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DOI
10.1029/2018GL078502

Publication date
2018

Document Version
Final published version

Published in
Geophysical Research Letters

Citation (APA)
Waldman, R., Brüggemann, N., Bosse, A., Spall, M., Somot, S., & Sevault, F. (2018). Overturning the Mediterranean Thermohaline Circulation. *Geophysical Research Letters*, *45*(16), 8407-8415. https://doi.org/10.1029/2018GL078502

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL078502

Key Points:
- Because of the Earth's rotation, the sinking of the overturning circulation occurs near the boundaries, away from open sea convection sites
- An estimation of sinking is derived from the observed deepening and barotropization of the main northwestern Mediterranean boundary current
- We update the conceptual view of the Mediterranean overturning circulation from offshore *conveyor belts* to boundary *sinking rings*

Supporting Information:
- Supporting Information S1

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Received 24 APR 2018
Accepted 25 JUL 2018
Accepted article online 7 AUG 2018
Published online 17 AUG 2018

Overturning the Mediterranean Thermohaline Circulation

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Abstract For more than five decades, the Mediterranean Sea has been identified as a region of so-called thermohaline circulation, namely, of basin-scale overturning driven by surface heat and freshwater exchanges. The commonly accepted view is that of an interaction of zonal and meridional *conveyor belts* that sink at intermediate or deep convection sites. However, the connection between convection and sinking in the overturning circulation remains unclear. Here we use a multidecadal eddy-permitting numerical simulation and glider transport measurements to diagnose the location and physical drivers of this sinking. We find that most of the net sinking occurs within 50 km of the boundary, away from open sea convection sites. Vorticity dynamics provides the physical rationale for this sinking near topography: only dissipation at the boundary is able to balance the vortex stretching induced by any net sinking, which is hence prevented in the open ocean. These findings corroborate previous idealized studies and conceptually replace the historical offshore conveyor belts by boundary *sinking rings*. They challenge the respective roles of convection and sinking in shaping the oceanic overturning circulation and confirm the key role of boundary currents in ventilating the interior ocean.

Plain Language Summary The oceanic thermohaline or overturning circulation is a global circulation that ventilates the deep ocean, that is, the bulk of the global oceanic volume. It has been historically represented as a so-called *conveyor belt* that sinks at deep convection sites. Those areas are known to undergo intense vertical exchanges as a result of surface cooling and to determine the physical properties of deep waters. However, because of the Earth's rotation, the ocean can hardly sink far from the coasts, which questions the commonly accepted equivalence between convection and sinking. In this study, we focus on the Mediterranean Sea which displays an overturning circulation and we use both a numerical model and observations to address where and why this sinking occurs. We find that indeed, little to no sinking takes place at convection sites, whereas boundary currents undergo intense sinking within 50 km of the coast. Our physical analysis confirms that it is due to the Earth's rotation prohibiting any significant sinking away from the coast. Hence, we propose to view the thermohaline circulation as *sinking rings* of boundary currents that deepen along their path rather than conveyor belts that sink offshore.

1. Introduction

The Mediterranean Sea is a semienclosed sea connected to the world ocean by a two-way exchange flow at Gibraltar Strait (Béthoux, 1979; Bryden et al., 1994; Jordà et al., 2017). This flow implies the existence of an overturning cell within the basin to flux mass from surface to intermediate depth. Indeed, the Mediterranean Sea is characterized by a superposition of intermediate and deep, zonal and meridional overturning cells that drive a so-called thermohaline circulation (Bergamasco & Malanotte-Rizzoli, 2010; Millot & Taupier-Letage, 2005; Somot et al., 2006; Tsimplis et al., 2006; Wüst, 1961). This circulation has been studied for more than five decades and is thought to be driven by the convection phenomenon, which connects intermediate and deep layers to the surface at a few specific sites (Leaman & Schott, 1991; Roether et al., 1996; Schott et al., 1996; Schroeder et al., 2008; Testor et al., 2018; Wüst, 1961). Thus, owing to its accessibility for measurements and its overturning circulation, the Mediterranean Sea has been the first (MEDOC-Group, 1970) and probably most extensively (Testor et al., 2018) documented deep convection region.

However, several arguments suggest that open ocean convection does not support the sinking of the overturning circulation. Despite strong observed vertical exchanges in deep convection areas (Margirier et al., 2017; Schott & Leaman, 1991), large eddy simulations suggested that no net downward mass flux is associated to them (Jones & Marshall, 1993; Send & Marshall, 1995). In addition, several idealized simulations of buoyancy-forced marginal seas argued for the existence of intense downwelling close to the boundary, within cyclonic boundary currents driven by the surface buoyancy loss (Spall, 2004, 2008, 2010; Spall & Pickart, 2001; Straneo, 2006). Recently, Katsman et al. (2018) confirmed these findings by diagnosing the subpolar North Atlantic sinking in realistic global simulations. Observational evidence for this coastal downwelling lies in the deepening and barotropization of boundary currents around deep convection areas that could drive per se the downwelling of the overturning circulation (Cenedese, 2012; Holte & Straneo, 2017; Pickart & Spall, 2007; Send & Testor, 2017).

The aim of this study is to determine where the sinking of the Mediterranean Thermohaline Circulation occurs and what physical forces drive it. To this end, we performed a historical hindcast simulation of the Mediterranean Sea with the eddy-permitting NEMOMED12 model over the period 1990–2012 (see supporting information Text S1 for details on the run). NEMOMED12 was extensively validated against observations in the main Mediterranean dense water formation sites (Beuvier et al., 2012; Hamon et al., 2016; Waldman & Herrmann, 2017; Waldman & Somot, 2017). In addition, we diagnosed the physical drivers of downwelling from the modeled vorticity balance. Finally, we used glider transport measurements to estimate the sinking rate along a key boundary current.

2. Modeled Overturning

Two key overturning circulations of the Mediterranean Sea are the zonal overturning cell that drives the two-way exchange at Gibraltar (Somot et al., 2006) and the western meridional overturning cell associated with the much studied dense water formation of the northwestern Mediterranean Sea (Leaman & Schott, 1991; MEDOC-Group, 1970; Schroeder et al., 2008; Testor et al., 2018). We also acknowledge the existence of a deep eastern overturning cell associated with dense water formation in the Adriatic Sea (Roether & Schlitzer, 1991), although we will focus in the following on the former two cells. Both of them can be identified from the modeled zonal and western meridional overturning stream functions which show a maximum at respectively 129-m depth (Figure 1b) and 930-m depth (Figure 1a). Above and below this maximum, water masses are advected, respectively, away from and toward the longitude and latitude of Gibraltar Strait, which implies by continuity that the same flux of water has to sink across this depth. The stream functions reach a maximum of, respectively, 0.94 Sv at 2.4°E and 0.10 Sv at 39.6°N, meaning that these volume fluxes have to downwell, respectively, east and north of those coordinates. Only the zonal overturning can be evaluated against transport estimates at Gibraltar Strait, where its maximum value of 0.79 Sv compares well to an estimated inflow and outflow of 0.84 and 0.87 Sv (Jordà et al., 2017). Eighty-seven percent of the zonal cell sinking takes place in the eastern Mediterranean, east of the Sicily channel, where the vertical maximum stream function reaches 0.82 Sv. We will henceforth focus on the deep western and the intermediate eastern sinkings.

The modeled vertical velocities at the respective depths of the deep western (Figure 2a) and the intermediate eastern (Figure 2b) overturning cells are highly heterogeneous. In both basins, vertical motions are small in the open sea but exceed ~1 m/day within typically 100 km of the boundary and are generally strongly downward in the vicinity of the boundary. The northwestern Mediterranean Sea accounts for 100% of the deep western overturning rate, whereas all eastern subbasins contribute to the intermediate sinking, with a predominant contribution of the Levantine (38%) and Aegean (34%) Seas (see Table 1 for basin contributions to sinking). Note that the western bathymetry contour is closed at 930-m depth, so that the total net sinking is null and what sinks north of 39.6°N (Figure 1a) has to upwell south of this latitude. Also, the total eastern sinking (−0.85 Sv) is almost equal to the zonal overturning rate at the Sicily channel (0.82 Sv) despite the inclusion of some Tyrrhenian Sea overturning in the latter. Figures 1c and 1d display the deep northwestern and intermediate eastern downwelling rate as a function of distance from the boundary. It confirms that most of the downwelling occurs within 50 km of the boundary, whereas the offshore domain is characterized by net upwelling. Consistently, boundary layer theory and high-resolution numerical calculations demonstrate that

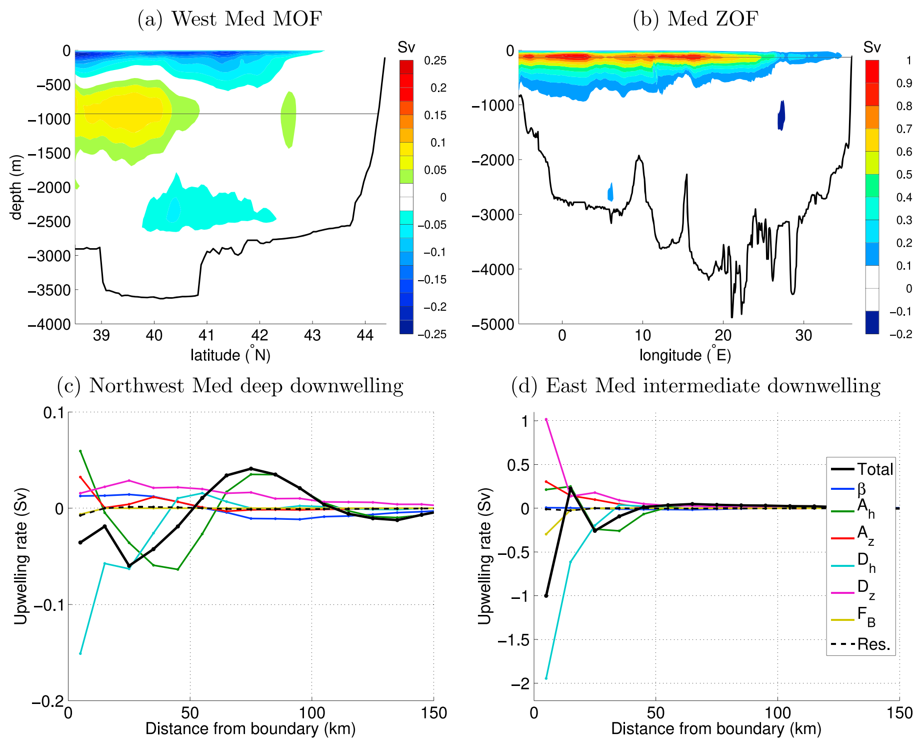

Figure 1. NEMOMED12 average (1990–2012): (a) western meridional and (b) zonal overturning stream functions (respectively, MOF and ZOF in sverdrup, 1 Sv = 10^6 m^3/s). (c) Deep (930-m depth) northwestern and (d) intermediate (129-m depth) eastern upwelling rates as a function of distance from border. In (a) and (b), the black line represents the respective depths of maximum overturning. In (c) and (d), vertical transport is integrated every 10-km distance from the boundary; for example, transports at 15-km distance integrate all locations between 10 and 20 km away from the nearest boundary. We also display the following contributions to the upwelling deduced from the vorticity balance: planetary beta effect β, horizontal and vertical advection A_h and A_z and dissipation D_h and D_z, bottom friction F_B, and residual error Res.

the width of the downwelling region scales with the baroclinic Rossby radius (Barcilon & Pedlosky, 1967; Spall, 2004, 2010) and predict the existence of an offshore upwelling region (Pedlosky & Spall, 2005). Most strikingly, 122% of the eastern Mediterranean sinking occurs within 10 km of the boundary, partially compensated by upwelling offshore. This is a first confirmation that the sinking of the Mediterranean overturning circulation does not occur in open sea intermediate or deep convection sites.

We now aim at assessing the respective contributions of documented convective regions and boundary current areas (Figure 2) to the downwelling. We define the main western Mediterranean deep convection region in the Gulf of Lions (DW; Waldman et al., 2018) and eastern intermediate convection areas in the Cretan and Levantine Seas (CIW; Theocharis et al., 1993; Velaoras et al., 2017, and LIW; Malanotte-Rizzoli et al., 2014; Millot & Taupier-Letage, 2005) based on historical observations. Boundary current regions include all areas located within 50 km of the boundary; their net vertical transport is hence equivalent to the first 50 km of Figures 1c and 1d. The Aegean archipelago is included in this category as 99% of its area lies within 50 km of the border. Table 1 reveals that open sea convection areas are no significant source of sinking. The DW and LIW sites even show net upwelling, consistently with the offshore upwelling found in Figures 1c and 1d. On the contrary, boundary current regions contribute to more than 100% of the downwelling. In the deep northwestern Mediterranean, all boundary areas downwell, although the northern region, called the Northern Current (Millot & Taupier-Letage, 2005), is the largest contributor and amounts to 100% of the total sinking. In the intermediate eastern Mediterranean, the southern Ionian and Levantine boundary currents and the Aegean archipelago area account for 102% of the total downwelling (respectively 33%, 38%, and 32%). Surprisingly, downwelling can be intense far from convective areas, as is the case in the southern Ionian Sea. Despite large seasonal variations of both overturning cells, the above results remain valid throughout the year (see Text S4).

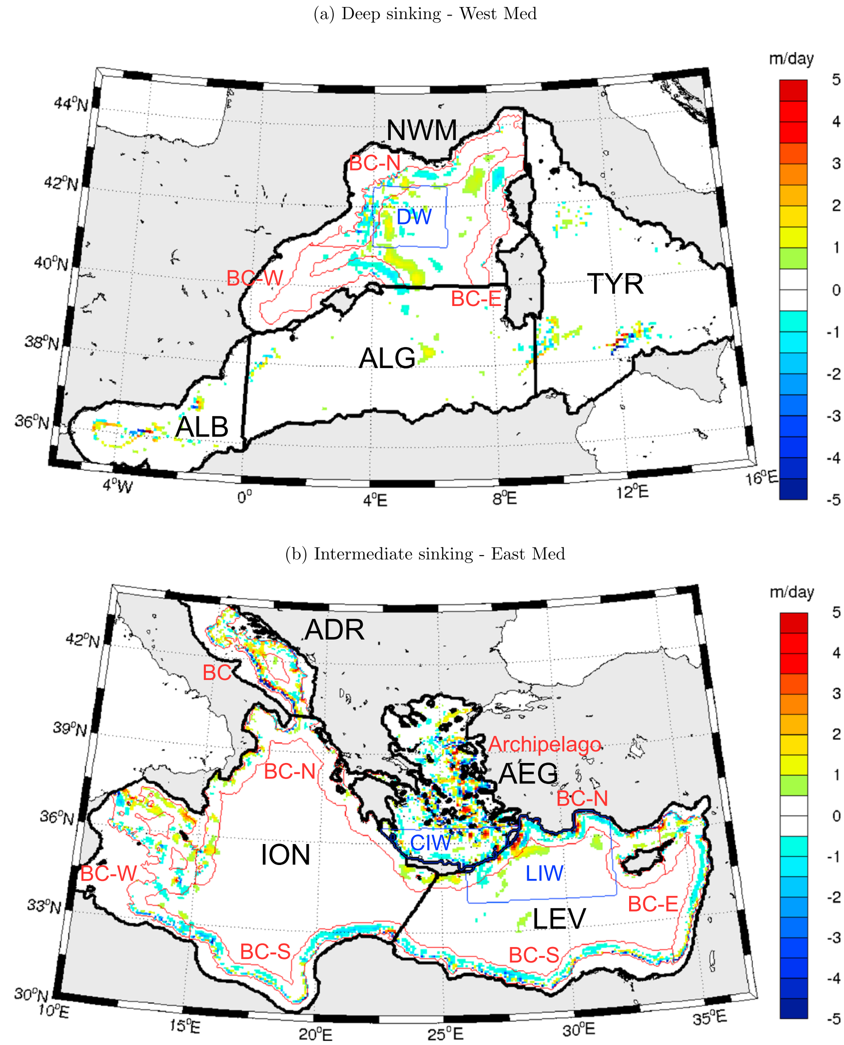

Figure 2. NEMOMED12 average vertical velocities (m/day) in the (a) deep (930 m) western and (b) intermediate (129 m) eastern Mediterranean. The following basins are displayed: (a) Alborán, Algerian, Northwestern Mediterranean, and Tyrrhenian Seas and (b) Adriatic, Aegean, Ionian, and Levantine Seas. The main western deep convection (DW) and eastern intermediate convection (CIW, LIW) areas are shown in blue, as well as boundary current areas (BC) in red with their cardinal location when relevant.

3. Vorticity Dynamics

The contrast between intense downwelling along the border and almost no net vertical motion in the interior ocean can be interpreted in light of vorticity dynamics. Indeed, as a result of the Earth's rotation, any vertical motion induces planetary vortex stretching (or compression) that must be balanced over the long run. In the interior ocean, the flow is close to geostrophic balance for which only the planetary beta effect permits limited vertical motion where meridional flow occurs (Spall & Pickart, 2001). On the contrary, near the coast, the presence of topography and intense boundary currents allows other contributions to balance the vortex stretching, which permits stronger sinking (Spall, 2010).

To clarify that, we diagnose how vertical motions are balanced in the vorticity equation by isolating the vortex stretching term and integrating it from surface (see details in Texts S2 and S3). The model's diagnostic vorticity balance for steady motion writes as

$$f\frac{\partial w}{\partial z} = \beta v - \mathrm{Curl}(\boldsymbol{A_h}) - \mathrm{Curl}(\boldsymbol{A_z}) - \mathrm{Curl}(\boldsymbol{D_h}) - \mathrm{Curl}(\boldsymbol{D_z}) - \mathrm{Curl}(\boldsymbol{F_B}) \tag{1}$$

Table 1
Basin Contributions to NEMOMED12 Average Deep (930 m) Western and Intermediate (129 m) Eastern Sinking (Sv)

Basin	Deep western upwelling rate	Basin	Intermediate eastern upwelling rate
Western Mediterranean	0.00 Sv	Eastern Mediterranean	−0.85 Sv
Alborán	+0.04 Sv	Adriatic	Total: −0.10 Sv BC: −0.11 Sv
Algerian	+0.01 Sv	**Aegean**	Total: −0.29 Sv CIW: −0.02 Sv **Archipelago (Total-CIW): −0.27 Sv**
Northwestern Mediterranean	Total: −0.07 Sv DW: +0.02 Sv **BC-W: −0.05 Sv** **BC-N: −0.07 Sv** **BC-E: −0.05 Sv**	**Ionian**	Total: −0.14 Sv **BC-S: −0.28 Sv** BC-W: −0.02 Sv BC-N: +0.10 Sv
Tyrrhenian	+0.01 Sv	**Levantine**	Total: −0.32 Sv LIW: +0.06 Sv **BC-S: −0.32 Sv** BC-E: −0.13 Sv BC-N: −0.07 Sv

Note. Main downwelling regions are in bold.

meaning that the vortex stretching $f\frac{\partial w}{\partial z}$ is balanced by the beta effect βv minus the vorticity (Curl) of lateral and vertical momentum advection $\boldsymbol{A_h}$ and $\boldsymbol{A_z}$, lateral and vertical dissipation $\boldsymbol{D_h}$ and $\boldsymbol{D_z}$, and bottom friction $\boldsymbol{F_B}$. Note that surface friction is applied as a surface boundary condition on $\boldsymbol{D_z}$. Integrating from surface and neglecting surface vertical velocities yield the diagnostic balance for vertical motions:

$$w(z) = \frac{1}{f}\int_z^0 [-\beta v + \mathrm{Curl}(\boldsymbol{A_h}) + \mathrm{Curl}(\boldsymbol{A_z}) + \mathrm{Curl}(\boldsymbol{D_h}) + \mathrm{Curl}(\boldsymbol{D_z}) + \mathrm{Curl}(\boldsymbol{F_B})]\mathrm{d}z \tag{2}$$

Finally, we diagnose the physical contributions to downwelling as a function of distance from the boundary (Figures 1c and 1d). For that we integrate horizontally equation (2) for the deep northwestern and intermediate eastern Mediterranean sinking every 10-km distance from the boundary. For simplicity, we note the resulting vertical transport equation (in sverdrup) as

$$\mathrm{Total} = \beta + A_h + A_z + D_h + D_z + F_B + \mathrm{Res.} \tag{3}$$

where Res. is the residual error.

For both downwelling regions, lateral dissipation near the boundary provides the main balancing of vertical motions in the vorticity equation (Figures 1c and 1d). Horizontal advection redistributes the sinking offshore by extracting the anticyclonic vorticity provided by dissipation at the border. It explains the downwelling peak 20-40 km away from the border. Reversely, vertical diffusion and advection force upwelling, the remaining terms being an order of magnitude lower. Hence, the physical rationale for the absence of downwelling in the open sea is that there is no possible balancing for the vortex stretching induced by any sinking. We note in particular the weakness of the beta effect, indicating that the geostrophic vorticity balance is rarely met and permits very limited sinking. This constraint arises from the Earth's rotation, so that our results are general to open sea convective regions of the global overturning circulation. We explored the sensitivity to lateral boundary conditions (see Text S5). Under full no-slip conditions, results are mostly unchanged, whereas under full free-slip conditions, bottom friction becomes dominant in the upper ~500-m depth in the vorticity balance, but lateral dissipation remains the major driver below and boundary sinking prevails. We conclude that interactions of the flow with topography, coupled with lateral advective processes, determine the location of sinking within 50 km of the boundary.

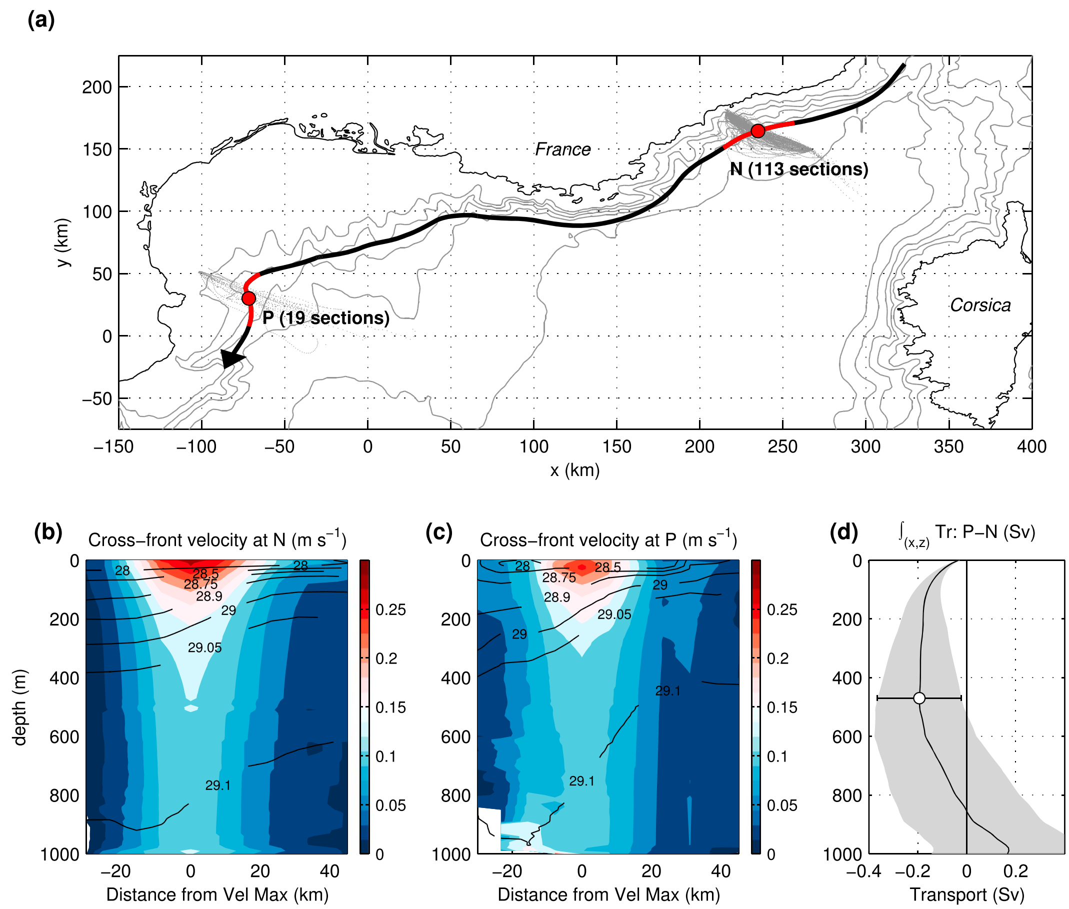

Figure 3. (a) Map of the glider sections (gray dots) at two locations along the Northern Current (thick black arrow): off Nice (N) and Perpignan (P). Isobaths are displayed every 500 m. (b) Mean cross-frontal velocity (shades) and potential density (contours) section off Nice as a function of depth and distance from the velocity maximum (negative distance toward the coast). (c) Same off Perpignan. (d) Mean transport difference integrated from surface and from the coast to 45 km offshore of the velocity maximum, yielding by continuity an estimate of the downwelling rate. The black line is the average, while the shaded area shows the error estimated from observed velocity variances.

4. Observed Sinking

So far, we have strong modeling evidence of the boundary sinking of the Mediterranean overturning circulation. We now estimate from in situ measurements the downwelling rate along the Northern Current. For that, we compute the vertically integrated transport at two repeated glider crossings of the Northern Current 370 km apart from each other (Figure 3a; see Text S6 for details). Continuity tells us that any alongshore transport convergence (respectively divergence) induces downwelling (respectively upwelling) at the basis of the water column. We assume no cross-shore transport, consistently, with Send and Testor (2017)'s observations. We indeed find a slowdown of the surface-intensified jet (Figures 3b and 3c), corresponding to a barotropization of the flow and inducing downwelling down to 840-m depth (Figure 3d). The sinking is found significant in the 0- to 540-m depth layer, with a maximum of -0.19 ± 0.17 Sv at 470-m depth, corresponding to a $7 \pm 6\%$ slowdown of the upper 470-m Northern Current transport. This first direct observational estimation of downwelling validates modeled results and provides further evidence that boundary currents are a major conduit of sinking in the Mediterranean Sea.

5. Conclusions

We conclude by proposing a revised schematic of the Mediterranean overturning circulation (Figure 4a) and of the relation between convection and sinking (Figure 4b). We argue that the Mediterranean overturning circulation can be comprehensively described by following boundary currents, without any direct contribution from intermediate or deep convection sites (Figure 4a). This conceptually replaces the historical offshore

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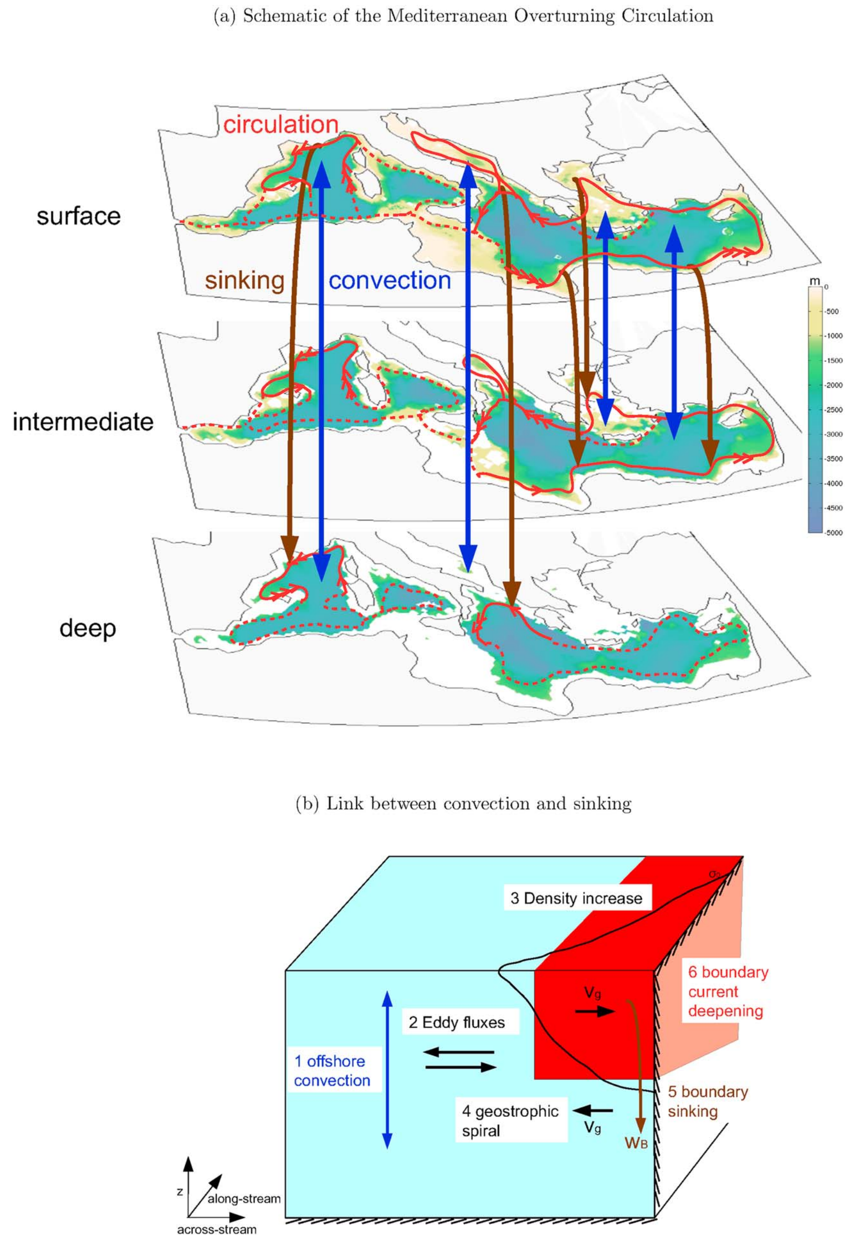

Figure 4. (a) Revised schematic of the Mediterranean overturning circulation: surface buoyancy loss drives cyclonic boundary currents that become deeper and more barotropic through the sinking process. Offshore, convection mixes water masses vertically but induces no net sinking. Red lines display the associated surface, intermediate, and deep circulations (bathymetry in shading) with arrows for their acceleration or slowdown. The deep western and eastern cells and the intermediate zonal cell are in solid; the remaining circulation in dashed lines is not detailed. (b) Schematic link between convection and sinking: the buoyancy loss in convective areas is transmitted to boundary currents through eddy fluxes. This drives an along-stream density increase that induces an across-stream geostrophic spiral. The no-normal flow boundary condition imposes strong downwelling near the boundary, hence deepening the boundary current.

conveyor belts by boundary *sinking rings*. Vorticity dynamics predict that the stretching induced by any downwelling cannot be balanced far from the boundaries. Hence, although open sea convection sites undergo intense vertical exchanges, they experience no significant sinking. On the contrary, boundary currents sink through their interaction with the boundary, which induces by continuity a deepening and barotropization of the flow (Holte & Straneo, 2017; Send & Testor, 2017; Spall, 2004; Spall & Pickart, 2001; Straneo, 2006). This is illustrated in Figure 4a for the deep western and eastern overturning cells and for the intermediate zonal cell. At any depth, the availability of topography determines where significant sinking can occur.

Key sinking regions are not necessarily in the vicinity of convective areas, as was illustrated in the southern Ionian Sea. Nonetheless, convection does play a central role, although indirect, in the overturning circulation (Figure 4b). Convective regions lose buoyancy to the atmosphere, and eddies generated by baroclinic instability transmit buoyancy from the boundary current into the basin interior to balance it (Marshall & Schott, 1999; Spall, 2010). This increases density downstream of the flow, which forces an across-stream geostrophic spiral (Spall & Pickart, 2001). Although such spiral is by far weaker than the along-stream transport, the no-normal flow boundary condition imposes significant downwelling near the boundary, which in turn deepens the boundary current (Holte & Straneo, 2017; Send & Testor, 2017; Spall & Pickart, 2001; Straneo, 2006).

Our results raise a series of questions that have far-reaching implications for the understanding of the overturning, its biogeochemical and climatic roles, and the involvement of boundary currents. First, what is the privileged mode of interaction between the surface and deep ocean? Strong vertical turbulent exchanges do not need any net volume flux to occur. In particular, oceanic convection is generally associated with intense upward heat (Chanut et al., 2008) and nutrient (Severin et al., 2014) supply and with downward carbon and oxygen storage (Rhein et al., 2017). Hence, locally, convection acts as a climate buffer and a stimulating agent for biology, but only its coupling with the sinking process can turn this local overturning global. Thus, sinking is a fundamental link in the overturning chain, although its exact role in shaping the global circulation, climate, and biogeochemistry remains unclear. Second, where and how does the sinking actually happen? We have shown that the Earth's rotation prevents any significant sinking far from boundaries, which also holds true for open sea convective regions such as the Labrador, Irminger, Nordic, and Weddell Seas. We believe that boundary processes are crucial to sinking and deserve more attention in observations and modeling (de Lavergne et al., 2016). Regarding observational efforts in deep convective basins, most of the focus has been put on open sea convection sites so far, where most water mass transformations are believed to take place (Estournel et al., 2016; Testor et al., 2018). We advocate for a systematic survey of key boundary currents and their downstream transition to better document the sinking. In terms of modeling, we evidenced that boundary processes control the location of sinking: improving the representation of those boundary currents is at least as important as the modeling of convection to get the overturning circulation right in numerical models.

Acknowledgments
We thank Caroline Katsman for useful interactions and Casimir de Lavergne for his feedbacks on the manuscript. This work is a contribution to the HyMeX program (*HYdrological cycle in the Mediterranean EXperiment* — www.hymex.org) through INSU-MISTRALS support. This work is part of the Flagship Pilot Study on Air-Sea Coupling within the Med-CORDEX initiative (www.medcordex.eu). Support for MAS was provided by the National Science Foundation grant OCE-1558742. Model outputs are publicly available at mistrals.sedoo.fr/?editDatsId=1499&datsId=1499&project_name=HyMeX, and glider observations are available at the HyMeX database (mistrals.sedoo.fr/HyMeX/).

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