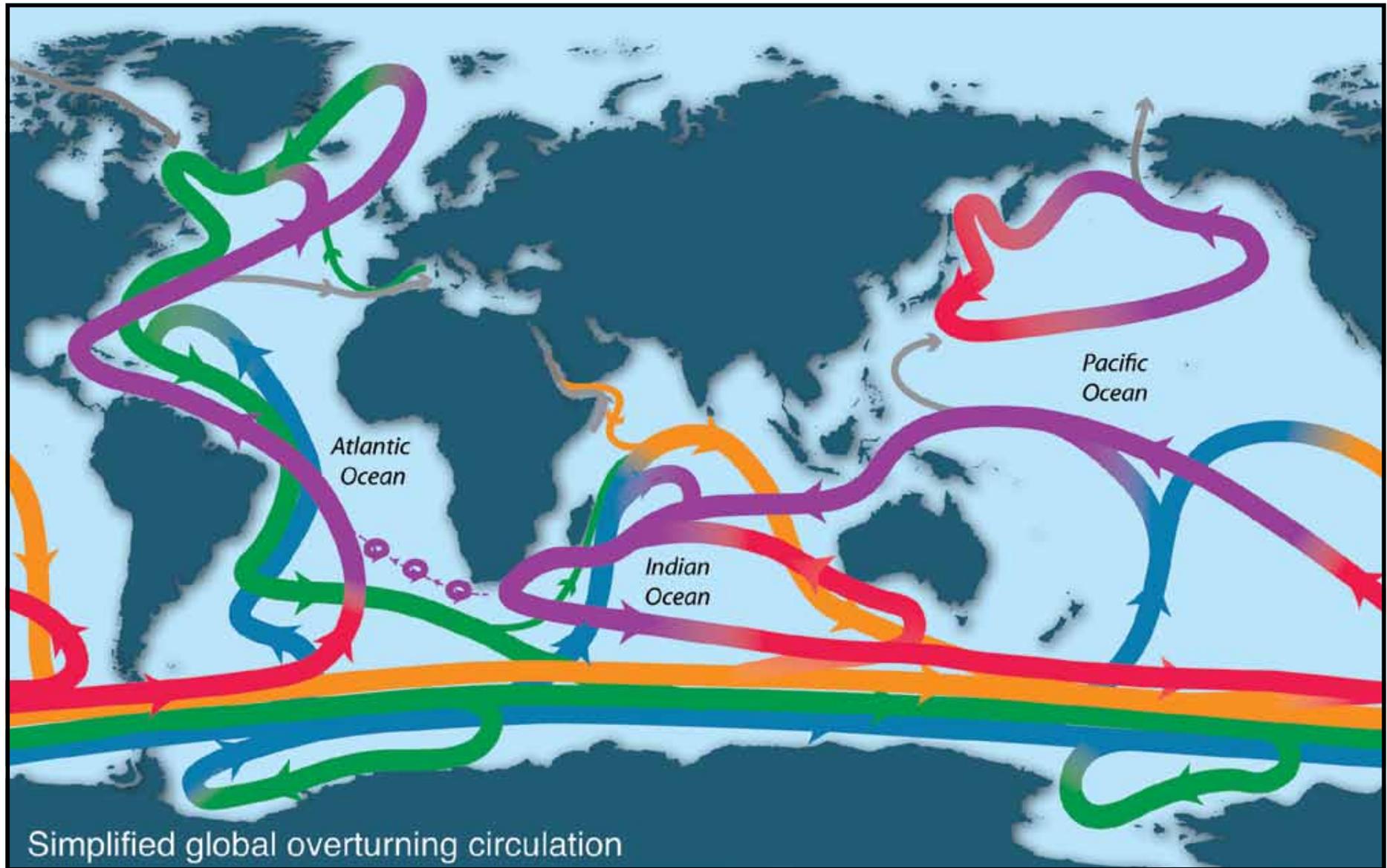


La circulation thermohaline de 1800 à nos jours

Casimir de Lavergne

MathsInFluids, février 2021

La circulation thermohaline aujourd'hui



- I. Découverte de la circulation thermohaline**

- II. Moteurs de la circulation thermohaline**

- III. Une strate exclue de la circulation**

I. Découverte de la circulation thermohaline

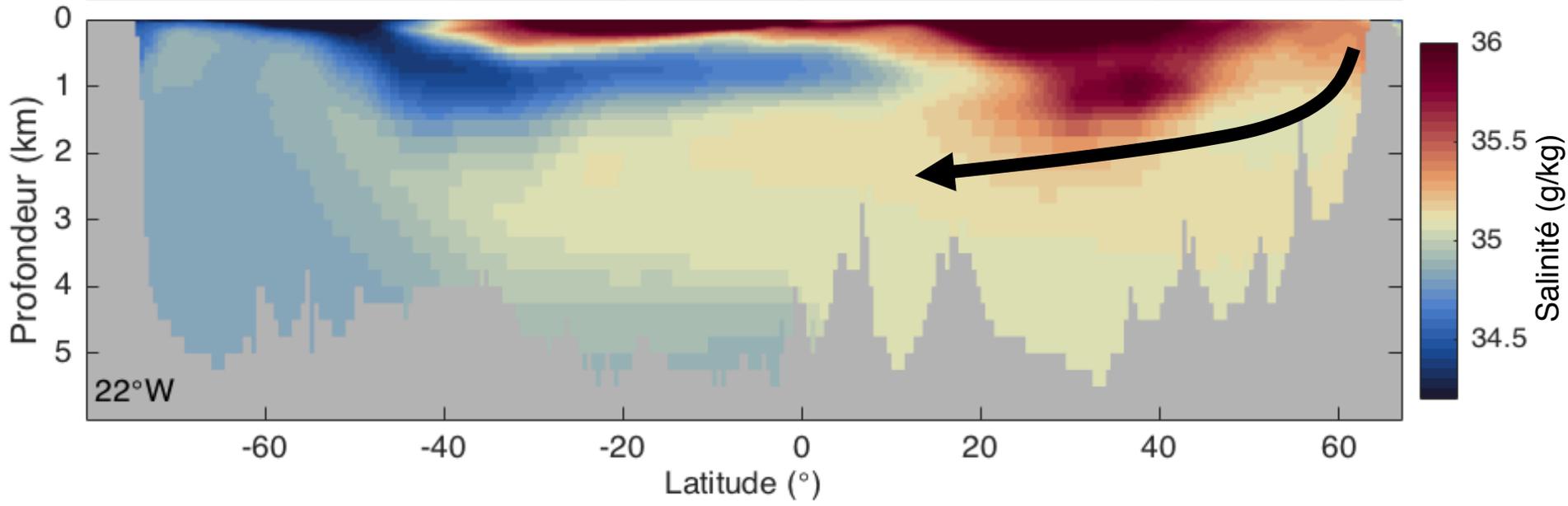
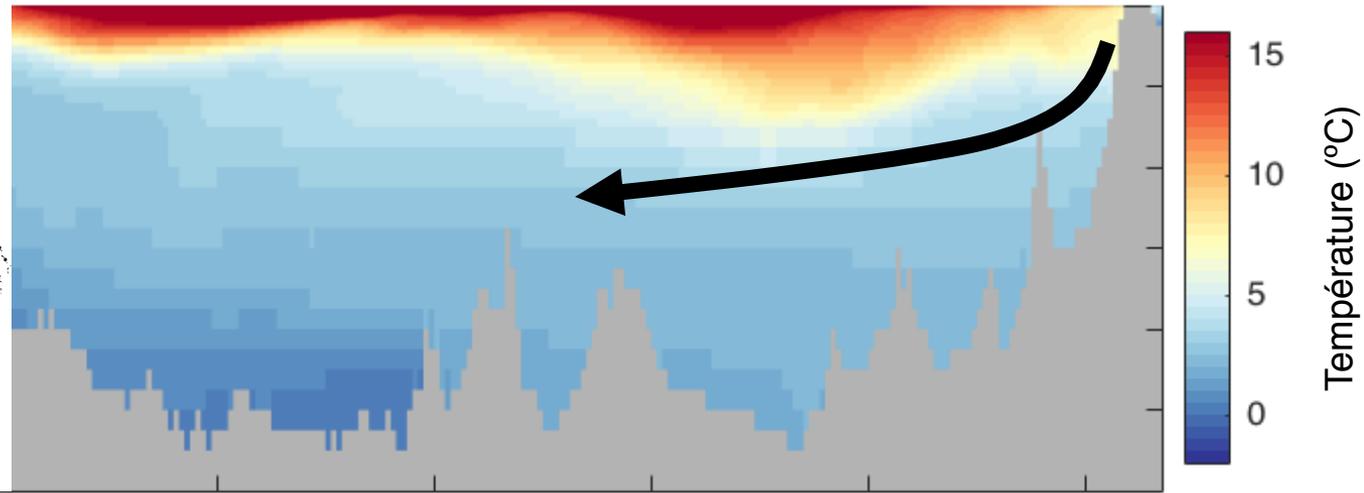
II. Moteurs de la circulation thermohaline

III. Une strate exclue de la circulation

Benjamin Thomson (1798)

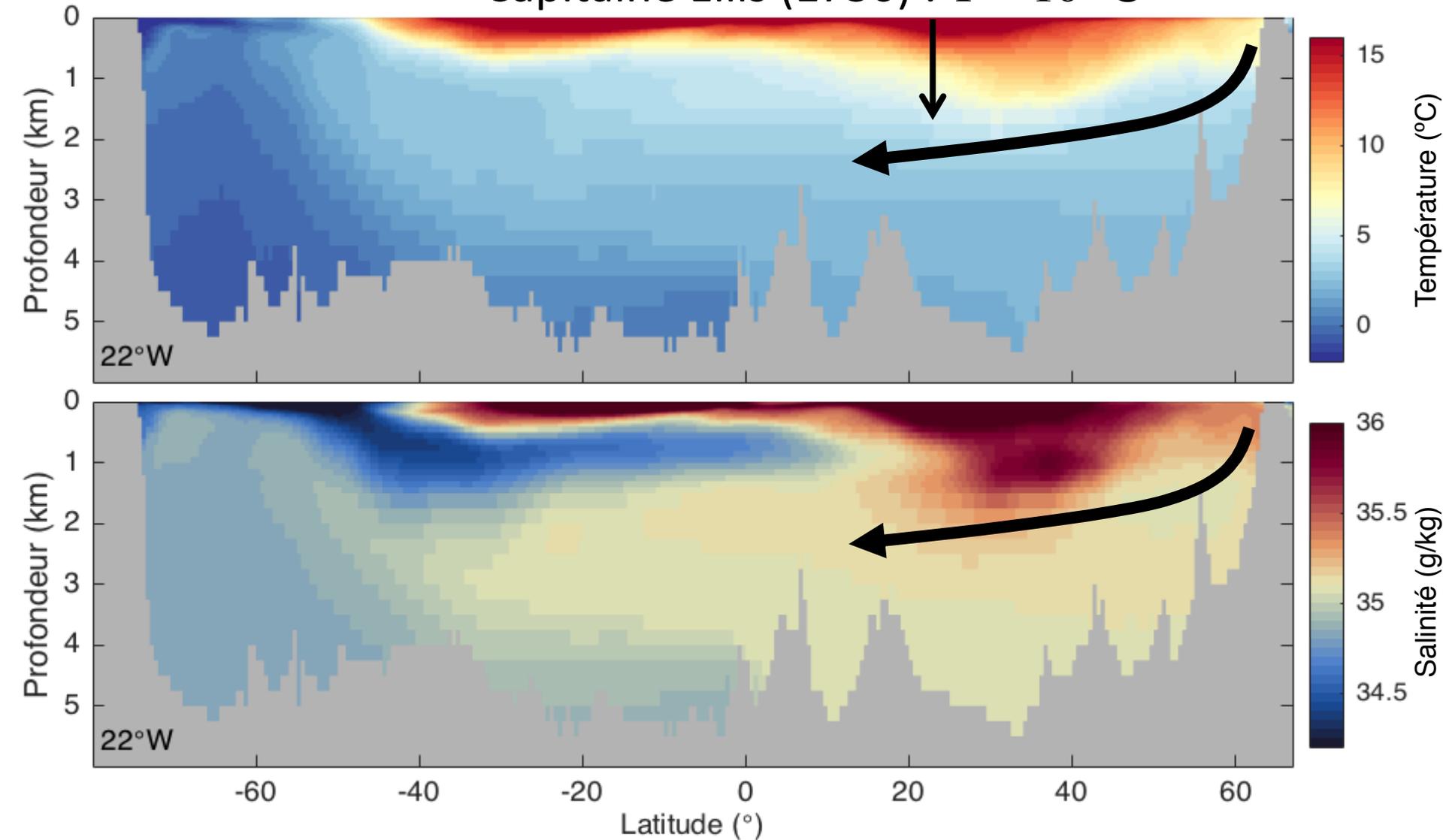


The propagation of heat in fluids (1798).



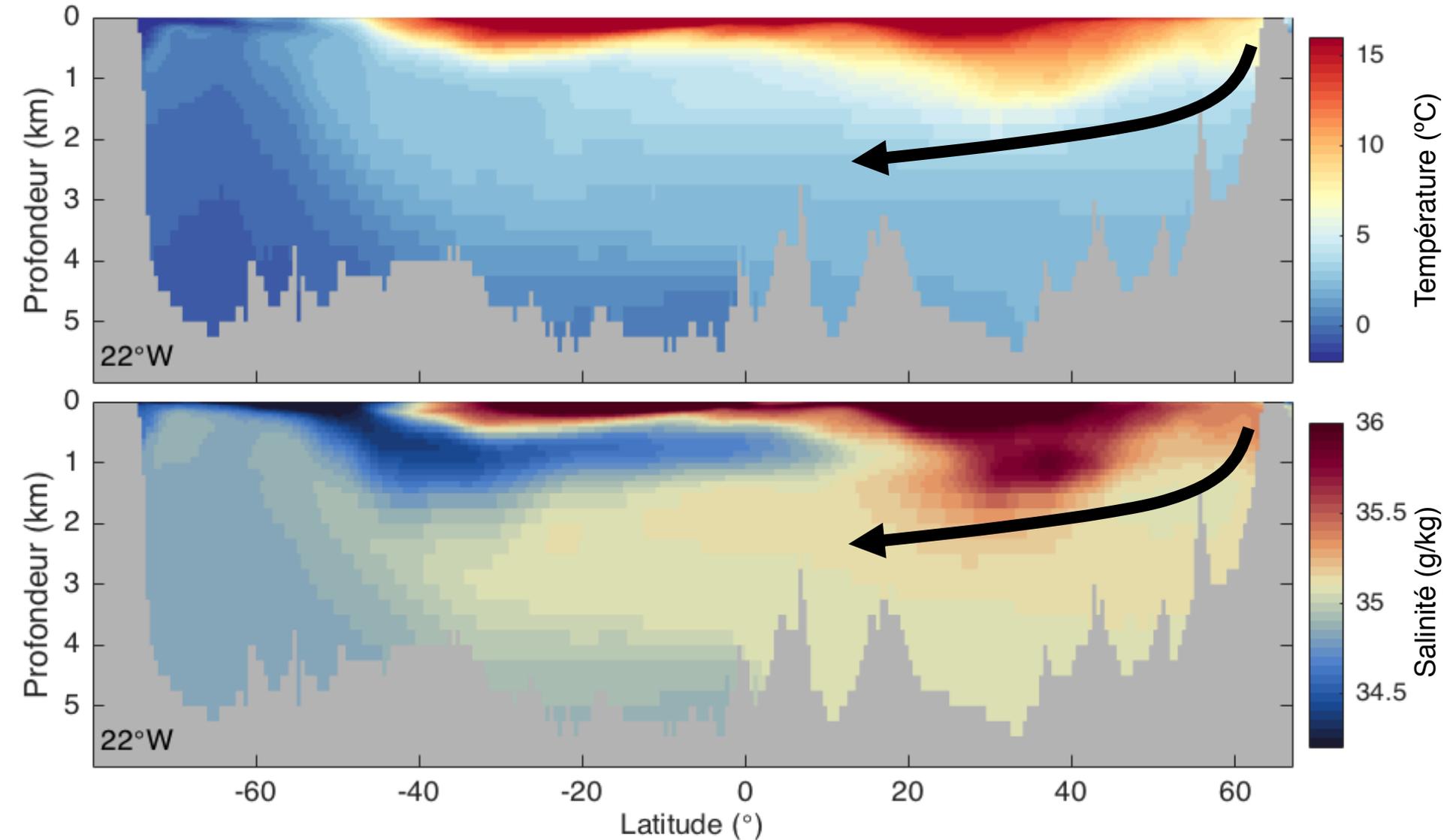
Benjamin Thomson (1798)

Capitaine Ellis (1750) : $T \sim 10\text{ }^{\circ}\text{C}$

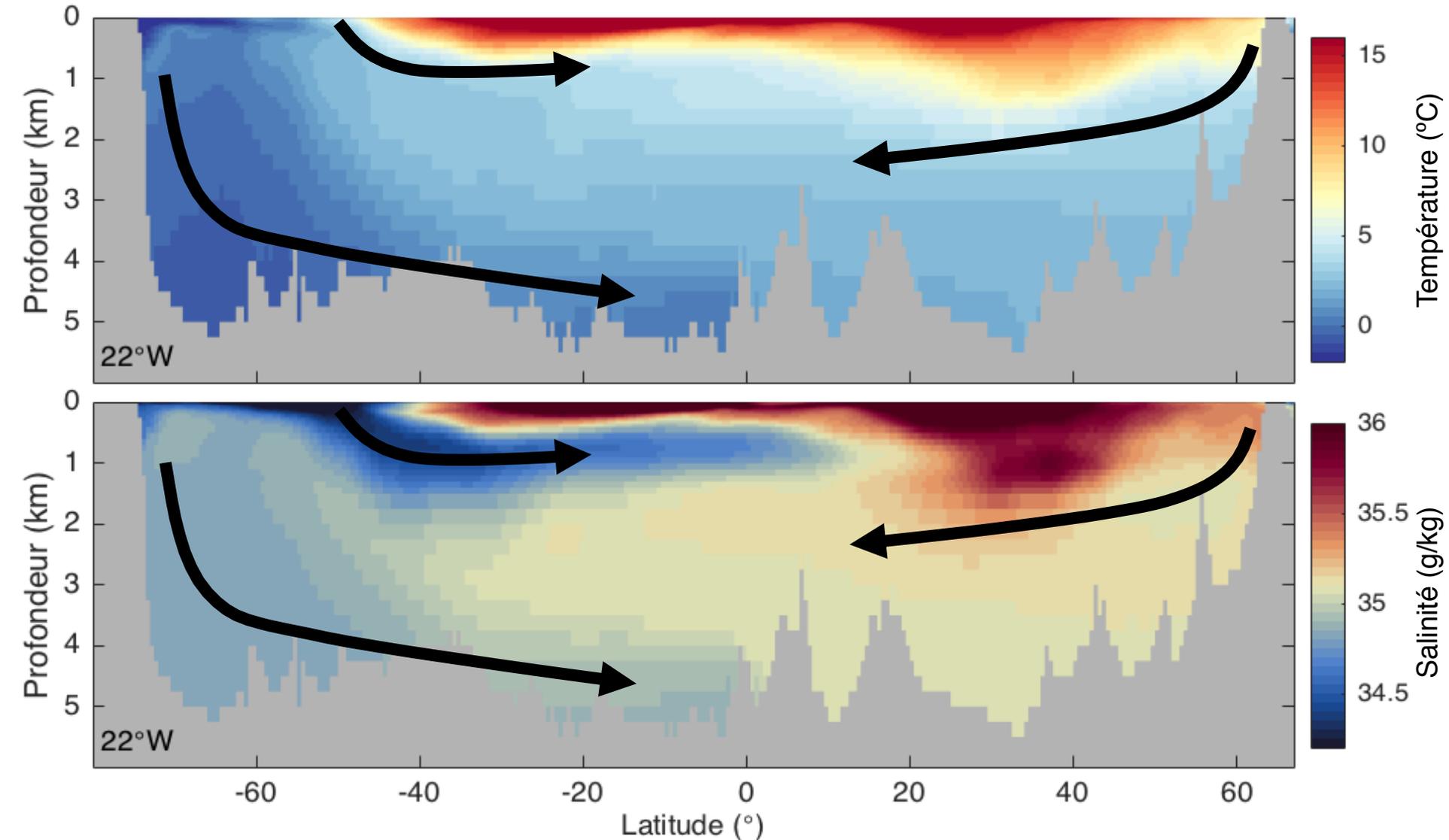


Benjamin Thomson (1798)

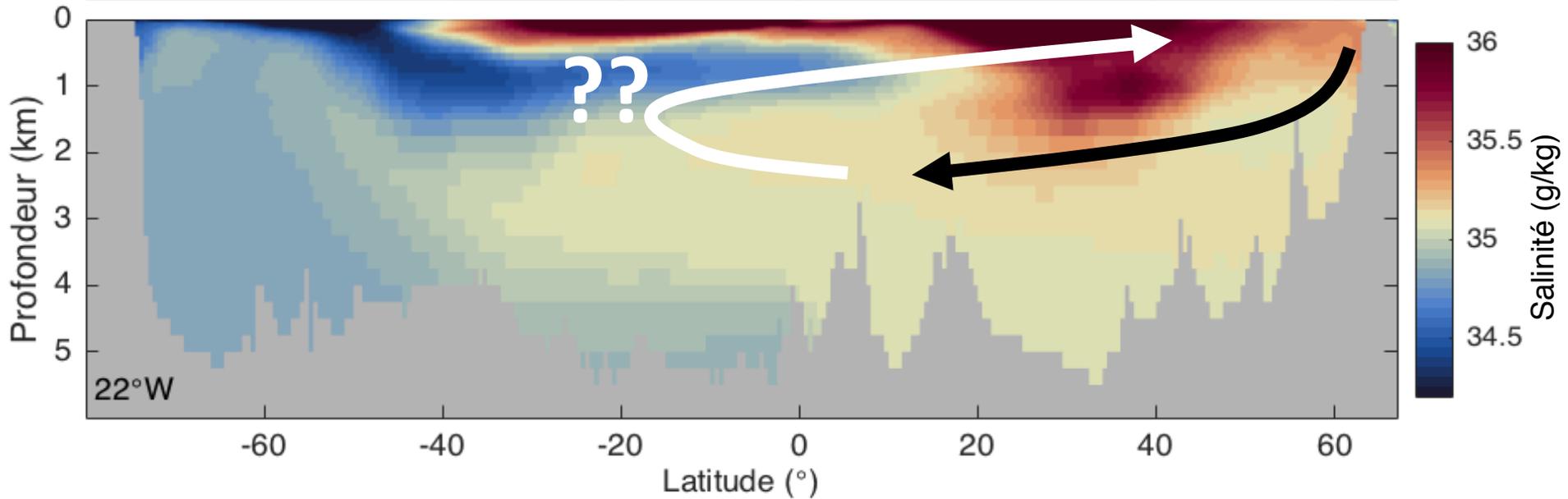
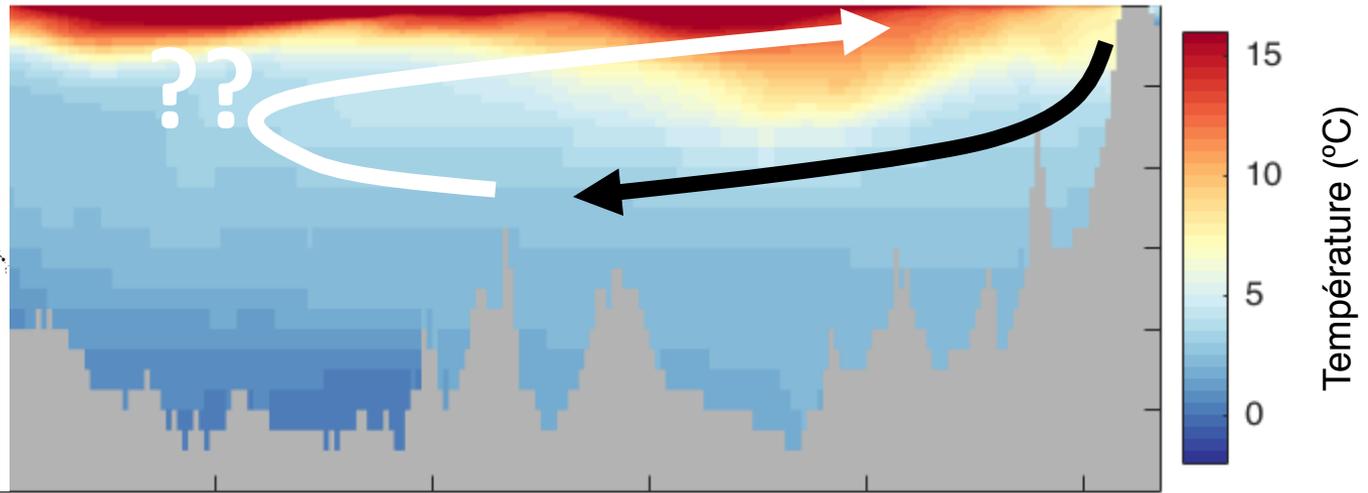
La circulation n'est pas mesurée mais déduite des traceurs.



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Benjamin Thomson (1798)



The abyssal circulation

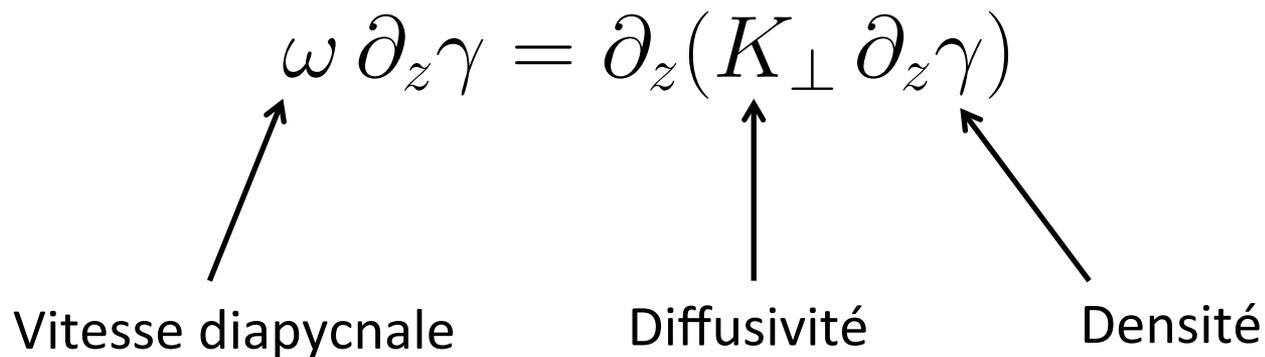
(Received 18 February, 1958)

« It seems likely that the low temperature of deep waters in the world ocean is maintained in the face of downward diffusion of heat from the warm surface layers by a very slow upward component of velocity in the deep water. »

La circulation et la stratification sont maintenus par le mélange des eaux profondes avec des eaux plus légères. Mathématiquement :

$$\omega \partial_z \gamma = \partial_z (K_{\perp} \partial_z \gamma)$$

Vitesse diapycnale Diffusivité Densité



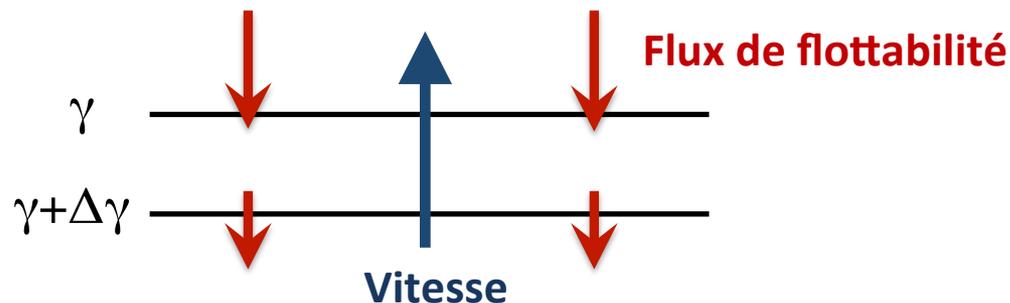
The abyssal circulation

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Abyssal recipes

WALTER H. MUNK*

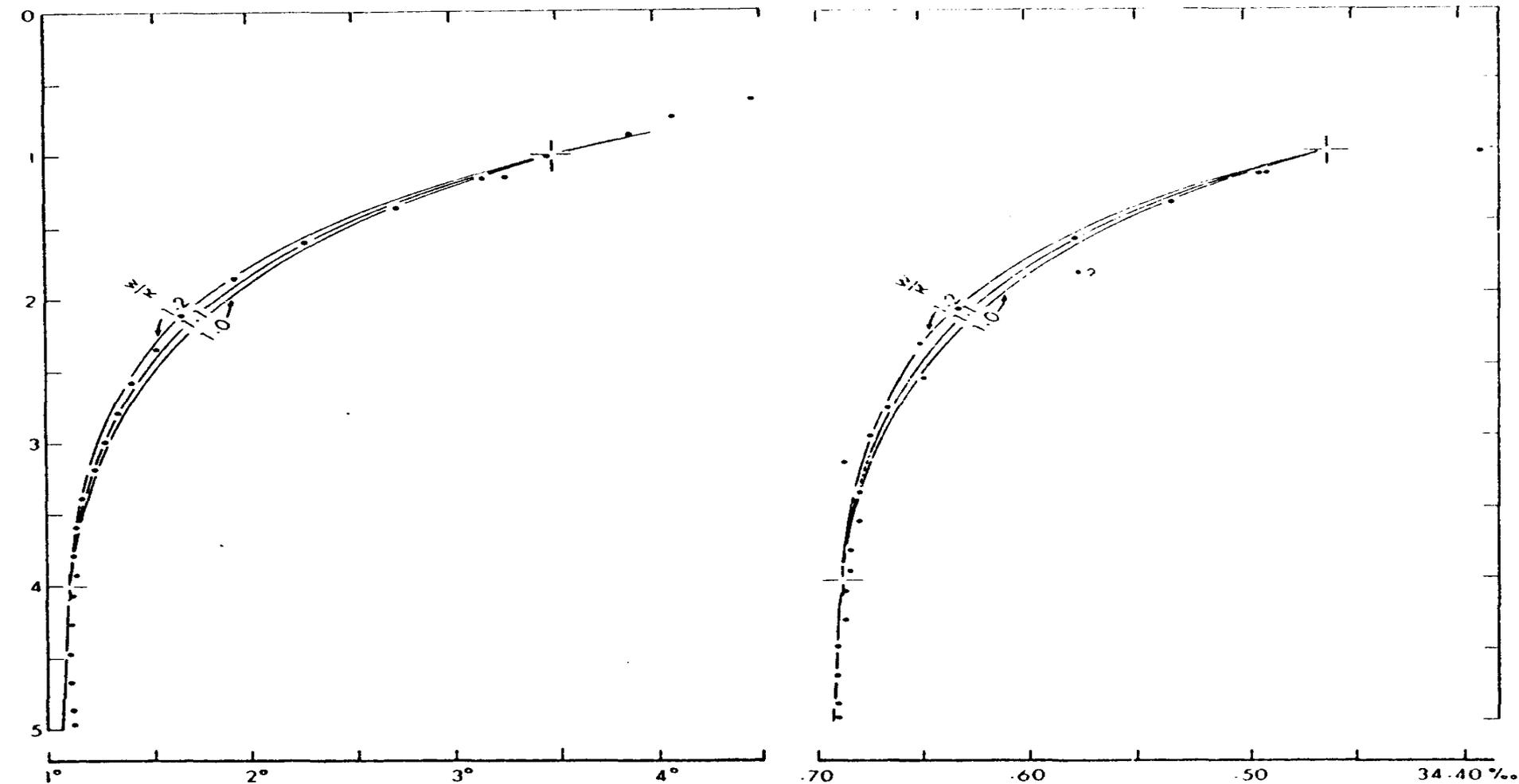


Fig. 3. Potential temperature and salinity as functions of depth (km) at station *Calcofi* 1964: # 60-190, 33° 17'N, 132° 42.5'W (salinity at depth 1859 m was questioned in the original observations). Curves labeled w/x (in units km^{-2}) are based on equation (1).

Abyssal recipes

WALTER H. MUNK*

(Received 31 January 1966)

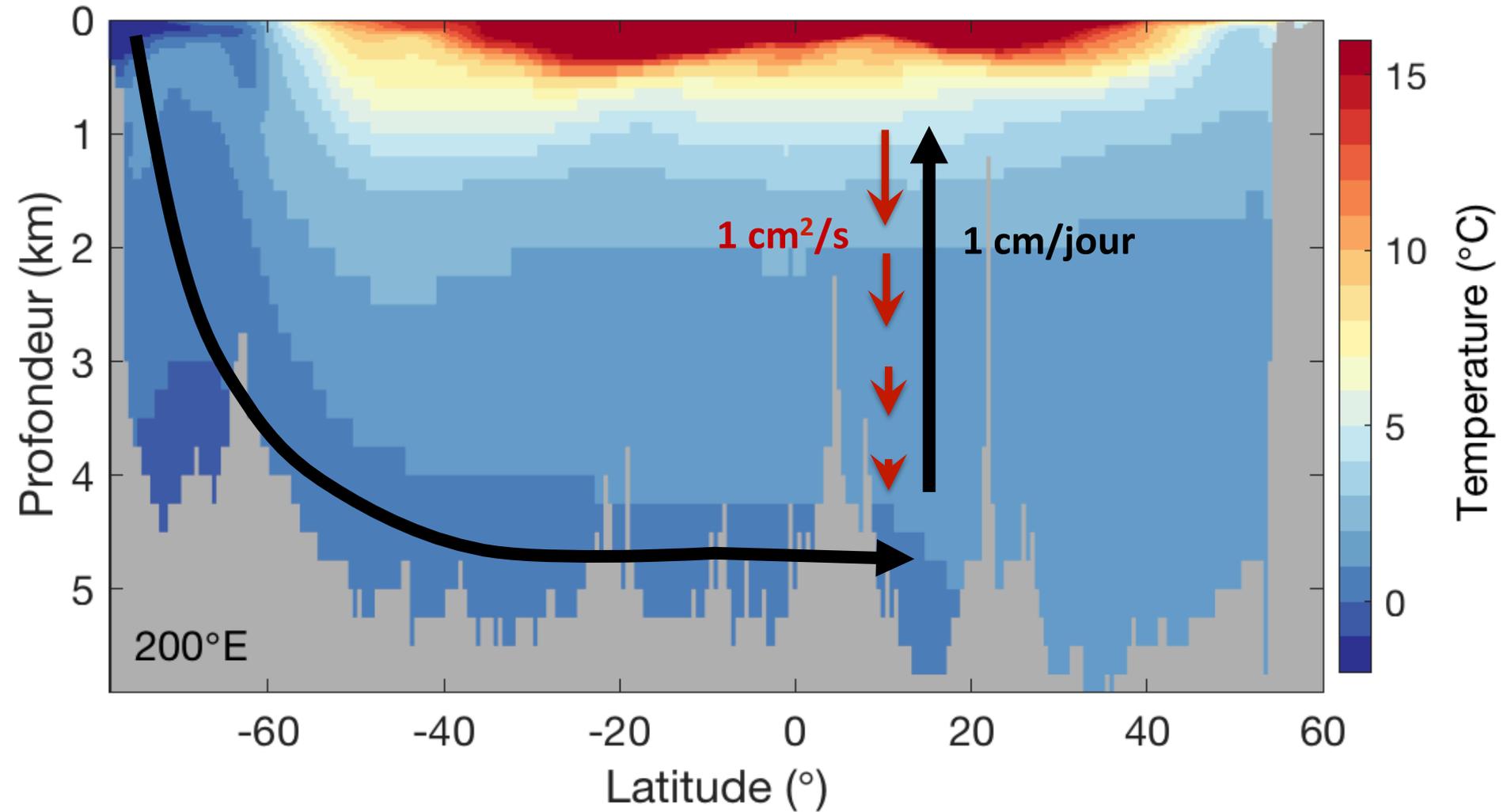
Abstract—Vertical distributions in the interior Pacific (excluding the top and bottom kilometer) are not inconsistent with a simple model involving a constant upward vertical velocity $w \approx 1.2 \text{ cm day}^{-1}$ and eddy diffusivity $\kappa \approx 1.3 \text{ cm}^2 \text{ sec}^{-1}$. Thus temperature and salinity can be fitted by exponential-like solutions to $[\kappa \cdot d^2/dz^2 - w \cdot d/dz] T, S = 0$, with $\kappa/w \approx 1 \text{ km}$ the appropriate “scale height.”

$$\omega \partial_z \gamma = \partial_z (K_{\perp} \partial_z \gamma)$$

$$\omega(z) = K_{\perp} \partial_{zz} \gamma / \partial_z \gamma \approx \text{constant}$$

Abyssal recipes

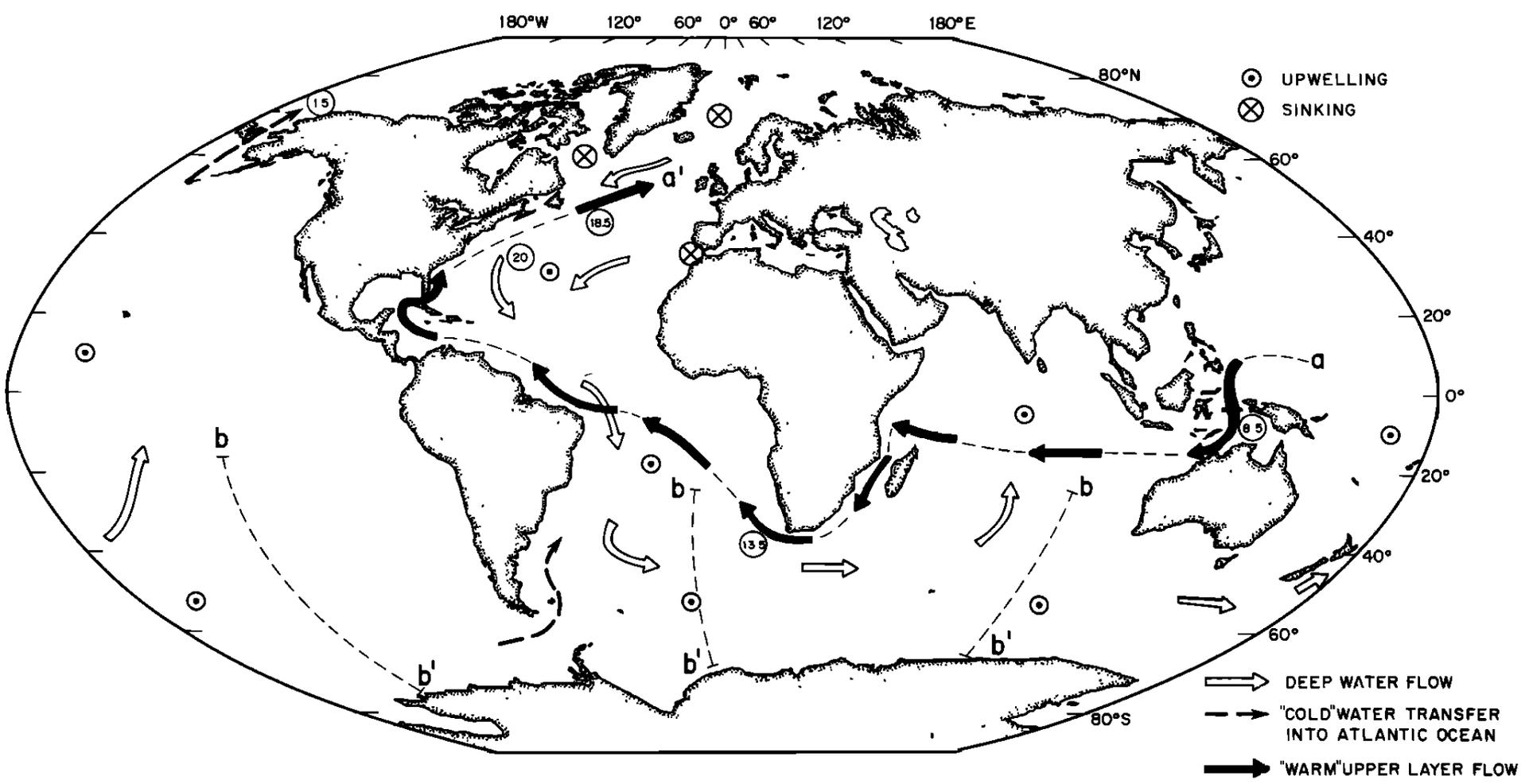
WALTER H. MUNK*



Interocean Exchange of Thermocline Water

ARNOLD L. GORDON

Lamont-Doherty Geological Observatory of Columbia University, Palisades, New York



The biggest chill (1987).

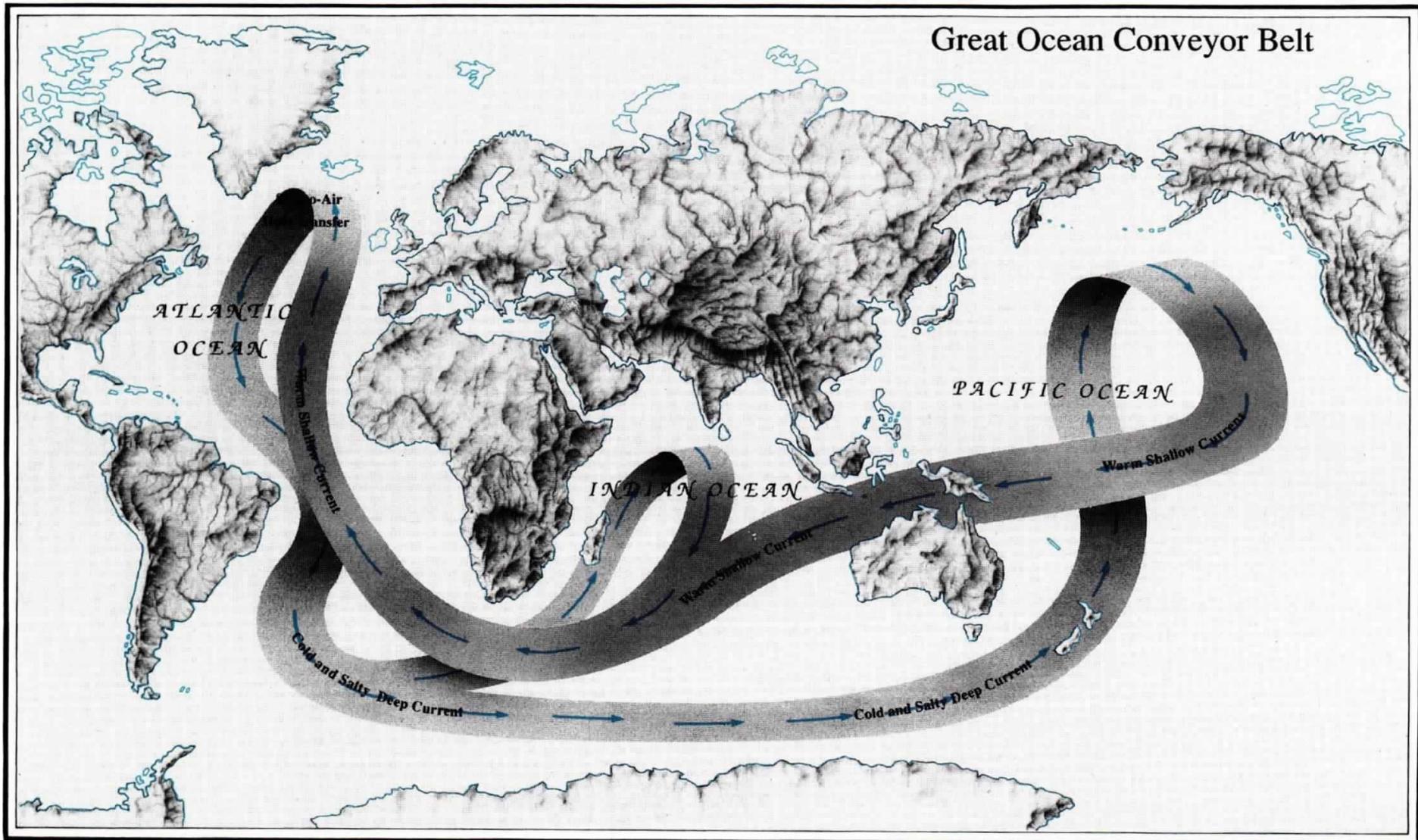
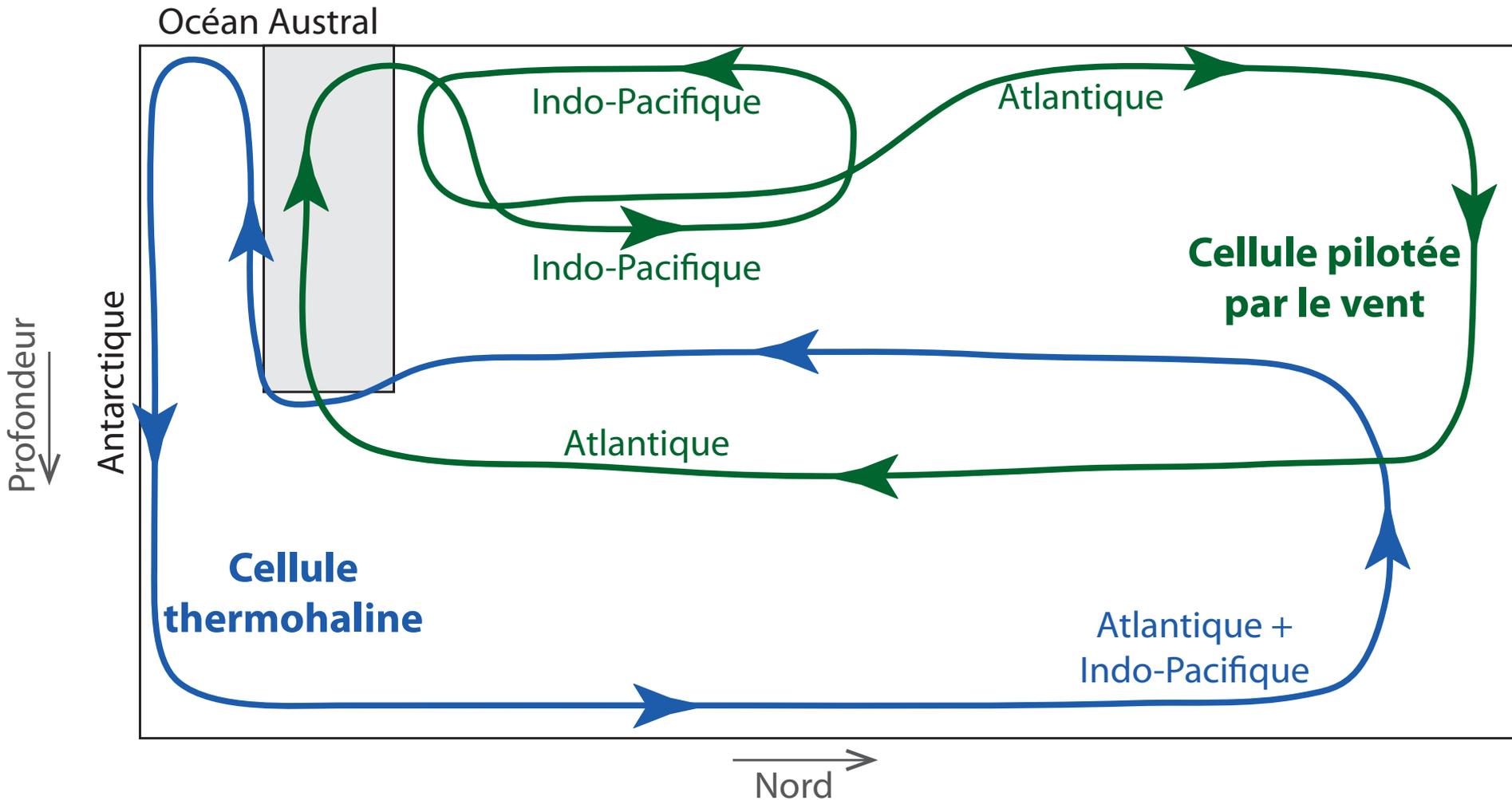


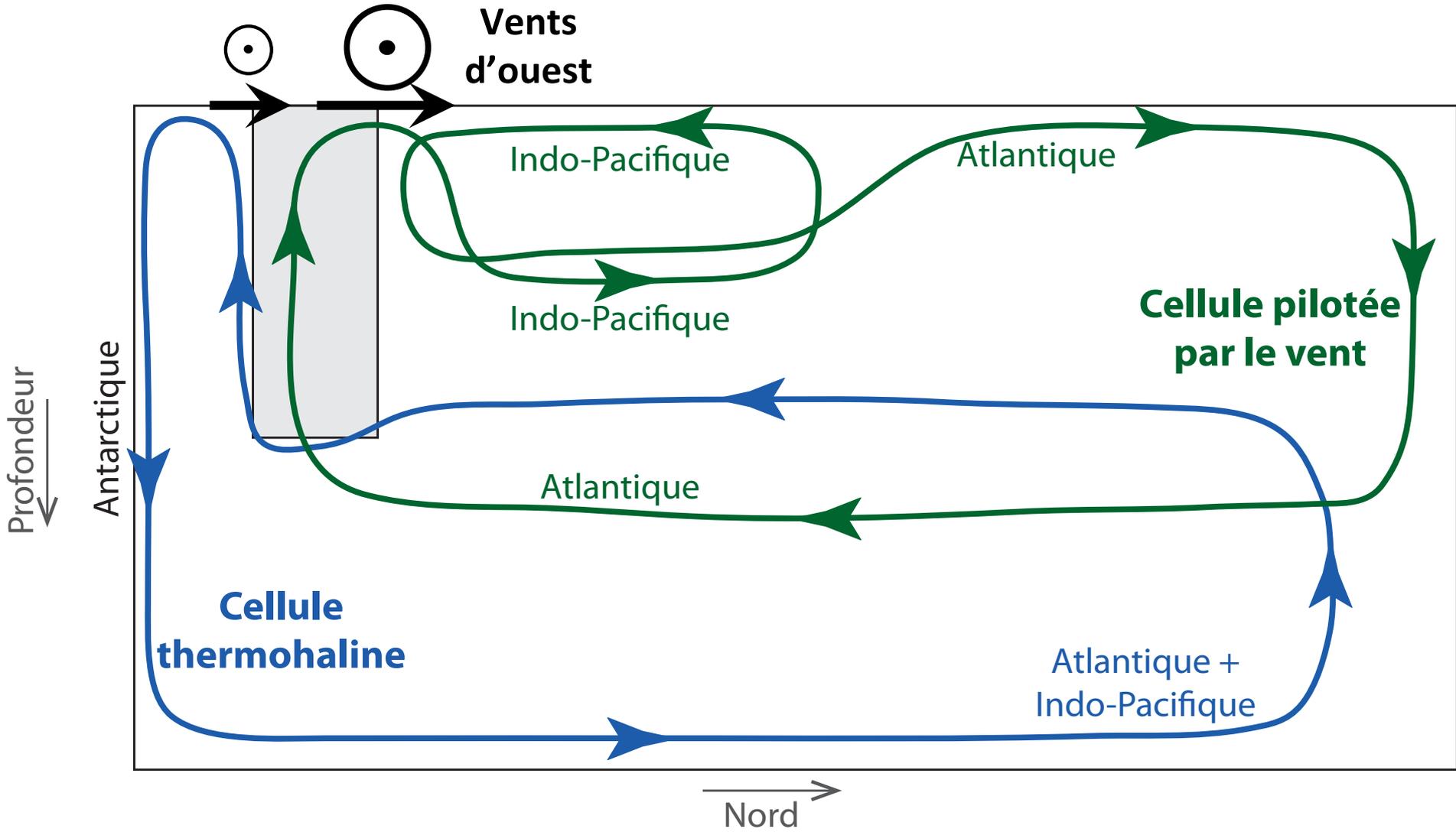
Fig. 1: The great ocean conveyor logo (Broecker, 1987). (Illustration by Joe Le Monnier, Natural History Magazine.)

Toggweiler et Samuels (1993)

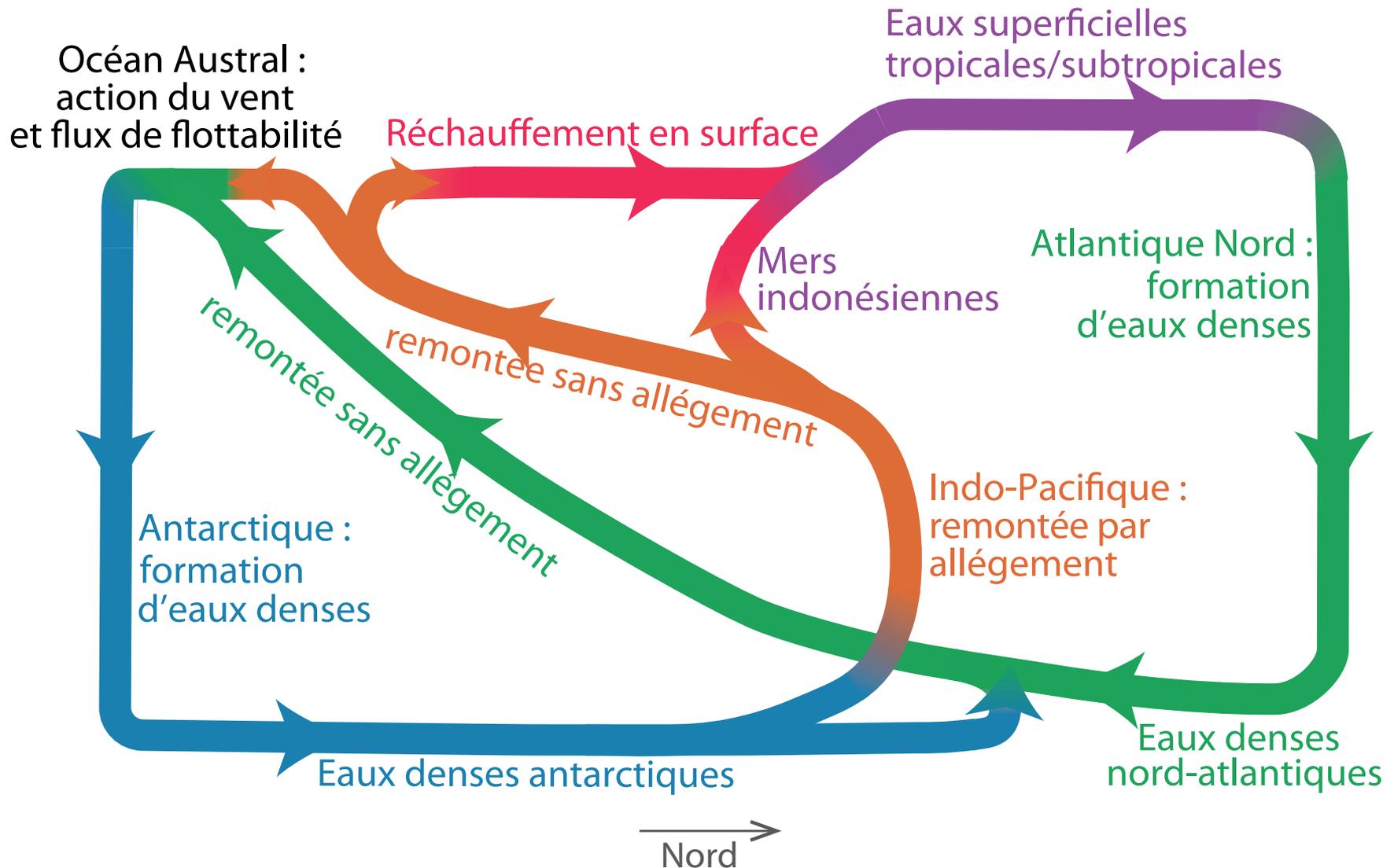
- Deux cellules.
- Rôle pivot de l'océan austral.



Dans le canal ré-entrant : $\oint v dx = -\frac{1}{\rho f} \oint \partial_x p dx = 0$

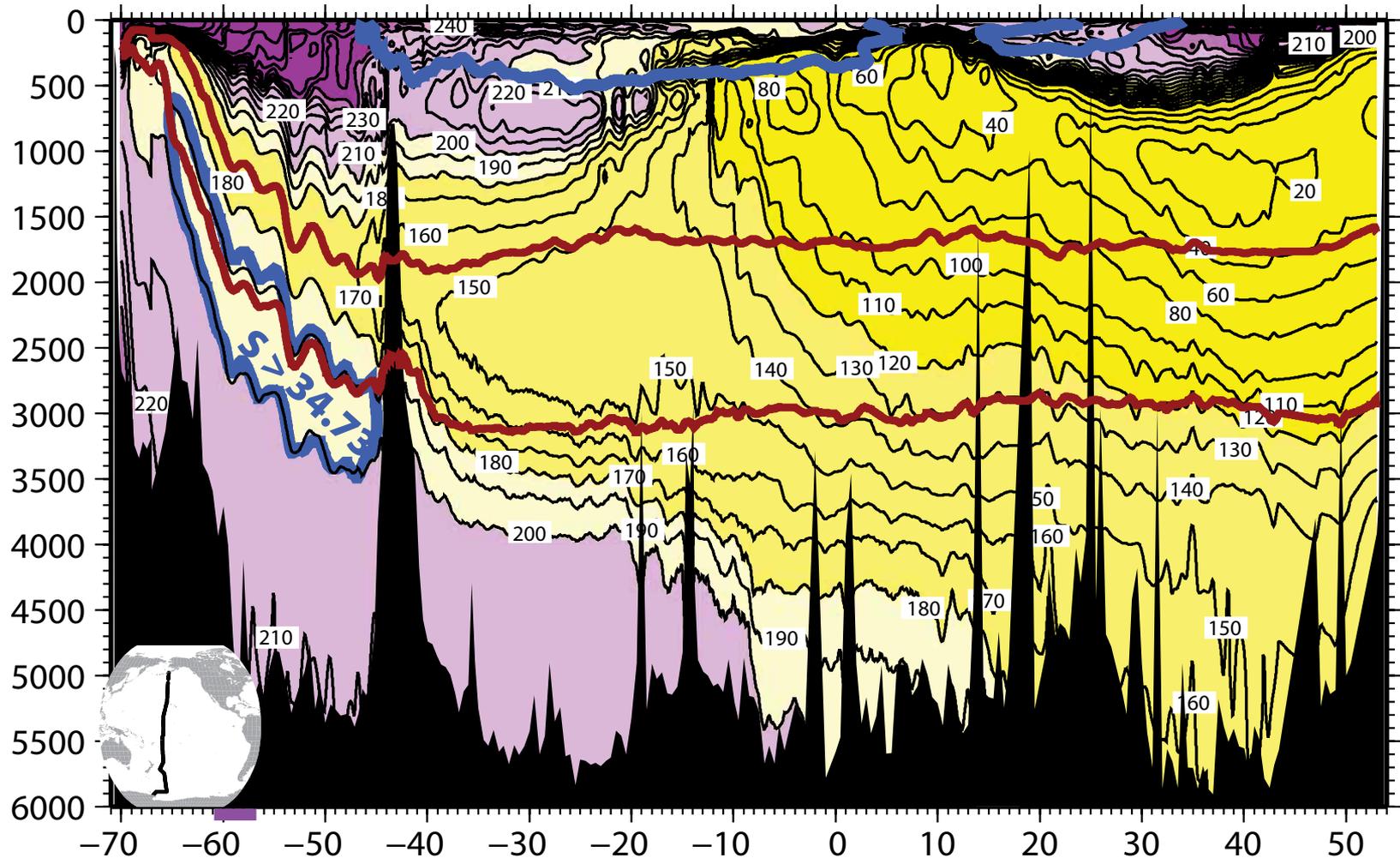


- Deux cellules imbriquées : circulation en huit.

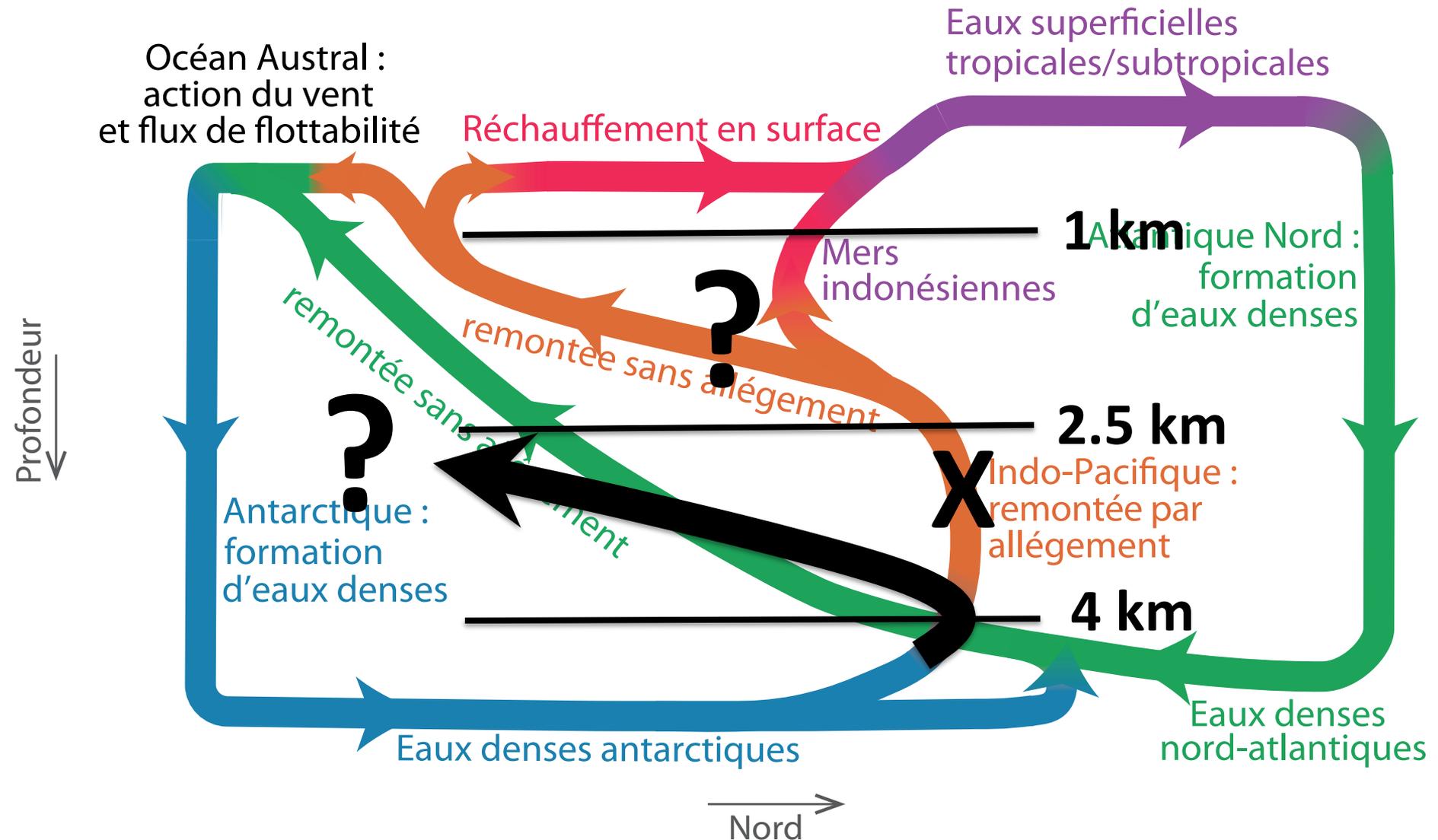


- Deux cellules imbriquées : circulation en huit.

(c) Oxygen ($\mu\text{mol kg}^{-1}$): Pacific Ocean at 165°–170°W



- Deux cellules imbriquées : circulation en huit.



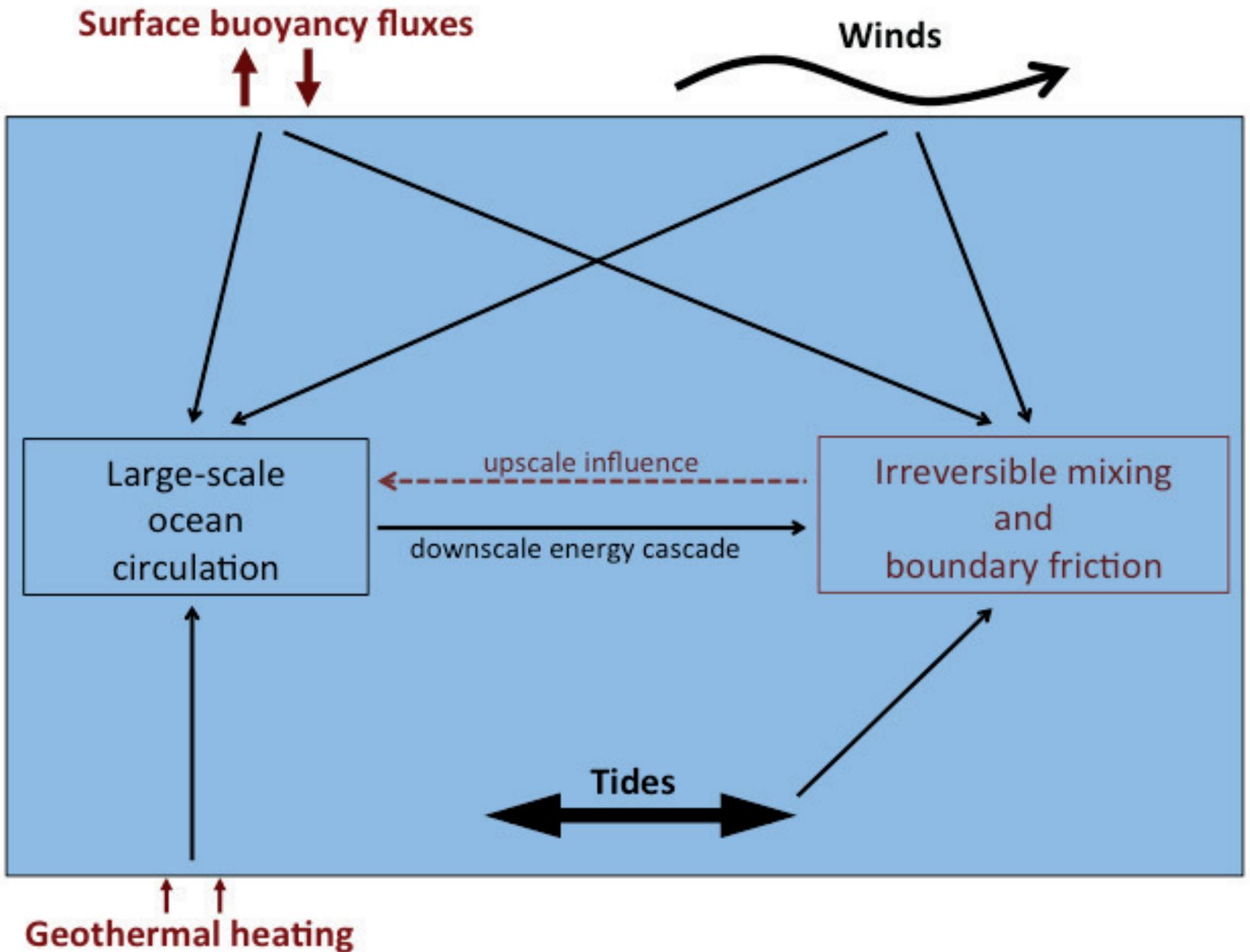
I. Découverte de la circulation thermohaline

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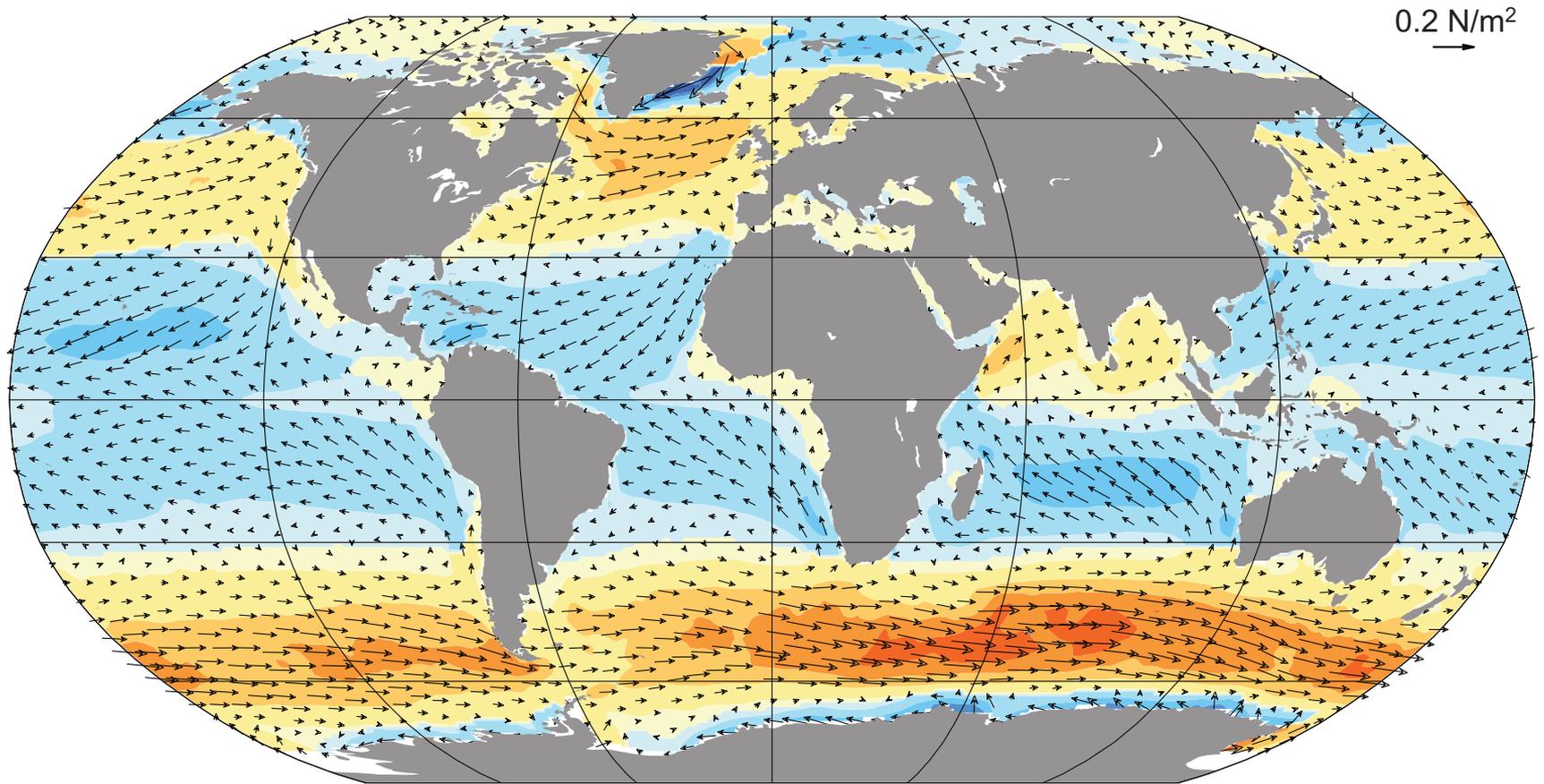
III. Une strate exclue de la circulation

Les courants océaniques proviennent de...

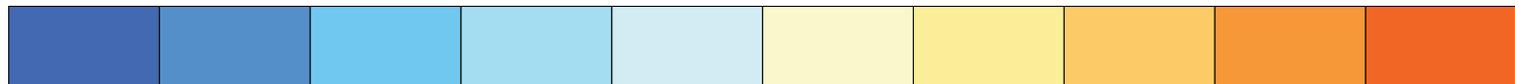
1. L'action du vent sur la surface
2. Les échanges d'eau et de chaleur à la surface
3. Le chauffage géothermal
4. L'attraction gravitationnelle de la Lune et du Soleil



1. L'action du vent sur la surface



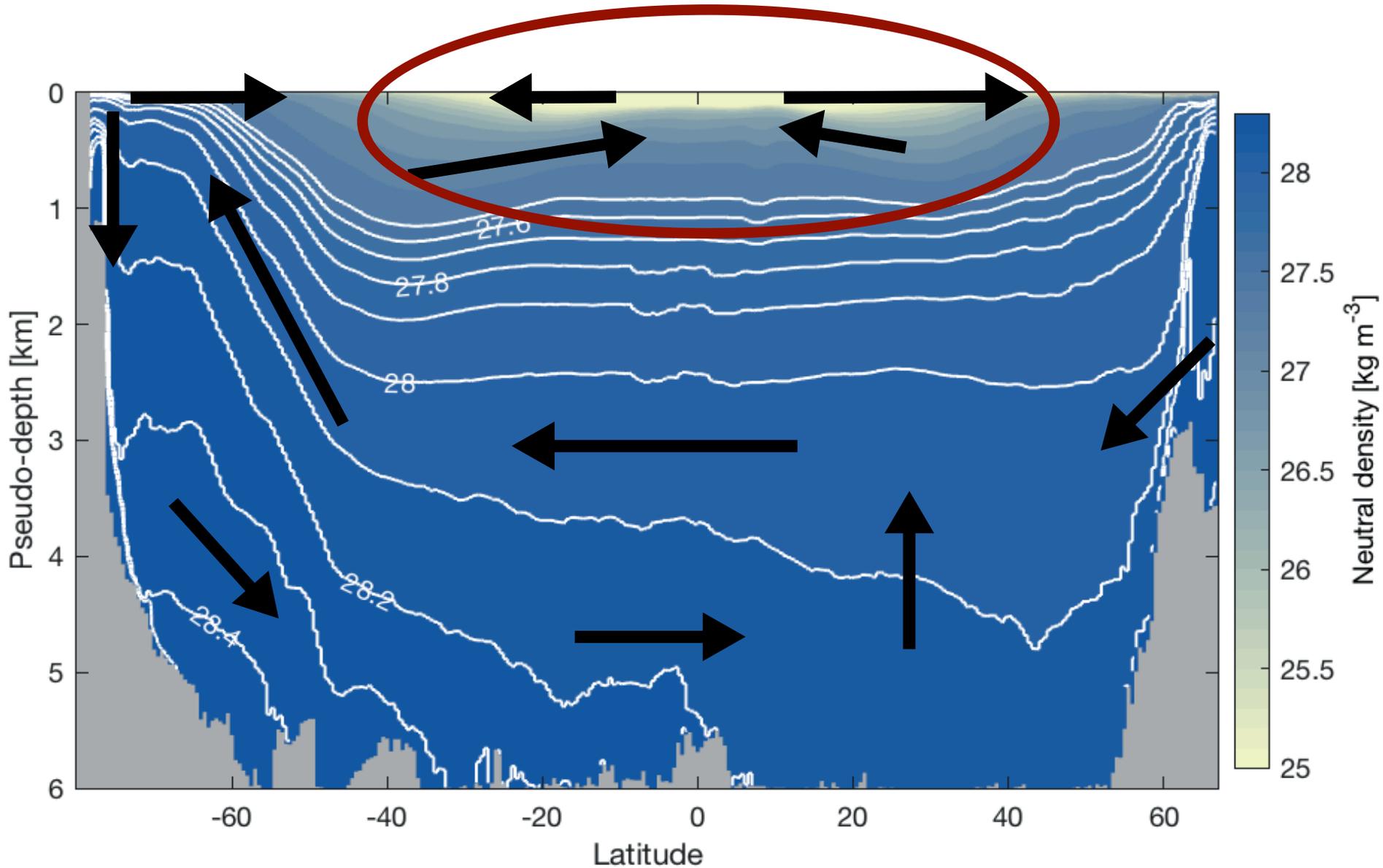
0.2 N/m^2
→



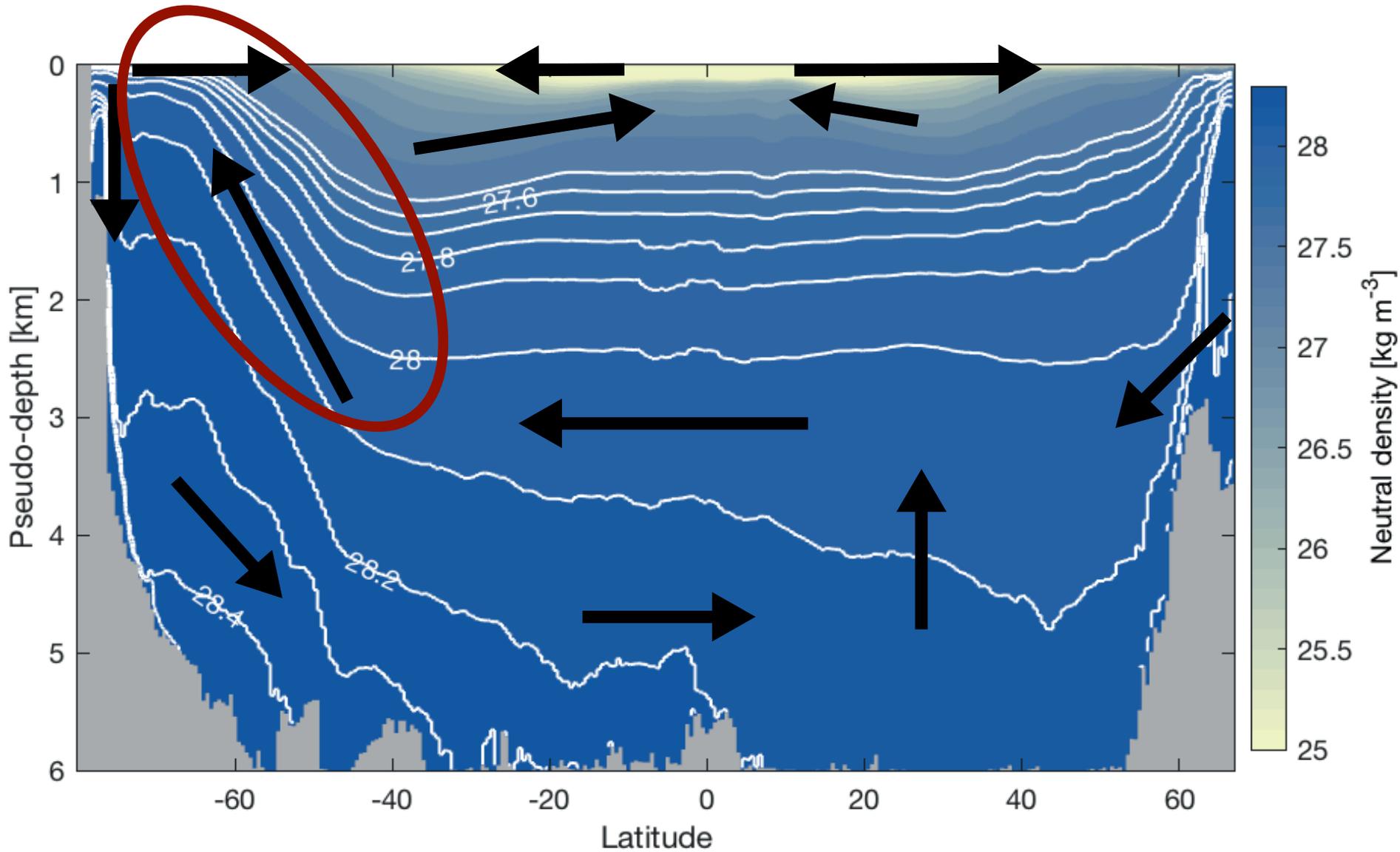
-0.2 -0.15 -0.1 -0.05 0 0.05 0.1 0.15 0.2

Tension de vent (N/m^2)

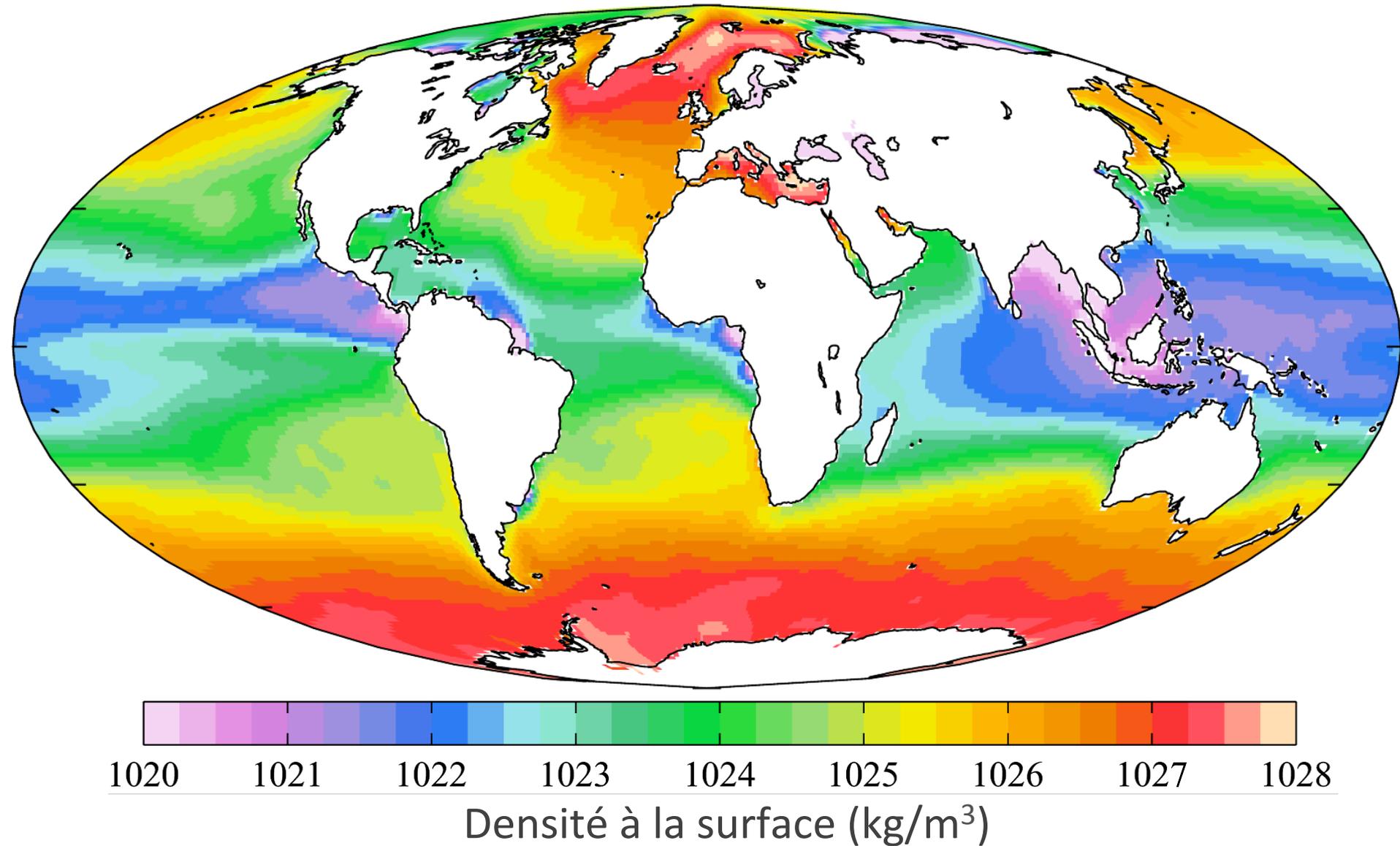
Le moteur essentiel des courants superficiels...



...et de l'ascendance australe

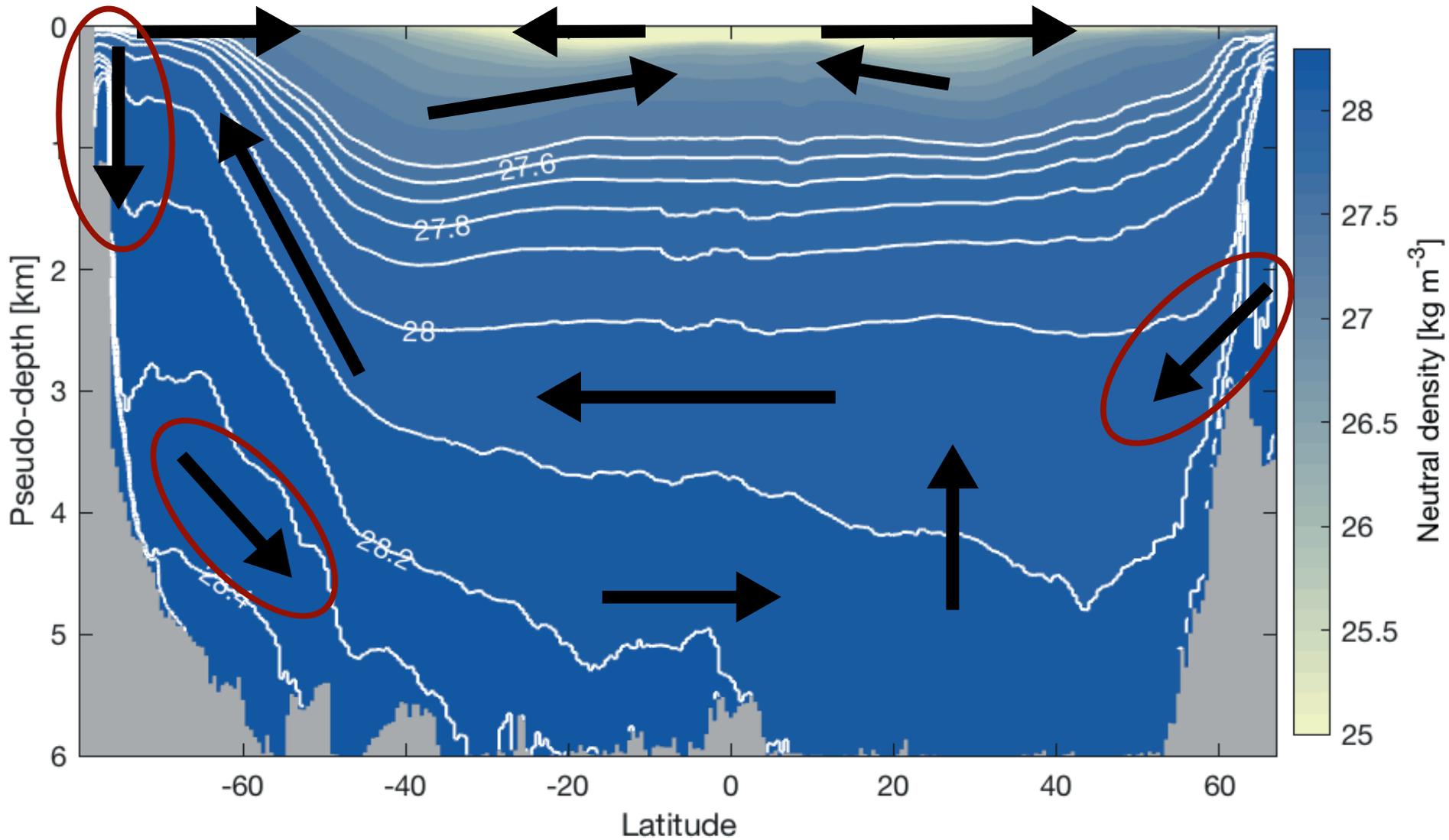


2. Les échanges d'eau et de chaleur à la surface

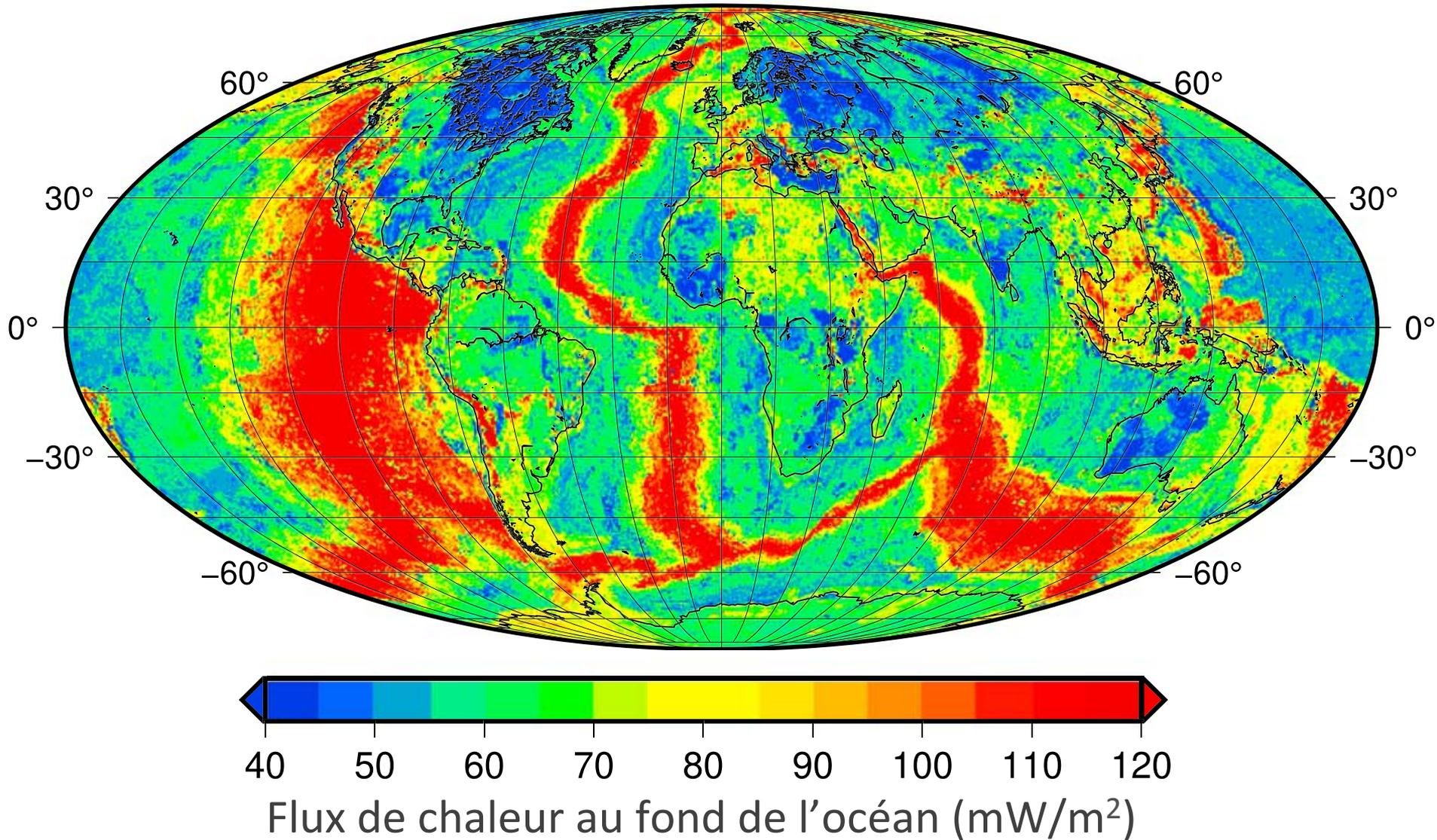


Source : World Ocean Atlas

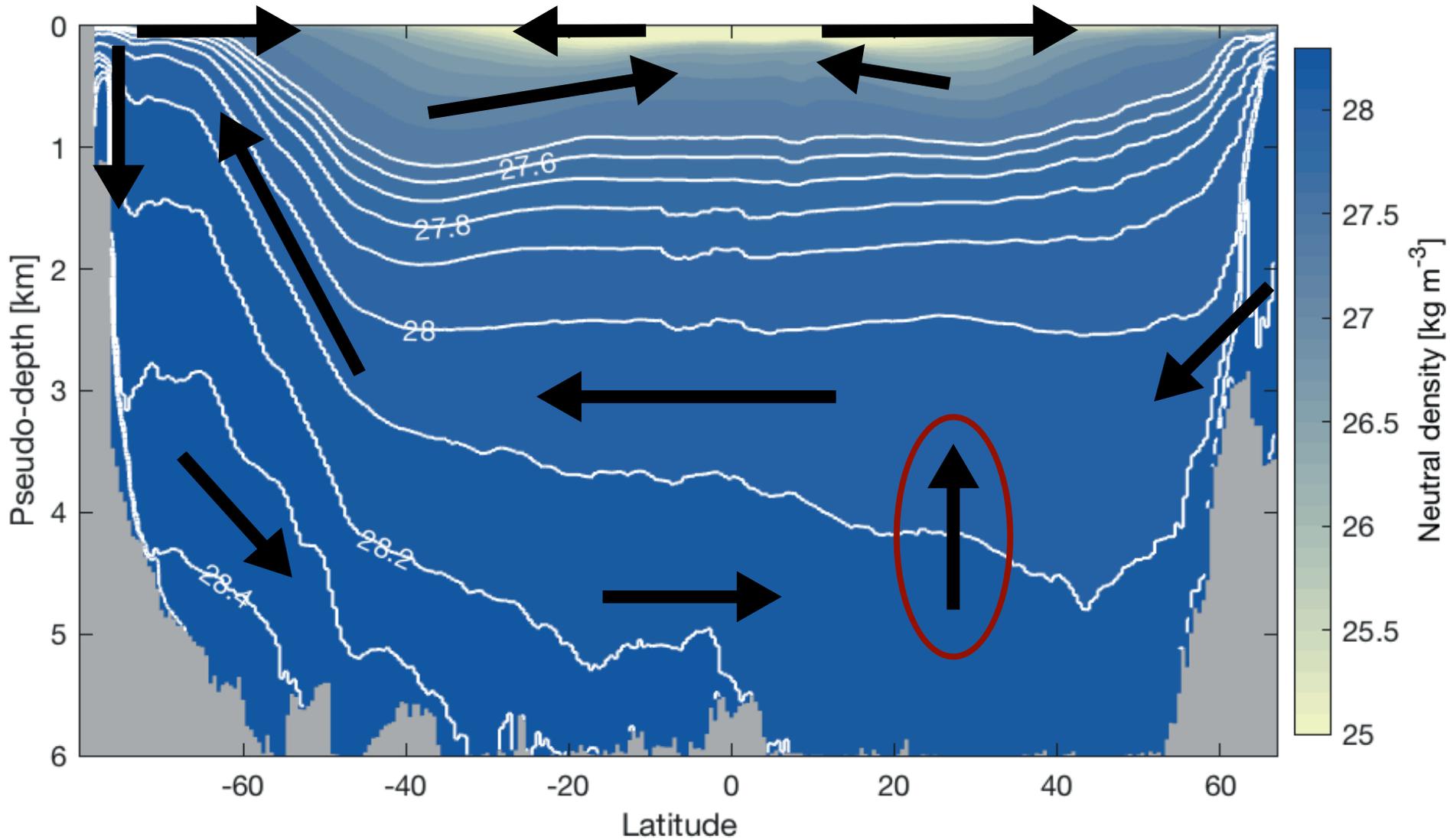
Un moteur des courants descendants



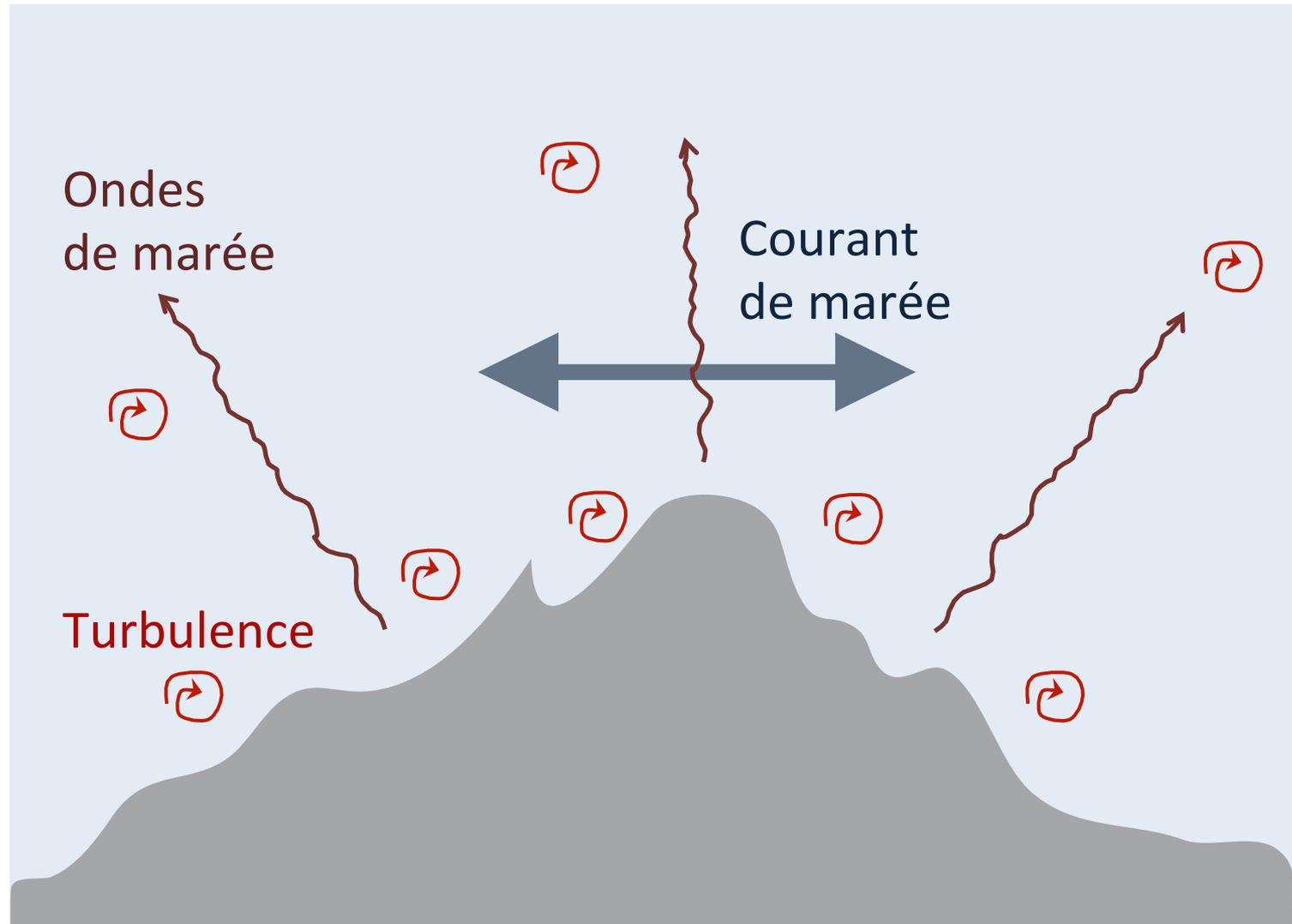
3. Le chauffage géothermal



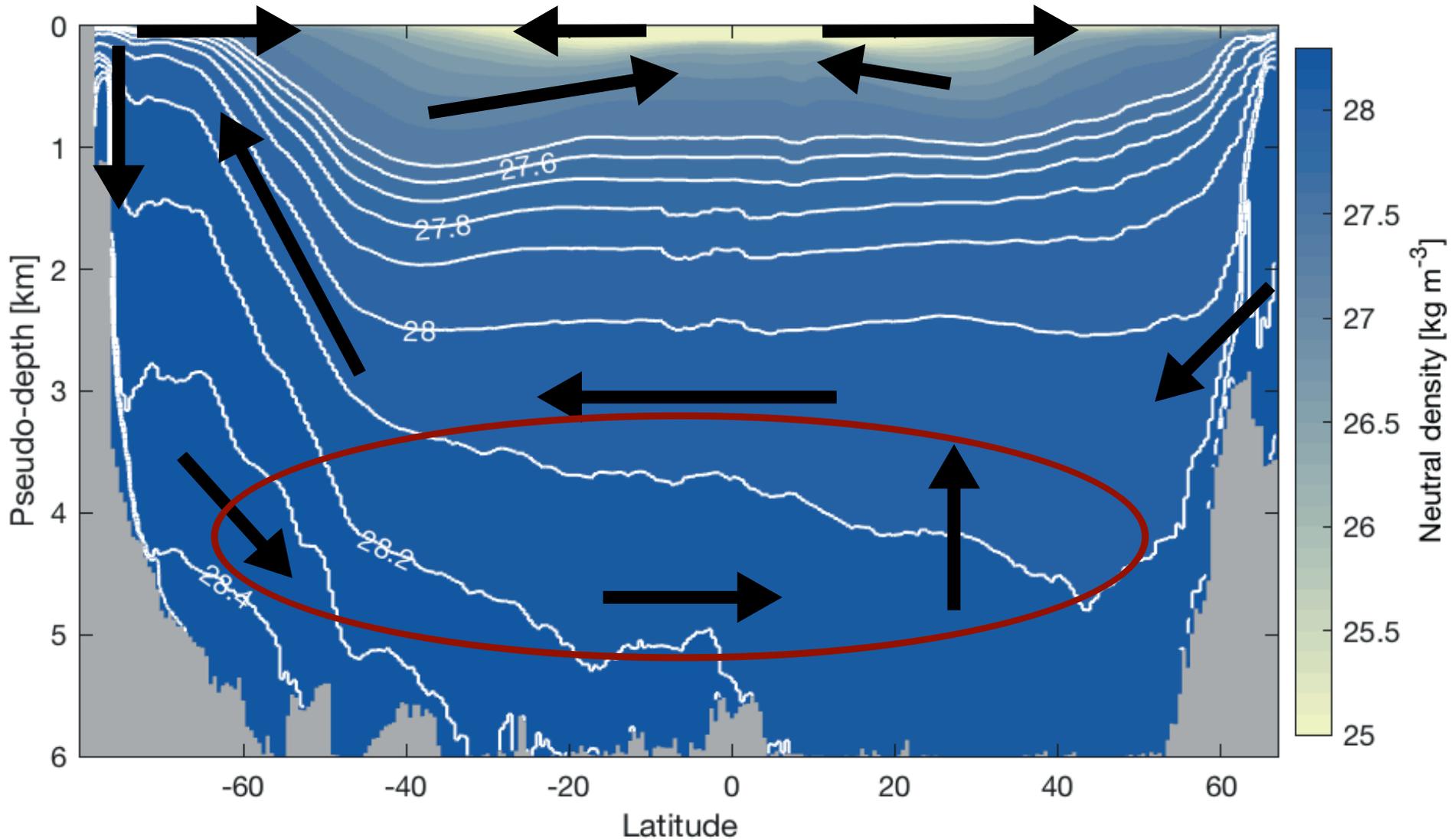
Un moteur de l'allégement abyssal



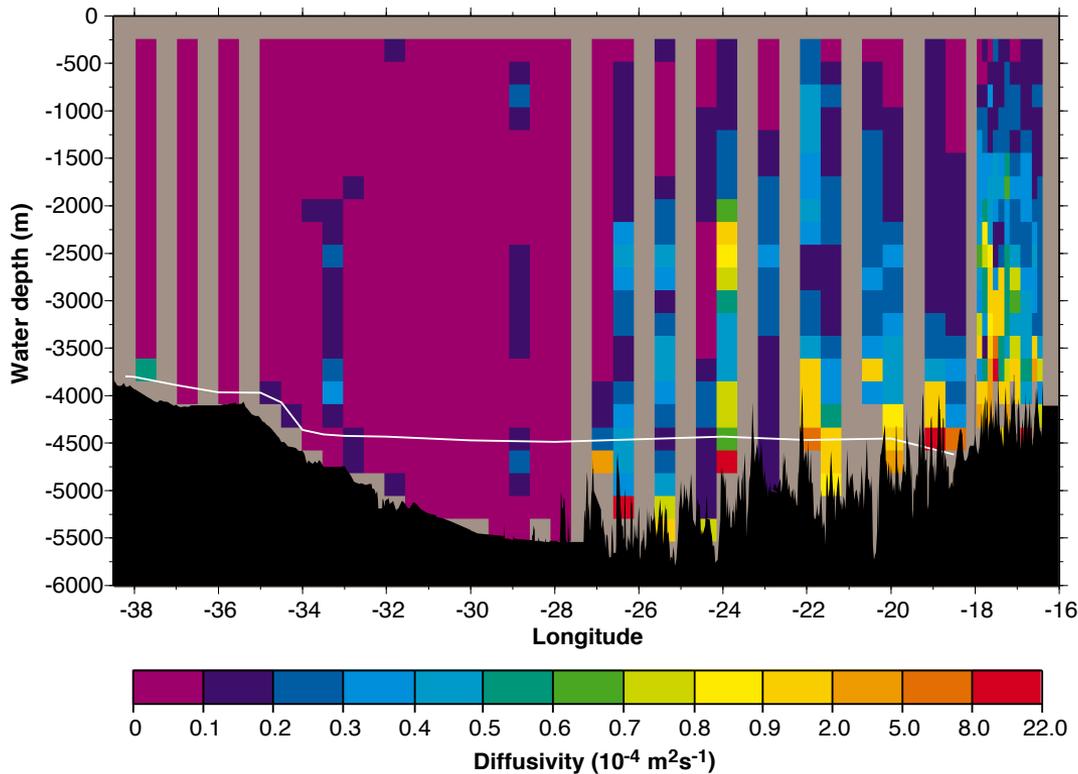
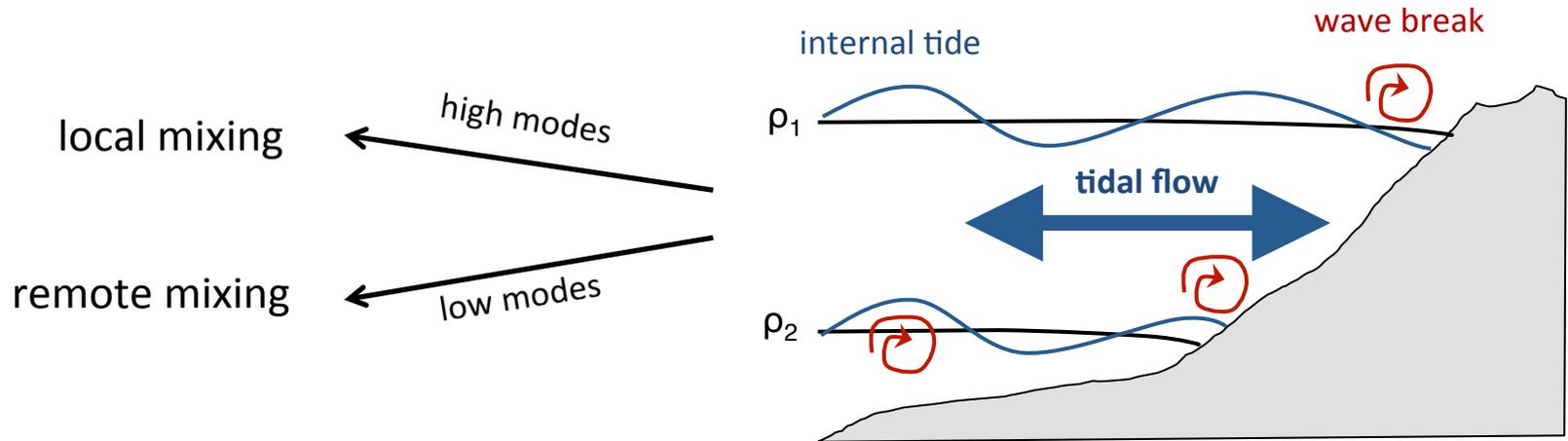
4. L'attraction gravitationnelle de la Lune et du Soleil



Un moteur de l'allégement en profondeur



Le mélange dû à la marée interne

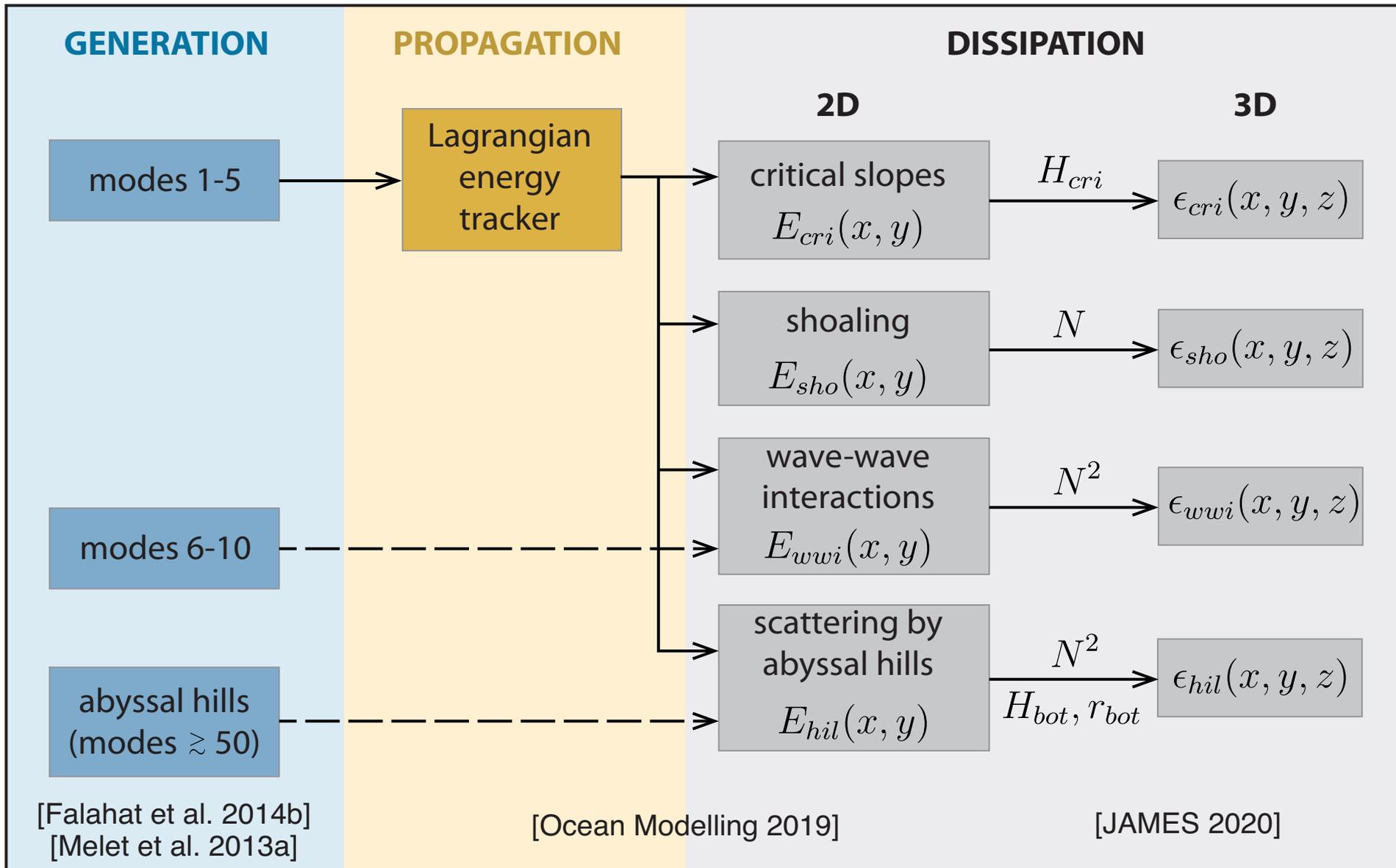


Transect of turbulent diffusivity across the Brazil Basin.

From Polzin et al. (1997).

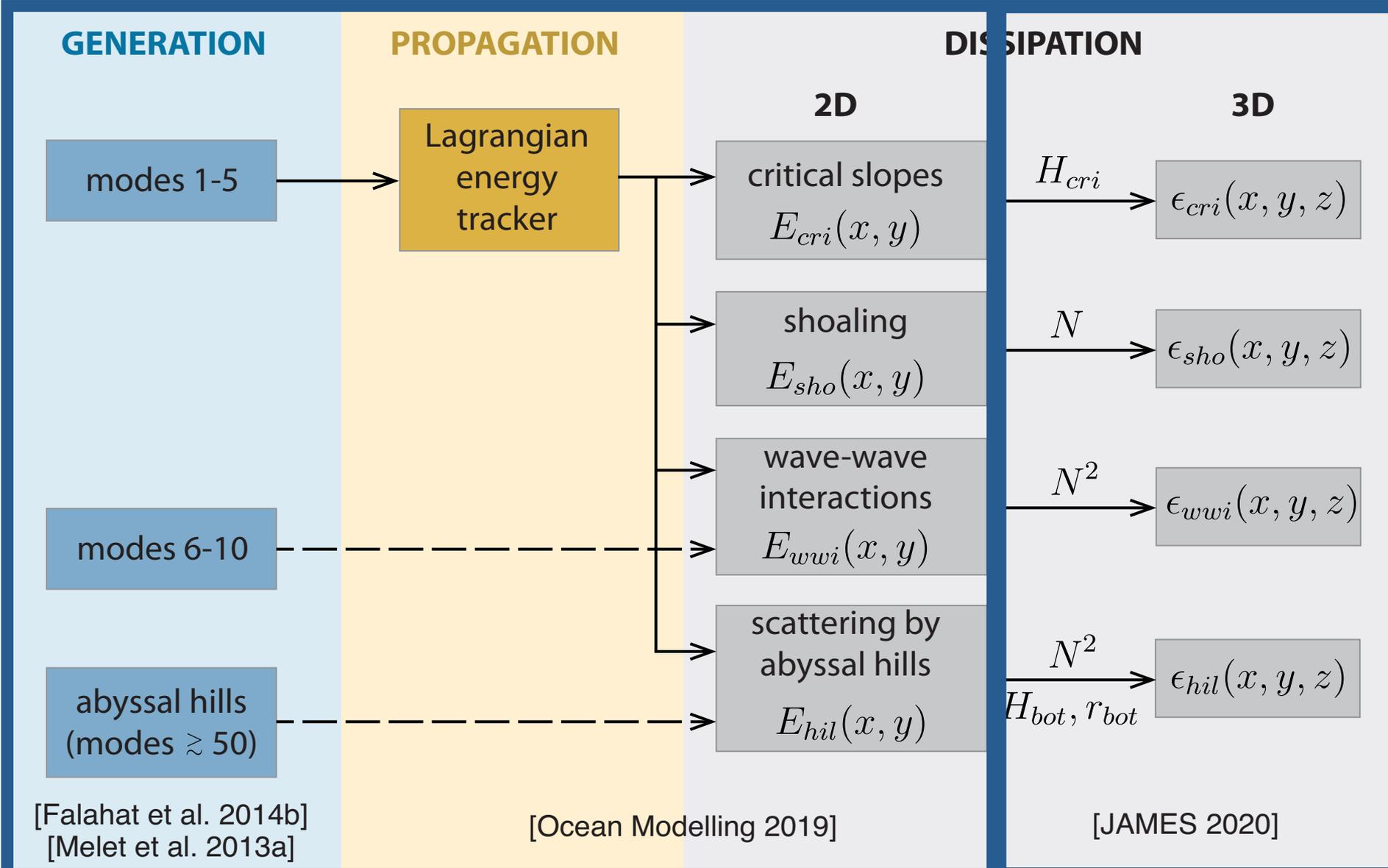
Methodologie d'une cartographie

Mode-by-mode tracking of energy from sources to sinks

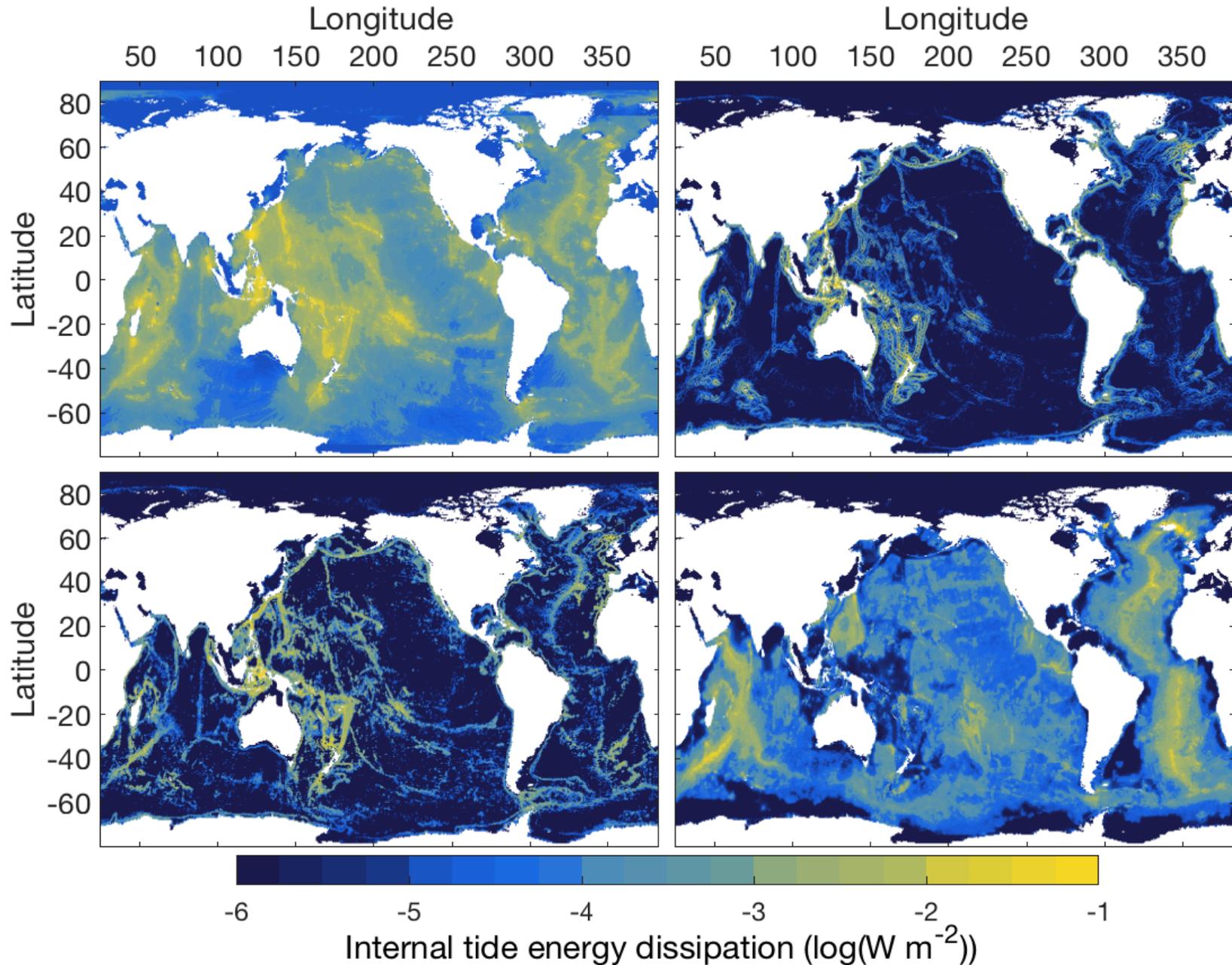


Methodologie d'une cartographie

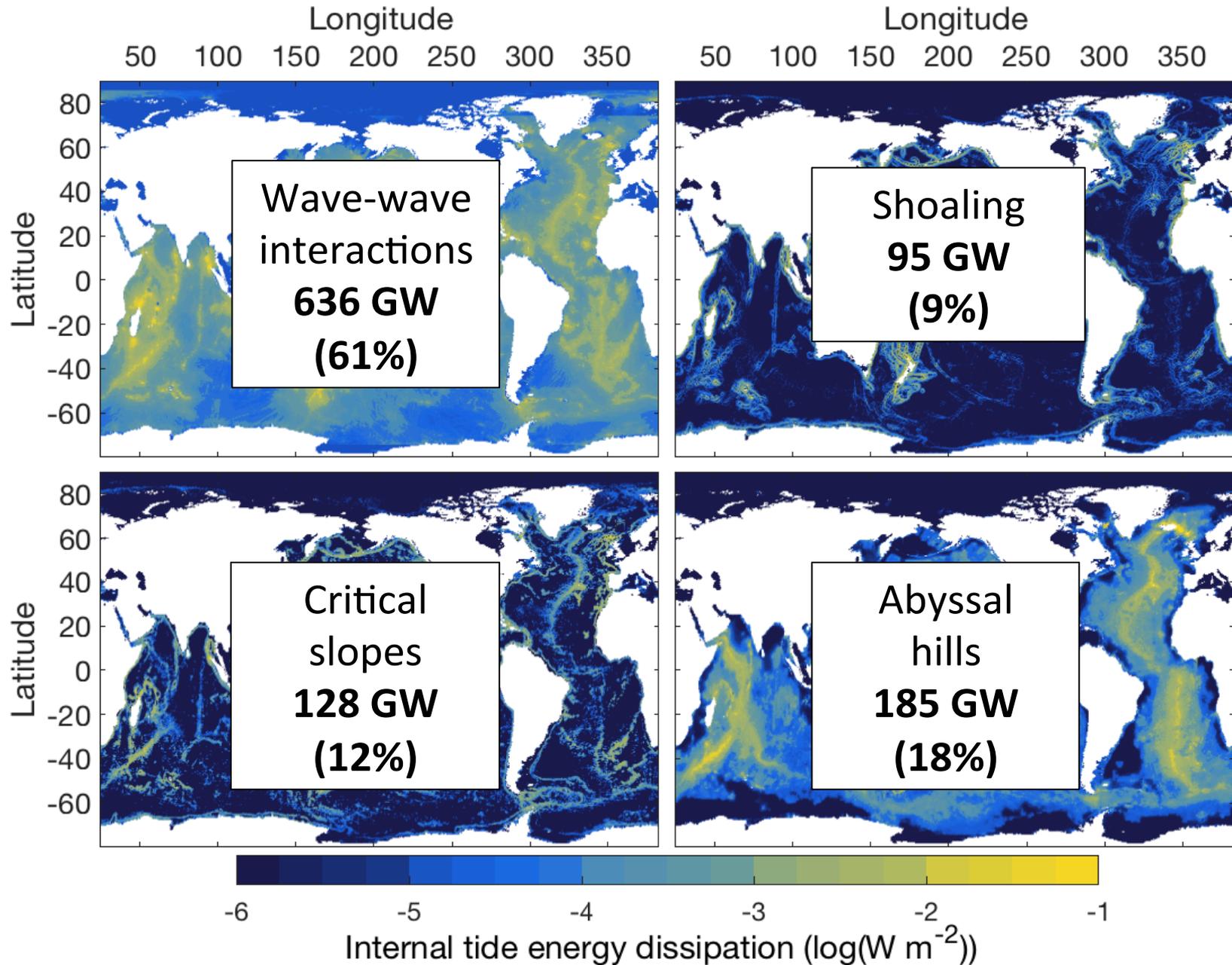
Static 2D maps of depth-integrated dissipation Vertical structures



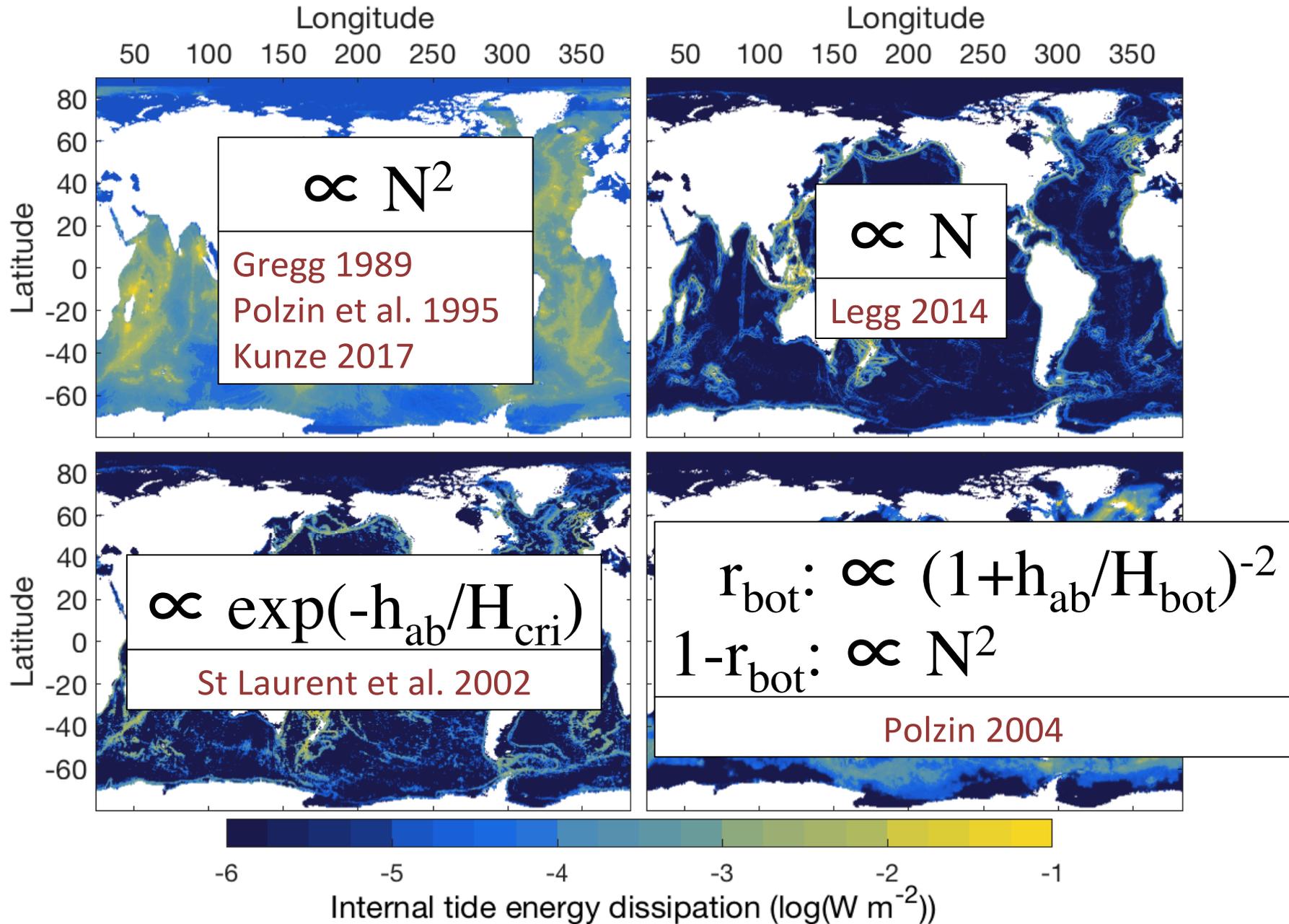
4 cartes statiques...



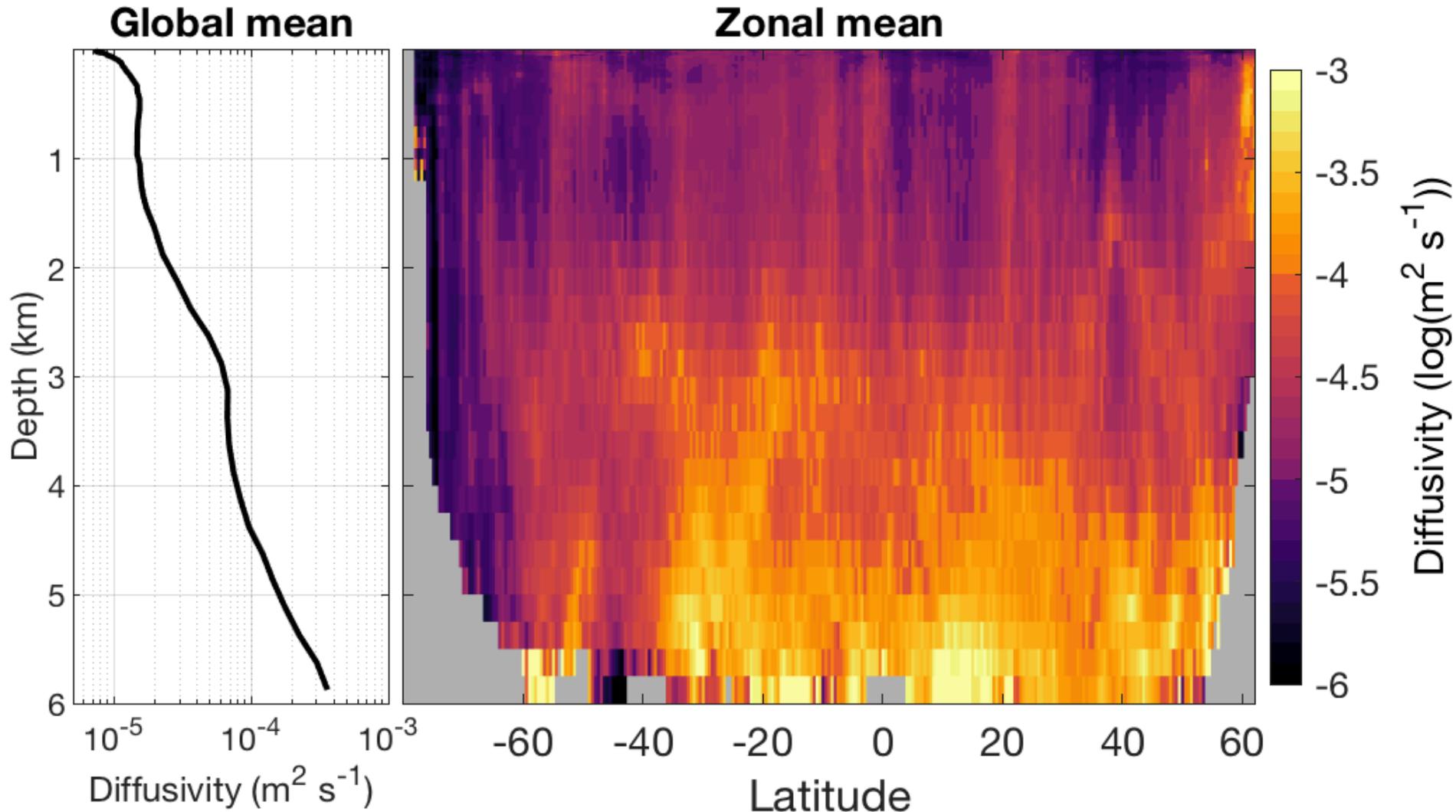
4 cartes statiques...



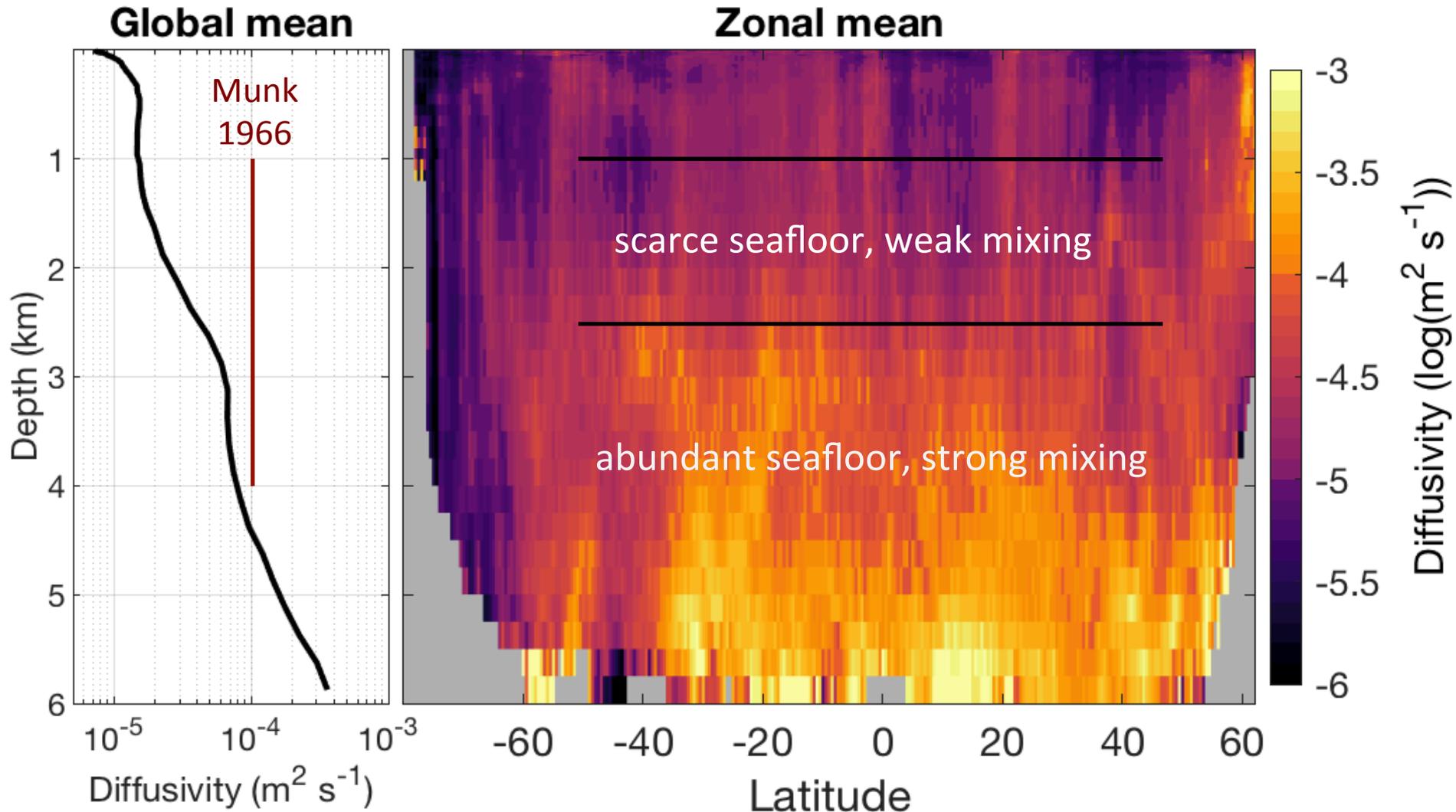
...et 4 structures verticales



Une carte 3D réaliste de la diffusivité

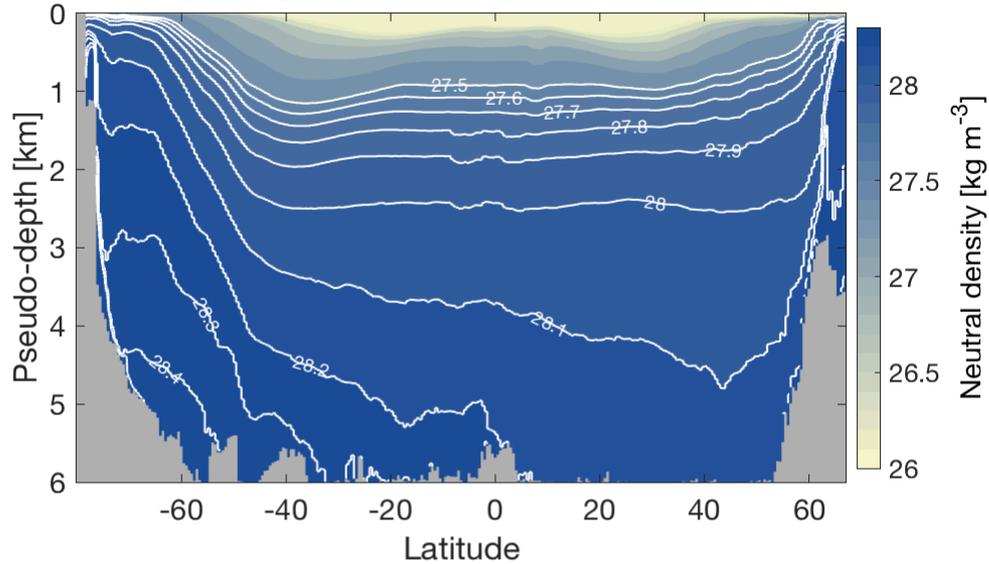


Une carte 3D réaliste de la diffusivité

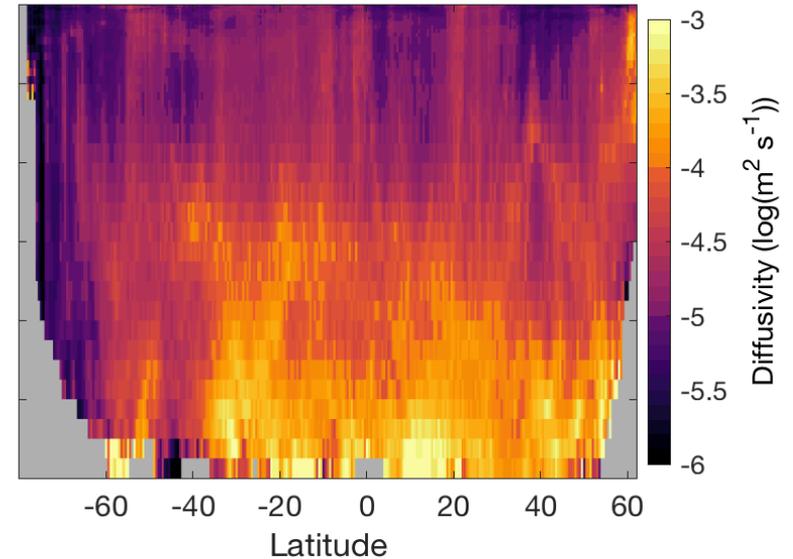


Budget de densité à la Walin (1982)

Gouretski & Koltermann 2004



de Lavergne et al. 2020



Local density balance

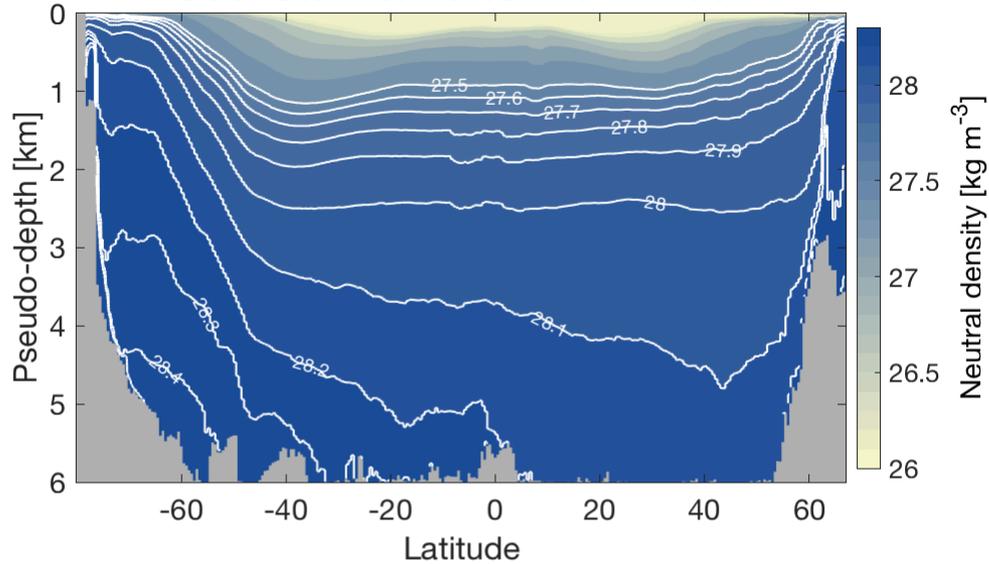
$$\omega \partial_z \gamma = \partial_z (K_{\perp} \partial_z \gamma)$$

\Leftrightarrow

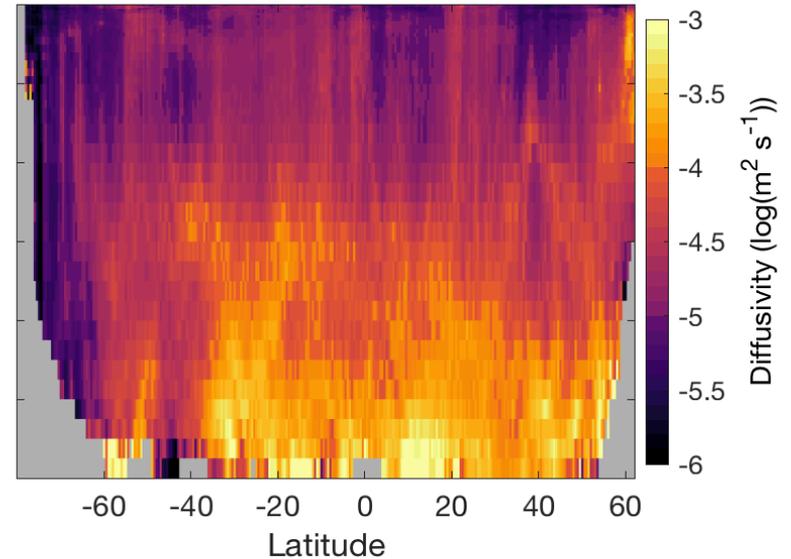
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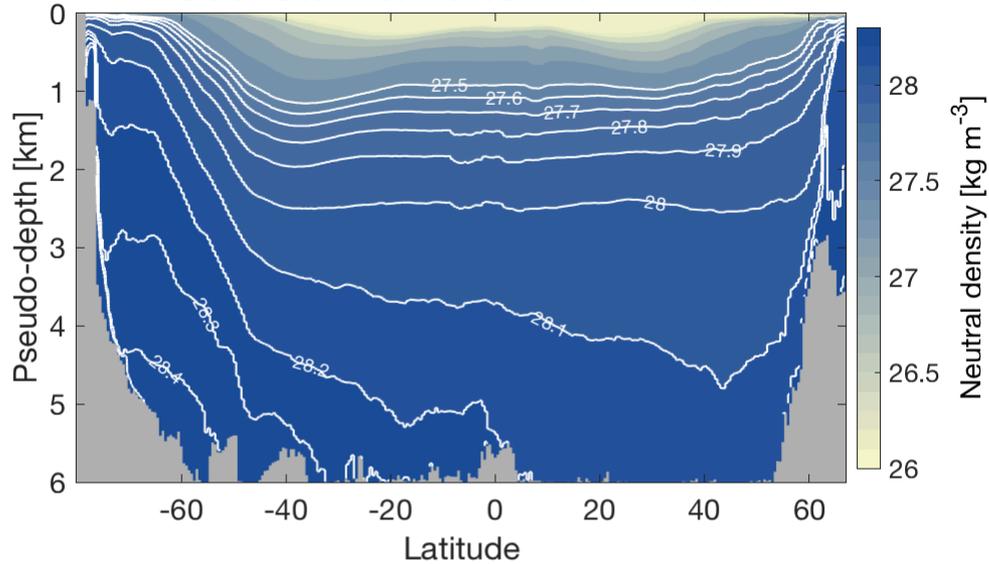
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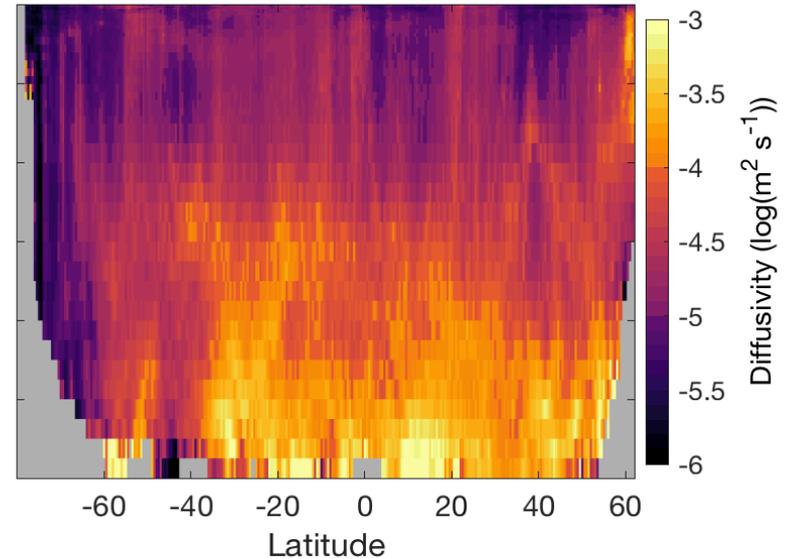
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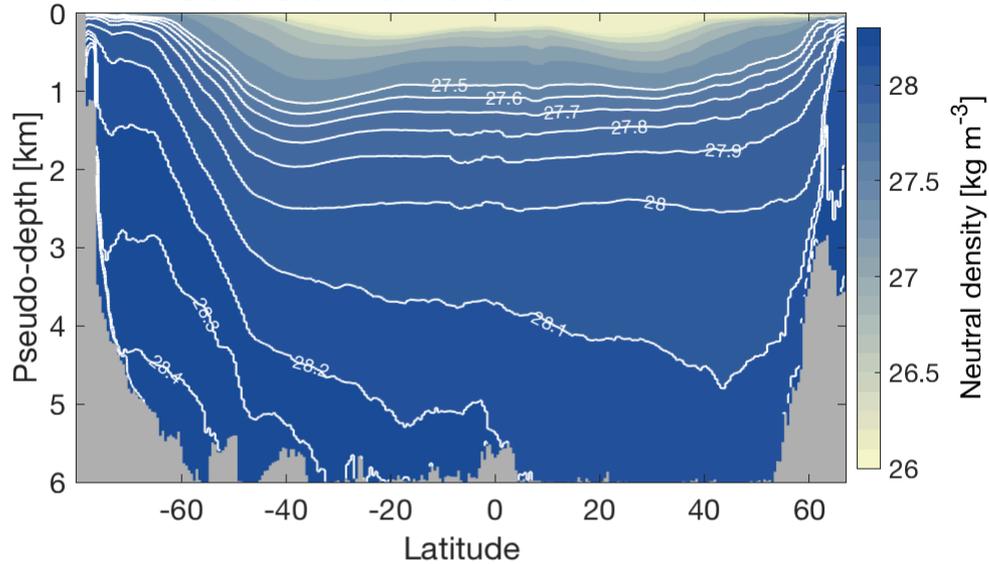
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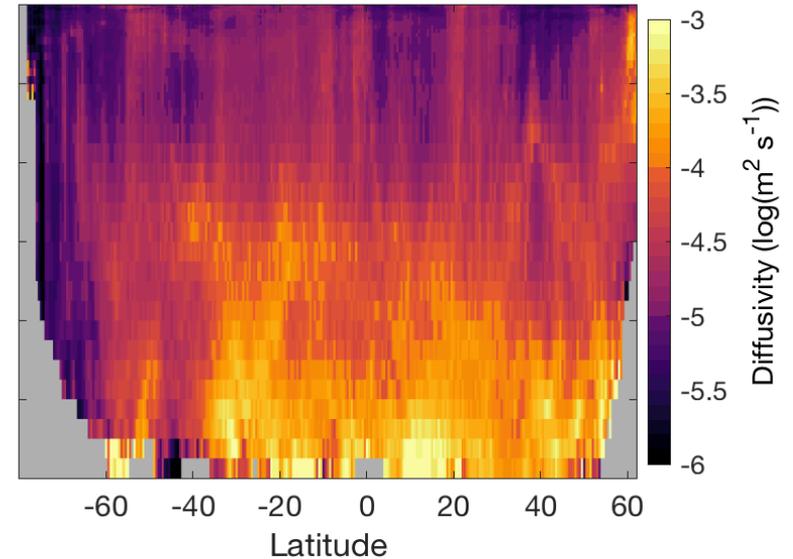
$$\boxed{\omega} = \boxed{\partial_{\gamma} (K_{\perp} \partial_z \gamma)}$$

Budget de densité à la Walin (1982)

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de Lavergne et al. 2020



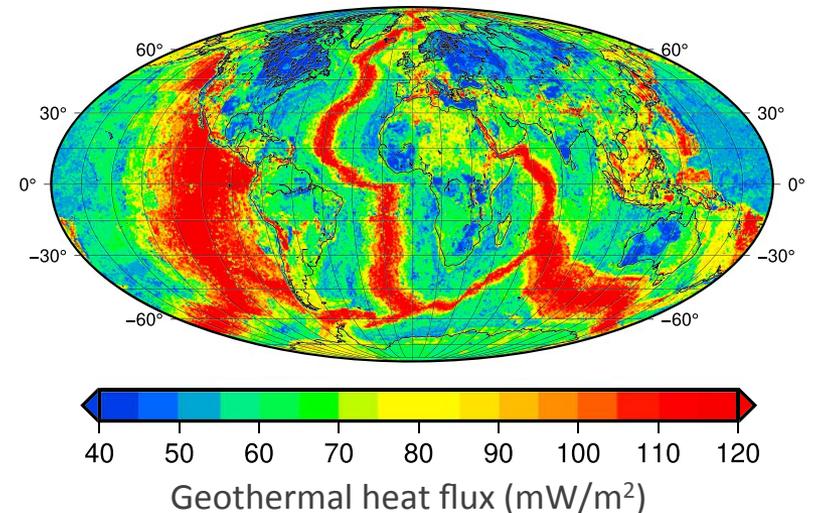
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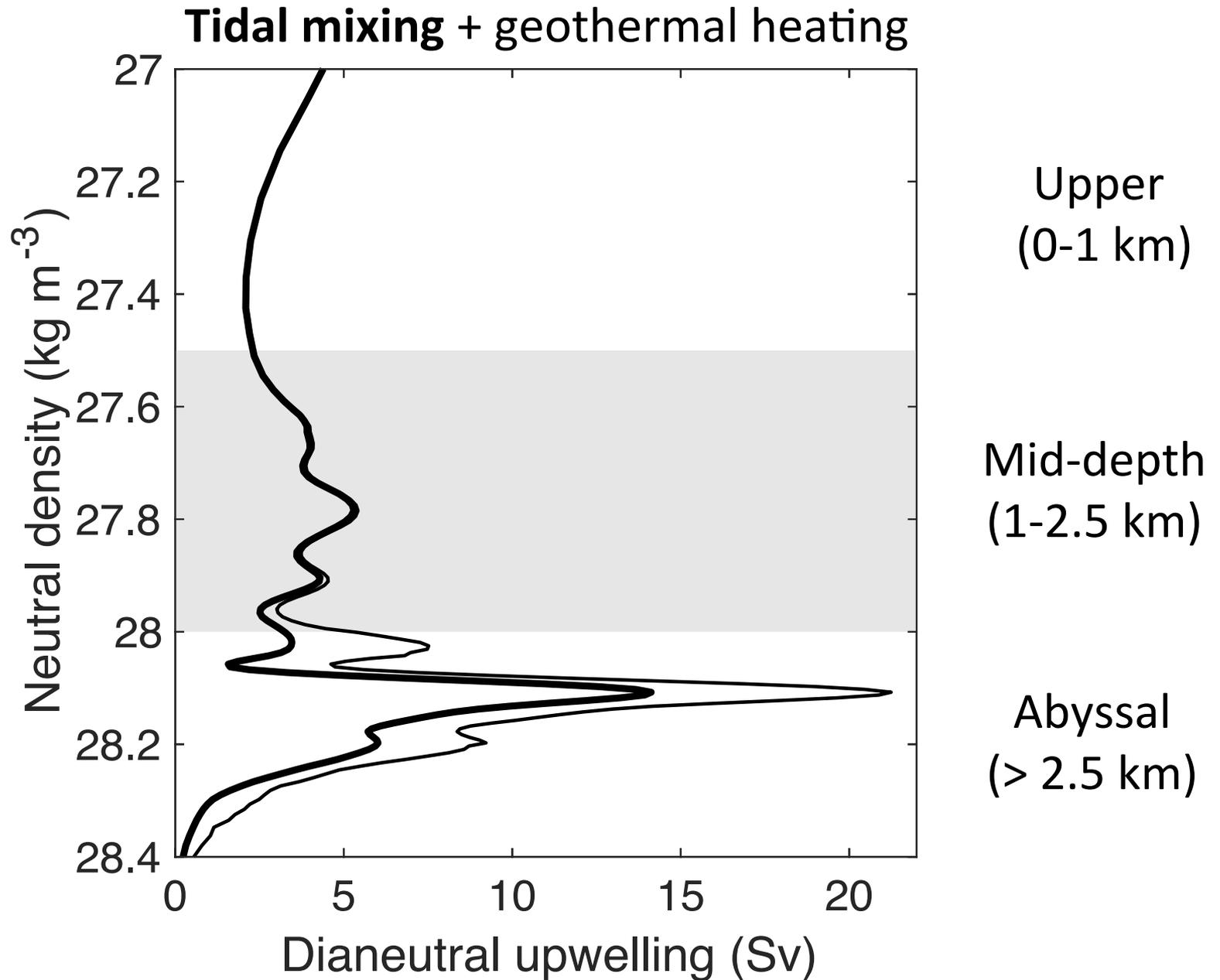
\Leftrightarrow

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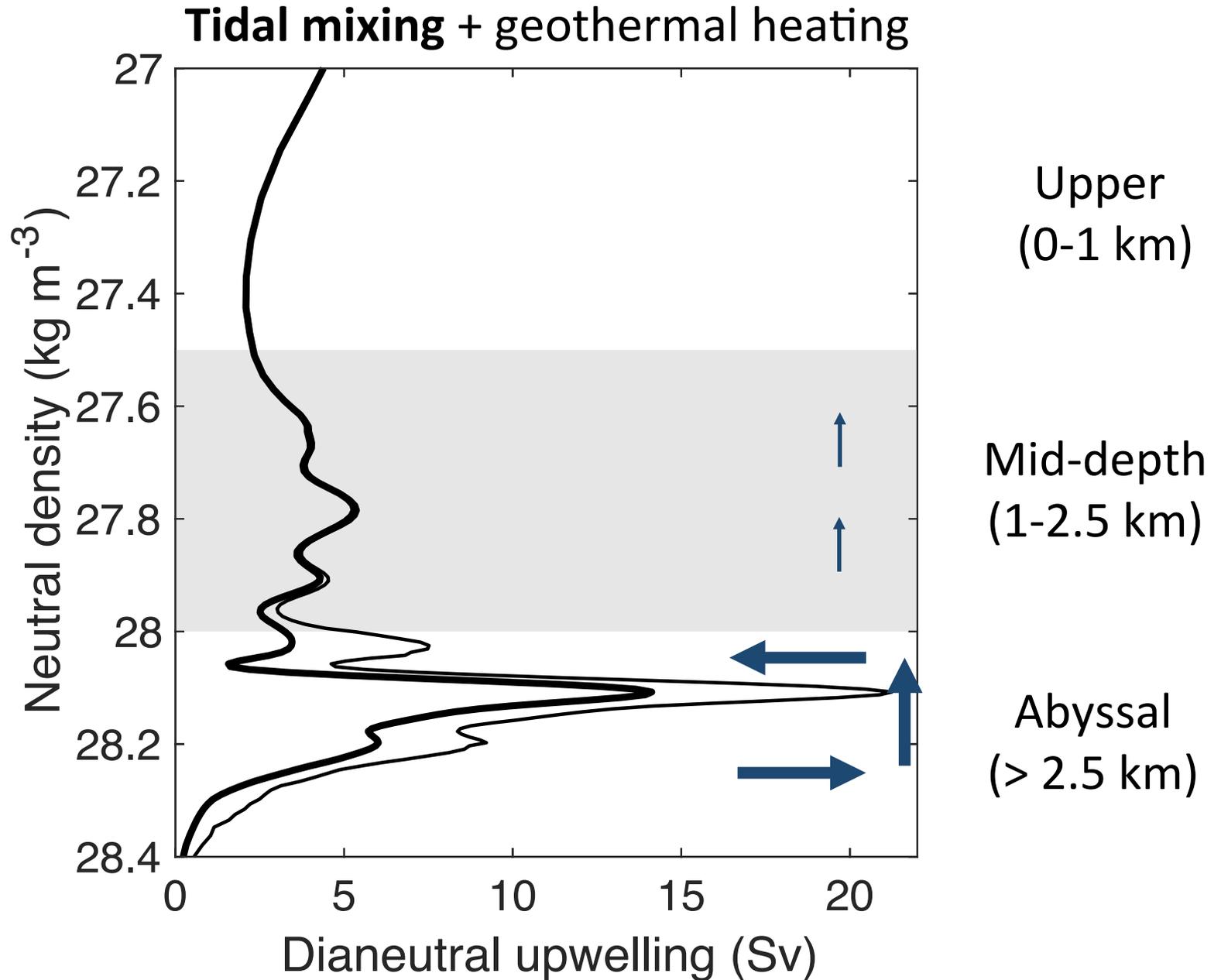
Lucazeau 2019



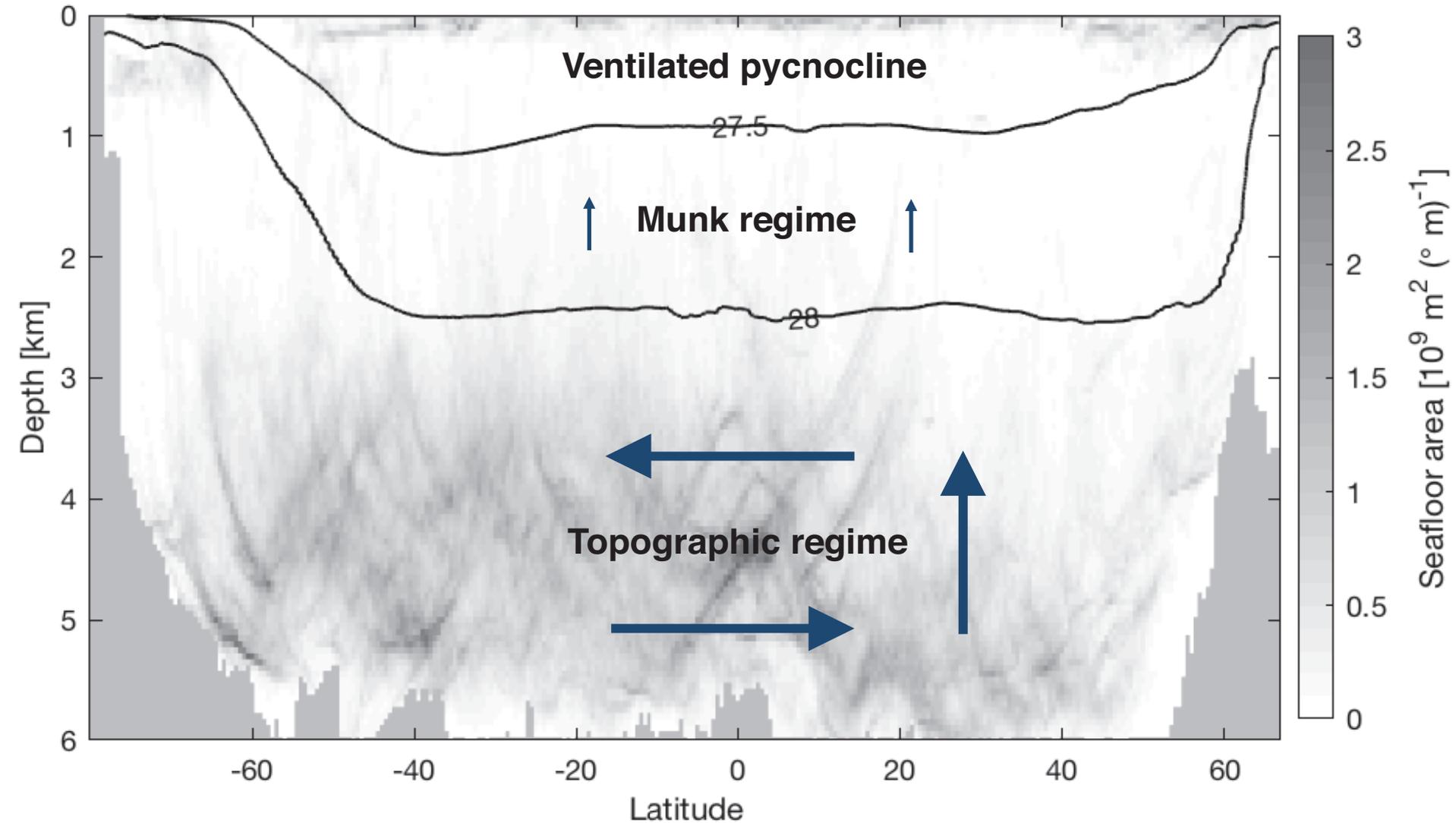
Application à l'océan mondial



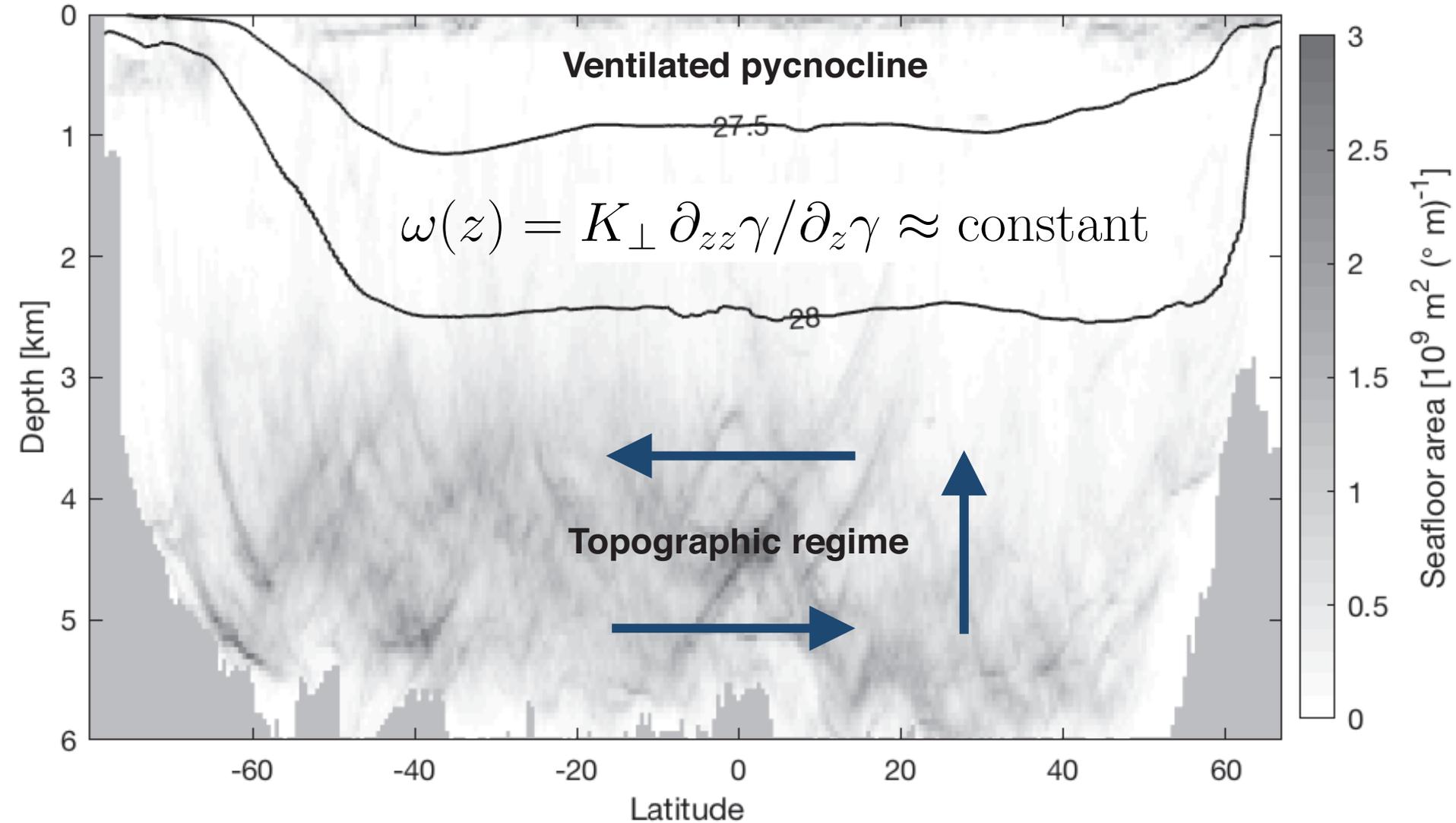
Application à l'océan mondial



Trois régimes océaniques



Trois régimes océaniques

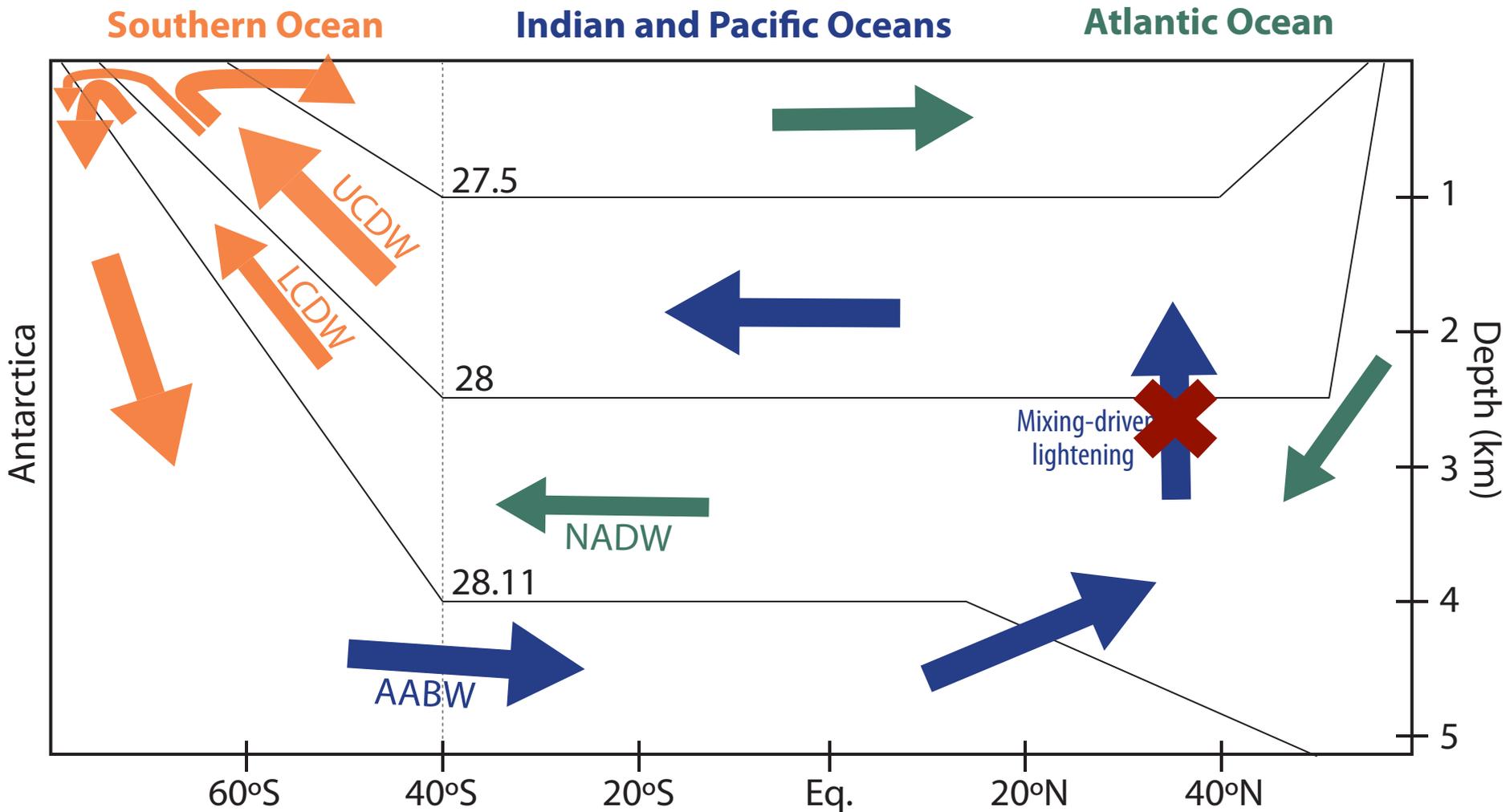


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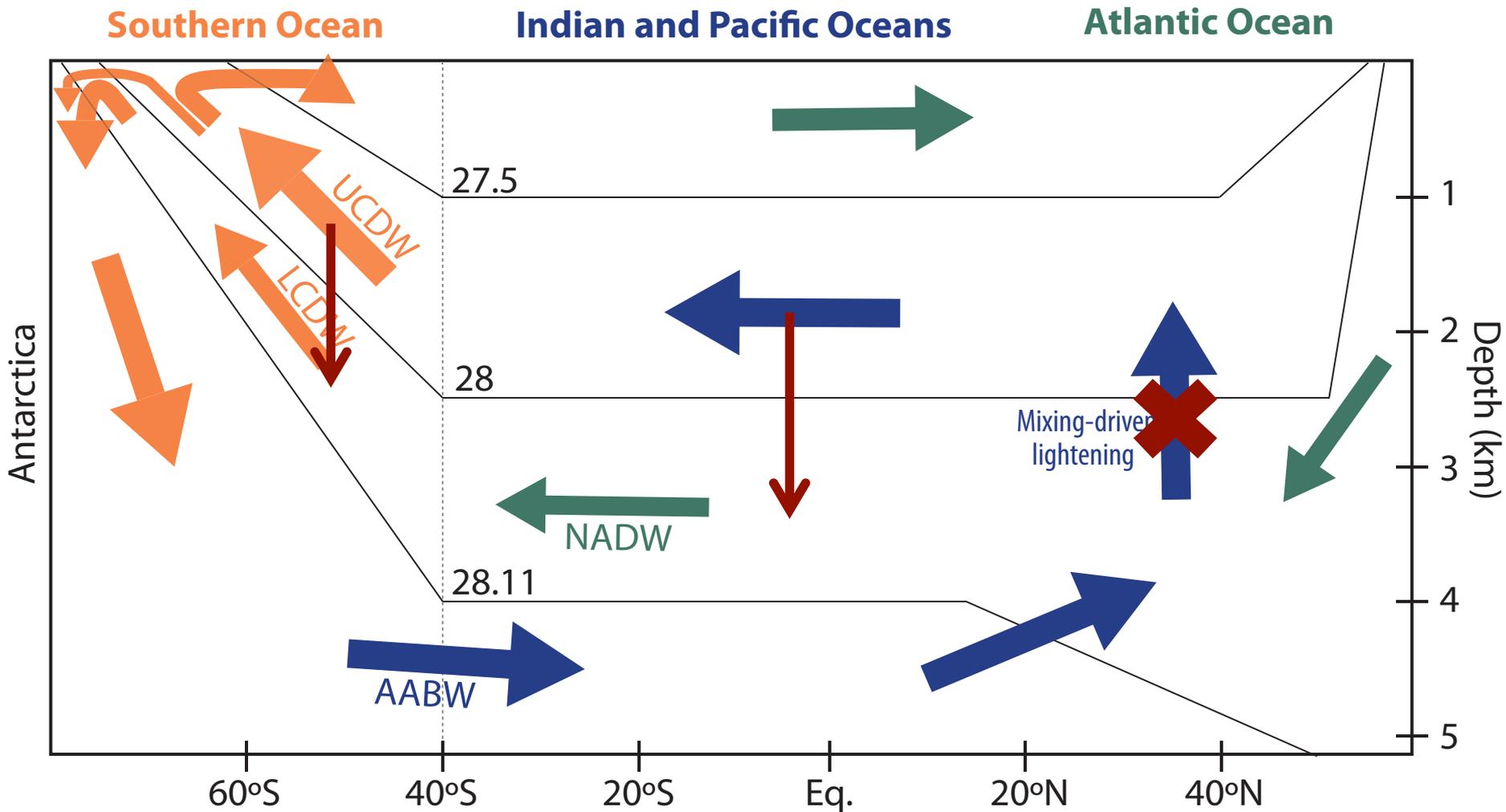
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La circulation thermohaline en 2013



La circulation thermohaline en 2013



La circulation thermohaline en 2022 ?

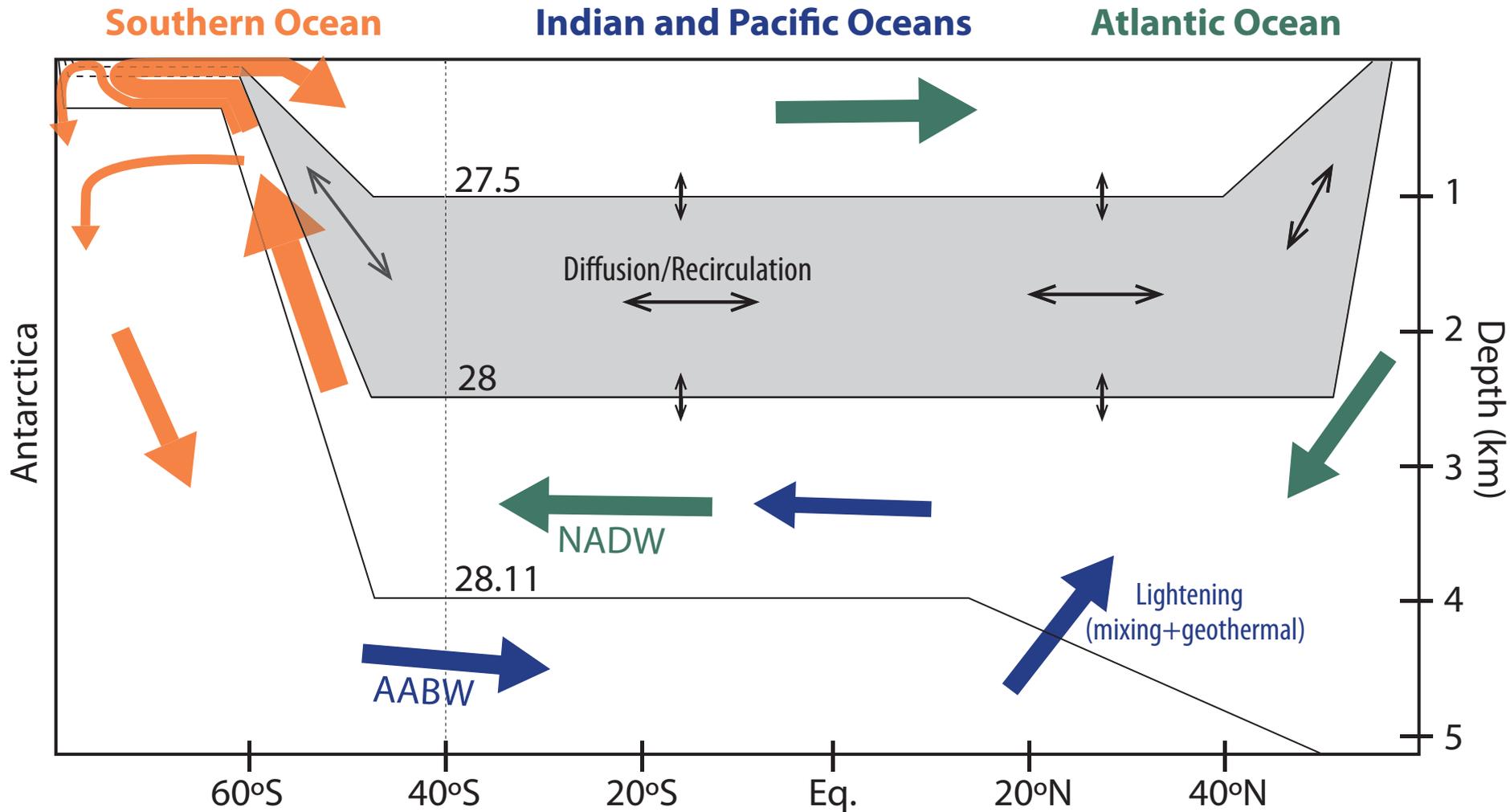


Illustration : une section à travers le Pacifique

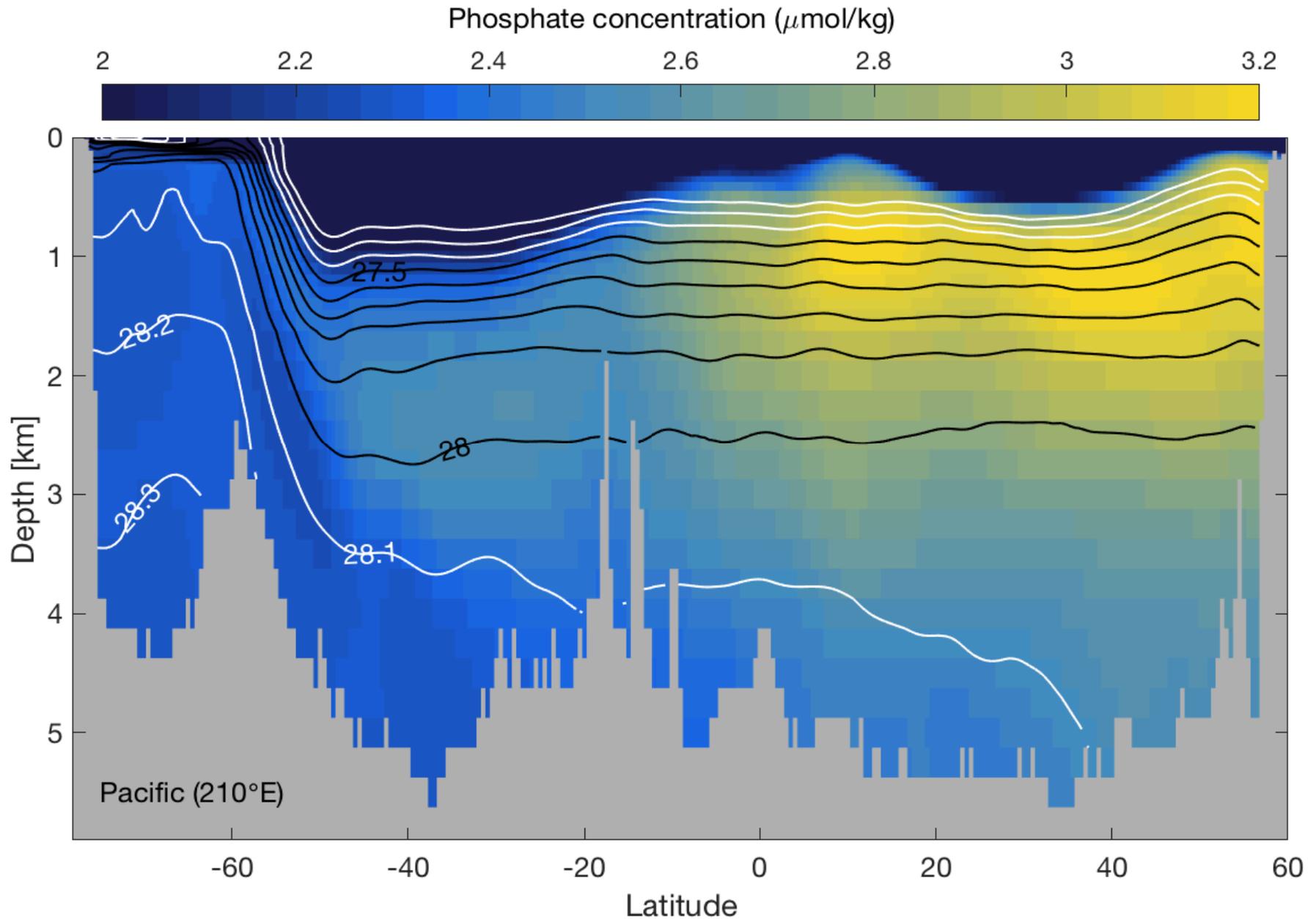


Illustration : une section à travers le Pacifique

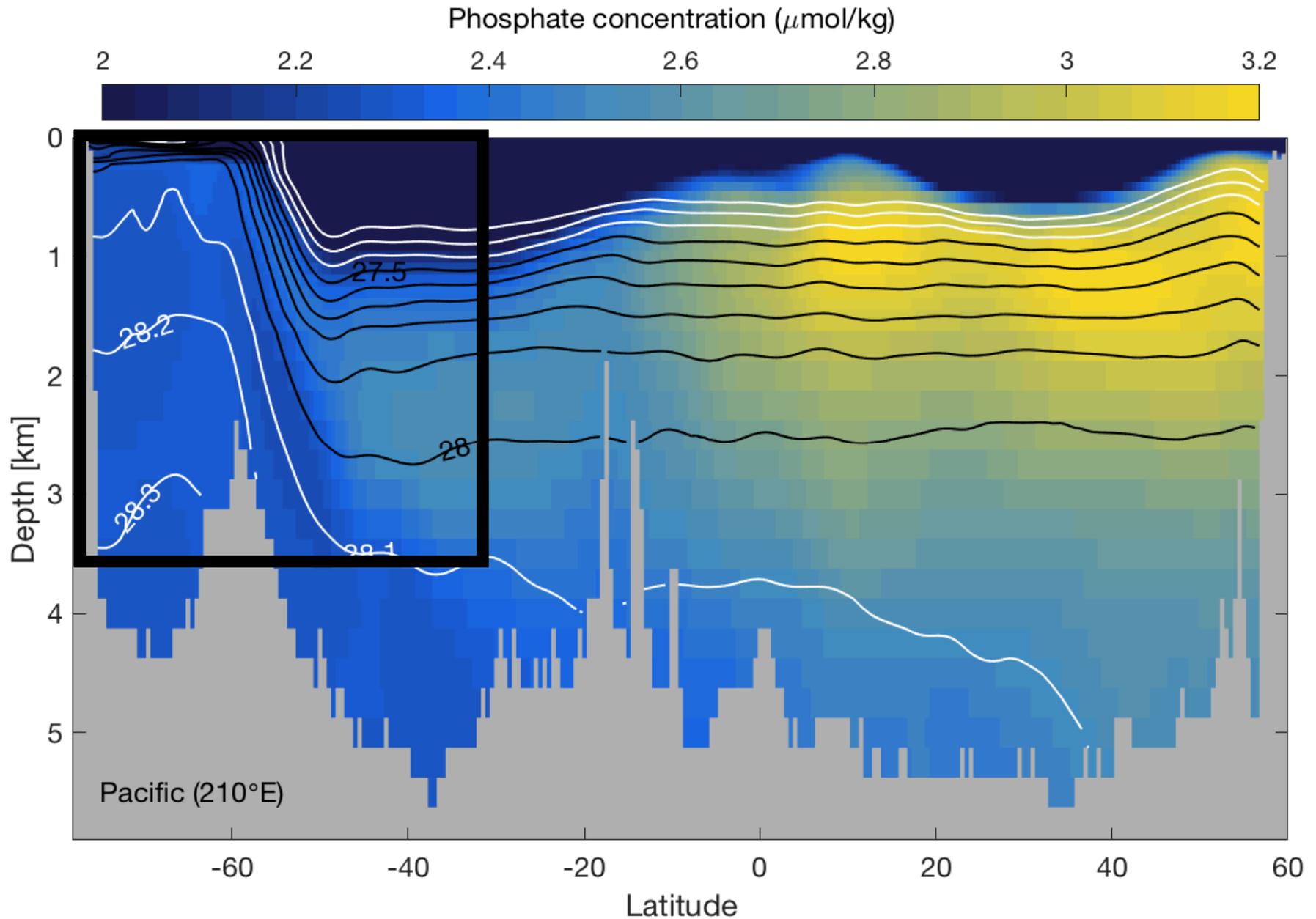


Illustration : zoom sur l'océan austral

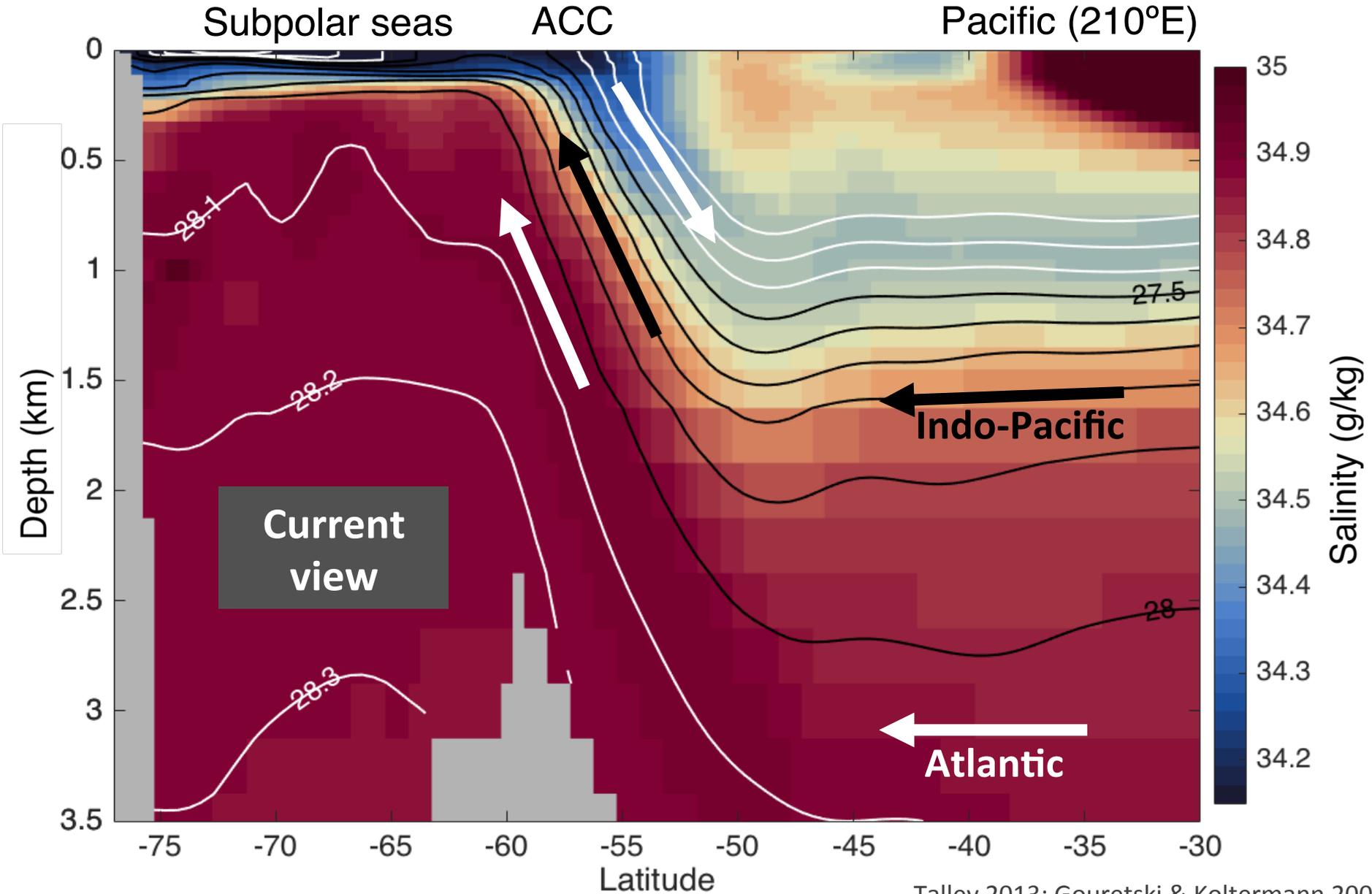
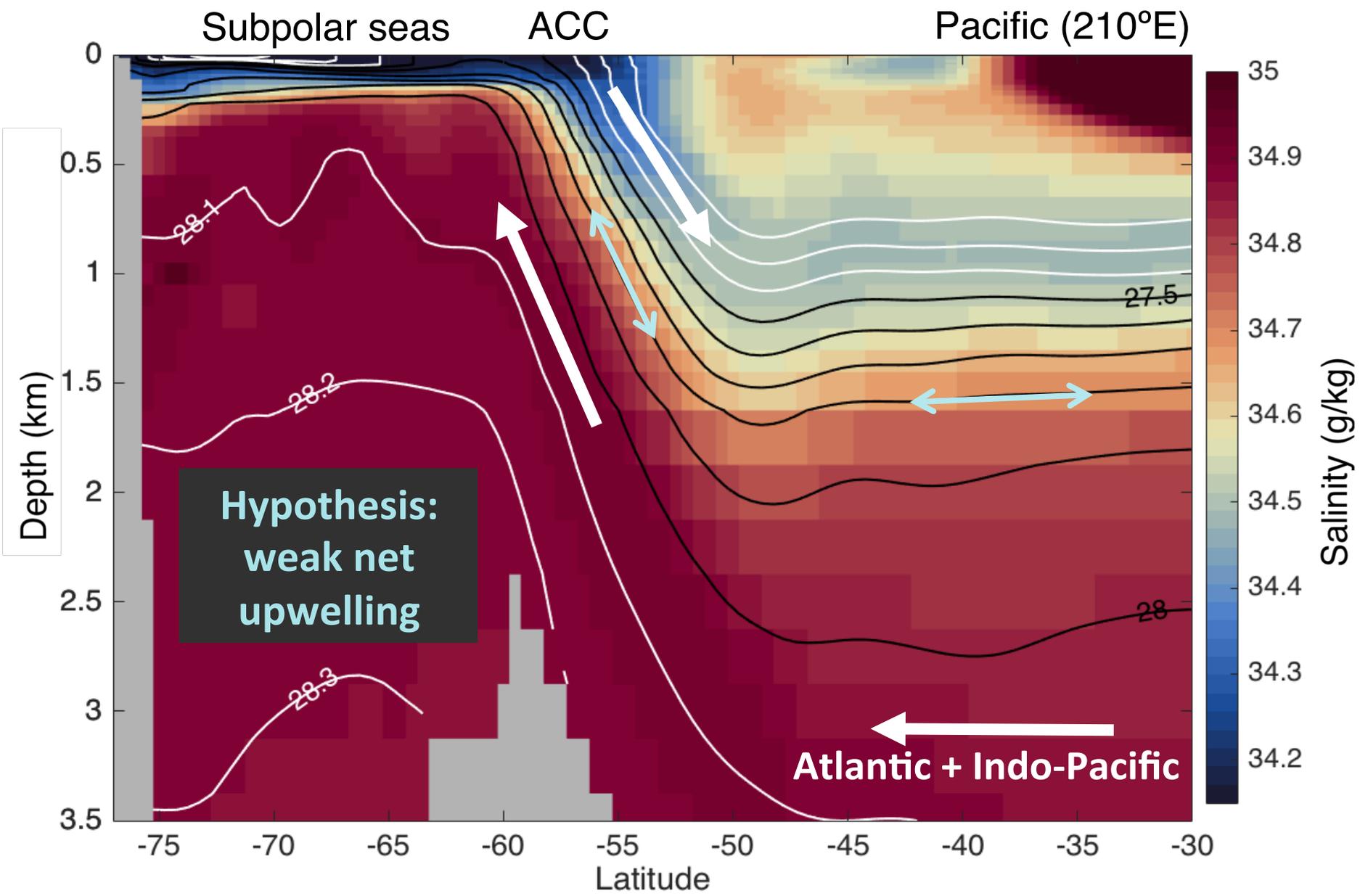
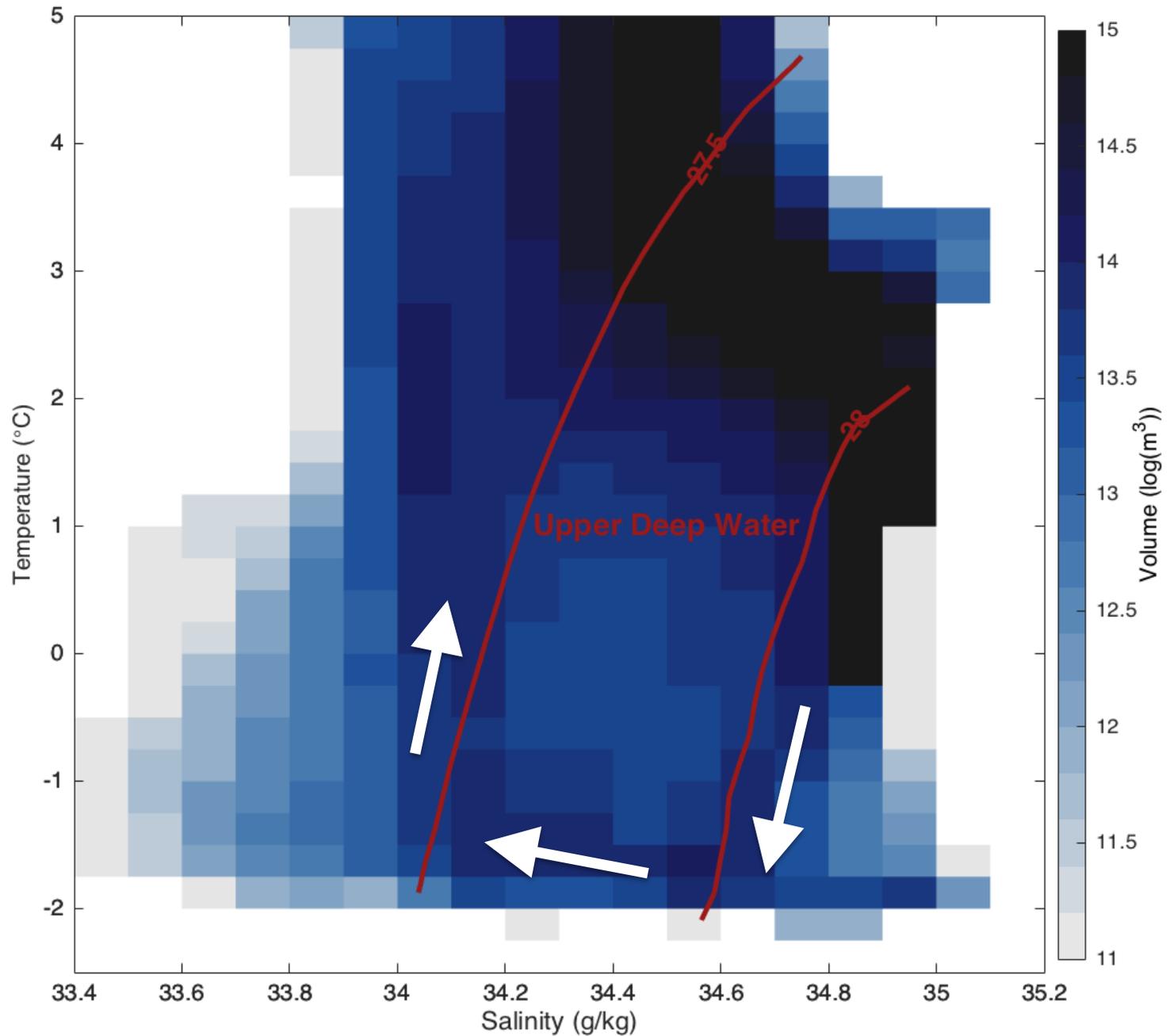


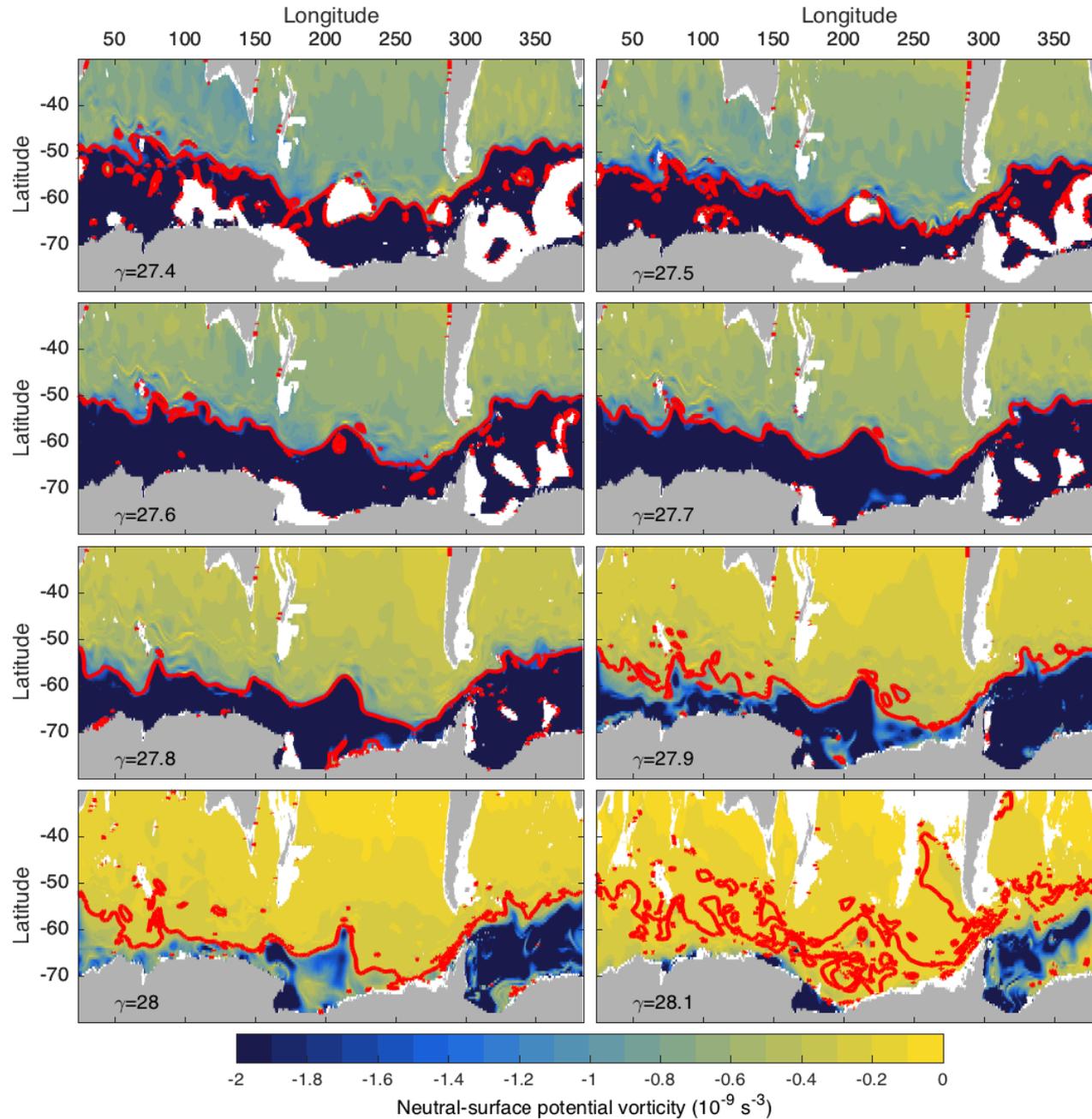
Illustration : zoom sur l'océan austral



Indice : distribution du volume de l'océan austral



Indice : vorticité potentielle dans l'océan austral



Conclusions

- **La circulation thermohaline est un concept fluctuant.**
 - Mais ses schémas sont extrêmement influents.
- **Des cartographies du mélange et du chauffage géothermal permettent de quantifier ces moteurs.**
 - Impliquent un allègement confiné aux grandes profondeurs (> 2.5 km).
- **La circulation thermohaline pourrait délaissier une strate de mi-profondeur (25-30 % du volume total).**
 - Ce qui réduirait son influence sur les traceurs, la ventilation, le climat.