Project ANR DEEPER

Deep-ocean diapycnal mixing in CROCO/ROMS Simulations

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+ Many collaborators from LOPS, and from LEGOS, LOCEAN, INRIA, UCLA, Uni. of Cambridge.

Atelier LEFE Fines échelles - 11 Oct. 2024

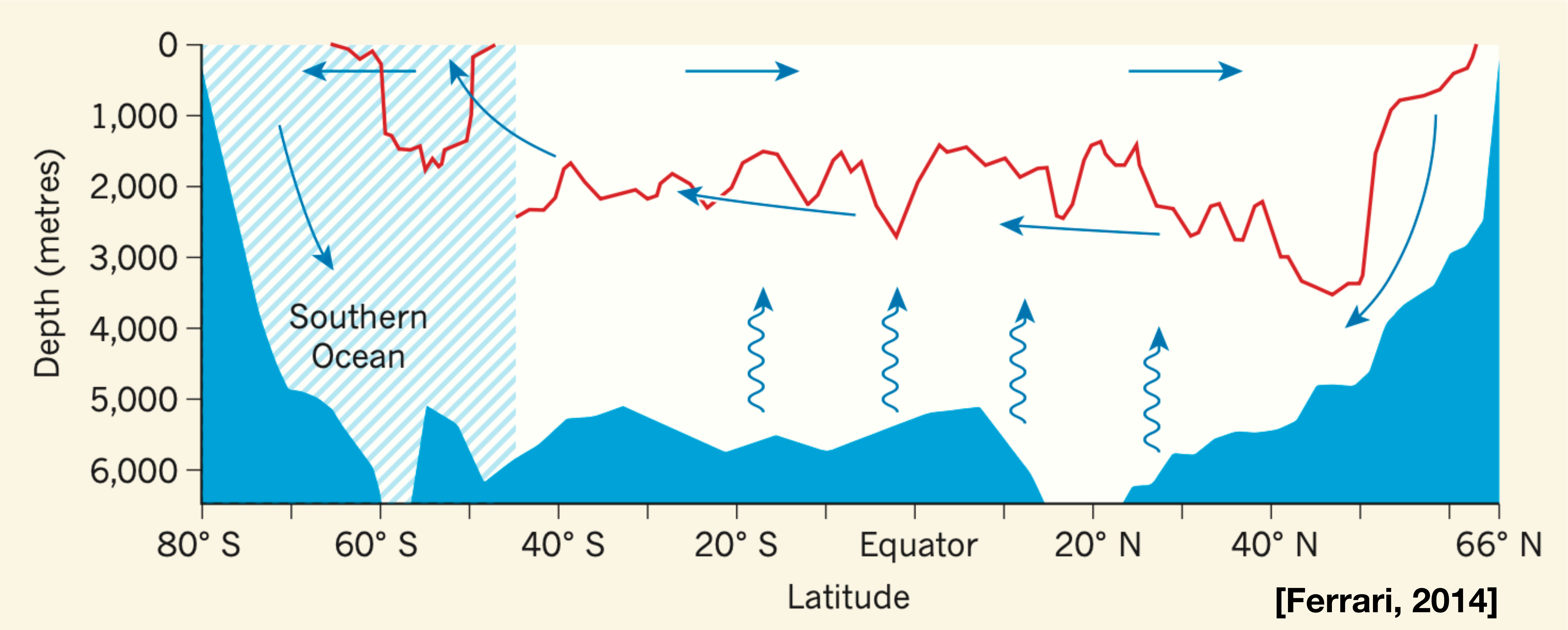
Deep-ocean diapycnal mixing

- **Introduction**: Mixing in the ocean
- Modeling the (deep) ocean at submesoscale resolution
- Quantifying diapycnal mixing in numerical models
- Mixing in seamount wakes

Diapycnal mixing in the ocean

The ocean **meridional overturning circulation** is instrumental for storing and regulating heat and carbon fluxes.

Dense bottom waters need to continuously lifted to the ocean surface though **mixing** with lighter water = **diapycnal mixing**



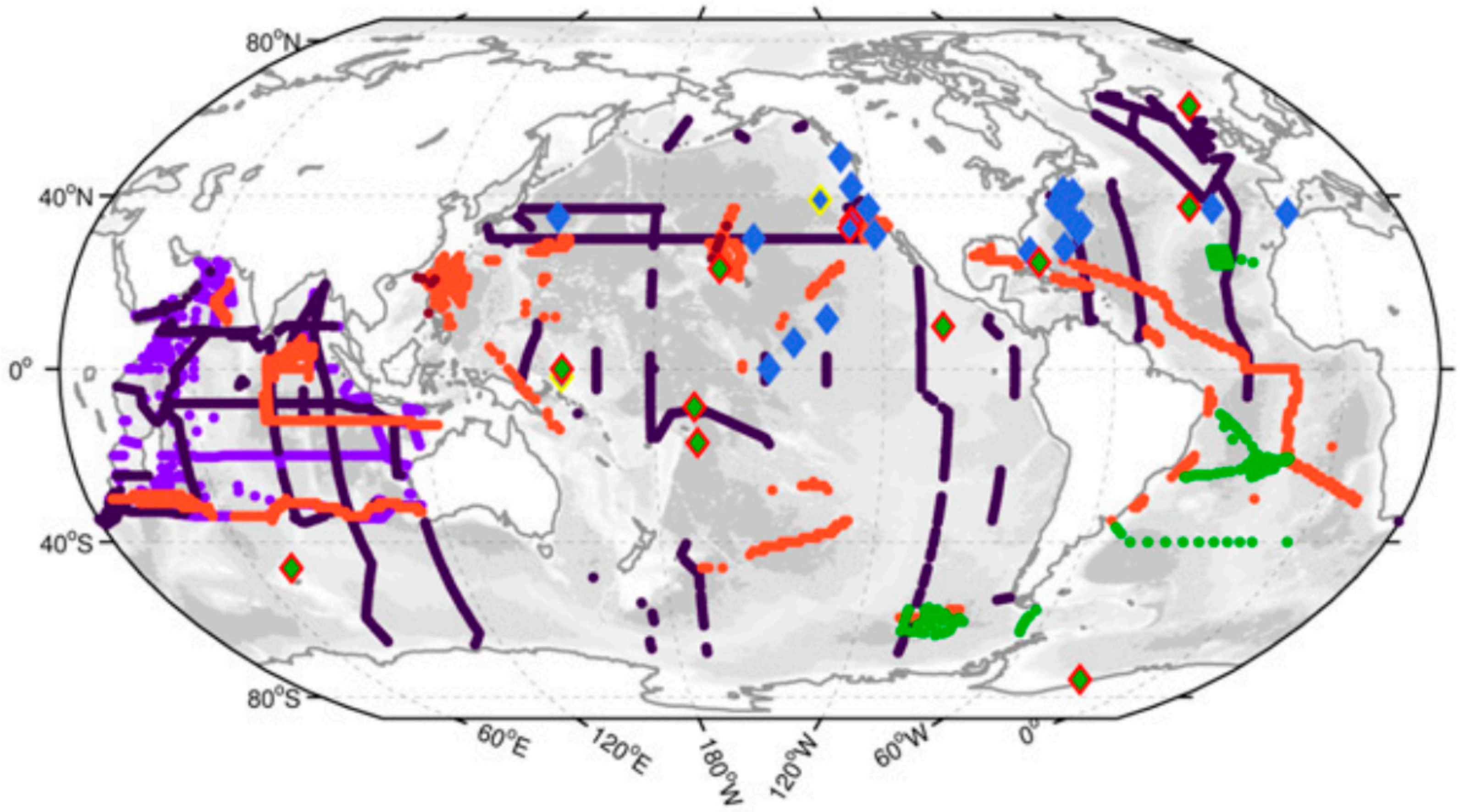
Diapycnal mixing in the ocean

1960s: Munk calculated that an average $\kappa = 10^{-4}\ m^2/s$ was needed to upwell deep waters.

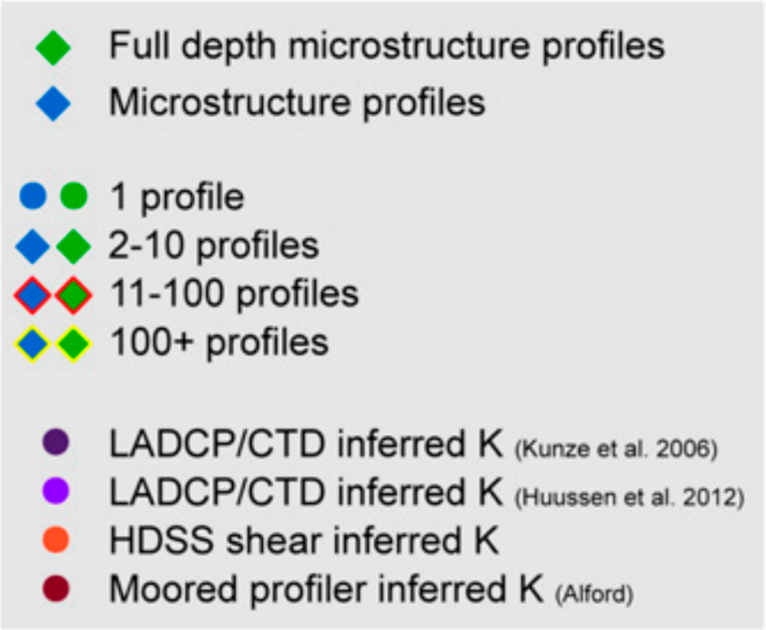
1980s: microstructure measurements and tracer release exp. revealed that $\kappa = 10^{-5}\ m^2/s$ in most of the ocean (e.g., Gregg, JGR 1987)

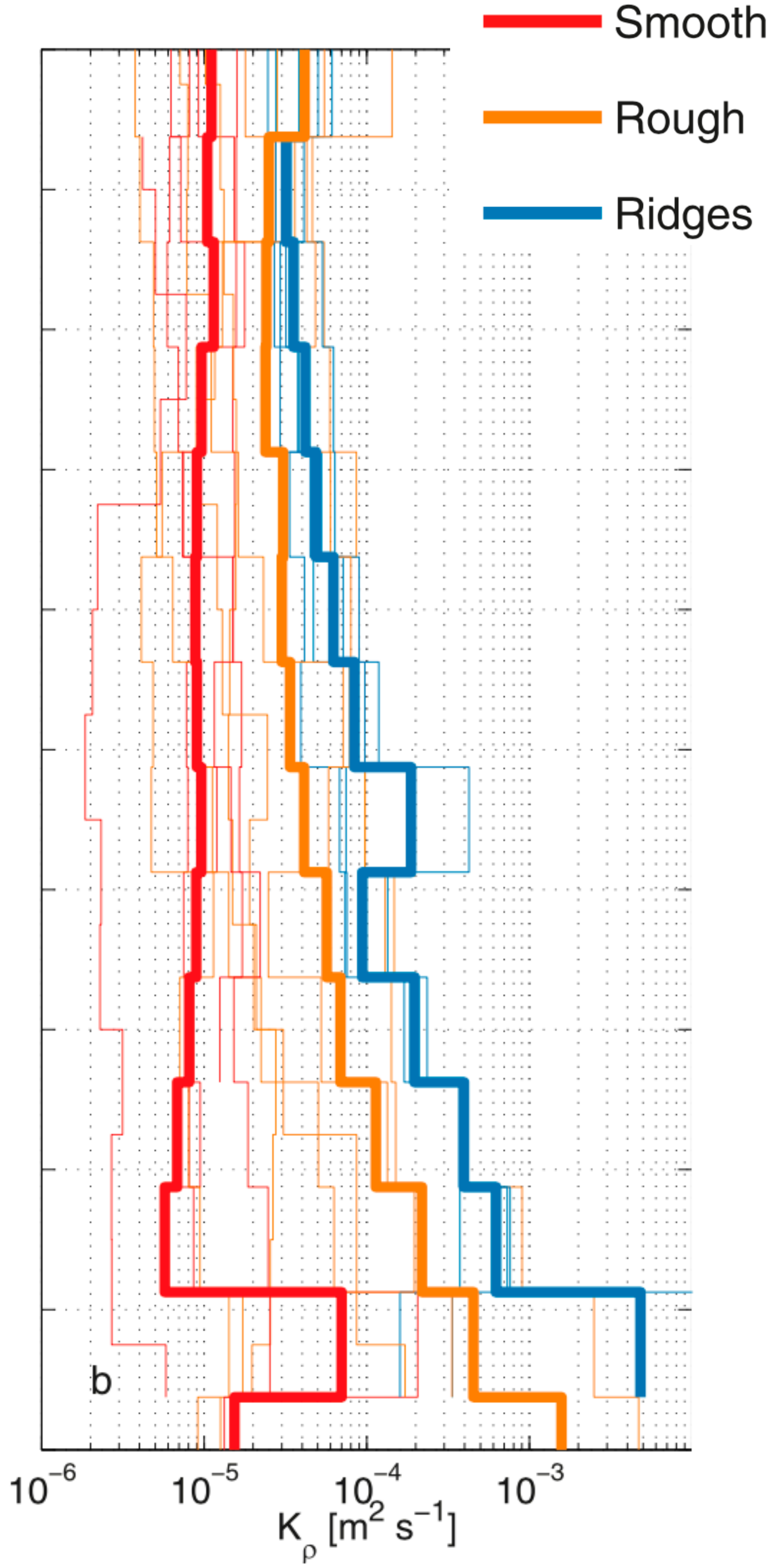
1990s: mixing is enhanced over rough topography

2014: compilation of data confirm the enhanced mixing over rough and steep topography



(c) Observations of mixing





[Waterhouse et al, 2014]

The diapycnal mixing profile and values matter for shaping the global circulation

Deep-ocean diapycnal mixing

- Introduction: Mixing in the ocean
- **Modeling the (deep) ocean at submesoscale resolution**
- Quantifying diapycnal mixing in ROMS/CROCO
- Mixing in seamount wakes

Modeling the (deep) ocean at submesoscale-permitting resolution

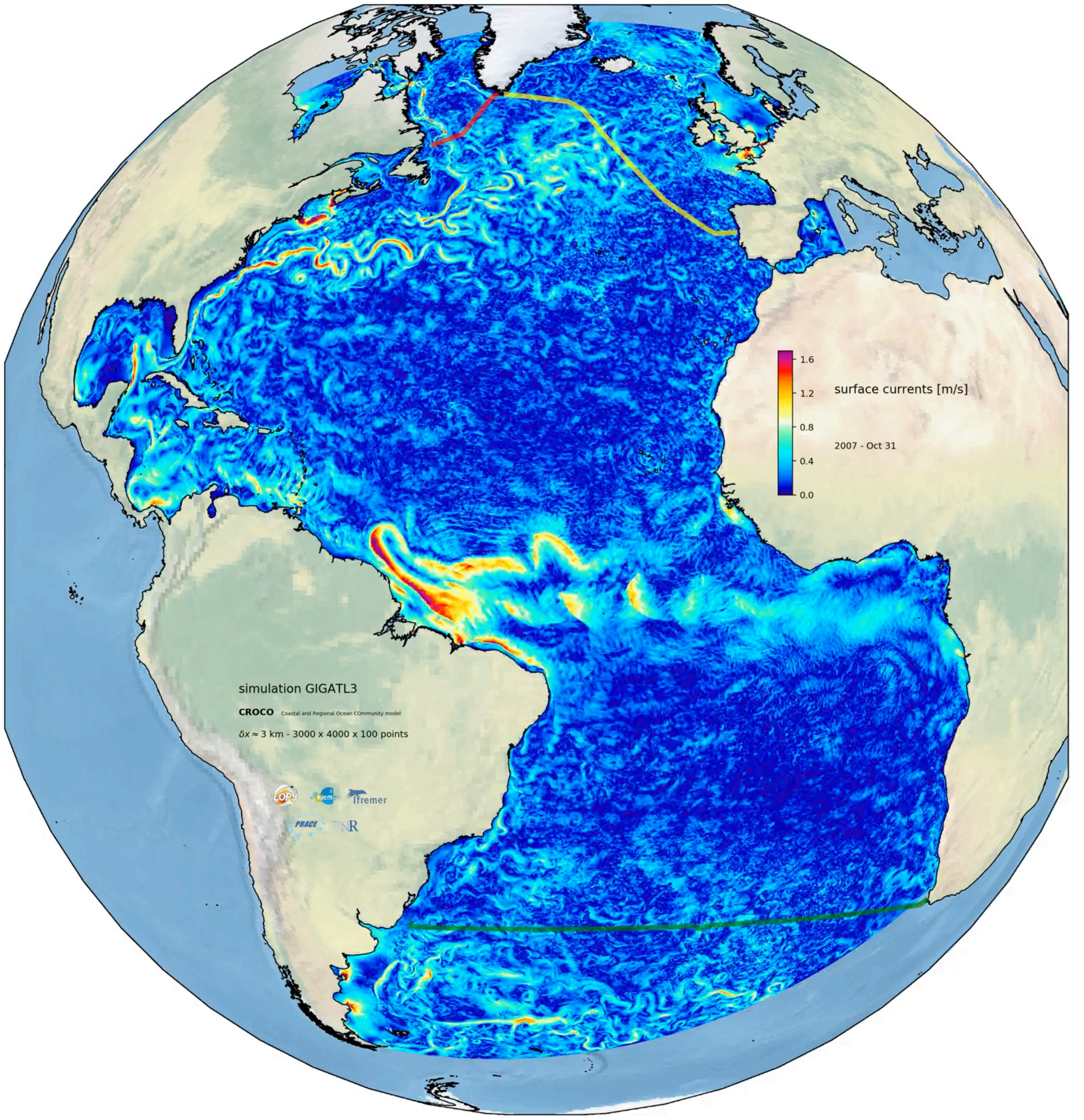
GIGATL at 6/3/1 km

Hierarchy of Fully realistic simulations of the Atlantic Ocean with CROCO

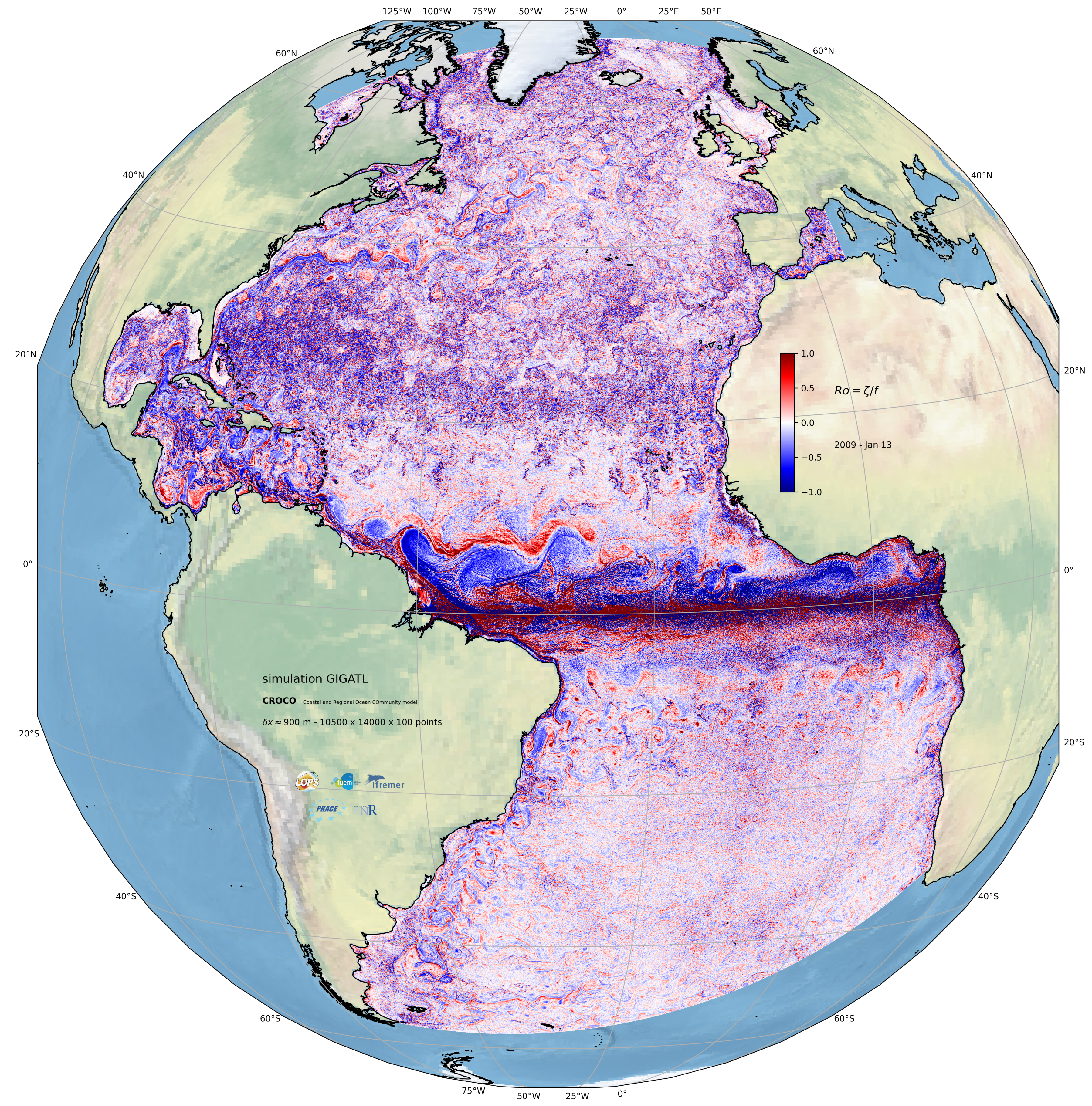
Including **tides** (or not) and
hourly surface forcings (or not)

Horizontal resolution **1 km** with 100 topography following levels (refined at the bottom)

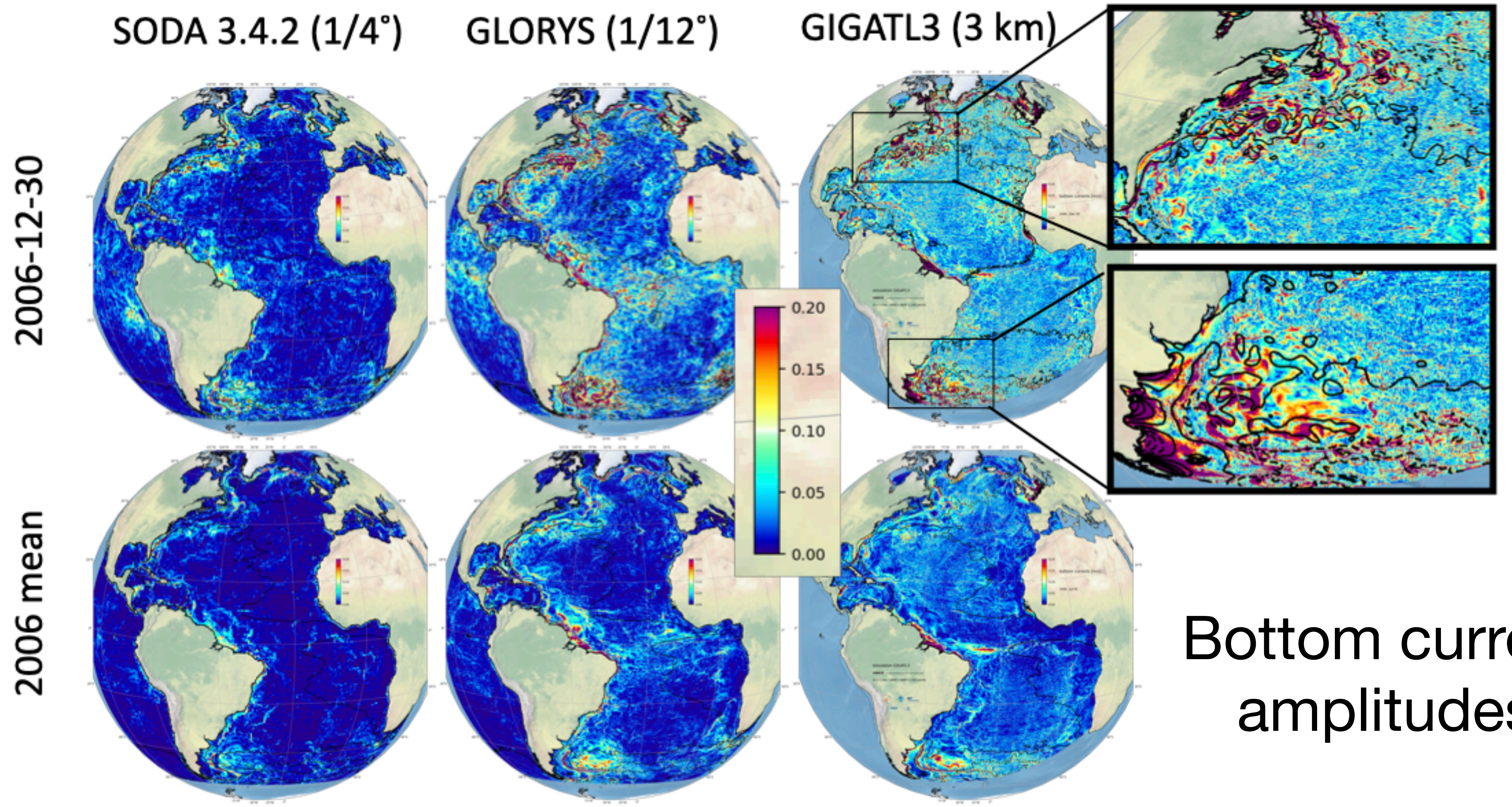
= 10500 x 14000 x 100 points



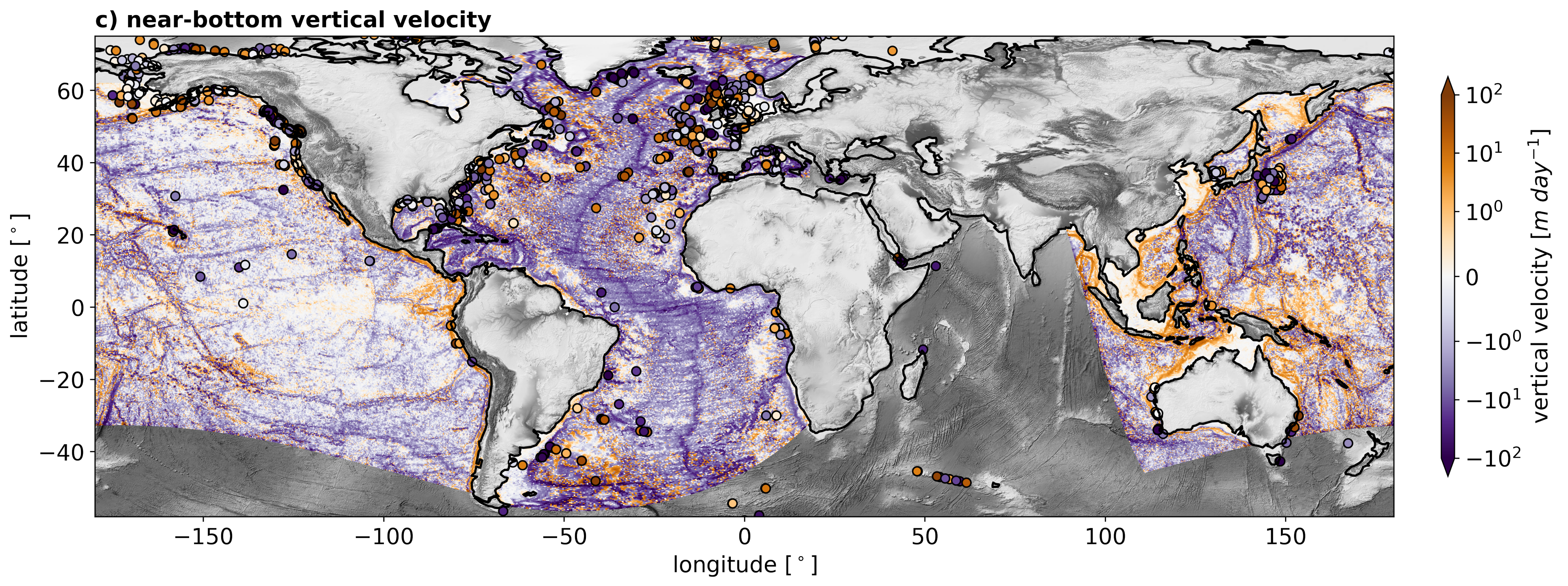
Modeling the (deep) ocean at submesoscale-permitting resolution



Surface Relative vorticity in GIGATL1



Bottom current amplitudes

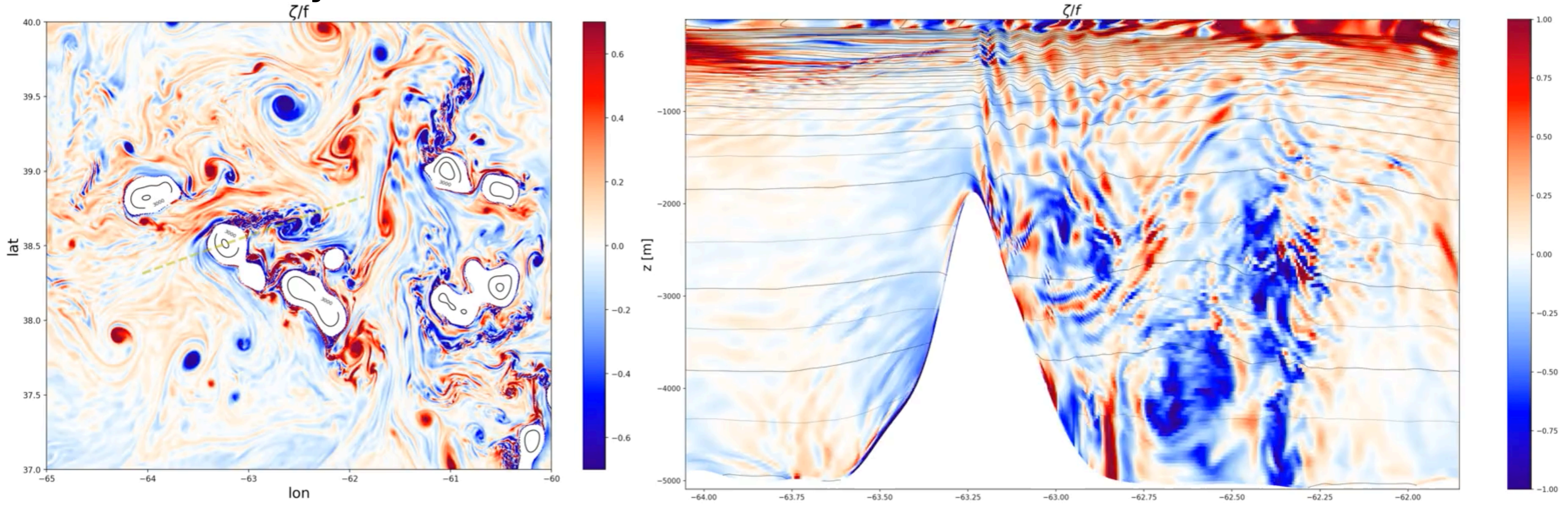


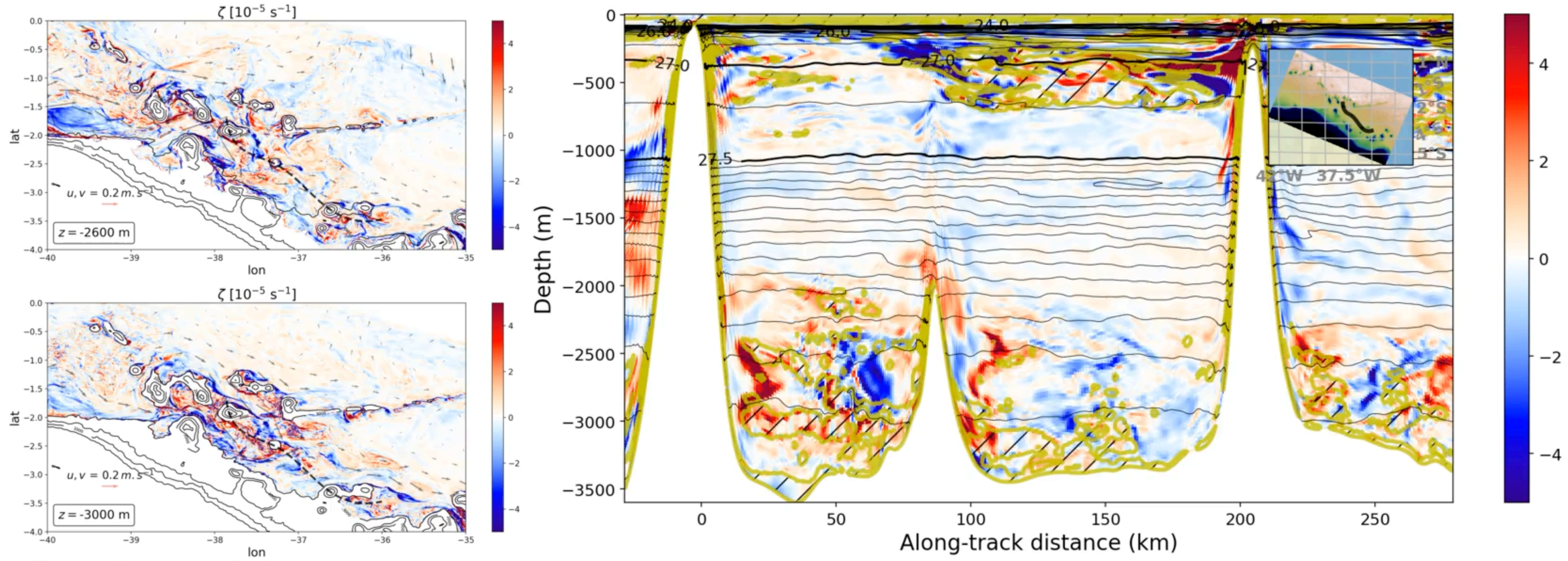
Near-bottom vertical velocities [Schubert et al, in rev]

More info on https://github.com/Mesharou/GIGATL

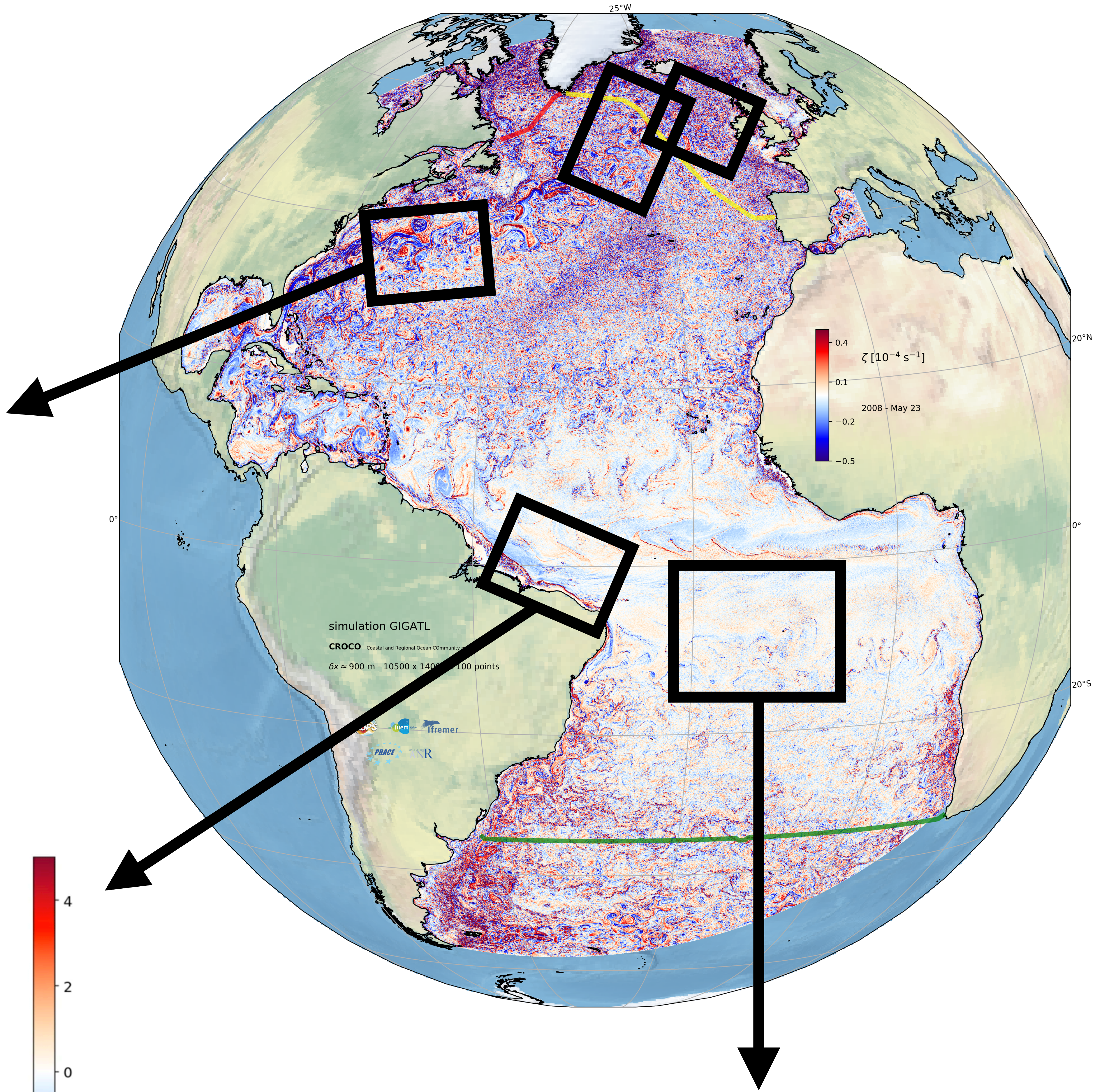
Nesting one step further:

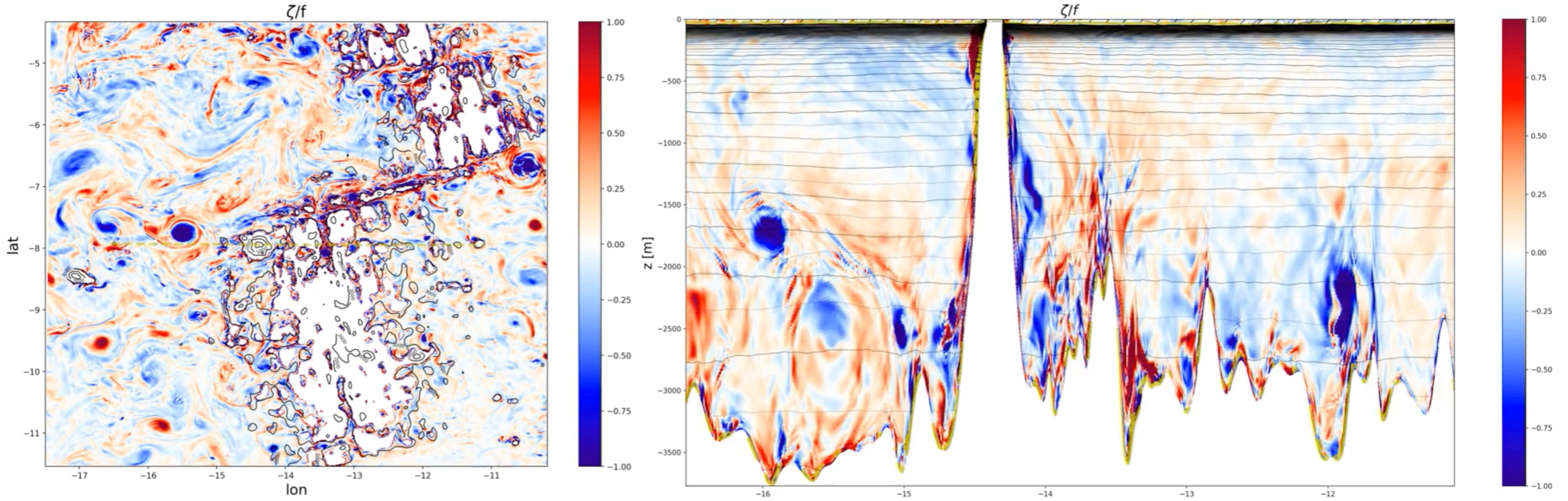
Relative vorticity at z = 4000 m





Relative vorticity at z = 3000 m





Relative vorticity at z = 3000 m

New-England seamounts - dx = 500 m - **256 levels**
Equatorial seamounts- dx = 800 m - **300 levels**
Mid-Atlantic Ridge - dx = 800 m - **300 levels**

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Mixing in ROMS/CROCO and other similar models

Equation for tracers:

$$\frac{\partial T}{\partial t} + \overrightarrow{\nabla} \cdot (\vec{u}T) = \mathscr{F}_{Forc} + \mathscr{F}_{Vmix} + \mathscr{F}_{Hmix}$$

Parameterized mixing = $\left\{ \begin{array}{l} \text{Parameterized vertical mixing (KPP, } k-\epsilon\text{, etc.):} \\ \text{(eventually) explicit horizontal mixing} \end{array} \right.$

$$\mathscr{F}_{Vmix} = \frac{\partial}{\partial z}\left(\kappa \frac{\partial T}{\partial z}\right)$$

$$\mathscr{F}_{Hmix}$$

Numerical mixing = all other numerical effects (implicit mixing from advective operators UP3/UP5/WENO5, discretization errors, time-stepping, etc.)

Quantifying diapycnal mixing

Different strategies can be used to estimate the effective (parameterized + numerical) diffusivity:

- **Tracer release experiments [e.g. Ledwell et al., 1995]**
- Water-mass transformations budgets [e.g. Drake et al, 24]
- Effective diffusivity based on APE changes [Winter et al, 95, Griffies et al, 00, etc]
- Tracer variance decay [e.g. Burchard & Rennau, 08, Klingbeil et al, 19]
- Forward/backward advection [see G. Roullet]
- **Online buoyancy budget [Capo etal, 24, Schifano et al, submitted]**

Quantifying diapycnal mixing

Method 1: online tracer diagnostics

$$\frac{DT}{Dt} = \underbrace{T_t}_{T_{rate}} + \underbrace{\vec{u} \cdot \vec{\nabla} T}_{T_{adv}} = \underbrace{-\vec{\nabla} \cdot \vec{F^T}}_{T_{rhs}}$$

$$\frac{DS}{Dt} = \underbrace{S_t}_{S_{rate}} + \underbrace{\vec{u} \cdot \vec{\nabla} S}_{S_{adv}} = \underbrace{-\vec{\nabla} \cdot \vec{F^S}}_{S_{rhs}}$$

1. Diagnose non-advective tracer fluxes for all terms online (including approximate implicit terms)

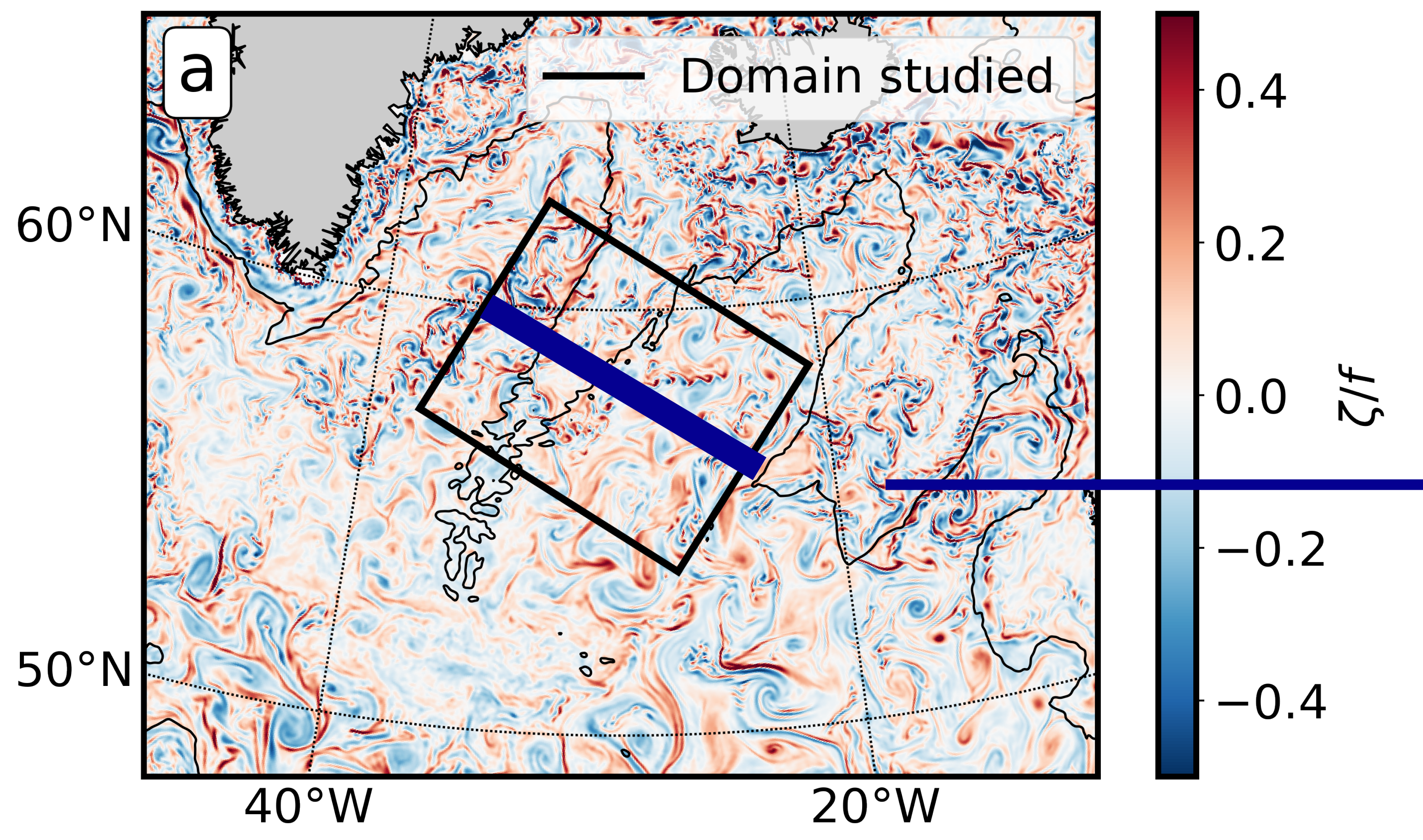
2. Compute a buoyancy flux

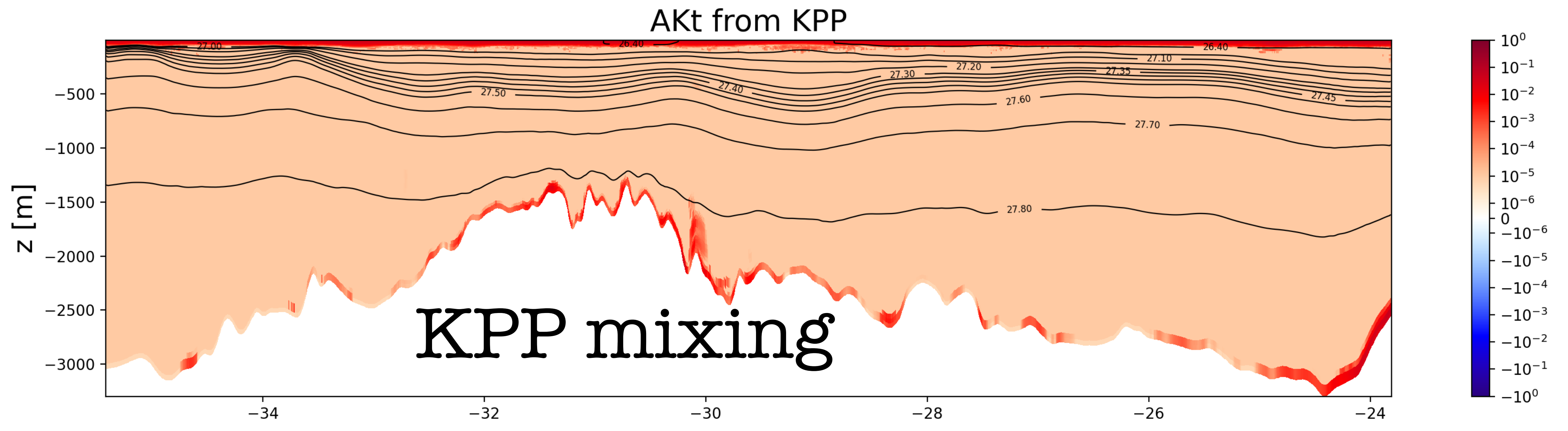
$$\vec{F^B} = -g(-\alpha \vec{F^T} + \beta \vec{F^S})$$

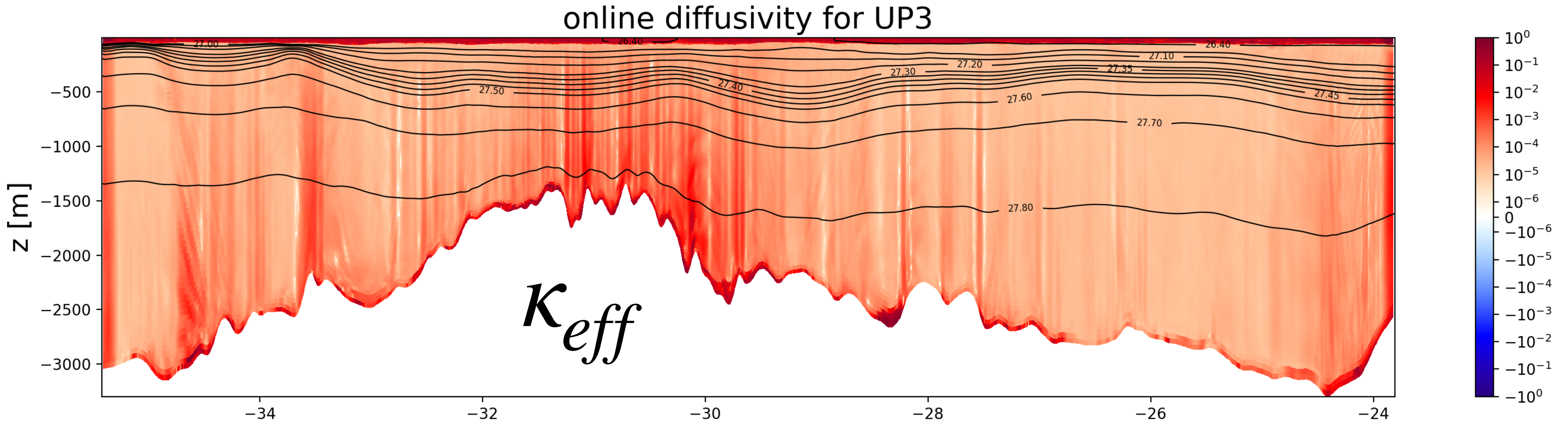
3. Project in the diapycnal direction (based on local adiabatic gradients) to obtain an effective diffusivity

$$K_{eff} = \vec{F^B} \cdot \frac{\vec{\nabla} b}{\left|\vec{\nabla} b\right|^2}$$

Online diagnostics of diapycnal mixing







With UP3 advection (+ SPLINES in the vert.)

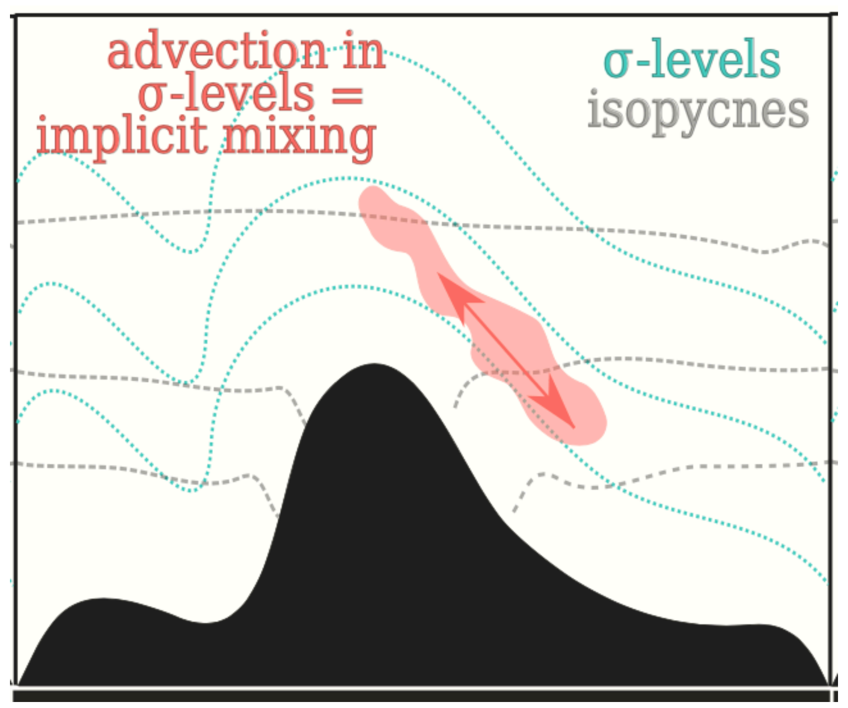
Using a **regional CROCO simulation over the Reykjanes Ridge**

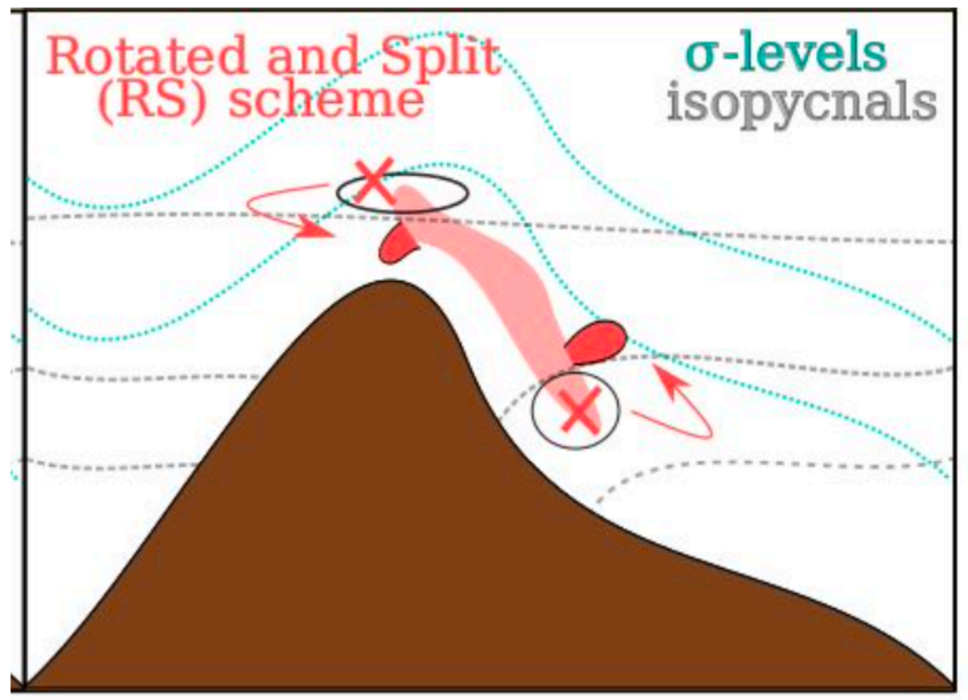
Horizontal res. = 800 m
Vertical res. = 100 levels
KPP vertical mixing

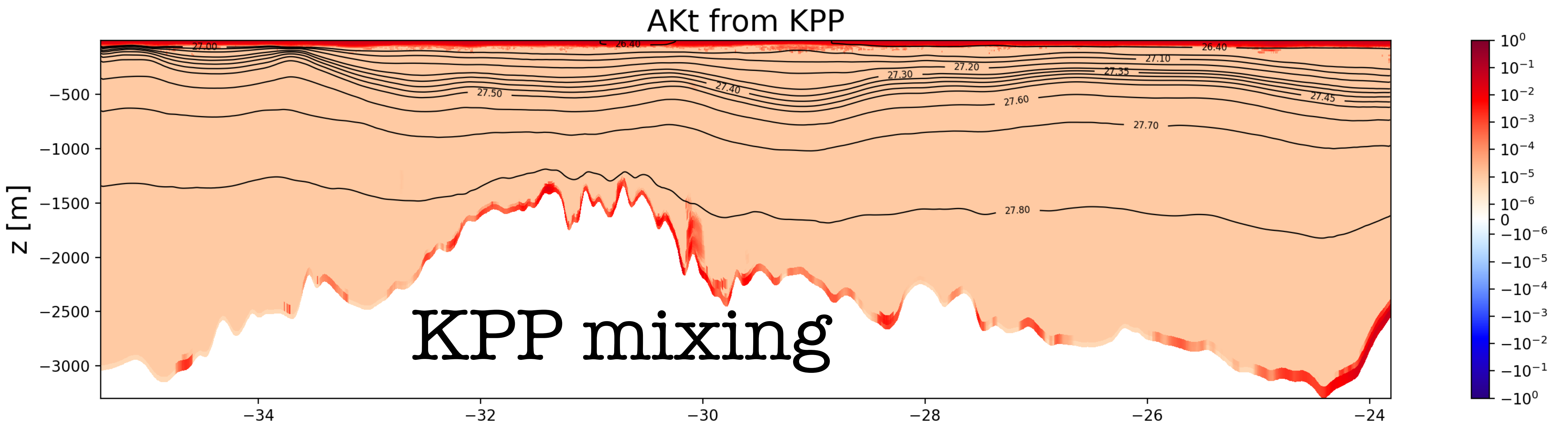
Including tides
+ hourly atmospheric forcings

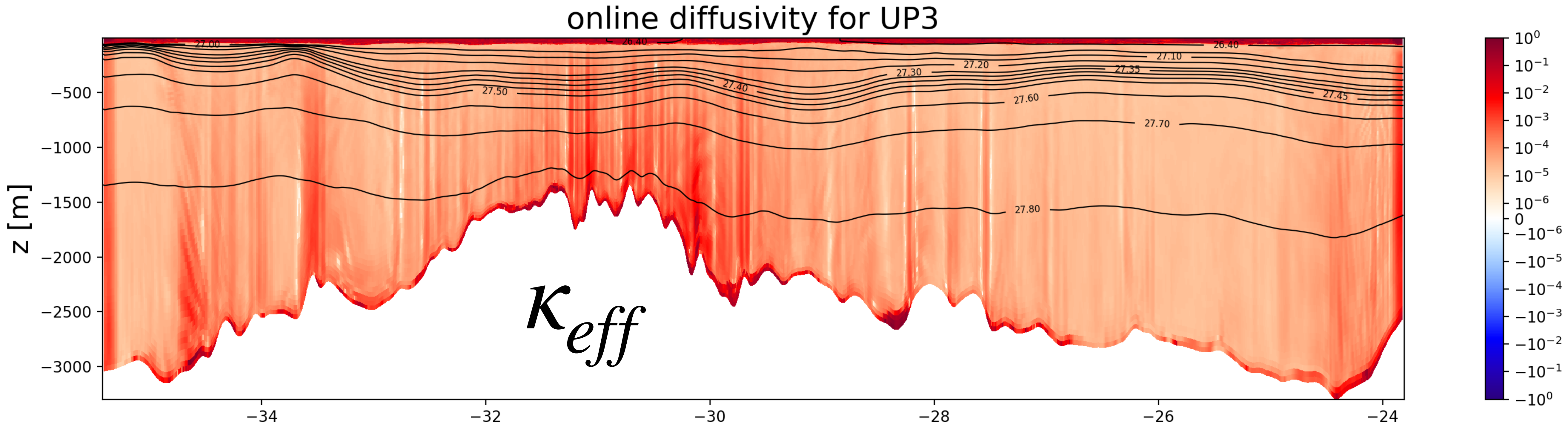
Online diagnostics of diapycnal mixing

Effective diffusivity dominated by implicit part of the horizontal advective scheme:





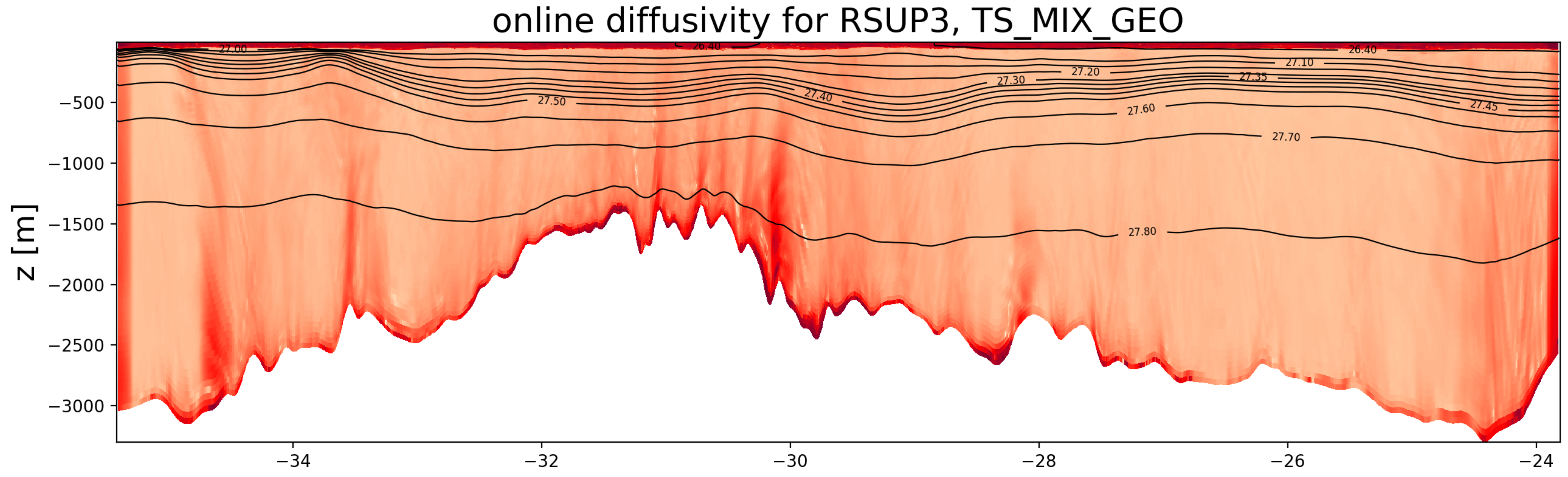


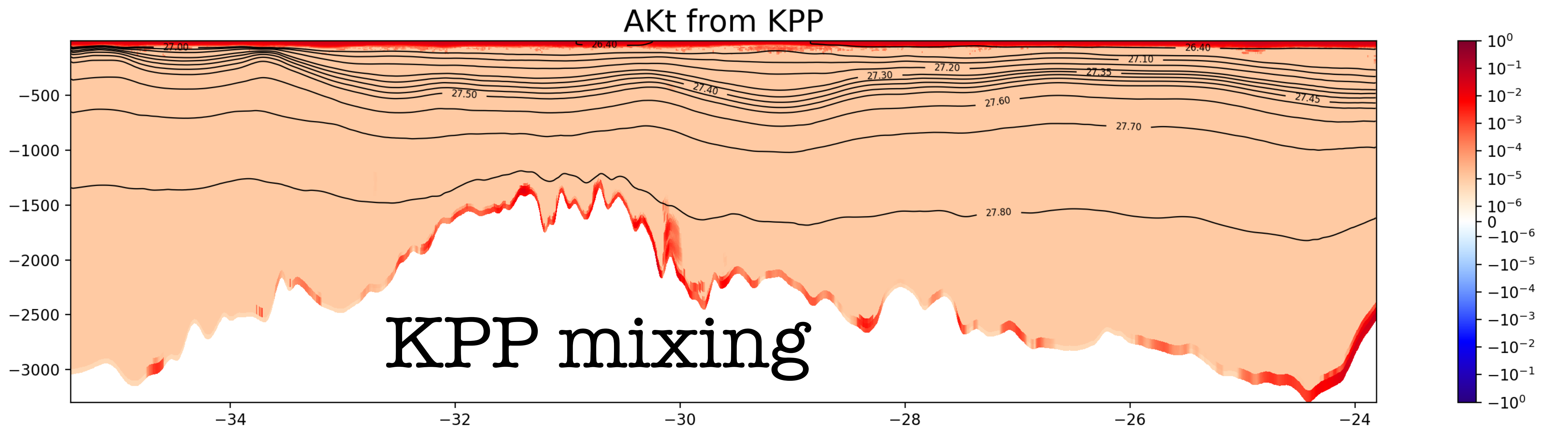


With UP3 advection (+ SPLINES in the vert.

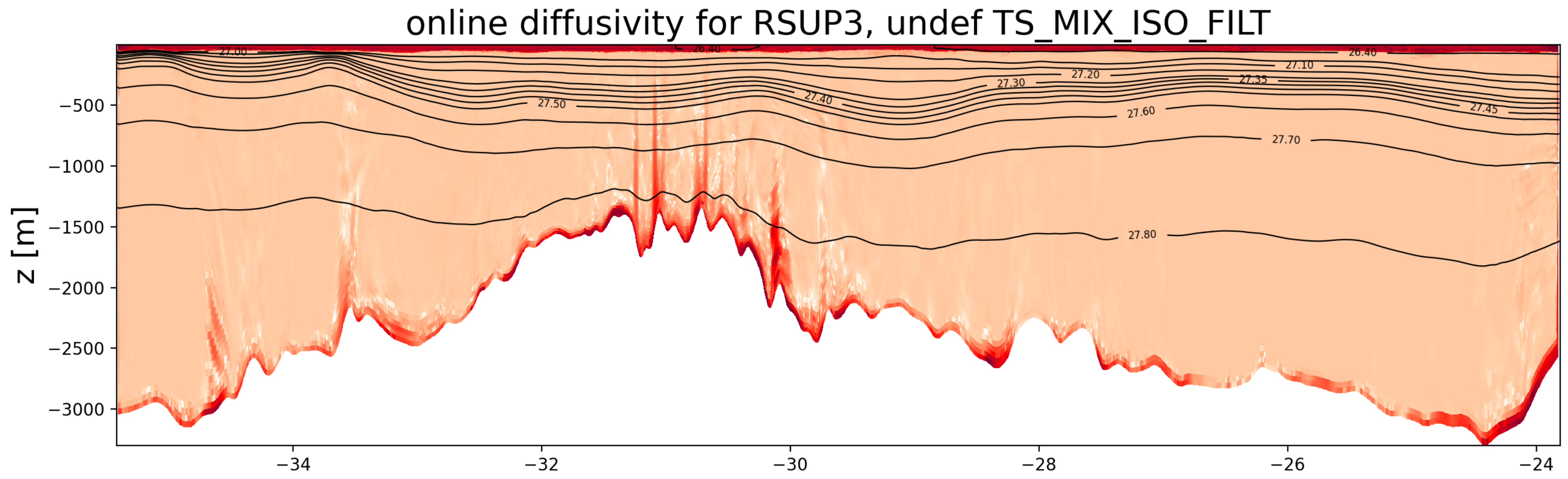
Solutions exist to limit this diapycnal mixing in the form of **isoneutral mixing operators (RSUP3/5)** [Griffies et al (2000), Marchesiello et al (2009), Lemarié et al (2012), Lemarié et al (2015)]

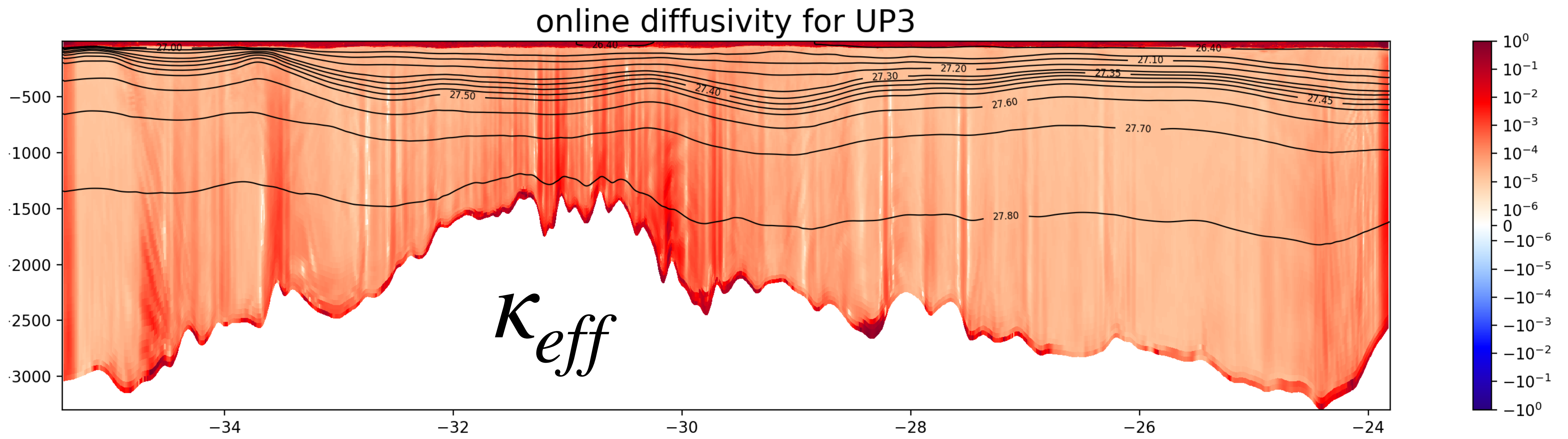
Online diagnostics of diapycnal mixing





With **geopotential** diffusion (= RSUP3 + TS_MIX_GEO)

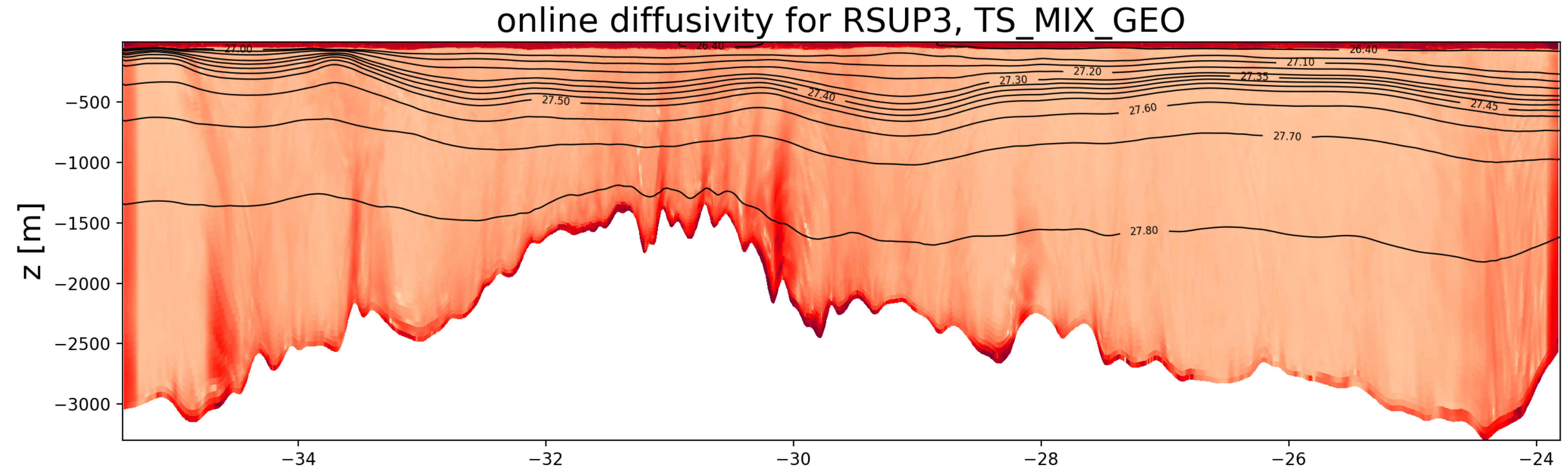


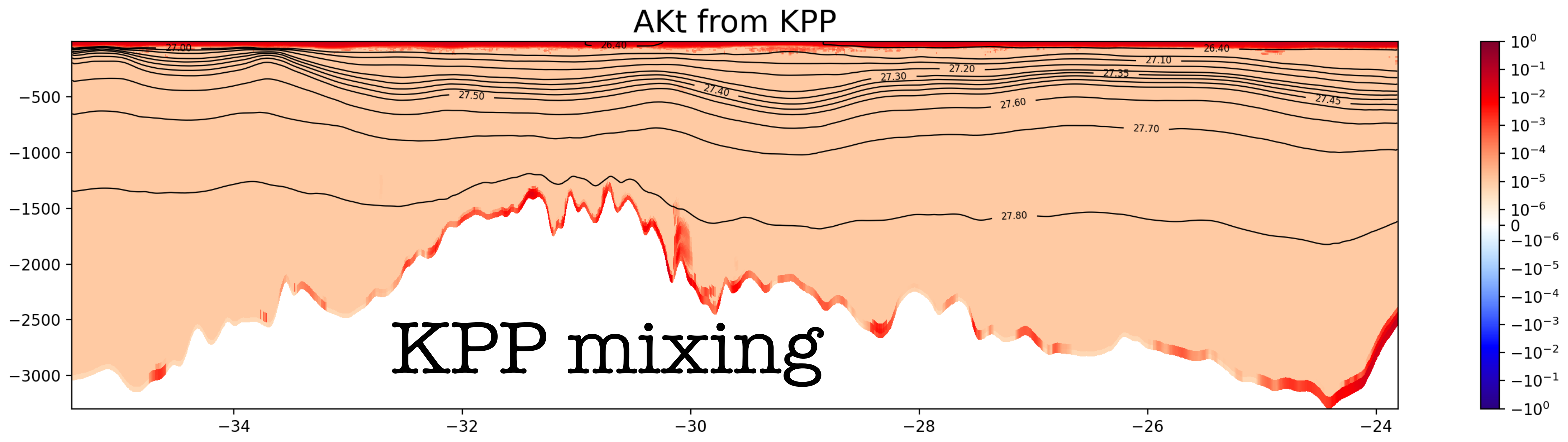


With **isoneutral** diffusion (=RSUP3 + TS_MIX_ISO)

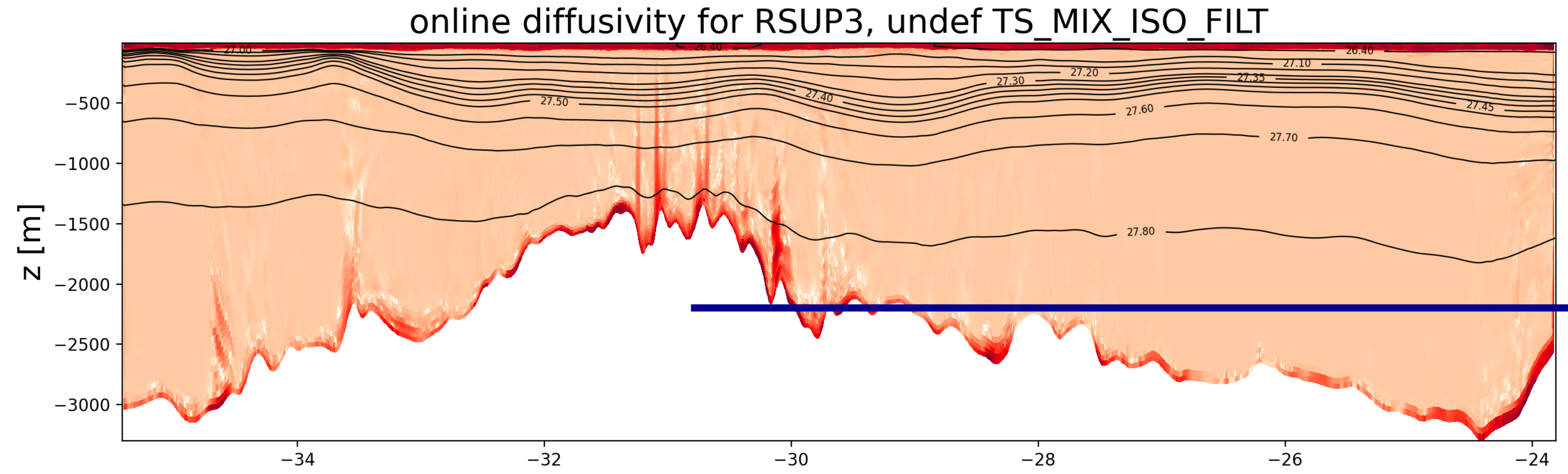
With UP3 advection (+ SPLINES in the vert.

Online diagnostics of diapycnal mixing





With **geopotential** diffusion (= RSUP3 + TS_MIX_GEO)

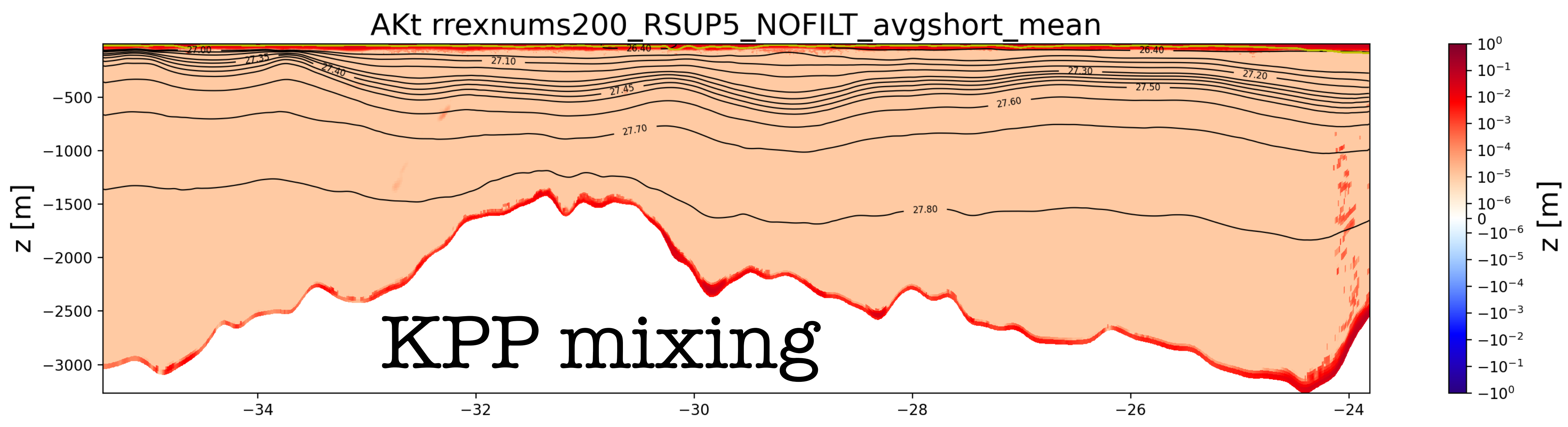


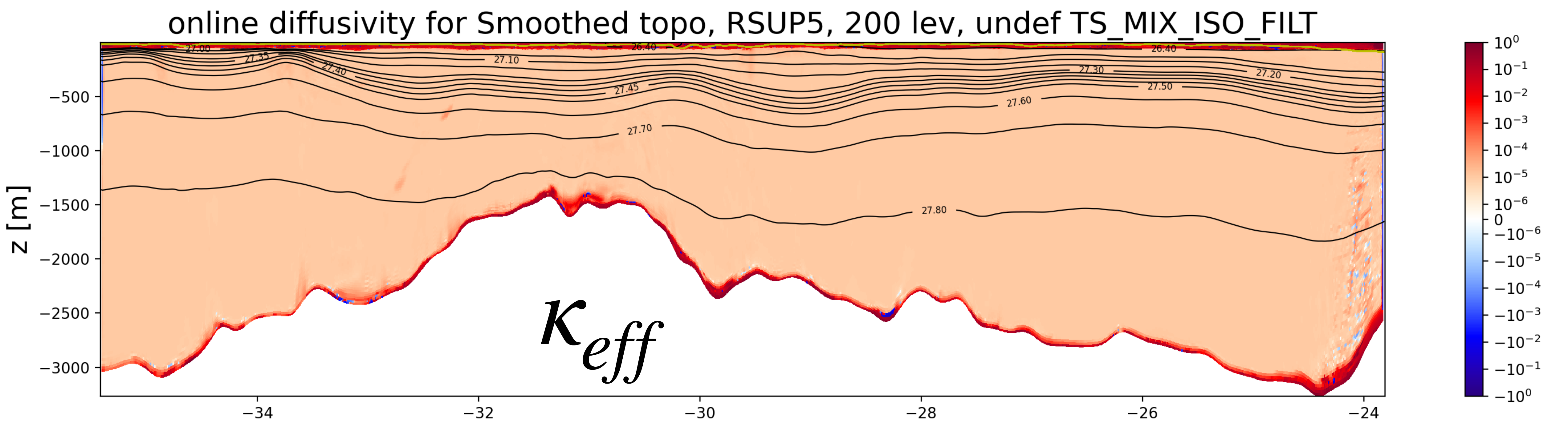
Limitations of the maximum slope values $\alpha_m = \dfrac{\partial_x \rho}{\partial_z \rho} < 0.05$ and of the grid slope ratio $s_m = \alpha_m \dfrac{dz}{dx} < 1.$

With **isoneutral** diffusion (=RSUP3 + TS_MIX_ISO)

Online diagnostics of diapycnal mixing

With **smoother topography:**

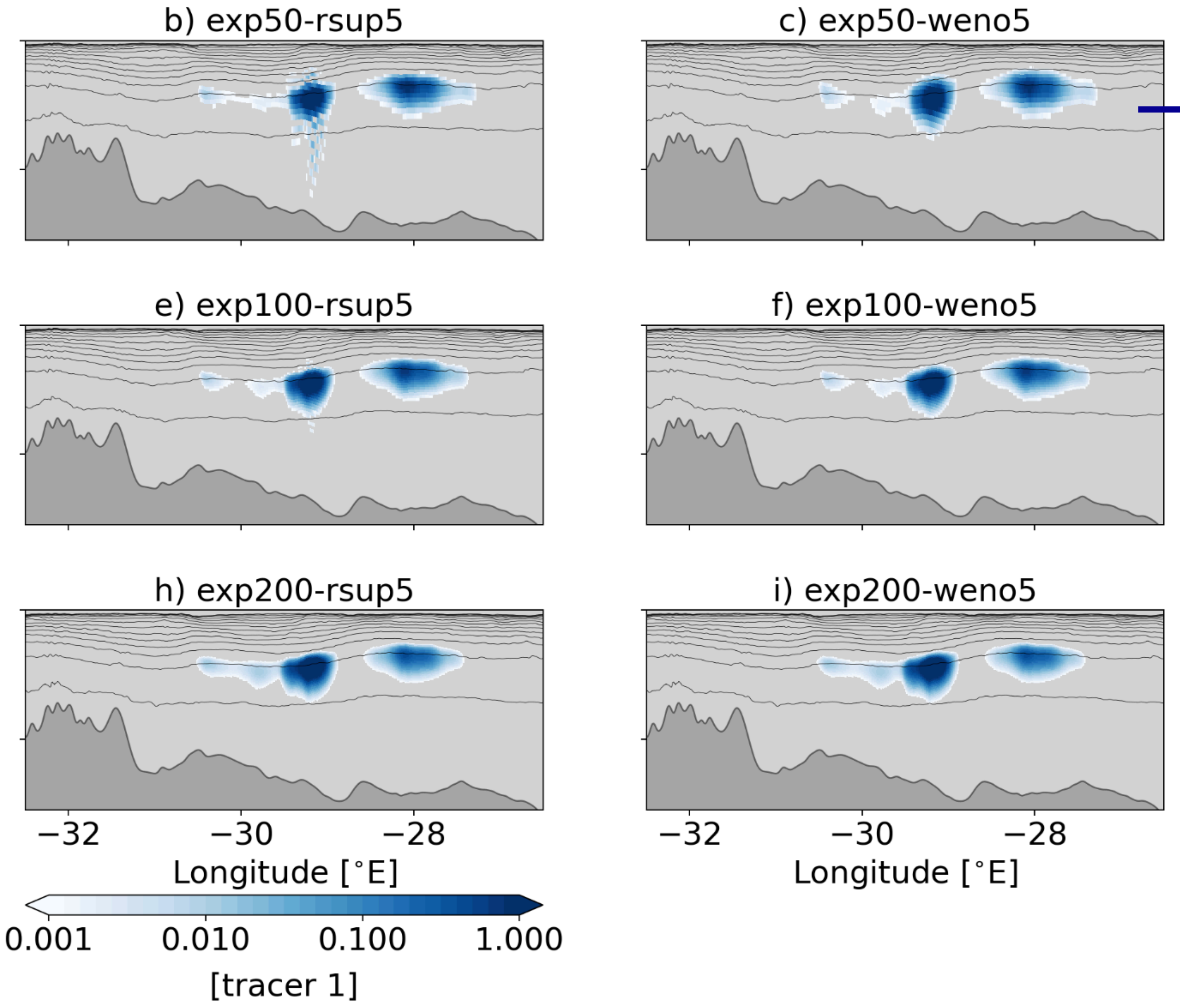


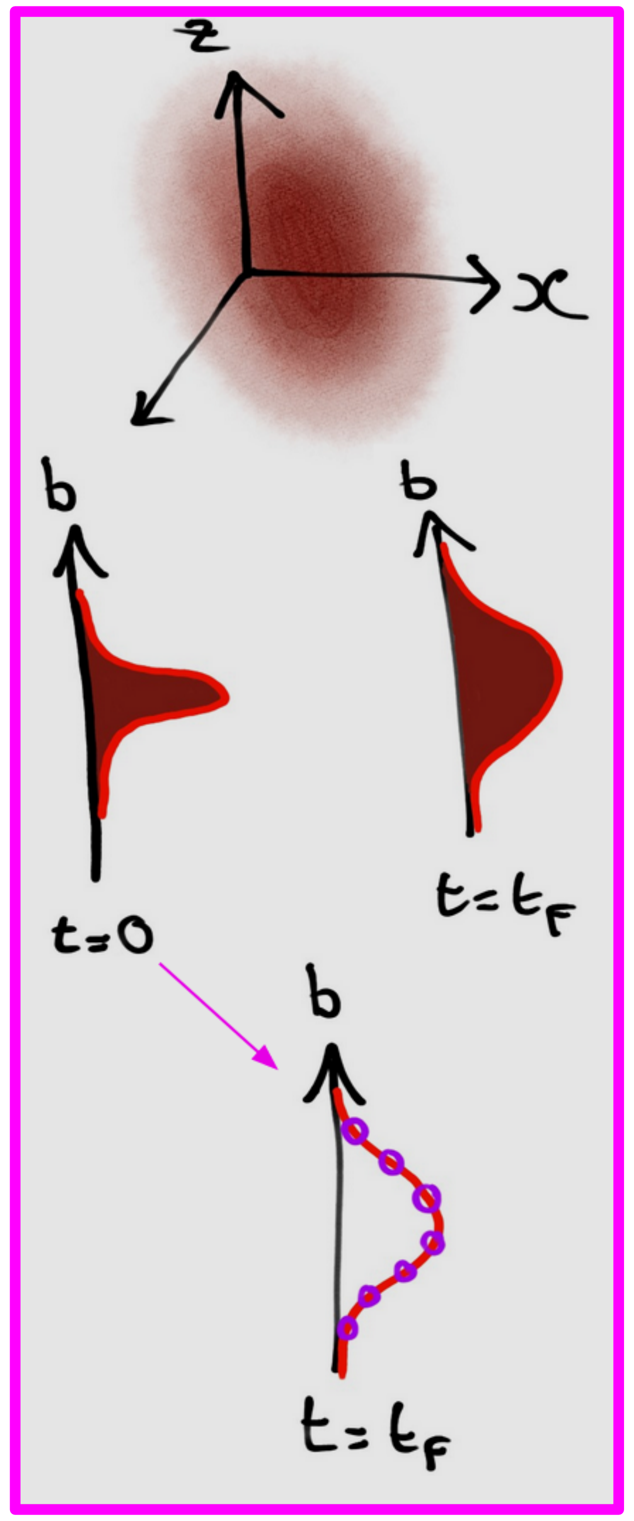


effective mixing = parameterized mixing

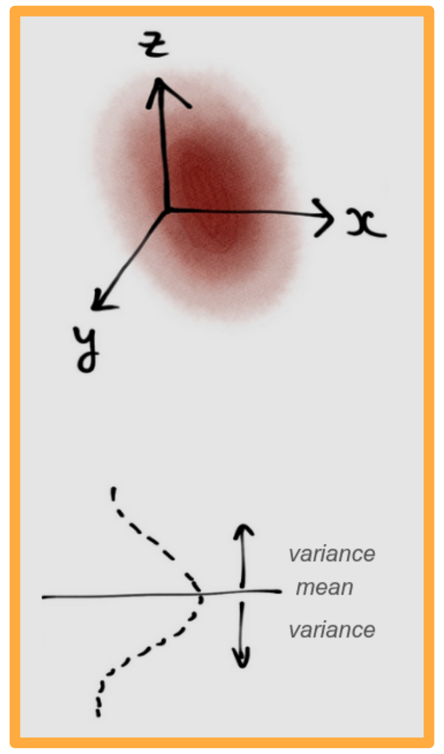
Quantifying diapycnal mixing

Method 2: Passive tracer releases





fit with a 1D model [Ledwell et al., 95] = K_{fit}



Growth rate of the tracer concentration variance in buoyancy space [Taylor, 22, Ruan & Ferrari, 21]

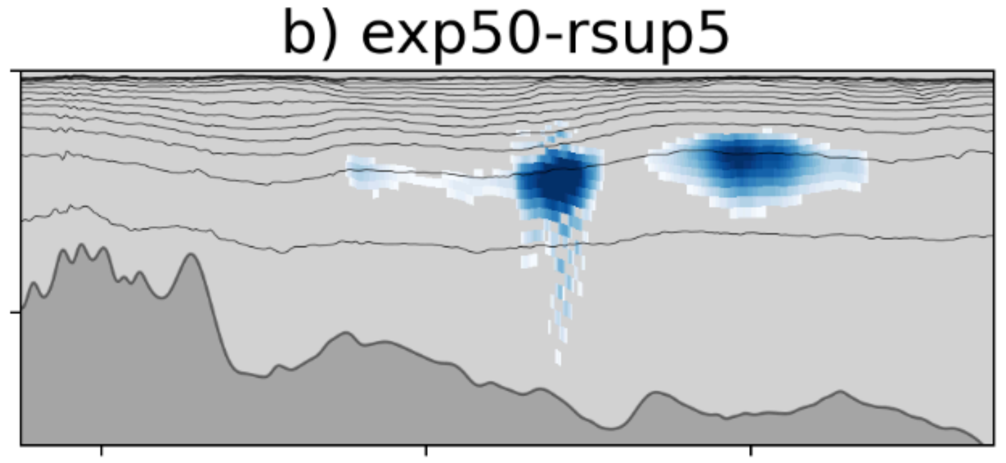
$$K_{\text{tracer}} \equiv \frac{1}{2}\frac{\partial_t \overline{(b-\overline{b})^2}}{\overline{|\nabla b|^2}}$$

$$\overline{(\cdot)} = \frac{\iiint (\cdot) c \,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z}{\iiint c \,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z}$$

Quantifying diapycnal mixing

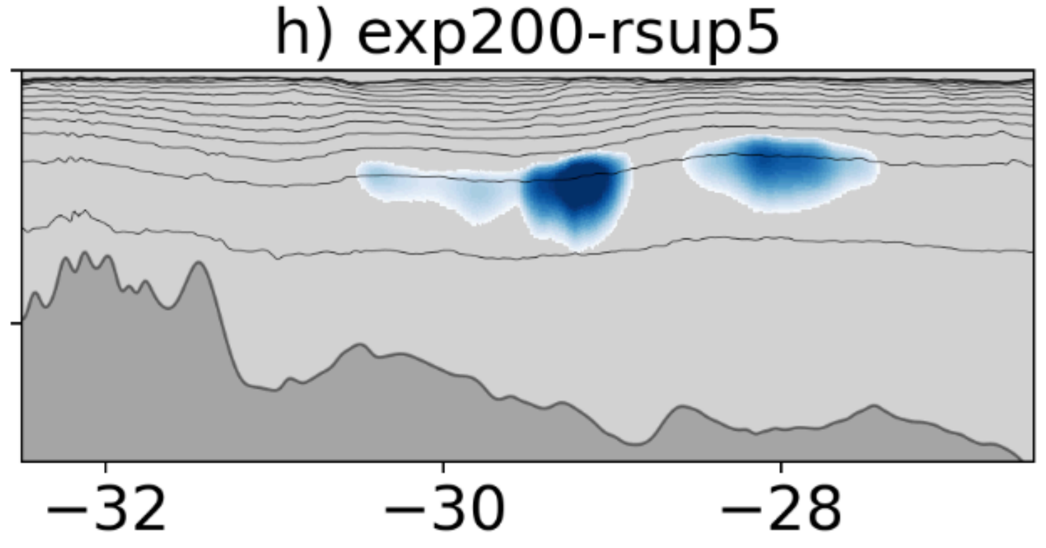
Method 2: Passive tracer releases

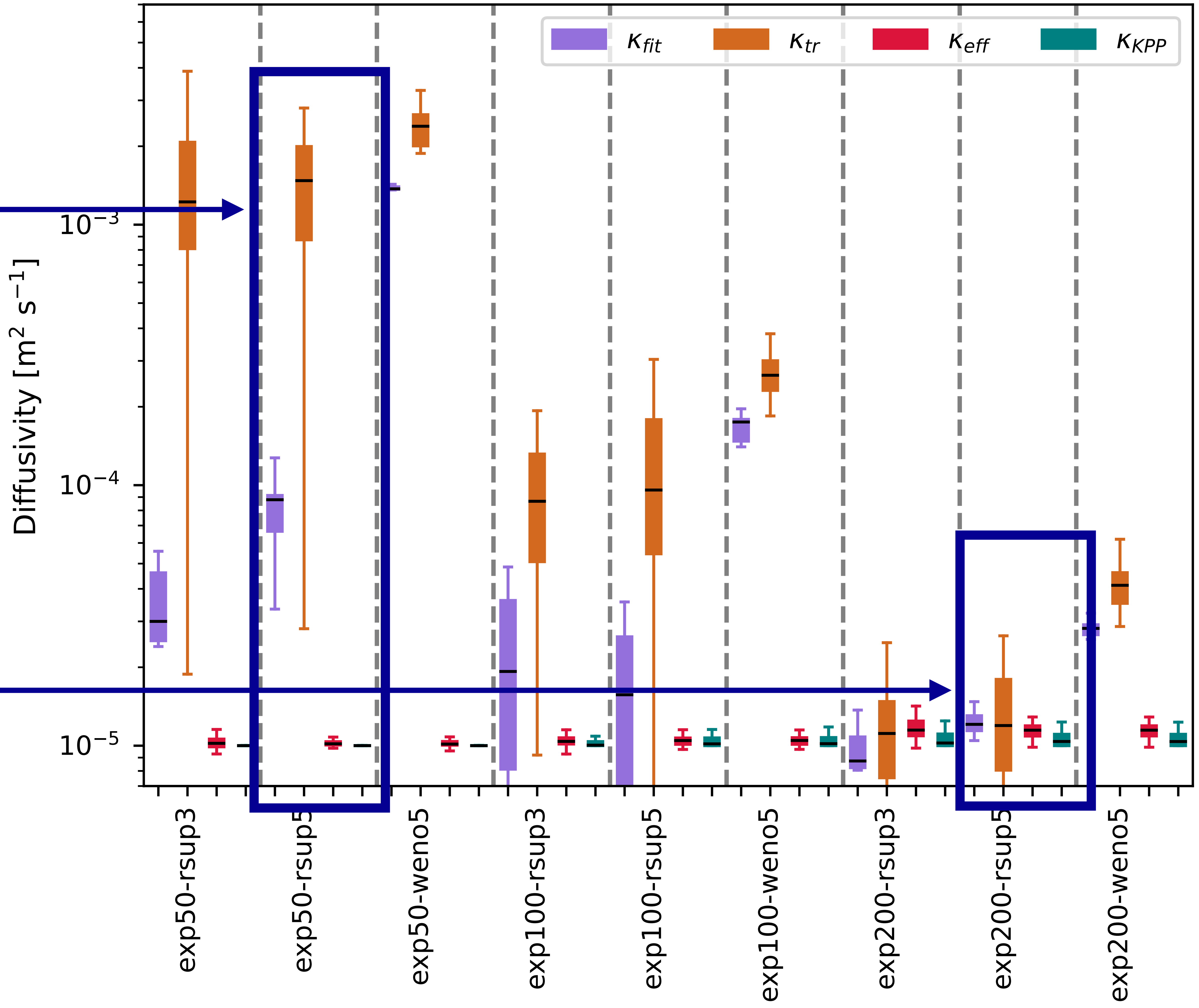
50 vert. lev.



Dispersive effects at low vert. res.

200 vert. lev



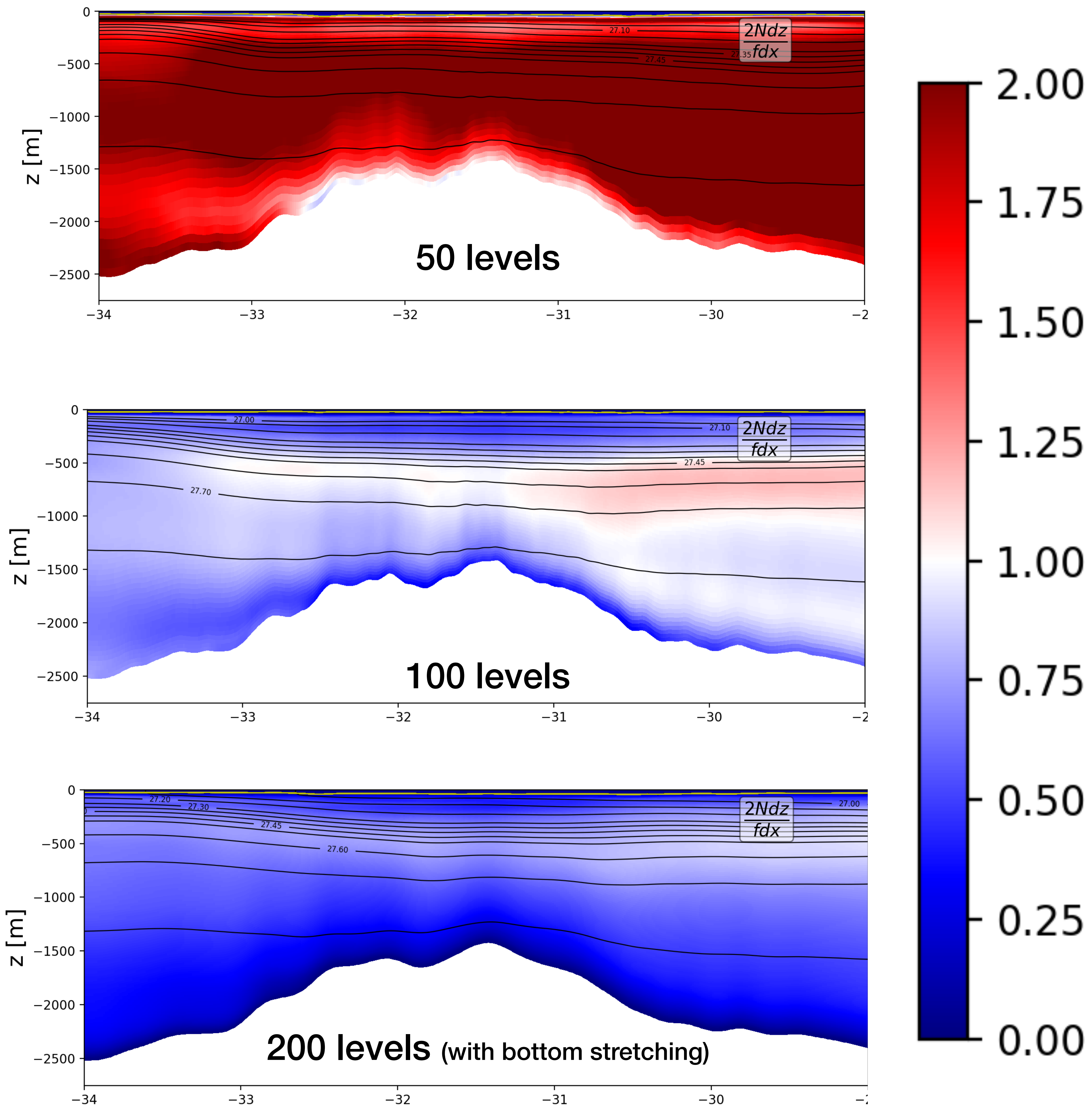


Very good agreement between all methods with 200 levels [and low numerical mixing]

[Schifano et al, submitted]

Instabilité BICK?

$$\frac{2Ndz}{fdx}$$

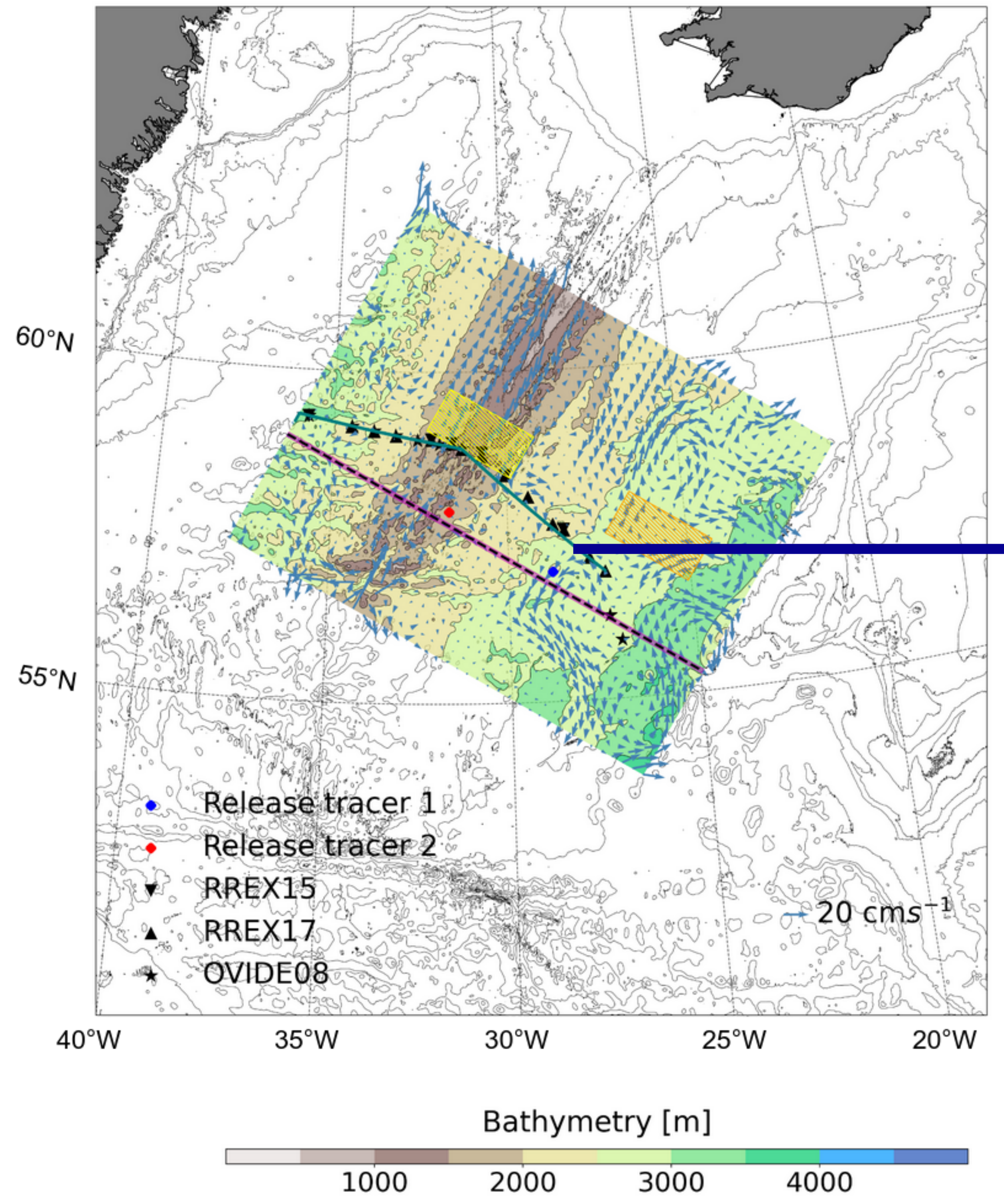


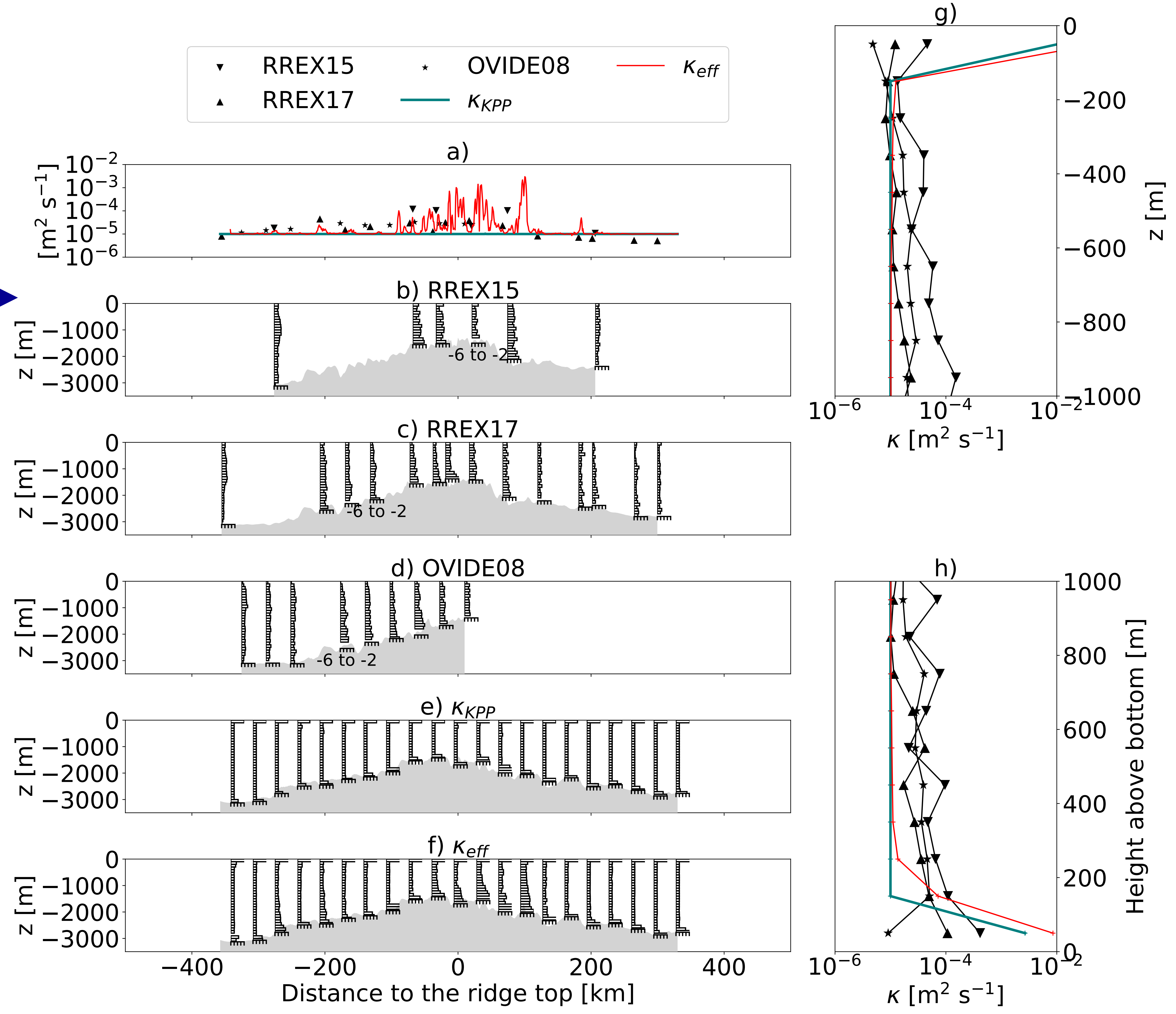
Instability criteria: $\frac{2Ndz}{fdx} > 1$

BICK possible for low vert res (50 levels) outside of the mixed-layer.

Diapycnal mixing in observations

Observations from RREX and OVIDE cruises:





- Mixing too low with KPP in the interior [Richardson numbers not small enough]
  - -> remove background and increase critical Richardson ? [Thakur et al. (2022); Momeni et al. (2024)]
- Implicit diffusion adds diffusivity above slopes, where it is needed… but not necessary for good reasons

[Schifano et al, submitted]

Conclusion 1

We have tested online diagnostics of effective diffusivity, and tracer-based diagnostics, which agree well when vertical resolution is sufficient.

✳ Other type of budgets (based on WMT and APE) are currently underway.

If you care about diapycnal diffusivities, you have to be careful with the numerical choices (and the topography smoothing) to avoid too high numerical diffusivities, even at sub-kilometre resolution.

Developments in rotated diffusion operators, higher-order schemes, or the Brinkman penalization approach [Debreu et al., 20,22] may be needed to improve the limitations related to high topographic gradients.

Realism of KPP or $k - \epsilon$ in this class of simulations remains to be more carefully assessed. Grey zone concerning internal waves driven mixing.

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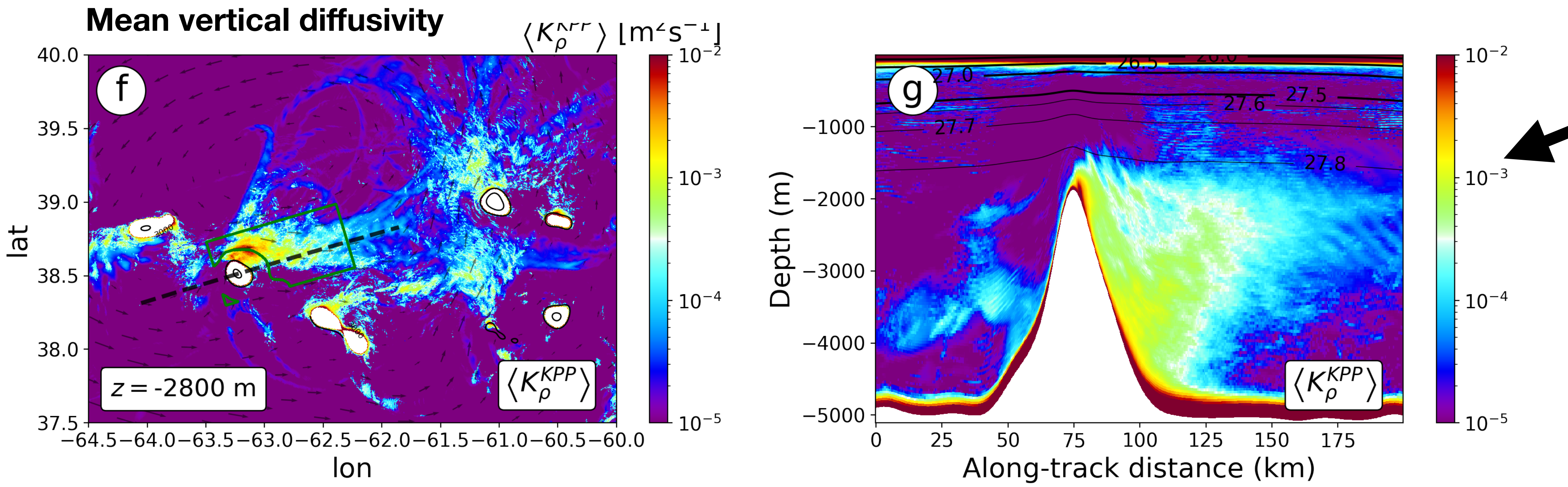
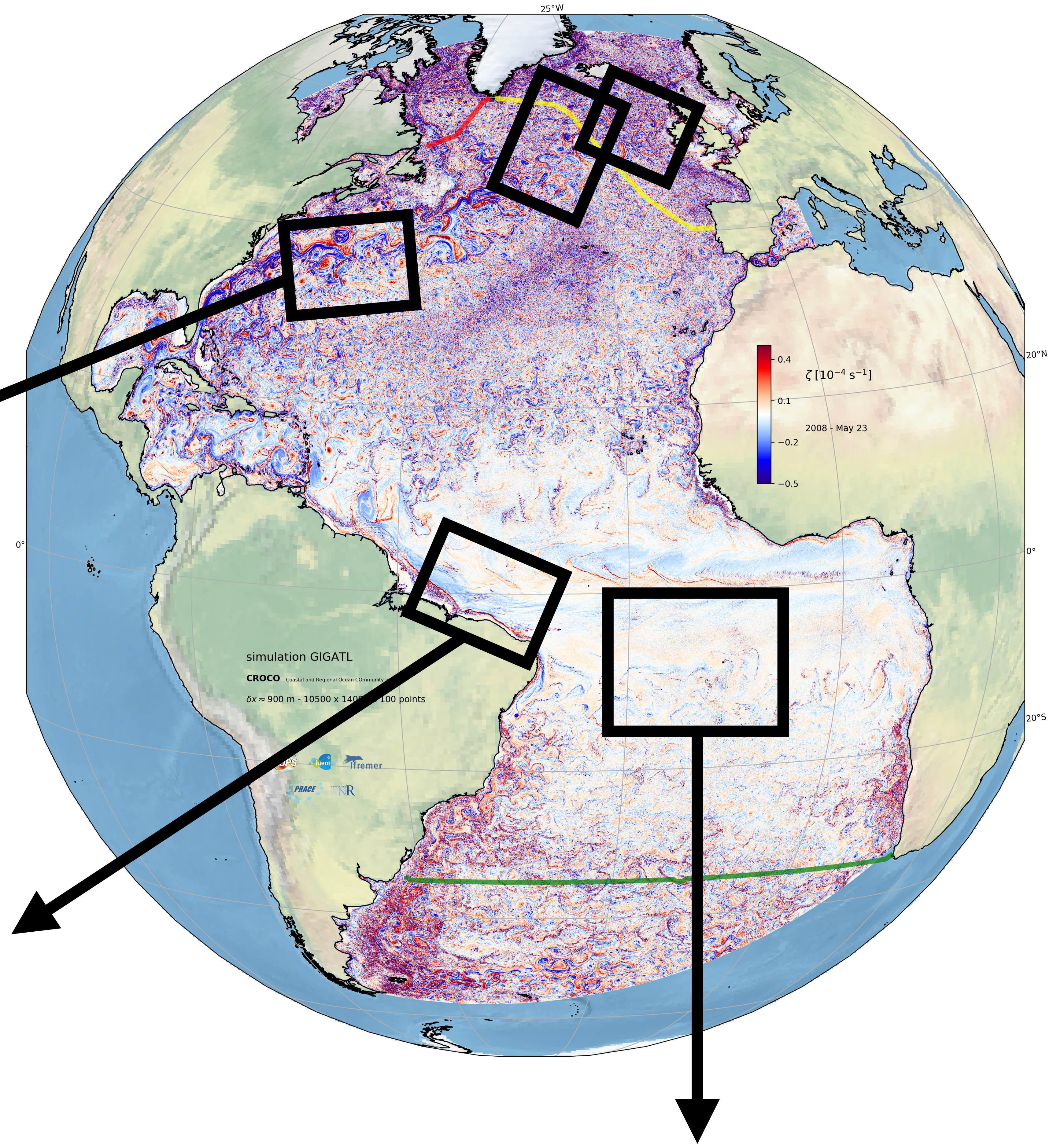
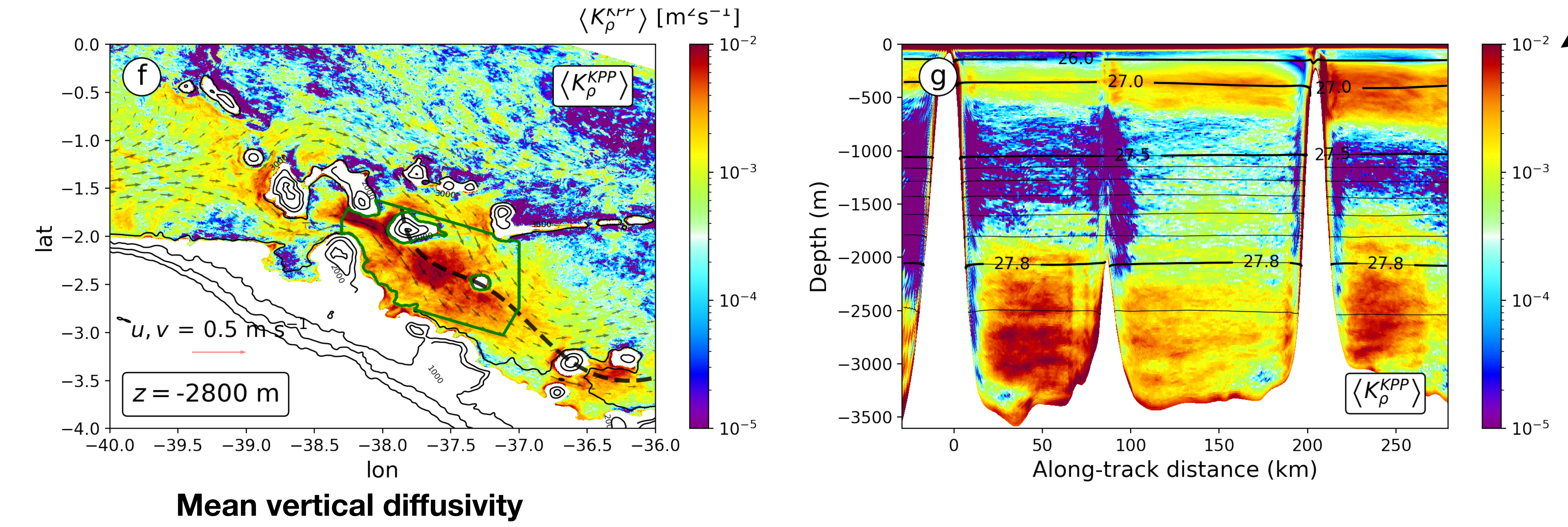
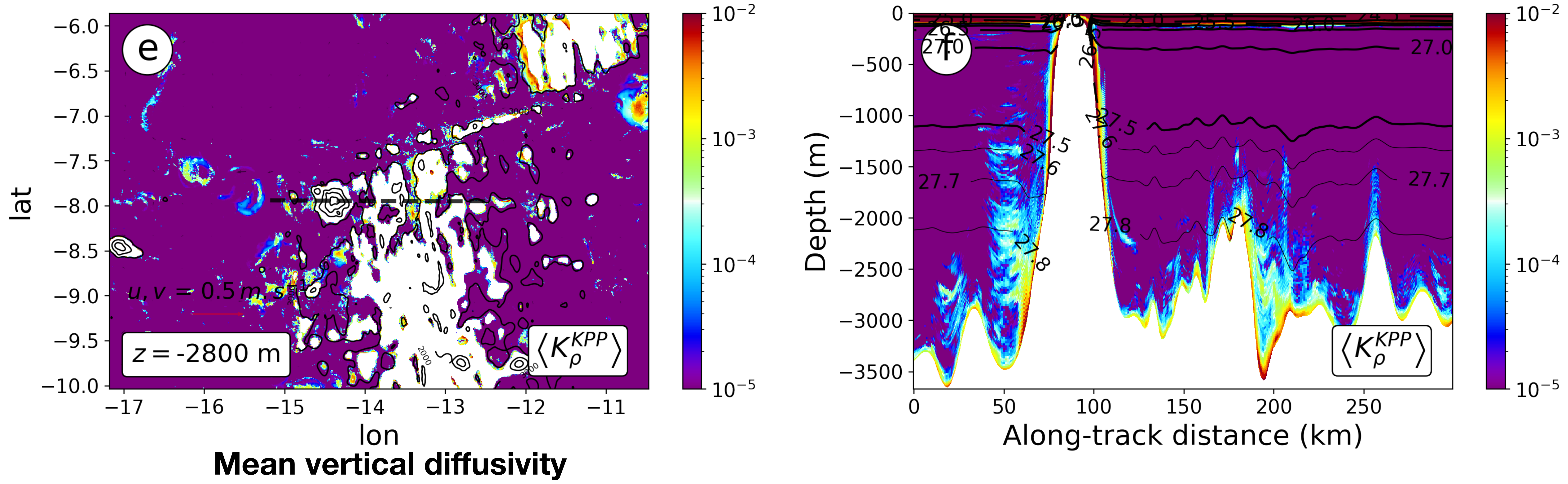
Mixing in seamount wakes







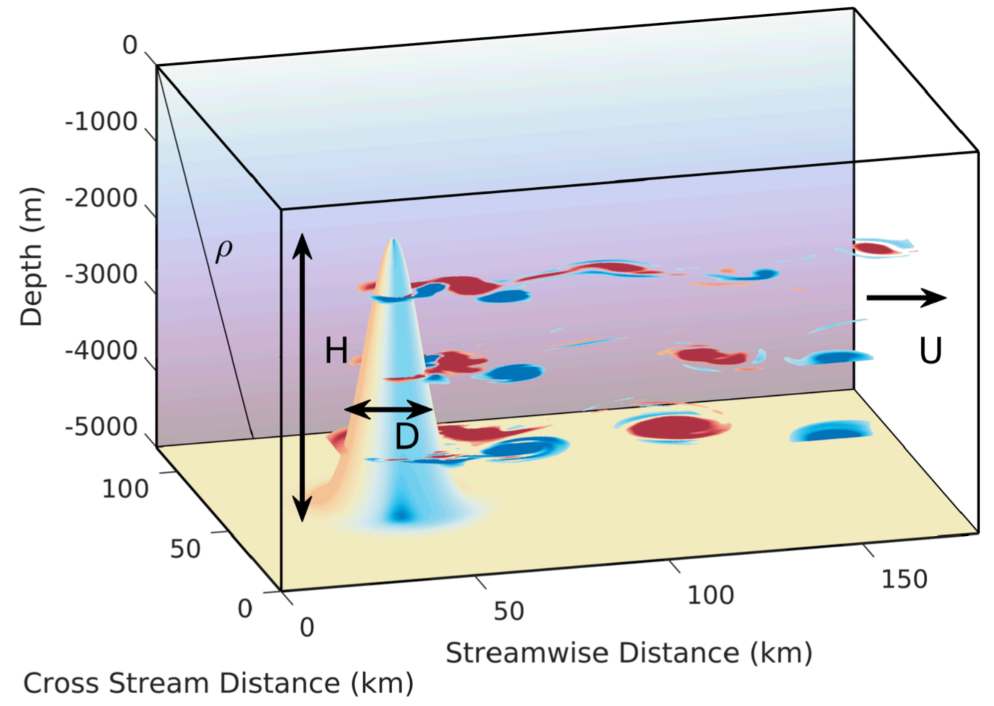


Enhanced diffusivities in seamount wakes

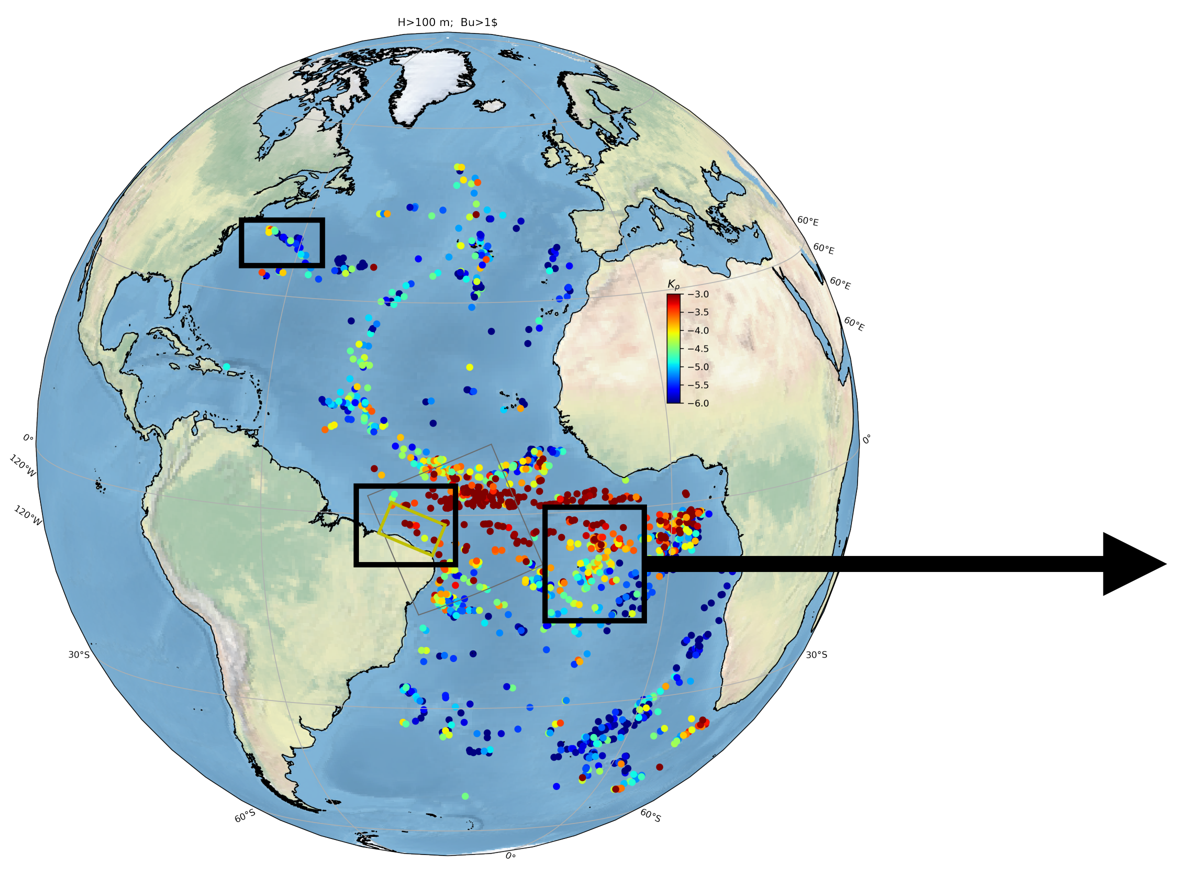
Mixing in seamount wakes

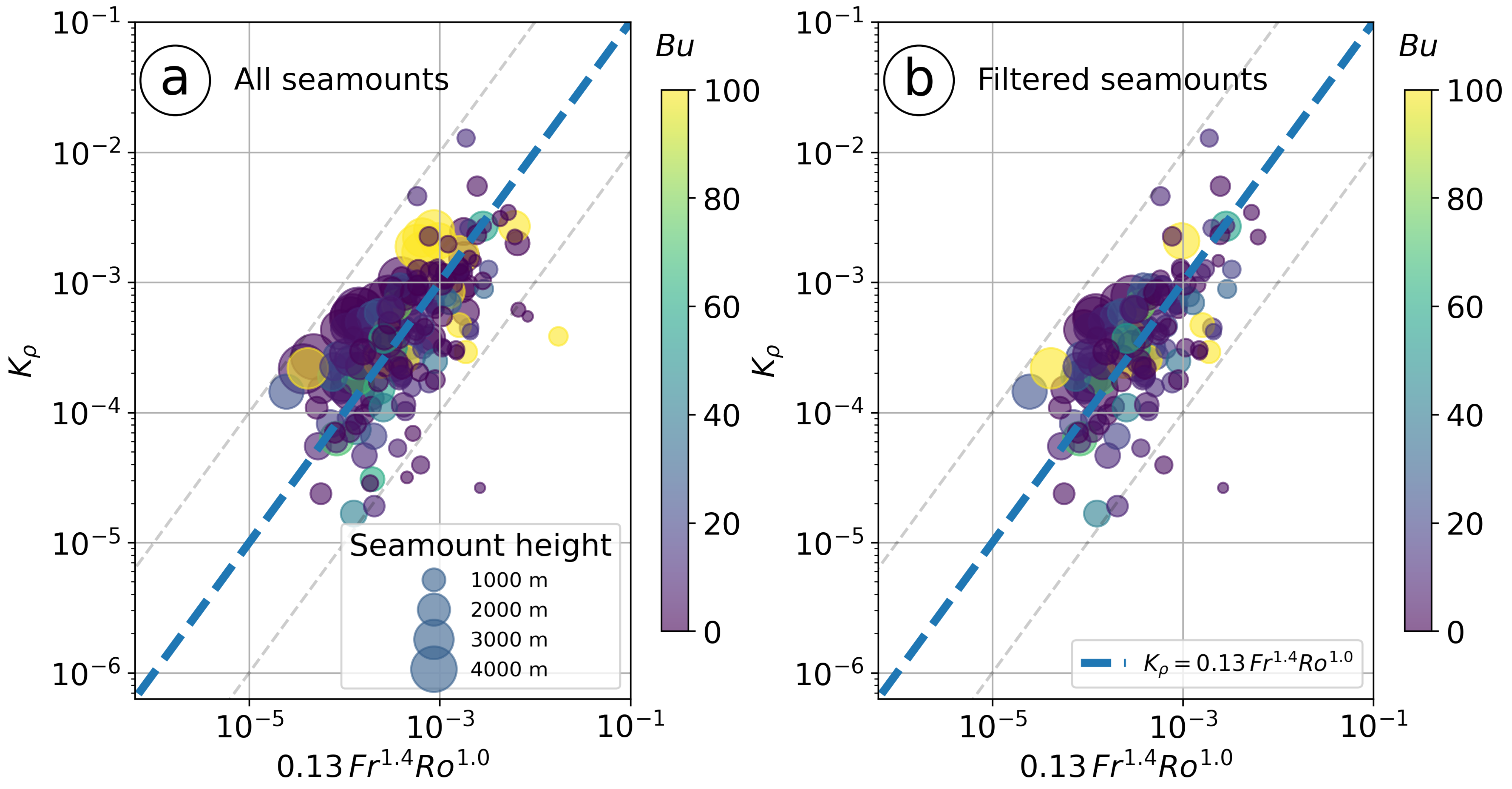
Coming up with a scaling for seamount wakes mixing:

- Rossby Number: $Ro = \dfrac{U}{fD}$
- Froude Number: $Fr = \dfrac{U}{NH}$



- Directly diagnosed from realistic simulations:



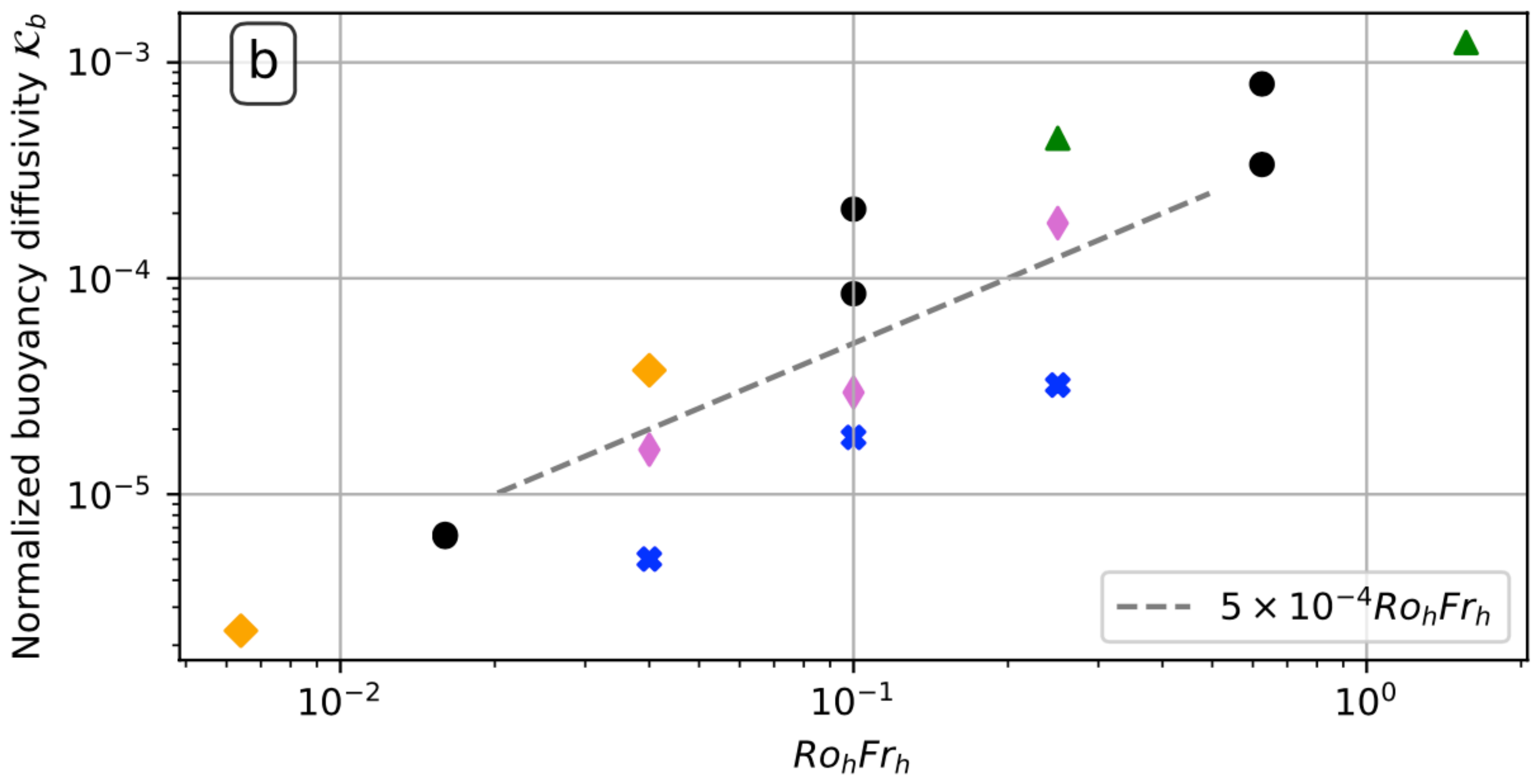


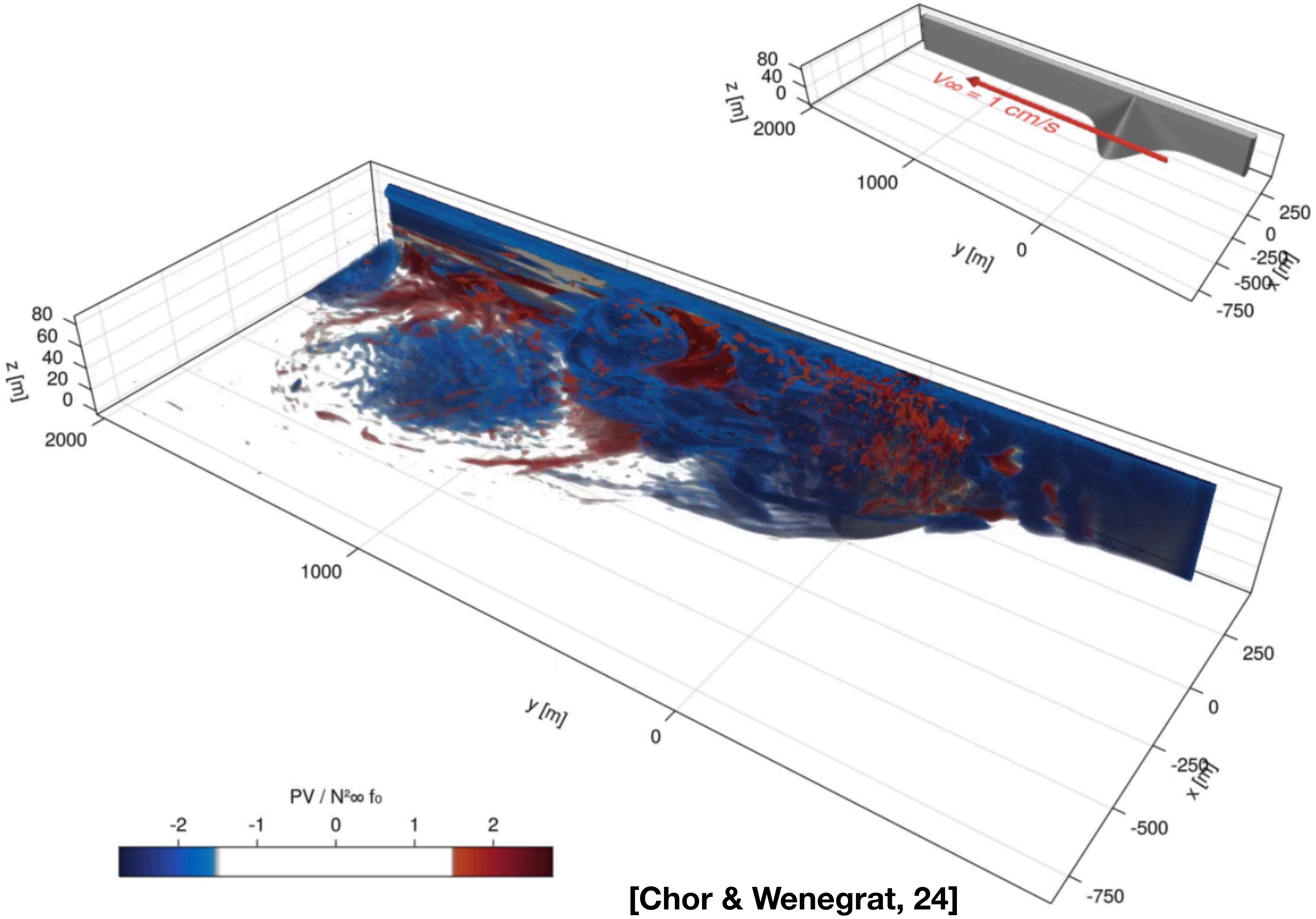
$$\longrightarrow \quad K_\rho \sim K_1\, Fr^{1.4}\, Ro^{1}$$

Mixing in seamount wakes

Coming up with a scaling for seamount wakes mixing:

- Recent results from LES with Oceananigans [1.6 m x 2 m x 0.6 m] points to $K_\rho \sim \; Fr\, Ro$



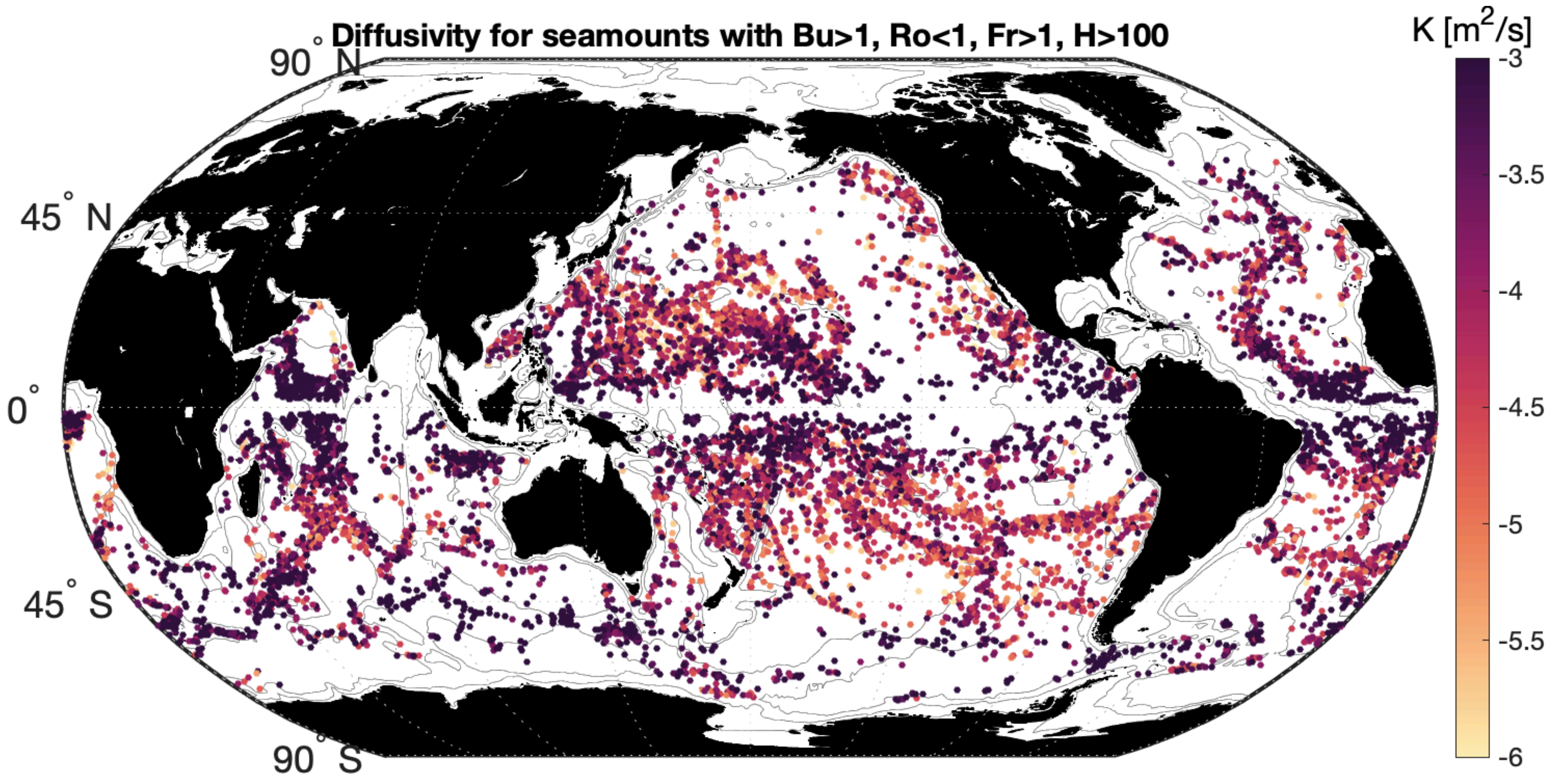


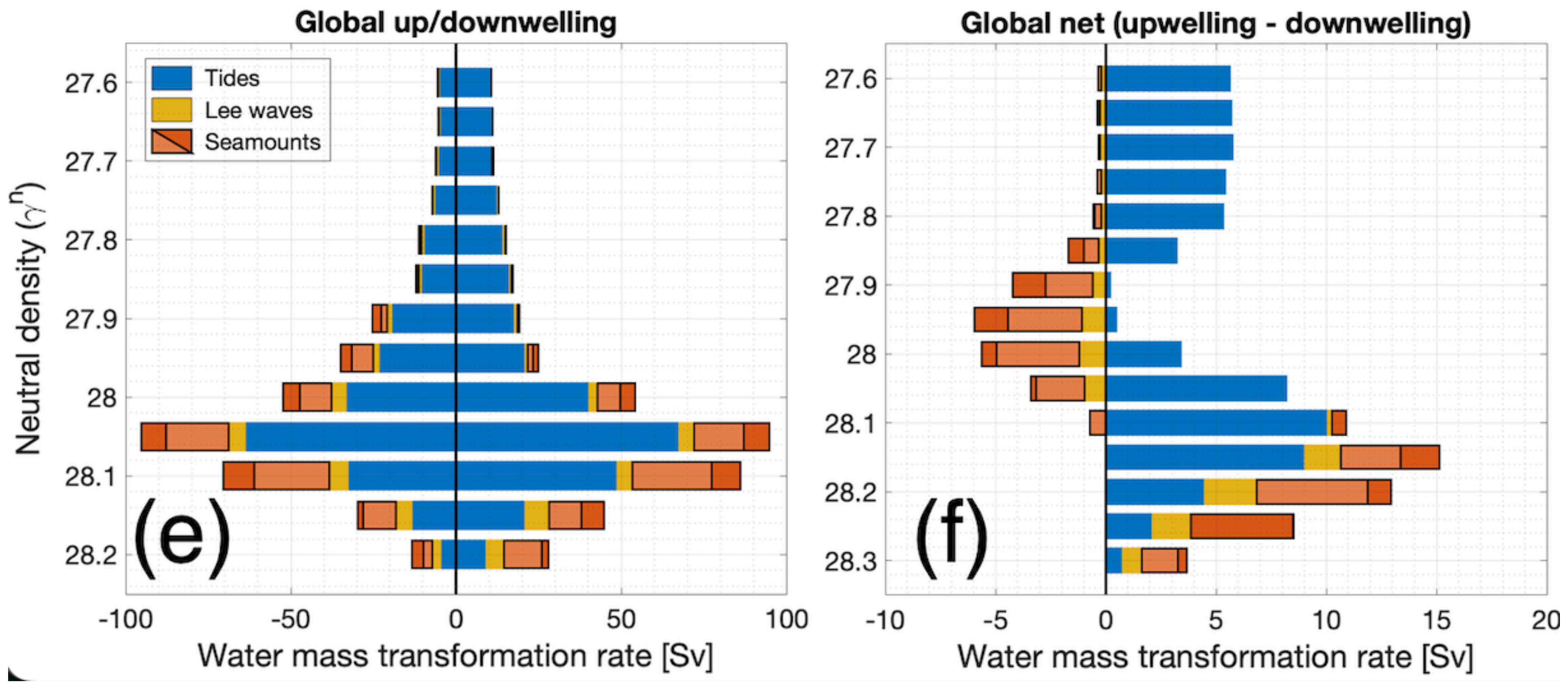
[Chor & Wenegrat, 24]

Mixing in seamount wakes

Global impacts for upwelling of deep-ocean waters:

- Scaling for seamount wakes mixing:
$$K_\rho \sim K_1 \, Fr^{1.4} \, Ro^1$$
- A global census of seamounts (H,D)
- A global climatology of currents and stratification (U, N)





Mashayek, A., J. Gula, L. Baker, A. Naveira Garabato, L. Cimoli, J. Riley & C. de Lavergne, 2024 : On the role of seamounts in upwelling deep-ocean waters through turbulent mixing, *Proc. Natl. Acad. Sci. U.S.A.*,

Seamount-induced mixing is a significant player (compared to internal waves) in both the upwelling and downwelling components of the transformation, as well as in the net global- or basin-scale diapycnal transfers.

Conclusion 2

Scalings highlight a potentially significant impact of seamount wakes on global ocean mixing

Processes still remain to be understood in a more realistic context

Modeling has not converged yet (unresolved processes) - toward LES

More observations are needed to assess models and build parameterizations (of turbulence, but also of topography itself!)

Thanks for your attention