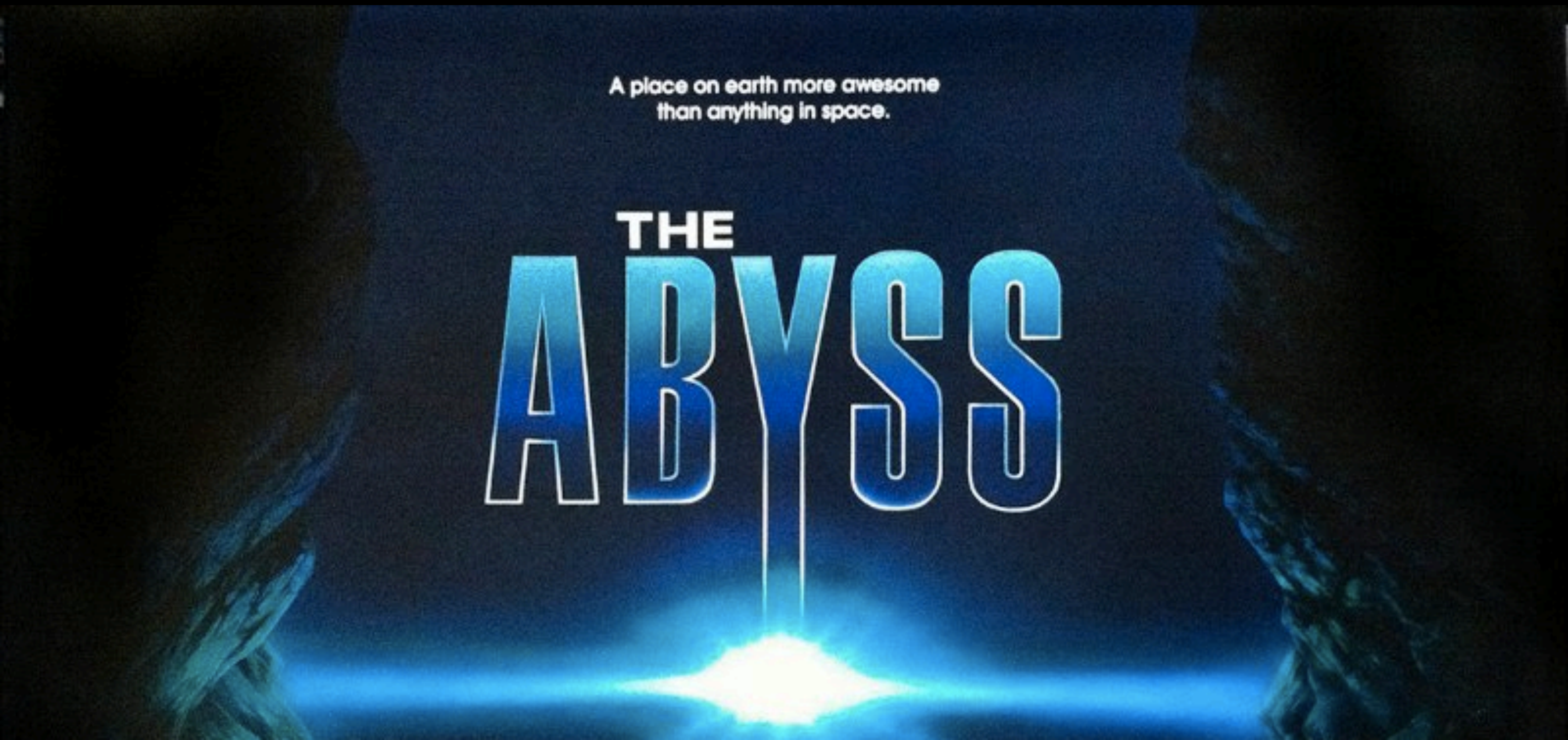
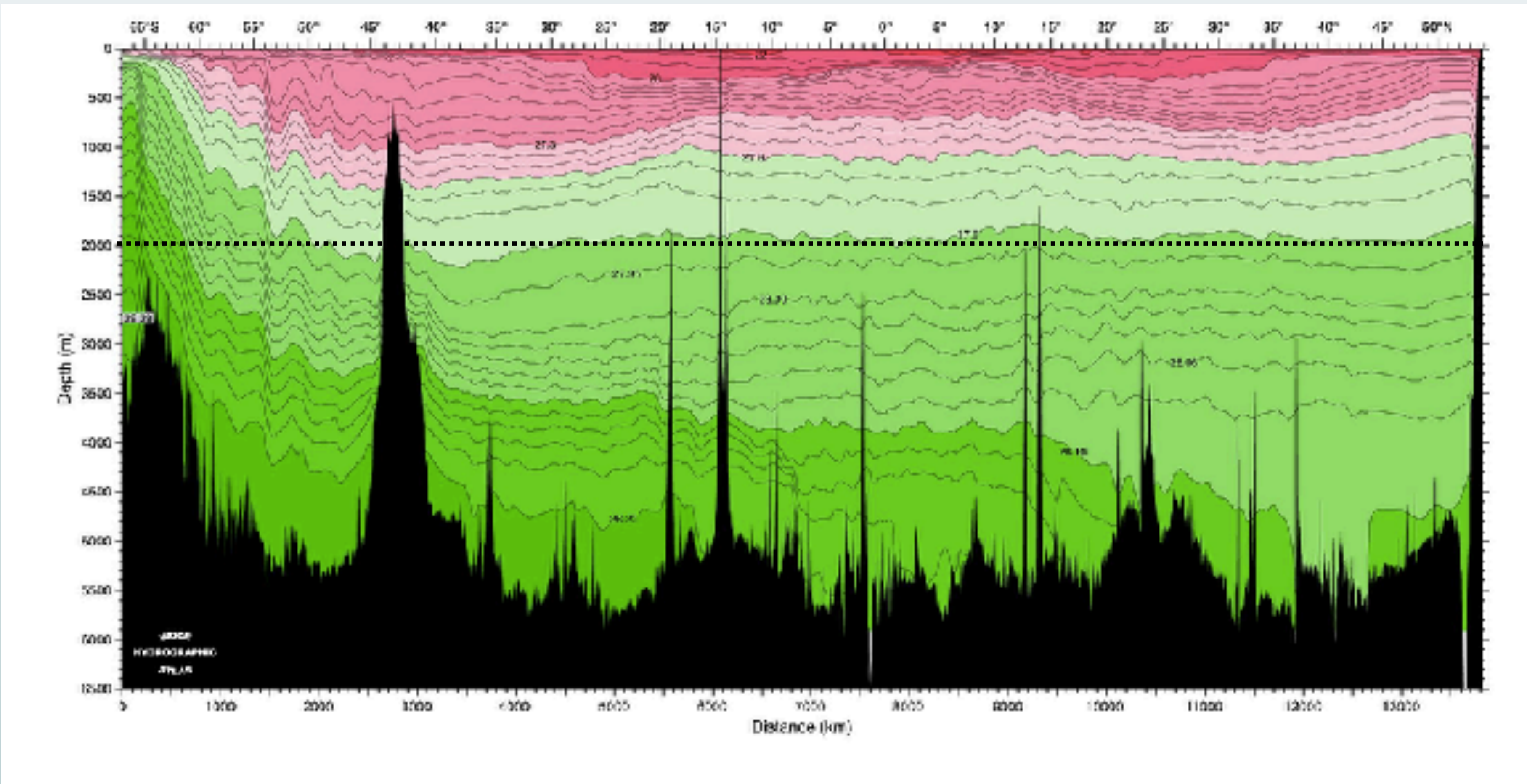
Bottom Boundary Layers & Abyssal Circulation

Raffaele Ferrari
Earth, Atmospheric and Planetary Sciences, MIT
KITP, Santa Barbara, May 14 2018



Ocean density distribution

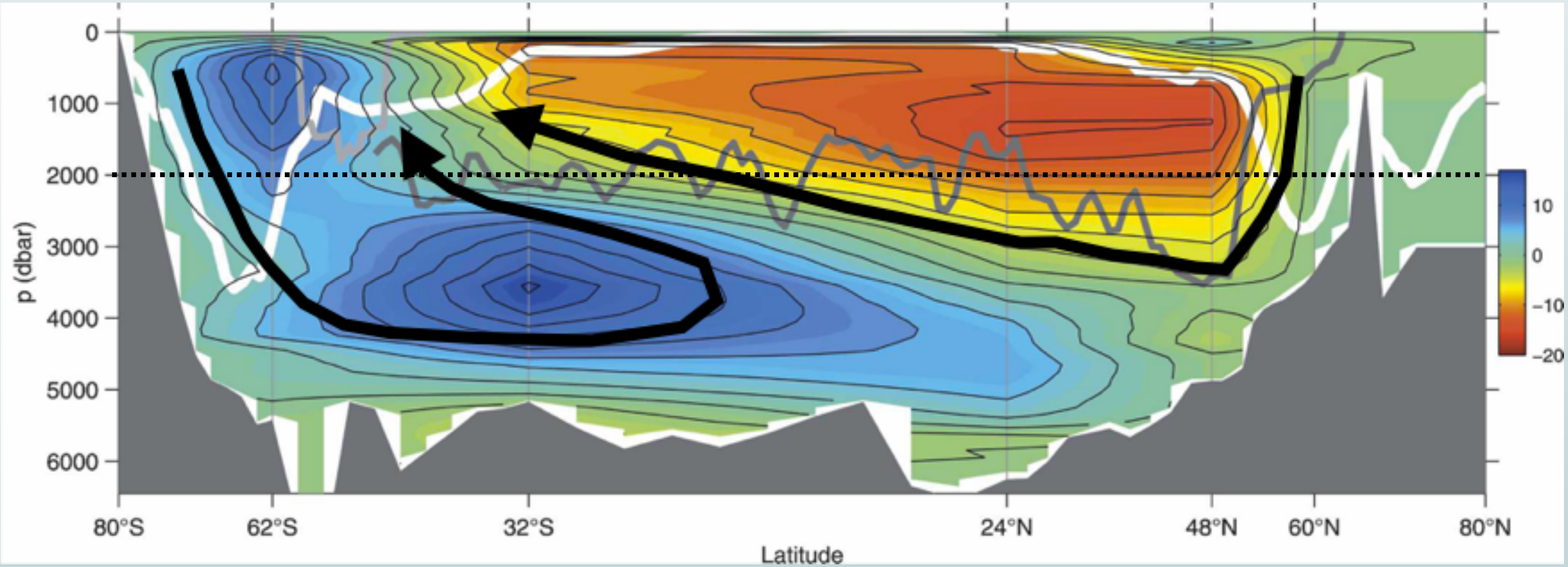
Strong stratification



WOCE section P15, 165 W

Meridional overturning circulation

Vigorous overturning crossing density surfaces below 2000 m



Lumpkin and Speer, 2007

The classical recipe for the abyssal ocean circulation

Key ingredients for the recipe:

1. The ocean bottom is at leading order flat
2. Upwelling and turbulent diffusivity are approximately constant throughout the ocean

Munk, 1966	Stommel and Arons, 1960
$wb_z \simeq \kappa_T b_{zz} \geq 0$	$\beta v \simeq f w_z \geq 0$
$\kappa_T \simeq 10^{-4}\mathrm{m}^2\mathrm{s}^{-1}$	cyclonic gyre

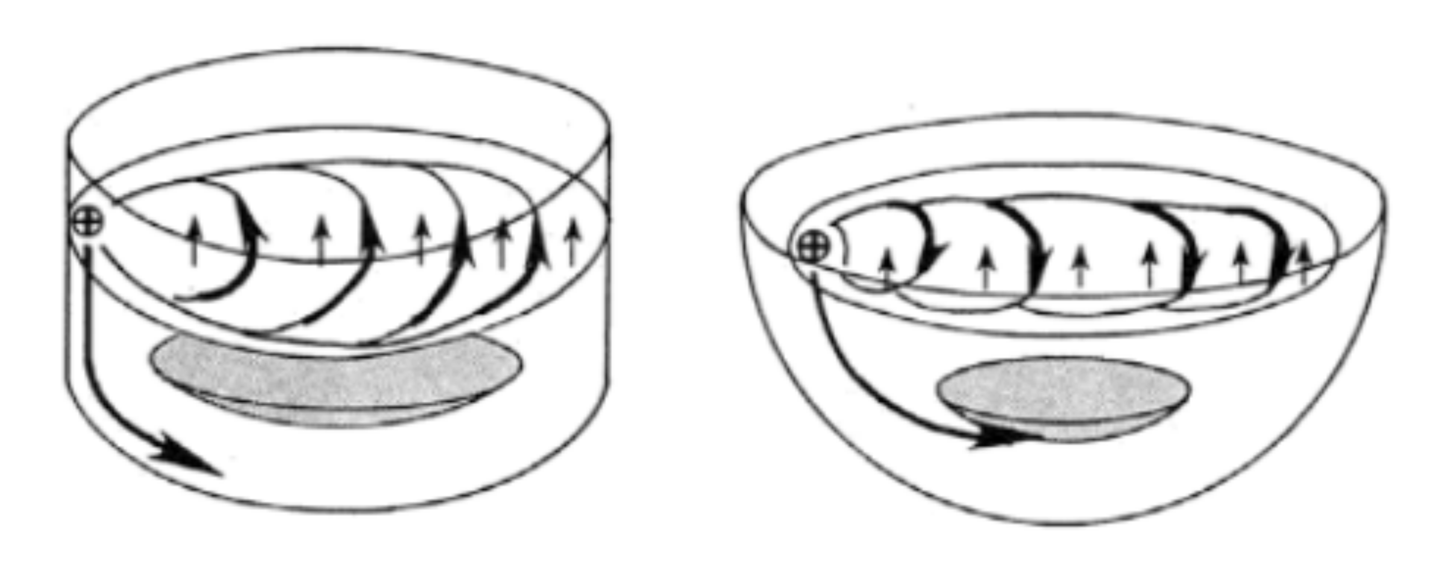
Ingredient 1: flat bottom

The sense of the circulation changes if the boundaries are sloping

$$wA = S_0 \quad \Longrightarrow \quad \partial_z w = -w\frac{\partial_z A}{A} = -S_0\frac{\partial_z A}{A^2}$$

$$\beta v = f\partial_z w = -fS_0\frac{\partial_z A}{A^2} \leq 0$$

cyclonic gyre　　　　anticyclonic gyre



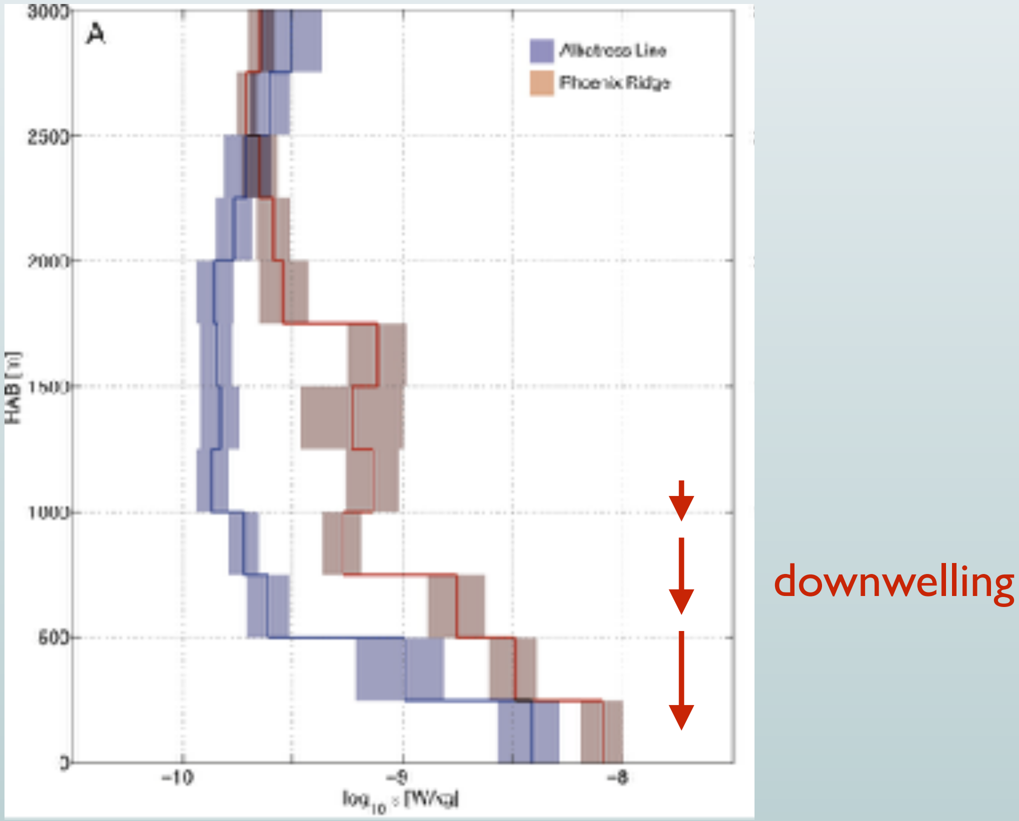
McDougall 1989, Rhines 1993

Ingredient 1I: constant mixing

The vertical profile of mixing is not uniform

$$wb_z \simeq \partial_z(\kappa_T b_z) = \partial_z(\Gamma\epsilon) \leq 0$$

vertical downwelling



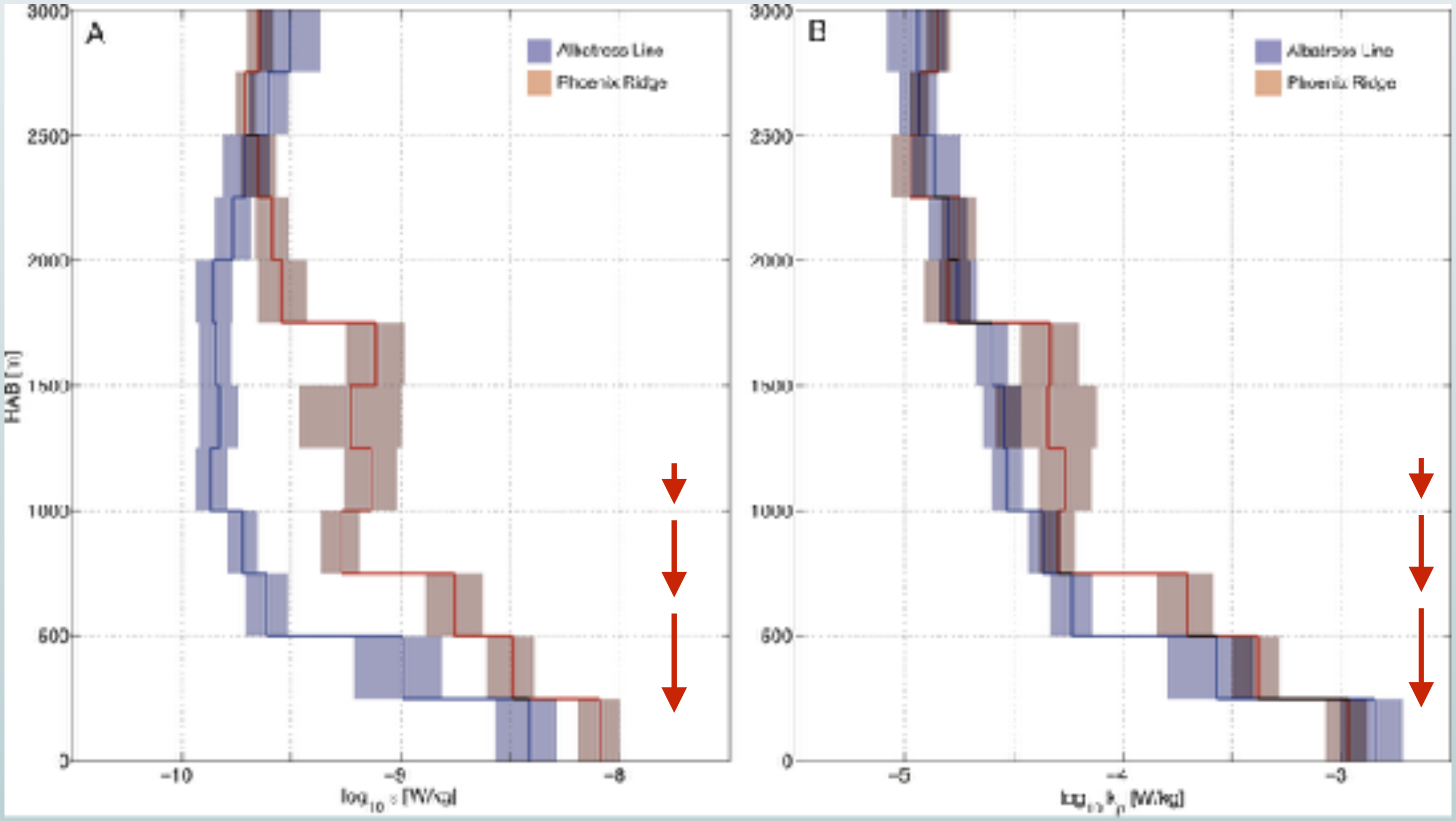
St Laurent et al. 2012

Ingredient 1I: constant mixing

The vertical profile of mixing is not uniform

$$wb_z \simeq \partial_z(\kappa_T b_z) = (\partial_z \kappa_T)b + \kappa_T(\partial_z b_z) \leq 0$$

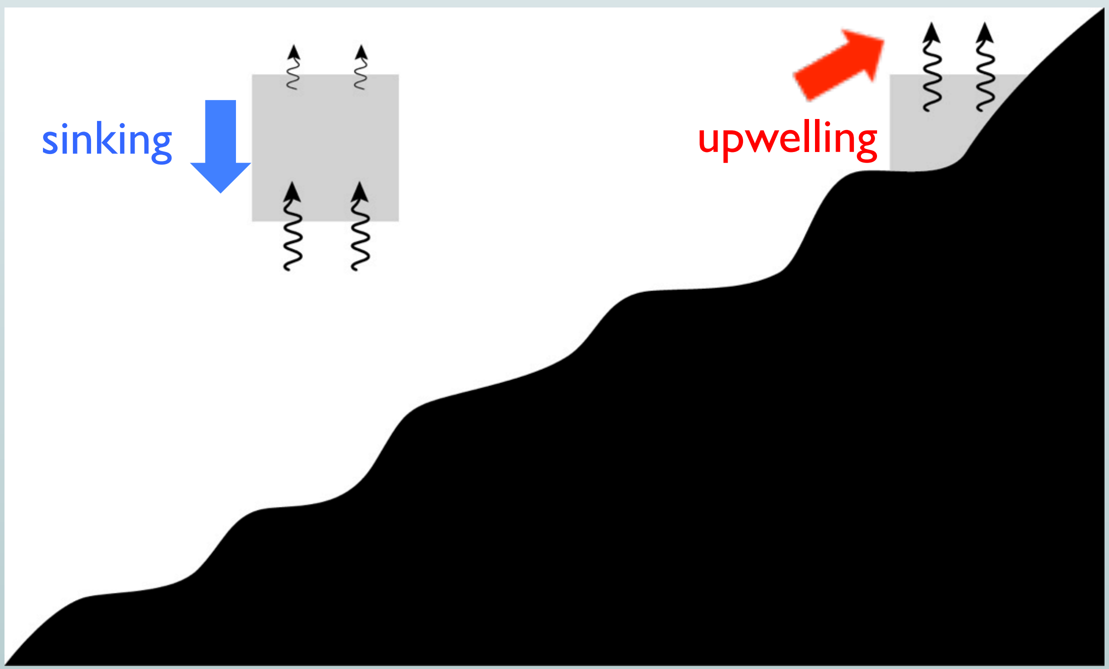
vertical downwelling



St Laurent et al. 2012

Ingredient 11: constant mixing

- Bottom enhanced mixing drives
  - downwelling in the interior
  - upwelling along the ocean seafloor



Diapycnal up/downwelling in the ocean

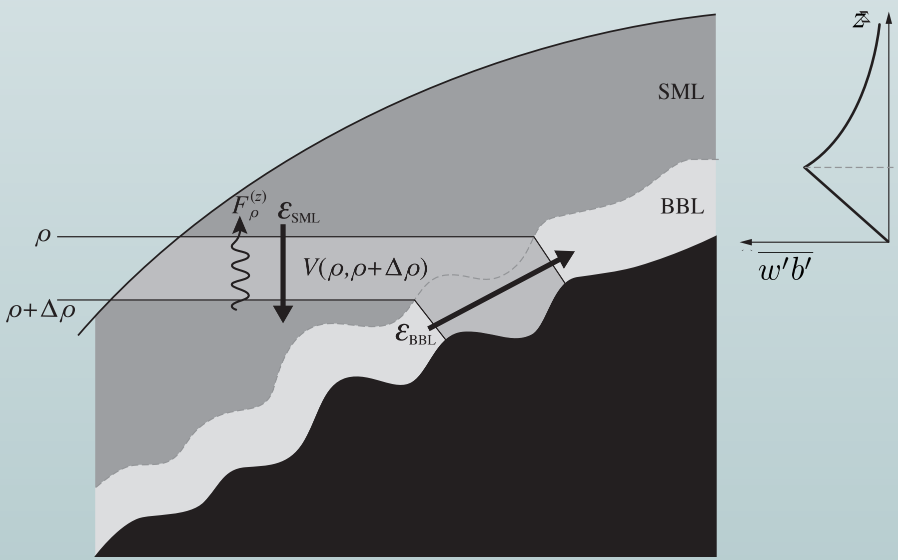
Diagnosing diapycnal velocities

- Diapycnal sinking occurs in the stratified mixing layer (SML)

$$\mathcal{E}_{SML} \equiv \iint_{SML} e \; \mathrm{d}A = -\iint_{SML} \frac{\partial_z \overline{w'b'}}{\partial_z \bar{b}} \; \mathrm{d}A < 0$$

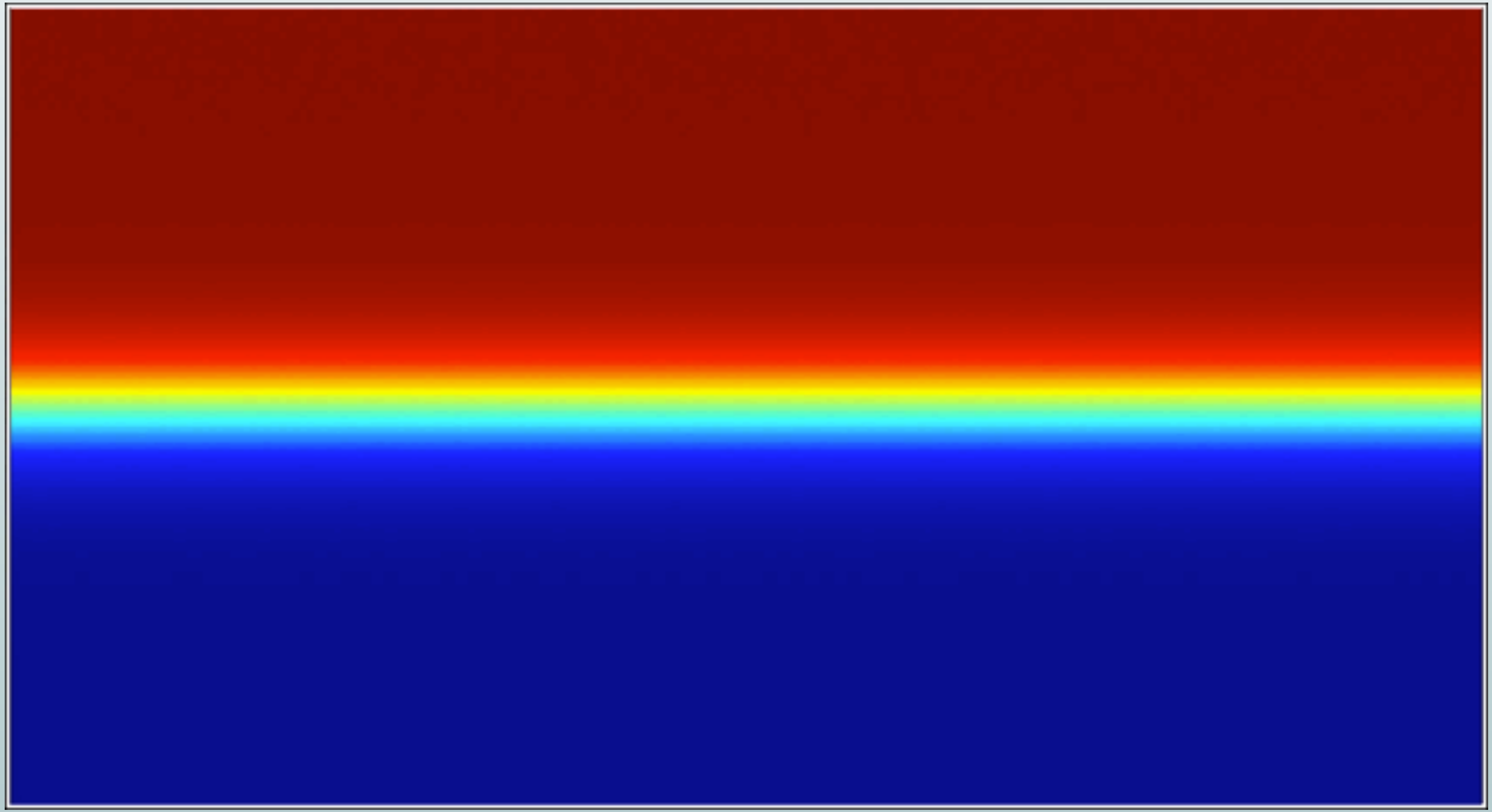
- Diapycnal upwelling occurs in the bottom boundary layer (BBL)

$$\mathcal{E}_{BBL} \equiv \iint_{BBL} e \; \mathrm{d}A = -\iint_{BBL} \frac{\partial_z \overline{w'b'}}{\partial_z \bar{b}} \; \mathrm{d}A > 0$$

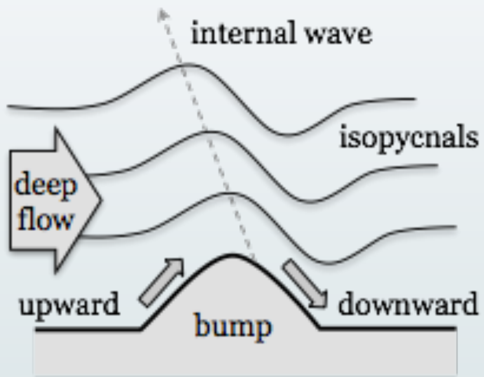


Estimating $\partial_z \overline{w'b'}$

- Breaking waves generate buoyancy flux in SML
  - estimate rate at which internal waves are generated
  - estimate rate at which internal waves break



Topographic wave radiation



To estimate energy radiation into internal waves the following data are required

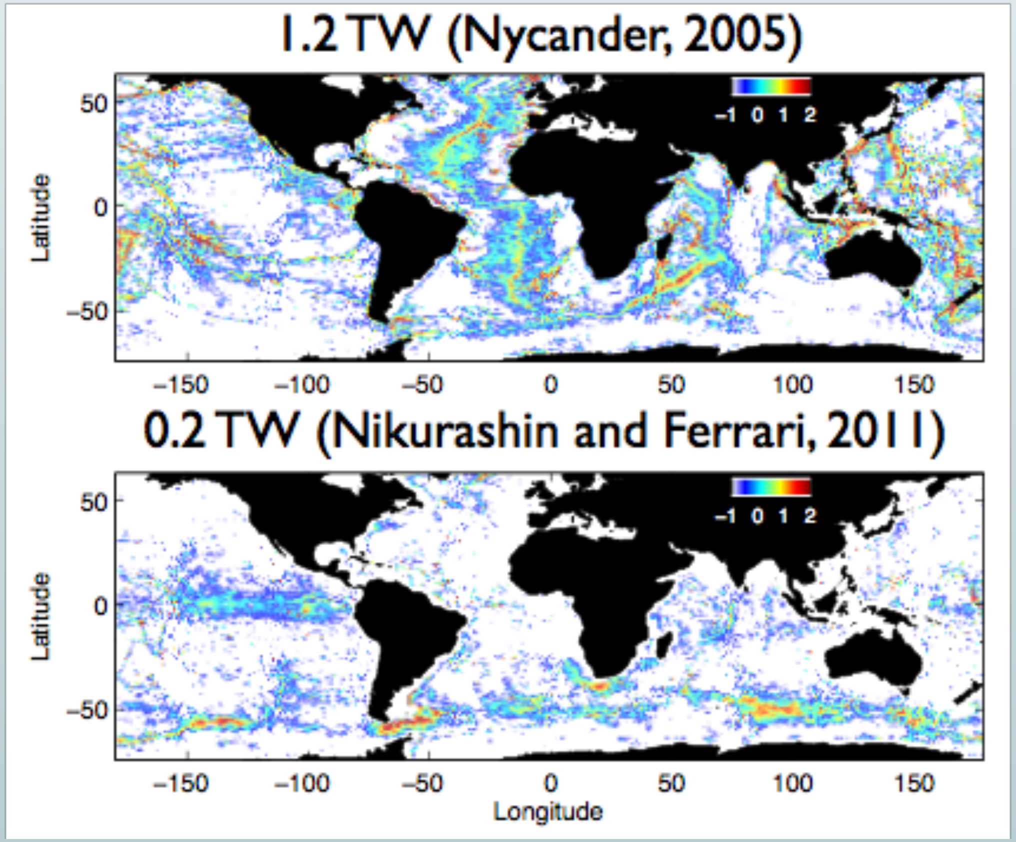
- bathymetry
- bottom stratification
- bottom flow velocity

TIDAL MOTIONS (1.2 TW)

- linear theory for internal tides
- satellite altimetry (big bumps)
- WOCE hydrography
- TPXO.6 barotropic tidal model

GEOSTROPHIC MOTIONS

- linear theory for lee waves
- ship soundings (small bumps)
- WOCE hydrography
- 1/8° GFDL ocean model



Turbulent buoyancy flux profile

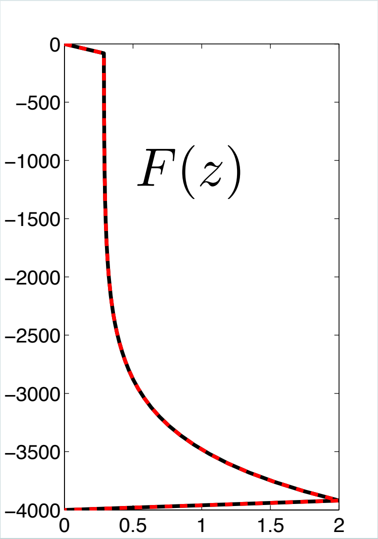
- The topographic wave radiation gives the upward energy flux

$$E(x,y) = E_{tides}(x,y) + E_{geostrophic}(x,y)$$

- Assuming that q=30% of this energy flux generates a turbulent kinetic energy flux with an e-folding scale of 500m

$$\epsilon(x,y,z) = q\,F(z)E(x,y)$$

$$\int_{-H}^{0} F(z)\,\mathrm{d}z = 1$$



- Using Osborn (1980) formula

$$\overline{w'b'} = -\Gamma\epsilon(x,y,z)$$

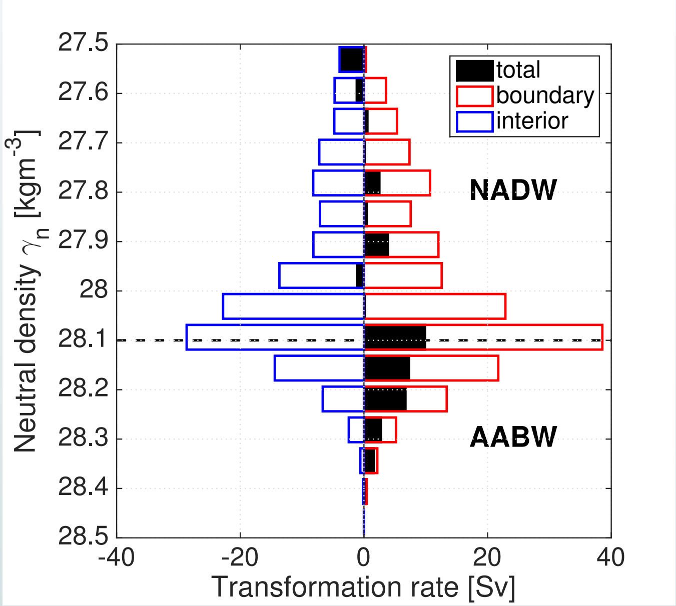
Diapycnal in the deep ocean

Diapycnal transports

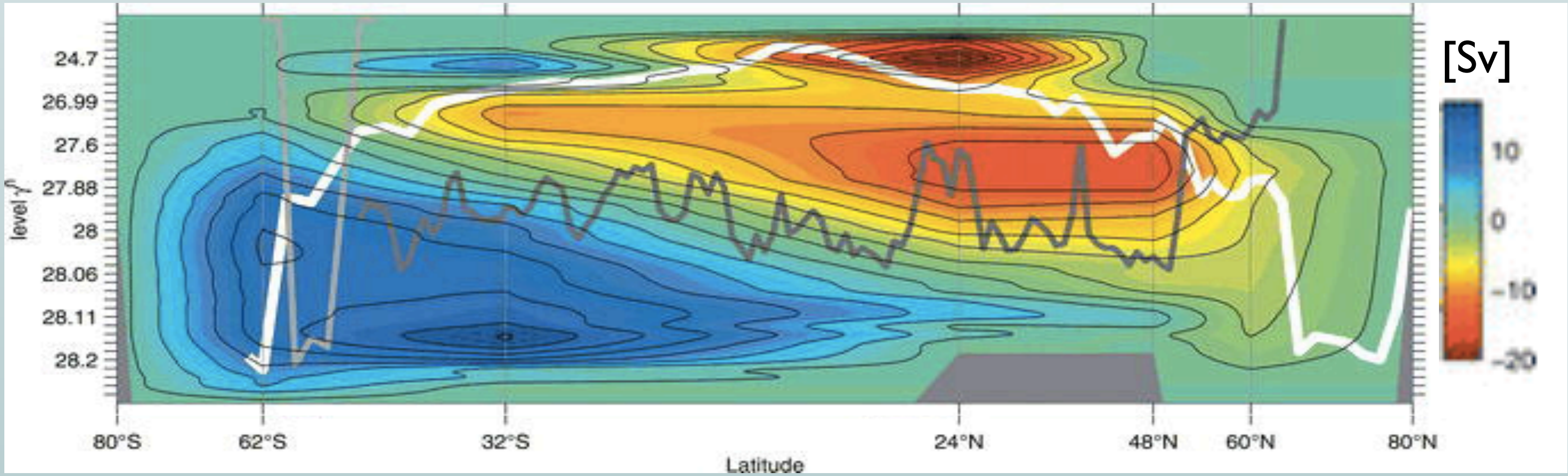
$\mathcal{E}_{SML}$

$\mathcal{E}_{BBL}$

$\mathcal{E}_{tot} = \mathcal{E}_{SML} + \mathcal{E}_{BBL}$



Overturning circulation



Ferrari et al. 2016

Toward a new Abyssal Recipe

Simplified dynamics
(Callies and Ferrari, JPO 2018)

Continuously stratified planetary geostrophic equations

$$f\hat{\mathbf{z}} \times \mathbf{u}_H = -\nabla p + b\hat{\mathbf{z}} - r\mathbf{u}_{\mathbf{H}}$$

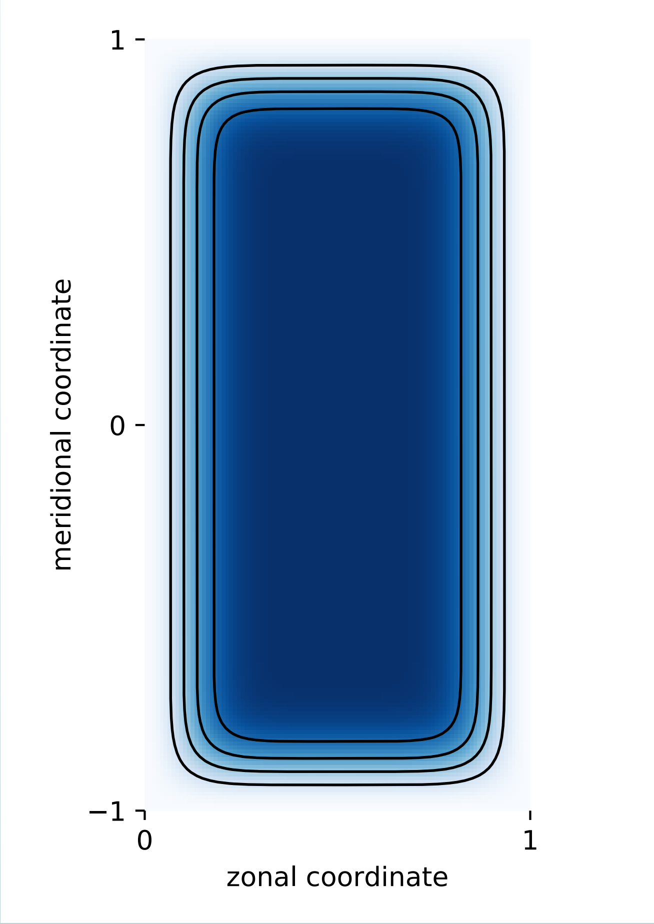
$$\nabla \cdot \mathbf{u} = 0$$

$$b_t + \mathbf{u} \cdot \nabla b = \nabla \cdot (\kappa_T \nabla b)$$

1. The Rayleigh friction as a momentum closure simplifies boundary layers (cf. Stommel vs. Munk gyre)
2. Turbulent diffusivity increases toward the ocean bottom
3. The bottom topography is not flat

Spindown circulation

Bathymetry



Initially uniform stratification

$$b = N^2 z$$

Boundary conditions

$$b = 0 \quad \text{at} \quad z = 0$$

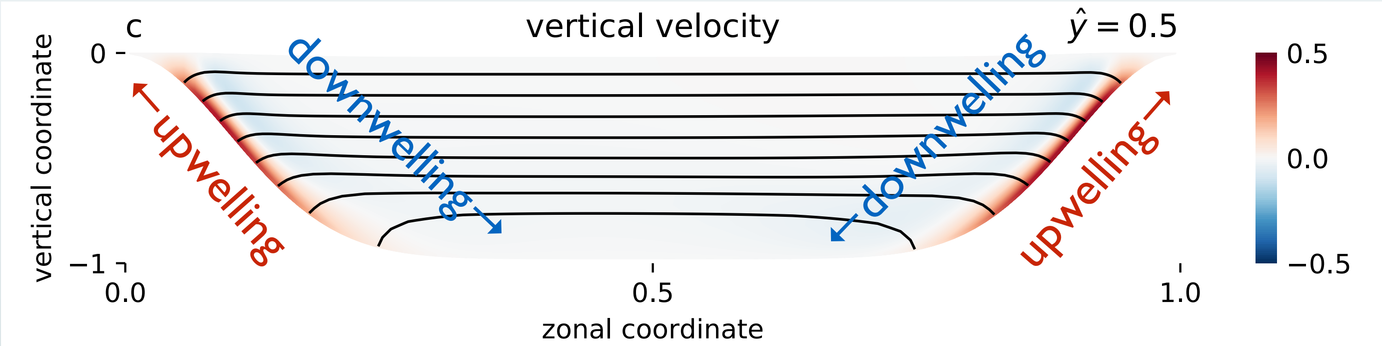
$$\hat{\mathbf{n}} \cdot \nabla b = 0 \quad \text{at} \quad z = -h(x, y)$$

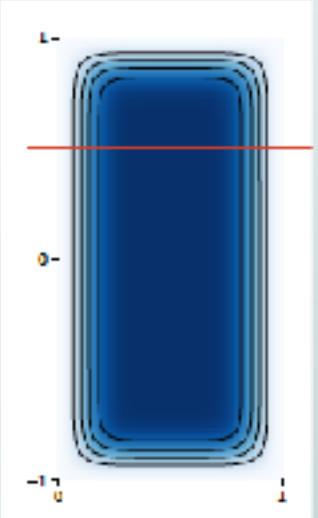
$$\hat{\mathbf{n}} \cdot \mathbf{u} = 0 \quad \text{at} \quad z = 0, -h(x, y)$$

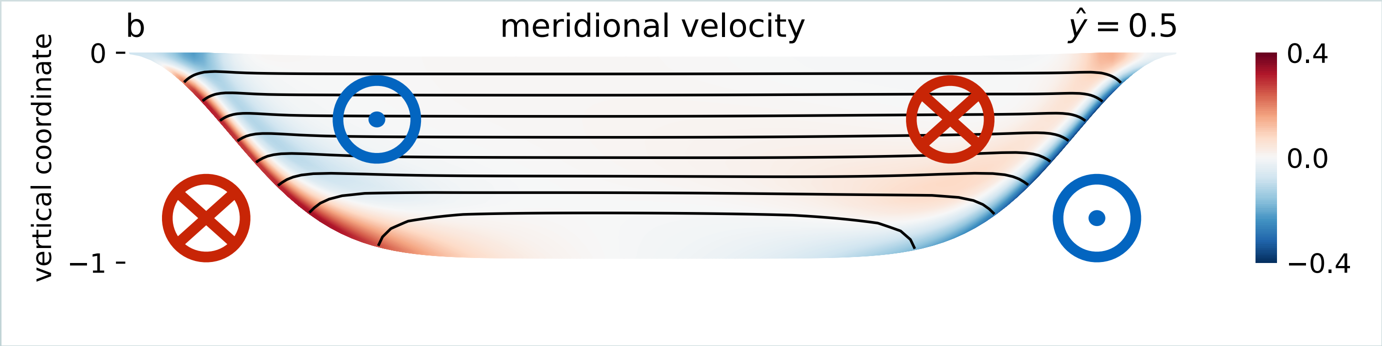
Turbulent diffusivity profile

$$\kappa_T = \kappa_0 e^{-(z+h)/d}$$

Spindown circulation



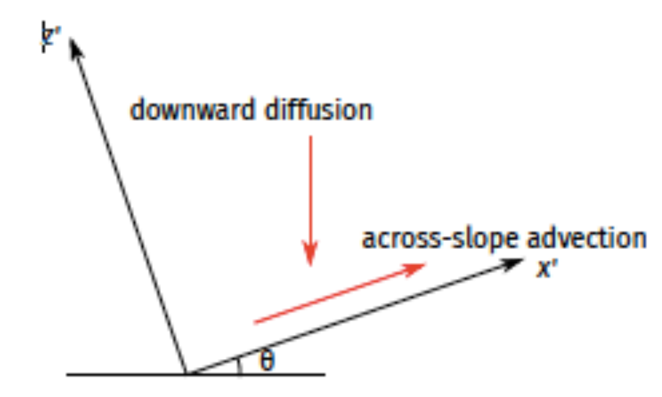




Boundary layer solution

- Boundary layers satisfy a local balance between downward diffusion and across-slope advection
- Transforming into along- slope coordinates

$$b \equiv N^2 z + b = N^2 \sin\theta x' + N^2 \cos\theta z' + b'$$

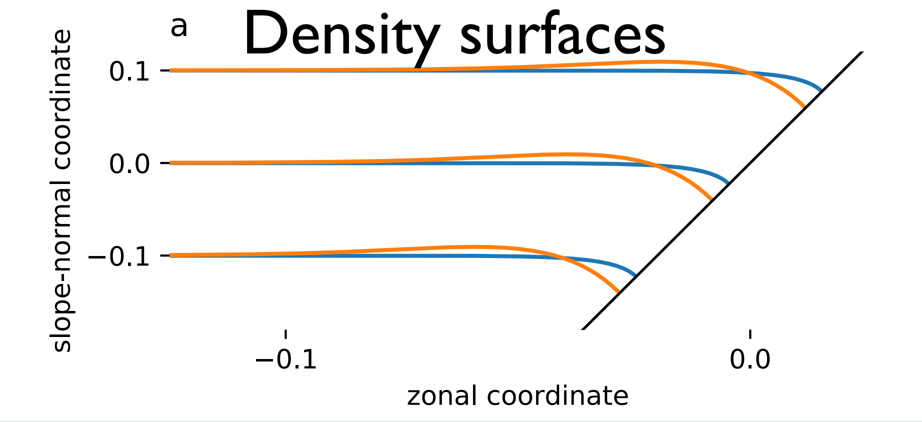


Buoyancy budget

$$b_t' + u' N^2 \sin\theta = \left[\kappa_T \left(N^2 \cos\theta + b_{z'}'\right)\right]_{z'}$$

Momentum budget

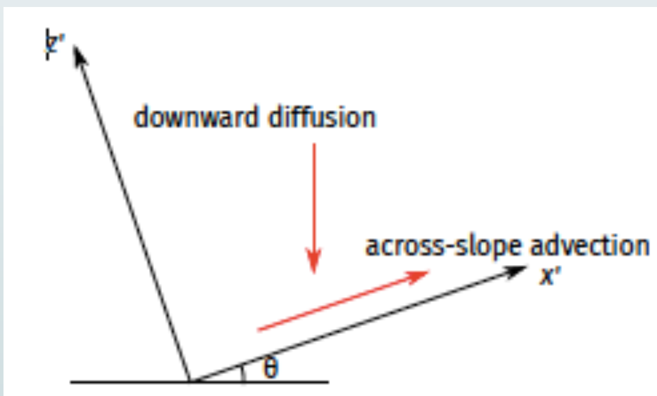
$$\left(f_0^2 + r^2\right)\cos^2\theta \; u' = r \sin\theta \; b'$$

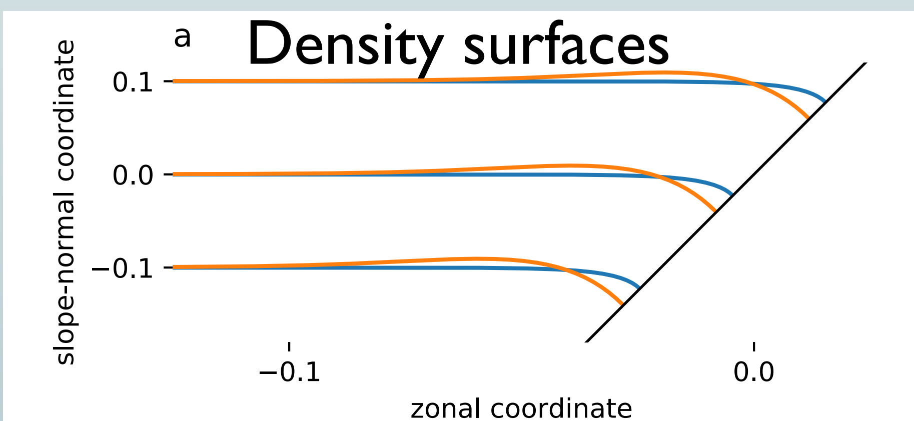


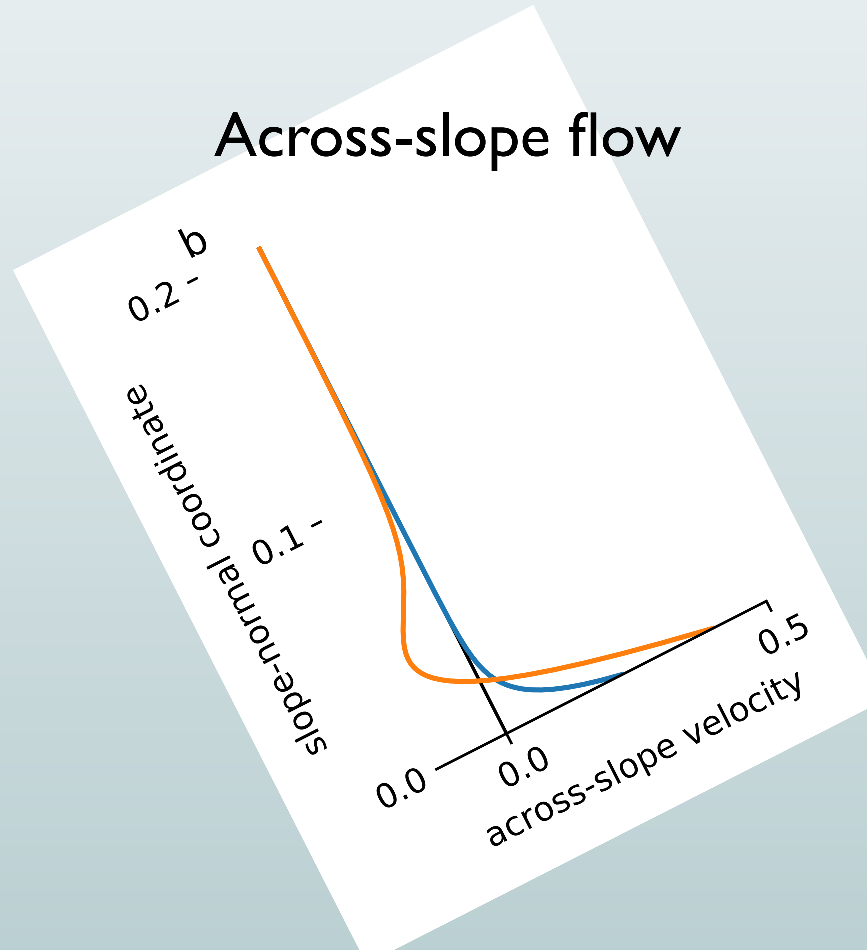
cf. Phillips (1970), Wunsch (1970), Garrett et al. (1993)

Boundary layer solution

Boundary layers satisfy a local balance between downward diffusion and across-slope advection



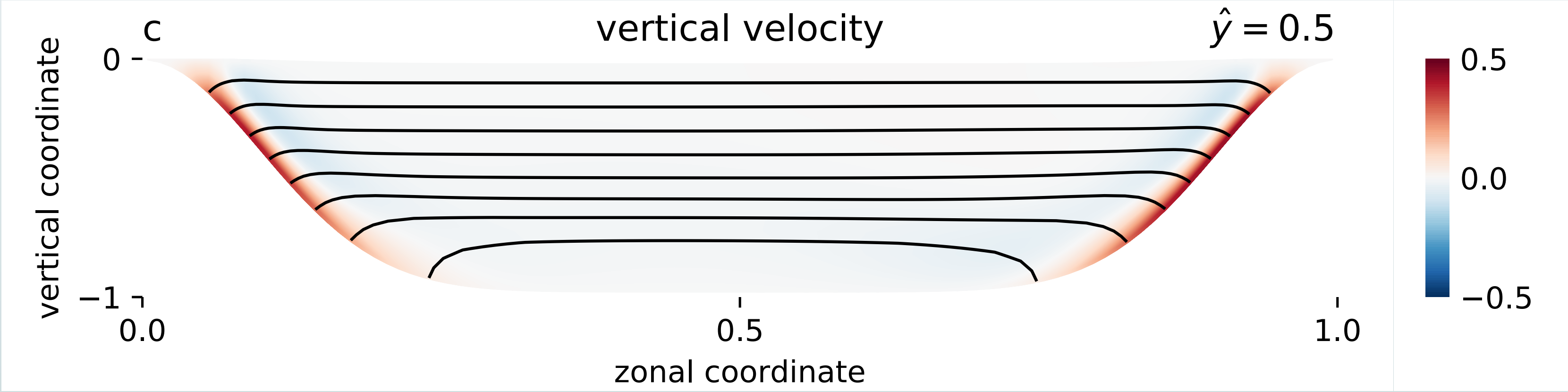




cf. Phillips (1970), Wunsch (1970), Garrett et al. (1993)

Boundary layer solution

Boundary layers reach steady sate on slopes, but not over flat bathymetry



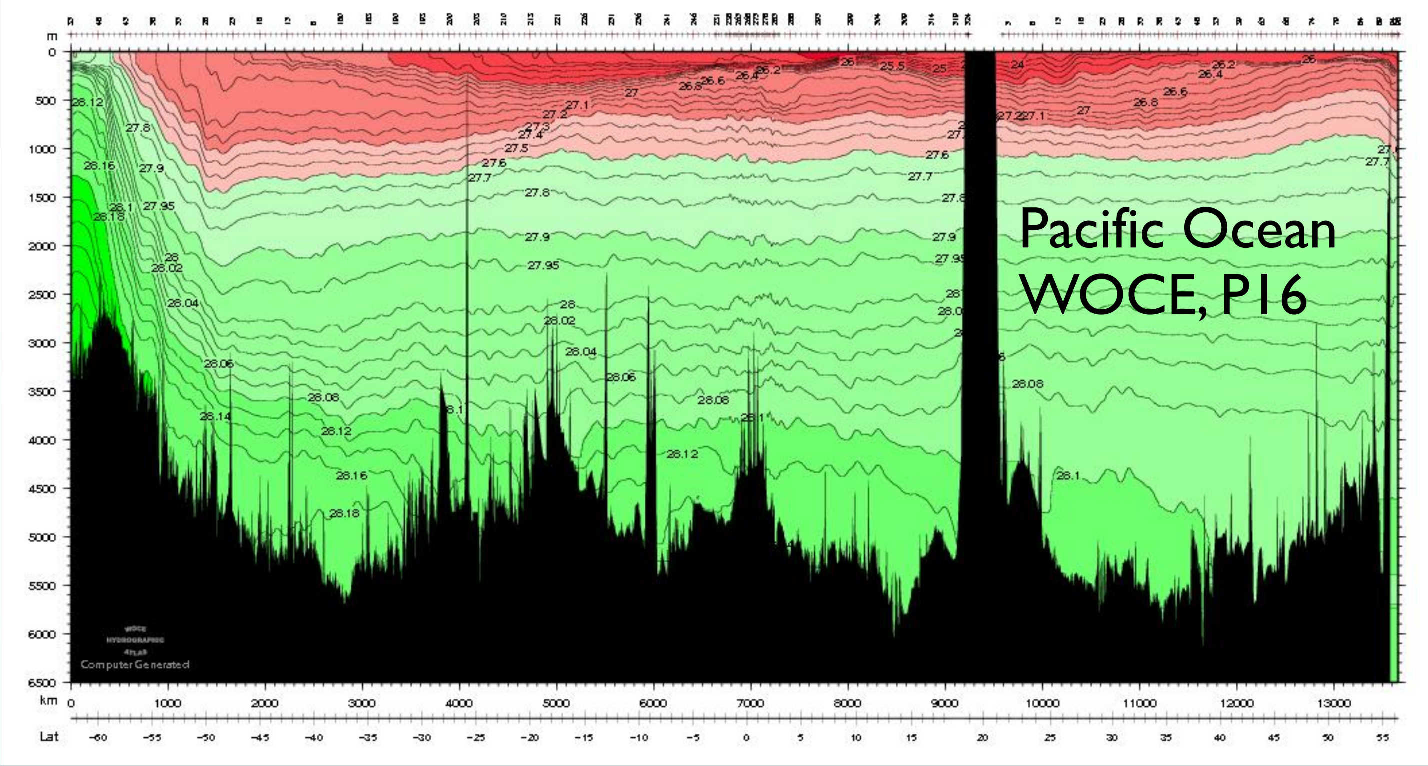
On slopes, diffusive fluxes can be balanced by across-slope advection (local balance).

But on flat bathymetry, no dense water can be upwelled.

Basin-scale lateral advection must enter the budget there.

Equilibrated circulation

In the Southern Ocean, winds and mesoscale eddies set the mean isopycnal slope. Together with surface buoyancy fluxes, this sets the stratification at the northern edge of the Southern Ocean.

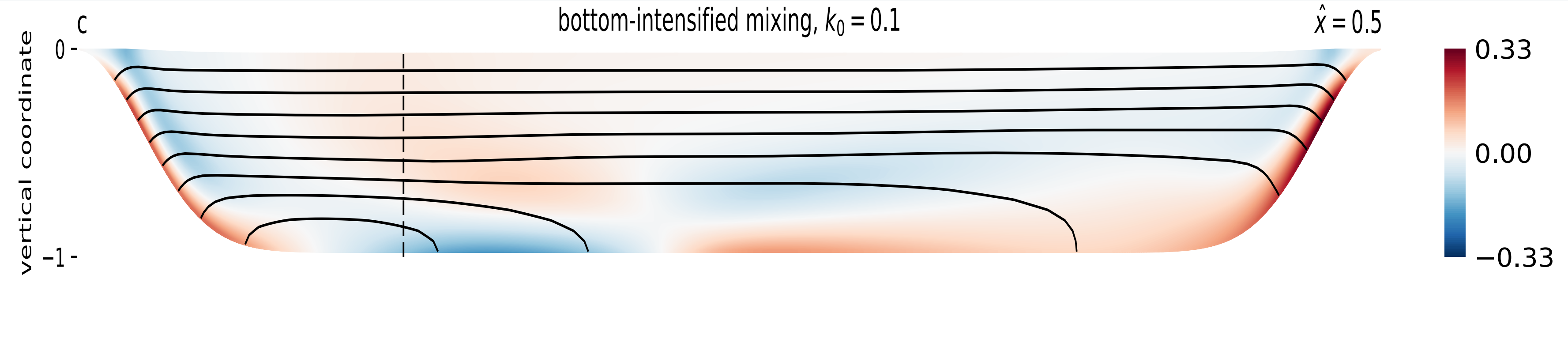


Mimic Southern Ocean processes by restoring to prescribed stratification

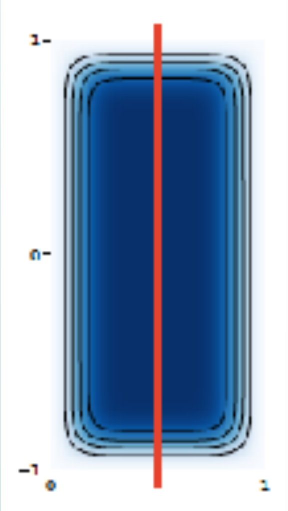
$$b_t + \mathbf{u} \cdot \nabla b = \nabla \cdot (\kappa_T \nabla b) - \lambda(y) \left(b - N^2 z\right)$$

Equilibrated circulation

The basin stratification is set in the south

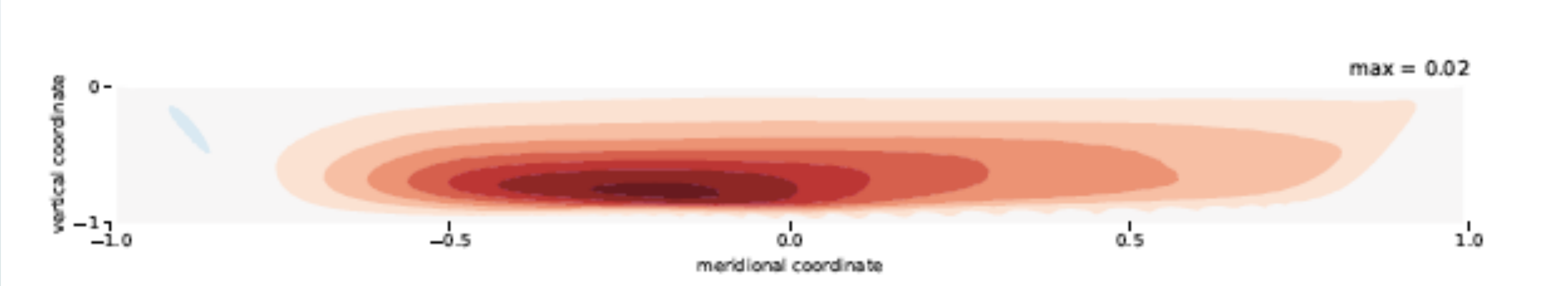


Outside the boundary layers on slopes and a weakly stratified benthic layer, the stratification in the basin matches that prescribed in the south.

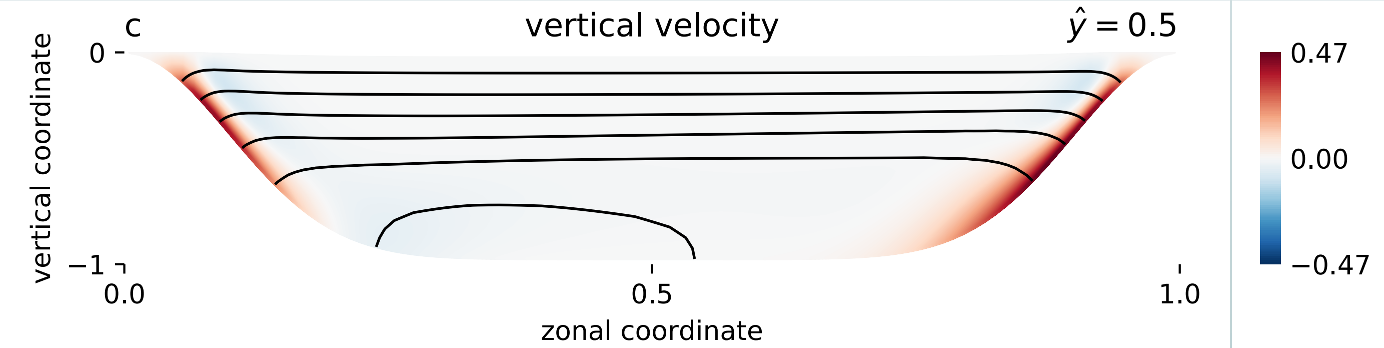


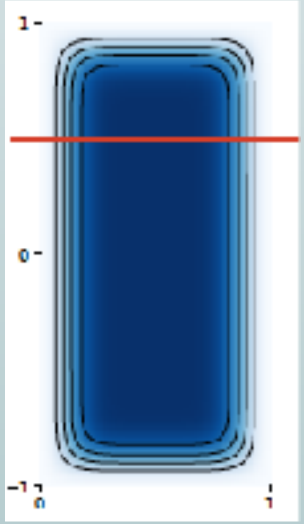
Equilibrated circulation

An overturning circulation develops in the basin



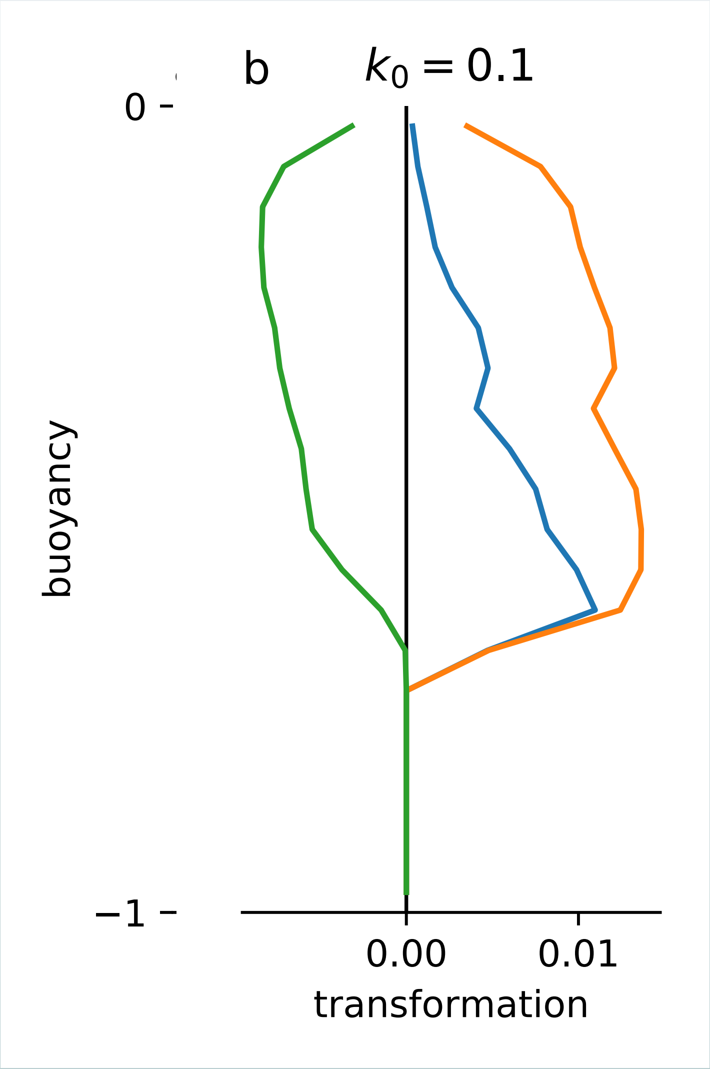
The upwelling is confined to along-slope boundary layers





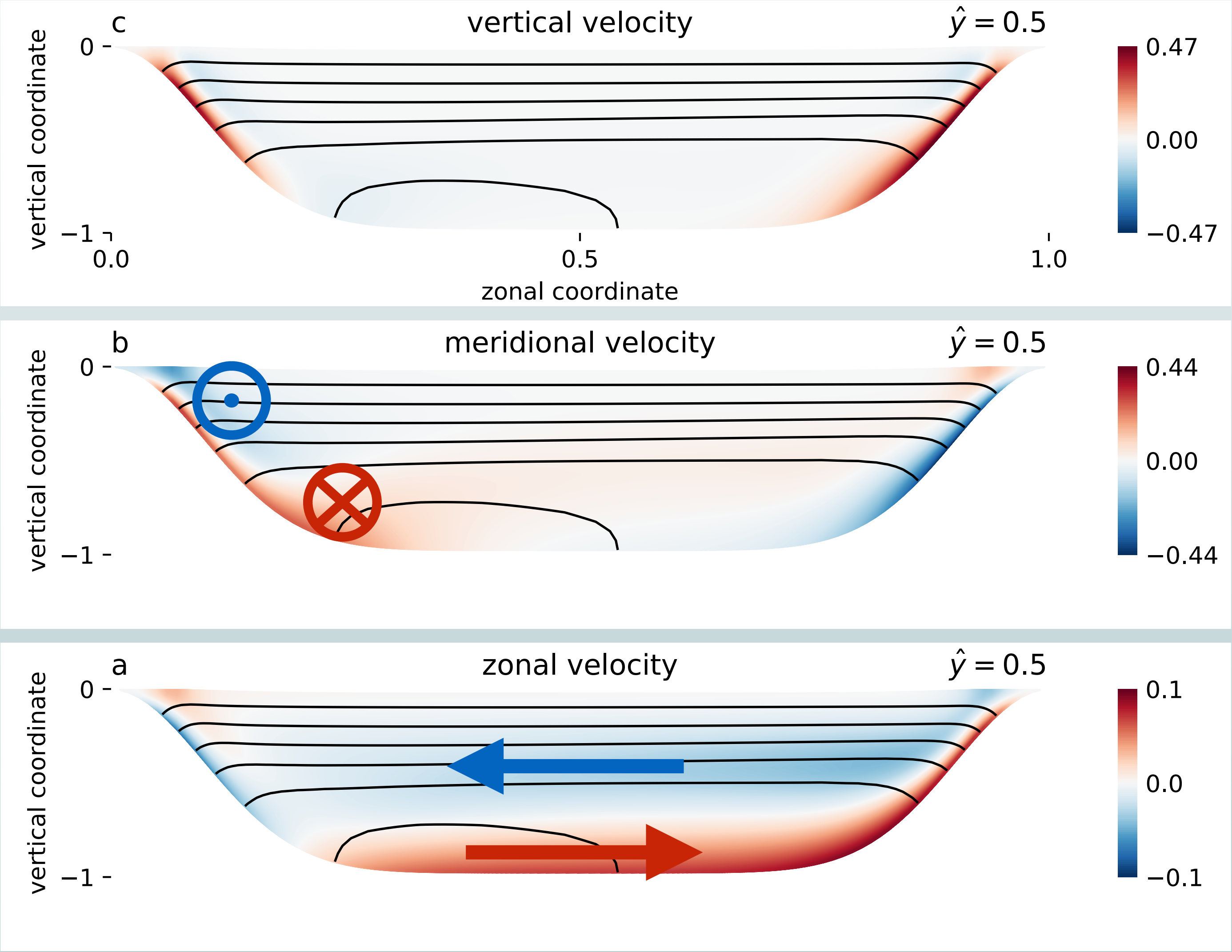
Equilibrated circulation

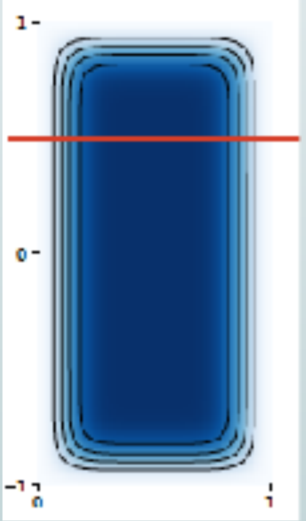
Large compensation between the up- and down-slope transports



Equilibrated circulation

A basin-scale circulation exchanges fluid with the boundary layers





Equilibrated circulation

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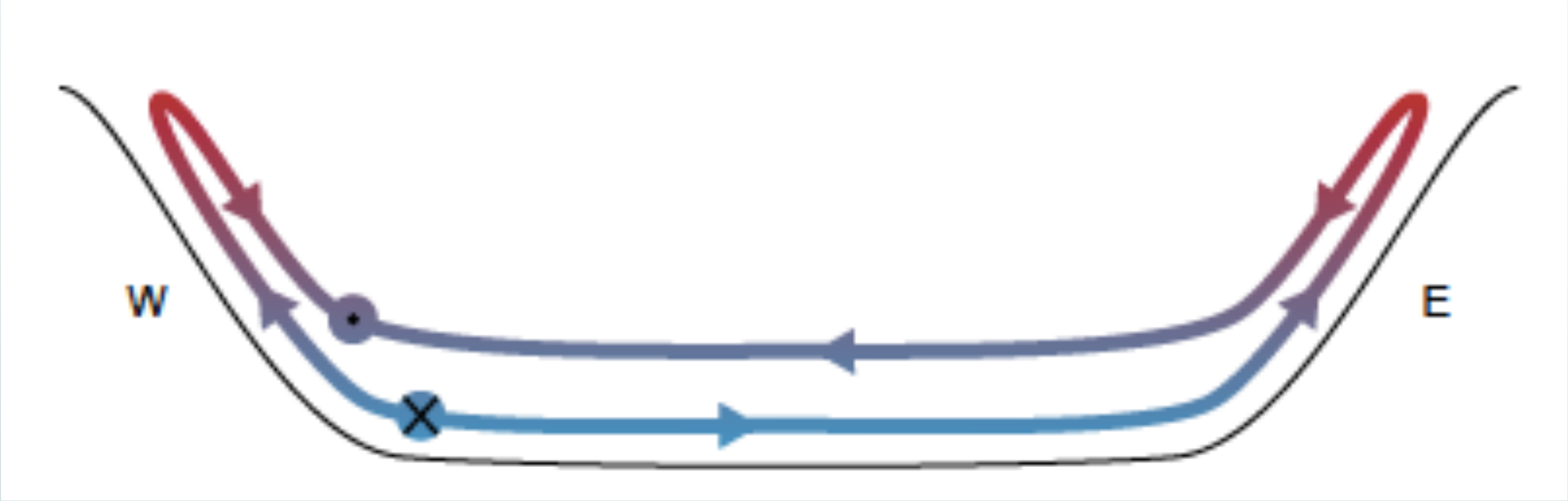
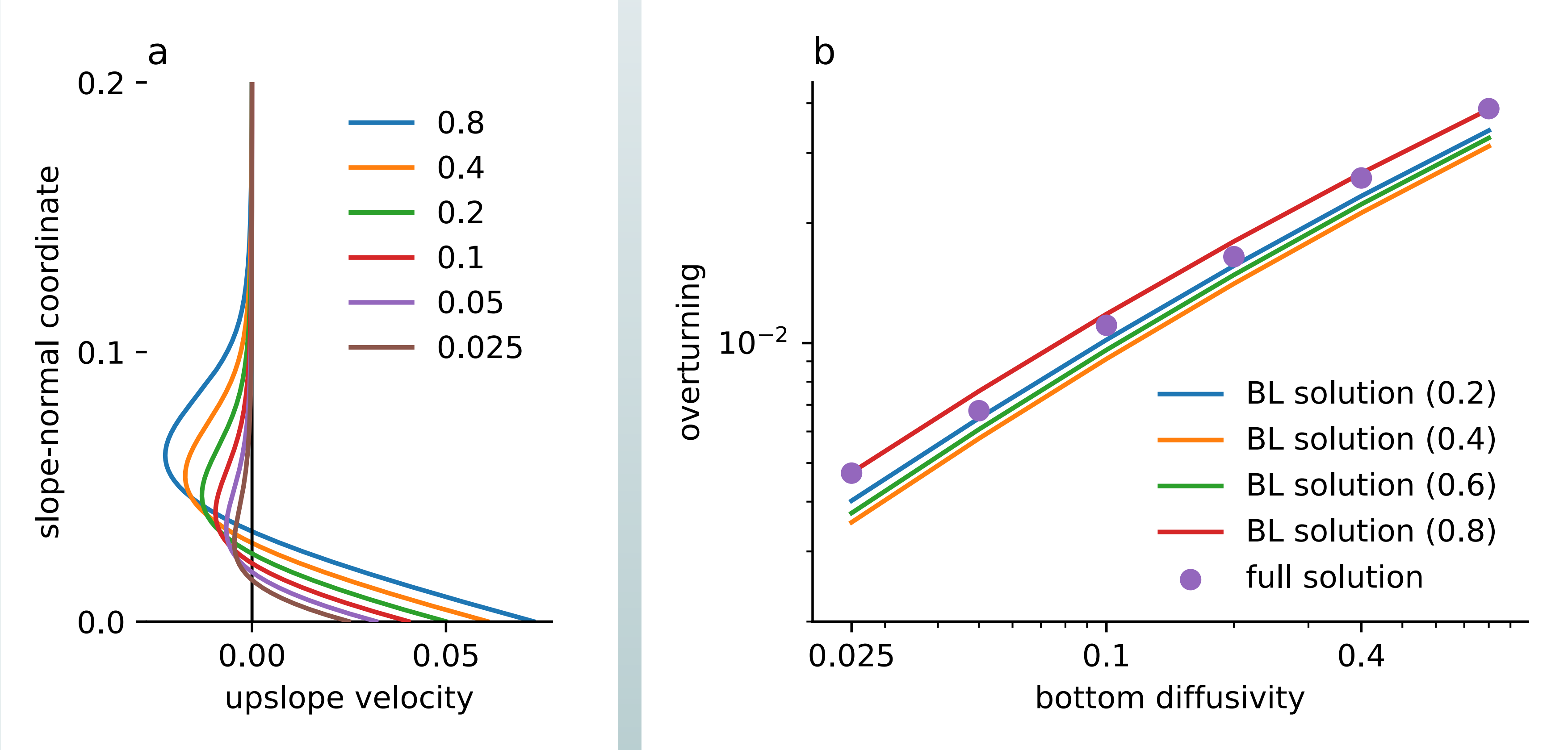


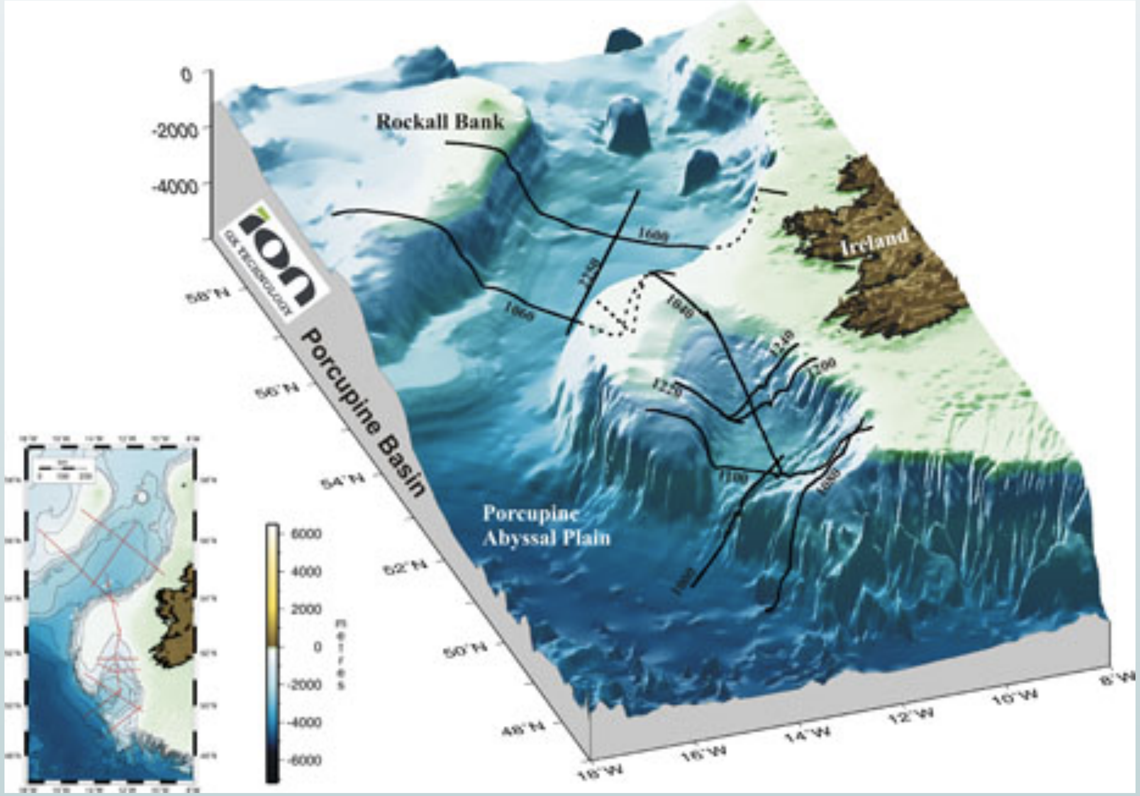
Equilibrated circulation

Integrating the up-/downslope transport along the perimeter of the basin yields a prediction for the net transformation and thus the overturning.



Testing the theory

Field campaign in the bathtub-like bowl of the Rockall Trough



Co-PIs: R. F., Matthew Alford, Alberto Naveira Garabato, Kurt Polzin

Conclusions

- Bottom-intensified mixing drives a pattern of up- and downwelling on slopes
- A basin-scale circulation supplies dense water to the boundary layer upwelling and exports transformed water
- Boundary layers constrain the global solution; they yield a prediction for the net overturning
- The configuration of the real ocean is more complicated, but elements of our "bathtub" case are expected to carry over

Ali Mashayek

Joern Callies

Henri Drake