Water mass formation: A climate dynamics perspective

Eli Tziperman[1] and Kevin Speer[2]

[1]Weizmann Institute of Science

[2]Florida State University

Outline:

- Consider water mass formation/ ventilation processes within two of the vertical circulation cells and examine dynamical issues & observations:

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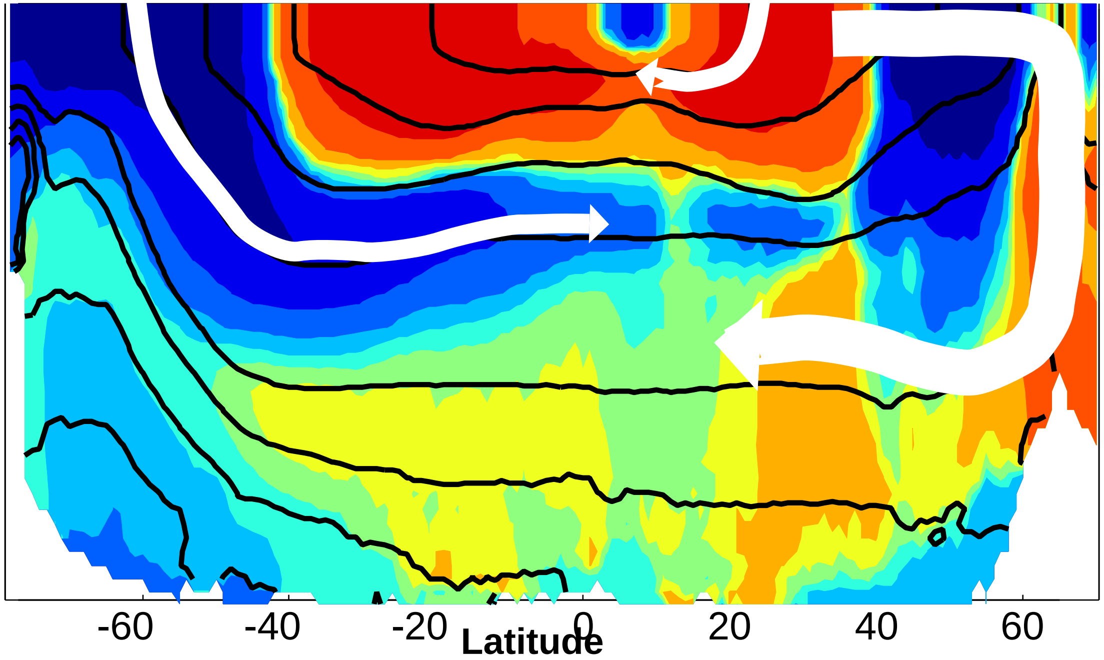
Outline:

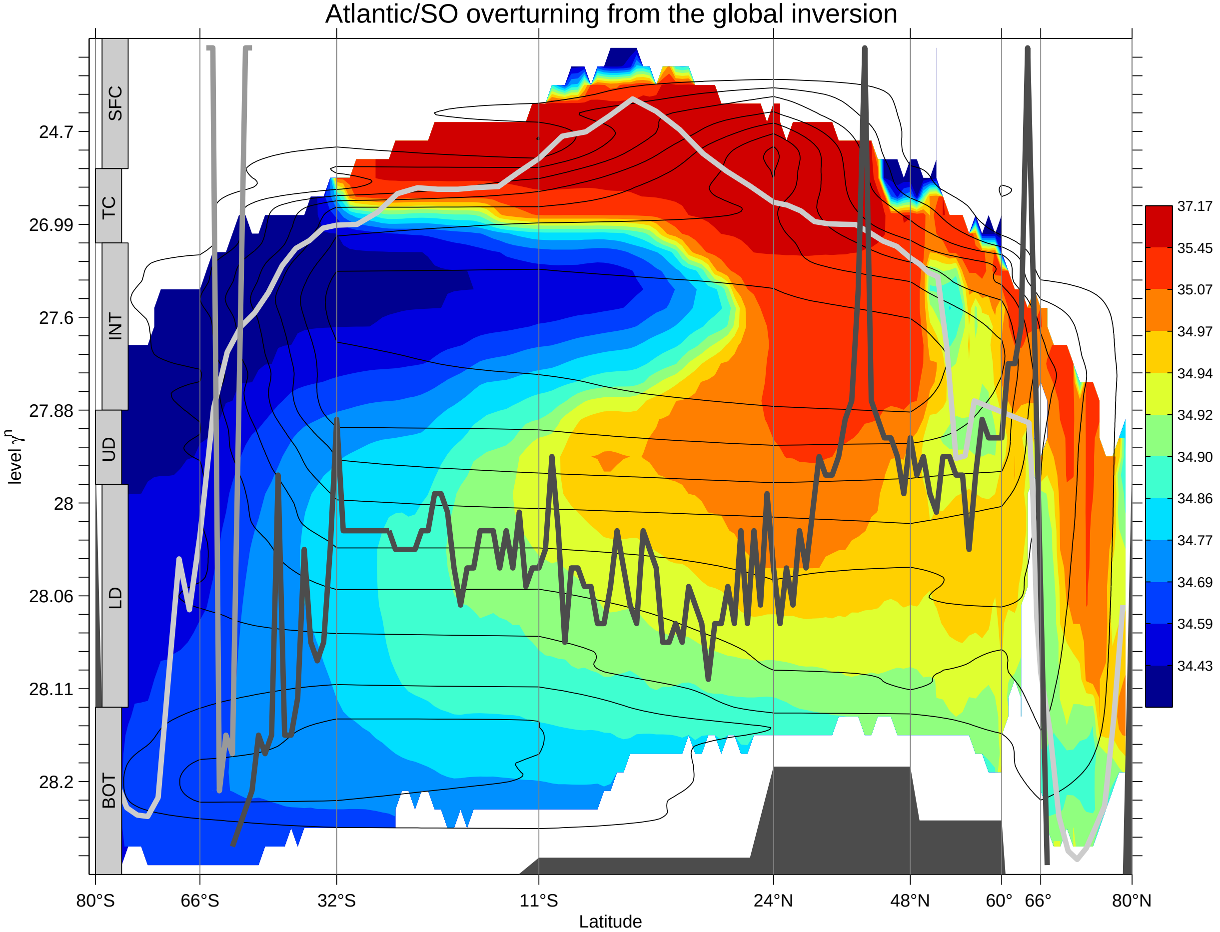
- Consider water mass formation/ ventilation processes within two of the vertical circulation cells and examine dynamical issues & observations:
  - Deep cell (NADW, Labrador Sea Water): & Is the THC near an instability point? CFC, transient tracers, hydrography, surface fluxes
  - Shallow Ekman cell in Pacific: Decadal ENSO variability: advection from mid latitudes or waves? Repeat hydrography, transient tracers, CFC, drifters
- In both cases, the paleo-climate perspective is very useful as well...

Deep cell & meridional overturning/ thermohaline circulation stability



Deep cell & thermohaline circulation stability

Start from observations/ inverse model of meridional overturning circulation:



Overturning streamfunction in North Atlantic, as funct of neutral density (Speer & Lumpkin '03); superimposed on WOCE salinity climatology (Hamburg SAC).

Complex picture; not clear what dynamical questions one may want to ask.

$\Rightarrow$ too complicated, MOC$\neq$THC; need simple models to guide us first;

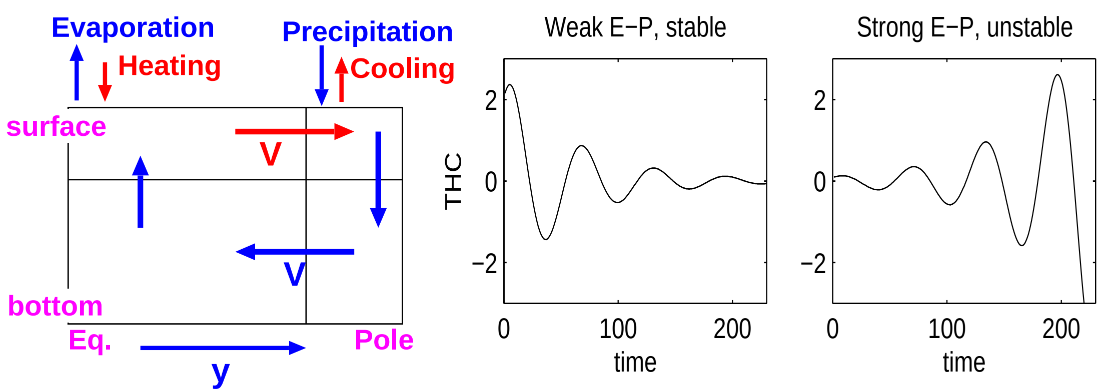
Restart with a somewhat simpler system...

Deep cell & thermohaline circulation stability

Box models Ocean GCM Coupled GCM Observations

♣ Consider a box model of the thermohaline circulation... Now MOC=THC.

♠ Stronger fresh water fluxes ⇒ weaker THC. A sufficiently weak THC suddenly becomes unstable and may flip (Walin 85; Marotzke et al 88; Tziperman et al 94)



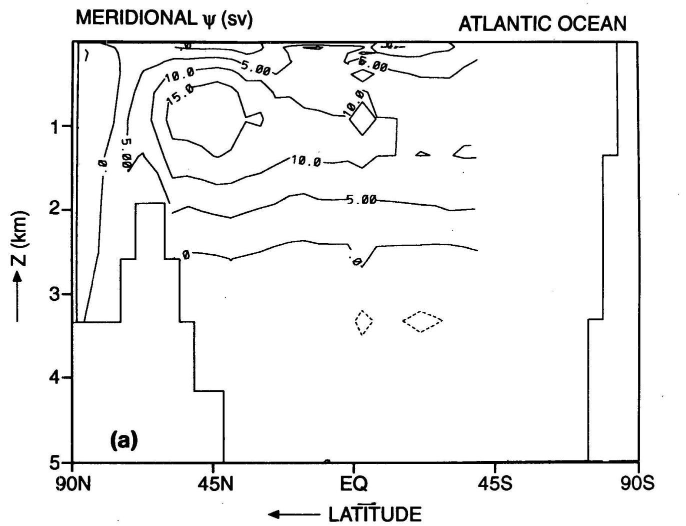
Lesson 1: The meridional overturning may become unstable in simple box models when the fresh water forcing is increased.

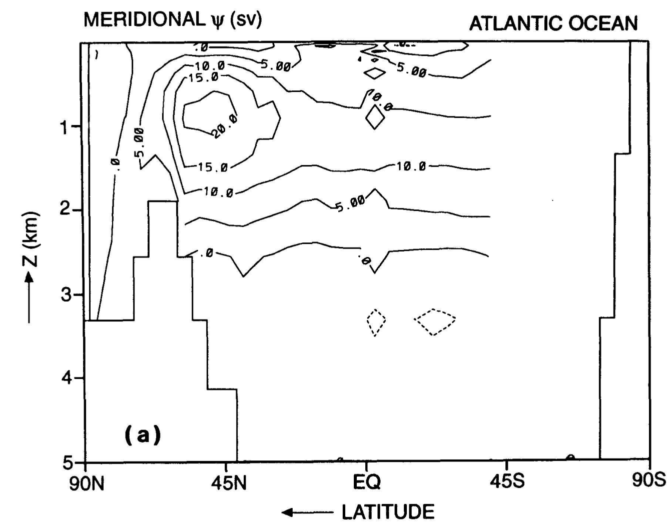
Lesson 2: the threshold between strong and stable THC and weak and unstable THC seems to be not far from present-day amplitude of the THC.

But it's ridiculous, of course, to conclude this from a 4-box model, or is it...?

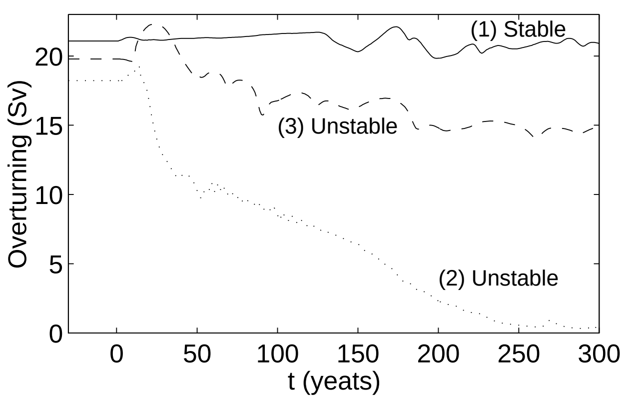
Deep cell & thermohaline circulation stability

Box models **Ocean GCM** Coupled GCM Observations





An unstable THC ↑ A present-day like, stable, THC ↑



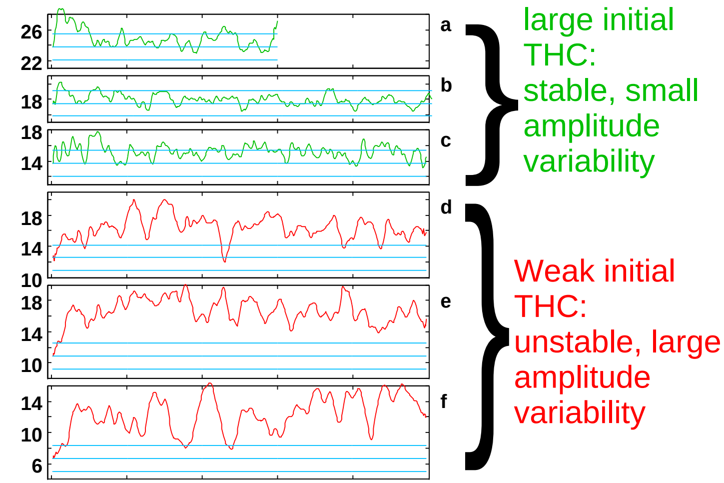
← A weak initial THC is unstable, a strong one is stable. Present-day very close to stability threshold. Like box model. (Tziperman et al 94)

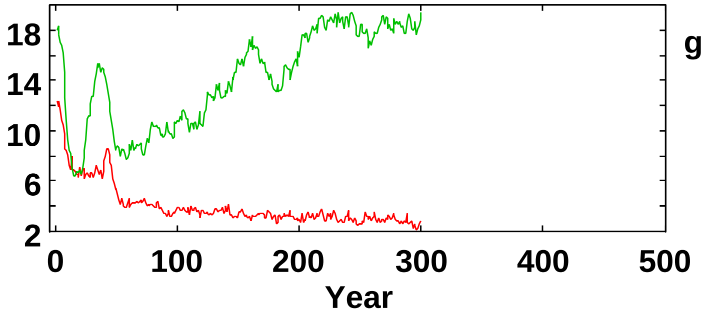
But the ocean GCM is forced by “mixed” boundary conditions, ignoring atmospheric feedbacks etc, would this still hold in a coupled GCM?

Deep cell & thermohaline circulation stability

Box models   Ocean GCM   **Coupled GCM**   Observations

A weak initial THC is unstable and leads to large variability. a strong initial THC is stable and shows a weaker variability. Present day THC seems near the stability threshold: a reduction of 25% leads to an instability.





A strong initial THC recovers from a fresh water pulse (Manabe & Stouffer 93); a weak one does not, and just collapses to zero (Tziperman 97).

⇒ The proximity of present-day THC to a stability threshold is a very robust feature of nearly all THC models. (in greenhouse context: Schmittner & Stocker 99)

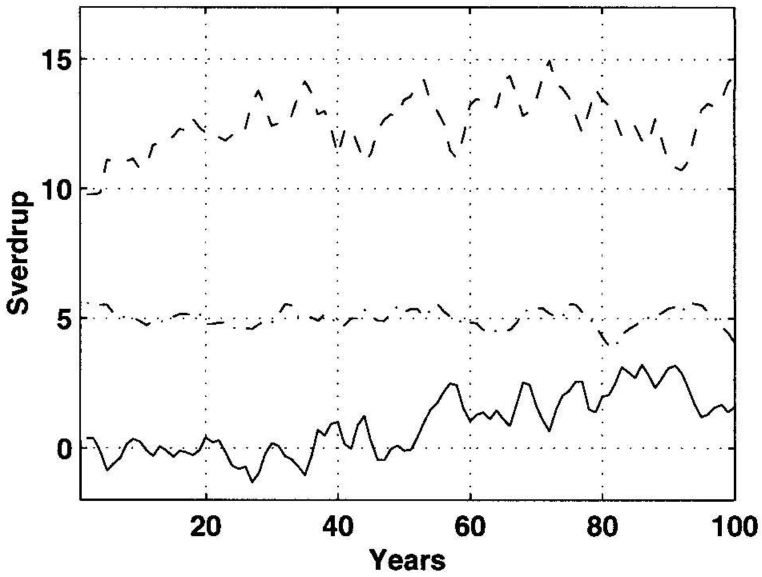
Next, how realistic *is* the CGCM? Examine details of water mass formation...

Deep cell & THC: details of model climate instability

Box models Ocean GCM **Coupled GCM** Observations

So, what actually happens when the CGCM THC becomes unstable and increases/ oscillates?

A time series of model formation rates at three main sites in North Atlantic: Norwegian Sea (dash-dot), SE of Greenland (dash) and Labrador sea (solid):



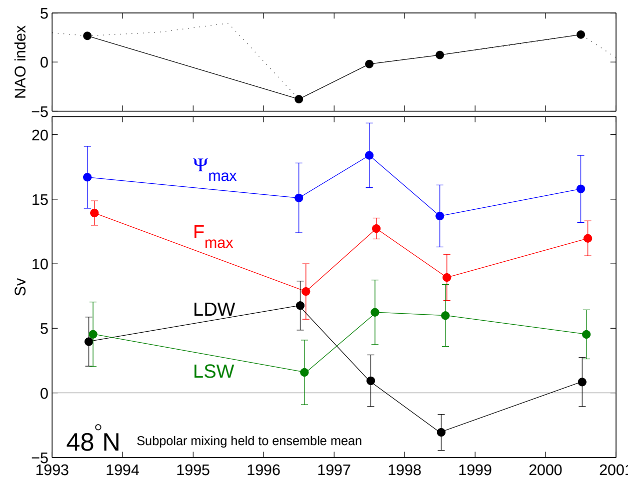
$\Rightarrow$ We find that, in the model:
Labrador formation starts only for unstable runs;
The THC variability in the stable model runs is of a few (2-3) Sverdrup

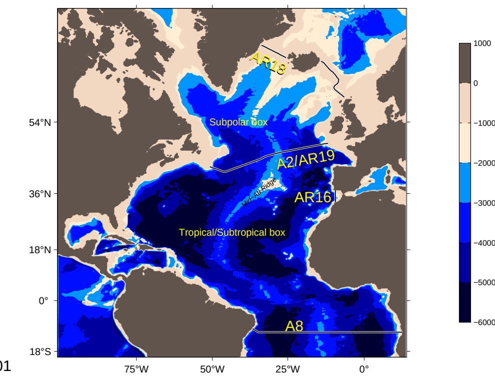
But what about the real ocean? Turn to WOCE observations...

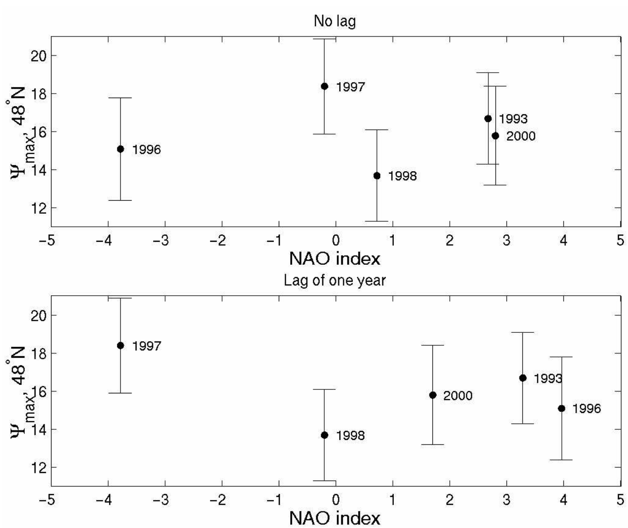
Deep cell & THC: Observations

Hydrography Transformation CFC Physical processes

Blue: Interannual variability of MOC at 48N (inverse box); red: transformation for air-sea flux; green: Labrador sea water; black: Lower deep water.





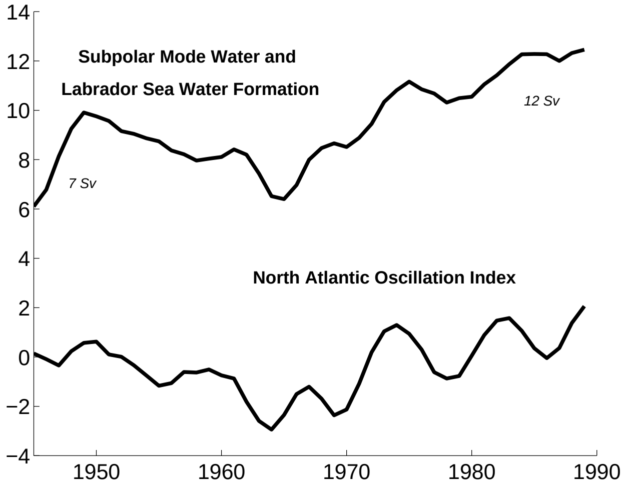


← Amplitude of interannual variability of the meridional overturning cell (thermohaline circulation) is 3-4Sv

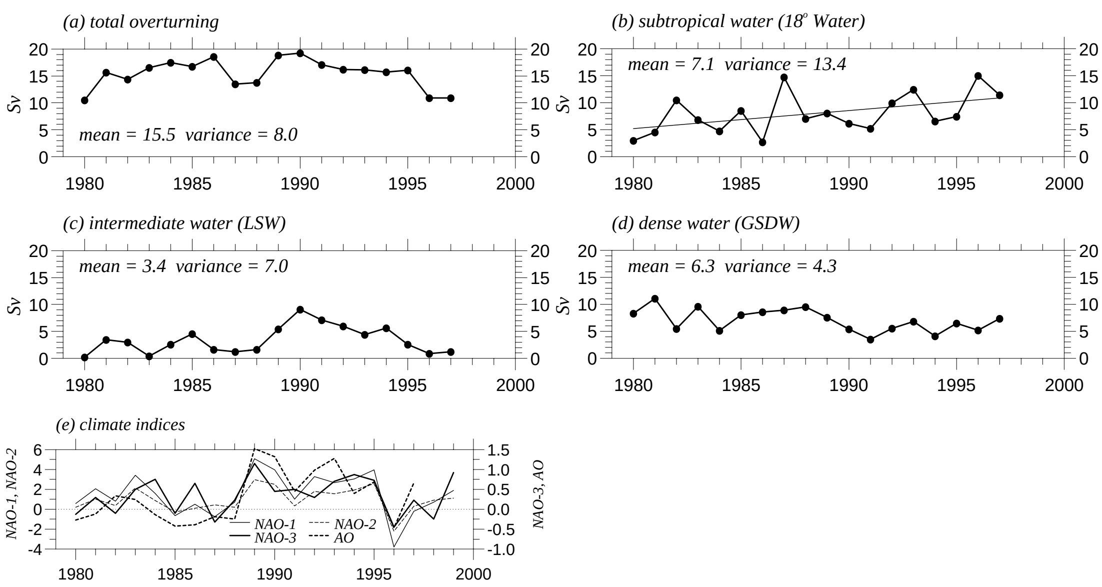
⇒ Internal NAO-like variability partially cancels, leaving little relation to NAO in the total MOC (Speer, Lumpkin & Koltermann 2003).

Deep cell & THC: Observations

Hydrography **Transformation** CFC Physical processes



Variability estimates can be obtained from air-sea flux formation rates and model-based estimates (Speer 1998) ⟶



⟵ Formation rates from air-sea fluxes & NAO indexes (Marsh 2000)

Note: Much non-local - adiabatic - variability in intermediate waters occurs due to wind-forced circulation changes.

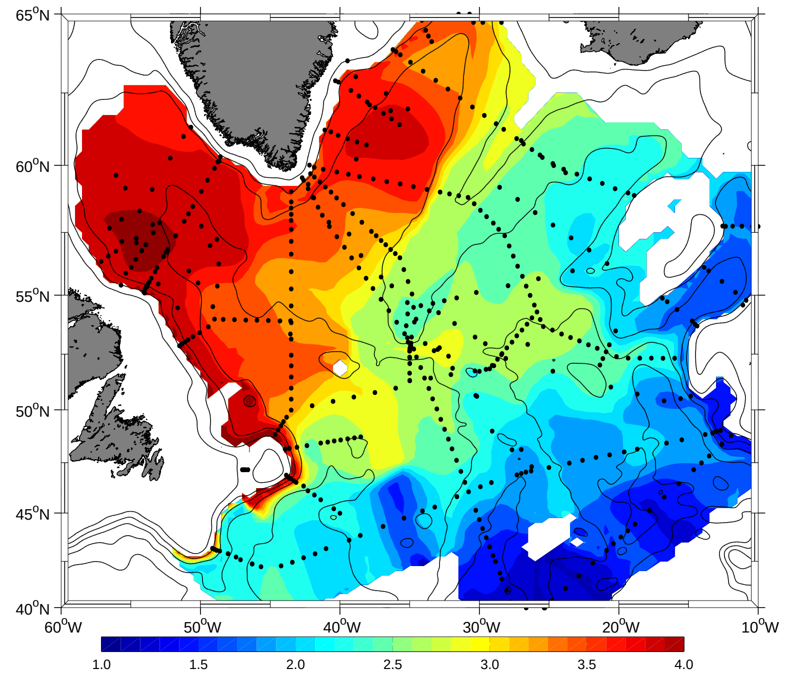
Deep cell & THC: Observations

Hydrography Transformation **CFC** Physical processes

1997: hydrographic & CFC data: 456 CFC stations, 2300 measurements in LSW layer (IFM Kiel; LDEO, New York; SOC Southampton; SIO San Diego, IUP Bremen)

- CFC inventory of LSW north of 40° N: 2300+-250 tons
- Mean LSW formation rates 1970-1997: 4.4-5.6 Sv
- Variability: denser LSW modes only formed at high NAO index: 1.8-2.4 Sv low NAOI; 8.1-10.8 high NAOI
- model confirmed CFC-Method

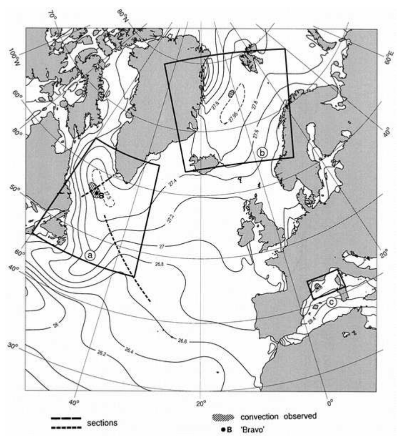
(Rhein et al., 2002, J. Phys. Oceanogr. 32, 648-665; Boening et al., 2002, Geophys. Res. Lett.)

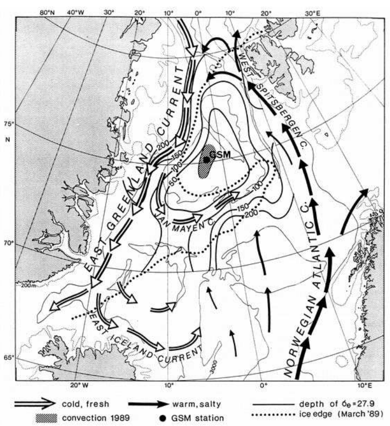


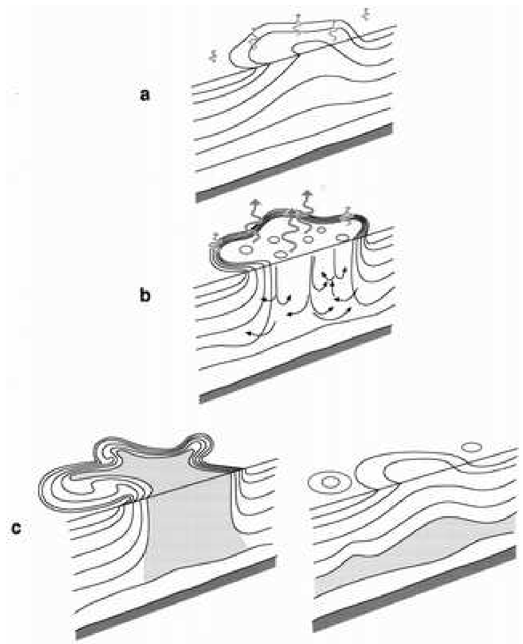
Mean CFC Concentration in Labrador Sea Water, 1997: LSW Spreading and Formation Rates

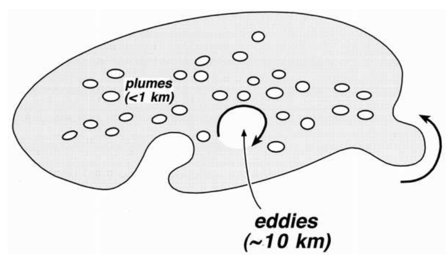
Deep cell & THC: Observations

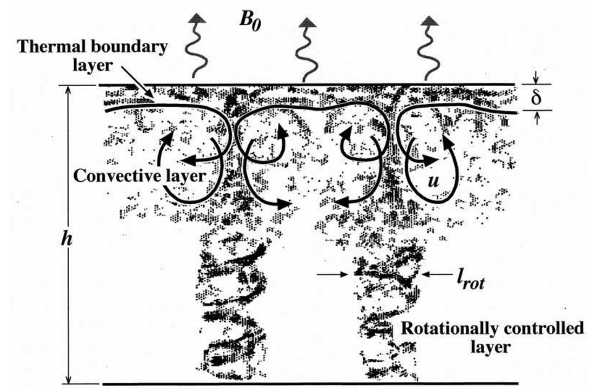
Hydrography   Transformation   CFC   **Physical processes**

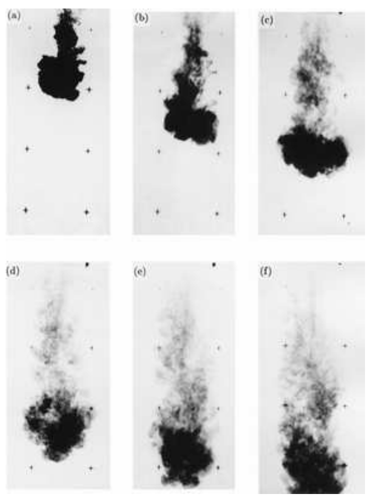












Formation sites; complex interplay with local currents

Multiple scales involved

←(Marshall & Schott 99)→

complex interaction with rotation

Models are very sensitive to parameterization of these unresolved processes

Deep cell & THC: models vs WOCE observations

Coarse GCMs used 4 THC stability:

- Mean = $\sim$18 Sv
- Total variability = $\sim$2-3 Sv
- LSW variability: 0...
- Formation sites: SE of Greenland, Norwegian Sea
- Formation process: vertical convection sites at a few semi random grid points
- Sensitivity to sub-grid scale mixing/ formation processes

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WOCE observations:

- Mean: 16 ± 2 (Lumpkin&Speer '02); 15 ± 2 (Ganachaud&Wunsch '00);
- Total variability: $\sim$4-6 Sv
- LSW variability: $\sim$8Sv (Rhein et al., '02)
- Formation sites: Labrador Sea (Irminger sea), GIN Sea
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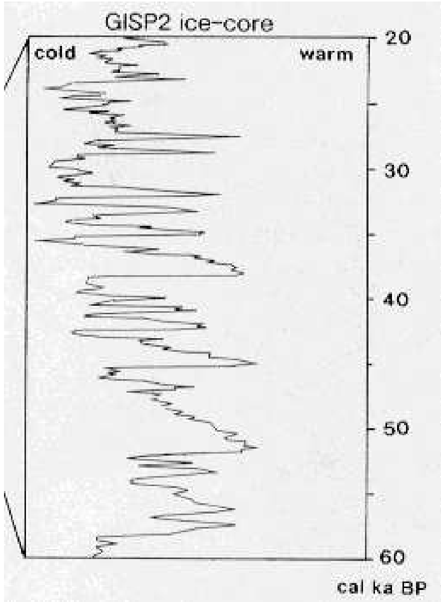
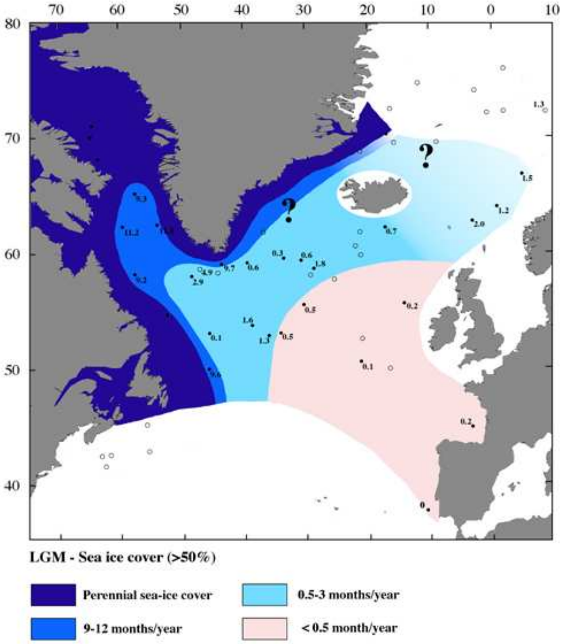
Model Deep Water cell is clearly quite different from WOCE observations...
Bottom line: Model simulation of Deep Water formation clearly needs to improve for us to believe that the THC is indeed close to a stability threshold.

Deep cell & THC stability: paleo perspective

- For some time it was believed that the THC shut down during last glacial maximum. More recent proxy data & analysis indicate no shutdown (Legrand & Wunsch 95; Bigg, Wadley, Stevens et al 2000; Yu, Francois, Bacon 1996; Matsumoto & Lynch-Stieglitz 1999; Weaver, Eby, Fanning et al 1998; Kitoh, Murakami & Koide 2001)
- Furthermore, shutdown of THC in CGCMs has no major global effect.
- $\Rightarrow$ Need another climate component that can be a major player in climate changes, abrupt or not. Perhaps sea ice? Tropics+atmosphere?



$\longleftarrow$ Temperature proxy in GISP2 Greenland ice core.
Sea ice reconstruction during the Last Glacial Maximum (de Vernal 2000) $\longrightarrow$



If sea ice caused abrupt climate changes, should we worry about greenhouse response of THC?

Deep cell & THC stability: future observations?

What observations do we need to find how close is the THC to a stability threshold?

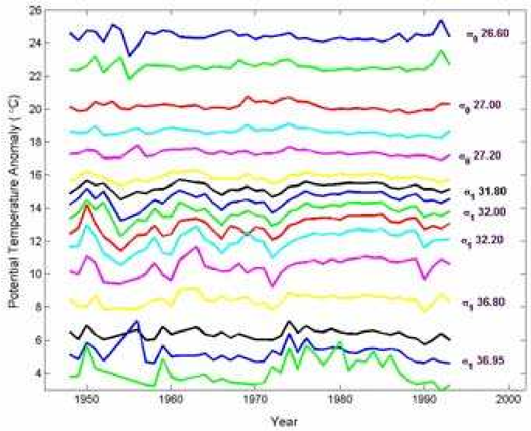
- First obvious gap is lack of reliable air-sea fresh water fluxes
- But no less important: measure the response of meridional atmospheric moisture fluxes to changes in ocean circulation
- paleo perspective suggests going beyond THC & studying/ observing sea ice dynamics
- mixing, mixing, mixing...

and, of course, models still have long way to go to improve reliability and fit to even existing observations of deep cell water mass formation, both mean and variability

Applied climate research: Med water and global warming

High salinity Mediterranean Sea water spreads at intermediate depths in the Atlantic, giving NADW its characteristic saltiness that distinguishes it in the World Ocean.

Outflow variability and trends in Med Water properties: temperature near Med Water outflow for 1950-1992:



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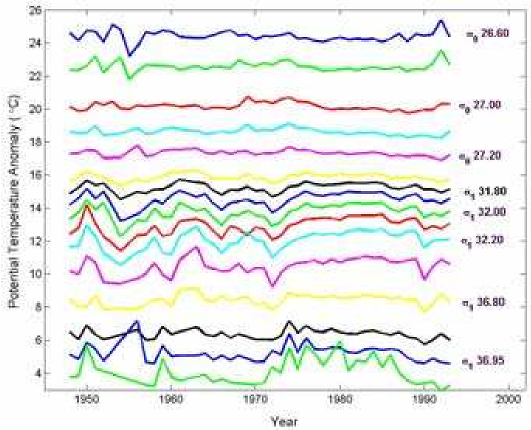

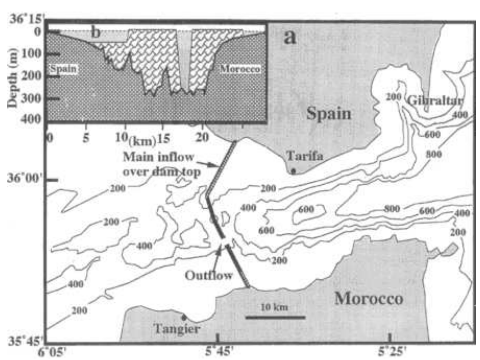

Now that the Straits of Gibraltar are dammed, inflow and outflow are set by scientists in Spain and Morocco. (Johnson, EOS 1997)

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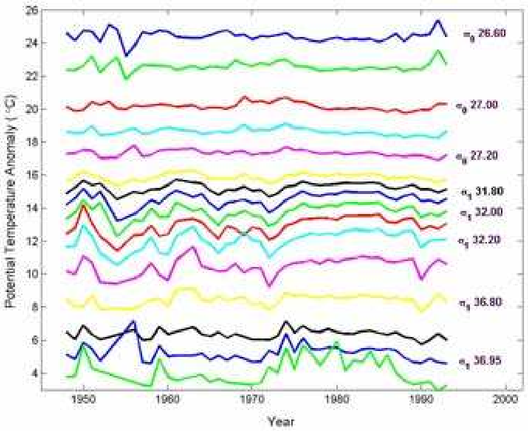
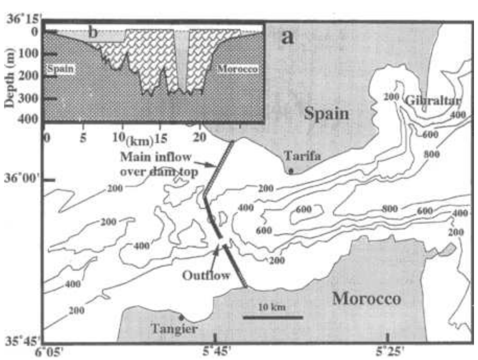
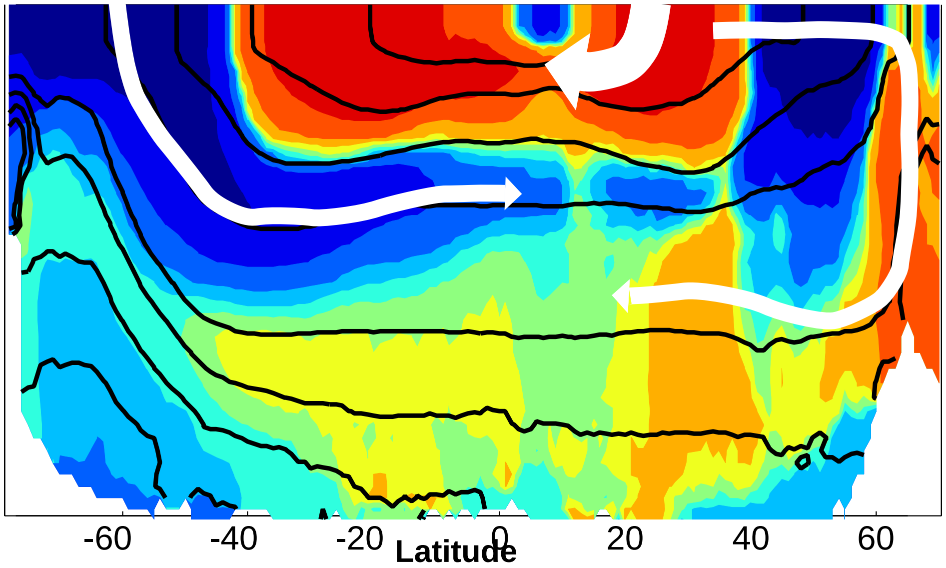




Now that the Straits of Gibraltar are dammed, inflow and outflow are set by scientists in Spain and Morocco. (Johnson, EOS 1997)

Global warming may be easily prevented by closing the dam, thereby shutting off the NADW, cooling northern hemisphere and starting a new ice age.

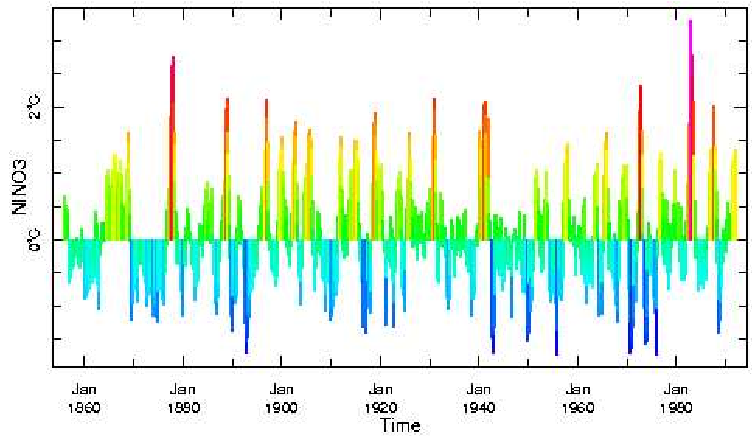
Shallow cell and decadal variability of ENSO



Shallow cell and decadal variability of ENSO

The observation: ENSO events (every 3-5 years) vary on an inter-decadal (>10 years) time scale:

The question: what causes the inter-decadal variability in El Nino characteristics?



East Pacific Equatorial temperature, 1860-1991 (Kaplan nino3)

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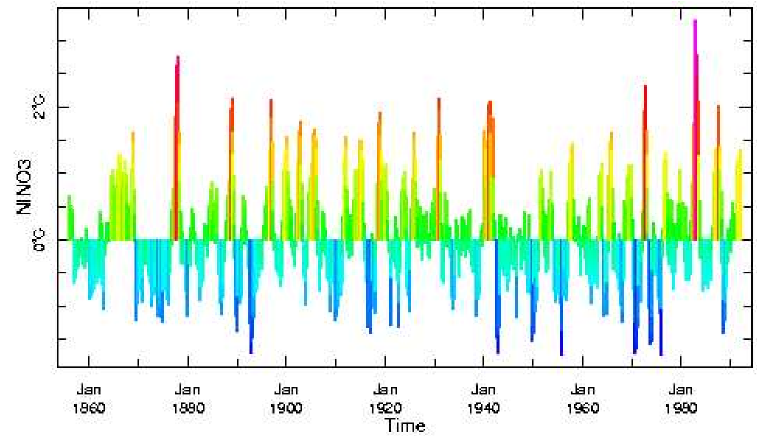
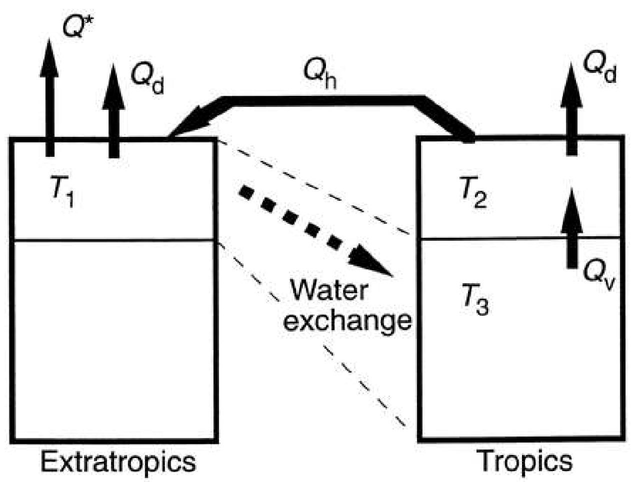


East Pacific Equatorial temperature, 1860-1991 (Kaplan nino3)

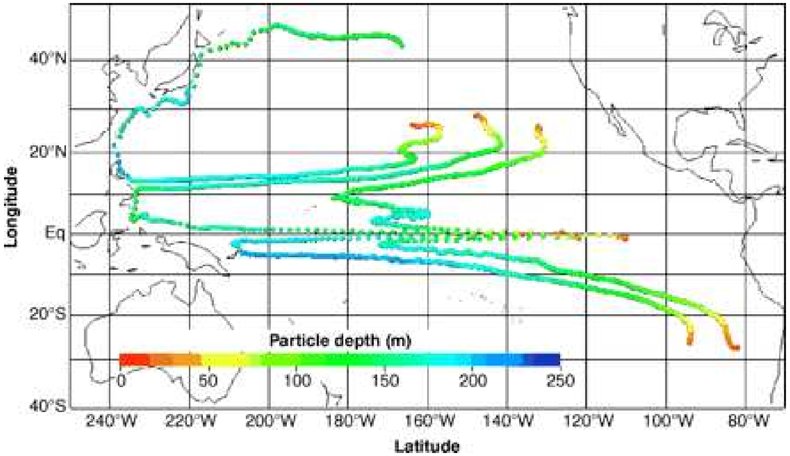
The question: what causes the inter-decadal variability in El Nino characteristics?

The difficulty: equatorial time scales are too short

A possible resolution: decadal signal is created at mid-latitudes, & influences tropical Pacific via advection of Mid-lat water toward tropics (Gu & Philander, 1997).



Inter-decadal ENSO variability: advection or waves?



← Trajectories of water parcels from mid-latitude to the equatorial Pacific (Gu & Philander, 1997)

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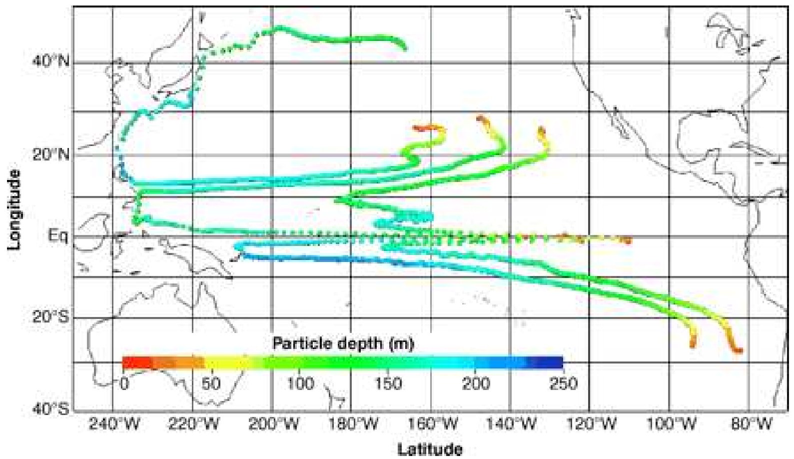

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However: We know that in many cases in the ocean, *waves* carry the information from one location to another. Specifically in this context: (Jin 2001; Capotondi & Alexander 2001; Lysne, Chang & Giese 1997)

The plan: consider this alternative wave teleconnection view using modeling tools first, and then check what do WOCE data tell us abut this...

Reformulating the question: What's the sub-surface tropical Pacific temperature sensitive to?

The head-against-wall approach:

Run model for a few years; change initial temperature at some mid-latitude grid point; run again; is tropical Pacific affected? Repeat for all mid-lat pts.

$\Rightarrow$ absolutely impossible with $\ll 10^5$ grid pts

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Easier way out: **adjoint method**: Let "cost" be

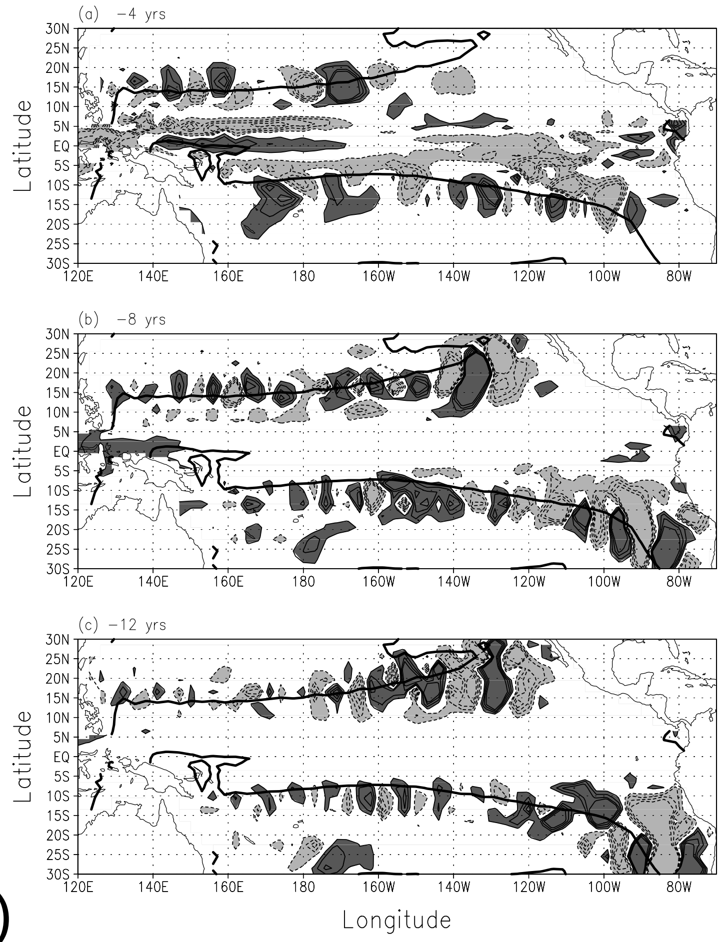
$J(\mathbf{T}_{final}) = \int_{\text{East Equatorial Pacific}} T(\text{sub surface}; t = t_{final})$

Adjoint model calculates the sensitivities $\vec{\lambda}(t) = \partial J / \partial T(\mathbf{x}, t)$: (e.g. Marotzke et al 1999; Sirkes & Tziperman 2001)

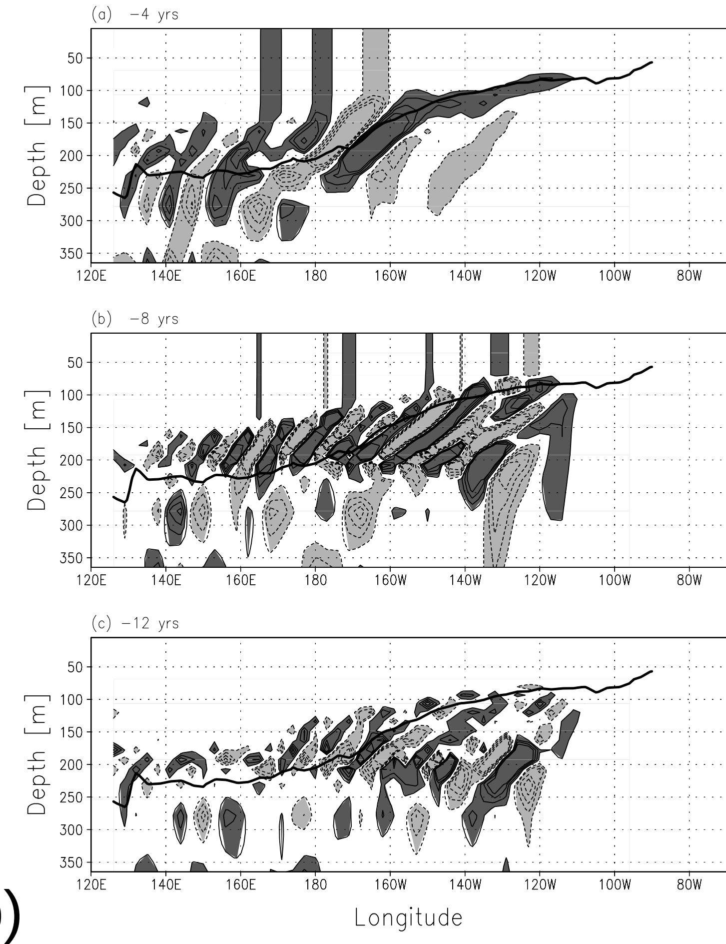
Find the areas and times in which a temperature perturbation would most efficiently affect the equatorial thermocline at a later time t_{final}.

The sensitivity results

(a) Sensitivity to temperature anomalies 4, 8, 12 yr before affecting equator; (b) Same, vertical section at 15N (Galanti & Tziperman, 2002)



(a)



(b)

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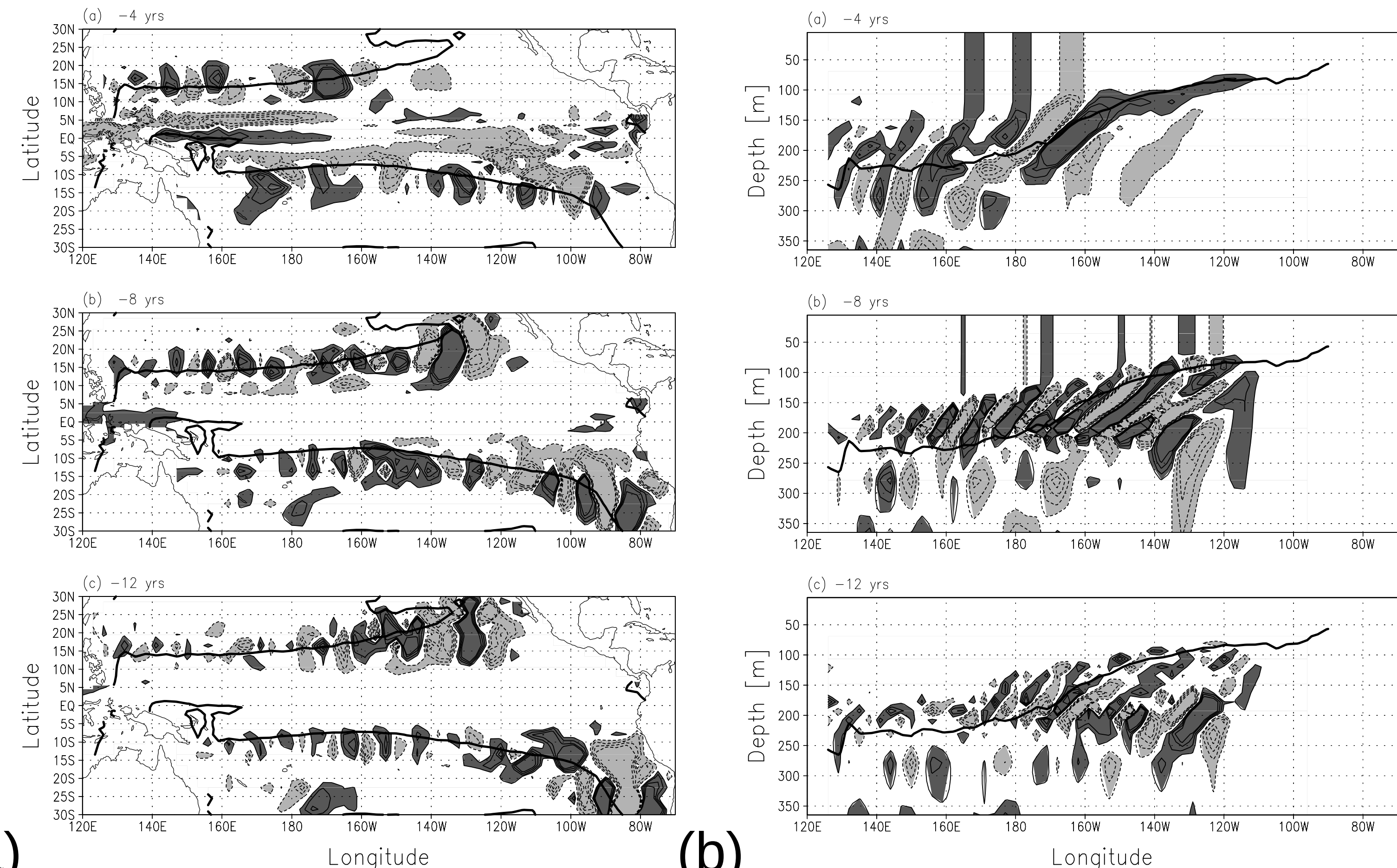


(a) (b)

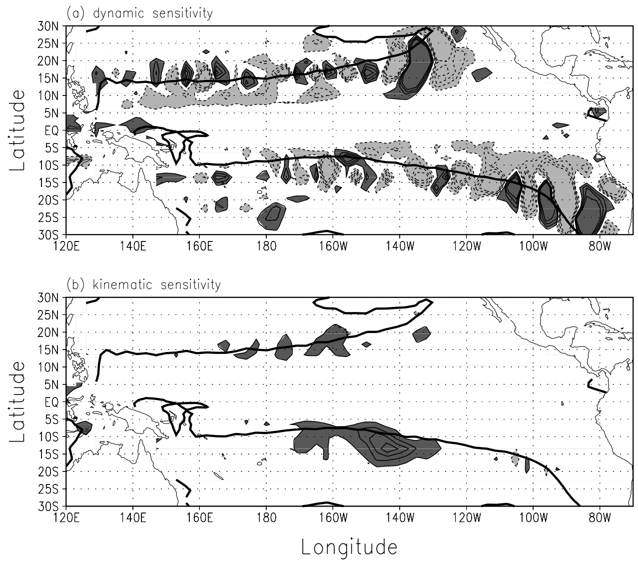
$\Rightarrow$ Equatorial thermocline is especially sensitive to long waves propagating from 25-30 degrees toward equator. So a wave teleconnection is indicated.

The sensitivity results: is it actually waves?

Dynamic sensitivity: to processes that vertically move the isopycnals, such as waves

Kinematic sensitivity: to processes that do not change the density, such as long-isopycnal advection

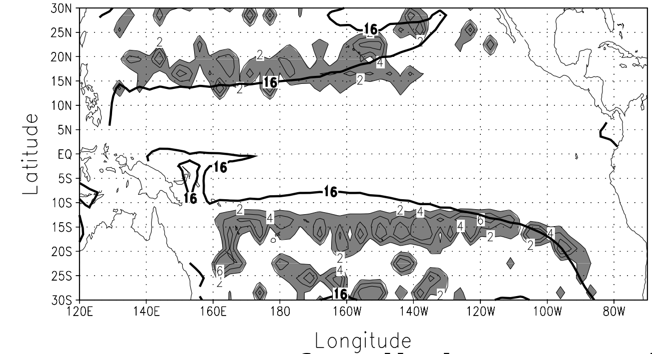
(Marotzke et al 1999)



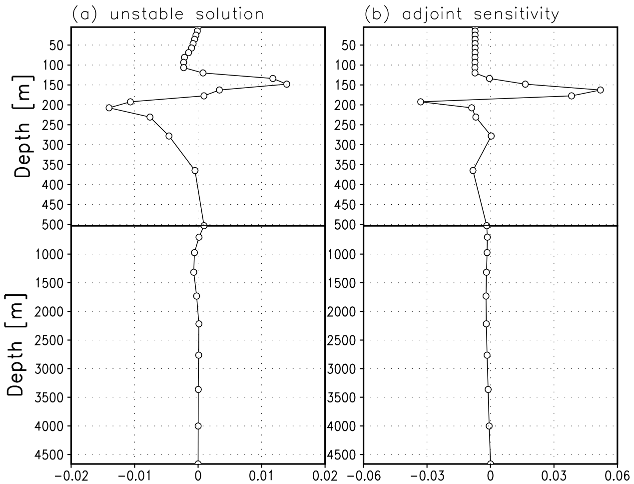
Dynamic (upper) vs Kinematic (lower) sensitivity based on the adjoint results.

Dynamic sensitivity dominates, indicating sensitivity to waves rather than long-isopycnal advection.

Why is the equator sensitive to mid-lat waves at these particular latitudes?

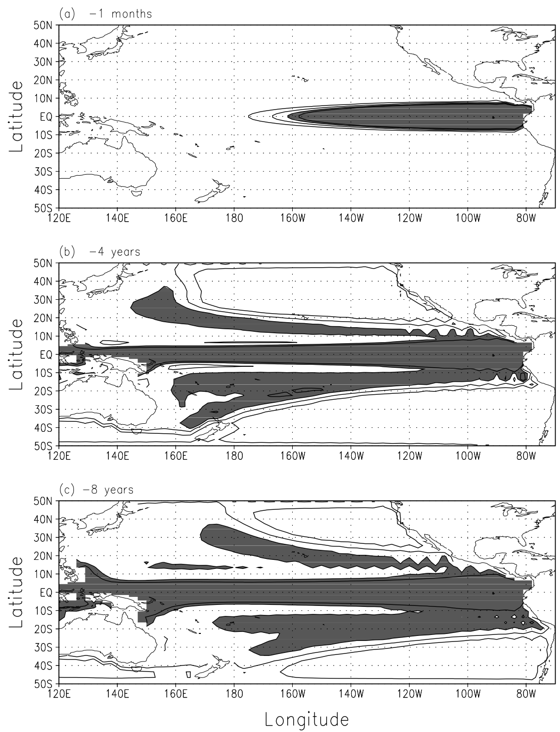


These latitudes are baroclinically unstable, waves traveling there are amplified ⟶

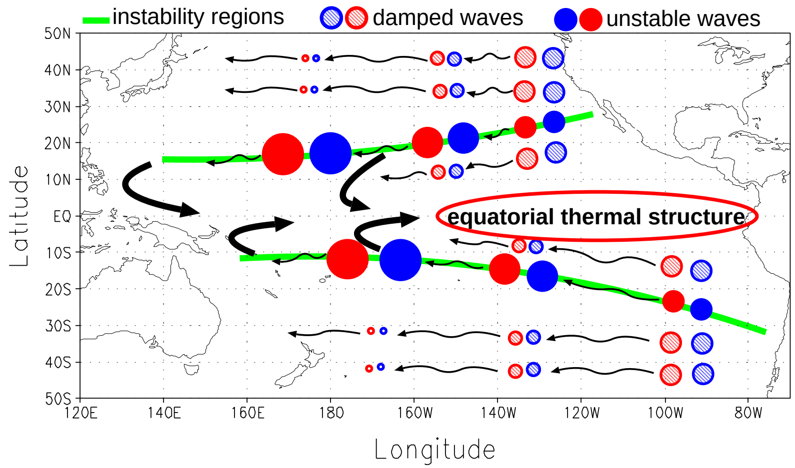


⟵ Vertical structure of adjoint sensitivities is very similar to unstable QG normal modes. Dominated by critical layers.

An idealized adjoint run with horizontally uniform stratification: no preferred latitudes ⟶



Summarizing the adjoint sensitivity results

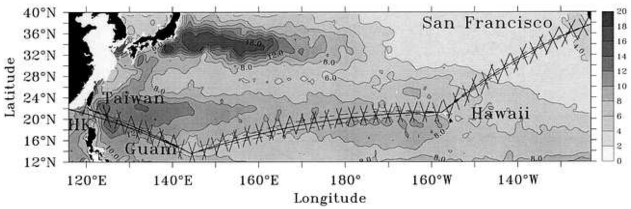


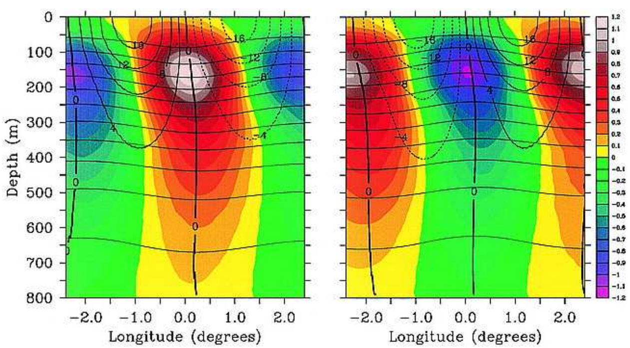
So, adjoint sensitivity indicates baroclinically unstable Rossby waves; other model results indicate a possible advective path.

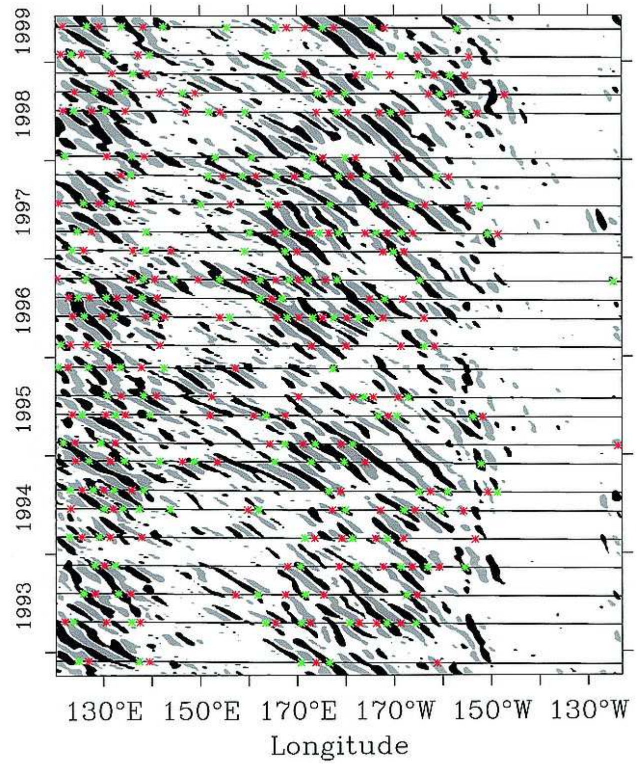
Which one is right? Turn to observations...

Shallow cell and decadal variability of ENSO: observations

Hydrographic data (Roemich et al 2001) of vertically tilted wavy features propagating near tropical Pacific:



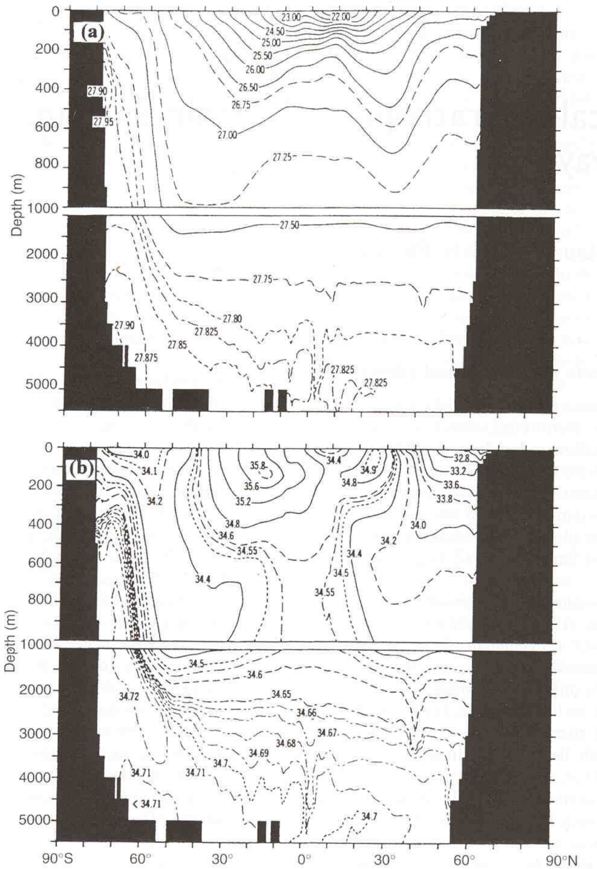


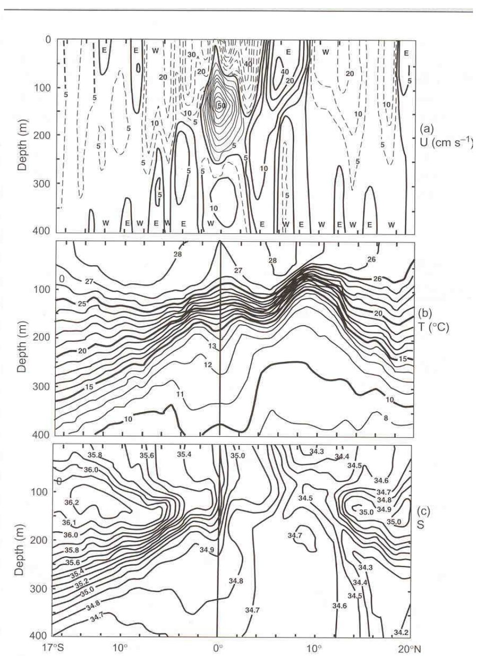


So, WOCE data indicate eddies/ waves/ instability may be relevant...?

Shallow cell and decadal variability of ENSO: observations of advective teleconnection

Salinity Tritium/ CFC Model particle trajectories

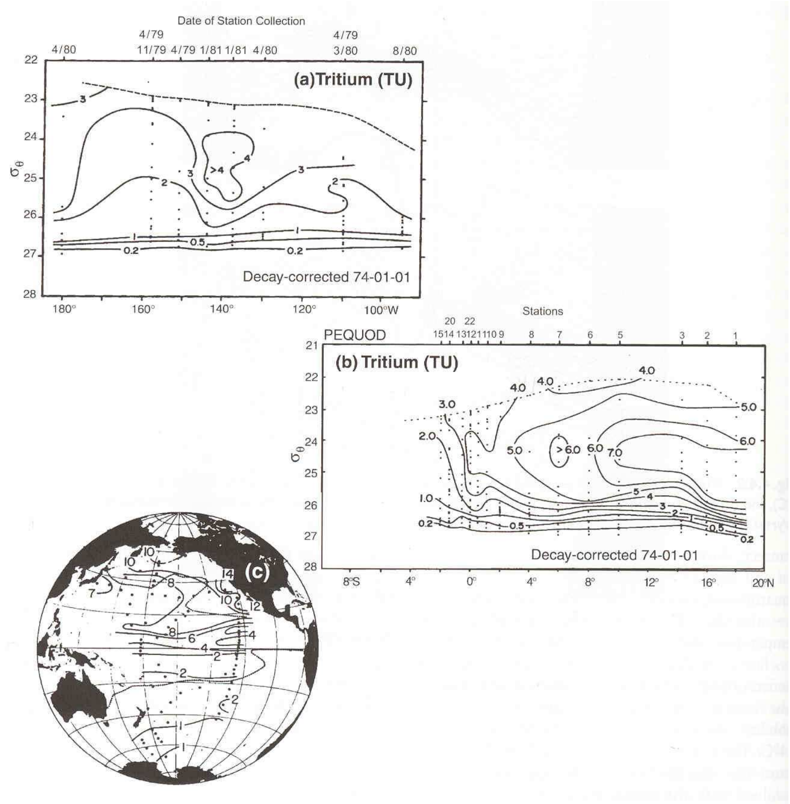




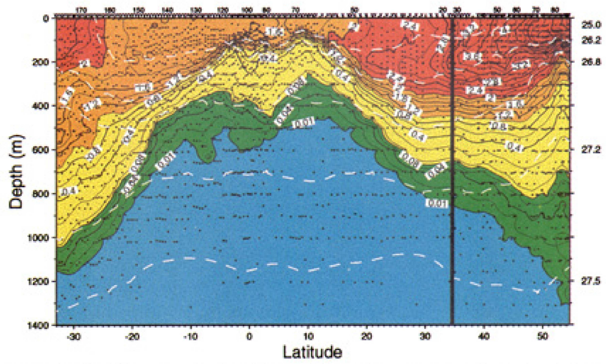
Spreading (advection/ diffusion/ eddies?!) of salinity tongues toward base of equatorial thermocline from both hemispheres (Defant 1936; Levitus 82; Wyrtki & Kolonski 84; Liu & Philander 01). Spreading is initiated by Ekman pumping in the subtropical convergence zone outcropping (Montgomery 1938).

Shallow cell and decadal variability of ENSO: observations of advective teleconnection

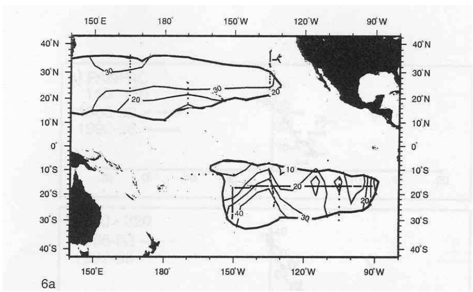
Salinity **Tritium/ CFC** Model particle trajectories



Tritium (Fine et al, 1981; 1987)



CFC (Fine et al 2001)



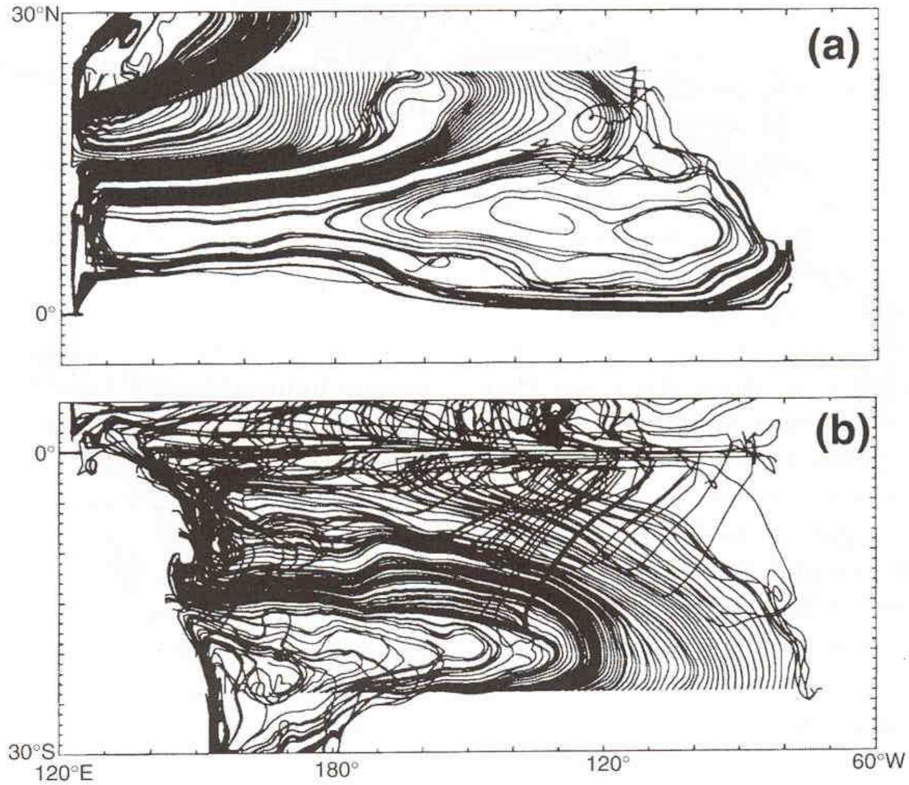
CFC subduction rates (≈drifters...) (O'Connor, Fine et al 2002)

Tritium: shows spreading toward equator, like salinity but with age information.

CFC: quantitative estimates of ventilation at each density range.

Shallow cell and decadal variability of ENSO: observations of advective teleconnection

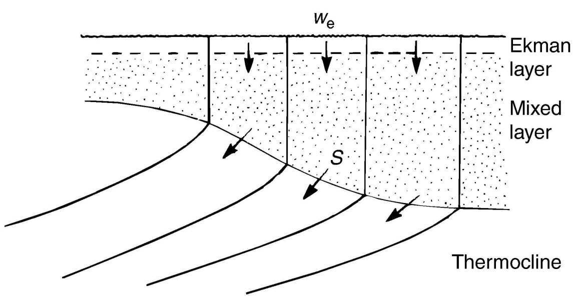
Salinity Tritium/ CFC **Model particle trajectories**



Particle trajectories from model simulations (Liu & Huang 98; velocity field from Ji et al 95)

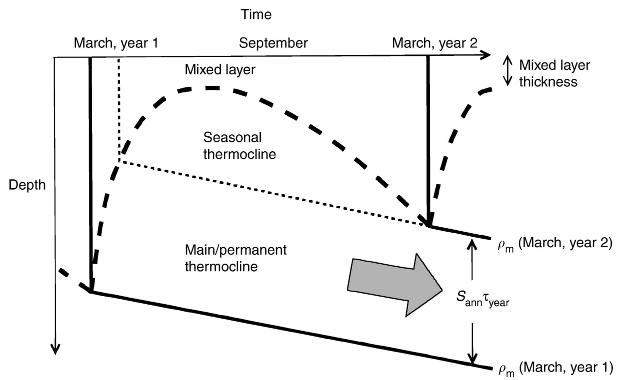
Also: The intermediate cell plays a role in the advective tropical-mid latitude teleconnection by renewing the sub-thermocline equatorial water, and from there diffusing into the thermocline depth range.

Shallow cell subduction: physical processes

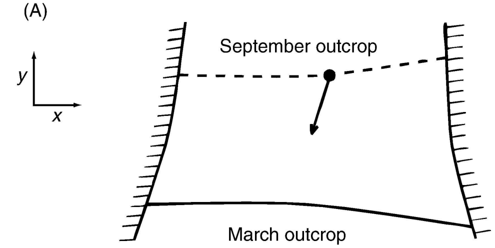


Subduction into the thermocline via mean gyre flow (Marshall 93)

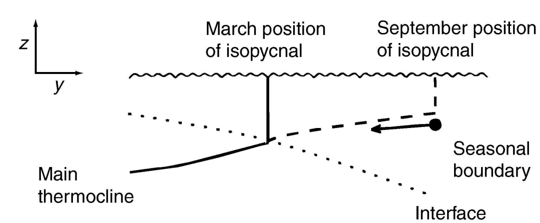
(R.G. Williams 2001) ⟶

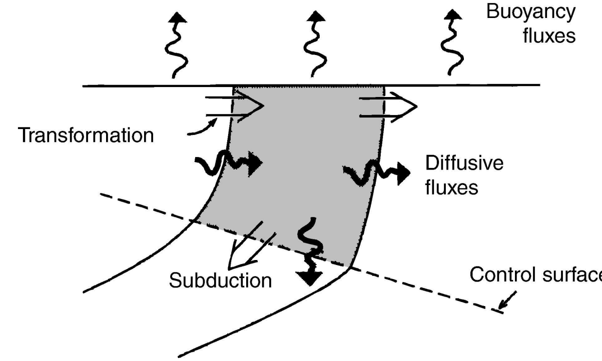


(A)

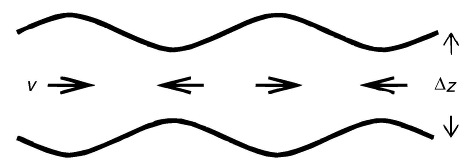


(B)





(A)



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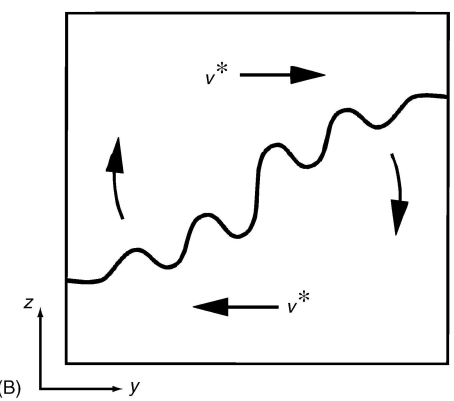
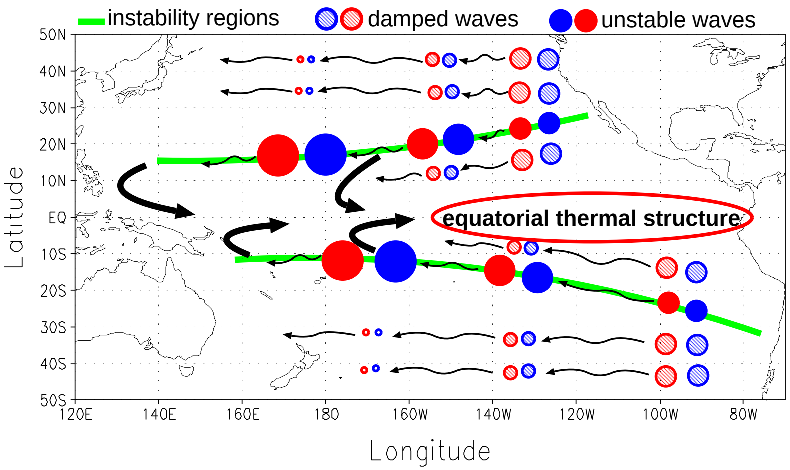


Role of seasonal cycle in subduction process

Eddy transport & bolus velocity

Synthesis of WOCE data & theory: mid-latitude to ENSO teleconnection & decadal ENSO variability

Two options for a teleconnection between fast tropics and slow mid-latitudes:



Teleconnection via baroclinically unstable Rossby waves

Data: WOCE repeat hydrography data (Roemmich et al 2001) possibly a wave propagation/ instability signal

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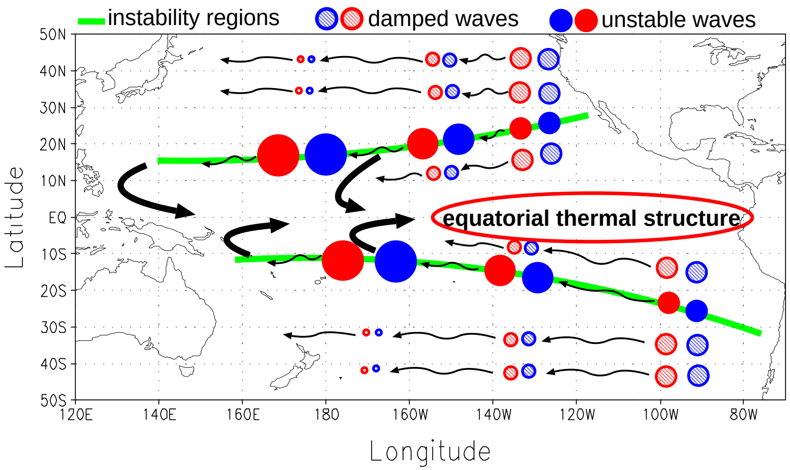

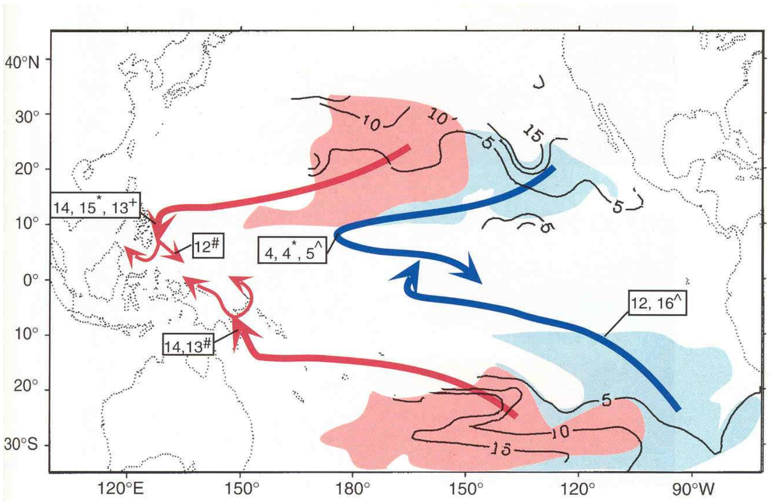

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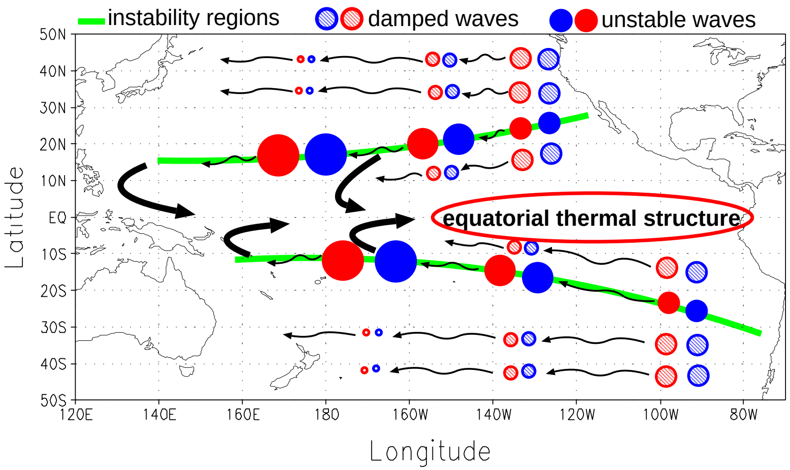

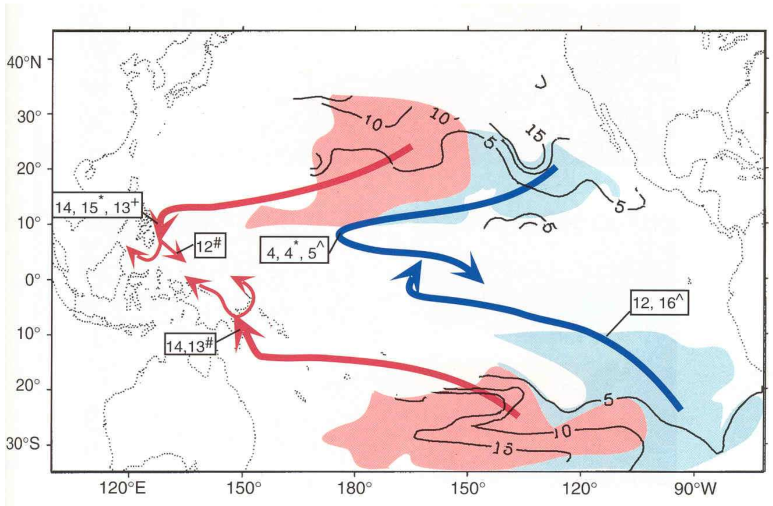

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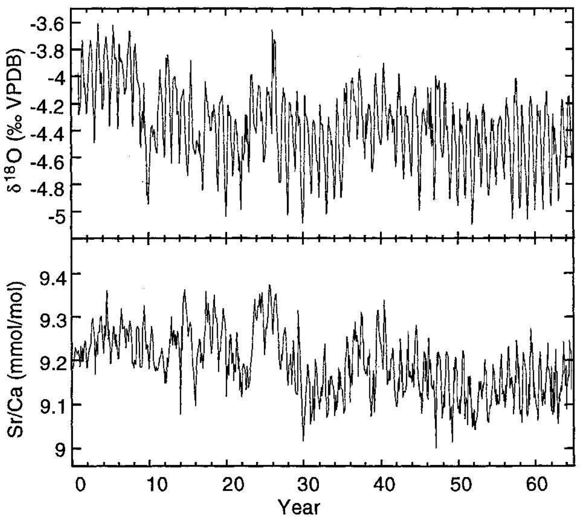
What's a good dynamicist to do when there is plenty of data supporting one hypothesis: believe the less well supported one and hope for more data...

(In the presence of eddies, advection/ waves distinction is less clear anyway...)

More on what the shallow water mass formation cell can do to El Nino

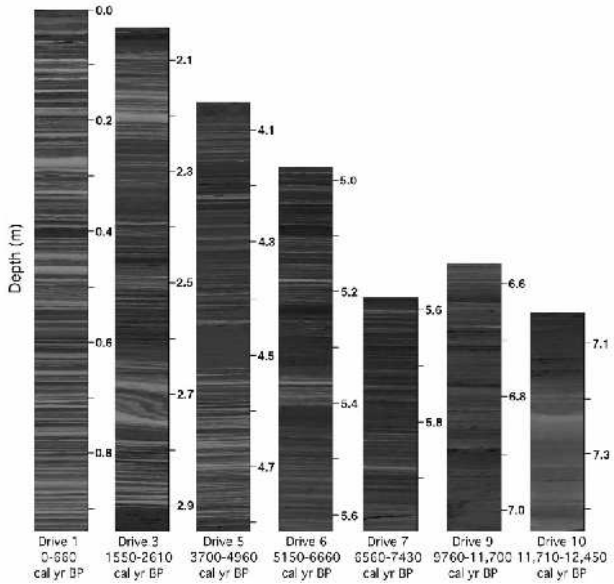
- Paleo ENSO perspective: changes possibly due to different of basic stratification/ shallow cell



Coral $\delta^{18}O$ isotopes, Indonesia

Double period ($\sim$15 years) & weaker amplitude some 7,000-15,000 years ago $\longrightarrow$

$\longleftarrow$ Same period 120,000 years ago



Gray bands in lake sediments, Ecuador

- Also, ENSO can be either self-sustained or damped, & may have shifted between the two regimes in the past few decades

Shallow cell and El Nino: additional observations?

- ENSO's dynamics strongly depends on the strength of the ocean-atm coupling.
  - Coupling strength depends on latent heat response to SST anomalies
  - $\Rightarrow$ We need to know the latent heat flux response to SST anomalies, not just its climatological value. Presently not well known/ parameterized:
    - Differences between NCEP and COADS as large as 20 W/m2. http://puddle.mit.edu/~detlef/OSE/GODAE_WS/node3.html (Stammer, Fukumori, Wunsch)
    - In warm ENSO events, a 1C SST anomaly $\rightarrow$ 2.5 mm/day rain; diabatic atmospheric latent heating of over 70, yet NCEP reanalyzes gives only 50. http://www.cgd.ucar.edu/cas/papers/jgr2001a/jgr_interann.html (Trenberth, Stepaniak, Caron)
- Also, quantitative observations of the role of eddies in the ocean-teleconnection to equator...

Conclusions

- Stability of meridional overturning circulation in the Atlantic Ocean:
  - A hierarchy of models of indicates that a somewhat weaker overturning circulation may lead to a climate instability
  - However, major discrepancies between water mass formation & transformation (mean, variability, physical processes) in models & obs, put the above results in question
  - Need obs of the response of fresh water fluxes to changes in SST/ ocean circulation
- ENSO and the shallow cell in the equatorial Pacific:
  - A teleconnection between the equator and mid-latitudes may be either via waves or long-isopycnal advection.
  - Need obs of the response of latent heat fluxes to SST anomalies, poorly known & controlling ocean-atm coupling
- Bottom line: would be useful to go beyond climatological fluxes; need information on the response of fluxes to climate/ SST perturbations.