



Introduction to Coupled Ocean-Atmosphere Variability

Magdalena A. Balmaseda
European Center for Medium Range Weather Forecast, Reading, UK

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
 - Some examples of air-sea interaction
- **The ocean and its circulation**
 - Some facts
 - Wind driven and thermohaline circulations
- **Modes of variability at different time scales**
 - From diurnal to decadal
 - Known modes
 - **ENSO**
- **The El Nino 2015/16**

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.
 - Response to large-scale spatial SST gradients**
 - Response over warm pool: deep atmospheric convection**
 - Response to sharp SST fronts**

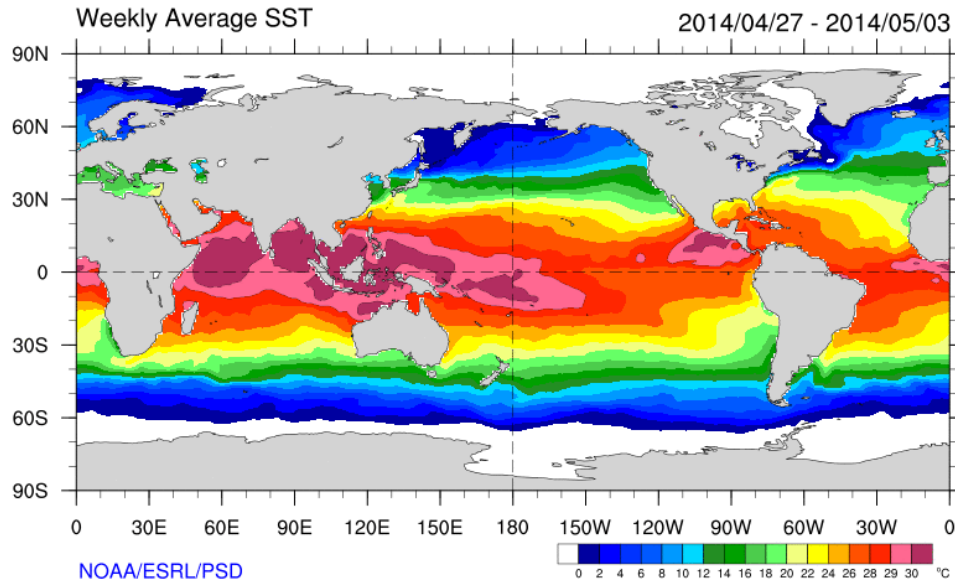
example: mid latitude storm tracks over western boundary currents

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

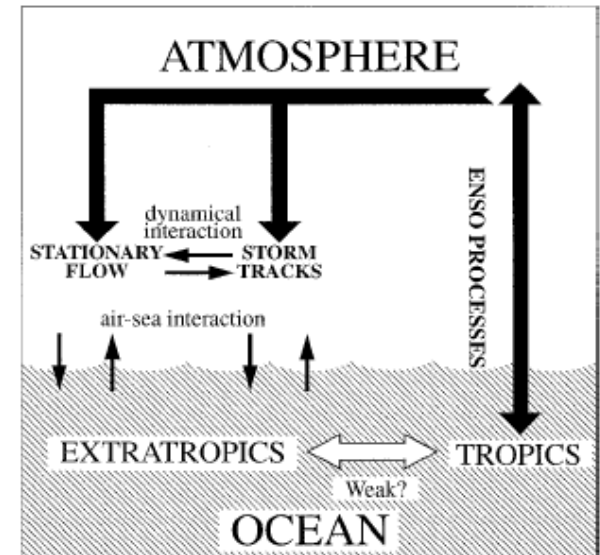
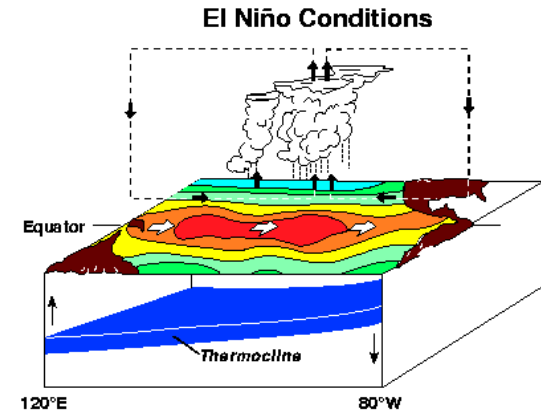
Hasselmann 1976

Latif et al 2002, Timmermann 2005...

Traditional view: Atmosphere response to SST

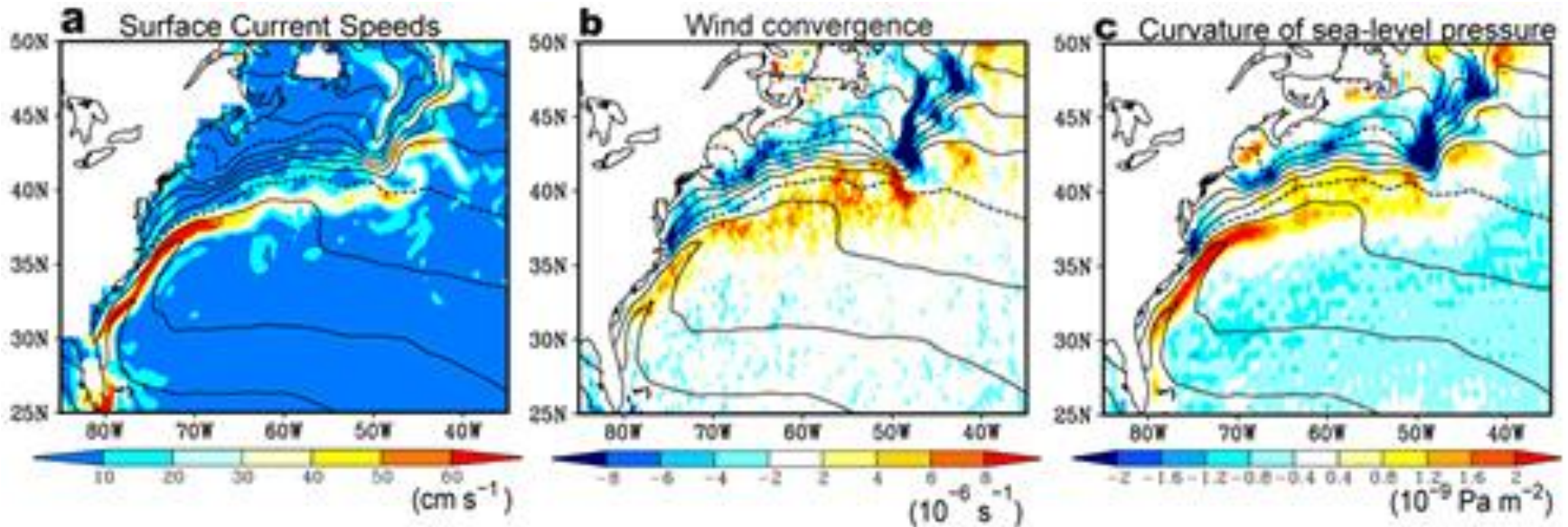


- Large Scale Pressure Gradients, mainly in the tropics
- Convective forcing



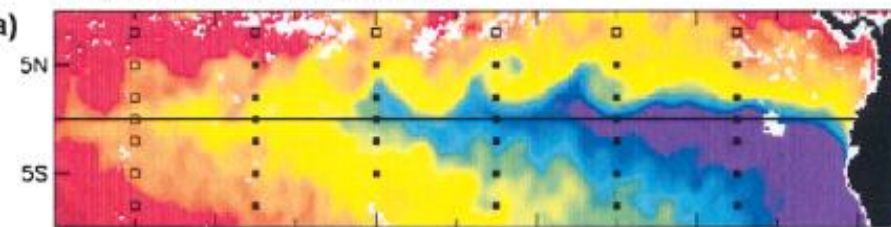
Lau 1977

O-A interaction over SST fronts



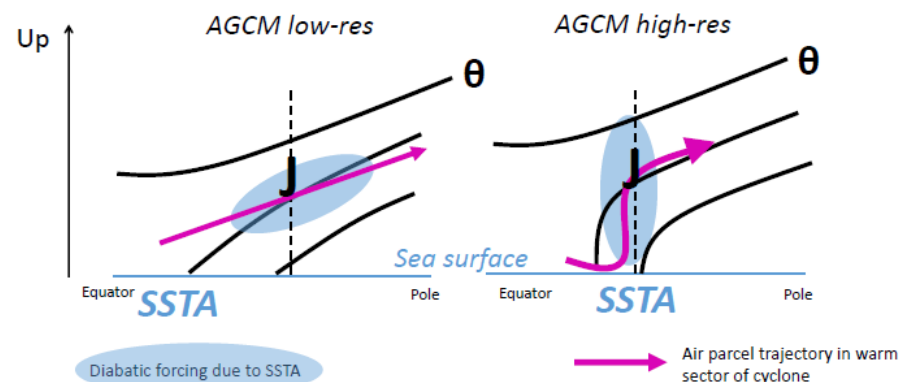
Minobe et al 2008

TMI Sea Surface Temperature



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

A new paradigm?



From Czaja, 2016

Air-Sea Interaction in Tropical Cyclones



Heat Flux exchange: ocean mixing and upwelling
Wind-Wave interaction
Ocean Initial conditions also matter

From Ginis 2008

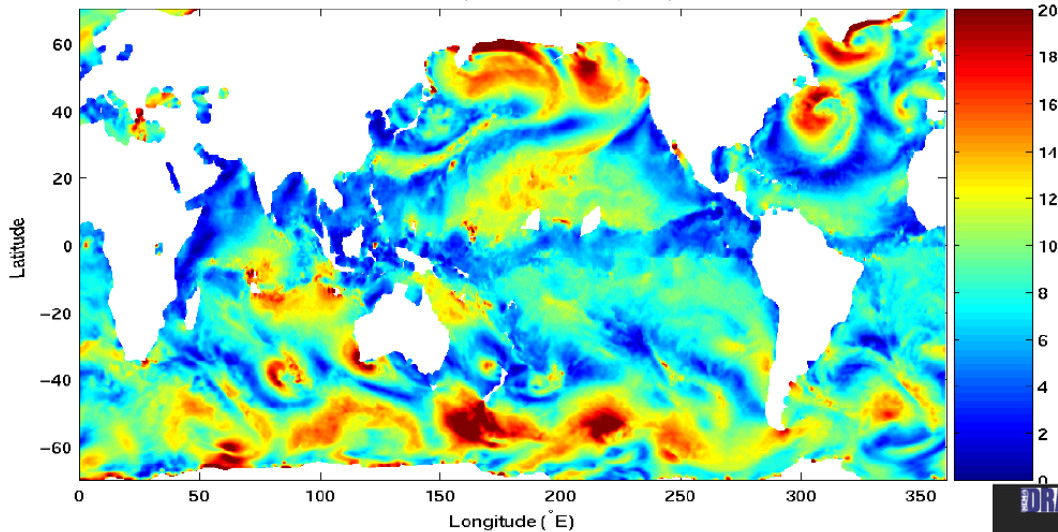
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 - **ENSO**
- The El Nino 2015/16

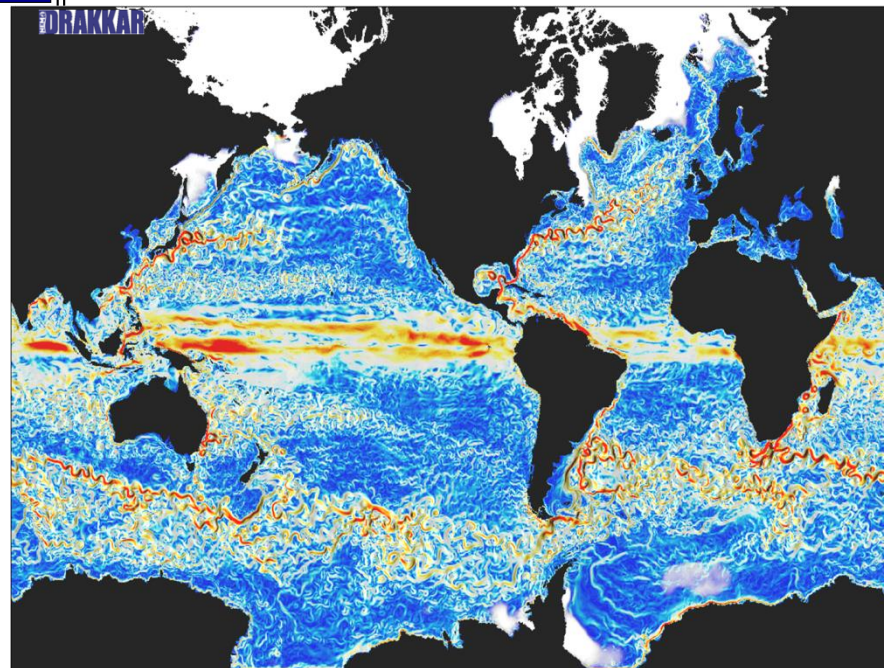
Some facts

- **Spatial/time scales** The radius of deformation in the ocean is small ($\sim 30\text{km}$) compared to the atmosphere ($\sim 3000\text{km}$).
Radius of deformation = c/f where c = speed of gravity waves. In the ocean $c \sim < 3\text{m/s}$ 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 \sim 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?

Blended 12-hourly Winds: 6AM, 1 April 2004



Atmospheric wind speed (12h)

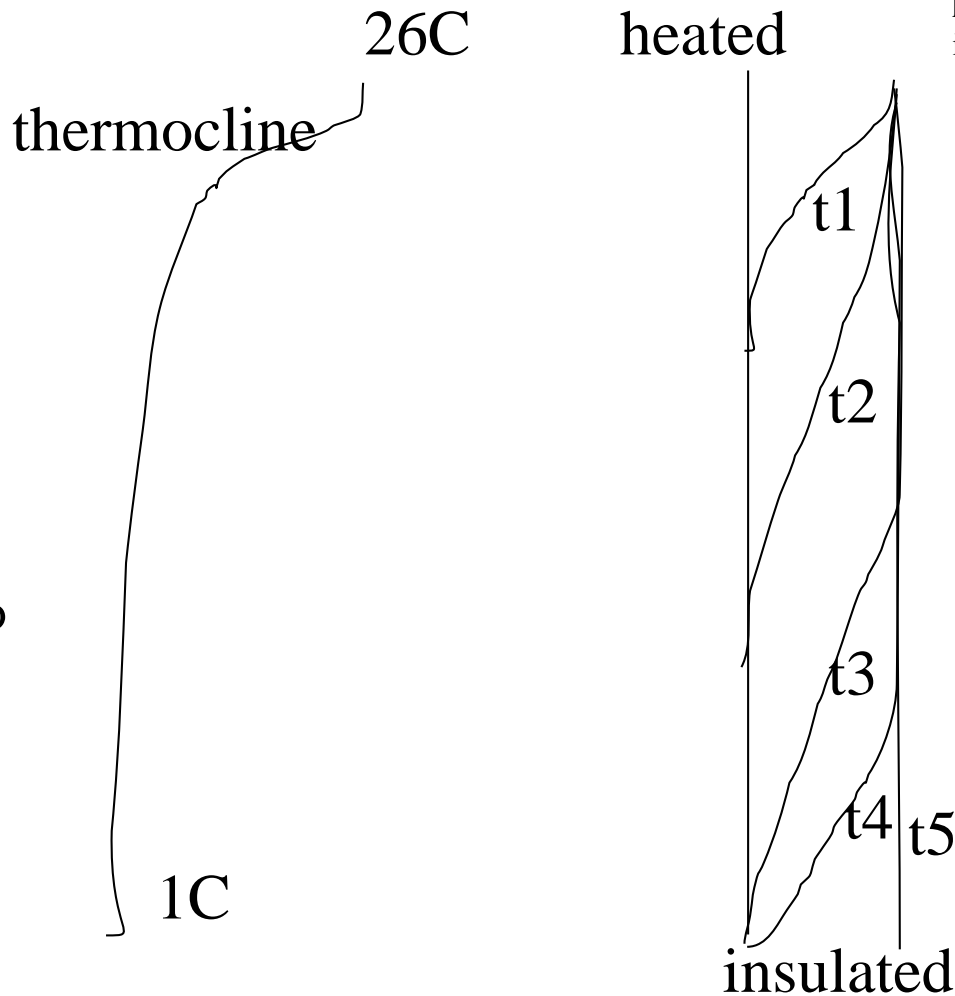


Ocean current speed (model simulation, 5 day mean)

What maintains the ocean stratification?

Thought experiment:

The temperature profile becomes homogeneous (well mixed) with increasing time $t_1, t_2, t_3 \dots$



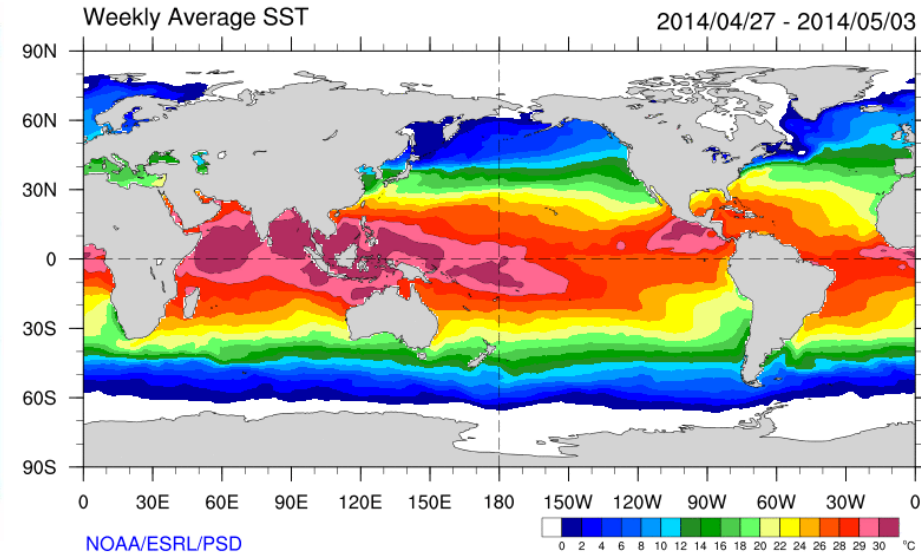
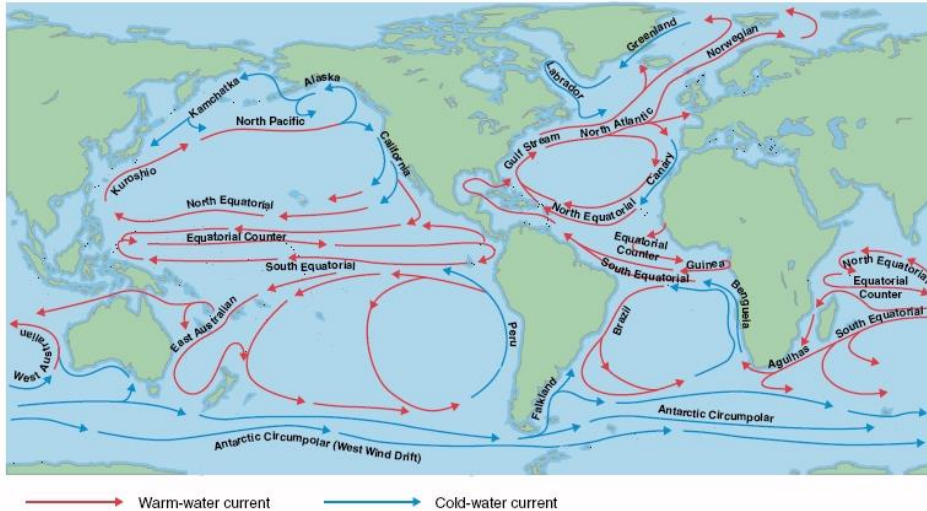
•**Ellis 1751:** The temperature of the ocean at the equator is warm (heated by the atmosphere) at the surface, but is cold at depth: i.e. the ocean is not in thermal equilibrium.

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 ($c \sim 2-3\text{m/s}$) (months)
 - Planetary Rossby waves (months to decades)

Wind driven circulation

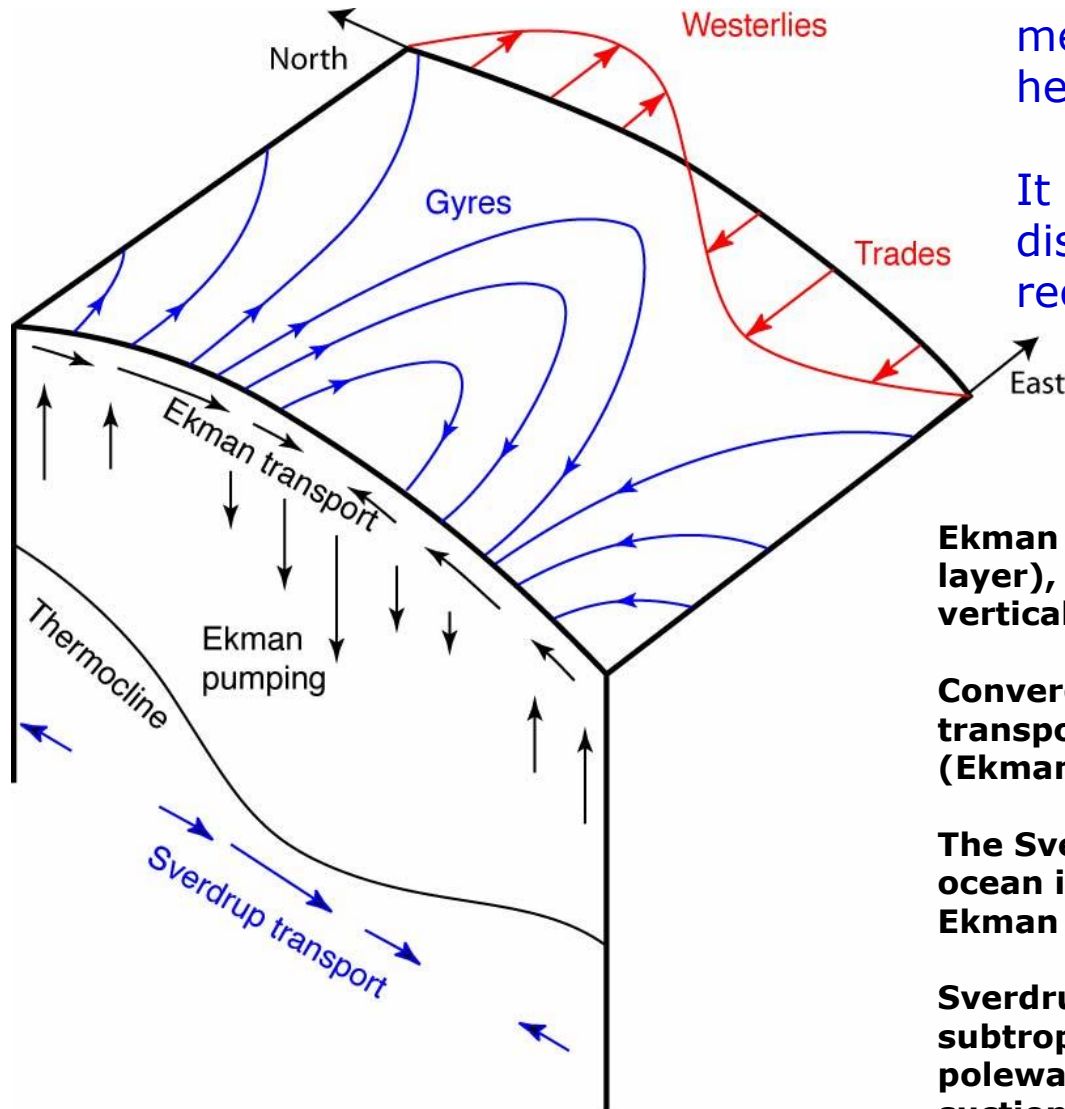
Sverdrup (1947), Stommel (1948), Munk (1950)



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, ENSO, 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.

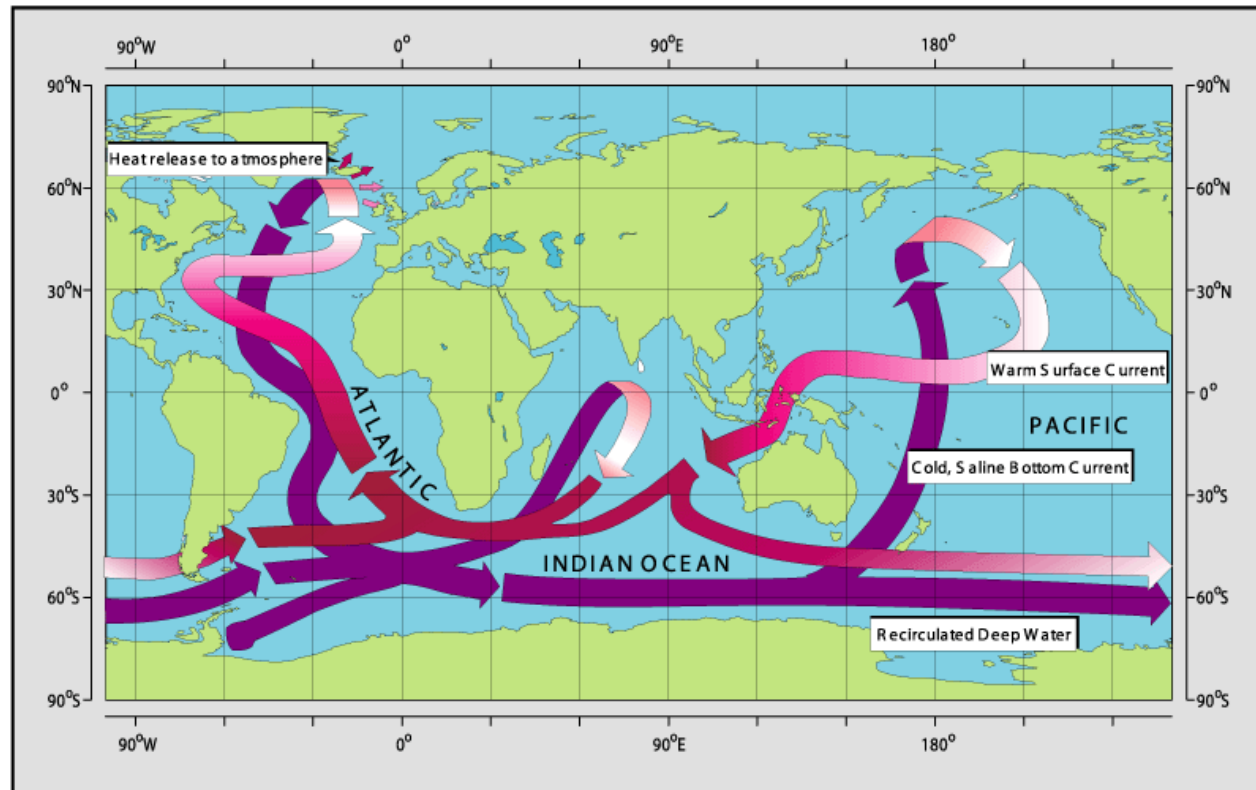
Western Boundary Currents (WBC)

- Narrow Currents flowing poleward on the western part of the basins.
 - Conceived 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



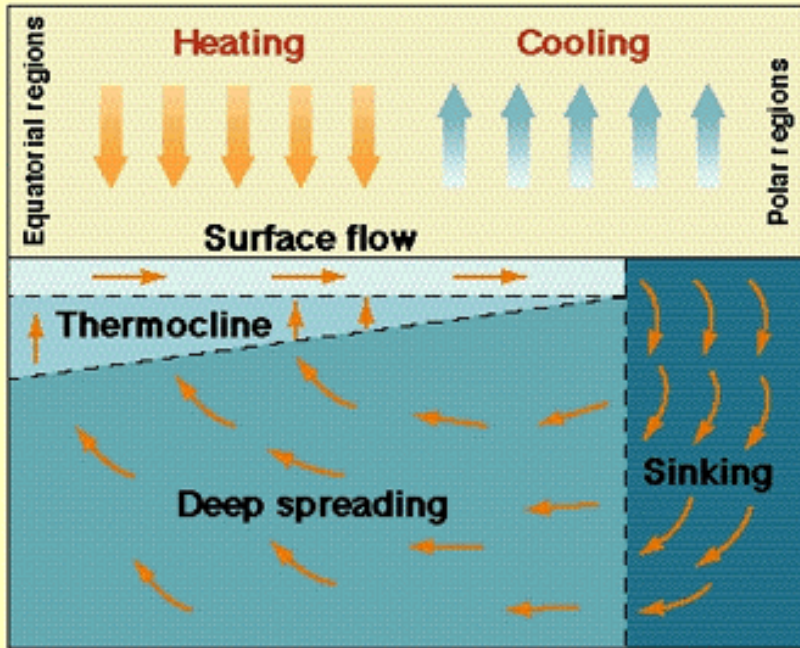
Thermo+Haline= Circulation driven by density differences.

Related to localized deep water formation areas.

Important for meridional heat transports and ocean stratification.

Thermohaline circulation

Model of Pure 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.

Meridional Heat transport: MOC x Stratification

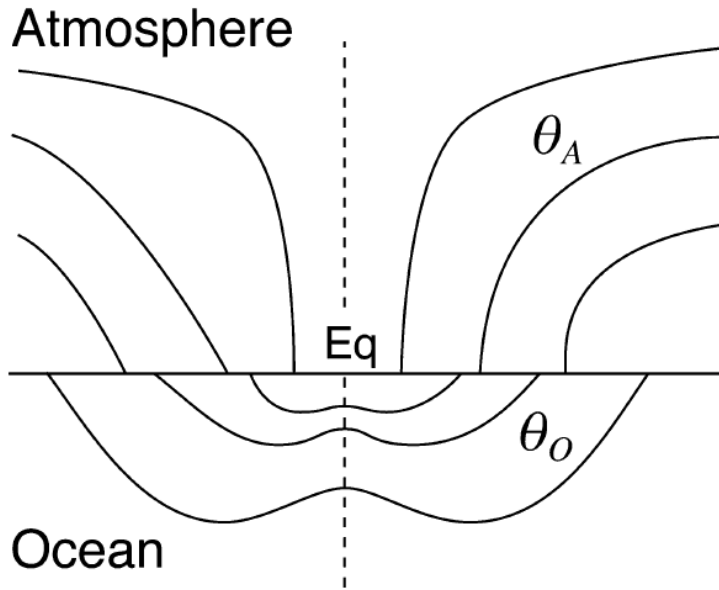
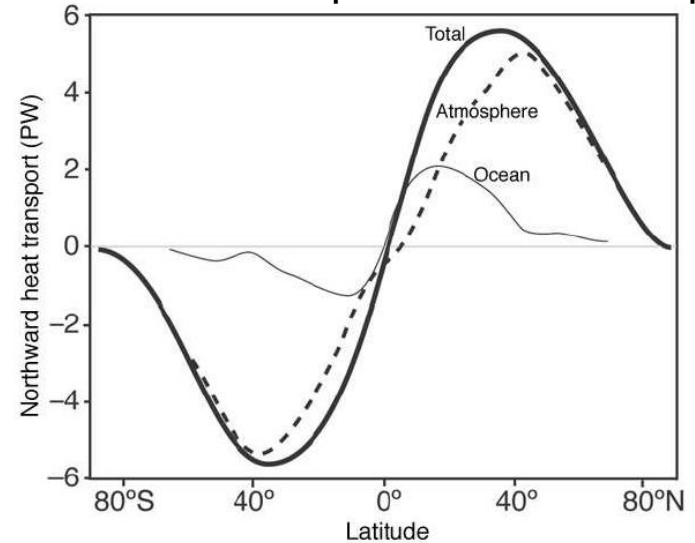


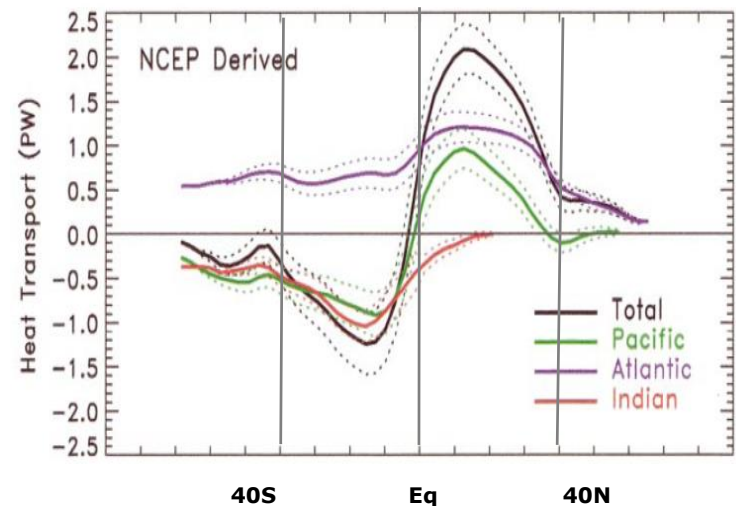
FIG. 2. Schematic of the distribution of atmospheric moist potential temperature (θ_A , i.e., moist static energy) and oceanic potential temperature (θ_O) as a function of latitude and height (black contours). The equator is indicated as a vertical dashed line.

Stratification of Ocean/Atmosphere
From Czaja and Marshall 2006.

Ocean and atmosphere heat transport



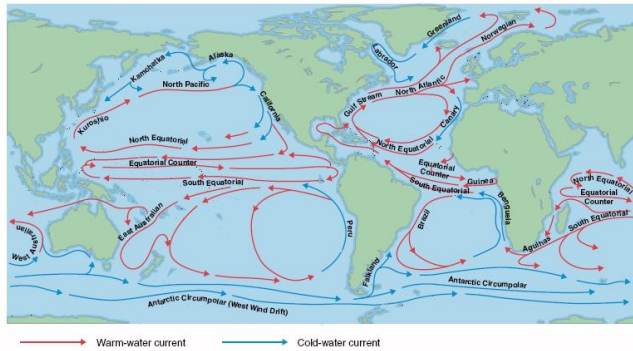
Oceanic heat transport by basins



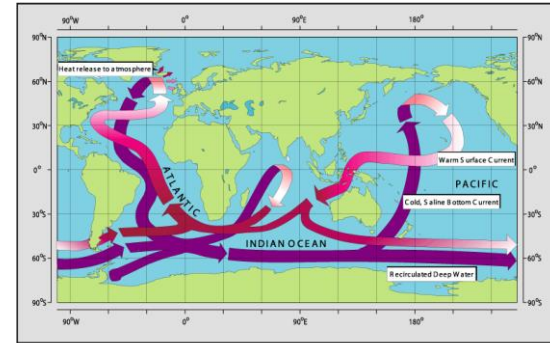
Trenberth and Caron 2001

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.

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

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

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

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

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

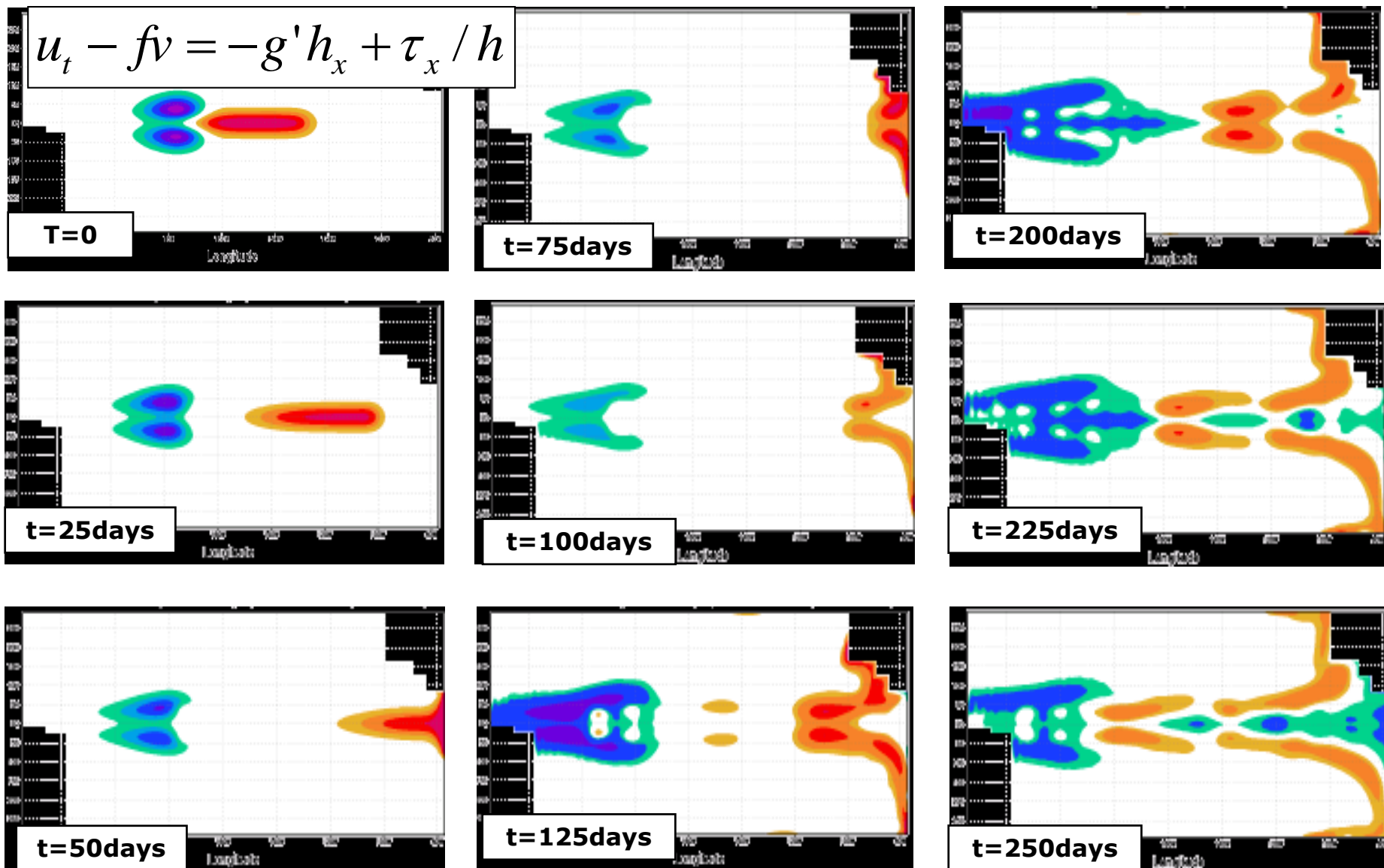
➤ Speed decreases with latitude

$$a = c / f; \text{ Rossby Radius of deformation}$$

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

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

Kelvin & Rossby waves and Delayed Oscillator

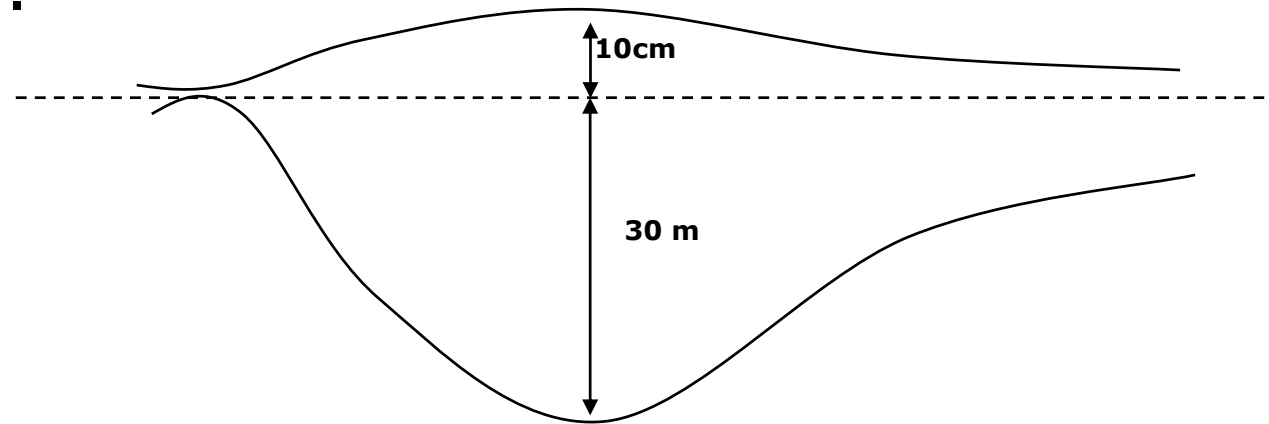


Vertical Stratification and Satellite altimetry

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

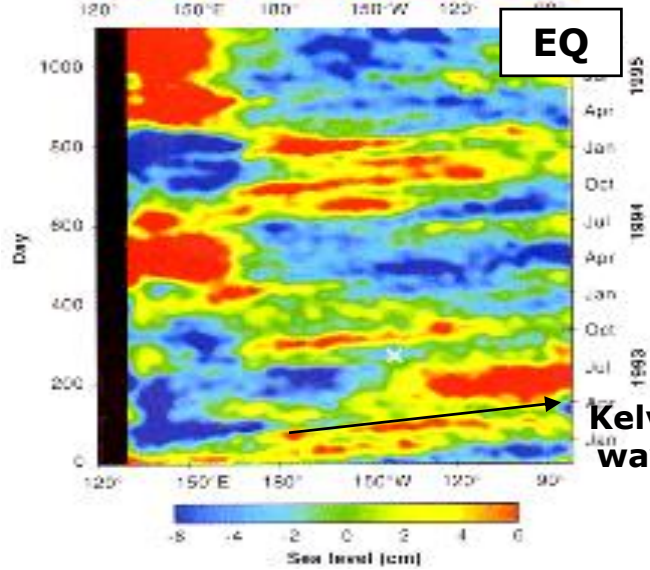
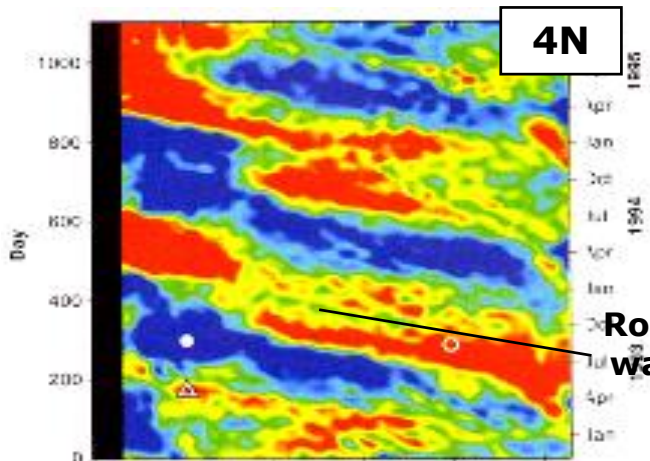
Typically $g' \sim g/300$

- 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

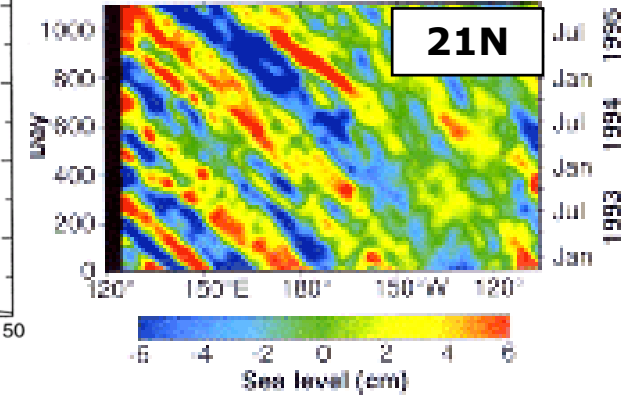
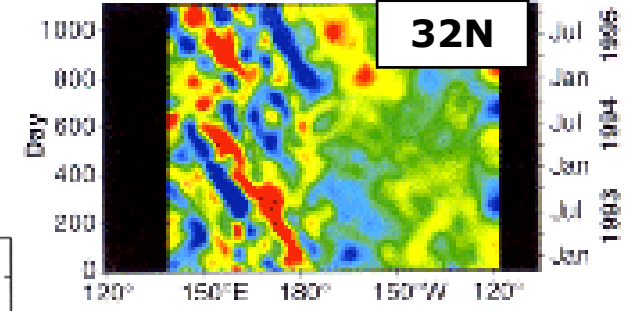
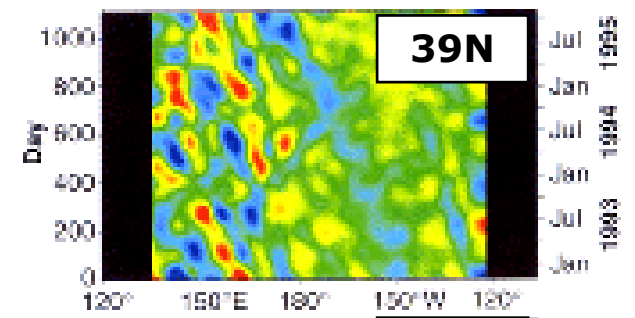
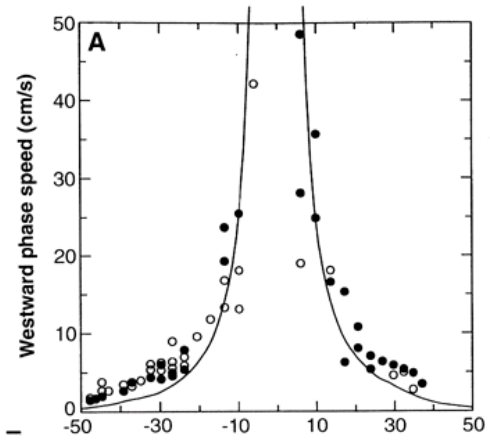
Rossby/Kelvin Waves from Space



Rossby waves

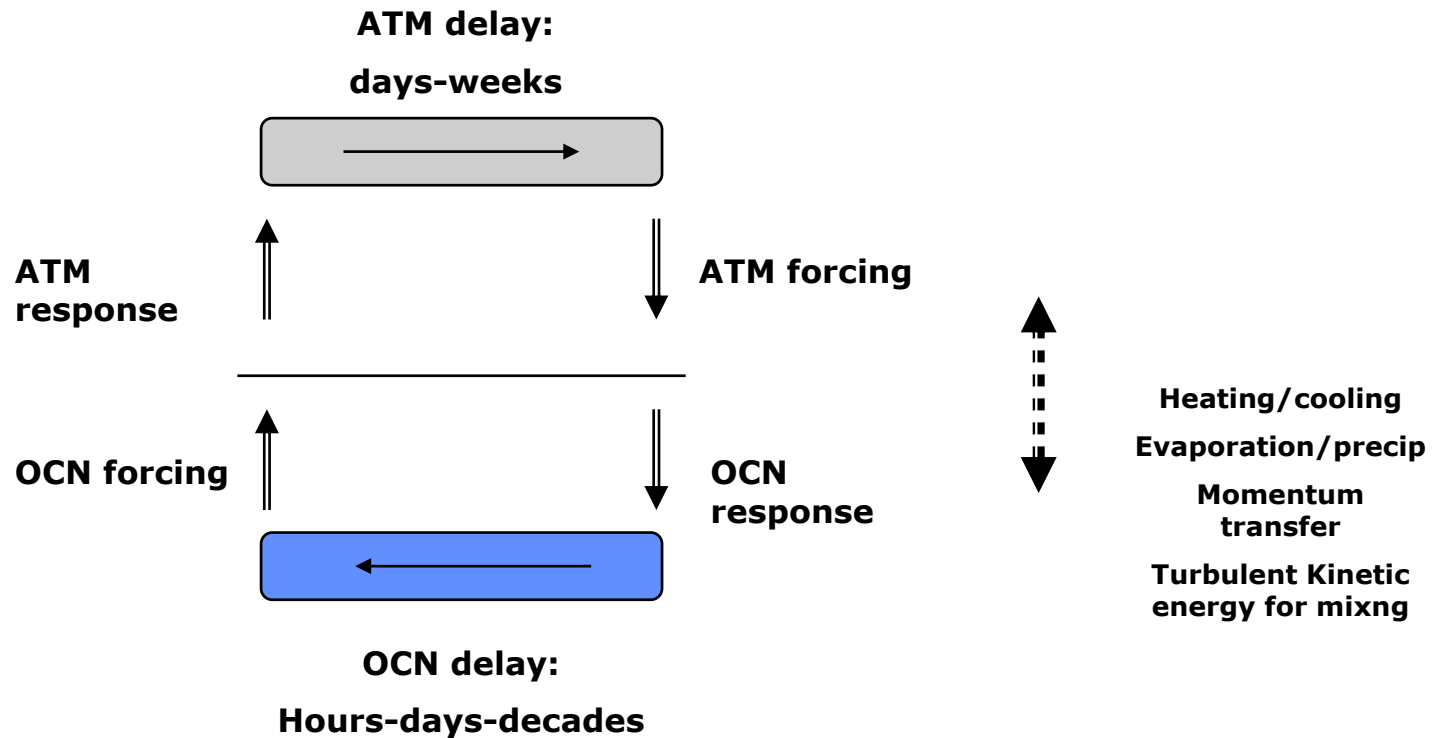
Kelvin wave

Phase speed as a function of latitude



Chelton et al 1996

Time scales for ocean-atmosphere interaction



days	weeks	Months/years	Decades and beyond
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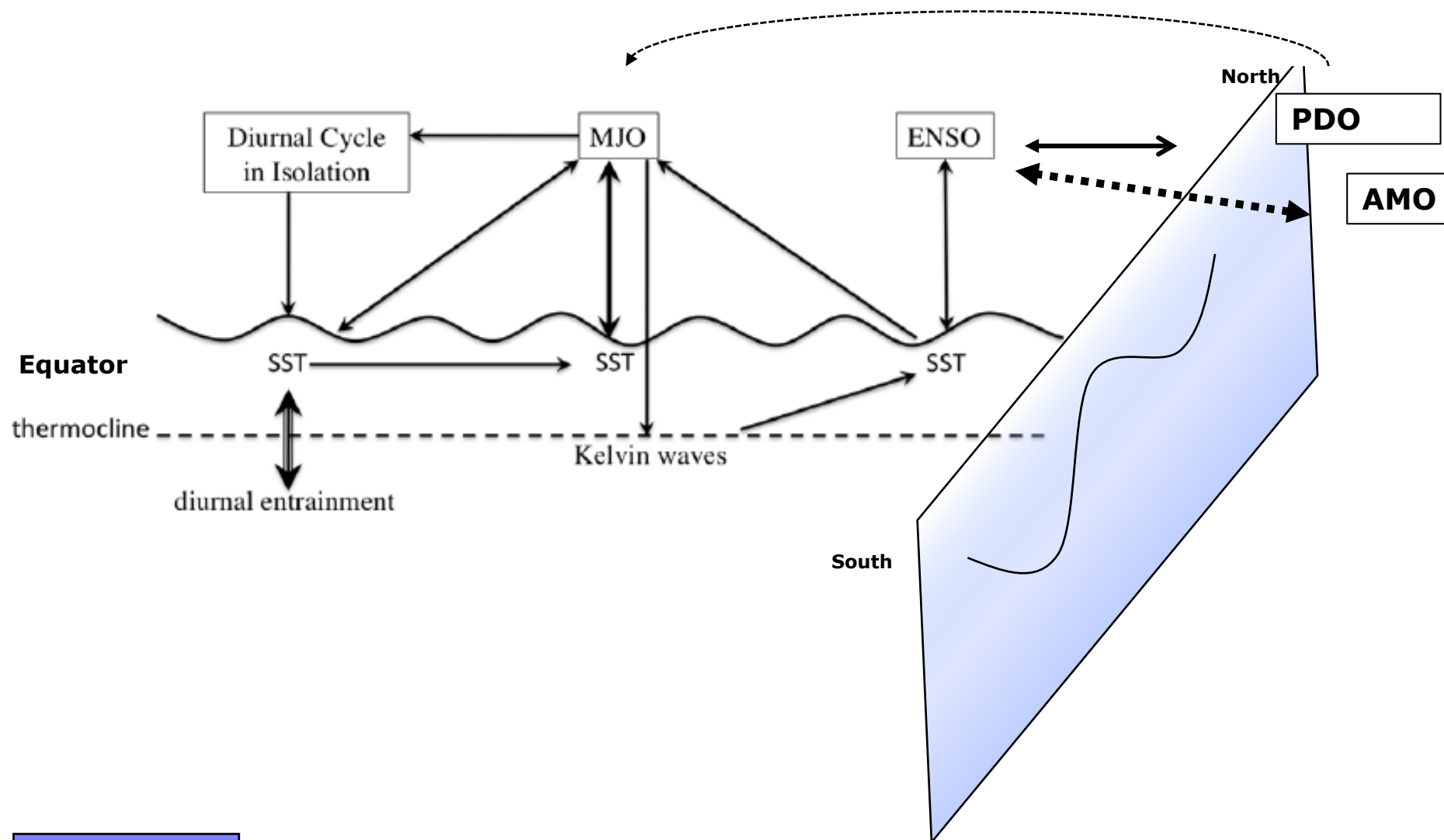
Boundary layer processes
 Tropical cyclones
 Surface waves
 Diurnal Cycle

Madden-Julian Oscillation
 Tropical Instability Waves

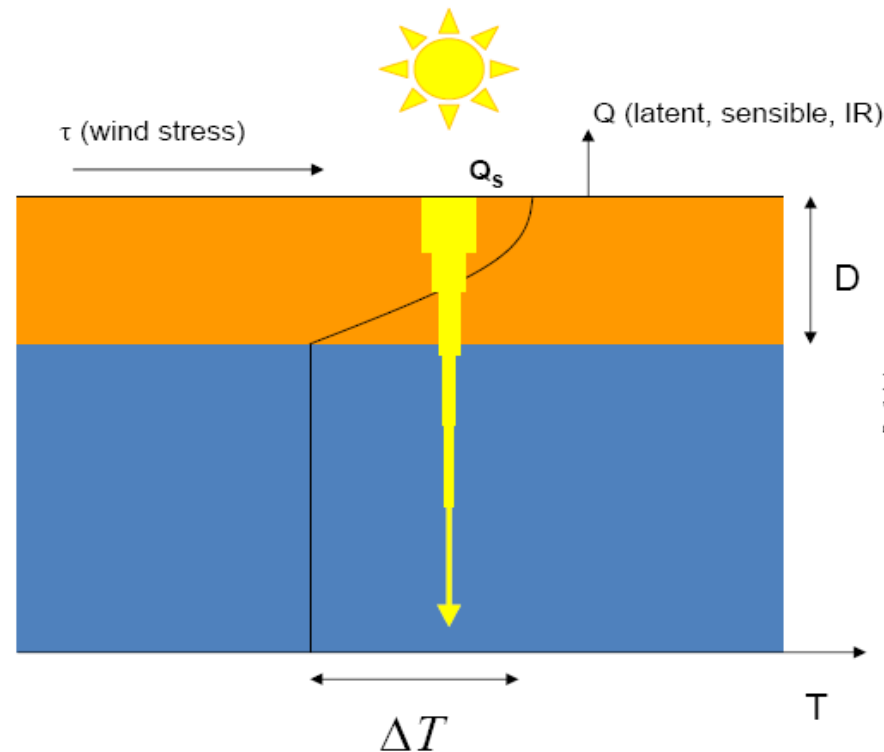
Equatorial Ocean Dynamics:
 ENSO, IOD
 Seasonal ML variations:
 NAO?

Subtropical Gyre, Rossby Waves, THC, MOC
 Pacific/ Atlantic Decadal Variability

Air-Sea coupling: Scale interaction



Diurnal Warm Layers: amplification of diurnal cycle

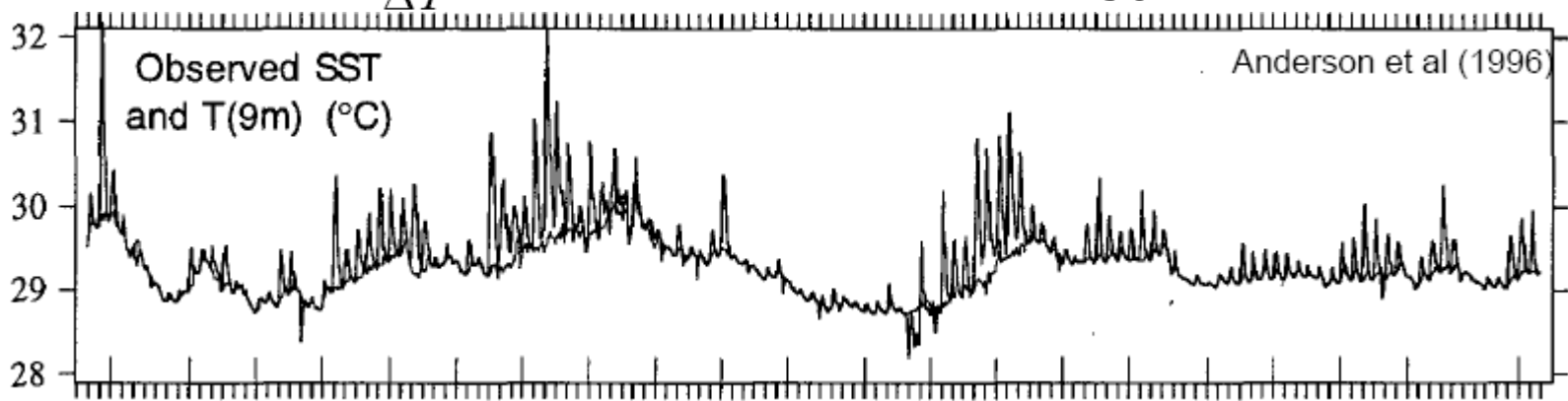


Stably stratified (warm) thin layers form during the day.

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

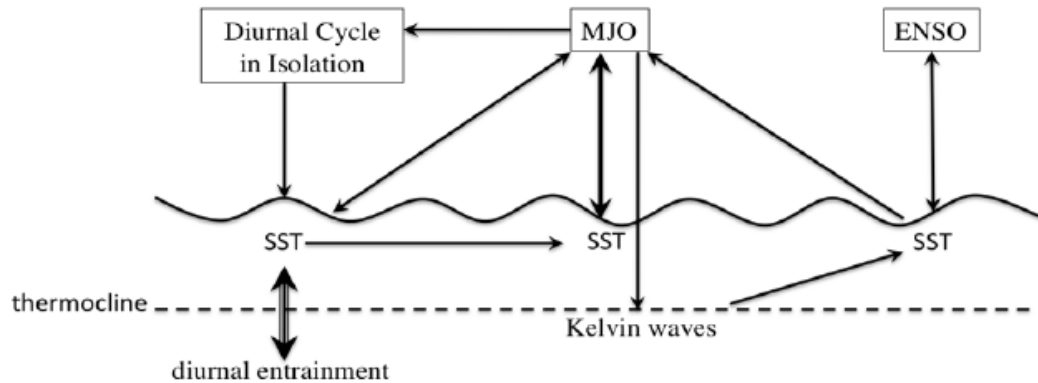
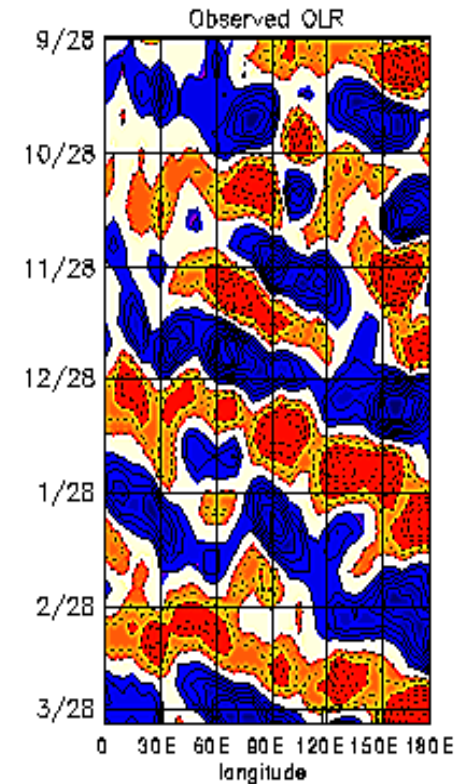
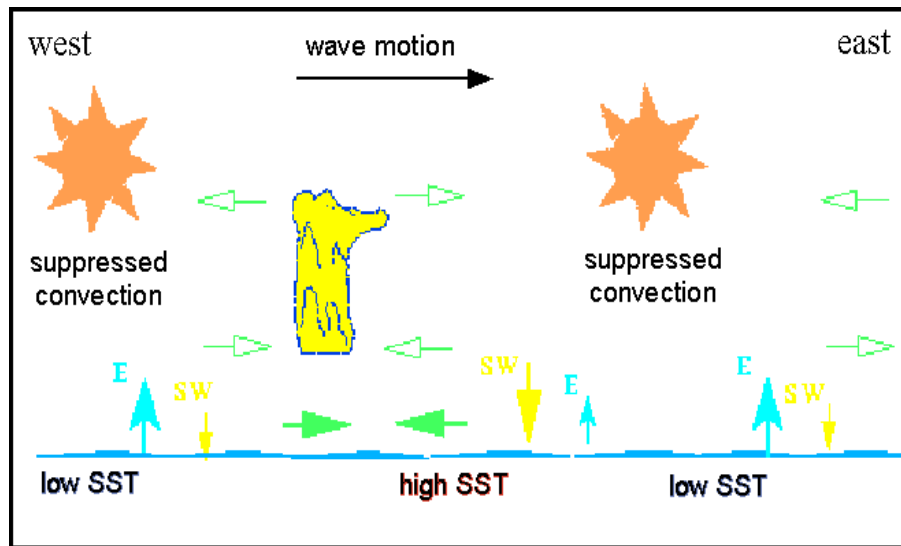
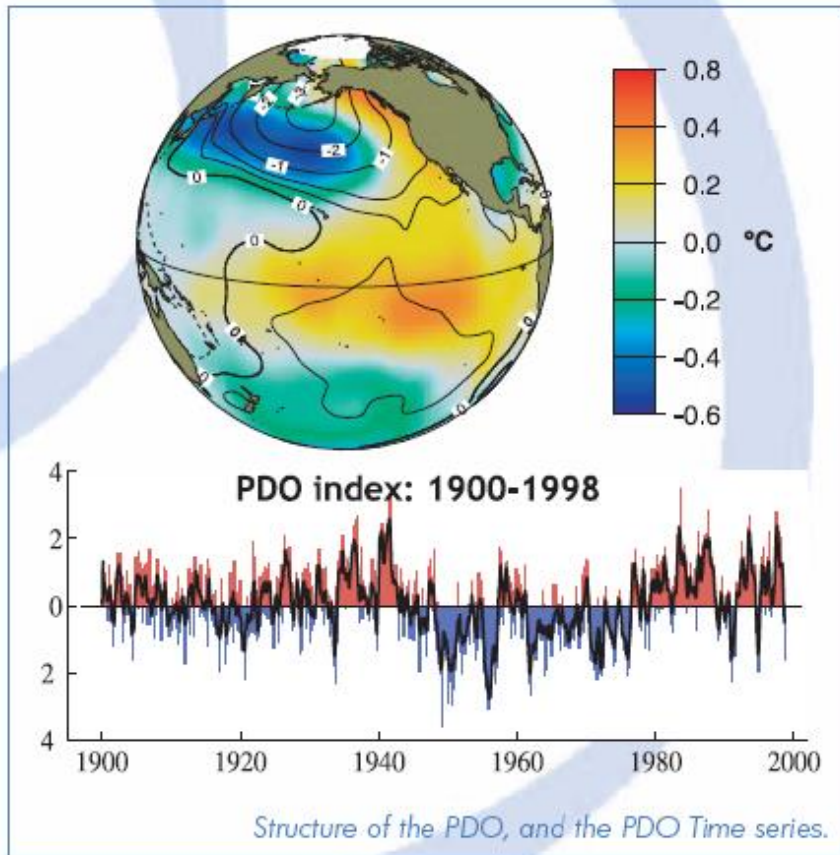


Figure 1: Schematic diagram of cross-scale air-sea interactions between the MJO and diurnal cycle and between the MJO and ENSO. Arrows denote directions of influences.

- 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

Decadal: Pacific Decadal Oscillation

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

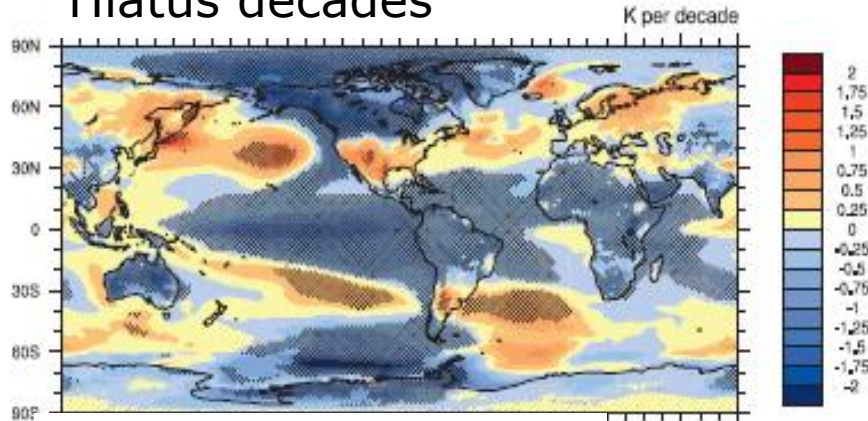


- Influences marine ecosystems (Mantua et al 1997), North American rainfall (Latif and Barnett 1994,1996, Waliser 2008)
- Latif et al, using results from a coupled model, hypothesized there is a coupled feedback (meridional SST gradients and gyre circulation).
- Link with ENSO decadal variability.
- More recently, link with ocean heat absorption and hiatus decades

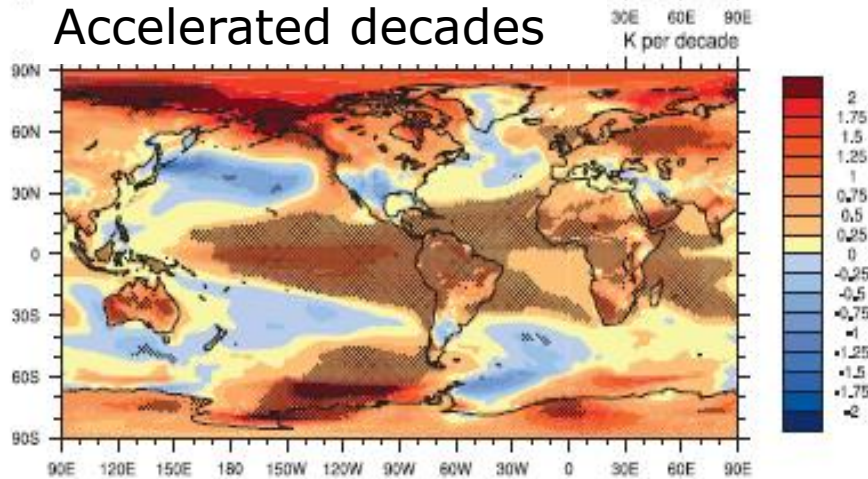
PDO, Hiatus decades and deep ocean warming

SST trends

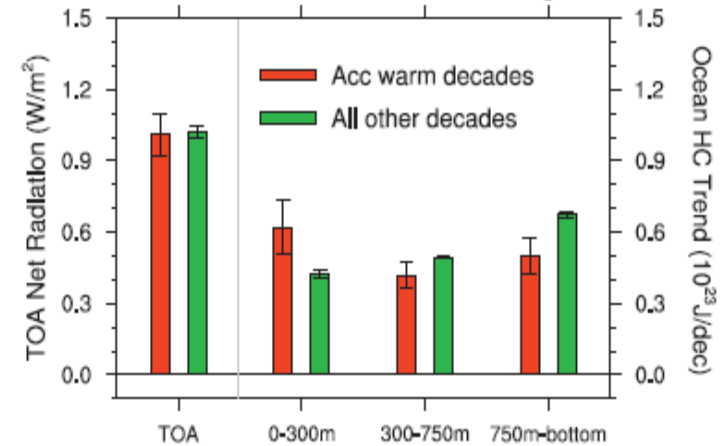
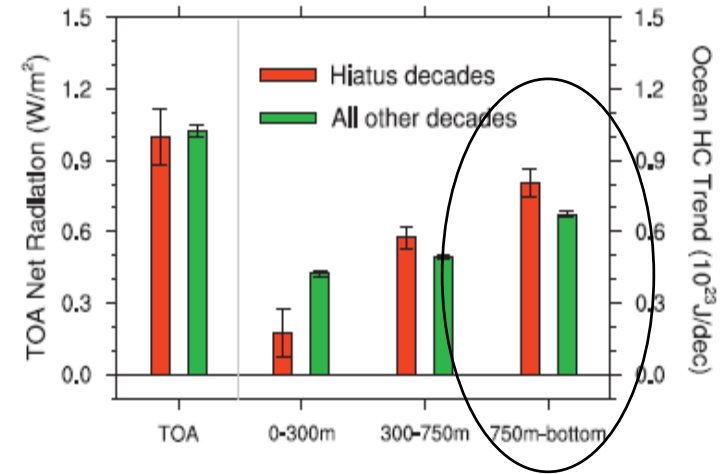
Hiatus decades



Accelerated decades



Warming Rates



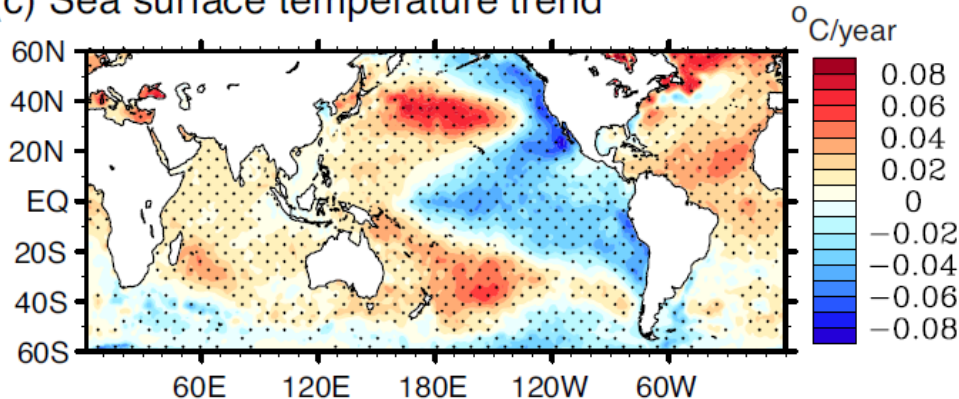
Meehl et al 2011, NG, Meehl et al 2013, JCLim

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

Stronger surface warming and stratification in accelerated decades.

PDO and wind driven circulation

(c) Sea surface temperature trend

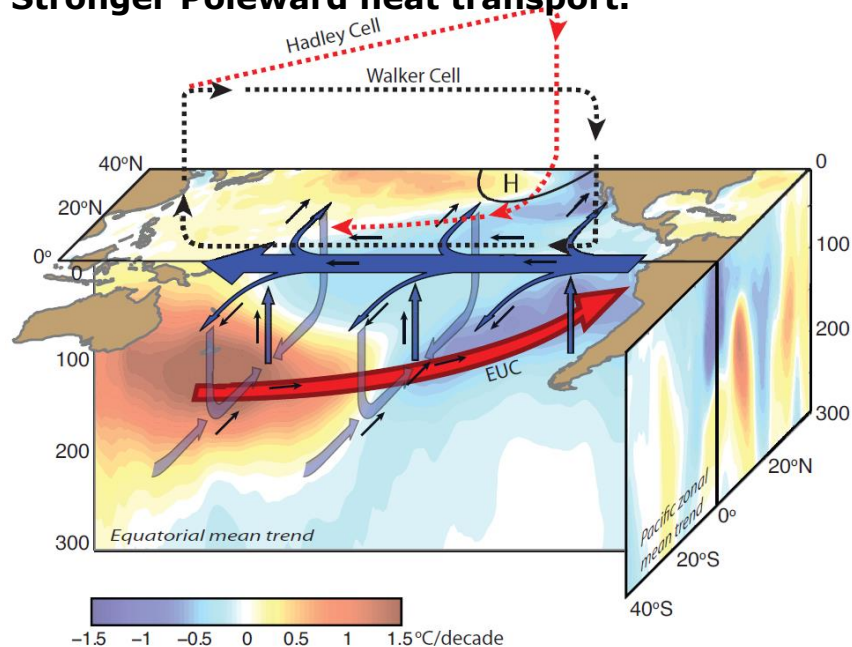


Intensified Walker circulation steepens the Equatorial Thermocline.

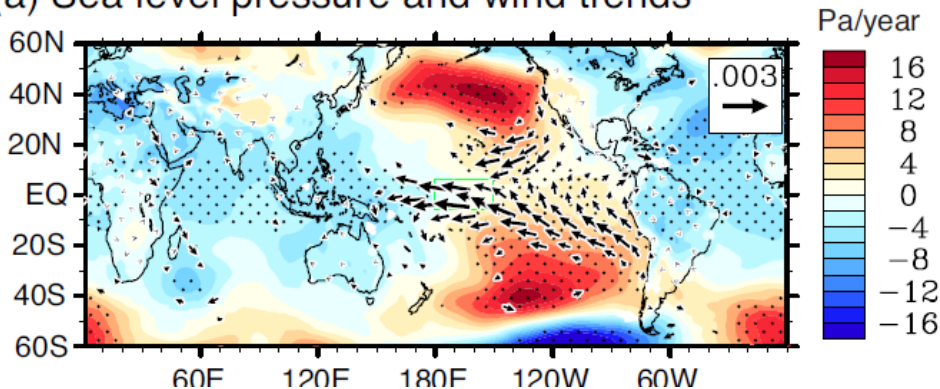
Intensified Hadley circulation, stronger gyres.

Stronger-deeper Ekman pumping and subduction. Increased ocean heat absorption

Stronger Poleward heat transport.

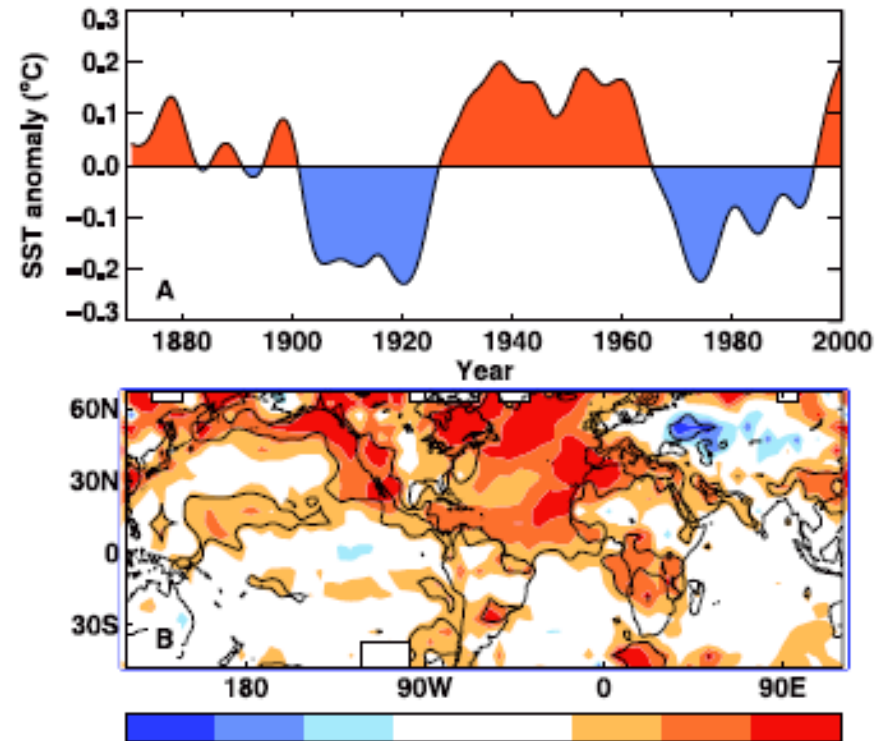


(a) Sea level pressure and wind trends



From England et al 2014

Atlantic Multidecadal Oscillation: AMO



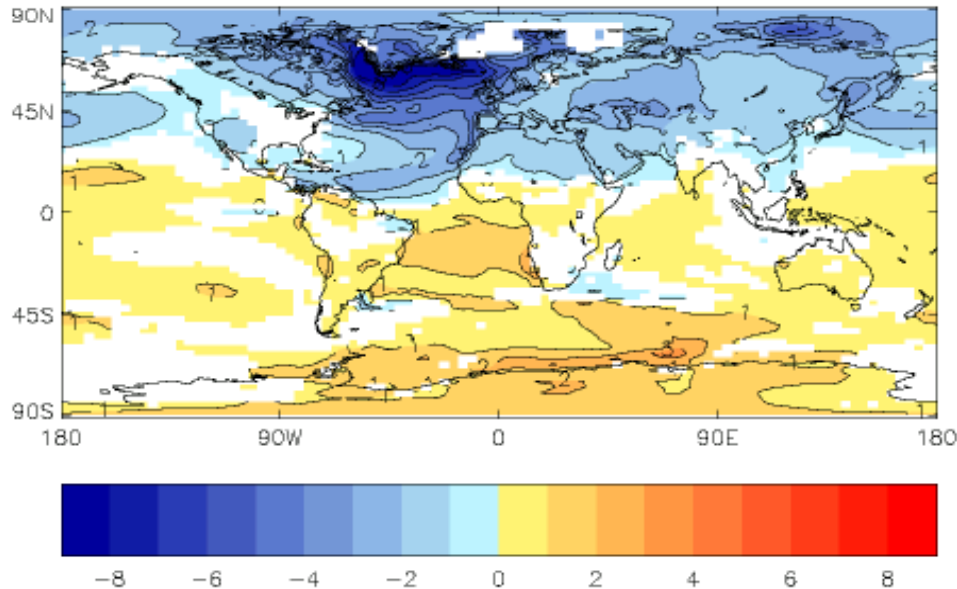
From King et al
2005

- 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.
- 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

A weakening of the AMOC can also explain the increased heat uptake by the deep ocean (and hiatus of the surface warming).

Interannual Time scales: ENSO

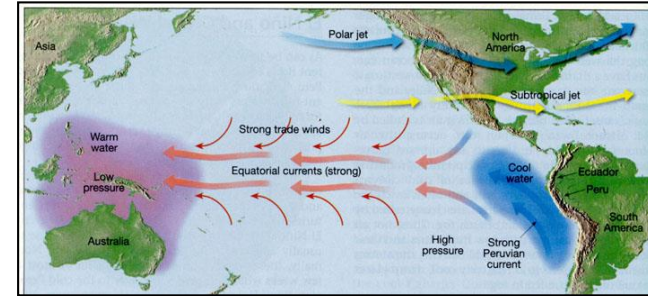
ENSO: El Nino -Southern Oscillation

Largest mode of O-A interannual variability

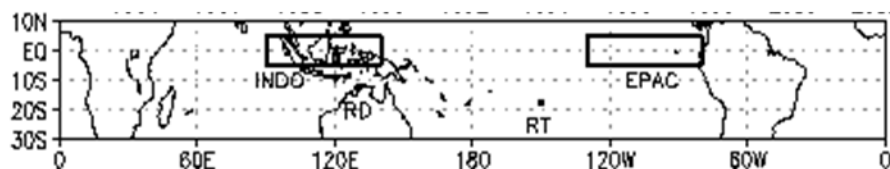
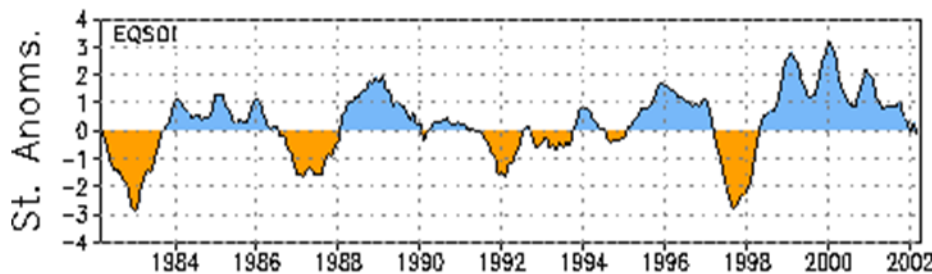
Best known source of predictability at seasonal time scales

It affects global patterns of atmospheric circulation, with changes in rainfall, temperature, hurricanes, extreme events

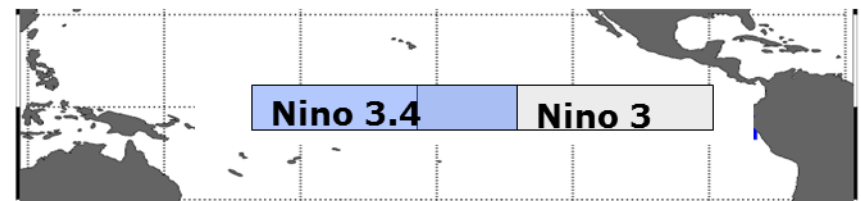
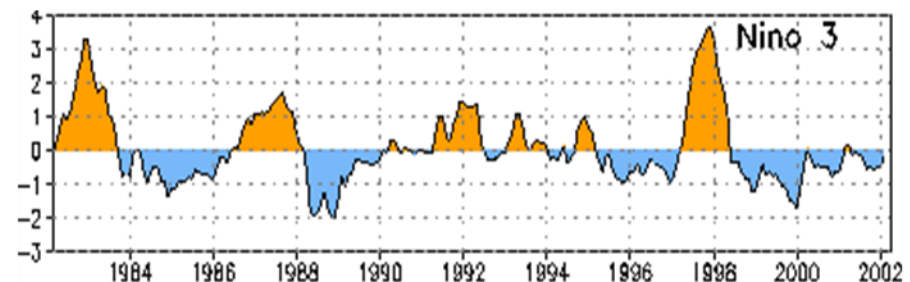
SOI: Southern Oscillation Index (SLP Darwin – Tahiti)



Sea Level Pressure (SOI)

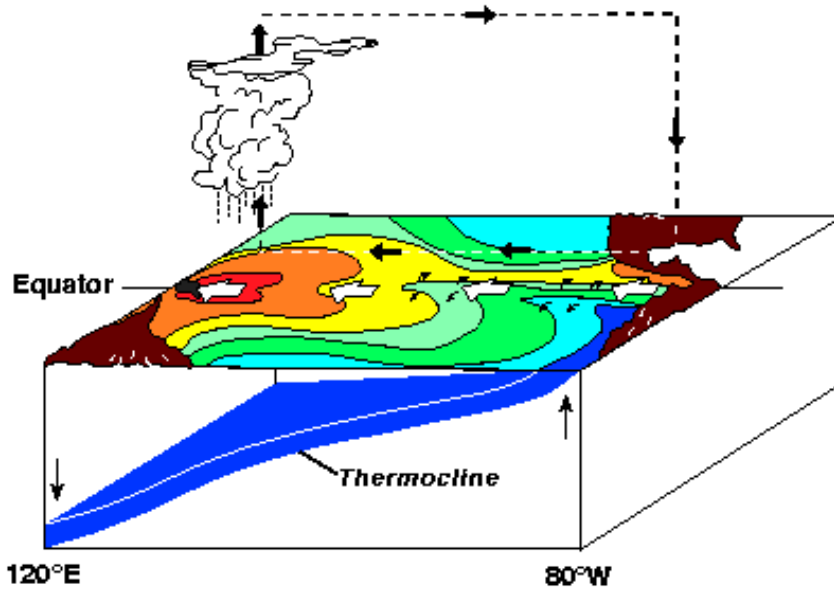


Sea Surface Temperature (Nino 3)



EL Nino (warm) and La Nina (cold)

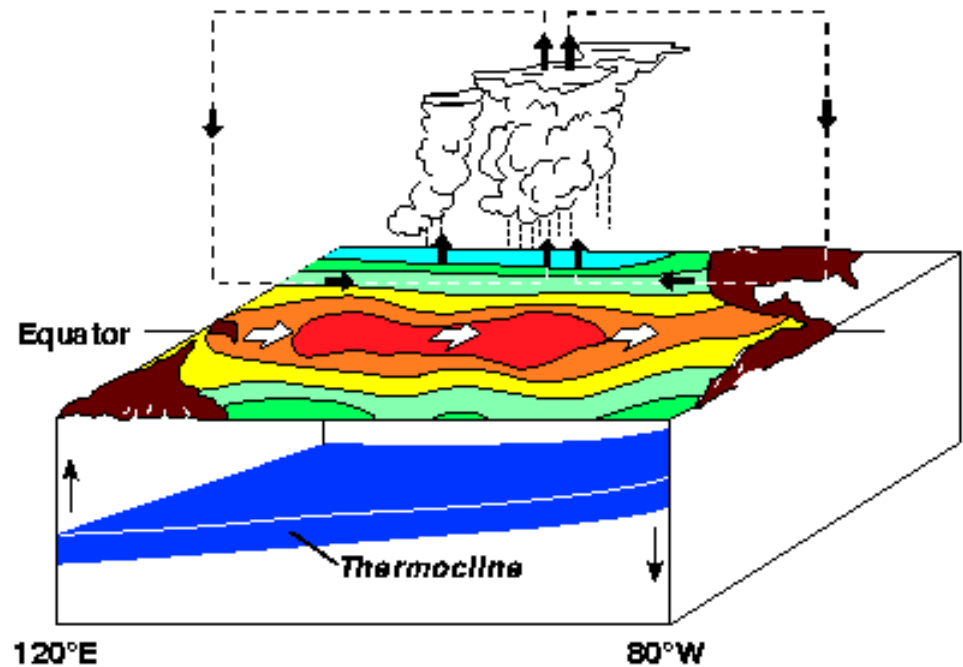
La Niña Conditions



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

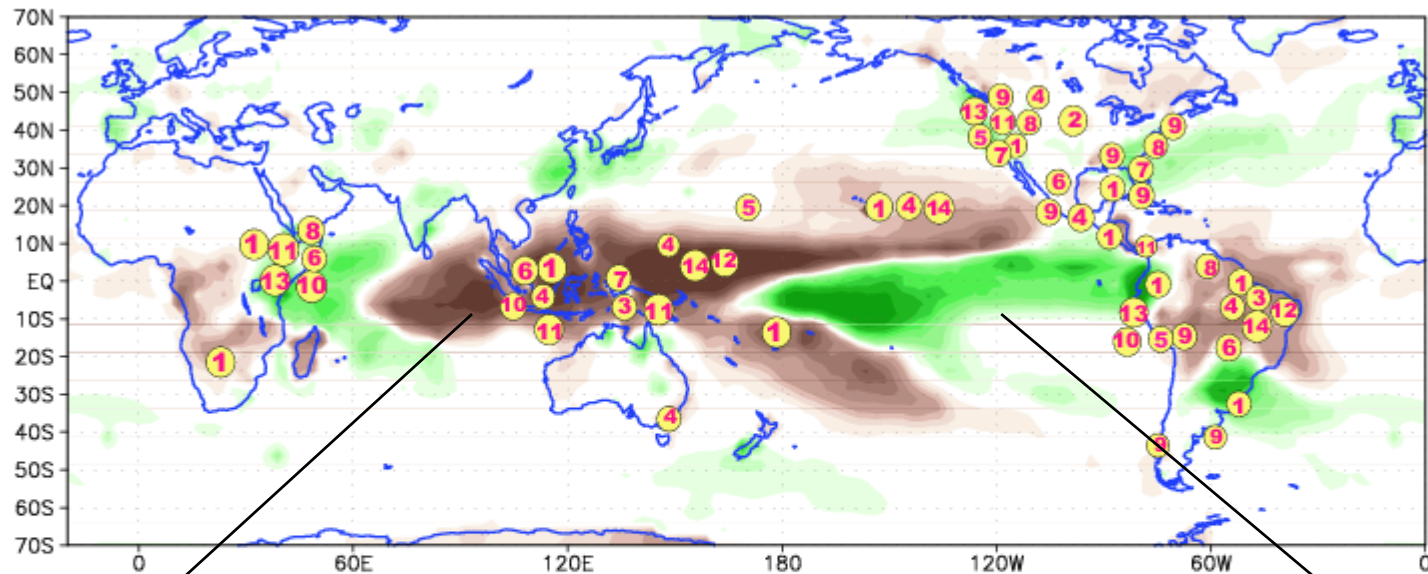
El Nino is associated with reduced easterly (maybe even westerly) winds at the surface, a reduced thermocline slope and warm water in the east.

El Niño Conditions



El Niño and Large Scale Precipitation

Societal Impacts from 1997/98 El Niño



Decreased
Precipitation

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

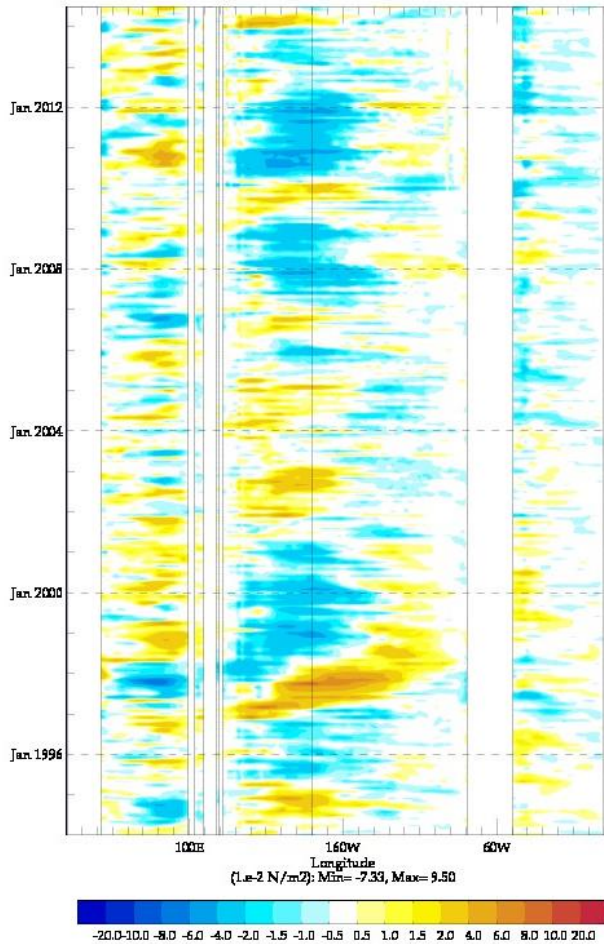
Increased
Precipitation



Climate Prediction Center

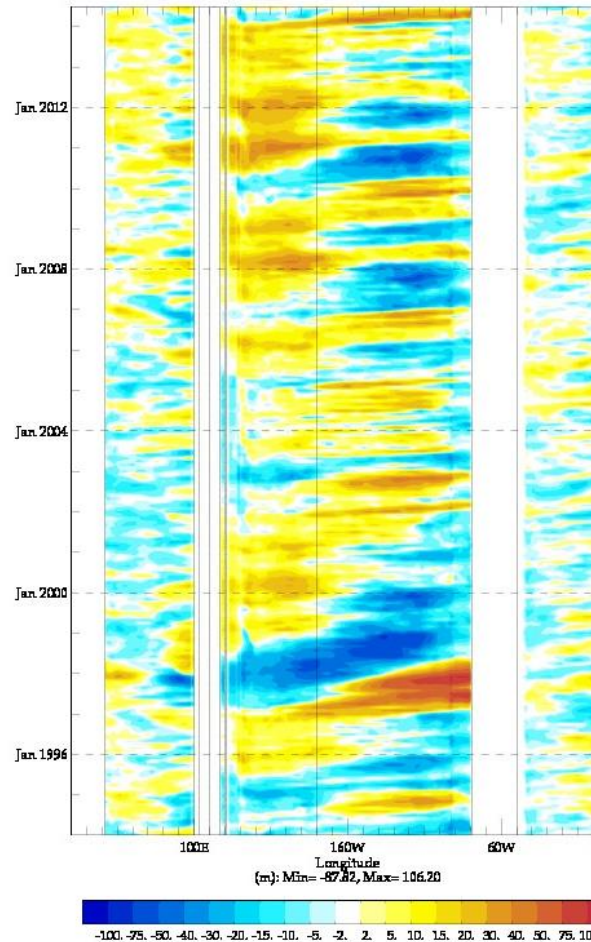
Last 20 years of Equatorial Anomalies

Taux Anomalies

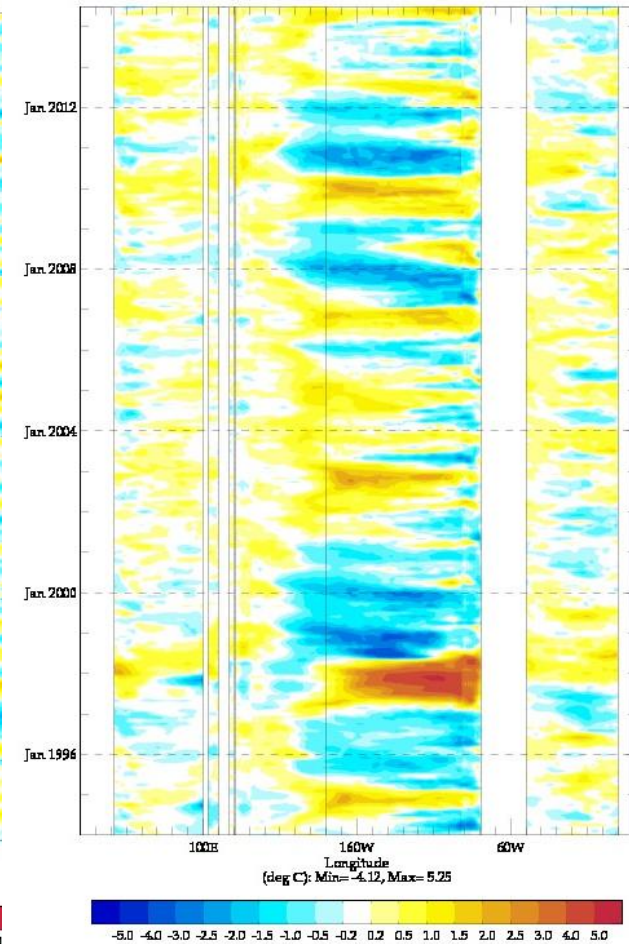


D20 Anomalies

anomaly (1981-2009 climate). Last date 2014/07



SST Anomalies



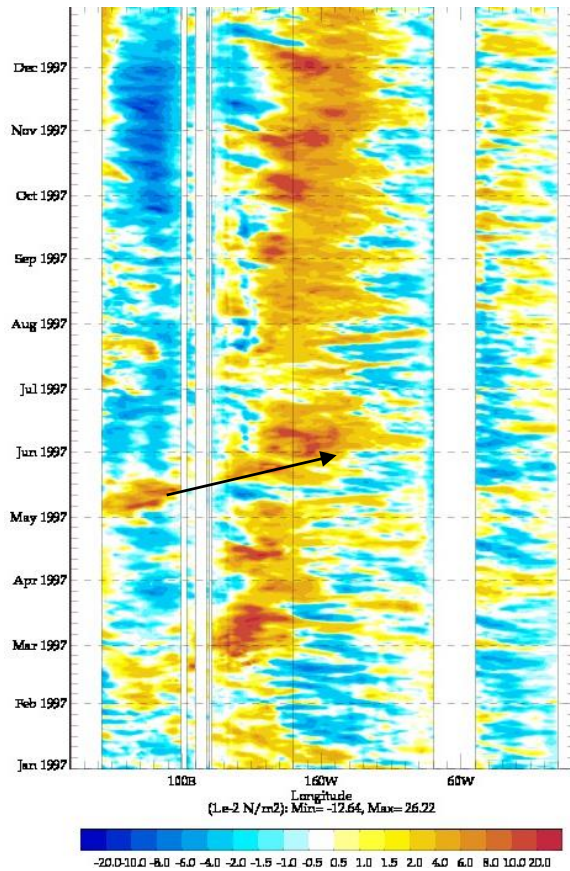
Note the strong 1997-8 El Niño and 1998-9 La Niña in Taux, D20 and SST

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

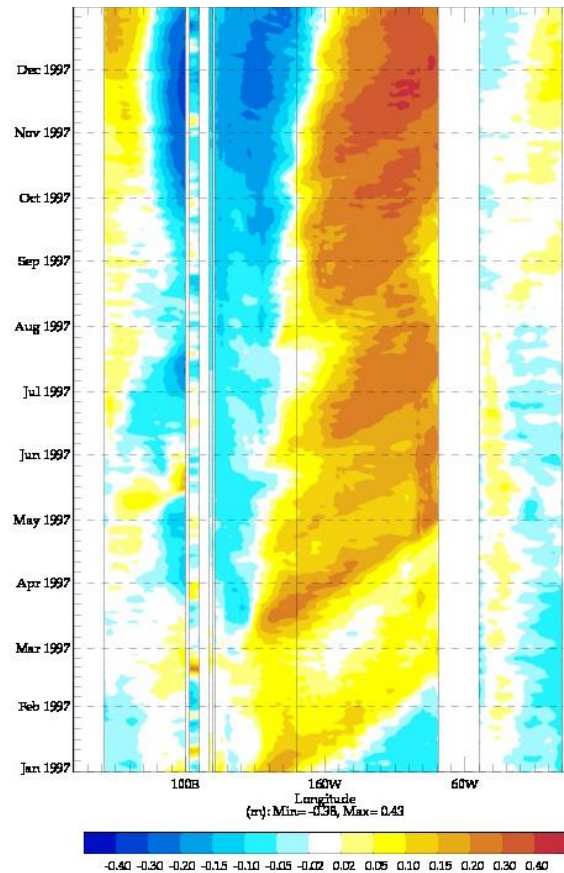
Until 2014, when a strong Kelvin wave was generated....

Daily Equatorial Anomalies: Jan 1997-Jan 1998

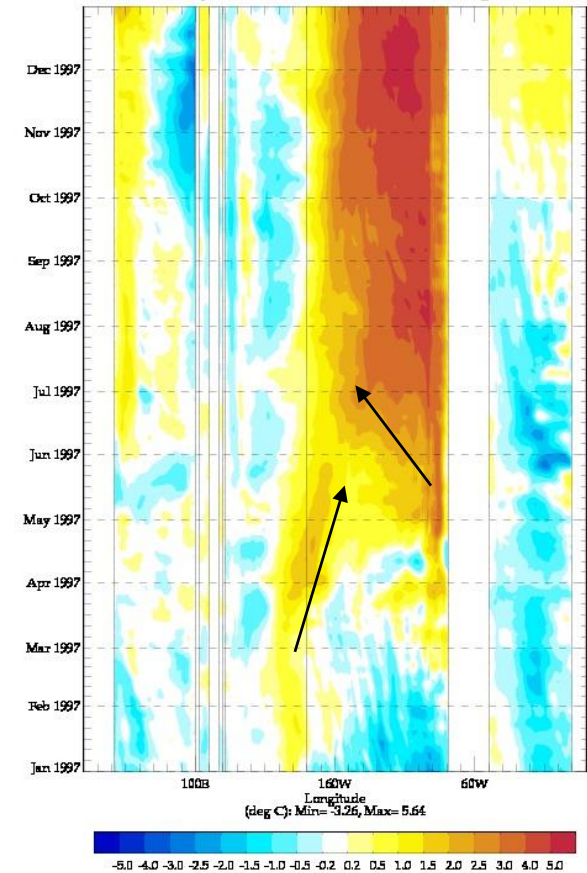
Taux Anomalies



SL Anomalies



SST Anomalies



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

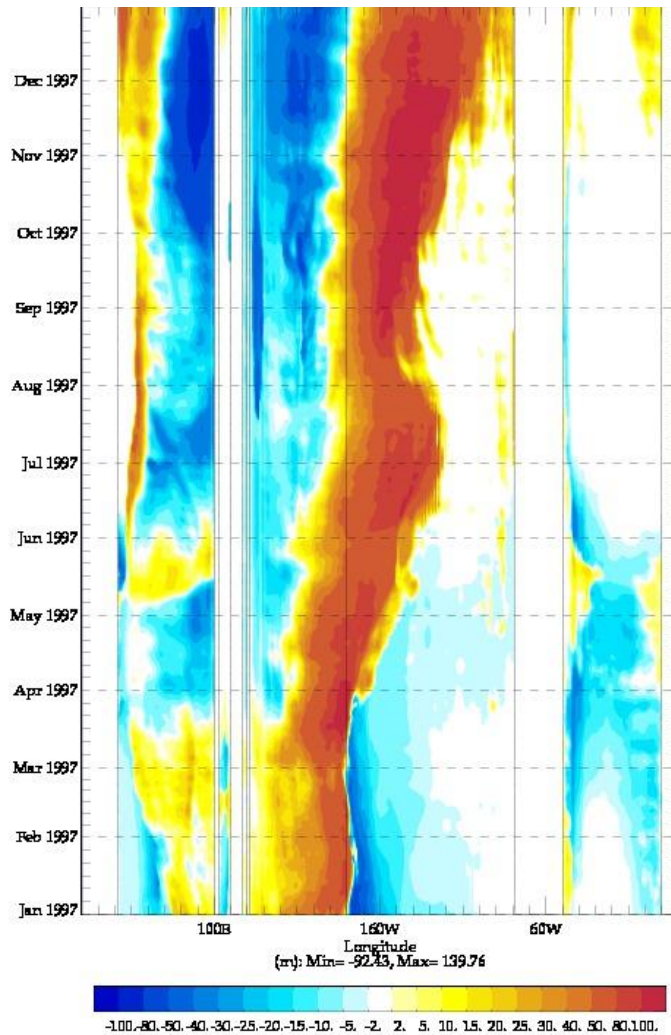
Associated eastward propagating groups of Kelvin waves. The latest reaching the Eastern Coast

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

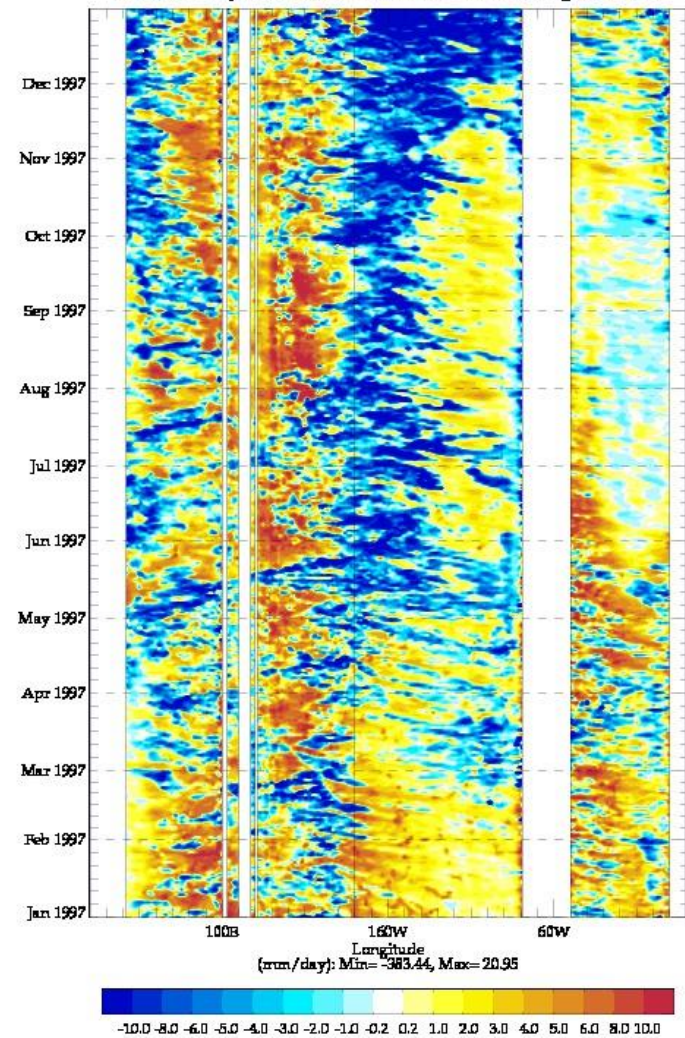
May/June 1997: More WWB . Or is this already ENSO? Bjerknes feedback in action.

Daily Equatorial Anomalies: Jan 1997-Jan 1998

D28 Anomalies "Warm Pool"



Fresh Water Flux Anomalies Blue is into the ocean



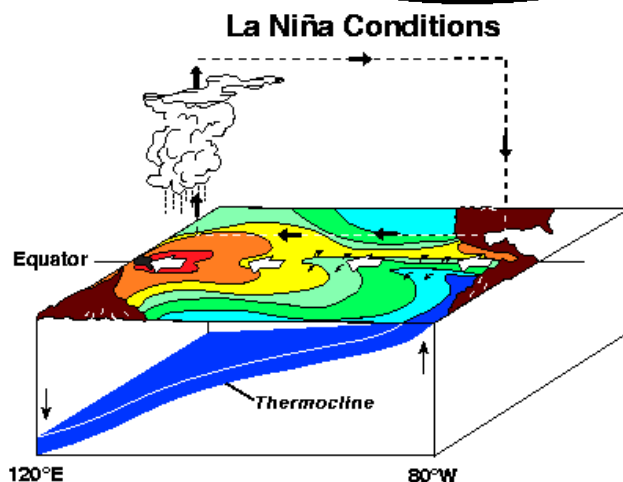
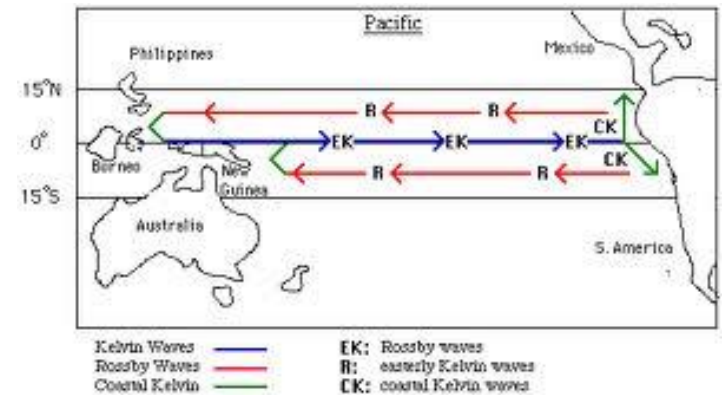
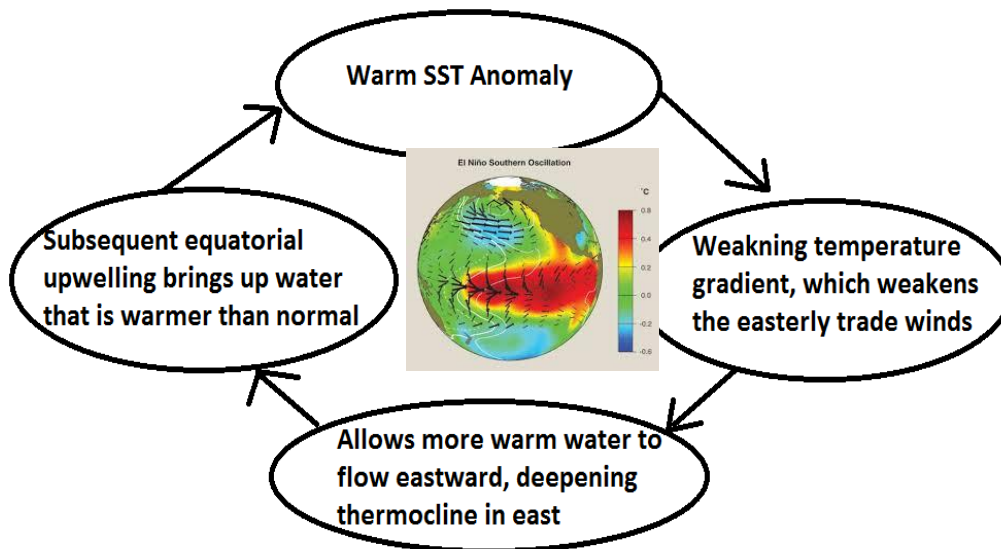
Warm pool moves to the Central Pacific, taking with it the Atmospheric Deep Convection and Rainfall

Multitude of conceptual models for EL Nino

Bjerknes Feedback

&

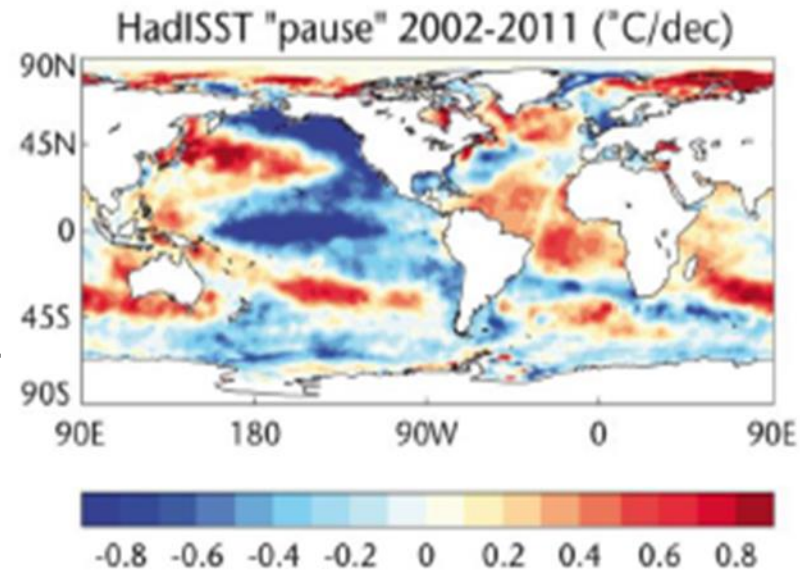
Equatorial Waves



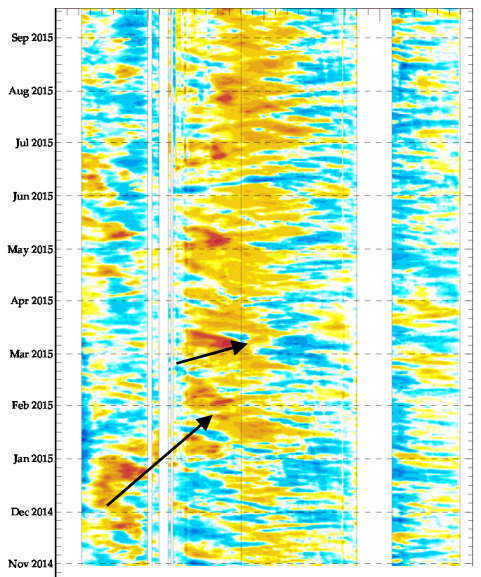
- 1. Delayed Oscillator Mechanism: BF+ Resonant Basin mode**
It does not explain the "a-periodicity". Mostly adiabatic
- 2. System switching between 2 equilibriums.**
Switch is external: seasonal cycle, stochastic
- 3. Coupled Instability, stochastically triggered.**
Very unpredictable? How does it end?
- 4. Discharge/recharge mechanism**

The 2015/16 strong El Nino and the false alarm in 2014

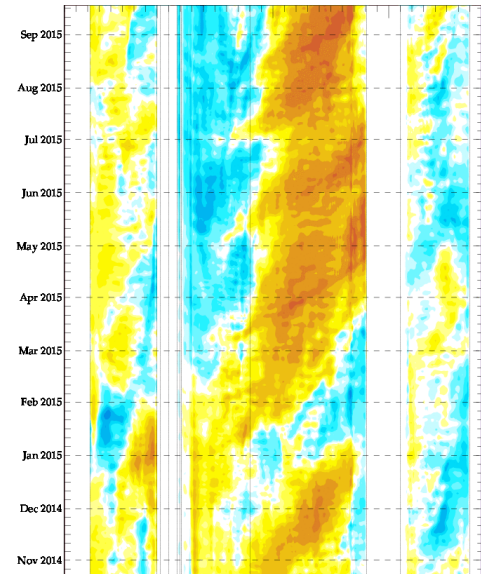
- Great expectation in 2014 for a big El Nino
 - Last one was in 1997/98
 - There had been a hiatus decade (since ~2015) with negative phase of PDO
 - Long lasting Californian drought
 - Models and Experts predicted the possibility of a large warm event



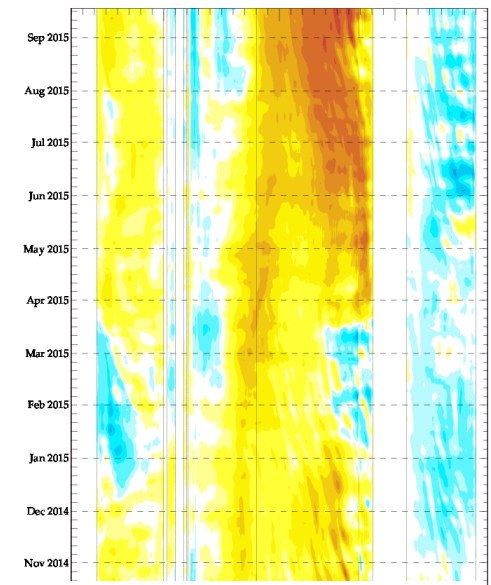
Taux Anomalies



D20 Anomalies



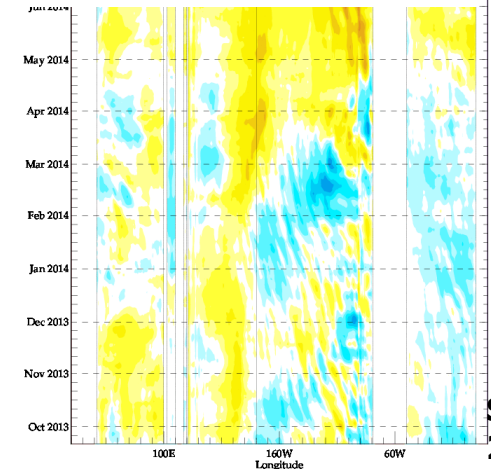
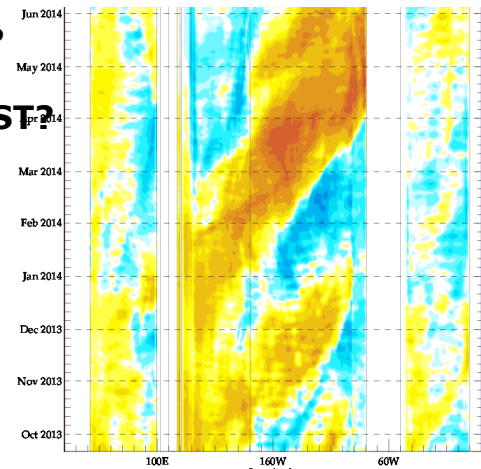
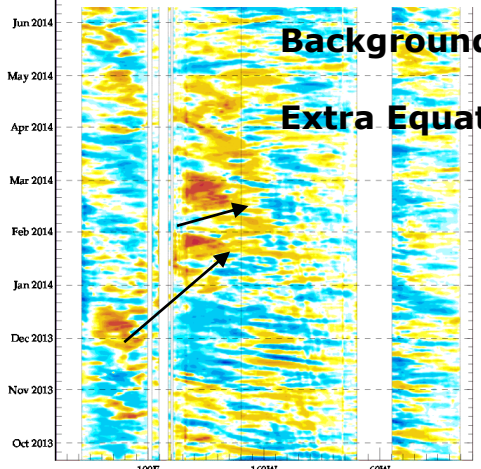
SST Anomalies



Sep 2015

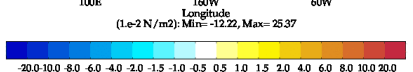
Oct 2014
Sep 2014
Aug 2014
Jul 2014
Jun 2014

Background State?
Extra Equatorial SST?

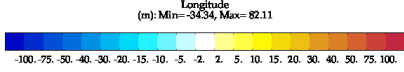


Sep 2014

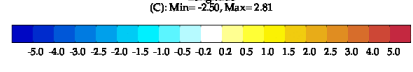
Sep 2013



g c

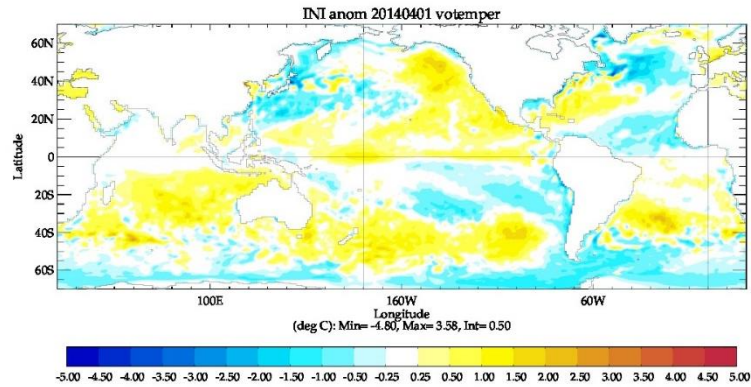


/a

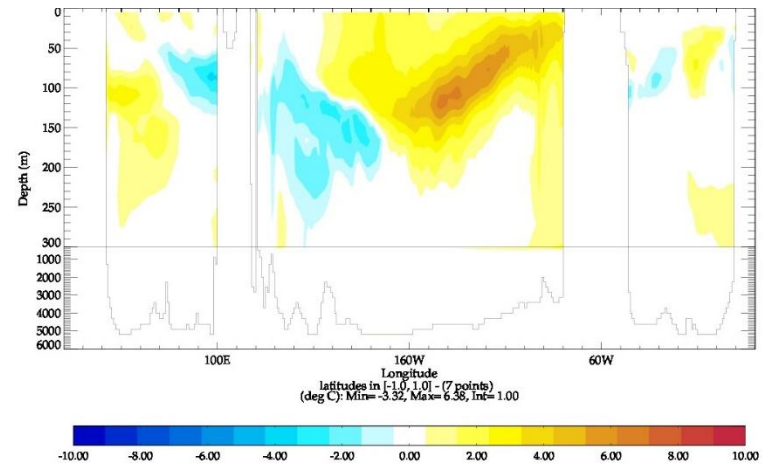
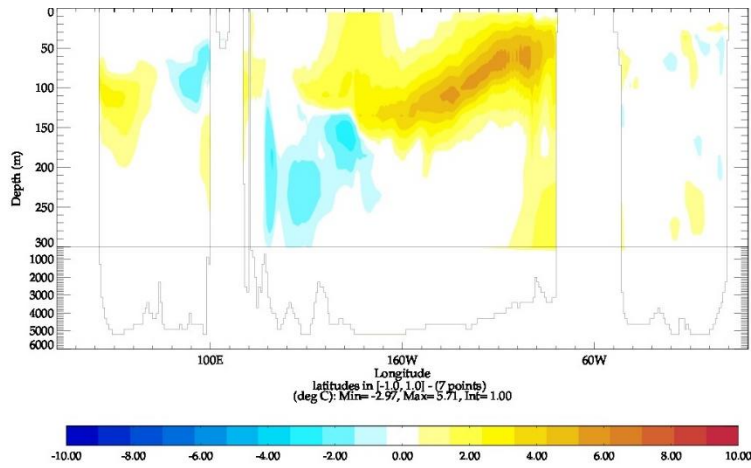
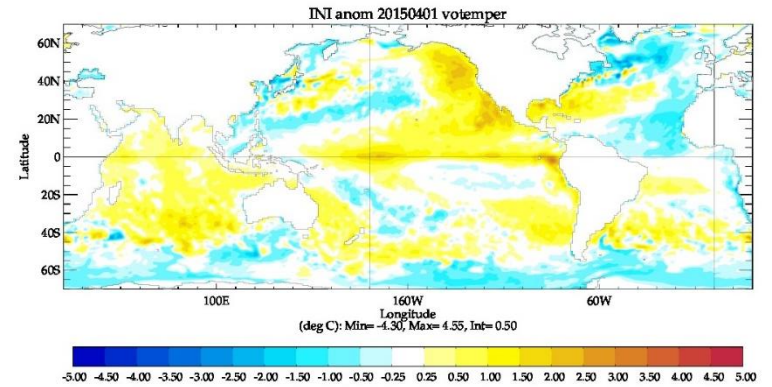


Temperature Anomalies

APR 2014

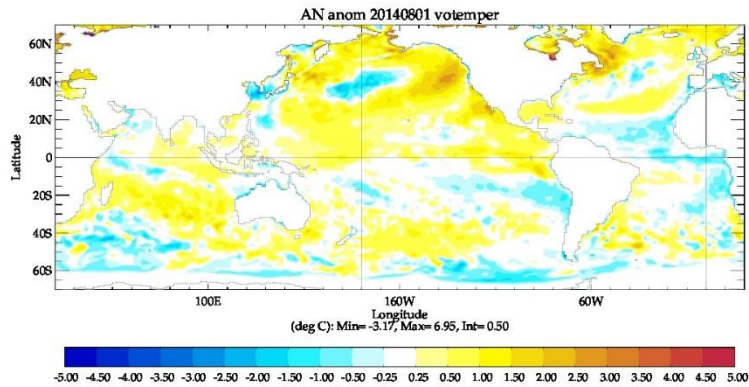


APR 2015



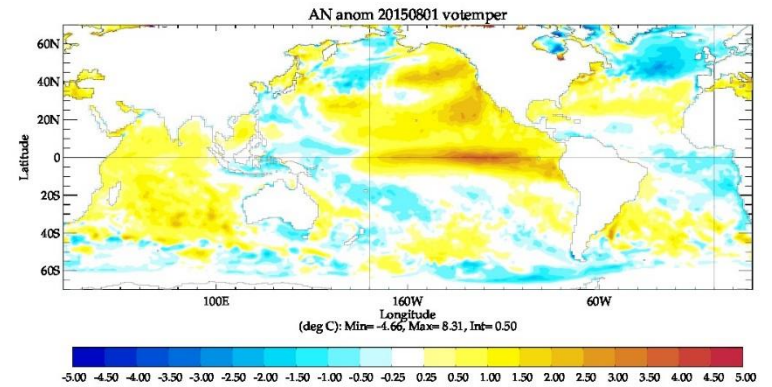
Temperature Anomalies

AUG 2014

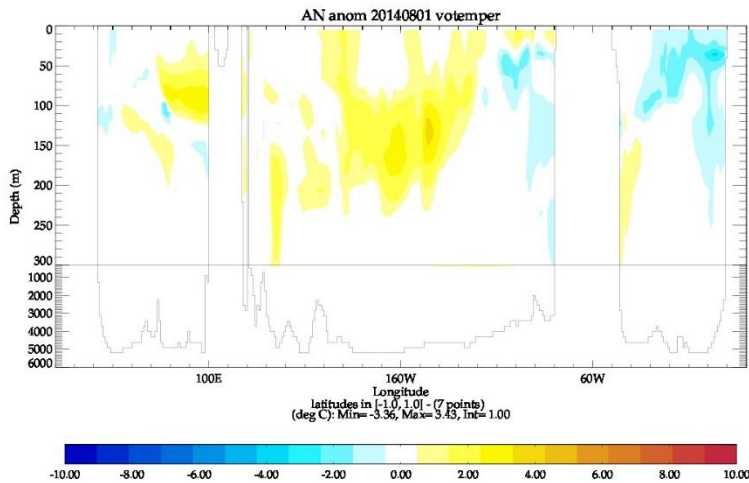


an_anom_20140801_votemper_20140801_JJ Sep 18 2015

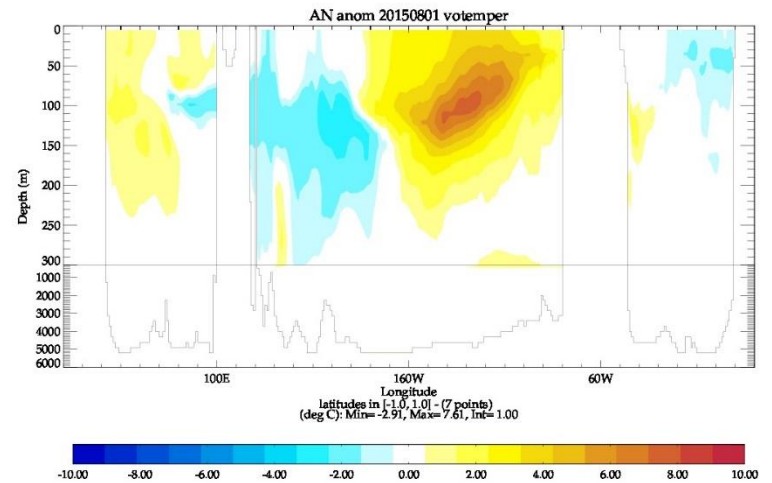
AUG 2015



an_anom_20150801_votemper_20150801_JJ Sep 21 2015



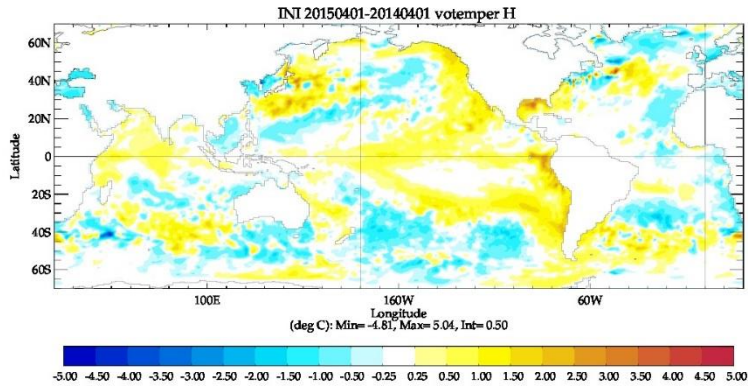
an_anom_20140801_votemper_20140801_JJ Sep 18 2015



an_anom_20150801_votemper_20150801_JJ Sep 21 2015

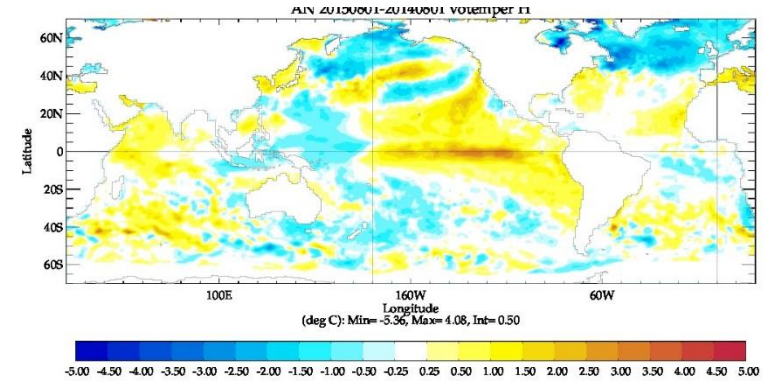
Growth of Perturbations: Temperature

INI Pert: APR 2015-2014



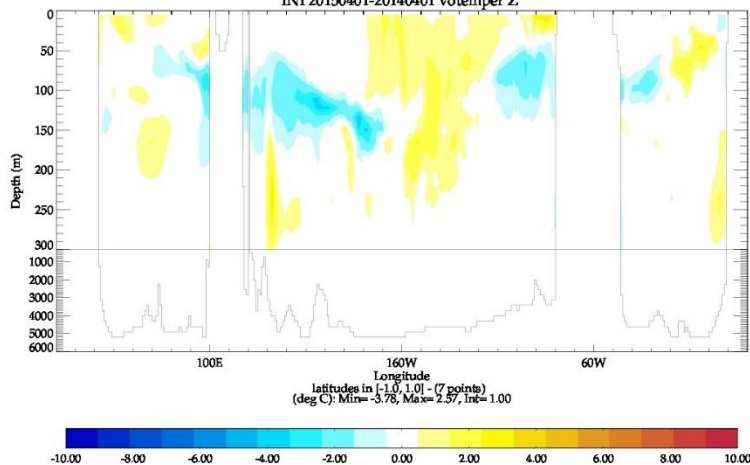
ini_dif_votemper_20150401-20140401_f0 Sep 18 2015

Final Pert: Aug 2015-2014



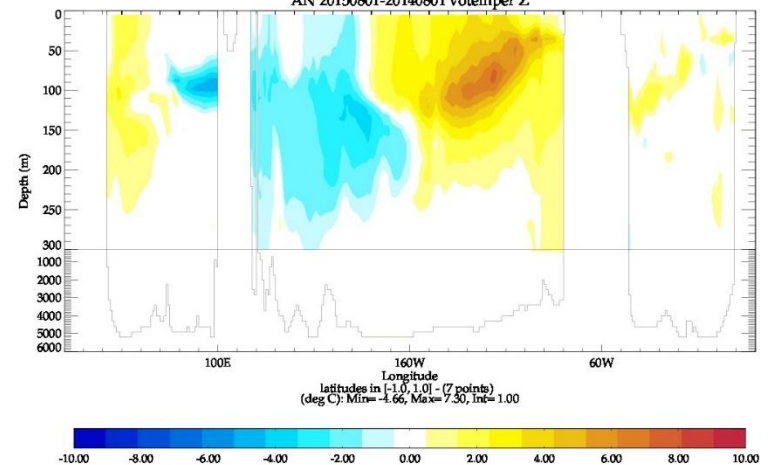
an_dif_votemper_20150801-20140801_f0 Sep 18 2015

INI 20150401-20140401 votemper Z



ini_dif_votemper_20150401-20140401_z0 Sep 18 2015

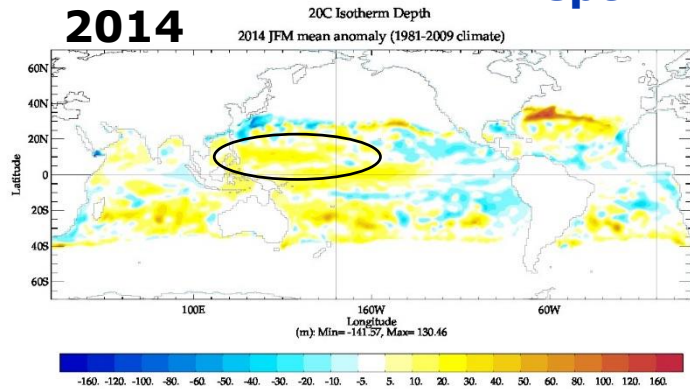
AN 20150801-20140801 votemper Z



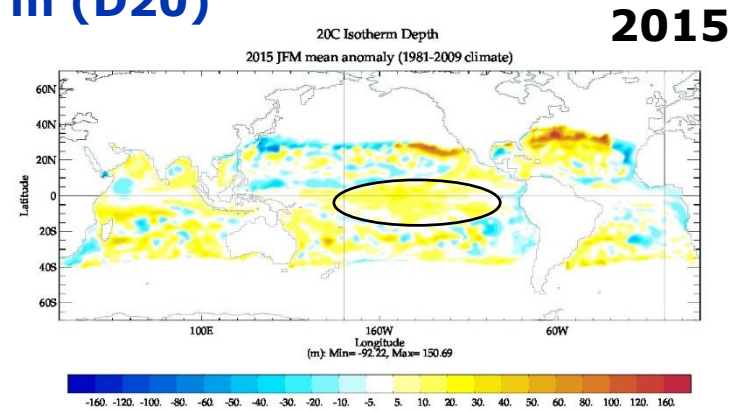
an_dif_votemper_20150801-20140801_z0 Sep 18 2015

Another view

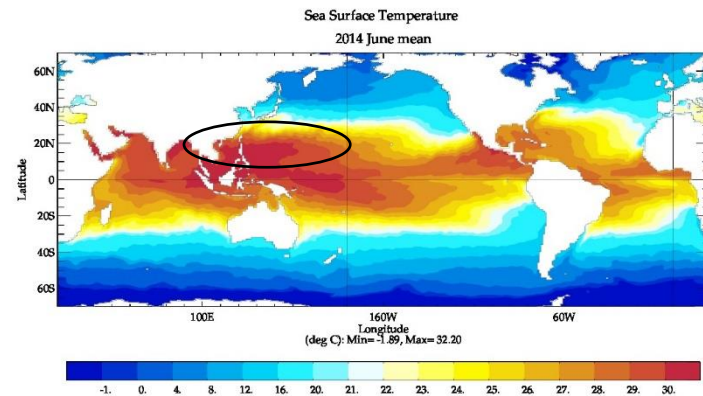
Depth 20C Isotherm (D20)



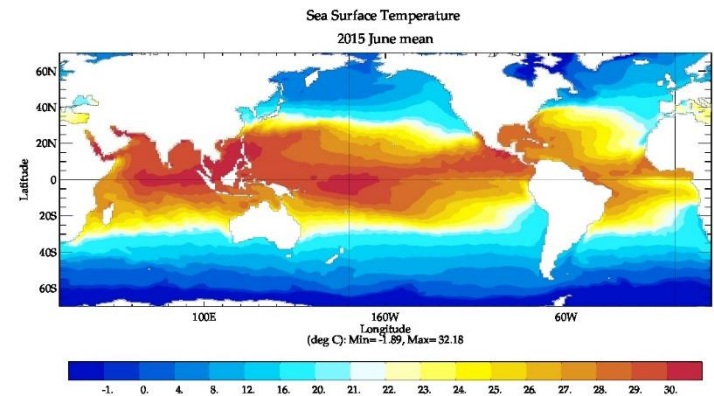
JFM



SST



June

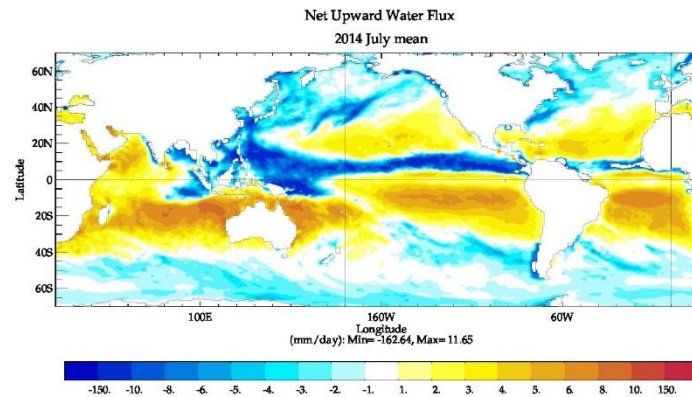
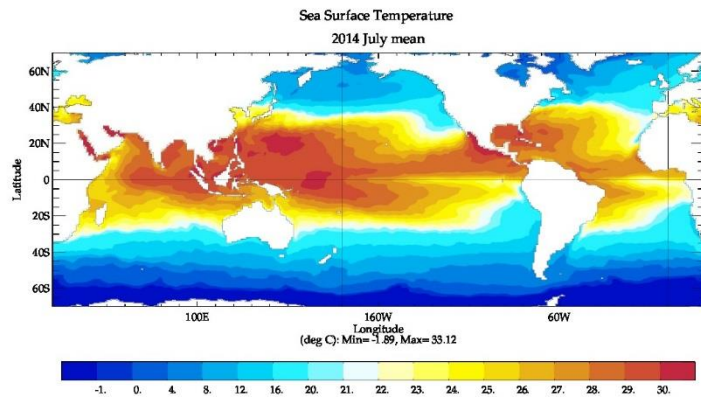


- North-West Trop Pac thermocline is deeper in JFM 2014. Possibly causing off Equatorial SST peak values later in June and associated convection.
- In Central/East Eq Pac thermocline is deeper in 2015, possibly helping to lock convection at Equator, and preventing the seasonal northward migration of the ITZC

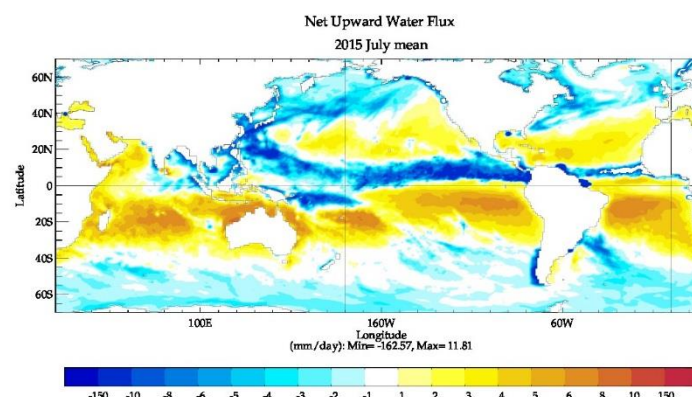
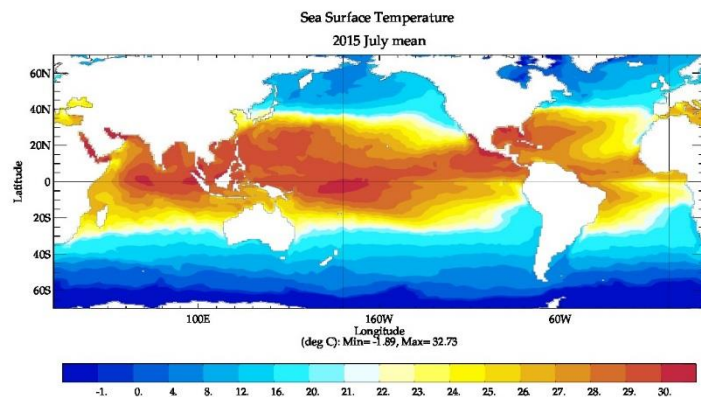
SST

P-E

July 2014



July 2015



- Note SST > 30deg North-West Trop Pac in 2014. In Central Pac in 2015.
- Note narrower ITZC in 2014. Broader and 2015
- Note ITZC northward migration in 2014, while it stays broad and close to the Eq in 2015
- In 2015 the convection in West Pac is suppressed (and SST cooling).

El Nino 2015/16: example of scale interactions

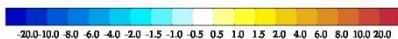
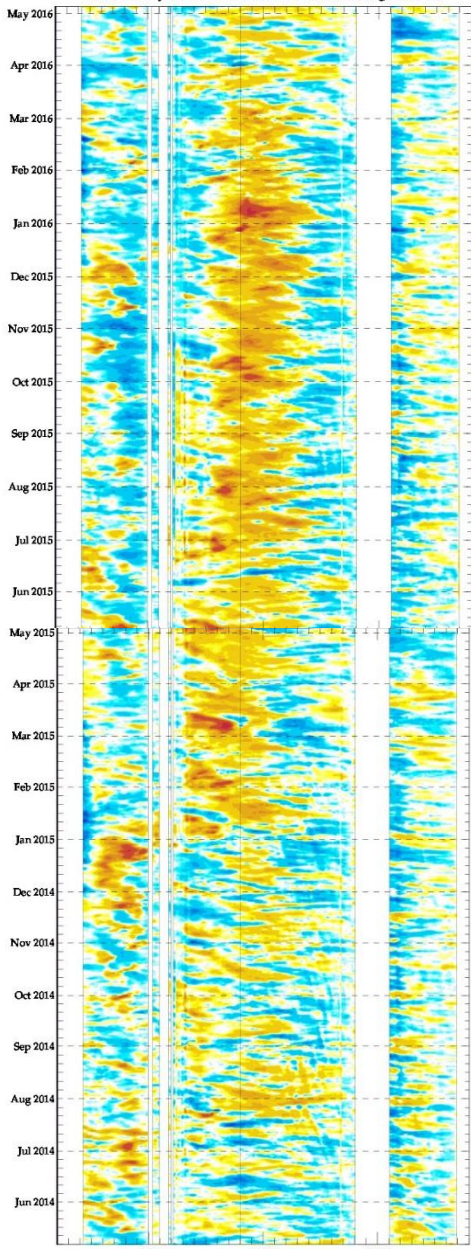
- **Interaction with low frequency variability:**
 - The events of 2014 prepare the ground for El Nino 2015
- **Interaction of intraseasonal variability:**
 - Do some properties of the WWB determine the outcome (timing, freq, strength, fetch)
 - Are these properties “random”? Or are they modulated by background state?
- **Interaction with the seasonal cycle: poleward migration of ITZC**
 - Possible role of the extra Equatorial anomalies.
- **Interaction with mean state:**
 - threshold values of SST to trigger deep convection

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

Taux Anomalies

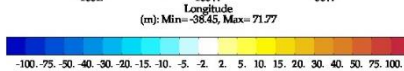
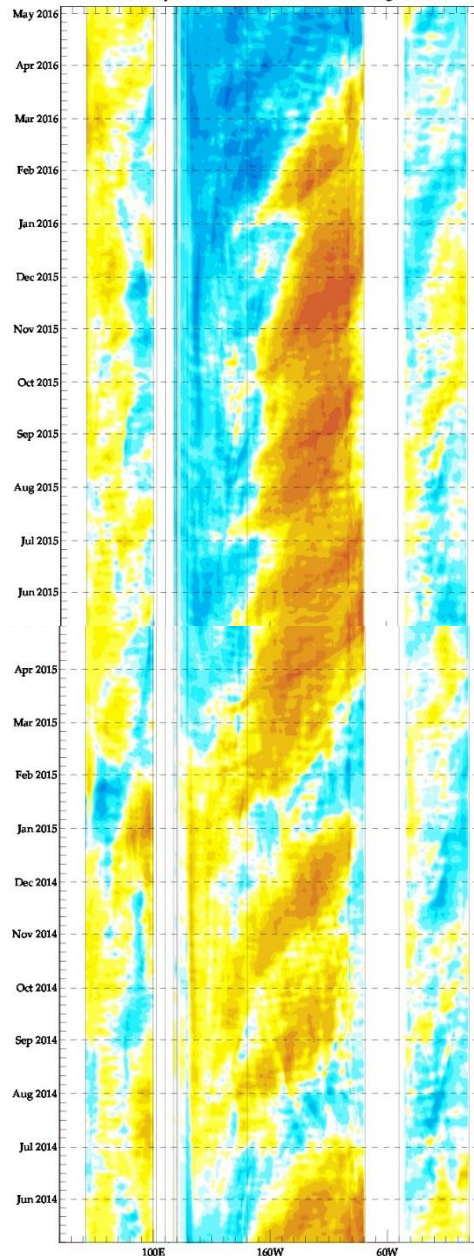
Last 365 daily anomalies (1981-2009 climate) ending 20160506



rain

D20 Anomalies

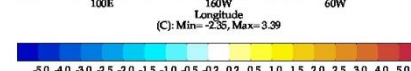
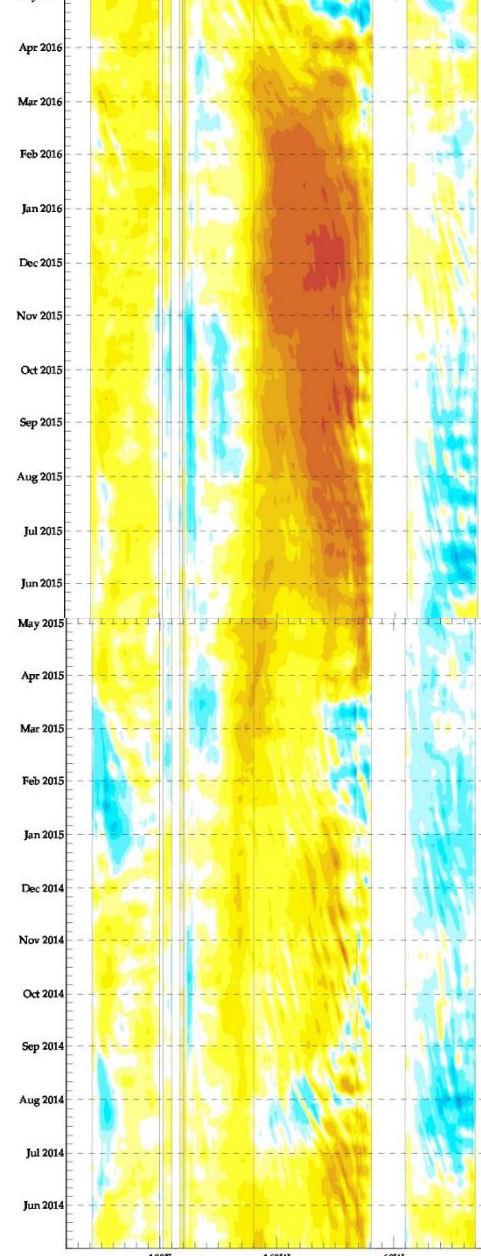
Last 365 daily anomalies (1981-2009 climate) ending 20160506



1e

SST Anomalies

Last 365 daily anomalies (1981-2009 climate) ending 20160506



May
2016

May
2015

May
2014

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Some additional References

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