AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2017GL072615

Key Points:
- Temperature and salinity of the Mediterranean outflow in the Strait of Gibraltar have been monitored for the period 2004-2016
- The monthly mean temperature shows a seasonal cycle with lower temperature during summer
- Temperature and salinity of the Mediterranean outflow in the Strait of Gibraltar reveal an increasing trend during the last decade

Supporting Information:
- Supporting Information S1

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Citation:
Naranjo, C., J. García-Lafuente, S. Sammartino, J. C. Sánchez-Garrido, R. Sánchez-Leal, and M. Jesús Bellanco (2017), Recent changes (2004–2016) of temperature and salinity in the Mediterranean outflow, *Geophys. Res. Lett.*, *44*, 5665–5672, doi:10.1002/2017GL072615.

Received 16 JAN 2017
Accepted 30 MAY 2017
Accepted article online 1 JUN 2017
Published online 15 JUN 2017

Recent changes (2004–2016) of temperature and salinity in the Mediterranean outflow

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Abstract Temperature and salinity series near the seafloor at Espartel Sill (Strait of Gibraltar) have been used to analyze the thermohaline variability of the Mediterranean outflow. The series shows temperature drops by the end of most winters/early springs, which are the remote response to Western Mediterranean Deep Water (WMDW) formation events in the Gulf of Lion that uplift old WMDW nearby the strait. This process distorts the seasonal cycle of colder/warmer water flowing out in summer/winter likely linked to the seasonality of the Western Alborán Gyre. The series shows positive trends in agreement with previous values, which are largely increased after 2013. It is tentatively interpreted as the Western Mediterranean Transition (WMT) signature that started with the very cold winters of 2005 and 2006. It was only after the large new WMDW production of 2012 and 2013 harsh winters that WMT waters were made available to flow out of the Mediterranean Sea.

1. Introduction

The Western Mediterranean Deep Water (WMDW) was considered to have had practically constant values of potential temperature (θ), salinity (S), and potential density (σ_θ) between 1909/1910, the time of the Thor Expedition, and the 1970 cruise of the Jean Charcot [*Lacombe et al.*, 1985]. Recent studies of the Mediterranean Sea and, more specifically, of its Western basin (WMb henceforth) have disclosed temperature and salinity trends in the Mediterranean Waters (MWs), mainly WMDW and Levantine Intermediate Water (LIW, see Table S1 in the supporting information). Despite being nonuniform in space and time, the data used provide values in the order of $+10^{-3}$[units] yr^{-1} for both variables with a tendency to increase during the last decades. Because temperature and salinity trends act in opposite directions upon the density, it is not clear whether the MWs density is currently changing, though some recent studies indicate trends in this variable as well (Table S1) [*Bethoux and Gentili*, 1996, 1999; *Grignon et al.*, 2010; *Krahmann and Schott*, 1998; *Leaman and Schott*, 1991; *Rohling and Bryden*, 1992; *Schröder et al.*, 2006; *Smith et al.*, 2008; *Tsimplis and Bryden*, 2000; *Vargas-Yáñez et al.*, 2010; *Zunino et al.*, 2009].

Every winter, the strong buoyancy loss caused by cold and dry winds over the Gulf of Lion (GoL, Figure 1), drives the WMDW formation by open ocean convection [*Marshall and Schott*, 1999; *Medoc*, 1970] and by cascading of shelf water via submarine canyons [*Houpert et al.*, 2016; *Puig et al.*, 2013]. Despite an expectable year-to-year variability, the first one is a rather regular process, while cascading is more intermittent [*Houpert et al.*, 2016]. The volume of new WMDW is anomalously high in years when both processes occur. In particular, the very harsh winters of 2004–2005 and 2005–2006 formed large volumes of saltier, warmer, and denser WMDW in the GoL [*Schroeder et al.*, 2008] that reached the seafloor, spread laterally, and gave rise to a new vertical pattern of the deep layers in the WMb. These major events have been identified with the starting of a Western Mediterranean Transition (WMT) [*Commission Internationale pour l'Exploration Scientifique de la Méditerranée*, 2009; *Zunino et al.*, 2012], in analogy with the Eastern Mediterranean Transient during the 90s of last century [*Roether et al.*, 1996]. The new formed WMDWs leave a typical hook-shaped signature in the *TS* diagram [*López-Jurado et al.*, 2005; *Schroeder et al.*, 2008], which makes them easily recognizable in the WMb's interior. Successive winters tend to produce warmer and saltier waters than they used to, adding complexity to the layer structure of the water column, while—seemingly—older WMDWs go on being uplifted [*Schroeder et al.*, 2016]. These authors have tracked the progression of the 2005–2006 WMDWs (i.e., the WMT) from the formation sites toward the east (Tyrrhenian Sea) and west (Alborán Sea). Over time, these waters will eventually flow out through the Strait of Gibraltar (SoG), the most suitable site for monitoring the overall changes of the MWs before being incorporated to the global ocean.

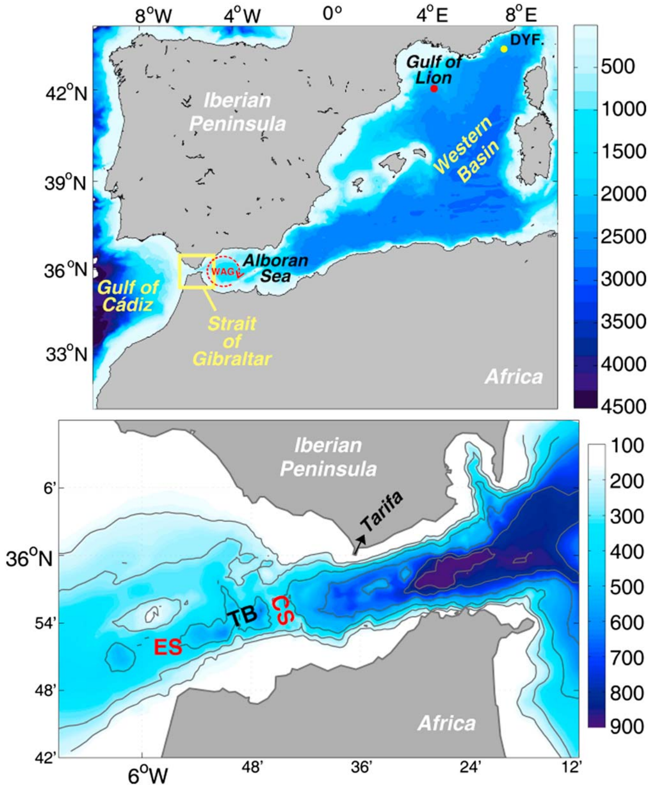

Figure 1. (top) The western Mediterranean basin, the Strait of Gibraltar, and the Gulf of Cádiz. The mooring in the Gulf of Lion is marked with a red point; in the Ligurian Sea the DYFAMED station mentioned in Table S1 is also indicated with a yellow dot and DYF initials; the Western Alboran Gyre in the Alboran Sea is also marked with a red-dashed circle. (bottom) A detailed bathymetry of the Strait of Gibraltar, indicating the main features named in the manuscript; CS shows Camarinal Sill (290 m), TB is for Tangier Basin and ES for Espartel Sill (360 m), and the last represents the location where the data of this manuscript were measured.

Despite not being able to detect them, *Schroeder et al.* [2016] predicted their appearance in the SoG by year 2015, thus creating expectation about the correctness of the prediction.

Since year 2004, a mooring station has monitored the Mediterranean outflow (MOW) at Espartel Sill (ES, Figure 1), the westernmost gateway of the SoG, and the data collected are the core of the present study. A noteworthy remark regarding this issue is the notable tidal mixing underwent by the MWs, while a small fraction of the overlying North Atlantic Central Water (NACW) is entrained by the MOW as it flows past the main sill of Camarinal (CS, Figure 1) [*Sánchez-Garrido et al.*, 2011; *Wesson and Gregg*, 1994]. The last makes the MWs undistinguishable when they reach ES [*García-Lafuente et al.*, 2011; *Naranjo et al.*, 2015]. In particular, the typical hook-shaped signature of the WMT in the interior of the WMb will most probably be lost at ES. In spite of that trends inferred from the mixed MOW should have the potential for its identification.

On the other hand and according to *García-Lafuente et al.* [2007, 2009], the replenishment of the deep/bottom layer of the WMb that follows the WMDW formation in the GoL will rise the interface with the overlying water masses and generate an internal signal that radiates away. If strong enough, it will reach the eastern approach of the SoG, uplift the interface there, and facilitate the withdrawal of colder (and older) WMDW. This remote response must be delayed by the time it takes the signal to travel from the GoL to the SoG, which under a two-layer (LIW over WMDW) approximation and realistic values of the layers thickness and density difference, will range from few tens of days to around 2 months.

Thus, the processes of WMDW formation in the GoL is expected to impact the observations at ES in two different ways: a quick response that leaves a cold signature the same year of the convection shortly after it occurs, and another signal to appear years later linked to previous (and major) formation processes such as the WMT, which presently would show up as a warming and salting trend. The first issue was formerly addressed in *García-Lafuente et al.* [2007] and is revisited in section 3 of this study along with the seasonal cycle with which it interferes. The preceding section 2 presents the data and the data processing. Section 4 addresses the second issue, and finally, section 5 discusses and summarizes our findings.

2. Data and Data Processing

2.1. Data Sets

The monitoring station at ES is nominally located at 35°51.7′N and 5°58.2′W (Figure 1) at a depth of 362 m and was first deployed in October 2004. The line is 20 m tall and includes a Conductivity-Temperature sensor

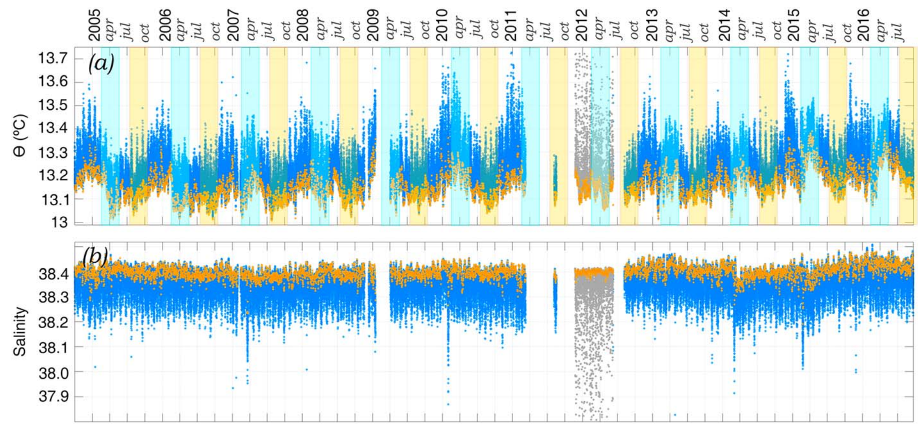

Figure 2. (a) Potential temperature (blue dots) at ES station. Grey points correspond to observations at CS transferred at ES after applying the correction explained in the text. Orange dots show the θ_{min} series (see text). Shaded-blue strips indicate the period of the year when the signal of deep convection in the GoL is expected to show up at ES and covers from mid-February to mid-May (see Figure 3 and caption there), while yellow strips mark the summer period (mid-July to mid-October). (b) Salinity (blue dots) at ES, which include the data transferred from CS to ES (grey dots). Orange dots show the $S_{\Theta min}$ series (see text).

(CT, Seabird SBE37-SMP) at about 14 m above the seafloor that measures the temperature and salinity of the deepest (and, hence, densest) outflowing water through the SoG. An uplooking acoustic Doppler current profiler (ADCP) equipped with a pressure sensor was atop the line. The pressure data (corrected for the known distance ADCP-CT) were used to calculate θ. The sampling interval was fixed to 30 min for all the instruments. The series spans from October 2004 to September 2016 with an important gap from March 2011 to August 2012, partially filled with data coming from CS (see below). The CT probes were regularly calibrated to remove the drift of the sensors in the data (which turned out to be $O(10^{-3})$°Cyr^{-1} for temperature and $O(10^{-3})$ yr^{-1} for salinity in our case), which are comparable to the trends reported in Table S1. Therefore, calibration becomes a critical step.

2.2. Data Processing

Time series collected anywhere in the SoG are unavoidably affected by tidal fluctuations (Figure 2), which are noise for long-term variability studies. *García-Lafuente et al.* [2007] argued that the sample of minimum θ in each semidiurnal tidal cycle is the best proxy for the less mixed Mediterranean water flowing out over ES. A selection of these samples results in a tidal-free series (except for fortnightly variability, which is not removed), decimated to a data every 12.4 h approximately. This series will be denoted by θ_{min} from now on, whereas $S_{\Theta min}$ and $\sigma_{\theta min}$ will stand for the salinity and the potential density anomaly series, respectively, corresponding to the decimated samples of θ_{min}.

In year 2011 the station suffered several accidents and the mooring position was provisionally relocated to CS in November 2011. It was moved back to ES in August 2012 after solving the problem, but this caused a considerable data gap from March 2011 to August 2012 in ES series. According to *García-Lafuente et al.* [2011], θ_{min} series at ES is 0.11°C warmer and $S_{\Theta min}$ is 0.09 units fresher than their analogue at CS on average. Applying these corrections, the data at CS have been employed to partially fill the gap (see Figure 2 and caption there).

3. Seasonal and Interannual Variability

3.1. Seasonal Pattern

Figure 3 shows that the monthly means of θ_{min} at ES exhibit a seasonal cycle with warmer (cooler) water during early winter (summer). This seasonality has been ascribed to a more robust and permanent Western Alborán Gyre (Figure 1) in summer months that facilitates the drainage of WMDW residing in the southern Alborán Sea [*Naranjo et al.*, 2012] and, possibly, to a smaller contribution of the little fraction of NACW participating in the MOW, which is colder in summer due to the upwelling cycle in the Atlantic façade of the

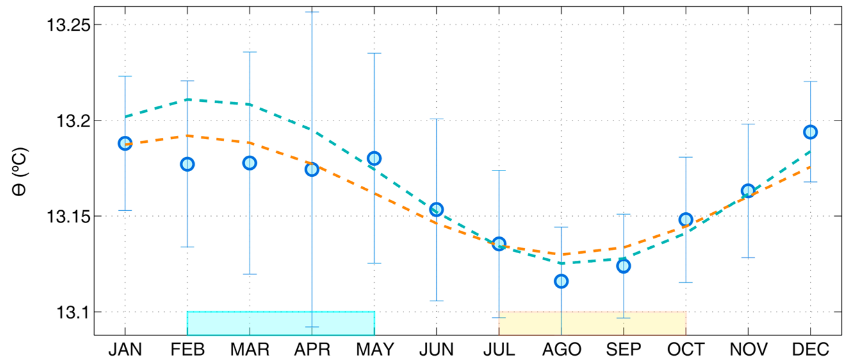

Figure 3. Monthly means (dots) and standard deviation (bars) of the 12 yearlong θ_{min} series. Ticks are for the midmonth day because January value has been obtained by averaging the values of all Januaries and so on. Orange line shows the fit to a single harmonic of annual frequency, while green line is the same fit after excluding February, March, and April. Light-blue and yellow bars indicate the time windows used in Figure 2 to analyze the ES response to the WMDW formation in the GoL and the summer period, respectively.

Iberian Peninsula [*García-Lafuente et al.*, 2015]. The fitting of these means to an annual harmonic (orange line in Figure 3) is only moderately satisfactory. No clear seasonality is found in $S_{\Theta min}$ series (not shown), so that the seasonal cycle of $\sigma_{\theta min}$ resembles the specular image of θ_{min} cycle.

The error bars in Figure 3 show much greater variability from February to May, a fact already inferable in Figure 2a. Excluding February, March, and April from the fitting, the curve adjusts the rest of the months much better than it does when including all months. The enhanced variability during these months also suggests that other processes are acting and, possibly, overcoming those outlined above. One of them is the commented remote response to events of WMDW formation in the GoL, already addressed in *García-Lafuente et al.* [2007], and revisited next.

3.2. Interannual Variability: Deep Water Formation Events

The formation of WMDW in the GoL is usually replicated by a sudden decrease of θ_{min} at ES about 1–2 months later. Should it happen by the end of winter (February–March), the response at ES would be detected in March–May, causing the departure of θ_{min} from its expected average seasonal value in Figure 3 during this part of the year. The blue-shaded rectangles in Figure 2a help to illustrate the fact that the winter and early spring θ_{min} drop happens most years but that it is not as regular as the every-year summer minimum (yellow-shaded rectangles), which determines the dissimilarity of variance in one or the other period (Figure 3). Specifically, the θ_{min} drop can be observed in February (2007, 2014, and 2015), in late April–May (2008 and 2009), even can display several minima (2013), be absent (2010 and possibly 2011) lasts a short time (2014 and 2015), or spreads over most of the time window (2005, 2006, and possibly 2012). Under the hypothesis of its remote origin in the GoL, its variability, strength (measured in terms of the magnitude of θ_{min} drop), and duration will depend on the characteristics of the deep convection. Mild winters are expected to produce weak or no signature, while harsh winters will produce a strong one. Table S2 summarizes the estimated amount of WMDW formed in different years reported in the literature [*Beuvier et al.*, 2012]; *Herrmann et al.*, 2017, 2009, 2010; *Rhein*, 1995; *Somot et al.*, 2016].

Years with high formation rates (in bold in Table S2) tend to produce winter θ_{min} drops that are sustained in time (2005, 2006, 2009, and 2012, see Figure 2), which can even merge with the summer minimum (case of years 2006 or 2009, also 2005 to a lesser extent). Year 2013 shows a weird pattern in the sense that several θ_{min} drops were registered in winter and early spring. The last one, particularly large, took place by mid-May and kept θ_{min} low until late October (Figure 2a) after merging with the summer minimum. It recalls the behavior of the other four above mentioned years with a delay of 1–2 months, a recall further confirmed by the anomalously high convective winter [*Waldman et al.*, 2016], which is in line with what happened those years (Table S2).

4. Long-Term Trends

The series θ_{min}, $S_{\ominus min}$, and $\sigma_{\theta min}$ have been linearly fitted in order to investigate trends in the MOW at ES. Table S3 shows positive trends for temperature, which is statistically significant at the 95% confidence level following *Thomson and Emery* [2014], and also for salinity, although they are not significant at this level. Potential temperature of the MOW (its deepest portion at least) has been increasing from 2005 to now at a mean rate of (6.89 ± 3.24) 10^{-3}°Cyr^{-1}, and salinity at (1.34 ± 1.56) 10^{-3} yr^{-1} (Table S3). Density does not show any significant trend, partially because of the opposite effect of θ and S on it. The result agrees with *Borghini et al.* [2014], who conclude that the density of the MWs did not vary over the period 1961–2008 near the entrance of Alborán Sea.

There is the concern that trends of θ and S in the interior of the WMb have increased during the last years [*Borghini et al.*, 2014; *Marty and Chiavérini*, 2010; *Schroeder et al.*, 2016]. To this regard, Figure 2a shows a more or less steady θ trend from the beginning of the series until year 2013 approximately, and a noticeable steepening afterward, which almost quadruplicates the one for the whole period ((20.7 ± 14.7) 10^{-3}°Cyr^{-1} at 95% significance level, Table S3). Salinity also shows a nearly fourfold increase of the estimated trend during the same period, although it is not significant at the 95% level (Table S3).

The trend of potential temperature for the whole series is the same order of magnitude of trends reported in Table S1, which is also the case for salinity. The largely increased short-term trends for the 2012–2016 period (Table S3) are clearly above all trends in Table S1 and third row of Table S3 (series before 2013), indicating a marked change by the end of the series. The last produces a noticeable dissimilarity of trends in ES series before and after this particular year. A discussion about this issue is given in the next section.

5. Discussion and Conclusions

A number of fluctuations at different time scales are detected in the MOW series recorded at ES, from the locally generated tidal variations caused by strong flow-topography interaction, to erratic events of unusual low salinity originated in the Atlantic side of the SoG visible in Figure 2b (neither of them addressed here), to lower frequency signals whose source is in the Mediterranean Sea (sections 3.1, 3.2, and 4).

Two different physical processes have been discussed to explain this variability: the seasonal changes of circulation in the Alborán Sea or, more specifically, the Western Alborán Gyre dynamics, which drives an annual cycle in θ_{min} with minimum in summertime [*García-Lafuente et al.*, 2009; *Naranjo et al.*, 2012], and the WMDW formation in winter, which produces a sudden decrease of θ_{min} at ES in late winter and early spring. This process distorts the seasonal cycle (Figure 3), induces a marked interannual variability (Figure 2a) obviously related to the year-to-year variability of the deep convection itself, and, in the end, is connected to the long-term trends reported in the deeper layers of the WMb (Table S1). It is also connected with deep water ventilation processes such as the progression of the WMT toward the Atlantic, whose footprint, whatever it may be, will expectedly show up in the MOW at ES station.

Because of its interest, we focus on the last issue. After deep convection, the new WMDW formed will spread laterally along the isopycnals of its own density, giving rise to a vertical structure of interleaving layers not necessarily organized by age but by density. Mixing driven by double-diffusive and—more effective—salt finger processes [*Bryden et al.*, 2014] would erode this pattern and transform the layered ocean into a continuously stratified one where the subtle θ and S differences between layers (i.e., between WMDW formed in different years) have faded out. Obviously, the greater the differences, the longer it will take to erode the layered pattern.

Previously to year 2004, winters were rather mild, WMDW formation was scarce (Table S2) and, presumably, exhibiting quite similar characteristics. It depicts a favorable scenario in which, according to *Borghini et al.* [2014], mixing processes acted to produce a small but steady positive θ and S trend in the interior of the WMb. The heat and salt convergence at the top of the WMDW layer in the manner discussed in *Bryden et al.* [2014] would be the underlying physical process. The situation changed dramatically with the major WMDW formation events in 2004–2005 and 2005–2006 winters which produced WMDW of consistently different thermohaline characteristics (the WMT) than the preexisting ones. According to *Schroeder et al.* [2016], the signal has not only not been eroded, but it is still clear enough to allow for tracking its spatial evolution in

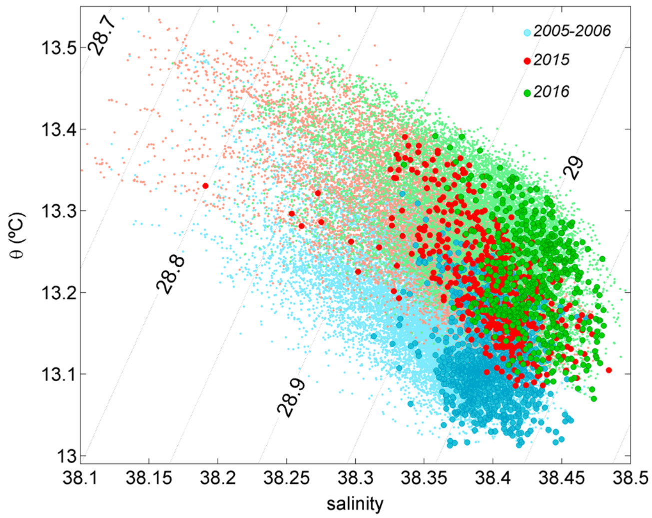

Figure 4. Thermohaline properties of the MOW for the 2005–2006 years (blue dots) in comparison with years 2015 and 2016 (red and green dots, respectively). Small dots are for the whole data set, while thick dots represent the θ_{min} series.

the WMb until (in their study) year 2015, 10 years after it was produced. Even more, from this rather regular spatial evolution, *Schroeder et al.* [2016] predicted its spillover through the sills of the SoG by 2015.

With this background in mind, what would the footprint of the MOW at the SoG look like? The horizontal spreading is not enough to overflow the main sill of the SoG, whose depth is slightly less than 300 m, while the top layer of the 2005–2006 WMDW layer is deeper than 1000–1500 m in the WMb. The water would be piled up in the nearby Alborán Sea and the westward progression of the signal stopped, although the Bernoulli aspiration discussed in *Stommel et al.* [1973] or *Naranjo et al.* [2014] would give some chance for small spillover. A new twist occurred in years 2012 and 2013 when again major events of WMDW formation did take place [*Durrieu de Madron et al*., 2013; *Waldman et al*., 2016]. They reached the seafloor and raised old WMDW, in which category the WMDW of years 2005 and 2006 is now included, enabling them to flow over the SoG's sills. When they do, tidal mixing will erode the characteristic hook-like footprint that these waters exhibit in the θ-*S* diagram when they are in the WMb, and the only expected signature in the ES series would be an increase of the trends due to their warmer and saltier nature. As a matter of fact, Table S3 shows an increase of θ_{min} and $S_{\Theta min}$ positive trends from 2013 onward, and Figure 4 further confirms that the θ-*S* characteristics of the MOW in years 2015–2016 are consistently saltier and warmer than in 2005–2006 (the first complete years of the series), which opens the possibility that this increase is the footprint of the WMT at the SoG predicted by *Schroeder et al.* [2016]. Previously to year 2013, trends in ES series were smaller (Table S3) and—probably—steadier. More interesting, they recall the pattern (delayed by almost a decade) of the trends in DYFAMED station showed in Figure 4 of *Borghini et al.* [2014]. In summary, even when the major deep convection events of 2004–2005 and 2005–2006 winters were detected at ES by the sudden drop of θ_{min} in March–April those very years, the WMDW flowing out in the MOW until 2013 had basically pre-2005 characteristics, with trends similar to those in the WMb's interior before 2005. It is not until the new major convection of years 2012–2013 that the waters formed in years 2005–2006 (i.e., the WMT) are able to flow out through the SoG once they have been uplifted by the newer WMDW formed those years.

Another minor issue is why the WMT signal is blurred at ES when it is so clear in the WMb, even in the Alborán Sea according to *Schroeder et al.* [2016]. The explanation is the tidal mixing in the SoG, which is able to change the salinity of the outflowing MWs by 0.1 units (on average) during each tidal cycle due to the small fraction of NACW entrained by the MOW [*García-Lafuente et al*., 2007]. It is more than enough to erase the hook-like signature of the WMT. A more subtle question is why signals are much better seen in θ_{min} than in *S* series (for instance, the annual response to the deep convection), when the WMT was triggered by the LIW salinification during the late 90s and first years of this century rather than by cooling [*Schroeder et al*., 2010]. As discussed in *García-Lafuente et al.* [2017], the reason is that at monthly to annual time scales, a fraction as small as 5% of NACW in the MOW is able to obliterate salinity signals coming from the WMb; only long-term salinity changes would show up. This does not apply to temperature, since the temperature difference between the NACW and the underlying MWs is much less than for salinity. Consequently, Mediterranean signals are better seen in θ series. In view of these drawbacks a final question would be whether or not ES is better than CS for monitoring the changes in the MOW sourced in the Mediterranean Sea. The answer is in Figure 2 where the small fragments of series collected at CS and transferred at ES site after correction for completeness (grey dots) show even more tidal variability than ES series themselves. The erosion of weak

Mediterranean signals carried by the MWs would be very similar in both sites, and no recognizable improvement would be achieved in CS.

Acknowledgments

The monitoring station deployed at Espartel Sill has been maintained in the frame of the Spanish Government funded "INGRES" projects (REN2003-01608, CTM2006-02326, CTM2009-05810/MAR, and CTM2010-21229-C02-01/MAR). It also contributes to the Mediterranean Sea monitoring network of the HYDROCHANGES Programme sponsored by the CIESM. C.N. and J.C.S.G. were supported by the Spanish Funded Project CTM2013-40886P, and S.S. acknowledges a postdoc contract of Junta de Andalucía linked to Excellence Project RNM1540 (MOCBASE). Over this decade of data collection many scientific teams generously helped during the maintenance cruises (INGRES, STOCA-INGRES, and STOCAL), and we thank all them. We are also grateful to the crew of the Spanish Oceanographic Institute R/Vs, Odón de Buen, Francisco Paula Navarro, Coornide de Saavedra, Ramón Margalef, and Ángeles Alvariño. The data sets from the Espartel mooring are available at Pangaea database, https://doi.pangaea.de/10.1594/PANGAEA.873943.

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