The western Alboran gyre helps ventilate the western Mediterranean deep water through Gibraltar

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Abstract.
Variable properties of the Mediterranean outflow and the variability of the Western Alboran Gyre are analyzed by means of 5-year long time series of near bottom potential temperature at Espartel Sill in the Strait of Gibraltar and altimetry data in the Alboran Sea. Geostrophic velocity at the southern edge of the gyre and potential temperature at Espartel sill are significantly correlated (correlation coefficient 0.67), suggesting that the intensification of the Alboran Gyre favors the ventilation of Western Mediterranean Deep Water. The analysis of historical temperature profiles shows that Western Mediterranean Deep Water in the Alboran Sea can be suctioned from a layer between 500 and 700 m depth for typical changes of the gyre intensification.

Keywords: Western Mediterranean Deep Water; Deep Water Ventilation; Strait of Gibraltar; Alboran Gyre.

1. Introduction

The question of how the Western Mediterranean Deep Water (WMDW) is ventilated through the Strait of Gibraltar is of key importance for the renewal of the Mediterranean Sea. WMDW has to flow over Camarinal sill (CS, see Fig. 1) whose depth (290m) is less than the depth of the interface between WMDW and the overlying waters in the Alboran Sea. The Mediterranean outflow is formed by the WMDW, the Levantine Intermediate Water (LIW, by far the most important contributor) and other waters of Mediterranean origin *Millot* [2009]. WMDW is the densest, hence the deepest, of all the Mediterranean waters and therefore the most energy-demanding to be drained out to the Atlantic Ocean over the depths of CS. In a pioneering paper *Stommel et al.* [1973], using Bernoulli equation arguments, showed that WMDW could be aspired from depths as great as 700 m in the Alboran basin, a possibility confirmed few years later by *Whitehead* [1981] in laboratory simulations and by *Kinder and Parrilla* [1987] who presented for the first time experimental evidence of WMDW west of CS thus proving that this water had overflowed the sill.

Bryden et al. [1994] and *Vargas et al.* [2006] showed that the outflow over CS occurs in a pulsating way driven by tidal forces that move back and forth a volume of water three to five times larger than the mean flow [*Garcia Lafuente et al.,* 2000]. Tide is also the main source of energy to suction deep waters located in the eastern approach of the Strait and to bring them west of CS into the Atlantic Ocean. Actually, the ventilation of WMDW would comprise two separated, though linked, set of processes. The first one would include all processes leading to make WMDW available for suction in the westernmost part of the Alboran basin close to the Strait of Gibraltar or, in other words, to carry WMDW towards the eastern approach of the Strait. *García Lafuente et al.* [2009] identified some of these processes such as the re-filling of the western Mediterranean basin with newly formed WMDW, or favorable meteorological conditions able to diminish the net barotropic flow through the Strait of Gibraltar, or the presence of a large Western Alboran Gyre (WAG). The second set of processes comprise all physical forcing that influence the total current over CS since the larger the current here, the greater the depth from which deep water in the eastern approach of the Strait can be suctioned. Tidal strength (the fortnightly cycle) plays a relevant role in this mechanism, a fact acknowledged by *Kinder and Bryden* [1990] who suggested that pure WMDW overflows CS during all spring tide periods.

Bryden and Stommel [1982] presented currentmeter observations at 500m depth in the southwestern Alboran Sea (see the black triangle in Fig. 1) showing a rather permanent flow of WMDW (mean=4.6 ± 4.3cm s^{-1}) heading towards the Strait of Gibraltar with potential temperature (θ hereafter) ranging from 12.81ºC to 13.01ºC, typical of this water. They also observed a marked upwards slope of the isotherms towards the African shore, suggesting that the main path of WMDW ventilation follows the southern part of the Alboran Sea, a result further confirmed by numerical models (*Parrilla et al.,* 1986; *Speich et al*., 1995 and references therein) and reproduced by the model used in this work as well. On the basis of these observations *Bryden and Stommel* [1982] put forward for the first time the idea that the WAG may facilitate the drainage of WMDW, as the gyre provides energy to uplift deep water to depths where it can be easily aspired when they eventually reach the eastern entrance of the Strait.

New experimental evidence of direct WMDW suction over CS has been provided by *Garcia Lafuente et al.* [2007], who showed two cold pulses typical of WMDW in a time series of θ measured at Espartel Sill (ES, Fig. 1) during the winters of years 2005 and 2006. More recently, *García Lafuente et al.* [2009], using a longer series θ at ES, re-visited the role of the WAG in facilitating the aspiration of WMDW through the Strait. They carried out an Empirical Orthogonal Function analysis of altimetry data of the Alboran Sea and showed that the time coefficients of the second empirical mode were significantly correlated with θ at ES. Since this mode captured a significant fraction of the temporal variability of the WAG, they conclude that the presence of a well developed gyre facilitated the suction of WMDW -identified by relative minima of θ in the time series- through ES (and, hence, through CS) supporting the *Bryden and Stommel* [1982] hypothesis. However, part of the WAG variability in *Garcia Lafuente et al.* [2009] was also explained by the first empirical mode, which was uncorrelated with θ at ES. The question deserved further attention and has been addressed in this work using long time series of θ and Sea Surface Height (SSH) from altimetry in the Alboran Sea. The Massachusetts Institute of Technology general circulation model (MITgcm, *Marshall et al.* [1997]) has been also run to illustrate some basic aspects of the whole process.

2. Data and data processing

2.1 In situ measurements

In October 2004 an oceanographic station was deployed in ES to monitor the Mediterranean outflow. A conductivity-temperature (CT) probe installed 10 m above the sea floor measured the θ–S characteristics of the outflow at a sampling rate of 30 min. Due to its proximity to the bottom, the probe detected the densest water flowing out from the Mediterranean Sea. Six conductivity-temperature-depth (CTD) casts along the cross-section CA (Fig. 1) were carried out in June 2009 to show the spatial structure of the Mediterranean water masses in the eastern part of the Strait. The CTD probe was lowered as close as possible to the bottom to register the characteristics of the deepest, densest water. Historical CTD data of the Alboran Sea from the MEDATLAS database (MEDAR group, 2002) have also been used in this study.

As in *García Lafuente et al.* [2009], θ series at ES are used here to follow the variability of the WMDW in the outflow. Salinity was another possibility that was discarded because temperature is a better choice to discriminate WMDW against LIW, the other important water mass in the outflow. The θ series shows large tidal fluctuations that act as noise for long-term variability on which this work focuses on. Following *García Lafuente et al.* [2007, 2009], tides have been removed by selecting the sample of minimum θ within each semidiurnal cycle, which decimates the series to about a value every 12 hours. Since it will be correlated to SSH data from AVISO, whose sampling interval is a week, θ series has been further decimated to weekly values by extracting the coldest sample every week. The resulting series will be referred to as θ_{min} series hereafter.

2.2 Satellite data

Geostrophic surface velocities derived from altimetry provided by AVISO have been used to determine the WAG variability. These data have spatial and temporal resolutions of ¼ degree and one week, respectively, and span the period October-2004 to October 2009, which coincides with the CT time series. For the purpose of this work, the variable U_{SWAG} defined as the spatial average of the zonal component of the geostrophic velocity in the grid points marked in Fig. 1 has been used as a proxy of the WAG variability. Large absolute values of U_{SWAG} correspond to a well-developed gyre that, in our hypothesis, has more potential to uplift WMDW from greater depths in the Alboran Sea.

3. Experimental results

3.1 The WAG and the temperature in ES

Figure 2 shows the time evolution of U_{SWAG} and θ_{min} and their low-passed contributions. Its mean value is 24 cm s^{-1} with a standard deviation (STD) of ± 11 cm s^{-1}, and does not exhibit a well-defined seasonality although the low-passed series suggests greater westward velocity in summer months. Taking into account that AVISO geostrophic velocities are inferred from sea level gradients, summer maximum would correspond to a well-developed WAG, in good agreement with previous works dealing with the WAG variability [*Vargas-Yánez et al.*, 2002].

The more than six year long time series of θ_{min} in ES shows cold peaks close to 13ºC (Fig. 2b) that roughly matches the time evolution of U_{SWAG}. Warmer values above 13.2ºC are found by the end of the different years when U_{SWAG} also presents (absolute) minimum values associated with a weaker WAG. The cross correlation coefficient between both series is 0.46 at the 95% significance level. The coefficient raises to 0.61 if high-frequency variability is removed (low-passed series) and it further increases to 0.67 if θ_{min} series is shifted back 2 weeks with respect to U_{SWAG}. This fact is interpreted as a time-delayed response if the WAG intensity is a driving force for uplifting WMDW in the Alboran Sea.

3.2 Spatial evolution of potential temperature depth.

The mean value of θ_{min} at ES is 13.10 ºC, a value that can be taken as representative of the WMDW that leaves the Strait of Gibraltar through ES. Using long time series of simultaneous observations in CS and ES, *Garcia-Lafuente et al.* (2011) showed that vigorous tidal mixing in Tangier basin (TB, Fig. 1) increases the WMDW temperature by 0.12 ºC on its way from CS to ES, so that the representative θ_{min} at CS would be 12.98 ºC. Eastwards of CS the cross-area of the outflow increases markedly and the Mediterranean layer flows rather slowly. This fact reduces greatly water mixing, so we can assume that θ remains constant along streamlines. Figure 3a shows that, in the eastern approach of the Strait, WMDW still maintains the tendency of remaining attached to the African side and that θ=12.98 ºC can be found in the depth range 300-600 m, shallower in the south. Historical MEDAR θ data in the southern half of the western Alboran Sea (Fig. 4) show that this water resides, on average, at 520m depth, although the banking of WMDW against the African slope would allow this water to be found at shallower depths more to the south. This description shows the continuous uplifting of the WMDW from the Alboran Sea to the west until it finally crosses ES and flows out to the North Atlantic Ocean.

3.3 Temporal variability

Taking the STD as representative of the typical variability, θ_{min} at ES would be 13.10±0.05ºC although Fig. 2b shows that it fluctuates between 13.01ºC and an anomalous maximum of 13.26 ºC by the end of 2009. Correcting these values for mixing in Tangier basin, θ_{min} at CS would be 12.98±0.05ºC (12.93ºC to 13.03ºC interval), which would be also representative of θ_{min} variability eastwards of CS in our hypothesis of very reduced mixing. Isotherms 12.93ºC and 13.03ºC are marked with gray lines in Fig. 3a and indicate the layer in the eastern part of the Strait that would be evacuated to the North Atlantic under the typical fluctuations of the forcing responsible for the observed variability at ES. It occupies the depth range between 670 m and 250 m depth. However, extreme θ_{min} values at ES of 13.01ºC in Fig. 2a, which would reduce to 12.89ºC at CS and eastwards, would displace the lower bound to the sea bottom (Fig.3a), suggesting that all the Mediterranean layer in the eastern approach of the Strait is potentially drainable to the Atlantic under extreme forcing.

Further east, the depth range associated with the STD-size fluctuations at ES is 440 to 600m if we only consider the mean profile (gray portion of the mean profile in Fig. 4) but increases to 230 to 780m if the variability of the profile, indicated by the dashed lines, is taken into account (double-headed arrow in Fig. 4). In case of extreme fluctuations, this depth could exceed 800-900m.

4. Numerical model

The correlation between U_{SWAG} and θ_{min} supports the hypothesis of *Bryden and Stommel* [1982] that the WAG helps uplift WMDW. For that, the WMDW in the western Alboran Sea must flow westwards along the African slope in the same direction as the overlaying Atlantic layer in the southern part of the WAG. The observations of *Bryden and Stommel* [1982] confirm they do but whether this preferred path of the WMDW is determined by the general circulation of the Mediterranean Sea (remote influence) or it is more a consequence of the water exchange through the Strait (local influence) remains unclear. A second issue to investigate is to which extent the uplifting of WMDW in the southern Alboran Sea is directly influenced by the dynamic of the Strait. Both topics have been addressed by process-oriented numerical simulations using the MITgcm.

The model domain extends from 9ºW to 1ºE and is horizontally discretized by a curvilinear orthogonal grid with minimum grid size in the Strait (Δx, Δy=5*00 m),* gradually increasing to 4-5 km in the Alboran Sea, and 8-10 km near the open boundaries (Fig.5a). The vertical spatial coordinate is discretized with 46 z-levels.

The model was run from a very simplified initial state in which the Mediterranean side was filled with two water masses representing LIW and WMDW of θ-S characteristics (13.2 ºC, 38.55) and (12.8ºC, 38.45), respectively. Initially LIW occupied the 600 uppermost meters, the rest being filled with WMDW. The Atlantic side was occupied by Atlantic water of (15.5 ºC, 36.2) θ-S characteristics. Both basins, initially at rest, were separated by a barrier that was removed at t=0 (lock-exchange initial condition). Orlanski radiation boundary condition [*Orlanski*, 1976] for both velocity and tracers were imposed at the open boundaries. No other external forces (meteorological, tides) were applied.

The model evolves to a final state characterized by a well developed WAG occupying the western Alboran Sea encircled by a swift Atlantic jet of 1 ms^{-1} typical speed (Fig.5b) that leaves the domain by the eastern boundary to form eventually the Algerian current. The deep circulation (Fig. 5c) shows a vein of LIW/WMDW at 500 m depth that enters the western Alboran basin along the trough located north of the Alboran Island and flows southwestwards to the African continental slope where it veers towards the Strait to contribute to the outflow. Its mean speed at the grid points used to compute U_{SWAG} is 4.8 cm s^{-1}, quite close to the mean value of 4.6 cm s^{-1} provided by *Bryden and Stommel* [1982] at the same depth a short distance to the west. The spatial distribution of isotherms across the Alboran basin (Fig. 5d) reproduces the pattern reported by these authors and illustrates the uplift of WMDW in the south where it is noticeably shallower (<300m) than it was initially (600m). Figure 3b shows that the model also accumulates WMDW in the southern part of the Strait, matching the observations in Figure 3a. Since no forcing was imposed on the open boundaries, this pattern would be linked to the dynamics of the exchange rather than to remote forcing acting across the boundaries.

To assess the direct influence of the Bernoulli aspiration caused by high velocities over CS on the uplifting of WMDW in the Alboran Sea, another numerical experiment was carried out in which the WAG was isolated from the strait dynamics by closing the strait at t=100 days, 50 days before the situation presented in Figure 5b. The surface circulation 50 days later is yet characterized by a large WAG (Fig. 6a), now extending more to the north as it is not constrained by the Atlantic jet. Figures 6b-c show that the depth of the isotherm *12.85ºC* is fairly similar in the closed and open-strait experiments except for the small area in front of the Strait's entrance where the closed-strait simulation shows it deeper and somewhat displaced northeastwards (consequence of the new enlarged shape of the WAG). Farther away from this area the circulation appears to be quite independent of the strait status indicating that the gyre is the main responsible for the banking of WMDW against the African slope. On the other hand, the shallowness of the isotherm in front of the strait in the open-strait run is attributable to Bernoulli suction, whose effect is only noticeable around this area.

5. Discussion and conclusions

The analysis of the different datasets in this work has showed the good correlation between the geostrophic velocity of the WAG and the near-bottom potential temperature at ES, which gives support to the hypothesis that a well developed WAG helps ventilate WMDW from the Alboran Sea and, hence, from the Mediterranean Sea. The ventilation is a two-step process starting with the uplift of WMDW produced by the WAG, whose final result is to facilitate the arrival of WMDW to the eastern entrance of the strait from where it is eventually aspired by the enhanced currents over CS. Once the sill has been surpassed, the WMDW flows without major topographic restrictions towards the Atlantic Ocean while mixing with the surrounding waters.

Some attempts have been made to investigate the depth from which WMDW can be aspired by this two-step mechanism. Using θ as a tracer, historical data from MEDAR in the southern half of the western Alboran basin (Fig. 4) indicate that θ_{min}=12.98 ºC (the mean value of θ_{min} at CS) is found at z_0=520m. This would be the representative depth from which the coldest/densest WMDW can be suctioned. Numerical results presented in Fig. 5c strongly suggest that water at 500 m depth flowing at 4.8 cm s^{-1} leaves the Mediterranean Sea. The coincidence in turn suggests that this velocity would correspond to the minimum value able to uplift resident WMDW in Alboran over the sills of the Strait.

When the time variability of θ_{min}, scaled by its STD at ES, is incorporated into the analysis then z_0 becomes a layer between 440 and 610 m (thick gray line in Fig. 4). If the correlation between θ_{min} and U_{SWAG} stands, the upper bound of this layer would coincide with the maximum depth from which a weakened WAG of U_{SWAG}=11 cms^{-1} (the mean, 24 cms^{-1}, minus the STD, 13 cms^{-1}) could uplift, on average, water for feeding the outflow. Similarly, the lower bound would be the maximum depth from which a strengthened WAG of U_{SWAG}=37 cm s^{-1} (mean+STD) would suction water. Obviously the WMDW characteristics in the suctioned water will be much clearer in the second case. Under extreme situations, both the lower and upper ends of the depth interval will change. For instance, judging from the θ transect in Fig. 3a, the lower bound can move downwards to 800-900m if we consider the extreme situations that forces the periodically observed presence of θ_{min} as low as 13.01ºC in the Mediterranean outflow at ES (Fig. 2b). On the contrary, there are unusual situations in which the WAG in the western Alboran Sea disappears and is replaced by a coastal jet of Atlantic water flowing attached to the African shore [*Vargas-Yáñez et al.*, 2002]. In this case, the downwards transfer of momentum would act to stop the flow of WMDW towards the Strait while the general circulation would facilitate a major drainage of the LIW residing at intermediate depths in the northern part of the Alboran basin, thus changing markedly the proportion of the different Mediterranean waters in the outflow.

It must be noticed that the water exchange is responsible for the WAG generation, which in turn uplifts WMDW from the deep part of the Alboran basin and makes it available for suction at the eastern approach of the Strait. From this point of view, the two-step process of WMDW evacuation from the western Alboran Sea is triggered by the internal dynamics of the exchange whose spatial reach exceeds the Strait dimensions. This conclusion is supported by the simple lock-exchange experiment that reproduces the well-documented deep circulation of the western Alboran Sea (*Bryden and Stommel,* 1982; *Parrilla et al.,* 1986), with WMDW being uplifted and flowing towards the Strait over the African shelf. The closed-Strait experiment confirms that this uplift is driven by the WAG although the final escape of the WMDW from the Mediterranean Sea needs of the Bernoulli suction triggered by the very high velocities over CS.

The aspiration of WMDW depends on the availability of this water at the depths from which it can be suctioned. The WAG forcing discussed here is one mechanism but it is not the only one. There are some others as commented in Section 1. Should any of them prevail over the WAG forcing, the correlation between θ_{min} and U_{SWAG} would diminish. Most probably, this was the case by the end of the winter of year 2005 (and to a lesser extent of year 2006), when an extraordinary production of new and very dense WMDW reached the bottom of the western Mediterranean basin and uplifted old WMDW to shallower depths [*Schroeder et al.*, 2008]. Its footprint was a very cold pulse in θ_{min} at ES (Figure 2b) that was not echoed by a similar fluctuation of U_{SWAG} (Figure 2a). The signal that a fluctuating WAG could have induced in θ_{min} would have been masked by this process, as discussed in *García Lafuente et al.* [2009].

The last remark concerns the meteorological variability that acts at –relatively- short time scale. It has been discussed above since it is implicitly included in both θ_{min} and altimetry time series. However, it is not included in the numerical simulations for two reasons. First, the main objective of the model was to address process-oriented studies to assess the role of the WAG in the ventilation of WMDW. Meteorological forcing would obviously modulate the whole process, but it is not expected to produce significant changes. The second and more important reason is that the main factor driving subinertial variability in the Strait of Gibraltar and, hence, in the western Alboran Sea is the atmospheric pressure variability over the whole Mediterranean basin, whose parameterization in a reduced model domain such as the one used in this work is far from being trivial (see Garcia Lafuente et al., 2002). The detailed numerical analysis of the meteorological forcing on the exchange trough the Strait requires the nesting of a Mediterranean basin-scale model, like the barotropic model used in Garcia Lafuente et al. (2002), with a reduced-domain model like the one used in this work. Such study is presently under way and it is not addressed here as it is out of the scope of this work.

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Figure captions

Fig 1 Map of the Strait of Gibraltar. ES and CS indicate the location of Espartel and Camarinal sills; TB is Tangier Basin and CA indicates the Ceuta-Algeciras CTD section mentioned in the text. Dashed gray line shows the model section used in Figure 3. Dashed black rectangle in Alboran Sea indicates the area where MEDATLAS profiles have been selected. Arrows depict the western Alboran gyre and indicate surface velocity in August 2008 from altimetry data. Crosses indicate the positions to compute U_{SWAG} (see text section 2.2). Black triangle indicates the currentmeters site in by Bryden and Stommel (1982). The diamond represents the Alboran Island.

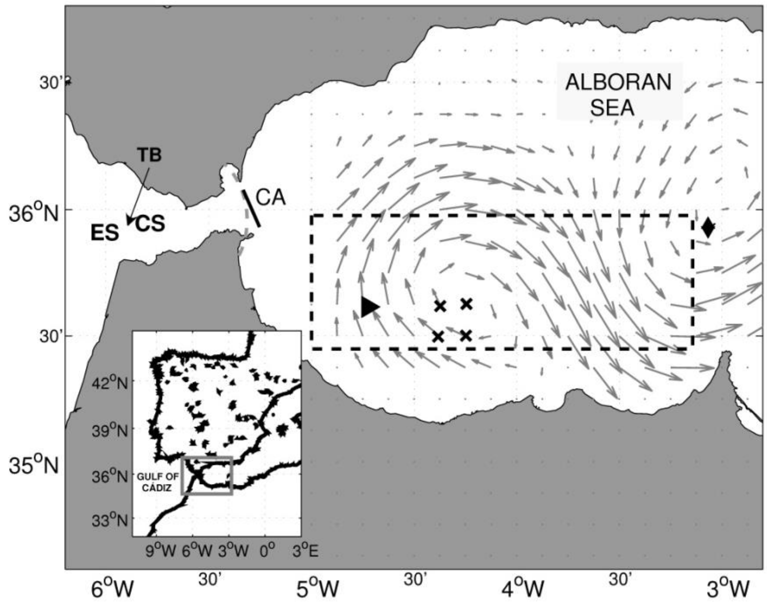
Fig 2 (a) Gray line: U_{SWAG} time series derived from altimetry data. Black line: low-passed filter signal. (b) Gray line: θ_{min} time series in Espartel sill. Black line: low-passed filter signal. Dashed line indicate the mean minimum and maximum values of θ, 13.05 and 13.15 ºC respectively (θ± STD)

Fig 3 (a) Potential temperature measure in cross-section CA marked in Fig.1, x-axes is latitude (ºN); CTD data were collected from 10:16 to 14:09h in June 16th, 2009. (b) Model results in a similar section (dashed gray line in Fig.1).

Fig 4 Spatially averaged vertical profiles of potential temperature below 260 m depth from the MEDATLAS database in the southern part of the western Alboran basin (the inset shows the whole profile). Dashed lines indicate ±1 STD, shadow area indicates de θ_{min} interval variation in ES corrected by de mixing factor.

Fig 5 (a) Computational grid used in the study (only 50% of the grid points are shown for the sake of clarity), the black rectangle encloses the Strait of Gibraltar and the Western Alboran Sea. (b) Modeled surface velocity. The diamond represents Alboran Island. (c) Same as a) at z=500 m depth. Isobaths z=100, 200,2000 m are given by gray lines (d) Cross section S, (panel c) of temperature and zonal velocity. Light contours are for negative velocities. Darker contours indicate areas of $u < -0.02$ m s^{-1}

Fig. 6 (a) Surface velocity of the Western Alboran Sea in the closed-Strait experiment. (b) Depth of the isotherm surface θ=12.85ºC (in meters) after 50 days of the Strait closure. (c) Same as (b) for the open-Strait run.



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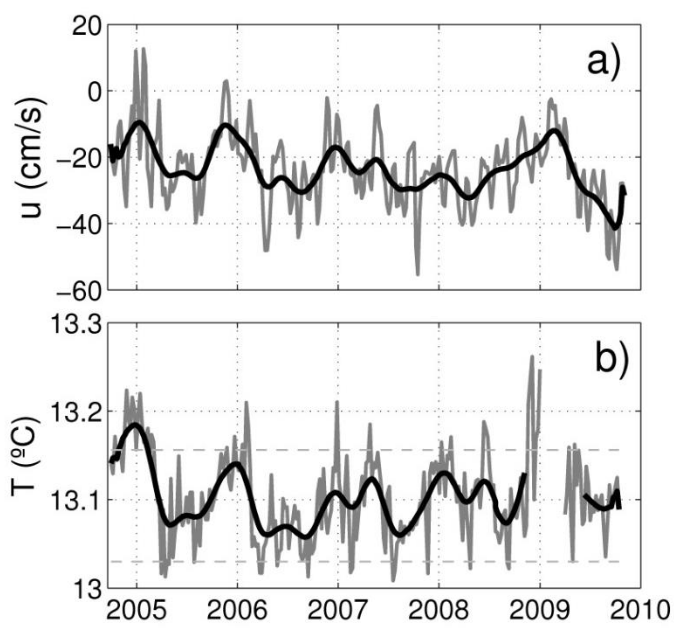

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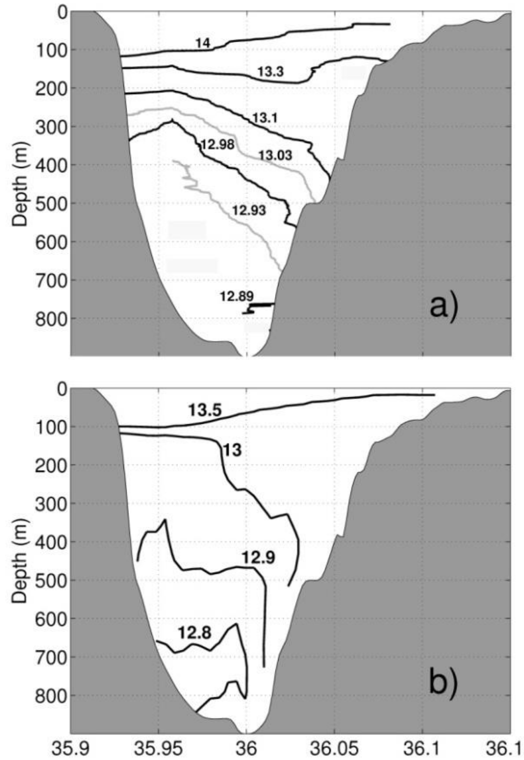

Fig 3 (a) Potential temperature measure in cross-section CA marked in Fig.1, x-axes is latitude (ºN); CTD data were collected from 10:16 to 14:09h in June 16th, 2009. (b) Model results in a similar section (dashed gray line in Fig.1).

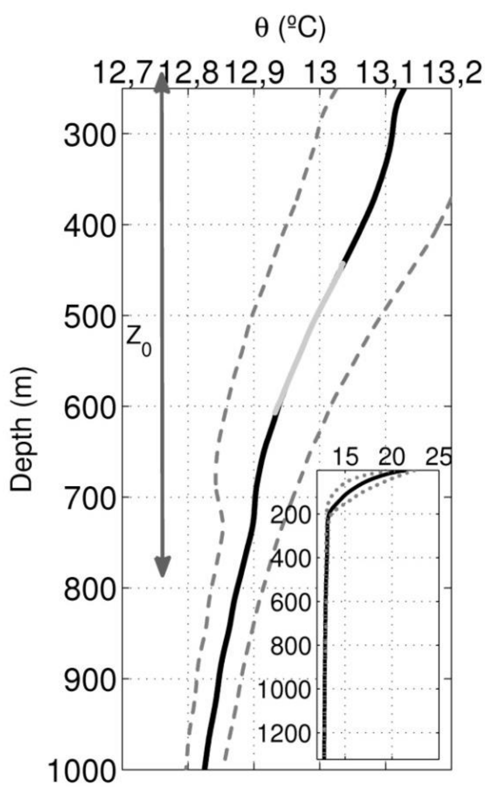

Fig 4 Spatially-averaged vertical profiles of potential temperature below 260 m depth from the MEDATLAS database in the southern part of the western Alboran basin (the inset shows the whole profile). Dashed lines indicate ±1 STD, shadow area indicates de θ_{min} interval variation in ES corrected by de mixing factor.

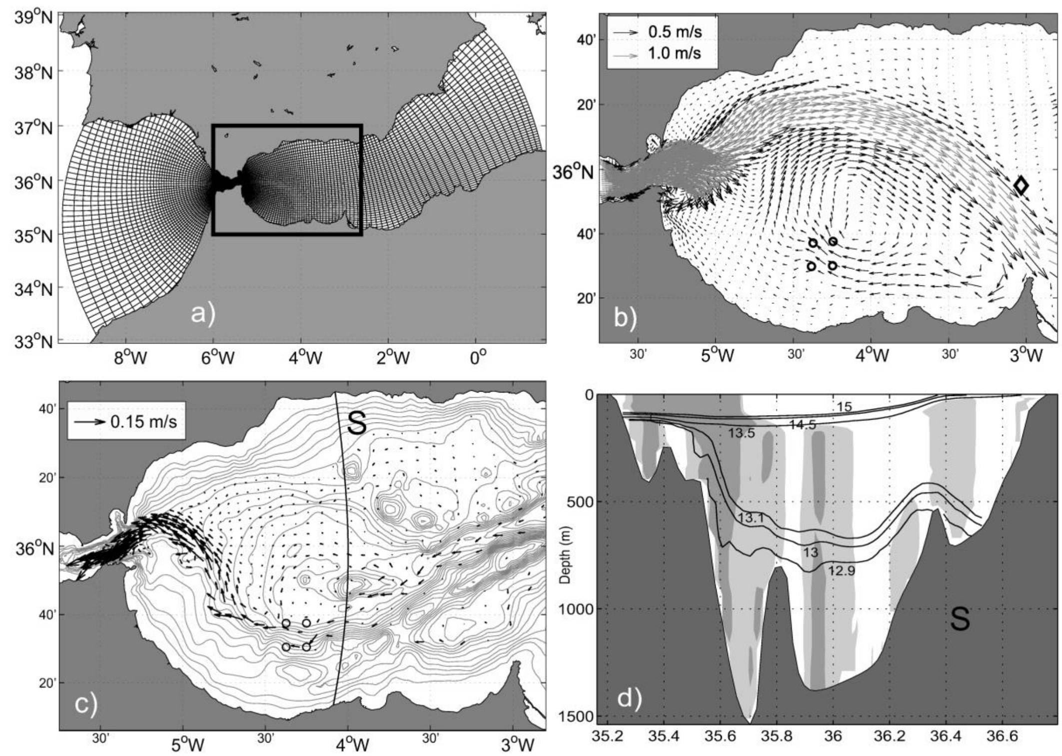

Fig 5 (a) Computational grid used in the study (only 50% of the grid points are shown for the sake of clarity), the black rectangle encloses the Strait of Gibraltar and the Western Alboran Sea. (b) Modeled surface velocity. The diamond represents Alboran Island. (c) Same as a) at z=500 m depth. Isobaths z=100, 200,…2000 m are given by gray lines (d) Cross section S, (panel c) of temperature and zonal velocity. Light contours are for negative velocities. Darker contours indicate areas of $u < -0.02$ m s^{-1}

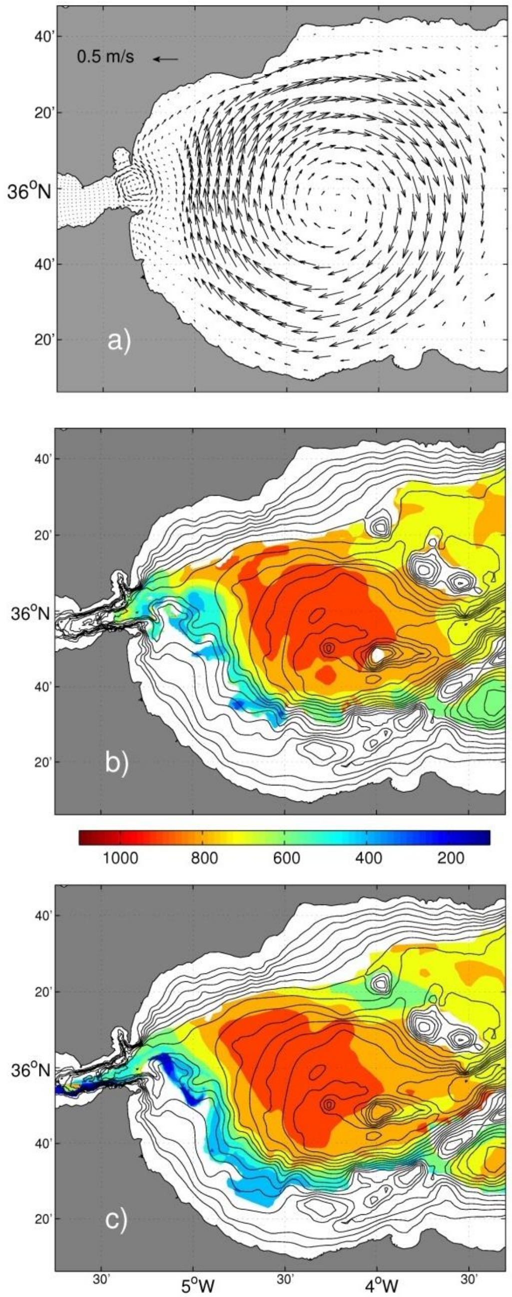

Fig. 6 (a) Surface velocity of the Western Alboran Sea in the closed-Strait experiment. (b) Depth of the isotherm surface θ=12.85ºC (in meters) after 50 days of the Strait closure. (c) Same as (b) for the open-Strait run.