On the buoyancy-driven theory of the Atlantic Meridional Overturning Circulation

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AMOC Meeting, Brest, 4 May 2017

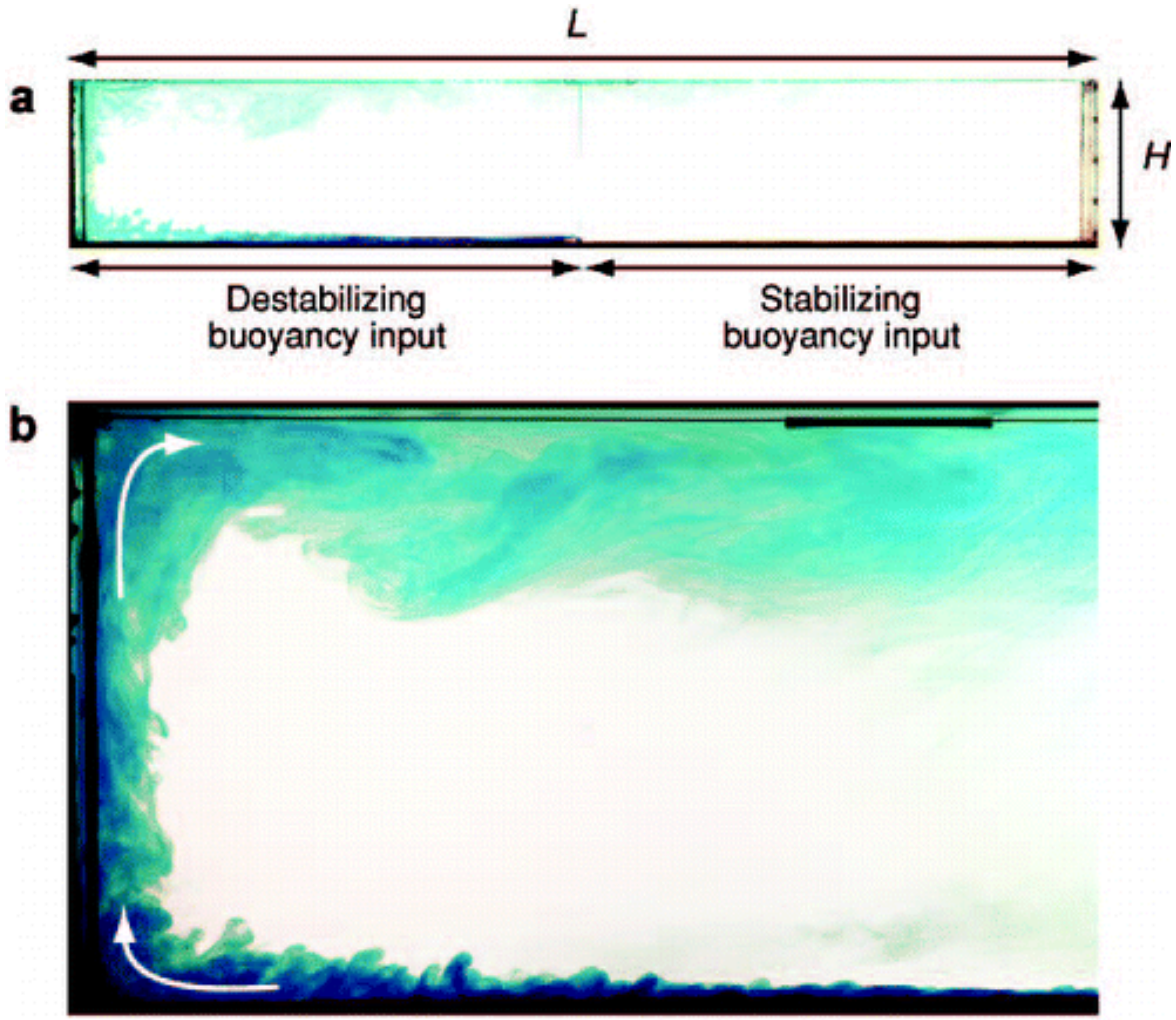
Outline

- A survey of thermodynamic and mechanical effects on AMOC strength
- Buoyancy-Driven theory of AMOC and Theory of Available Potential Energy
- Importance of ocean state for estimating driving forces
- Conclusions

Strength of AMOC is determined both by thermodynamic and mechanical effects

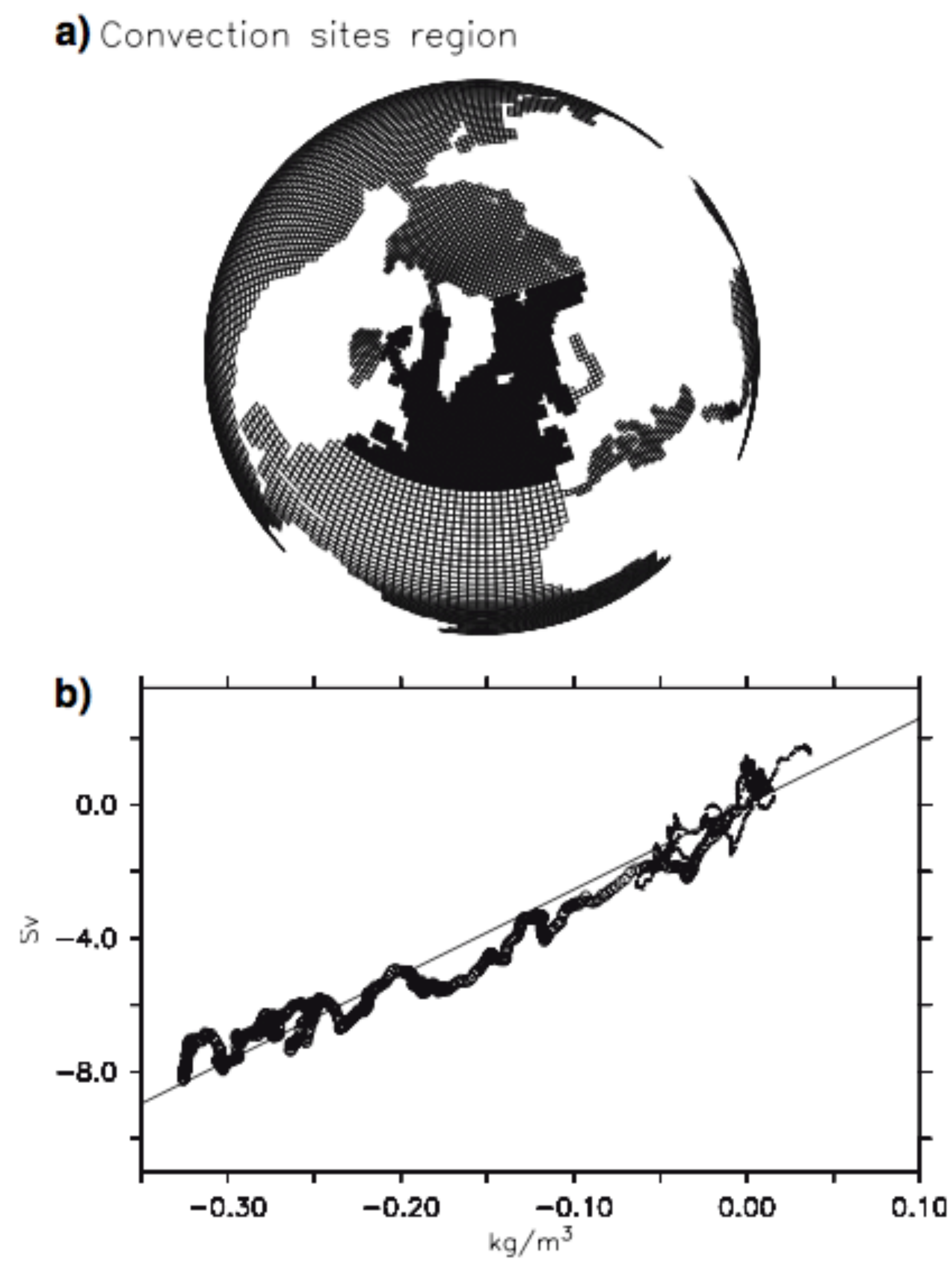
AMOC strength increases with strength of buoyancy source

GCM world: Swingedouw et al. (2007)



Hughes GO, Griffiths RW. 2008.
Annu. Rev. Fluid Mech. 40:185–208

Laboratory Experiments



Bryan (JPO, 1987): Thermocline depth and AMOC strength increase with vertical diffusivity

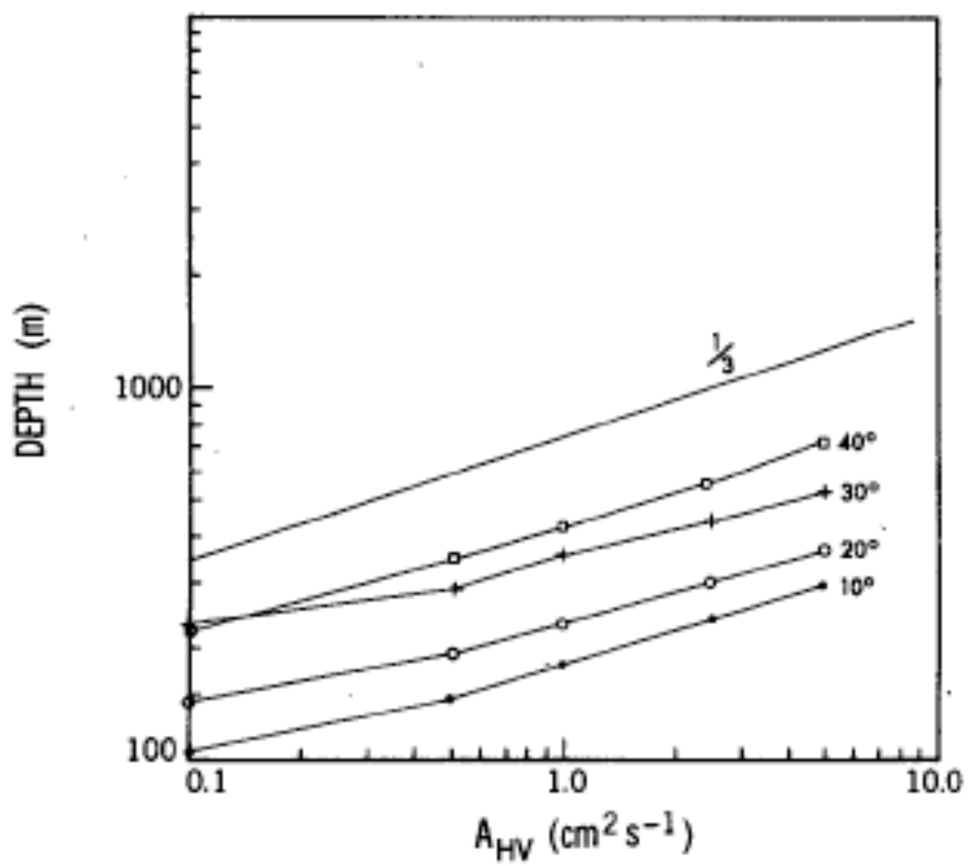


FIG. 4. Dependence of thermocline *e*-folding scale depth on vertical diffusivity at selected latitudes.

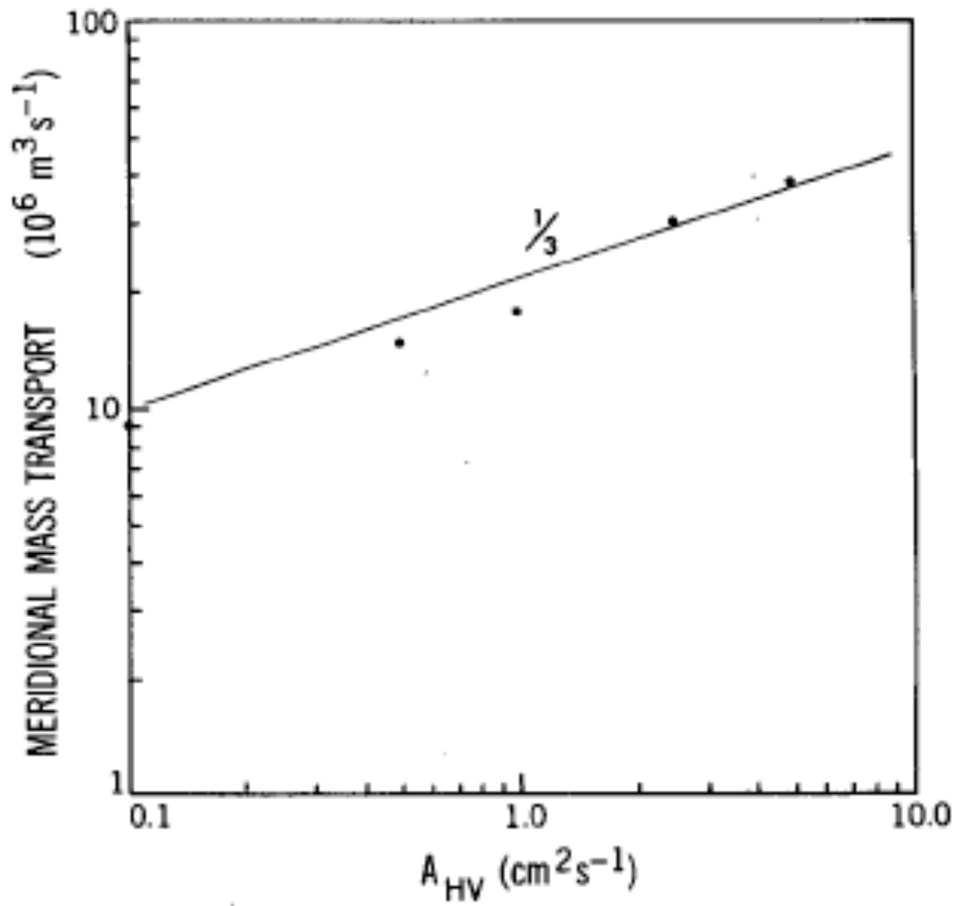


FIG. 8. Dependence of meridional overturning streamfunction on vertical diffusivity.

Vertical mixing is primarily driven by winds and tides, hence mechanically-driven

Drake Passage Effect
Toggweiler and Samuels (1993)

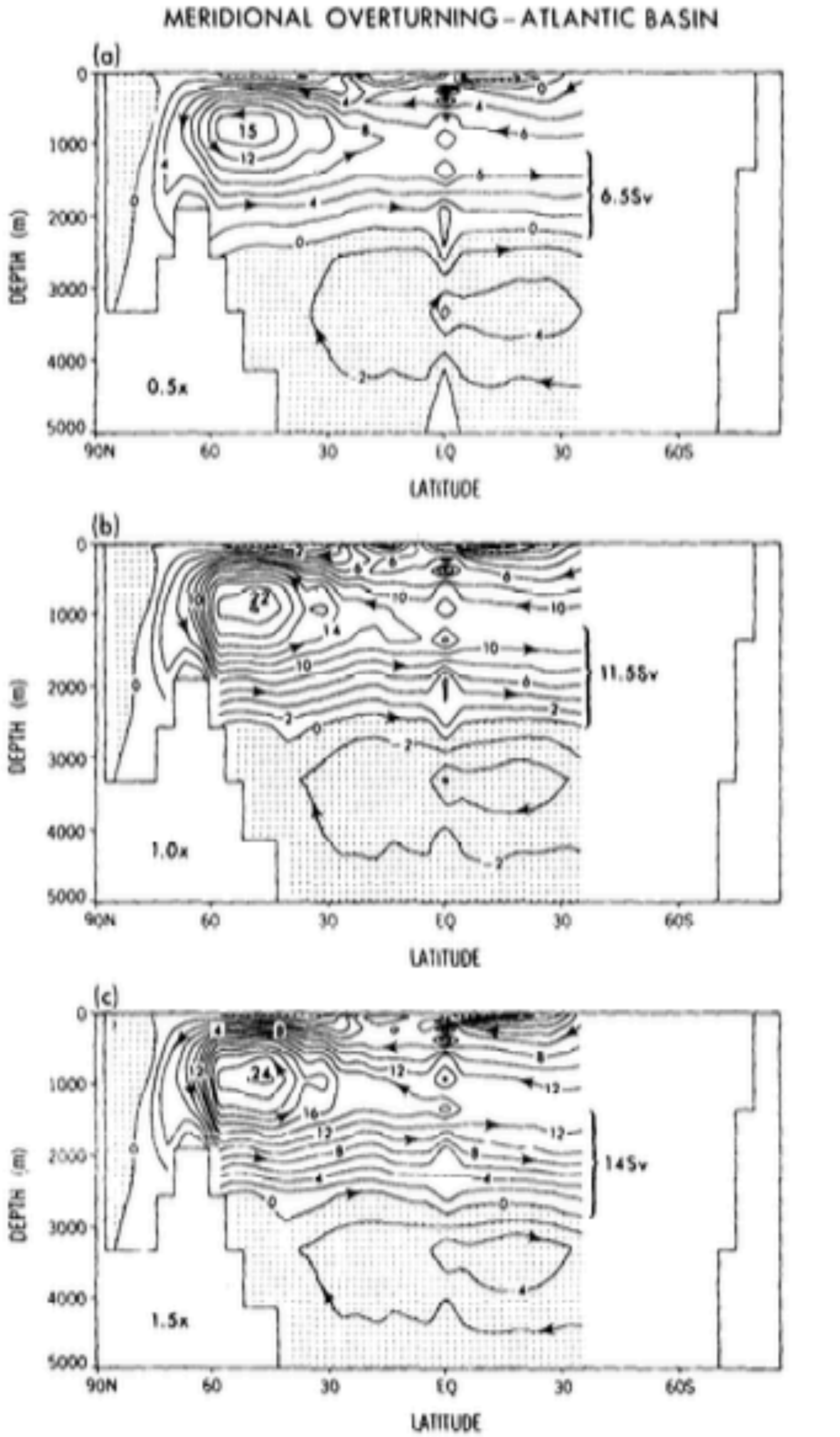
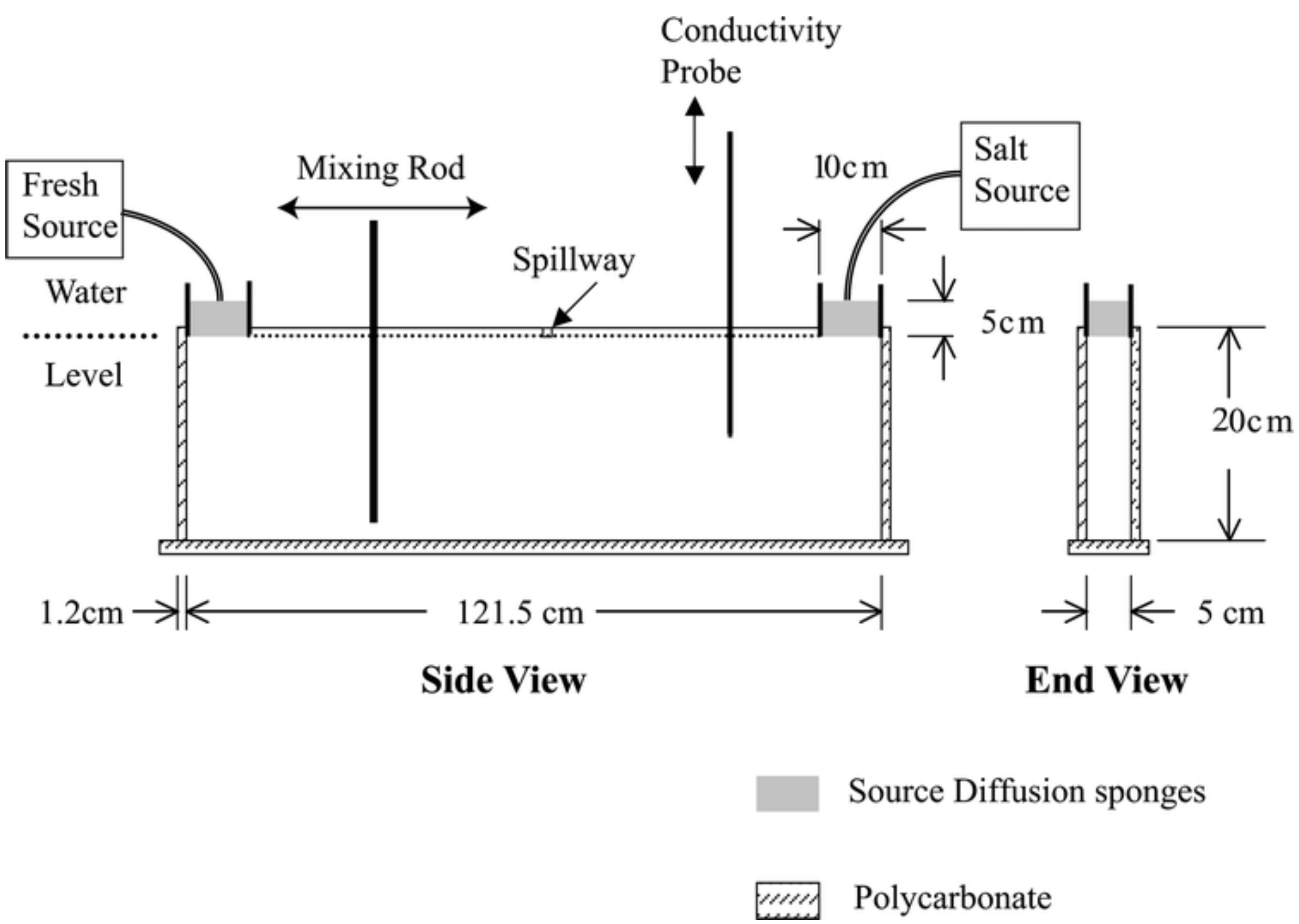


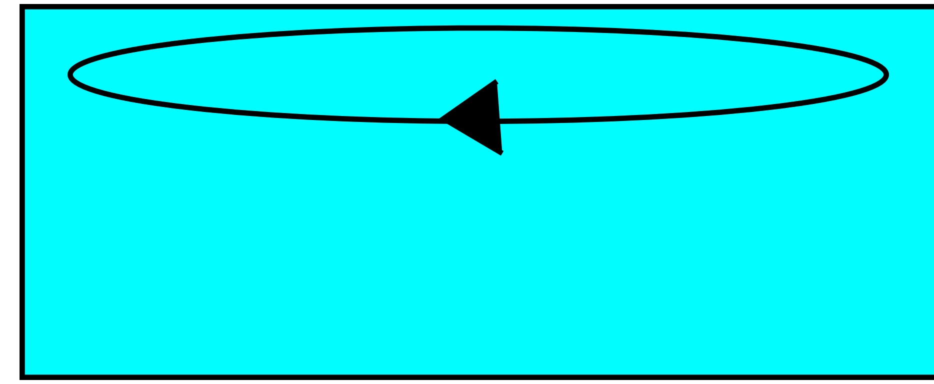
Fig. 3. Meridional overturning in the Atlantic basin from the 0.5× (top), 1.0× (middle) and 1.5× (bottom) wind sensitivity experiments. The flow between stream lines is 2 Sv. The outflow of deep water (of North Atlantic origin) through the South Atlantic scales with the wind stress applied south of 30°S. The model's outflow is indicated by the bracketed streamlines between roughly 1300 and 2600 m.

Strength of AMOC appears to linearly increase with strength of zonal wind at altitude of Drake Passage

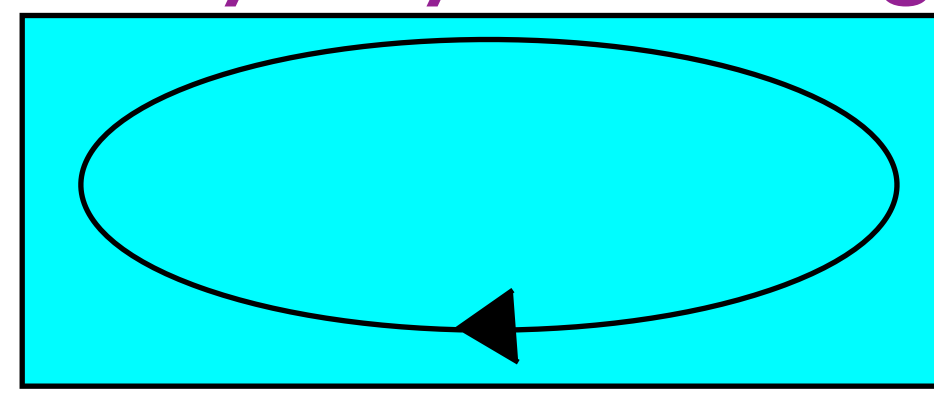
Whitehead and Wang (JPO,2008)

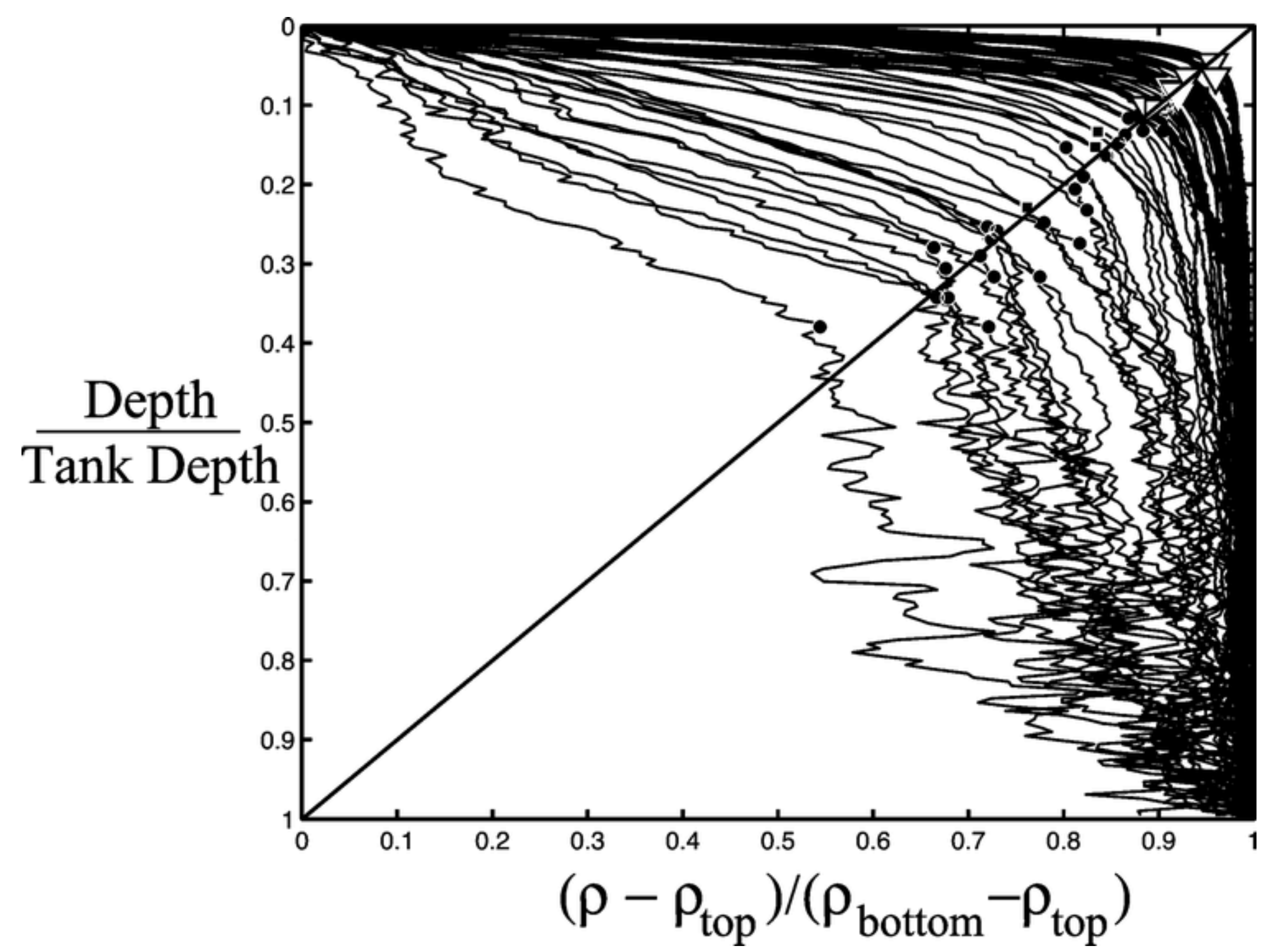


Buoyancy only



Buoyancy + Stirring





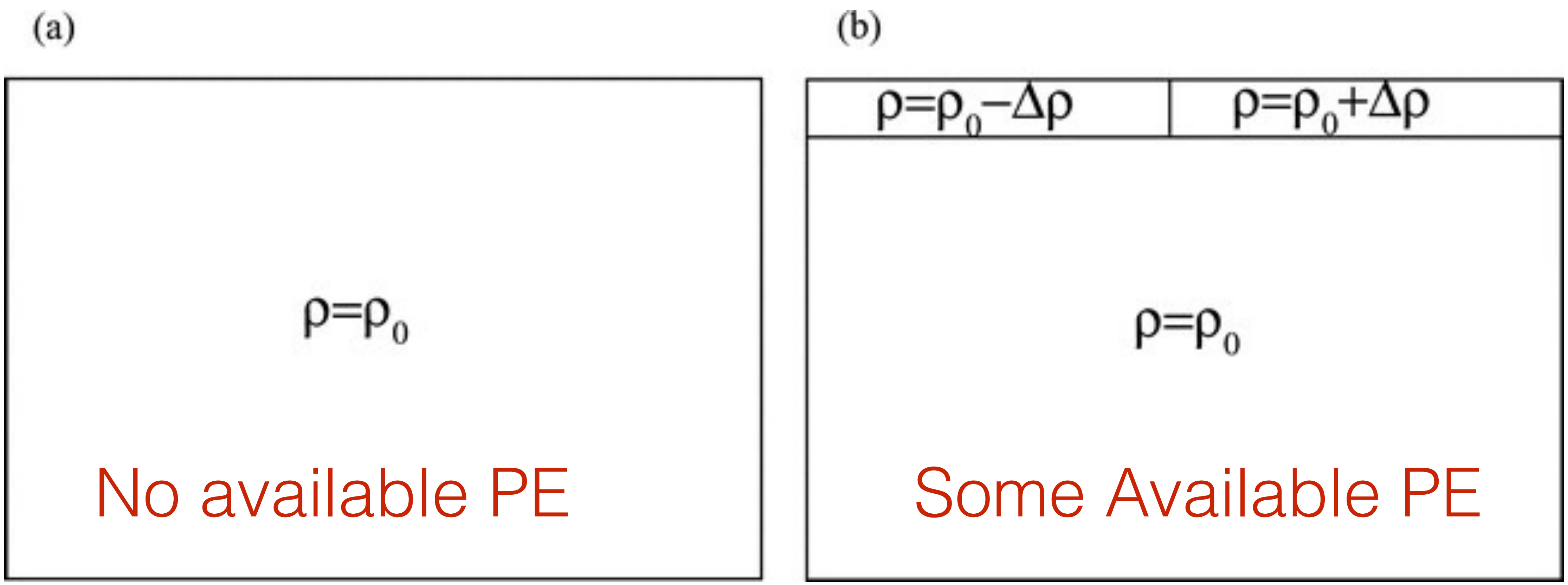
Turbulent stirring causes overturning to increase

Buoyancy-Driven or Mechanically-Driven?

What about
Mechanically-controlled buoyancy-driven
circulation?

Tailleux (2009); Tailleux and Rouleau (2010)

The same value of potential energy (PE) may reveal very different situations



PE = PEr + APE

Hughes et al., (JPO, 2009)

Lorenz (1955) theory of available potential energy

Boussinesq Momentum Equations

Coriolis

Buoyancy

+ Wind

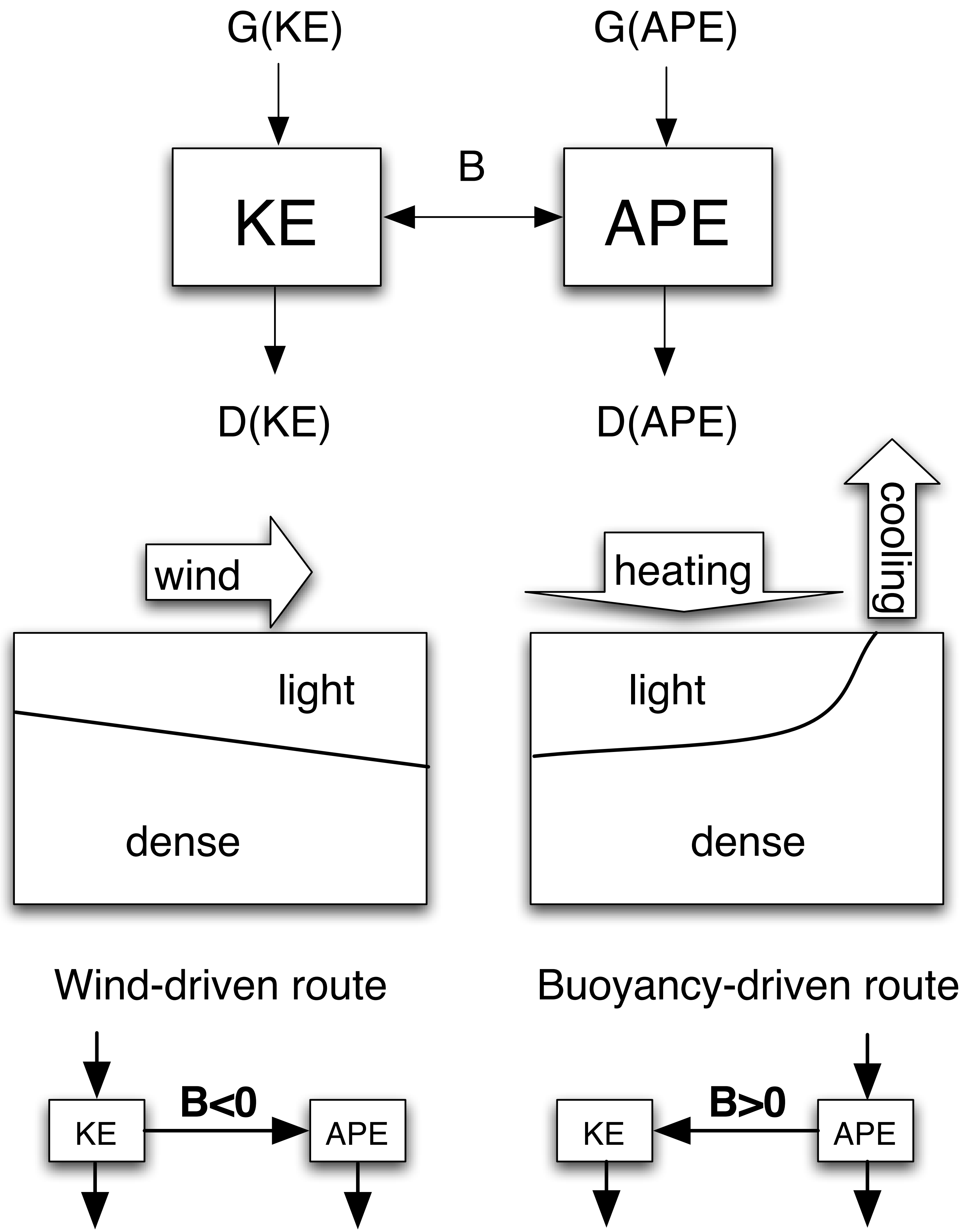
Wind

$$\frac{D\mathbf{u}}{Dt} + f\mathbf{z}\times\mathbf{u} + \frac{1}{\rho_0}\nabla_h\left(p - p_r(z)\right) = \frac{\partial}{\partial z}\left(A_v\frac{\partial\mathbf{u}}{\partial z}\right)$$

$$\frac{\partial(p - p_r)}{\partial z} = -g\left(\rho(S,\theta,z) - \rho_r(z)\right)$$

Wind-driven route versus buoyancy-driven route

Gregory and Tailleux (2011) Clim. Dyn.



Energetics: Filter out Coriolis

Multiply by horizontal velocity

$$\rho_0 \frac{D}{Dt}\frac{\mathbf{u}^2}{2} = -\mathbf{u}\bullet\nabla_h p + \rho_0 \frac{\partial}{\partial z}\left(A_v \frac{\partial}{\partial z}\frac{\mathbf{u}^2}{2}\right) - \rho_0 A_v \left(\frac{\partial \mathbf{u}}{\partial z}\right)^2$$

Integrate vertically

$$\int_{-H}^{0}\rho_0 \frac{De_k}{Dt}\,dz = -\int_{-H}^{0}\mathbf{u}\bullet\nabla_h(p-p_r)\,dz + \mathbf{u}\bullet\tau_s - \int_{-H}^{0}\rho_0 A_v\left(\frac{\partial\mathbf{u}}{\partial z}\right)^2 dz$$

APE to KE conversion

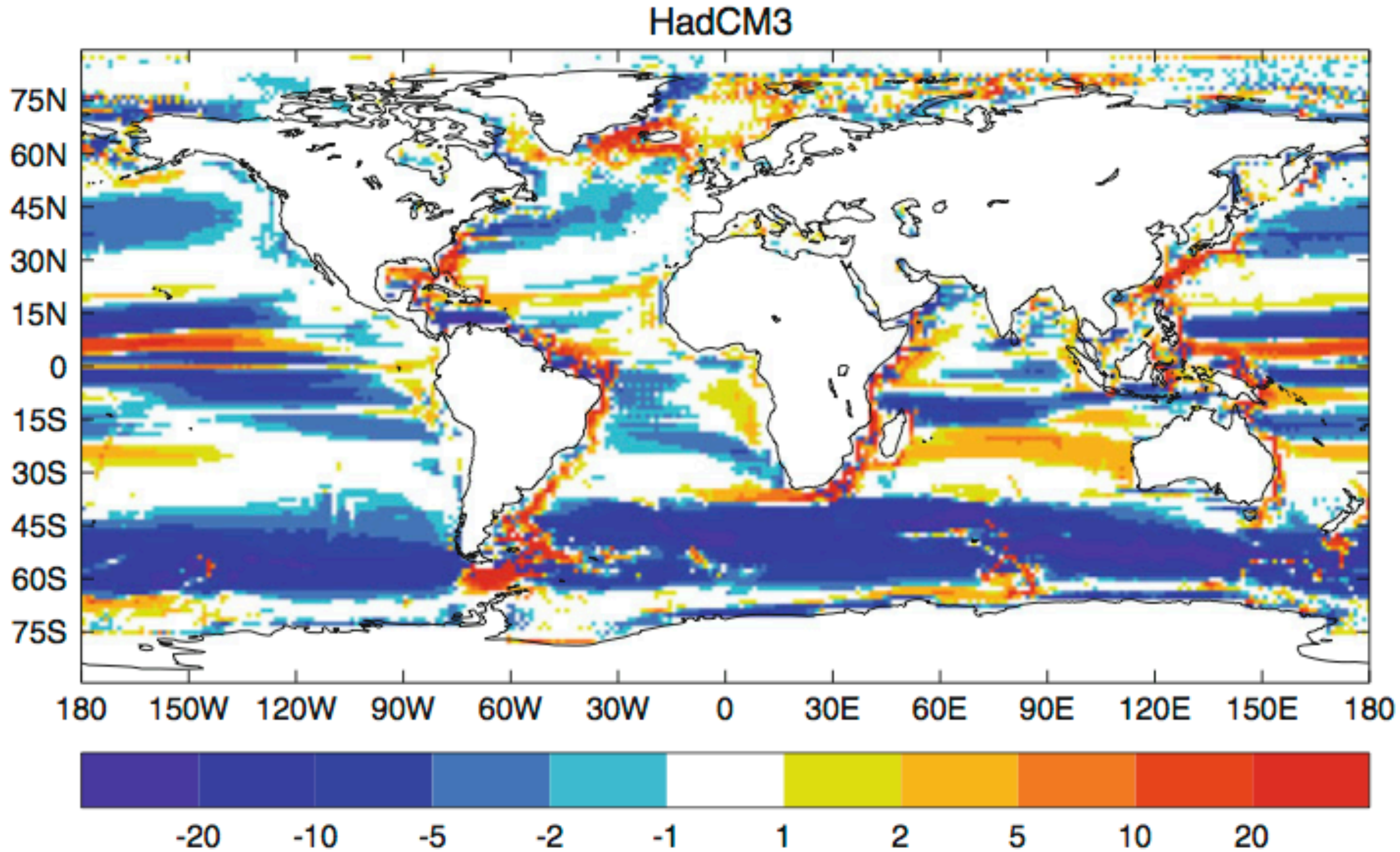
Wind work

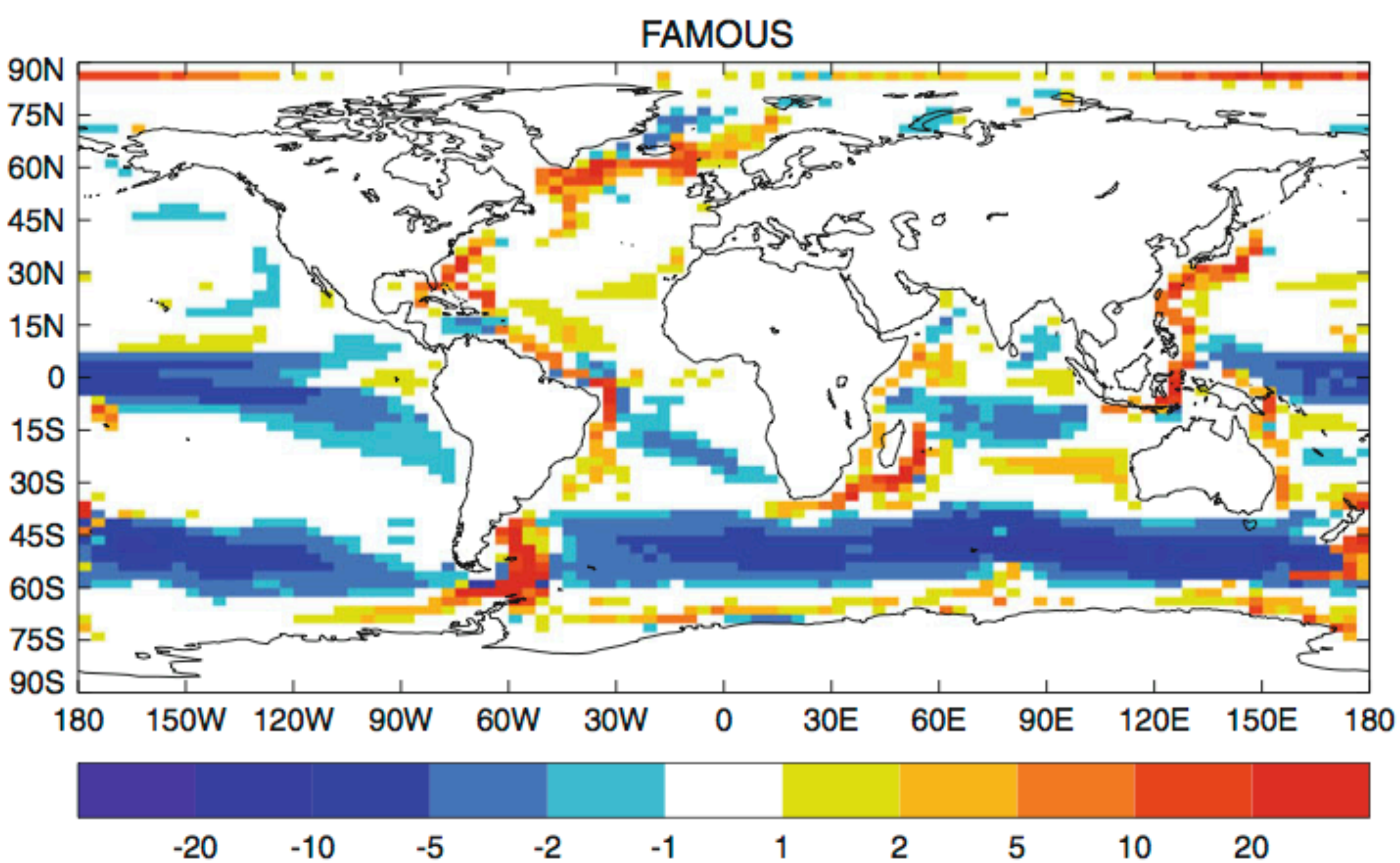
Viscous Dissipation

From Gregory and Tailleux, 2011

Local APE to KE Conversion ($mW.m^{-2}$)

$$-\int_{-H}^{0} \mathbf{u}\bullet\nabla_h P\, dz$$





Buoyancy-Driven Regions (High Latitudes, Western Boundaries)

Wind-Driven Regions (ACC, Equator,...)

Isolation of the wind forcing and viscous dissipation

$$\int_{-H}^{0} \rho_0 \mathbf{u} \bullet \frac{\partial}{\partial z}\left(A_v \frac{\partial \mathbf{u}}{\partial z} \right) dz = \mathbf{u}_s \bullet \boldsymbol{\tau}_s - \int_{-H}^{0} \rho_0 A_v \left(\frac{\partial \mathbf{u}}{\partial z} \right)^2 dz$$

Isolation of the buoyancy forcing and mixing?

$$-\int_{-H}^{0} \mathbf{u} \bullet \nabla_h (p - p_r) dz = \text{Buoyancy} + \text{Mixing} + \ldots$$

Buoyancy-driven theory seeks to link pressure gradient work to surface buoyancy fluxes and interior mixing processes

Local Definition of Available Potential Energy = Work of buoyancy force from rest state to actual state = quadratic positive definite for small amplitude

$$e_a(S,\theta,z) = \int_{z_r(S,\theta)}^{z} \frac{g\left(\rho(S,\theta,z') - \rho_r(z')\right)}{\rho_0} dz' \approx \frac{N^2\left(z - z_r\right)^2}{2}$$

APE density satisfies local evolution equation

$$\rho_0 \frac{De_a}{Dt} = (\rho - \rho_r)gw - \rho_0 \alpha g(z - z_r)\frac{D\theta}{Dt} + \rho_0 \beta g(z - z_r)\frac{DS}{Dt}$$

Manipulate and integrate vertically

$$-\int_{-H}^{0} \mathbf{u} \bullet \nabla(p - p_r) dz = \rho_0 g |z_r| \left(\beta S_0 (E - P) - \frac{\alpha Q}{c_p} \right) - \int_{-H}^{0} \rho_0 K_v N_r^{\,2} \, dz - \int_{-H}^{0} \rho_0 \frac{De_a}{Dt} dz - \nabla \bullet \int_{-H}^{0} p' \mathbf{u} \, dz$$

Production by surface buoyancy fluxes

Dissipation by Mixing

Horizontal Transfers

State Dependent Wind and Buoyancy Forcing

Wind Forcing depends on Ocean Surface Velocity

$$G(KE) = \iint_S \mathbf{u}_s \bullet \tau_s \, dx\, dy$$

Buoyancy Forcing depends on Lorenz Reference Depth

$$G(APE) = \iint_S g|z_r| \left(\rho_0 \beta S_0 (E - P) - \frac{\alpha Q}{c_p} \right) dx\, dy$$

Buoyancy-Driven Theory of the AMOC

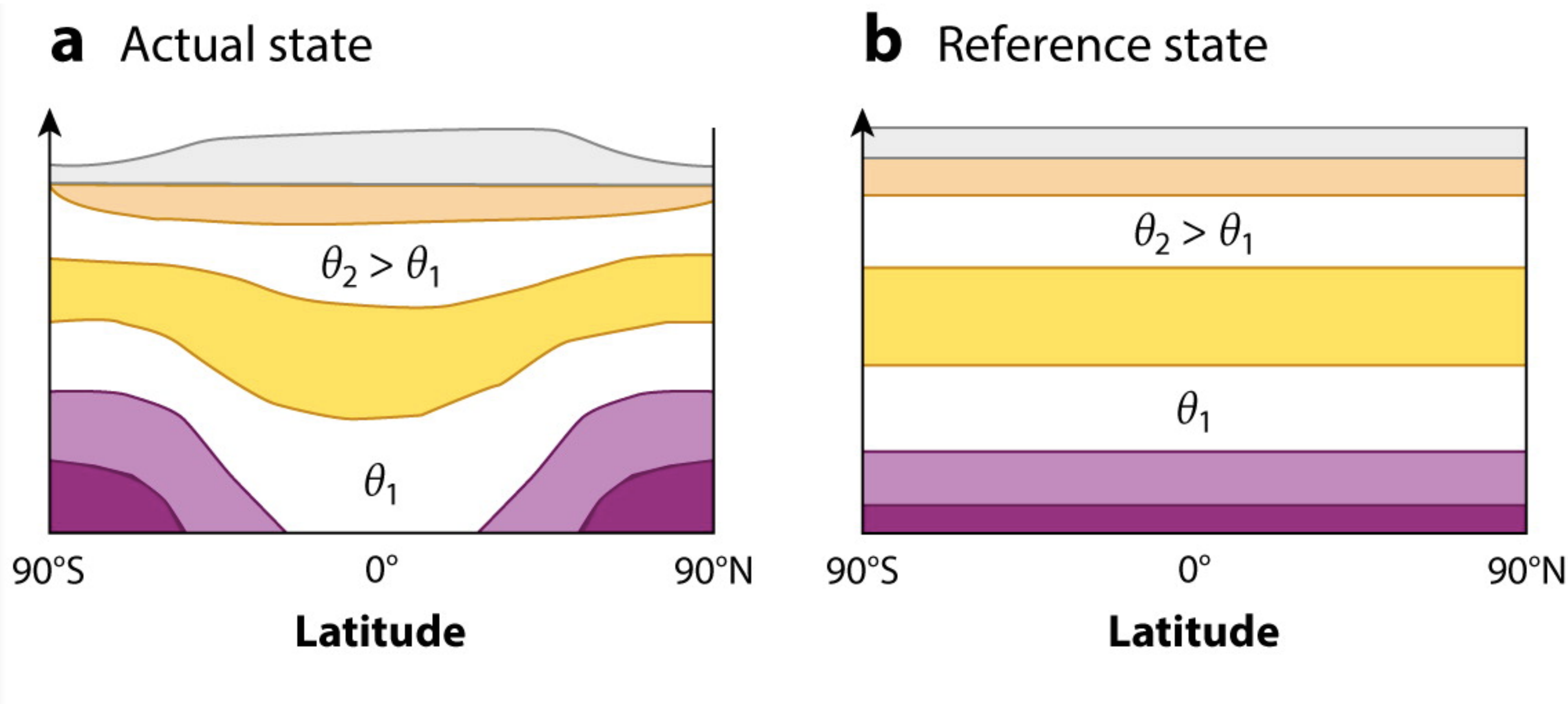
Unknown Proportionality Factor

$$\Psi_{AMOC} = k_{atlantic} \iint_{Atlantic} g|z_r| \left(\rho_0 \beta (E-P) - \frac{\alpha Q}{c_p} \right) dxdy$$

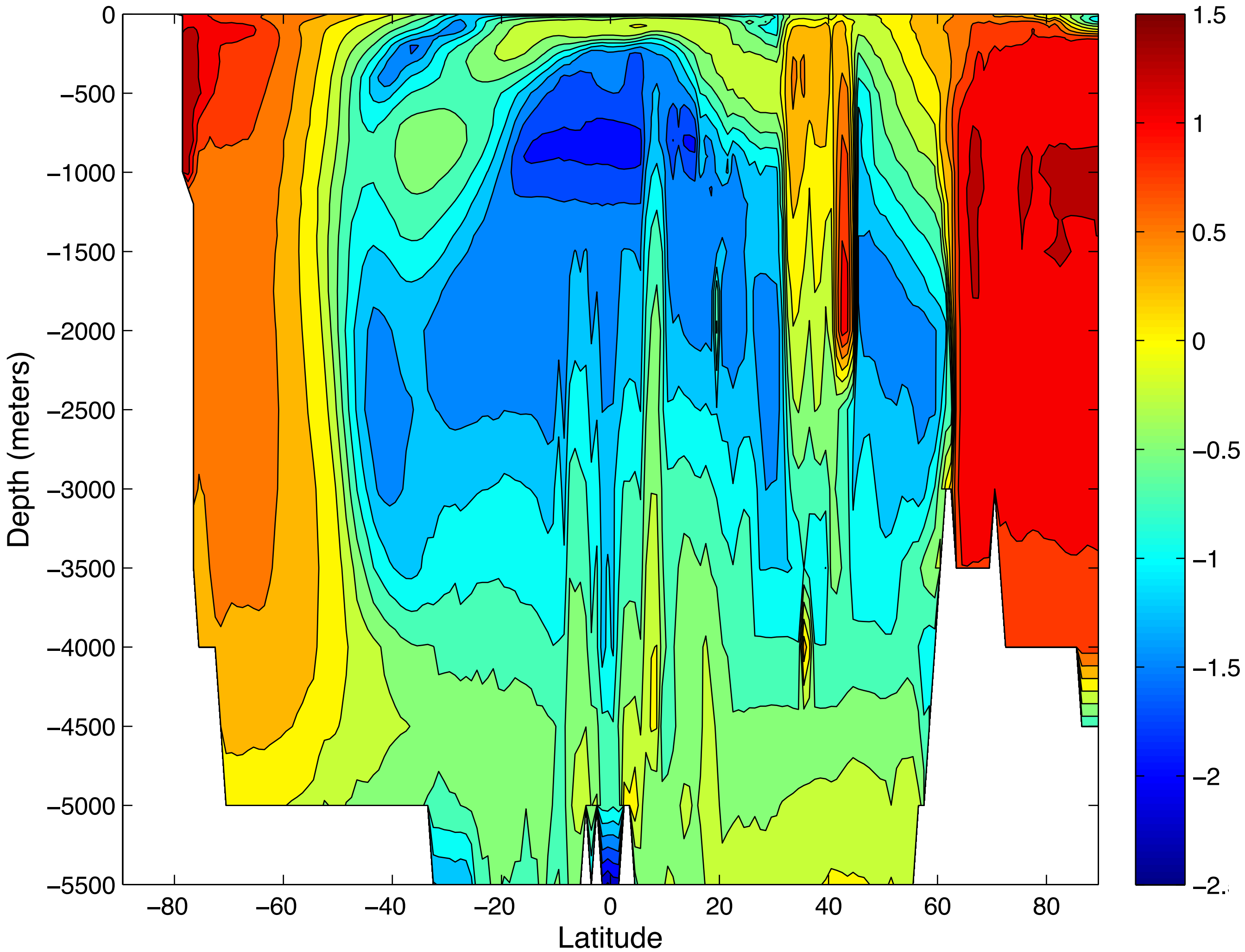
Mechanically-controlled Reference Depth (e.g., mixing)

Buoyancy Forcing

Lorenz (1955) theory of available potential energy and its moist extension (1978,1979)



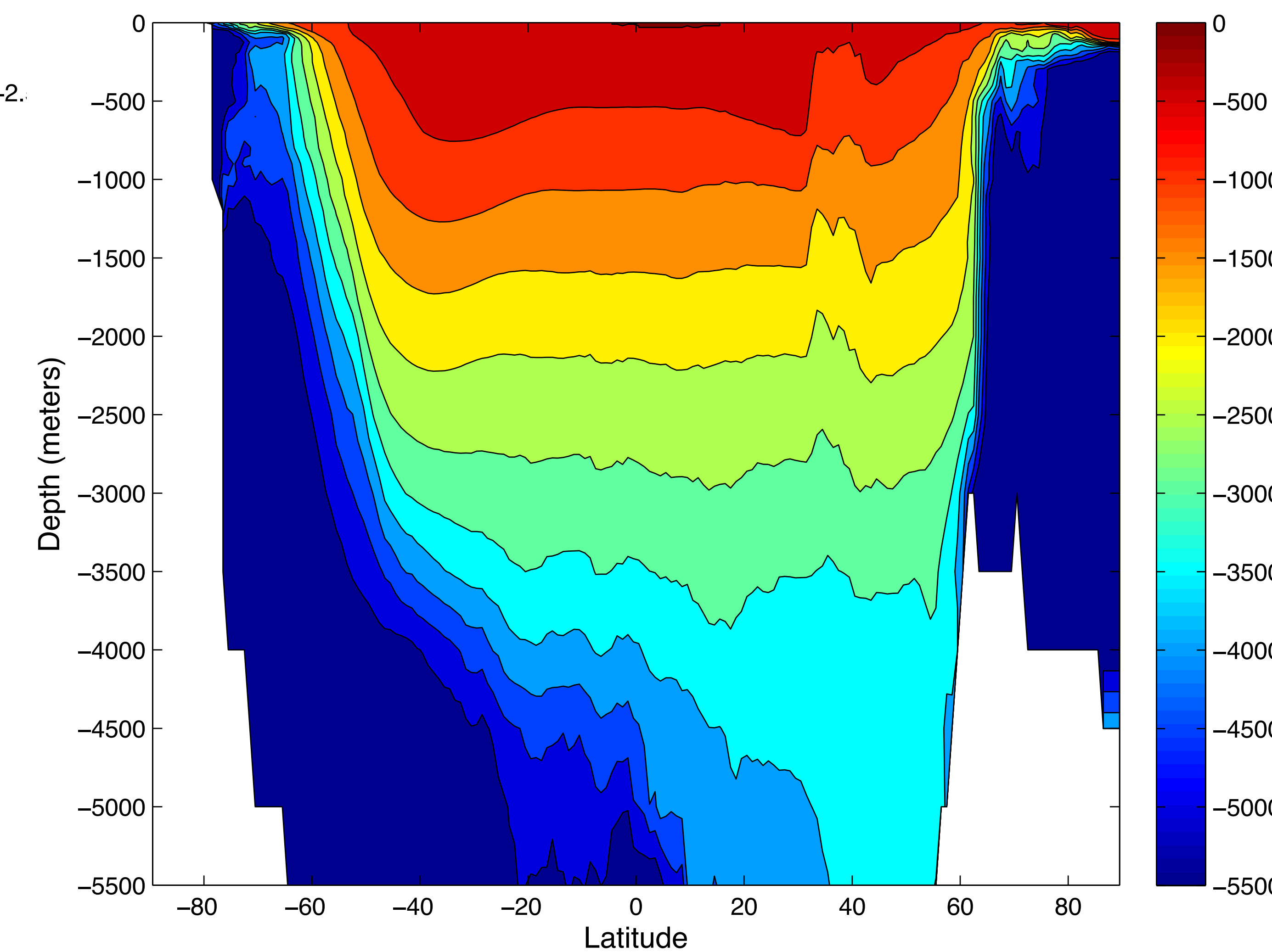
Tailleux, ARFM, 2013



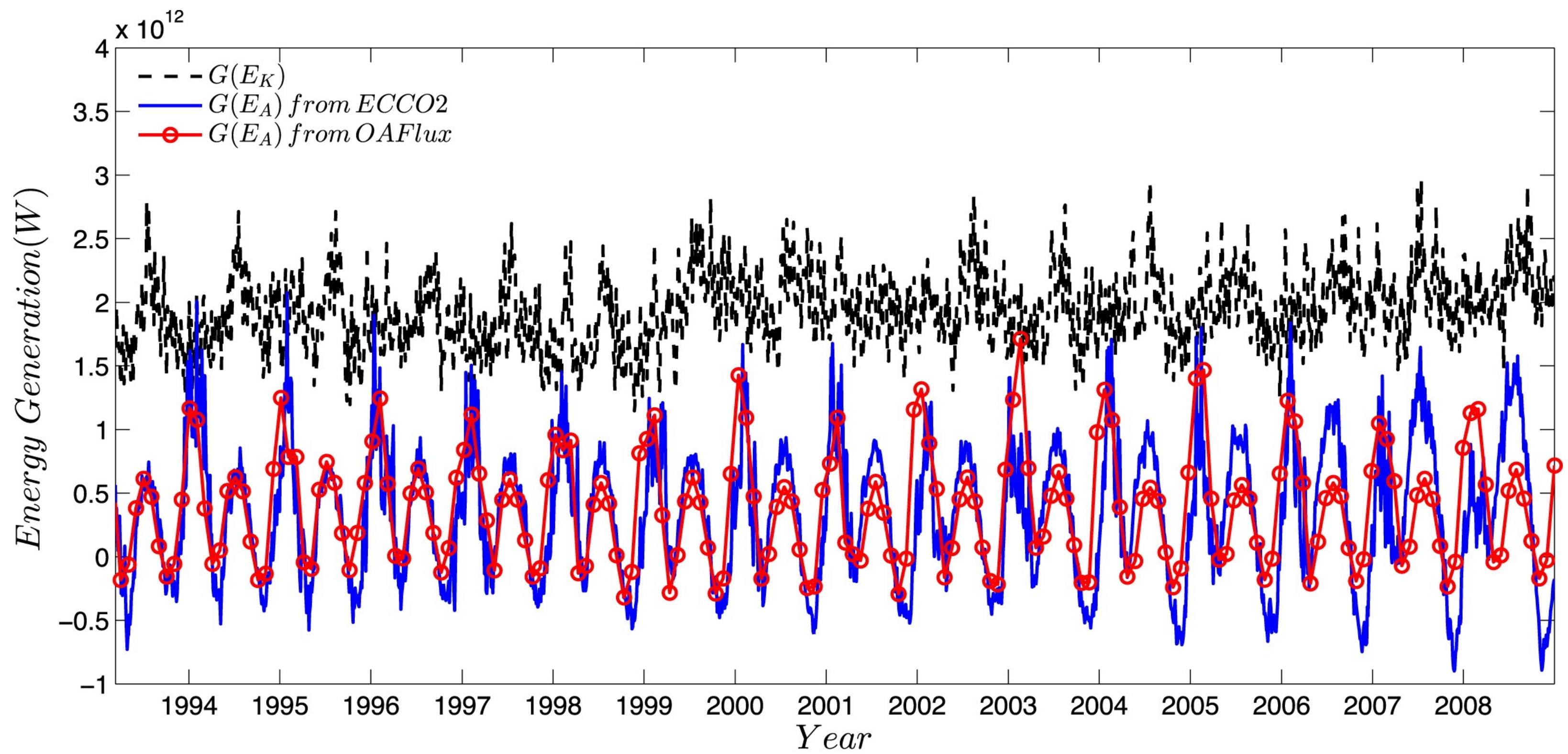
Decimal Logarithm of zonally-averaged APE density

Zonally-averaged Reference position

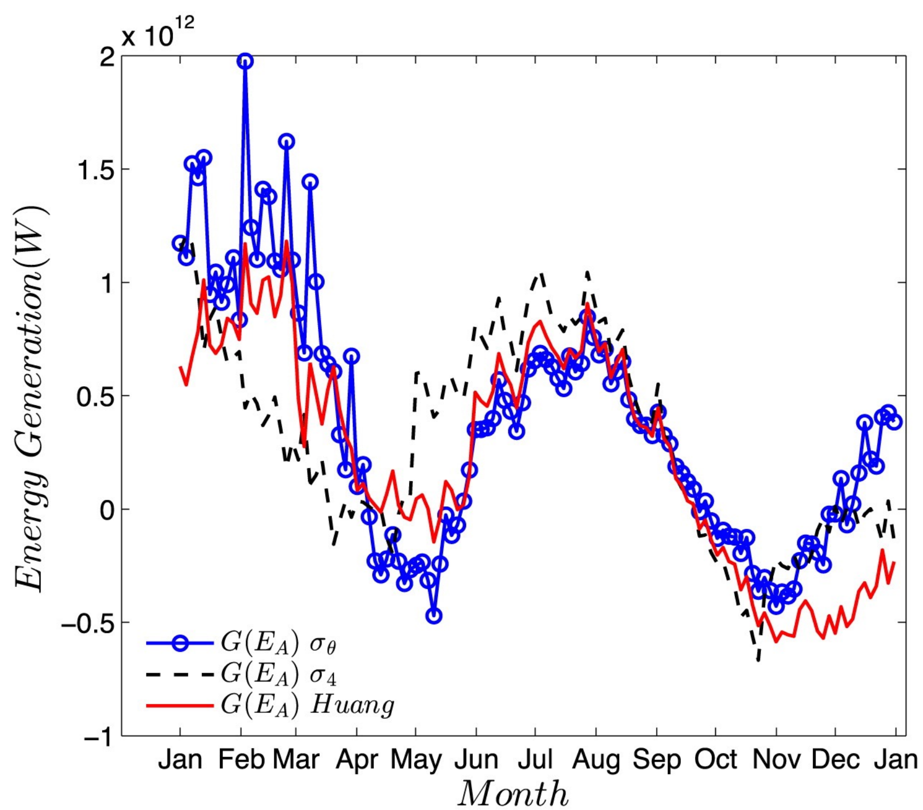
Tailleux 2013, Saenz et al. (2015)



From Zemkova et al. (JPO, 2015)



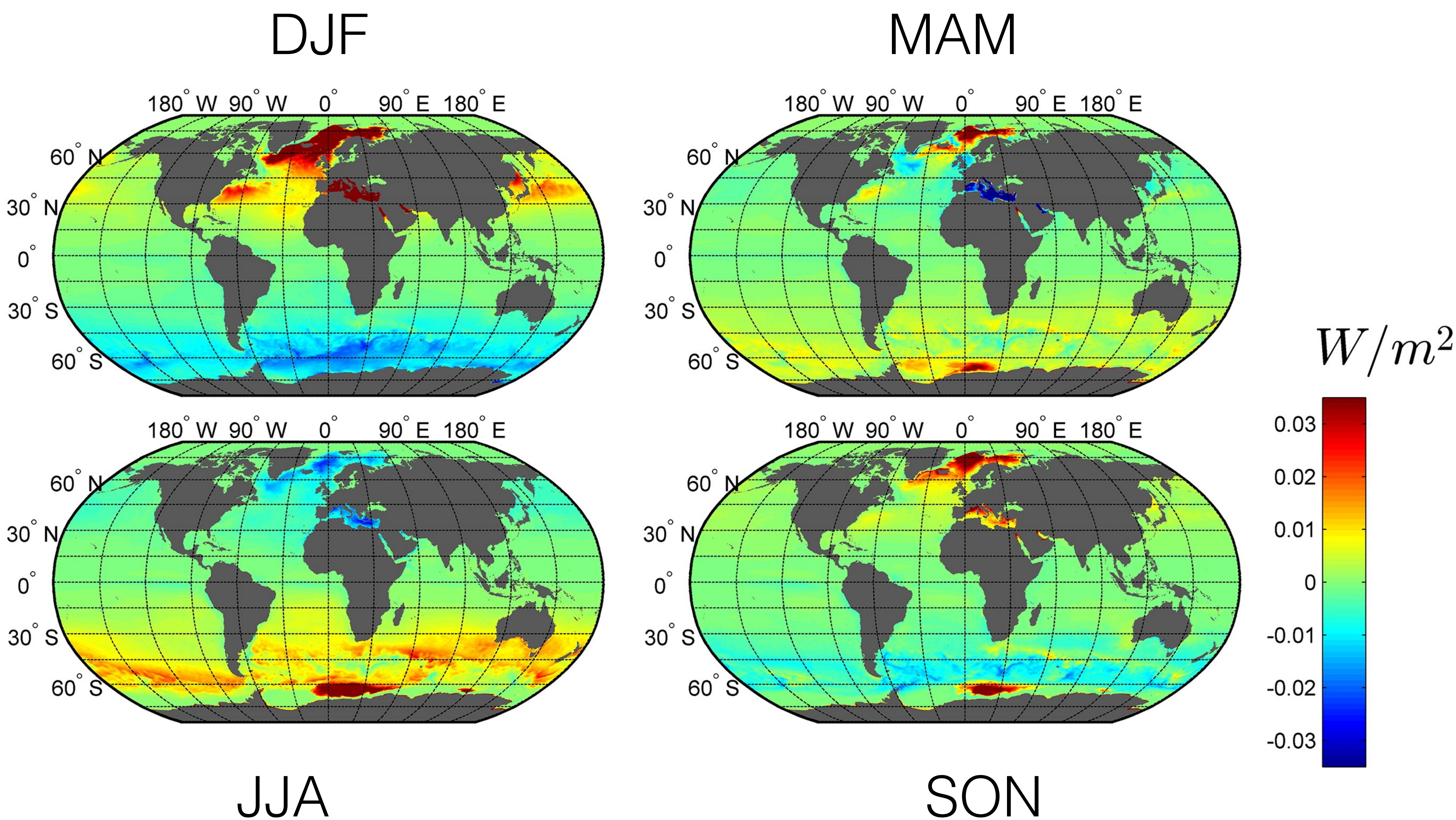
(a)



(b)

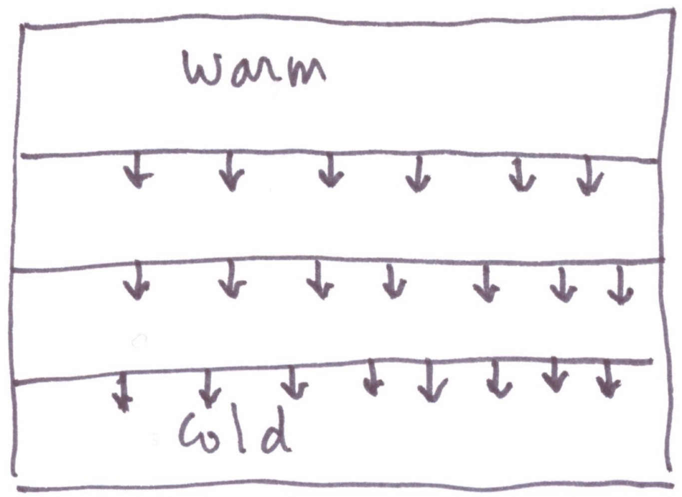
Seasonally averaged APE generation rate from ECCO2

From Zemkova et al. (JPO, 2015)



Increasing mixing controls G(APE) through increasing thermocline depth

Laminar case

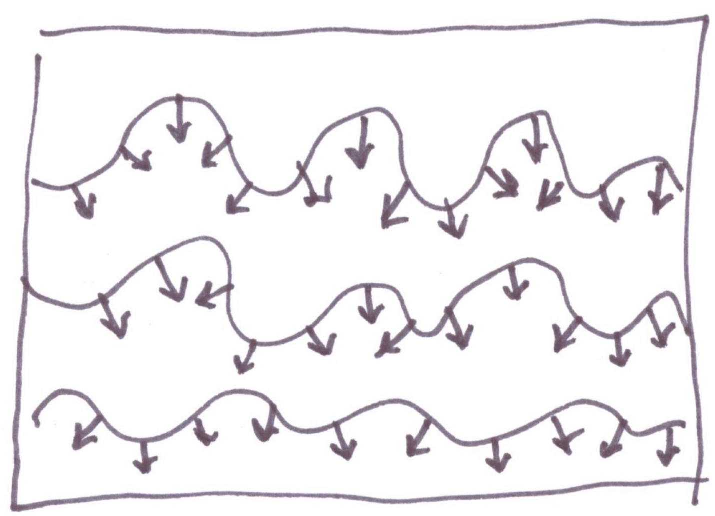


Total Heat Flux =

$$-\kappa_T A_{laminar} \rho C_p \frac{\partial T}{\partial z}$$

$$= F_{laminar}$$

Turbulent case



Total heat Flux =

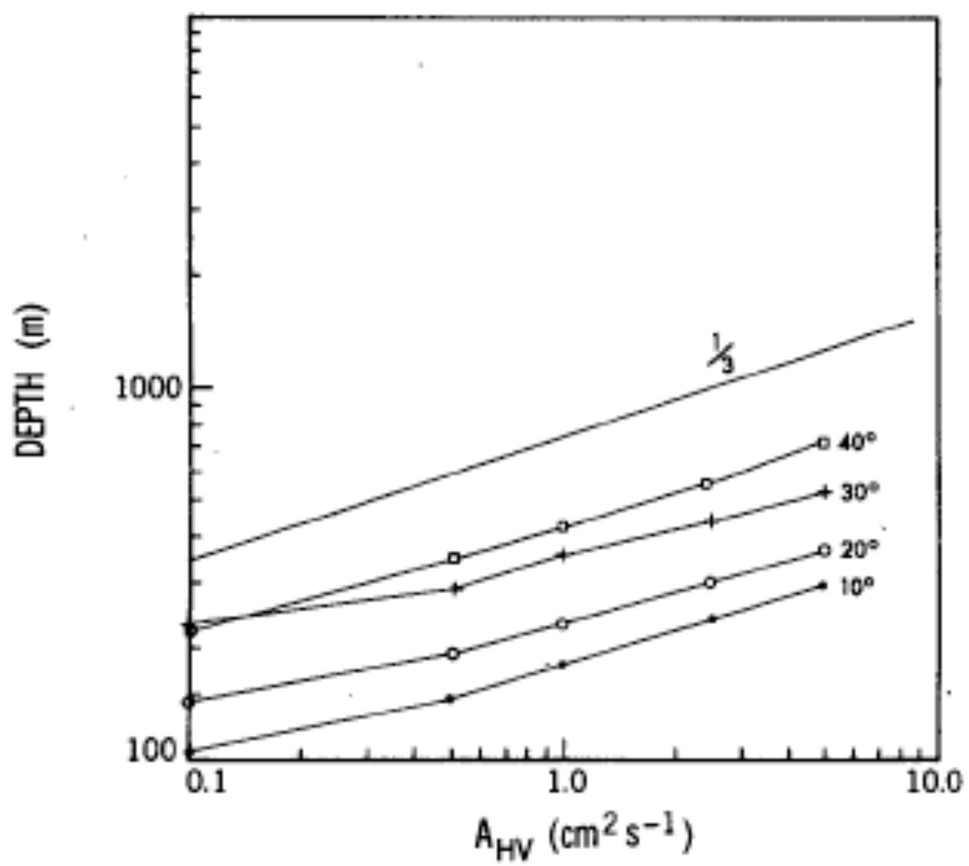
$$-\kappa_T A_{turbulent} \rho C_p \left\langle \frac{\partial T}{\partial n} \right\rangle$$

$$= F_{turbulent}$$

One shows that: $\left\langle \frac{\partial T}{\partial n} \right\rangle \simeq \frac{A_{turbulent}}{A_{laminar}} \times \frac{\partial T}{\partial z}$

$$\Rightarrow \quad F_{turbulent} = \left(\frac{A_{turbulent}}{A_{laminar}} \right)^2 F_{laminar}$$

Bryan (JPO, 1987): Thermocline depth and AMOC strength increase with vertical diffusivity



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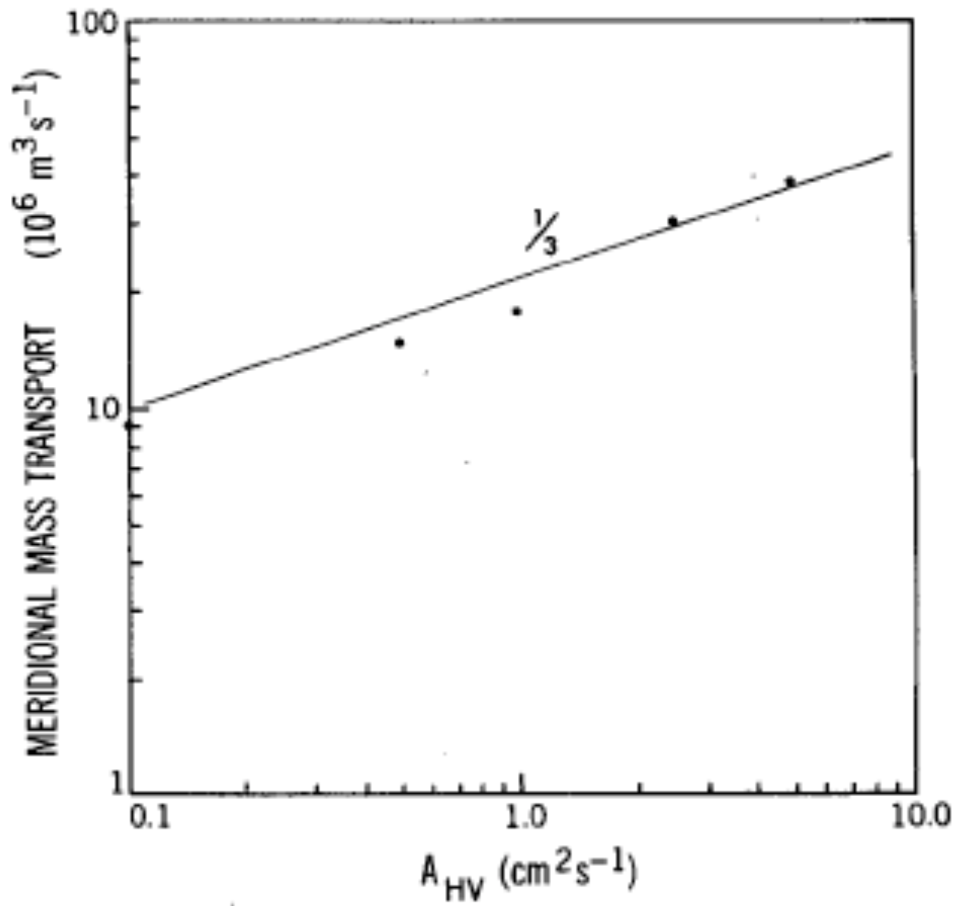

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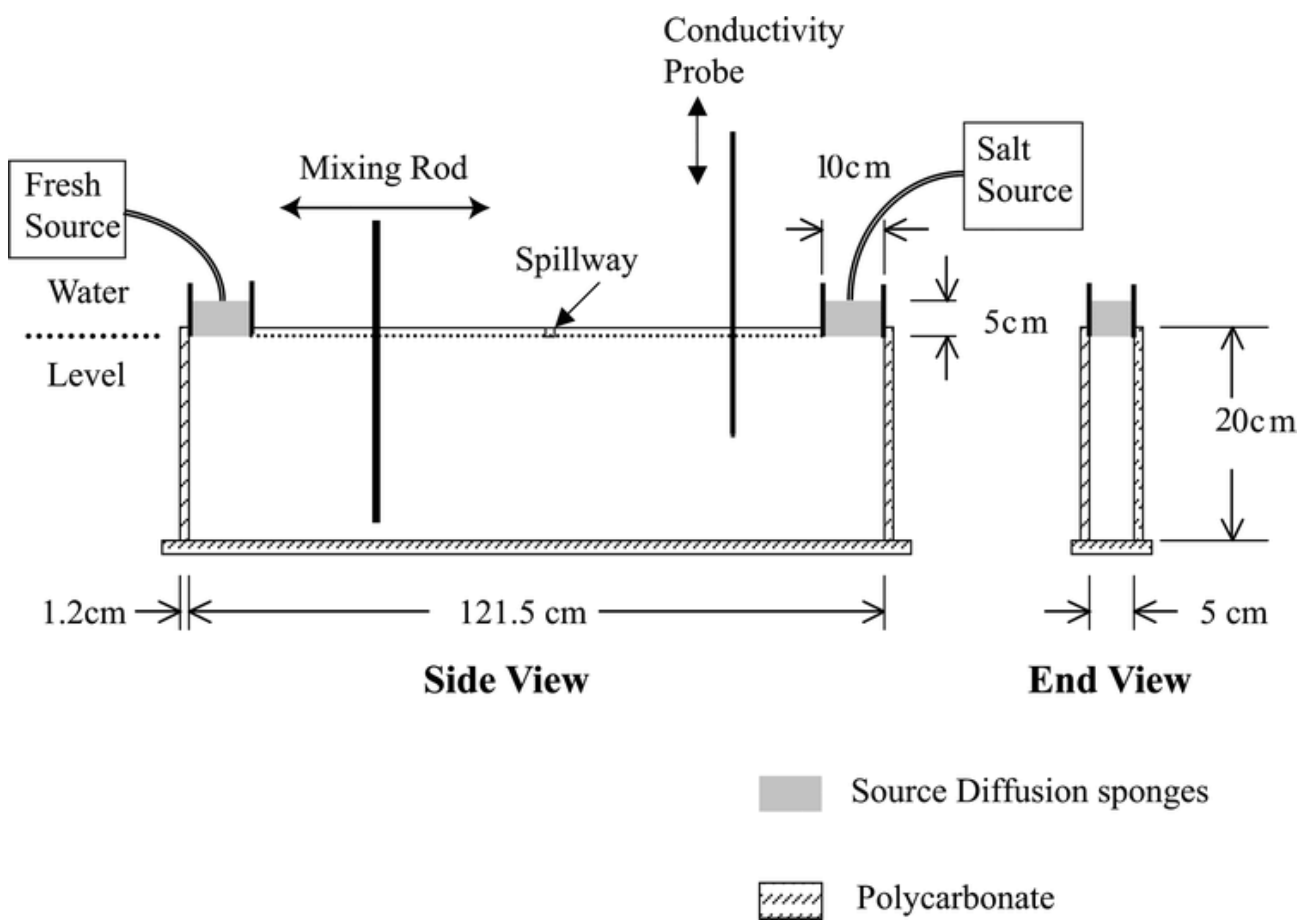
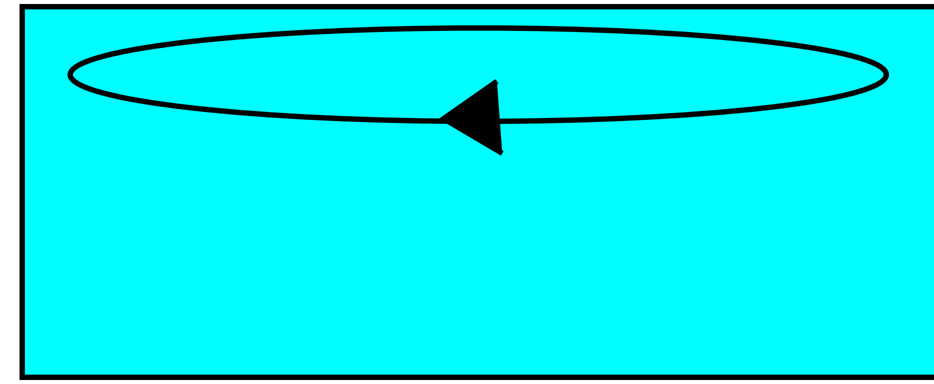
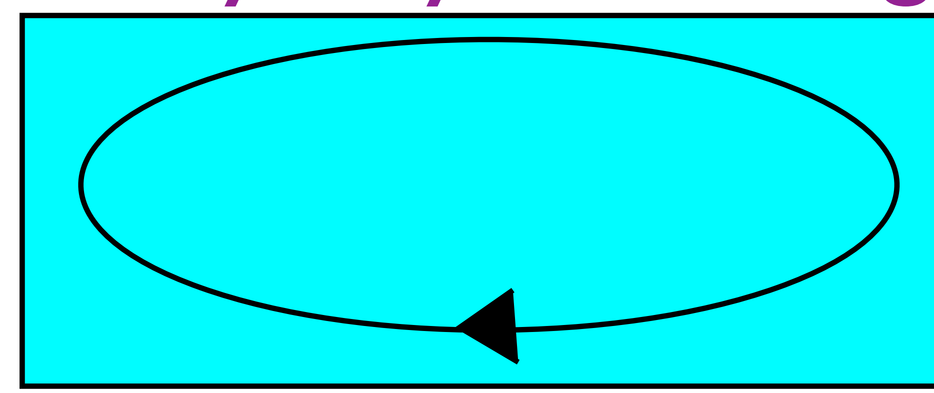
Whitehead and Wang (JPO,2008)

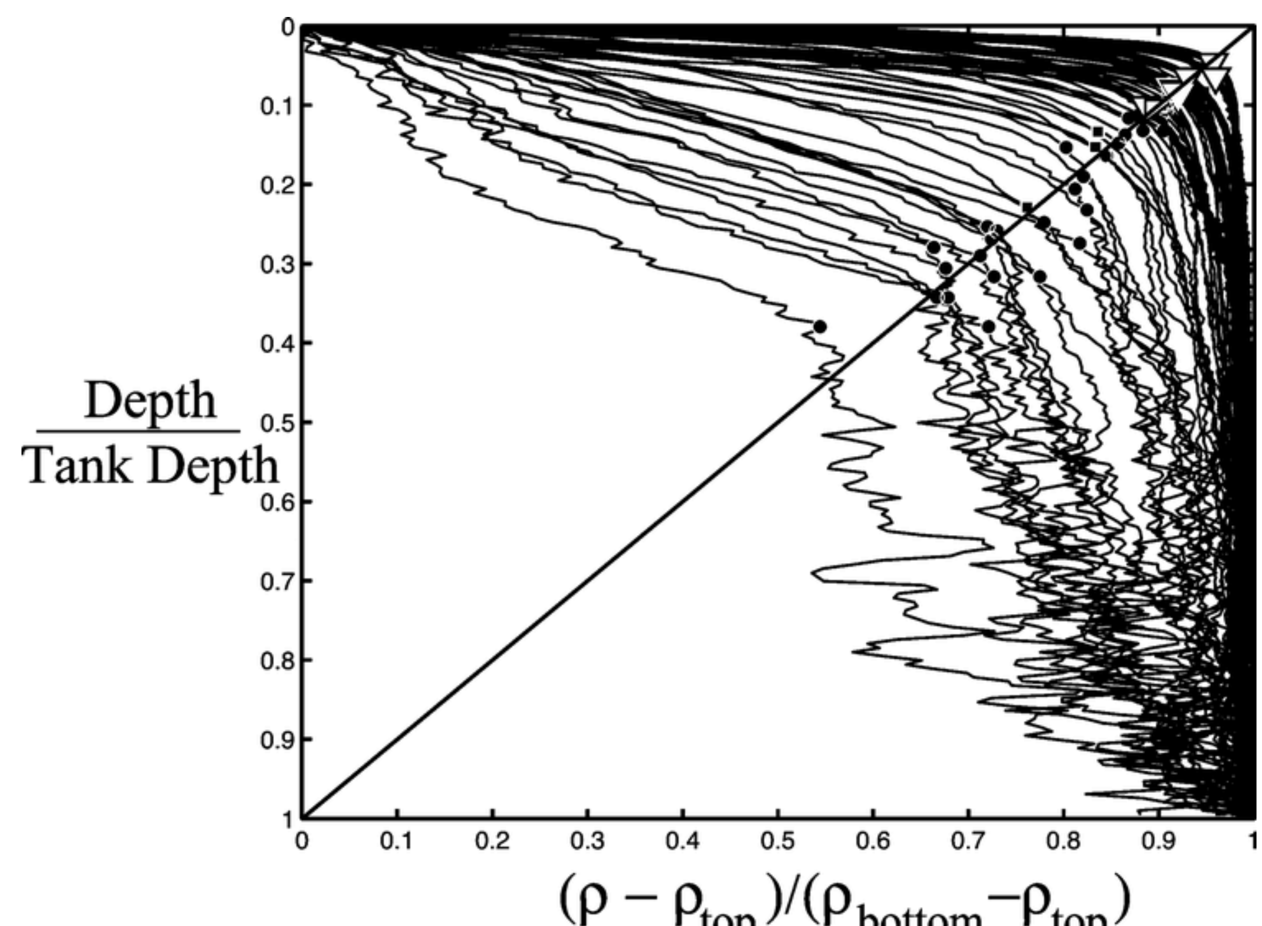


Buoyancy only



Buoyancy + Stirring





Stirring causes stratification to deepen, increasing APE production, increasing overturning

Increase in zonal wind at Drake Passage increases net heating over ACC, which in steady state requires increasing net cooling in Northern Polar Regions thus increasing G(APE) and AMOC

GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 13, PAGES 1873-1876, JULY 1, 1999

Atlantic deep circulation controlled by heating in the Southern Ocean

Hiroyasu Hasumi and Nobuo Suginohara

Center for Climate System Research, University of Tokyo, Japan

Abstract. Thermohaline circulation has been considered to be driven by localized buoyancy loss through the sea surface at high latitudes and broadly distributed buoyancy gain elsewhere. Our numerical modeling study, however, shows that buoyancy gain for the Atlantic deep circulation is localized in the Southern Ocean. Wind-induced upwelling there causes efficient heat transfer to the deep ocean, and controls intensity of the Atlantic deep circulation as thermohaline circulation.

buoyancy loss of North Atlantic Deep Water (NADW) in the northern North Atlantic and buoyancy gain somewhere else. Here we try to answer this question by carrying out numerical experiments.

Model and Experiments

The OGCM used in this study is CCSR-OGCM [*Hasumi and Suginohara*, 1999a] with the Uniformly Third-Order Polynominal Interpolation Algorithm (UTOPIA) [*Leonard*

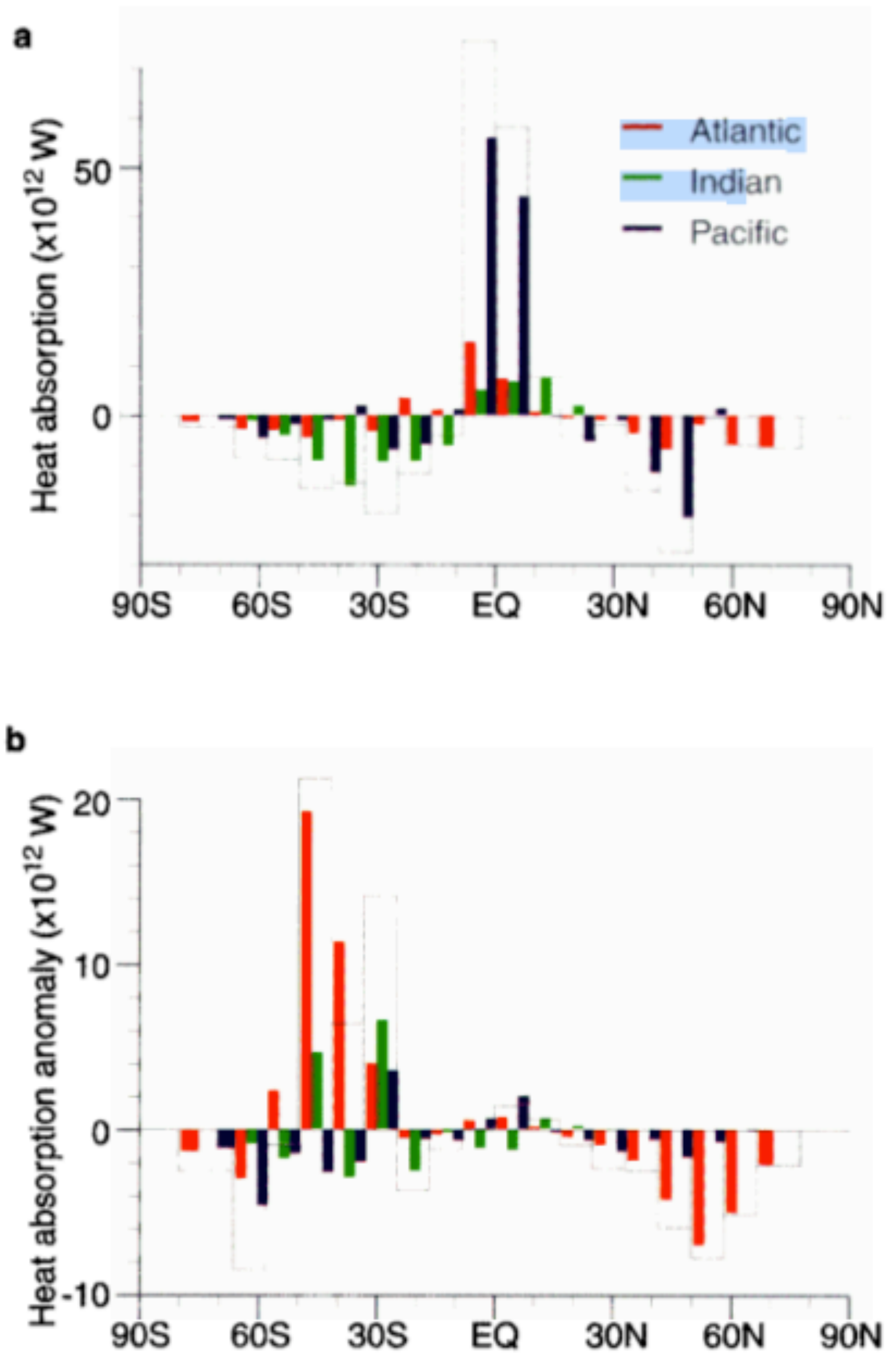
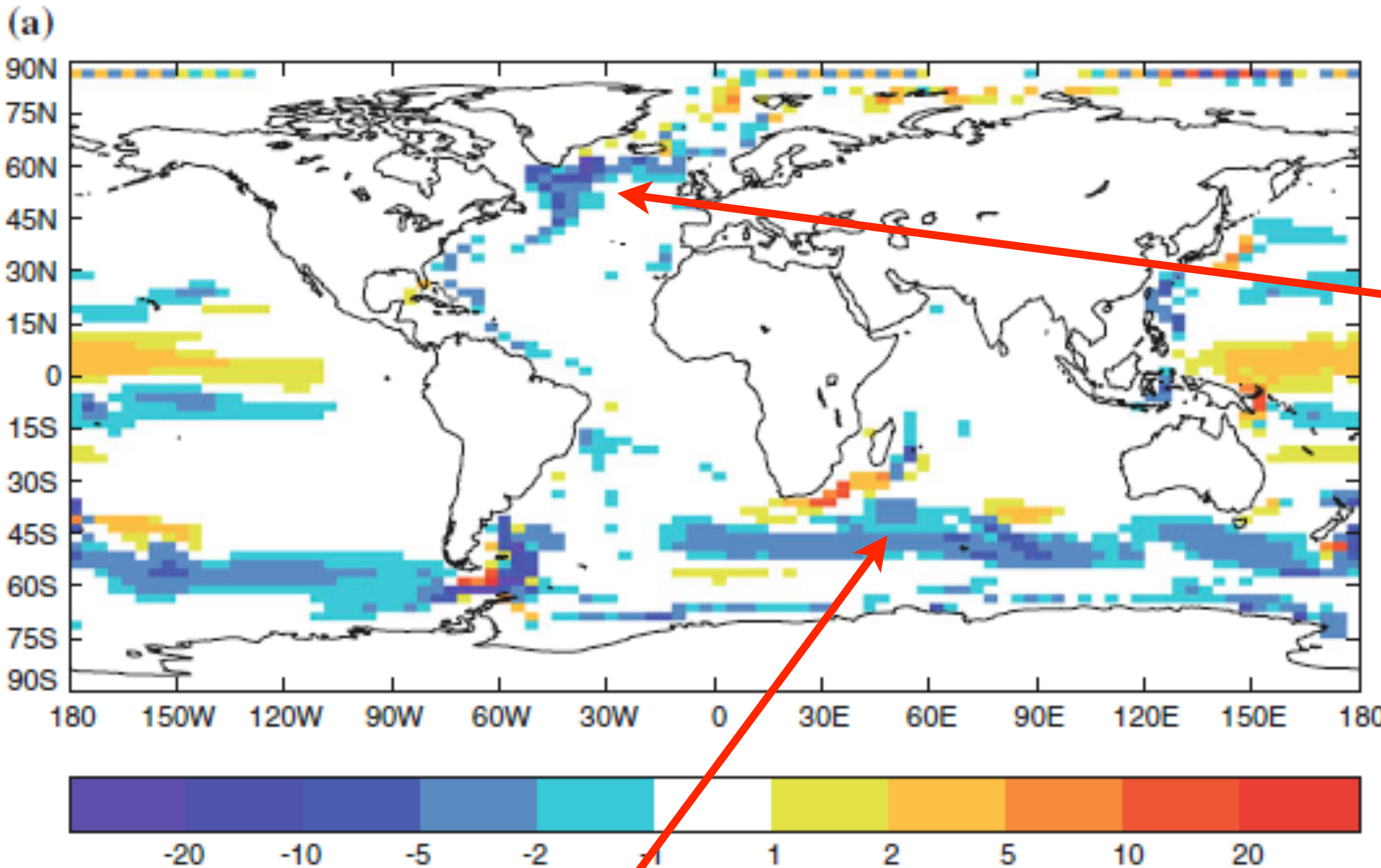


Figure 3. (a) Annual-mean heat flux for the case of no wind stress over the Southern Ocean. Each bcx shows heat absorbed by the ocean in the latitudinal band indicated by the width of the box. Contribution of each oceanic basin is shown by color bars. (b) Anomaly from (a) for the control case.

Hasumi and Suginohara (1999)

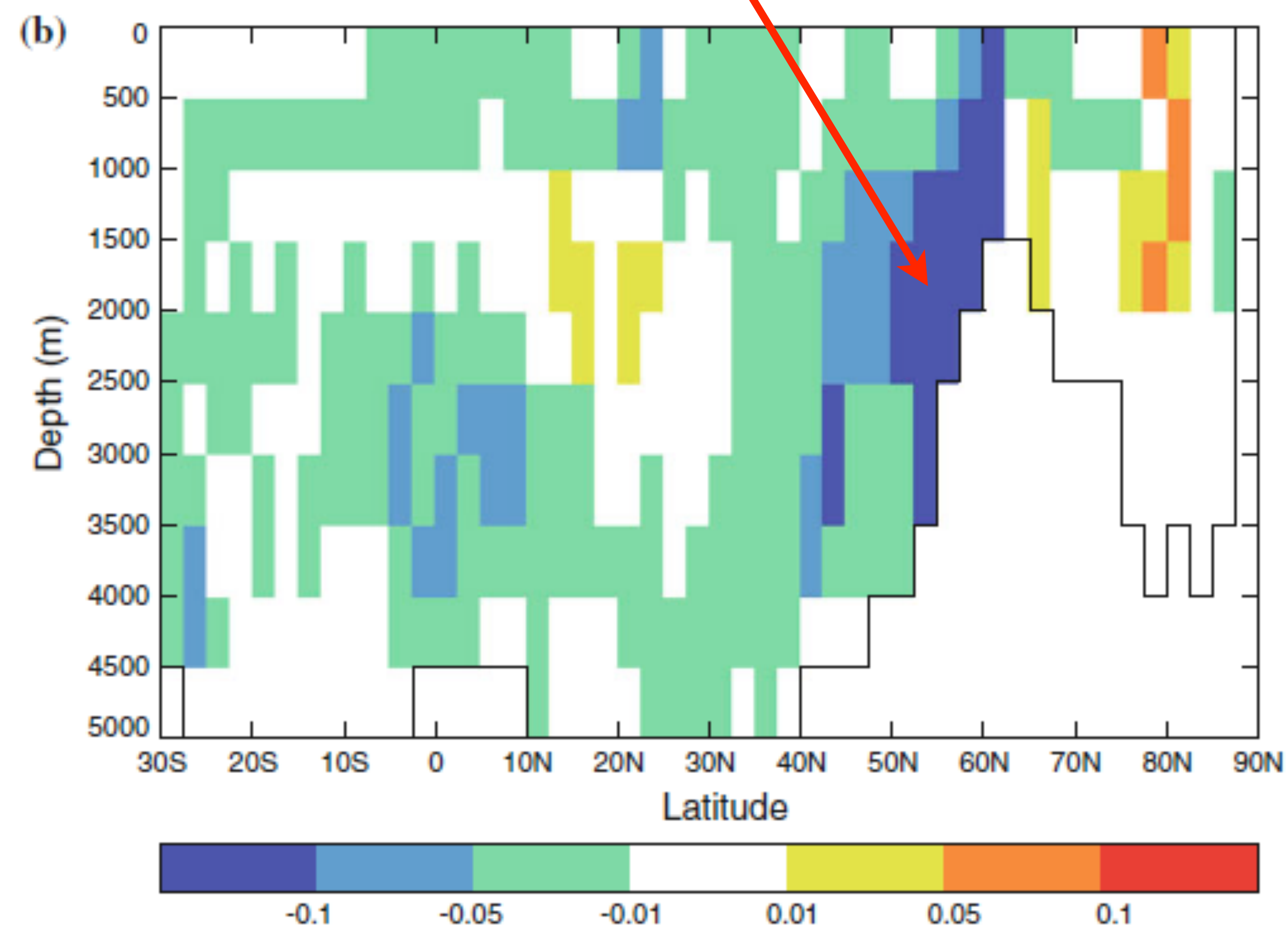
Climate Change

From Gregory and Tailleux, 2011



Global warming reduces APE production by buoyancy

Global warming increases APE production by the wind



Conclusions

- Buoyancy-driven theory posits that AMOC strength proportional to APE production rate by high-latitude cooling. Physics of proportionality constant not really understood though: research needed!

- APE production rate is state dependent. Ocean is a mechanically-controlled heat engine. Mixing and winds helps buoyancy forcing out.

- Determination of ocean stratification as important as determination of formation rates for inferring past AMOC variations