Overturning of the Mediterranean Thermohaline Circulation

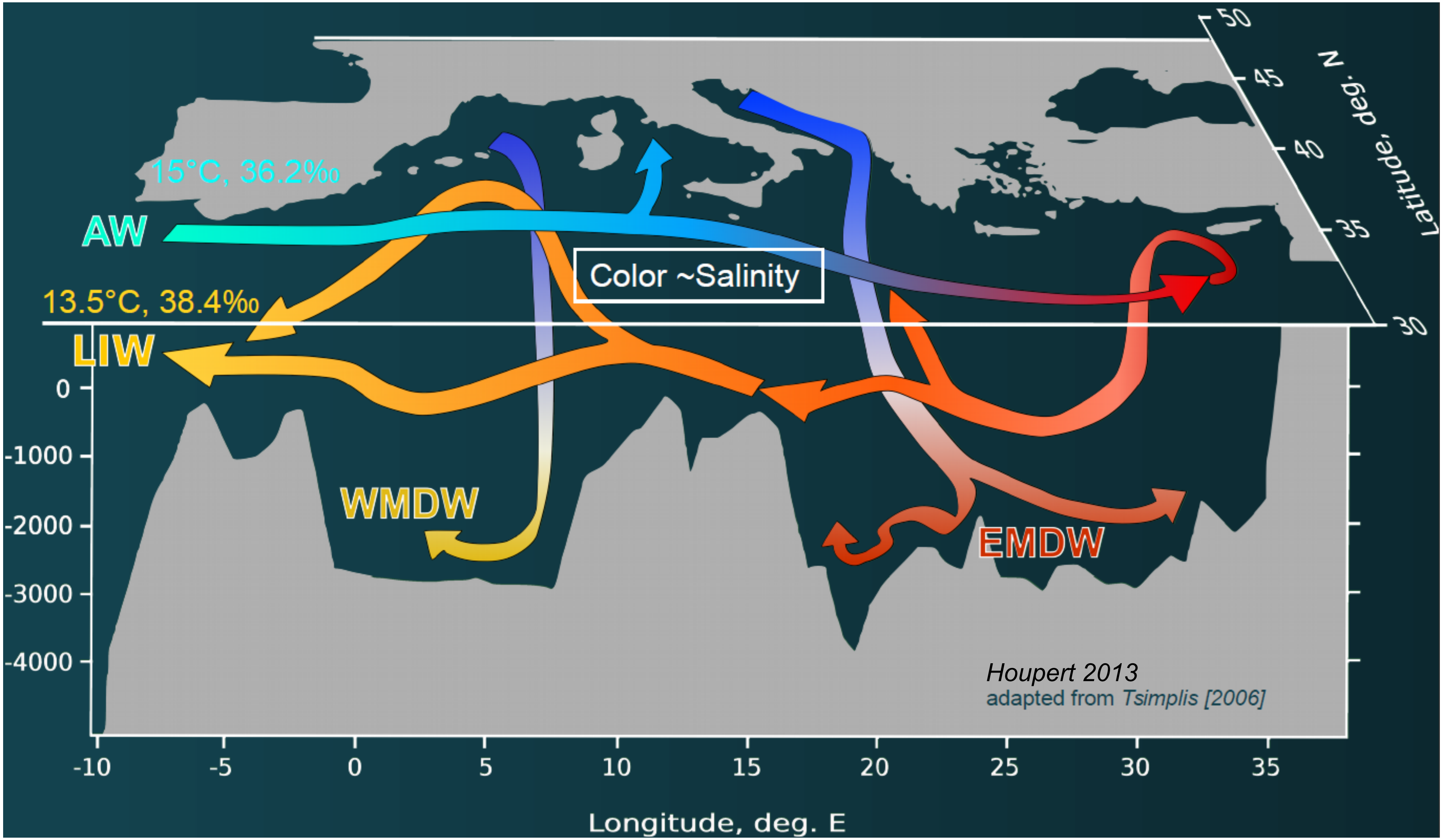
Robin Waldman[1], Nils Brüggemann[2], Anthony Bosse[3], Rémi Pagès[4], Samuel Somot[1], Michael Spall[5], Florence Sevault[1], Melika Baklouti[4]

[1] CNRM, Météo France / CNRS, Toulouse, France
[2] University of Hamburg, Hamburg, Germany
[3] University of Bergen, Bergen, Norway
[4] MIO, Toulon, France
[5] WHOI, Woods Hole, USA

The Mediterranean thermohaline circulation

→ Oceanic convection and sinking are usually assumed to be equivalent.

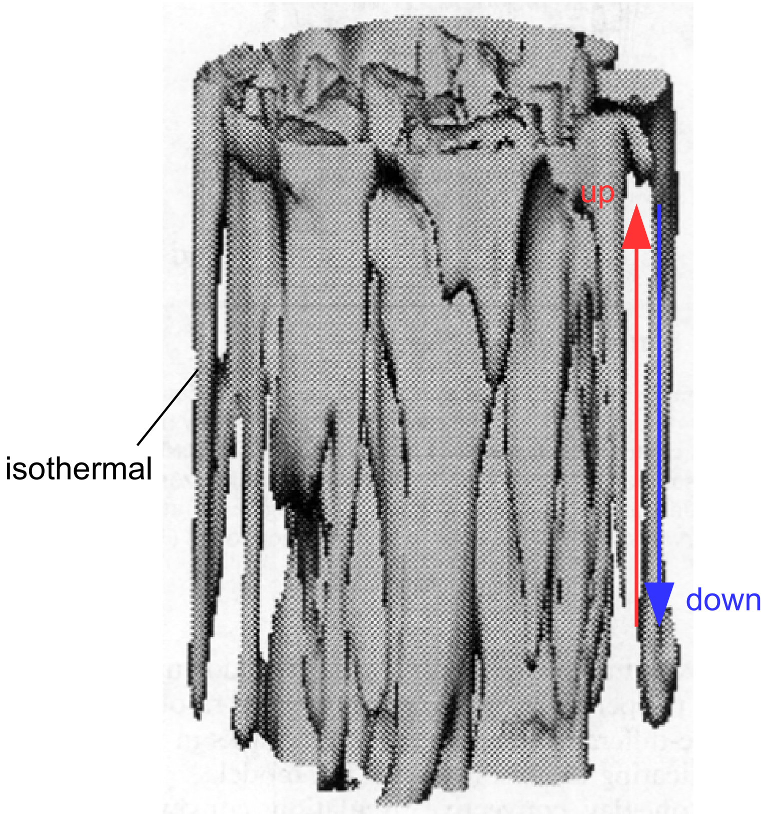
Schematic of the Mediterranean Thermohaline Circulation



Convection = Sinking?

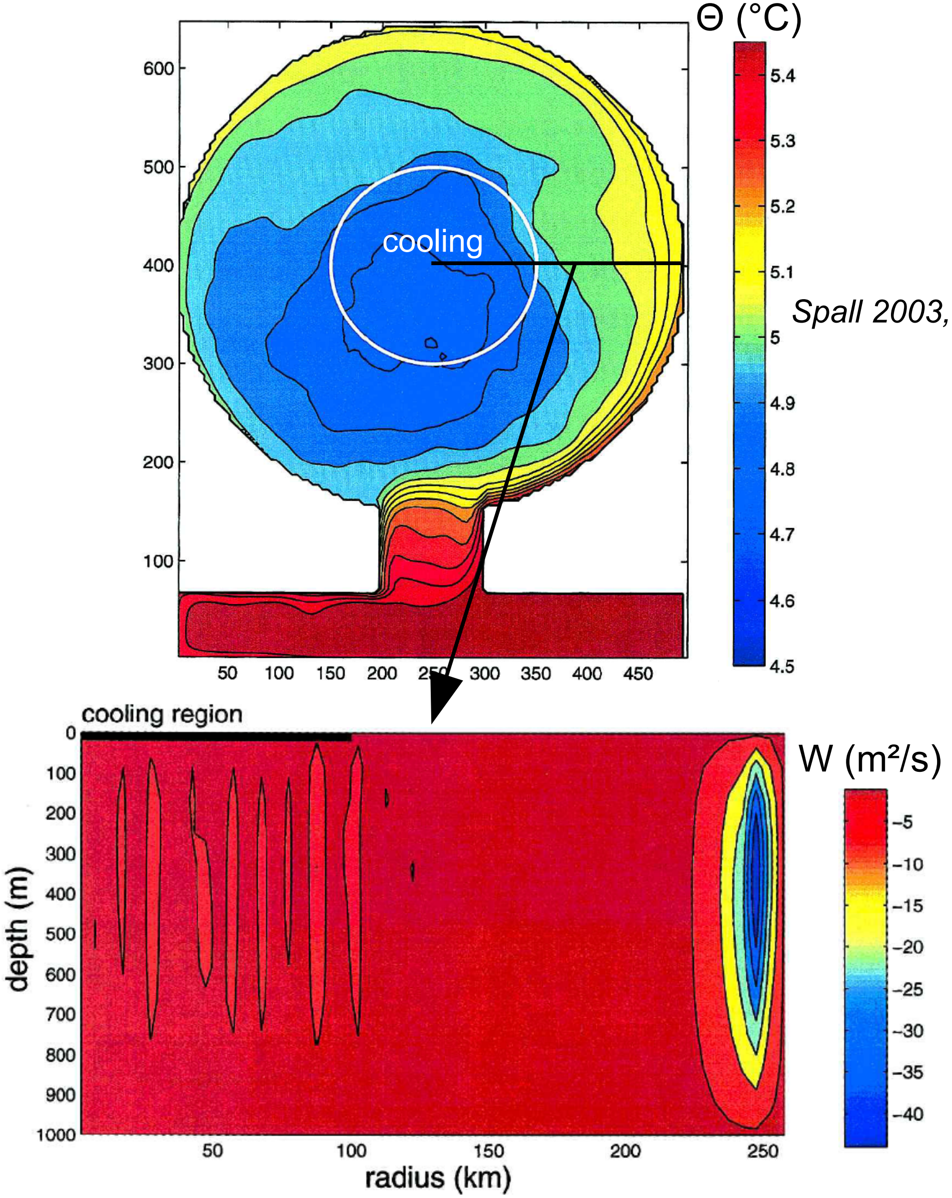
→ Idealized simulations suggest they are separate

Snapshot of a convective « chimney » from a large eddy simulation



Jones and Marshall 1993

Downwelling from an idealized eddy-resolving (5km) model



Spall 2003, 2004

Questions

→ Where and how does the Mediterranean thermohaline circulation sink?

→ What role does it play on biogeochemical exports?

NEMOMED12 + Eco3M-Med

→ Hindcast 1990-2012 physical and biogeochemical simulation (after 10-year spin-up)

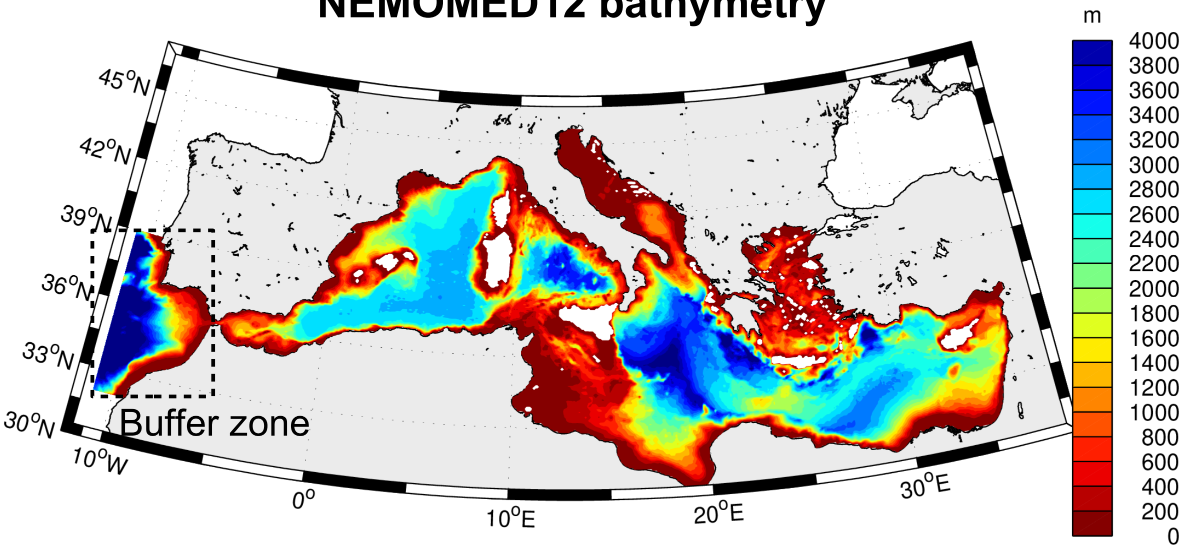
Physics: NEMOMED12

- 75 levels (1 to 130m thick), 1/12° (5.5-7.5km)
- Flux forcing by ALDERA (12km) with SST damping
- 3D restoration in the Atlantic buffer zone
- Monthly river / Black Sea runoff climatology

Biogeochemistry: Eco3M-Med

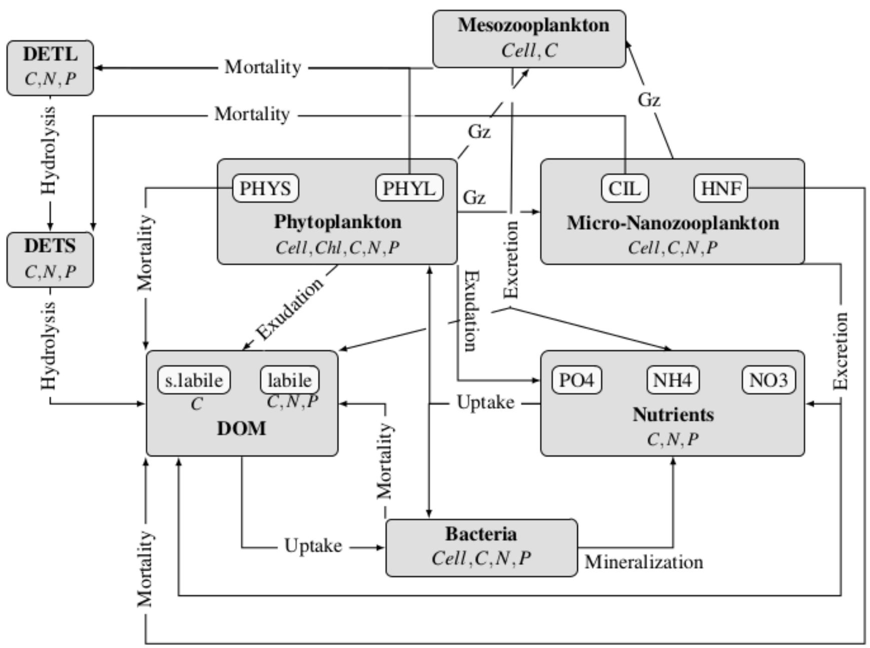
- Offline forcing from NEMOMED12
- 6 plankton functional types
- A pool of dissolved organic matter and 3 pools of inorganic matter
- 2 compartments of detrital organic matter

NEMOMED12 bathymetry



Beuvier et al 2012, Hamon et al 2016

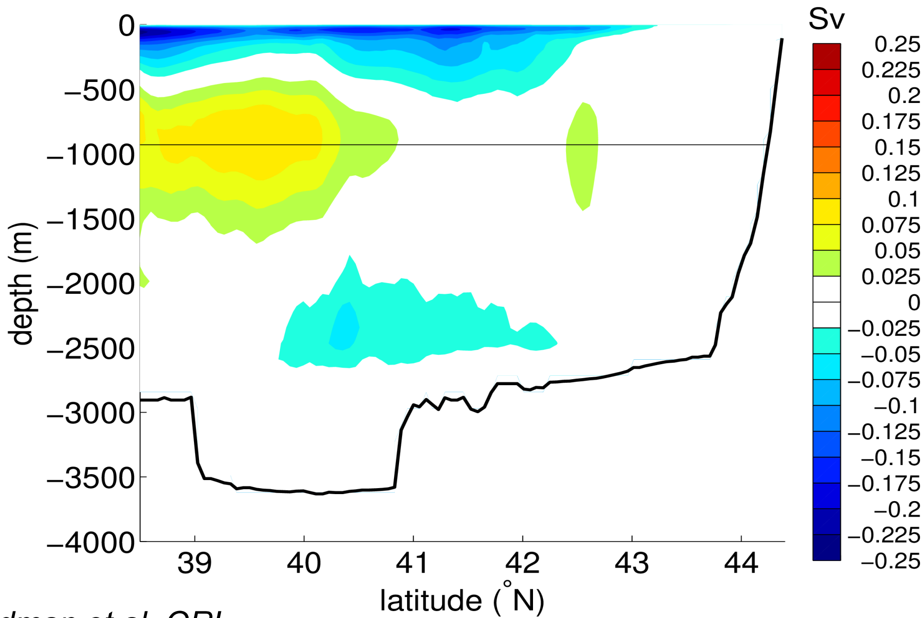
Eco3M state variables



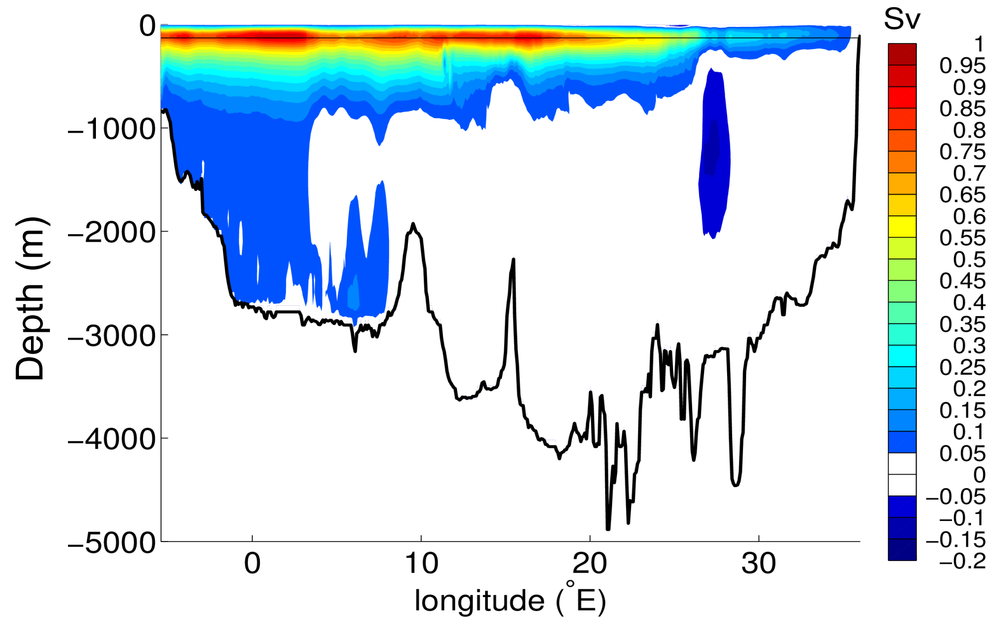
Baklouti et al 2006a, Pagès et al submitted

Overturning circulations

West Med. Meridional Overturning Streamfunction



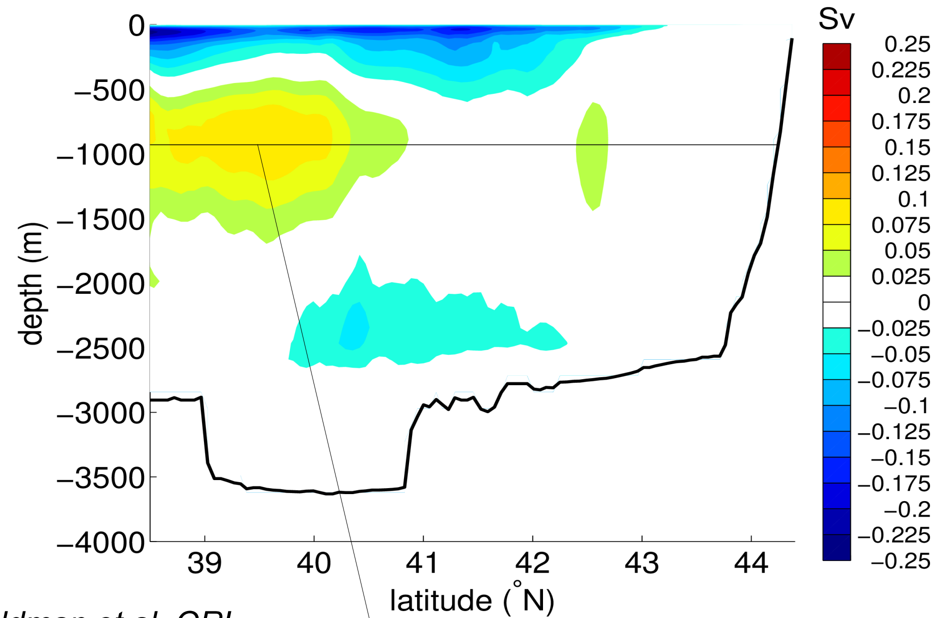
Med. Zonal Overturning Streamfunction



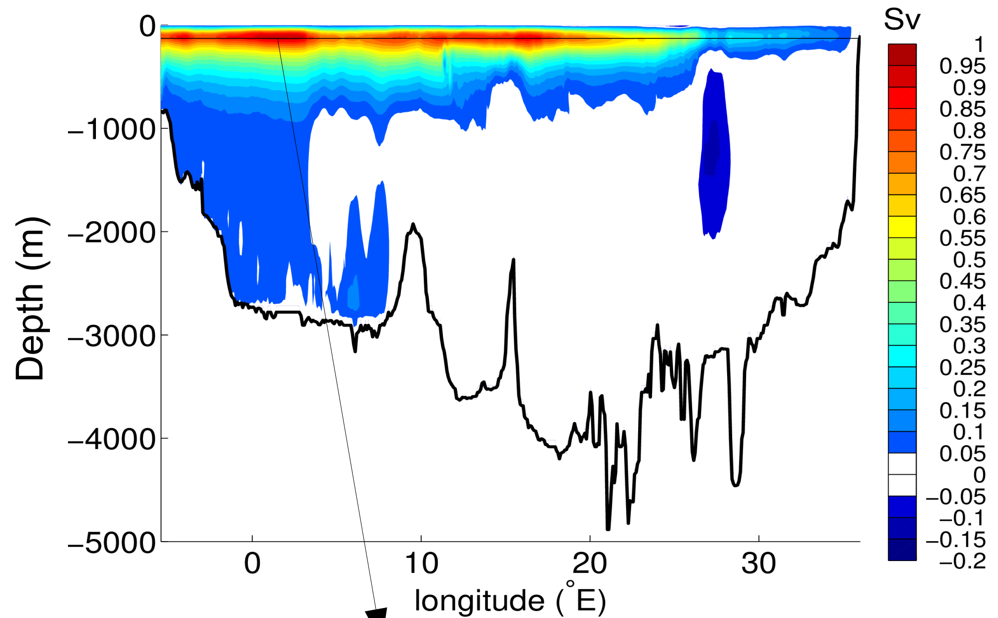
Waldman et al, GRL, 2018b

Regions of downwelling

West Med. Meridional Overturning Streamfunction

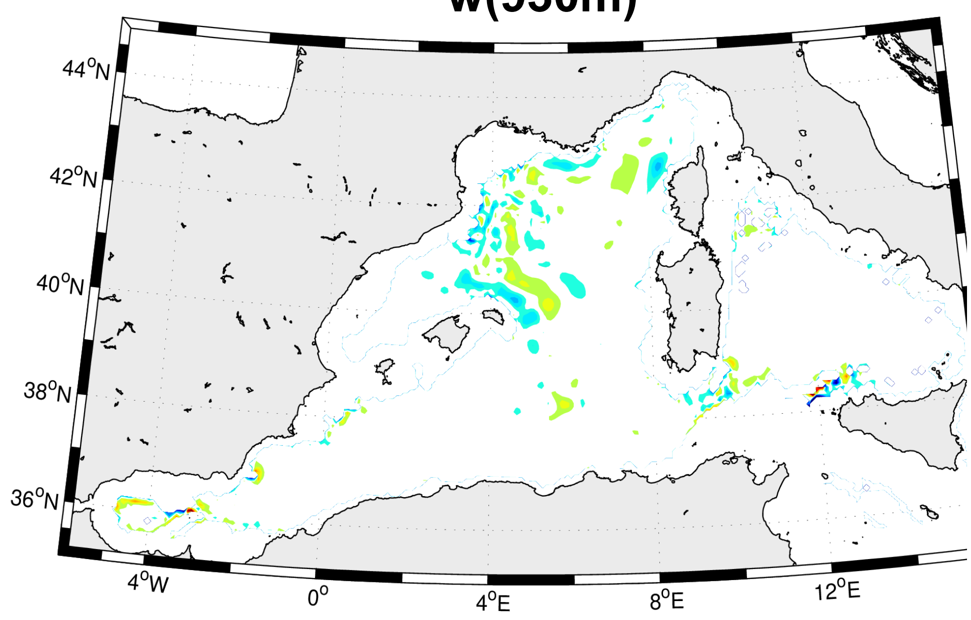


Med. Zonal Overturning Streamfunction

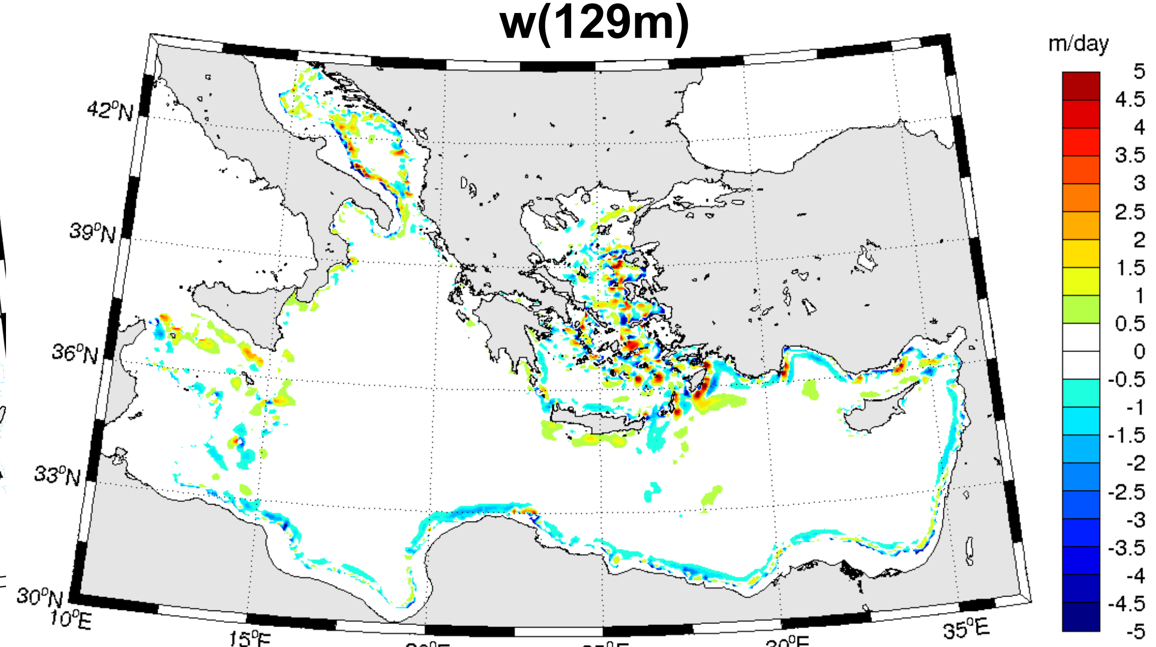


Waldman et al, GRL, 2018b

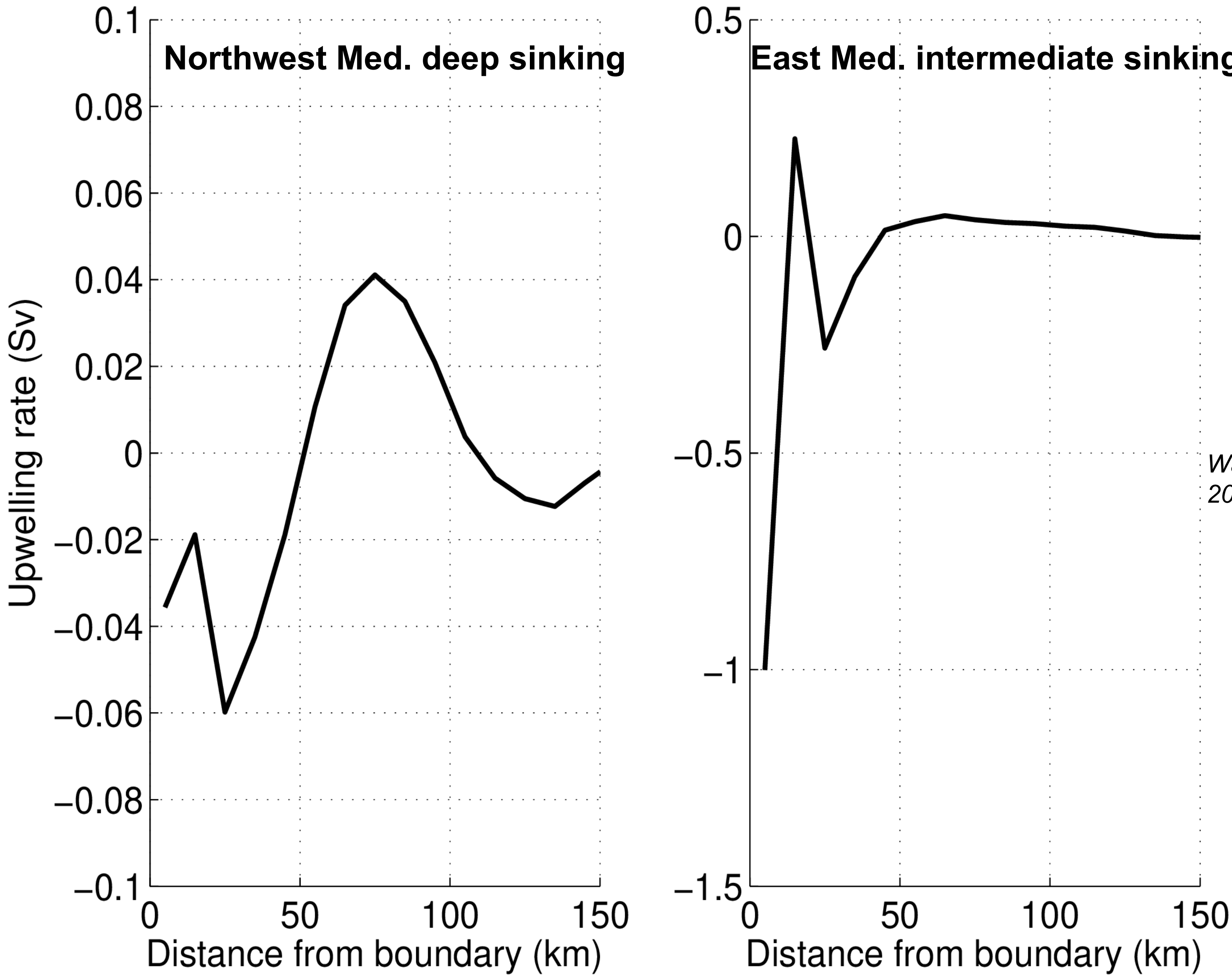
w(930m)



w(129m)



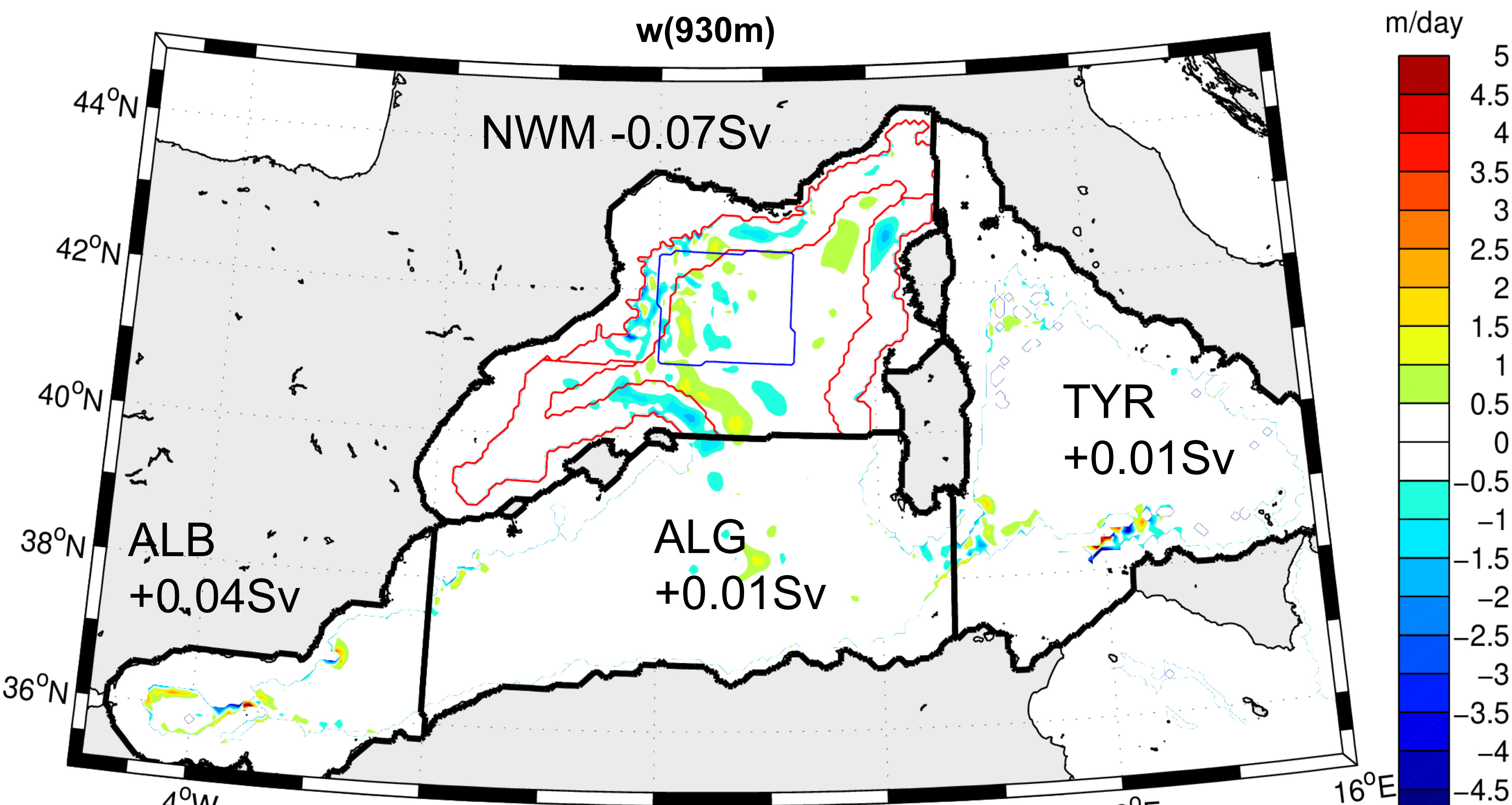
Regions of downwelling



Waldman et al, GRL, 2018b

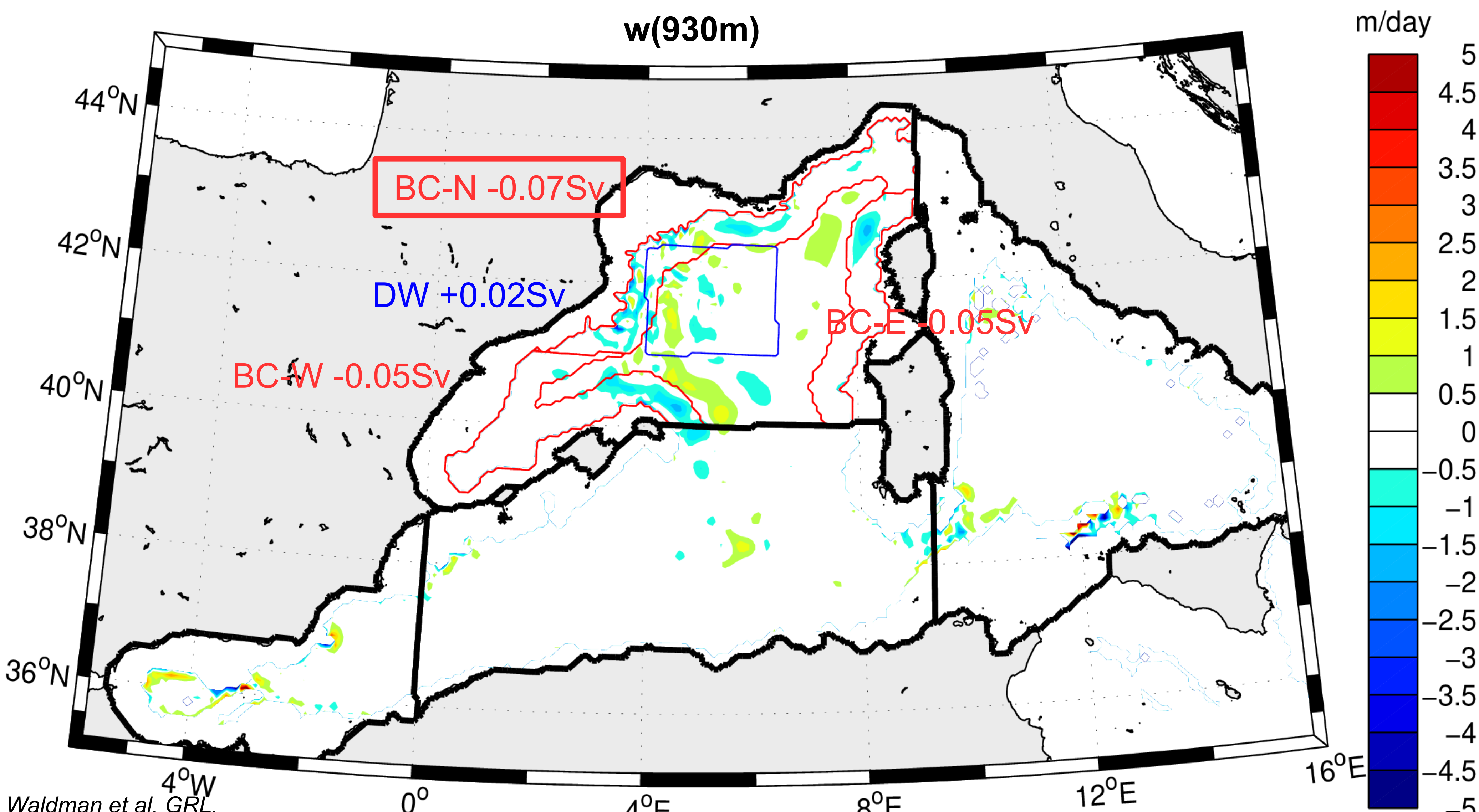
- Most of the sinking within 50km of the coast

Regions of downwelling



Waldman et al, GRL, 2018b

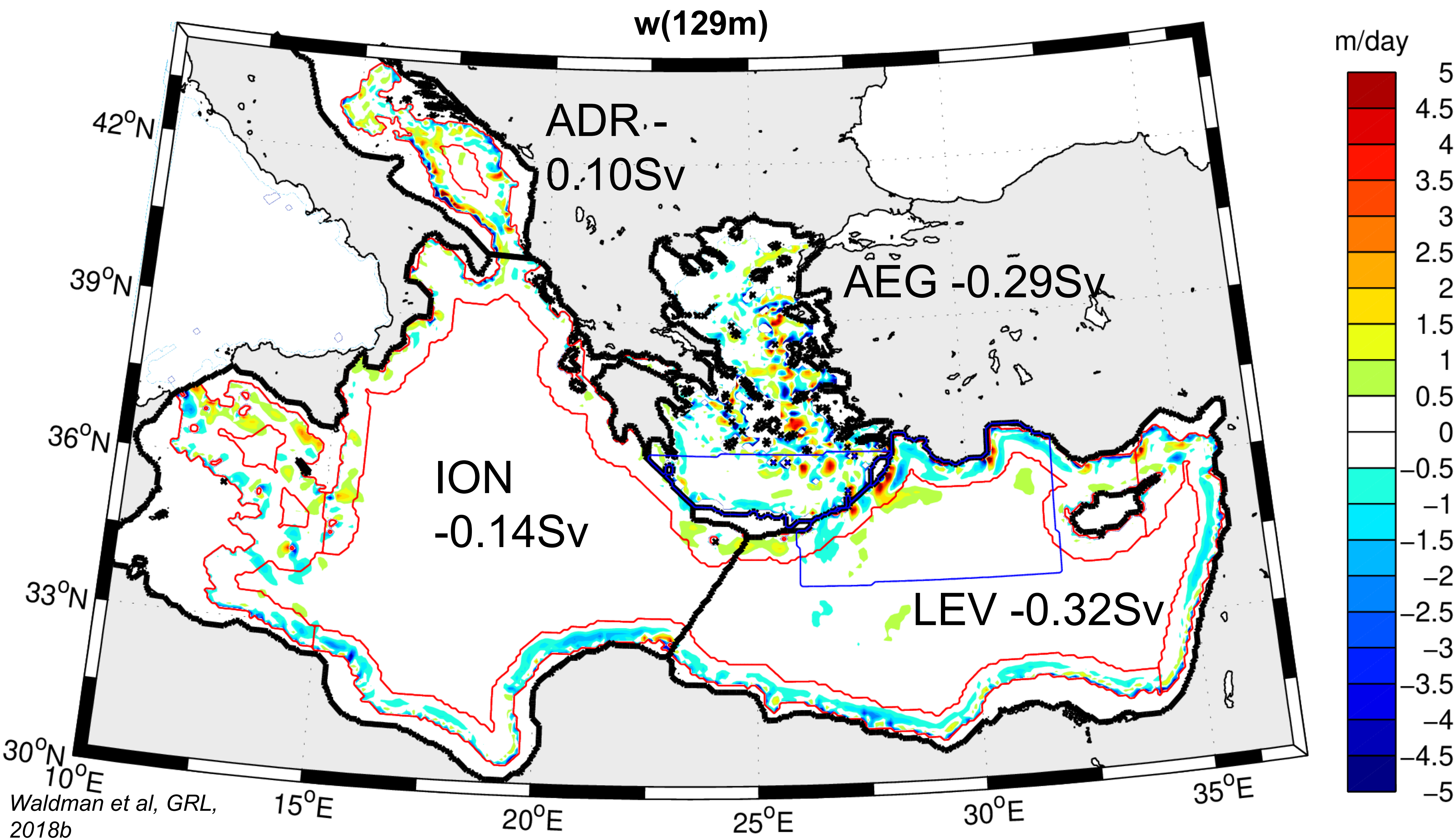
Regions of downwelling



Waldman et al, GRL, 2018b

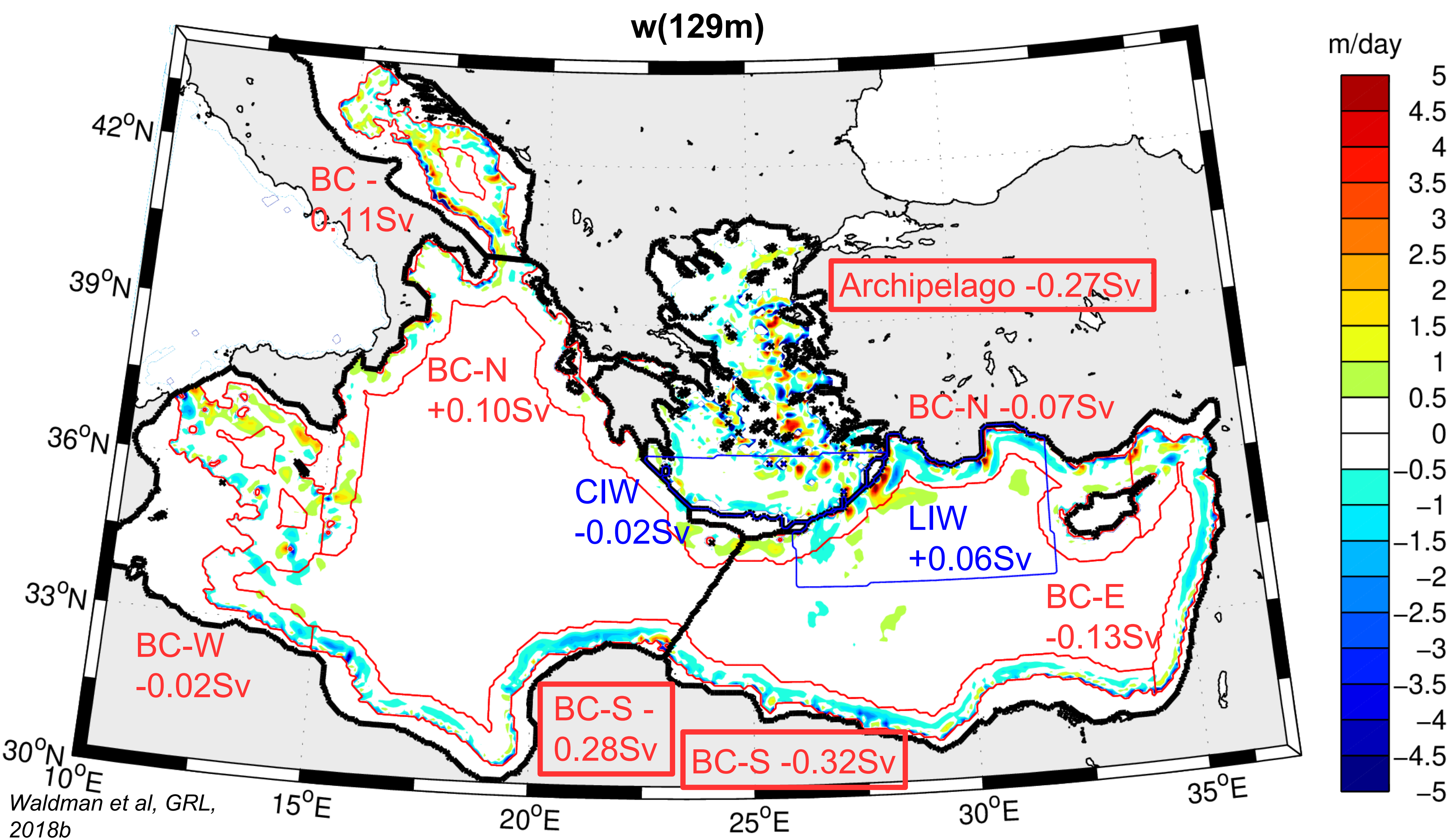
- No sinking in the deep convection area
- The Northern Current dominates the sinking

Regions of downwelling



Waldman et al, GRL, 2018b

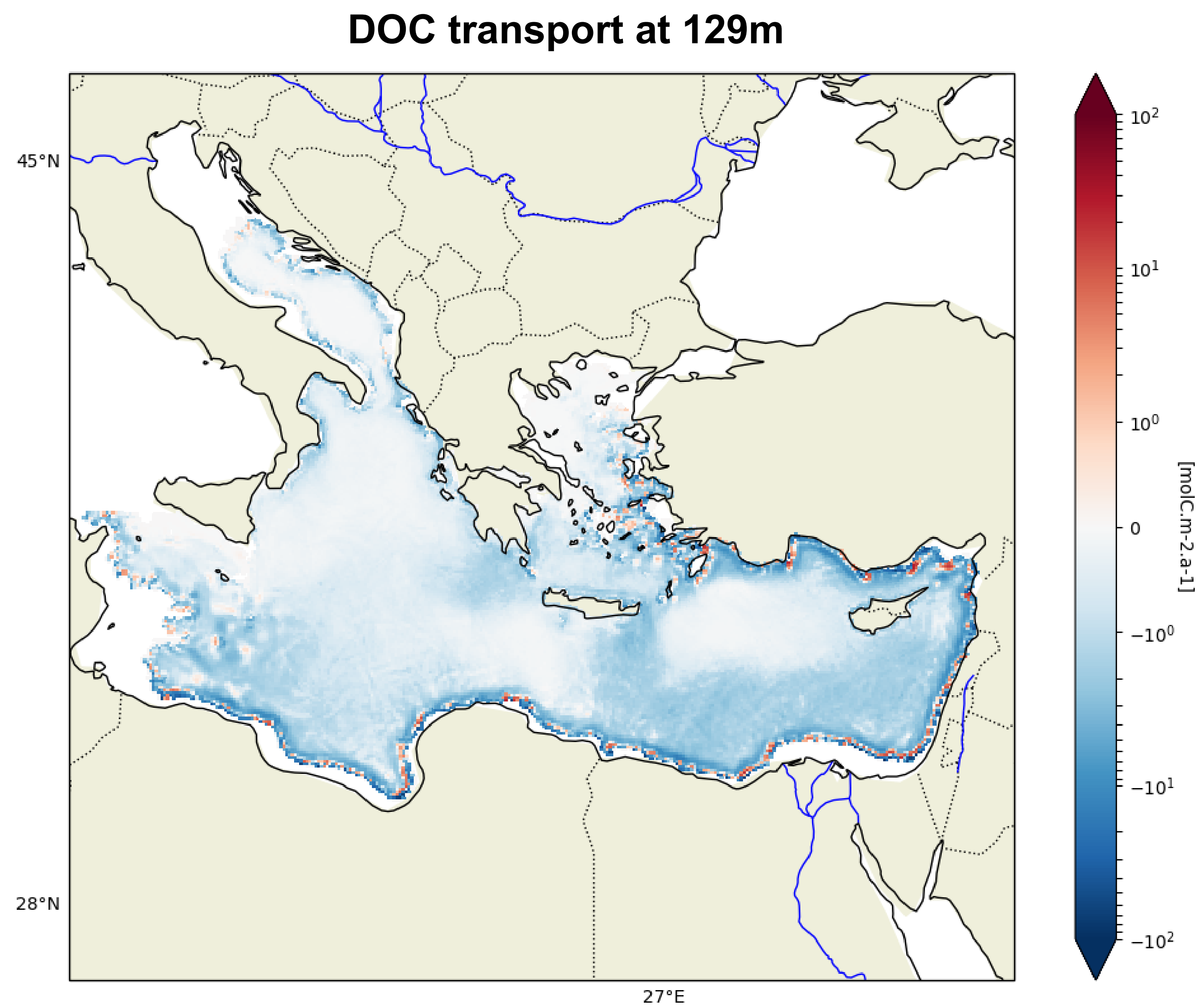
Regions of downwelling



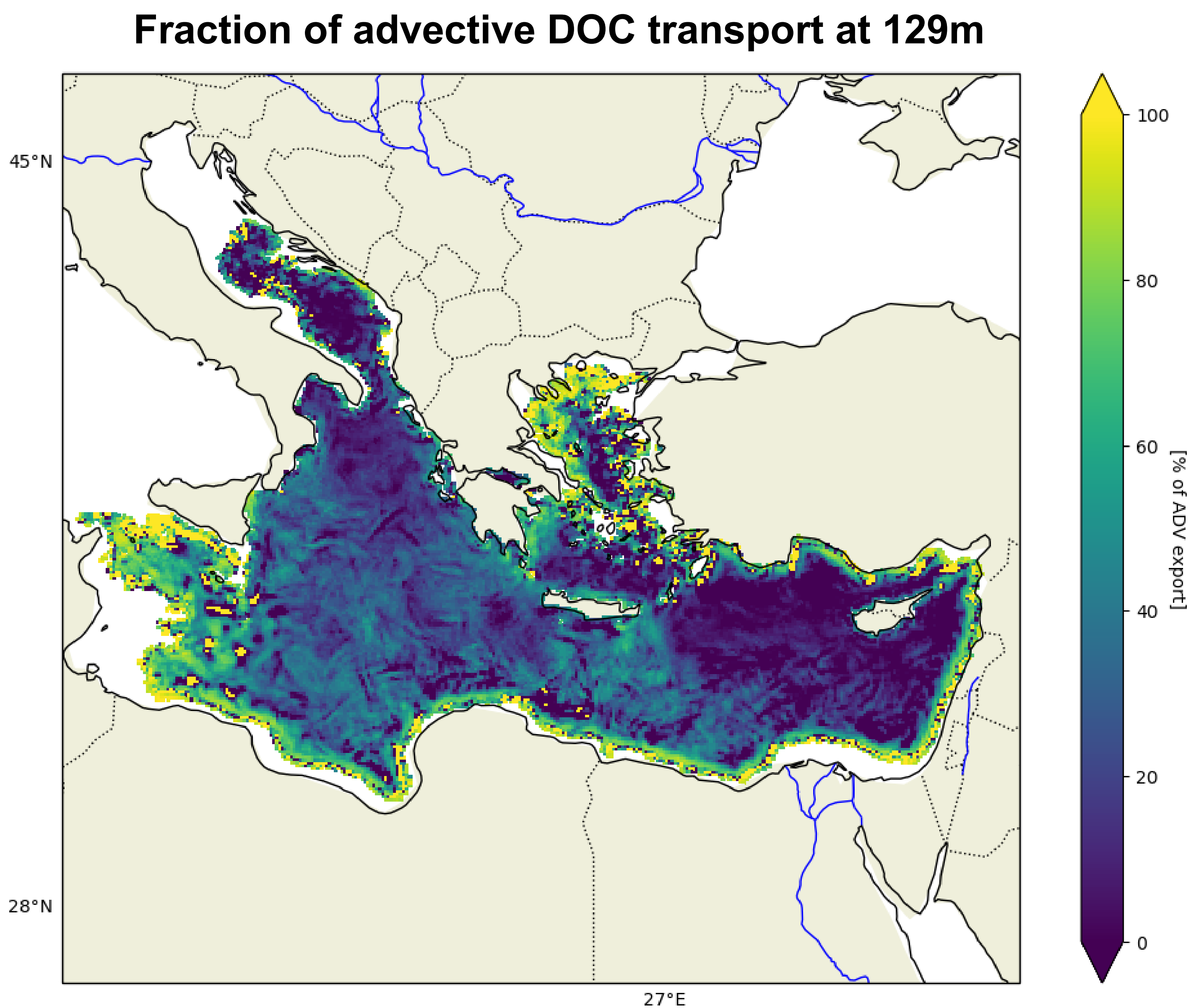
Waldman et al, GRL, 2018b

- No sinking in the intermediate convection areas
- The Libyan and Egyptian Currents and the Aegean archipelago dominate the sinking

Dissolved organic carbon export



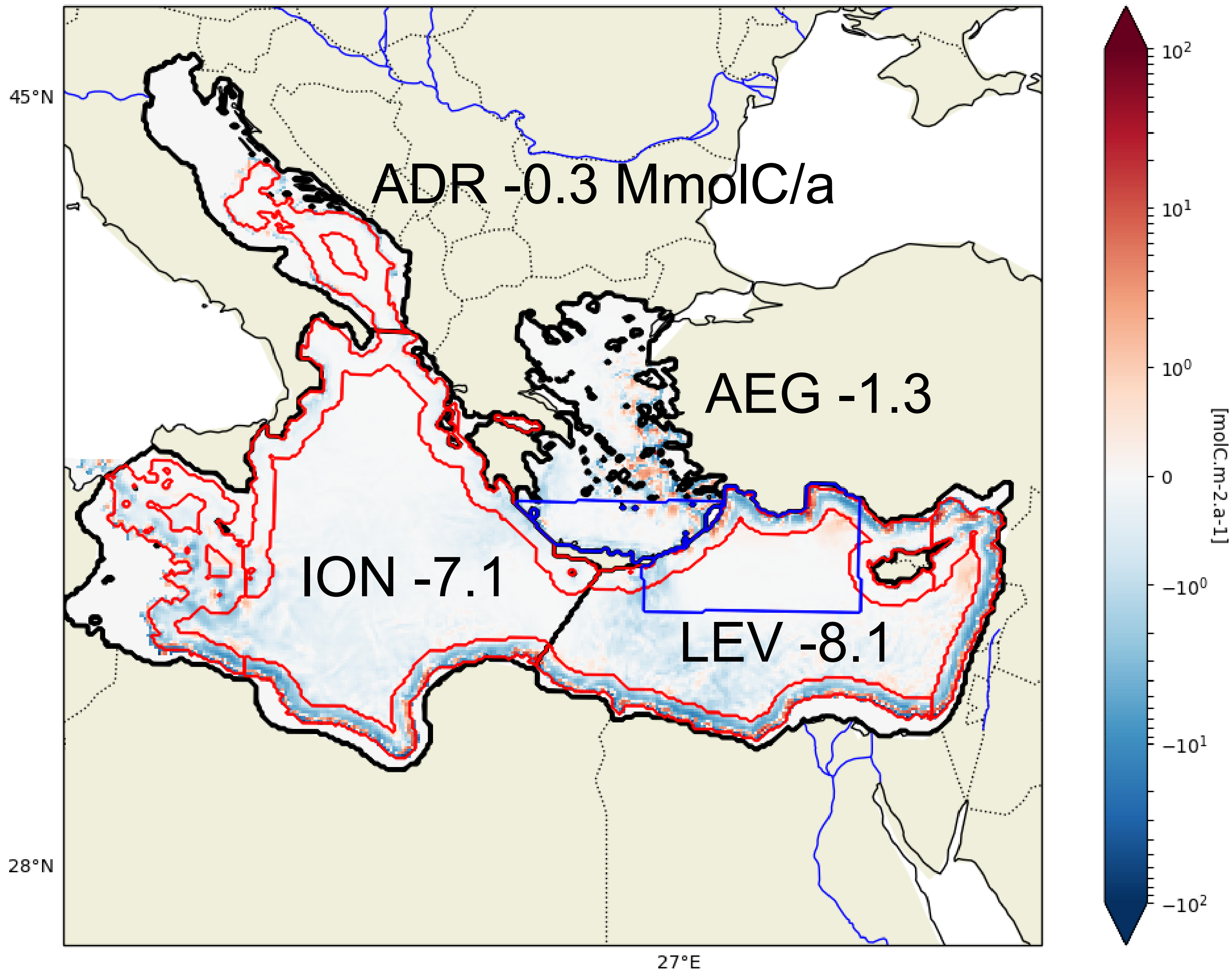
Dissolved organic carbon export



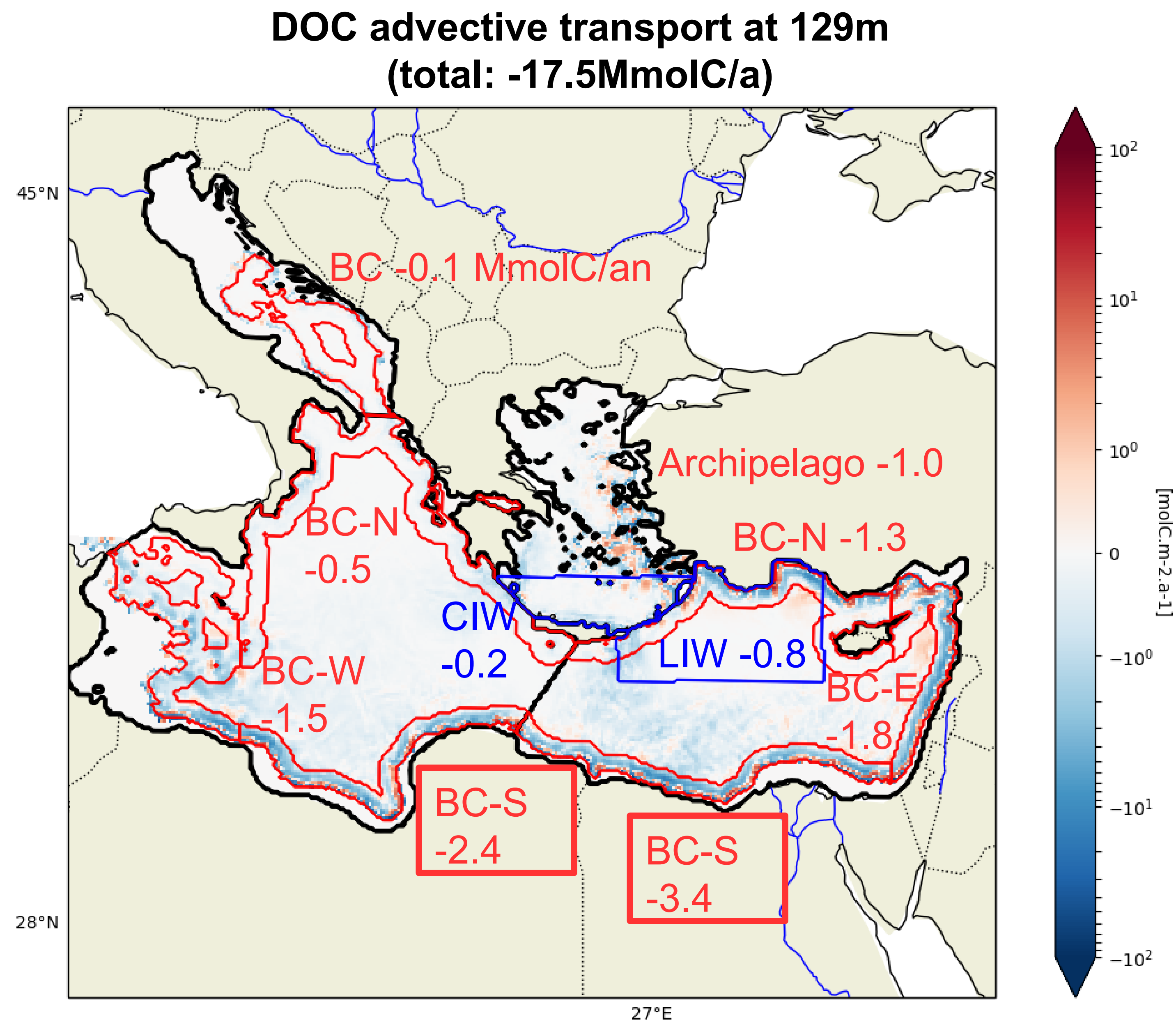
→ 41% of the DOC export at 129m depth is advective

Dissolved organic carbon export

DOC advective transport at 129m
(total: -17.5MmolC/a)



Dissolved organic carbon export



→ 69% of the advective export occurs within 50km of boundaries

From vorticity to downwelling

→ Vertical velocities induce an intense vorticity that must be balanced over the long run (Vallis 2006, Madec 2008):

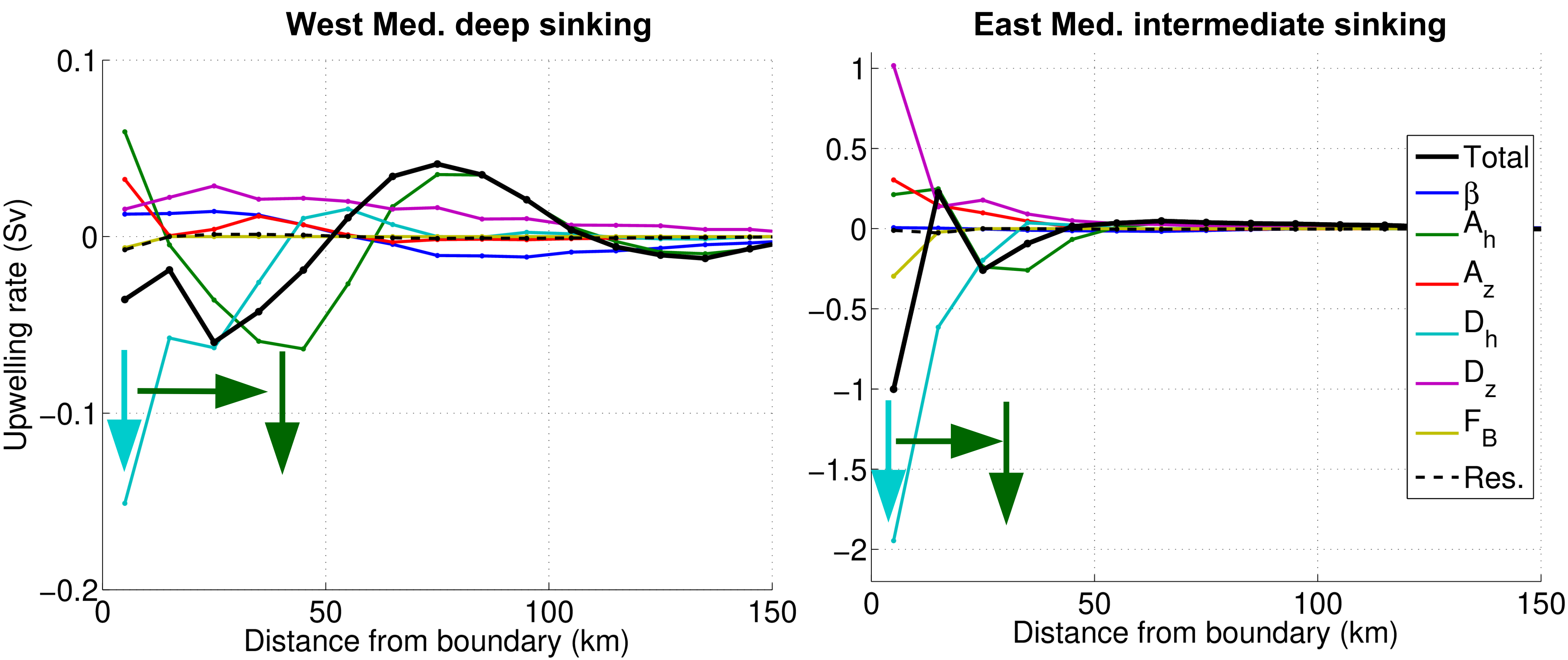
Planetary vortex stretching $f \frac{\partial w}{\partial z}$

→ Diagnostic vorticity balance of vertical velocities (Vallis 2006, Madec 2008):

$$\overline{w(z)} = \frac{1}{f} \int_z^0 \left(Curl\left(\overline{A_h}\right) + Curl\left(\overline{A_z}\right) - \beta \overline{v} + Curl\left(\overline{D_h}\right) + Curl\left(\overline{D_z}\right) + \overline{F_B} \right) dz$$

- $\overline{w(z)}$: Vertical velocity (from vortex stretching)
- $Curl(\overline{A_h})$: Lateral advection
- $Curl(\overline{A_z})$: Vertical advection
- $-\beta \overline{v}$: Beta effect
- $Curl(\overline{D_h})$: Lateral dissipation
- $Curl(\overline{D_z})$: Vertical dissipation (+Surf. friction)
- $\overline{F_B}$: Bottom friction

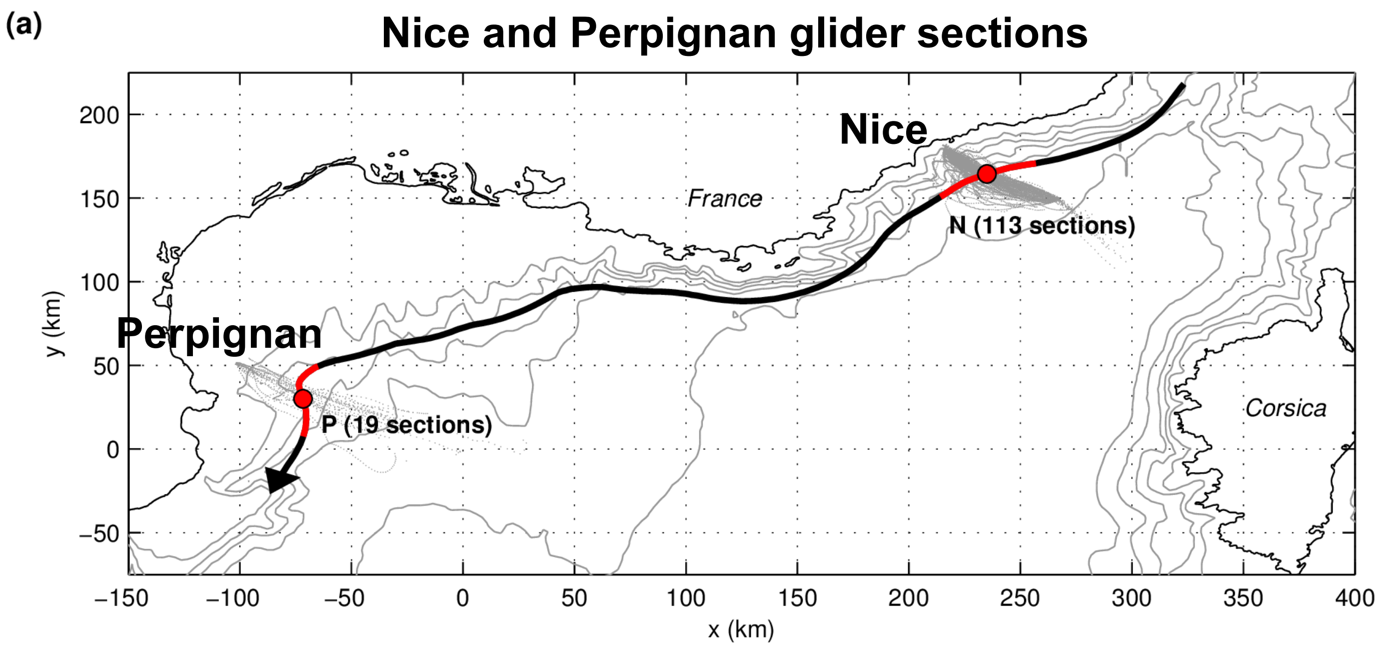
Boundary sinking and vorticity

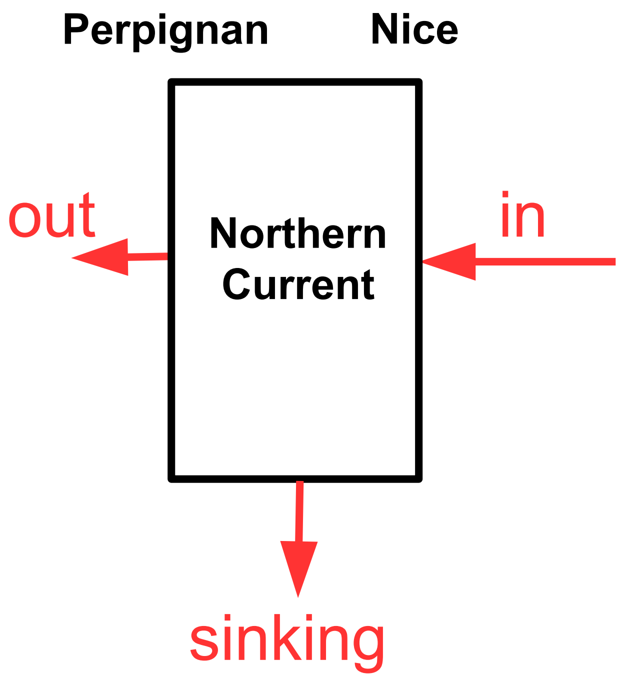


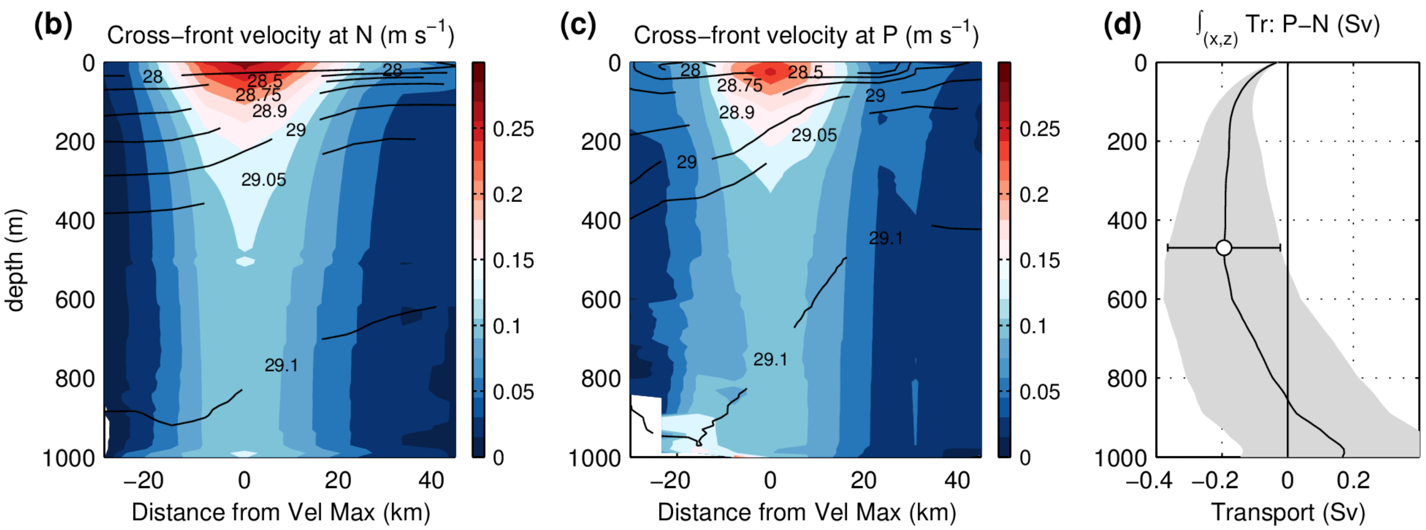
Waldman et al, GRL, 2018b

- Lateral dissipation at the coast allows the sinking
- Lateral advection shifts the sinking offshore

Transport along the Northern current



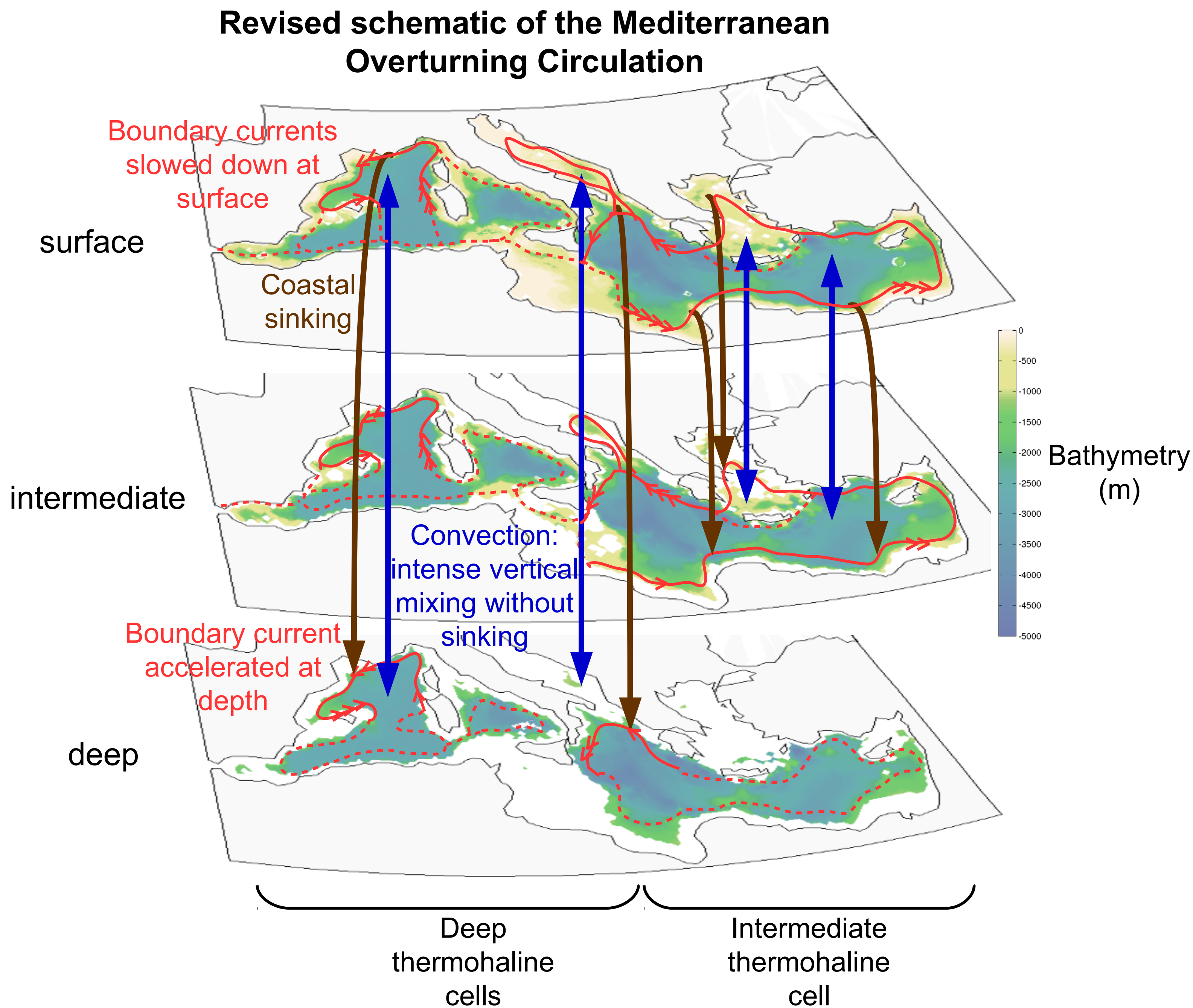




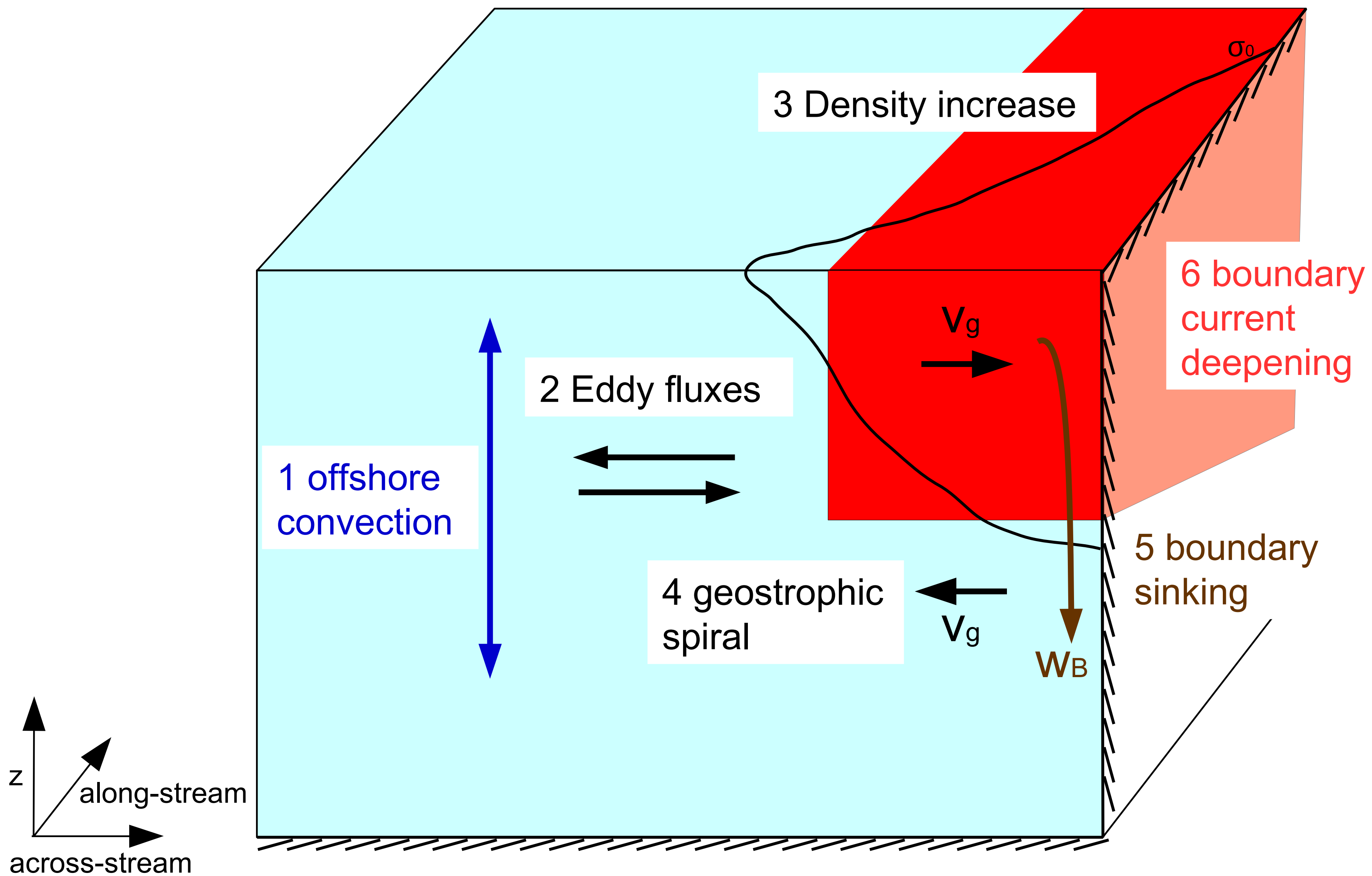
Waldman et al, GRL, 2018b

→ Estimated 0.19±0.17Sv of sinking at 470m depth along the Northern Current

From the « conveyor belts » to the « sinking rings »

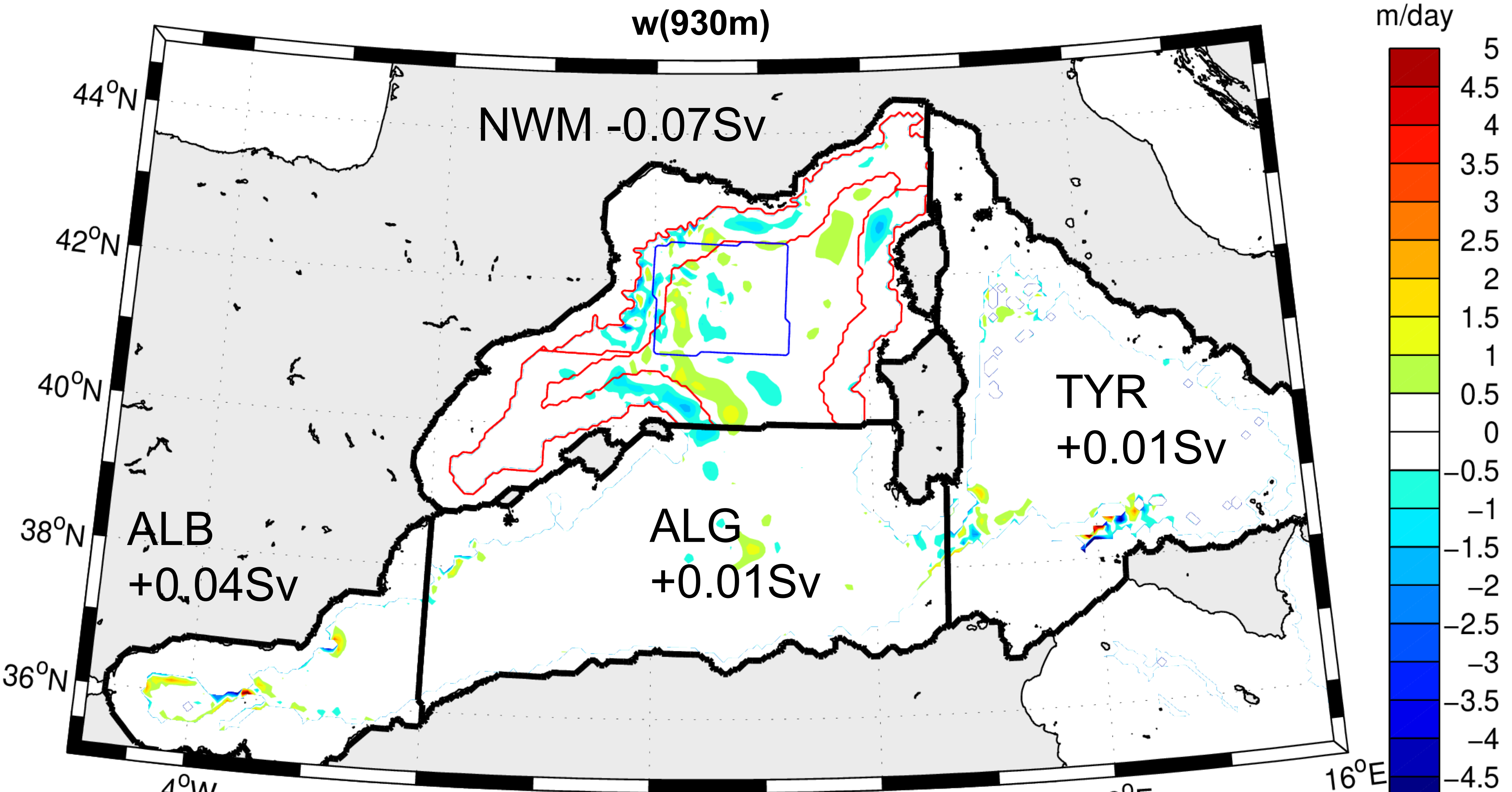


Link between convection and sinking



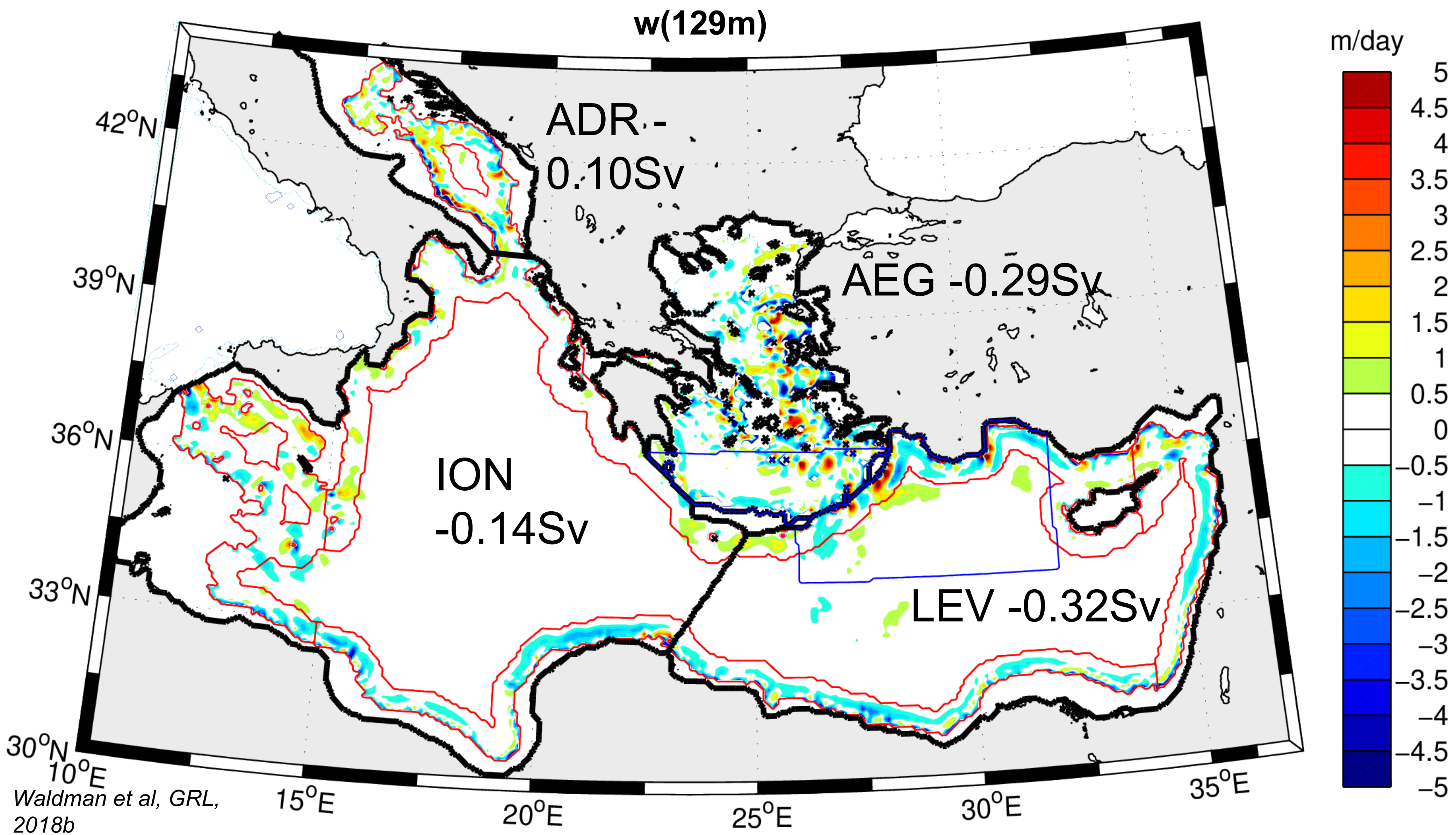
Waldman et al, GRL, 2018b

Annex: regions of downwelling



Waldman et al, GRL, 2018b

Annex: regions of downwelling



Waldman et al, GRL, 2018b

Annex: w from vortex stretching

1. The momentum trend in NEMO model (Vallis 2006, Madec 2008):

$$\frac{\partial \mathbf{U}_h}{\partial t} = -\left[(\nabla \times \mathbf{U}) \times \mathbf{U} + \frac{1}{2}\nabla\left(\mathbf{U}^2\right)\right]_h - f\,\mathbf{k} \times \mathbf{U}_h - \frac{1}{\rho_o}\nabla_h p + \mathbf{D} + \mathbf{F}$$

Momentum trend — Advection (→ 0) — Coriolis — Pressure gradient (→ 0) — Dissipation — Friction

2. Computation of its Curl=vorticity (Vallis 2006):

$$\frac{\partial \zeta}{\partial t} = Curl(A_h) + Curl(A_z) - \beta v + f\frac{\partial w}{\partial z} + Curl(D_h) + Curl(D_z) + F_B$$

Vorticity trend (→ 0) — Lateral advection — Vertical advection — Beta effect — Planetary vortex stretching — Lateral dissipation — Vertical dissipation (+Surf. friction) — Bottom friction

3. Assumption of steady state (1980-2012 mean) and vertical integration:

$$\overline{w(z)} = \frac{1}{f}\int_z^0 \left(Curl(\overline{A_h}) + Curl(\overline{A_z}) - \beta\,\overline{v} + Curl(\overline{D_h}) + Curl(\overline{D_z}) + \overline{F_B}\right) dz$$

Vertical velocity (from vortex stretching) — Lateral advection — Vertical advection — Beta effect — Lateral dissipation — Vertical dissipation (+Surf. friction) — Bottom friction

Annex: w from vortex stretching

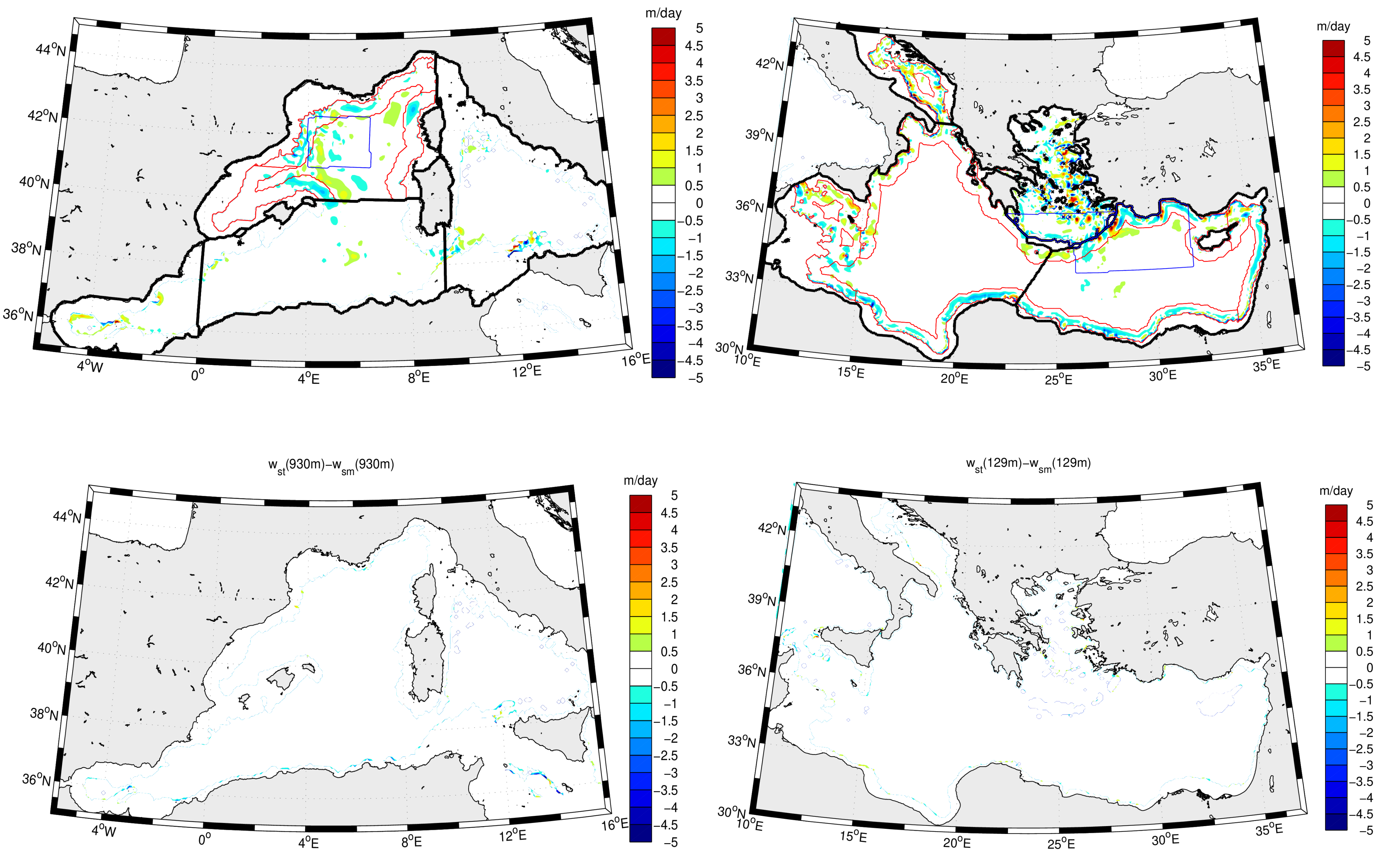
1) Recovering online the terms of the momentum budget (neglecting ATF, KEG, SPG, HPG and ATF)
2) Computing the model's curl to deduce the vorticity balance
3) 4-point interpolation of the vorticity trend terms to the T-grid, and 9-point smoothing of w to be comparable to the stretching from the vorticity budget. Each w is ponderated by the grid cell volume to mask land points.
4) Vertical integration of the vorticity trend terms from surface (assuming w(0)=0) to deduce w from stretching and the contributions to it.
5) Horizontal integration to deduce downwelling rates per basin

→ Remaining approximations:

- Vorticity trend and non-physical terms (pressure gradient, divergent advection, Asselin filter) neglected, small error
- Approximations related to smoothing – interpolation: small error except locally
- w(0)=0, small error

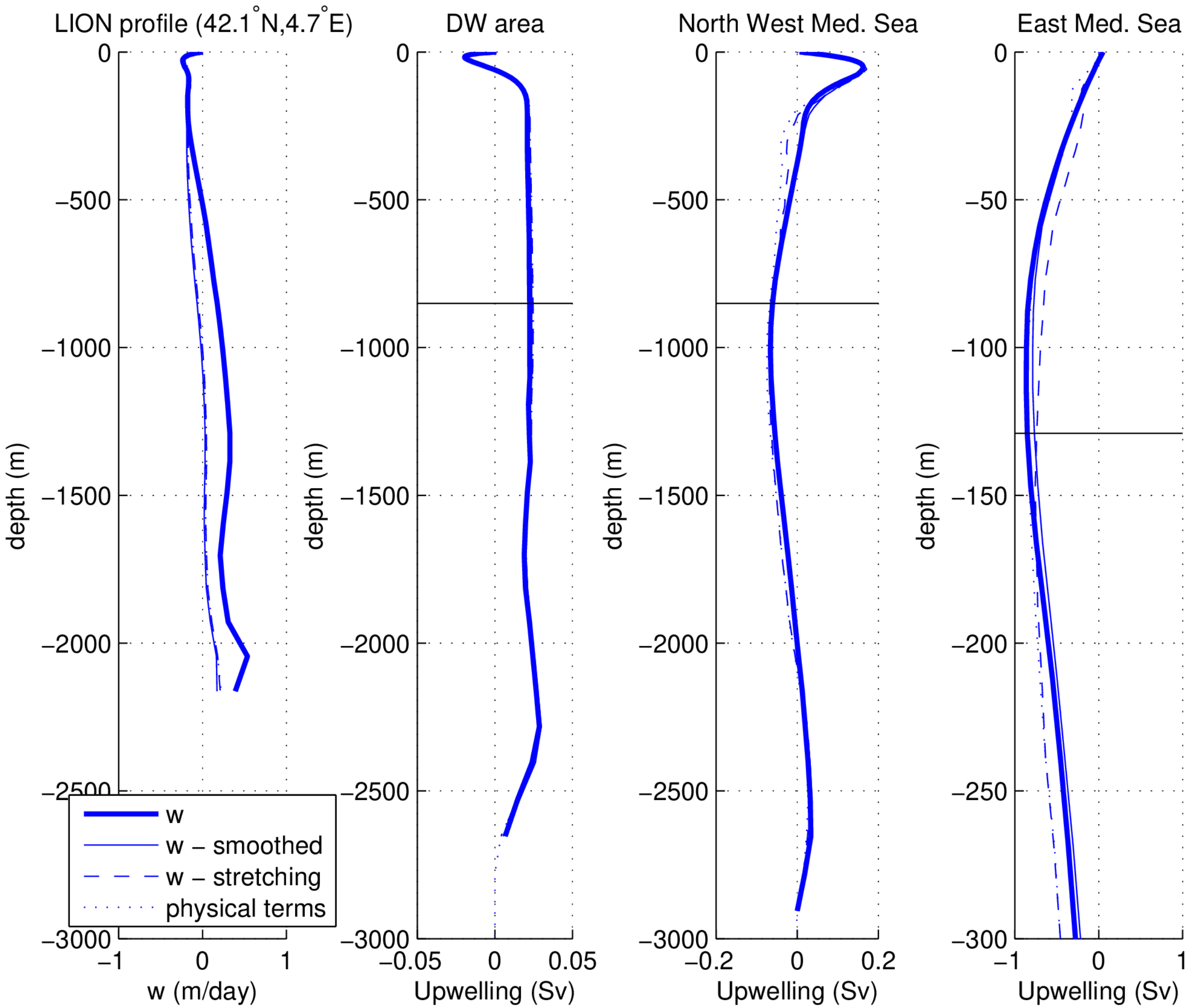
Annex: w from vortex stretching

- High accuracy of the w reconstruction.



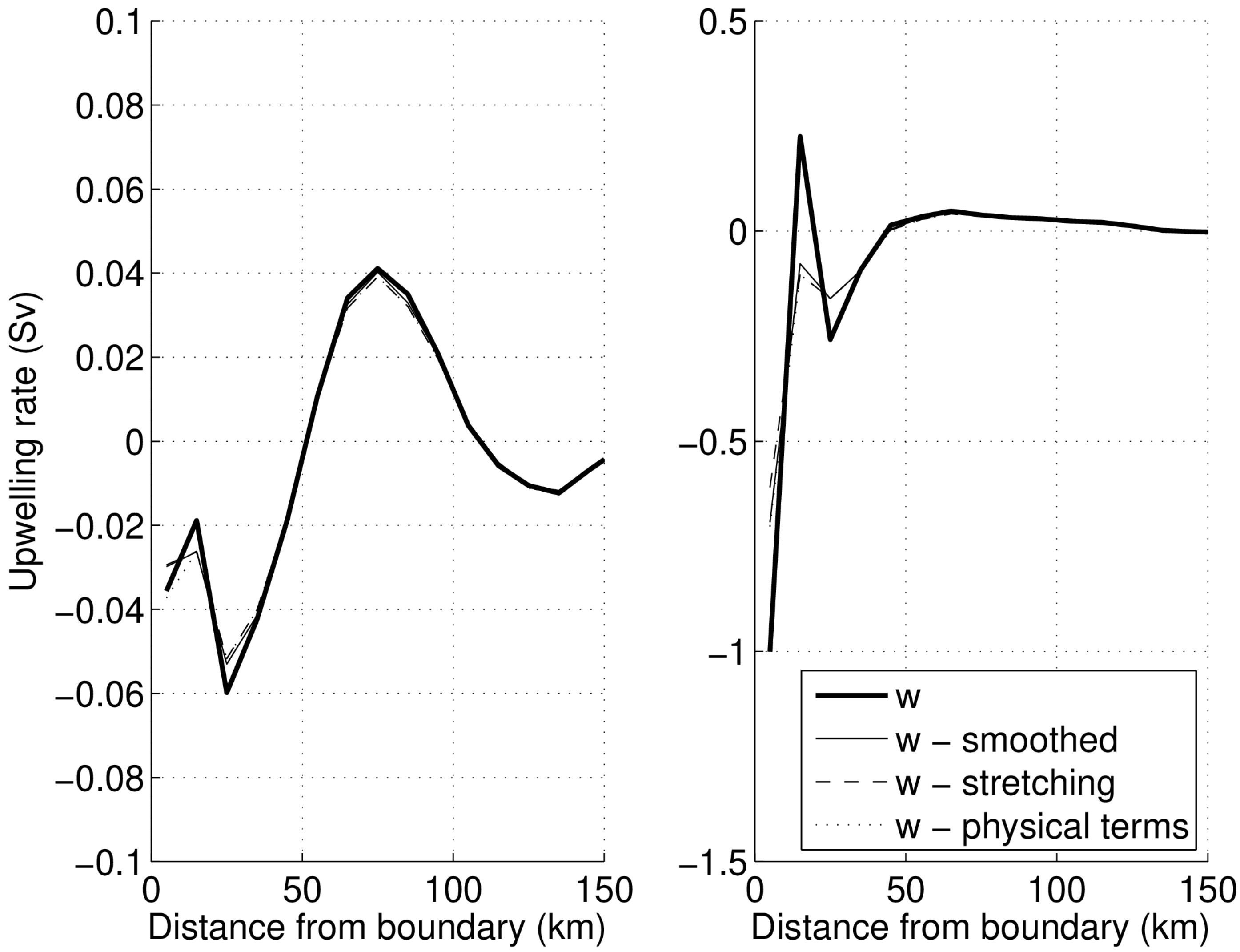
Annex: w from vortex stretching

- The 9-point smoothing of w can generate large differences locally but mostly conserves the integrated volume flux
- The interpolated stretching works almost perfectly far from borders (the DWF area), and the biases are reasonable when including borders (~1-10%)
- The sum of physical terms of the vorticity budget (excluding trend, pg, keg, atf, w(0)) is very close to the stretching term



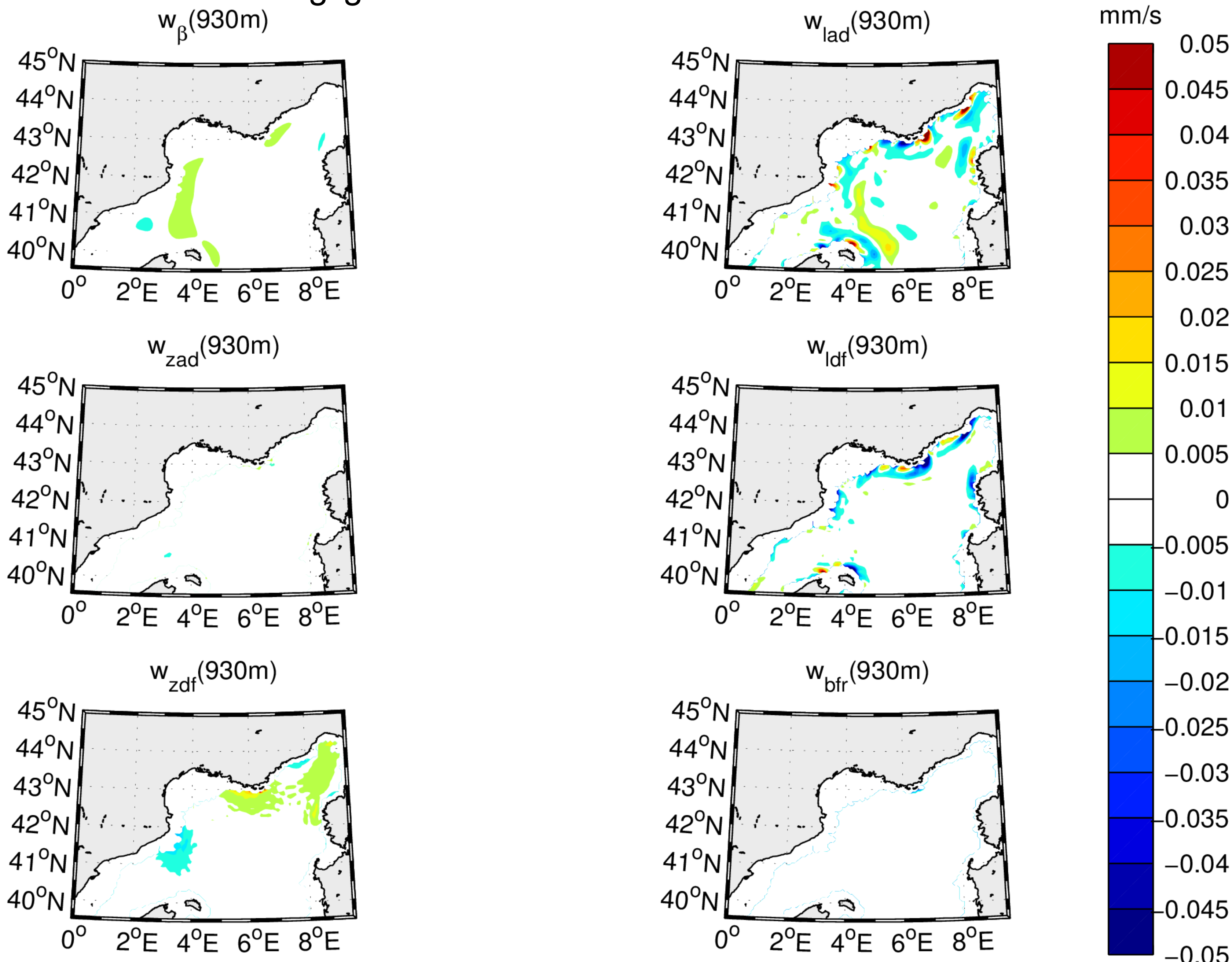
Annex: w from vortex stretching

- w stretch captures very well the downwelling as a function of distance from the coast
- Most of its «error» is close to the boundary and due to the inherent smoothing



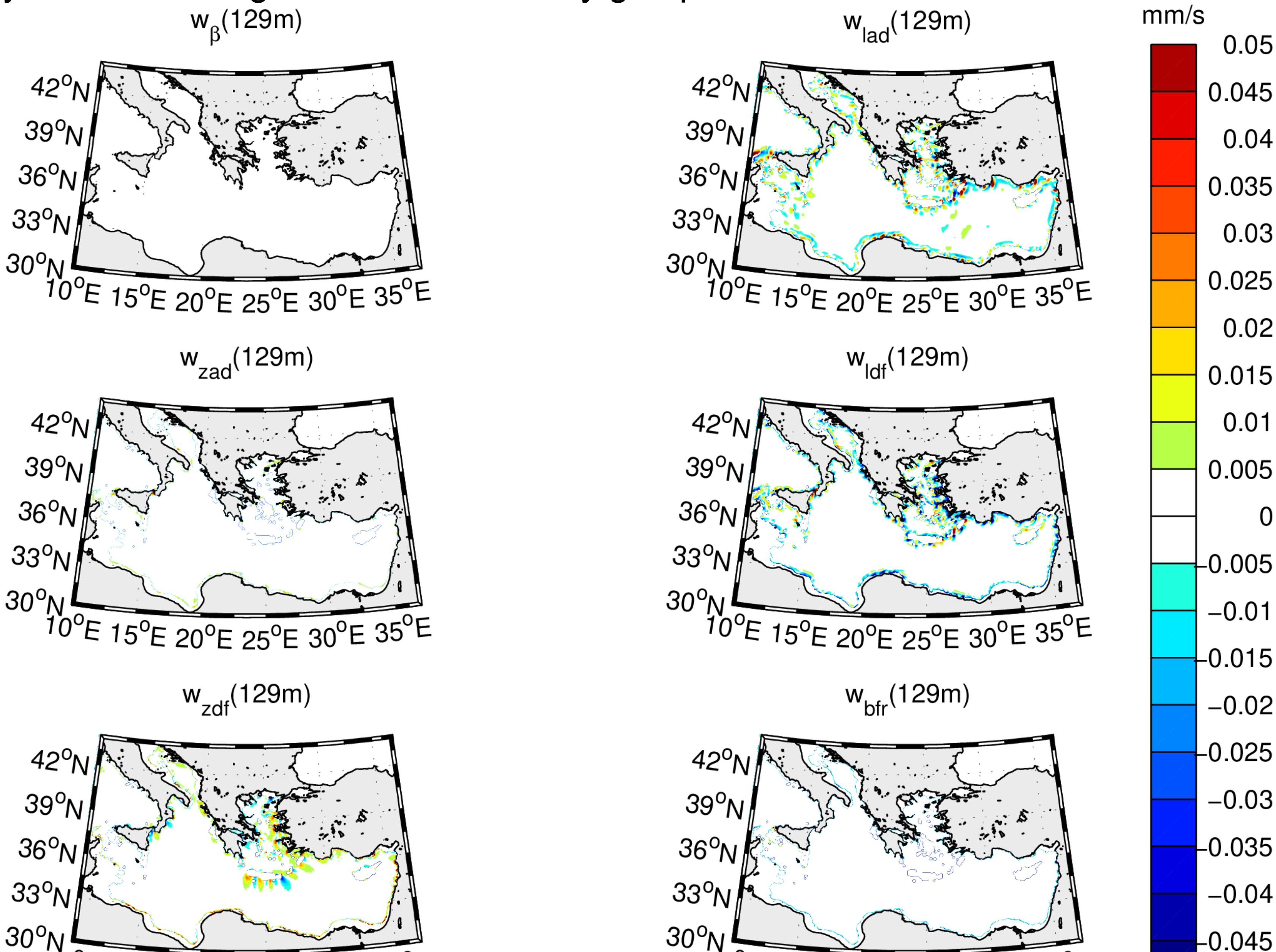
Annex: spatial pattern of contributions

- In the NWMed, both Dh and Ah determine the spatial pattern of the downwelling, the former close to the coast and the latter offshore.
- Dz and beta are also non-negligible



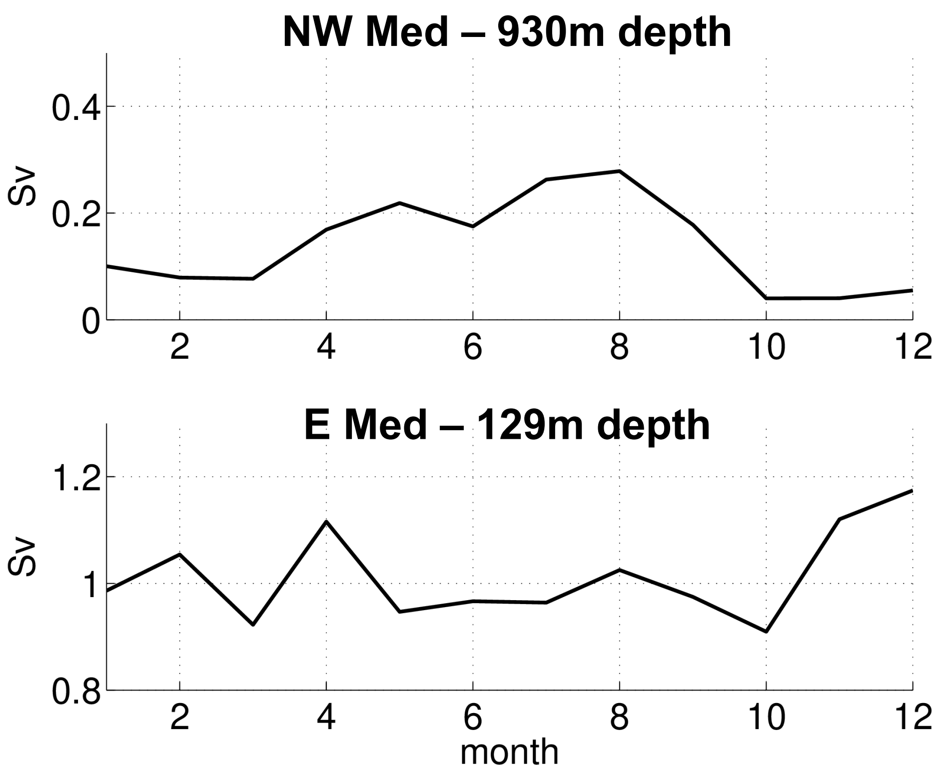
Annex: spatial pattern of contributions

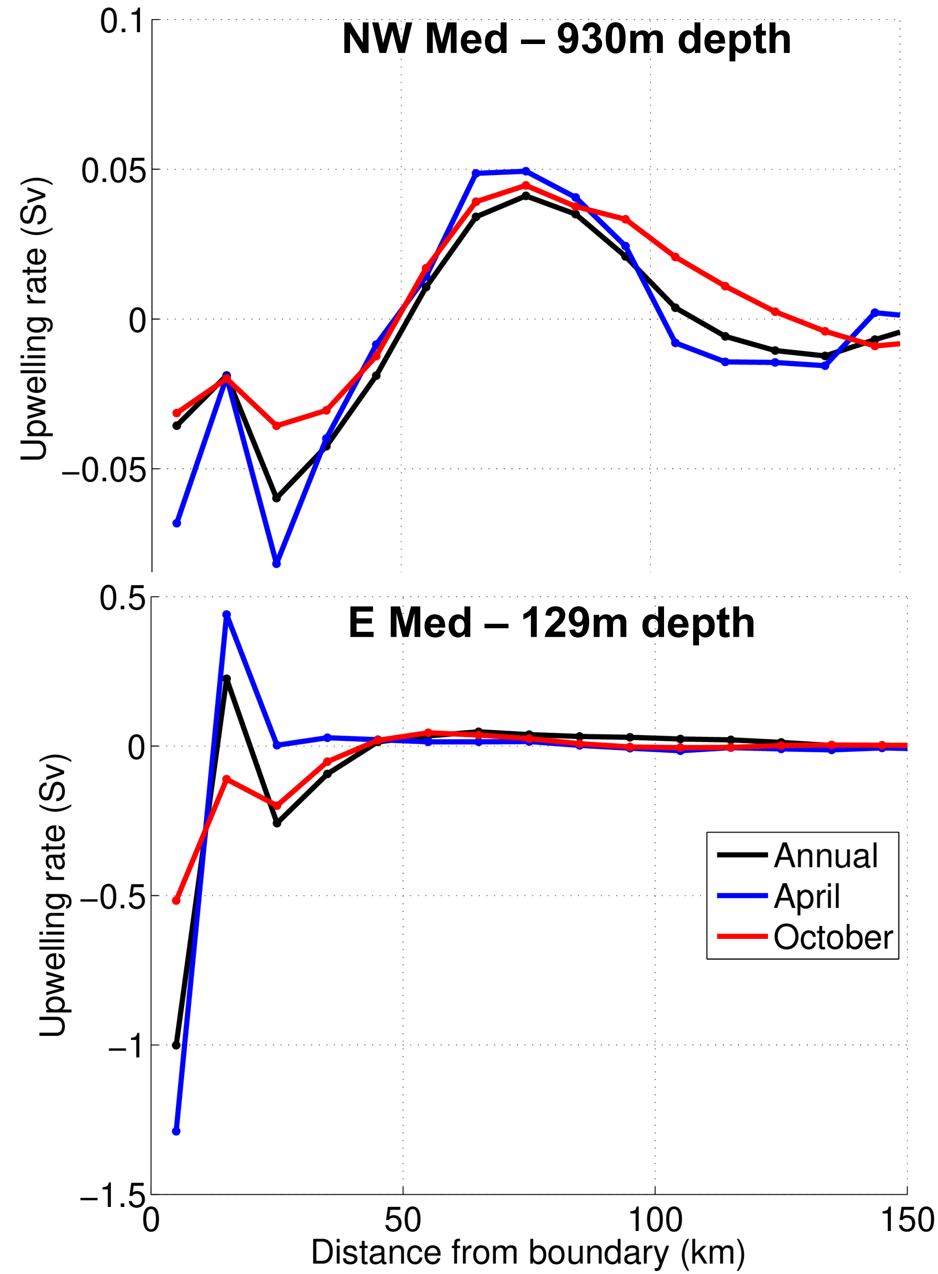
- In the EMed, most of the downwelling (~85%) occurs at the last grid point because of Dh, but also Ah exports some of it (~15%) offshore.
- Dz is also important and counteracts Dh and Ah, and bottom friction contributes marginally to downwelling at the last boundary grid point.



Annex: sensitivity to seasonal cycle

- There are indeed large seasonal variations of the overturning (especially deep)
- The sinking remains coastal throughout the year





Annex: sensitivity to seasonal cycle

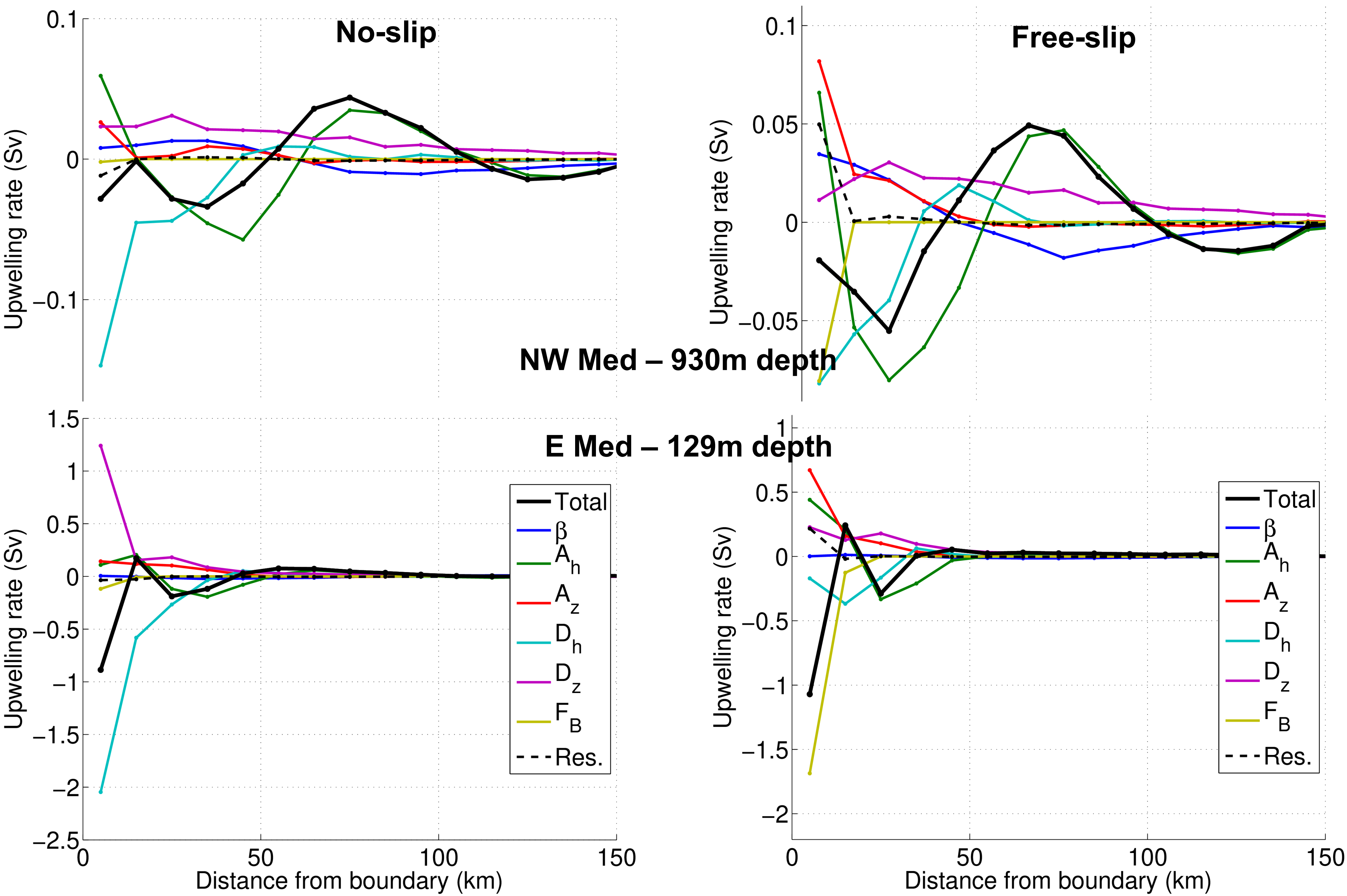
- The location of sinking varies a lot throughout the year
- But the main coastal regions previously identified remain, and convective regions don't contribute to sinking

Basin	Deep western upwelling rate	Basin	intermediate eastern upwelling rate
Western Mediter-ranean	$0.00Sv$ / $0.00Sv$	Eastern Mediter-ranean	$-0.89Sv$ / $-0.77Sv$
Alborán	$+0.12Sv$ / $-0.03Sv$	Adriatic	Total: $-0.18Sv$ / $-0.11Sv$ BC: $\mathbf{-0.20Sv}$ / $-0.13Sv$
Algerian	$+0.02Sv$ / $0.00Sv$	Aegean	Total: $-0.37Sv$ / $-0.15Sv$ CIW: $-0.03Sv$ / $+0.04Sv$ Archipelago (Total - CIW): $\mathbf{-0.34Sv}$ / $\mathbf{-0.19Sv}$
Northwestern Mediter-ranean	Total: $\mathbf{-0.09Sv}$ / $+0.05$ DW: $+0.03Sv$ / $+0.06Sv$ BC–W: $-0.02Sv$ / $\mathbf{-0.06Sv}$ BC–N: $\mathbf{-0.10Sv}$ / $\mathbf{-0.04Sv}$ BC–E: $\mathbf{-0.09Sv}$ / $-0.02Sv$	Ionian	Total: $-0.05Sv$ / $-0.28Sv$ BC–S: $\mathbf{-0.15Sv}$ / $\mathbf{-0.22Sv}$ BC–W: $-0.05Sv$ / $+0.01Sv$ BC–N: $+0.21Sv$ / $-0.10Sv$
Tyrrhenian	$\mathbf{-0.06Sv}$ / $\mathbf{-0.02Sv}$	Levantine	Total: $-0.30Sv$ / $-0.24Sv$ LIW: $+0.02Sv$ / $+0.12Sv$ BC–S: $\mathbf{-0.15Sv}$ / $\mathbf{-0.23Sv}$ BC–E: $-0.05Sv$ / $-0.05Sv$ BC–N: $-0.05Sv$ / $-0.01Sv$

Table SI 1. *Basin contributions to NEMOMED12 April / October average deep (930m) western and intermediate (129m) eastern sinking (Sv). Main downwelling regions are in bold.*

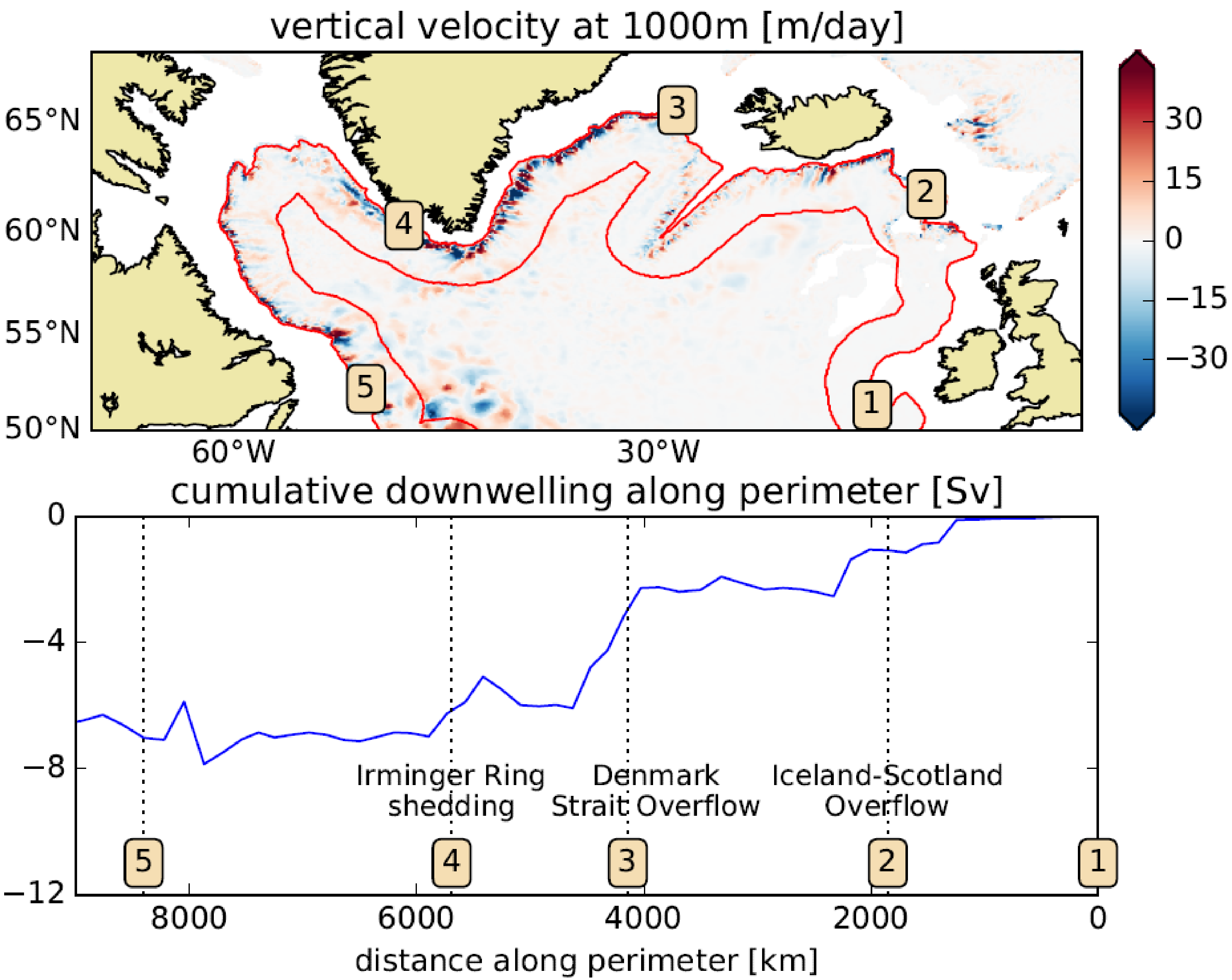
Annex: sensitivity to lateral boundary conditions

- The location of sinking varies a lot throughout the year
- But the main coastal regions previously identified remain, and convective regions don't contribute to sinking



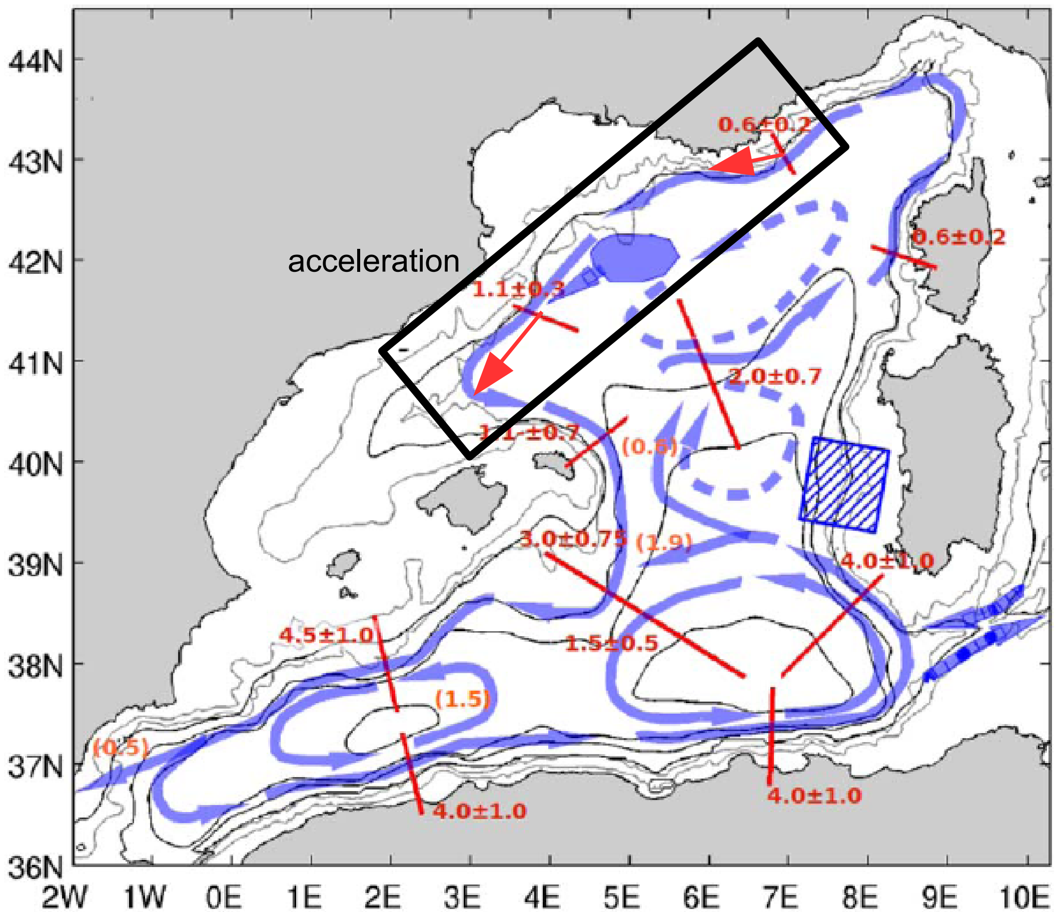
Annex: Subpolar North Atlantic

- Downwelling in the Subpolar North Atlantic, POP 1/10°, normal year forcing (courtesy Nils Brüggemann)



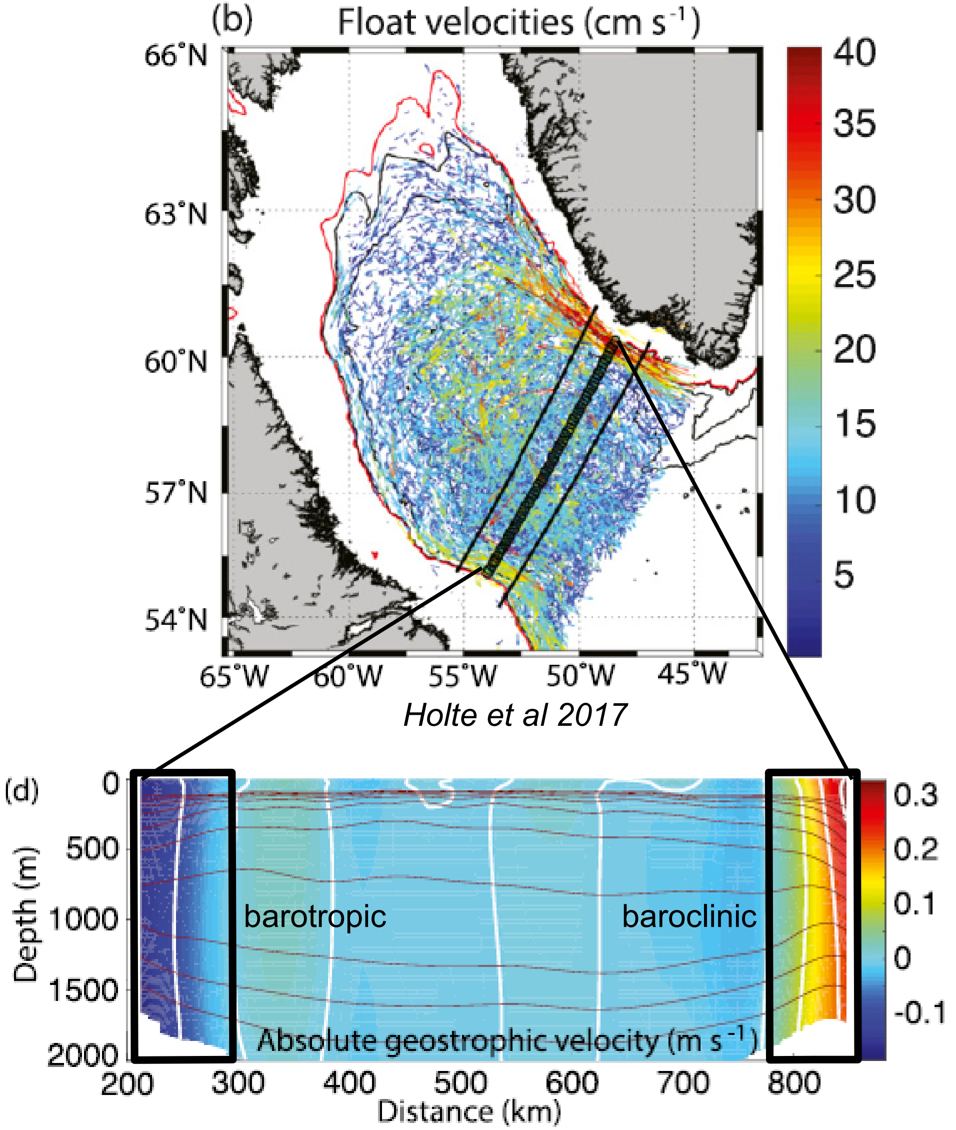
Annex: observed acceleration of deep boundary currents

Deep (>1200m) transport deduced from float drifts



Send et al 2017

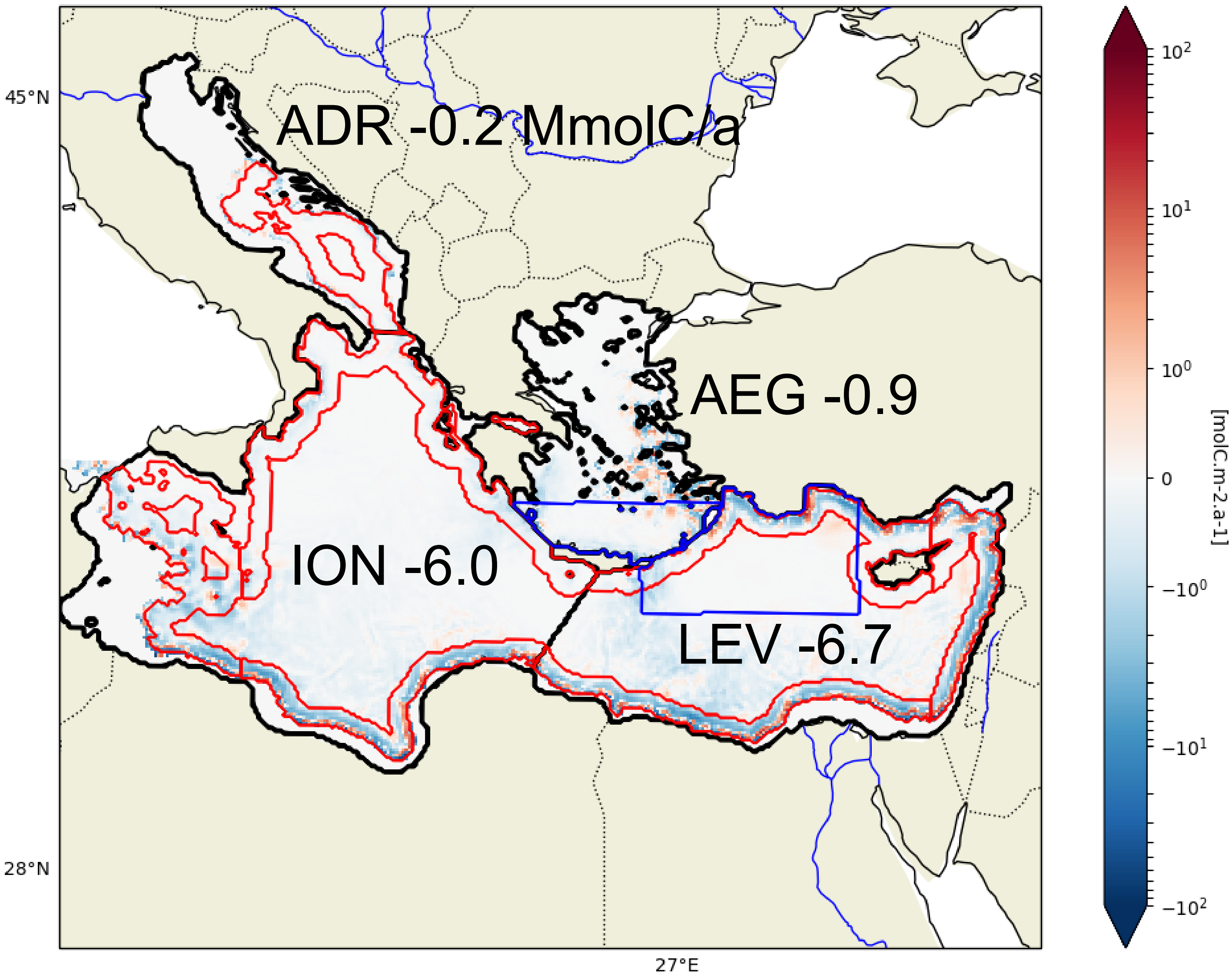
Velocity cross-section deduced from float drifts



Holte et al 2017

Annex: DOC export in Eco3M-Med

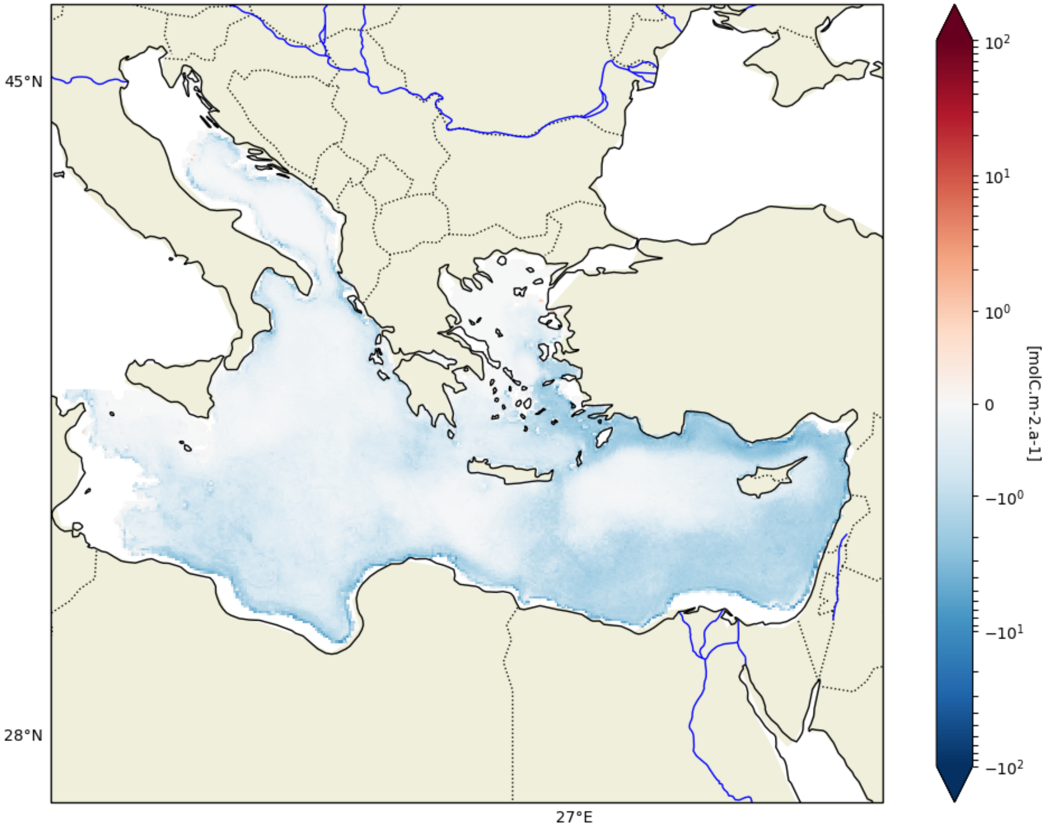
DOC advective transport at 129m
(total: -13.8MmolC/a)



→ 71% of the advective export occurs within 50km of boundaries

Annex: DOC export in Eco3M-Med

DOC diffusive transport at 129m



DOC advective transport at 129m

Annex: DOC export in Eco3M-Med

Table 1: Average advective, diffusive and total export of dissolved organic carbon at 129m depth ($MmolC.a^{-1}$).

Domain	Sub-domain	Export ADV	Export DIF	Total
MED	Total	14.5	22.3	36.8
WMB	Total	0.7	0.7	1.4
EMB	Total	13.8	21.6	35.4
Adriatic	Total	0.2	0.4	0.6
	BC	0.1	0.3	0.4
Aegean	Total	0.9	2.0	2.9
	CIW	0.2	0.9	1.1
	Archipelago	0.6	1.1	1.7
Ion	Total	6.0	7.4	13.4
	BC-S	2.1	1.6	3.7
	BC-W	1.2	0.8	2.0
	BC-N	0.5	1.0	1.5
Lev	Total	6.7	11.8	18.4
	LIW	0.6	2.0	2.6
	BC-S	2.8	1.9	4.7
	BC-E	1.4	1.6	3.0
	BC-N	1.0	2.2	3.2