Warming, salting and origin of the Tyrrhenian Deep Water

J.-L. Fuda,[1] G. Etiope,[2] C. Millot,[1] P. Favali,[2] M. Calcara,[2] G. Smriglio,[2] and E. Boschi[2]

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[1] Data collected from 1996 to 2001 down to 3,500 m in the Tyrrhenian sub-basin with ship-handled and moored instruments show 5-year T and S trends (0.016 °C/yr, 0.008/yr) that are the largest ever evidenced in Mediterranean deep waters. This is not consistent with the usual hypothesis that Tyrrhenian Deep Water (TDW) is a mixture of eastern water flowing from the Sicily Channel and western water flowing from the Sardinia Channel partly since both are reported to encounter lower trends. We argue that TDW might result from a dense water formation process occurring within the Tyrrhenian itself, in a region never reported up to now, east of the Bonifacio Strait. Whatever the validity of our hypothesis, climatic changes are occurring in the whole sea and are efficiently specified with long time series. *INDEX TERMS:* 1635 Global Change: Oceans (4203); 4215 Oceanography: General: Climate and interannual variability (3309); 4243 Oceanography: General: Marginal and semienclosed seas; 4594 Oceanography: Physical: Instruments and techniques. **Citation:** Fuda, J.-L., G. Etiope, C. Millot, P. Favali, M. Calcara, G. Smriglio, and E. Boschi, Warming, salting and origin of the Tyrrhenian Deep Water, *Geophys. Res. Lett.*, *29*(19), 1898, doi:10.1029/2001GL014072, 2002.

1. Introduction

[2] Dense Water Formation (DWF) occurs in several zones of the Mediterranean Sea from the Atlantic Water transformation (AW, 0–200 m). The main waters formed in the eastern basin are the Levantine Intermediate Water (LIW) and denser waters formed in the Aegean and Adriatic. The whole former, and the upper part of the latter named EOW (Eastern Overflow Water), flow through the Sicily Channel (~460 m) and cascade down to ~2,000 m into the Tyrrhenian. In the western basin, the Western Mediterranean Deep Water (WMDW) is formed in the Liguro-Provençal, basically as a result of AW and LIW mixing; its upper part can flow through the Sardinia Channel (sill at ~2,000 m) into the Tyrrhenian (Figure 1).

[3] At ~2,000 m, WMDW trends were evaluated at 0.001 °C/yr (1909–1955) and 0.002 °C/yr | 0.001/yr (1955–1989) [*Rohling and Bryden*, 1992], 0.003 °C/yr | 0.001/yr (1959–1996) [*Béthoux and Gentili*, 1999], and at 0.002 °C/yr | 0.001/yr (1960–1995) [*Krahmann and Schott*, 1998]. The accentuation of the WMDW warming and salting starting in the early 60s has been linked to climatic changes and/or anthropogenic environmental modifications [e.g., *Leaman and Schott*, 1991; *Boscolo and Bryden*, 2001]. In the Tyrrhenian, trends of 0.019 °C/yr | 0.005/yr (1973–1992) were reported at 600–1,500 m [*Zodiatis and Gasparini*, 1996]. In the Ionian and Levantine, trends of 0.002 °C/yr and 0.001 °C/yr (1960–1991) were also evidenced at ~3,000 m [*Tsimplis and Baker*, 2000].

[4] Data near 42°N–03°E (1973–1994, *Pascual et al.*, 1995) evidence trends of 0.035 °C/yr at 0 m and 0.020 °C/yr at 80 m. *Krahmann and Schott* [1998] have evaluated AW trends in the whole Liguro-Provençal at 0.004/yr (1960–1995; no change in T). They conclude that significant trends at the LIW level (250–500 m) do non–exist in the whole western basin and that "this excludes eastern basin sources for the deep -western- trends as speculated by *Rohling and Bryden* [1992] and *Leaman and Schott* [1991]". Also, the ~10-year old changes in the deep eastern basin ("the Transient") have not altered markedly the LIW T-S characteristics [*Roether et al.*, 1998].

[5] The Ustica Island surroundings (southern Tyrrhenian) are surveyed since 1996 to deploy a deep-sea observatory, the GEophysical and Oceanographic STation for Abyssal Research [GEOSTAR; *Beranzoli et al.*, 2000]. In this work we report data sets from CTD's and thermistors moored during several-month and from CTD casts performed during the last decade. These T and S records represent the first significant data set concerning Tyrrhenian Deep Water (TDW) that has not been extensively studied yet, and whose characteristics were previously inferred from hypotheses [*Hopkins*, 1988; *Millot*, 1999] that will be reconsidered.

2. Evidence for the TDW Warming and Salting

[6] A SBE16 CTD equipped with a pump was moored (Jun. 1999–Feb. 2000) at 38°54'N–13°19'E, 10 m a.s.f. (3504-dbar) ~25 km north-east of Ustica (Figure 1). Sensors calibrated in Feb. 1996 and Mar. 2000 did no significantly drift. Both θ and S display some variability and unexpectedly large trends estimated to be 0.029 °C/yr and 0.010/yr (Figure 2a).

[7] A more complex mooring was then set exactly at the same place (Dec. 2000–Oct. 2001). A RCM8 modified to get a T 0.002 °C resolution was set at 10 m a.s.f. A SBE37 CTD (sensors calibrated in Nov. 2000, equipped with a pump) was set at 100 m a.s.f. A SBE39 T recorder (calibrated in Nov. 2000) was set at 300 m a.s.f. A modified RCM8 was set at 400 m a.s.f. We inter-calibrated 4 instruments in the 12–14°C range in our lab in Dec. 2001. The almost perfect correlations between the SBE37 values and those from the 3 other instruments allow calibration curves having similar/utmost accuracies. Even though the records in Figure 2a display significant seasonal/interannual variability (together with a varying T stratification), the trends previously evidenced are confirmed (0.020 °C/yr at 10 m a.s.f.; 0.014 °C/yr and 0.009/yr at 100 m a.s.f.

[8] A ship-handled SBE911+ CTD (sensors calibrated in Jul. 1996 and Feb. 2000) was operated 8 km from the

[1]Laboratoire d'Océanographie et de Biogéochimie, COM-CNRS, La Seyne, France.
[2]Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy.

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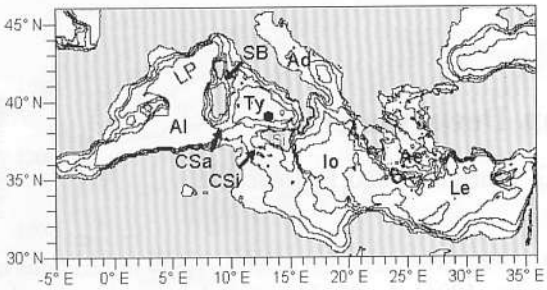

Figure 1. Map showing the various sub-basins: Liguro-Provençal (LP), Algerian (Al), Tyrrhenian (Ty), Adriatic (Ad), Ionian (Io), Aegean (Ae) and Levantine (Le). SB, CSa and CSi stand for Strait Bonifacio, Sardinia Channel and Sicily Channel, respectively. The moorings and casts are indicated by the dot.

moorings 4 years apart. The max and min reported in Figure 2a were measured below 400 m a.s.f. (to provide information comparable to that from the moorings data) in Oct. 1996 (considering the deepest -down to 3470 dbar- out of 4 profiles performed between the 19th and the 21st), in Sep. 2000 (down to 3441 dbar) and Dec. 2000 (down to 3470 dbar). The ship-handled CTD values are remarkably aligned with the moored CTD's and thermistors ones. From late 1996 to late 2001, the 5-year warming and salting were 0.016 °C/yr and 0.008/yr.

[9] Complementary information about the variations in time and space is provided by fig. 2b. CTD profiles 1 (Sep. 1987) and 2 (Mar. 1990) are the sole recent ones in the our database [*MEDATLAS Group*, 1997] at <40 km from the moorings. No trend (if any) can be evidenced over this 3-year period but deepest values are clearly <12.83 °C and <38.44. Our 4 casts in Oct. 1996 (profiles 3–6) evidence an homogeneity below ~2,800 m and deepest values near 12.900 °C and 38.455 whilst, in Sep.–Dec. 2000 (profiles 7–8), values at >2,400 m have increased near 12.970 °C and 38.495. Min and max values from Jun. 1999 to Feb. 2000 (full circles) and from Dec. 2000 to Oct. 2001 (crosses) are also plotted. Figure 2b provides evidence for trends that i) are significant at least since 1990 and ii) concern a relatively thick (>1000 m) deep layer assumed to represent TDW.

3. A New Hypothesis for the TDW Origin

[10] Averages from the database and 1992 data [*Zodiatis and Gasparini*, 1996] reveal that the θ and S at >3,000 m increased from 1960 to 1990, with weak trends (0.001 °C/yr | 0.001/yr), comparable to those reported for WMDW (fig. 2c–d). Our observations are thus consistent with the historical data and demonstrate that θ and S have been increasing in the deep Tyrrhenian for several decades, especially the latter, during which the trends appear one order of magnitude greater than before and than those already reported for the other deep sub-basins.

[11] To analyse these trends, we specify the processes and circulation features heretofore expected in the Tyrrhenian. Before the early 90's, the TDW θ-S values (12.75–12.85 °C, 38.42–38.46) are close to the WMDW ones (12.70–12.75 °C, 38.40–38.44) (fig. 2b–c), and much lower than the LIW and EOW ones (θ > 13.60 °C, S > 38.70 in the Sicily Channel; *Sammari et al.*, 1999). This indicates that TDW mainly originates in the western basin. WMDW enters the southern Tyrrhenian through the Sardinia Channel, where it was up to now expected to cascade down to the deepest part of the Tyrrhenian and be transformed into TDW through mixing with eastern waters [*Hopkins*, 1988; *Millot*, 1999].

[12] In the Sicily Channel, LIW and EOW have similar core salinities (38.75–38.80), but LIW is warmer (θ > 14 °C) than EOW (θ < 13.65 °C) [*Sammari et al.*, 1999]. The LIW σ is 29.10–29.15, so that it remains mainly at 200–600 m (i.e. it does not sink so much) within the western basin. Due to its relatively large σ (> 29.15), EOW is (in our opinion) the sole water that was shown to cascade down to ~2,000 m and create there a sharp interface in both T and S [*Sparnocchia et al.*, 1999]. Obviously, as cascading is associated with intense mixing processes, EOW can hardly be identify within the cascading zone and afterwards. *Millot* [1999] expected the EOW mixing with the resident waters (thought to be mainly WMDW) to lead to TDW at 600–2,000 m, and unmixed WMDW to occupy the whole Tyrrhenian below ~2,000 m. The latter point is contradicted by the present observations that show (fig. 2c, d) that water below ~2000 m has always been warmer (0.1 °C) and saltier (0.01–0.03) than WMDW. At a time when the EOW cascading was not yet discovered, these differences (below ~2,000 m) had already been noticed by *Hopkins* [1988] who expected that TDW below ~2,000 m (down to ~3,500 m) resulted from mixing between WMDW and LIW.

[13] Assuming that such waters (LIW and WMDW) entering the Tyrrhenian at relatively shallow depths (less than 460 m and 2000 m, resp.) and generally recognised at quite different levels (200–600 m and 1,000–2,000 m, resp.) could produce a water found down to 3,500 m can reasonably be questioned. We thus propose to reconsider the formation mechanism of TDW below 2,000 m and to analyse both its characteristics and trends in light of the new data sets above described.

[14] To explain the TDW trends below ~2,000 m assuming an origin such as suggested by *Hopkins* [1988] but involving EOW instead of LIW, one hypothesis is that "the Transient" led to a density increase of EOW which should have been able, during the last decade, to sink deeper and to modify TDW down to ~3,500 m. Let us remind that LIW was not altered markedly by "the Transient" according to *Roether et al.* [1998]. We do not think [*Sammari and Millot*, 2000] that the data presently available [*Sammari et al.*, 1999; *Astraldi et al.*, 2000] in the Sicily Channel are adequate to estimate such possible changes so that testing this hypothesis might be impossible. Now, data were collected from Oct. 2000 to Mar. 2001 with a SBE16 in the region (south of Ustica) and at a depth (1870 m) where the interface between eastern and western waters (as a result of the cascading of the former) is roughly located. Most of the time, the CTD was within western waters (θ ~13.05 °C and S ~38.51). But, on some occasions, values of θ ~13.25–13.45 °C and S ~38.56–38.62 clearly associated with eastern waters were measured, as a result of the interface lowering. In situ densities were σ ~37.350 for western waters and as low as 37.340–37.345 for eastern waters. It is thus clear that, after having cascaded, the densest eastern waters are less dense than the western waters found there at ~2000 m.

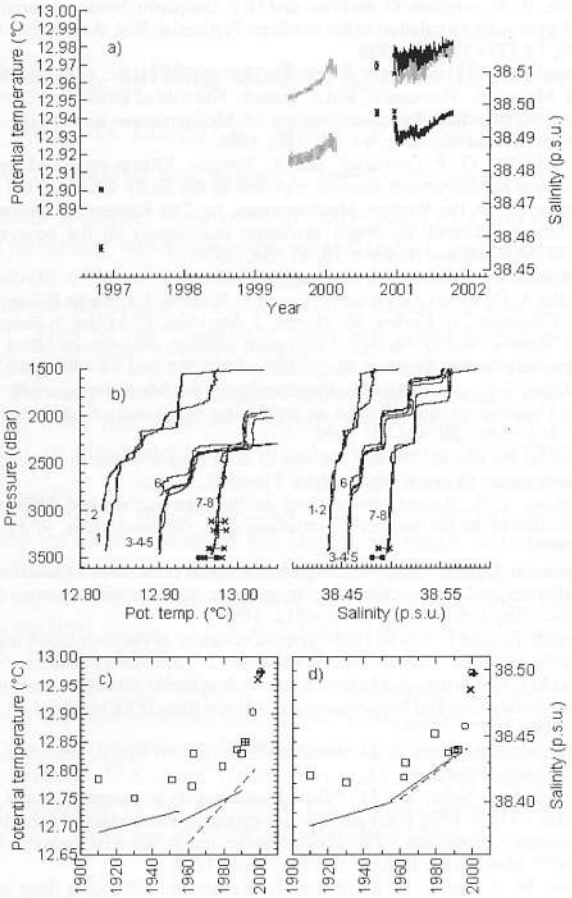

Figure 2. (a) θ and S at 38°54'N–13°19'E: Jun. 1999 to Feb. 2000 from a SBE16 moored at 3504 dbar; Dec. 2000 to Oct. 2001 from a RCM8 (3115 dbar), a SBE39 (3212 dbar), a SBE37 (3406 dbar) and a RCM8 (3504 dbar in grey). θ and S intervals delimited by crosses represent the extreme values below 3115 dbar (the level of the uppermost time series) for the deepest Oct. 1996, Sept. 2000 and Dec. 2000 profiles. (b) θ and S profiles from the MEDATLAS database at lt;40 km from the moorings in Sep. 1987 (1) and Mar. 1990 (2); profiles collected at <8 km from the moorings in Oct. 1996 (3–6), Sep. 2000 (7) and Dec. 2000 (8). θ and S intervals delimited by full circles represent the extreme values of the Jun. 1999–Feb. 2000 time series whilst the intervals delimited by crosses represent the extreme values of the Dec. 2000-Oct. 2001 time series (see fig. 2a). (c, d) Time evolution of the TDW characteristics. For a given year, θ and S values below 3,000 m within the Tyrrhenian were averaged: MEDATLAS data (open squares), literature data for 1992 (crossed squares), data from Oct. 1996 and Sep.–Dec. 2000 CTD casts (open circles). The "x" indicate average values of the Jun. 1999–Feb. 2000 time series. The "+ " on c) indicates the average θ from all Dec. 2000–Oct. 2001 time series whilst the "+" on d) indicates the S average from the SBE37 time series only. Trends reported in the literature for WMDW in the Algero-Provençal are represented by solid lines [*Rohling and Bryden*, 1992] and dashed lines [*Béthoux and Gentili*, 1999].

[15] We thus conclude that, a fortiori, eastern waters cannot be dense enough to mix with waters found at ~3500 m, which implies that TDW is of western origin. In addition, we note that a water mass (such as TDW) cannot be considered as a mixture of waters having lower trends (such as WMDW and LIW, see section 1 and fig. 2c, d). As TDW encountered at 2,500–3,500 m (Figure 2b), is different from WMDW (fig. 2c, d), we hypothesize that TDW might be mainly generated by a DWF process within the Tyrrhenian itself. Several arguments support the hypothesis that a zone convenient for DWF could be east of the Bonifacio Strait.

[16] First, ECMWF fields show that, during wintertime episodes of strong, dry and cold westerly winds (Mistral), maxima of wind stress (1–2 N/m^2), evaporation (15–20 mm/d) and heat (IR + sensible + latent) losses (500–1000 W/m^2) in this specific region are similar to those in the Liguro-Provençal where DWF of WMDW occurs [*Leaman and Schott*, 1991; *Schott et al.*, 1996]. The specificity of this region comes from the funnelling effect imposed to westerly winds by the high-relief of both Corsica and Sardinia. Our analysis is thus basically different from that of *Rhein et al.* [1999] who considered values averaged over the whole Tyrrhenian, and thus concluded that "convection is excluded as a source for changes of TDW".

[17] Second, IR satellite images and thus all statistical analyses show that surface water there is relatively cold all year long, especially in winter [*Santoleri et al.*, 1995]. This zone was shown to be occupied by a year-round cyclonic gyre, extending at depth and surrounding cold dense waters [*Artale et al.*, 1994]. Associated processes were said by these authors to be an upwelling that enhances mixing of AW and LIW, making the region a privileged place for vertical exchanges between the different water masses. But DWF resulting from a mixing of AW and LIW was never said to occur there, neither by these authors nor, to our knowledge, by other ones.

[18] Third, we have considered historical CTD data from our database before 1990, not to consider data collected during the trends increase (see fig. 2c, d). Fig. 3 shows that the deep values of θ-S profiles east of the Bonifacio Strait (depths there are >1,500 m) display a striking continuity with the deepest Tyrrhenian values, contrary to those representative of the waters coming from the Algerian sub-basin or from the Eastern basin. Remember also that TDW below ~2,000 m is warmer (by ~0.1 °C) than WMDW, which could be related to LIW east of the Bonifacio Strait being saltier (by 0.1–0.2) than in the Liguro-Provençal (hence requiring a less intense cooling in the DWF process).

[19] It is thus clear, from all available data sets, that ocean-atmosphere interactions (ECMWF fields), SST distribution [*Santoleri et al.*, 1995], upper stratification and circulation [*Artale et al.*, 1994], and deep hydrological structure [*MEDATLAS Group*, 1997] east of the Bonifacio Strait are very similar to what is encountered in the Liguro-Provençal where WMDW is formed. We hypothesise that TDW can be formed in the same way as WMDW, i.e. as a DWF process involving AW and LIW mainly. With such an origin, trends in the deep Tyrrhenian can be attributed to processes already invoked for the WMDW trends and/or to trends that might occur in waters (especially LIW) originating from the eastern basin [*Astraldi*

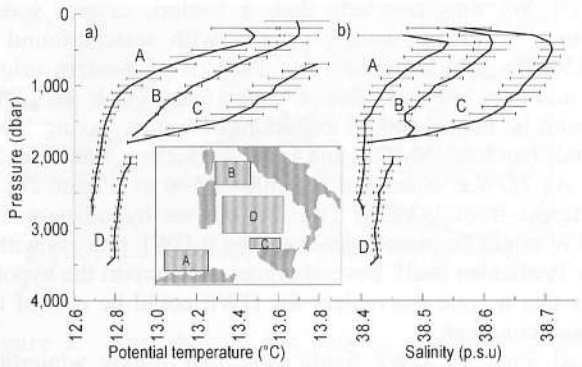

Figure 3. Average profiles of θ (a) and S (b) computed from the MEDATLAS database before 1990 in the following zones: south-eastern part of the Algerian, where WMDW enters the Tyrrhenian (zone A); east of the Bonifacio Strait, where DWF is suspected to occur (zone B); the submarine valley immediately north of Sicily, where LIW and EOW inflow from the eastern basin (zone C); area corresponding to all MEDATLAS profiles deeper than 2,000 m (zone D). Average profiles in the latter zone are shown from 2,000 m. Bars represent one standard deviation.

et al., 1999, 2000], and/or trends that might occur in AW itself (that is an hypothesis not made yet!).

4. Conclusion

[20] Significant warming and salting was evidenced during the last decade with ship-handled and moored instruments at 2,500–3,500 m in the Tyrrhenian sub-basin. These trends, which are the largest for the Mediterranean deep waters, concern the water generally called TDW (Tyrrhenian Deep Water). Our analyses of the TDW characteristics and trends led us to reconsider its origin, usually assumed to be the mixing of LIW and WMDW that are waters located at upper and different levels, whilst they are said to display lower trends. Even though the available data do not allow checking whether the Eastern Mediterranean Transient has been sensed in the Sicily Channel, we show that the densest eastern water that has cascaded into the Tyrrhenian from Oct. 2000 to Mar. 2001 at least was less dense than the western water resident there. Even though water found in the Tyrrhenian above ~2,000 m is mainly originated from the eastern basin, we conclude than water found below (down to ~3,500 m) is formed within the western basin and we hypothesise that it has resulted from a dense water formation process occurring for a while east of the Bonifacio Strait. Supporting arguments come from the analysis of ECMWF fields, SST data analyses, hydrological databases and specific in situ experiments.

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J.-L. Fuda and C. Millot, Laboratoire d'Océanographie et de Biogéochimie, COM-CNRS, La Seyne, France. (cmillot@ifremer.fr)

G. Etiope, P. Favali, M. Calcara, G. Smriglio, and E. Boschi, Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy. (geostar@ingv.it)