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Special Section:

Dense Water Formations in the North Western Mediterranean: From the Physical Forcings to the Biogeochemical Consequences

Key Points:

- The deep circulation in the Mediterranean Sea is revealed by profiling floats
- Multiannual average transports in the deep layers were estimated
- The spreading of the Western Mediterranean Deep Water and the Tyrrhenian Deep Water is characterized

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Direct Observations Reveal the Deep Circulation of the Western Mediterranean Sea

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Abstract Direct observations of the deep water circulation in the western Mediterranean Sea are presented, based on the analysis of autonomous profiling floats drifting at 1,200 and 1,900 m depth during the 1997–2002 period. The amount of water circulating in the basin is quantified, revealing several distinct gyres and boundary currents. It was also possible to follow the spreading of the newly formed Western Mediterranean Deep Water (nWMDW) and Tyrrhenian Deep Water (TDW), two main components of the deep water in the western Mediterranean, from their origin, based on their temperature and salinity signature. Both boundary currents and isolated eddies carrying the water into the interior are important for this.

1. Introduction

The western Mediterranean Sea is a complex system that has many features of a global ocean basin like the Atlantic Ocean. This includes a density-driven circulation (Robinson & Golnaraghi, 1994) which mixes and injects surface waters deep into the basin (1,000–2,500 m depth). The fate of this water mass determines how the deep western Mediterranean absorbs, stores, and redistributes heat, O_2, carbon, biological and chemical substances, and pollutants. Its spreading/circulation is virtually unobserved with direct methods, and has been largely an estimation based on indirect observations and budget calculations up to now.

The deep water of the western Mediterranean Sea occupies the depth range of approximately 1,000 m to the bottom (usually around 2,500 m), and consists of two known distinct components, the "Western Mediterranean Deep Water" (WMDW), usually at 1,500–2,500 m, and the "Tyrrhenian Deep Water" (TDW), usually 1,000–1,500 m deep (Rhein et al., 1999). The WMDW is formed normally every year by deep convection processes, known to occur in the Gulf of Lions when surface water is made dense enough for mixing and sinking by surface cooling and evaporation during winter meteorological conditions (Marshall & Schott, 1999; MEDOC Group, 1970). The freshly formed deep water is sometimes referred to as nWMDW in order to distinguish it from the older WMDW. Many experiments have documented the convection process, resulting first in vertically mixing/homogenizing the water column from surface to a given depth, and then spreading/sinking of this denser water into the horizons usually occupied by this water (Send & Käse, 1998). This water gradually fills the deep basin as a younger WMDW, as can be deduced from CFC (freon) concentrations, since the recent contact with the surface leads to high Freon concentrations (Rhein, 1995).

The only direct observations of this water spreading away from the Gulf of Lions were 100 km southwestward along the boundary on a mooring, based on temperature and current measurements (Send et al., 1996), several isolated eddies found far offshore (Testor & Gascard, 2006), and recent research cruises showing the spreading of the dense water during the particular events of 2005 (Lopez-Jurado et al, 2005; Schroeder et al., 2010) and 2012 (Durrieu De Madron et al., 2013). Freshly formed WMDW from typical winters can be identified by its higher temperature and higher salinity resulting from the recent mixing with warm and saline intermediate water above. Freon budget calculations over decades can be used to estimate the amount of deep water formed (Rhein, 1995) and have yielded rather larger volumes than typical results derived from the observed size and volume of the convection area (the latter are consistent with more recent estimates (Testor et al., 2017)). The TDW is the result of relatively older WMDW which has entered the Tyrrhenian Sea through the Channel of Sardinia-Tunisia, circulated there, been mixed with Levantine Intermediate Waters (LIW) located above, and flowed back into the western basin with lower

Freon concentrations (Rhein, 1995). As pointed out by Fuda et al. (2002), the TDW could also result from local dense water formation processes in the Tyrrhenian basin, just in front of the Bonifacio Strait. The TDW lies above the more recently formed WMDW and it can be identified by being warmer than the typical water at those depths and density levels in the western Mediterranean (see later Figure 4).

Observations of the currents and circulation in the deep layers (below 1,000 m depth) of the western Mediterranean Sea have been sparse. Current meter moorings have been deployed at very few locations around the boundary of the basin, with only single instruments in the deep layer (Millot, 1999). These are too few to provide estimates of the volume of water circulating. Indirect measurements based on density differences and derived pressure gradients ("geostrophic" currents) lack of a reference level for the pressure calculations and have their limitations. Moreover, the method of profiling floats (Davis et al., 1991) which drift at prescribed depths is usually employed in the Mediterranean Sea to study the circulation at intermediate depth (300–500 m). In the experiment analyzed here, floats were programmed to drift at larger depths of 1,200 and 1,900 m depth, periodically rising to the sea surface for location by satellite fixes and for measuring vertical profiles of temperature and salinity. This data set was already used and presented by Testor et al. (2005a). A total of 17 floats were deployed in the years 1997 and 1999 which collected data until 2002, corresponding to a total of 29 float years of data and providing 1,309 deep flow vectors and profile measurements. Velocity measurements have been discarded when floats are likely to have been running aground between two positions at surface, e.g., when the bathymetry between two surfacings reaches shallower levels than the float parking depth.

2. Deep Circulation as Observed by Profiling Floats

Figure 1 shows all the available float displacements in the deep layer, i.e., at 1,200 and at 1,900 m. We display and analyze them together assuming that the deep circulation is not very different between these two depths, due to the small density gradients in the deep Mediterranean and similar intensity order of 5 cm/s. Already visually, one can discern the general circulation pattern, with one gyre in the north and two gyres in the southern half of the basin (Testor et al., 2005a). A stream function calculation (mapping the currents

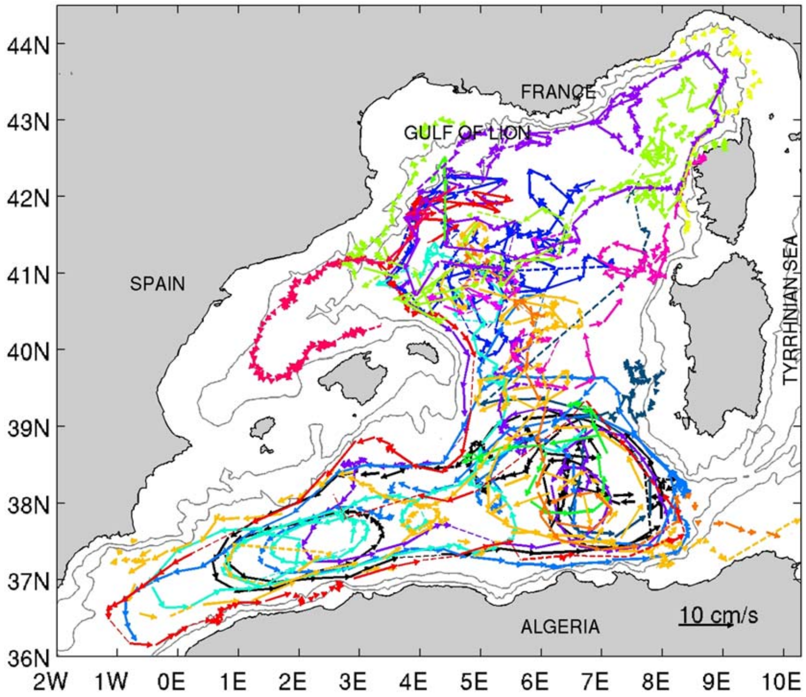

Figure 1. Eight day displacement vectors of all profiling floats available for the 1,200 and 1,900 m levels. Each float is plotted with a different color. The arrows correspond to the estimated displacement of the floats while they are at depth. During each ascent, surface interval, and descent, there is a separate displacement as visible from the gap between successive vectors. The depth contours mark the 1,000 and 2,000 m isobaths. The scale arrow shows the displacement that would result from an average speed of 10 cm/s during the submerged interval.

in geographical boxes into average current vectors and fitting those to a scalar function whose contours are mean streamlines) confirms this view (not shown). Care is required in the interpretation of the float "trajectories" since the floats do not really follow water parcels over extended periods. Because they surface periodically (here every 8 days), they leave the water parcel at depth, experience different displacements during ascent/descent and while at the surface, and then may enter a new parcel when they reach the deep layer again. While we tried to minimize this effect by programming the floats with an extremely short surface interval of 4 h, trajectories are only indicative of the qualitative spreading behavior. We therefore performed quantitative analyses only using the 8 day displacements as independent vectors.

All the current vectors in the vicinity of representative sections around the boundary of the basin were projected onto sections defined by a cross-shore coordinate using the potential vorticity f/H (with f the Coriolis parameter and H the bottom depth, being averages over the float dive). This yields the current distributions across the boundary circulation around the basin shown in Figure 2. The current data have been binned along each section and averaged. Assuming these currents are representative of the multiannual average of the depth layer 1,000–2,500 m, volume transports of the deep water circulation can then be estimated from the smoothed profiles for each section. There is uncertainty in these estimates due to the small sample in many cases, the unknown shape of the distribution of currents toward the boundary (coast), and the assumptions of vertical and temporal representativeness of the measurements. But the overall distribution is surprisingly consistent and the data can be fit together in a consistent volume-preserving fashion within the error bars, as shown in Figure 3. At each section in Figure 2, multiple methods were used to estimate the water volume transport through it. These included parabolic and Gaussian fits to the raw and to smoothed (red arrows shown in Figure 2, bin averaged over the distance from the shore) data, with fixed and variable boundary current scale widths and positions for the fits, and also simple averages of all values in the boundary current domain to yield a mean velocity and its uncertainty. This gives a range of uncertainty resulting from assumptions made about the boundary current and from the scatter of the data that were averaged for each section. This uncertainty is reported in Figure 3.

Figure 3 presents the quantitative circulation diagram derived from the boundary volume transport estimates (based on Figure 2). There is a general cyclonic (anticlockwise) circulation around the deep western Mediterranean, as expected from previous observations and due to the Coriolis force imparted by the earth's rotation. The sense of the deep circulation also follows the surface general circulation features identified so far (Millot, 1999; Poulain et al., 2012), although the surface circulation is generally more intense and dominated by strong eddies that might hide other general circulation features. Three deep subgyres are clearly resolved, and the boundary circulation transport increases from east of the Gulf of Lions toward the exit at the Strait of Gibraltar, building up from approximately 0.6 Sv to over 4 Sv, which may include recirculations. Part of the increase must be due to the (mean) water volume transferred (order of 0.5 Sv) into the deep pool in the Gulf of Lion by deep convection there, possibly with a contribution due to water cascading from the shelf (Bethoux et al., 2002; Palanques et al., 2012; Puig et al., 2013). A larger part of the transport increase appears to be due to the merging with interior circulation gyres. The data are consistent with 0.5 Sv exiting through the Strait of Gibraltar, which is comparable to the source volume provided in the Gulf of Lion and consistent with previous estimates of the Mediterranean outflow (Gascard & Richez, 1985; Fenoglio-Marc et al., 2013) where the total of about 1 Sv results from a mixing of nearly half LIW and half WMDW through hydraulic control. Our data show a continuing circulation in the south of 3–4 Sv, and in addition to these boundary flows there are strong interior recirculations of 1–3 Sv strength. Other quantitative results are a typical basin-wide spreading over 200 km in 200 days and an overall mean speed of 3.8 ± 0.1 cm/s at 1,200 m depth and of 4.2 ± 0.1 cm/s at 1,900 m depth assuming Gaussian distributions. This is suggestive of a small deep baroclinic component that one could probably not observe with smaller velocity data sets since the standard deviation of the current amplitudes is 2.3–2.4 cm/s at these depths. To detect such a shear in geostrophic flow profiles from CTD data would require a substantial set of high-quality hydrographic observations (the expected density difference is 0.003 σ units over 50 km).

The available observations cast severe doubt on the continuity of the boundary circulation west of Sardinia. Even though several floats were deployed just to the south of this region with the purpose of following a northward boundary flow, there is not a single float trajectory that moved along the depth contours (or f/H contours) at that location. One float remained at the 2,000 m isobath there for nearly 6 months without any northward displacement, even though that is the distance from the coast where a deep boundary current

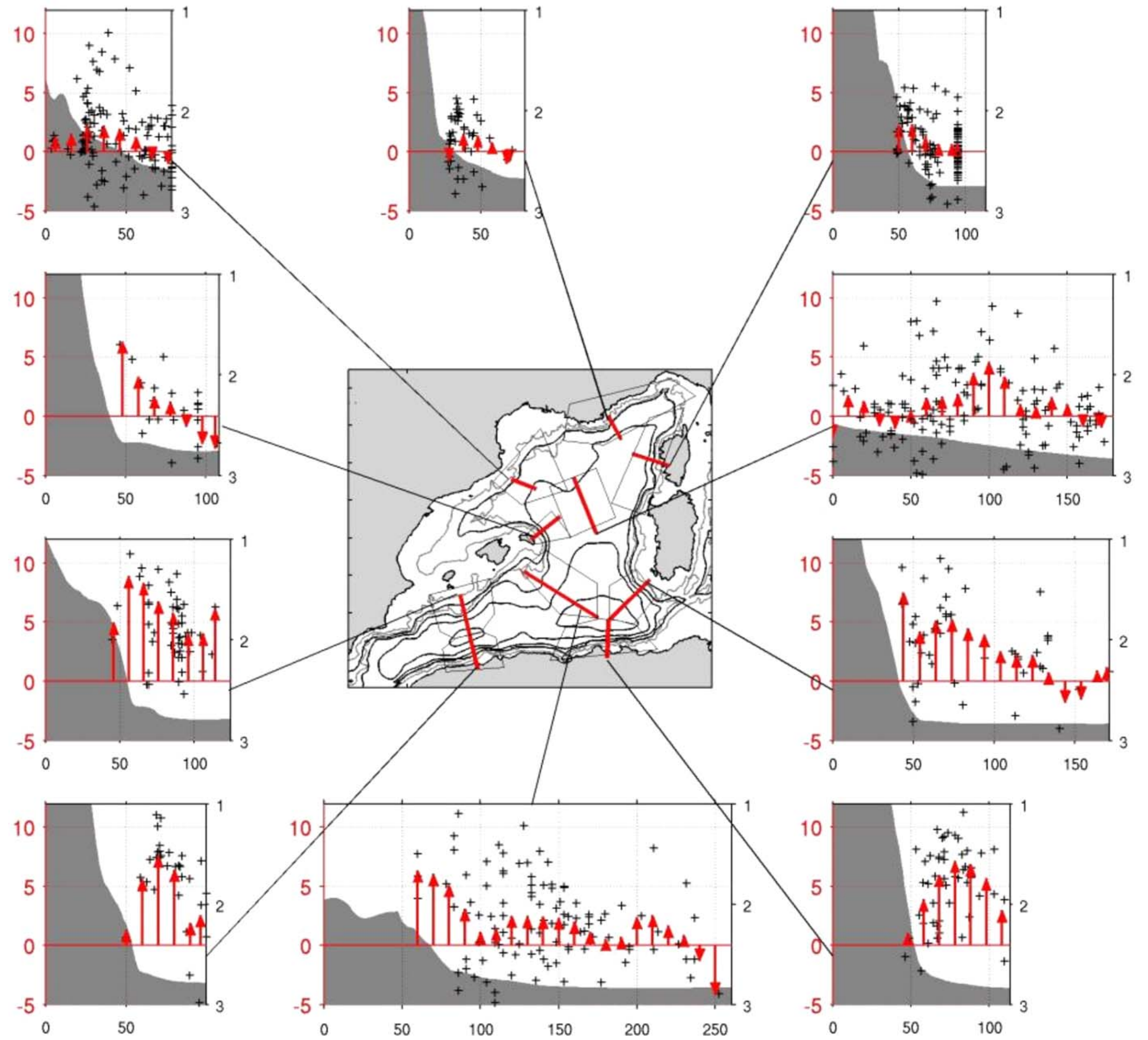

Figure 2. Estimated boundary current flow profiles at selected locations around the basin. Float displacements from 50 to 100 km upstream/downstream of each section were mapped onto the section using f/H as a cross-profile coordinate, yielding the black velocity crosses. Bin-averaging and then filtering those data into a single smooth profile yields the red velocity arrows. The transport values and uncertainties are shown in Figure 3. Red *y* axes refer to the velocities (red arrows) in cm/s versus the distance in km to the coast (*x* axis), along the red lines indicated in the central subplot. Black *y* axes refer to the depth at those locations (grey shading shows the bottom). The vertical axis is positive for currents oriented along the general cyclonic circulation identified in this basin.

would have its core. This leads us to deduce that the usually continuous boundary current flow is interrupted in that region, possibly by the topographic features which are known to lead to shedding of eddies into the basin interior (Testor et al., 2005b). The float data exhibit strong indications of eddies transporting the boundary water masses into the interior in this area (see below). However, the boundary water mass types approaching from the south do appear farther north along the boundary, which leads to the inference that there is an intermittent or eddy-based transport mechanism along the boundary, or that the water masses take a more interior pathway to the north. This may represent an equivalent mechanism to the North Atlantic Deep Water flowing not in a boundary current but an interior pathway south of the Grand Banks/Newfoundland (Bower et al., 2009).

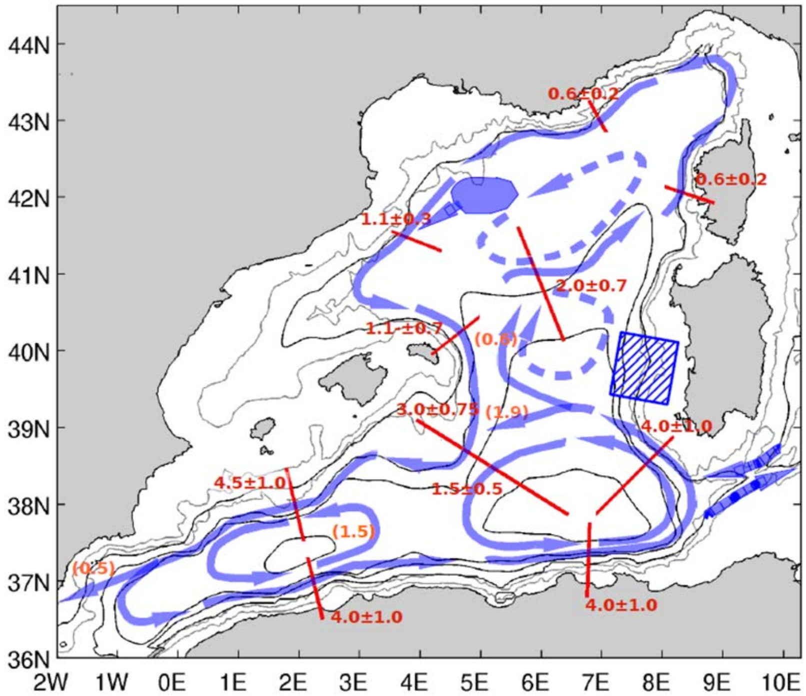

Figure 3. Schematic of circulation with transport numbers. The overall pattern is derived from the stream function calculation (see text). The elliptical patch in the Gulf of Lions indicates the convection region. The volume transport values marked (in Sv = 10^6 m^3/s) and their uncertainty are estimated from the data shown in Figure 2. Inferred (not directly measured) transports are shown in brackets. The dashed circulation arrows are hypothesized, since the 2 Sv estimated for the interior section (the north Balearic front) south of the convection region must recirculate somewhere, but we have no information where this happens. The hatched area off Sardinia is the location where we postulate a blocked or interrupted boundary circulation. The thin black lines show the 1,000 and 2,000 m depth contours again, the thicker black lines give some f/H contours which show closed isolines in the southern gyres.

3. Thermohaline Properties and Spreading of the Deep Waters

The profiling capability of the floats allows the collection not only of flow/trajectory information but also of profiles of scalar properties during ascent, depending on the sensors attached. In our experiment, temperature and conductivity (and thus salinity) profiles were obtained every 8 days. This allows us to diagnose the spreading of the water masses of interest. Newly formed nWMDW can be identified by warmer temperatures compared to the surroundings. The signal is very small, at most 0.05°C above the background 12.81°C, but it is nonetheless safe to say that water warmer than 12.83°C has a recently convected origin (or contribution, since it will mix along its subsequent pathway). Similarly those waters are saltier (+0.05) than the surroundings because of the mixing with relatively warm and saline intermediate waters circulating above. Several floats were deployed in the Gulf of Lions during or just after the active deep mixing phase in February 1999, and these floats show the temperature signature of new deep water for many months. Figure 4a gives a map of the distribution of those anomalies in the depth layer of 1,800–2,000 m. It shows clearly that the water spreads and circulates in the boundary current, i.e., it escapes the convection region and is transported away. This is another important direct proof of the conceptual picture that has been presented until now for the spreading of the newly formed deep waters in general (Millot, 1999; Send et al., 1996; Testor & Gascard, 2006). Some of the anomalies are also found far away in the southern Mediterranean, and we interpret this as proof that the new water may survive in isolated "blobs" for extended periods (order of 1 year), without being mixed into the deep pool. Individual inspection of those remote profiles confirmed the fact that they contain water with a recent convection signature, except for few warm anomalies (especially in the east of the basin) that are actually a signature of TDW. For such profiles, one can find an even more pronounced signature in temperature at the TDW levels (Figure 4b).

The other deep water mass, TDW, enters the basin from the southeast, just south of Sardinia. It can also be recognized by a warm temperature anomaly, best in the depth range 900–1,200 m, compared to the usual

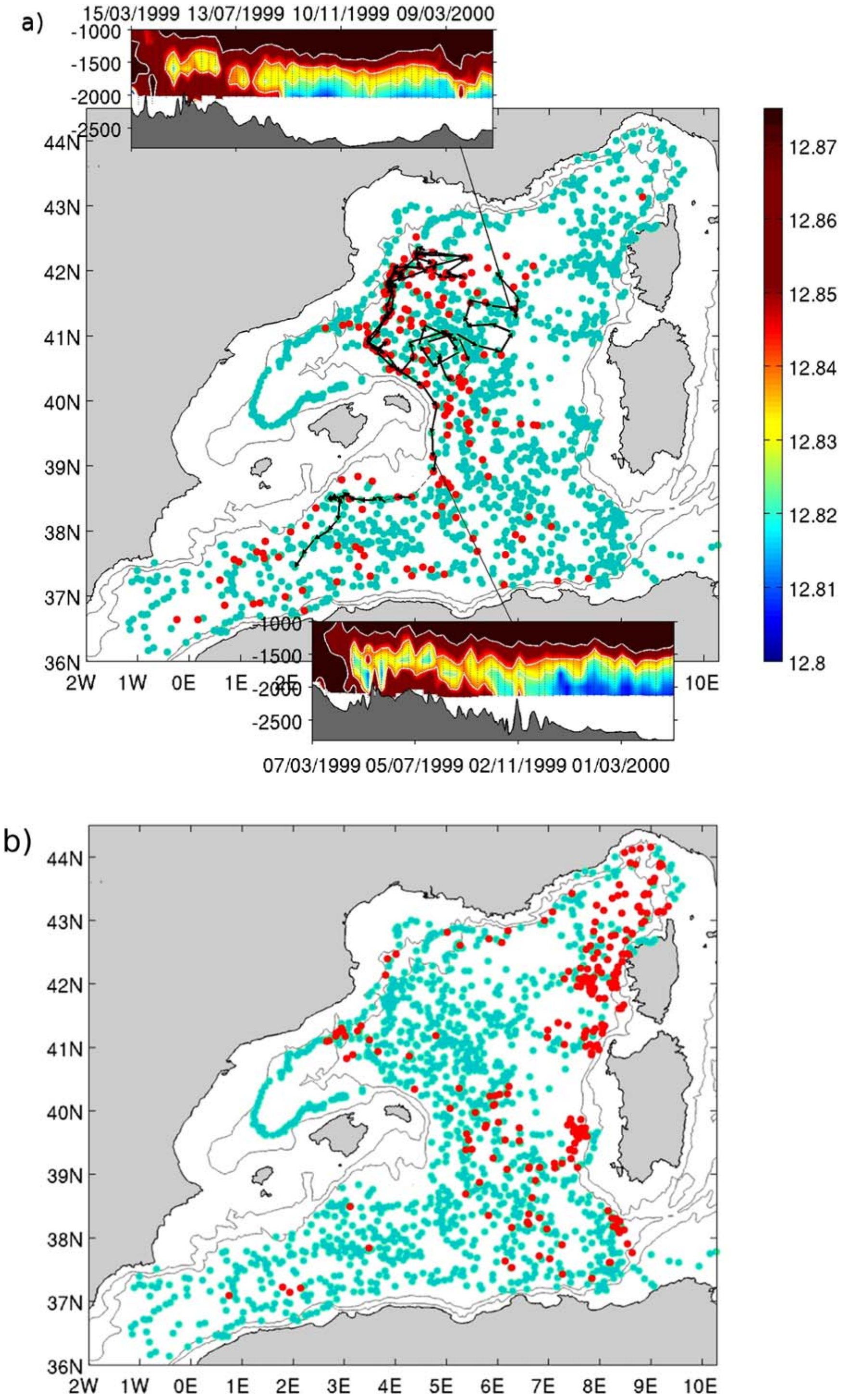

Figure 4. (a and b) (top) Spatial distribution of 1,900 m potential temperature and (bottom) average potential temperature over 1,000–1,200 m depth in boundary currents and in interior eddies. Red dots mark locations with (top) water warmer than 12.82°C, which indicated the presence of newly formed nWMDW, and (bottom) warmer than 13.04°C, which shows the presence of TDW that recently entered the basin. The nWMDW figure shows two examples of float potential temperature evolution over time and depth (m) from floats deployed right after active convection in the Gulf of Lions (those are the floats whose trajectory is marked in black). The warm bottom layer indicating freshly convected water can be detected far away from the convection site, and even after 6–12 months. White contours are 12.827, 12.841, and 12.87°C.

interior temperatures in the basin. Typically, temperatures above 13.02°C indicate some presence/contribution of TDW in this depth range (Figure 4b). Normally the TDW would follow the boundary circulation like the WMDW, but it encounters the eddy generation region off Sardinia soon after entering the basin. The large number of TDW anomalies in the interior southern basin, mostly associated with small-scale eddying motion in our float trajectories, show that much of this water mass does indeed leave the boundary and enters the interior, some even carried far to the east in the southern gyres. Another part of the water is found farther north in the boundary current off Corsica.

4. Conclusion

The deep circulation in the western Mediterranean Sea derived here is based on a quantitative analysis of all available float trajectories in the deep water. It has uncertainties and raises some questions which will undoubtedly lead to further studies and discussions on the processes establishing this multiannual average circulation and the spreading of WMDW and TDW. In this sense, we regard it as a first step toward observation-based in-depth studies of these circulation processes. Our findings are benchmarks and reference data sets below 1,000 m for numerical models of the Mediterranean physical, climate, and biogeochemical system. This will enable testing and improvements of simulation and forecast models, which are needed for understanding and predicting changes in the Mediterranean system.

Our results represent a multiannual average circulation over a period of 5 years and do not address any interannual variability. This was the first large scale experiment with profiling floats in the Western Mediterranean and the deployment of 17 floats allowed us to characterize the circulation over their lifetime. We would recommend to sustain such a density of floats in the western basin. Profiling floats being more reliable now, a deployment of 3–4 profiling floats each year would be enough to sustain the coverage once this number of 15–20 is reached. The detection and quantification of interannual variability of the deep layers in the western Mediterranean Sea could be then approached.

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