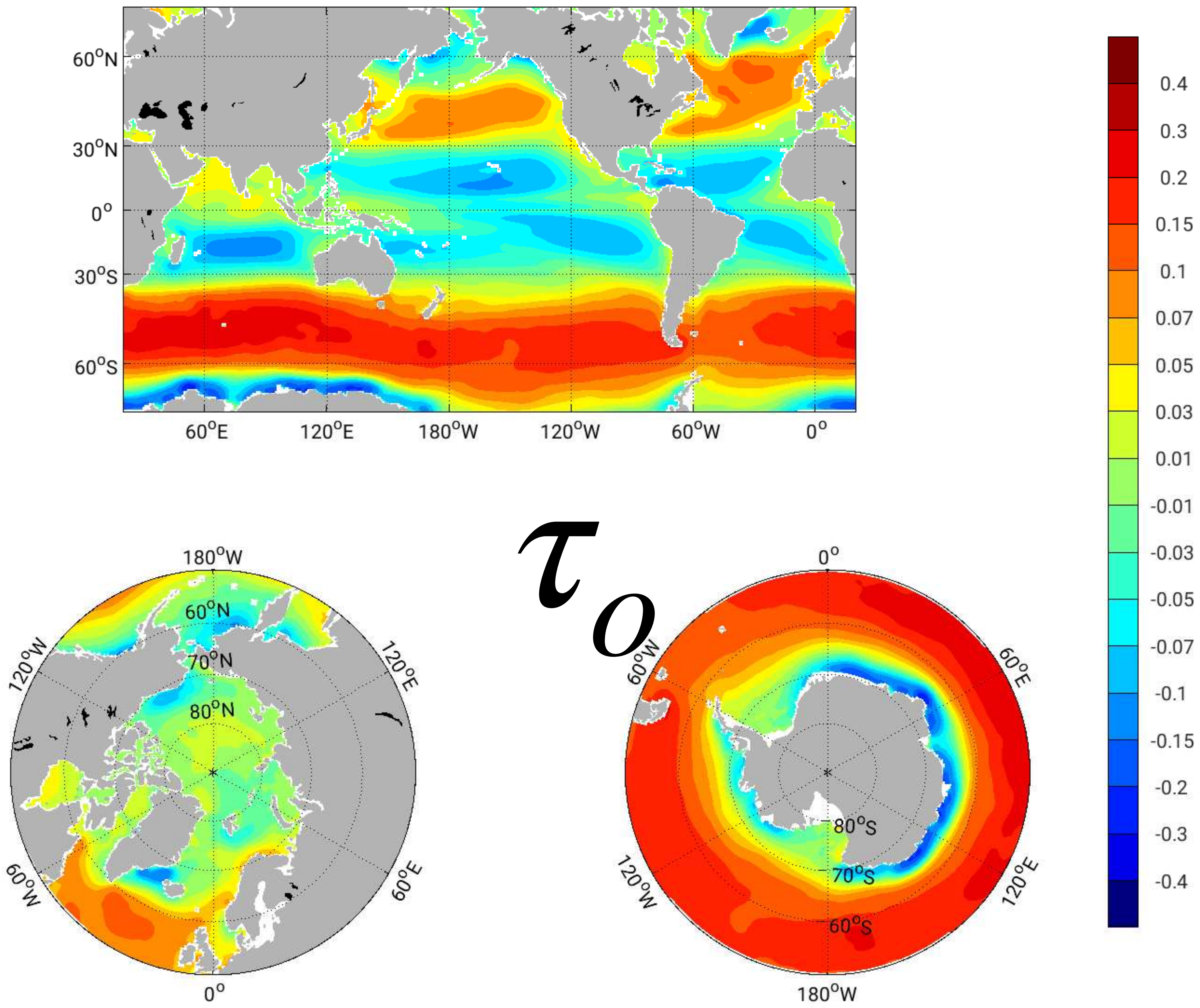
The main features of the large-scale ocean circulation: flow in horizontal plane

Streamfunction of depth integrated flow (Sv): ψ

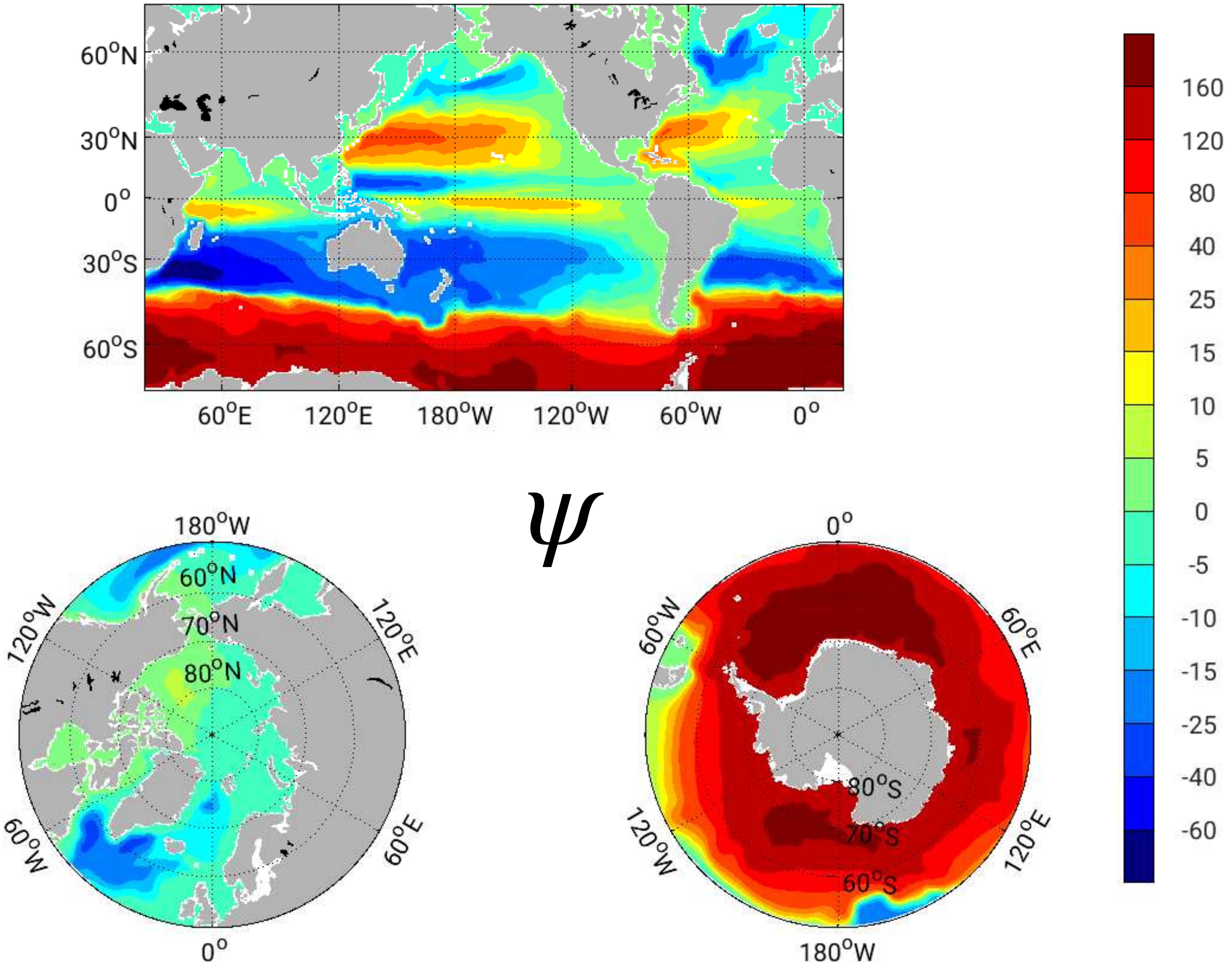
Subtropical gyres: maximum in Southern Ocean

Fast east-west current around Antarctica

East-west wind surface wind stress: τ



τ_o

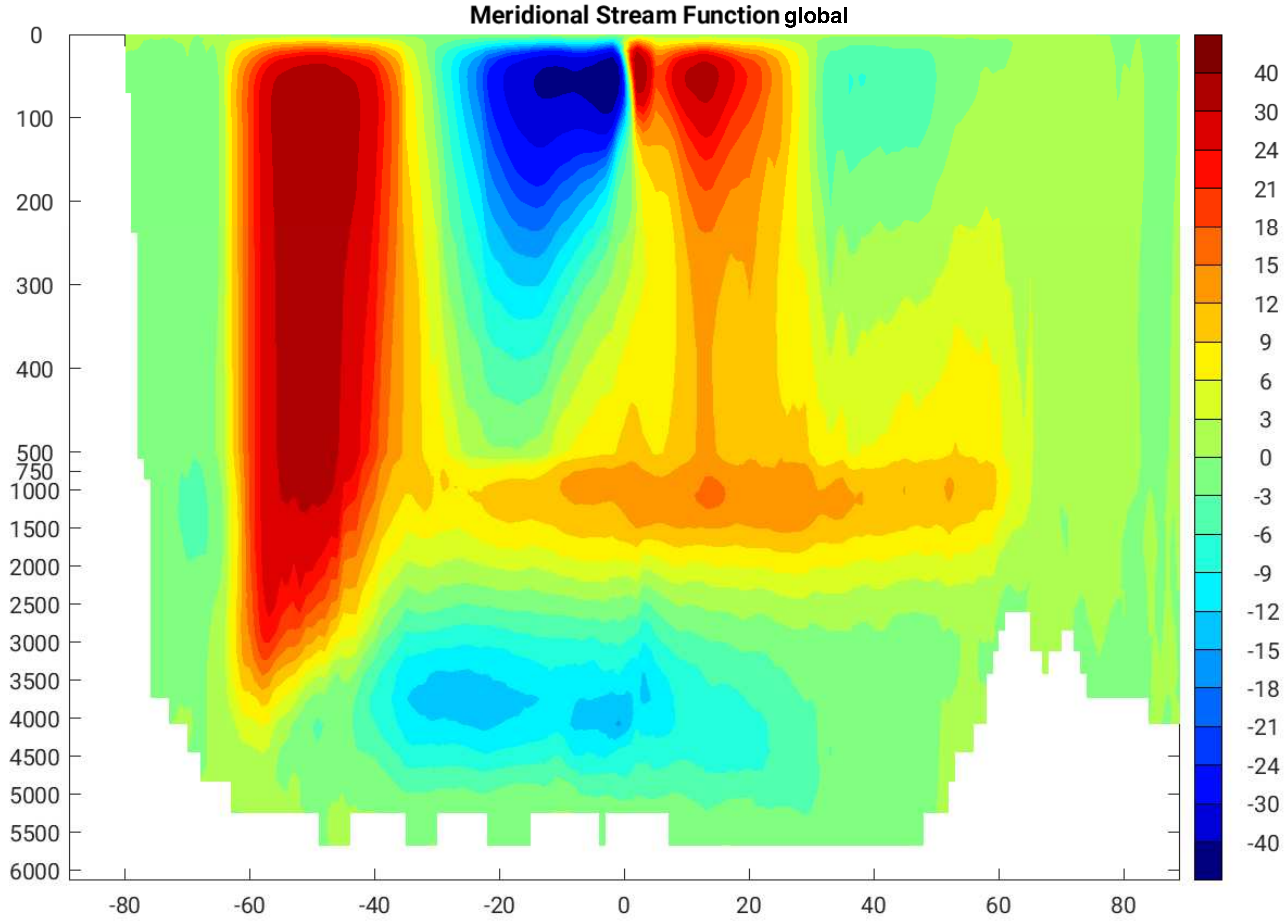


ψ

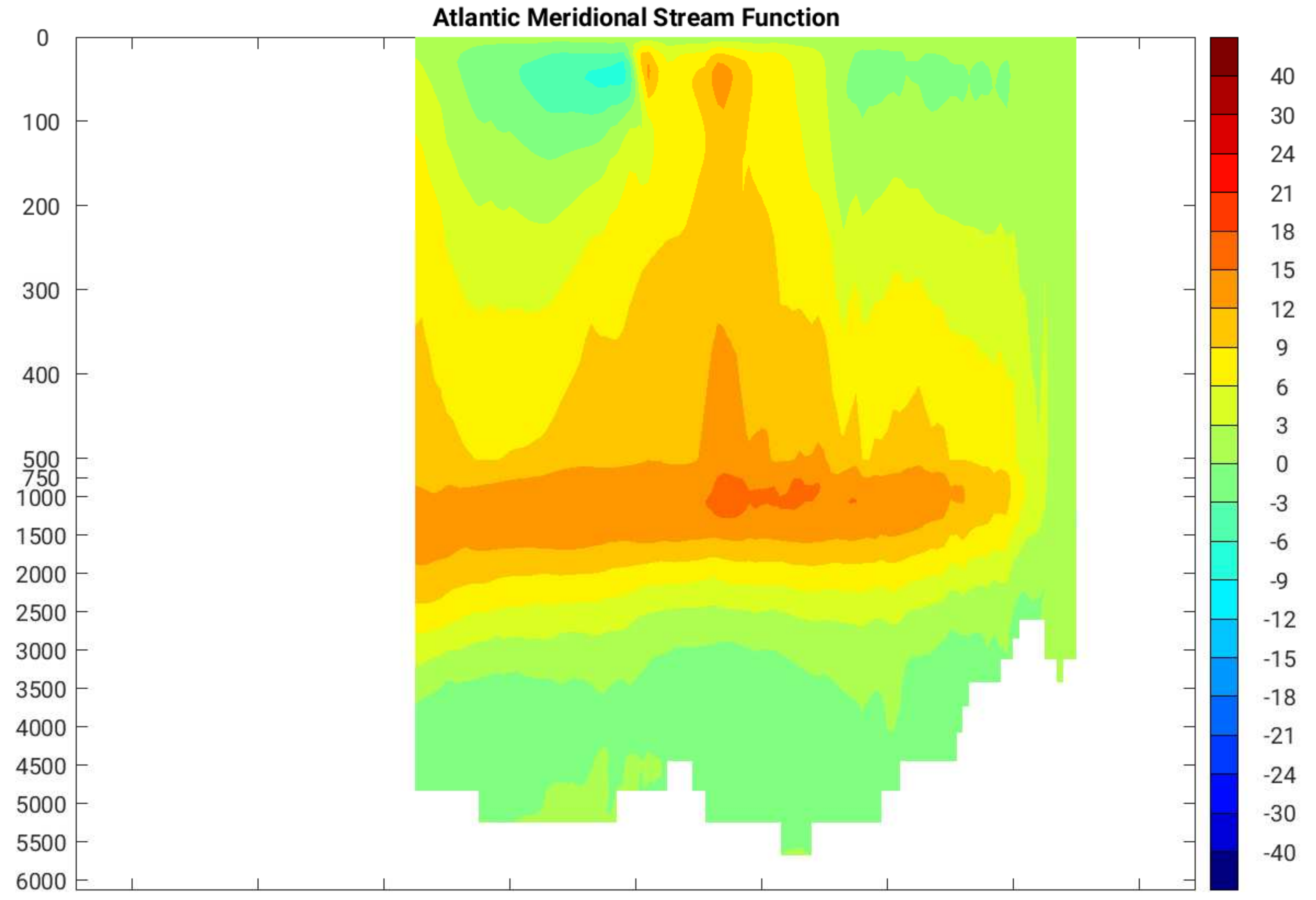
ECCO V4r4 overview plots

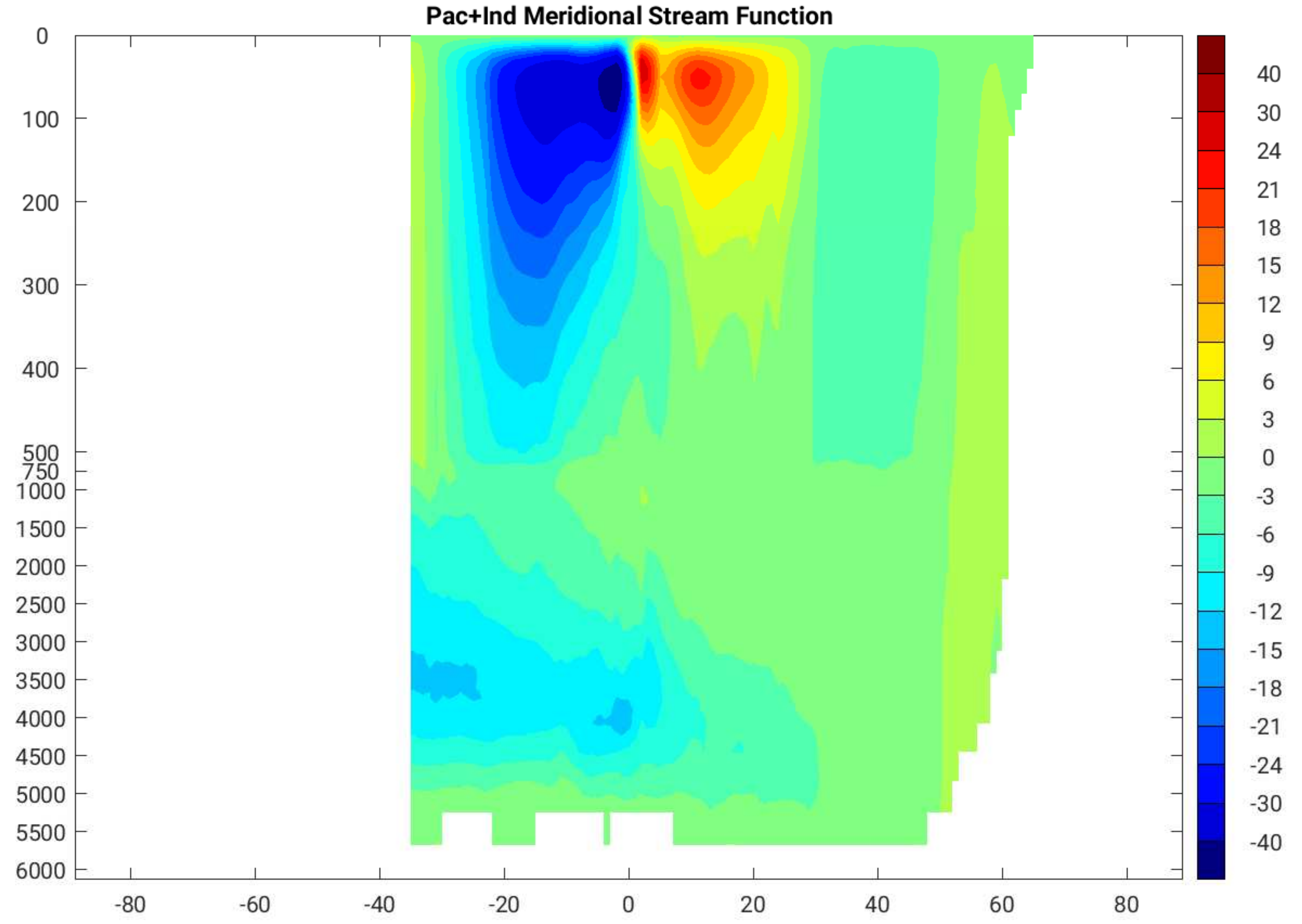
The main features of the large-scale ocean circulation: flow in vertical plane

Streamfunction of longitudinally integrated flow (Sv): ϕ



$$\phi$$





ECCO V4r4 overview plots

A minimal model for ψ and ϕ: 1.5 layer reduced gravity

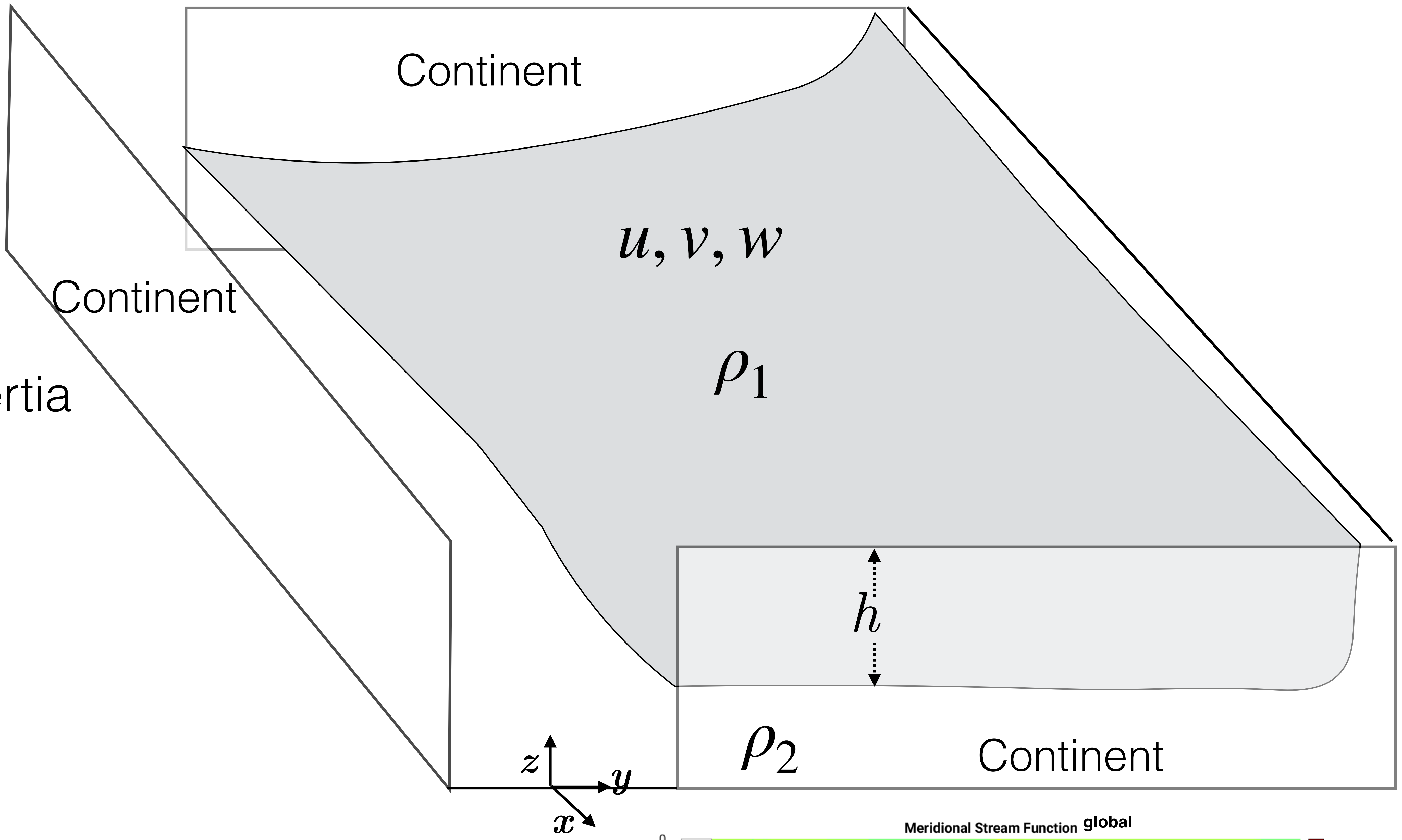
A layer of density ρ_1 is above a layer of density ρ_2;

ρ_1, ρ_2 are constant;

The lower layer is at rest;

Determine h, u, v, w of the top layer

Hydrostatic balance, mass conservation, neglect inertia



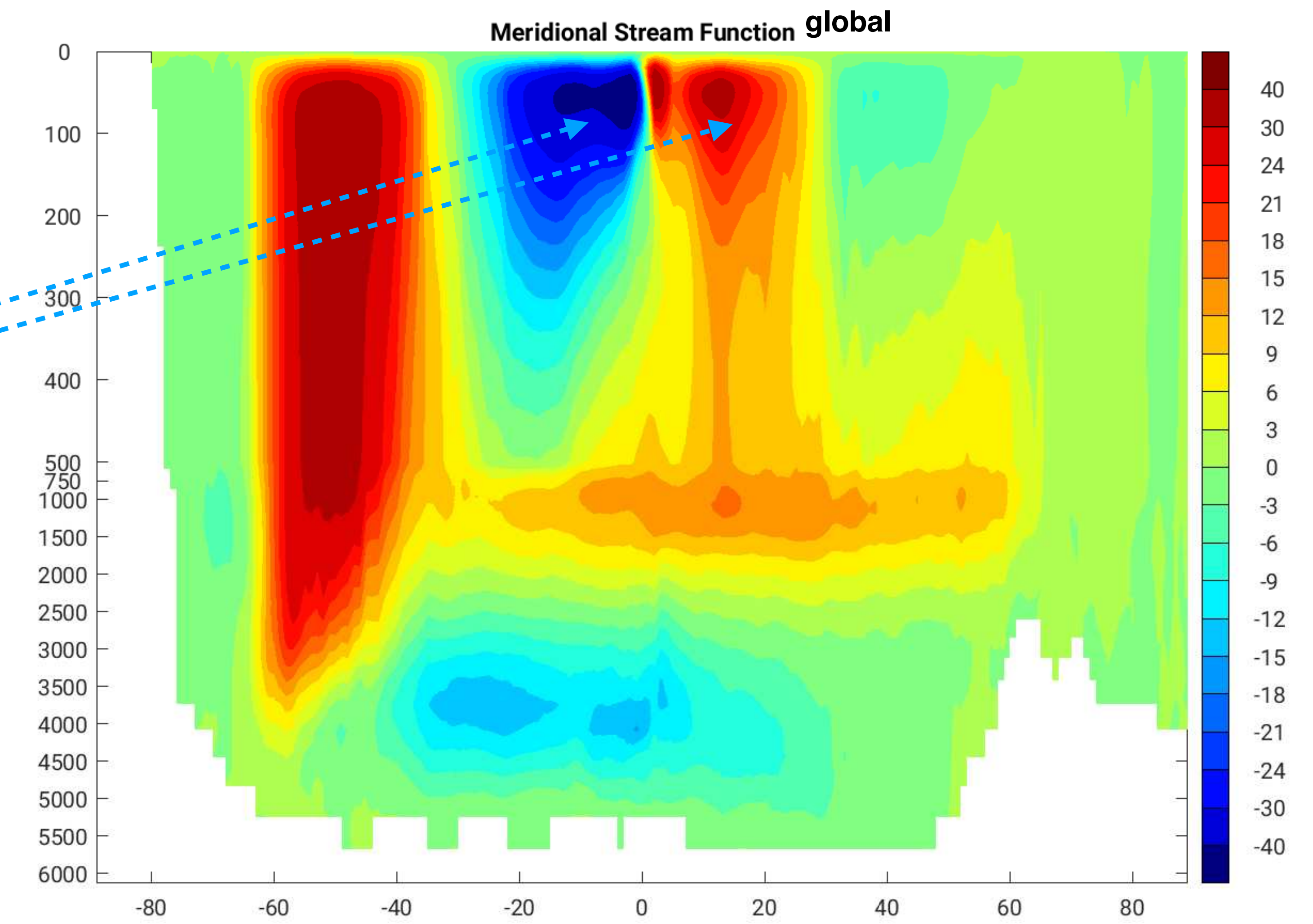
$$\partial_x u + \partial_y v + \partial_z w = 0$$

$$fv = g'\partial_x h - \partial_z \tau(y,z) \qquad g' \equiv g\frac{\rho_2 - \rho_1}{\rho_2}$$

$$fu = -g'\partial_y h - rv \qquad f \equiv \beta y$$

Coriolis force = pressure gradient + friction

$$\tau(y,z) = \tau_o(y)e^{z/d} \qquad z < 0 \quad d \ll h$$



Wind stress acts in shallow Ekman layer: model appropriate
for the barotropic ψ and shallow overturning cells inside basins

Solution for *h*, ψ, ϕ

The vertically integrated vorticity equation is

$$\beta \partial_x (h^2/2) = -\frac{f^2}{g'} \partial_y \left(\frac{\tau_o}{f} \right) - r \partial_x^2 (h^2/2)$$

The active layer depth scales as ($f = \beta y$)

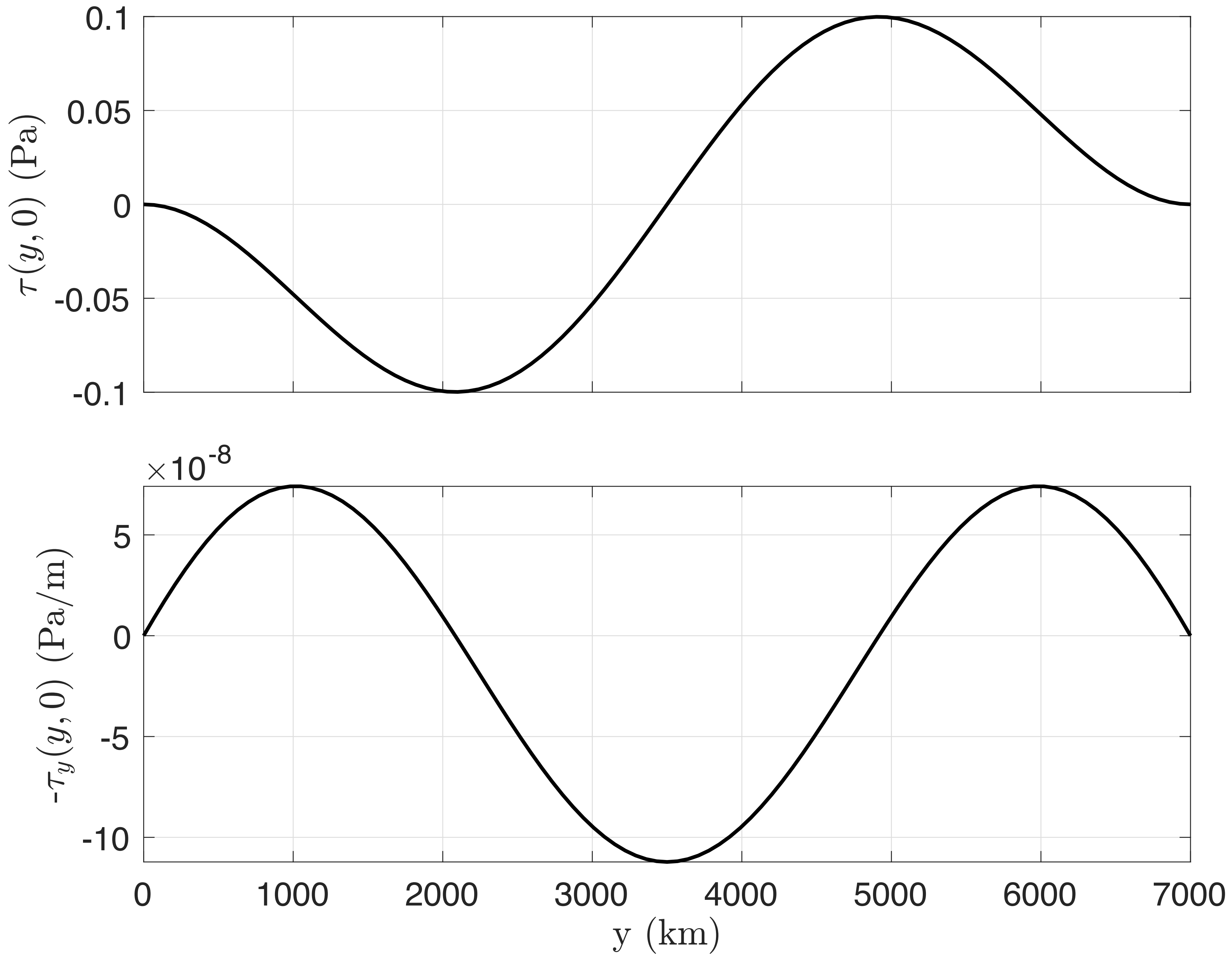
$$h \sim \sqrt{x_e L_y \partial_y \tau_o / g'}$$

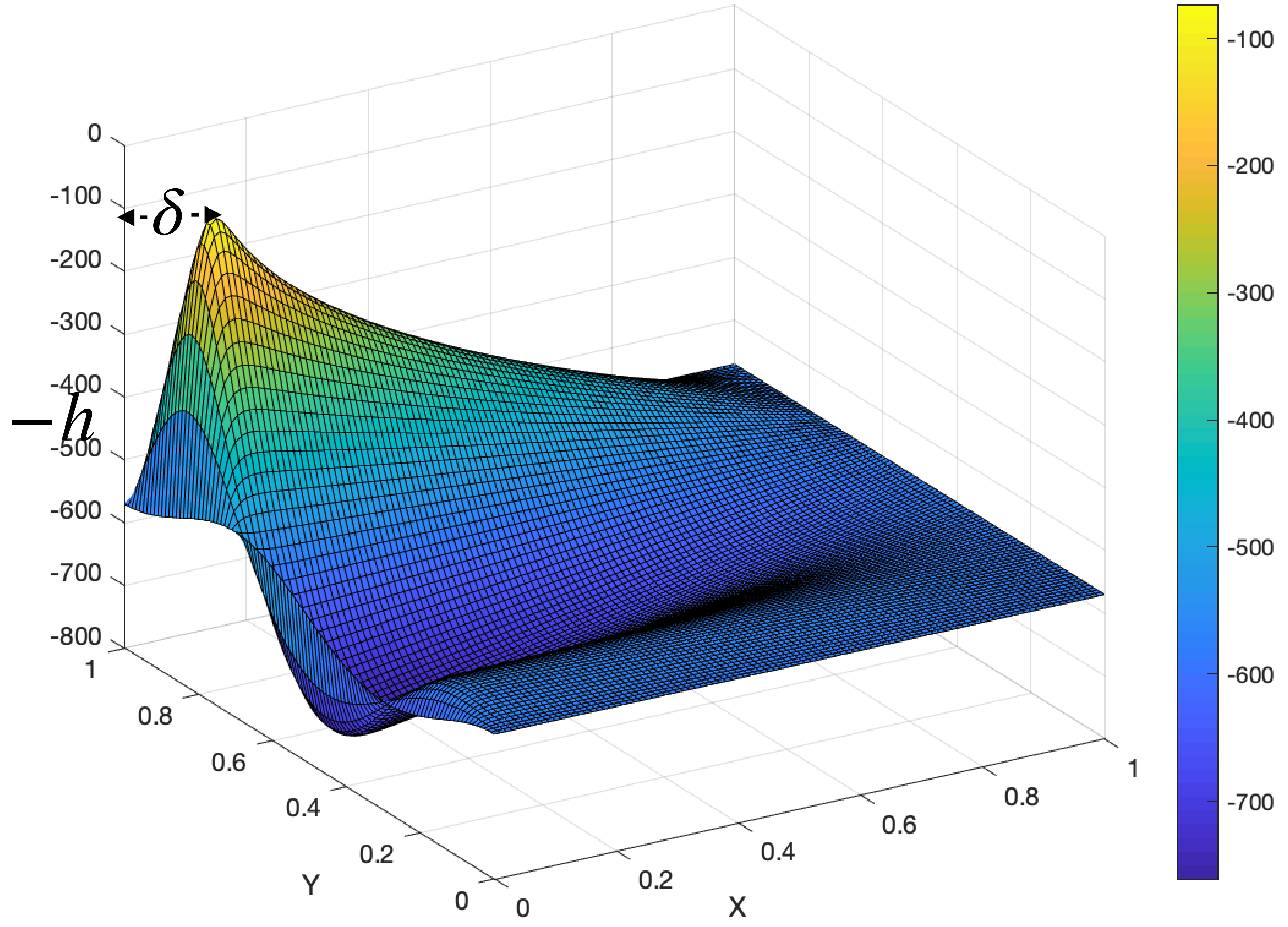
h gets deeper with stronger wind stress, wider basins and weaker stratification.

The surface wind stress, τ_o, has easterlies and westerlies

The resulting h has valleys and hills;
a steep change near the thin western boundary

$$h^2 = \frac{(x_e - x)}{g'} 2y^2 \partial_y \left(\frac{\tau_o}{y} \right) - 2y \frac{x_e}{g'} e^{-x/\delta} \partial_y \tau_o + H^2;$$





Solution for h, ψ, ϕ

The depth-weighted horizontal velocity is given by

$$hu = -\partial_y \psi(x, y)\,;$$

$$hv = \partial_x \psi(x, y) - \partial_z \phi(x, y, z)$$

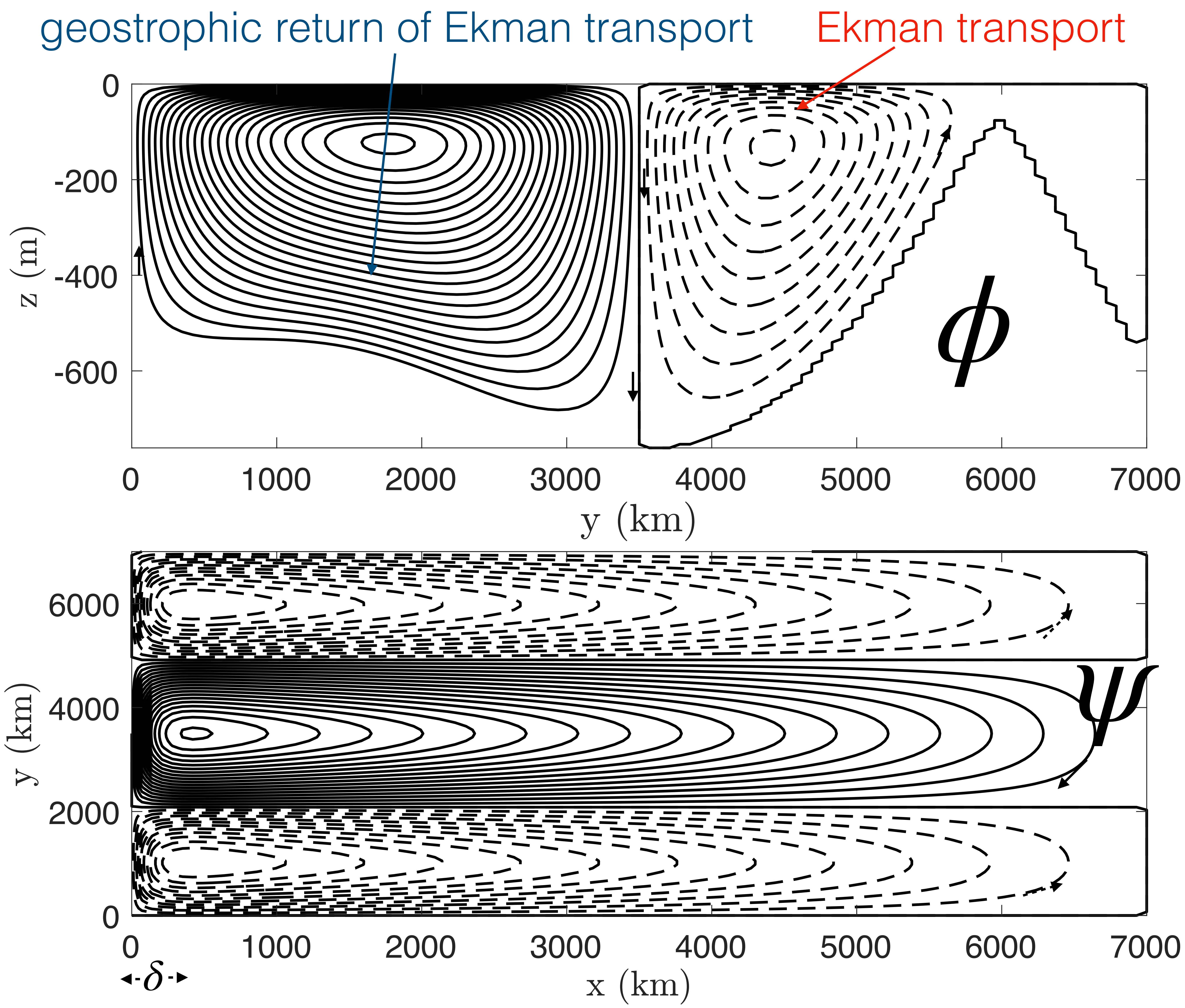
$$\psi \equiv \beta^{-1}(x_e - x - x_e e^{-x/\delta})\partial_y \tau_o$$

$$\phi \equiv \frac{h\tau(y, z)}{\beta y} - \frac{\tau_o}{\beta y}(z + h)$$

w can be obtained integrating mass-conservation $\partial_x u + \partial_y v + \partial_z w = 0$ and using the condition that h is a material surface

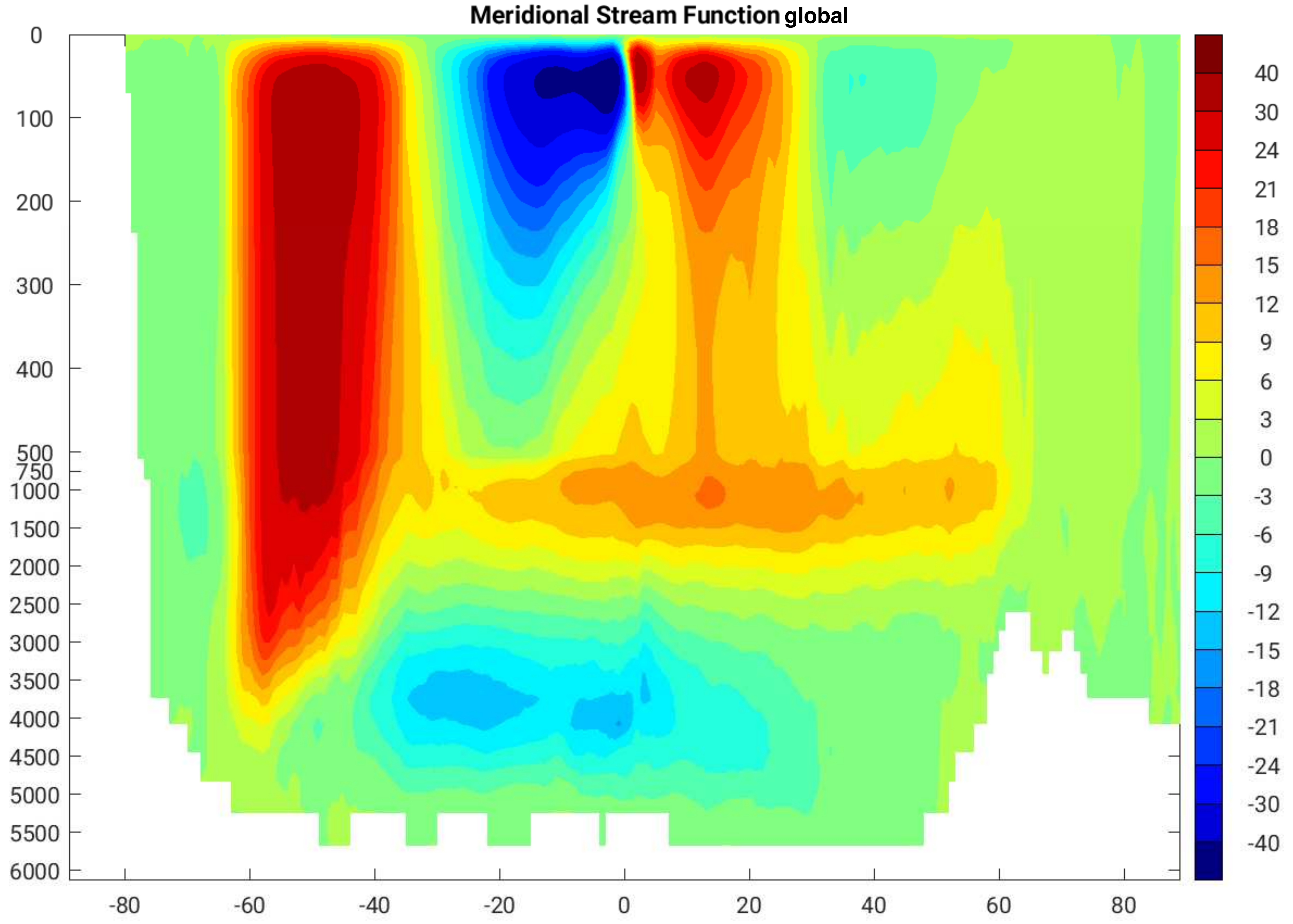
$$w\big|_{z=-h} = -\mathbf{u}\big|_{z=-h} \cdot \nabla h$$

ϕ and ψ are almost in quadrature in latitude: ϕ transports across gyres, creating a complex 3-D flow

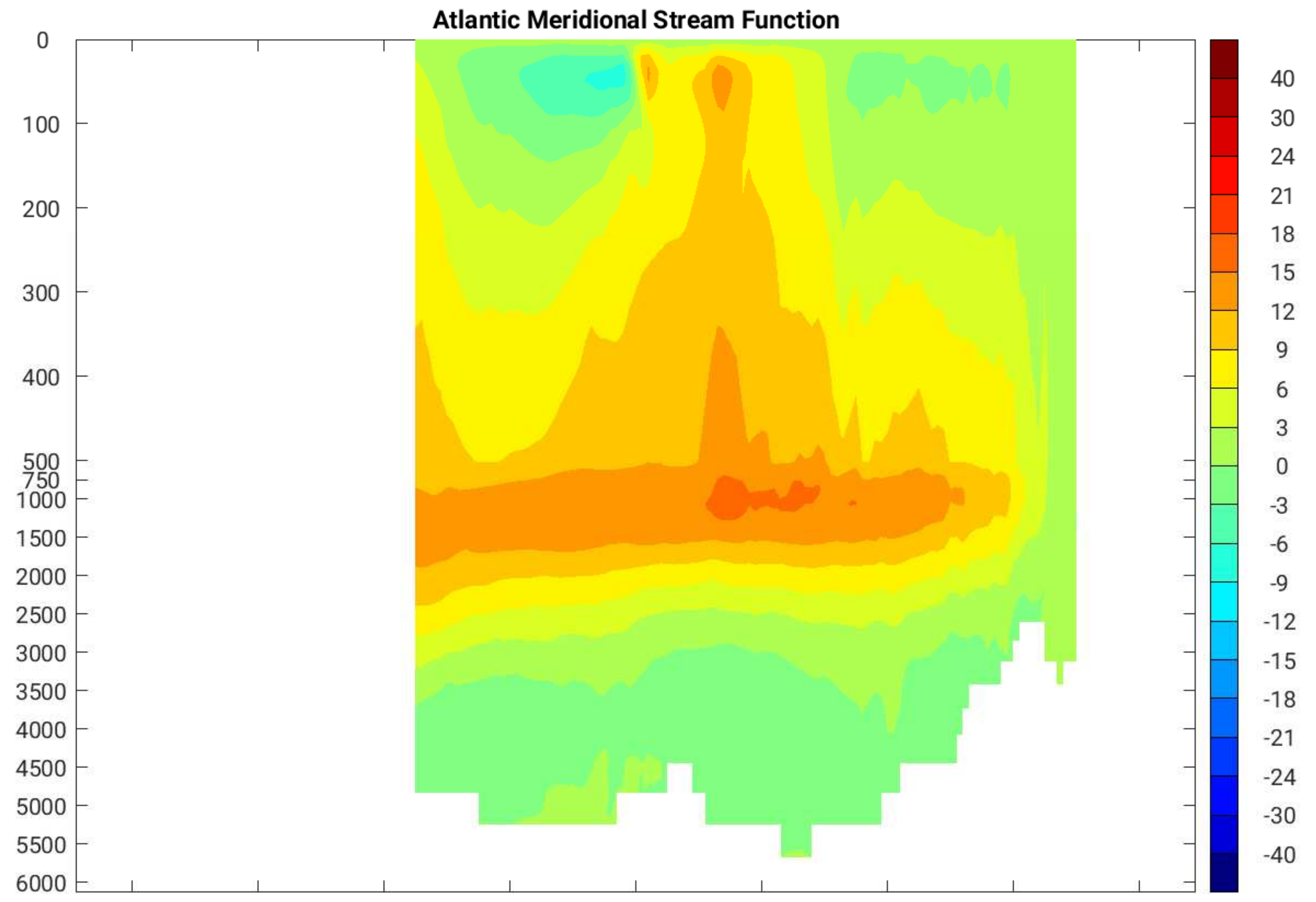


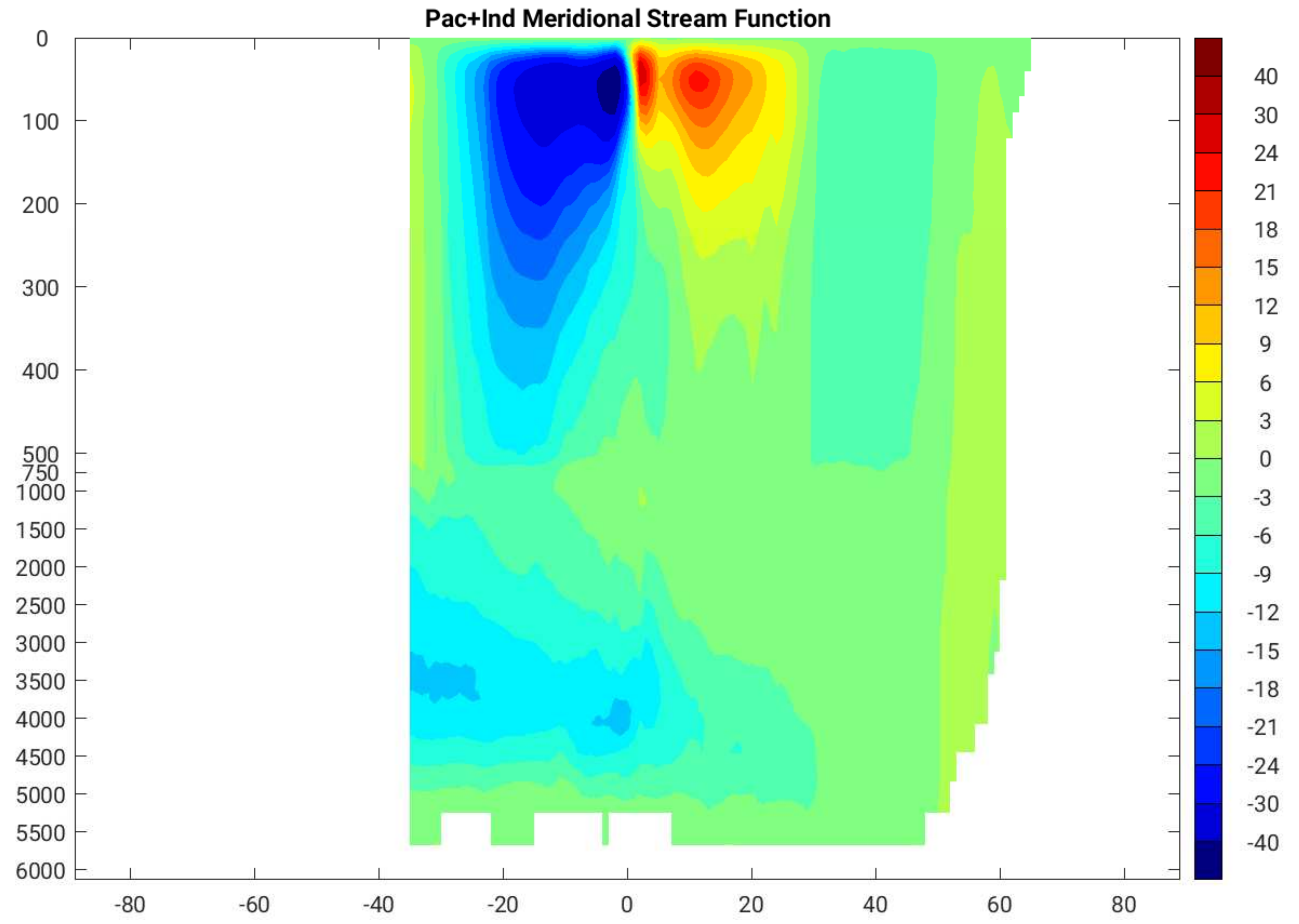
The main features of the large-scale ocean circulation: flow in vertical plane

Streamfunction of longitudinally integrated flow (Sv): ϕ



ϕ





ECCO V4r4 overview plots

Stratification and MOC in the ACC: effect of wind

Buoyancy balance in the Antarctic Circumpolar Current

$$\partial_t b + \partial_x(ub) + \partial_y(vb) + \partial_z(wb) = \partial_z(\kappa_v \partial_z b)$$

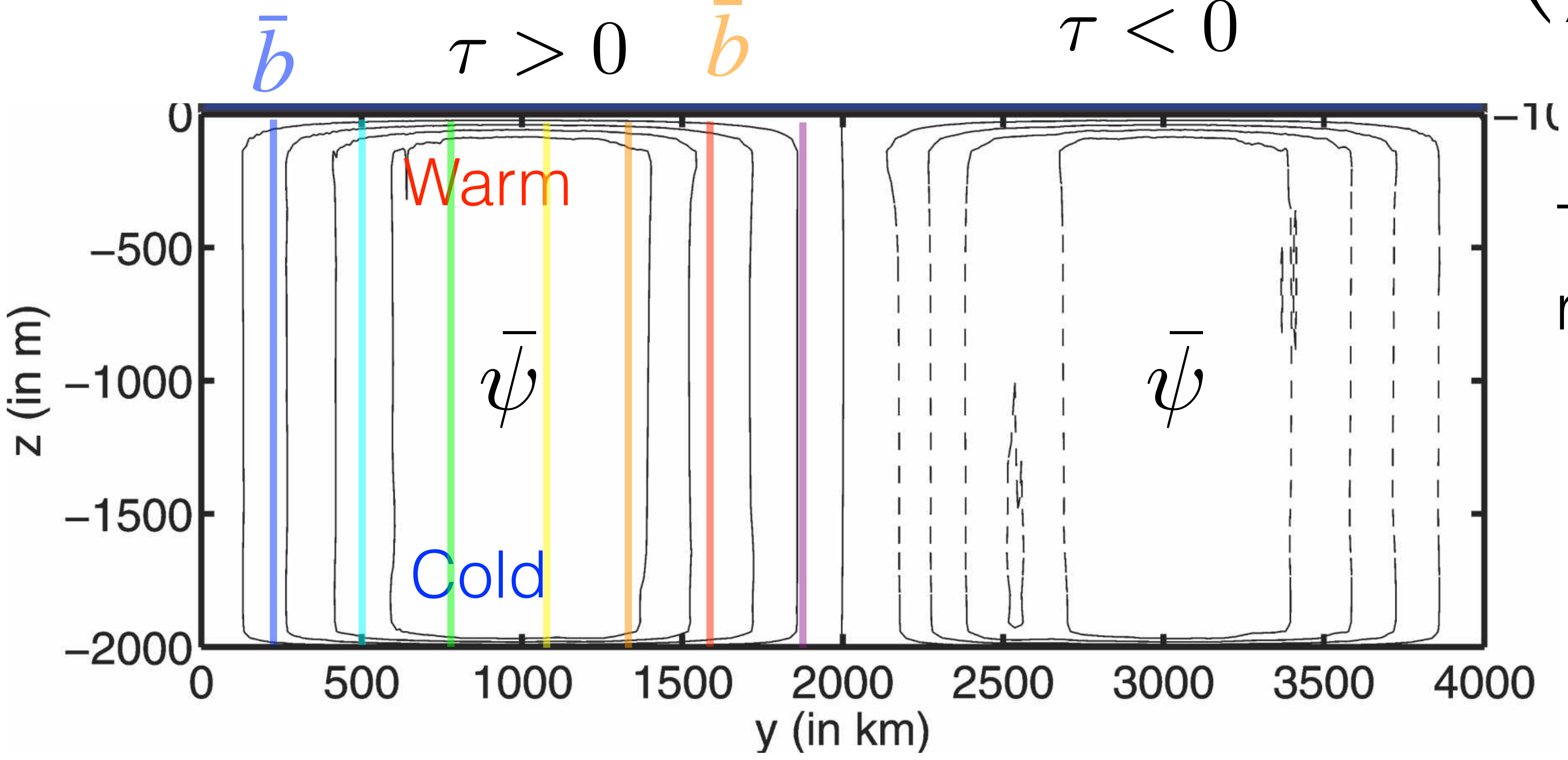
Zonally and time-average

$$\bar{v}\partial_y \bar{b} + \bar{w}\partial_z \bar{b} + \partial_y(\overline{v'b'}) + \partial_z(\overline{w'b'}) = \partial_z(\kappa_v \partial_z \bar{b})$$

In the top Ekman layer $\bar{V} = -\frac{\tau}{\rho f}$ In the bottom Ekman layer $\bar{V} = \frac{\tau}{\rho f}$

Below the Ekman layer and above the bottom Ekman layer

$$\bar{p}_x = 0 \implies \quad \bar{v} = 0, \quad \bar{w} = -\partial_y\left(\frac{\tau}{\rho f}\right), \quad \implies \bar{\psi} = -\frac{\tau}{\rho f}$$



The mean overturning circulation reaches the bottom

In a thermally stratified fluid it transports heat **equatorward** for westerly wind-stress $\tau > 0$

Stratification and MOC in the ACC: effect of wind

Buoyancy balance in the Antarctic Circumpolar Current

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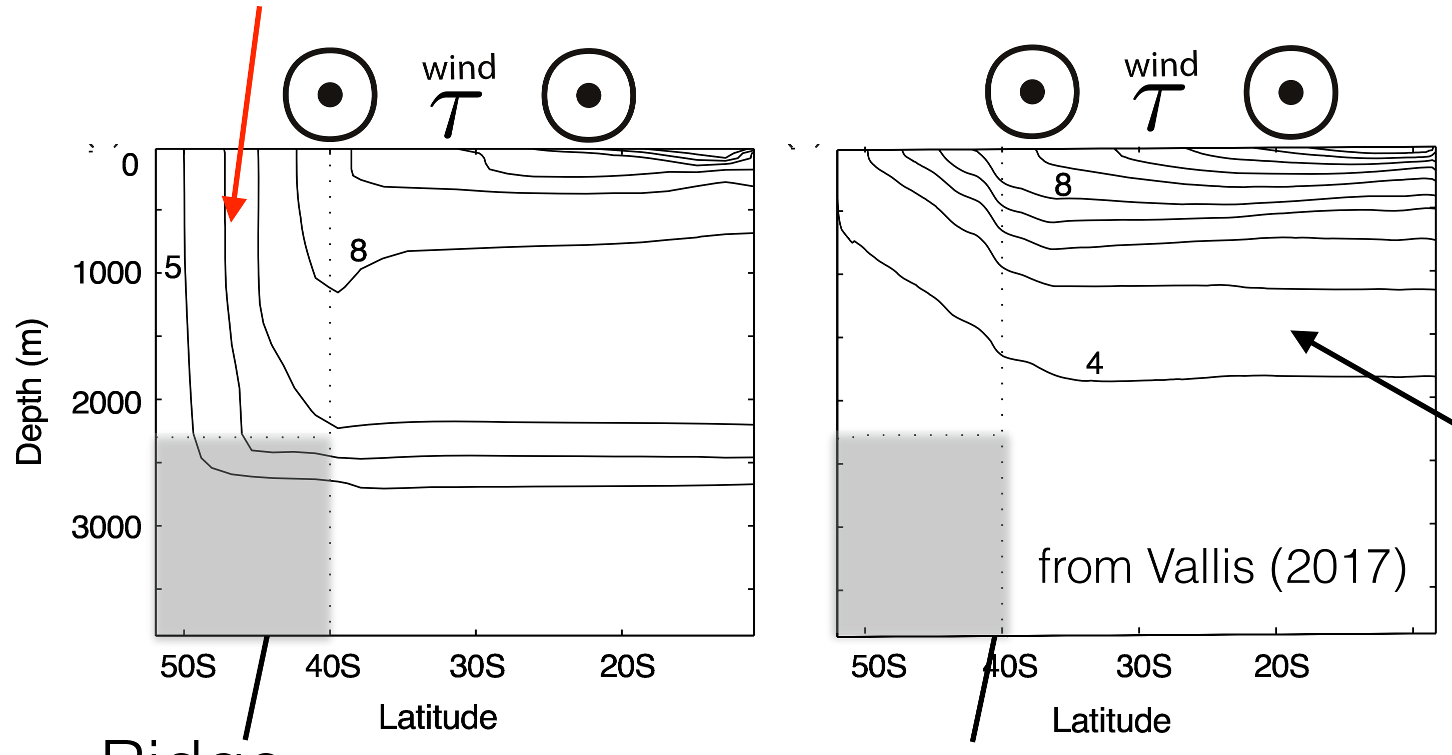
For adiabatic eddies $\dfrac{\overline{v'b'}}{\partial_z \bar{b}} = -\dfrac{\overline{w'b'}}{\partial_y \bar{b}}$

Eddy transport is along isopycnals $\psi^* = \dfrac{\overline{v'b'}}{\partial_z \bar{b}}$

The total transport is $\psi^* + \bar{\psi}$ with $\bar{\psi} = -\dfrac{\tau}{\rho f}$

Large APE reservoir



Advection by residual=eulerian + eddy $= \bar{\psi} + \psi^*$

Buoyancy contours

Ridge

Channel edge

No eddies: large APE

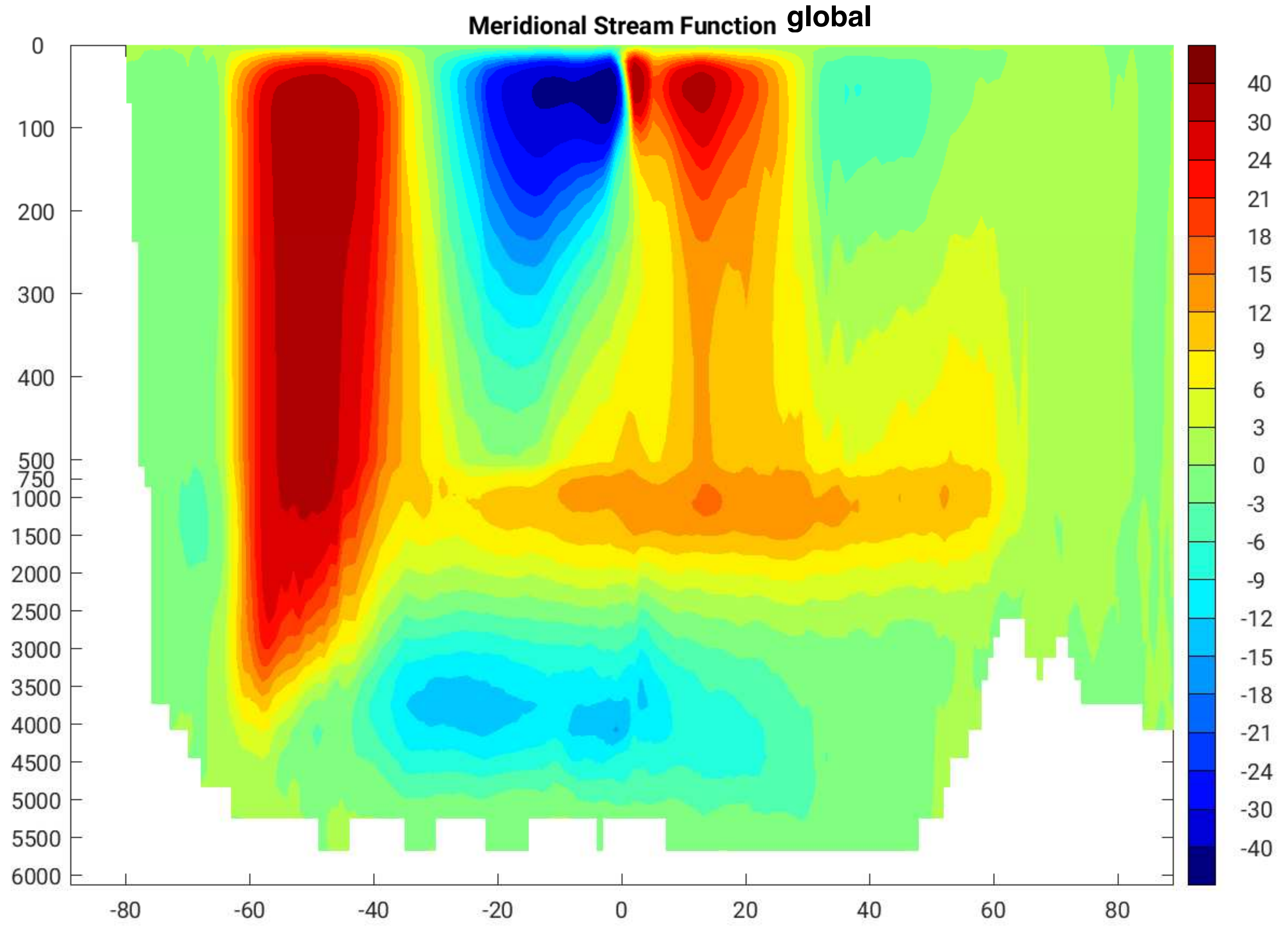
With eddies: APE is converted

The eddy transport can be parametrized in terms of mean buoyancy

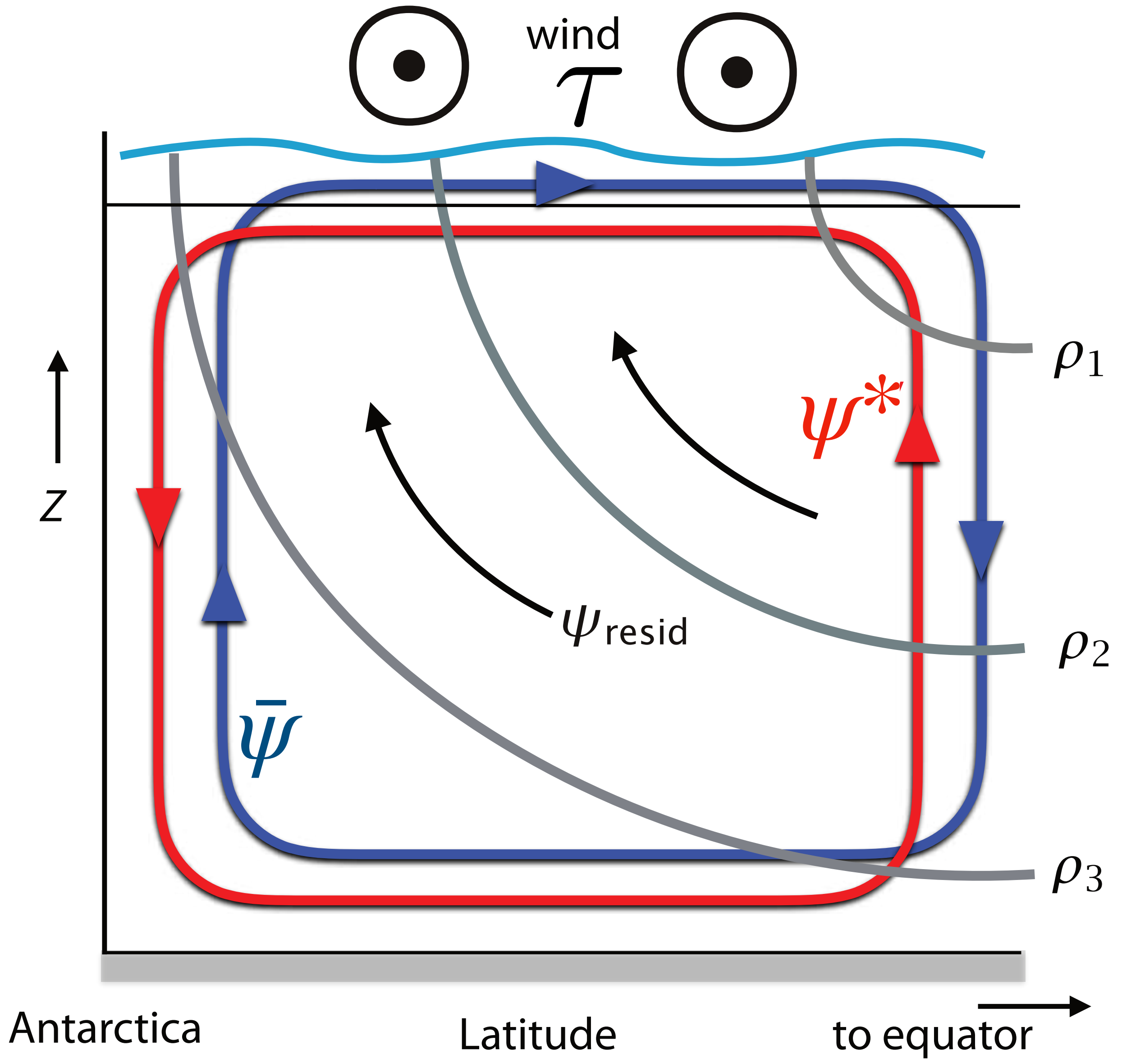
$\overline{v'b'} = -\kappa_a \partial_y \bar{b}$ the horizontal eddy flux is down-gradient

$\overline{w'b'} = \kappa_a \frac{(\partial_y \bar{b})^2}{\partial_z \bar{b}}$ the vertical eddy flux is upgradient

the total eddy flux is neither down- nor up-gradient: it is advective



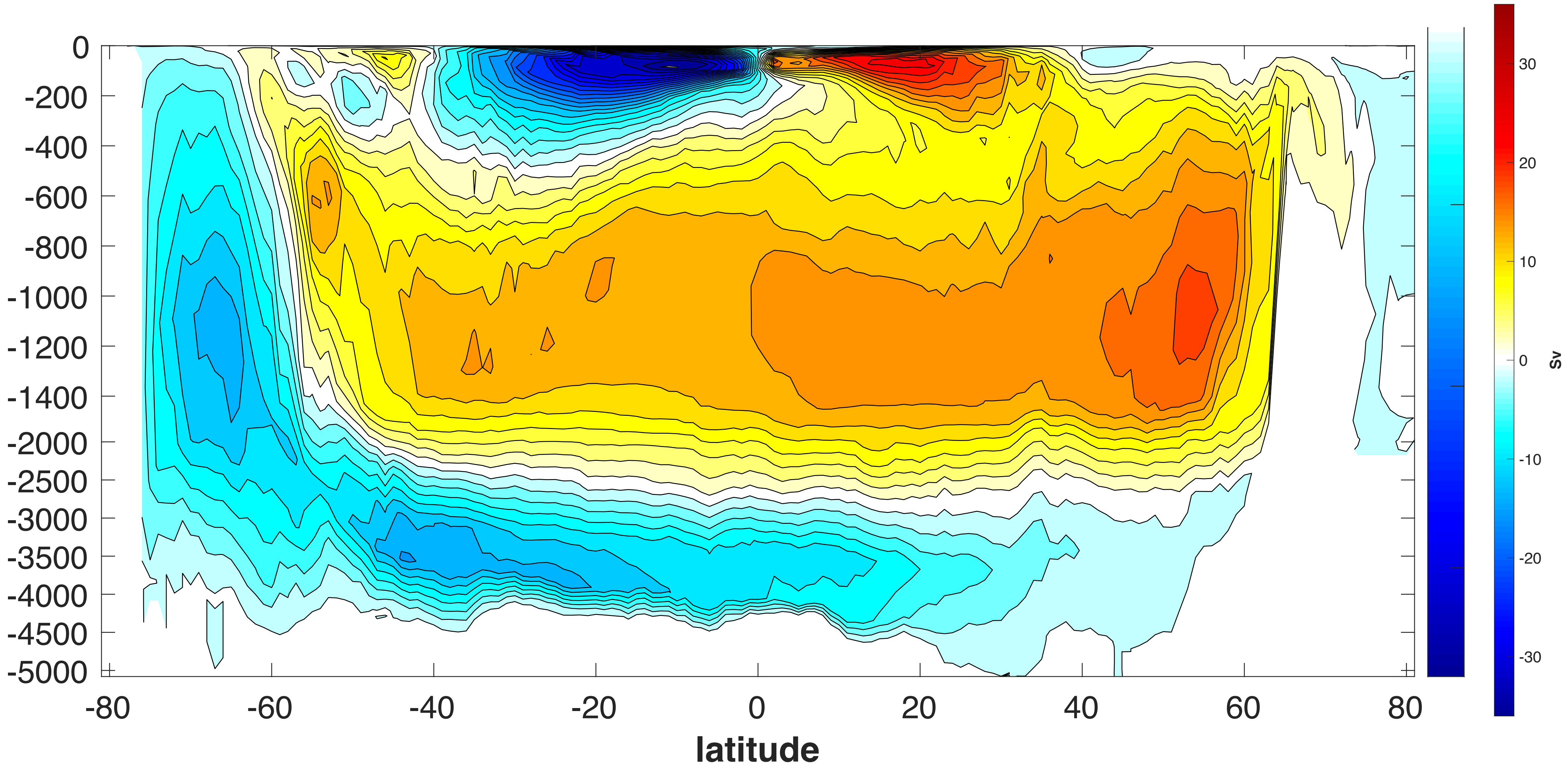
The eddy overturning streamfunction is $\psi^* = -\kappa_a \frac{\partial_y \bar{b}}{\partial_z \bar{b}} = \kappa_a \partial_y z$ proportional to the isopycnal slope



from Vallis (2017)

There is competition between $\bar{\psi}$ and ψ^*

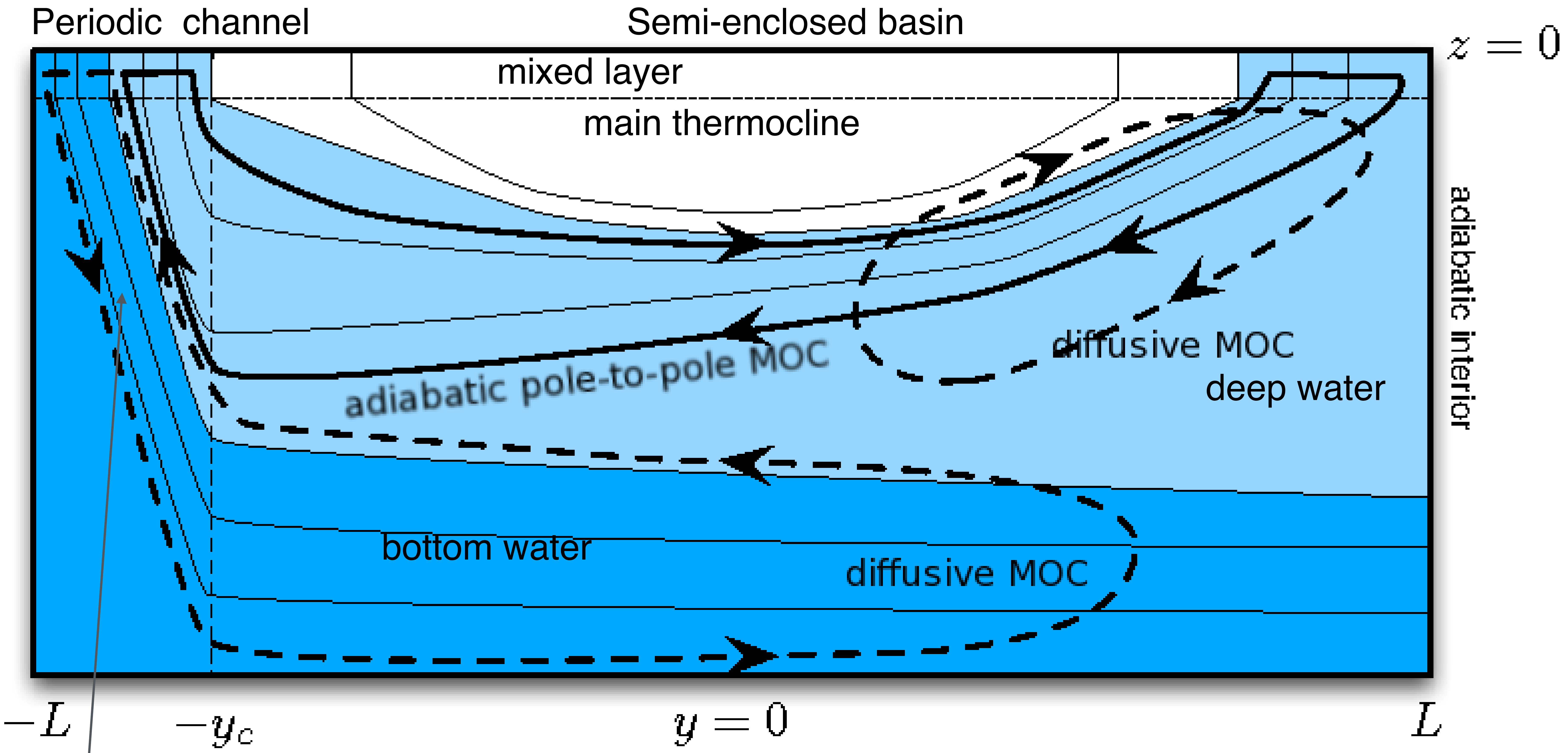
What matters is $\bar{\psi} + \psi^* = \psi_{resid}$



Latitude-integrated residual overturning in ECCO v4 vs. MOC

Marshall, J. and Radko, T., 2003. Residual-Mean Solutions for the Antarctic Circumpolar Current and Its Associated Overturning Circulation. J. Phys. Oceanogr.,

The quasi-adiabatic overturning in a single basin: Atlantic



Competition between Ekman suction and eddy restratification determine stratification in ACC

Three types of isopycnals: outcrop in basin only (white);

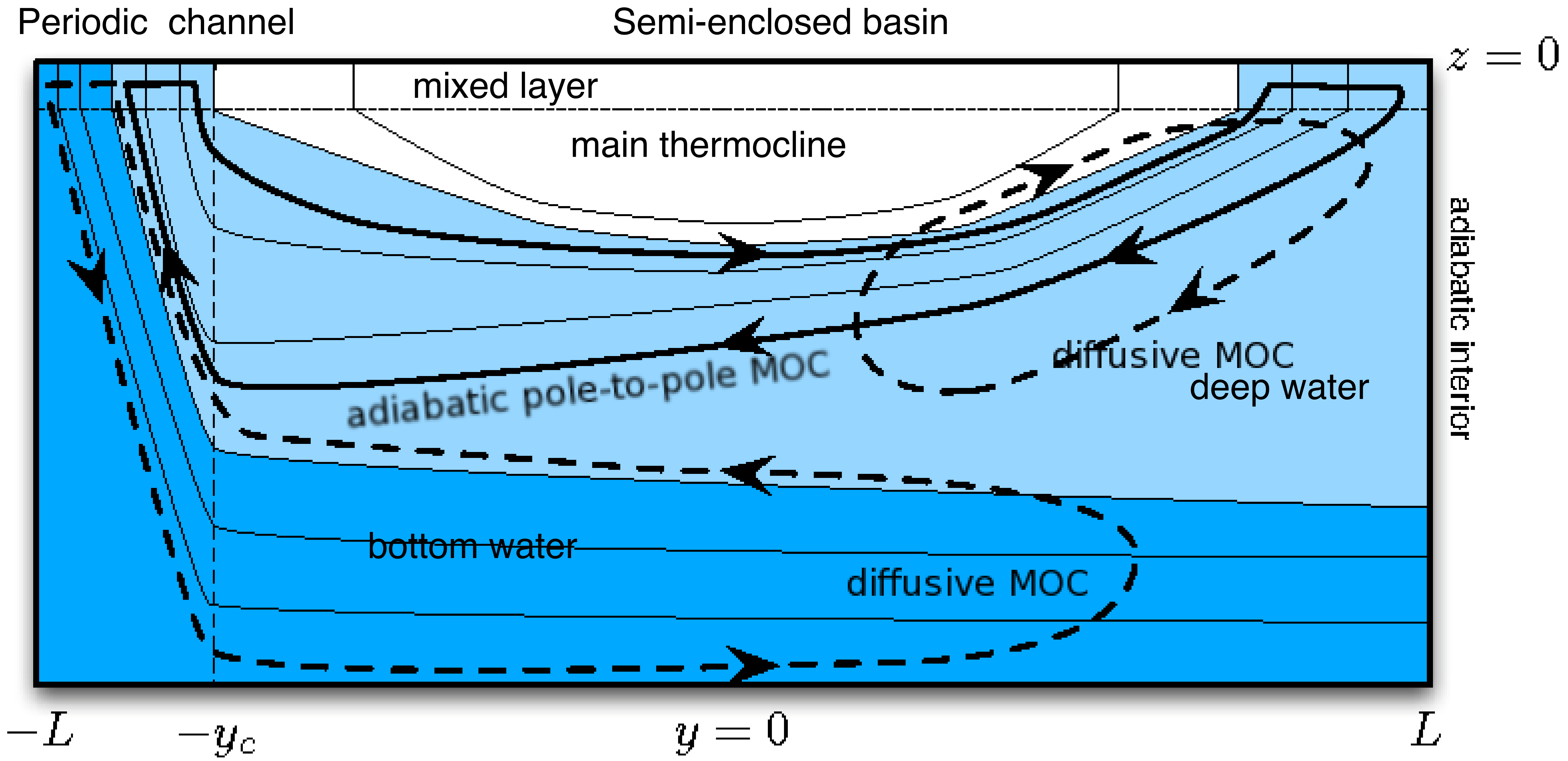
outcrop in ACC and basin (light blue);

outcrop in ACC only (blue)

Three types of circulation: main thermocline (white); intermediate/deep OC (light blue); abyssal OC (blue)

Wolfe, C.L. and P. Cessi, JPO 2010

The quasi-adiabatic overturning in a single basin: Atlantic



Necessary conditions for a quasi adiabatic pole-to-pole cell:
1) Isopycnal outcropping in channel and basin;
2) Diapycnal fluxes in the mixed layer

Ancillary features:
1) Weak diffusive cells in the abyss and in the Northern Hemisphere
2) Abyssal and adiabatic cells share a boundary

The residual (mean + eddy) circulation in 1.5 layer reduced gravity context

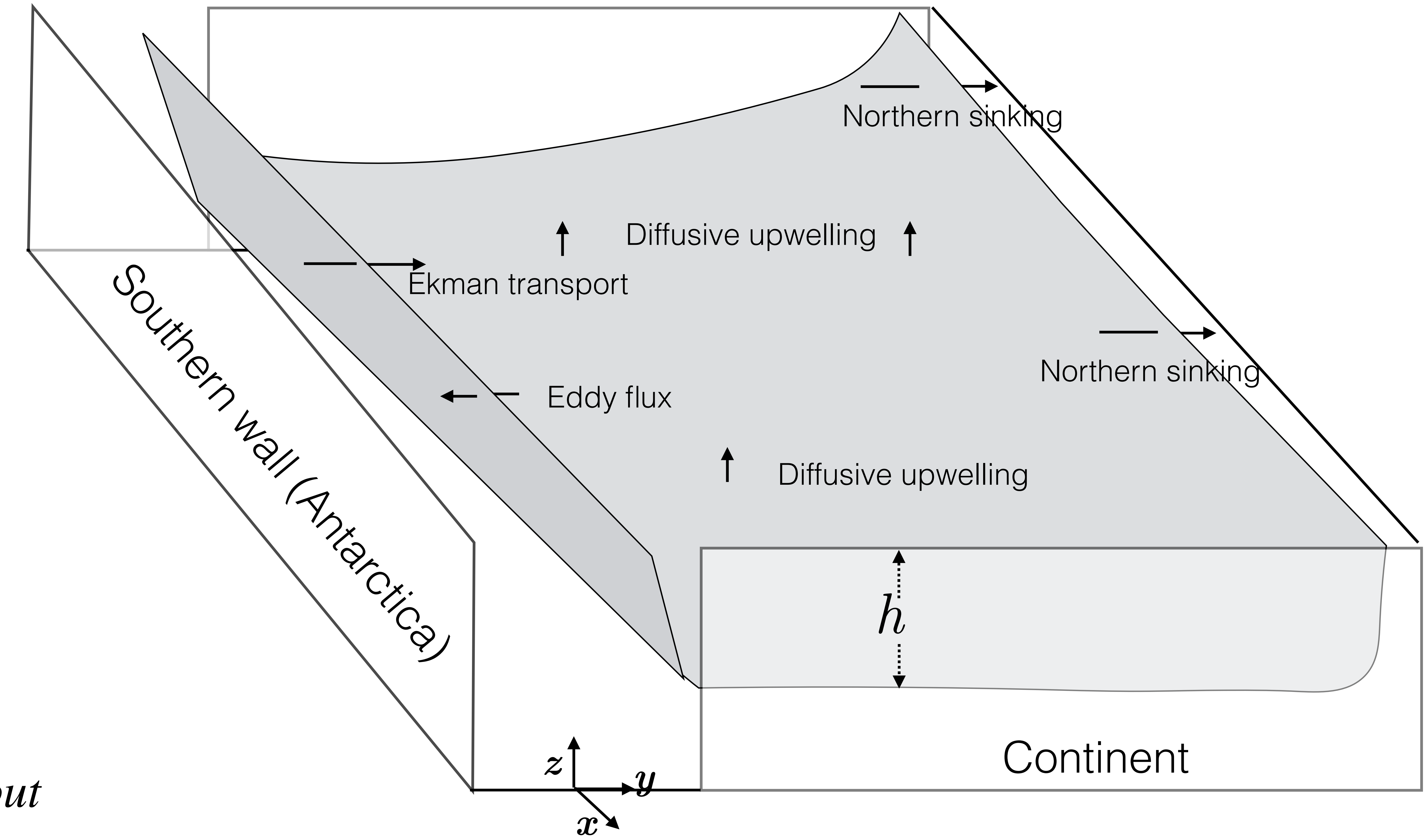
Integrate continuity over the layer depth

$$\partial_x(hu) + \partial_y(hv) - w^*|_{z=-h} = 0$$

Take the zonal integral

$$\partial_y(\bar{h}\bar{v} + \overline{h'v'}) - \overline{w^*}|_{z=-h} = 0$$

Integrate in latitude between the outcrops



$$\bar{h}\bar{v}|_{SHout} + \overline{h'v'}|_{SHout} + \int_{Area} w^*|_{z=-h} = \bar{h}\bar{v}|_{NHout}$$

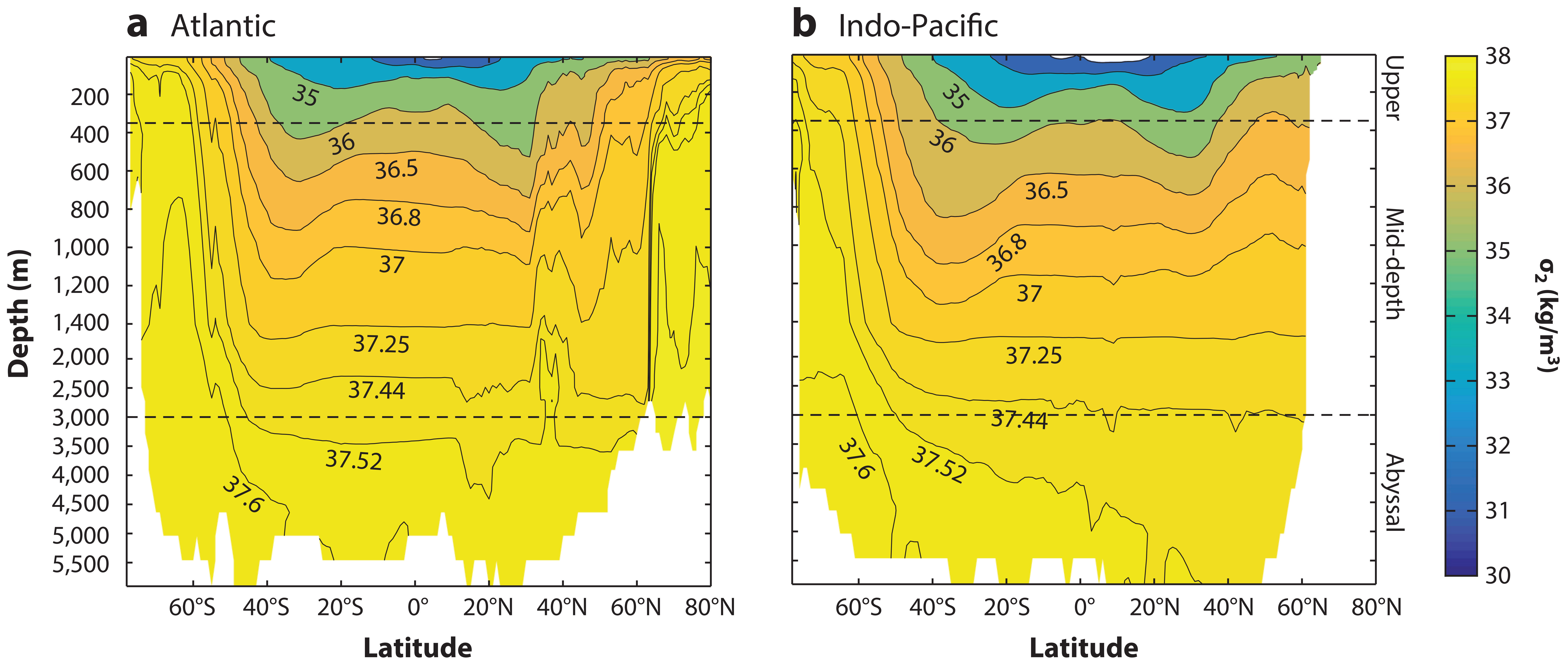
$$\underbrace{-\frac{\tau L_x}{\rho f_s}}_{Ekman\ transport} \quad \underbrace{-\kappa_a L_x \frac{h}{L_c}}_{eddy\ flux} + \underbrace{\kappa_v \frac{Area}{h}}_{diffusion} = \underbrace{\Delta b \frac{h^2}{2 f_n}}_{Northern\ sinking}$$

Solution in the absence of MOC: stratification in the channel

The dominant balance is $$\underbrace{-\frac{\tau L_x}{\rho f_s}}_{\textit{Ekman transport}} \quad \underbrace{-\kappa_a L_x \frac{h}{L_c}}_{\textit{eddy flux}} \approx 0$$

$$\frac{h}{L_c} \sim \frac{\tau}{\kappa_a \rho f_s}$$

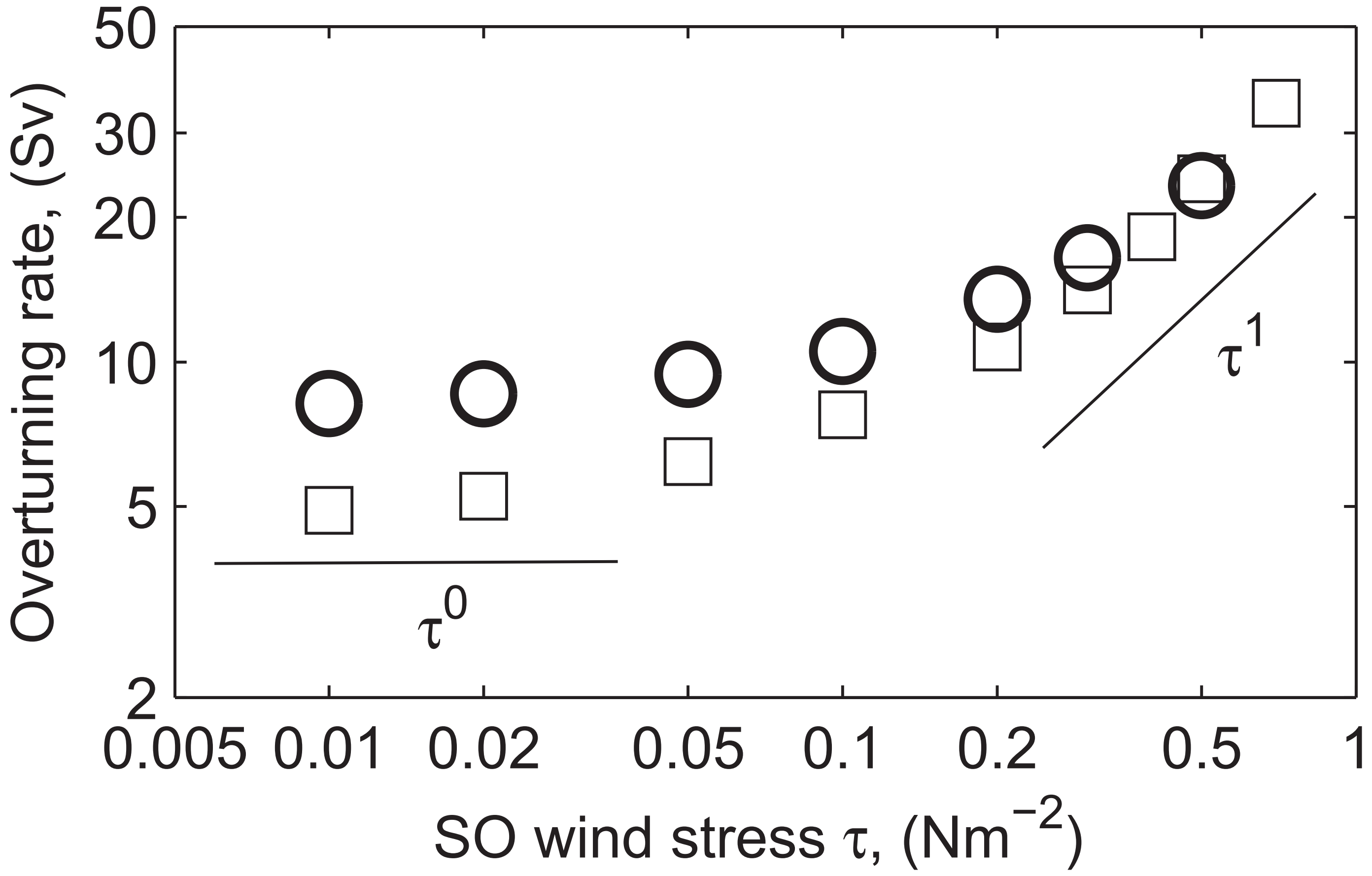
The slope is negative and about 1000m/1000km

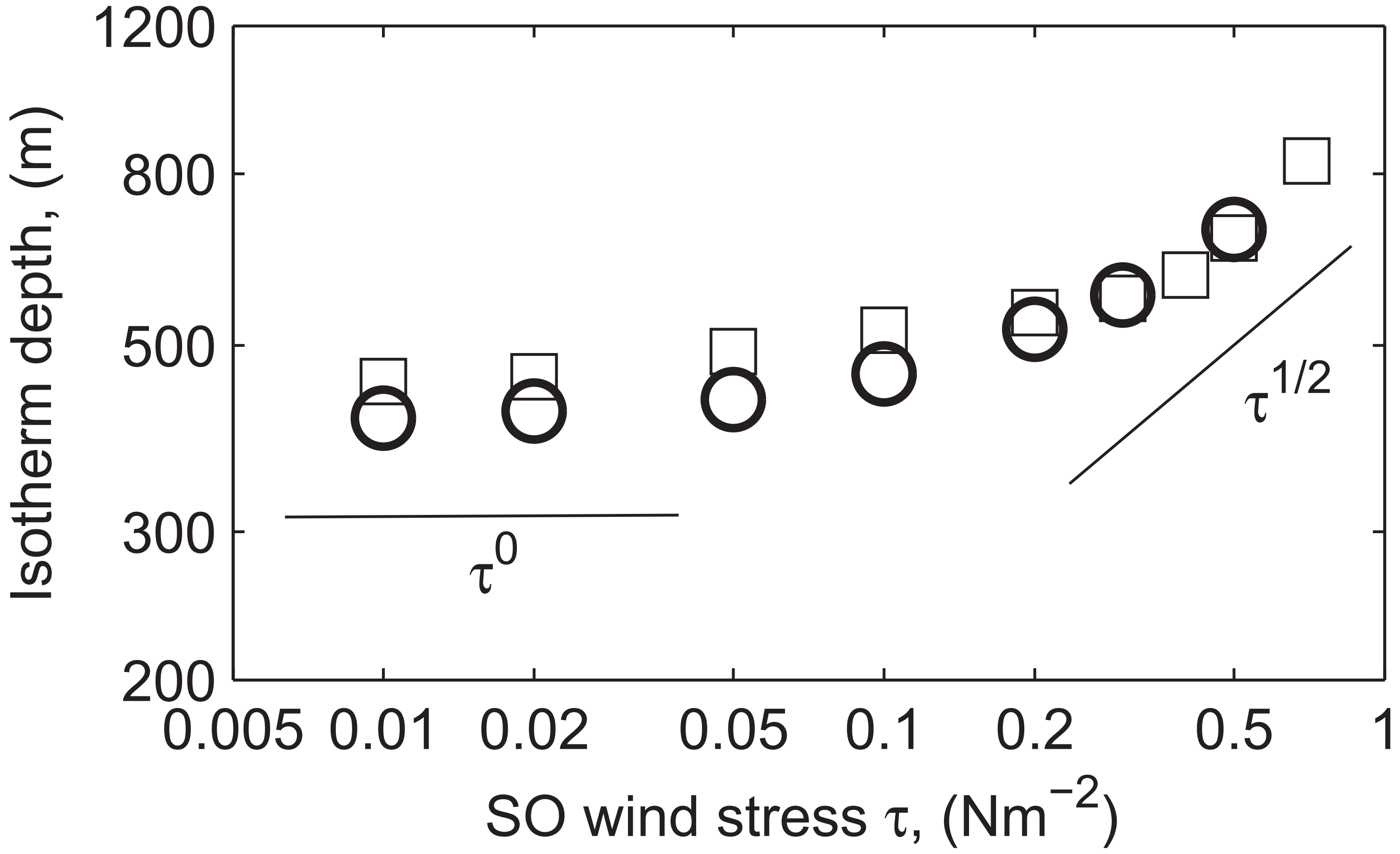


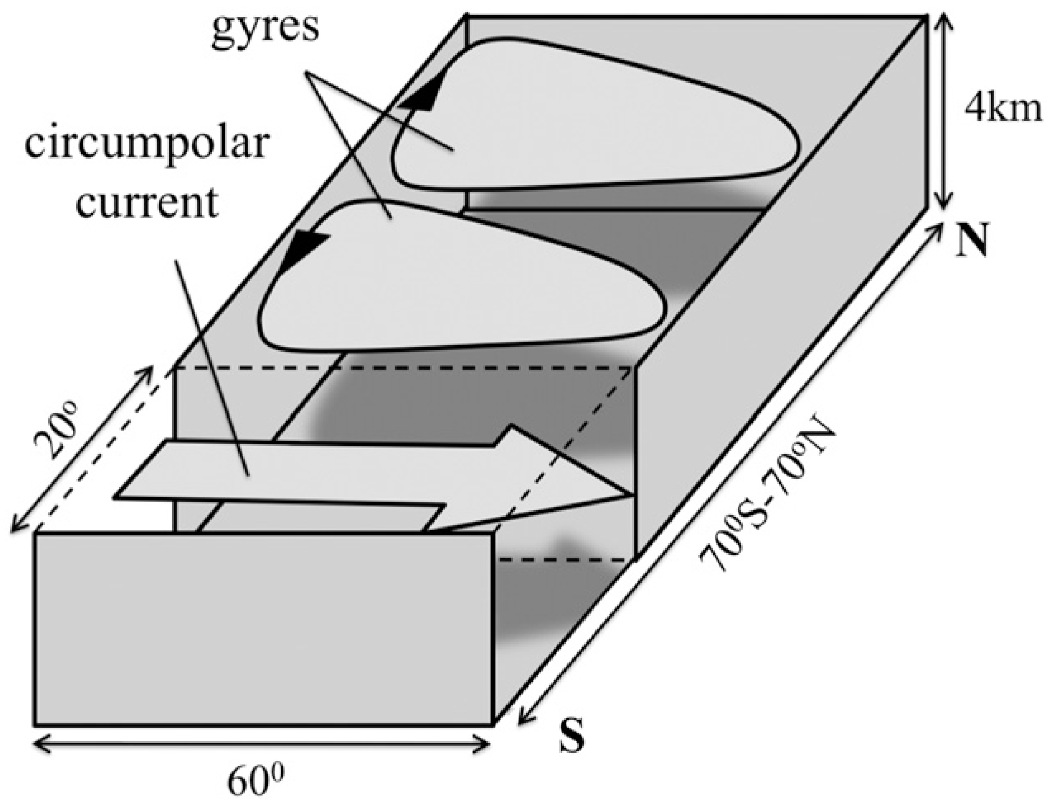
Solution in the adiabatic limit with eddies and wind-stress

The dominant balance is
$$\underbrace{-\frac{\tau L_x}{\rho f_s}}_{\textit{Ekman transport}} \quad \underbrace{-\kappa_a L_x \frac{h}{L_c}}_{\textit{eddy flux}} \approx \underbrace{\Delta b \frac{h^2}{2 f_n}}_{\textit{Northern sinking}}$$

For weak eddies $MOC \sim \dfrac{\tau_s L_x}{\rho f_s}$ $\qquad h \sim \left(\dfrac{f_n \tau_s L_x}{\Delta b \rho f_s}\right)^{1/2}$ Same scaling as gyres but τ_s instead of $\partial_y \tau_s$







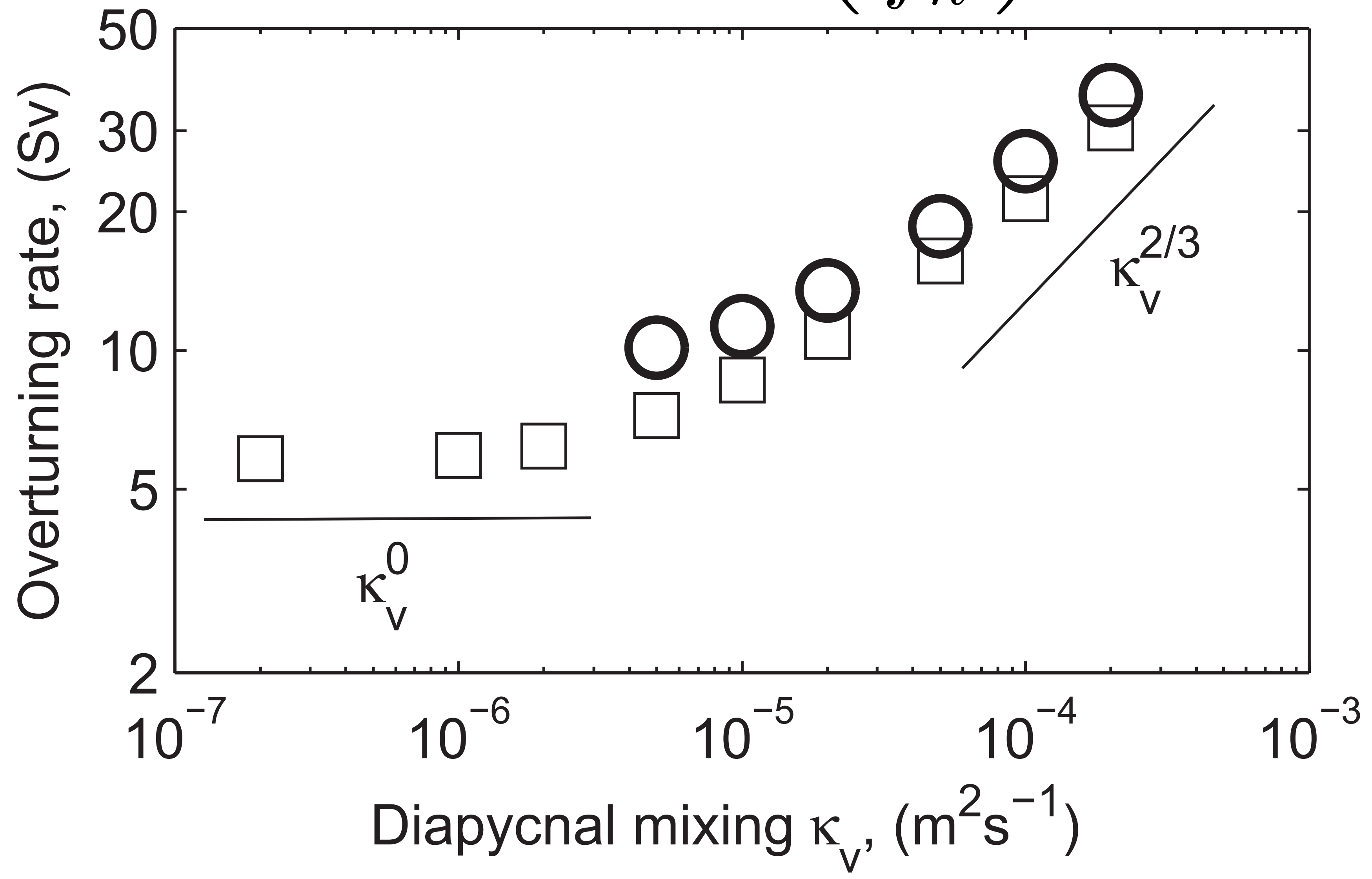
Results from a 3-D numerical model with surface winds and buoyancy

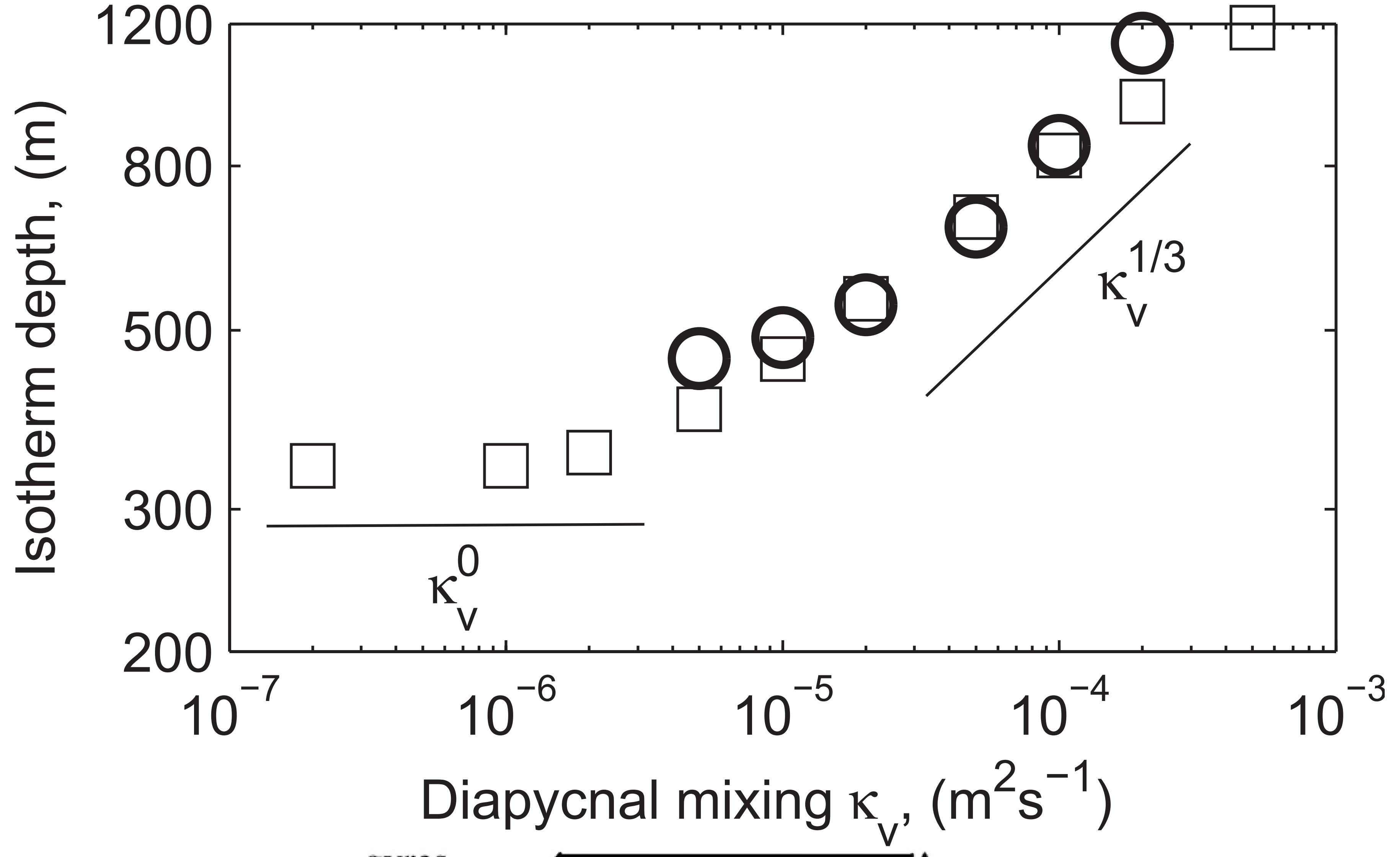
Nikurashin, M. and Vallis G.K. 2012 *JPO:* A Theory of the Interhemispheric Meridional Overturning Circulation and Associated Stratification

Solution in the diffusive limit appropriate for abyssal cell

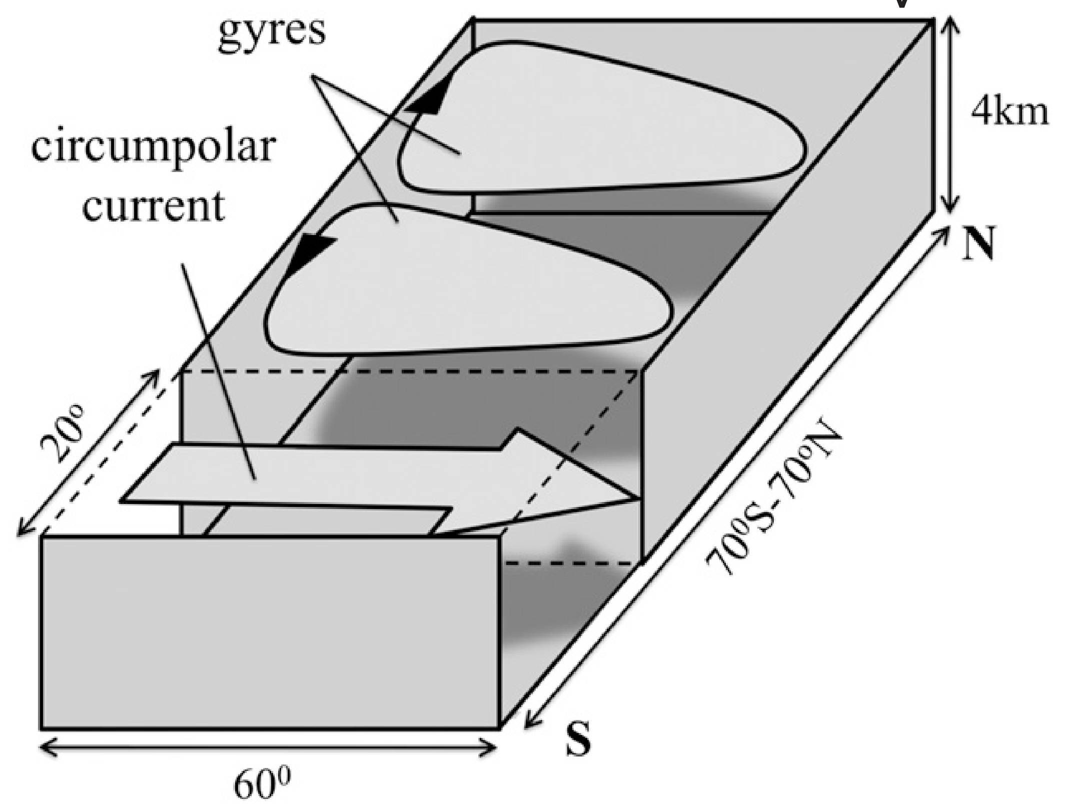
The dominant balance is $$\underbrace{\kappa_v \frac{Area}{h}}_{diffusion} \approx \underbrace{\Delta b \frac{h^2}{2f_n}}_{Northern\ sinking}$$

With solution $MOC \sim \left(\frac{\Delta b}{f_n}\right)^{1/3} (\kappa_v Area)^{2/3}$ $\qquad h \sim (f_n \kappa_v Area/\Delta b)^{1/3}$





Results from a 3-D numerical model with surface winds and buoyancy



Nikurashin, M. and Vallis G.K. 2012 *JPO:* A Theory of the Interhemispheric Meridional Overturning Circulation and Associated Stratification

Summary

The deep and abyssal stratification of the world ocean is set in the ACC region.

The surface Ekman transport in the periodic channel is returned at the bottom: it overturns isopycnals until they are vertical, producing a large amount of APE.

Some APE is converted into baroclinic eddies, restratifying, but not as much as in basin: stratification runs deeper in ACC.

In the weak-diffusion limit, residual overturning is along isopycnals shared with ACC.

The strength of ROC is a competition between Ekman versus eddy transport in ACC.

Simple models with parametrized eddy fluxes of buoyancy are helpful.

Quantitive results depend on the details of parametrization.

The dominant driver of the MOC is the wind-stress in the ACC.