OCEANS

MAINLY THE MOC

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Noble Lectures, Toronto 2019

http://tiny.cc/Vallis

General Outline

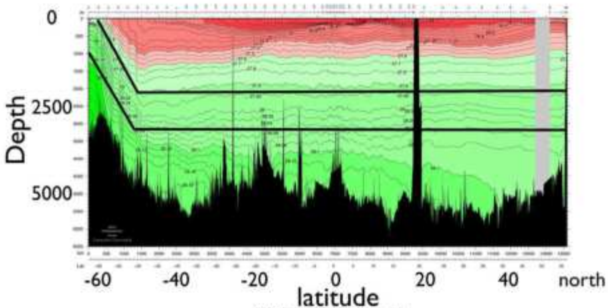
Today

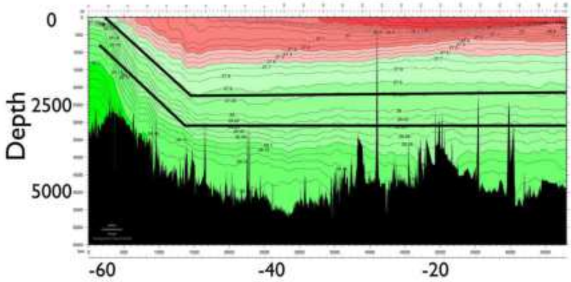
- Winds vs diffusion
- Single Basin MOC
- Dual Basin MOC

Tomorrow — Preliminary, Speculative, add more caveats here …

- Carbon Cycle and Ice Ages
- The Madden–Julian Oscillation.

Ocean Stratification (density), Pacific, 150° W





(Unequal contours)

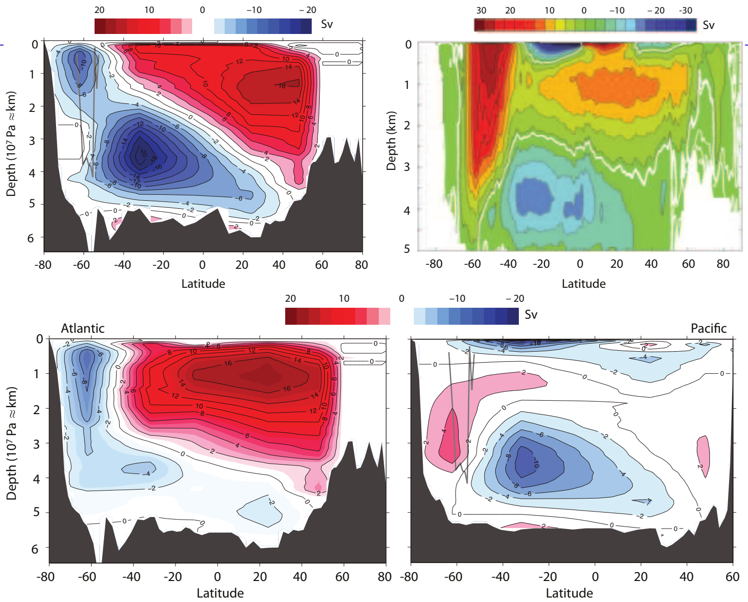
The MOC (Meridional Overturning Circulation

Global Residual

Global Eulerian

Atlantic residual

Pacific residual



The Deacon Cell in the ACC is analogous to the Ferrel Cell — transport quite different if eddies are included (residual vs Eulerian).

Residuals: Loic Joillon after Lumpkin and Speer (2007). Eulerian: ECCO, courtesy P. Heimbach.

Atmospheric Stratification

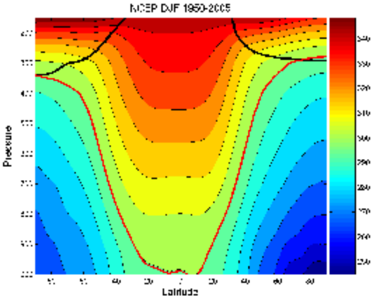
The atmosphere is heated from below and cooled from above. So the forcing itself has a tendency towards being statically unstable.

The level of stratification might be maintained by:

1. Vertical convection, moist or dry. Moves energy and moisture up.
2. Baroclinic instability. Moves energy upwards and sideways.   or

No shortage of ideas for maintaining stratification in the atmosphere!

Atmospheric Temperature

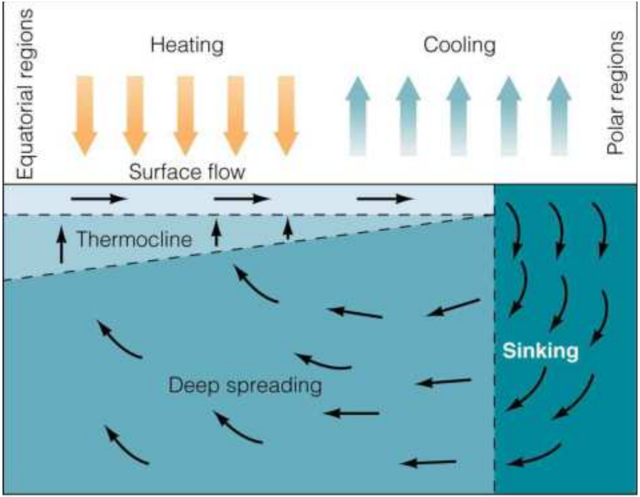


The Ocean

But the ocean is heated *and* cooled from above. In the absence of winds and mixing there will be no deep stratification (Sandström).

The Old Idea: A Mixing Driven Circulation

Robinson and Stommel (1959); Stommel and Arons (1960); Munk (66)



Upwelling diffusive balance:

$$w\frac{\partial T}{\partial z} = \kappa\frac{\partial^2 T}{\partial z^2}.$$

- *But*, the diffusivity needed to produce the observed circulation is too high.
- Needed value: $\kappa \approx 10^{-4}\ \mathrm{m^2\ s^{-1}}$ Observed value (turbulent diffusivity) in main thermocline: $\kappa \approx 10^{-5}\ \mathrm{m^2\ s^{-1}}$
- Values in abyss and in coastal regions is higher, but still insufficient.

The so-called 'missing mixing' problem.

Horizontal Convection

Fluid heated and cooled from above

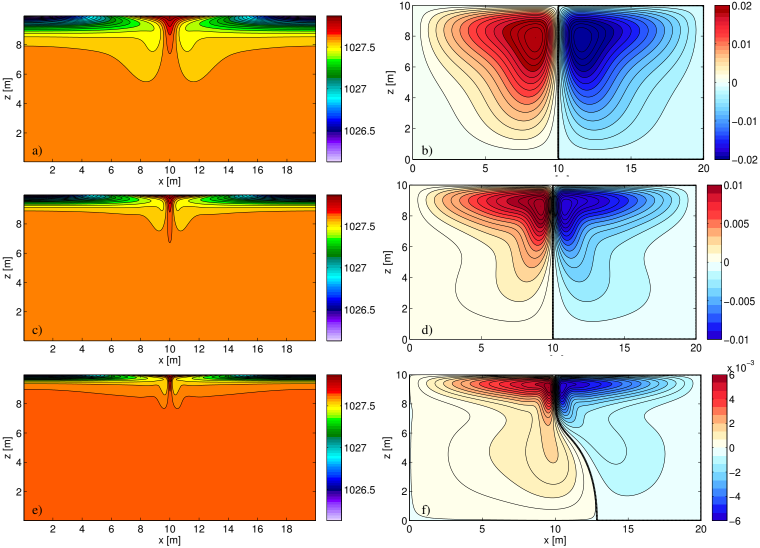
(Ilicak and Vallis, 2013)

Temperature

Streamfunction

hot cold hot

hot cold hot



$$Ra = (\Delta b L^3 / \nu\kappa)$$
$$= 10^6$$

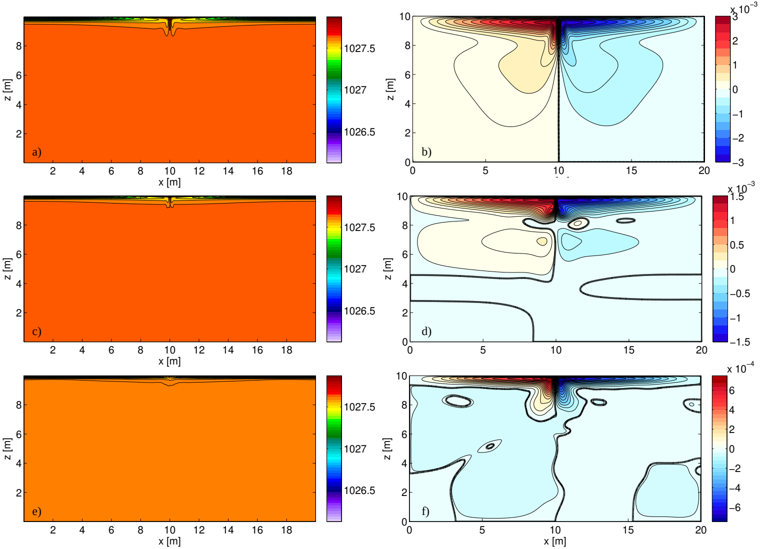
$$Ra = 10^7$$

$$Ra = 10^8$$

HORIZONTAL CONVECTION WITH STILL HIGHER RAYLEIGH NUMBER.

Temperature — Streamfunction

hot cold hot — hot cold hot



$Ra = 10^9$

$Ra = 10^{10}$

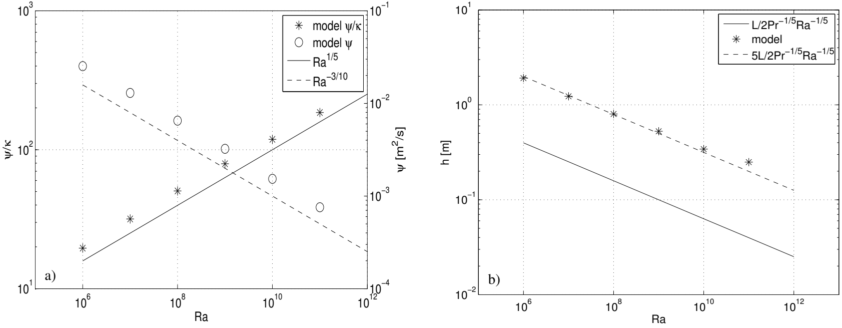
$Ra = 10^{11}$

For real ocean:

$Ra \approx 10^{30}$.

Scalings
(T. Rossby, 1965)

$$\Psi = Ra^{1/5}\sigma^{-4/5}\nu = (\kappa^3 L^3 \Delta b)^{1/5} \qquad H = L\sigma^{-1/5}Ra^{-1/5} = \left(\frac{\kappa^2 L^2}{\Delta b}\right)^{1/5}$$



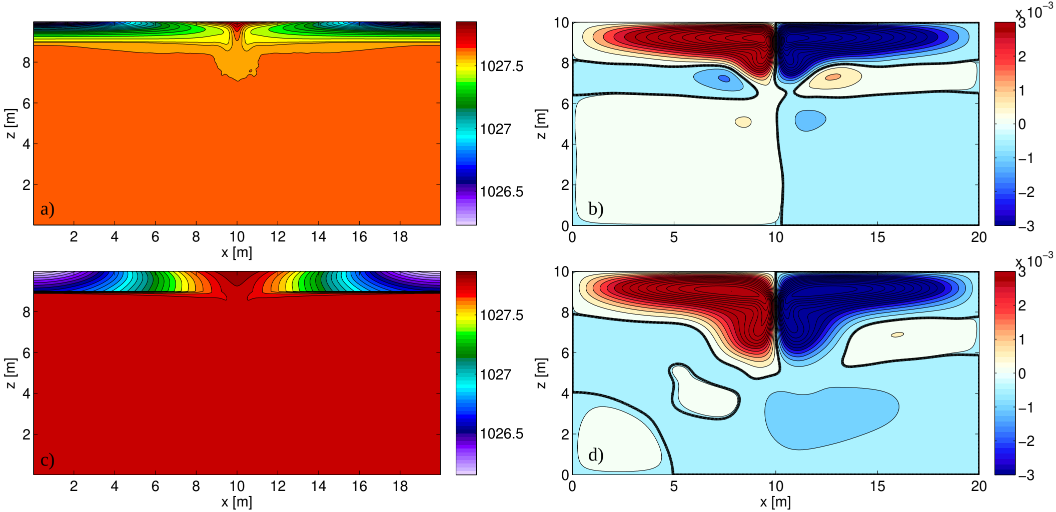
With rotation: $H = \left(\frac{\kappa f L^2}{\Delta b}\right)^{1/3}$

For realistic (molecular) oceanic parameters: $H \sim 10\,\mathrm{m}$!

Enhanced diffusion in upper ocean — a mixed layer

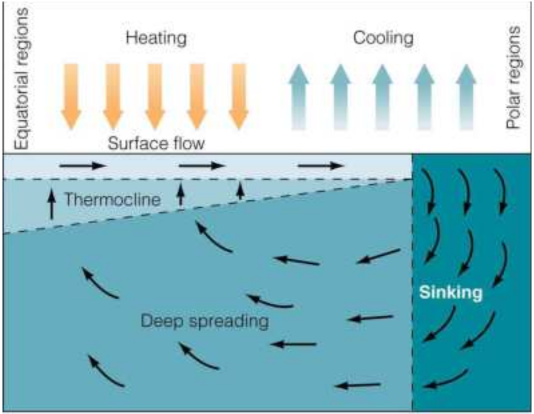
Beef up the Surface Fluxes

Surface fluxes are large, but still no deep stratification.



The Old Idea: A Mixing Driven Ocean Circulation

Robinson and Stommel (diffusive thermocline, 1959); Munk (abyssal recipes, 66).



NB Molecular $\kappa = 10^{-7}\ \mathrm{m^2\,s^{-1}}$.
Need a wind to create an eddy diffusivity, but that is still too small.

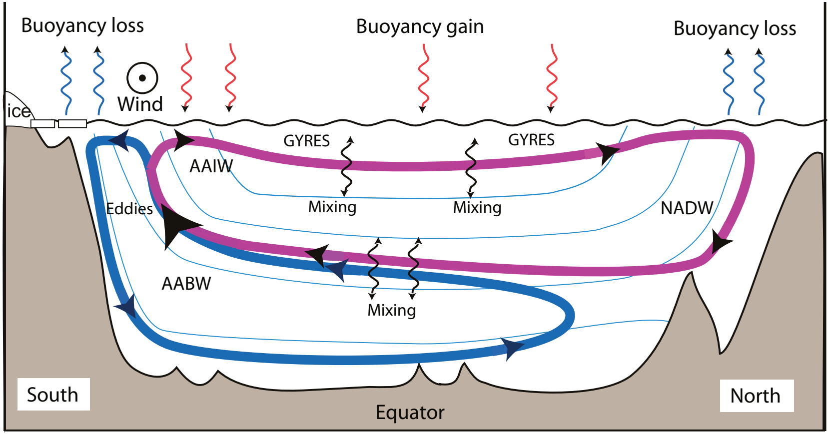
Upwelling diffusive balance:

$$w\frac{\partial T}{\partial z} = \kappa\frac{\partial^2 T}{\partial z^2}.$$

- *But*, the diffusivity needed to produce the observed circulation is too high.
- Needed value: $\kappa \approx 10^{-4}\ \mathrm{m^2\,s^{-1}}$
  Observed value in main thermocline: $\kappa \approx 10^{-5}\ \mathrm{m^2\,s^{-1}}$
- Values in abyss and in coastal regions may be much higher, but may be insufficient because abyssal stratification is small.

The so-called 'missing mixing' problem.

The New(ish) Idea: Interhemispheric Circulation

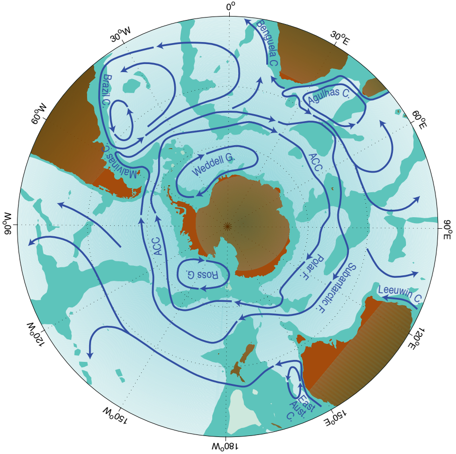


(from Vallis, 2017 adapted from Watson, Vallis, Nikurashin, 2015)

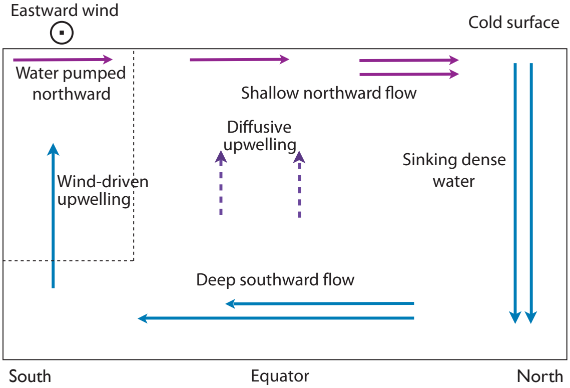
c.f., Toggweiler & Samuels, Doos and Webb, Gnanadesikan, Samelson, Wolfe and Cessi, others.

Interhemispheric Circulation

Plan View: ACC is re-entrant

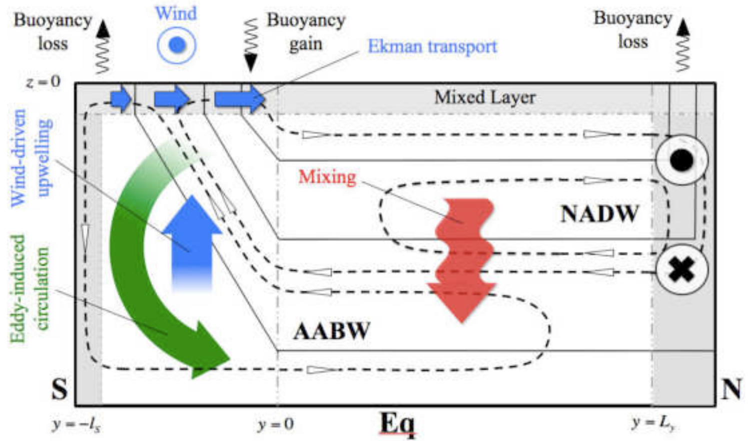


Elevation:



S. Rintoul

Interhemispheric Theory



Circumpolar Current region: wind-driven upwelling balanced by eddy-induced circulation

Ocean interior: downward mixing of buoyancy balanced by upward vertical advection

North Atlantic high latitudes: convection due to buoyancy loss

Match solutions in three regions so solutions are smooth.

Nikurashin and Vallis (2013)

Features of the Solution
(slightly simplified)

1. A wind-driven component:

$$f v \sim \frac{\partial \tau}{\partial z} \implies \psi_W \sim \frac{\tau_0}{f} \quad \text{or} \quad V_d \sim \frac{\tau_0 L}{f}$$

   ψ is streamfunction, V_d is volumetric transport ($\mathrm{m^3\,s^{-1}}$)

2. A diffusive component:

$$w \frac{\partial b}{\partial z} = \kappa \frac{\partial^2 b}{\partial z^2} \implies \psi_d \sim \frac{\kappa L}{h} \quad \text{or} \quad V_d \sim \left(\frac{\kappa^2 \Delta b L^4}{f}\right)^{1/3}$$

   b is buoyancy ('temperature'). Needs algebra as vertical scale is not known a priori.

Ratio:

$$\mathcal{R} = \left(\frac{\kappa^2 \Delta b f^2 L}{\tau_0^3}\right)^{1/3}$$

What wins — diffusion or wind? ($64,000).

And what, exactly *is* diffusion? Molecular? Turbulent diffusion? Is κ even well defined?

Features of the Solution

(For the professionals)

With parameterized mesoscale eddies...

Let $y = \ell \widehat{y}$, $z = h\widehat{z}$, $\psi = \widehat{\psi}\, \tau_0 / f_0$, etc.

Buoyancy evolution:	$\partial_y \widehat{\psi} + \widehat{s}_\rho \partial_z \widehat{\psi} = -\epsilon \left(\frac{\ell}{L}\right) \frac{\partial_{zz} \widehat{b}}{\partial_z \widehat{b}},$
Momentum balance:	$\widehat{\psi} = -\frac{\widehat{\tau}}{\widehat{f}} + \Lambda \widehat{s}_\rho,$
Boundary condition:	$\widehat{\psi}\big\|_{y=0} = -\epsilon \frac{\partial_{zz} \widehat{b}}{\partial_z \widehat{b}},$

where

$$\boxed{\Lambda = \frac{\text{Eddies}}{\text{Wind}} = \frac{K_e}{\tau_0 / f_0} \frac{h}{\ell} \sim 1} \quad \text{and} \quad \boxed{\epsilon = \frac{\text{Mixing}}{\text{Wind}} = \frac{\kappa_v}{\tau_0 / f_0} \frac{L}{h} \sim 0.1 - 1,}$$

The parameter h is a characteristic depth of the stratification, and will be a part of the solution.

Scaling

Weak diffusiveness

$$\epsilon \ll 1, \qquad \Lambda = 1, \qquad \text{and} \qquad \frac{\ell}{L} \ll 1$$

$$\boxed{h = \frac{\tau_0/f_0}{K_e}\ell, \qquad \Psi = \kappa_v \frac{K_e}{\tau_0/f_0}\frac{L}{\ell}}.$$

Depth of stratification is determined by wind and eddies only. Circulation is weak, and goes to zero with the diffusivity.

Strong diffusiveness

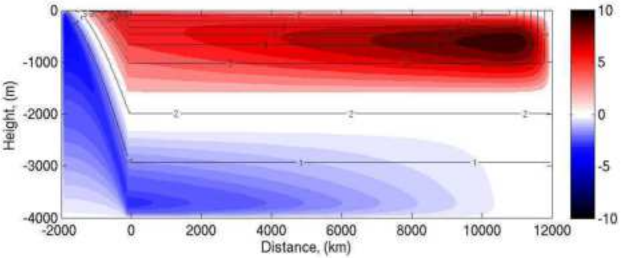
$$\epsilon \gg 1, \qquad \Lambda = \epsilon, \qquad \text{and} \qquad \frac{\ell}{L} \ll 1$$

$$h = \sqrt{\frac{\kappa_v}{K_e} L\ell}, \qquad \Psi = \sqrt{\kappa_v K_e \frac{L}{\ell}}$$

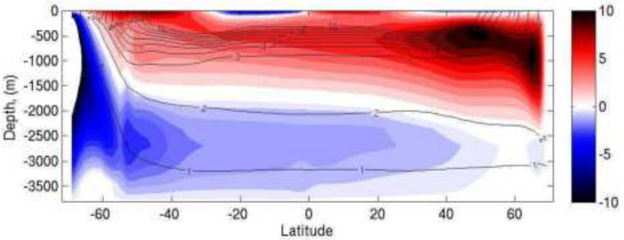
Depth of stratification is determined by diffusion and eddies. Circulation is stronger, goes as half power of diffusivity.

Results
Single Hemisphere

Theory:
Temperature (lines) and overturning circulation (Sv, colour).



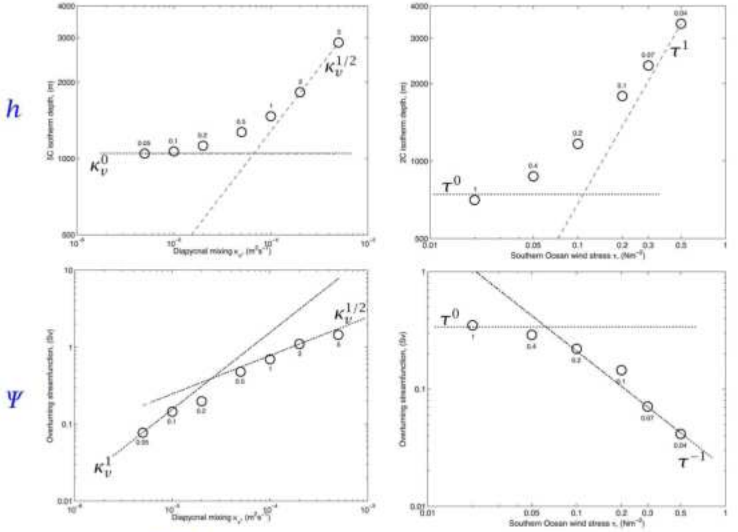
GCM simulation: (MOM)



Test of Scaling with GCM, Single Hemisphere

$$h = \begin{cases} \dfrac{\tau/f_0}{K_e}\,\ell \\[2em] \sqrt{\dfrac{\kappa_v}{K_e} L \ell} \end{cases}$$

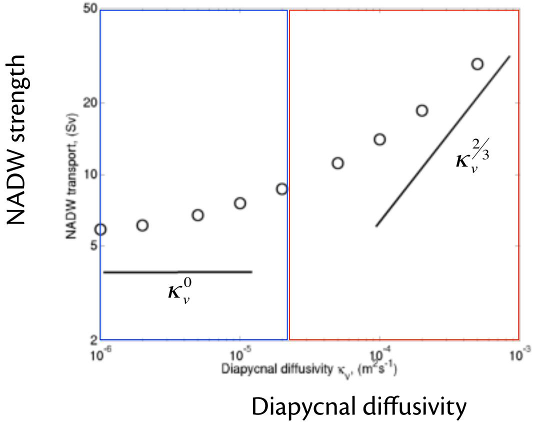
$$\Psi = \begin{cases} \kappa_v \dfrac{K_e}{\tau/f_0}\,\dfrac{L}{\ell} \\[2em] \sqrt{\kappa_v K_e \dfrac{L}{\ell}} \end{cases}$$

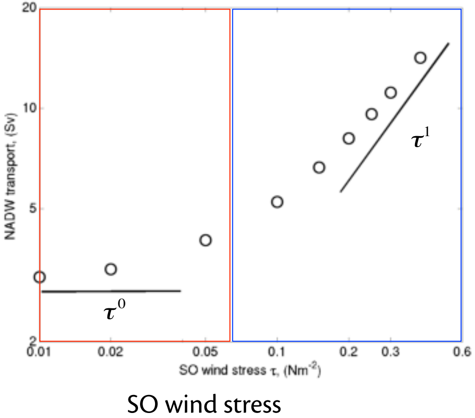


Diffusivity

Wind stress

Scaling Tests, Two Hemispheres





Note: NADW strength stays non-zero even as diffusivity goes to zero.

Conclusions so far...

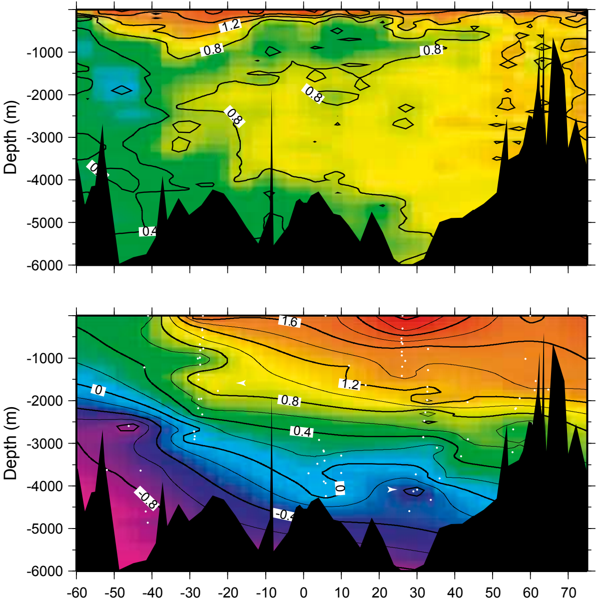
- Developed a conceptual model for deep stratification and overturning circulation.
  - Quantifies and extends various previous models.
  - Differs in fundamental ways from classical ideas of Stommel–Arons and Munk.
  - Deep circulation and stratification remains in the limit of zero diapycnal diffusivity.

Glacial and Modern Circulations

δ^{13}C in the Western Atlantic.

Modern

Glacial



Shoaling (thinning) of NADW to about 1,500 m. Expansion of AABW.

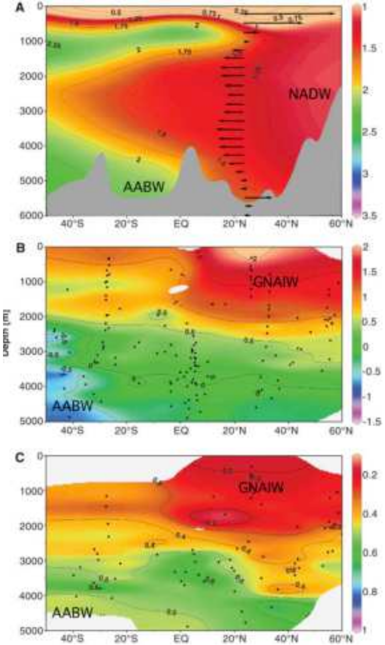
Curry and Oppo (2005) as reproduced by Ferrari et al (2014)

Glacial and Modern Circulations

Modern
Dissolved Phosphate

Glacial
δ^{13}C

Glacial
Cd (nmol/kg) in LGM



Shoaling (thinning) of NADW to about 1,500 m.

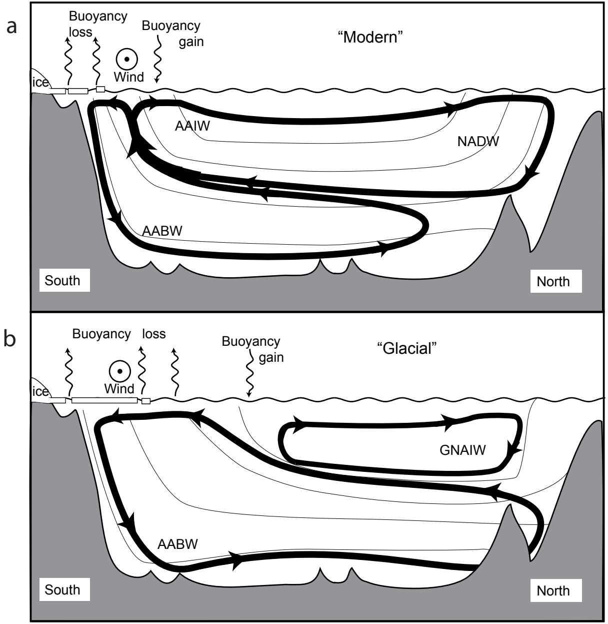
Expansion of AABW.

Stieglitz et al (2007)

Glacial and Modern Circulations

Modern

Glacial

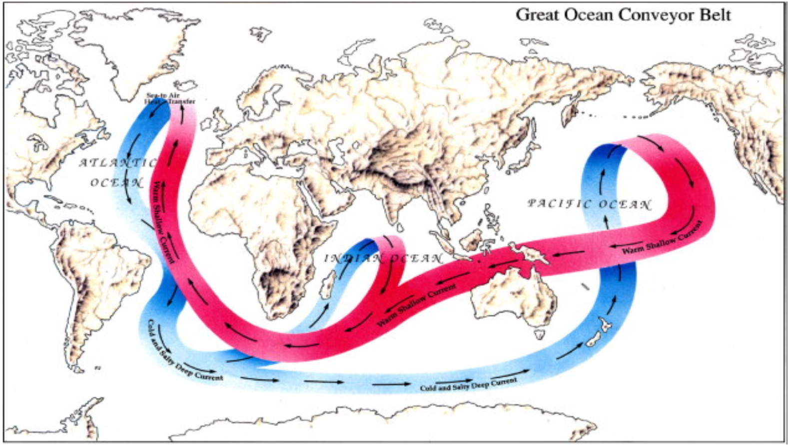


Watson, Vallis, Nikurashin (2014)

show movie!

Uh oh! — We've forgotten the Pacific!

The famous 'conveyor belt'



The original …

Wally Broecker
Arnold Gordon

Much maligned,
fairly and unfairly…

We have no complete theory for this.
(But see Thomson & Stewart, Ferrari and colleagues, Jansen and Nadeau …)

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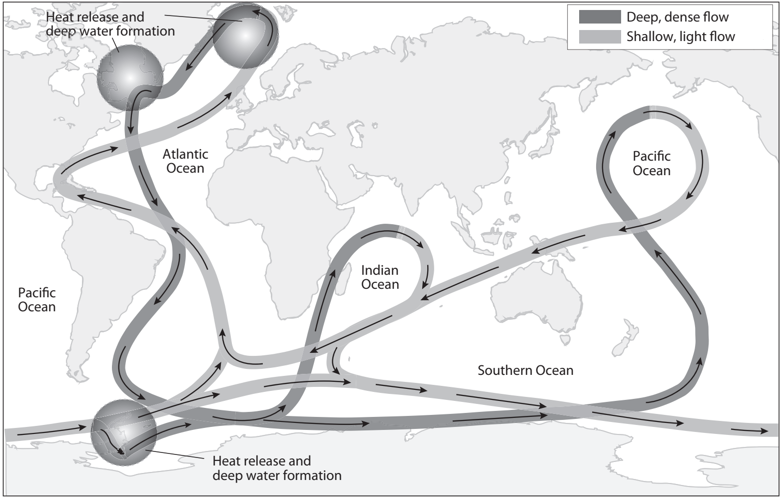

Artists impression...

Arnold Gordon

Wally Broecker

Much maligned,

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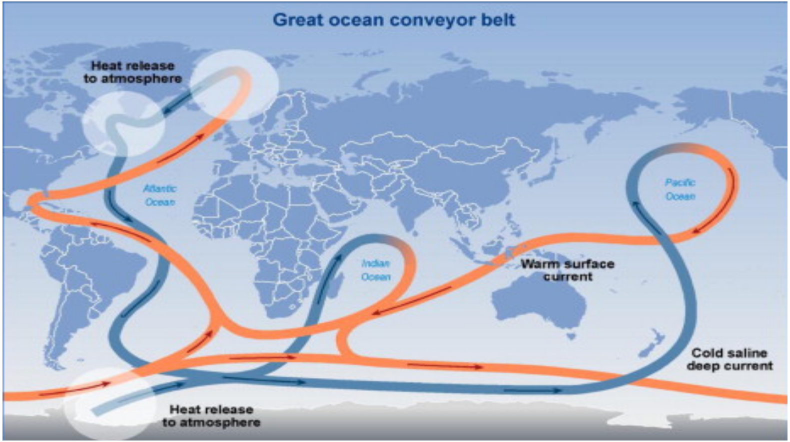

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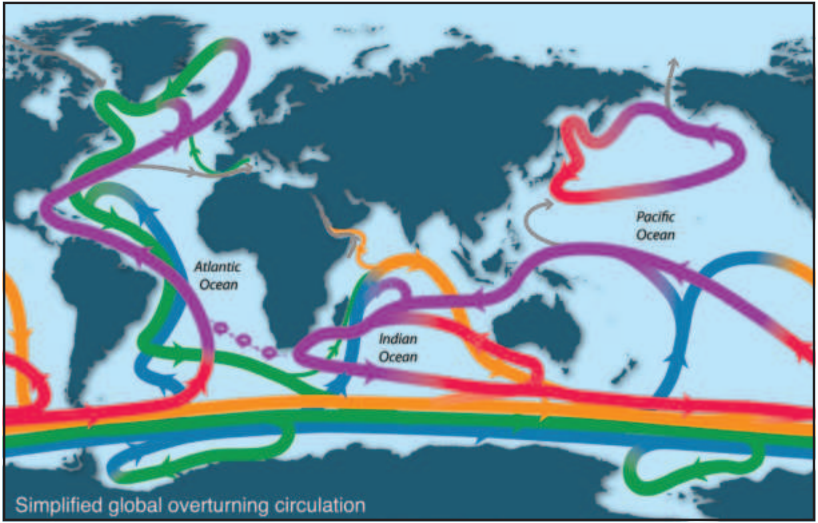
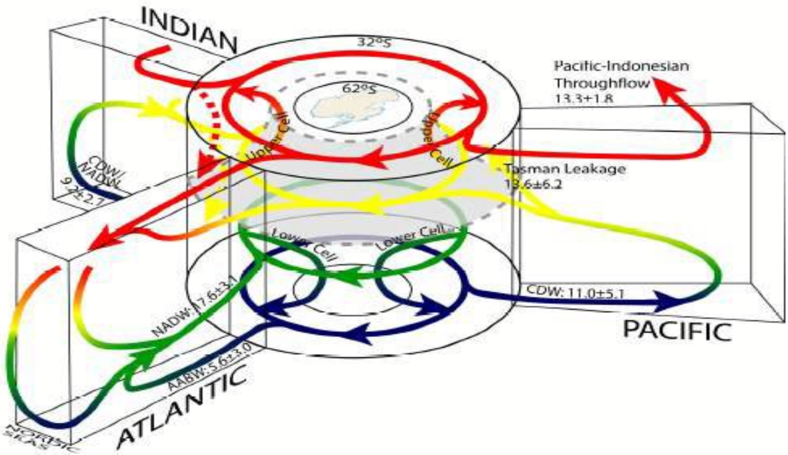


Talley, Lumpkin Speer, Schmitz

Uh oh! — We've forgotten the Pacific!

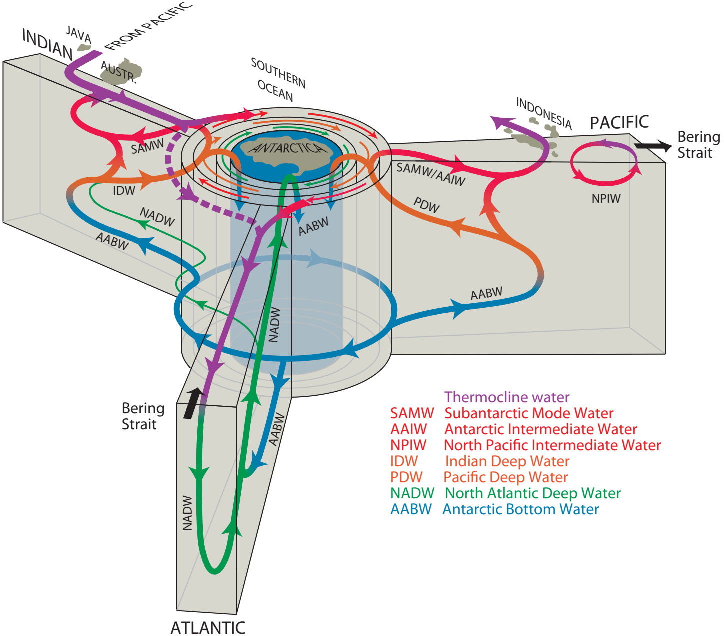
The famous 'conveyor belt'



Rich Lumpkin
Kevin Speer

Uh oh! — We've forgotten the Pacific!

The famous 'conveyor belt'



L. Talley

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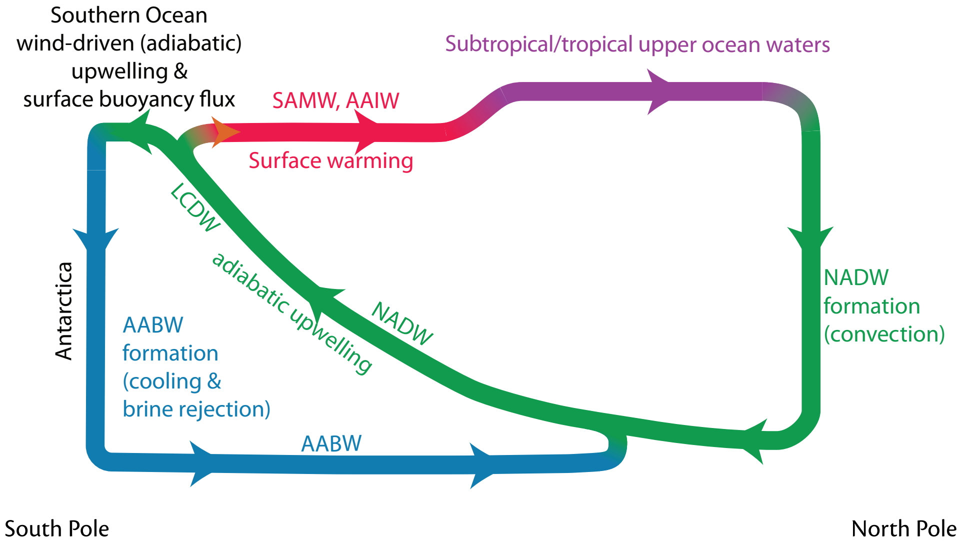

Atlantic only
from L. Talley

Uh oh! — We've forgotten the Pacific!

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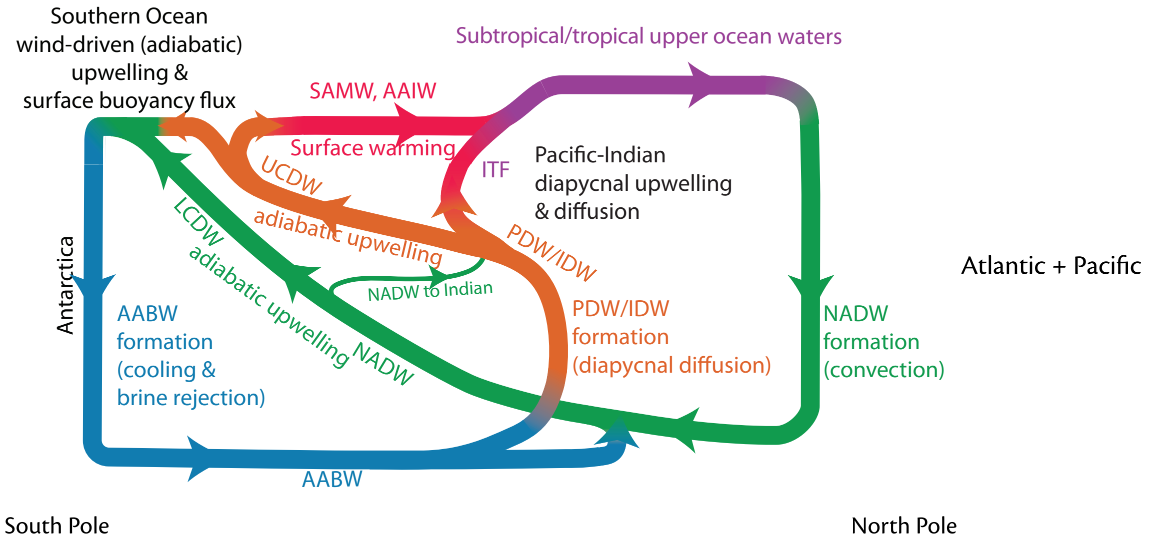
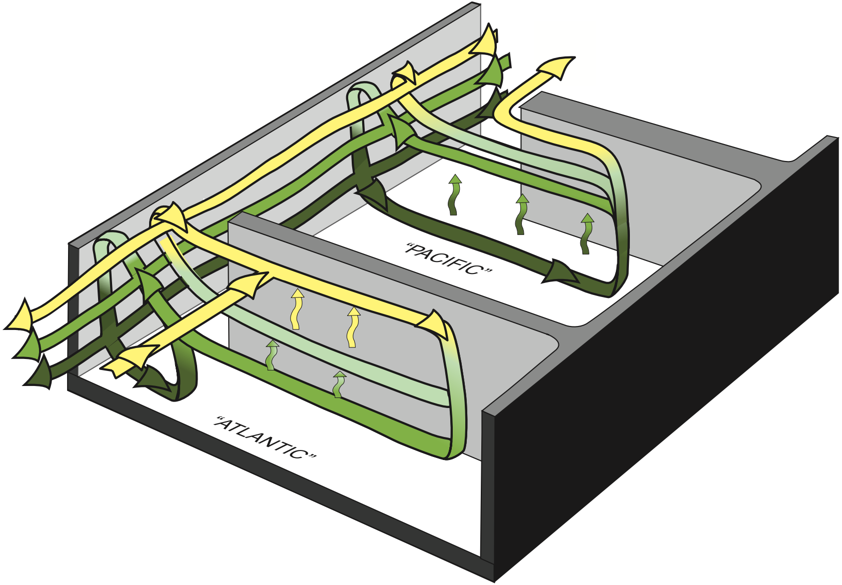


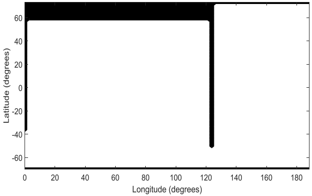
Two Basin Simulations
w/Jon Baker and Andrew Watson



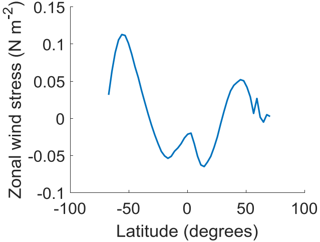
Baker, Watson, Vallis

Experiments with an OGCM

Model Set-up



(c)



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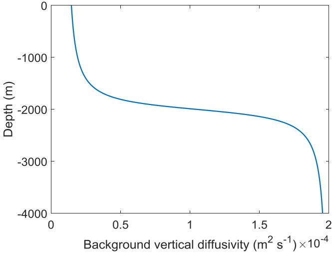
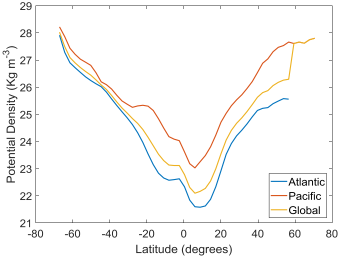
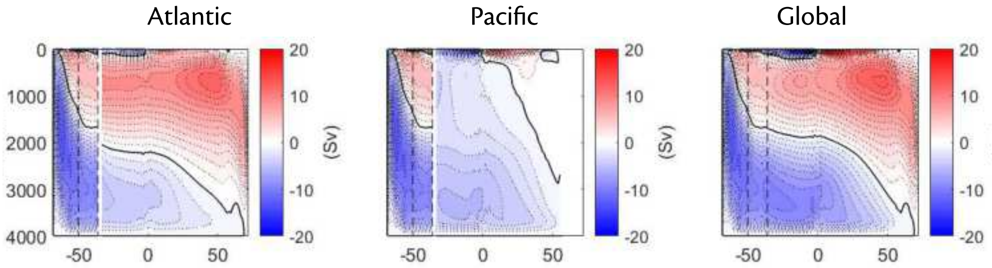




MIT GCM

Experiments with an OGCM
MOC

A control simulation



Change the Climate

(i) Mimic a glacial climate by changing the melting temperature of ice. (Convenience!)

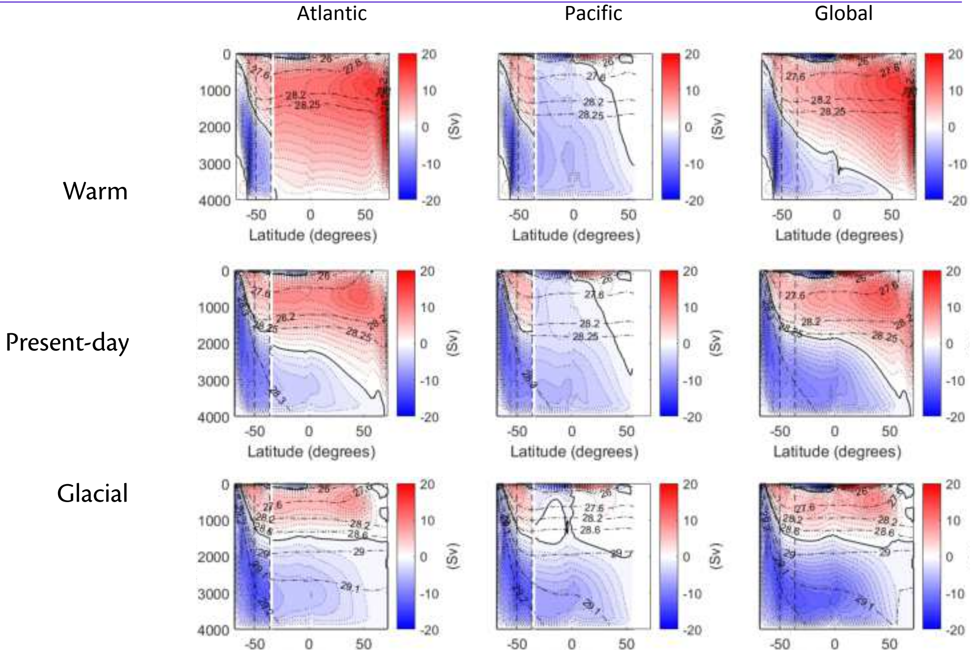
(ii) Lower the freezing point, less ice, like a warmer climate.

(iii) Raise freeing point, more ice, glacial climate.

- Thereby increase buoyancy loss in Southern Ocean, partly through brine rejection.
- Less effect in Northern Hemisphere.

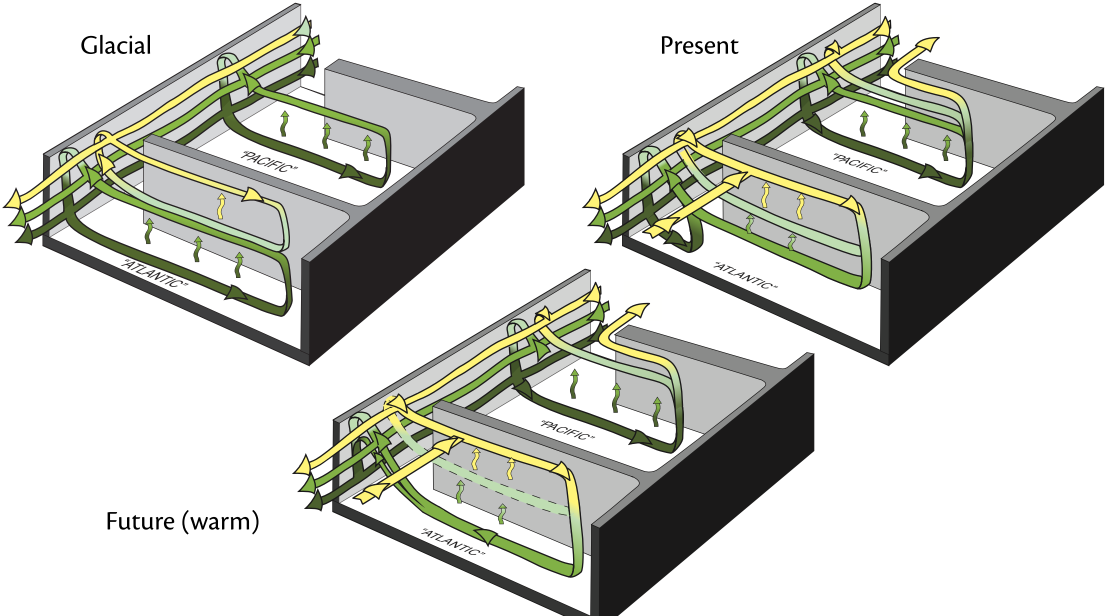
Experiments with an OGCM

Change the Southern Ocean Buoyancy Forcing



Past, Present and Future

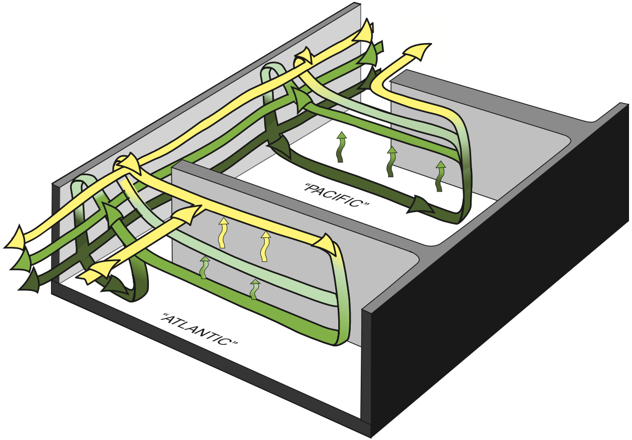
Change the Buoyancy Forcing in the South



Pathways and Mechanisms

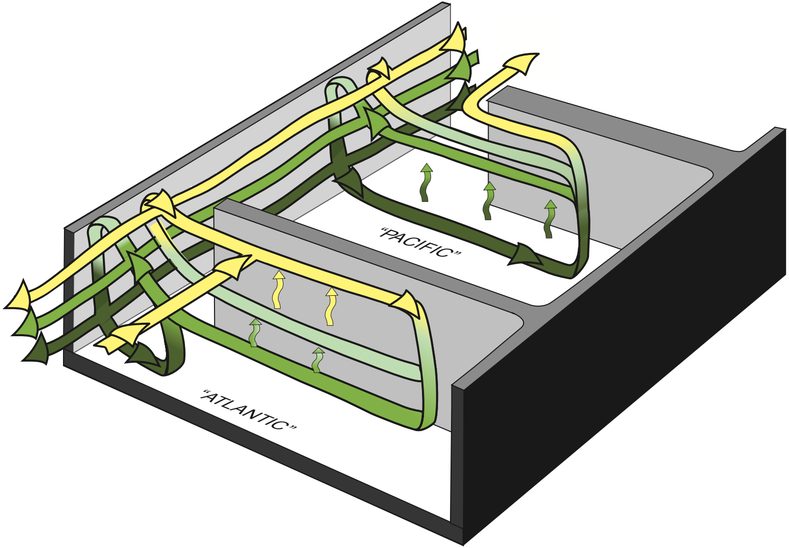
Present-day

1. NADW, as before.
   - a Wind-driven upwelling in Southern, southward drift, sinking.
   - b Sinking and return as AABW and as upper branch of NADW.
2. Some deep water advected into Pacific.
3. Diffusively upwells in Pacific
4. NADW driven by:
   - *(i)* Southern Ocean winds,
   - *(ii)* Diffusive upwelling in Pacific. (cf Ferrari et al., Jansen and Nadeau)



Present

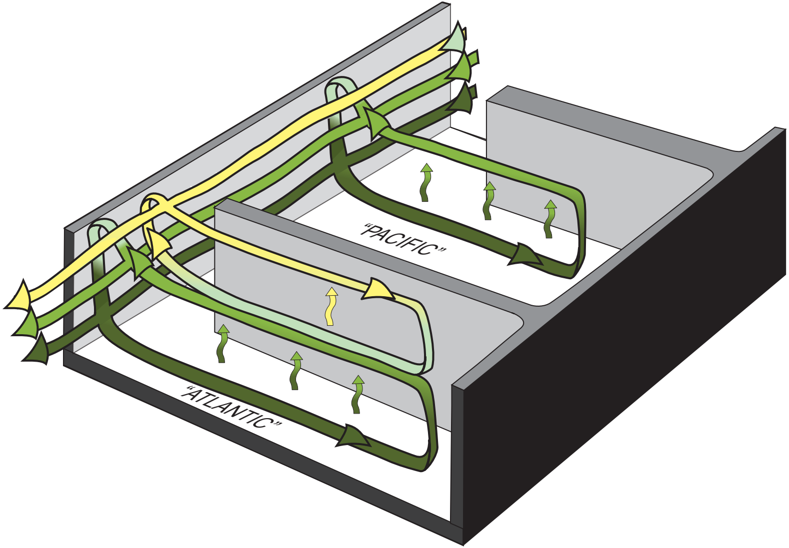
Change the Buoyancy Forcing in the South



- Lower NADW partially advected into Pacific and upwells.
- NADW driven by Southern ocean winds and (in part) diffusion.

Cold Past

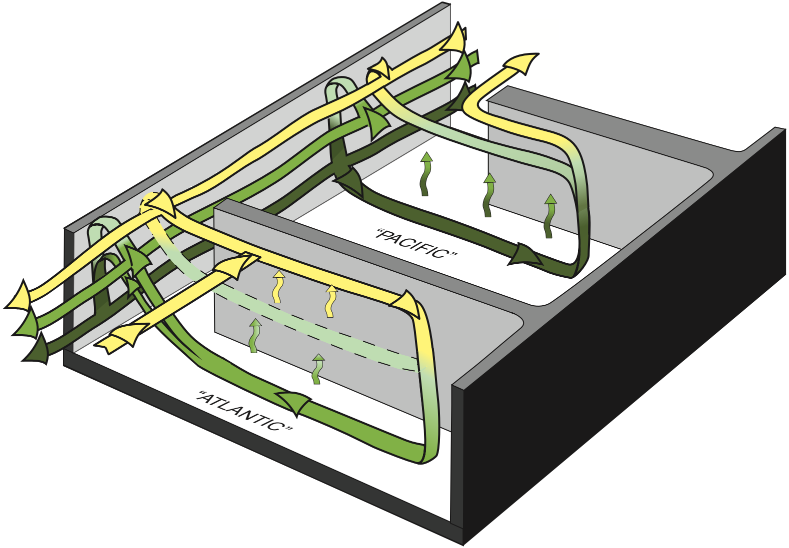
Change the Buoyancy Forcing in the South



- More buoyancy loss in Southern Ocean.
- Bottom (AABW) cell expands in Atlantic.
- NADW cell cannot link to bottom cell, and does not connect to lower Pacific Cell.
- Two basins essentially separate.
- NADW is primarily wind-driven, and diffusive upwelling in Pacific less important.

Warm future

Change the Buoyancy Forcing in the South



- Less buoyancy loss in Southern Ocean.
- Southern surface water too warm to form AABW cell in Atlantic.
- But not too warm to form an 'AABW' cell in the Pacific.
- NADW is diffusively and (in part) wind-driven.

Past, Present and Future

Cold Climate

- More buoyancy loss in Southern Ocean. Larger AABW cell.
- Atlantic becomes decoupled from Pacific.
- NADW wind-driven

Today's Climate

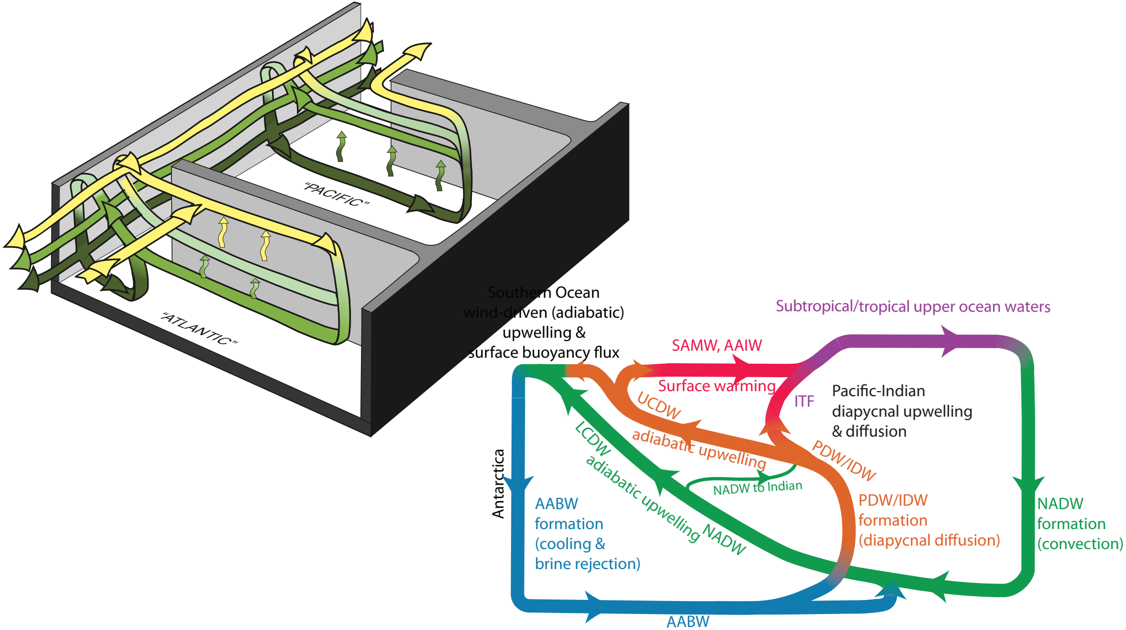
- Large NADW Cell.
- Small AABW Cell in Atlantic, larger in Pacific.
- NADW wind driven and (in part) diffusively driven.

Warm Climate

- Little buoyancy loss in Southern Ocean.
- AABW shrinks.
- NADW deepens. Diffusively and wind driven.

Comparison

Model and Observations Consistent for Present Day Circulation



So What Does it Mean

1. Adding a Pacific and Indian Ocean changes pathways (obviously!).
2. But the main buoyancy drivings of the Atlantic Circulation remain as before, with single basin.
   - Jansen and Nadeau find global average circulation similar to Atlantic only – pers. comm.
3. Buoyancy loss in Southern Ocean leads to growth of bottom cell (as in single basin).
4. Implications (speculations?) for carbon cycle...

Oceans

Carbon

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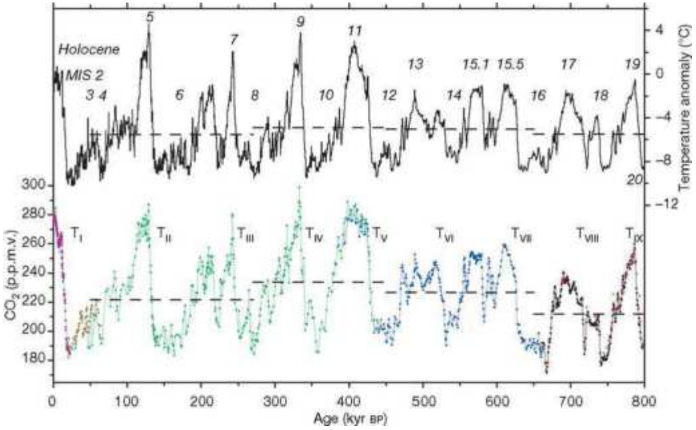
Noble Lectures, Toronto 2019

http://tiny.cc/Vallis

Temperature and CO_2

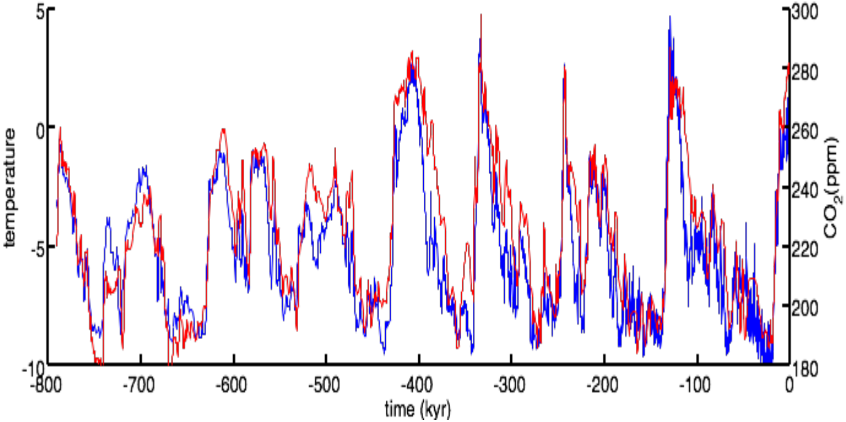


- Temperature is reconstructed by proxy:
  Isotopic fractions of $^{18}\delta O$ and deuterium (^{2}H) in snowfall are temperature-dependent.
- CO_2 lags temperature, especially during the cooling phase.
- CO_2 at LGM about 190 ppm, a major contributor to cool glacial climate.

From DOME (Antarctica). Luthi et al (2008).

Temperature and CO_2

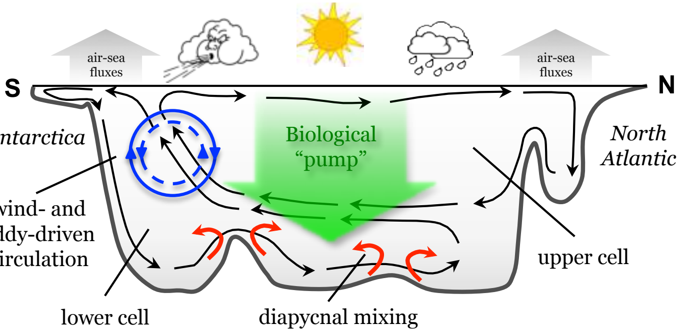
From EPICA (European Project for Ice Coring in Antarctica) www.climatedatainfo



Temperature blue, CO_2 red

CO_2 lags temperature, especially during the cooling phase.

Carbon Cycle and Ocean Circulation



Reference?

- High surface carbon levels in equatorial regions.
  - (a) Carbon flux into atmosphere.
  - (b) Carbon sinking in biological pump.
- 'Remineralization' at depth
- Advection and upwelling into Southern Ocean.
- Low surface carbon levels at higher latitudes.
  - (a) Carbon flux from atmosphere.
  - (b) Transport into abyssal ocean.

- In glacial climate more drawdown in Southern Ocean.
- More carbon transport and sequestration in deep ocean.
- Atmospheric CO_2 levels lower.

The Biological Pump

Biological production removes carbon from surface waters to form organic material. As organisms die and sink to the ocean interior, they decompose, releasing the carbon once again to the water, where it may be advected back to the surface.

Photosynthesis in upper ocean takes up carbon:

$$\boxed{H_2O + CO_2 + Nutrients \Longrightarrow CH_2O + O_2}$$

Needs light, and in reality more complicated. Nutrients are phosphates, nitrates, iron, silica

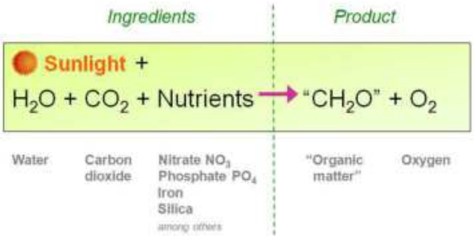
Organic matter sinks, and decomposes and respires (remineraliation):

$$\boxed{CH_2O + O_2 + Nutrients \Longrightarrow H_2O + CO_2}$$

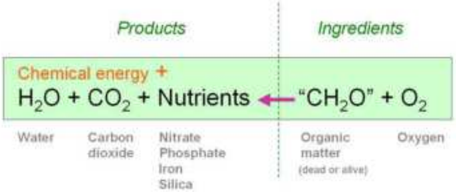
Carbon then advected back to the upper ocean by the circulation.

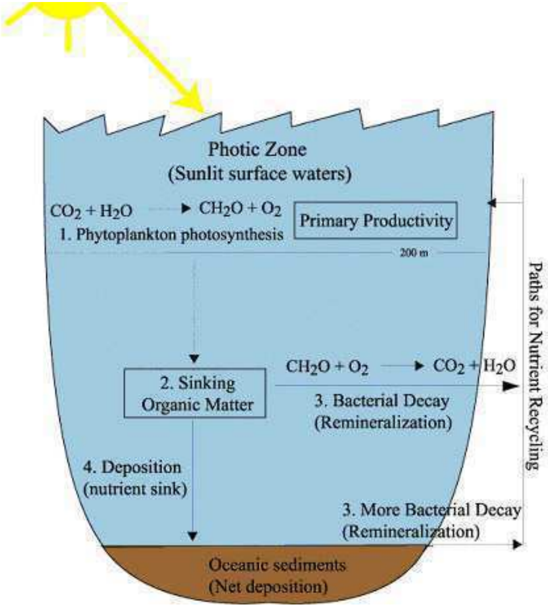
The Biological Pump

Photosynthesis



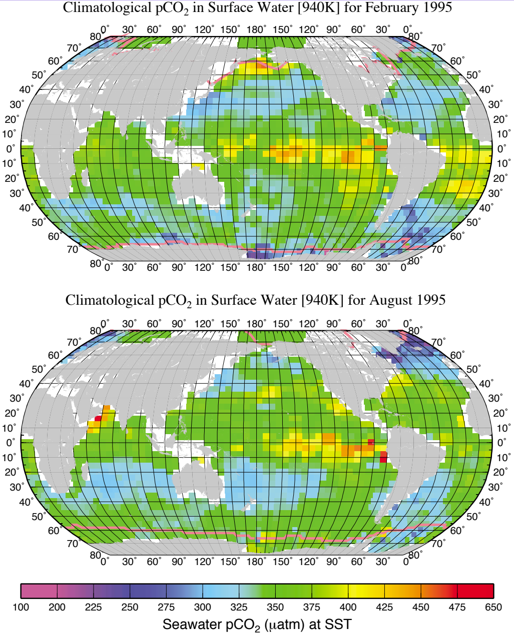
Decomposition (and respiration)





Surface Carbon (PCO_2)

Takahashi et al 2002



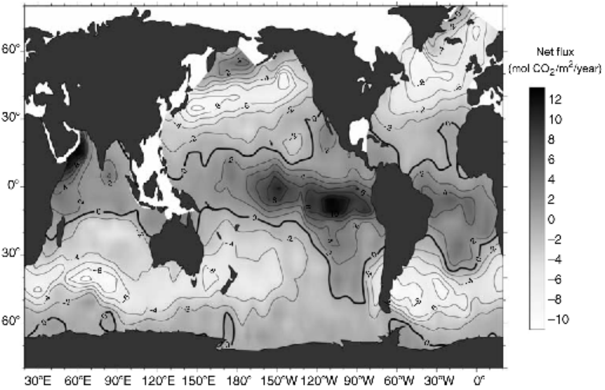
High values (red) in equatorial Pacific — flux to the atmosphere

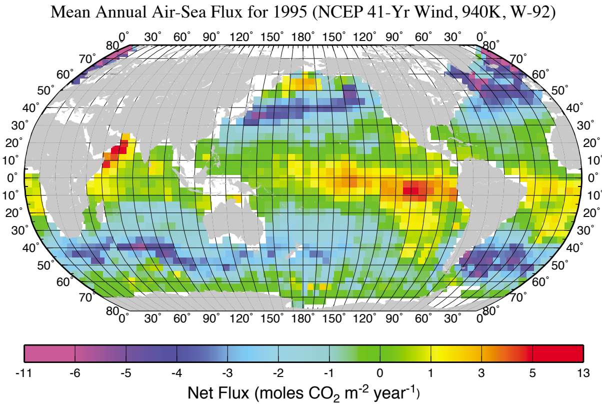
Low values (green → blue → purple) — flux to ocean.

Atmosphere-Ocean Carbon Fluxes

From ocean to atmosphere at low latitudes (dark or red shading).

From atmosphere to ocean at high latitudes (light or blue shading).





Sabine and Feely (2007), Takahashi et al (2002).

Simplified Carbon in the SAMBUCA Model

after Ito and Follows (2005).

Dissolved Inorganic Carbon (C) and Phosphate (P) only. Advected, diffused, and sedimented.

Phosphate:

$$\frac{\mathrm{D}P}{\mathrm{D}t} = \kappa \frac{\partial^2 P}{\partial z^2} + \frac{\partial}{\partial z} F_{\mathrm{bio}}$$

Carbon:

$$\frac{\mathrm{D}C}{\mathrm{D}t} = \kappa \frac{\partial^2 C}{\partial z^2} + R_{ed} \frac{\partial}{\partial z} F_{\mathrm{bio}}$$

F_{bio} is the downward flux of sinking organic material due to biological flux and remineralization. We take:

$$F_{\mathrm{bio}} = -C_P \exp(-z/H_{\mathrm{bio}}).$$

where C_P is proportional to phosphate content: $C_P = P \Delta z_1 / \tau_{\mathrm{bio}}$.

Model Results for 'Atlantic' and 'Pacific'

Sambuca

Atlantic | Pacific

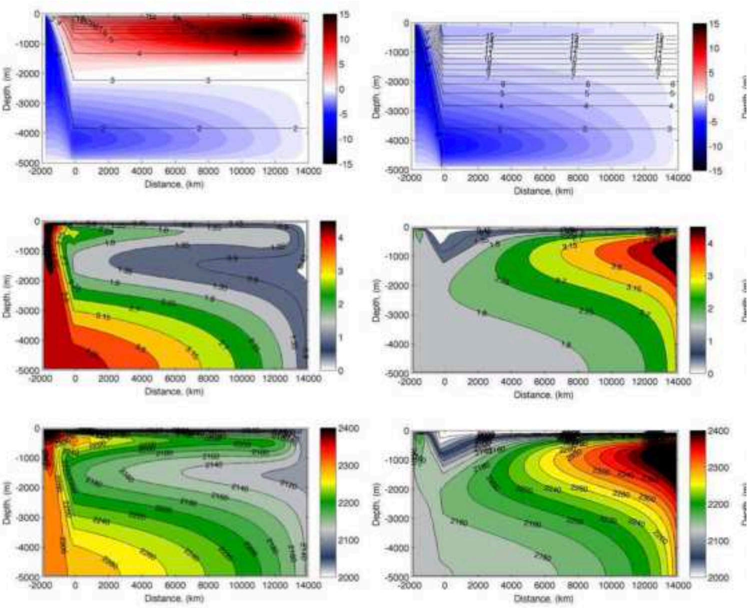
Circulation

Phosphate

Carbon

gray is low

red is high



Observations for Atlantic and Pacific

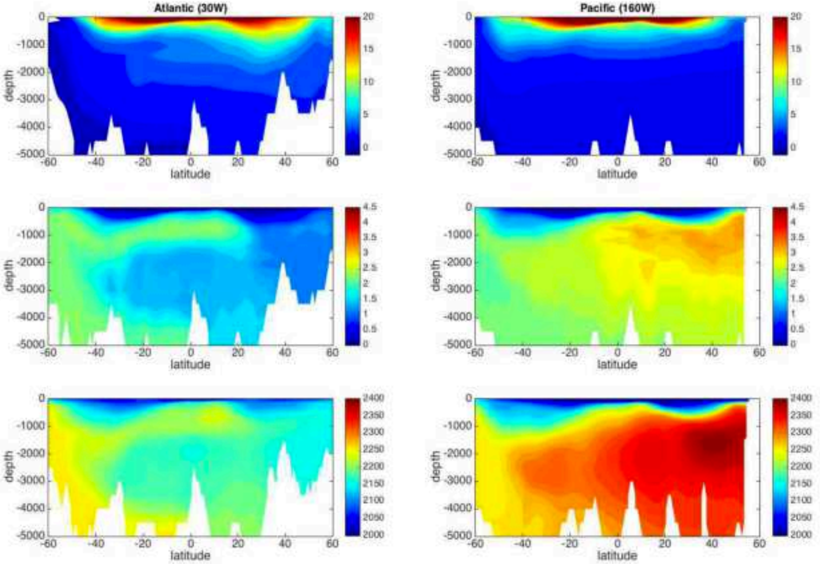
Temperature

Phosphate

Carbon

blue is low

red is high



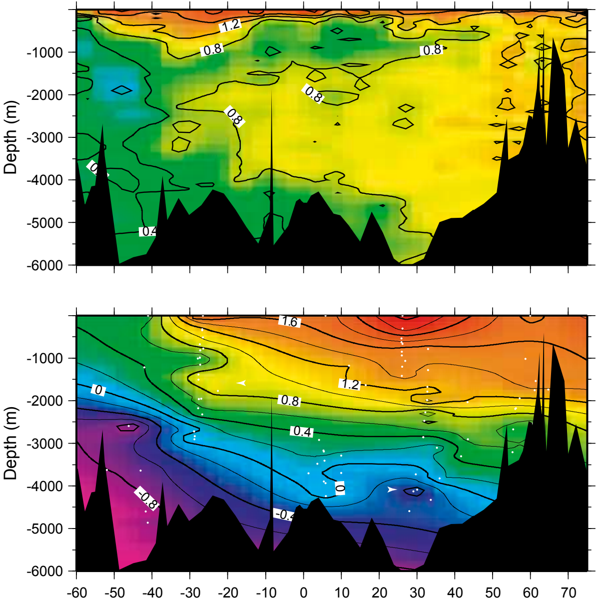
5 World Ocean Atlas (Garcia et al 2010); GLODAP (Key et al 2004).

Glacial and Modern Circulations

δ^{13}C in the Western Atlantic.

Modern

Glacial



Shoaling (thinning) of NADW to about 1,500 m. Expansion of AABW.

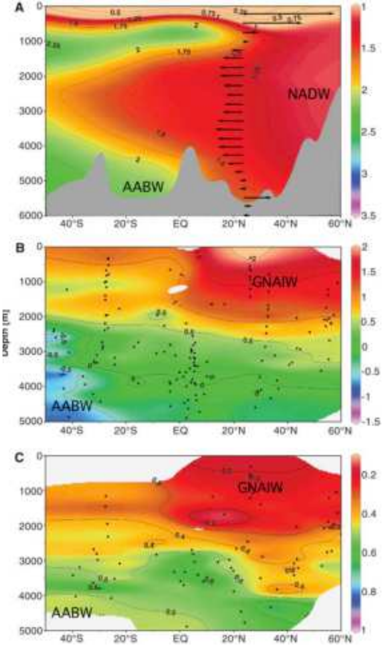
Curry and Oppo (2005) as reproduced by Ferrari et al (2014)

Glacial and Modern Circulations

Modern
Dissolved Phosphate

Glacial
$\delta^{13}C$

Glacial
Cd (nmol/kg) in LGM



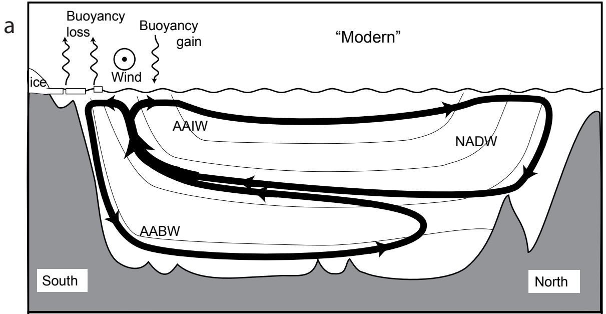
Shoaling (thinning) of NADW to about 1,500 m.

Expansion of AABW.

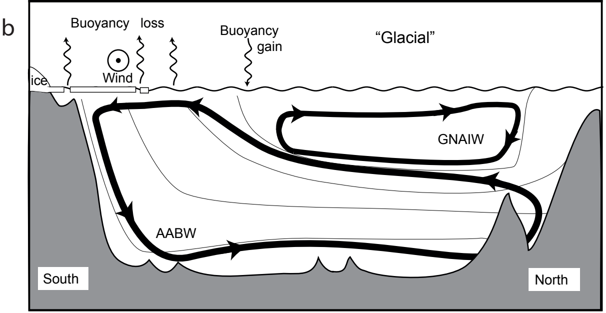
Stieglitz et al (2007)

Glacial and Modern Circulations

Modern



Glacial

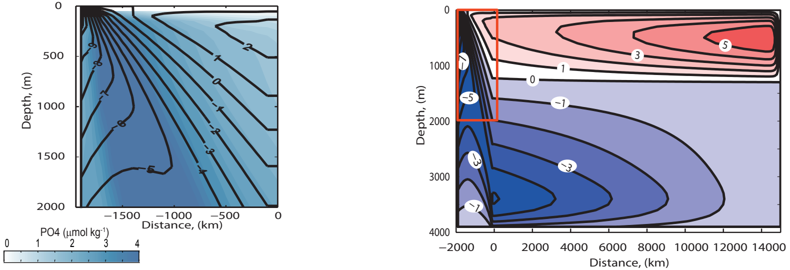


Watson, Vallis, Nikurashin (2014)

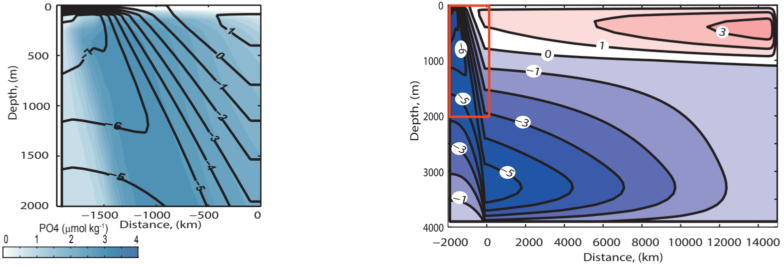
show movie!

RESULTS

a) “Modern”

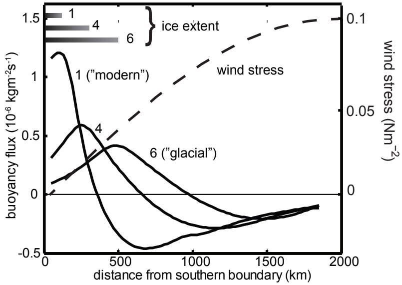


b) “Glacial”

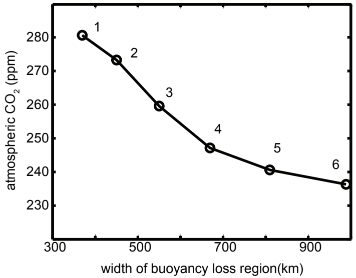


Results

Buoyancy forcing



Atmospheric CO_2



What's going on?

- Upwelling is moved north and there is a greater reach of the southwards flowing surface water.
- Longer residence time of surface water in Southern Ocean.
- More time for biota to remove carbon.
- Carbon levels in surface water is reduced, drawing more down from atmosphere.
- This carbon is then sequestered in the abyss.
- Is not returned by the circulation.

Conclusions and Speculations

A re-arrangement of the ocean circulation in glacial times draws down CO_2. We are suggesting a mechanism.

- Model produces plausible distributions of carbon for present day Atlantic and Pacific.
- A mechanism for the carbon dioxide draw-down in glacial periods and close correlation of temperature and CO_2:
  - Enhanced bottom cell.
  - Longer residence time at surface gives time for biota to photo-synthesize, and draw-down carbon.‘
  - Lower atmospheric CO_2.
- Results are reproduced by a full OGCM with carbon cycle— stay tuned…