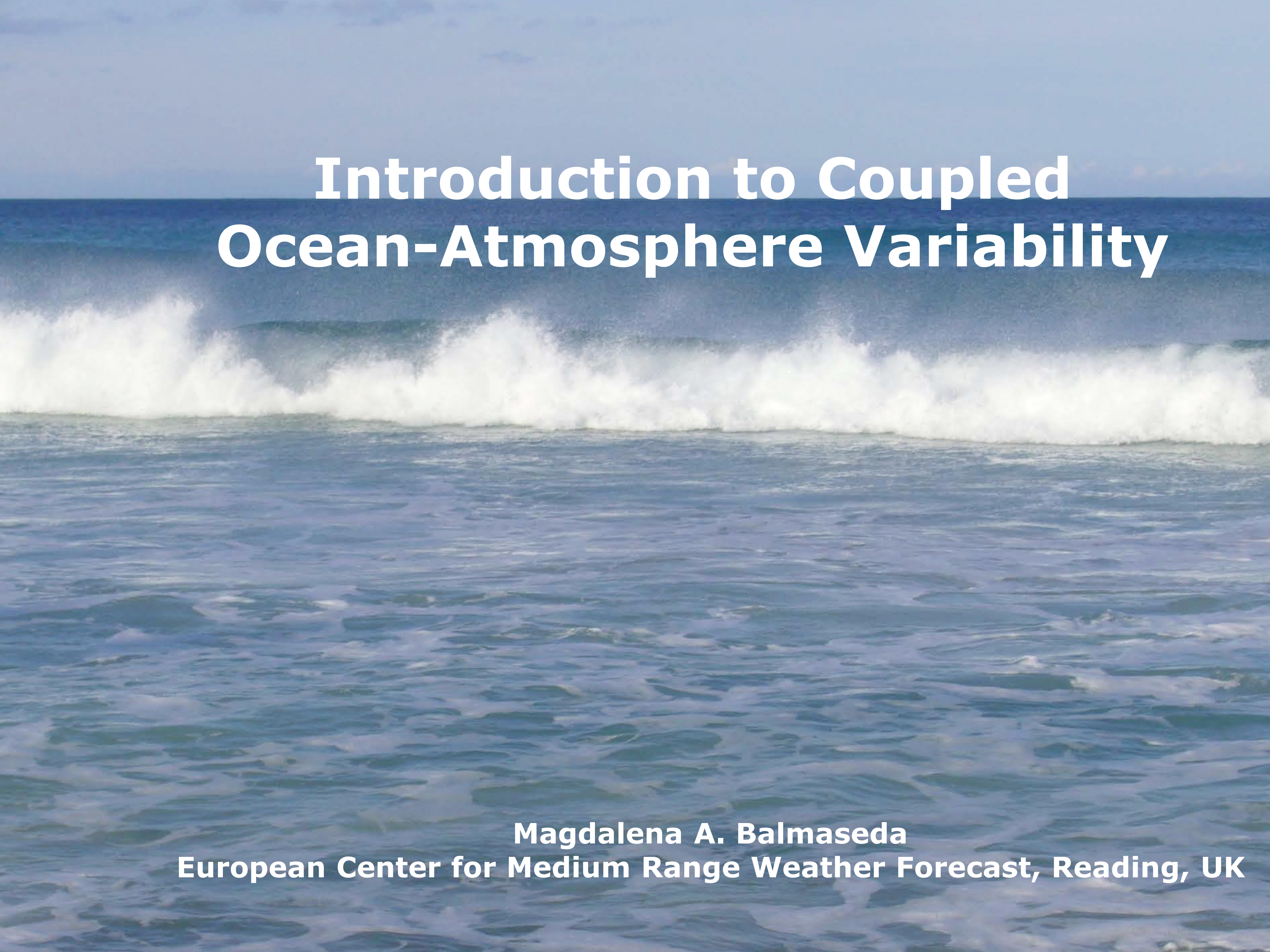

Introduction to Coupled Ocean-Atmosphere Variability

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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 of variability

- **Impact of the ocean in the ECMWF forecasting system**

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 over warm pool: deep atmospheric convection**

  iii. **Response to sharp SST fronts**

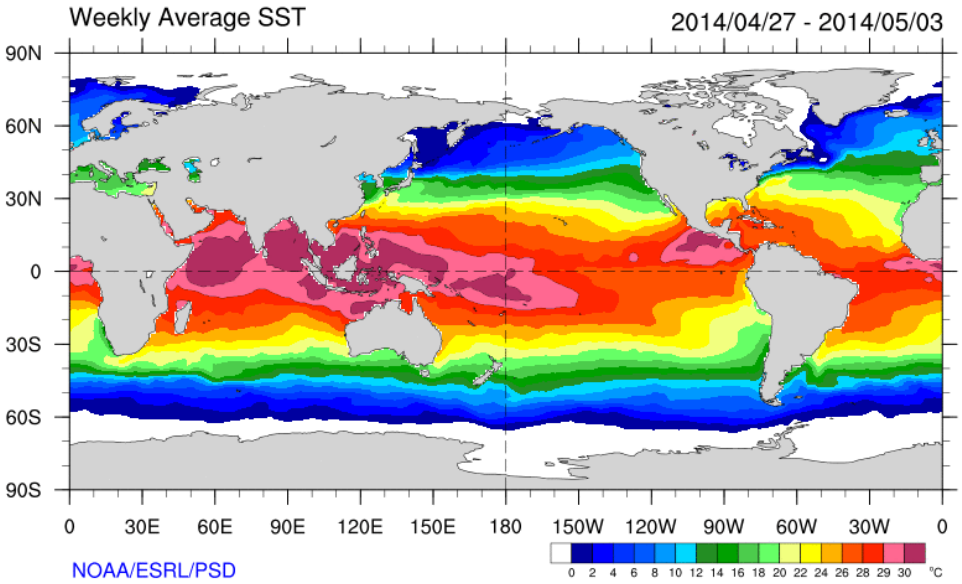
  example: mid latitude storm tracks over western boundary currents

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

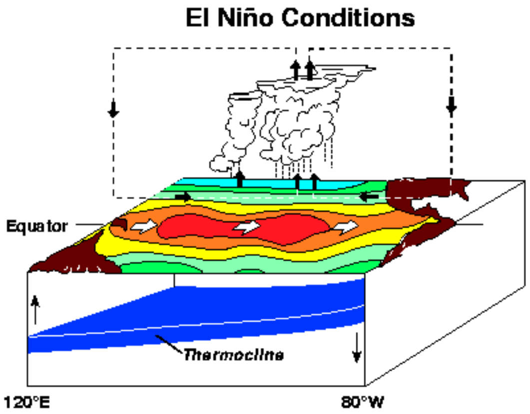
Hasselmann 1976

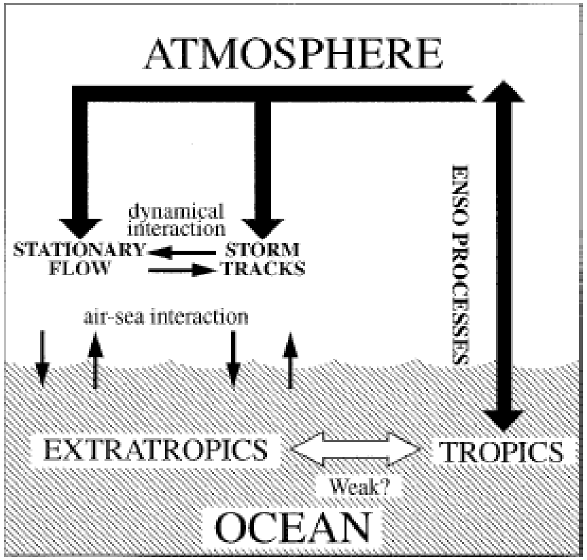
Latif et al 2002, Timmermann 2005…

Traditional view: Atmosphere response to SST



NOAA/ESRL/PSD

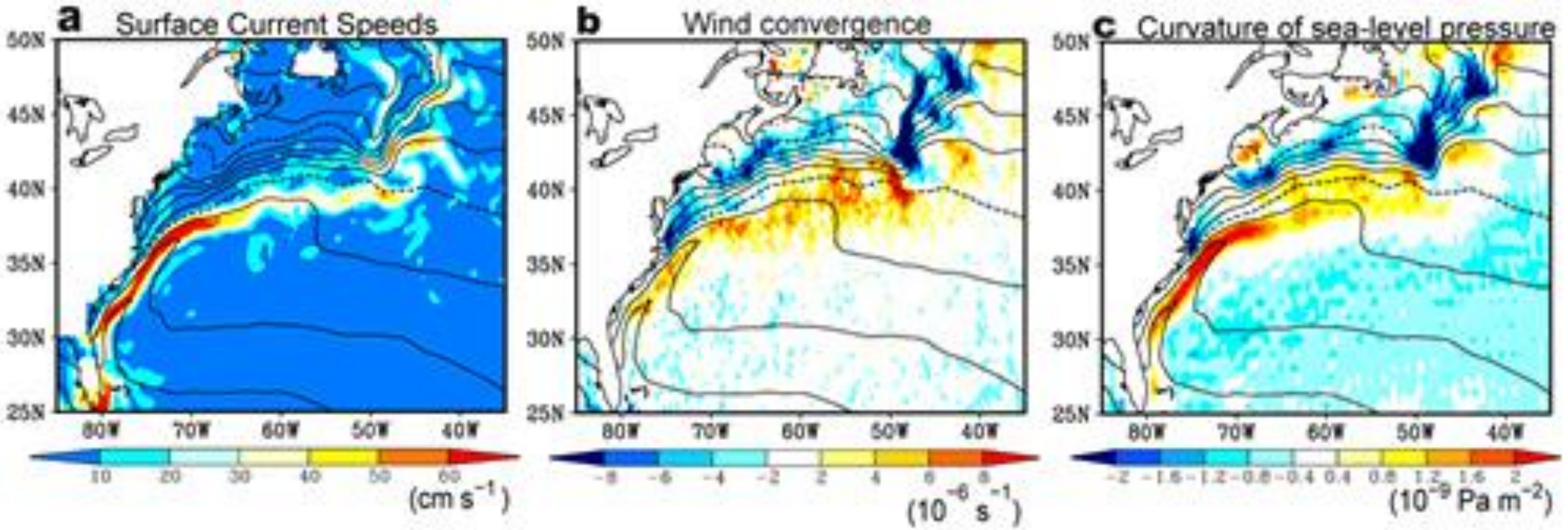




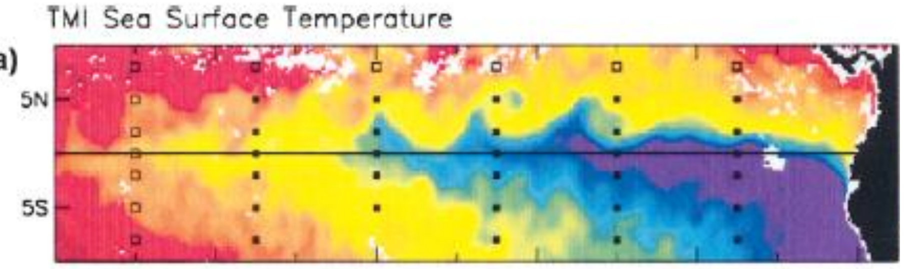
Lau 1977

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

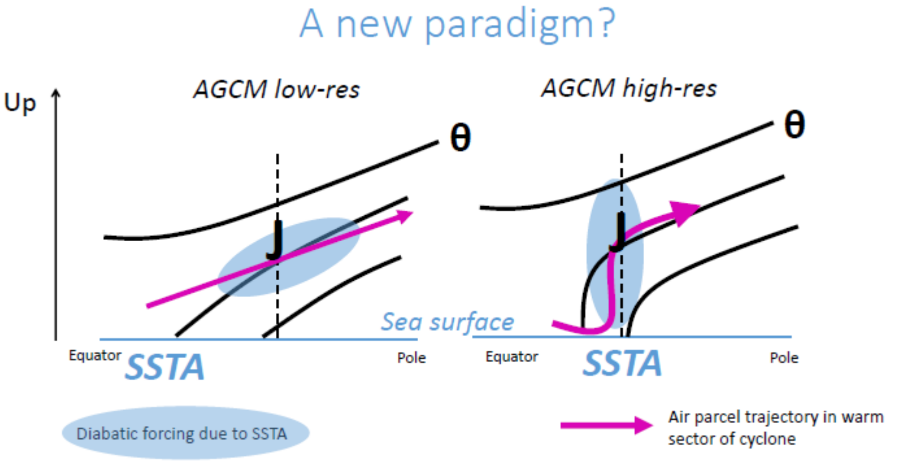
O-A interaction over SST fronts



Minobe et al 2008



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).



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

This talk will cover

- **Implications for Predictability**
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  - 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
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- **Impact of the ocean in the ECMWF forecasting system**

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

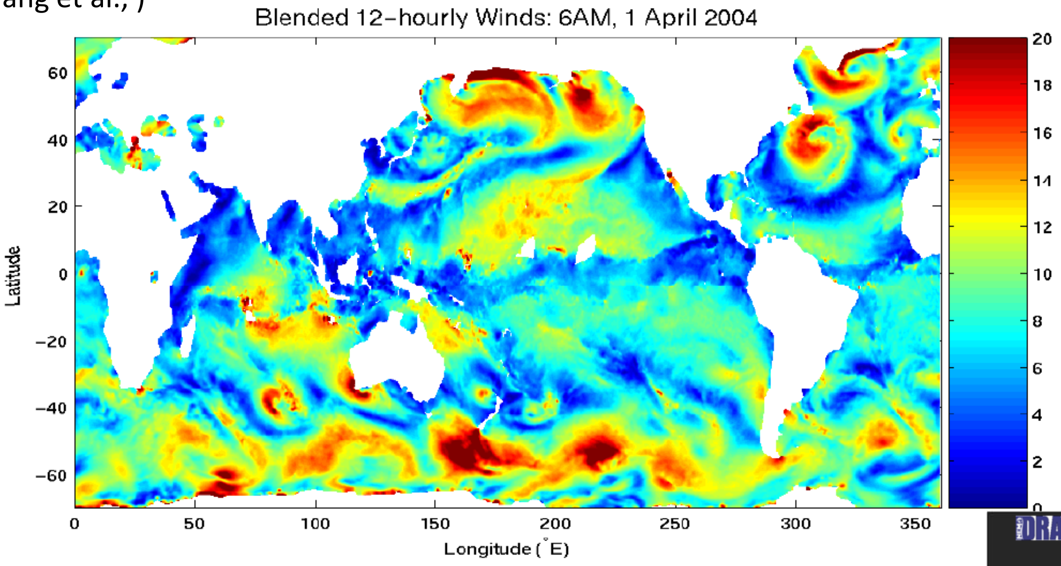
- **The ocean is strongly stratified in the vertical,** although deep convection also occurs

  Density is determined by Temperature and Salinity

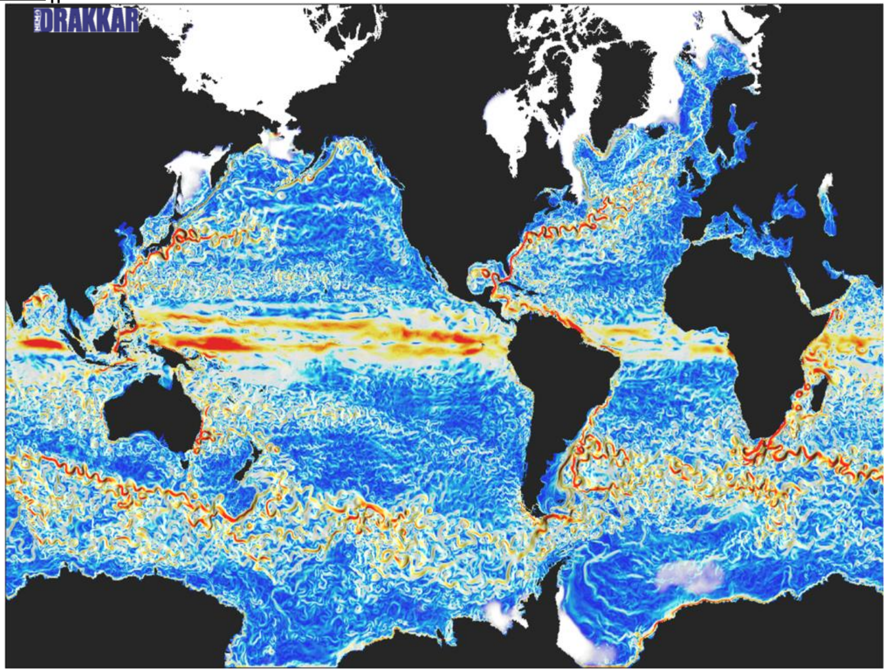
- **The ocean is forced at the surface** by the wind/waves, by heating/cooling, and by fresh-water fluxes.

- **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.,)

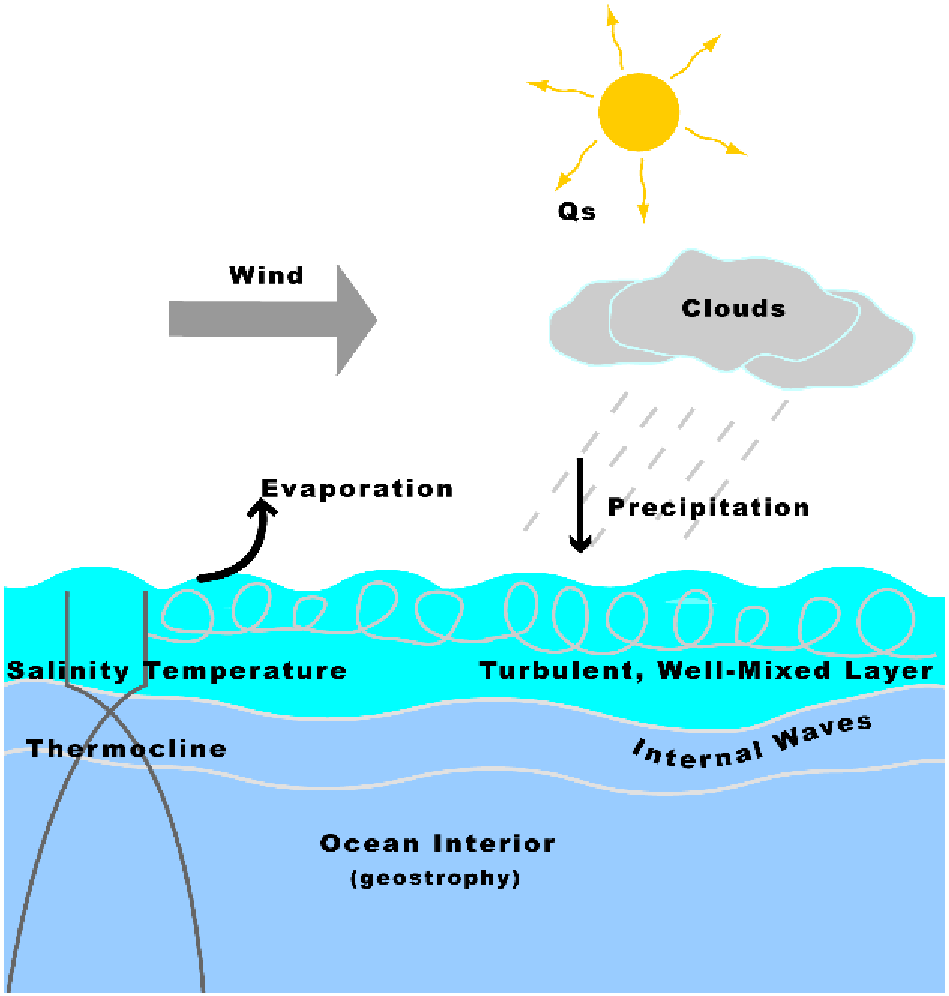


Atmospheric wind speed (12h)



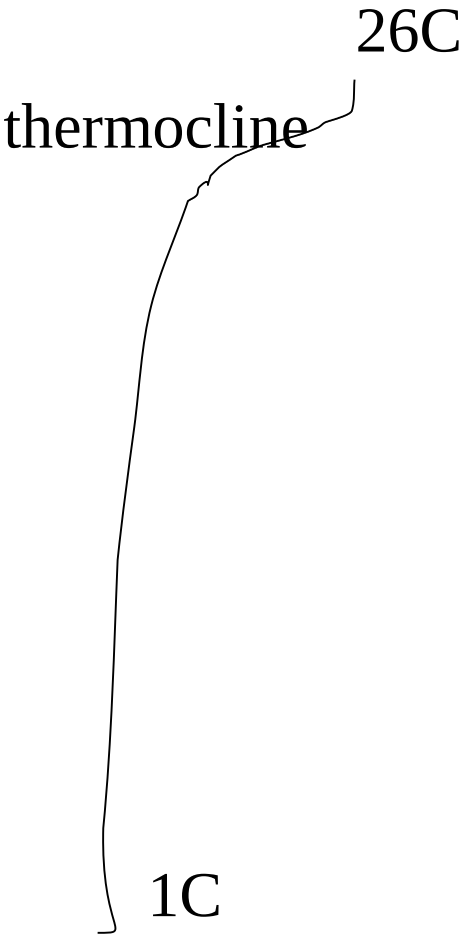
Ocean current speed **(model simulation, 5 day mean)**

Air-Sea Interaction



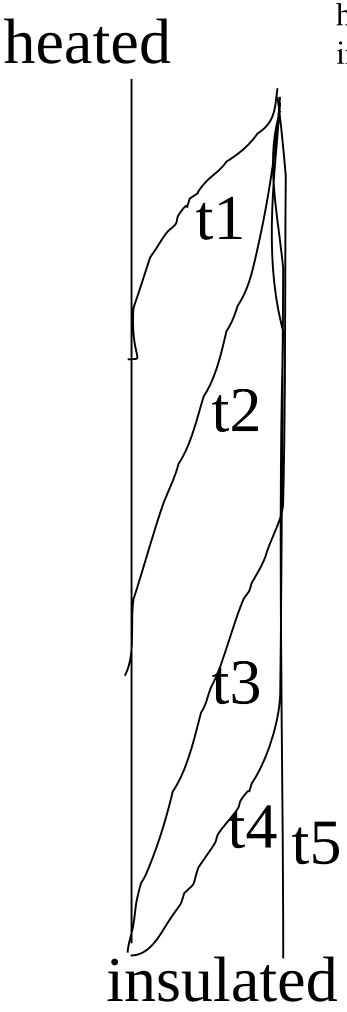
What maintains the ocean stratification?

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 …



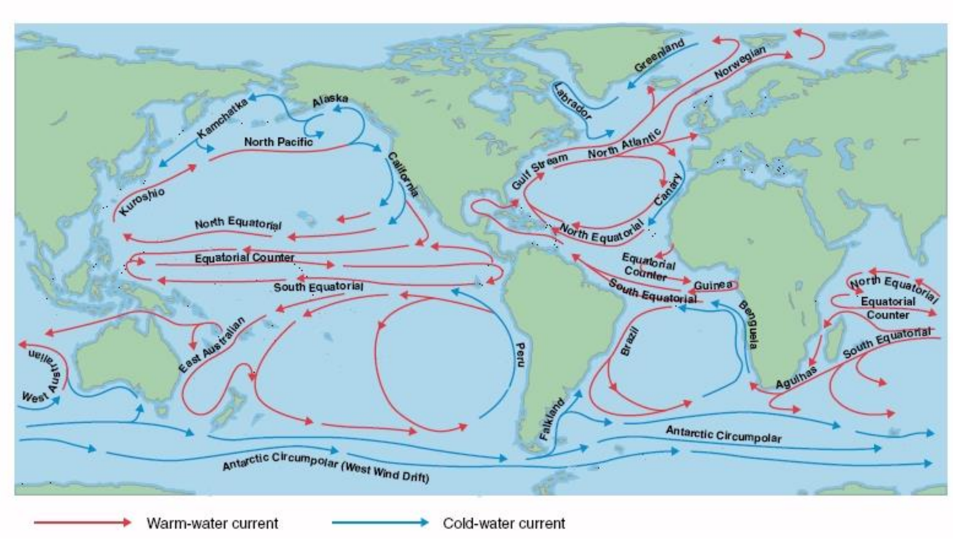
- **<u>Ellis 1751:</u>** The temperature of the ocean at the equator is warm (heated by the atmosphere) at the surface, but is cold at depth: i.e. the ocean is not in thermal equilibrium.

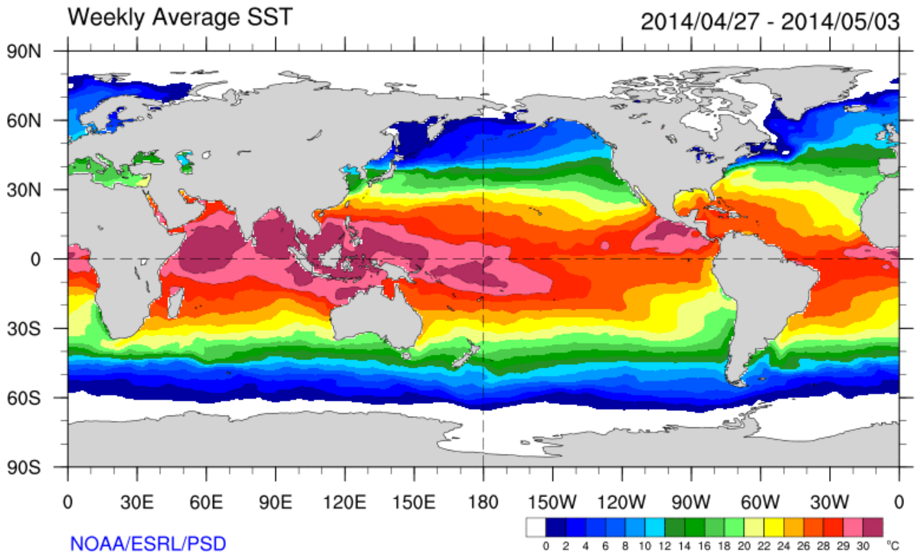
Ocean Circulation

- 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)

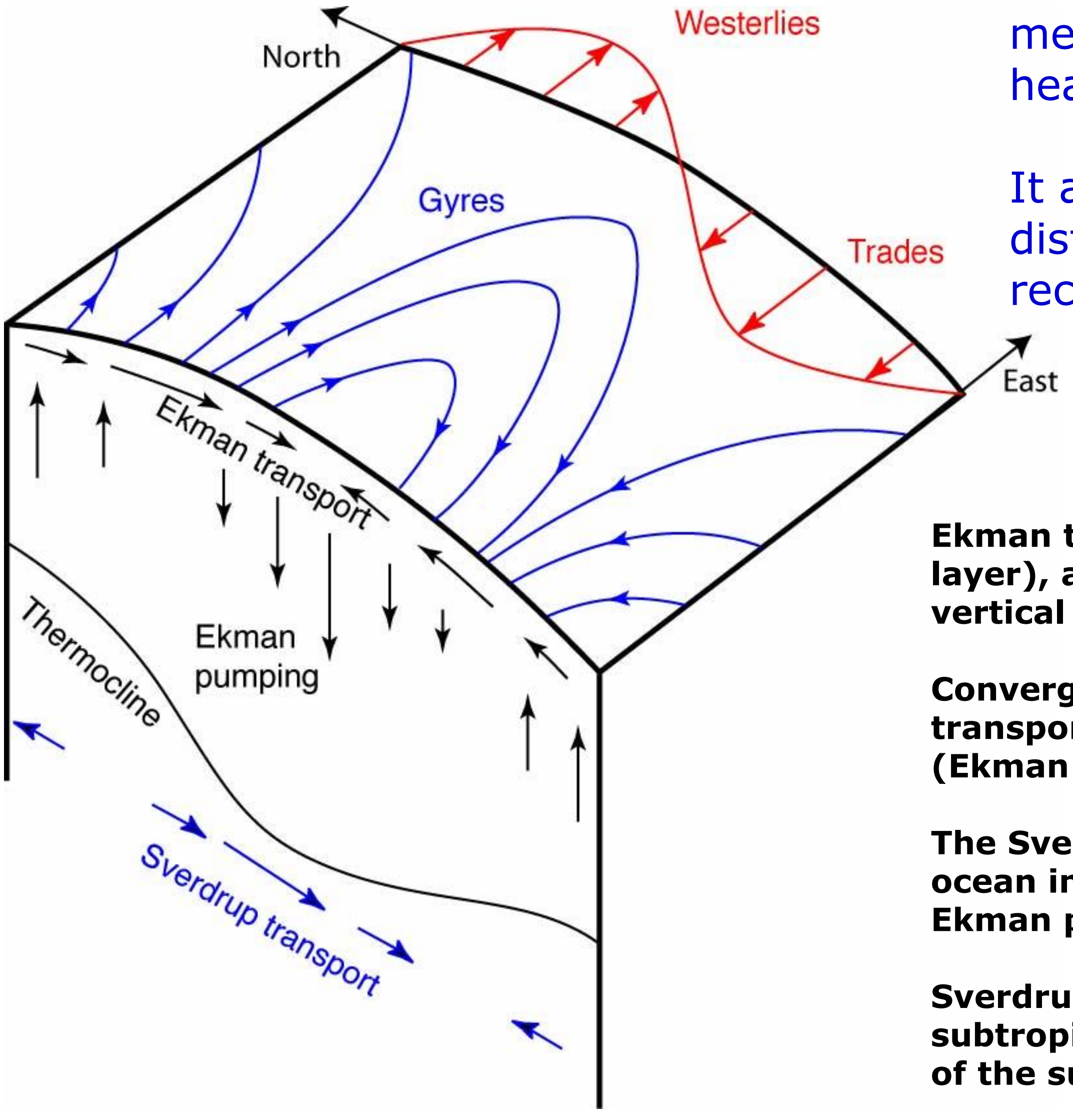




The surface circulation of the ocean is largely wind driven: sub-tropical gyres, western boundary currents, coastal upwelling. Note also the countercurrents which flow against the wind and the vigorous Antarctic circumpolar current

The wind driven circulation is responsible for important SST patterns, 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 and poleward -poleward of the subtropics

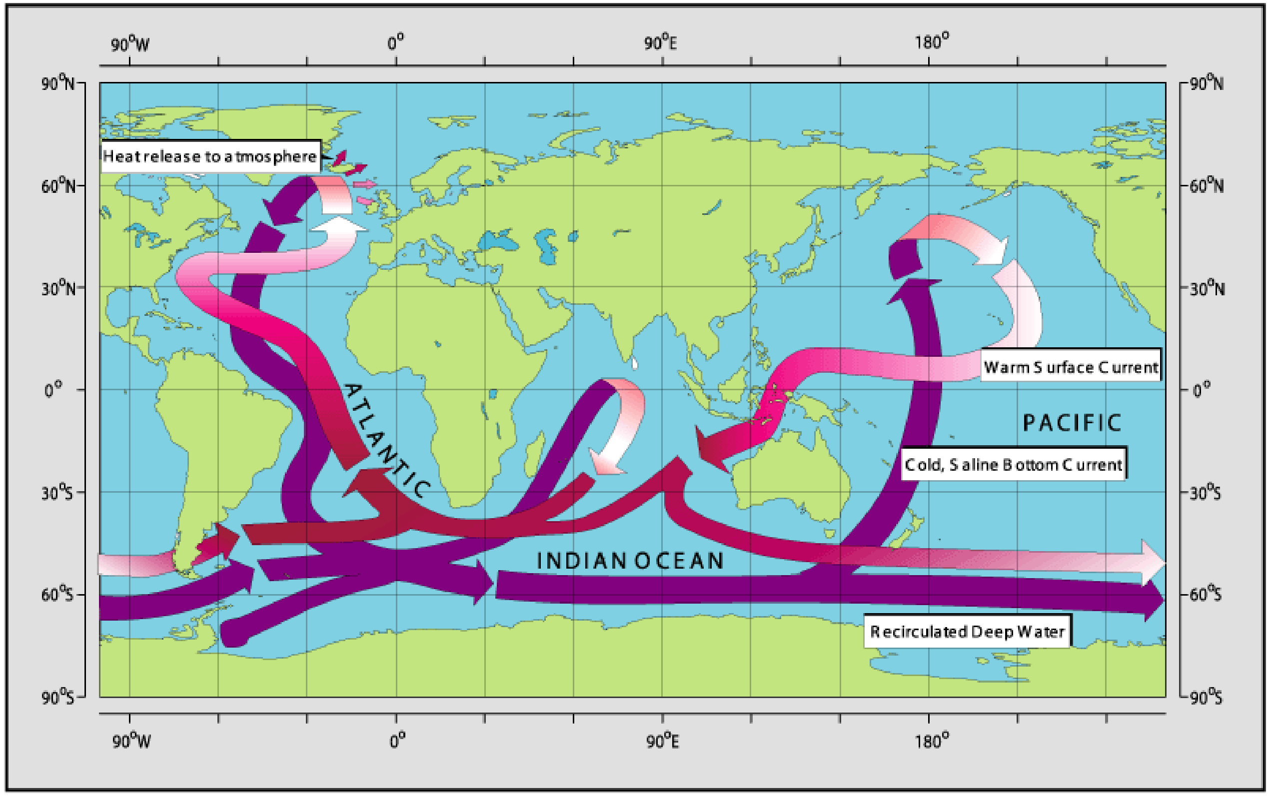
Western Boundary Currents (WBC)

- 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

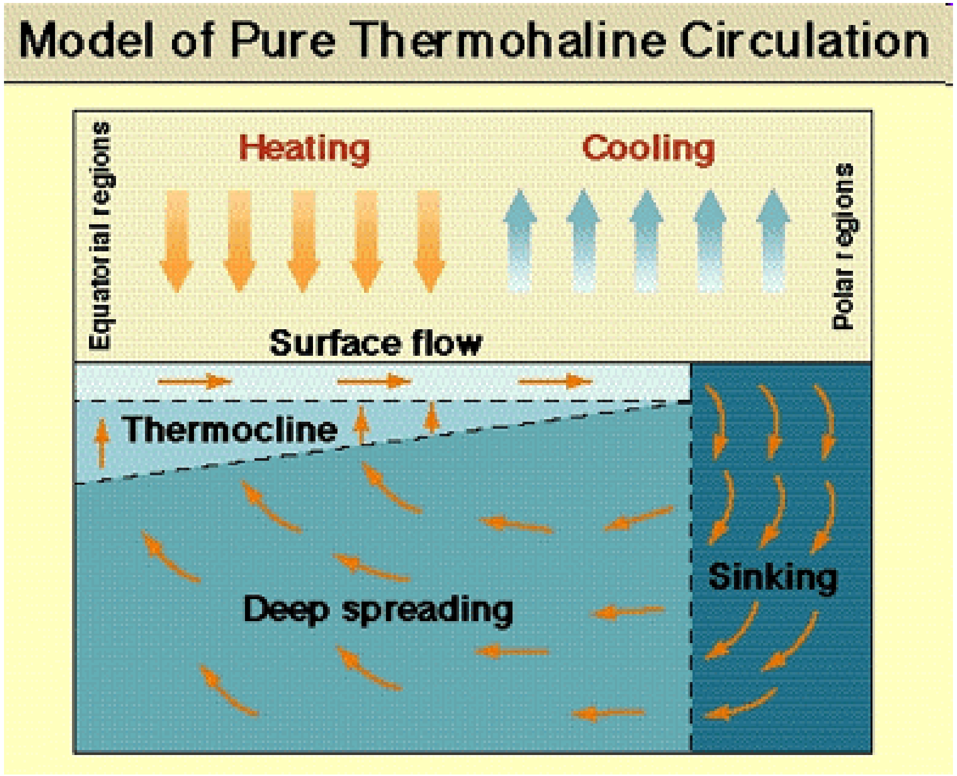


Thermo+Haline= Circulation driven by density differences.

Related to localized deep water formation areas.

Important for meridional heat transports and ocean stratification.

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.
- <u>Stommel box model can present bifurcations</u>. Different solutions depending on the balance between heat and fresh water fluxes.

Thermohaline Stability: Longworth,Marotzke, and Stocker, 2005

Generalization of the Stommel model by including diffusion and wind forcing.

The equations here are only for the diffusive case (no wind)

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

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

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

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

Φ is a salinity flux. P is precipitation

q is the circulation

T/S/ρ temperature/salinity/density

K_d is the diffusivity

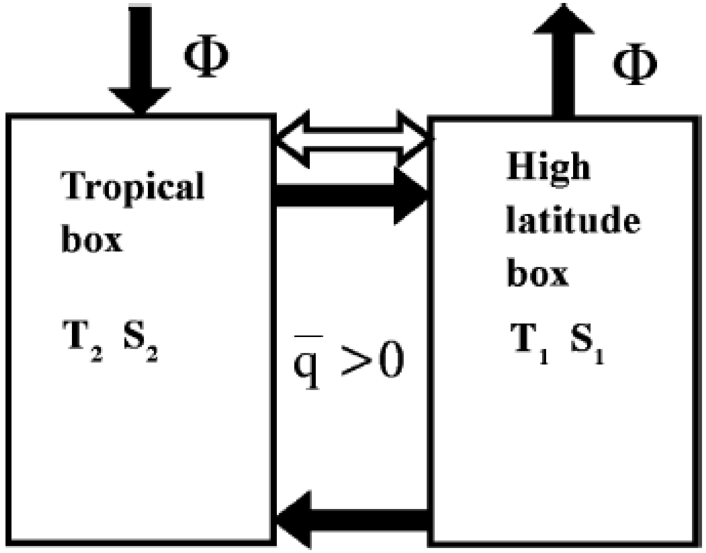


FIG. 1. The Stommel model with diffusion. Filled and unfilled arrows are the advective and diffusive flow components, respectively. Advective arrows reverse under flow reversal but diffusive arrows are unchanged.

Reducing the number of variables, taking time derivative of q, assuming constant temperature gradient and using the time derivative of S

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

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

We calculate now the equilibrium solution by setting the time derivative to zero. We treat q>0 and q<0 separately.

Equilibrium Solutions

1) Temperature dominated: 2 solutions

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

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

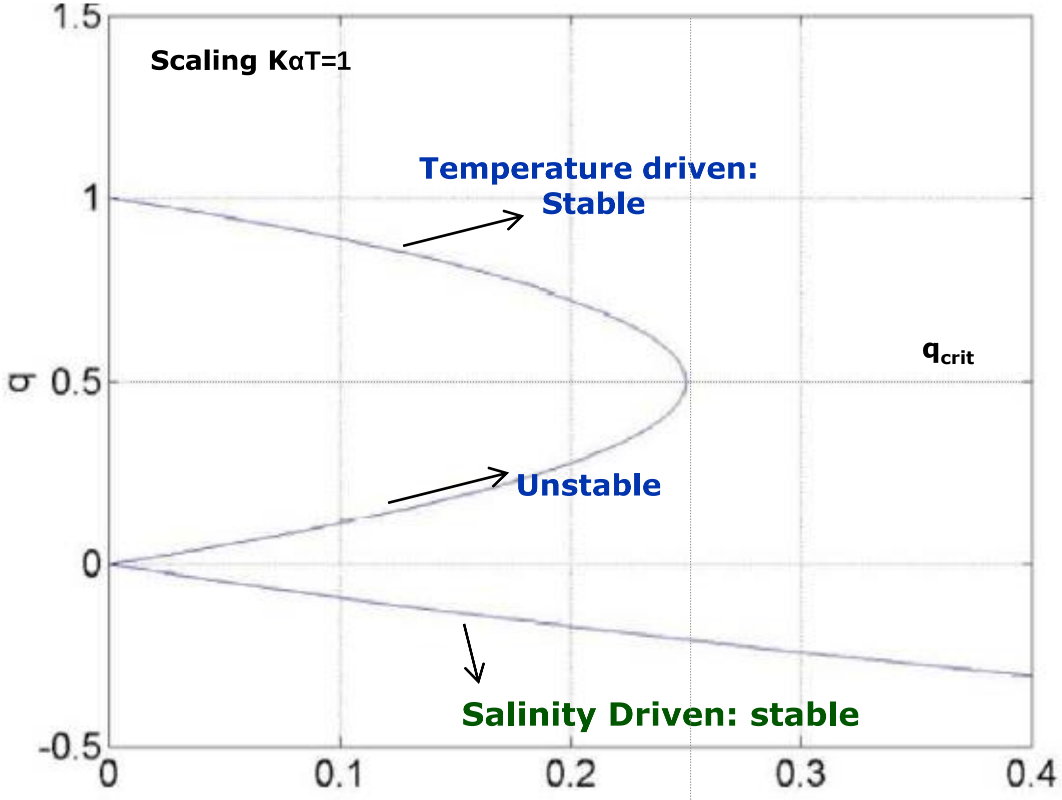
$$\frac{k\beta\Phi}{(k\alpha T + k_d)^2} < \frac{1}{4},$$

2) Salinity dominated (only possible for negative values of q)

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

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

Stommel Box model K_d=0



Scaling KαT=1

Temperature driven: Stable

Unstable

Salinity Driven: stable

$$\Phi_{crit} = \frac{(k\alpha T)^2}{4k\beta}$$

Stability and bifurcations
For weak values of the circulation (0<q<qcrit) the equibrium is unstable, and a bifurcation can exist between a salinity driven mode (q<0) and a temperature driven mode (q>0)

Meridional Heat transport: MOC x Stratification

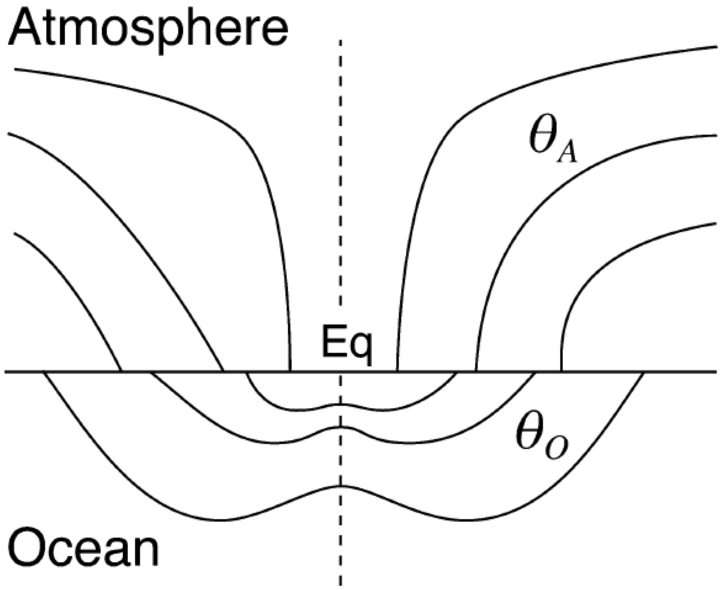
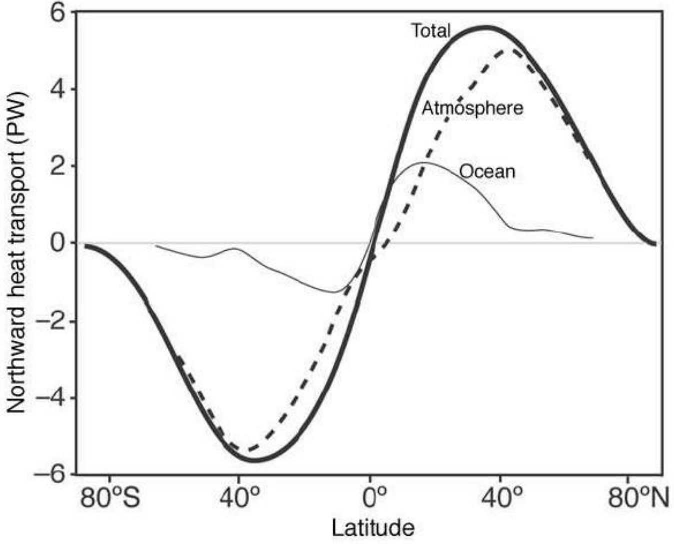


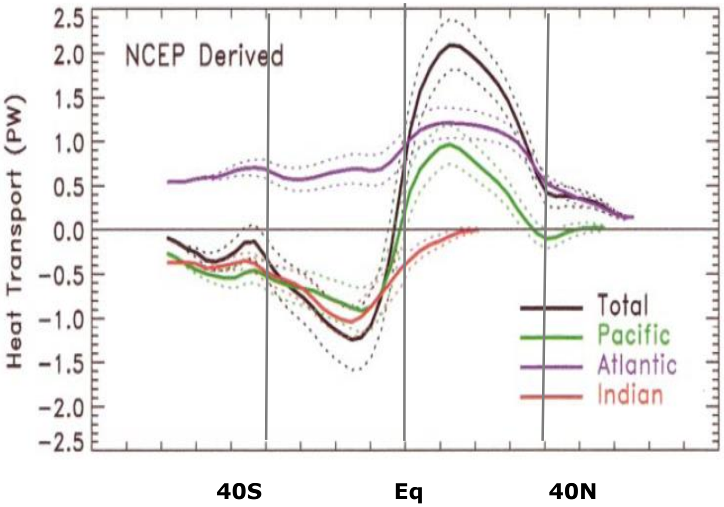
FIG. 2. Schematic of the distribution of atmospheric moist potential temperature (θ_A, i.e., moist static energy) and oceanic potential temperature (θ_O) as a function of latitude and height (black contours). The equator is indicated as a vertical dashed line.

Stratification of Ocean/Atmosphere
From Czaja and Marshall 2006.

Ocean and atmosphere heat transport



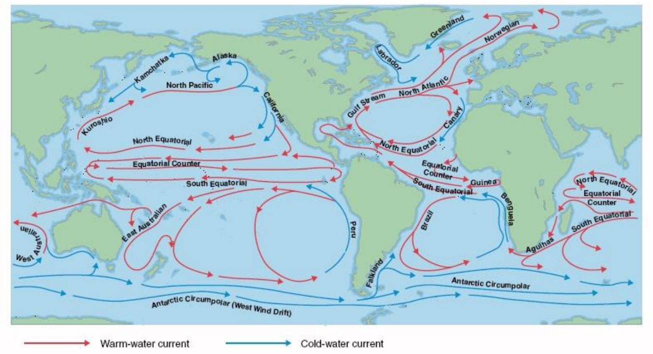
Oceanic heat transport by basins



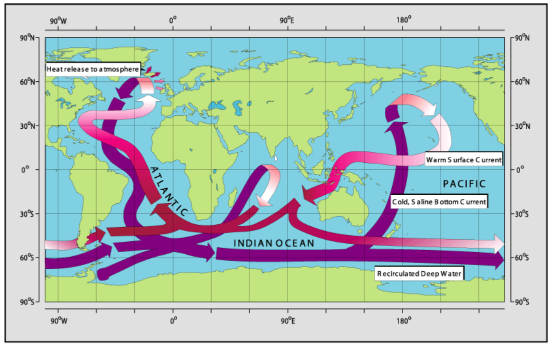
Trenberth and Caron 2001

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.

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

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

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

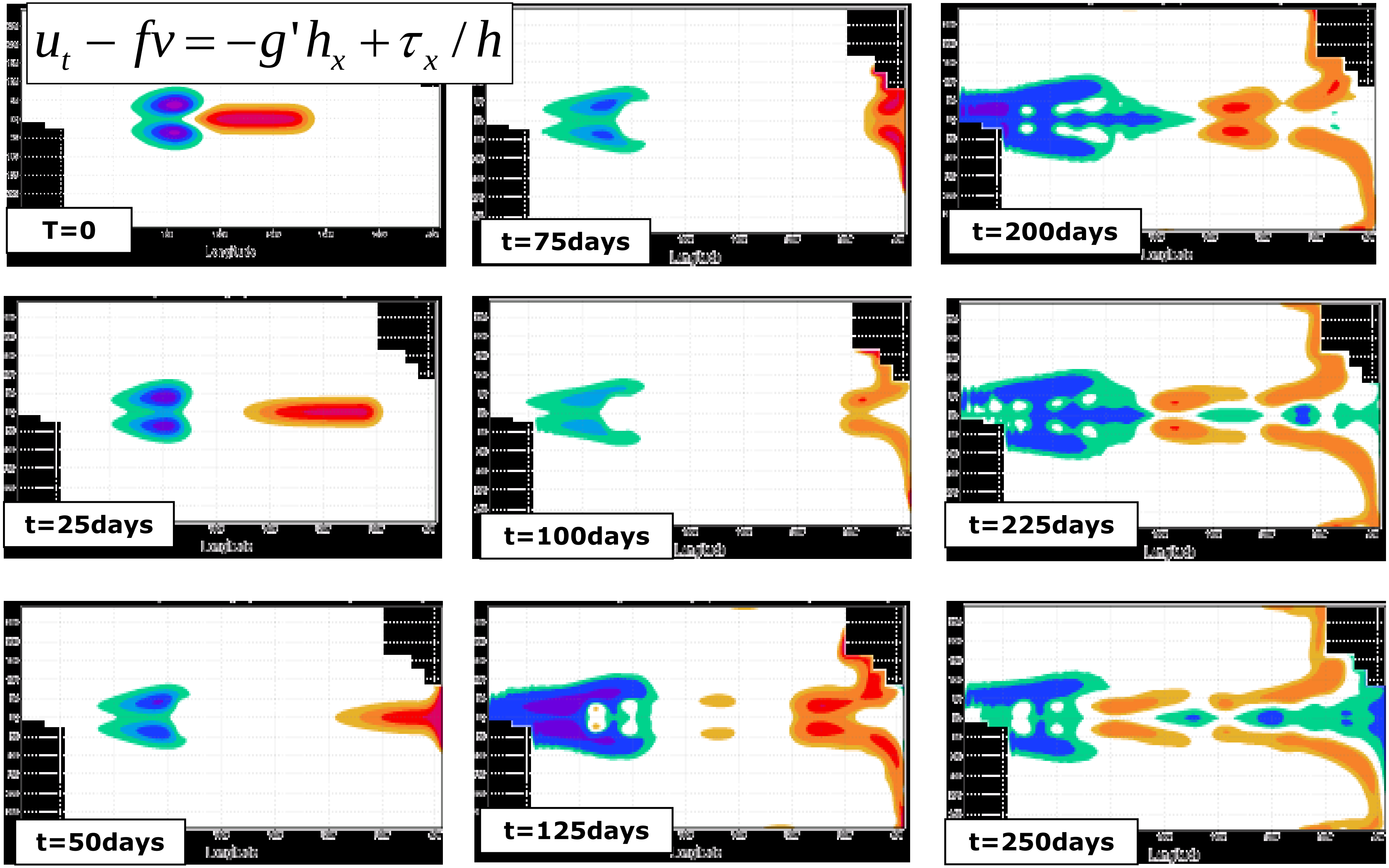
$$\omega = -\beta k/(k^2 + l^2 + f^2/c^2)$$

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

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

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

Kelvin & Rossby waves and Delayed Oscillator



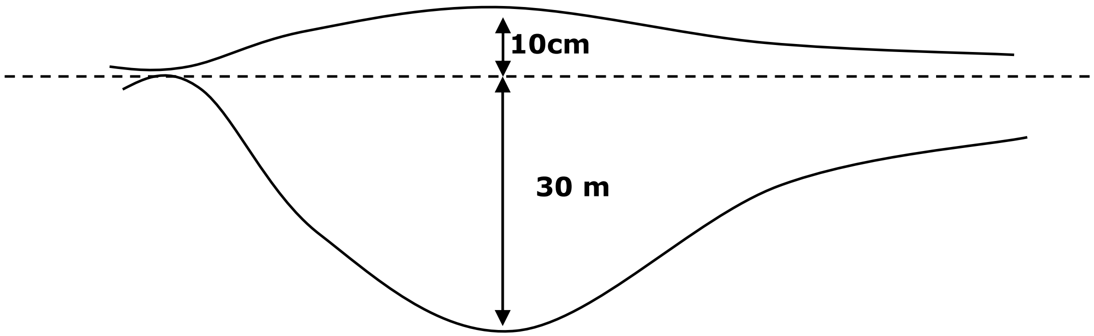
$$u_t - fv = -g' h_x + \tau_x / h$$

Observing waves from space: Vertical Stratification and Satellite altimetry

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

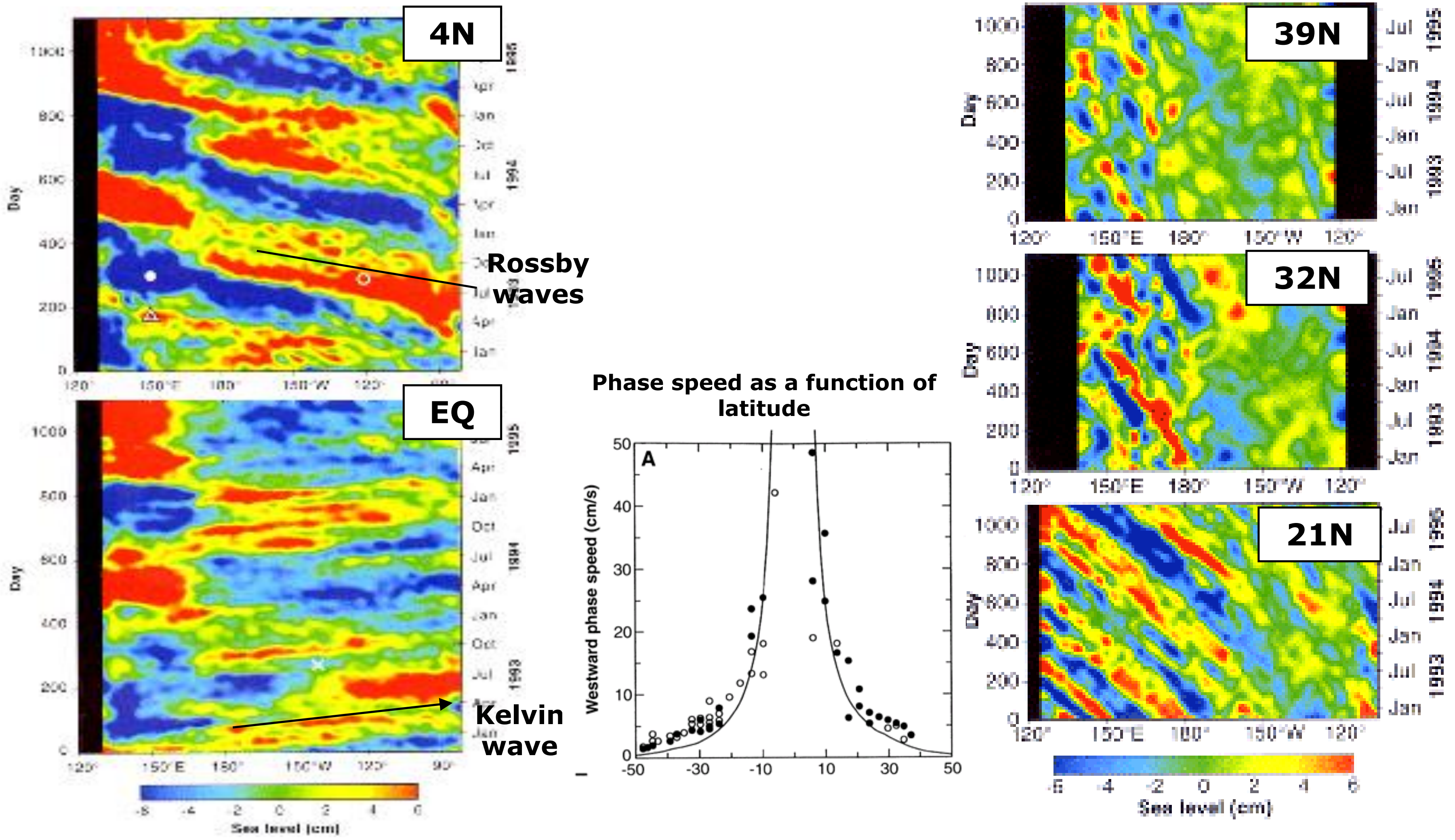
Typically g’~g/300

- 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

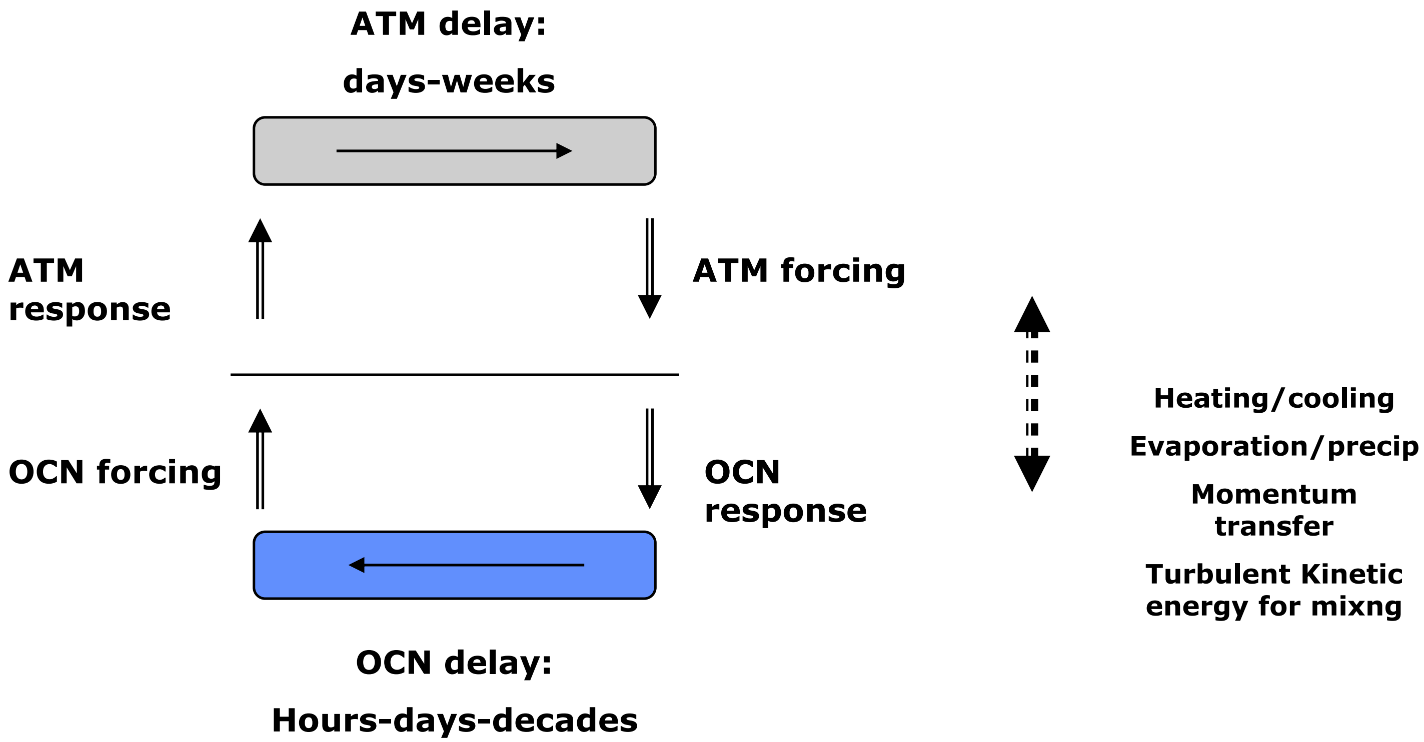
Rossby/Kelvin Waves from Space



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

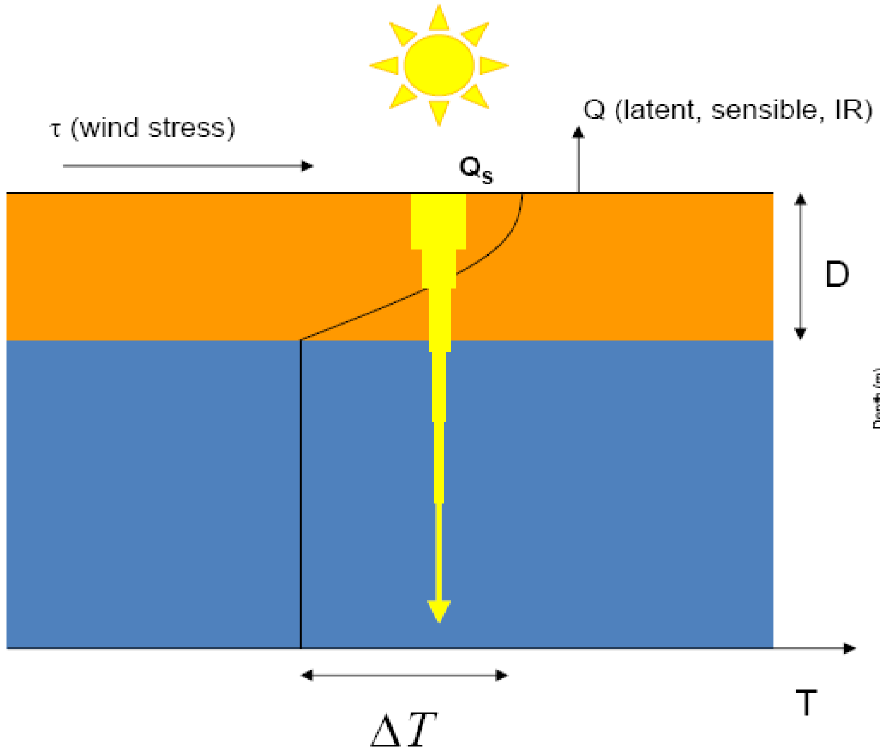
Evaporation/precip

Momentum transfer

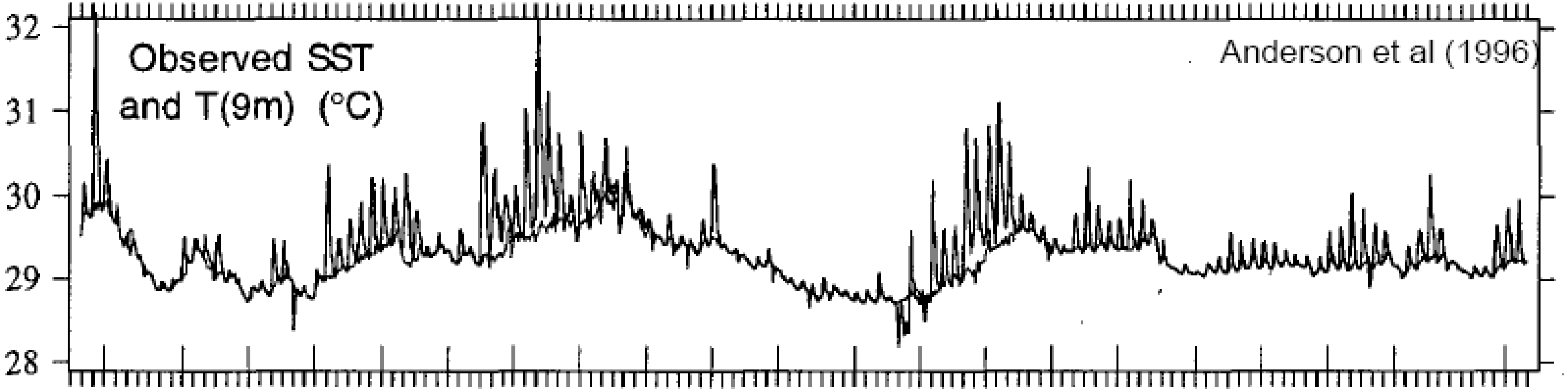
Turbulent Kinetic energy for mixng

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			

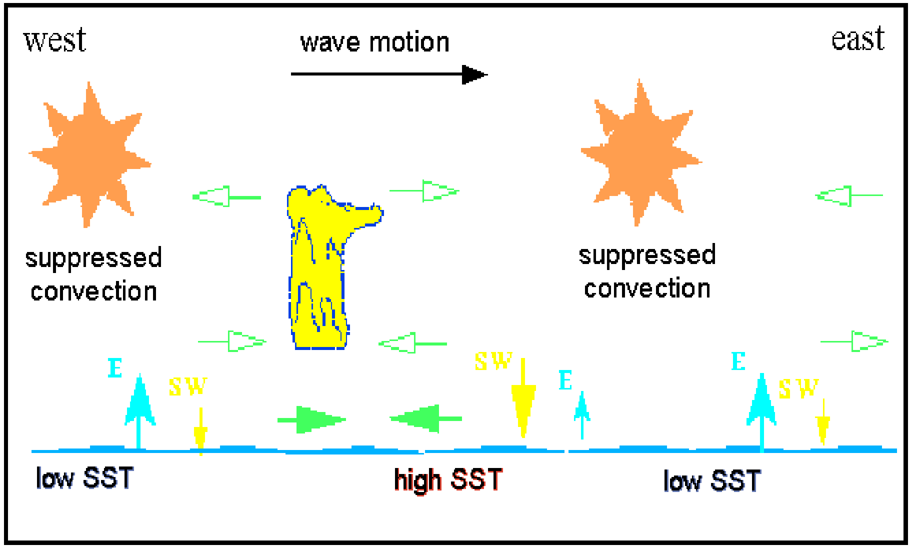
Diurnal Warm Layers: amplification of diurnal cycle

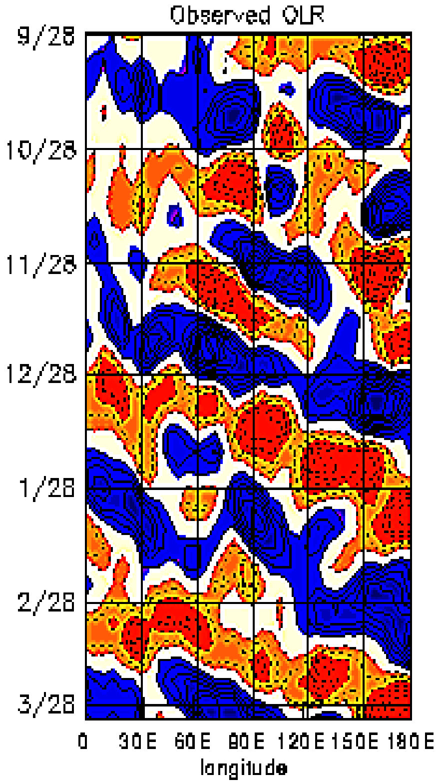


- Stably stratified (warm) thin layers form during the day.
- They isolate the deeper ocean by reducing vertical mixing.
- The increase the value of peak temperature.
- They trigger convection events, which can rectify in MJO



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





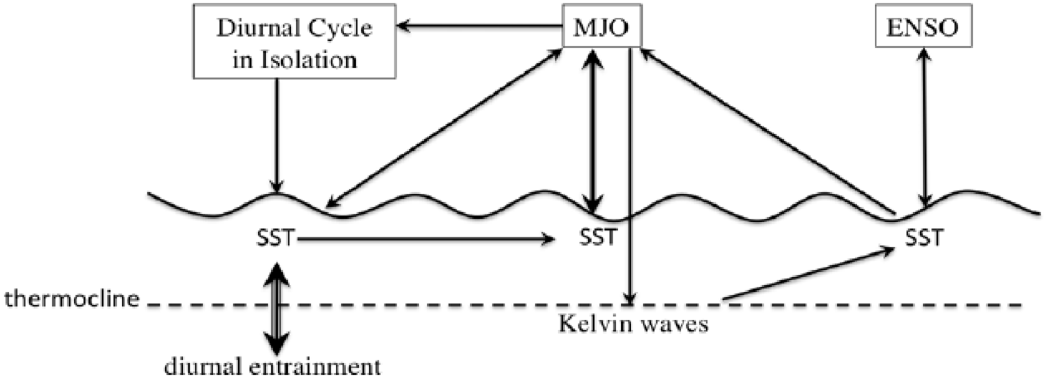
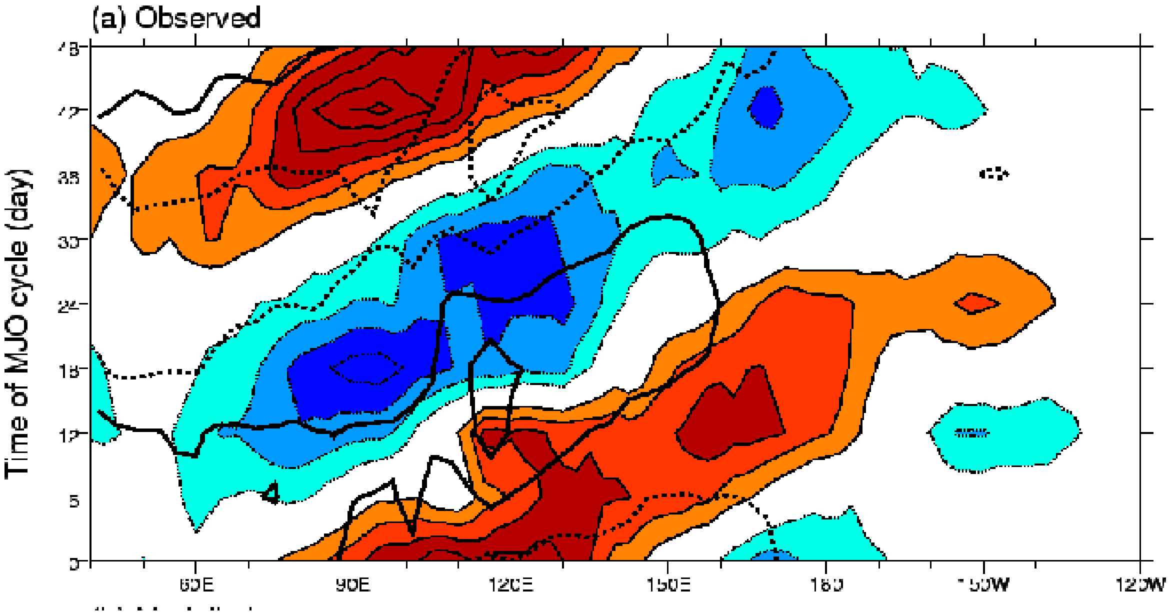


Figure 1: Schematic diagram of cross-scale air-sea interactions between the MJO and diurnal cycle and between the MJO and ENSO. Arrows denote directions of influences.

- 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

MJO: Coupled Mode



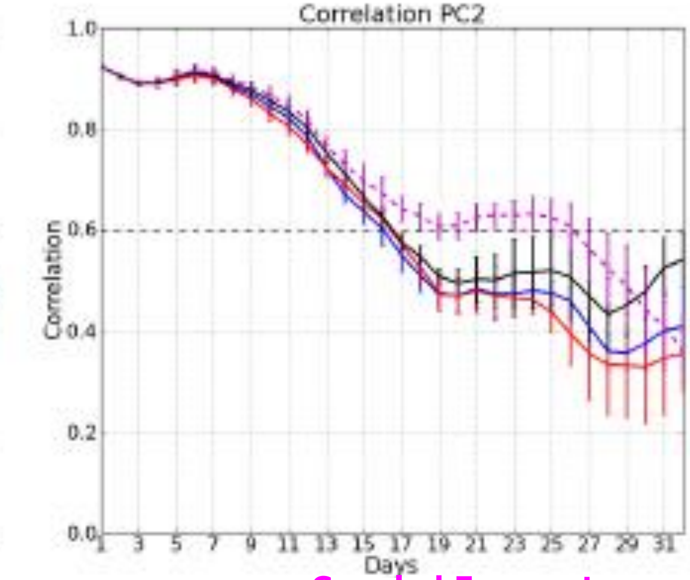
Composites of SST anomalies (contours) and OLR (colours) of MJO events. SST and convection are in quadrature.

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.

Coupled model produces better predictions of MJO than “observed” SST

MJO prediction

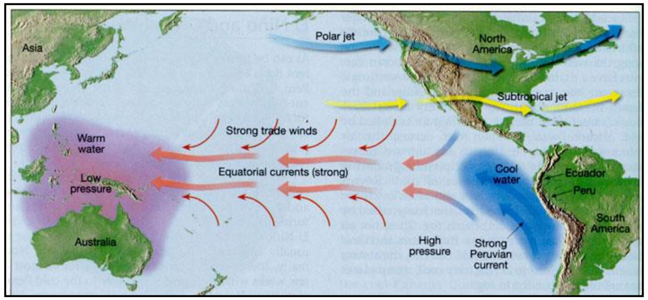


--- Coupled Forecast

Solid: prescribed SST different products

De Boisseson et al 2012

Interannual Time scales: ENSO



ENSO: El Nino -Southern Oscillation

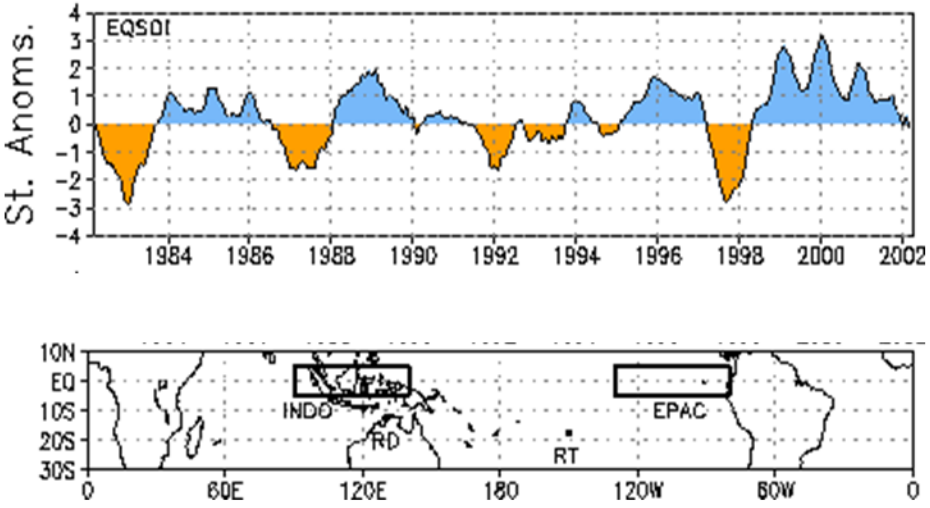
Largest mode of O-A interannual variability

Best known source of predictability at seasonal time scales

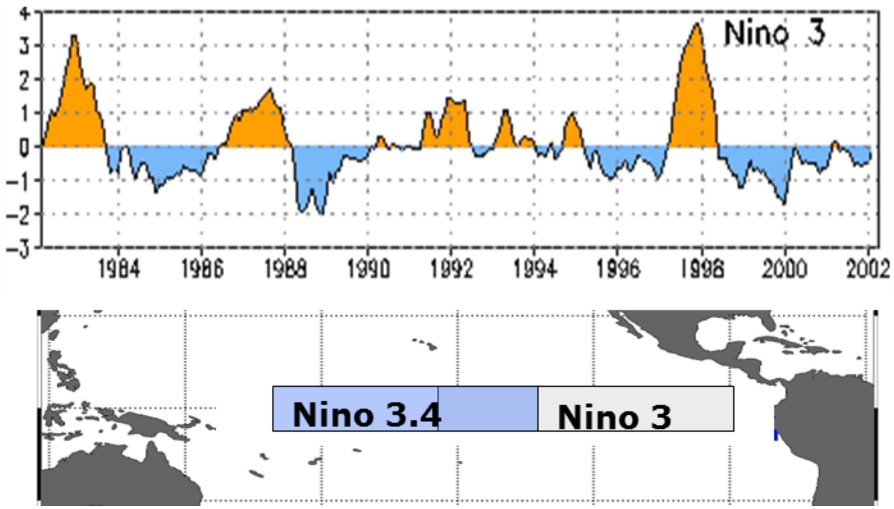
It affects global patterns of atmospheric circulation, with changes in rainfall, temperature, hurricanes, extreme events

SOI: Southern Oscillation Index (SLP Darwin – Tahiti)

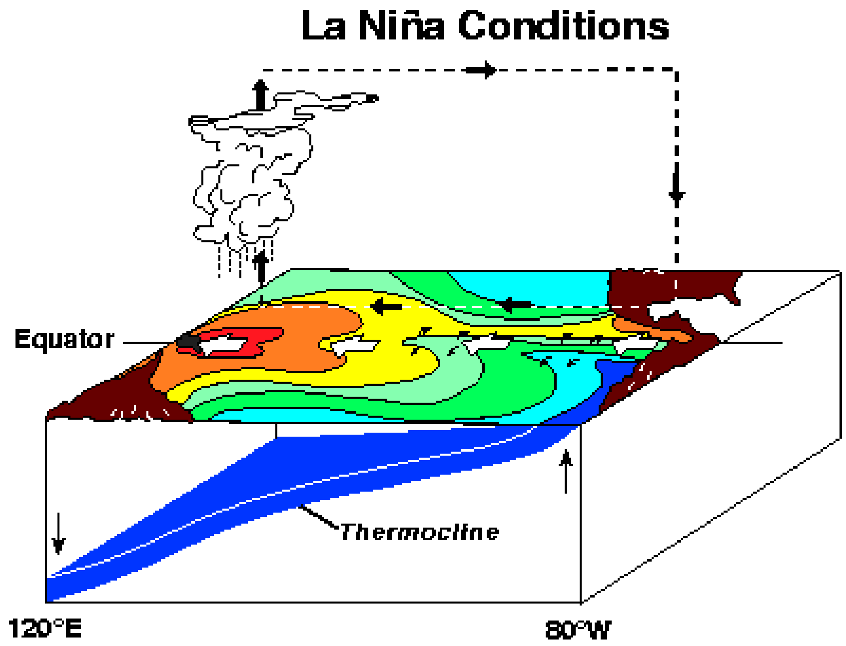
Sea Level Pressure (SOI)



Sea Surface Temperature (Nino 3)

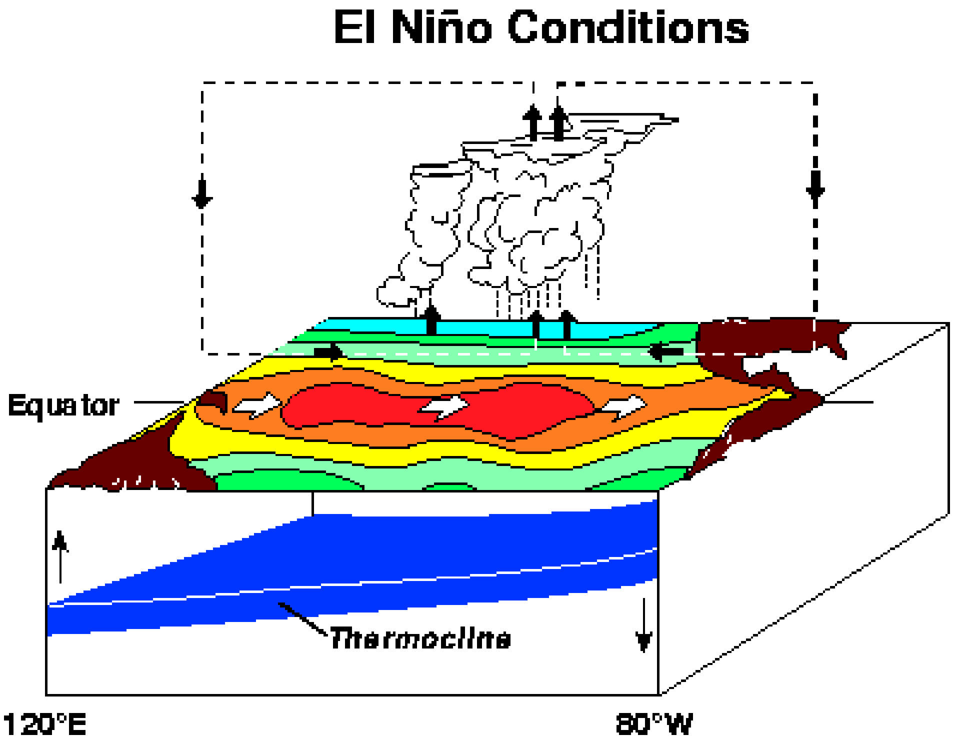


EL Nino (warm) and La Nina (cold)

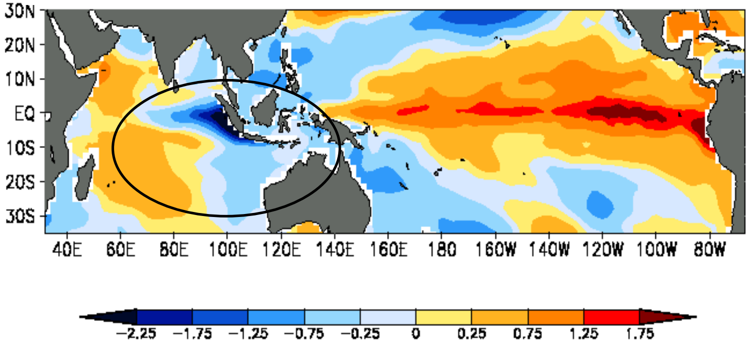


Normal/La Nina is associated with strong(er) easterly winds at the surface, a stronger thermocline tilt and cold water in the east.

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



Indian Ocean Dipole

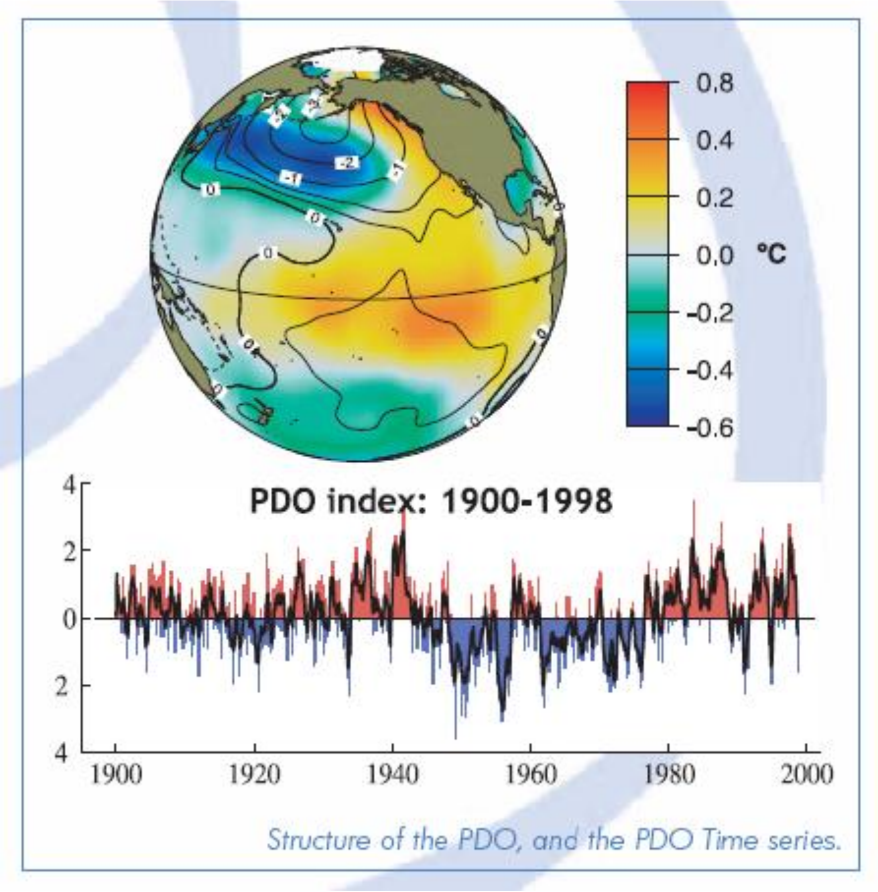


Question: is it independent of ENSO in the Pacific?

Experiments seems to suggest that IOD can be independent on the Pacific

- Changes in the slope of the thermocline in the Indian Ocean, related to changes in the winds, can create SST anomalies, resulting in a positive feedback.
- Important impacts on precipitation regime (some of them (wrongly?) attributed to El Nino

Decadal: Pacific Decadal Oscillation



Structure of the PDO, and the PDO Time series.

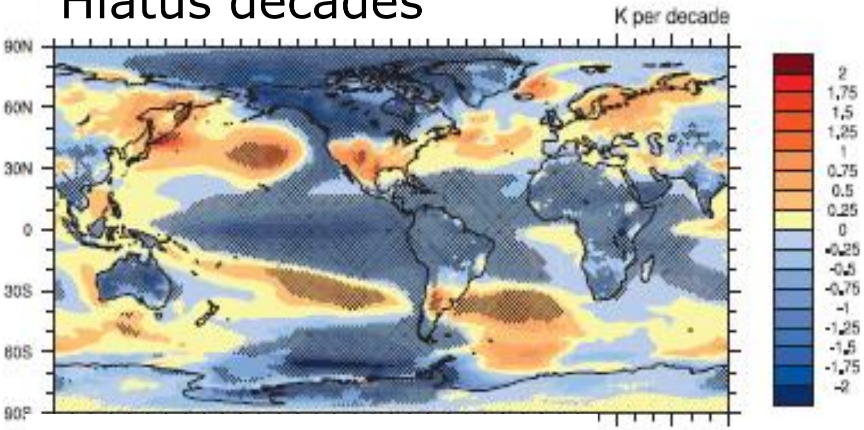
- Influences marine ecosystems (Mantua et al 1997), North American rainfall (Latif and Barnet 1994,1996, Waliser 2008)
- Latif et al, using results from a coupled model, hypotesized there is a coupled feedback (meridional SST gradients and gyre circulation).
- Link with ENSO decadal variability.
- More recently, link with ocean heat absorption and hiatus decades:
    - ➢ The –ve phase of the PDO is associated with larger heat absorption by the ocean, weaker ocean stratification, and reduced coastal ENSO activity. Stronger trades
    - ➢ The +ve phase of the PDO is associated with reduced heat absorption, stronger ocean stratification, more chances of coastal ENSO and weaker trades.

Meehl et al 2011, Balmaseda et al 2013, England et al 2014,….

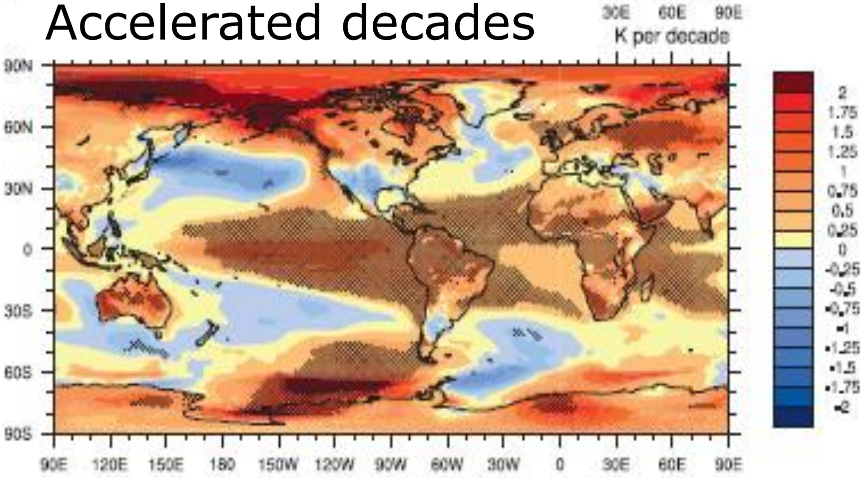
PDO, Hiatus decades and deep ocean warming

SST trends

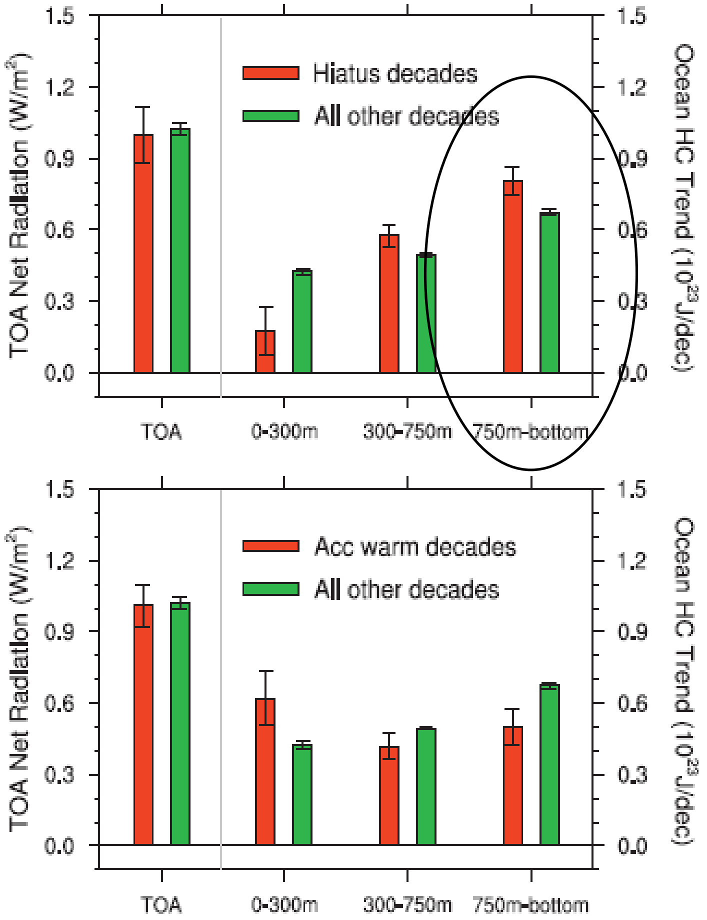
Hiatus decades



Accelerated decades



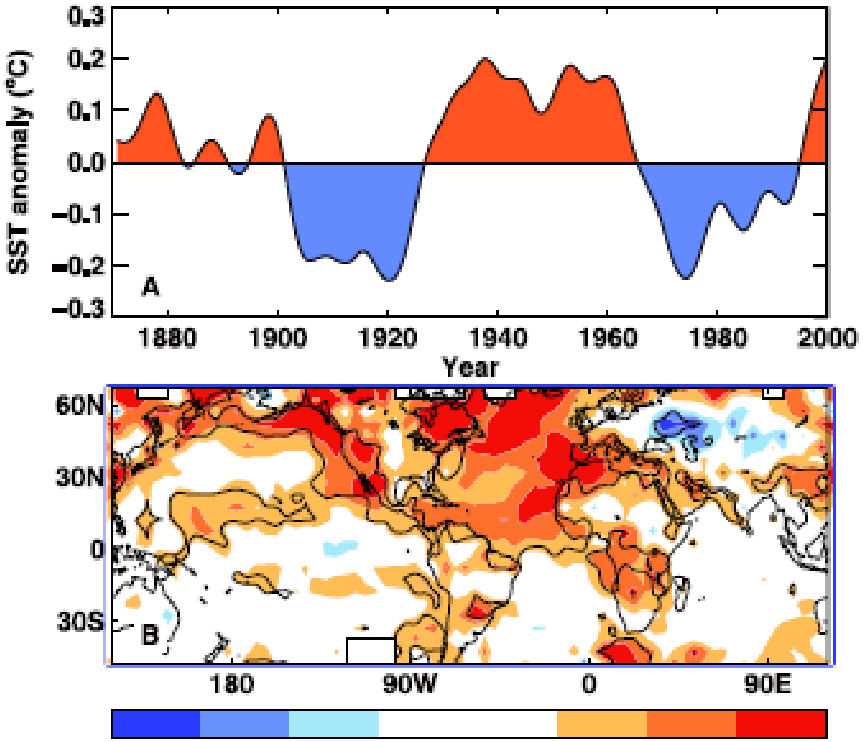
Warming Rates



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.

Atlantic Multidecadal Oscillation: AMO



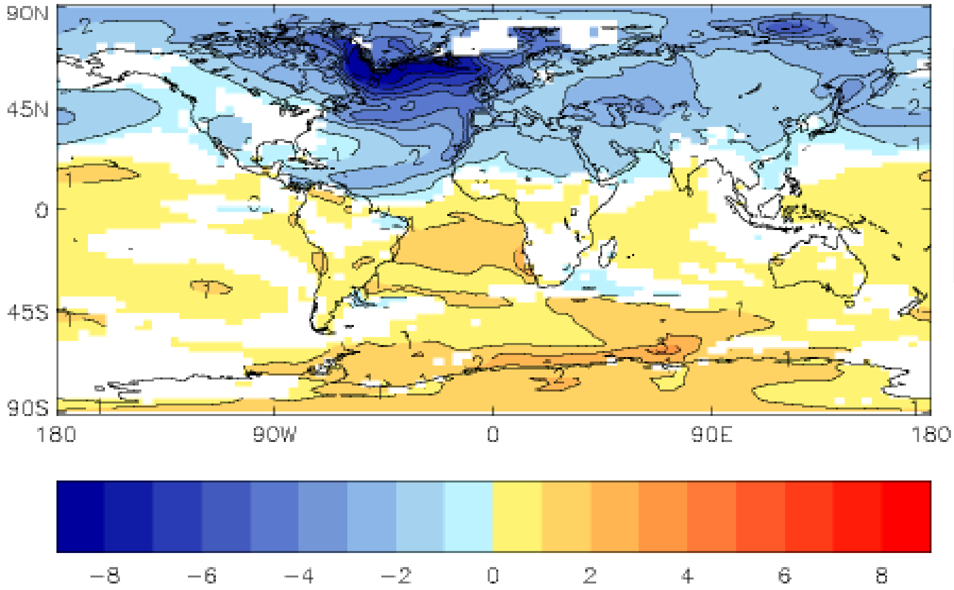
From King et al 2005

•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

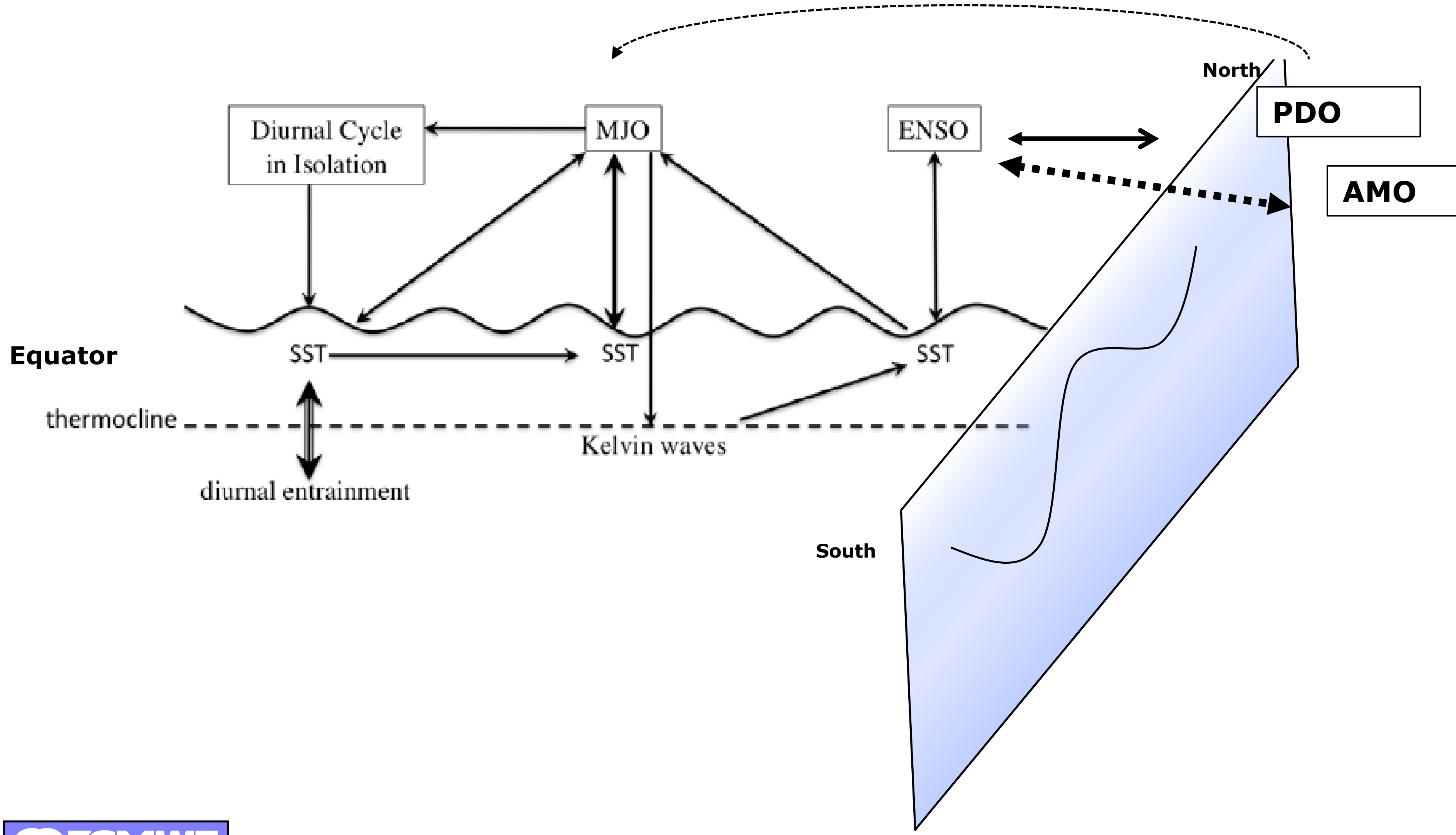
RAPID program is monitoring the AMOC at 26N since 2004.

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).

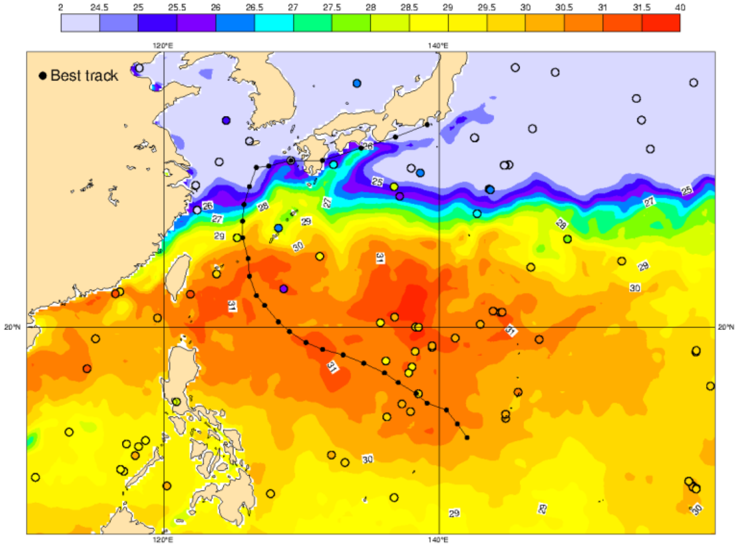
Variability: **Scale interaction**

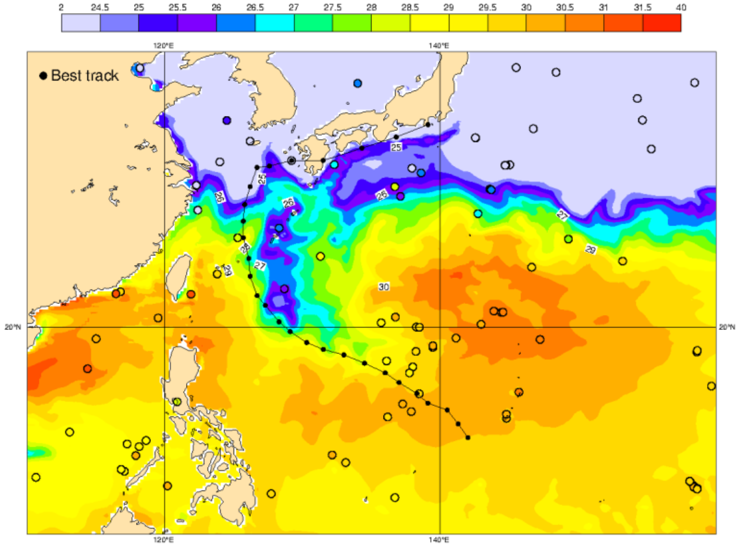


ECMWF has slowly embraced the ocean as a component of the forecasting system

1997	• Coupled model for Seasonal Forecasts
2002	• Coupled model for Monthly Forecast
2014	• Coupled model for Medium Range
2018	• Coupled model in Hres

Predicted SST with observations for TC Neoguri





Uncoupled forecast:

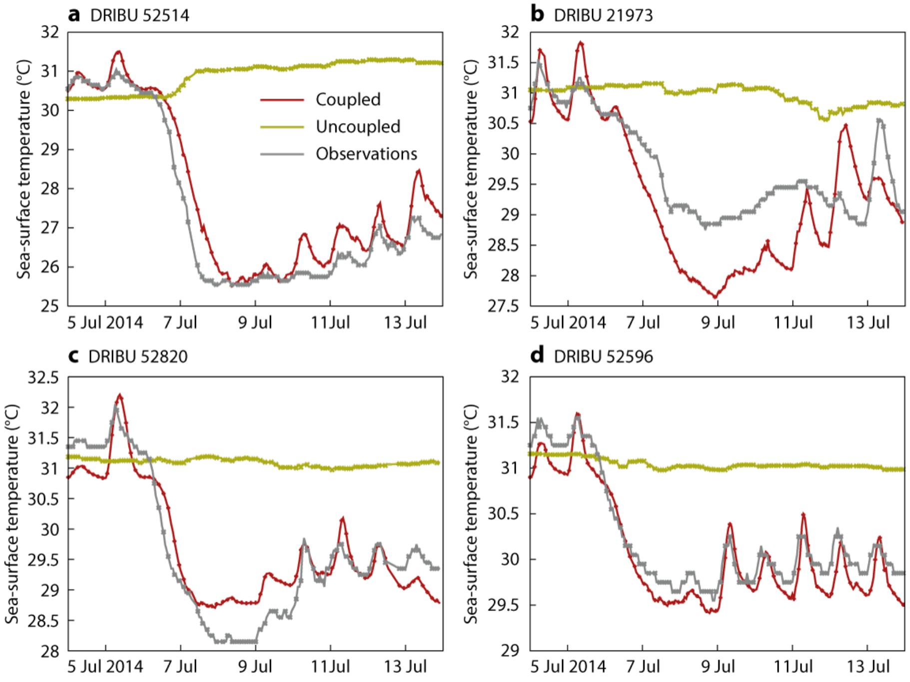
- Constant SST bad approximation

Coupled forecast:

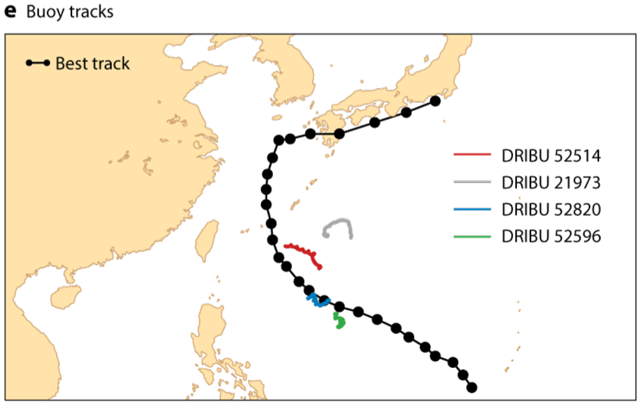
- Gets the SST cooling about right

Mogensen et al 2017

SST observations: TC Neoguri 2014

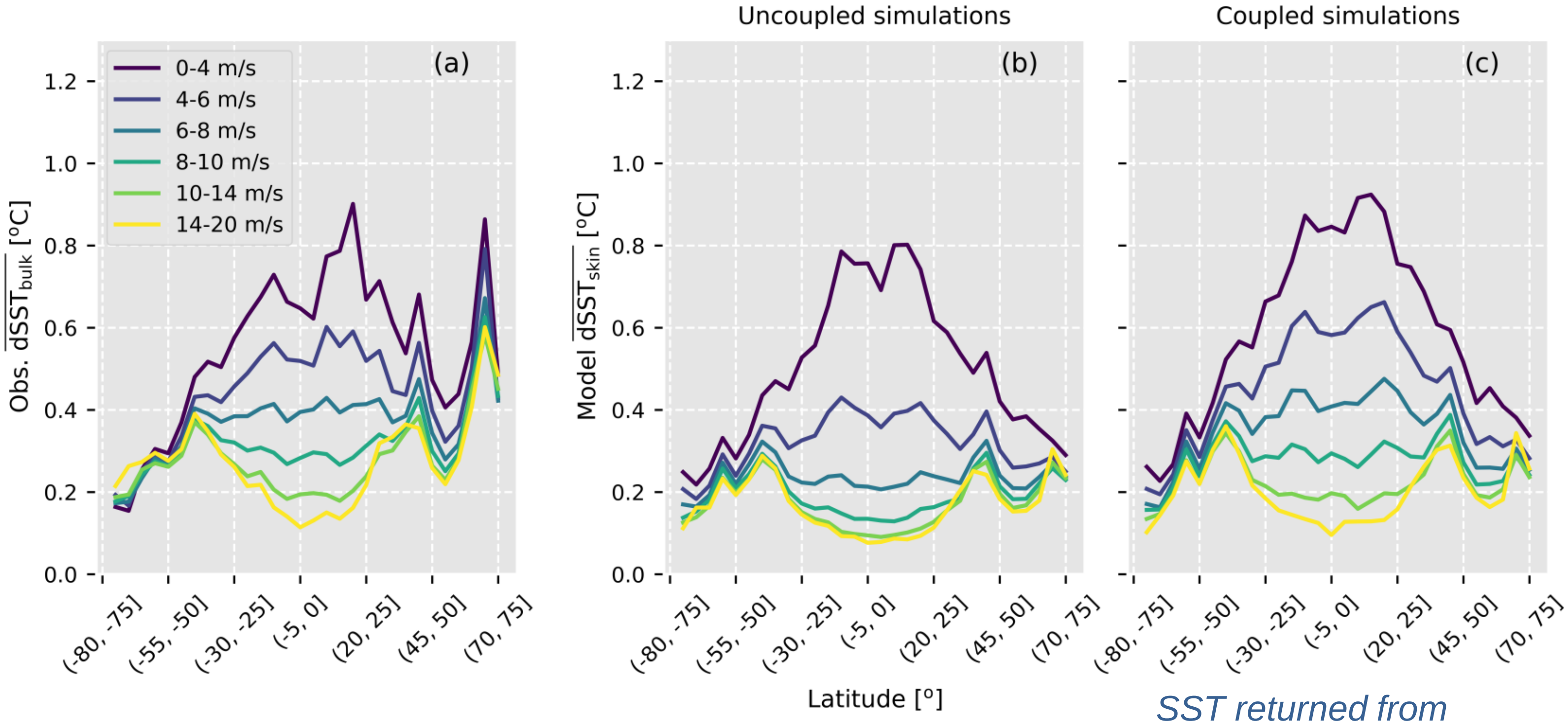


- ➢ The coupled model is able to simulate the cool wake after the TC with a realistic response
- ➢ The uncoupled model is obviously not able to simulate this



Mogensen et al 2017

Diurnal cycle of SST for different wind regimes

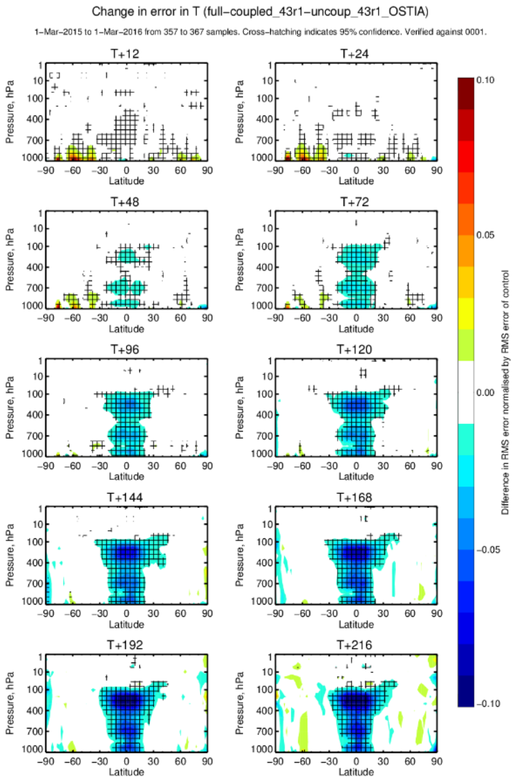


Progn equation for SST
(Zeng and Beljaars, 2005)

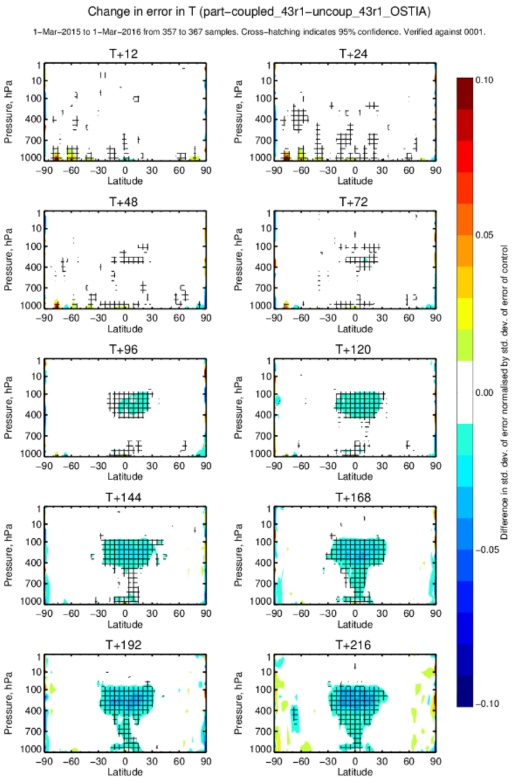
SST returned from NEMO 1m top layer
(Salisbury et al, TechMemo 826)

D. Salisbury, K. Mogensen

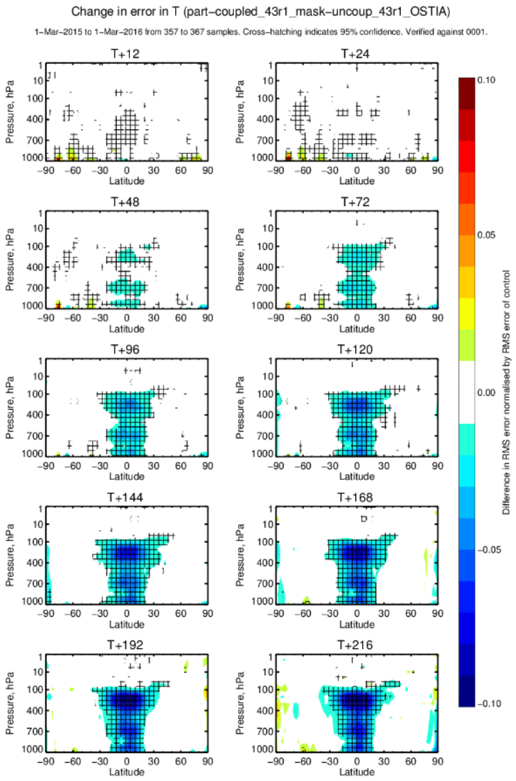
Impact of coupling (1 year, TCo1279):



Fully coupled

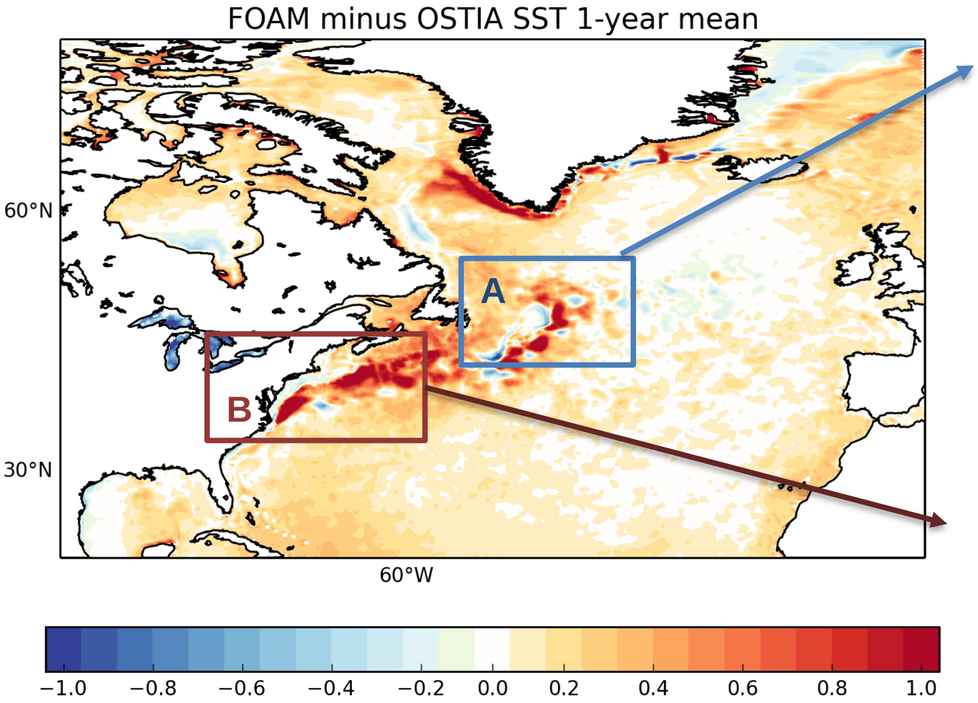


Partially coupled everywhere



Partially coupled extratropics

North Atlantic SST errors



A: Transition Zone

Flow-dependent errors in SEAS5 (decadal modulation)

Objective: Remove the problem in SEAS6

B: Gulf Stream Separation

High impact on prediction skill at all lead times

When can this be sorted out?
next 4 years**: parameterizations.**

next 10 years; 1/12 degree

F. Vitart, M. Balmaseda, H. Zuo, K. Mogensen

Summary of Coupled Ocean-Atmosphere Variability

- The ocean-atmosphere interaction involves **many time scales** and a **multiplicity of feedbacks:**
  - **Large scale**: mainly in the **tropics, and meridional SST gradients:** 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 responds to sharp SST fronts (WBC and TIWs)
    - Impact on storm tracks, blocking, teleconnections
    - Strong implications for modelling and predictability

- **The ocean affects predictability and prediction skill at different forecast ranges**
  - Extending the predictability horizon: large memory; dynamics and thermodynamics
  - Better representation of processes: MJO, tropical cyclones, diurnal cycle
  - The ocean also shows chaotic behaviour and regime transitions.
  - The ocean model in the coupled system also brings errors. WBC as main challenge

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