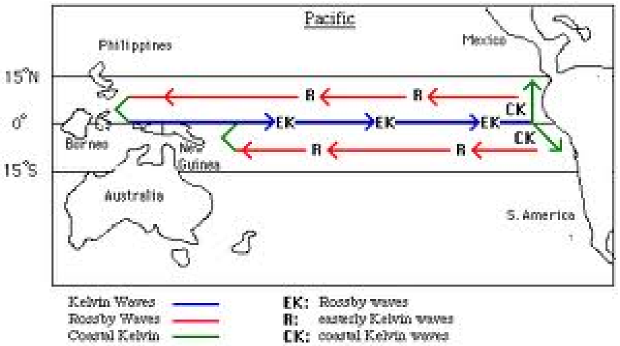
Weakning temperature gradient, which weakens the easterly trade winds

Allows more warm water to flow eastward, deepening thermocline in east

Subsequent equatorial upwelling brings up water that is warmer than normal

Bjerknes Feedback
+
Equatorial Waves





1. **Delayed Oscillator Mechanism: BF+ Resonant Basin mode**
   It does not explain the “a-periodicity”. Mostly adiabatic

2. **System switching between 2 equilibriums.**
   Switch is external: seasonal cycle, stochastic

3. **Coupled Instability, stochastically triggered.**
   Very unpredictable? How does it end?

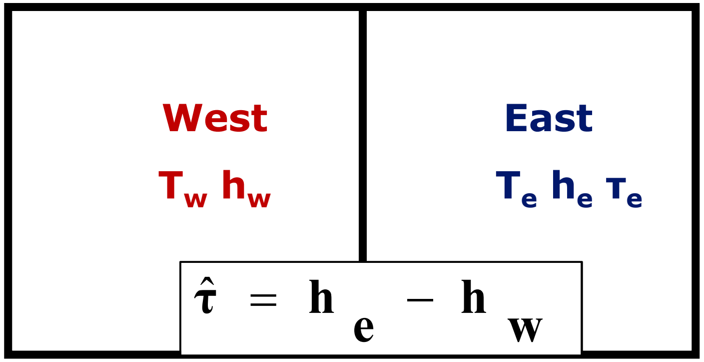
4. **All of the above. Discharge/recharge mechanism**

Recharge/Discharge mechanism

$$\frac{dh_W}{dt} = -rh_W - \alpha\hat{\tau}.$$

$$\frac{dT_E}{dt} = -cT_E + \gamma h_E + \delta_s \tau_E.$$

$$\hat{\tau} = bT_E, \quad \tau_E = b' T_E,$$



West

T_w h_w

East

T_e h_e τ_e

$$\hat{\tau} = h_e - h_w$$

R describes the Bjerkness Feedback for tropical ocean-atmosphere interaction. It leads to instability when

$$(R - r)/2 > 0$$

αbγ is the recharge/discharge mechanism, leading to oscillations for real **ω**

$$\bar{\omega} = \sqrt{\alpha b \gamma - (r + R)^2/4}$$

$$\boxed{\begin{aligned} \frac{dh_W}{dt} &= -rh_W - \alpha b T_E \\ \frac{dT_E}{dt} &= RT_E + \gamma h_W, \\ R &= \gamma b + \delta_s b' - c \end{aligned}}$$

μ Is the coupling intensity

$$b = b_0 \mu,$$

F.F Jin, Parts I and II, JAS, 1997

Kind of solutions

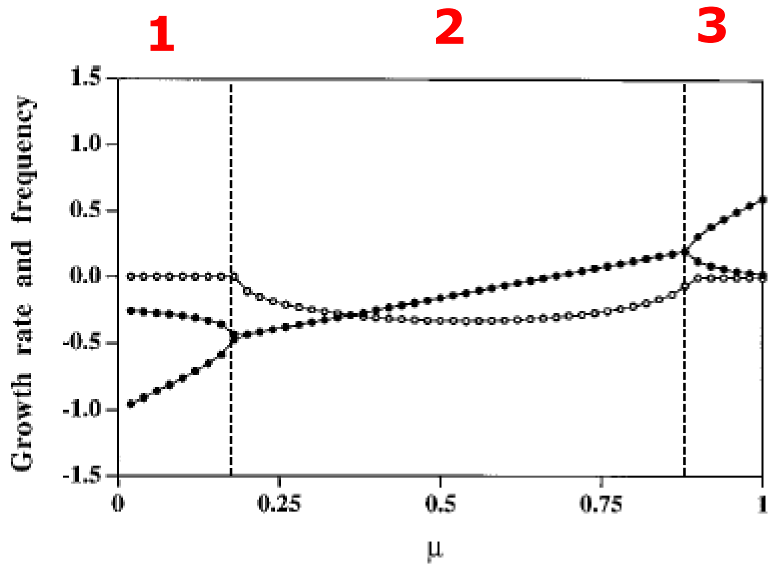


FIG. 2. Dependence of the eigenvalues on the relative coupling coefficient. The curves with dots are for the growth rates, and the curve with circles is for the frequency when the real modes merge as a complex mode (corresponding periods in years equal $\pi/3$ divided by the frequencies).

1. **Weak coupling: 2 decaying modes**
2. **Medium coupling: Oscillations**
3. **Strong coupling: 2 unstable modes**

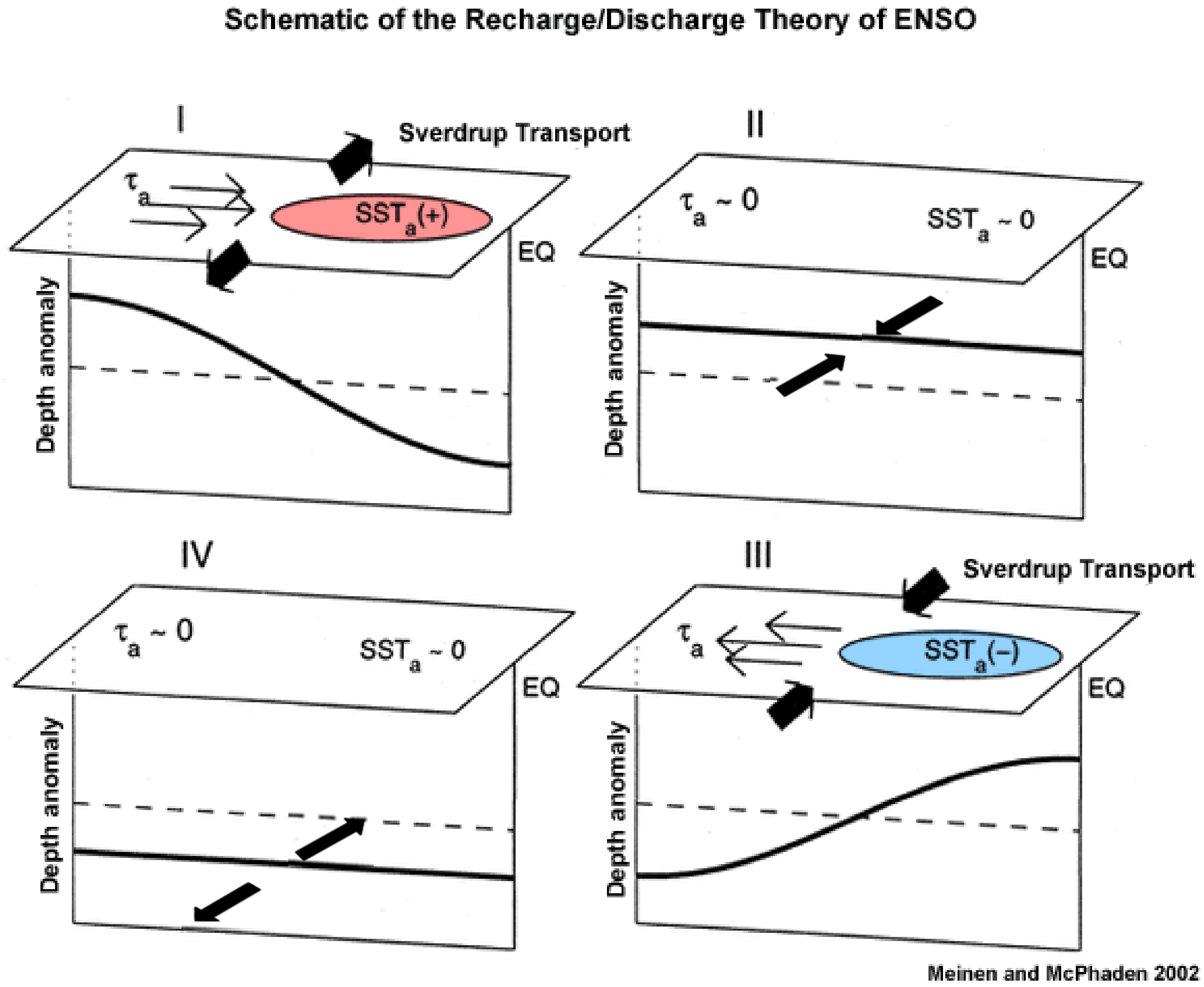
The parameters depend on the background ocean state

The presence of bifurcation leads to chaotic behaviour

Generalizations can include:

- **Seasonal cycle**
- **Stochastic forcing**
- **Kelvin waves**

Recharge/Discharge mechanism



F.F Jin, Parts I and II, JAS, 1997

El Nino Feedbacks: A complex Story

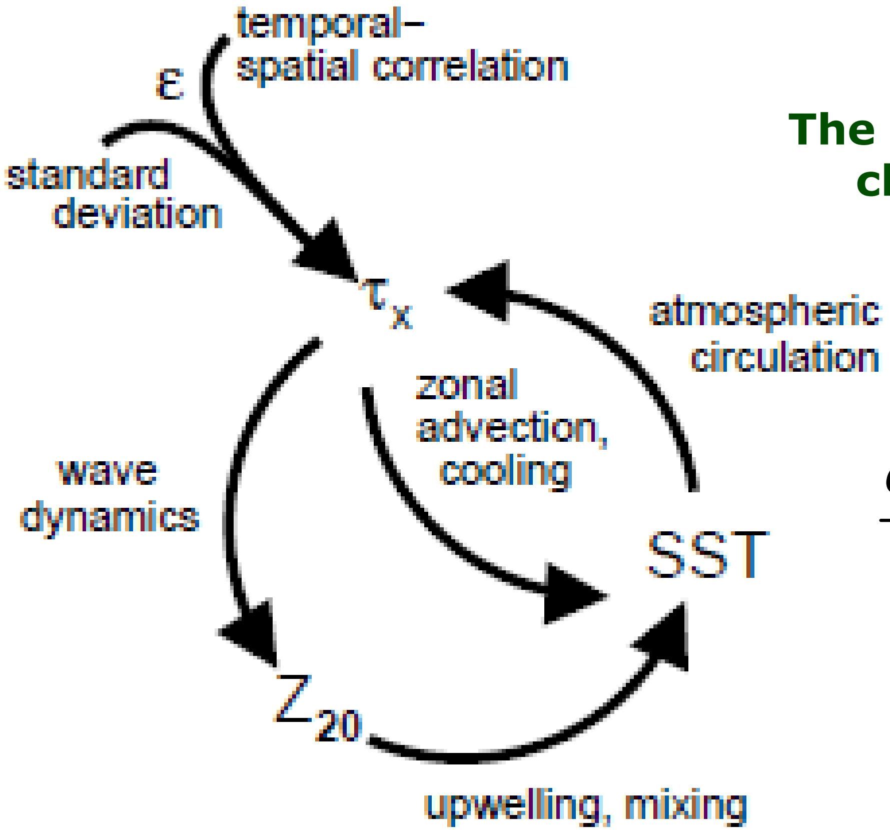


Fig. 1. The main feedbacks between wind stress (τ_x), SST and thermocline depth (Z_{20}) in the ENSO phenomenon and the external noise term ϵ.

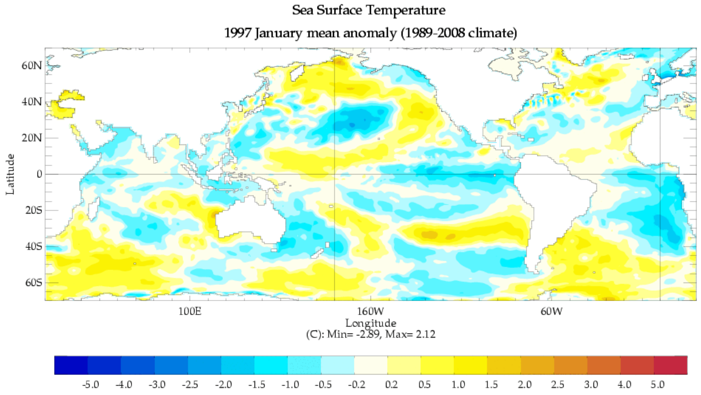
The strength of the feedbacks may change in a changing climate

$$\frac{\partial T}{\partial t} = \alpha Z_{20}(t-\delta) + \beta \tau_x - \gamma T$$

From Philip et al 2010

Jan 1997

SST anomalies

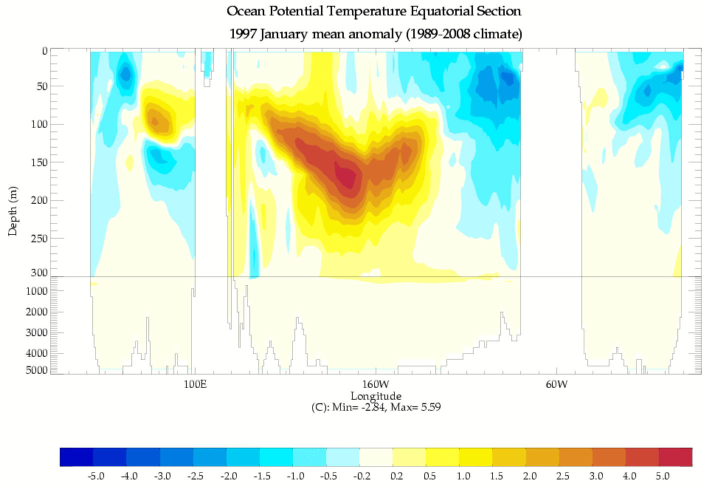


Sea Surface Temperature

1997 January mean anomaly (1989-2008 climate)

ECMWF Ocean Reanalysis ORA-S4

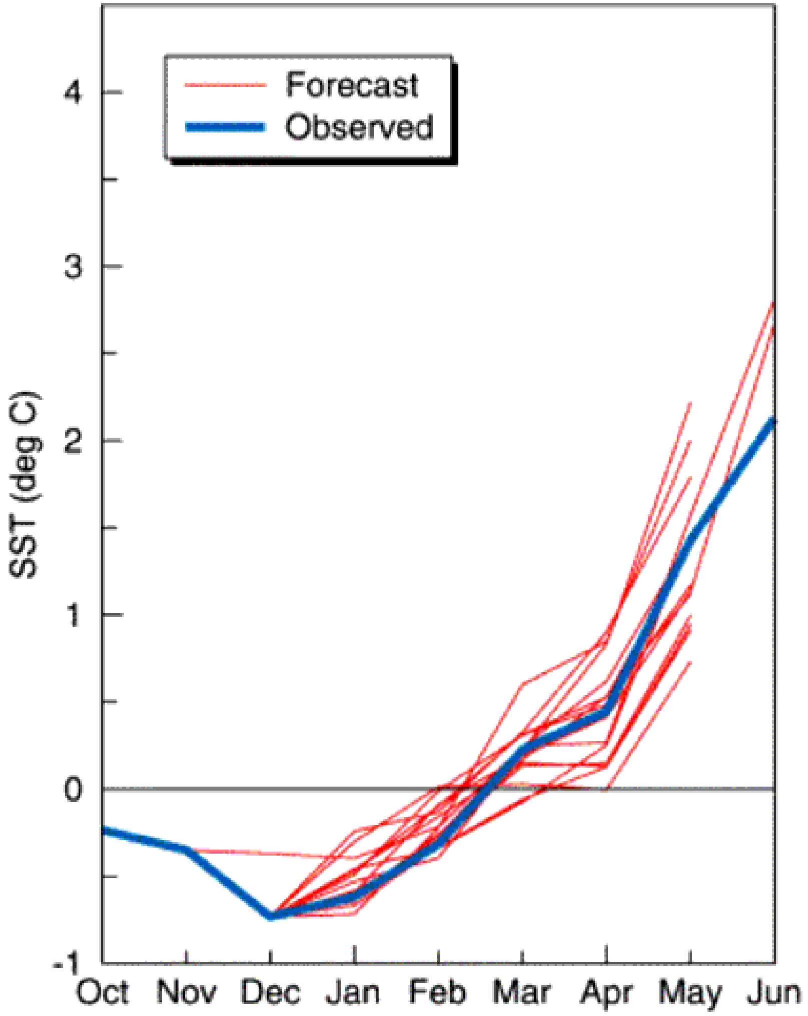
Lon/depth Temperature



Ocean Potential Temperature Equatorial Section

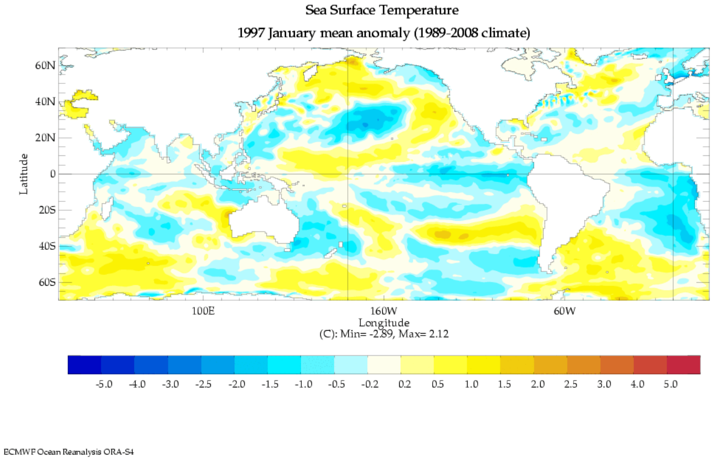
1997 January mean anomaly (1989-2008 climate)

ECMWF Ocean Reanalysis ORA-S4

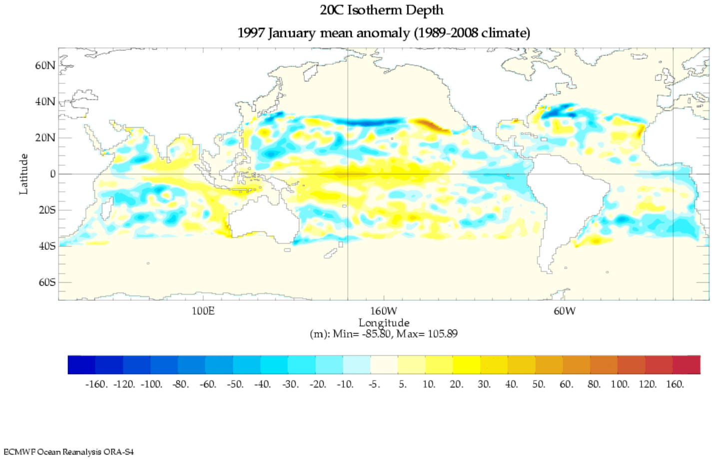


Jan 1997

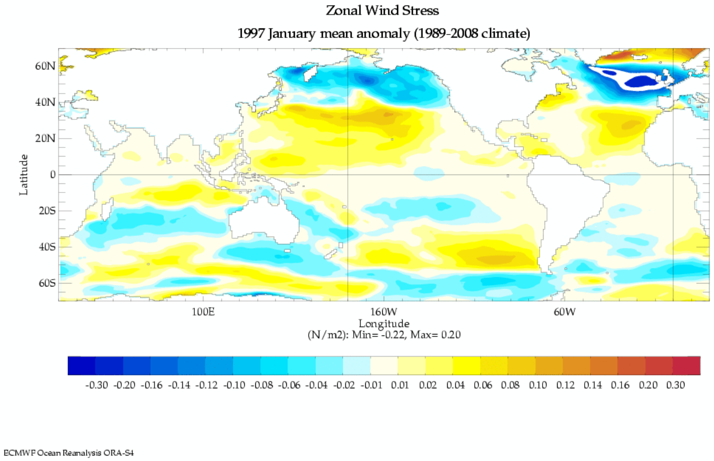
SST anomalies



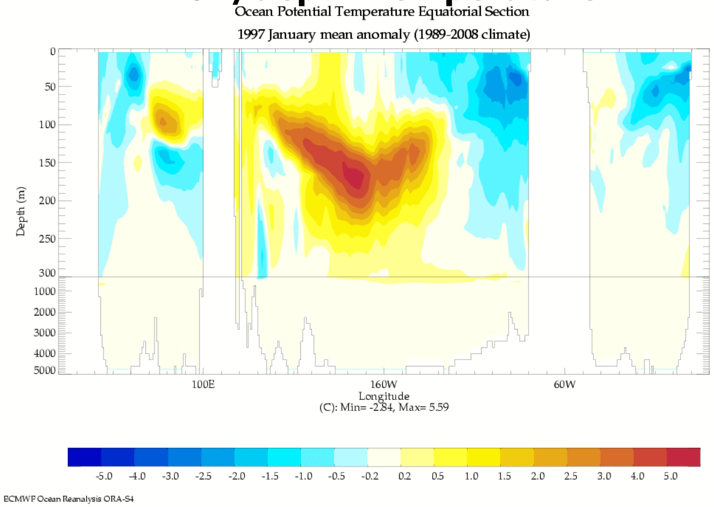
D20 anomalies



Taux anomalies

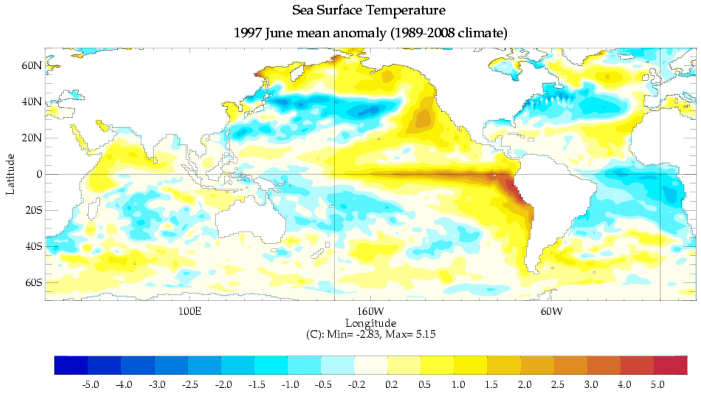


Lon/depth Temperature



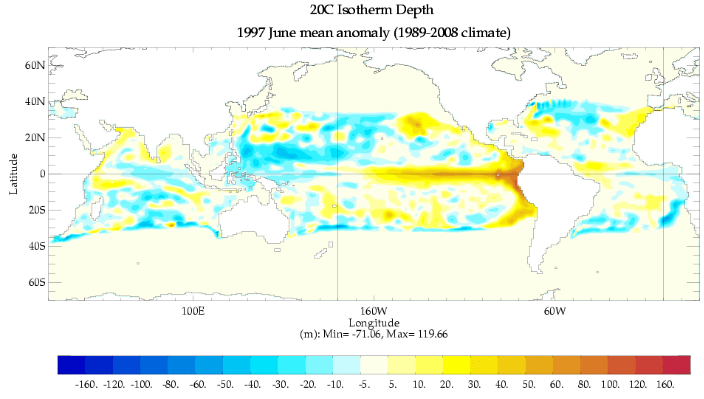
Jun 1997

SST anomalies



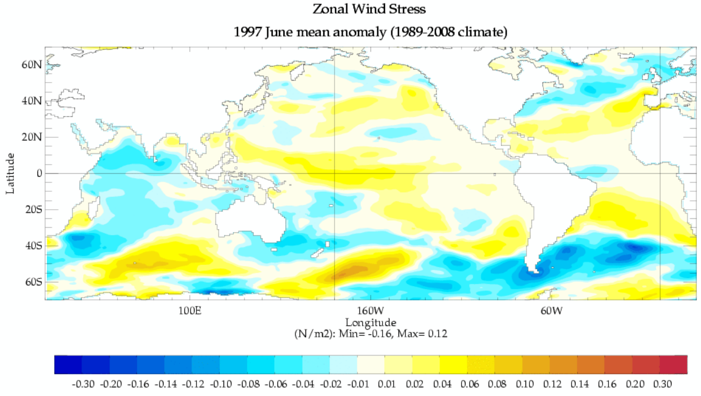
ECMWF Ocean Reanalysis ORA-S4

D20 anomalies



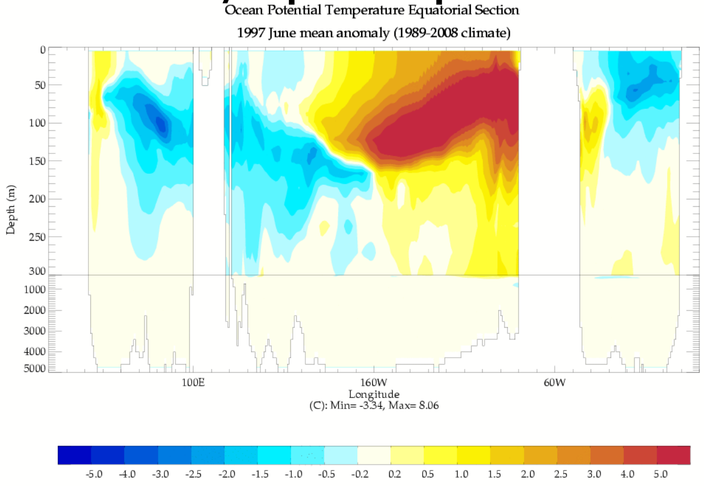
ECMWF Ocean Reanalysis ORA-S4

Taux anomalies



ECMWF Ocean Reanalysis ORA-S4

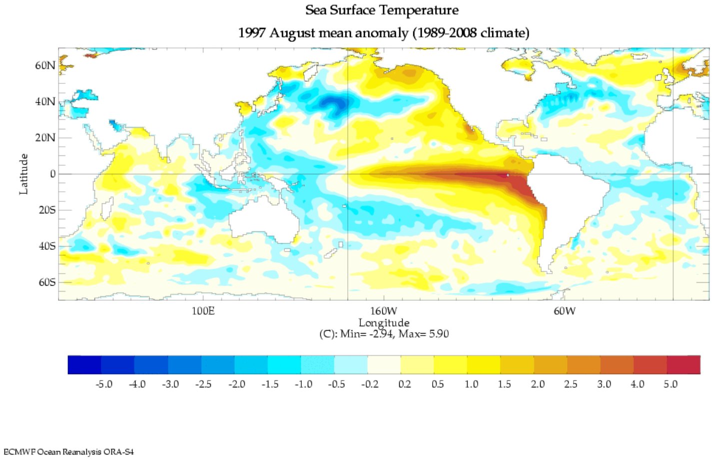
Lon/depth Temperature



ECMWF Ocean Reanalysis ORA-S4

Aug 1997

SST anomalies



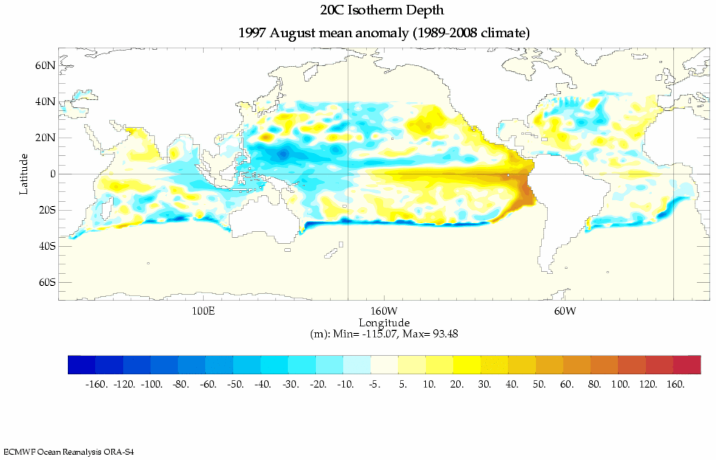
Sea Surface Temperature

1997 August mean anomaly (1989-2008 climate)

(C): Min= -2.94, Max= 5.90

ECMWF Ocean Reanalysis ORA-S4

D20 anomalies



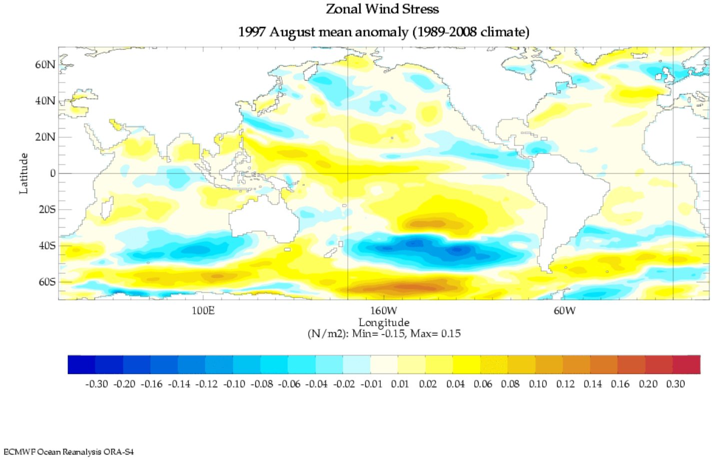
20C Isotherm Depth

1997 August mean anomaly (1989-2008 climate)

(m): Min= -115.07, Max= 93.48

ECMWF Ocean Reanalysis ORA-S4

Taux anomalies



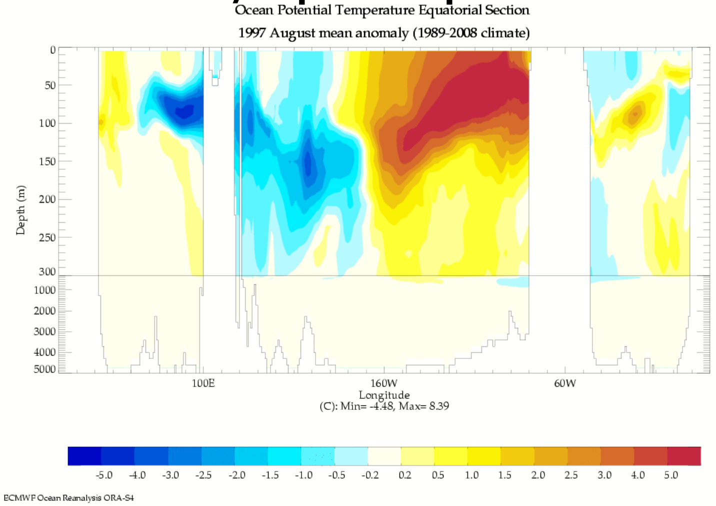
Zonal Wind Stress

1997 August mean anomaly (1989-2008 climate)

(N/m2): Min= -0.15, Max= 0.15

ECMWF Ocean Reanalysis ORA-S4

Lon/depth Temperature



Ocean Potential Temperature Equatorial Section

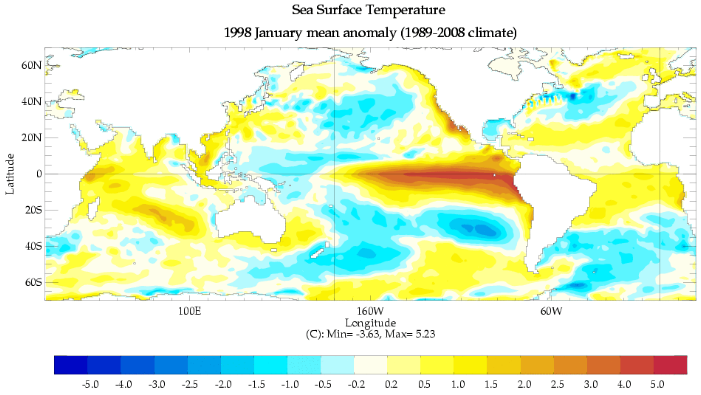
1997 August mean anomaly (1989-2008 climate)

(C): Min= -4.48, Max= 8.39

ECMWF Ocean Reanalysis ORA-S4

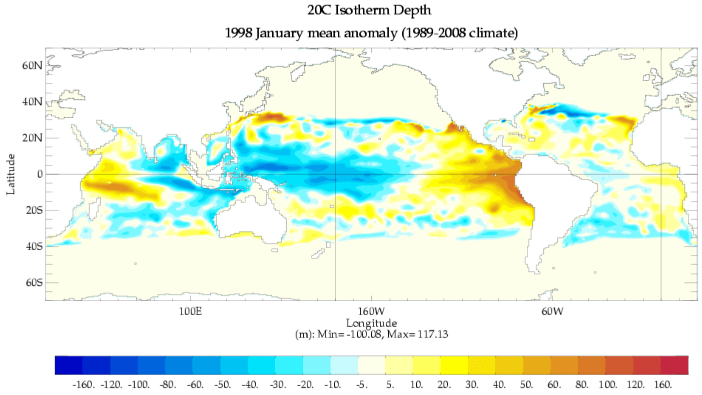
Jan 1998

SST anomalies


Sea Surface Temperature
1998 January mean anomaly (1989-2008 climate)

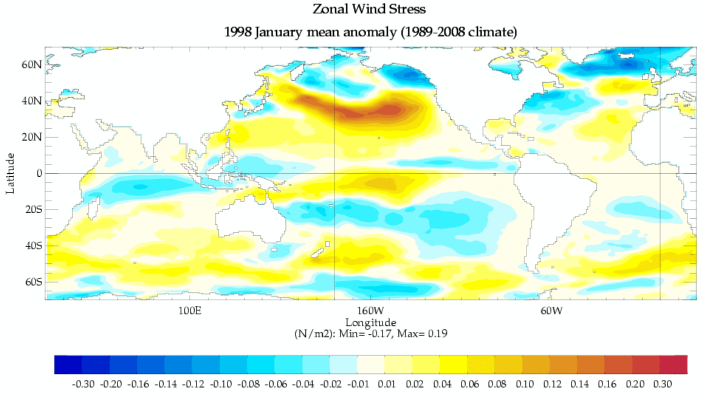
ECMWF Ocean Reanalysis ORA-S4

D20 anomalies


20C Isotherm Depth
1998 January mean anomaly (1989-2008 climate)

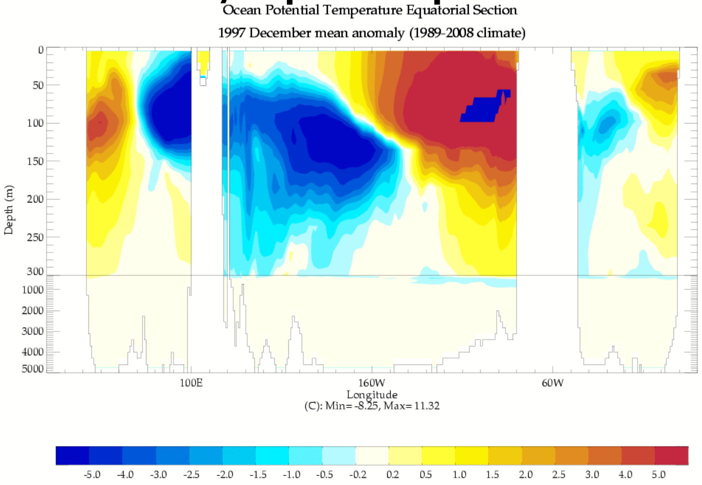
ECMWF Ocean Reanalysis ORA-S4

Taux anomalies


Zonal Wind Stress
1998 January mean anomaly (1989-2008 climate)

ECMWF Ocean Reanalysis ORA-S4

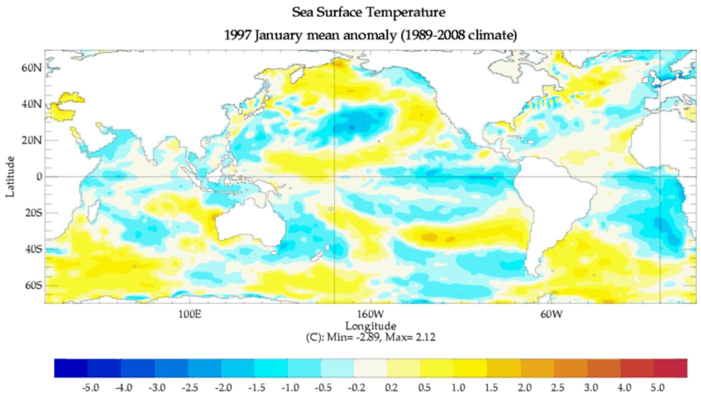
Lon/depth Temperature


Ocean Potential Temperature Equatorial Section
1997 December mean anomaly (1989-2008 climate)

ECMWF Ocean Reanalysis ORA-S4

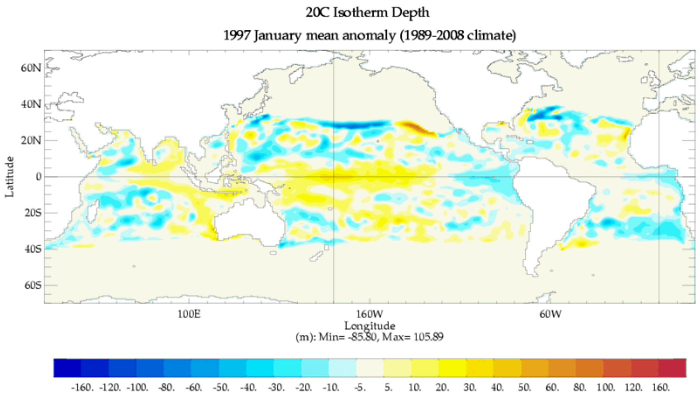
Jan 1997 - Dec 1998

SST anomalies



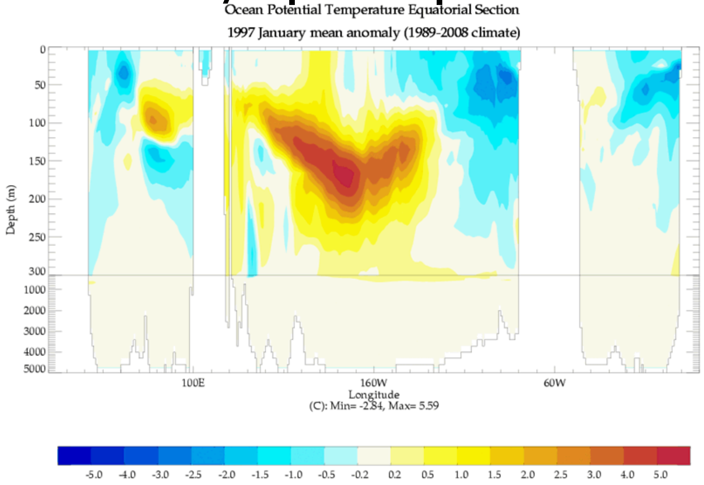
ECMWF Ocean Reanalysis ORA-S4

D20 anomalies



ECMWF Ocean Reanalysis ORA-S4

Lon/depth Temperature

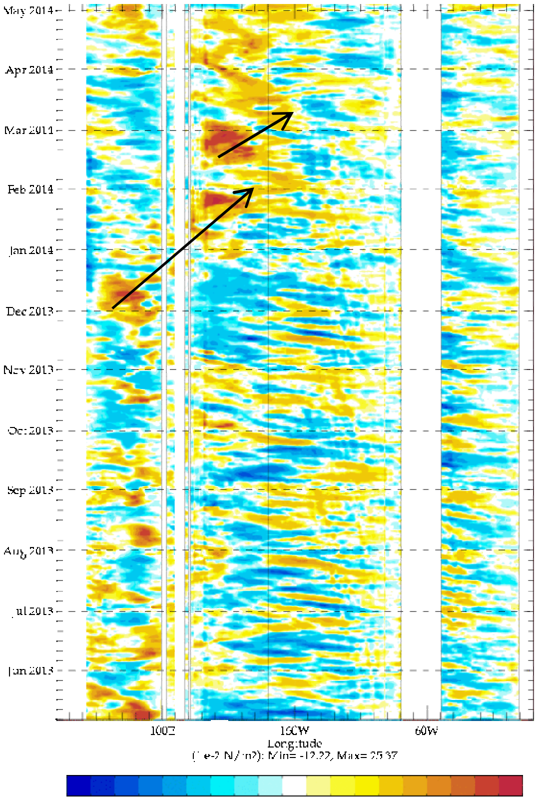


ECMWF Ocean Reanalysis ORA-S4

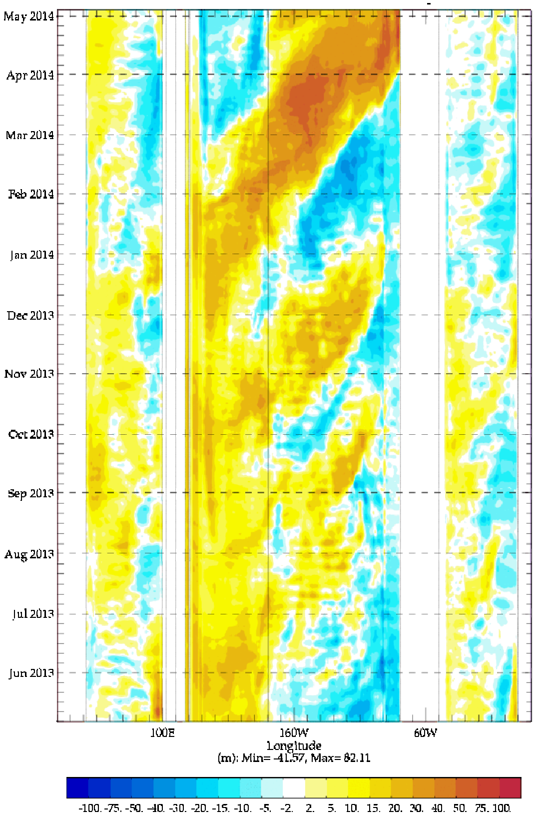
Equatorial Anomalies: May 2013-May 2014

Is a Strong El Nino coming?

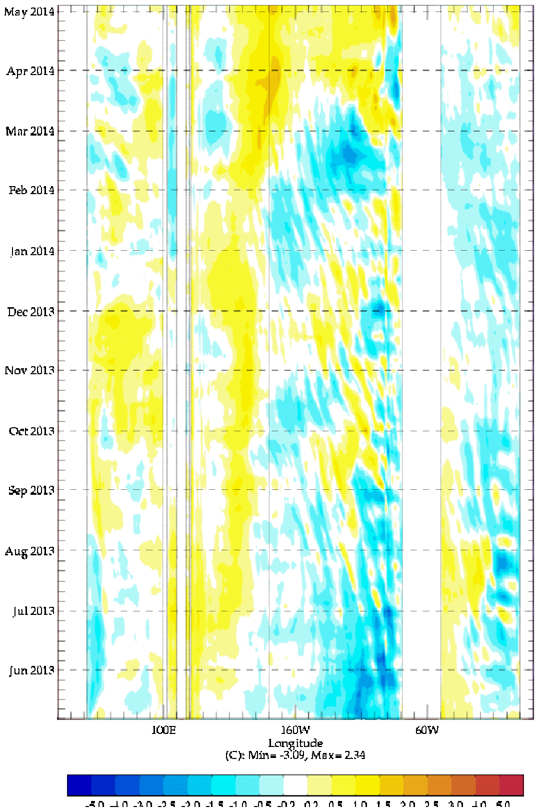
Taux Anomalies



D20 Anomalies



SST Anomalies



Strong Westerly Wind bursts (MJOs?) in the West Pacific ~ Feb/March 2014, propagating slowly eastward

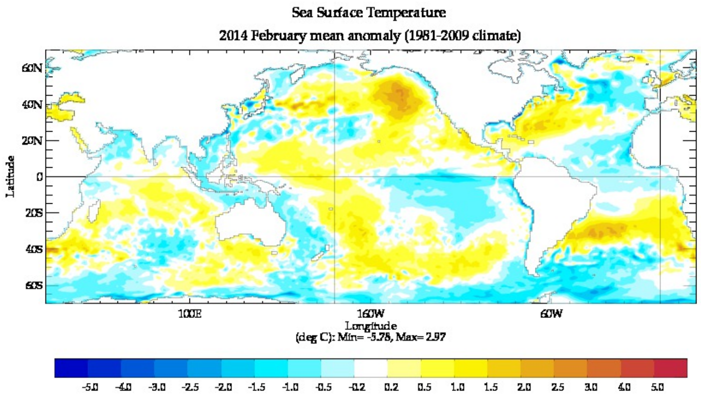
Associated eastward propagating groups of Kelvin waves. The latest reaching the Eastern Coast

SST anomalies develop in the West (as a displacement off the warm pool), and in the East, when the Kelvin waves arrive and depress the thermocline

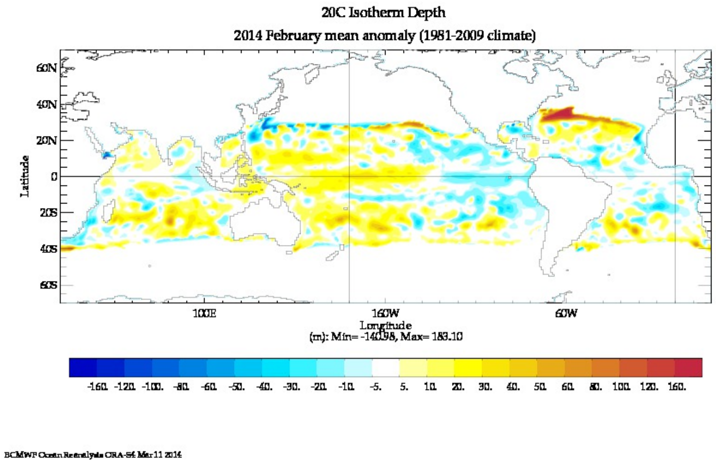
See also the multitude of time scales, including the Tropical Instability Waves (TWIs) in East Pac.

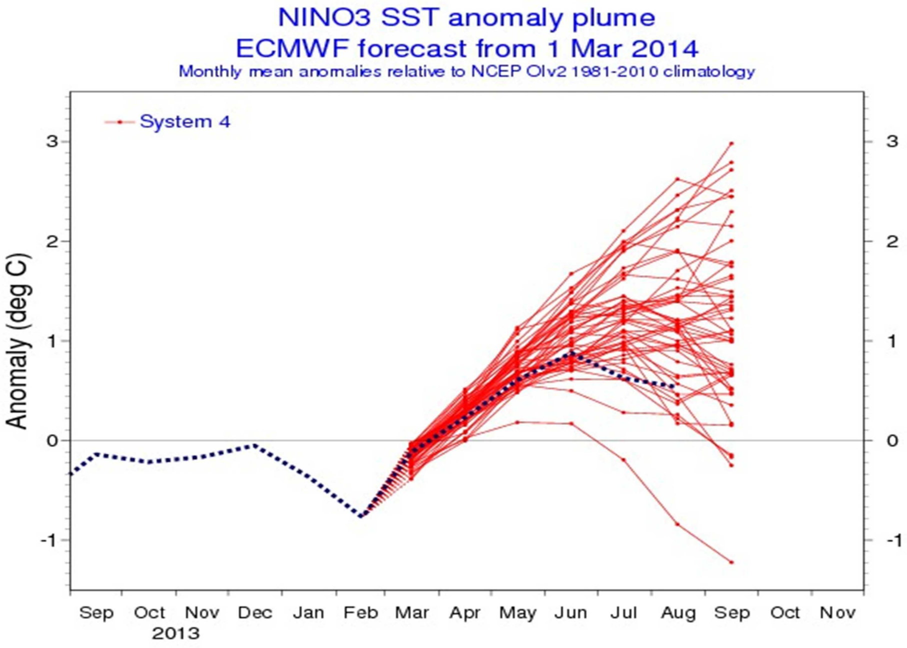
Feb 2014

SST anomalies

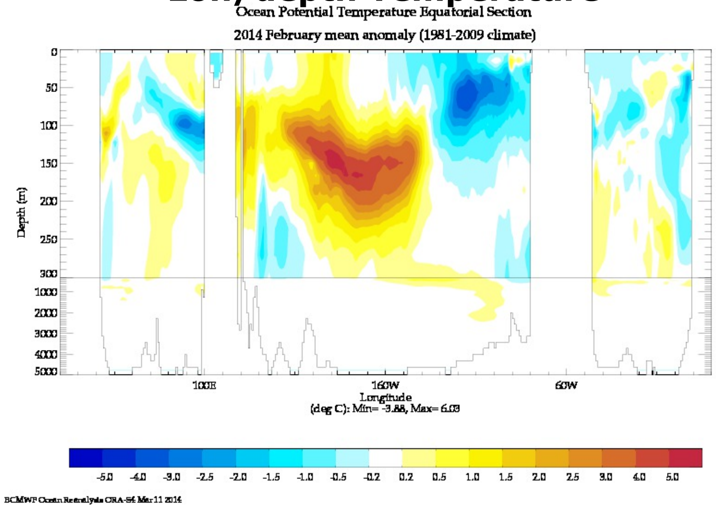


D20 anomalies



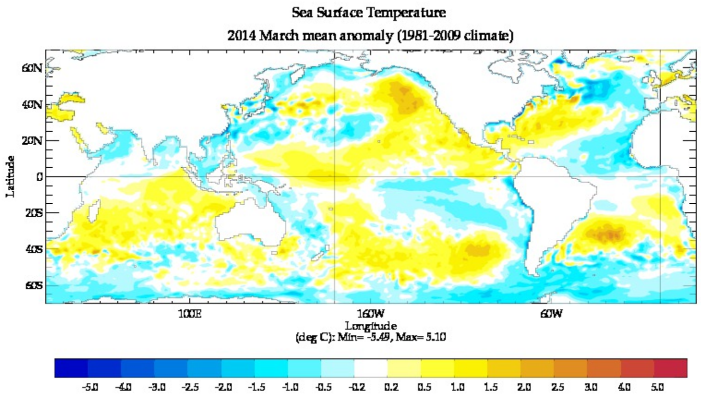


Lon/depth Temperature

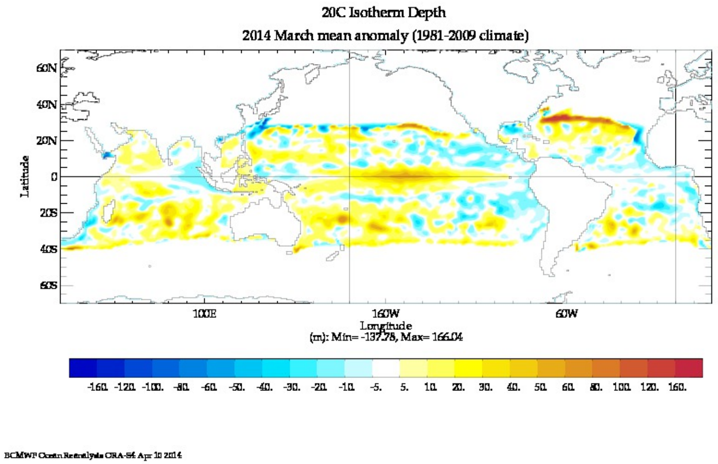


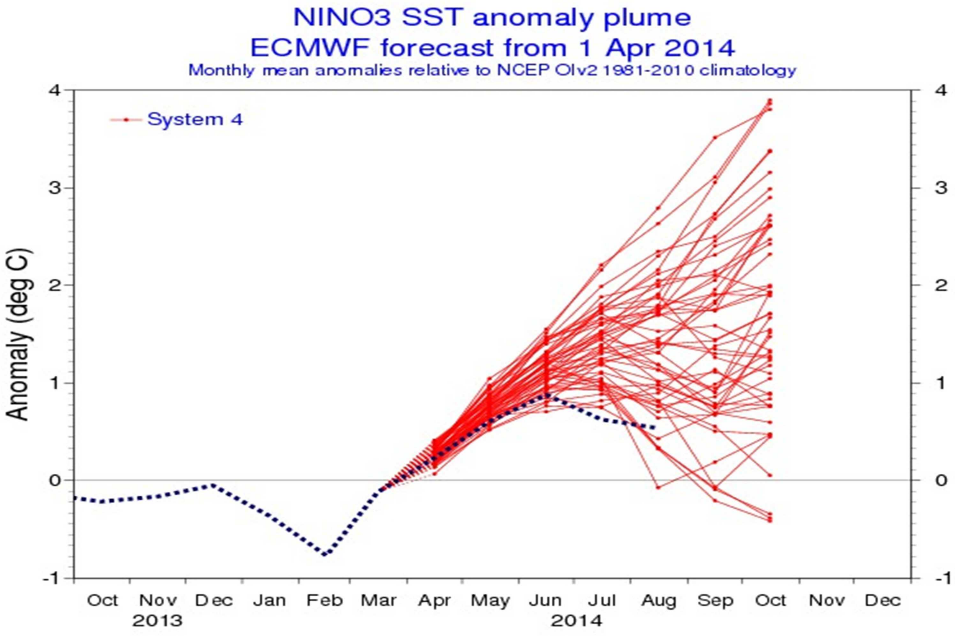
March 2014

SST anomalies

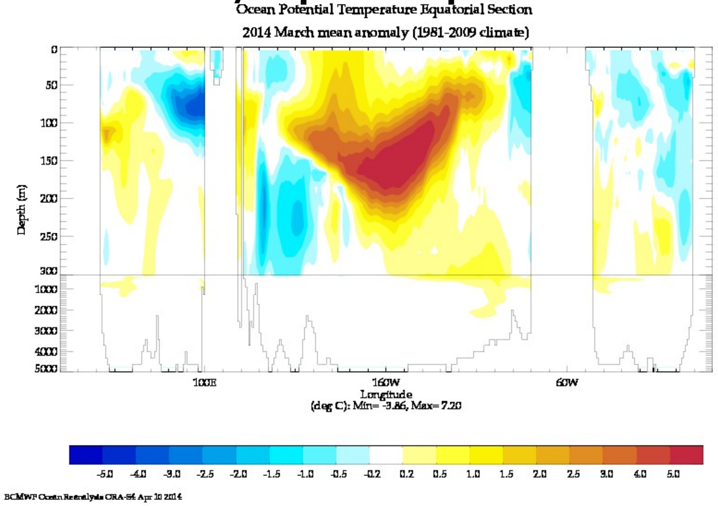


D20 anomalies



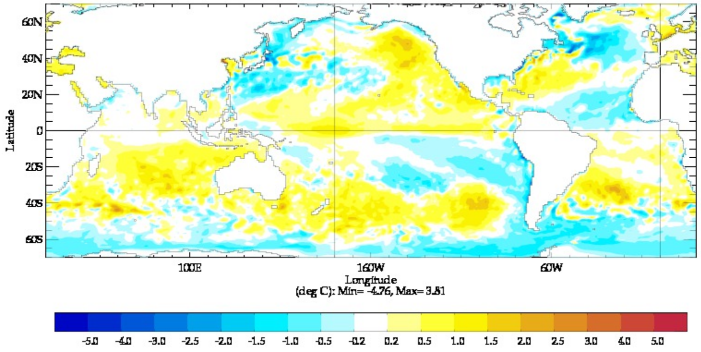


Lon/depth Temperature



April 2014

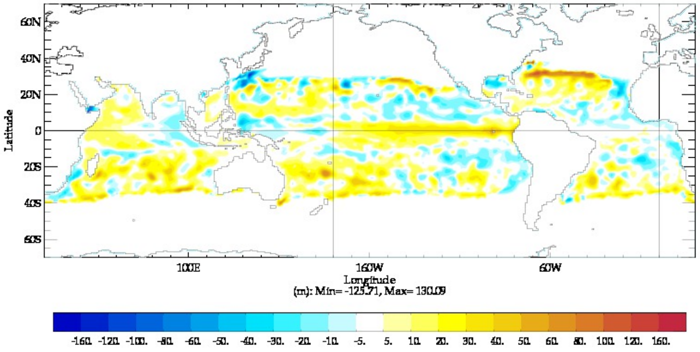
SST anomalies



Sea Surface Temperature

2014 April mean anomaly (1981-2009 climate)

D20 anomalies



20C Isotherm Depth

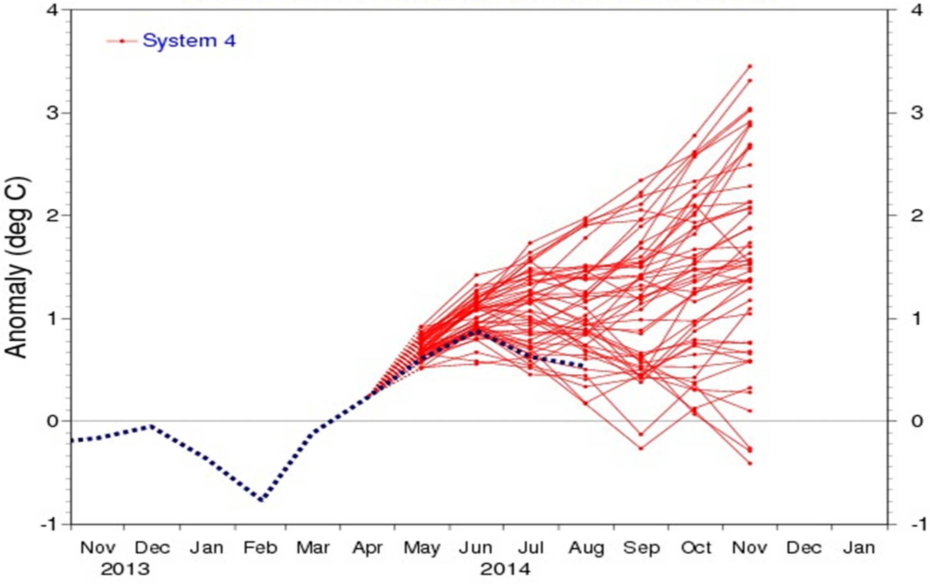
2014 April mean anomaly (1981-2009 climate)

ECMWF Ocean Reanalysis ORA-S4 May 10 2014

NINO3 SST anomaly plume

ECMWF forecast from 1 May 2014

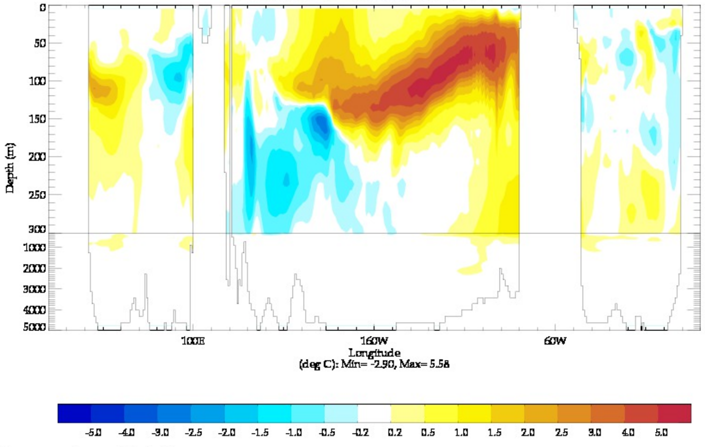
Monthly mean anomalies relative to NCEP OIv2 1981-2010 climatology



Lon/depth Temperature

Ocean Potential Temperature Equatorial Section

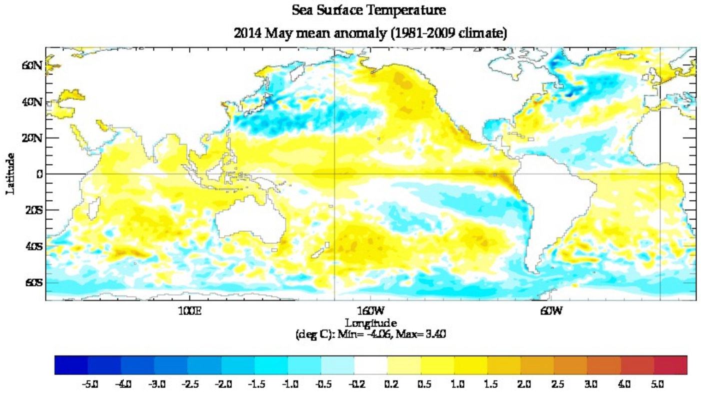
2014 April mean anomaly (1981-2009 climate)



ECMWF Ocean Reanalysis ORA-S4 May 10 2014

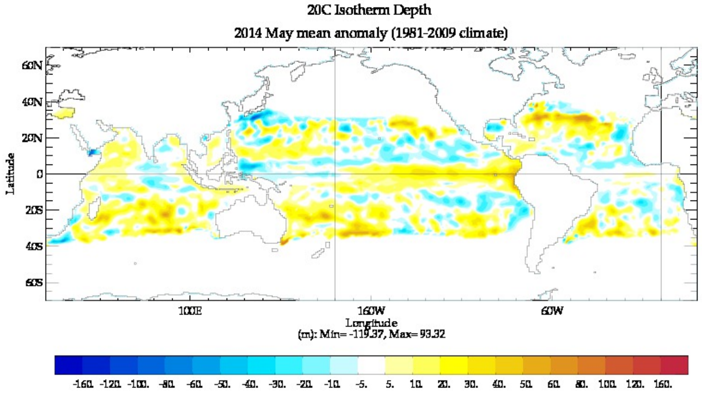
May 2014

SST anomalies



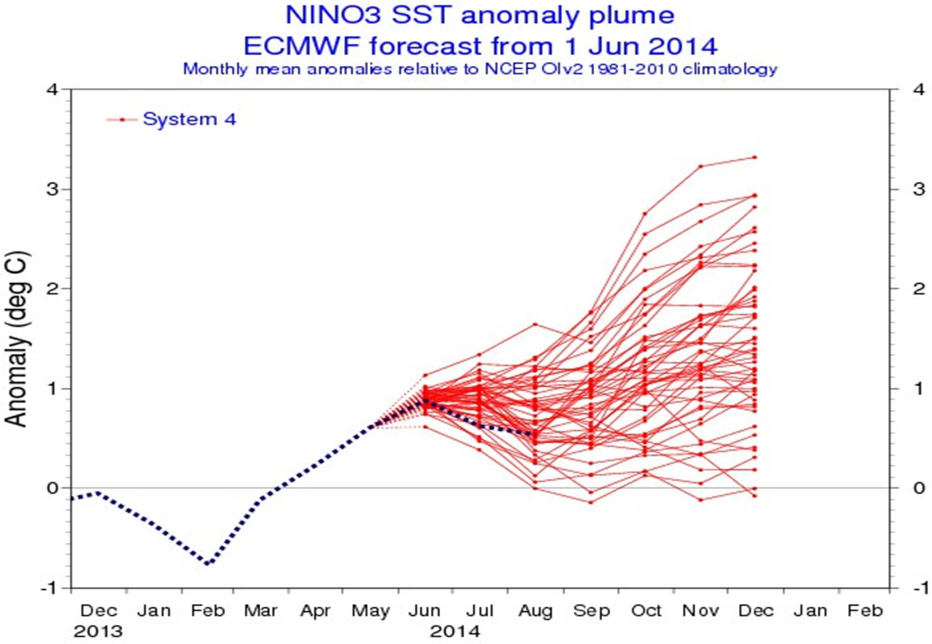
Sea Surface Temperature
2014 May mean anomaly (1981-2009 climate)

D20 anomalies



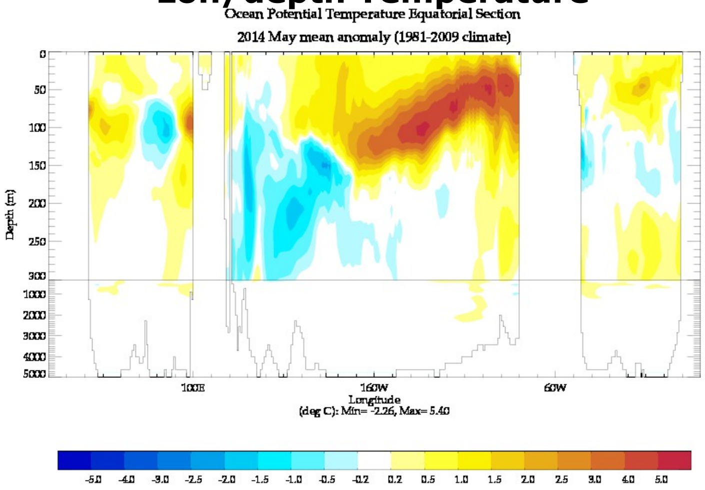
20C Isotherm Depth
2014 May mean anomaly (1981-2009 climate)

ECMWF Ocean Reanalysis ORA-S4 Jun 9 2014



NINO3 SST anomaly plume
ECMWF forecast from 1 Jun 2014
Monthly mean anomalies relative to NCEP OIv2 1981-2010 climatology

Lon/depth Temperature

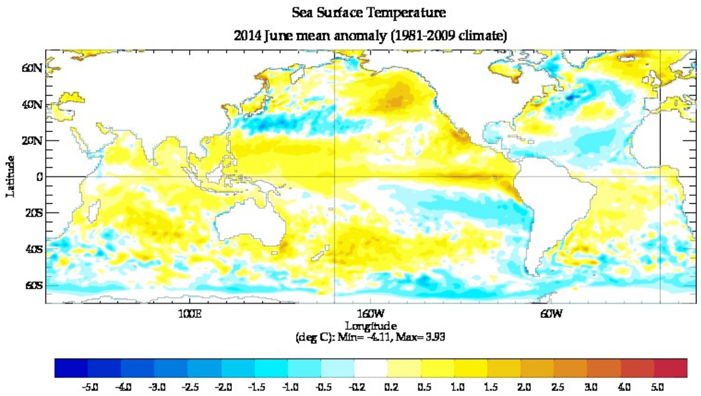


Ocean Potential Temperature Equatorial Section
2014 May mean anomaly (1981-2009 climate)

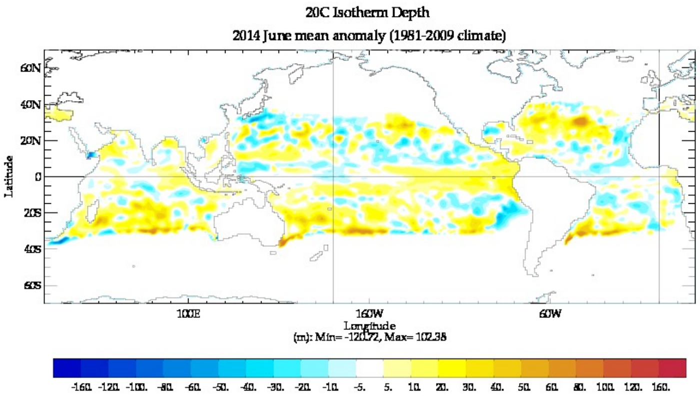
ECMWF Ocean Reanalysis ORA-S4 Jun 9 2014

Jun 2014

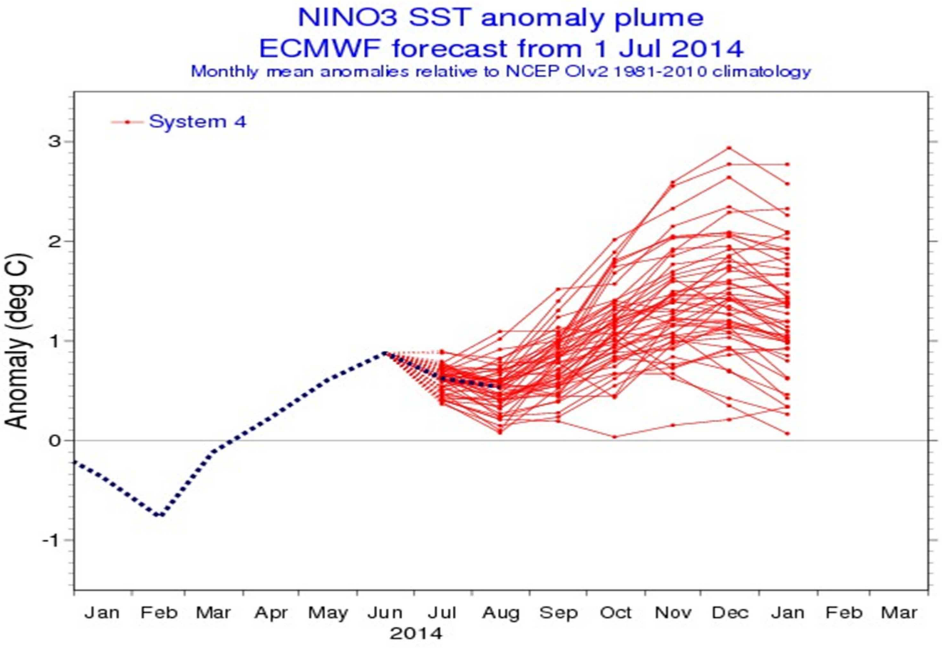
SST anomalies



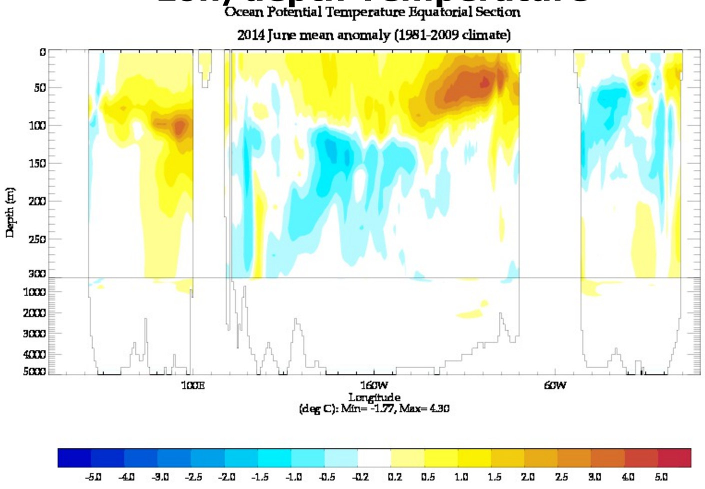
D20 anomalies



ECMWF Ocean Reanalysis ORA-S4 Jul 9 2014



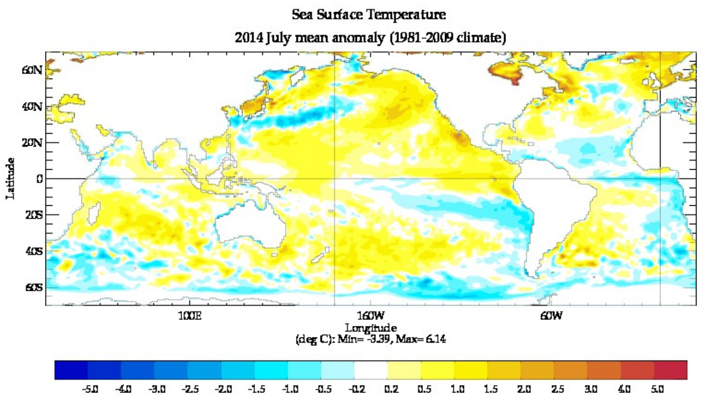
Lon/depth Temperature



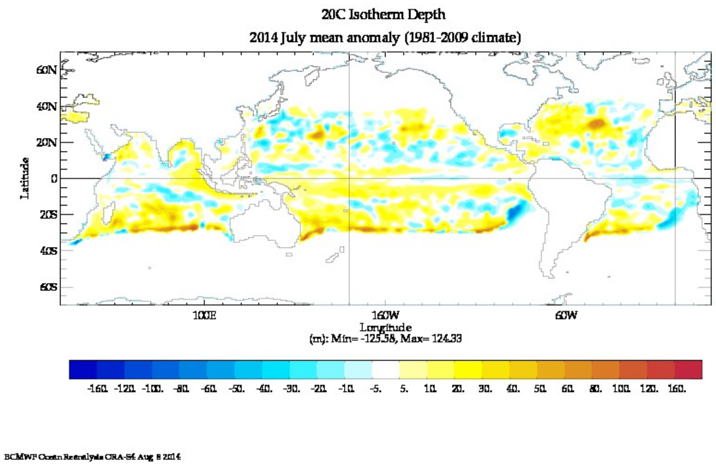
ECMWF Ocean Reanalysis ORA-S4 Jul 9 2014

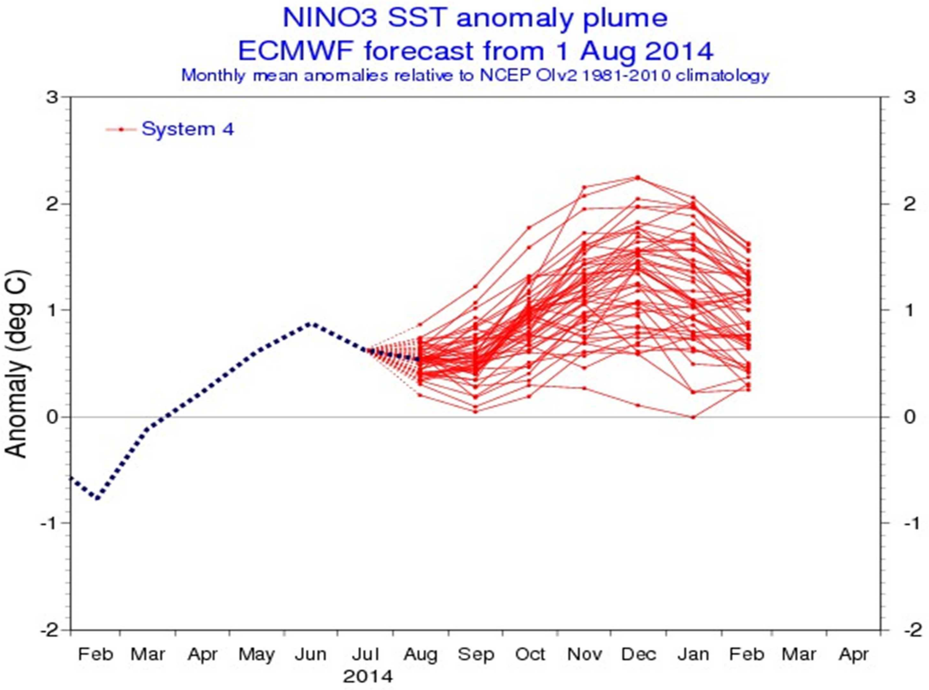
July 2014

SST anomalies

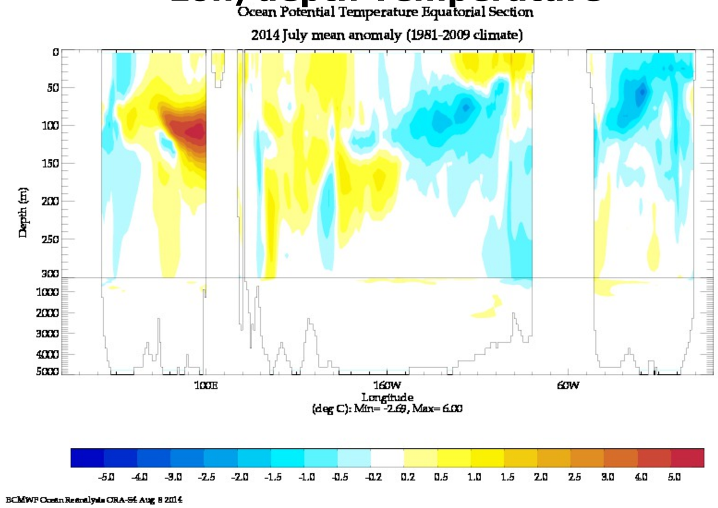


D20 anomalies

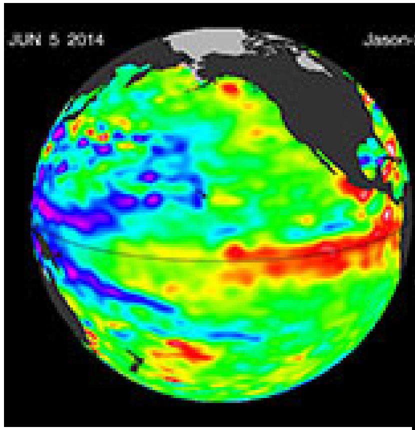




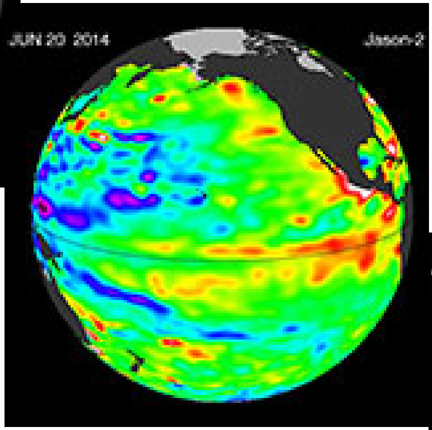
Lon/depth Temperature



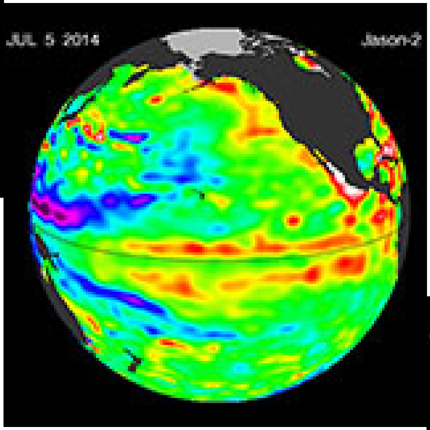
The reflection of an upwelling Rossby wave into an upwelling Equatorial Kelvin wave appears to kill El Nino?



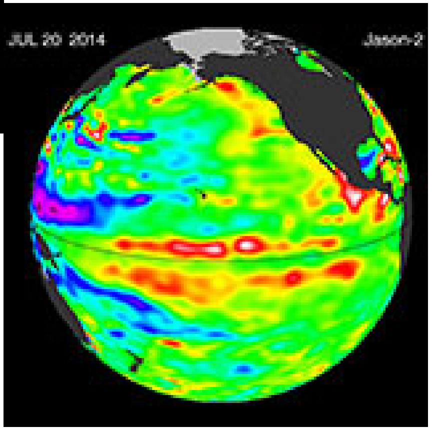
5th June



20th June



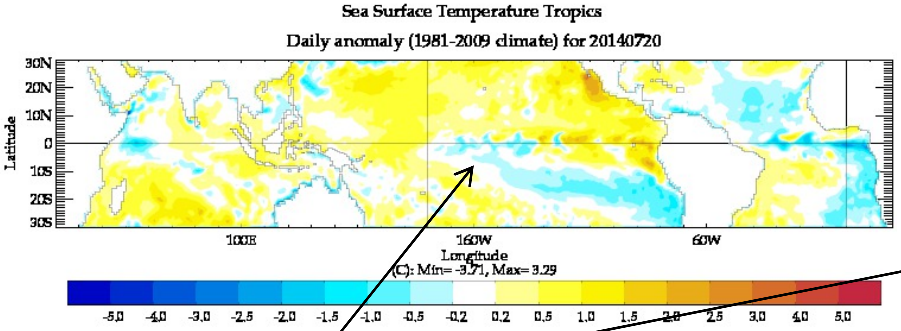
5th July



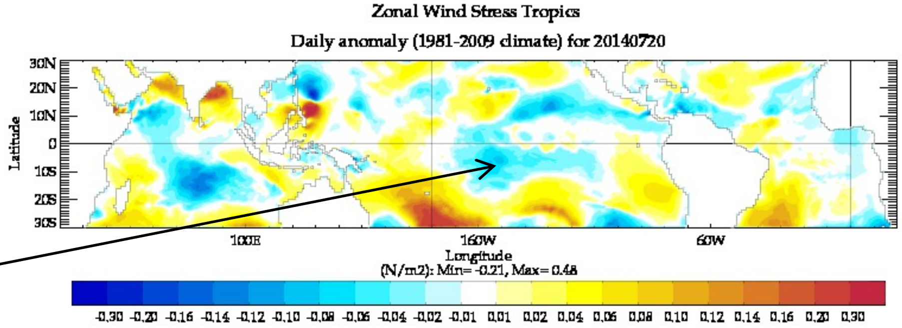
20th July

Is the atmosphere responding?

SST anomalies 20th July 2014

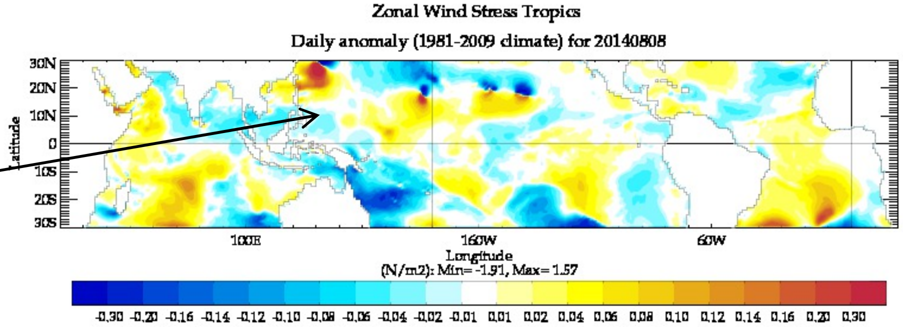


Taux anomalies 20th July 2014



Increased TIW activity

Taux anomalies 8th August 2014

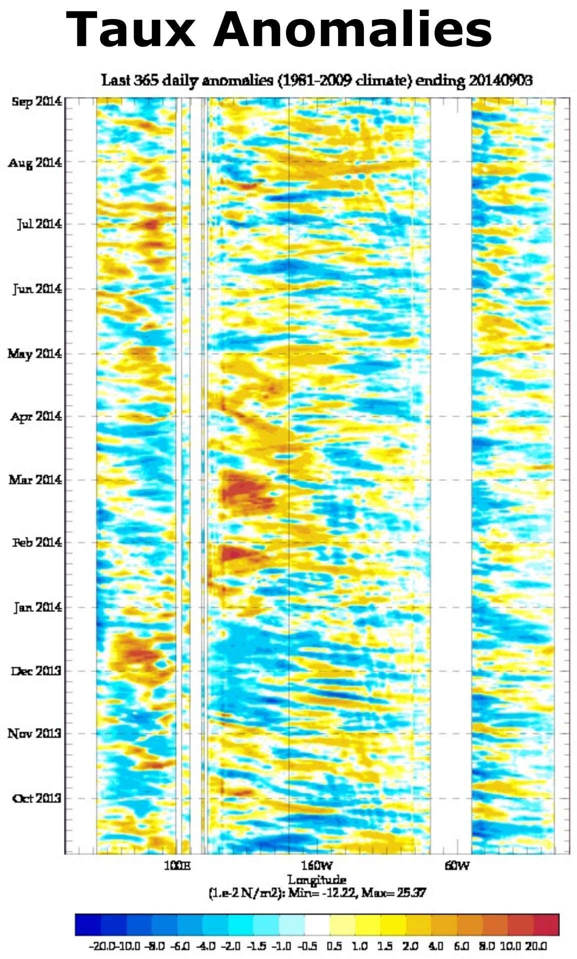


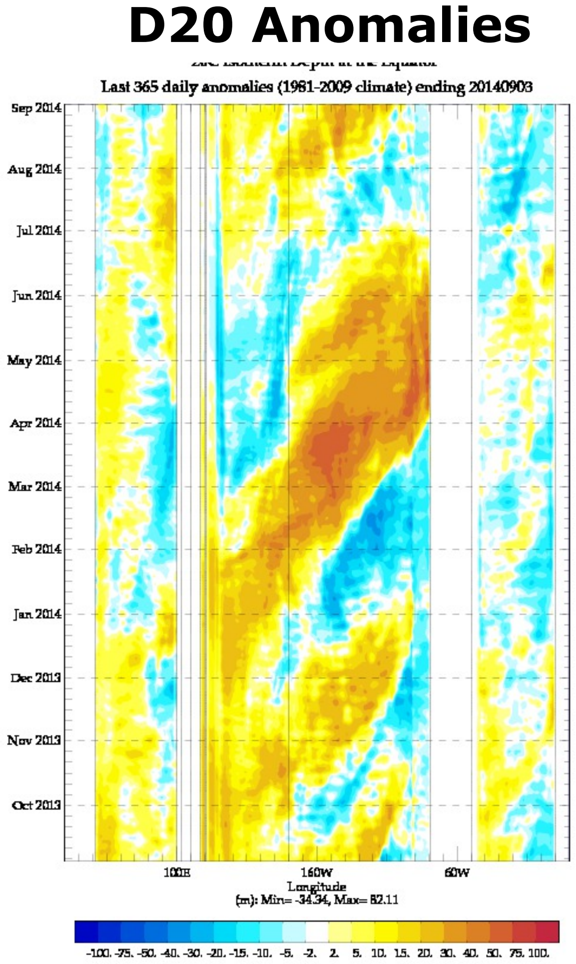
Unusual Tropical Cyclone activity in the Central Pacific

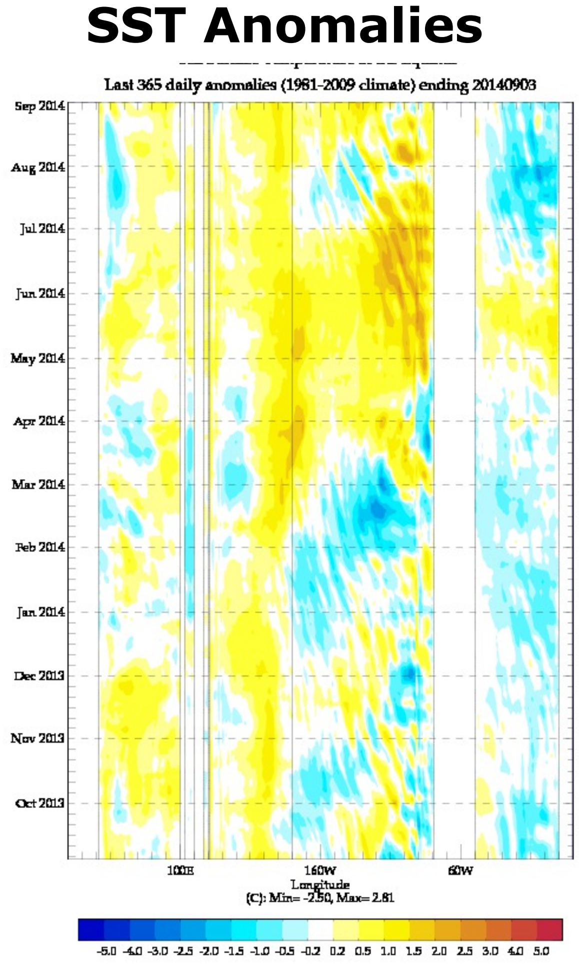
ECMWF Ocean Analysis Real Time Aug 8 2014

365 days of Equatorial Anomalies

Is a Strong El Nino coming?

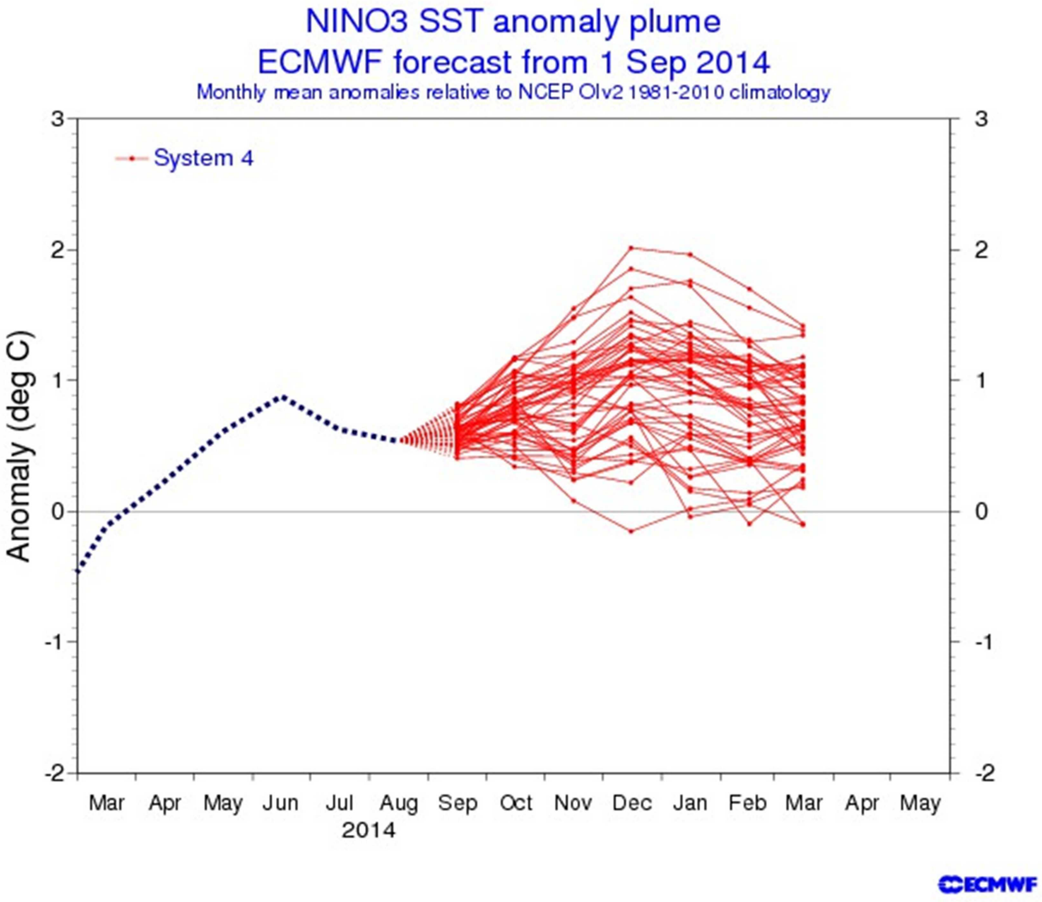

Taux Anomalies

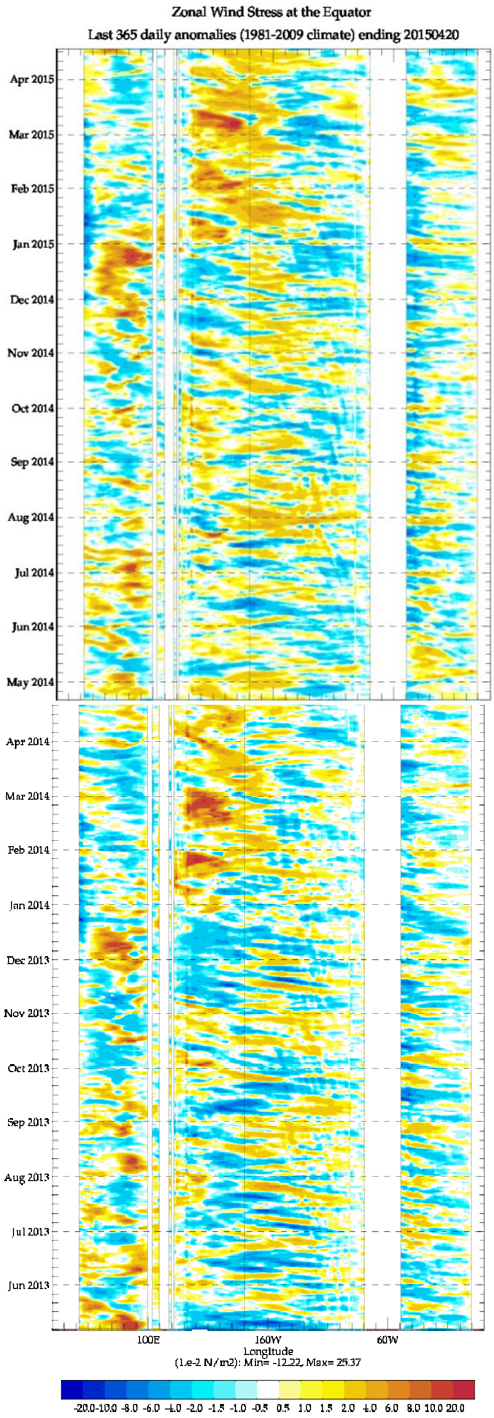

D20 Anomalies


SST Anomalies

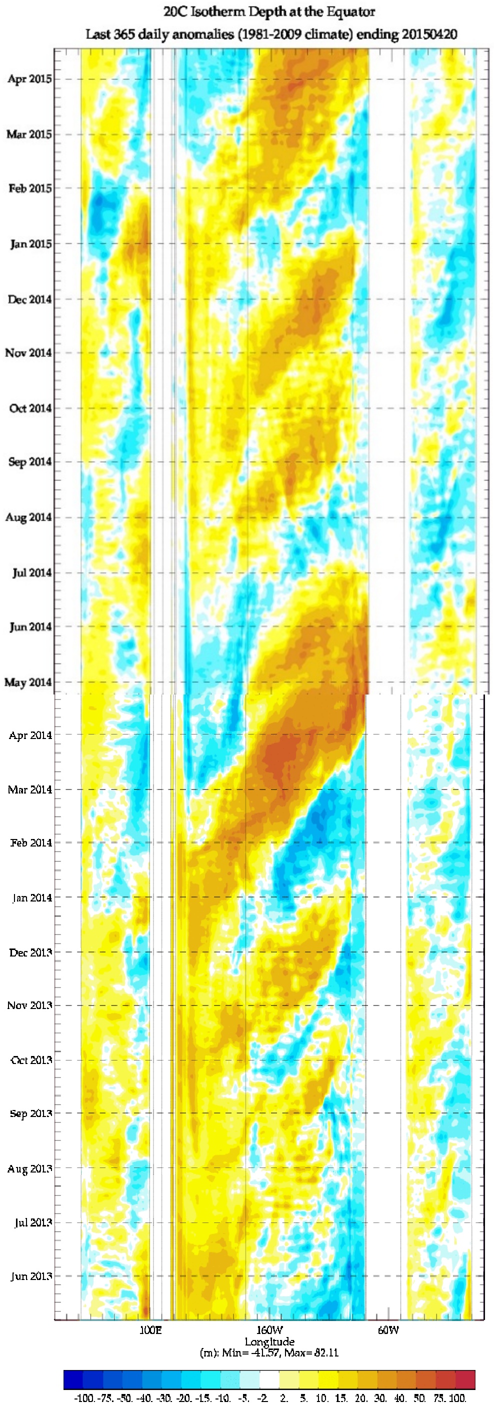
Not obvious Bjerknes feedback yet
But warm anomalies have recovered after the July cooling.
A Kelvin wave on its way. But would it be strong enough?

ENSO forecast by Sep 2014 are for a weaker El Nino

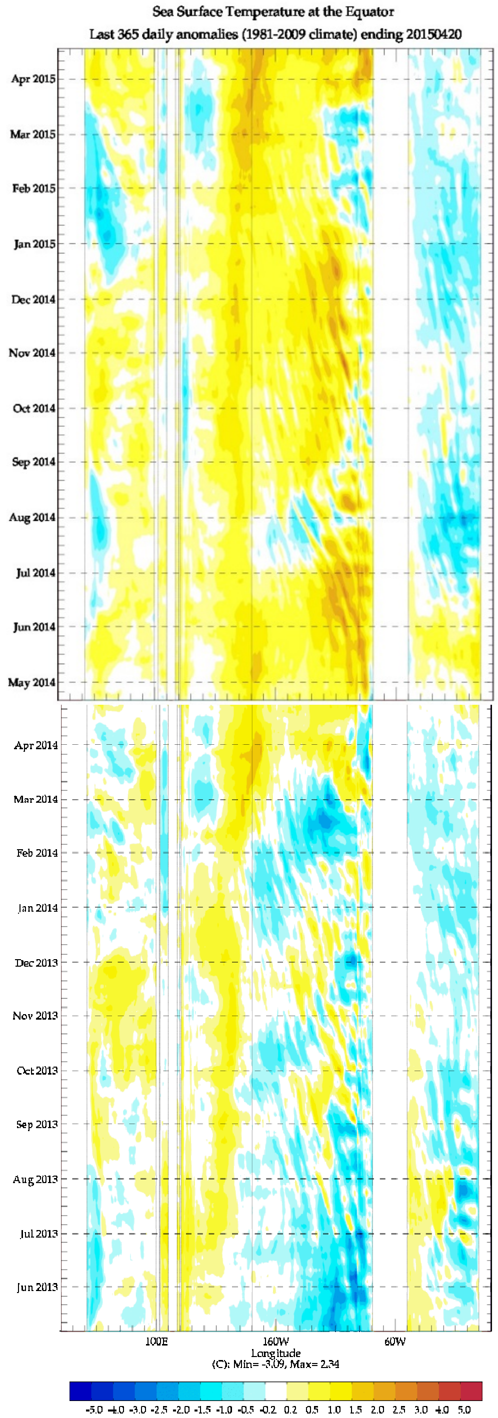



Zonal Wind Stress at the Equator
Last 365 daily anomalies (1981-2009 climate) ending 20150420
Apr 2015
Mar 2015
Feb 2015
Jan 2015
Dec 2014
Nov 2014
Oct 2014
Sep 2014
Aug 2014
Jul 2014
Jun 2014
May 2014
Apr 2014
Mar 2014
Feb 2014
Jan 2014
Dec 2013
Nov 2013
Oct 2013
Sep 2013
Aug 2013
Jul 2013
Jun 2013
100E
160W
60W
Longitude
(1.e-2 N/m2): Min= -12.22, Max= 25.37
-20.0 -10.0 -8.0 -6.0 -4.0 -2.0 -1.5 -1.0 -0.5 0.5 1.0 1.5 2.0 4.0 6.0 8.0 10.0 20.0

s


20C Isotherm Depth at the Equator
Last 365 daily anomalies (1981-2009 climate) ending 20150420
Apr 2015
Mar 2015
Feb 2015
Jan 2015
Dec 2014
Nov 2014
Oct 2014
Sep 2014
Aug 2014
Jul 2014
Jun 2014
May 2014
Apr 2014
Mar 2014
Feb 2014
Jan 2014
Dec 2013
Nov 2013
Oct 2013
Sep 2013
Aug 2013
Jul 2013
Jun 2013
100E
160W
60W
Longitude
(m): Min= -41.57, Max= 82.11
-100. -75. -50. -40. -30. -20. -15. -10. -5. -2. 2. 5. 10. 15. 20. 30. 40. 50. 75. 100.

es

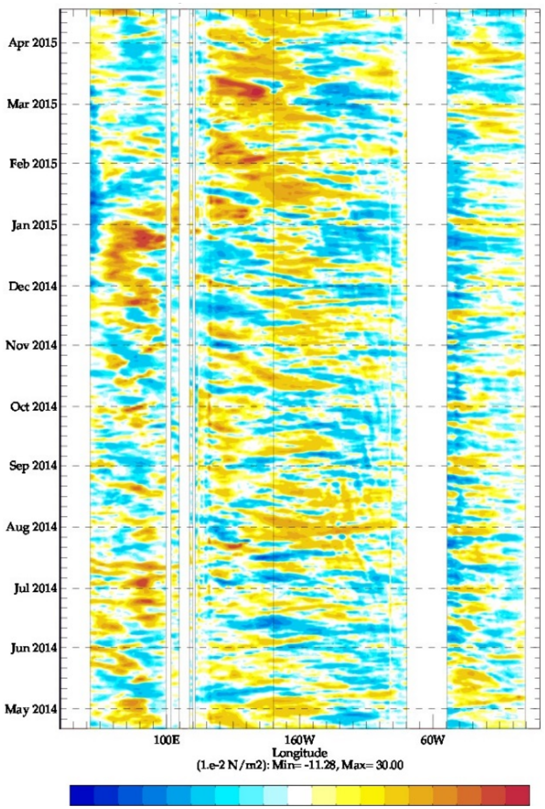

Sea Surface Temperature at the Equator
Last 365 daily anomalies (1981-2009 climate) ending 20150420
Apr 2015
Mar 2015
Feb 2015
Jan 2015
Dec 2014
Nov 2014
Oct 2014
Sep 2014
Aug 2014
Jul 2014
Jun 2014
May 2014
Apr 2014
Mar 2014
Feb 2014
Jan 2014
Dec 2013
Nov 2013
Oct 2013
Sep 2013
Aug 2013
Jul 2013
Jun 2013
100E
160W
60W
Longitude
(C): Min= -3.09, Max= 2.34
-5.0 -4.0 -3.0 -2.5 -2.0 -1.5 -1.0 -0.5 -0.2 0.2 0.5 1.0 1.5 2.0 2.5 3.0 4.0 5.0

ng

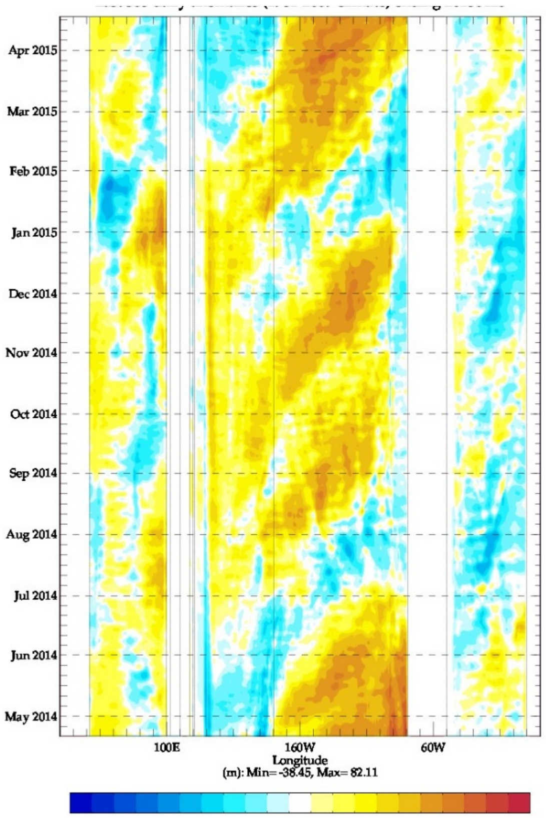
*ere *

Equatorial Anomalies: April 2014-April 2015

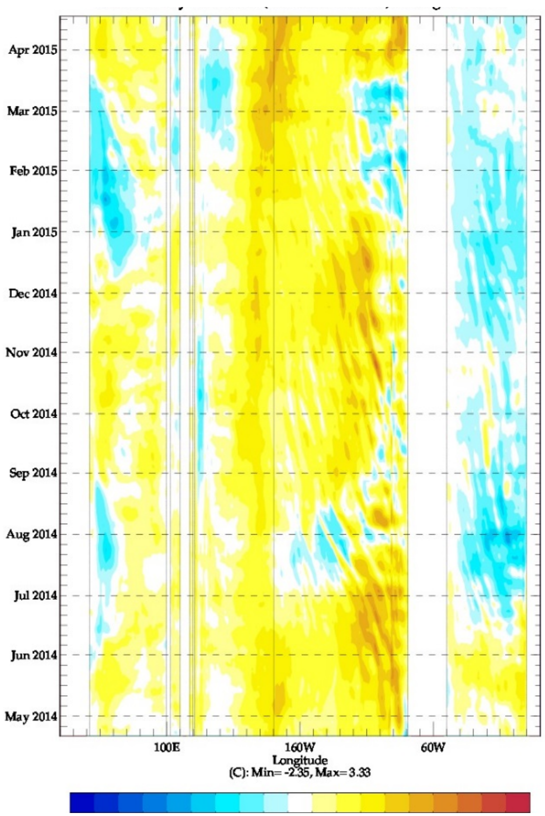
Is a Strong El Nino coming?



Taux Anomalies



D20 Anomalies



SST Anomalies

Strong Westerly Wind bursts (MJOs?) in the West Pacific ~ Feb/March 2014, propagating slowly eastward

Associated eastward propagating groups of Kelvin waves. The latest reaching the Eastern Coast

SST anomalies develop in the West (as a displacement off the warm pool), and in the East, when the Kelvin waves arrive and depress the thermocline

See also the multitude of time scales, including the Tropical Instability Waves (TWIs) in East Pac.

Summary of Coupled Ocean-Atmosphere Variability

- The ocean-atmosphere interaction involves **many time scales** and a **multiplicity of feedbacks.**
- This can lead to **chaotic behaviour** and **abrupt regime transitions**, but also to **predictability** (if oscillations, slow transitions, wave adjustment)
- The nature of air sea interaction can be large-scale and small scale
- **Large scale**: mainly in the **tropics**. Atmos responds to large and small scale SST anomalies and gradients. Organized deep convection and associated wind-driven circulation are key elements.
    - SST anomalies can trigger deep convection (diurnal, MJO, ENSO…)
    - Zonal SST gradients influence the Walker circulation (ENSO)
    - Meridional SST gradient influence the Hadley and Gyre circulations (decadal)
- **Small scale**: the atmos response to sharp SST fronts (WBC and TIWs) is receiving increased attention.
    - Impact on storm tracks, blocking, NAO and possible decadal variability.
    - Strong implications for modelling and predictability

Summary the 2014 El Nino

- The most watched El Nino ever
- It is being very entertaining.
- Does it fit within the conceptual models of ENSO?
- Nature continues to surprise us
- What about 2015?

Some additional References

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