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Large warming and salinification of the Mediterranean outflow due to changes in its composition

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Abstract

The Mediterranean Sea transforms surface Atlantic Water (AW) into a set of cooler and saltier typical Mediterranean Waters (tMWs) that are formed in different subbasins within the sea and thus have distinct hydrological characteristics. Depending on the mixing conditions along their route and on their relative amounts, the tMWs are more or less differentiated at any given place, and some mix together up to forming new water masses. We emphasise the fact that any of these Mediterranean Waters (MWs) must outflow from the sea, even if more or less identifiable and/or in a more or less continuous way. Historical data from the 1960s–1980s showed that the densest MW outflowing through the Strait of Gibraltar at Camarinal Sill South (CSS) was a relatively cool and fresh tMW formed in the western basin, namely the Western Mediterranean Deep Water (WMDW). At these times, the sole other tMW identified in the strait was the Levantine Intermediate Water (LIW); no mention was made there of, in particular, the two densest tMWs formed in the eastern basin (in the Aegean and the Adriatic) that are now named Eastern Overflow Water (EOW) when they reach the Channel of Sicily (where they cannot be differentiated). A fortiori, no mention was made of the Tyrrhenian Dense Water (TDW) that results from the mixing of EOW with waters resident in the western basin (in particular WMDW) when it cascades down to ~2000 m from the channel of Sicily. New measurements (essentially temperature and salinity time series) collected at CSS since the mid-1990s indicate that the densest MWs outflowing through the strait have been continuously changing; temperature and salinity there have been increasing, being actually (early 2000s) much warmer (~0.3 °C) and saltier (0.06) than ~20 years ago. These changes are one order of magnitude larger than the decadal trends shown for WMDW in particular. We thus demonstrate that, in the early 2000s, (i) the densest MW outflowing at Gibraltar is TDW and (ii) TDW is mainly composed of EOW (the percentage of MWs from the western basin, in particular WMDW, is lower): the densest part of the outflow is thus "more eastern than western". This Mediterranean Sea Transient (a shift from the western basin to the eastern one) could be linked to the Eastern Mediterranean Transient (a shift from the Adriatic subbasin to the Aegean one). Whatever the case, we demonstrate that the proper functioning of the Mediterranean Sea leads to a variability in its outflow's composition that can have consequences for the mid-depth water characteristics in the North-Atlantic much more dramatic than previously thought.

Keywords: Long-term changes; Mediterranean outflow

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1. Introduction

Because evaporation exceeds precipitation and river runoff, the semi-enclosed Mediterranean Sea continuously transforms Atlantic surface water (AW, CIESM, 2001: potential temperature $\Theta \sim 15$–$16\,^{\circ}\mathrm{C}$, salinity $S \sim 36.5$) into saltier (~ 38.5) and additionally cooler (hence denser) water. AW finally sinks (Lacombe and Tchernia, 1960) in the north of four subbasins of the eastern basin (the Levantine, the Aegean, the Adriatic) and of the western basin (the Liguro-Provençal). Note that we reserve the term "sea" for the Mediterranean and "basin" for the eastern and western parts of it; any smaller entity is a subbasin (this term being possibly omitted, http://www.ifremer.fr/lobtln/OTHER/Terminology.html).

This leads to four major typical Mediterranean Waters (tMWs) that have distinct hydrological characteristics. Recently proposed circulation diagrams highlight the similarities of the processes occurring in both basins and present a unified image of the circulation of all water masses in the whole sea that is mainly alongslope and counterclockwise (Millot and Taupier-Letage, 2005). As the tMWs circulate (together with AW in general) within the sea and outflow (contrary to AW) from the eastern basin into the western basin through the Channel of Sicily and into the ocean through the Strait of Gibraltar, there is some mixing between them so that they can be more or less differentiated. As shown hereafter, mixing of some of the tMWs in some specific places is so intense that they can be completely "lost".

The Levantine Intermediate Water (LIW) is the warmest and saltiest tMW; it is easily recognised on a Θ–S diagram anywhere in the sea as far as the western Alboran (Bryden and Stommel, 1982; Parrilla and Kinder, 1983; Gascard and Richez, 1985; Parrilla et al., 1986) where it is characterised by $\Theta \sim 13.1$–$13.2\,^{\circ}\mathrm{C}$, $S \sim 38.5$. Being the least dense tMW (hence at 200–600 m just below AW), it easily outflows through the Channel of Sicily and it was depicted (Millot, 1999) as outflowing in the northern part of the Strait of Gibraltar at 100–200 m. However, it has been clearly identified there only a few kilometres east from the sill (Kinder and Parrilla, 1987), i.e. never at the sill itself, hence never in its deeper part (down to ~ 300 m) known as Camarinal Sill South (CSS, Fig. 1).

According to classical (bottles and thermometers) hydrological data (in the 1960s–1970s) and CTD casts (in the mid-1980s, Fig. 1), the sole other tMW documented in the CSS surroundings was the Western Mediterranean Deep Water (WMDW) that is formed in the Liguro-Provençal mainly from an AW–LIW mixture. At these times, WMDW was filling most of the deep western basin and was documented (Kinder and Parrilla, 1987) at 100s-of-meter depths east of the sill with $\Theta \sim 12.75\,^{\circ}\mathrm{C}$. Just at the sill, an observation in the 1960s (Allain, 1964) of $\Theta \sim 12.9\,^{\circ}\mathrm{C}$ and the hypothesis in the 1970s (Stommel et al., 1973) that WMDW was raised up to ~ 300 m via a Bernoulli effect motivated dedicated surveys during the Gibraltar Experiment in the 1980s (Bryden and Kinder, 1991). Although pure WMDW was most likely outflowing during part of the tidal cycle only (Bryden and Stommel, 1982), it was reported west of the sill (Kinder and Parrilla, 1987), and one-week bottom time series at CSS (Pettigrew, 1989) showed $\Theta < 12.9\,^{\circ}\mathrm{C}$. Therefore, it has been agreed that WMDW was outflowing at CSS, hence mainly in the southern part of the strait (Kinder and Bryden, 1990), together with LIW in the northern part of it (this is still generally believed). Pure WMDW is still recognised below ~ 2000 m in the Liguro-Provençal and Algerian subbasins with $\Theta \sim 12.8$–$12.9\,^{\circ}\mathrm{C}$ and $S \sim 38.42$–38.45 (e.g. van Haren and Millot, 2004), which were typical values at CSS in the 1960s–1980s. Note that, to our knowledge, none of the other tMWs was identified at the sill, and their "necessary" presence there never mentioned prior to Millot (1999).

We show hereafter that WMDW in the early 2000s can no longer be identified at CSS and that the warmer and saltier waters found there since the mid-1990s have characteristics clearly corresponding, at times, to LIW or to another water (defined in Section 2) that results from a mixing between waters from the eastern basin and waters from the western one; hence, WMDW is expected to outflow actually from the sea as a component of the latter.

Apart from its varying composition, the dense Mediterranean outflow sinks west of the sill, mixing with the surrounding waters and creating a warm and saline tongue that can be identified throughout the whole North Atlantic at depths of 1000–1200 m. From a global perspective, the high-salinity water related to this tongue has been implicated in the preconditioning of the North Atlantic deep water formation and thus on the density driven circulation of the World Ocean (Candela, 2001).

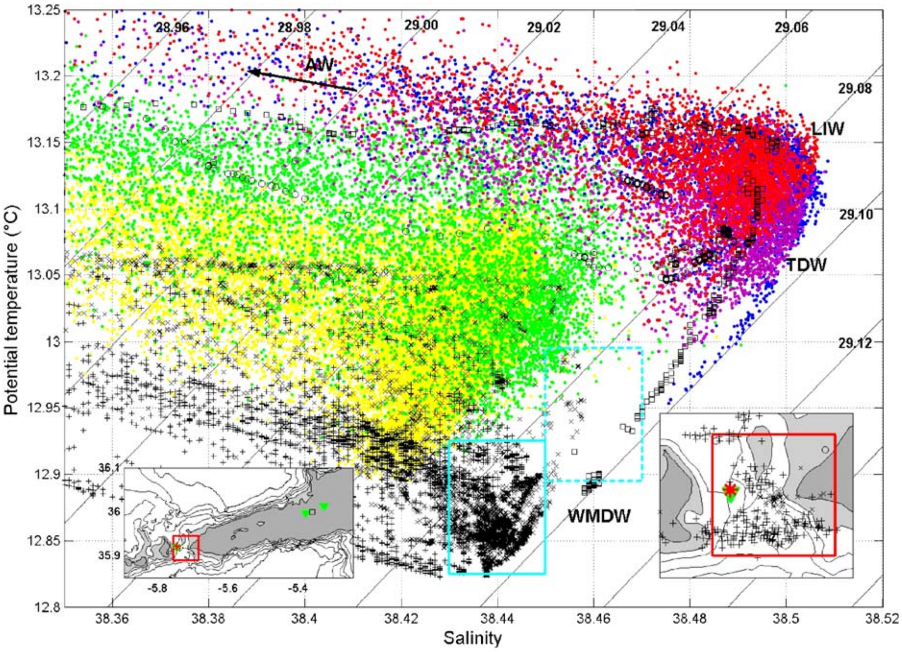

Fig. 1. Potential temperature-salinity (Θ-S) diagram of data sets available in the vicinity of the Camarinal Sill South (CSS) from CTDs either ship-based (i.e. casts; black, in 1985 (×), 1986 (+) and 1996 (○,□); the cast plotted with “□” was performed in early 1996 close to where the time series in Fig. 4 were recorded at the two nearby locations in the Alboran (▼)) or moored (i.e. time series in the red square; at ▼ in 1994 (yellow) and 1995 (green), at * in 2003–2004 (the blue, purple and red colours correspond to successive 5-month periods)). Hence, time progression is from black to yellow–green to blue–purple–red (not considering the 1996 cast). The cyan full-line rectangle schematises the WMDW characteristics near CSS in the mid-1980s while the dashed-line one schematises the characteristics that could result there, two decades later, from the decadal trends (that are actually encountered in the deepest part of the western basin).

2. Evidence, questions and hypotheses

Strangely, nothing has been said until recently (Millot, 1999) about the occurrence at Gibraltar of any of the other eastern-basin tMWs (the Aegean and Adriatic waters), which is not only possible but also necessary, since waters formed every year must finally outflow from the sea. The Aegean water is saltier and warmer than the Adriatic water; although previously reported (Lacombe and Tchernia, 1972) as less dense, the Aegean water became denser than the Adriatic water in the early 1990s, due to a succession of exceptional meteorological conditions, a phenomenon known as the Eastern Mediterranean Transient (EMT) (Roether et al., 1996). These two tMWs have always been documented (although not differentiated) in the Channel of Sicily (sill down to ~400 m) together with LIW (Guibout, 1987; Garzoli and Maillard, 1976), forming there the Eastern Overflow Water (EOW; CIESM, 2001). Being denser than the waters resident in the western basin, EOW cascades in the Tyrrhenian and mixes down to ~2000 m (Sparnocchia et al., 1999), which roughly corresponds to the WMDWs upper part elsewhere in the western basin (e.g. van Haren and Millot, 2004), hence forming the Tyrrhenian Dense Water (TDW; Millot, 1999) that is another Mediterranean water (a MW, not a tMW!). The relative amounts of Eastern Basin Water (EOW) vs. western basin ones (including WMDW, and/or old LIW and old TDW) will allow characterisation of the new TDW as a MW either “more western” or “more eastern”. LIW and TDW then flow alongslope counterclockwise in the Tyrrhenian (Millot, 1999) and are characterised, e.g. in the Channel of Sardinia, by a core at 13.8–14.0 °C and ~38.7 for LIW and by 13.0–13.5 °C and 38.5–38.6 for TDW (both are thus significantly warmer and saltier than WMDW).

Meanwhile, data collected since the 1960s (Lacombe et al., 1985) have shown (Béthoux et al., 1990) that WMDW was evidencing a warming and salinification (linear trends: ~+0.03 °C/decade, ~+0.01/decade) up to now attributed either to anthropogenic modifications (Rohling and Bryden, 1992), especially the Nile damming, or to change in Mediterranean climatic conditions (Béthoux et al., 1990). The first hypothesis assumes that WMDW would be made warmer and saltier via LIW, which is not supported by data analysis in the western basin (Krahmann and Schott, 1998); also, we think that the much larger long-term warming (~0.3 °C/decade) of the Spanish coastal waters (Pascual et al., 1995), where the stratification is permanent and mixing with eastern-basin waters negligible, could hardly be due to processes having occurred in the eastern basin only (Millot, 1999). Therefore, the first hypothesis cannot explain all observed features. Since the WMDW warming and salinification are comparable to those reported over similar periods for the eastern Atlantic at intermediate depths (Curry et al., 2003; Vargas-Yáñez et al., 2004) and for the whole ocean (Levitus et al., 2000) (~0.01 °C/decade), the second hypothesis can be suspected too. Both hypotheses assume that AW entering the sea has had stable characteristics over decades, which is a key point that should be tested first since a third hypothesis (Millot and Briand, 2002) is that the sea could have just been a place convenient for evidencing changes mainly occurring at the surface in the nearby Atlantic.

Two other interesting analyses address the Mediterranean outflow. The first concerns changes in a $10^\circ \times 10^\circ$ zone west of Gibraltar over the period 1955–1993; there, a warming (~0.1 °C/decade) and salinification (~0.02/decade) one order of magnitude larger than the trends in the whole eastern Atlantic (Curry et al., 2003; Vargas-Yáñez et al., 2004) are reported (Potter and Lozier, 2004) for the outflow, which should be reliable since computed directly from a large data set. However, these trends are said to result from the WMDWs trends, an argument that is unclear since the former are 2–3 times larger than the latter, furthermore WMDW necessarily represents only a part of the outflow. The second concerns the Bay of Biscay, where an even larger warming and salinification (~0.5 °C/decade, ~0.1/decade) of the outflow has occurred in 1995–2002 (Vargas-Yáñez et al., 2002); although CTD casts are relatively few and the trends relatively large, such a warming and salinification concerns the last decade only, hence being consistent with the analysis below.

In what follows, we show that the WMDW trends (~0.03 °C/decade, ~0.01/decade) are much lower than the actual (early 2000s) warming and salinification of the outflow at Gibraltar; we also explain why slight trends of a given tMW are not inconsistent with large changes in the outflow (for which we no more differentiate the tMWs from the MWs; for convenience, we also deal with the "MW outflow").

3. Initiation of a new monitoring strategy

Most hydrological data sets used to specify hydrological changes come from ship-based CTDs operated here and there or, at best, in specific places on a monthly/annual basis. Although they have allowed evidence of long-term changes (see above) and are still valuable and necessary, they cannot solve all problems (which is the case of any data set!). For monitoring purposes, they give scattered values and only one trend-number (inferred from linear regression), data significance cannot be estimated, covariance between different data sets cannot be computed, new data has a relatively low added value (still only one trend-number per place), trend-numbers from different places can hardly be compared (generally referred to different periods), and trend-numbers can hardly be memorised (since continuously changing). In addition, ship-based CTDs cannot allow sampling correctly any along-slope vein at intermediate and greater depths and the several-month interval generally performed is not efficient, even in passages (Sammari and Millot, 2000). Ship-based CTDs performed at much higher frequency (Pascual et al., 1995) (i.e. weekly, hence costly and effort demanding) can be envisaged only in the coastal zone. Obviously, ship-based CTDs will remain indispensable instruments for any kind of oceanographic study, even using the new strategy that we propose (see below).

Time series collected with moored autonomous CTDs (Fuda et al., 2002) provide complementary information and can solve some of the problems above-mentioned (Millot and Briand, 2002). A programme (http://www.ciesm.org/marine/programs/hydrochanges.htm) has been elaborated and CTDs are already set in key-places (passages, zones of tMW formation, areas of special interest) on short (~10 m) easily manageable sub-surface moorings for 1–2 years before recovery and re-deployment. To avoid any spatial variability and guarantee the maintenance of each CTD at roughly the same level/depth, if not exactly at the same place, topography must be relatively smooth, especially at shallow depths. Using short moorings is convenient since the shallower the depth (hence the larger the stratification and the greater the position's importance) the greater the deployments' relative accuracy. At depths >2000 m, as in most places, the goal is easy (relatively smooth topography and homogeneous water). Ship-based CTDs are still necessary to provide information on the spatial distribution of temperatures and salinities in the moorings' surroundings.

However, deploying and maintaining long-term moorings on the Gibraltar sill ("the key-place" to monitor both the AW inflow and the MW outflow) is more problematic due to the complex topography, the currents' intensity and the bio-fouling. Due to the cross-strait-sloping AW–MW interface, monitoring AW is advantageously done on the Moroccan side; since the greater the depth the lower the seasonal variability, the bio-fouling, and the fishing activity's risks, we chose a plateau at ~80 m (~5 km from the Moroccan coast near 35°52.8′N–5°43.5′W). To monitor MW, the most natural place is the deepest part (~300 m) of CSS that is steeply V-shaped. Because such topography does not allow easily maintaining moorings there, we chose a small plateau at ~270 m near 35°55.2′N–5°45.0′W (~1.1 km north of the sill's deepest part and ~10 km from the Moroccan coast, Fig. 1) close to points previously occupied (Pettigrew, 1989). We focus hereafter on data at ~270 m (that are consistent with those at ~80 m).

The Seabird SBE-37-SMPs we use in the programme have convenient accuracy (0.002 °C, 0.0003 S/m), resolution (0.0001 °C, 0.00001 S/m) and stability (0.0002 °C/month, 0.0003 S/m/month); they are equipped with a pump that flushes water before sampling every hour. They were deployed in early January 2003, recovered in early April 2004 and redeployed (also in October 2005). The non re-calibration after recovery is not problematic since (i) the CTDs are new and calibrated by the manufacturer just before deployment, (ii) absolute Θ and S are realistic and extrema (low-Θ's, high-S's) are similar at both points, (iii) the extrema time series at both points are significantly correlated, (iv) Θ and S variations are much larger than the nominal resolution limits of the sensors, (v) these limits are validated by statistics about other re-calibrations by the manufacturer. Using different colours for each of the three 5-month periods in Fig. 1 emphasises the fact that several-month variations can be demonstrated, hence validating the strategy of monitoring with moored autonomous CTDs.

Time series were previously collected at the sill at roughly the same position from April to October, in both 1994 and 1995 (Candela, 2001) with new Seabird SBE-16 SEACATs measuring (every 10 min) temperature, conductivity and pressure, with a satisfactory accuracy (0.01 °C, 0.001 S/m) resolution (0.001 °C, 0.0001 S/m) and stability (0.0002 °C/month, 0.002 S/m/month); the instruments were calibrated before the initial deployment in 1994. Although several instruments were set on moorings spanning most of the water column (from the bottom up to ~20-m depth), only those set at nominal depths of 253 m in 1994 and 190 m in 1995 are used here. Due to the current drag, both instruments had large depth excursions (reaching maxima of ~273 m and ~266 m, resp.), which allowed frequent samples of the deep MWs outflowing at the sill. We also collected temperature 10-min time series (the conductivity sensor was unreliable) with a SBE-26 SEAGAUGE, which has a rougher accuracy (0.02 °C) and resolution (0.01 °C), but similar stability (0.0002 °C/month). The instrument was set on the bottom at two neighbouring positions (see Fig. 1), in April–October 1994 (36°00.7′N–5°20.0′W, 863 m) and from October 1994 to April 1996 (35°59.8′N–5°23.0′W, 928 m).

We compare these temperature and salinity time series with all hydrological (CTD) casts we found in the MEDAR-MEDATLAS (MEDAR group, 2002) database that might be the sole ones available in the vicinity of CSS, the sill's deeper part: to our knowledge, data were collected there only in 1985, 1986 and 1996; we also use 1996 casts performed in the Alboran close to our moorings.

4. The data analysis

On the Θ–S diagram in Fig. 1, we first consider the 1985 and 1986 casts available over the whole depth (down to ~500 m) in the CSS surroundings, and especially their deeper part that clearly sampled WMDW. While most (not all) 1986 data are generally aligned between the WMDW and AW values, hence indicating the sole presence of these two waters and their mixing, the 1985 data and some 1986 data show relatively warm and salty intermediate waters that obviously resulted from mixing, in the CSS surroundings or more upstream, with LIW and/or TDW (probably "more western" at these times). If both groups of data are representative of the waters composing the MW outflow in the CSS surroundings, this one displays a relatively large interannual variability. However, the densest waters were characterised by $\Theta < 13.05$–13.07 °C and $S < 38.46$. We now consider the two

6-month time series collected in 1994 and 1995 at 190–250-m nominal depths on tall moorings that encountered frequent depth excursions down to 265–275 m, and the 15-month time series collected in 2003–2004 on a 10-m mooring at ~270 m. Although some values in 1994 could correspond to mixed WMDW, waters sampled in 1995 and 2003–2004 are warmer and saltier; the sole casts available in the study area since 1986 were collected in 1996 and are consistent with all time series. Therefore, MWs outflowing at CSS in 2003–2004 are much warmer (by ~0.3 °C) and saltier (by ~0.06), although roughly as dense (even denser), than ~20 years ago. This cannot be explained by the too slight WMDW warming and salinification trends, so that Fig. 1 demonstrates dramatic long-term changes in the hydrological characteristics of the densest MWs outflowing at CSS.

To specify these MWs' origins, and because data collected in the sea interior since the mid-1990s are not numerous enough, we hypothesise that the 2003–2004 data suggest the occurrence of three water masses. The densest is a mixture relatively cool (12.95–13.10 °C) and salty (38.47–38.50), the intermediate has a core significantly warmer (13.10–13.15 °C) and saltier (38.50–38.51) whilst the less dense is clearly AW (warmer and fresher). The intermediate has values exactly corresponding to LIW as reported ~20 years ago in the western Alboran (Bryden and Stommel, 1982; Parrilla and Kinder, 1983; Gascard and Richez, 1985; Parrilla et al., 1986), demonstrating that LIW, which did not markedly change in the western basin (Krahmann and Schott, 1998), is now occasionally outflowing at 270–300 m at CSS. Previous data in the CSSs vicinity (the 1985–1986 and 1996 casts) and deeper part (the 1994–1995 time series) just showed waters resulting from mixing with LIW, so that pure LIW was necessarily outflowing only north of CSS. Now, considering LIW in the Channel of Sardinia (13.8–14.0 °C, ~38.7) leads to estimation of a 0.7–0.8 °C cooling and a ~0.2 freshening due to mixing between the two places. Assuming that the densest water at CSS has followed a similar route (alongslope and counterclockwise) and has encountered similar mixing leads to values close to 13.0–13.5 °C and 38.5–38.6, which characterise TDW in the Channel of Sardinia. We conclude that TDW is the densest MW presently (early-2000s) outflowing at CSS together with LIW, TDW being "more eastern" than about two decades ago, a feature that we link to the *T* and *S* increases in the deep Tyrrhenian shown by Astraldi et al. (2002) and Gasparini et al. (2005).

The 15-day period from the 2003–2004 time series (1-h sampling interval) in Fig. 2 is representative of all time series collected there for what concerns the fortnightly signal due to the spring/neap internal tides (Lacombe and Richez, 1982; Bryden and Kinder, 1991). The peaks (defined by 1–2 values) are actually more complex (as indicated by the 10-min 1994–1995 time series), due to higher-frequency internal waves. The lowest Θ's and highest *S*'s characterise the less-modified MW outflow encountered there (the deepest part of CSS) and its variations on each semi-diurnal cycle. During spring tide (first half of the record), the MW outflow is always more or less modified by the tide (any plateau) while, during neap tide (second half of the record), the MW outflow can be pure (several-hour plateaus), as previously expected (Bryden and Stommel, 1982).

The 2003–2004 time series (Fig. 3) in low-Θ and high-*S* ranges suggest a trend in Θ (0.01–0.02 °C/year) and no significant trend in *S*, which might represent more interannual variability than decadal changes. Low-Θ variations mainly appear at mesoscale (several weeks/months) while high-*S*

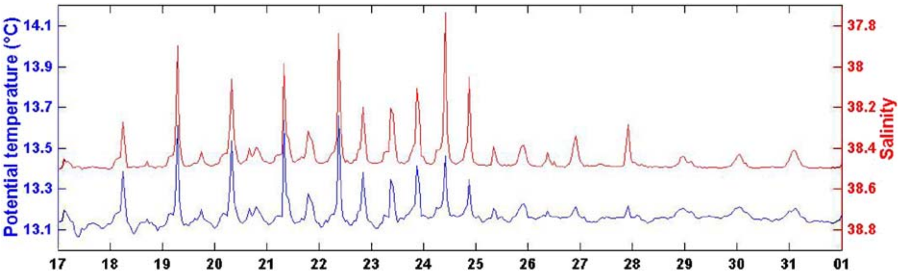

Fig. 2. The general features displayed by this 15-day period (March 17–April 1, 2004) are representative of the 15-month potential temperature and salinity time series in the sill's deeper part (CSS at ~270 m), and of older time series as well. The salinity scale is reversed to present a more concise figure.

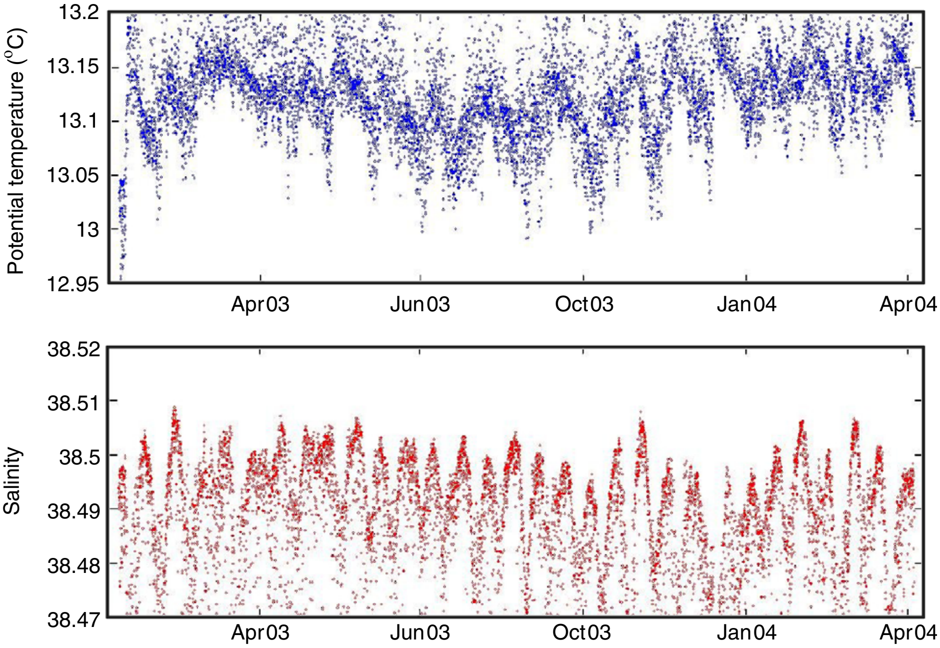

Fig. 3. The lowest potential temperatures and highest salinities measured from January 6, 2003, to April 6, 2004, in the sill's deeper part (CSS at ~270 m) display dominant variations that are markedly different (at several weeks/months for the temperature, fortnightly for the salinity).

variations are fortnightly mainly, which is strange but explainable. Note first that ~99% of the values from the whole data set (not shown) are in the Θ-range 12.95–13.5 °C (max: 14.5 °C) and S-range 38.0–38.51 (min: 37.1) when MWs (LIW + TDW) are in the 12.95–13.2 °C and 38.47–38.51 ranges; MWs thus represent $\sim\frac{1}{2}$ of the Θ-range and $\sim\frac{1}{10}$ of the S-range. We consider that the MWs are homogeneous in S (~38.5) and note that the fortnightly signal in S ranges from 38.50–38.51 to 38.47–38.48; as the observed S's result from the mixing of the MWs with AW (~36.5), the AW maximum percentage is thus ~1.5% only. If we now consider that the Θs in the range 13.2–12.95 °C mainly result from the mixing of a unique MW (~13.0 °C) with AW (15–16 °C), the AW percentage must reach ~10%, which is neither consistent with the analysis about S nor with the diagram itself. We thus consider that the MWs are heterogeneous in Θ and pursue our hypothesis about a schematic 3-layer system. Relying on ~1.5% of AW at most, and considering both LIW (~13.15 °C) and TDW (~13.05 °C), leads to an effect of the LIW/TDW ratio within the outflow that is ~3 times larger than the mixing with AW. Temperature variations due to variations of this ratio (more generally to the outflow heterogeneity) that are expected to occur at mesoscale can thus hide the fortnightly variations due to mixing with AW. The visual differences between the Θ and S variations in Fig. 3 are supported by spectral analysis, the fortnightly peak (~0.003 cph) on S being masked on Θ by relatively high energy levels at lower frequencies; similar differences exist, although reduced, for the older time series.

Figs. 1–3 demonstrate important characteristics of the outflow that should be taken into account to better understand its effects on the North Atlantic.

5. Inferences for the sea functioning

Are the long-term (decadal) changes in the outflow composition occurring more or less permanently, or can we consider that, during the previous decades, some dramatic event(s) occurred? In the Alboran time series (Fig. 4) at ~863 m up to late 1994, Θs~12.85 °C clearly correspond to WMDW that was no more outflowing at that time (yellow points, Fig. 1). Then, at 928 m nearby to the west, Θs dramatically (for such a depth) increased from ~12.85 °C in late 1994 to ~12.95 °C in early 1996. Such Θs (~12.95 °C) are consistent with a contemporaneous cast collected nearby (□, Fig. 1) that clearly identifies TDW (associated S ~38.47; values

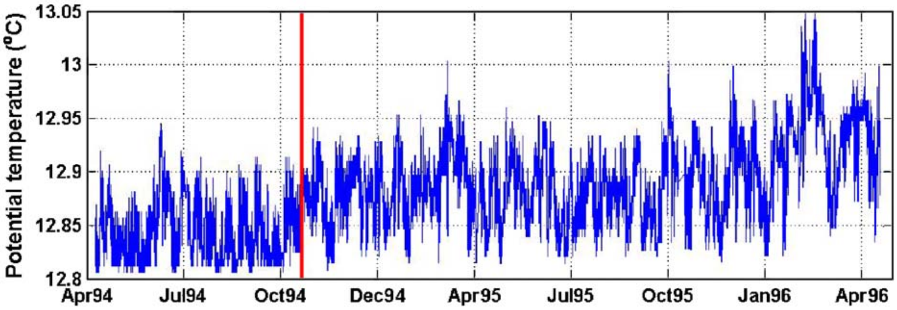

Fig. 4. Potential temperature recorded in 1994–1996 at two neighbouring positions in the Alboran subbasin (the two ▼ in Fig. 1) close to the bottom, first at 863 m and then at 928 m close in the west (separated by the red bar).

near 12.90 °C, 38.46 collected below ~930 m identify WMDW as it was in the mid-1990s). These large Θs correspond to waters having their upper part possibly outflowing at that time (an hypothetical 1996-time series would be spreading between the 1995-green and the 2003–2004-blue/purple/red ones) or not. Because the second part of the time series is deeper than the former, while WMDW is denser than TDW, the increase did not occur while we were measuring at 863 m; we thus demonstrate that at least one dramatic event (replacement of WMDW by TDW at ~900 m) occurred from late 1994 in the Alboran.

The data from the CTD casts in the CSS vicinity (in the range 0–500 m) and those from bottom (~270 m) time series just at CSS are scattered on Fig. 1 in a similar way, which demonstrates that waters found in the sill's deepest part can be found otherwise at shallower or greater depths. In addition, the differences between the 1994 time series and the 1985 casts are not so large, although they correspond to two different types of data collection, and they are of the order of those between the 1985 and 1986 sets of casts that are directly comparable. This suggests that, at least from the mid-1980s (eventually before) until ~1994, the variability at CSS was mainly interannual. Then, time series and casts at CSS, consistently with time series and casts in the Alboran, have been evidencing a continuous evolution towards higher Θ's and S's. All these data are thus consistent with a dramatic event having occurred in the CSS surroundings near 1994 that might have occurred earlier in other places of the sea.

In the Channel of Sardinia, marked cross-channel gradients indicative of the TDW–WMDW interface can be identified with the 13.0 °C isotherm and 38.5 isohaline that were at 1000–1500 m in 1968 (Garzoli and Maillard, 1976) and November 1993 (Bouzinac et al., 1999), and at 1300–1800 m in 1997 (Astraldi et al., 1999). In the Channel of Sicily, densest waters in the mid-1990s (Sammari et al., 1999) were much cooler (13.6–13.7 °C) than in the late 1960s (Garzoli and Maillard, 1976) (13.9–14.0 °C), hence much denser (~29.15 vs. 29.10), but changes have also occurred at shorter intervals: densest waters (<13.7 °C, <38.75) were located only on the Tunisian slope in November 1993 (Sparnocchia et al., 1999) while they occupied the whole deeper channel from May 1994 to July 1995 (Sammari et al., 1999). Therefore, our analysis indicates an increase in the EOW amount in the Channel of Sicily (between November 1993 and May 1994) and an increase in the TDW amount in the Channel of Sardinia (between November 1993 and 1997). This analysis is not inconsistent with the one by Gasparini et al. (2005) who conclude "the impact of the EMT on the western basin is maximum during the 1992–1994 period".

Even though we think that sampling interval (several months, CTD casts only) in the critical area between the Channel of Sicily and the Channel of Sardinia is far too large for accurately specifying the variability in the EOW/TDW characteristics linked to the EMT, it is clear for us that the replacement of WMDW by TDW at ~900 m in the Alboran (from late 1994) is linked with the EMT (what we cannot demonstrate). Indeed, the various delays are consistent with the advection speed (a few to several km/day) of intermediate/deep water from the Channel of Sicily to the Alboran (following an alongslope counterclockwise route, Millot, 1999) between late 1993 and late 1994. Although an increase of the EOW outflow in late 1993 might well have been produced by the EMT (consequent to severe winters in 1990–1993), we did not find any

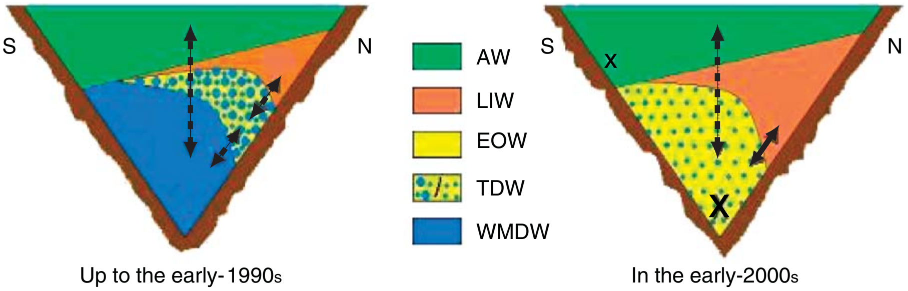

Fig. 5. Conceptual diagram of the distribution of the water masses across the sill from South (S) to North (N) up to the early 1990s (left) and in the early-2000s (right): Atlantic Water (AW), Levantine Intermediate Water (LIW), Eastern Overflow Water (EOW), Tyrrhenian Dense Water (TDW) and Western Mediterranean Deep Water (WMDW). The "X" figures the place where the time series in Figs. 1–3 were collected (CSS at ~270 m) while the "x" figures the place of the time series simultaneously collected (at ~80 m) but not analysed herein. The amounts of the various MWs and the interfaces between them display marked changes not only at decadal scale (as emphasised by the two parts of the figure), but also at mesoscale (full arrows), hence leading for instance LIW to be possibility encountered in the deeper part of CSS (at X) in the early 2000s (as shown in Fig. 1). Also to be noticed is that the internal tides (dashed arrow) more or less mix AW with the MWs over the whole depth (as shown in Figs. 2–3).

observation or numerical result accounting for either a specific advection speed of the phenomenon within the eastern basin or a specific beginning date of an outflow increase (of EOW and possibly LIW!). Therefore, the EMT remains a possible cause of the event together with a diminution in the WMDW formation rate during the last decades (M. Crépon, personal communication) that might have led TDW to be more and more different from WMDW (i.e. similar to EOW), hence TDW/EOW and LIW to be more and more identifiable at CSS. Whatever the case, in the interior of the sea, Θ and S profiles from profiling floats in the last years account for waters in the western basin being much warmer and saltier than historically, especially at depths from ~500 to 1800 m, and for no major changes in the eastern basin (P. Poulain, personal communication). More precisely, values in the deep eastern basin collected either before or after the EMT are well within a 1–2 standard deviation interval, which is not the case for actual values in the deep western basin that are out of such an interval (computed from ancient values). This is consistent with waters from the eastern basin having recently invaded most of the western basin (i.e. their relative amount is presently much larger than historically).

6. Conclusion

The conceptual diagram that we propose in Fig. 5 emphasises the fact that the typical Mediterranean Water (tMW) formed in the western basin (WMDW), which was clearly identified at Camarinal Sill South (CSS) up to the mid 1990s, is outflowing in the early-2000s only as a (minor) component of TDW, a Mediterranean Water (MW) that results from the mixing of the densest tMWs formed in the eastern basin (EOW) while cascading from the Channel of Sicily. Also schematised are the other major tMW (LIW), the variations in the composition of the outflow (full arrows) and the permanent occurrence of internal tides (dashed arrow).

Our major result concerns the fact that the densest waters outflowing at CSS in 2003–2004 no longer originate mainly from the western basin (WMDW) but from the eastern basin (LIW and TDW/EOW). Such a change is similar to the EMT (replacement of Adriatic water by Aegean water in the deep eastern basin) and can be considered as a Mediterranean Sea Transient (MST); additionally, the MST could be a consequence of the EMT. Although we previously foresaw (Millot, 1999) the EOW vs. WMDW competition, hence the fact that TDW could be "more eastern" or "more western", we did not imagine such large shifts in the Mediterranean Sea functioning and such dramatic changes in the Mediterranean outflow. This outflow can in fact encounter changes in Θ and S (~0.3 °C and 0.06 in a decade) much larger and rapid than those expected up until now from each tMW trend (e.g. ~0.03 °C/decade and 0.01/decade for WMDW), just because the amounts of the various tMWs formed (i.e. their contribution in the outflow) can change dramatically. The Mediterranean outflow, being a direct and continuous source of warm and salty intermediate water, plays a substantial role in the heat content and water formation processes in the northern Atlantic and hence in the density driven circulation of the World's Oceans (Candela, 2001). Hence, understanding the interannual variability of the Mediterranean Sea itself, in particular of the relative amounts of typical waters produced in the different formation zones, has a more global importance than previously thought.

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