Ocean Circulation and Climate

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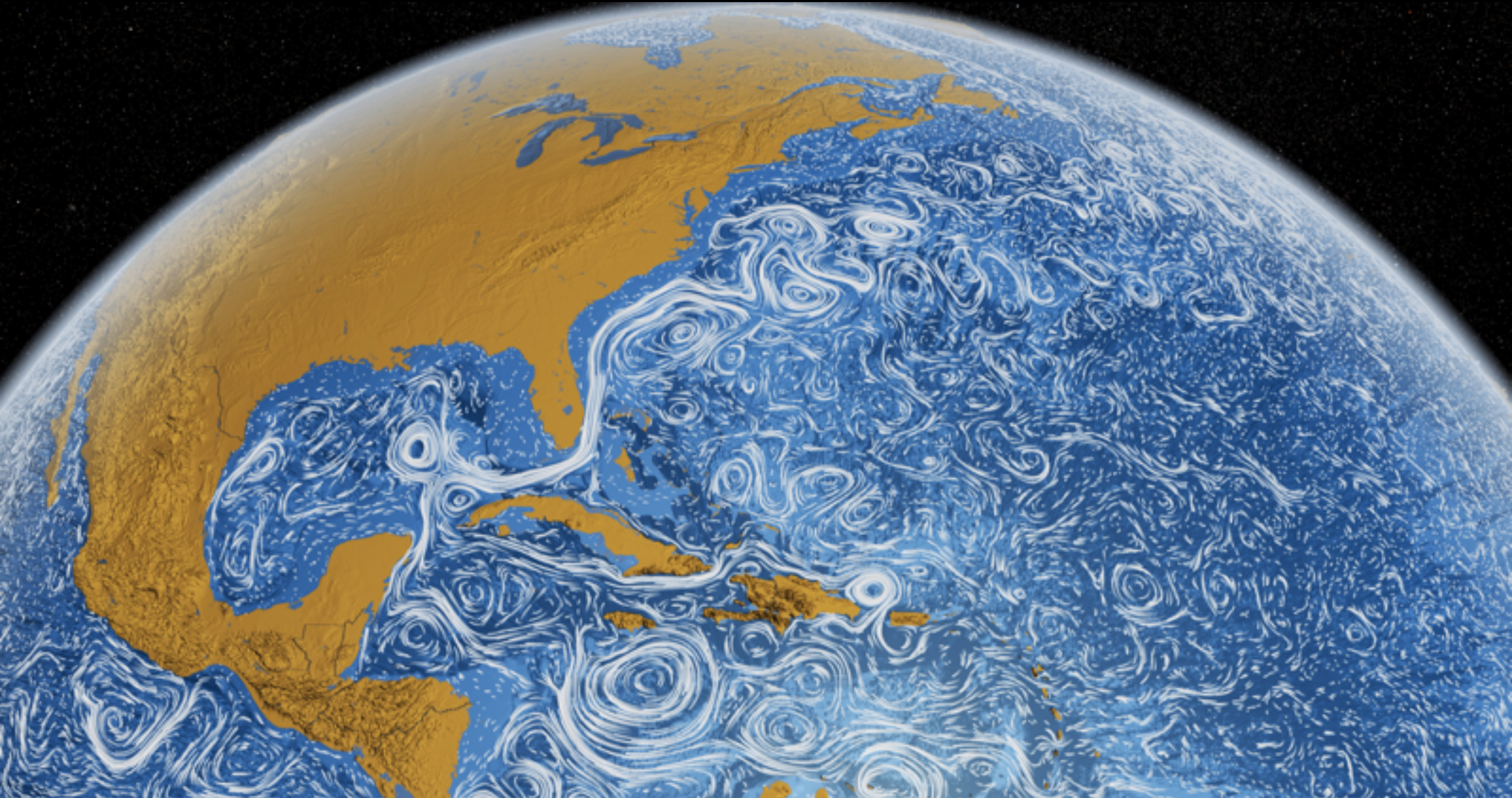
Les Houches, March 2-6 2015



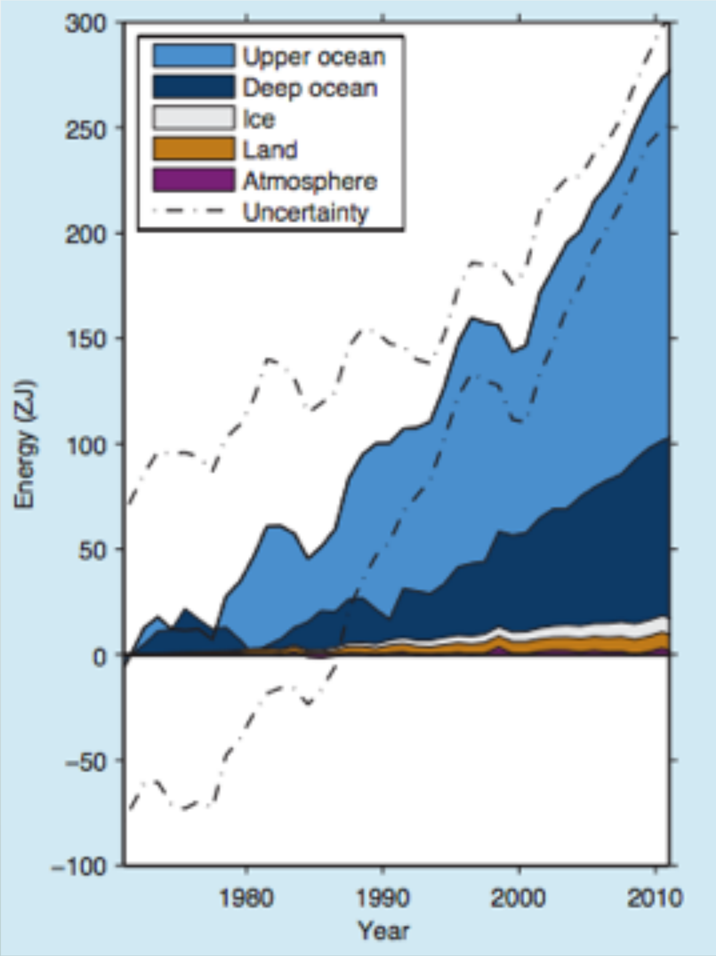
Outline

- The role of the deep ocean in climate
- Turbulent mixing and the deep ocean circulation
- Southern Ocean and the deep ocean circulation
- Future changes in the deep ocean circulation
- Past changes in the deep ocean circulation

Deep Ocean and Climate

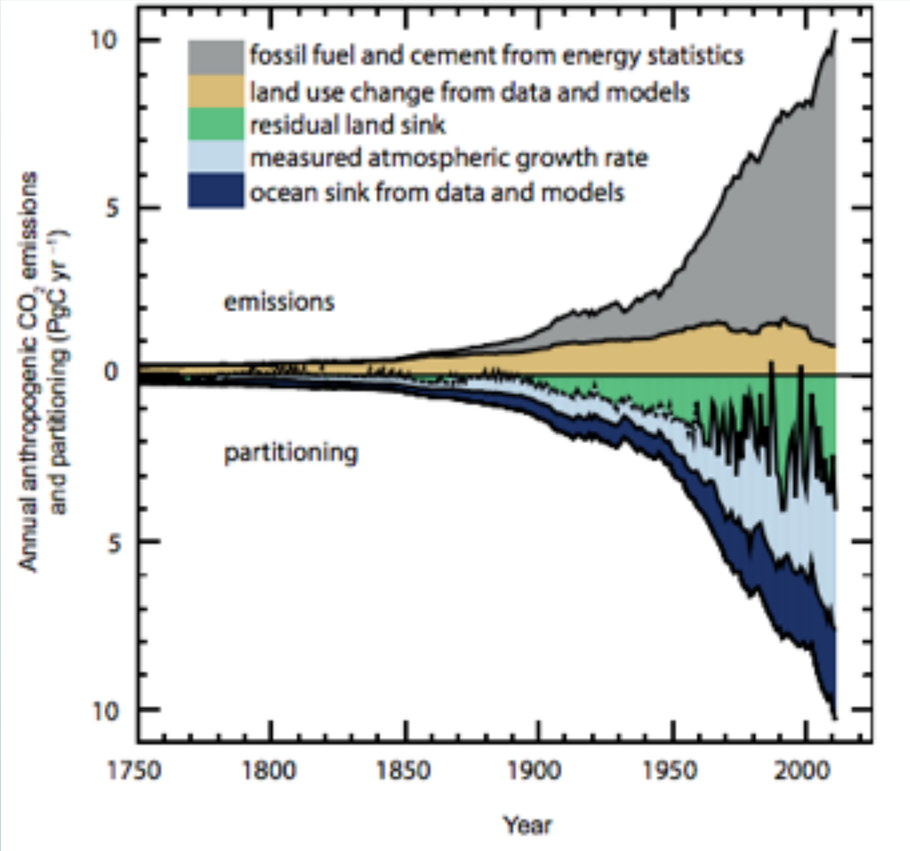
Ocean and Climate

Ocean Heat Uptake



IPCC, 2015, third chapter

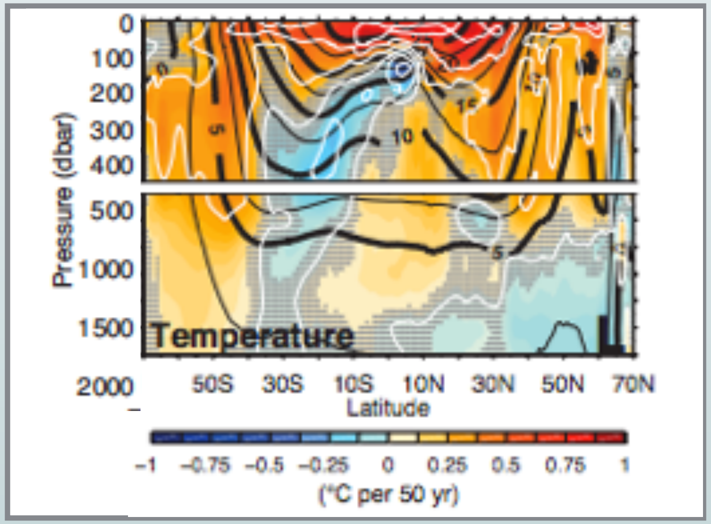
Ocean Carbon Uptake



IPCC, 2015, sixth chapter

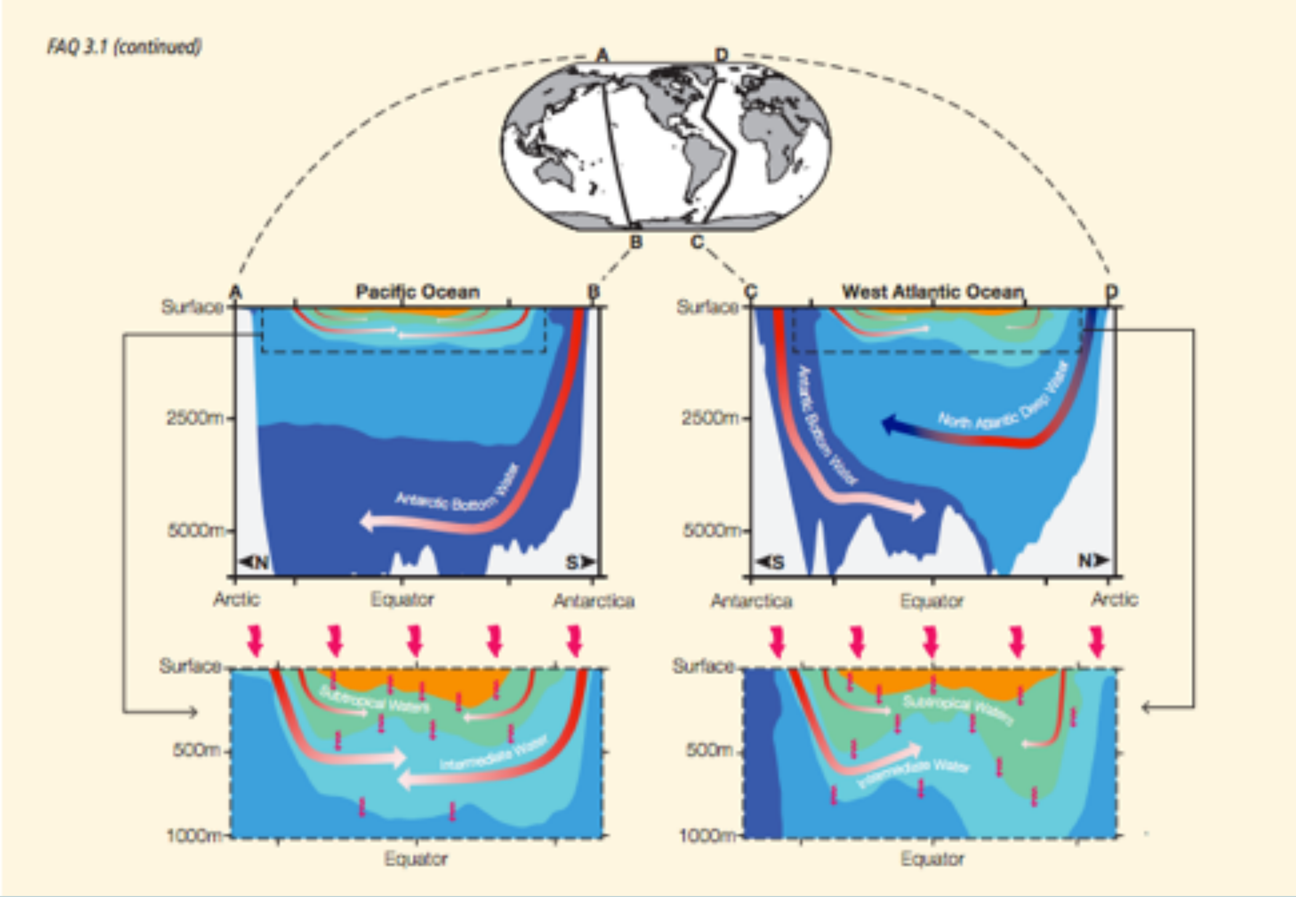
Ocean Heat Uptake

Observed temperature trends



Durack and Wijffels (2010)

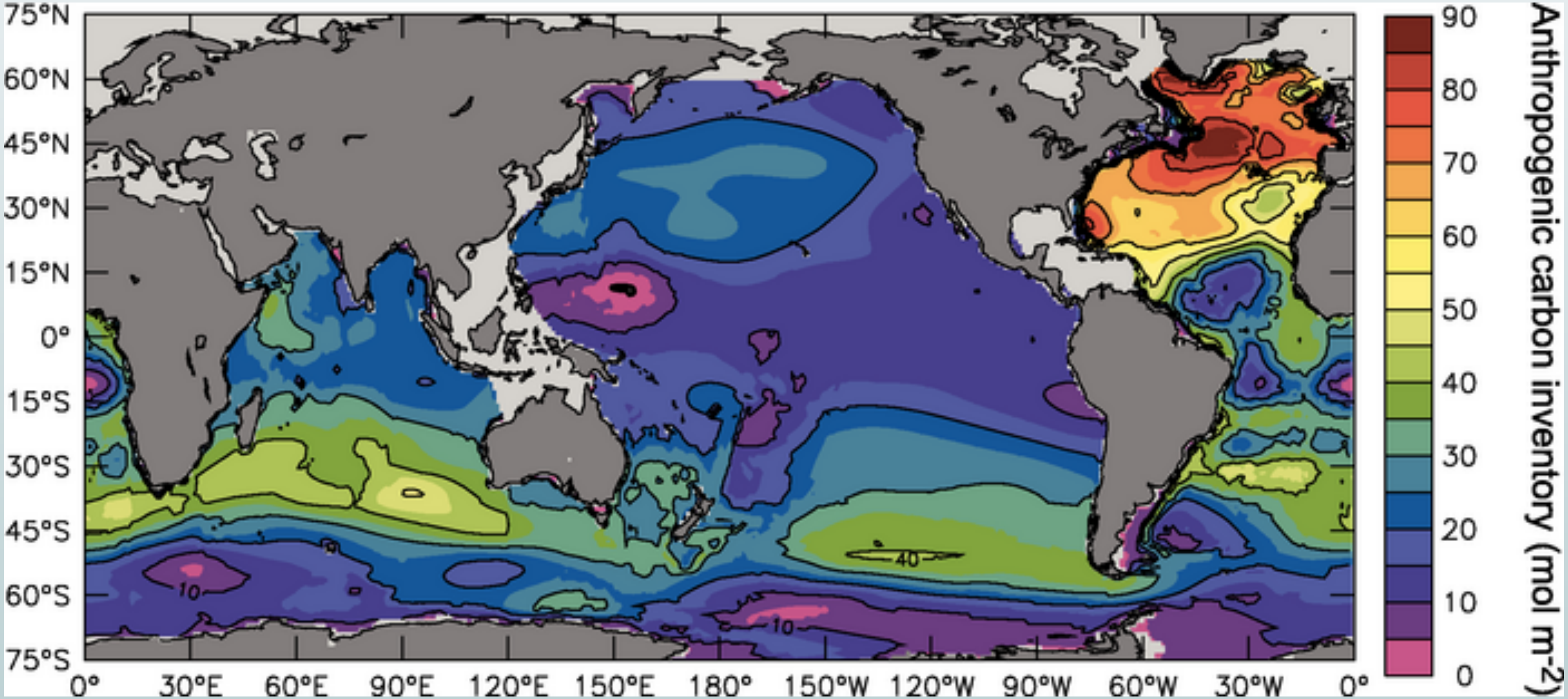
Pathways of ocean heat uptake



IPCC, 2015, third chapter

Ocean Carbon Uptake

Observed anthropogenic carbon inventory

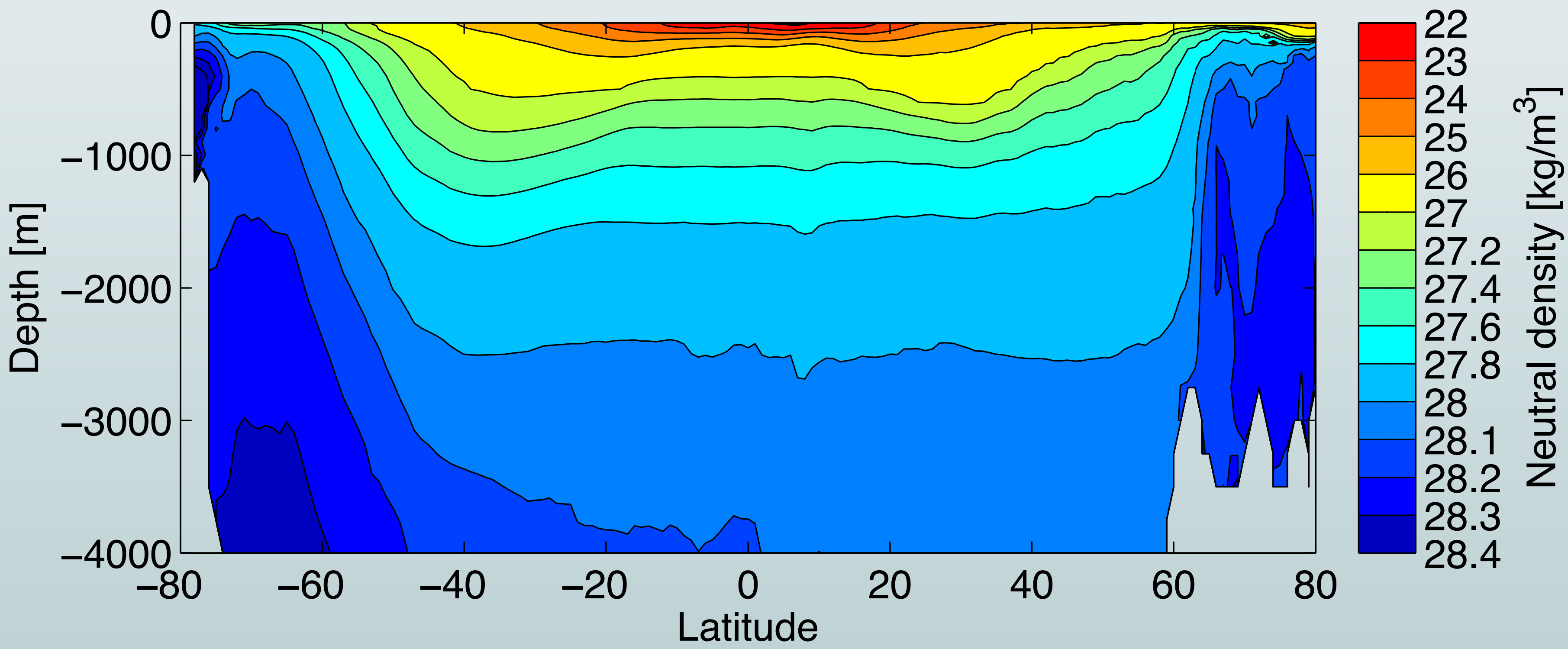


IPCC, 2015, sixth chapter

Deep Circulation and Mixing

A Theory of the Abyss

- Heat and carbon are taken up by the ocean at high latitudes
  1. theory for the deep ocean stratification
  2. theory for the deep ocean circulation



Zonally averaged neutral density from WOCE climatology

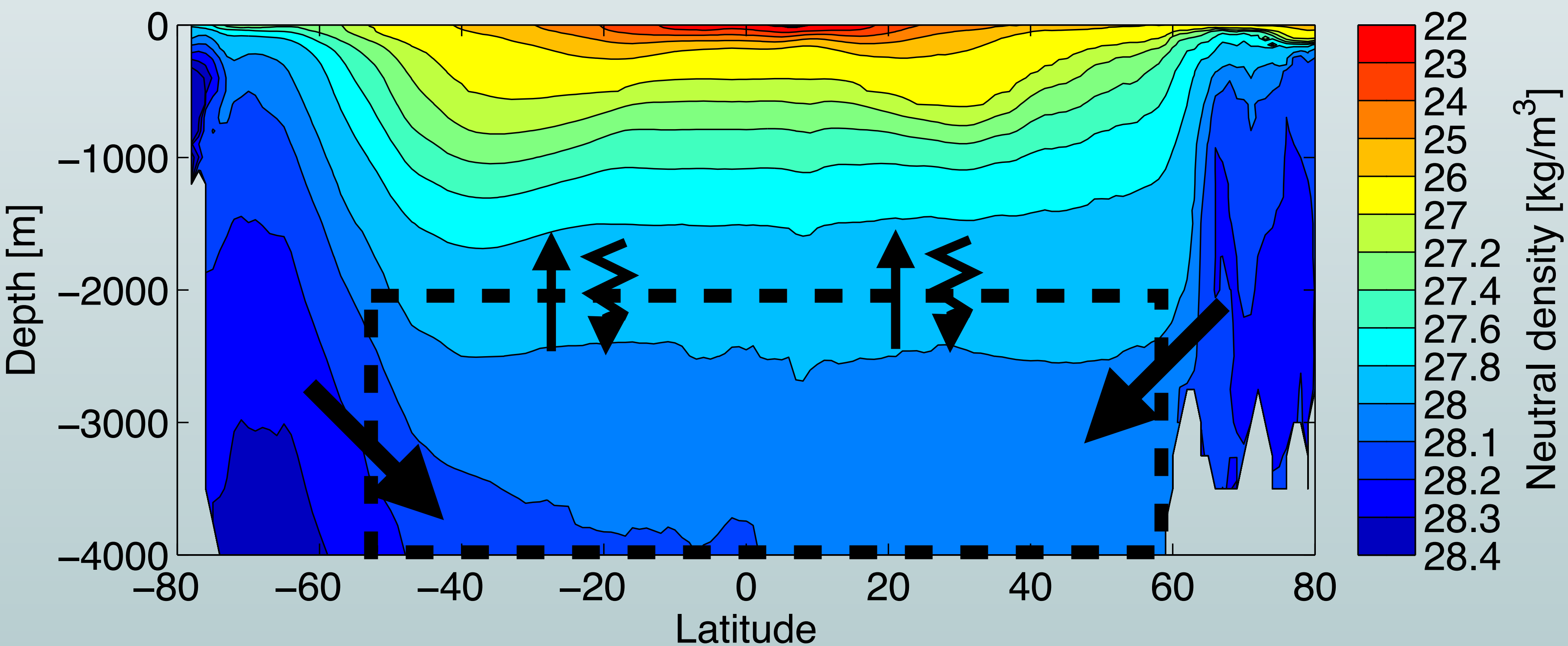
Abyssal Recipes

Abyssal recipes

Walter H. Munk*

(*Received* 31 *January* 1966)

$$w \frac{\partial \rho}{\partial z} = \frac{\partial}{\partial z}\left(\kappa \frac{\partial \rho}{\partial z}\right)$$



Abyssal Recipes

- Munk found that vertical profiles of density and ^{14}C in abyssal Pacific are consistent with 1-D balance

$$w\frac{\partial \rho}{\partial z} = \kappa_T \frac{\partial^2 \rho}{\partial z^2}$$

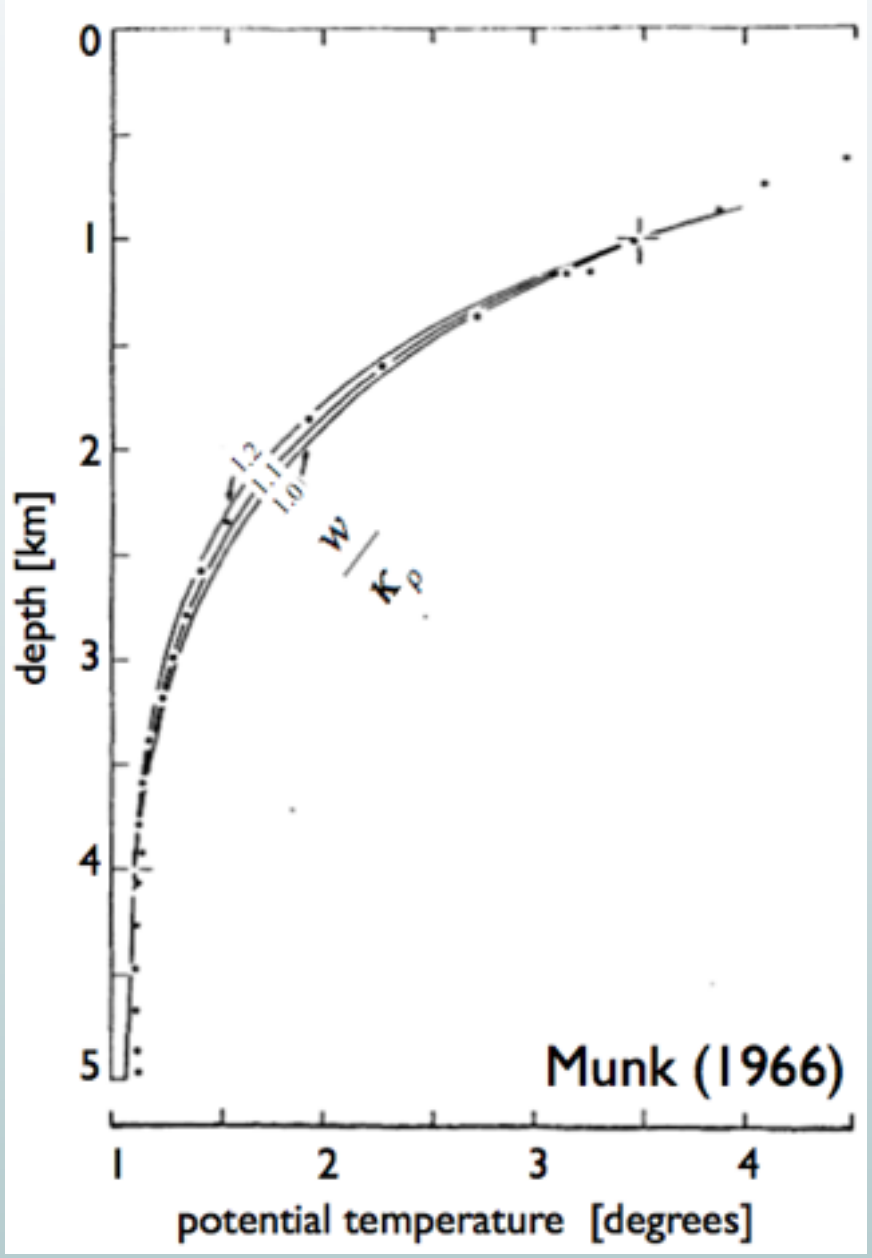
$$\rho(z) \propto \exp\left(\frac{wz}{\kappa_T}\right)$$

- Least-square curve field yield

$$w \sim 10^{-7}\ \mathrm{ms}^{-1}$$

$$\kappa_T \sim 10^{-4}\ \mathrm{m}^2\mathrm{s}^{-1}$$

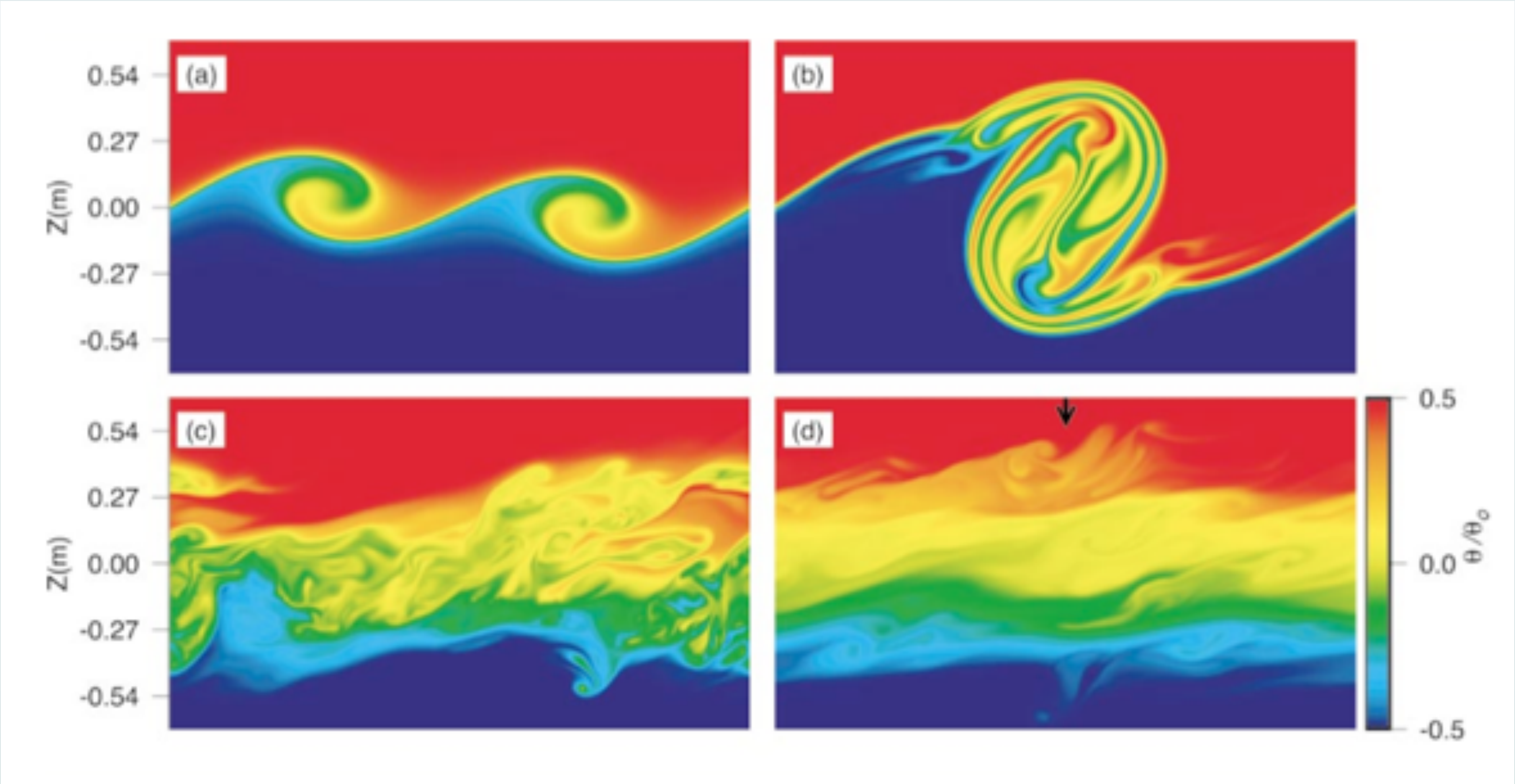
sufficient to balance 30 Sv of sense water formation rate



Turbulent mixing

- Mixing in the deep ocean below1000m is turbulent

  $\kappa_T \sim 10^{-4}\ \mathrm{m}^2\mathrm{s}^{-1} \quad \gg$ molecular diffusion
- Turbulent mixing is typically associated with breaking internal waves



Smyth et al. (2001)

Overturning Circulation

Parameter Sensitivity of Primitive Equation Ocean General Circulation Models

FRANK BRYAN

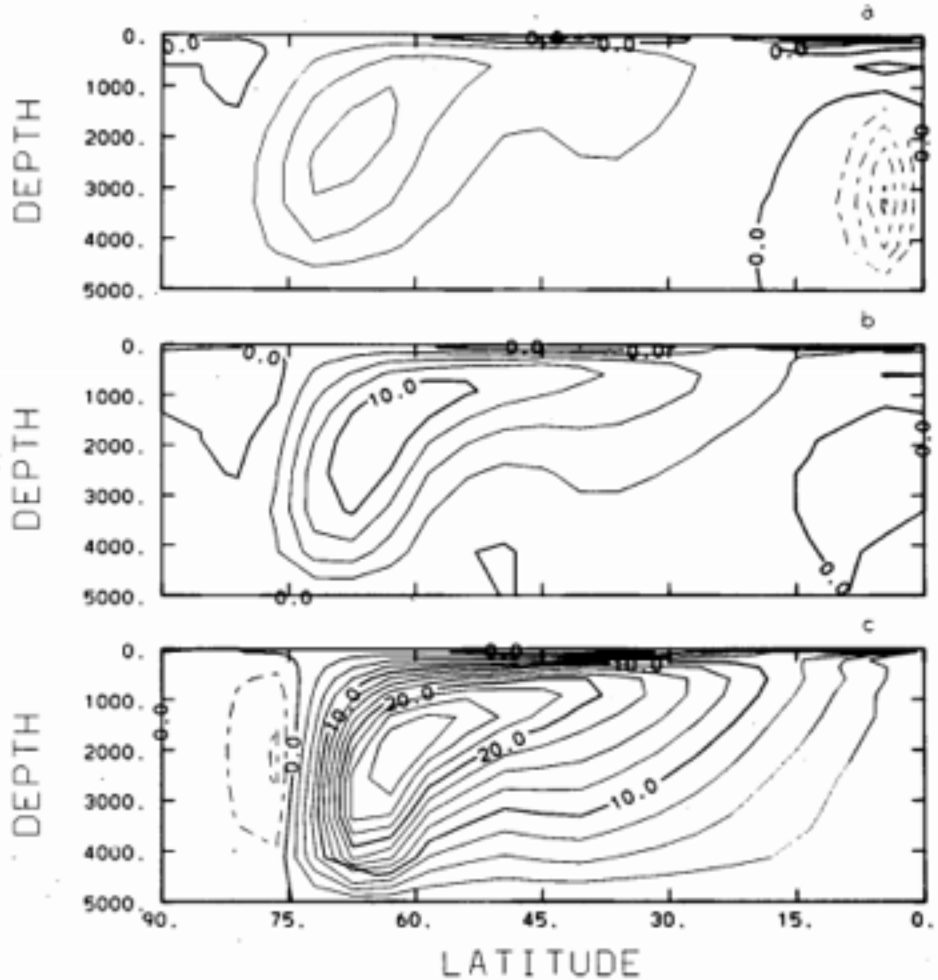


FIG. 7. Meridional overturning streamfunction for (a) A_{HV} = 0.1, (b) A_{HV} = 0.5, (c) A_{HV} = 2.5 (c.i. = 2.5 × 10^6 m^3 s^{-1}, solid contours indicate counterclockwise circulation).

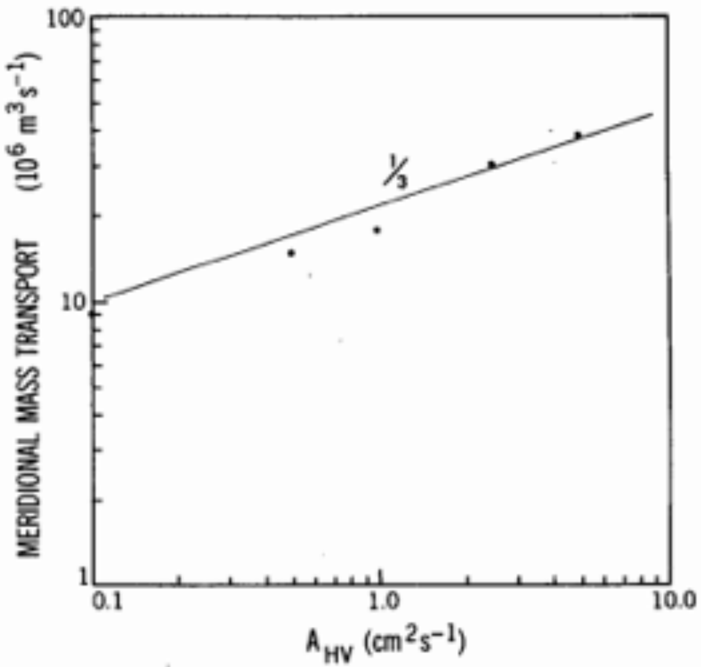
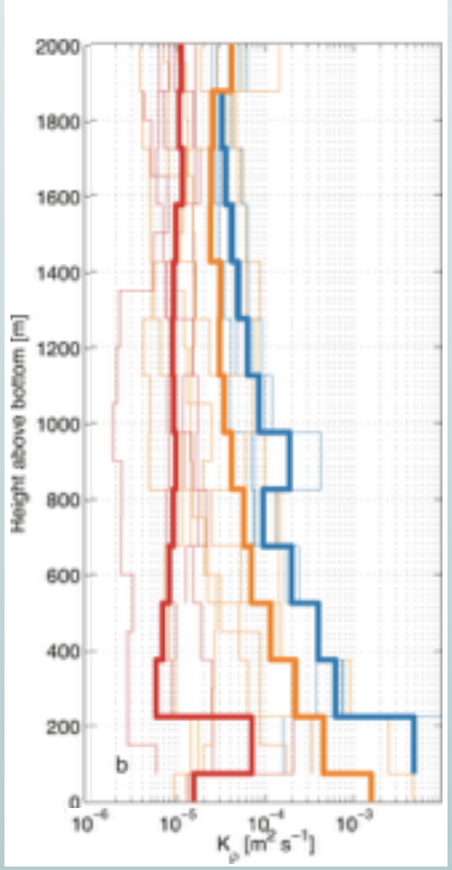


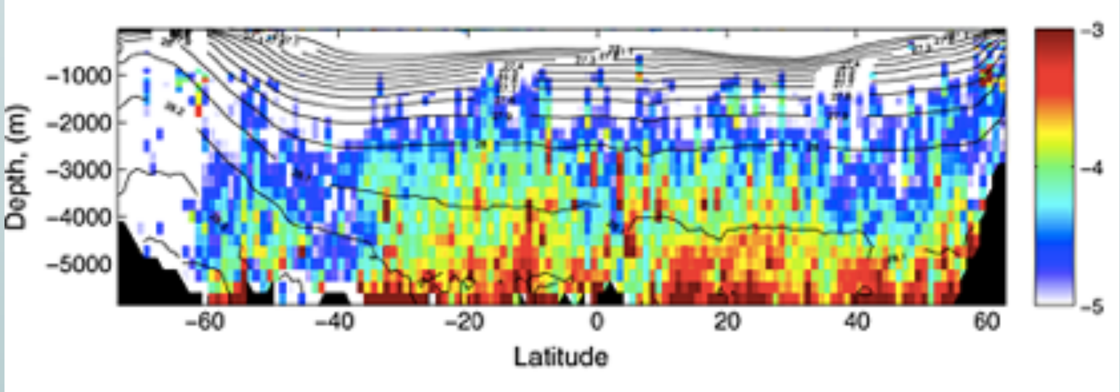
FIG. 8. Dependence of meridional overturning streamfunction on vertical diffusivity.

Missing Mixing

- Munk and Wunsch (1998) estimated that 2TW are needed to lift waters from the ocean bottom up to 1000m
- Internal waves are generated by tides and geostrophic eddies at the ocean bottom at a rate of 2TW (Waterhouse et al., 2014)
- Only a small fraction of the waves break in the deep ocean



Waterhouse at al. (2014)



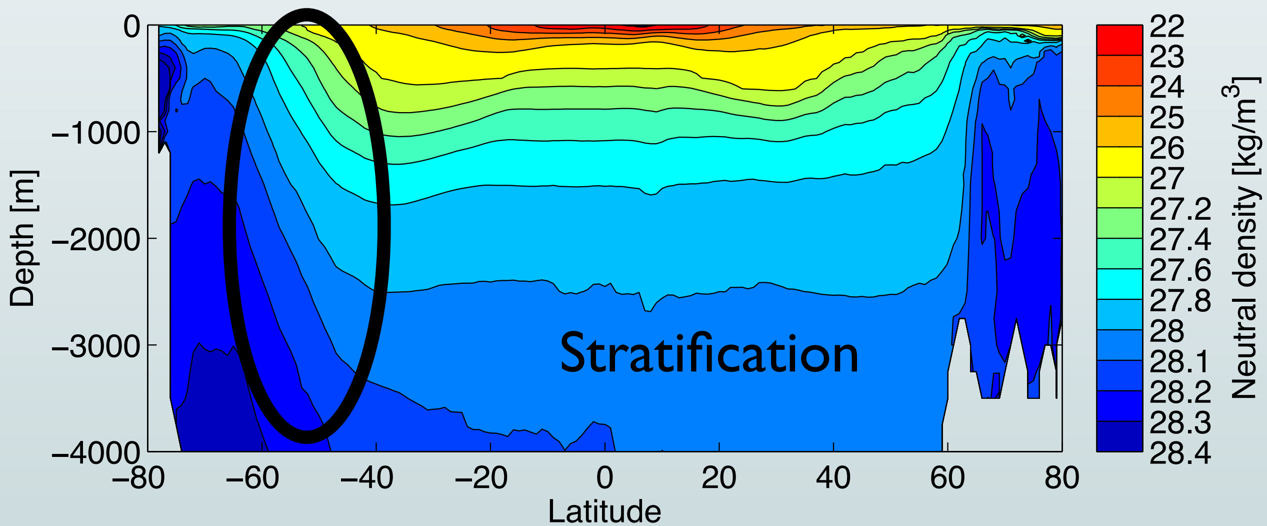
Nikurashin and Ferrari (2013)

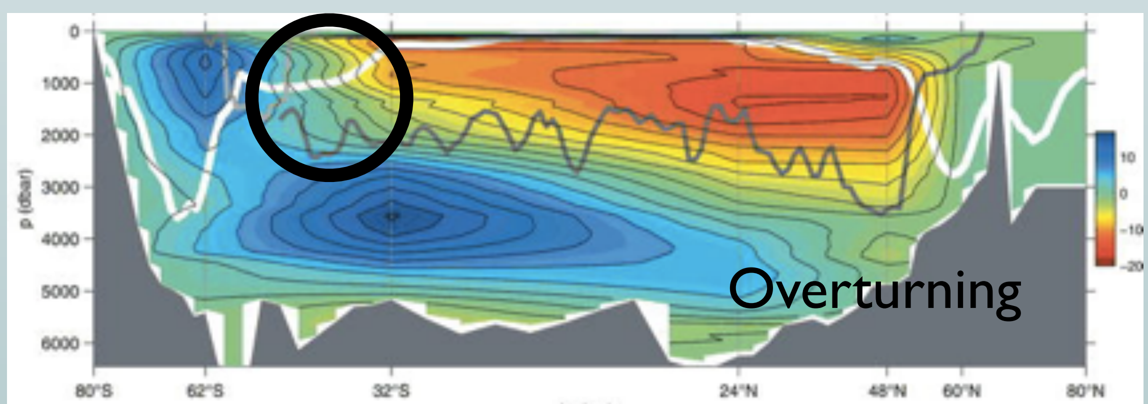
Southern Ocean

Overturning Circulation

Effect of Drake Passage on the global thermohaline circulation

J. R. Toggweiler* and B. Samuels*

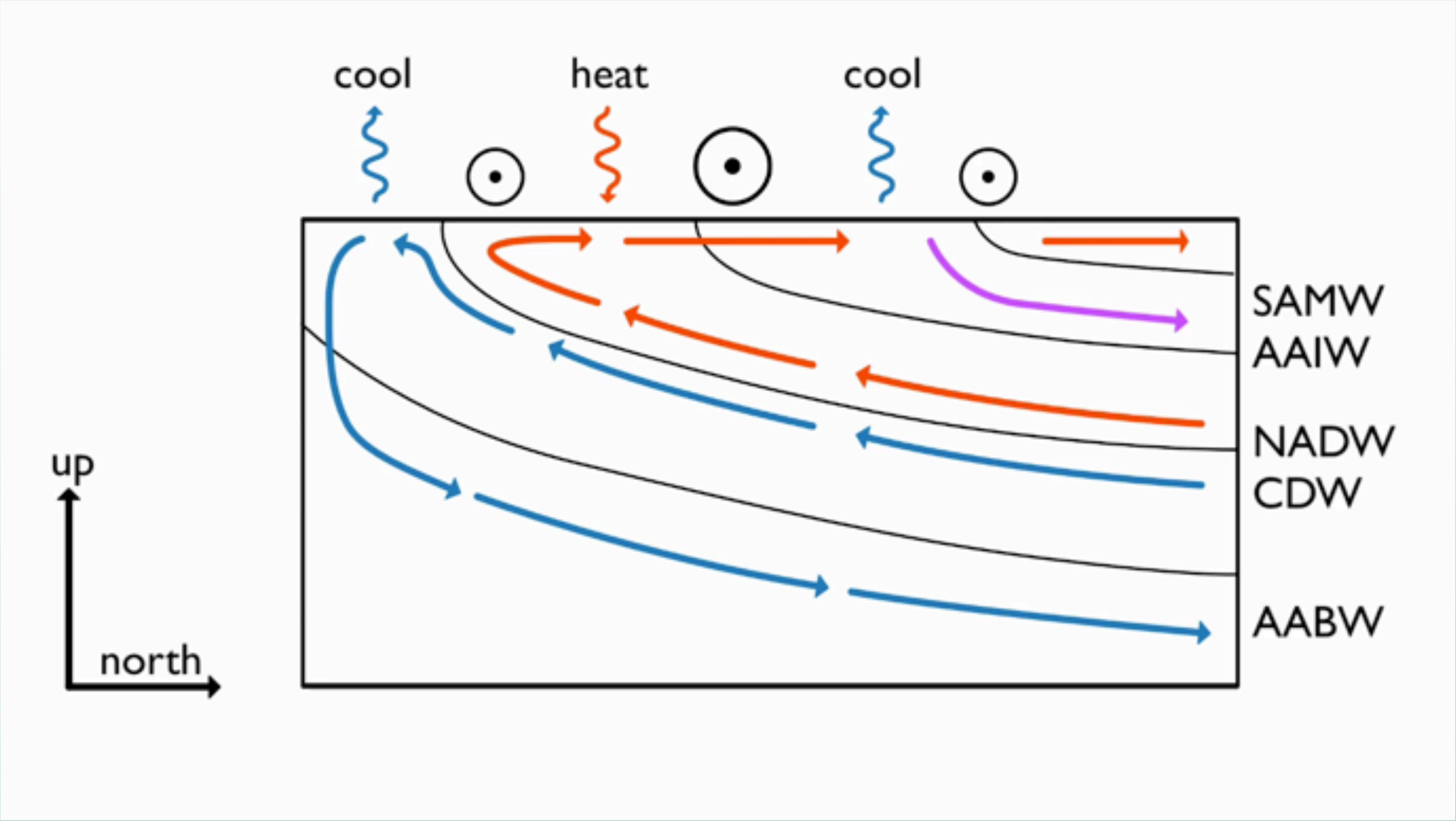




Lumpkin and Speer (2007)

Southern Ocean Dynamics

Idealized model of Southern Ocean circulation (Abernathey et al., 2011)



Movie generated by Ryan Abernathey

Southern Ocean Dynamics

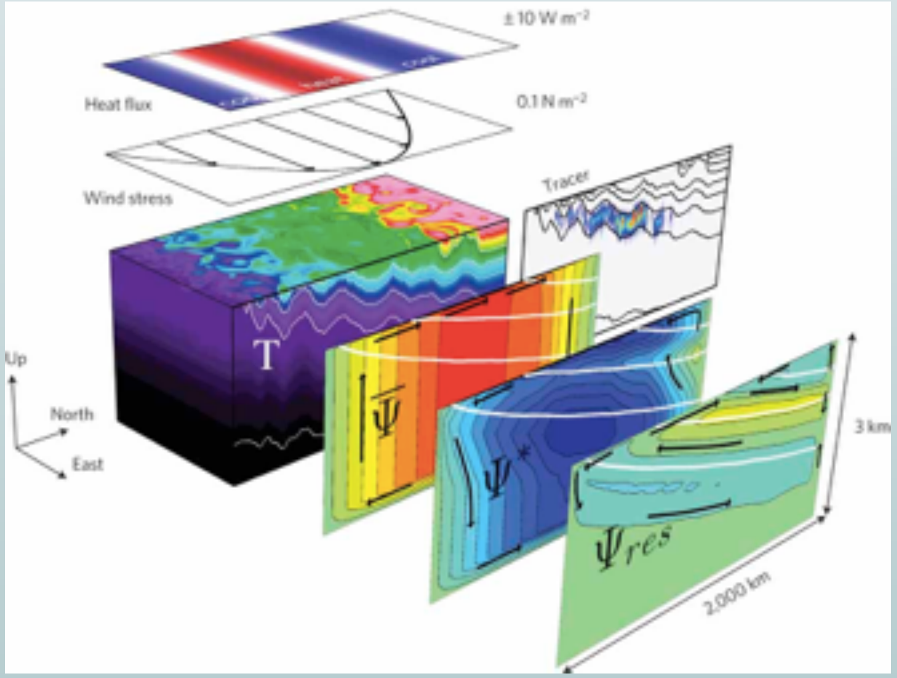
- Momentum and buoyancy budgets of the Southern Ocean

$$\psi_{res} = \psi_{wind} + \psi_{eddy} = -\frac{\tau}{f} + \frac{\overline{v'b'}}{\partial_z \bar{b}}$$

$$J(\psi_{res}, \bar{b}) = \partial_z \mathcal{B}$$

- Closure for lateral buoyancy fluxes (Gent and McWilliams, 1990)

$$\overline{v'b'} = -K_{eddy} \partial_y \bar{b}$$



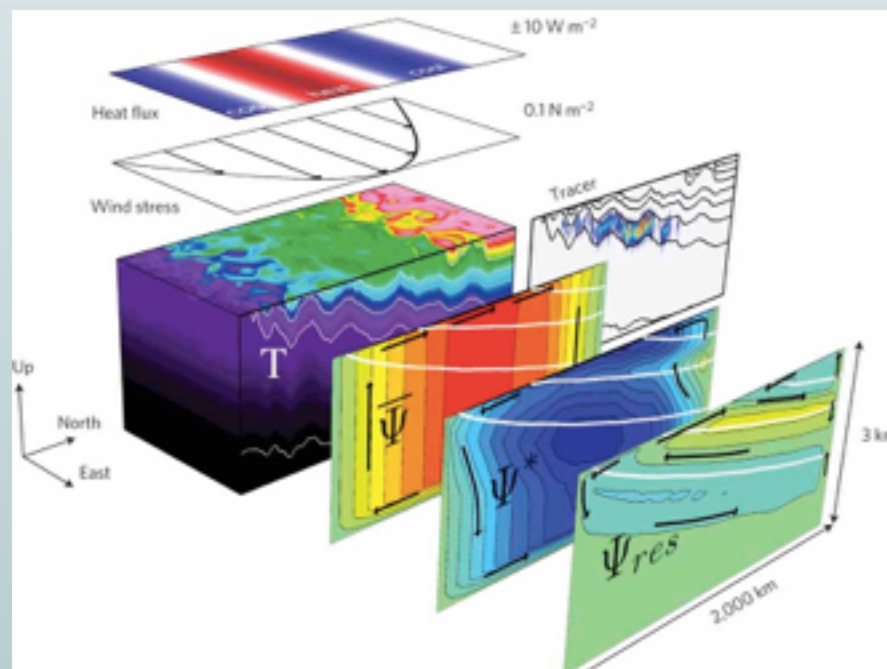
Marshall and Speer (2012)

Southern Ocean Dynamics

- Momentum and buoyancy budgets of the Southern Ocean

$$\psi_{res} = -\frac{\tau}{f} - K_{eddy}\frac{\partial_y \bar{b}}{\partial_z \bar{b}}$$

$$J(\psi_{res}, \bar{b}) = \partial_z \mathcal{B}$$



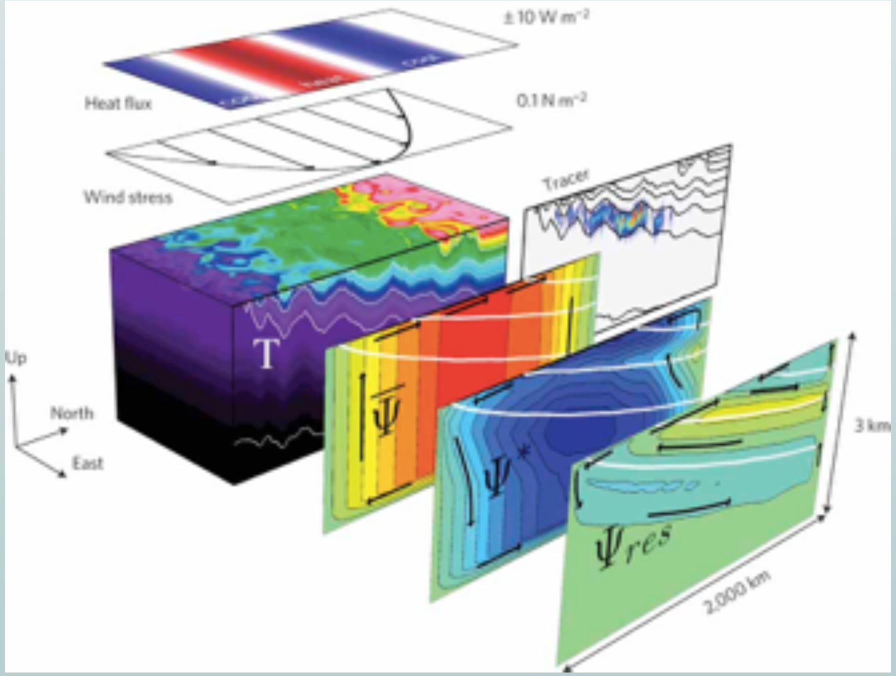
Marshall and Speer (2012)

Southern Ocean Dynamics

Momentum budget constrains isopycnal slopes (Wolfe and Cessi, 2010)

$$\psi_{res} = -\frac{\tau}{f} - K_{eddy}\frac{\partial_y \bar{b}}{\partial_z \bar{b}}$$

$$\Longrightarrow \qquad \text{slope} = -\frac{\partial_y \bar{b}}{\partial_z \bar{b}} \simeq \frac{\tau}{K_{eddy} f}$$



Marshall and Speer (2012)

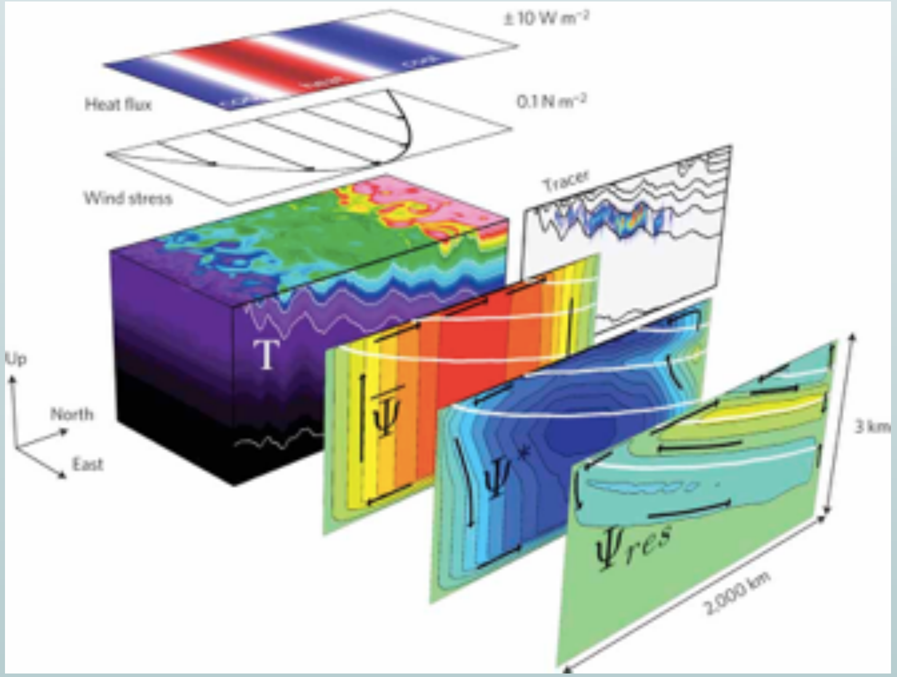
Southern Ocean Dynamics

Buoyancy budget constrains shape of circulation (Marshall and Radko, 2003)

$$J(\psi_{res}, \bar{b}) = \partial_z \mathcal{B}$$

$$\Longrightarrow \quad \text{mixed layer:} \quad \psi_{res}\, \partial_y \bar{b} = \mathcal{B}$$

$$\Longrightarrow \quad \text{ocean interior:} \quad J(\psi_{res}, \bar{b}) = 0$$

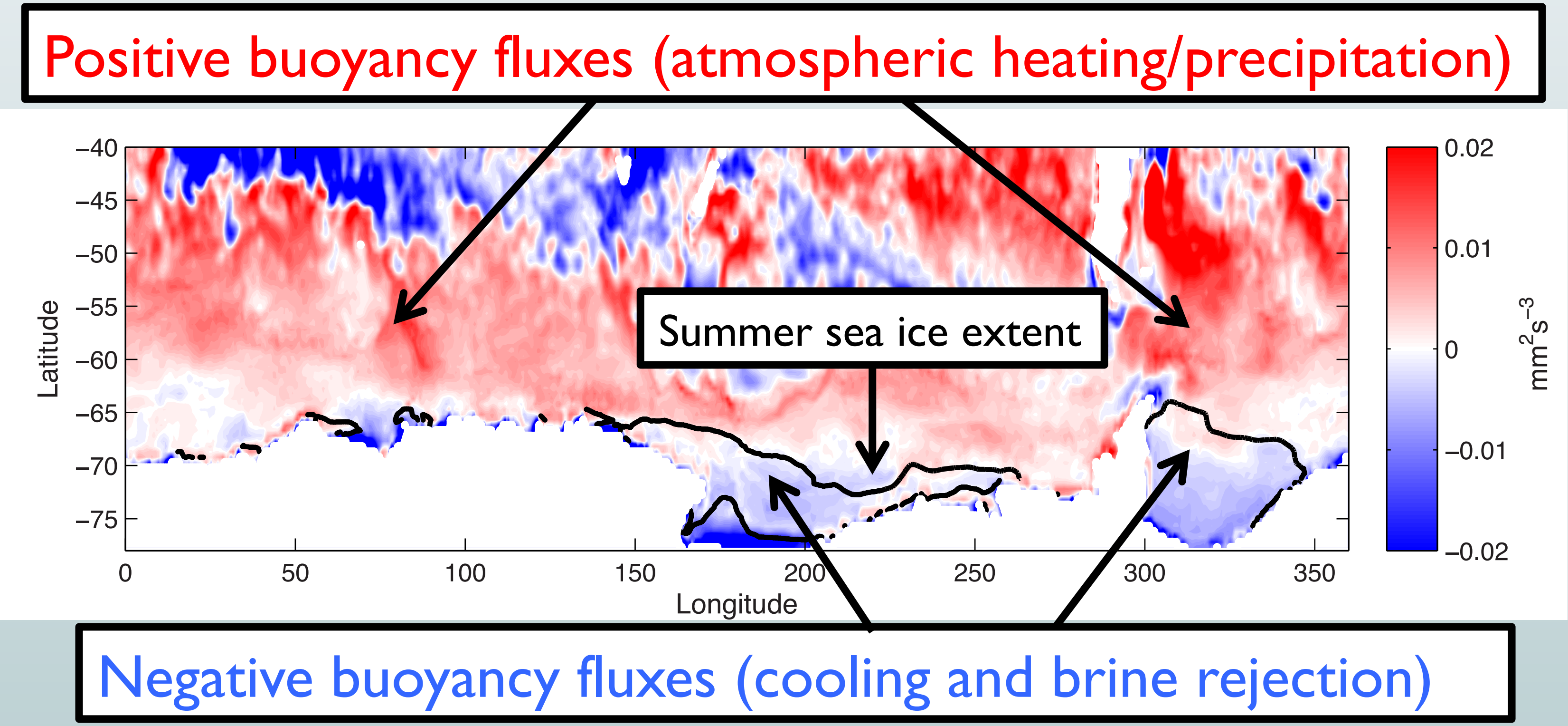


Marshall and Speer (2012)

Southern Ocean Air-Sea Fluxes

Air-sea buoyancy fluxes over the Southern Ocean

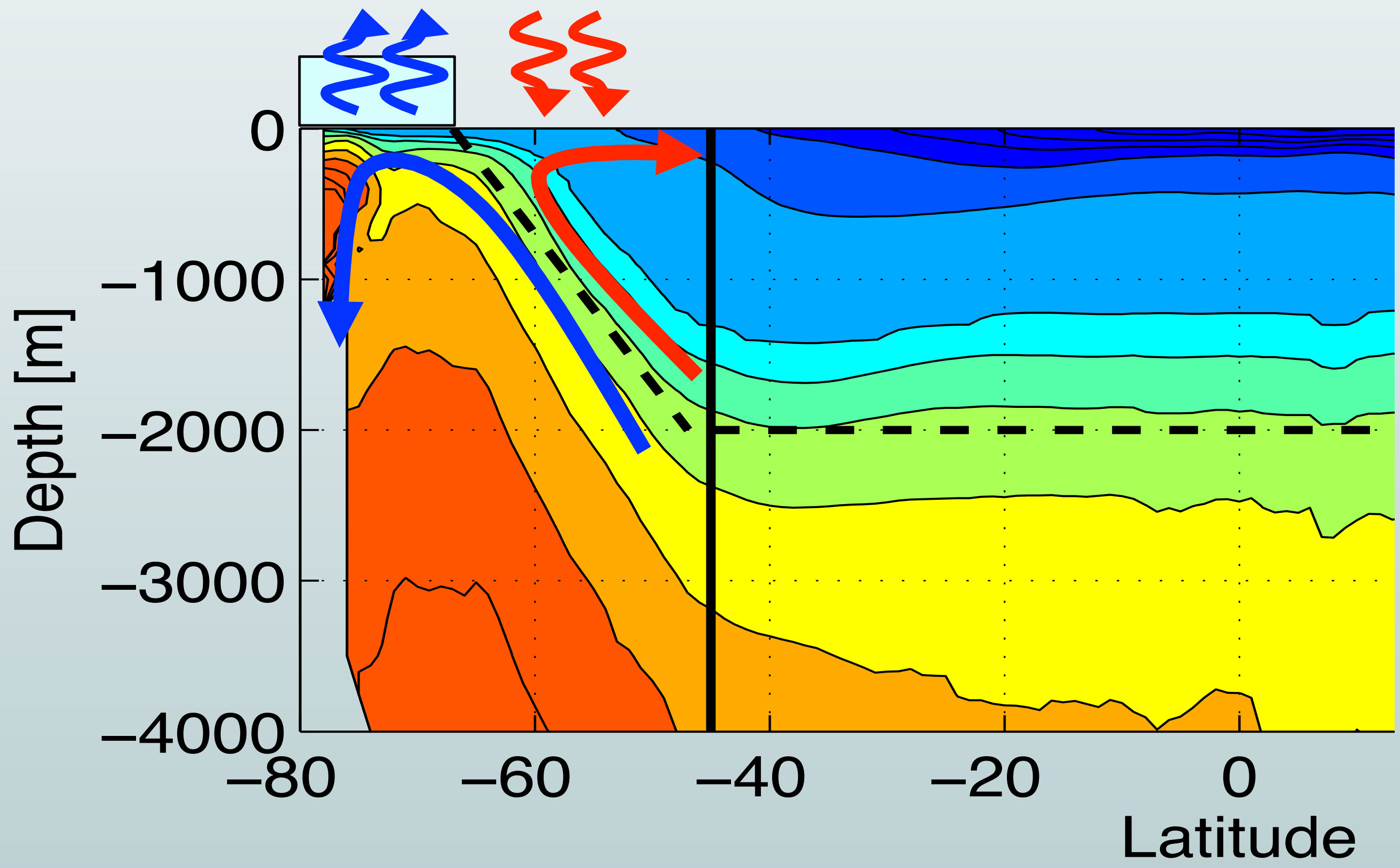
- the ocean loses buoyancy under permanent (summer) sea ice
- the ocean gains buoyancy north of the permanent sea ice



Southern Ocean State Estimate (Mazolff et al., 2013)

Southern Ocean Circulation

Southern Ocean branch of the overturning circulation

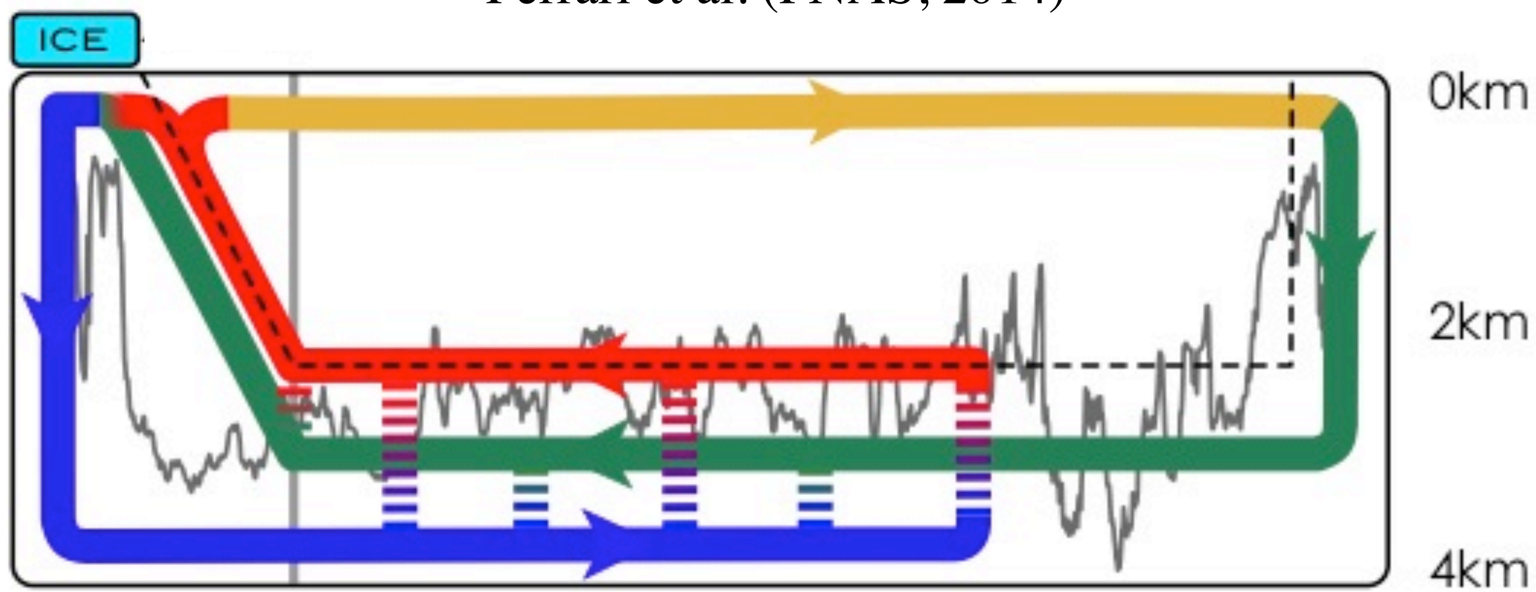


Deep Ocean Circulation

Global Ocean Circulation

- One global figure eight overturning circulation
- Density outcropping at the permanent sea ice edge is crucial

Ferrari et al. (PNAS, 2014)



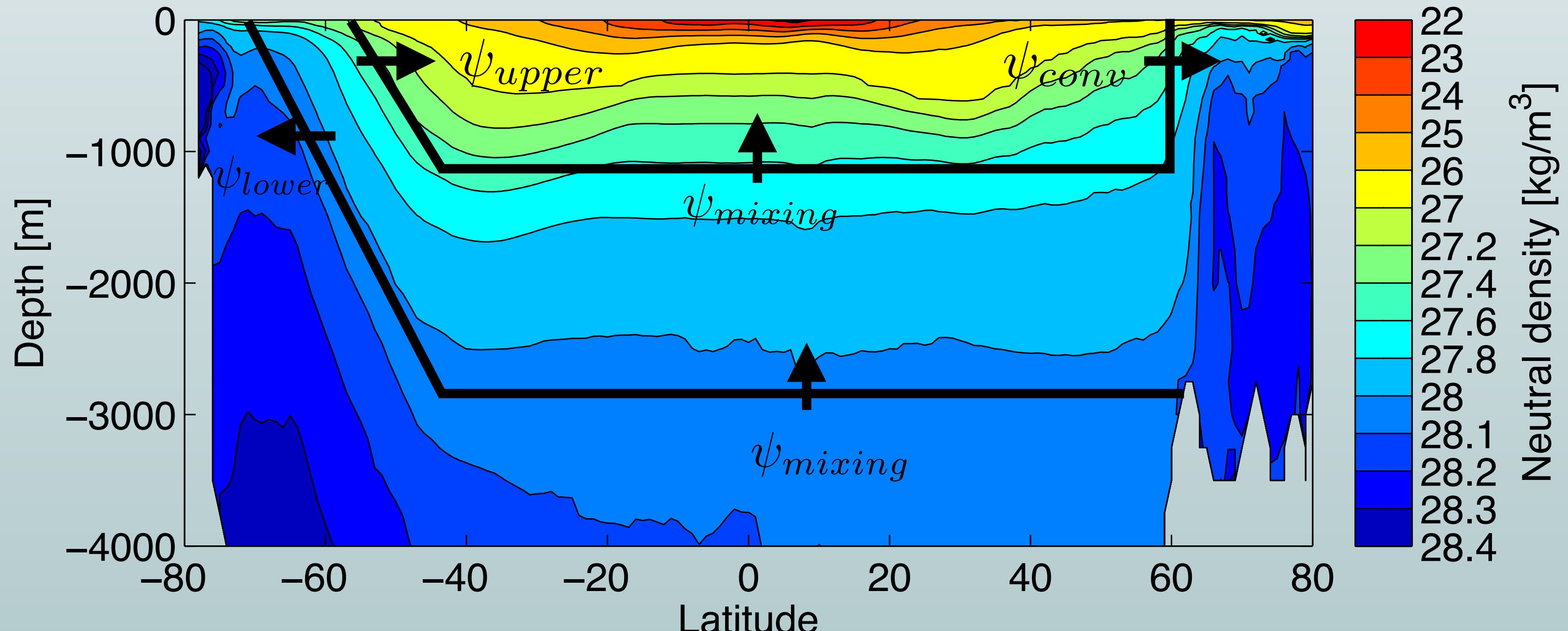
Global Ocean Circulation

- The upper cell of the Southern Ocean circulation must match
  - convection in the North Atlantic

    e.g. Gnanadesikan (1999)

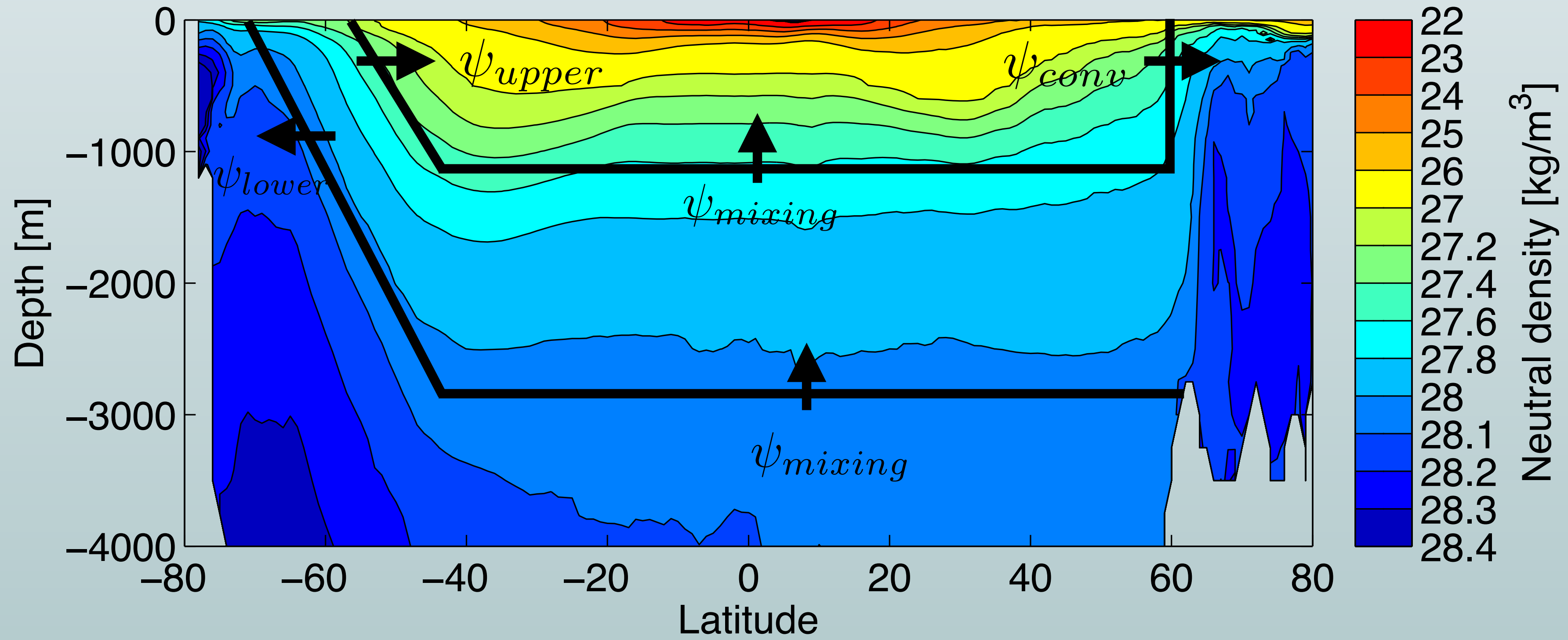
- The lower cell of the Southern Ocean circulation must match
  - mixing driven upwelling in the basins

    e.g. Nikurashin and Vallis (2011)



Global Ocean Circulation

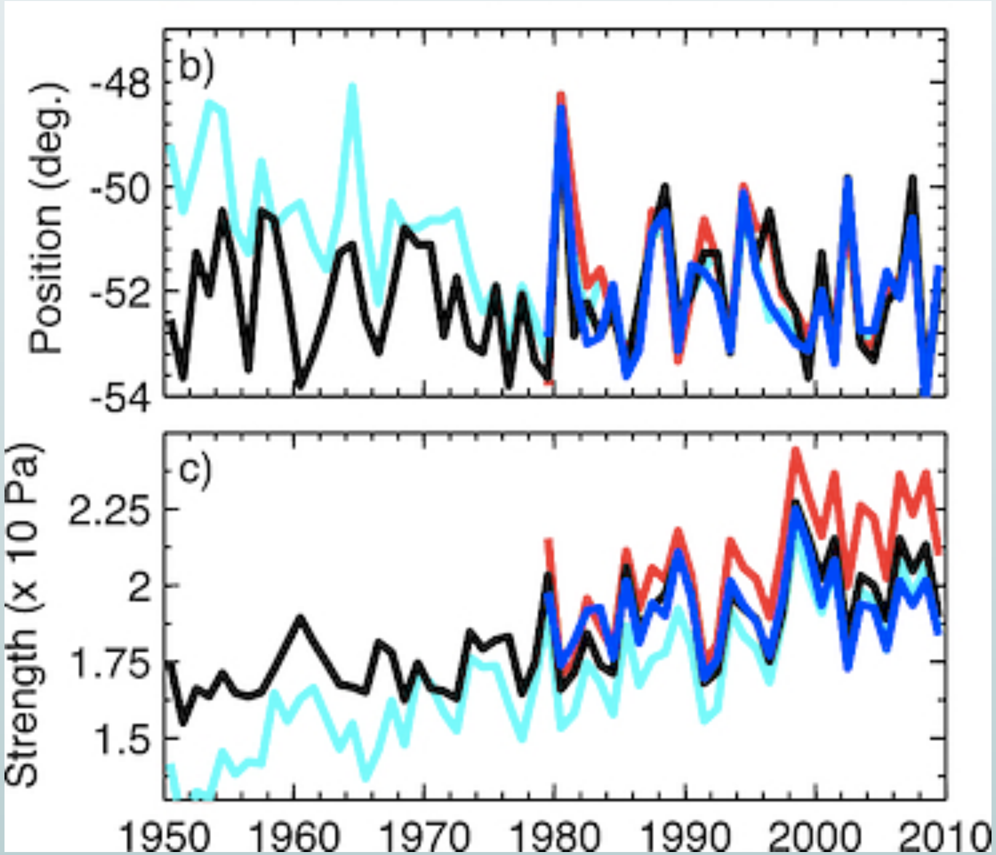
- Key controls
  - Southern Ocean winds, buoyancy fluxes, and eddies
  - North Atlantic buoyancy fluxes
  - Abyssal mixing



Future Climate

Changes in Roaring Forties

- Reanalyses show positive trend in Southern Annular Mode over last 30 years
  - strength of Southern Hemisphere westerlies increased
  - position of Southern Hemisphere westerlies did not change significantly



Swart and Fyfe (2012)

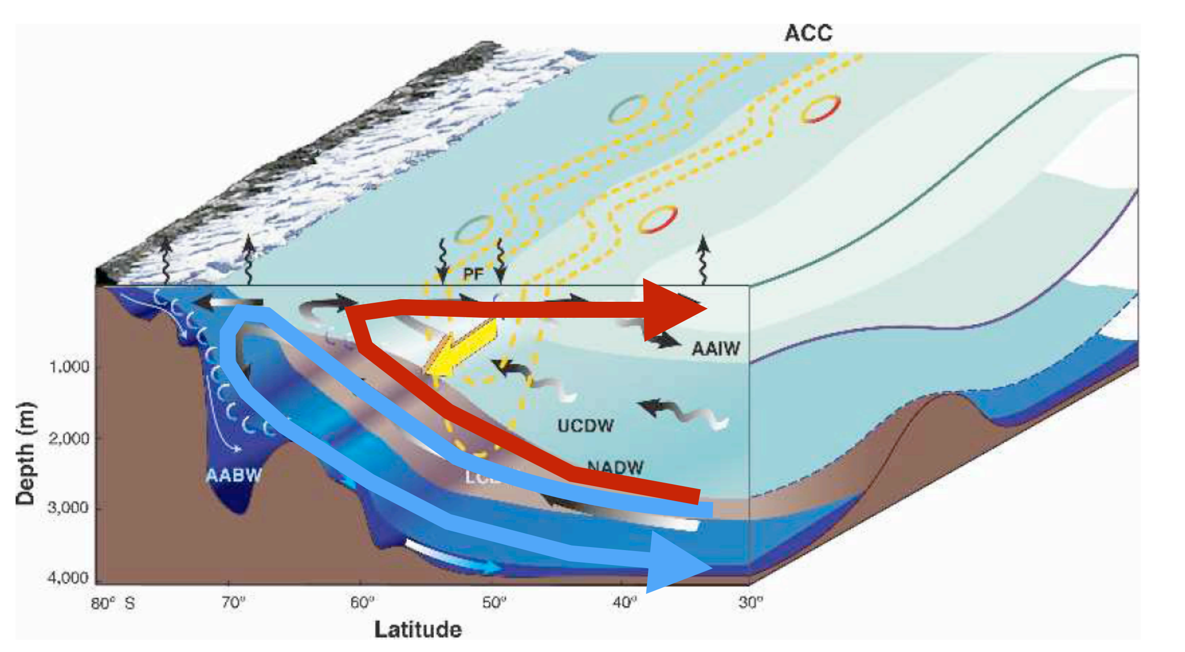
Changes in Roaring Forties

- Le Quéré et al. (2007) speculated that increase in wind strength would
  - strengthen upper cell and increase ocean release of deep carbon

$$\psi_{upper} = -\frac{\tau}{f} - K_{eddy}\frac{\partial_y \bar{b}}{\partial_z \bar{b}} > 0$$

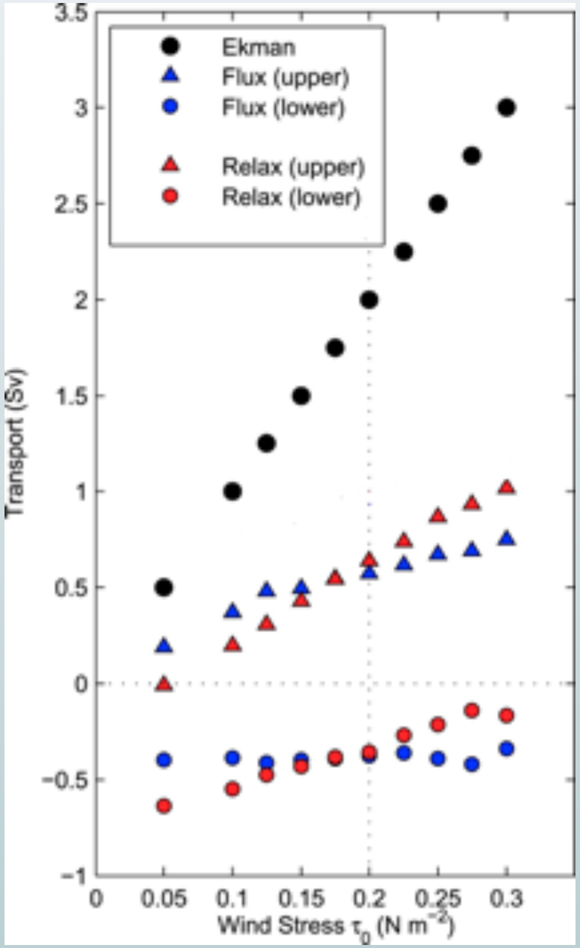
  - weaken lower cell and slightly decrease ocean release of abyssal carbon

$$\psi_{lower} = -\frac{\tau}{f} - K_{eddy}\frac{\partial_y \bar{b}}{\partial_z \bar{b}} < 0$$



Eddy compensation

- Increase in winds is accompanied by an increase in eddy activity
- Increase in eddy activity results in an increase in eddy diffusivity



$$\psi_{wind} = -\frac{\tau}{f}$$

$$\psi_{upper} = -\frac{\tau}{f} - K_{eddy}\frac{\partial_y \bar{b}}{\partial_z \bar{b}} > 0$$

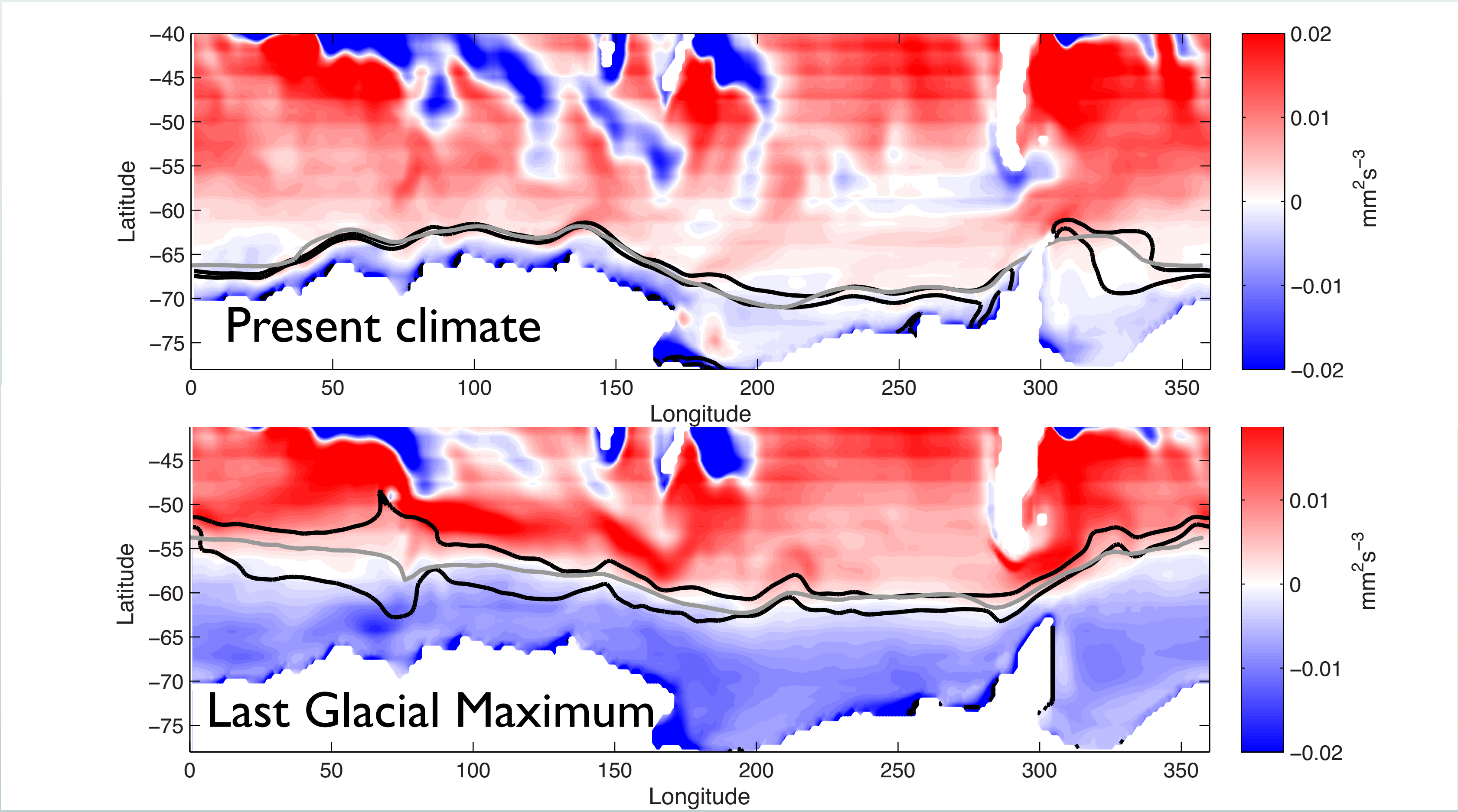
$$\psi_{lower} = -\frac{\tau}{f} - K_{eddy}\frac{\partial_y \bar{b}}{\partial_z \bar{b}} < 0$$

Abernathey et al. et al. (2012)

Last Glacial Maximum

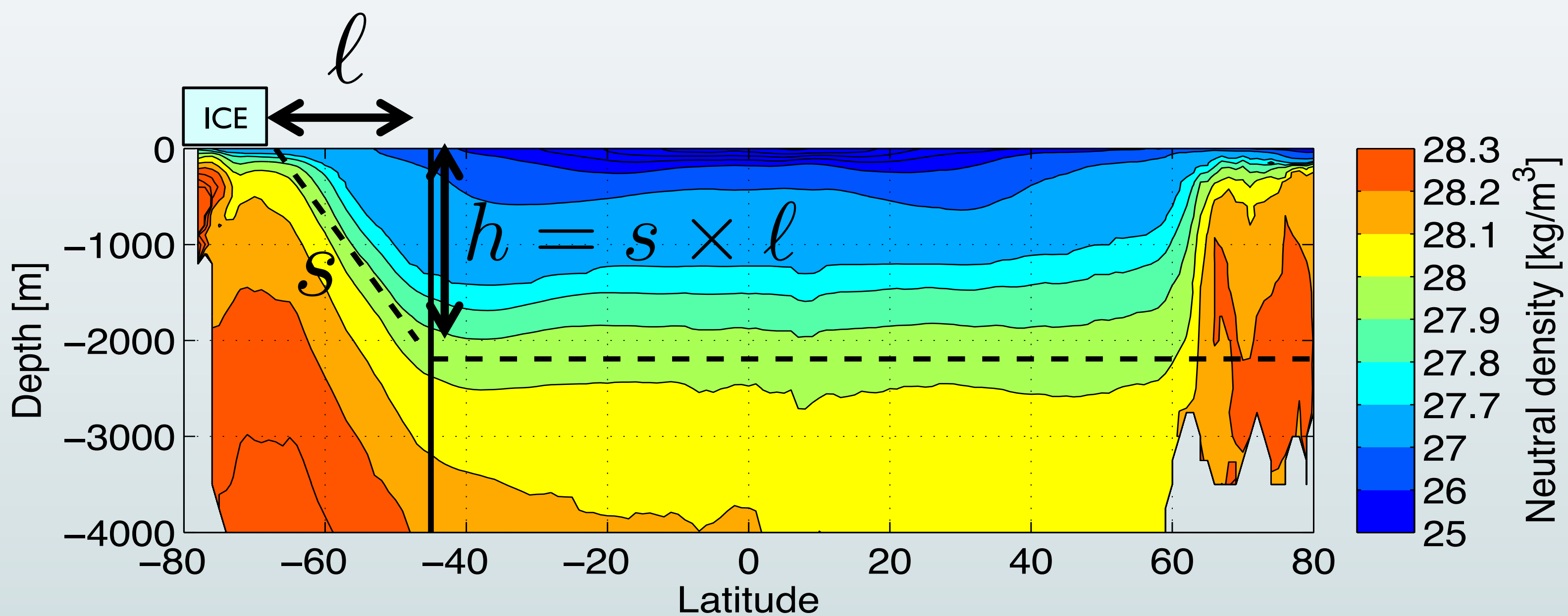
Changes in ice extent

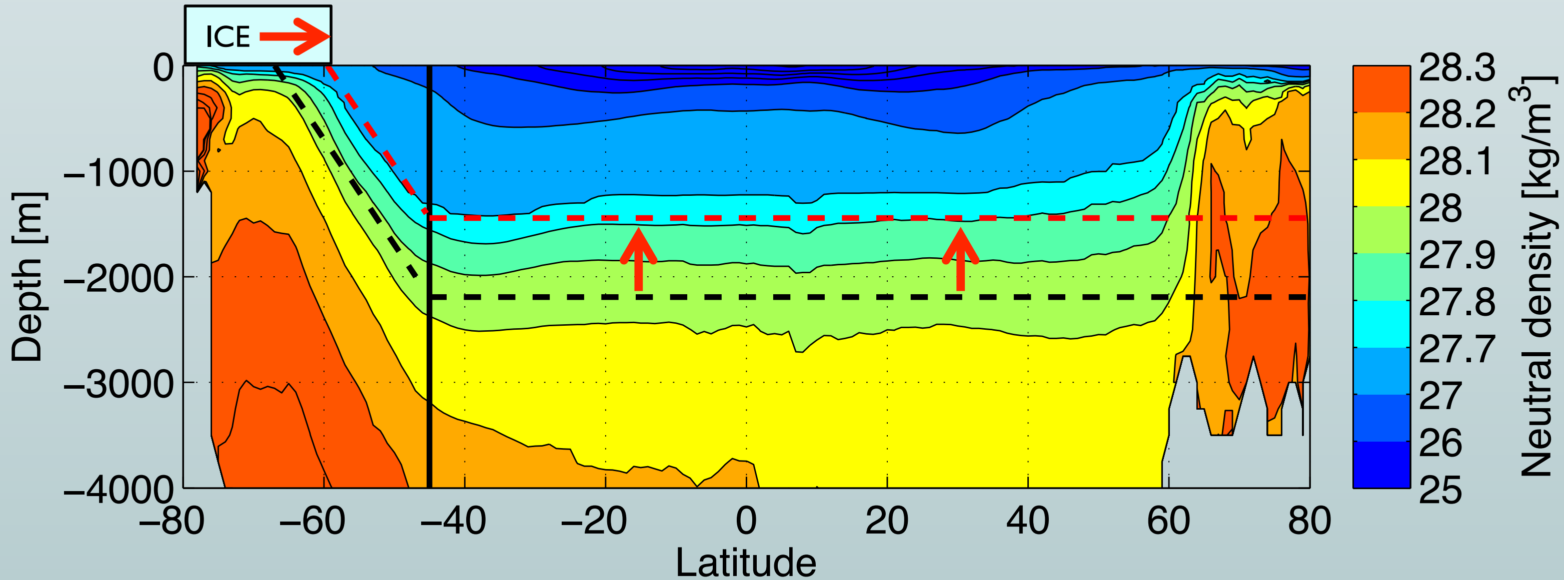
- Global overturning circulation spans three different basins
- Circulation in the Southern Ocean is not zonally symmetric



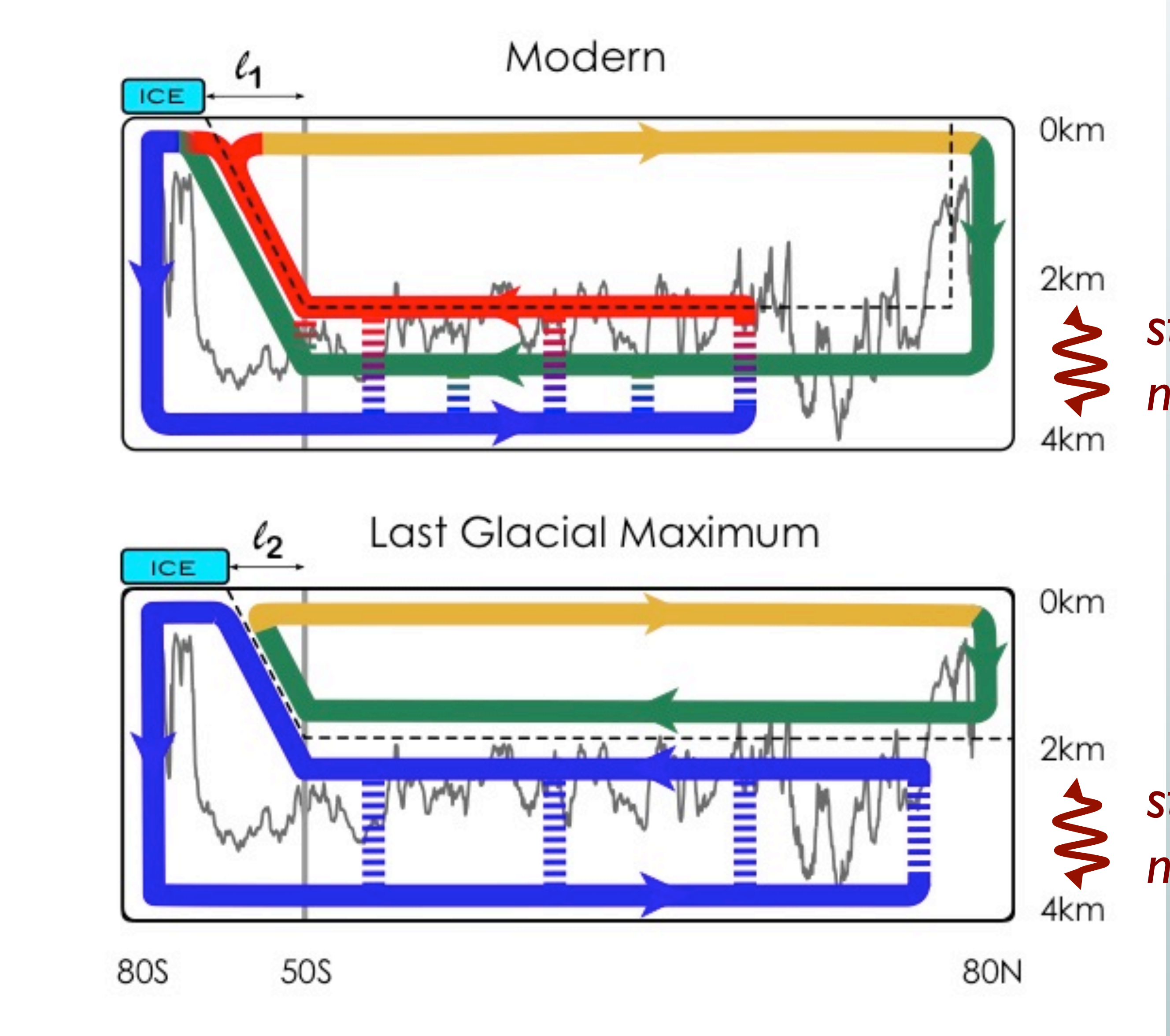
Ferrari et al. (2014) based on CCSM3 model (Otto-Bliesner at al. 2007)

Changes in Water Masses





Changes in Ocean Circulation

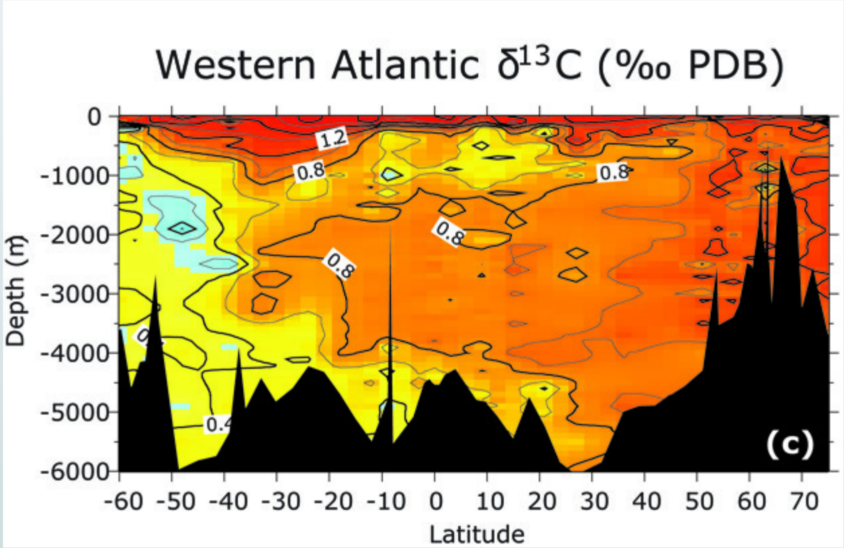


strong mixing

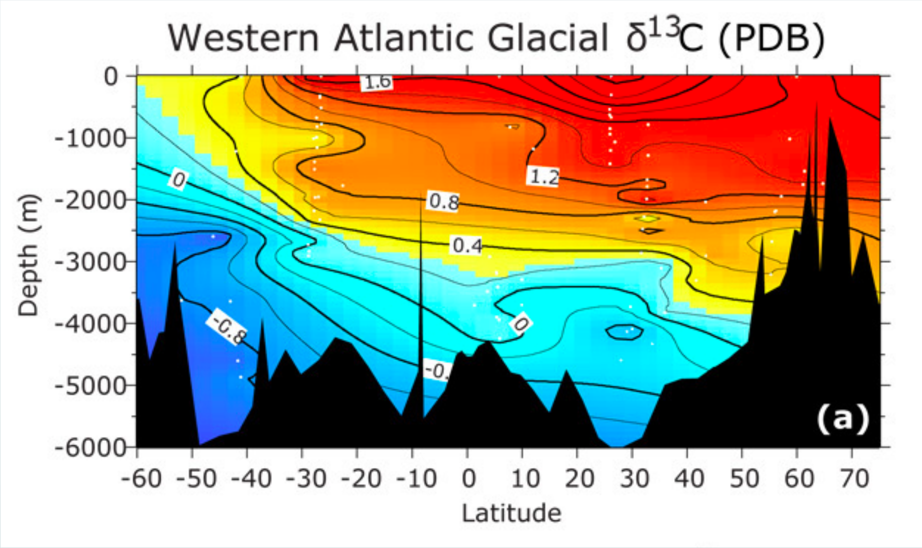
strong mixing

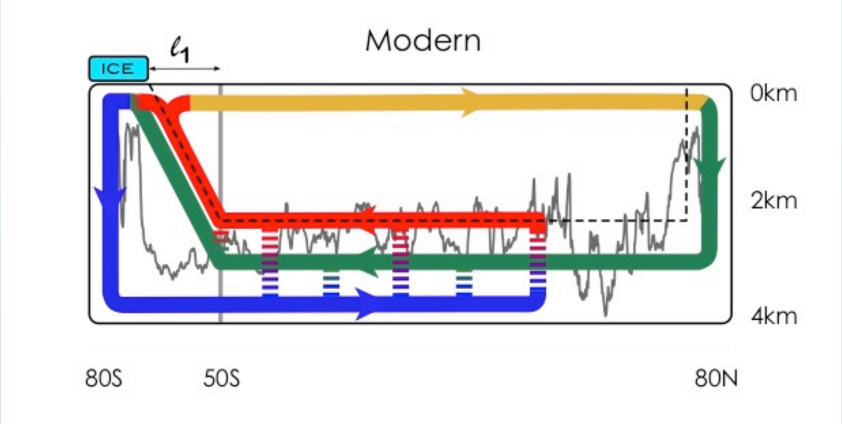
δ13C Observational Evidence

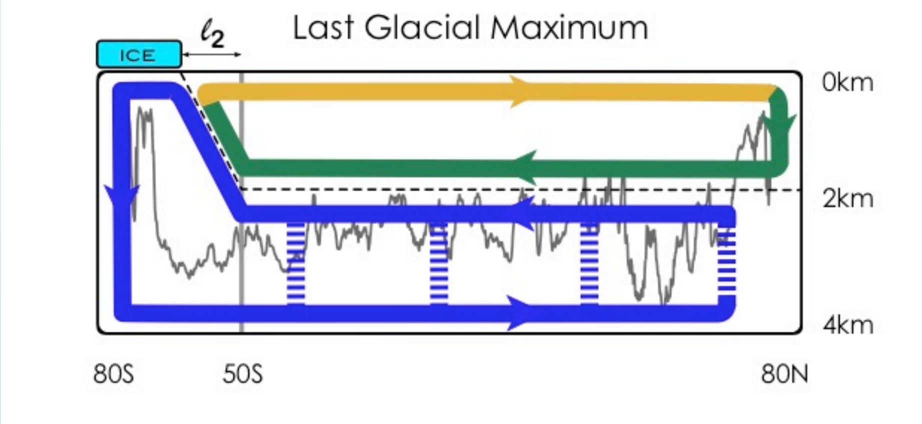
Modern



Last Glacial Maximum

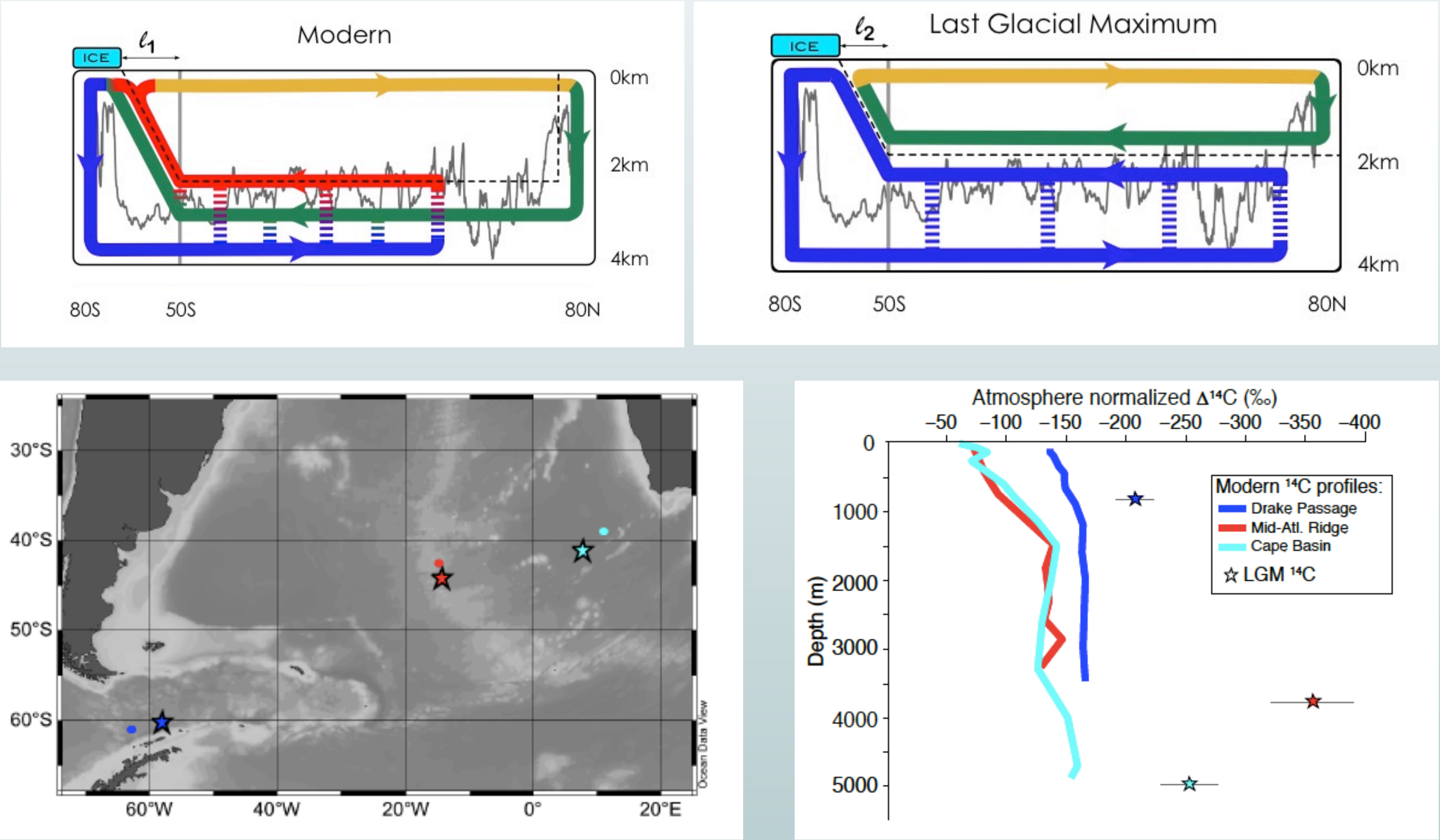






Ferrari et al. (2014)

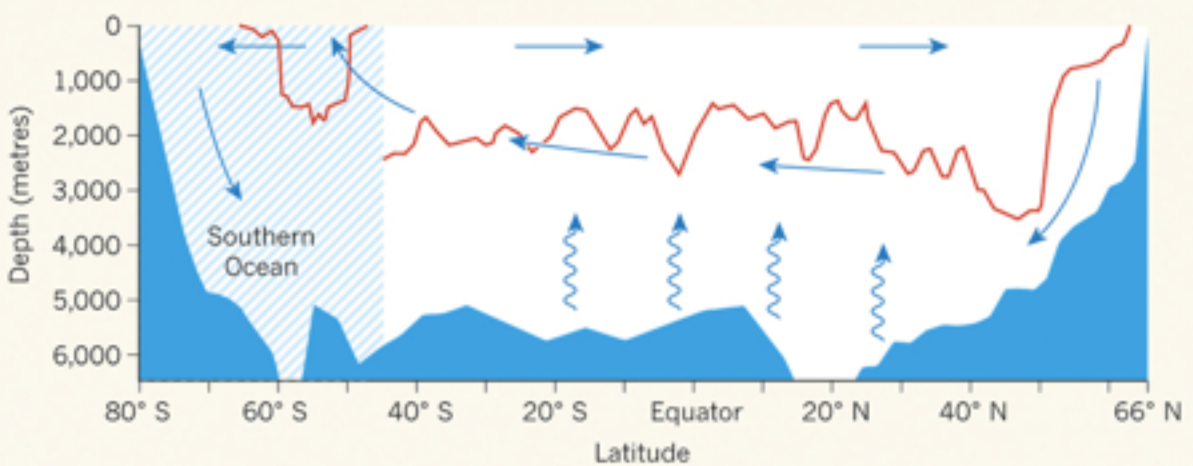
$\Delta^{14}C$ Observational Evidence



Burke et al. (2014)

Conclusions

- The deep ocean circulation and stratification is controlled by
  – winds and air-sea fluxes acting on the Southern Ocean
  – air-sea fluxes in the North Atlantic
  – mixing in the Atlantic, Indian and Pacific Oceans



Ferrari (2014)

- The theory must be extended to account for
  – uneven bottom topography
  – non-zonal structure of the Southern Ocean
  – presence of multiple closed basins

Conclusions

- The deep ocean circulation has not changed much in response to strengthening of the Southern hemisphere westerlies
  - no major changes in air-sea fluxes of carbon

- The deep ocean overturning circulation is composed of
  - a single figure eight cell in the modern climate
  - two separate cells at the Last Glacial Maximum
  - increased ocean storage of carbon