The Ventilated Ocean: What controls ocean stratification and overturning circulation and Lagrangian ocean modeling

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Many thanks to Patrick Haertel

Yale University

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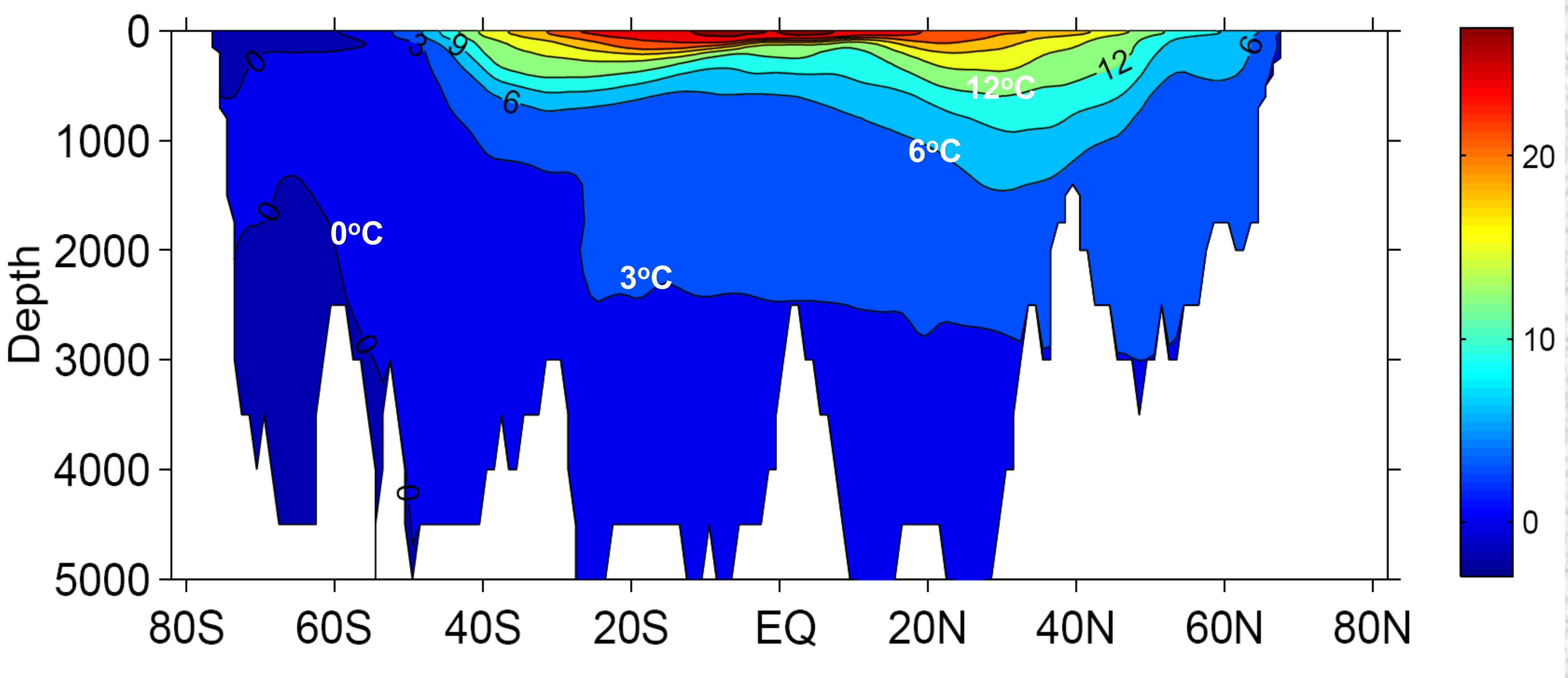
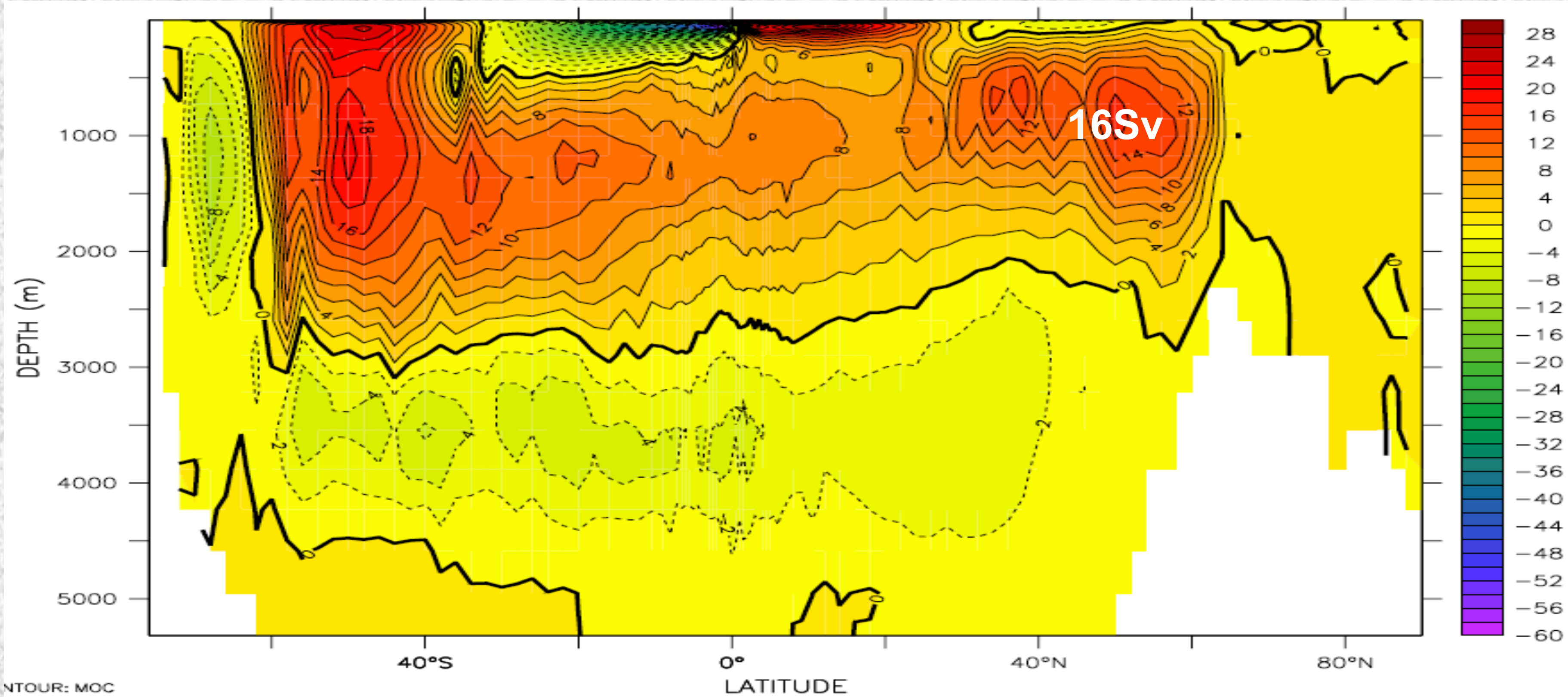
What controls ocean stratification and overturning circulation?

Atlantic ocean thermal structure

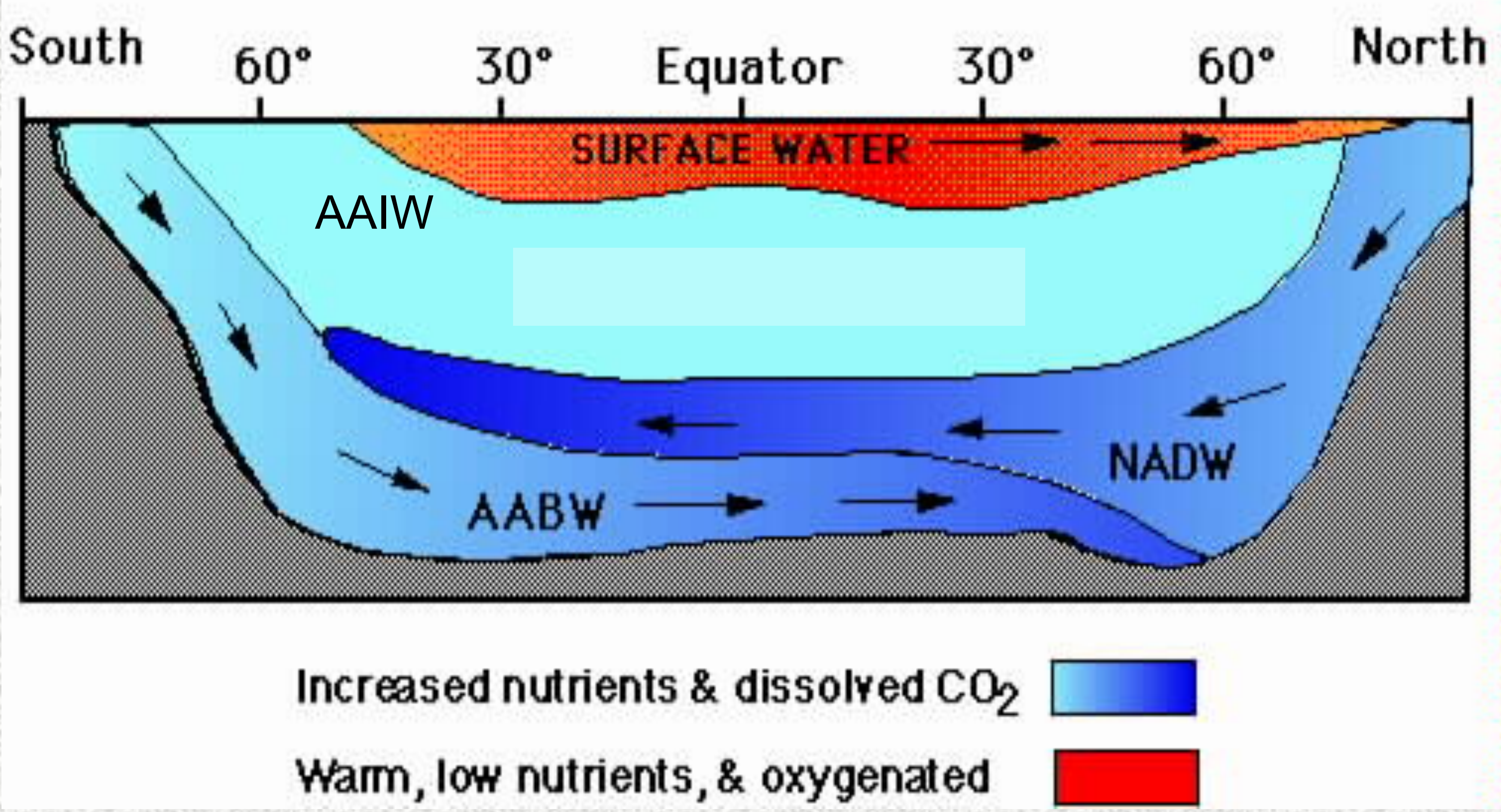


What controls ocean stratification and overturning circulation?

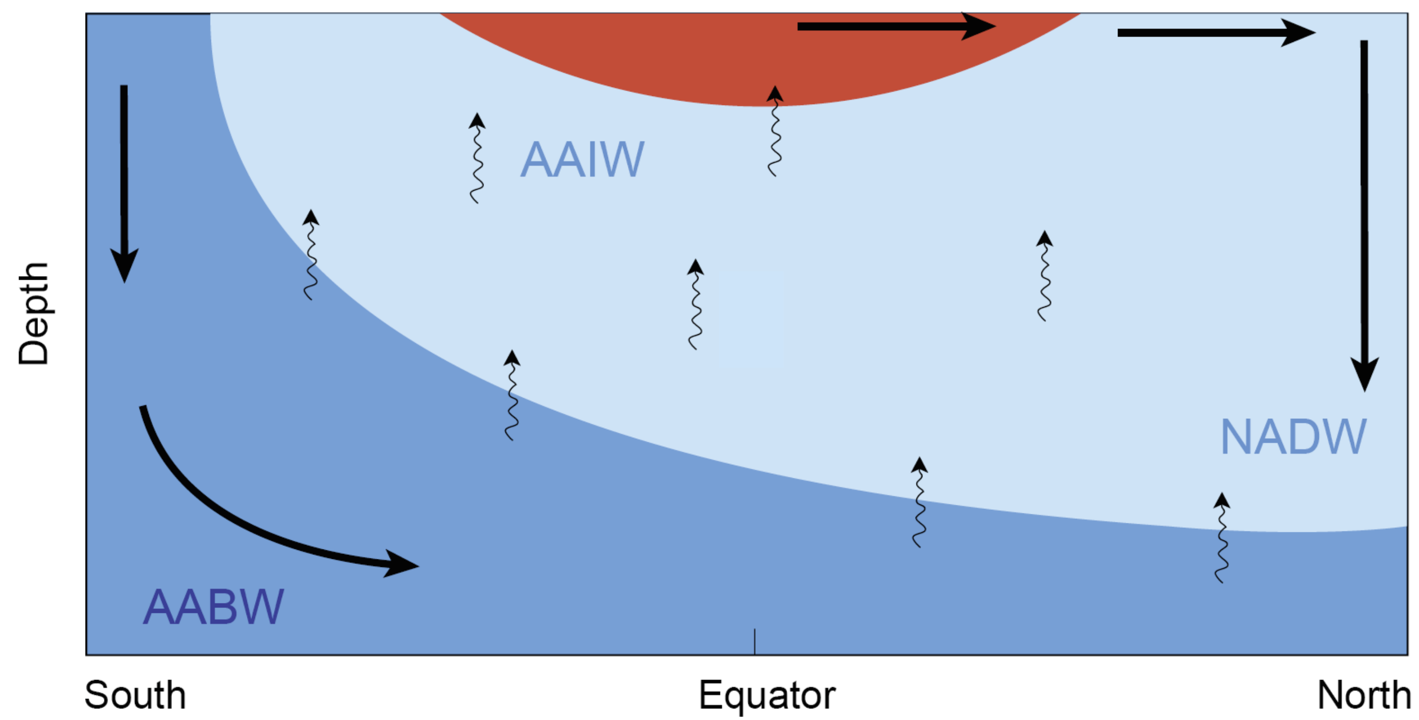
Meridional overturning circulation (MOC), GFDL model



Atlantic ocean circulation and water masses



Diffusive theories for the ocean thermal structure and overturning

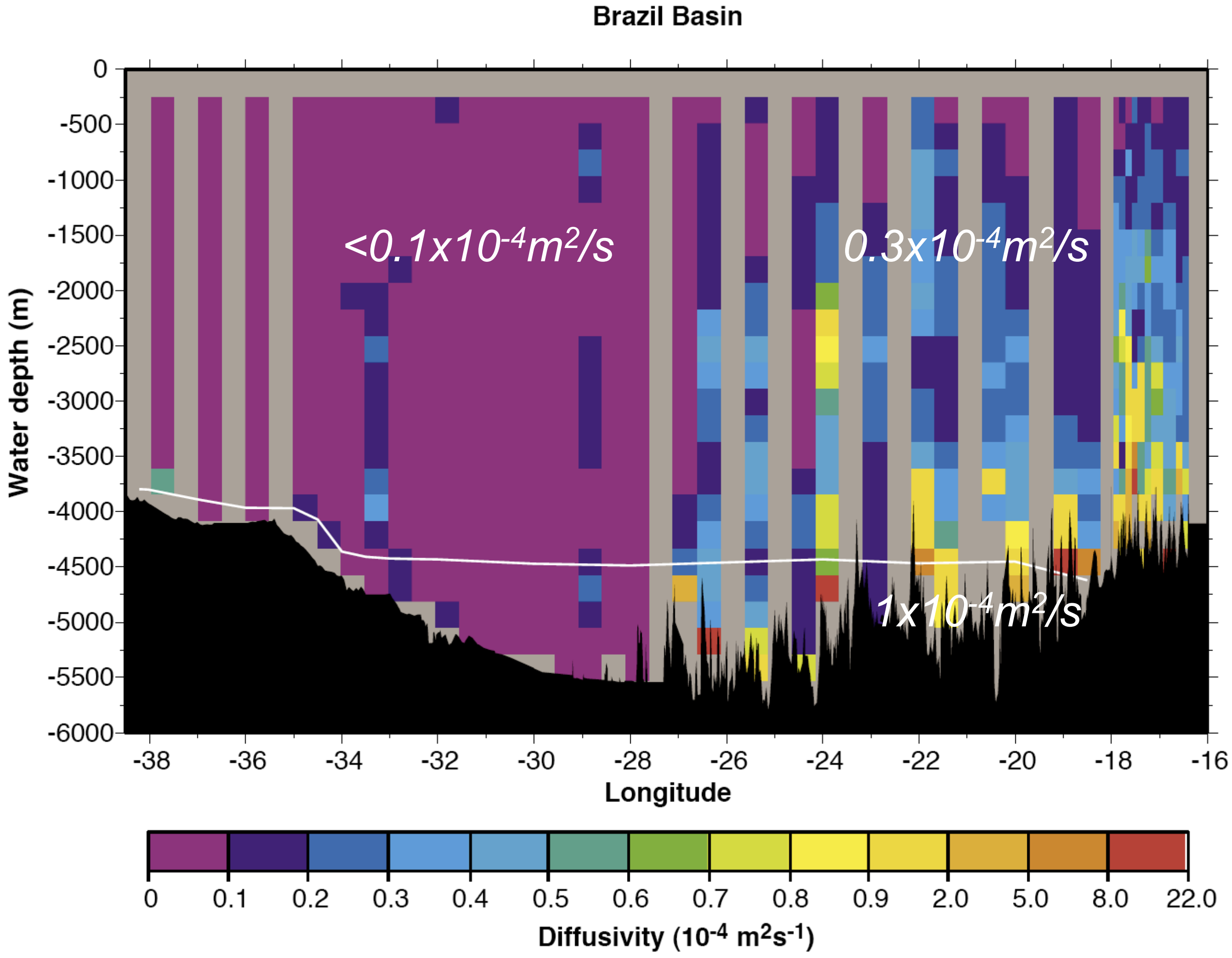


$$\boxed{w\frac{\partial T}{\partial z} = k_d \frac{\partial^2 T}{\partial z^2}}$$

k_d *- diapycnal (vertical) diffusivity*

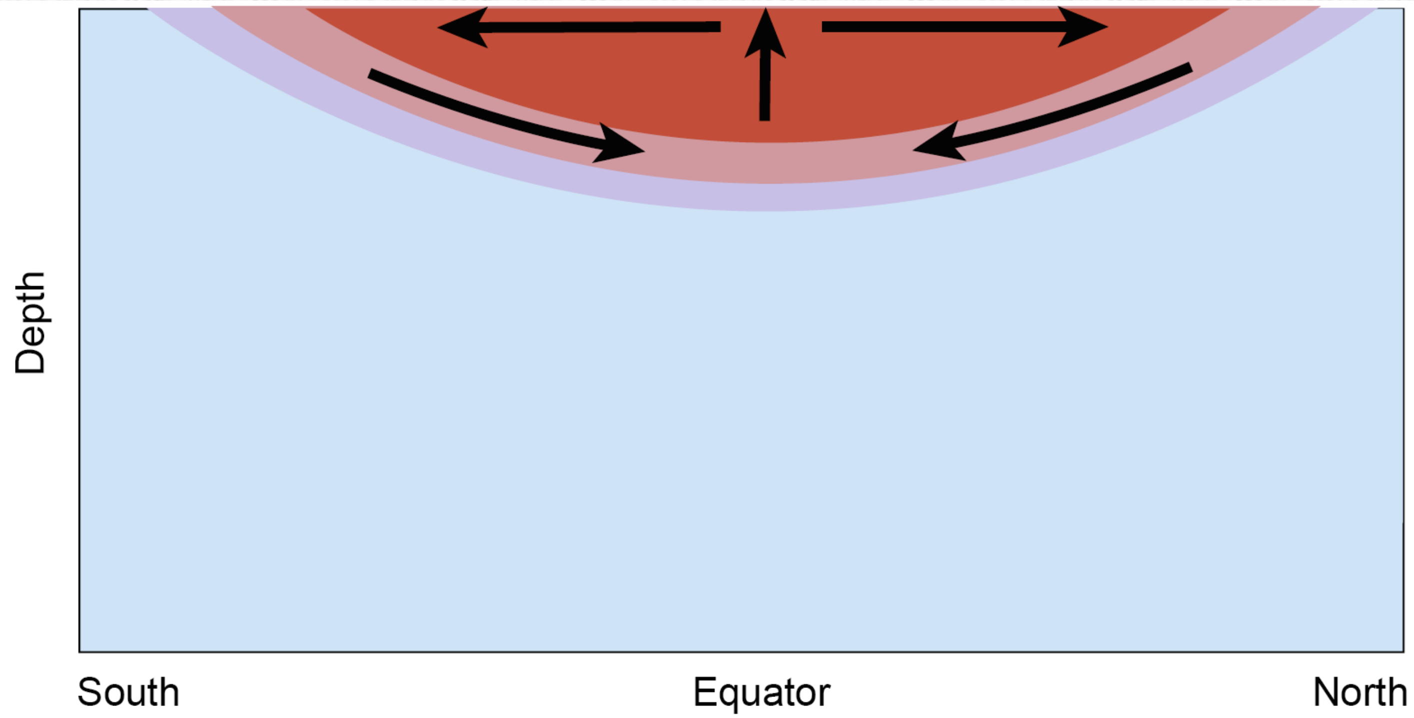
Stommel 1958, Stommel and Arons 1960, Veronis 1976, others: ***Downward diffusion of heat is balanced by a broad upwelling of cold water***

k_d - ***diapycnal (vertical) diffusivity***; *very patchy*
$0.1 \times 10^{-4} m^2/s$ in the upper and deep ocean to
$20 \times 10^{-4} m^2/s$ in patches near bottom topography



Polzin et al 1997 (also Ledwell et al 1993)

Adiabatic theories



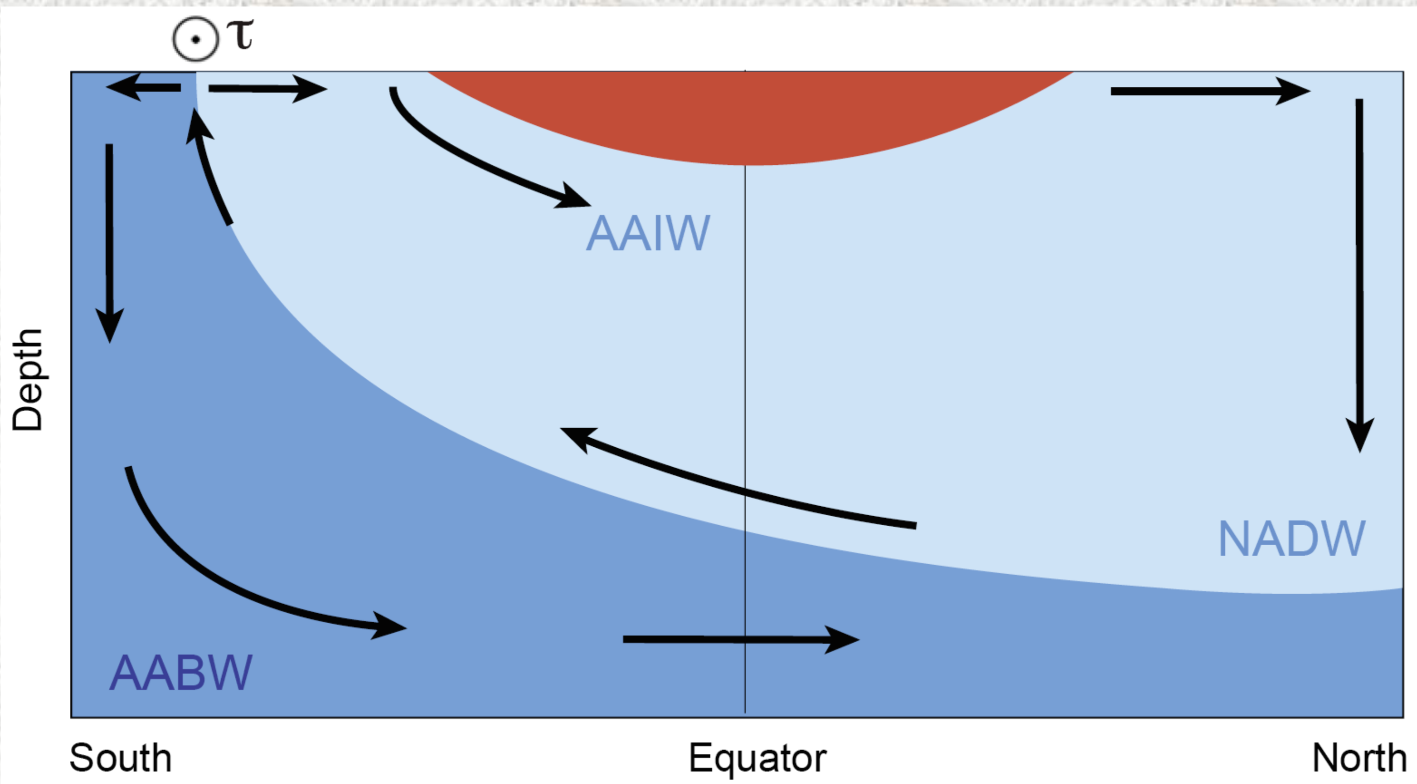
$$\frac{DT}{Dt} = u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} = 0$$

$$\frac{D}{Dt}\frac{f+\varsigma}{h} = 0$$

Luyten, Pedlosky, and Stommel 1983: "**The ventilated thermocline**"; *Ekman pumping pushes water down along isopycnal surfaces.*

Also, Iselin (1939), Welander (1959), Huang (1986)…

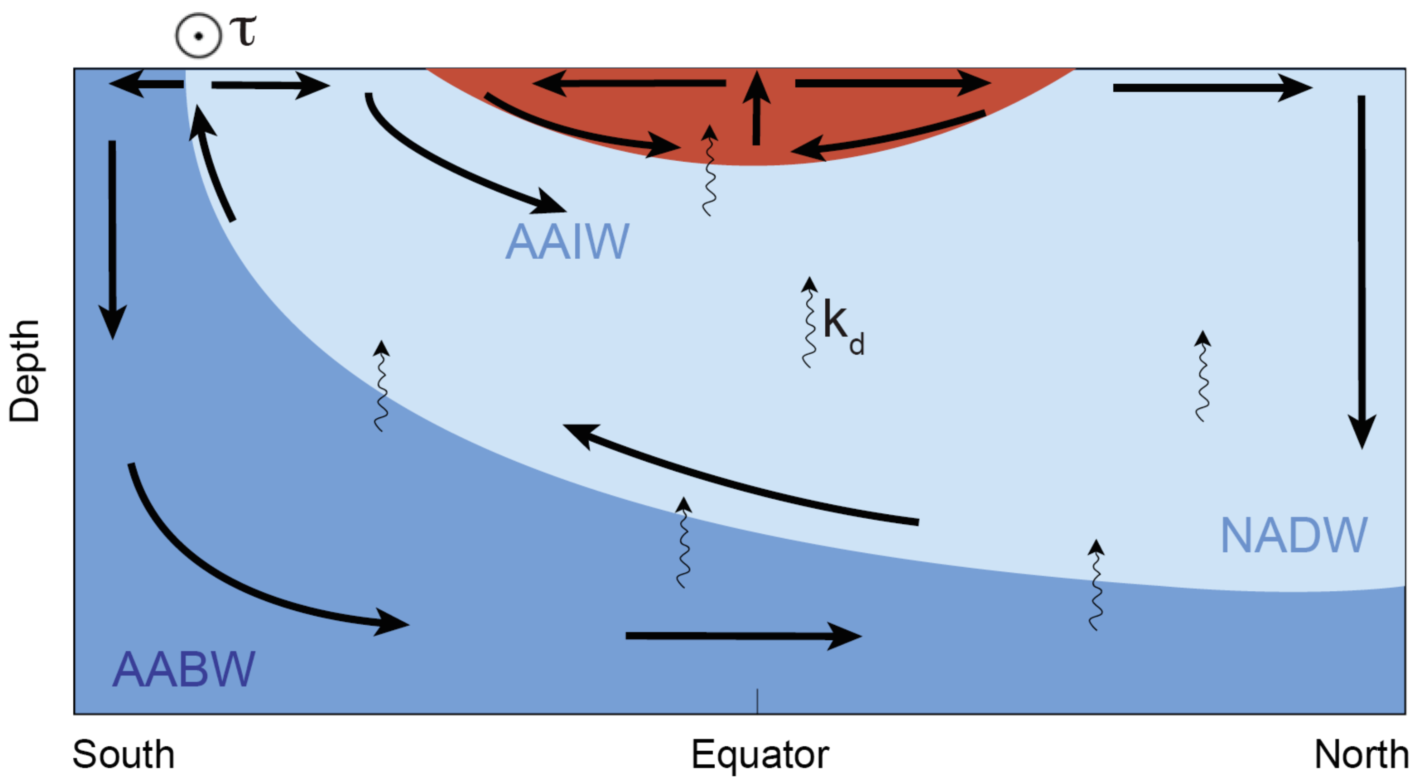
The importance of wind-driven upwelling in the Southern Ocean



τ – zonal wind stress in the Southern ocean

(e.g. Toggweiler and Samuels 1995, 1998, Gnanadesikan 1999)

A full schematic picture of ocean overturning



(e.g. Barreiro, Fedorov and co-authors 2008)

Questions:

What is the leading-order description for the ocean circulation and thermal structure? Is it diffusive or adiabatic?

If not diffusion, then what controls the ocean overturning circulation and stratification?

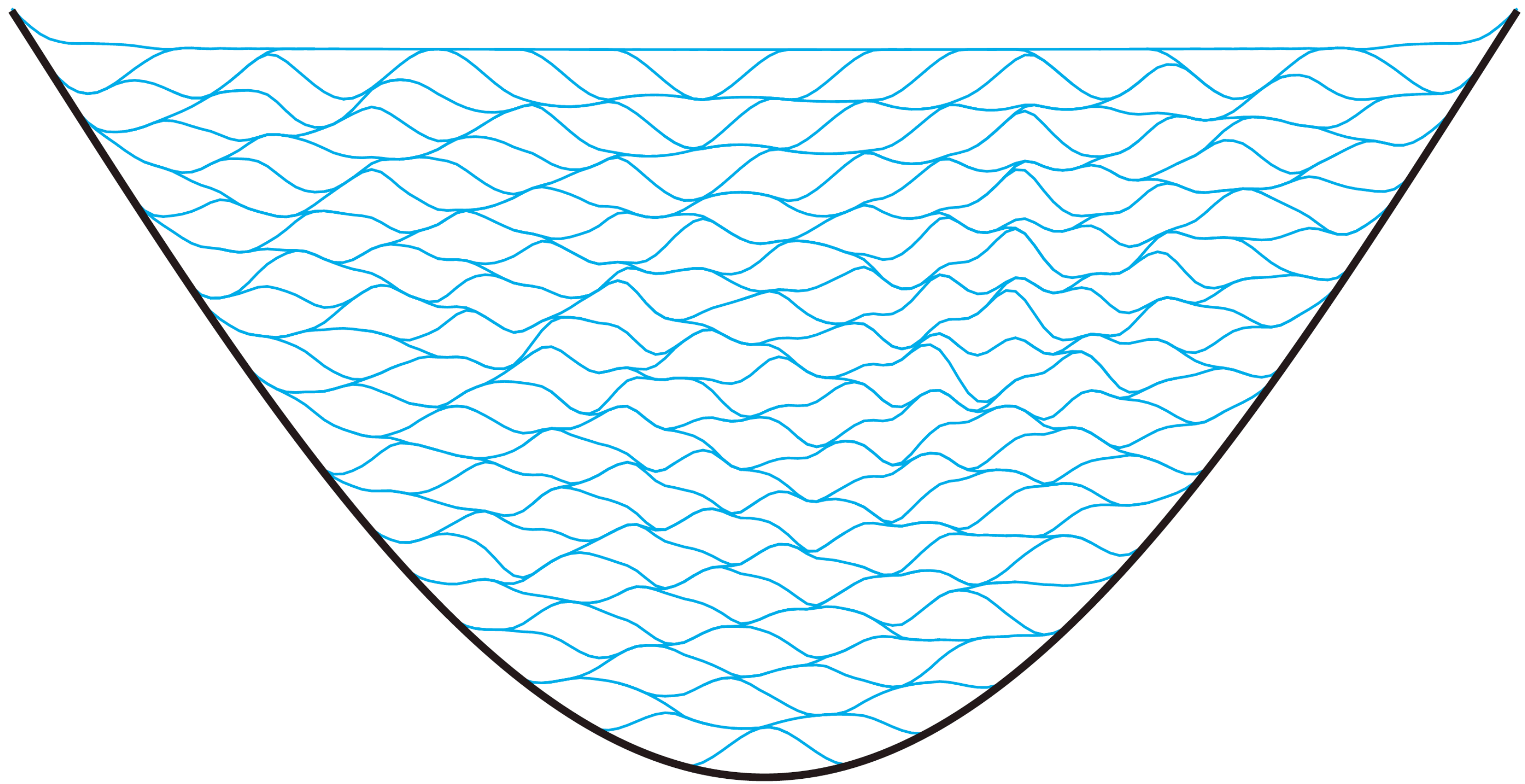
What is the role of diffusion (mixing)?

Approach:

Setting up a Lagrangian ocean model with a fully adiabatic interior flow (no mixing below the mixed layer)

Use the simplest ocean configuration that captures the main observed features of the ocean thermal structure

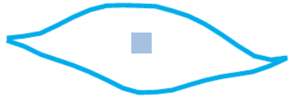
Lagrangian Ocean Model (Haertel et al 2010)



A stack of water parcels:

The stacking is done from the bottom up. Parcels conserve mass but change volume and shape. Pressure is hydrostatic. Dense parcels slide underneath less dense parcels.

Equations of motions: Lagrangian approach



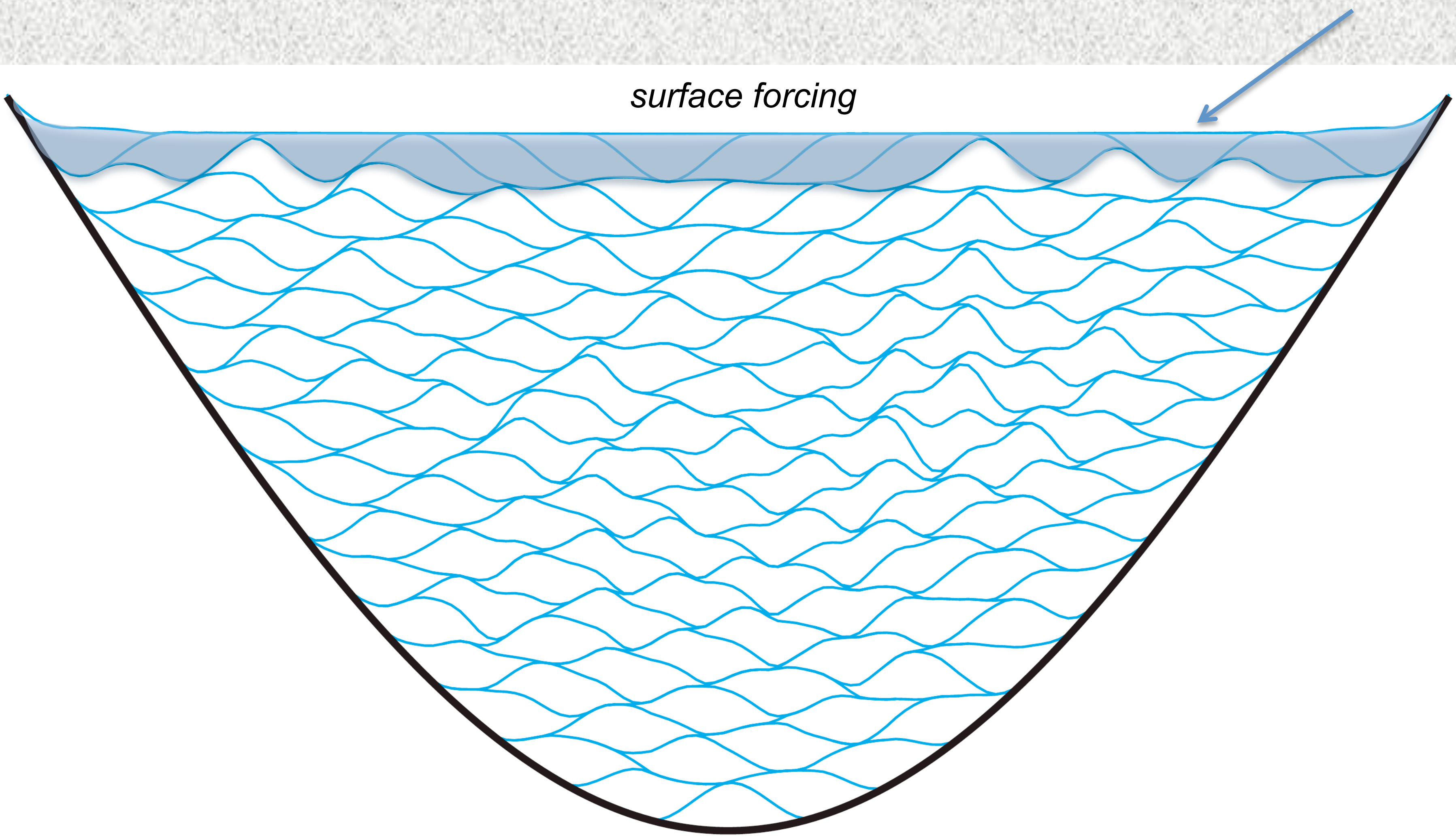
Newton's law :

$$\frac{d\boldsymbol{u}}{dt} = -f\,\boldsymbol{k} \times \boldsymbol{u} + \frac{1}{M}\int p\,ds + \nu\nabla^2\boldsymbol{u}$$

$$\frac{d\boldsymbol{x}}{dt} = \boldsymbol{u}$$

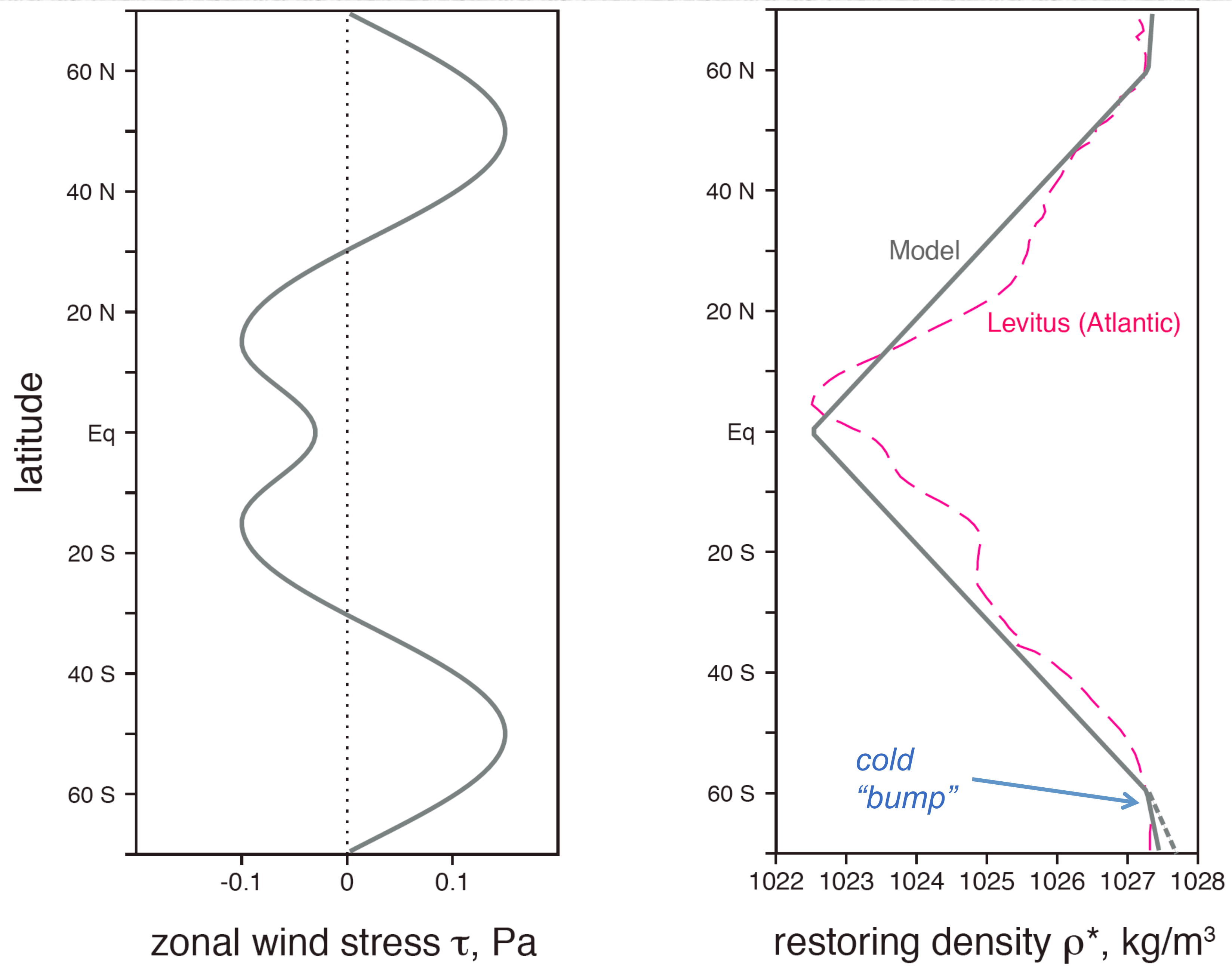
Density changes :

$$\frac{d\rho}{dt} = k_d \frac{\partial^2 \rho}{\partial n^2}$$

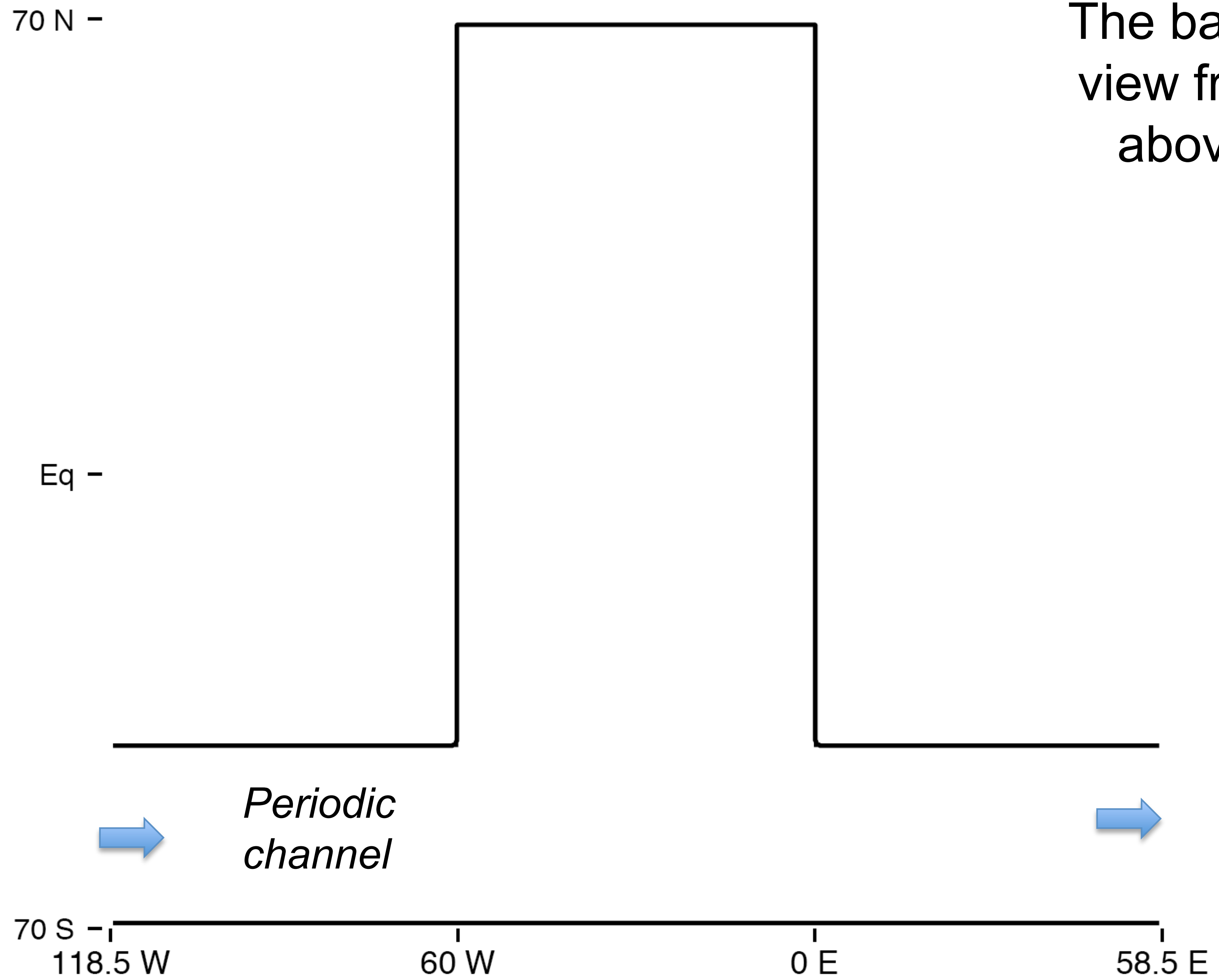


if $k_d = 0$, then below the surface layer $\dfrac{d\rho}{dt} = 0$

Surface forcing : zonal wind stress and density relaxation

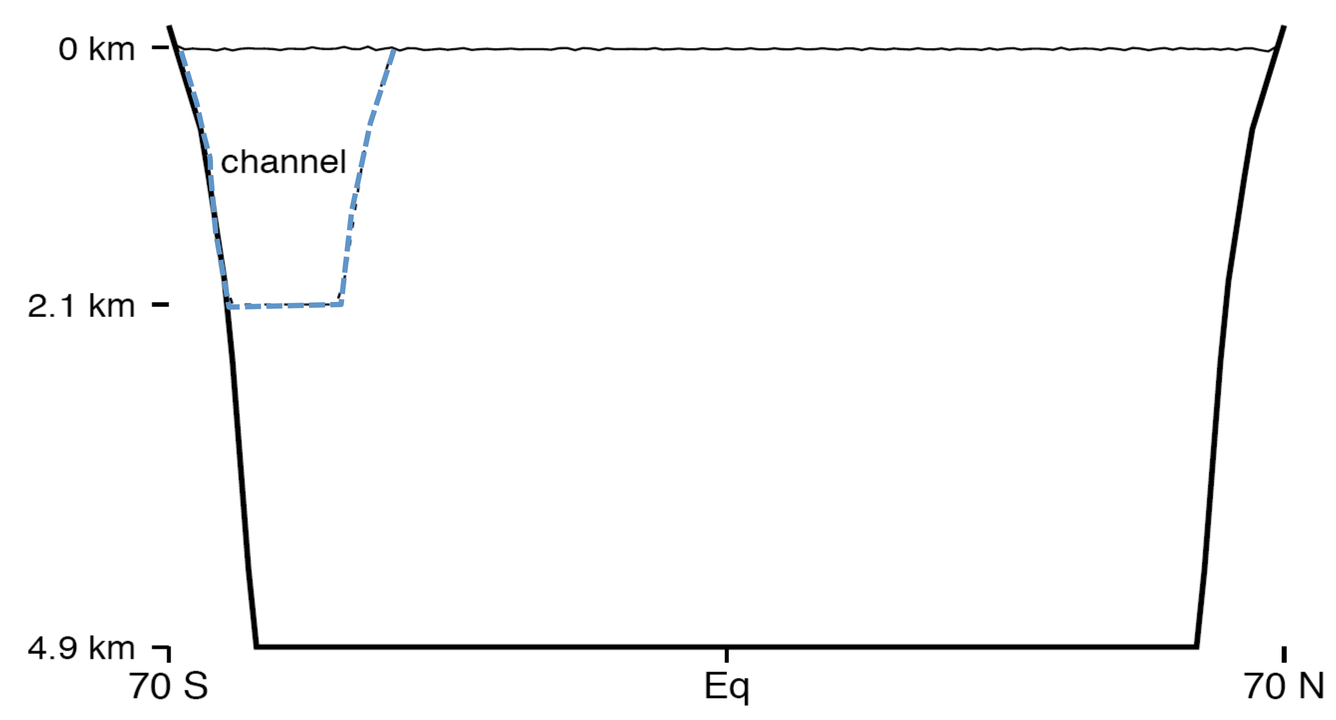


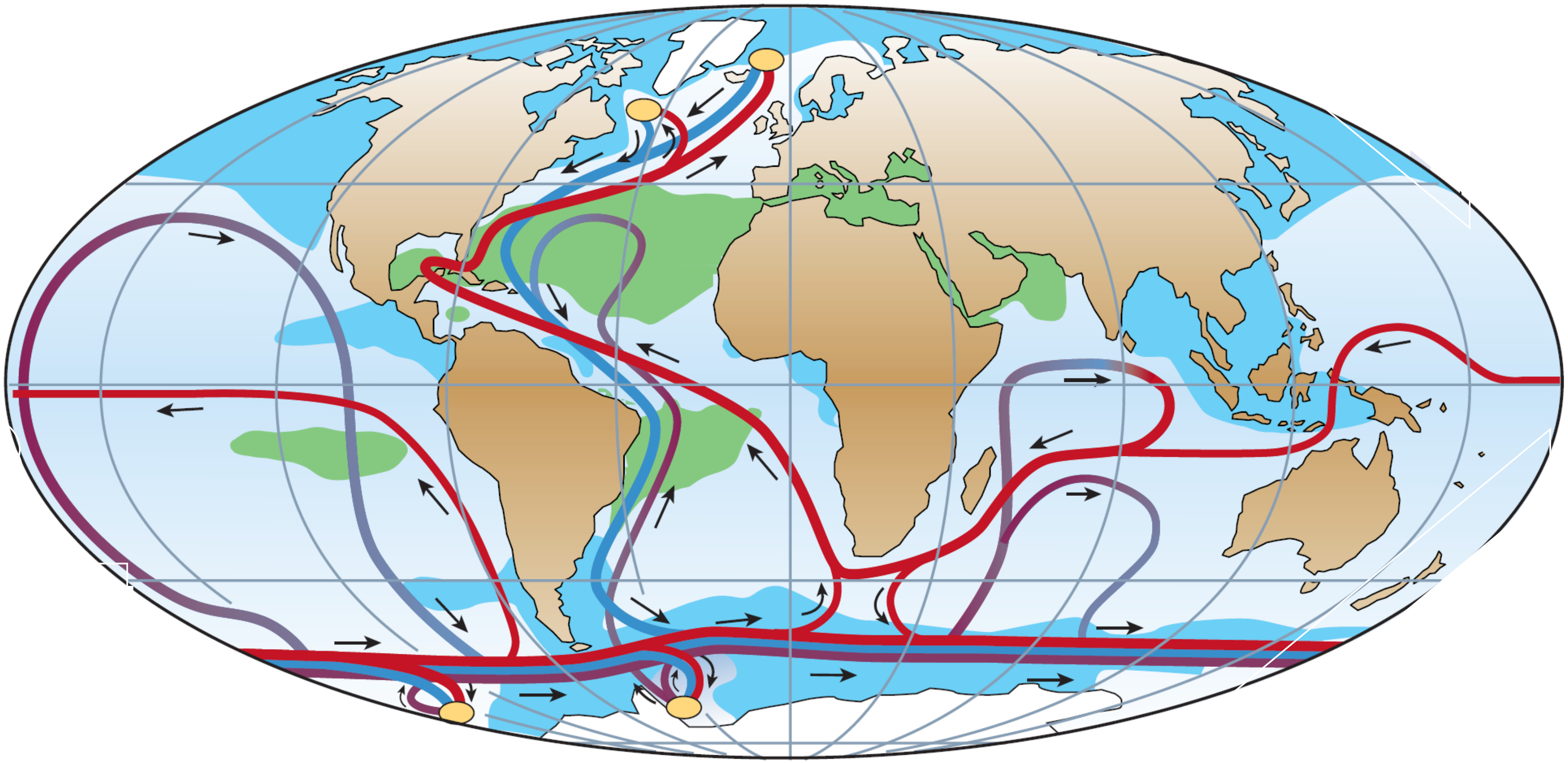
Model spatial configuration



The basin, view from above

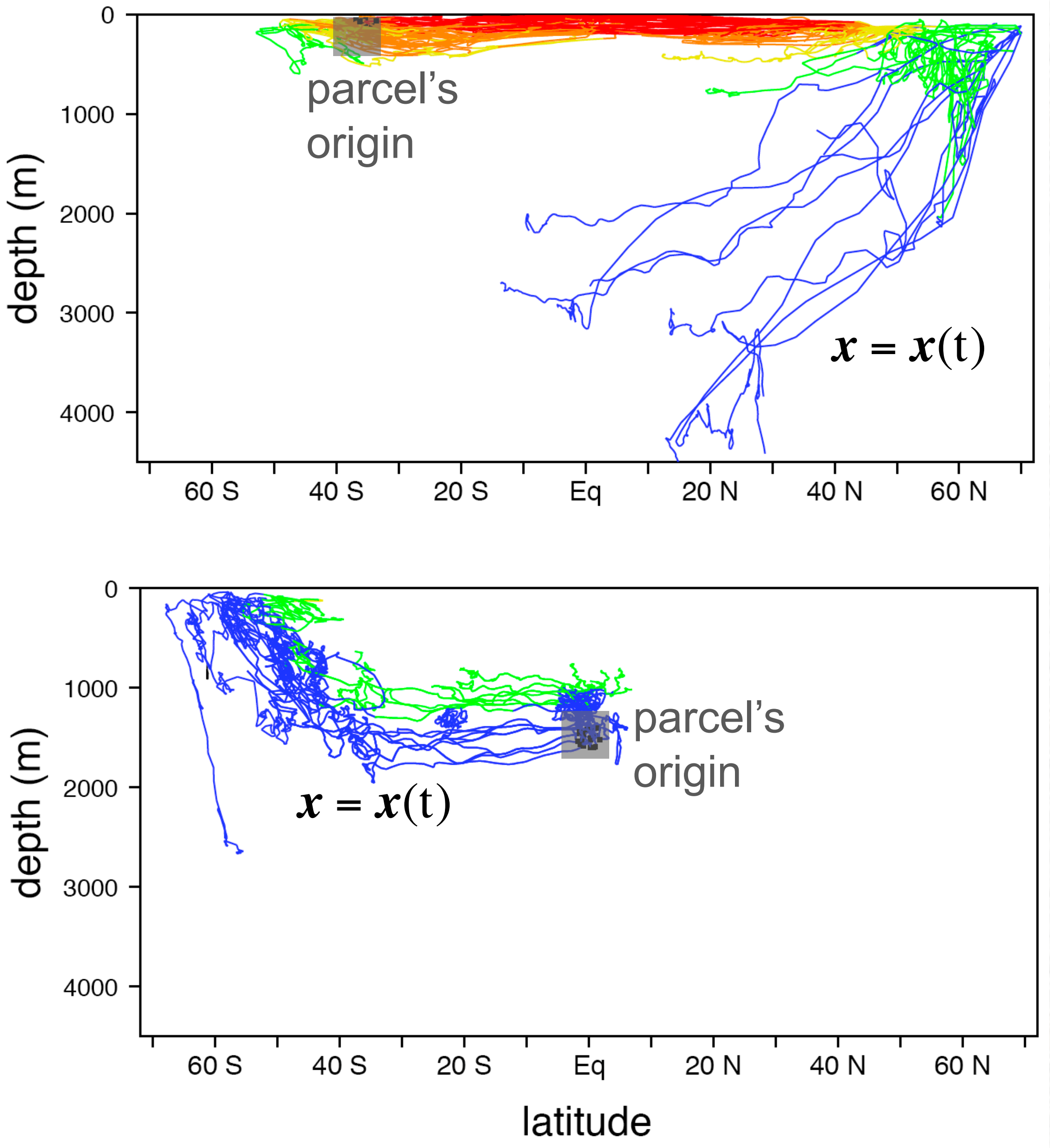
The basin, side view





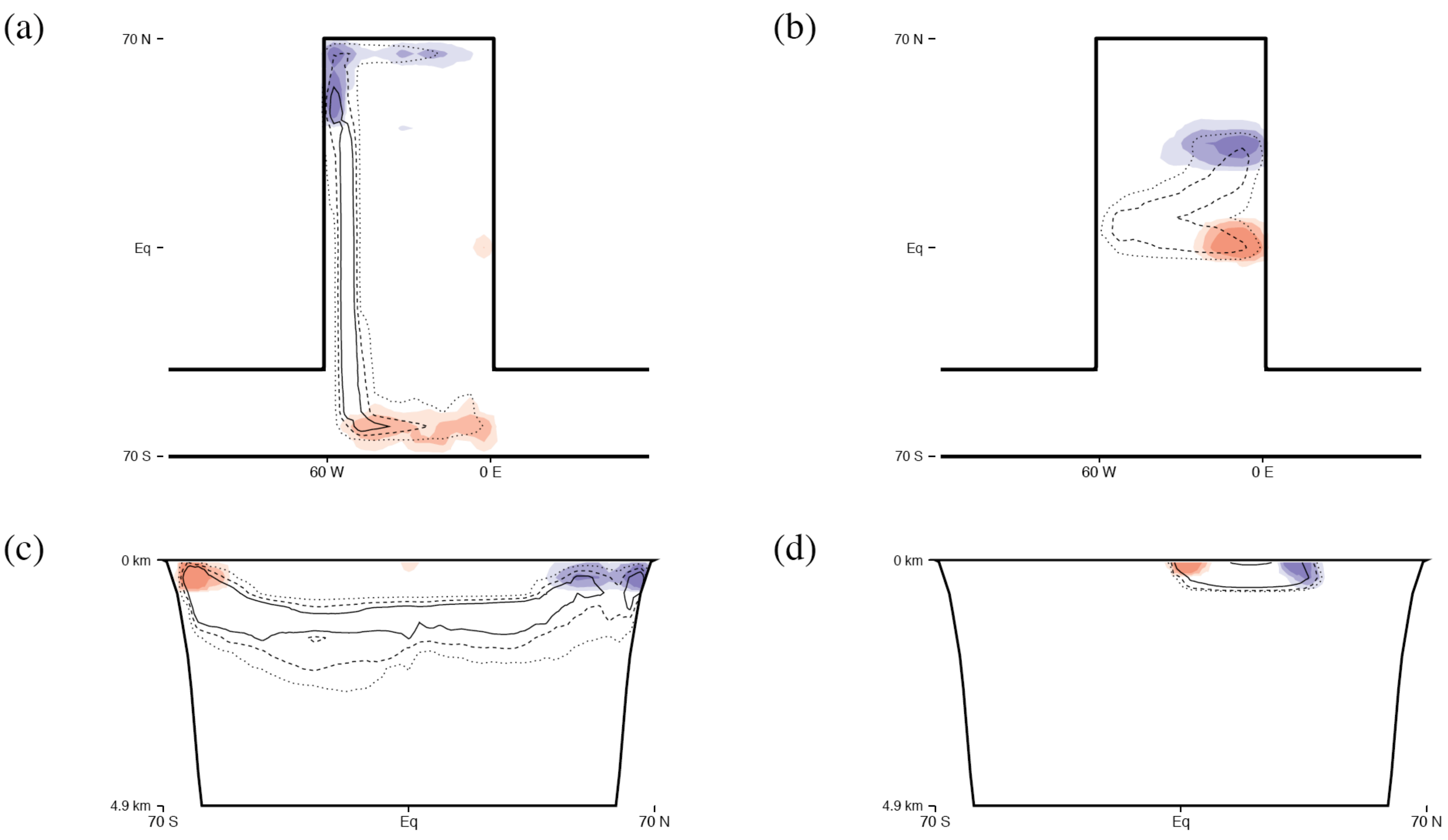
A cartoon of the global thermohaline circulation
after Rahmstorf 2003

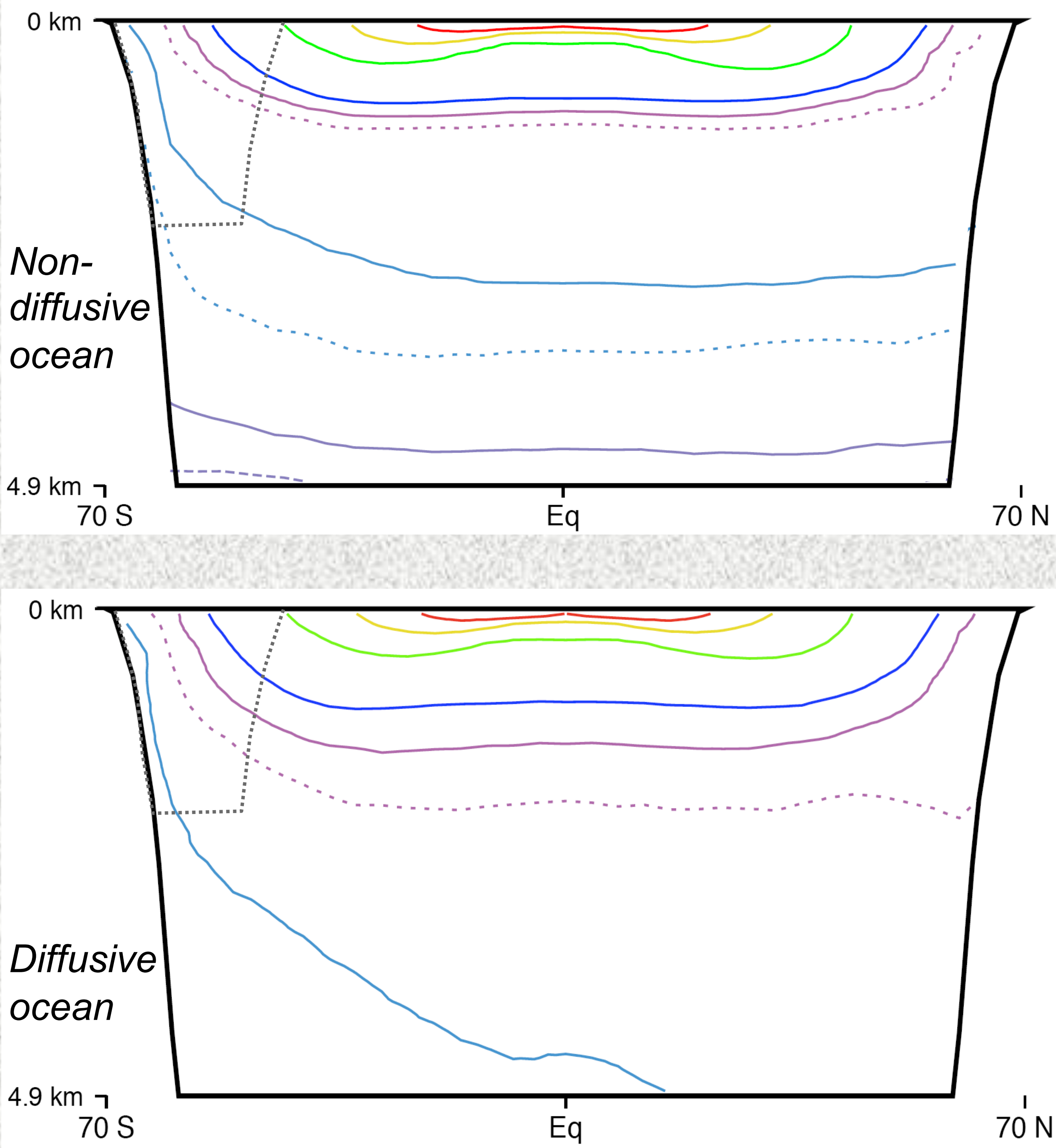
Examples of parcel's trajectories in the ocean



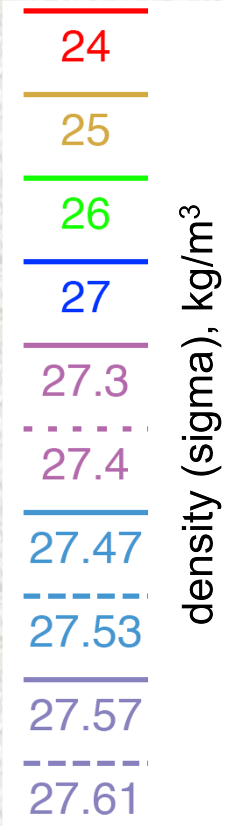
Blue – deep
Red – shallow

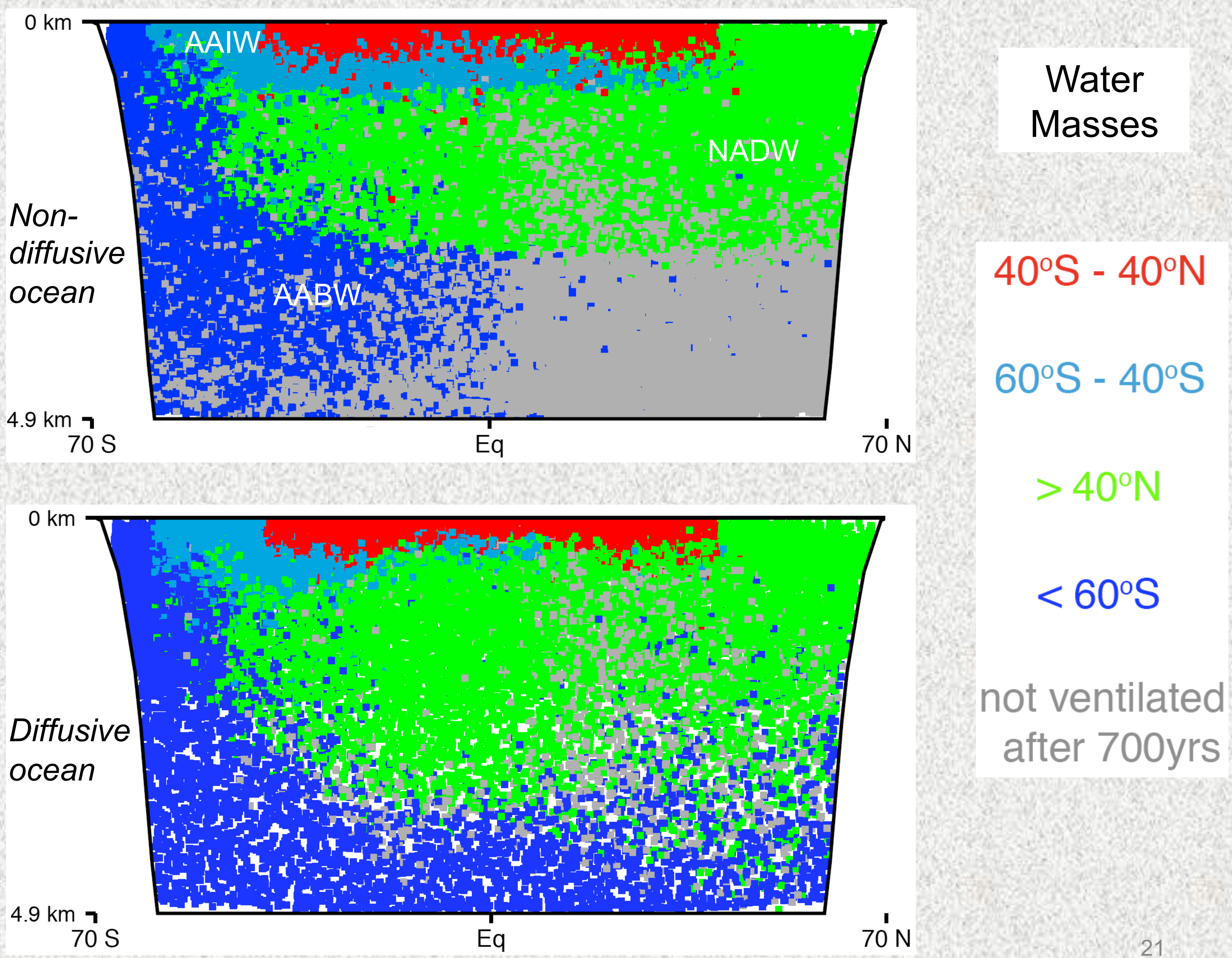
Examples of parcel routes : **Blue** – subduction, **red** – upwelling



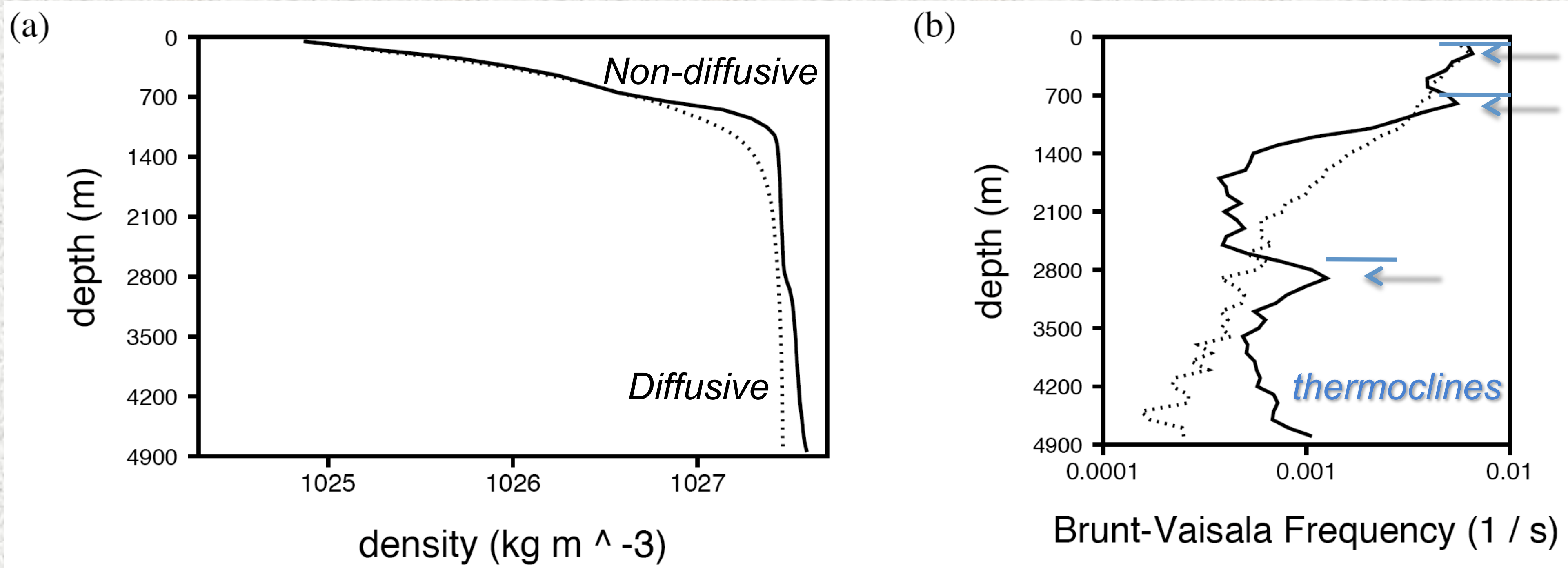


Ocean Stratification

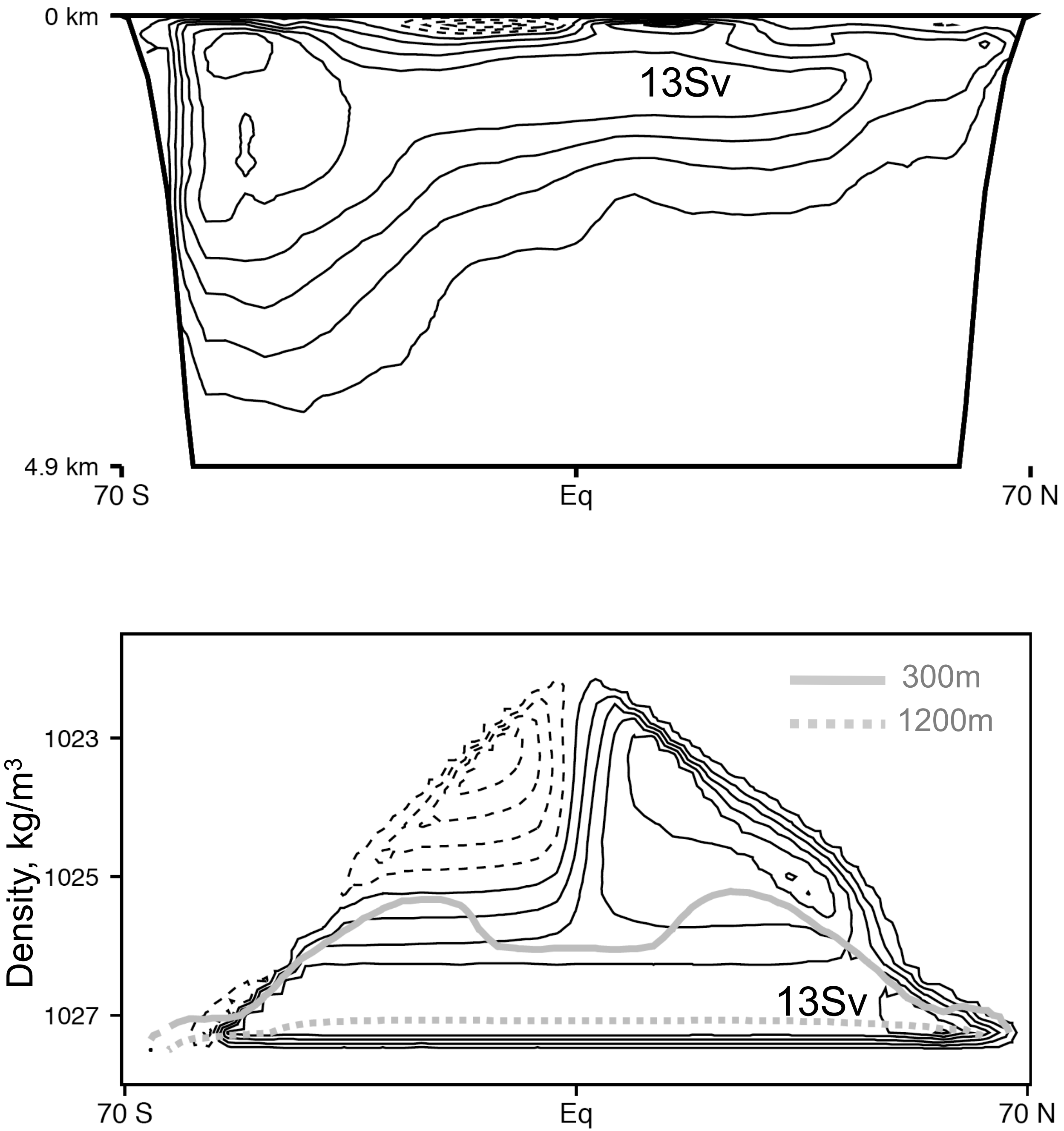



0 km
AAIW
NADW
Non-diffusive ocean
AABW
4.9 km
70 S
Eq
70 N
0 km
Diffusive ocean
4.9 km
70 S
Eq
70 N
Water Masses
40°S - 40°N
60°S - 40°S
> 40°N
< 60°S
not ventilated after 700yrs

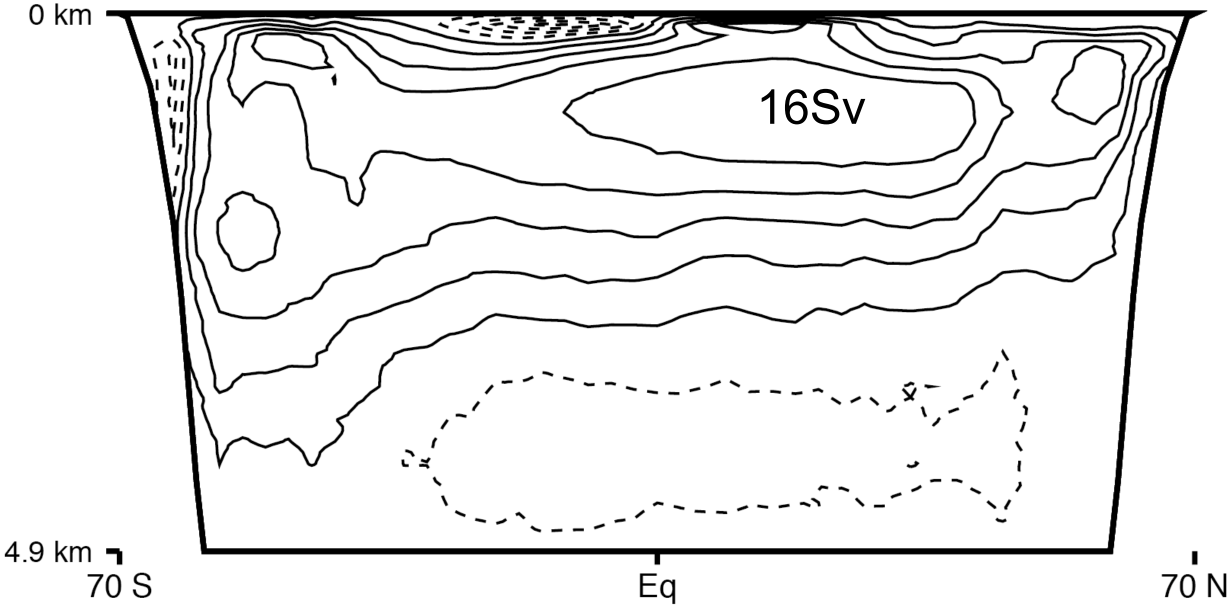
Stratification and buoyancy frequency at 10^{o}W, 30^{o}N

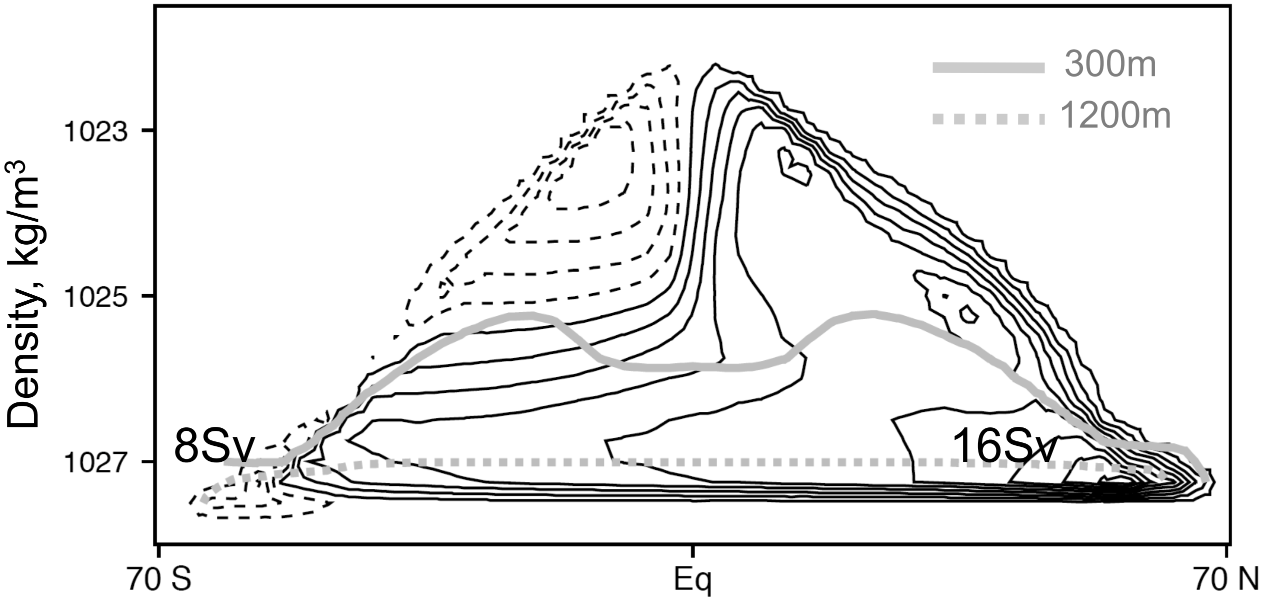


Overturning circulation: Non-diffusive

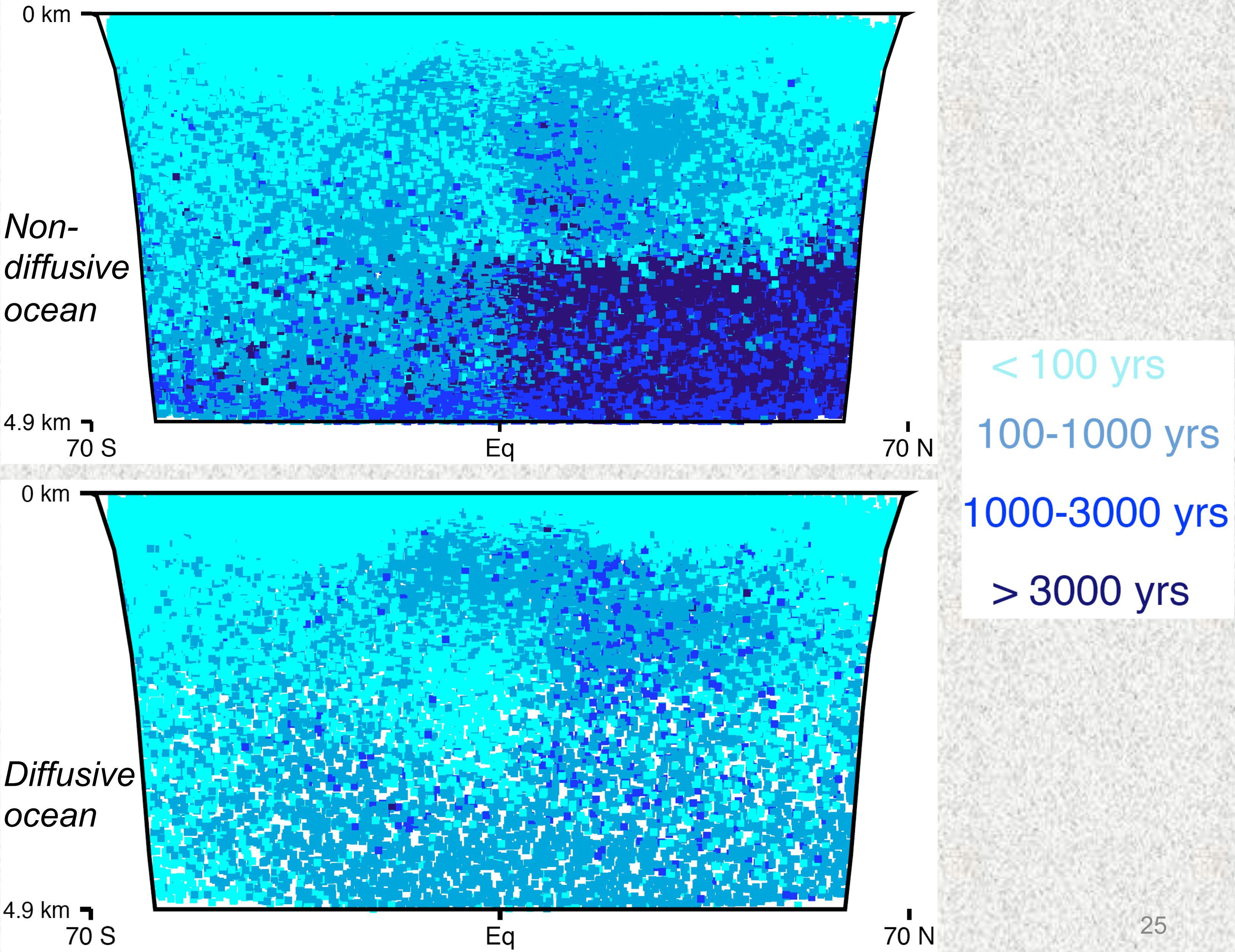


Overturning circulation: Diffusive ocean

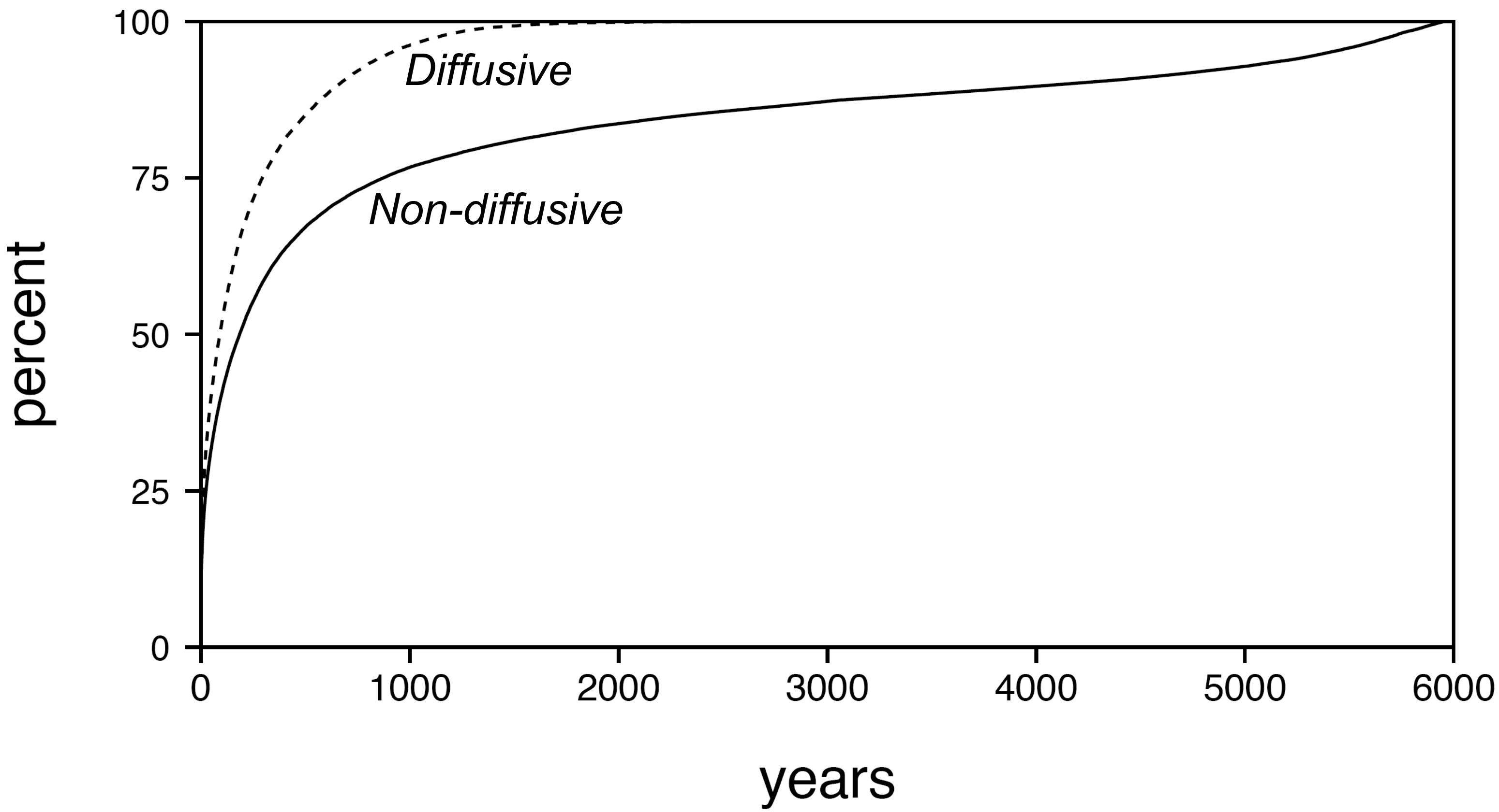




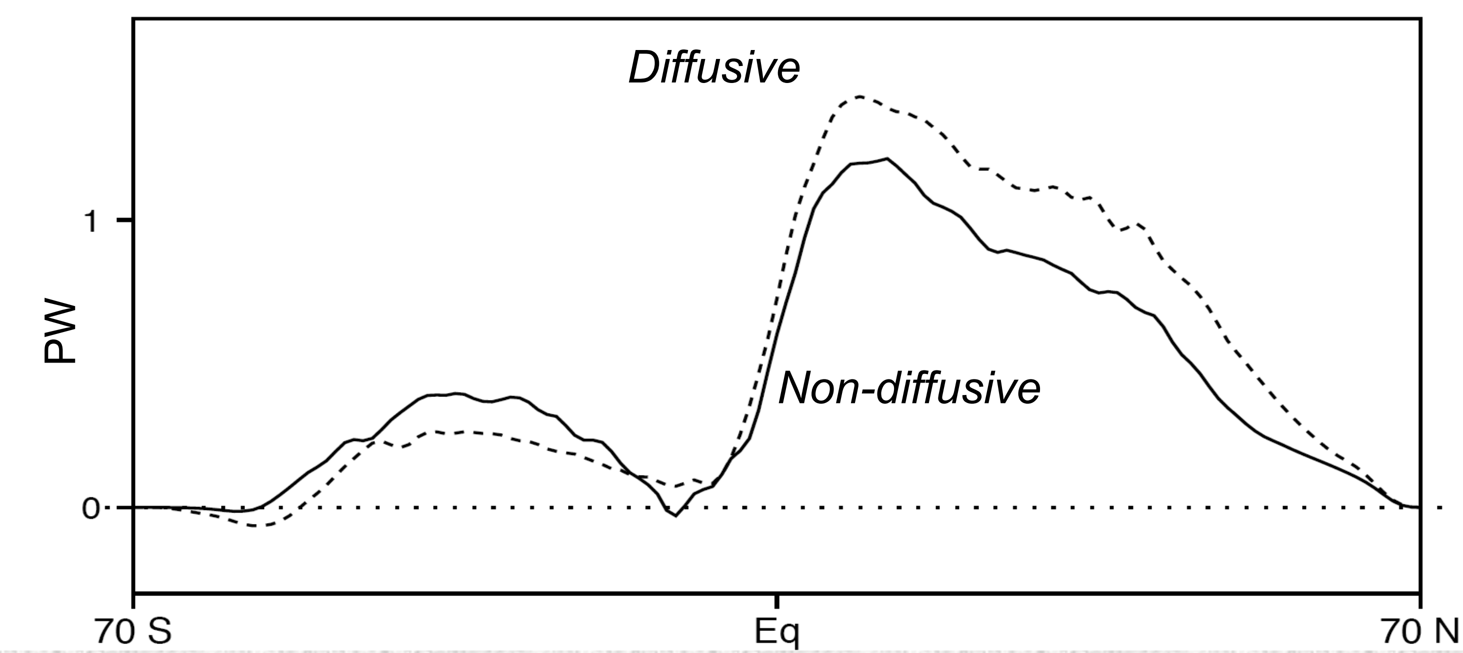
Water Ventilation Age / Transit times

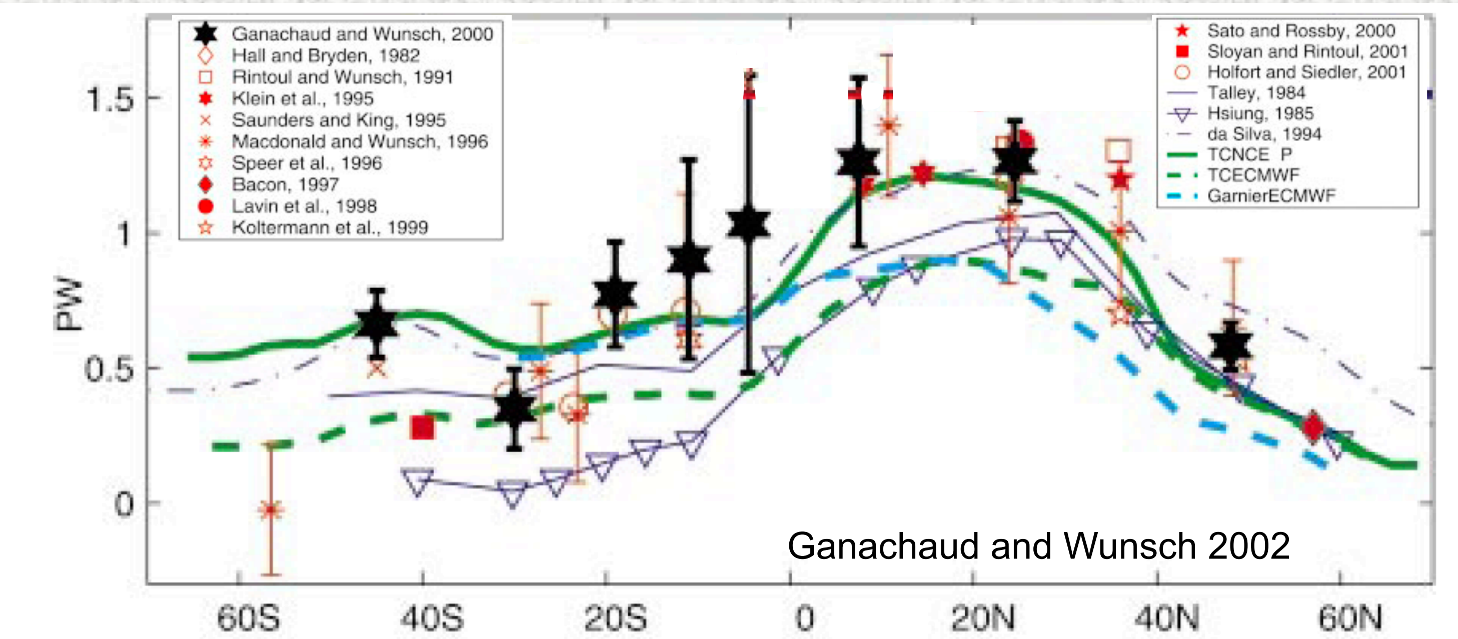


Model cumulative distribution of water ventilation ages (percentage of parcels younger than a certain "age")

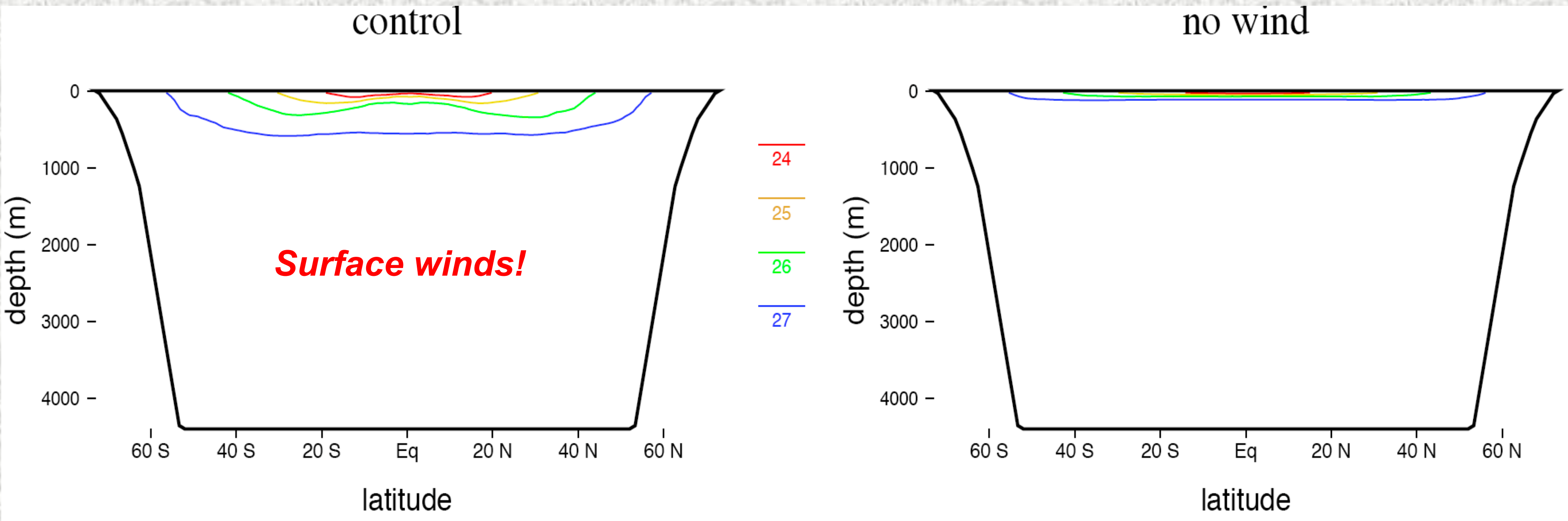


Northward heat transport in the Atlantic

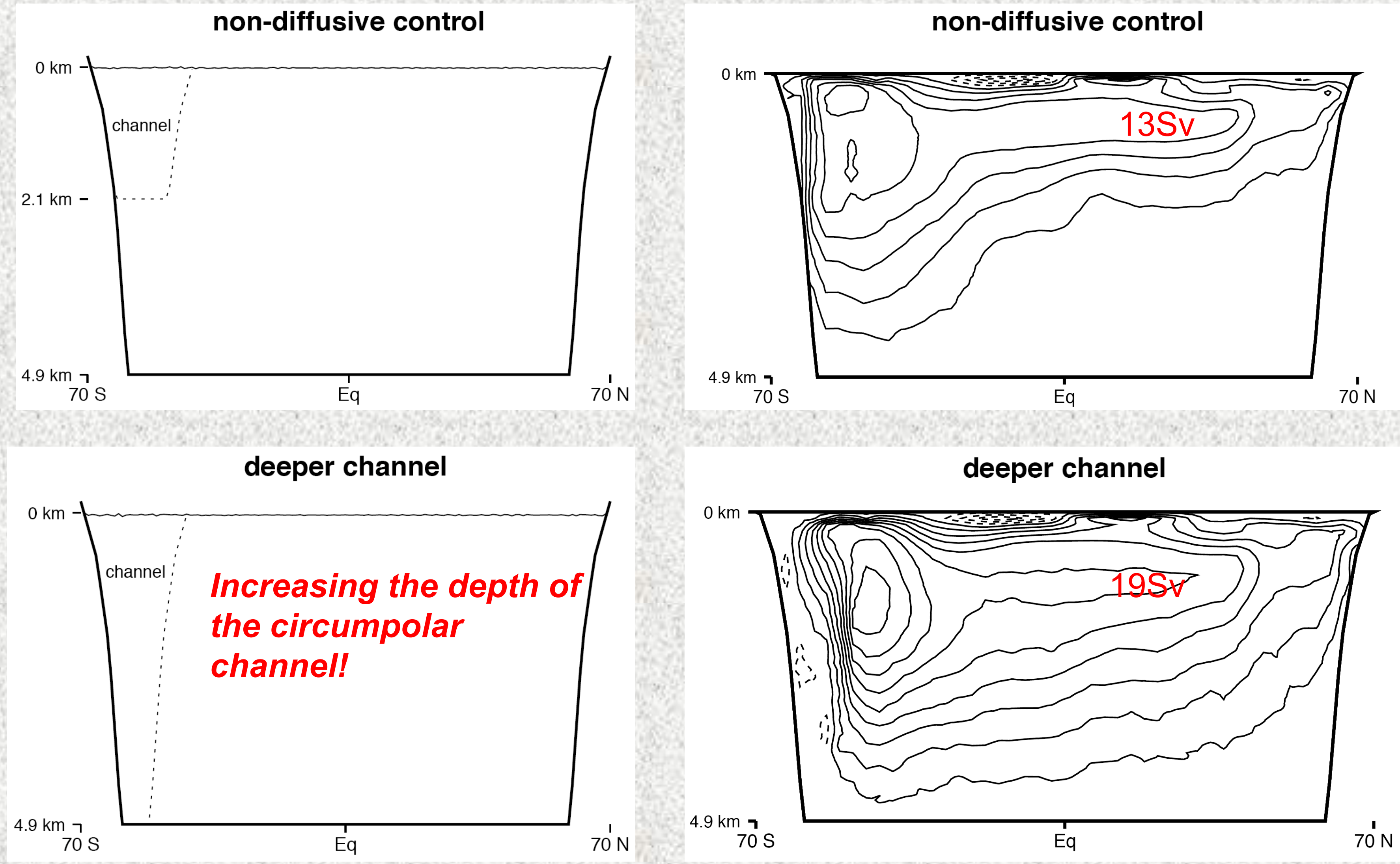




Non-diffusive ocean: what controls stratification and the AMOC intensity?



Non-diffusive ocean: what controls stratification and the AMOC intensity?



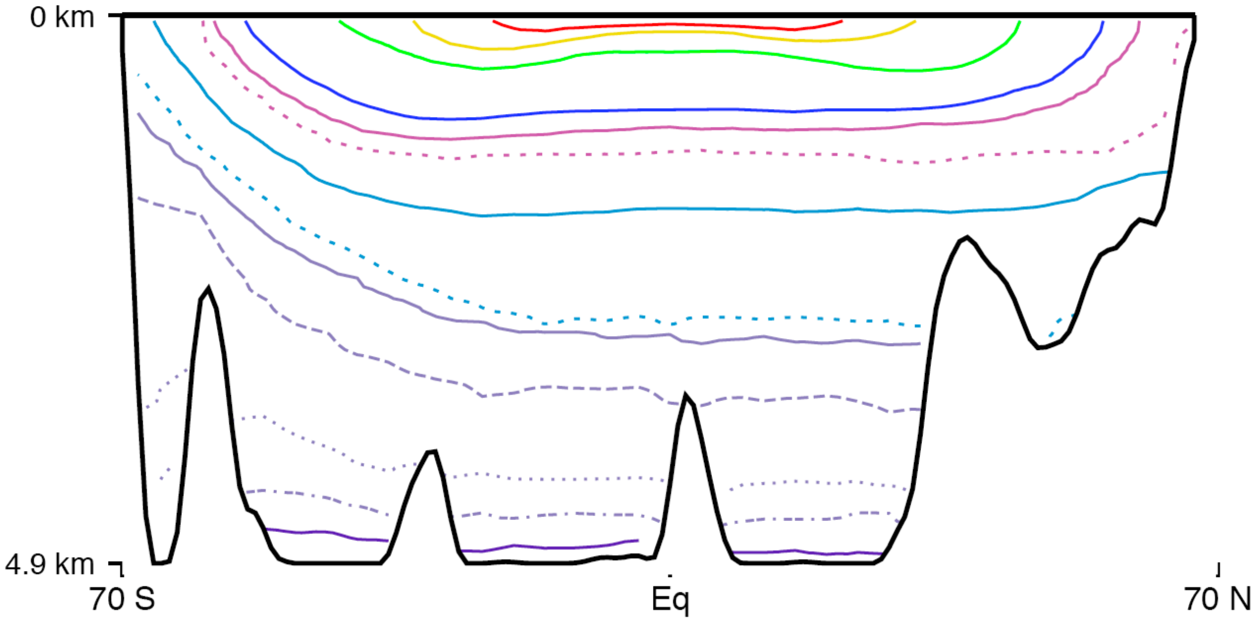
Summary:

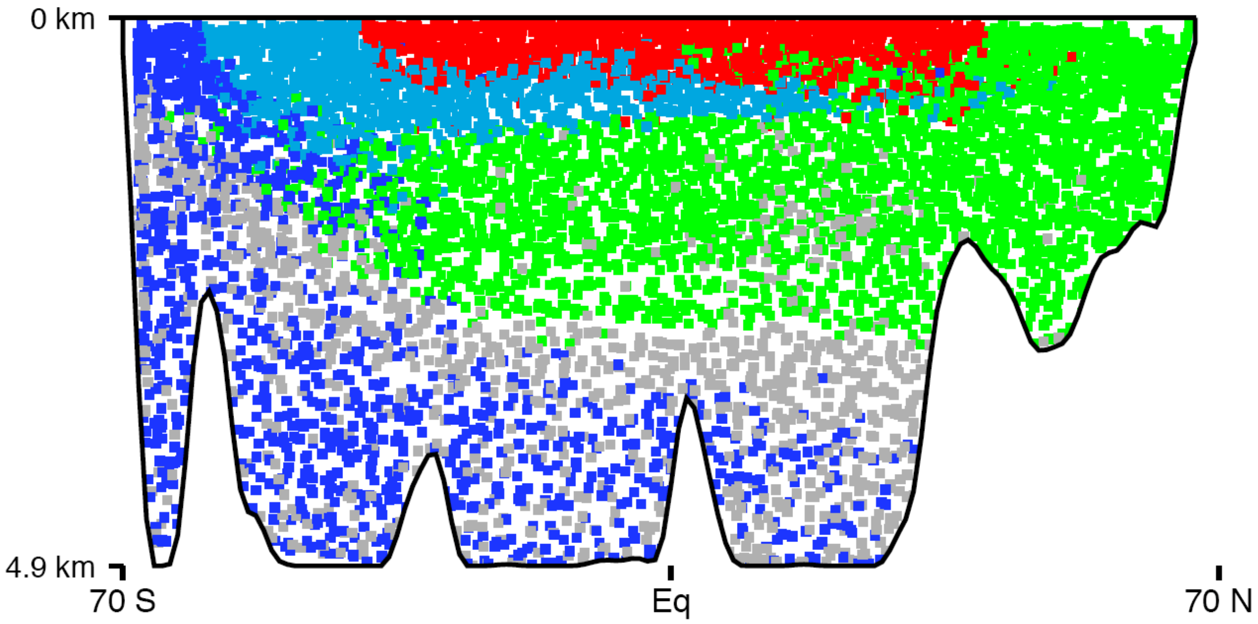
- An ocean with a fully adiabatic interior (no mixing) - “the Ventilated ocean” - gives the leading-order solution for the ocean overturning and stratification problem, as long as the model includes zonal winds, a circumpolar channel, and realistic distribution of surface density

- Deepening the channel or increasing the wind stress intensifies the overturning

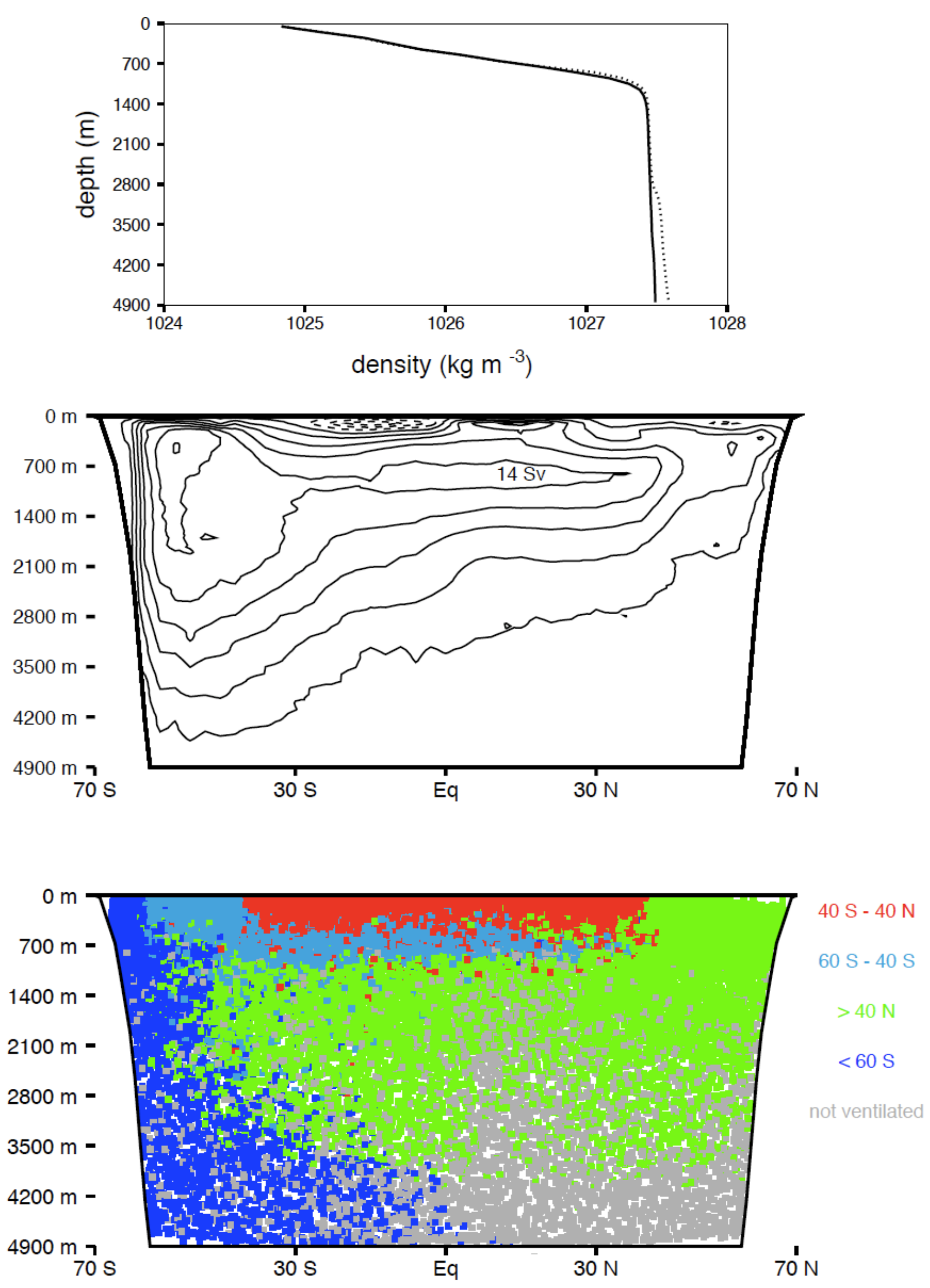
- Diffusion provides the second-order perturbations, increasing stratification in the deep ocean (between 1000 and 3000m) and producing a realistic bottom overturning cell

The role of bottom



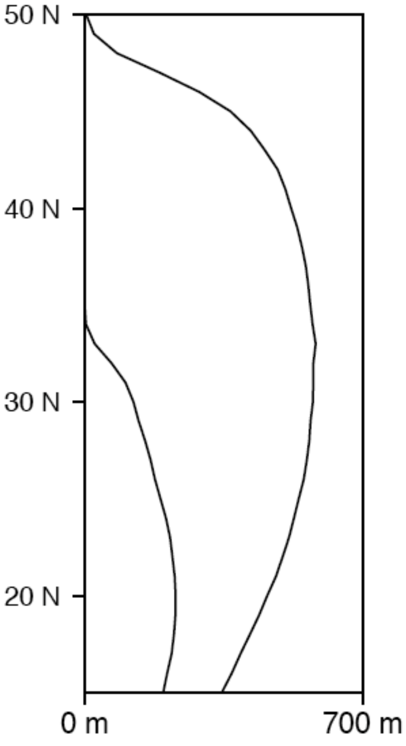


What controls stratification in the bottom ocean?

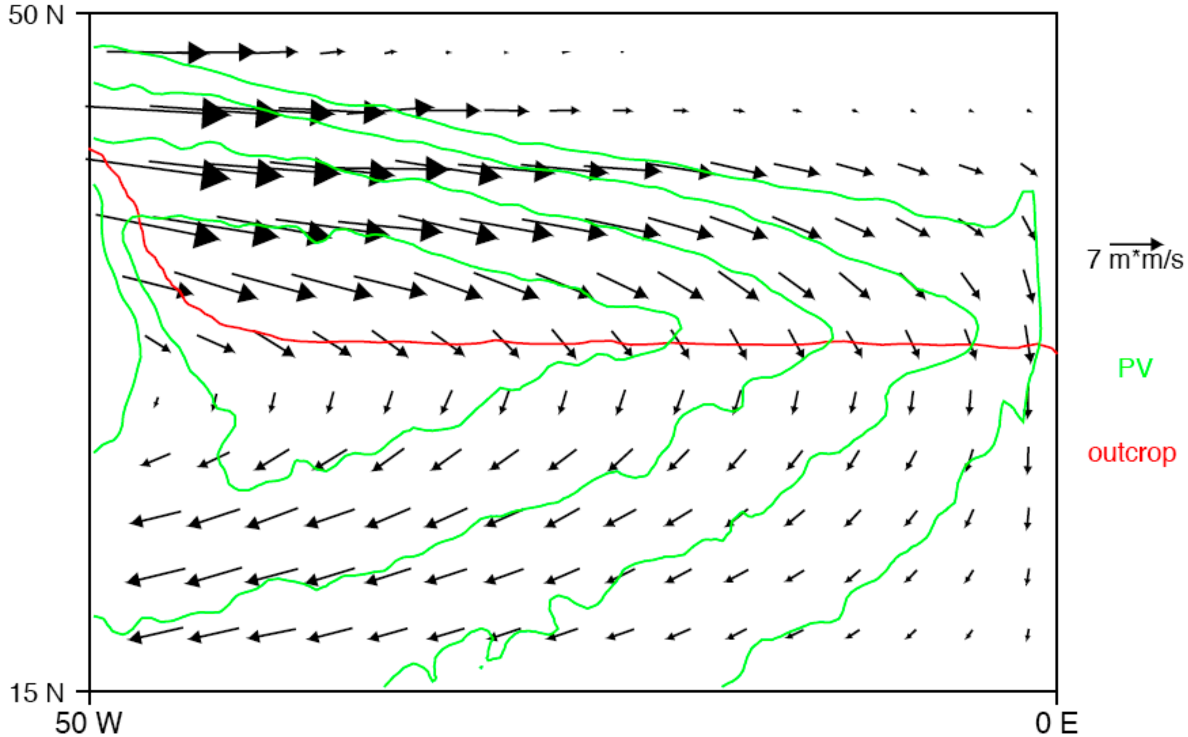


The ventilated thermocline

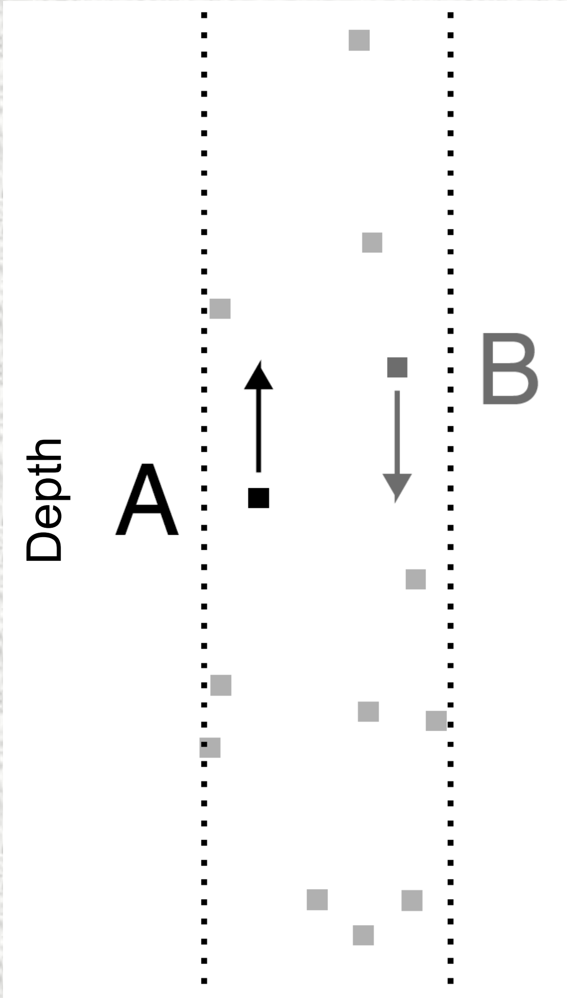
1025-26 kg/m³ density layer along 20°W



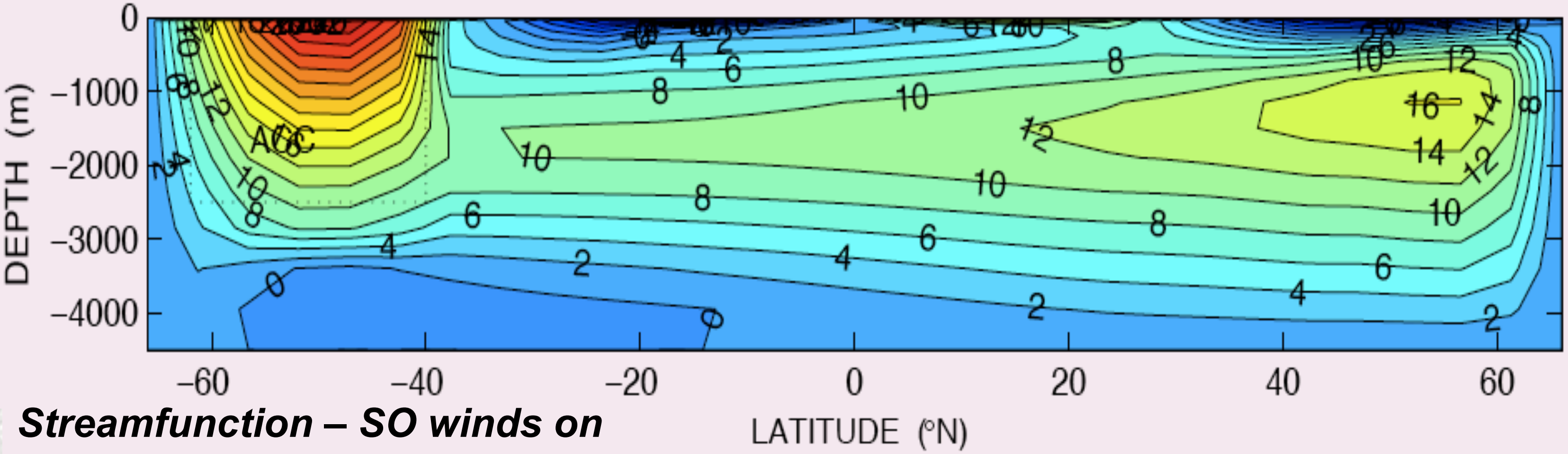
Currents and potential vorticity



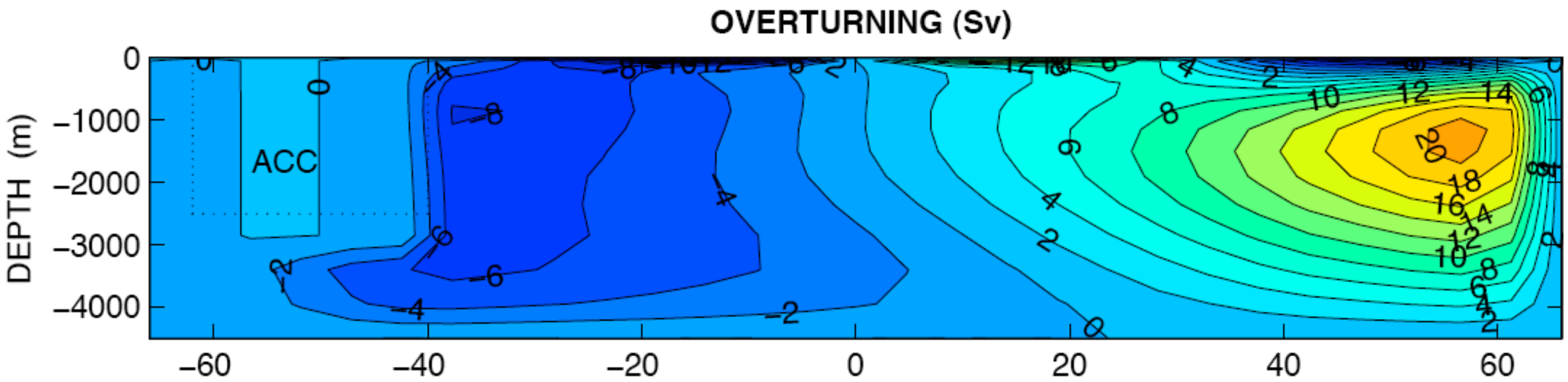
Convection



The convective adjustment scheme: The locations of a collection of parcels within a model column are marked with boxes. Parcel A is less dense than Parcel B, and the convective scheme simply switches their vertical positions (i.e. stacking order) to restore a stable stratification

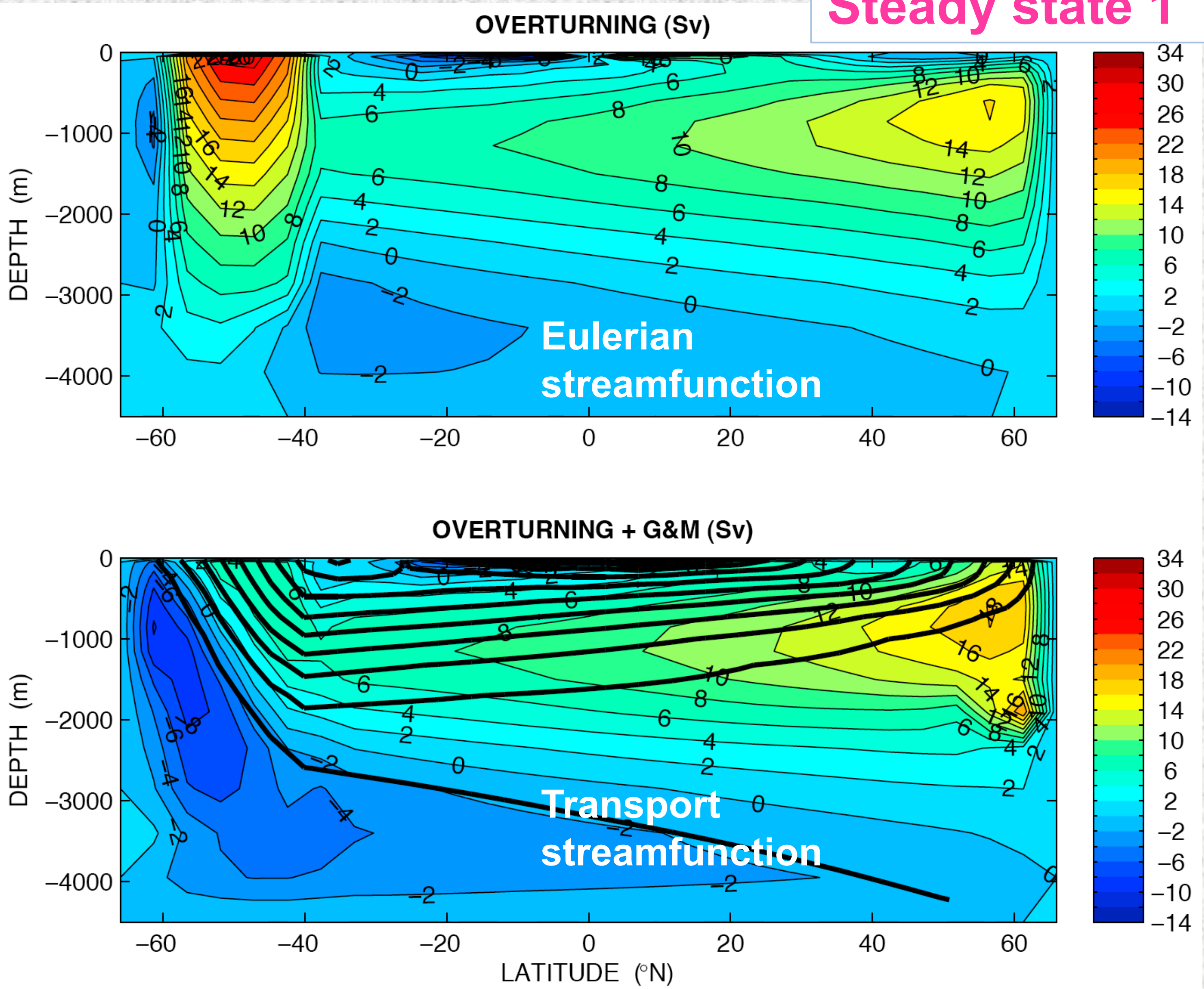


Streamfunction – SO winds on



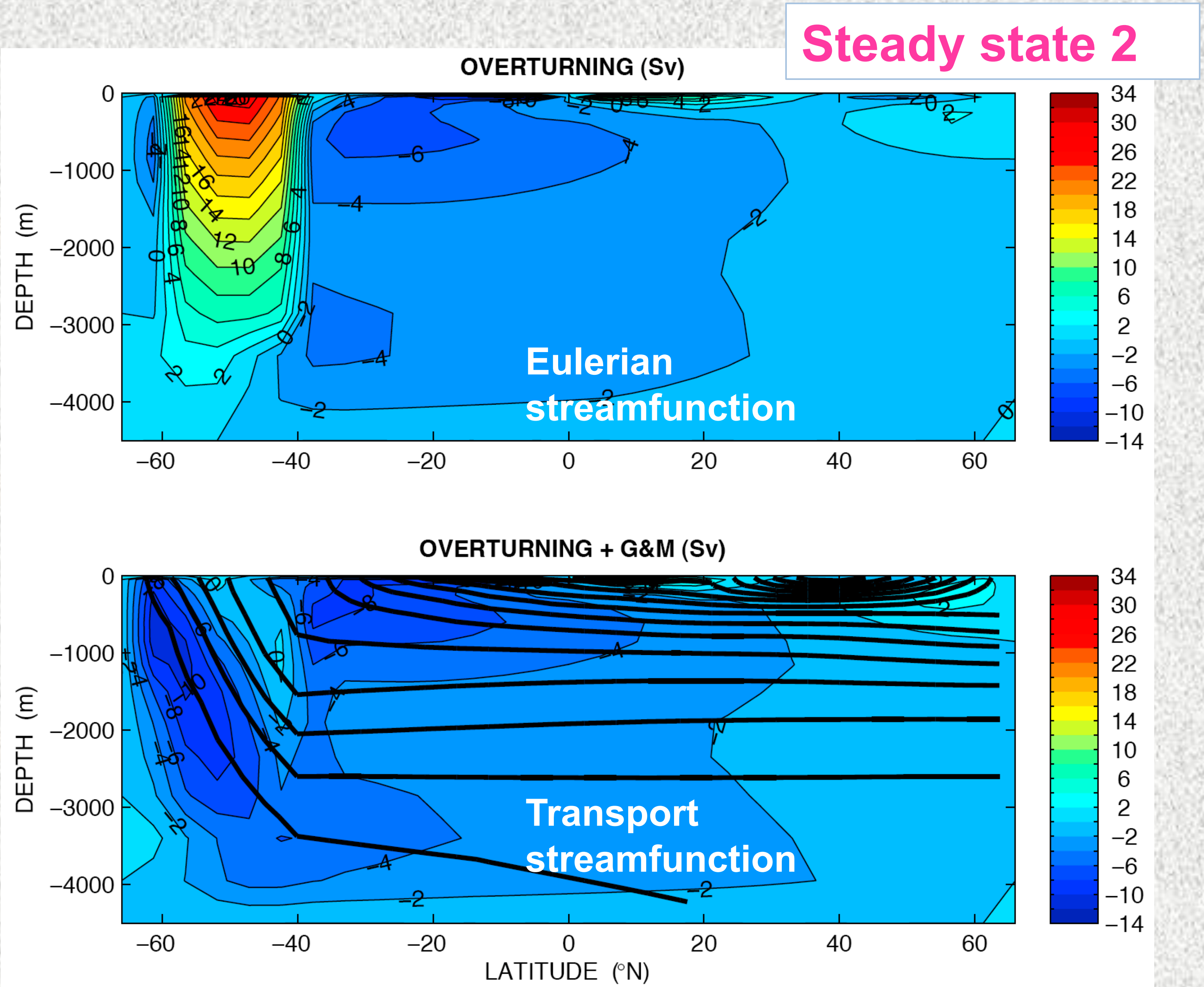
Streamfunction - SO winds off

Steady state 1



$K_d = 1\text{x}10^{-4}\ m^2/s$; $\tau = 0\ N/m^2$ (reference case); F=50cm/year

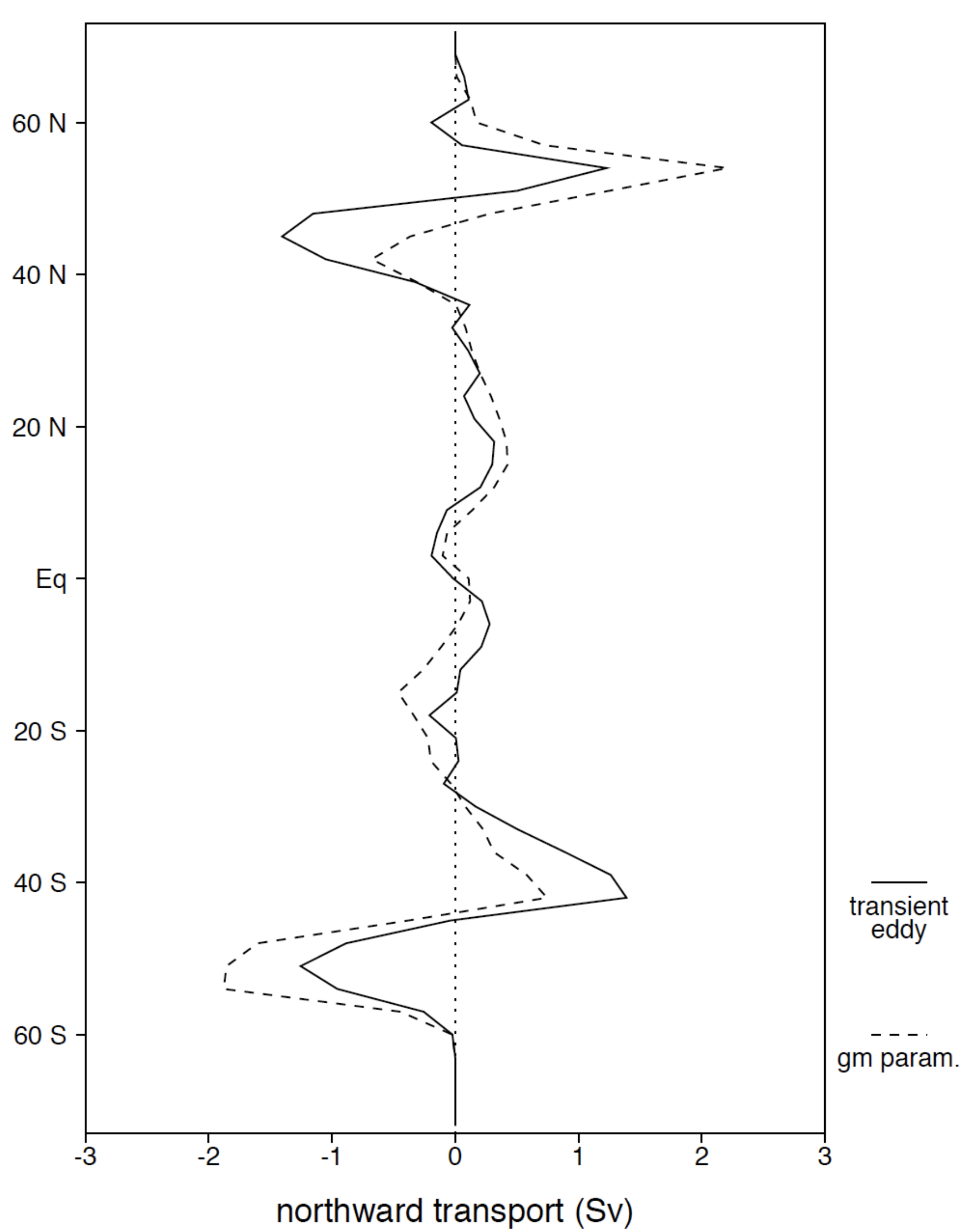
Thick lines - isopycnals



K_d = 1x10^{-4} m^2/s; τ = 0 N/m^2 (reference case); *F*=50cm/year

Thick lines - isopycnals

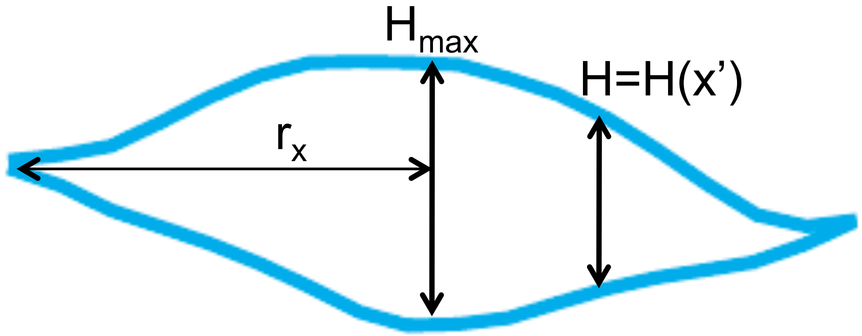
37



Adiabatic horizontal eddy mixing in the model:

***Northward bolus transport** of 1026-1027 kg m^{-3} layer thickness for 3^o model resolution in the non-diffusive run (solid line), $\int v'H'dx$, and **bolus transport** in a conventional GM parameterization with a coefficient of 500 m^2s^{-1} (dotted line)*

Parcel's shape

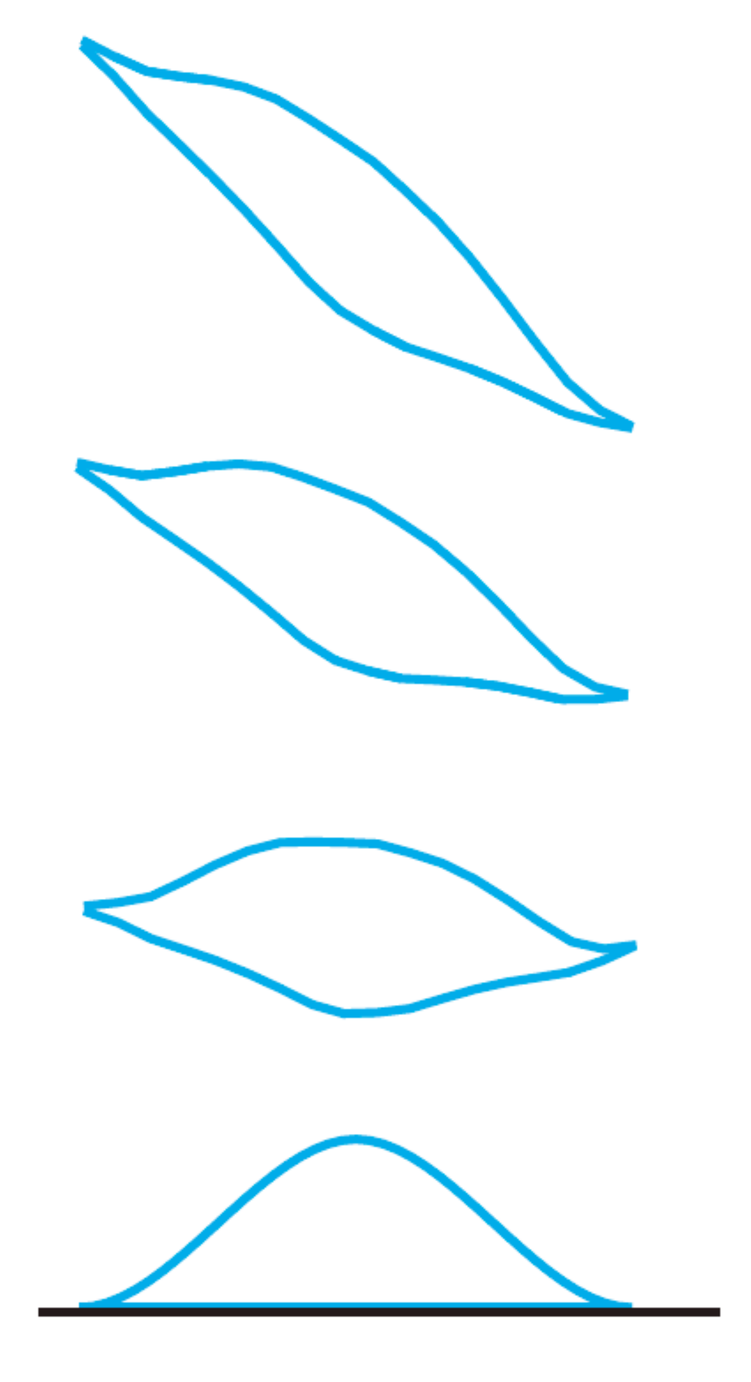


$$H(x', y') = H_{\max}\, p\left(\frac{|x'|}{r_x}\right) p\left(\frac{|y'|}{r_y}\right)$$

- parcel's thickness

p(x) - bell-shaped when set on a flat surface

$$p(x) = 1 + (2x - 3)x^2 \text{ for } x < 1$$

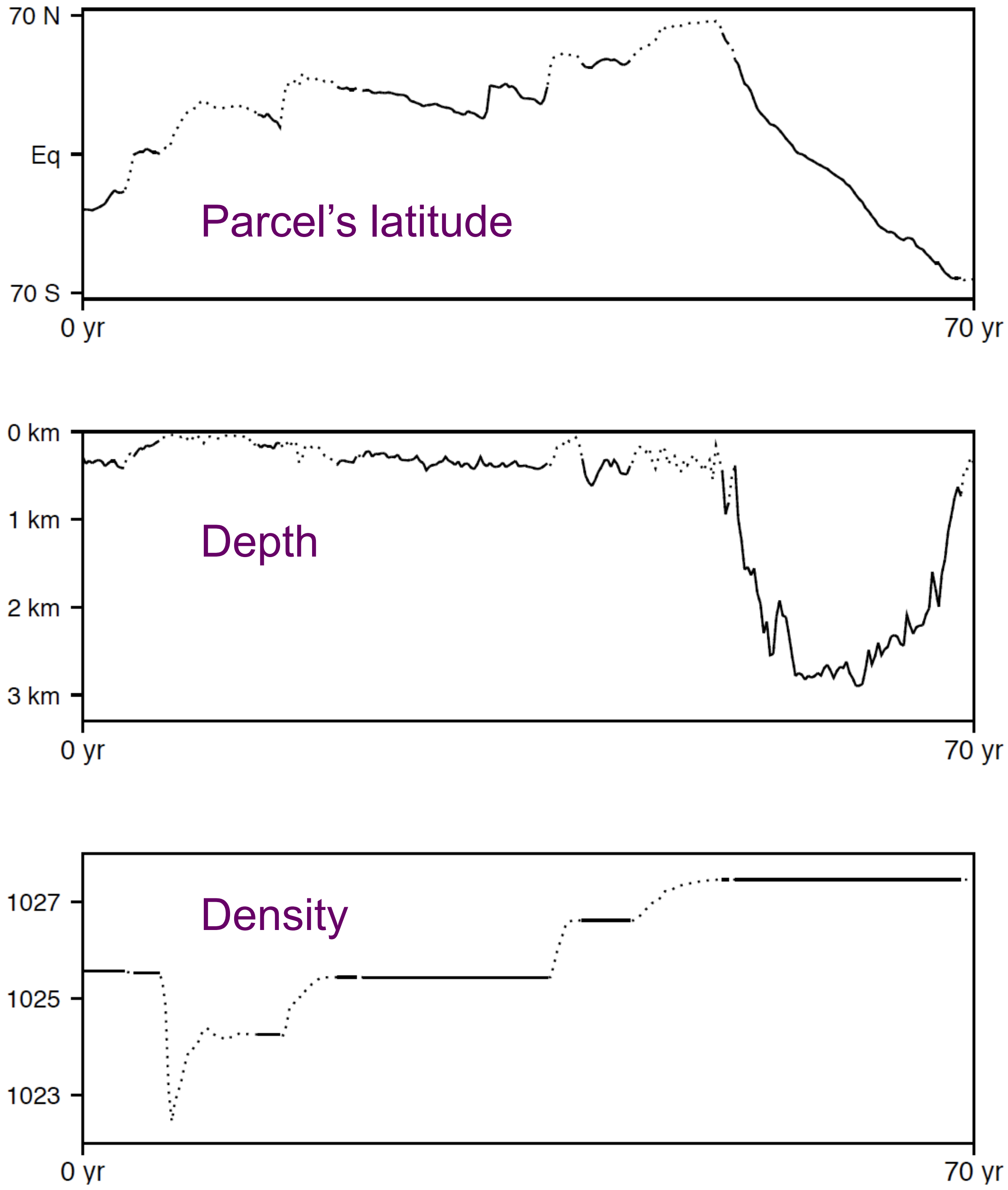


Parcel's shape

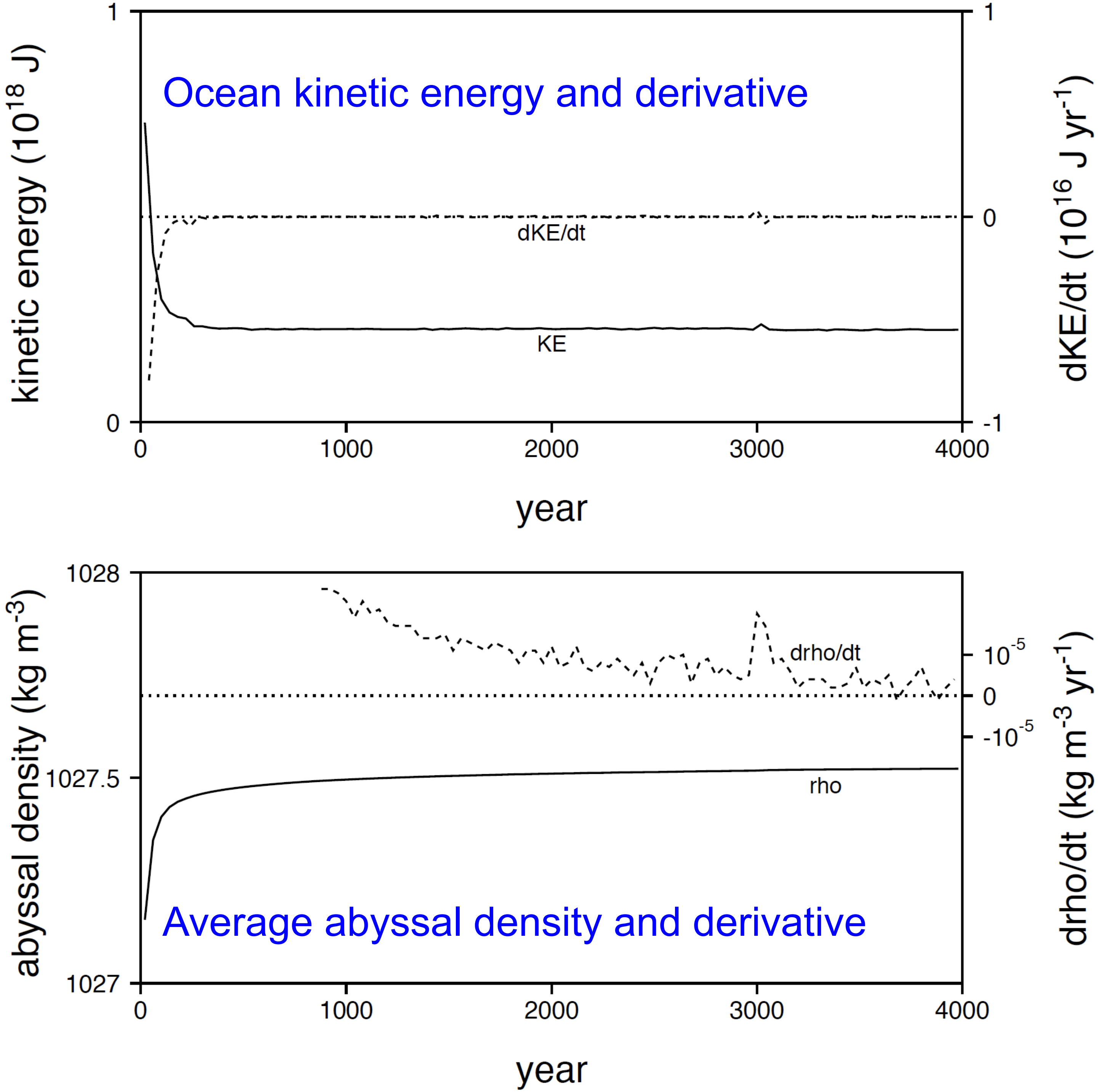
p(x) is fixed

$H_{max} = f(M, \rho)$

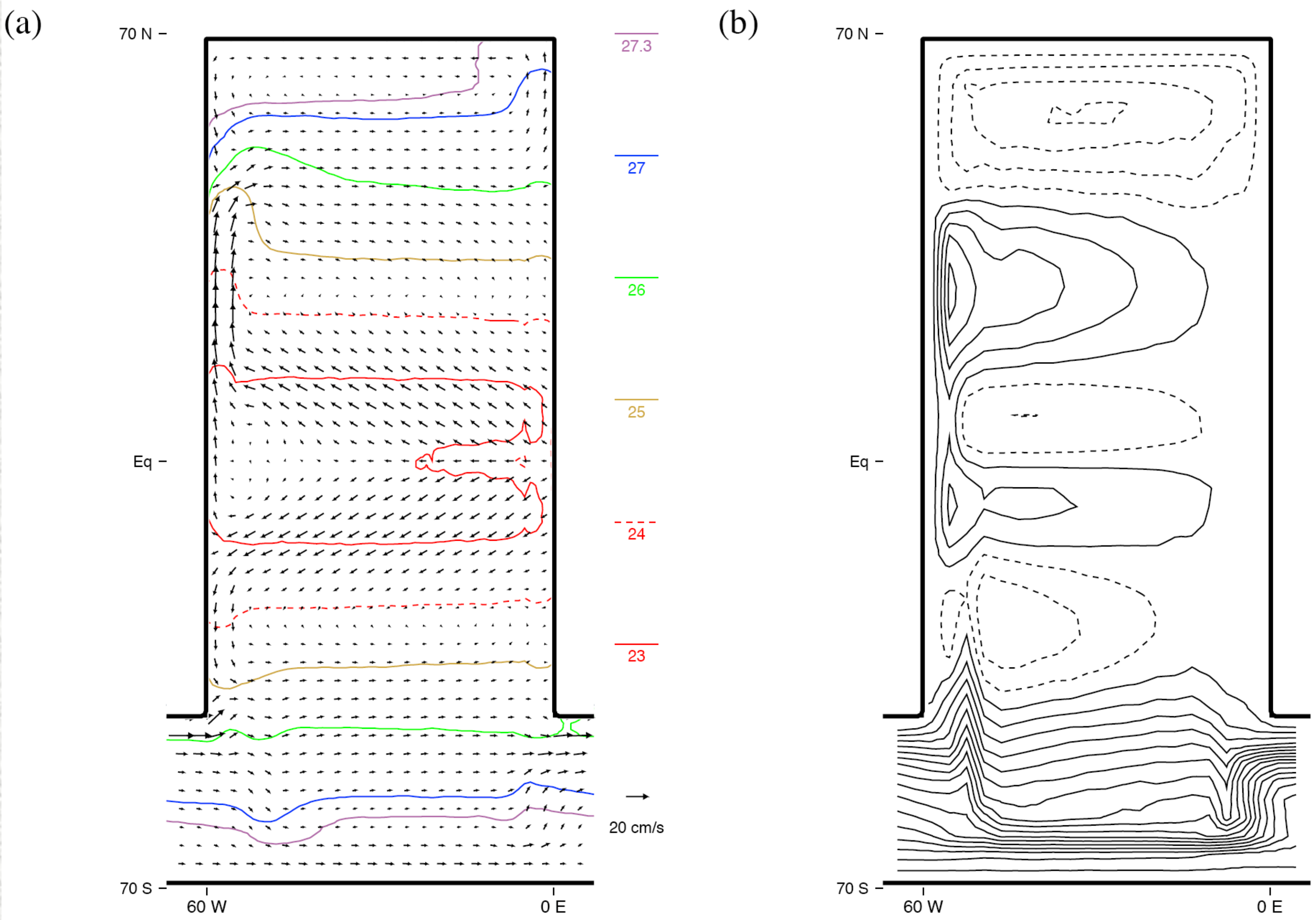
M – mass
ρ – density



An example of a parcel's position and density with time


Ocean kinetic energy and derivative
kinetic energy (10^{18} J)
dKE/dt (10^{16} J yr^{-1})
dKE/dt
KE
year
Average abyssal density and derivative
abyssal density (kg m^{-3})
drho/dt (kg m^{-3} yr^{-1})
drho/dt
rho
year

(a) Simulated surface density (kg/m^3) and ocean currents
(b) Barotropic stream function, 7 Sv intervals



Navier-Stokes equations: Eulerian approach

$$u_t = -\nabla \cdot (u\,\mathbf{u}) + v\left(f + \frac{u\tan\phi}{a}\right) - \left(\frac{1}{a\,\rho_\circ \cdot \cos\phi}\right) p_\lambda + (\kappa_m u_z)_z + F^u$$

$$v_t = -\nabla \cdot (v\,\mathbf{u}) - u\left(f + \frac{u\tan\phi}{a}\right) - \left(\frac{1}{a\,\rho_\circ}\right) p_\phi + (\kappa_m v_z)_z + F^v$$

$$w_z = -\nabla_h \cdot \mathbf{u}_h$$

Vertical velocity

$$p_z = -\rho\, g$$

Pressure

$$\theta_t = -\nabla \cdot [\mathbf{u}\,\theta + \mathbf{F}(\theta)]$$

Potential temperature

$$s_t = -\nabla \cdot [\mathbf{u}\,s + \mathbf{F}(s)]$$

Salinity

$$\rho = \rho(\theta, s, z).$$

Density