Featured Article

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Levantine Intermediate Water characteristics: an astounding general misunderstanding!

CLAUDE MILLOT

Aix-Marseille Univ., Mediterranean Institute of Oceanography (MIO), and CNRS/INSU, UMR 7294, 13288 Marseille cedex 09, France. E-mail: ailesetiles@gmail.com

SUMMARY: Levantine Intermediate Water (LIW) is a warm salty water formed in one out of four main zones of dense water formation in the Mediterranean Sea. LIW spreads as a density current and first appears on a θ-S diagram as a sharp peak that then smoothens out, often leading to the so-called "scorpion-tail" image with a θ (S) maximum above (below) the expected core. Both maxima have always been considered, somewhat fuzzily (even by us), as LIW characteristics without having ever been analysed theoretically. We question neither the "scorpion-tail" image nor the "core-method" nor qualitative analyses of either LIW or other waters characterized by similar extrema. But data from the Strait of Gibraltar demonstrate that characterizing and/or delimiting LIW by these maxima gives LIW a much greater importance than it actually merits so all quantitative analyses of LIW musts be reconsidered. Calculations made as simple as possible to simulate a warm salty layer of intermediate water (IW) mixing with waters lying above and below suggest that these maxima i) can be understood only when all three waters are considered together, ii) can evolve in different ways, iii) generally tend to move from the core of the IW layer outwards, and hence iv) can neither characterize nor delimit the IW in any way. Actual simulations with more sophisticated parameterizations are obviously needed. In addition, we suggest that what has to date been called LIW in the western basin in fact represents all intermediate waters formed in all zones of dense water formation in the eastern basin, i.e. not only Levantine waters but also, in particular, Aegean/Cretan waters. To provide a logical counterpart to WIW (Western Intermediate Water), we therefore suggest that, from the Channel of Sicily downstream, LIW should be renamed Eastern Intermediate Water (EIW).

Keywords: Mediterranean Sea, water mass, temperature, salinity, maximum, extremum.

RESUMEN: Las características de LIW: un malentendido asombroso. – El Agua Levantina Intermedia (LIW) es una masa de agua caliente y salada que se forma en el Mediterráneo Oriental. Se esparce como una corriente de densidad y aparece en un diagrama θ-S como un pico pronunciado que se va suavizando, produciendo a menudo una imagen de "cola de escorpión" con un máximo de θ (S) por encima (por debajo) del nivel esperado de su núcleo. Ambos máximos se han considerado siempre, de forma algo difusa, como características definidoras de LIW sin haber sido analizados nunca teóricamente. No cuestionamos aquí ni la imagen de "cola de escorpión" ni el "método del núcleo" ni los análisis cualitativos de LIW ni de otras masas de agua caracterizadas por extremos similares. Pero datos obtenidos en el Estrecho de Gibraltar demuestran que caracterizar y/o limitar LIW por estos máximos otorga a esta masa de agua una importancia mucho mayor que la que tiene en realidad, con lo cual todos los análisis cuantitativos de LIW hechos hasta ahora deben ser reconsiderados. Cálculos hechos de la forma más simple posible para simular una capa de agua intermedia (IW) caliente y salada mezclándose con las aguas que tiene por encima y por debajo sugieren que estos máximos i) sólo pueden entenderse cuando se consideran las tres aguas conjuntamente, ii) pueden evolucionar de formas distintas, iii) generalmente tienden a desplazarse desde el núcleo de la capa de IW hacia afuera, y en consecuencia iv) no pueden caracterizar ni delimitar a la propia IW de ninguna manera. Obviamente estas conclusiones hay que confirmarlas con simulaciones completas que usen parametrizaciones más sofisticadas. Además sugerimos que lo que hasta ahora se ha llamado LIW en la cuenca occidental, en realidad representa al conjunto de las aguas intermedias formadas en todas las zonas de formación de agua densa de la cuenca oriental, es decir no sólo en la Levantina sino también, y en particular, en la Egea/Cretense. Para tener un equivalente de la WIW (Agua Intermedia Occidental), sugerimos que a partir del Canal de Sicilia, el agua intermedia procedente de la cuenca oriental sea llamada EIW (Agua Intermedia Oriental) en lugar de LIW.

Palabras clave: mar Mediterráneo, masa de agua, temperatura, salinidad, máximo, extremo.

INTRODUCTION

The major aim of this paper is to present a simple proposal about the characteristics of so-called "Levantine Intermediate Water" (LIW), which are in fact a relative maximum in potential temperature (θ) and an absolute maximum in salinity (S) that generally appear respectively above and below the expected core of LIW. On a θ-S diagram and more or less everywhere in the Mediterranean Sea, but especially in the western basin, these maxima lead to a "scorpion-tail" image as given by e.g. the light green, cyan and blue diagrams in Figure 2. Our analysis can also apply to some other water masses formed in the sea (the Mediterranean Waters, MWs), as well as to waters having similar characteristics in the ocean for which such an image has been depicted for some time (Tchernia 1972). However, our primary focus will remain on LIW because, to our knowledge, it is the sole water mass that has been characterized and delimited using these θ and S maxima, even if in a somewhat fuzzy way (and even in our own papers!), which is something we wish to comment upon and criticize.

In this analysis we do not deal specifically with the θ and S values, nor do we address the circulation of LIW that we have already specified using the so-called "core method". Furthermore, we do not question any of the qualitative results about LIW that have been previously obtained within the sea. However, if we are correct in our conclusions, all papers (sic) that deal with quantitative results about LIW, especially at Gibraltar but also within the sea, will have to be thoroughly reconsidered. Because our work may be defined as being atypical and because the number of works dealing with the quantification of LIW is so large, we believe it is both useless and unfair to cite only some of them in this paper.

In order to properly understand i) the specificity given to LIW by its originally large θ and S values, ii) its necessary implication in the formation of all deep MWs, and iii) its mixing with the other waters, we must first describe our own view of both the sea functioning and the LIW circulation (Fig. 1). This view was first presented for the western basin in Millot (1987a,b), in total opposition to the pioneering view of Wüst (1961) to which some other papers continued to subscribe until the late 1990s. However, our view, which was first refined for the western basin (Millot 1999, Millot and Taupier-Letage 2005b) and then extended to the whole sea (Millot and Taupier-Letage 2005a), now seems to be widely accepted (e.g. Schroeder *et al.*, 2012).

The water deficit in the sea (O(1m/yr)) due to evaporation exceeding precipitation and river runoff (the EPR budget) leads to an inflow of Atlantic Water (AW) that circulates as a surface density current, hence alongslope counterclockwise (see Figs 1 and 2 of Millot and Taupier-Letage 2005a). AW thus flows first in the southern parts of both the western and the eastern basins, these being fairly arid regions off Africa, with the result that S(AW) continuously increases eastwards all year long while θ(AW) fluctuates seasonally; this is one of the factors that makes

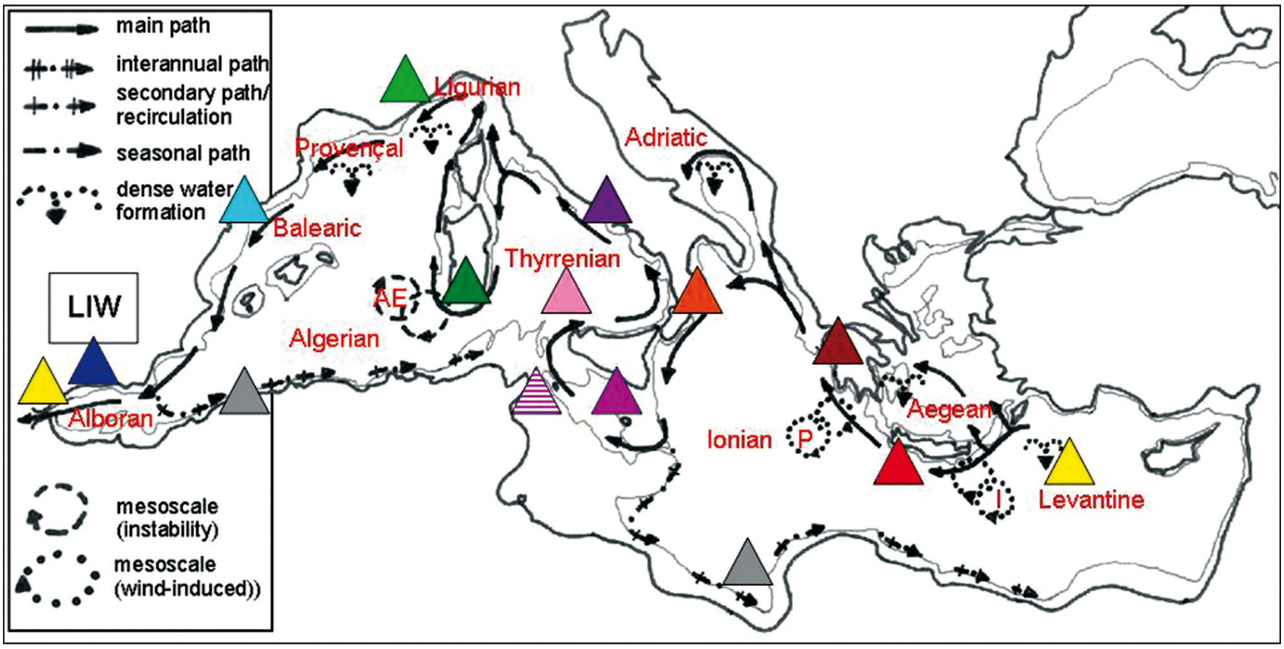

FIG. 1. – This is essentially (manual drawing) Figure 3 of Millot and Taupier-Letage (2005a); basic features in the western basin were already described by Millot (1987a-b, 1999) and the thin line represents the 500-m isobath. LIW is necessarily involved in the convection processes that occur in the Aegean, the Adriatic and the Liguro-Provençal sub-basins. LIW can be entrained offshore from its alongslope route by eddies such as Ierapetra (I), Pelops (P) and the Algerian eddies (AE), leading to a signature of sluggishly moving LIW in the basins' interior. The parts of LIW that cannot outflow directly through the Channel of Sicily and the Strait of Gibraltar continue circulating off Africa (named recirculations). The coloured triangles roughly locate the θ-S diagrams in Figure 2.

the S information more reliable than the θ information. Then, AW continues flowing in the northern parts of both basins. There, wintertime air-sea interactions in some specific sub-basins (i.e. parts of basins, the major ones as given in Fig. 1) cool and evaporate AW, thus increasing its density to the point that it sinks through dense water formation processes in specific zones of four major sub-basins (the Levantine, Aegean, Adriatic and the Liguro-Provençal). This may occur either in the open sea (convection) or on continental shelves (cascading). Roughly, and a priori in any of these four zones, AW can either be made slightly denser (forming intermediate waters), or it can be made significantly denser (more or less mixing with the waters below and forming deep waters). These MWs, once formed, will then spread from their formation zones as density currents as long as they are not trapped in a specific basin or sub-basin. If trapping occurs, mainly in the case of the deep MWs, they will then circulate only sluggishly and their upper levels will outflow only when they are uplifted by denser waters over the sills in what we call overflow. A direct consequence of this is that intermediate waters outflow on the right hand side of both the Channel of Sicily and the Strait of Gibraltar while the deep waters are forced to overflow on the left hand side of both passages.

Understanding the links between these density currents and the dense water formation zones is important to better comprehend the role of LIW and the consequences on its θ-S signature. Dense water is formed where strong wintertime northerlies blow cold and dry air masses from the land to the sea, hence roughly in an on-offshore direction, which implies that dense water should be mainly formed in the coastal zone. This is in fact the case over continental shelves where the thermal content is limited, so that densification over the shelf of the sole AW (due to its thickness) eventually freshened by river inputs, leads to cascading over the slope of fairly cool and fresh waters. Where there is no continental shelf, and just because of geostrophic adjustment, dense water tending to sink sucks AW that tends to flow cyclonically around the zone where this dense water is sinking, hence in particular between that zone and the coast/slope. Because such a geostrophic adjustment, and hence the dense water sinking, have a time scale larger than one year (Crépon *et al.* 1989), the largest surface densities at the beginning of a given winter are found offshore, which will be where convection will most likely occur. When the densification of AW is moderate, convection creates an intermediate water that then spreads over the denser waters as over a virtual shelf. When the densification of AW is large, the dense water formation process more or less involves all waters resident in the area. Since all waters (i.e. AW plus all the MWs formed in other zones upstream), naturally tend to flow alongslope, hence between the continental slope and this specific zone of convection (or even across that zone), a major consequence is that at least a part of each of these MWs will be involved in any convection process that forms deep waters. Another major consequence of this situation is that surface currents will not necessarily surround the zones of convection, and hence will not form "gyres". In particular in the eastern basin, the Asia Minor Current is sucked not only towards the Levantine, but also towards the Aegean and the Adriatic, so that only a part of this current will be involved in the LIW formation and only a fraction of this part will tend to flow cyclonically around the zone of LIW formation. Therefore, the gyre that could thus be formed would be markedly non-symmetrical and much more intense alongslope than offshore.

Whatever the case may be, AW reaches the east of the eastern basin with much larger S values than when it reaches the east of the western basin, just because of its longer stay in the southern arid regions off Africa. Therefore, AW arriving then in the Levantine, where it is named Levantine Surface Water (LSW), has a fairly large S. The direct consequence of this is that wintertime cooling of such high salt water does not need to be very intense in order to make it sink. This explains why LIW, the intermediate MW formed by convection from AW/LSW in the Levantine, is both salty and warm. Part of the Asia Minor Current penetrates into the Aegean so, depending on the season, the surface water found there can be even warmer and saltier than LSW (e.g. Theocharis *et al.* 1999). Though this is not an agreed acronym (CIESM 2001), let us call this surface water AeSW in order to differentiate it from the one chosen for the Adriatic Surface Water, which we will consequently call AdSW.

In the Aegean, the combined cooling/freshening of AeSW on the Cretan shelf plus convective mixing in the open Cretan sub-basin (Fig. 1) form another fairly important intermediate MW, which is the Cretan Intermediate Water (CIW, e.g. Theodorou *et al.* 1990). Let us specify that the Cretan sub-basin is the deepest part of the southern Aegean sub-basin, that another intermediate water (i.e. MIW, the Mirtoan Intermediate Water, cooler, fresher and denser than LIW) is sometimes recognized by those who specialize in this region (e.g. Theocharis *et al.* 1999), and that the EMT (the Eastern Mediterranean Transient, Klein *et al.* 1999) is an event that occurred in the late 1980s and early 1990s and that led to the Aegean temporarily producing a dense water denser than the one produced by the Adriatic [AeDW and AdDW, respectively, although these names are not agreed by CIESM (2001)]. An important point to note is that the density of CIW is markedly variable: while it was slightly denser than LIW during the pre-EMT period, it has been less dense than LIW since the EMT (A. Theocharis, personal communication), which might explain why it has not always been clearly differentiated from LIW.

While AW is flowing westwards thereafter, that is across the remainder of the Aegean, the north-eastern Ionian and the southern Adriatic, it mixes with fresh water from such major sources as the Black Sea and the Pô river that reduce its salinity. Meanwhile, wintertime air masses are cooler, so dense waters formed in the remainder of the Aegean and in the Adriatic are fairly fresh and cool. To our knowledge, no intermediate MW has ever been claimed to be formed in the Adriatic, which would make this sub-basin different from the three others where dense formation processes occur. However, it might also be the case that intermediate water is formed in such limited amounts that it has never been clearly identified there. Whatever the truth might be, if we consider only CIW and LIW, of which we know that CIW is generally said to be formed in lower amounts than LIW, then CIW has been clearly identified during the after-EMT period in both the north-eastern and north-western Ionian by a warm salty peak above the LIW one (e.g. Manca *et al.* 2006). Though on some occasions CIW has been recognized in the Channel of Sicily (e.g. Gasparini *et al.* 2005), the intermediate outflow from the eastern basin is considered in all papers to be that of LIW only: a conclusion which is quite strange!

The problems are not exactly the same for the intermediate waters formed in the western basin. Indeed, though there is only one zone of dense water formation in the Liguro-Provençal sub-basin, it spreads over a fairly large area. The AW characteristics and the meteorological conditions in either the east (the eastern Ligurian sub-basin) or the west (the western Provençal sub-basin) of this area are thus markedly different. Intermediate water was identified for the first time in the Ligurian by Lacombe and Tchernia (1960), who called it “Riviera Water”, since it was expected to be formed off the French Riviera (also named the Côte d’Azur). Then, Salat (1983) reported the formation of intermediate water in the western part of the Provençal off the Spanish continental slope. This “Spanish Water” had characteristics roughly similar to those of the “Riviera Water” although probably with significant differences (a detailed comparison between the two waters has still to be made). However, similar waters are certainly formed in the whole Liguro-Provençal sub-basin; they cannot be practically separated downstream from there and they are identified as a single water mass, mainly along the Spanish continental slope, by a θ relative minimum just above that of LIW. This water was identified for the first time at Gibraltar by Gascard and Richez (1985) while they were discussing previous studies (i.e. Lanoix 1974, who analysed 1962 data), though they did not find it in their own 1981 data. For more than a decade, this water was given the name Winter Intermediate Water (WIW) before it was decided, since all MWs are formed in winter, to call it Western Intermediate Water (still WIW, CIESM 2001). It is claimed that WIW only occasionally outflows at Gibraltar, but we believe rather (Millot 2009, in press) that it might not have been correctly observed. Indeed, i) WIW can be found only in the northernmost part of both the Alboran sub-basin and the Strait of Gibraltar (due to the Coriolis effect), ii) it has fairly variable characteristics (it is formed mainly by cooling of AW), and iii) it can be found in variable amounts (being formed not far upstream). Depending on the WIW abundance, LIW will flow below either a cooler (WIW) or warmer (AW) water, leading to a large variability in the “scorpion-tail” image. Whatever the case, WIW is correctly named.

Deep MWs mainly formed in the Aegean and the Adriatic are no longer differentiated when they overflow through the Channel of Sicily, where they are considered together as EMDW, the Eastern Mediterranean Deep Water; note that, even though deep MW has reportedly been formed in the Levantine, this does not seem to be presently supported by those who specialize in this sub-basin. Once through the Channel of Sicily, EMDW cascades into the Tyrrhenian and forms TDW, the Tyrrhenian Dense Water (Millot 1999). TDW can be identified at Gibraltar (as claimed by Millot 2009, in press) along with WMDW, the Western Mediterranean Deep Water formed in the Liguro-Provençal sub-basin (note that EMDW and WMDW are consistent acronyms).

To assume that each of the two basins of the sea forms an intermediate water and a deep water is no more than an oversimplification that results from our inability to separate slightly different MWs beyond a limited point. Whatever the case may be, such an oversimplification is found still too complex and is not yet accepted by those who specialize in the Strait of Gibraltar and continue to deal there with LIW and WMDW only!

Keeping the above overview of both the sea functioning and the LIW circulation in mind, let us now discuss in the next section the LIW characteristics all along its course as schematized in Figure 1. When we drafted this figure, we clearly had in mind the WIW characteristics as described here but we failed to attach sufficient importance to the role of CIW, which we do for the first time herein. We should note that the circulations of both CIW and WIW downstream from their zones of formation in the Aegean/Cretan and the Liguro-Provençal, respectively, are basically similar to that of LIW.

THE LIW CHARACTERISTICS

We illustrate the description of the LIW mixing and circulation with a selection of θ-S diagrams (Fig. 2) inferred from CTD vertical profiles that can only provide a rough idea of the LIW signature and cannot be too closely linked to each other since they have been selected in an almost particular way. We first selected in the MEDATLAS data base (MEDAR Group 2002) areas of ~1° in longitude by ~1° in latitude covering the continental slope in some specific areas as indicated by the coloured triangles in Figure 1. Because of the scarcity of profiles in the southern part of the Ionian, the selection there was made over a larger (several

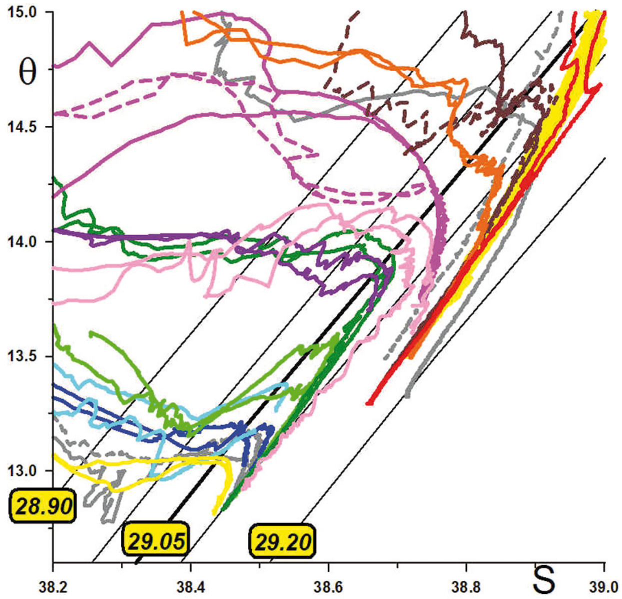

FIG. 2. – θ-S diagrams selected as indicated in the text in areas as indicated by the coloured triangles in Figure 1. In the Channel of Sicily, continuous (dashed) magenta diagrams were collected on the right (left) hand side of the channel. The 29.05 kg m^{-3} isopycnal is indicated to roughly estimate the variation of the LIW core density all across the sea together with other isopycnals that provide a density scale focusing on the range of interest.

degrees) area while, because of the large north-south gradients of the MWs distribution in the Alboran and the variability of the interactions with AW there, the area is ~2° in longitude by 0.5° in latitude. We then extracted the data from the available profiles and, because the data base only contains in situ temperatures, computed θ and σ_θ, the potential density anomaly. We then plotted θ-S diagrams, as well as θ(z) and S(z), and from these chose profiles aimed at illustrating our description. In this process, we unavoidably chose data possibly collected in different years. Some of the files in the data base do still have numerous errors while others display strange values and we rejected some that appear to represent abnormal situations; most of our criteria are thus subjective. For our analysis, we chose to select 15 areas with two profiles per area in order to give a rough overview of the variability of the LIW characteristics in the whole sea on a unique fairly clear figure (Fig. 2). For all of these reasons, the θ-S diagrams in Figure 2 cannot be used for any in-depth analysis. Rather, their function is to provide examples of the various shapes that the "scorpion-tail" image can take all across the sea and to illustrate our comments. But even in this and in any of these areas, the actual variability is tremendously larger than illustrated.

In its Levantine zone of formation (a patch of several yellow and almost straight diagrams in Fig. 2), LIW can hardly be isolated from the waters above and below; note that the waters above (LSW in the Levantine, AeSW, AdSW and CIW more downstream) are outside the displayed ranges. We rely on papers such as those of Theocharis *et al.* (1999), who say that LIW lies in the Levantine below LSW, forming a 50 to 600-m-thick layer with θ in the range 14.70-16.95°C and S in the range 38.85-39.15. In the simple calculations that we will propose in Section 3, we thus assume nominal values for such a warm salty intermediate water (we will call it IW to emphasize the possibility of dealing with more general cases) of 15.0°C and 39.0, which are the maximum values in most θ-S diagrams hereafter. Deep values in the Levantine, as well as in the other areas of the eastern basin, indicate the presence of EMDW; note that we do not focus on the differences between AeDW and AdDW, and that Figure 2 illustrates the huge variability of EMDW, in particular as compared to that of WMDW. As for all other MWs, LIW first amasses in its formation zone, which must be considered to be a reservoir that will be refurbished, year after year, by slightly different water and from which LIW will continuously spread as a density current, hence tending to form a vein flowing alongslope counterclockwise (Fig. 1).

Some LIW penetrates into the Aegean in the east of Crete, a part of it being then involved in the formation of AeDW while the remainder outflows from the Aegean in the west of Crete with more or less modified characteristics, in between CIW above and AeDW below. Some LIW follows the continental slope south of Crete and it is there (red diagrams in Fig. 2) that identifying LIW from its sharp peak (actually looking like a thorn) is the easiest. However, it is important to note that i) the θ, S and σ_θ values associated with this peak display a fairly large variability and ii) specifying an LIW thickness is much less obvious than locating a core. A part of this alongslope flow south of Crete can be entrained offshore, in the form of filaments, by the Ierapetra and Pelops anticyclones that are generated every summer by the Etesians. Such filaments are finally released in the basin interior where they form a background of sluggishly circulating LIW (related comments are made hereafter for the southern Ionian and the Algerian areas).

LIW flowing off the Peloponnese (brown diagrams) thus forms a recomposed vein that has already markedly modified and variable characteristics but can be recognized near σ_θ=29.05-29.10 kg m^{-3} by an almost truncated-peak shape. Note that a truncated shape is the one expected for such a vein composed of parts that have encountered different mixing processes. Note also that even if the mixing lines between LIW and the waters above and below are fairly straight, as would be expected for mixing between two water types (defined by a point on a θ-S diagram) they can, at most, be used to specify percentages of this or that water, but not interfaces (specifying interfaces would require dealing with $d\sigma_\theta/dz$ maxima). At lower densities, the two brown diagrams are different: one (solid line) displays a fresher, warmer and seemingly sharper peak associated with a σ_θ lower by ~0.1 kg m^{-3} (near σ_θ=28.95-29.00 kg m^{-3}) that indicates CIW (in agreement with e.g. Manca *et al.* 2006) while the other (dashed line) does not display any other peak. This example illustrates the huge variability encountered off the Peloponnese and the fact that the CIW outflow around the Peloponnese is less permanent and/or more reduced than the LIW recomposed vein. Because of the fairly large width of both the CIW and LIW veins as compared to the width of the Channel of Otranto (between the Adriatic and Ionian sub-basins), only their internal parts (the ones closest to the slope) will then penetrate into the Adriatic. Consequences similar to those in the Aegean will occur for the formation of AdDW in which both CIW and LIW will be involved, while the external parts of both will skip the Adriatic.

For the area east of Sicily, two peaks are indicated by the two orange diagrams. One peak, with σ_θ=29.05-29.10 kg m^{-3}, is still fairly truncated and the other, with a σ_θ lower by more than 0.1 kg m^{-3} (σ_θ=28.9-29.0 kg m^{-3}), is fairly sharp. Even though i) less dense waters (AW as a whole, σ_θ<~28.8 kg m^{-3}) are markedly different from those in the previous area, which is obviously consistent with the large variability associated with surface waters, and ii) both CIW and LIW might flow as recomposed veins that might have been involved in different processes in and/or out the Adriatic, these two orange peaks seemingly correspond to the brown peaks associated with CIW and LIW. Such continuity from the north-eastern Ionian to the north-western Ionian has already been emphasized by e.g. Manca *et al.* (2006). Additionally, it seems that the difference between the truncated versus the sharp shapes of both peaks is maintained. However, even if a sharp peak might allow a quite accurate definition of a core, we are still unable to specify any thickness for both CIW and LIW.

After the Adriatic, these intermediate waters (at least CIW and LIW, but also MIW, which probably cannot be differentiated from LIW after the Aegean) continue following the slope around Sicily so, when in the channel, they are mainly located on the right hand side of it. Since no intense processes occur along this course, mixing between them and with surrounding waters gives fairly smooth diagrams in magenta (solid lines) and a unique broad peak off Sicily (more exactly in the area 13-14°E by 36-37°N, mean depth ~500 m, maximum depth ~2000 m). Most impressively, since to our knowledge this is a feature never emphasized up to now, i) there seems to be continuity between the orange and solid-magenta diagrams and ii) the broadness of the magenta peak in the channel implies that it is far from being due to the sole LIW orange peak. As inferred from the analyses and figures made by Manca *et al.* (2006) further upstream and assuming the CIW and LIW amounts there will then outflow, it might be that LIW only represents some two-thirds to three-quarters of the total (CIW+LIW) intermediate outflow. Because these specific profiles were chosen somewhat arbitrarily (a more dedicated analysis has still to be done) and because we want to make our own work as clear as possible in its focus on the LIW characteristics, we will continue to deal hereafter with an LIW outflow. However, when considering the functioning of the sea and whatever the case may be with these profiles, we propose that the intermediate water from the eastern basin be called the Eastern Intermediate Water (EIW) as a logical counterpart to WIW. Even if the CIW outflow is fairly low it cannot be neglected, and dealing with an EIW outflow will always be more correct than dealing with an LIW outflow.

When considering a broad and smooth peak such as those on the solid-magenta diagrams, we lack sufficient theoretical studies to define both the core and the thickness of the layer it represents. It would seem to us that, with such a "scorpion-tail" image, one would intuitively associate the core roughly with a maximum of $d\sigma_\theta/dz$, in fact with the part of the curve perpendicular to the isopycnals (near σ_θ=28.9-29.0 kg m^{-3} for the solid-magenta diagrams), while a core of a water mass is normally associated with a minimum of $d\sigma_\theta/dz$, in fact with homogeneous values of the isopycnals over depth. Given such an assumption, one would link this broad peak on the solid-magenta diagrams mainly to the CIW peak on the orange diagrams, not to the LIW peak… though we are convinced that LIW is the major component of the outflow. Therefore, how can the core and vertical extent of the water associated with this broad peak be defined?

The sole visually-identifiable characteristics of these smooth solid-magenta diagrams are θ and S maxima that, for the first time, are separated from each other. Therefore, a link has historically been made between these maxima and the LIW vein (as stated above, we continue to use LIW although we in fact have EIW in mind), though we are not aware whether such a link has never been supported by numerical simulation. It should be noted that the dashed-magenta diagrams on the left hand side of the channel (off Tunisia, more exactly in the area 11°E-12°E by 36°N-37°N, mean depth ~200 m, maximum depth ~1000 m), have specific differences as well as similarities. These diagrams differ from those off Sicily in their upper part since LIW is outflowing mainly off Sicily and not off Tunisia. But they are similar in their lower part (σ_θ>~29.03 kg m^{-3}), in particular near the S maximum, which appears with similar values (38.76-38.77, σ_θ=29.07-29.08 kg m^{-3}) all across the channel (at 300-400 m in the east and 250-300 m in the west). If the S maximum (magenta) is directly due to the LIW peak (orange), which could be consistent with the similarities between the associated densities, one should ask the following questions: i) why are these maxima similar all across the channel while LIW outflows off Sicily and ii) is the remainder of the magenta broad peak associated with CIW and how? Otherwise it could be assumed that CIW and LIW have somehow mixed and merged together to form EIW and that EMDW is actually found all across the channel because depths are greater off Sicily so that there is room for both EIW and EMDW there. It may also be assumed that the S maximum is in the EMDW layer, being associated with specific densities, and hence at depths displaying an across-channel slope consistent with what is observed in any passage of the sea!

So far as the eastern basin is concerned, it must be noted that very variable situations can be encountered in the southern Ionian as LIW can either be absent (the fairly straight dashed-grey diagram) or else found in fairly unmixed conditions (the solid grey diagram peaked at σ_θ=29.0-29.1 kg m^{-3}) just below fairly cool and fresh water; note that this water is generally considered to be AW although some WIW might have been entrained up to there below AW (see comments for off Algeria). The presence of LIW in the southern Ionian can result from three major processes. LIW may have been swept away from the Cretan-Peloponnese slope by Pelops eddies, which can be followed for years (Hamad *et al.* 2006) and then released into the Ionian interior when the eddies die. LIW may have been entrained back into the eastern basin as a consequence of interactions with the meandering flow of incoming AW that sometimes spreads off Sicily. Finally, as indicated in our diagram (Fig. 1), some of the LIW found south of Sicily may continue circulating as a density current along the African slope (in what is called "recirculation") for a while. All this LIW (called "old LIW" in our own references) will then spread sluggishly throughout the whole basin before either mixing with surrounding water or being (re)involved in dense water formation processes and finally escaping through the Channel of Sicily.

In the western basin just north-west of Sicily (pink triangle in Fig. 1), the lightest intermediate waters from the eastern basin (σ_θ<28.9-29.0 kg m^{-3} on the solid-magenta diagrams), encounter fairly recent, fresh and cool water (as indicated on the other diagrams in the western basin). Before mixing, these two waters penetrate into each other so that the pink diagrams are irregular in their upper part, as displayed here. The core of these intermediate waters, as roughly defined by a maximum of $d\sigma_\theta/dz$, thus appears on the pink diagrams at greater densities (σ_θ=29.02-29.08 kg m^{-3}) than on the solid-magenta diagrams (σ_θ=28.9-29.0 kg m^{-3}) but lower than those associated with the LIW peak on the orange and brown diagrams (σ_θ=29.05-29.10 kg m^{-3}). Though these densities cannot be compared too closely, the peak on the pink diagrams, as well as on all diagrams collected downstream, might best be considered as an evolution of the CIW and LIW peaks combined together (as i.e. EIW) rather than an evolution of the LIW peak alone. In their deeper parts, the numerous small-scale features on both pink diagrams illustrate the mixing processes that are occurring while EMDW is cascading; one diagram indicates EMDW as yet unmixed at the start of its cascade while the other diagram indicates the cascading of EMDW down to the WMDW layer lying below ~2000 m. Note that on this second diagram, which indicates in fact TDW, the displayed S maximum is more pronounced (though with lower S values) than in the first diagram.

Because the Channel of Sicily is fairly wide and deep, LIW (we still have in mind EIW) does not have to markedly modify its immersion while crossing it and, contrary to EMDW, LIW does not markedly cascade into the Tyrrhenian. Furthermore, no major processes occur in that sub-basin; diagrams become fairly smooth and not very different from central Italy (violet) to southern Sardinia (dark green), where most of the LIW vein flows while part of it crosses the Channel of Corsica. In the Tyrrhenian, LIW is generally located just below AW as WIW is seldom encountered there; as a consequence, the absence of a θ minimum associated with WIW makes it difficult if not impossible to identify a θ maximum on the "scorpion-tail" image, while an S maximum can always be identified. On entering the Algerian sub-basin, LIW is eroded from time to time by mesoscale Algerian eddies that are generated by instability processes affecting the AW vein off Algeria and filaments are entrained in the sub-basin interior (the dedicated study by Millot and Taupier-Letage (2005b) is very demonstrative and could probably be directly applied to the Ierapetra and Pelops regions). In the Ligurian (light green profiles), the locally-formed WIW, which is characterized by a fairly large θ minimum (compared with the LIW θ maximum), starts flowing above LIW so a θ maximum automatically reappears, without providing any specific information about the LIW upper limit. Here, as in the Provençal sub-basin, LIW is involved in the formation of deep water (WMDW) as it has been in both the Aegean and the Adriatic sub-basins.

Roughly similar diagrams just modified as a consequence of mixing are then encountered in the western Balearic (cyan), the northern Alboran (blue), the entrance of the Strait of Gibraltar (yellow), and off western Algeria (grey). We should note that i) the LIW peak shape is strongly dependent on the WIW θ minimum, and ii) this θ minimum does not decline continuously downstream in Figure 2 as it should be with diagrams collected during a unique experiment. In particular the lowest minimum off Algeria (from data we have collected personally) indicates that, in the Liguro-Provençal sub-basin, WIW can have much lower values than those displayed here, and that this fairly unmixed WIW has been entrained there away from the Spanish slope by AW when it forms the so-called "Almeria-Oran jet" (as the north-eastern branch of an anticyclonic circulation in the eastern Alboran). This is one of the processes that can also entrain some LIW off Algeria, especially when WIW flows along Spain in limited amount. However, with regard to the eastern basin, two other processes must also be considered. Filaments of LIW can be swept away from southern Sardinia by the Algerian eddies (which can have lifetimes of ~3 years and may drift across the whole Algerian) and some of the LIW can leave the Spanish slope and continue circulating for a time as a density current along the African slope (what is called "recirculation" in Fig. 1). Ultimately, all three pro-

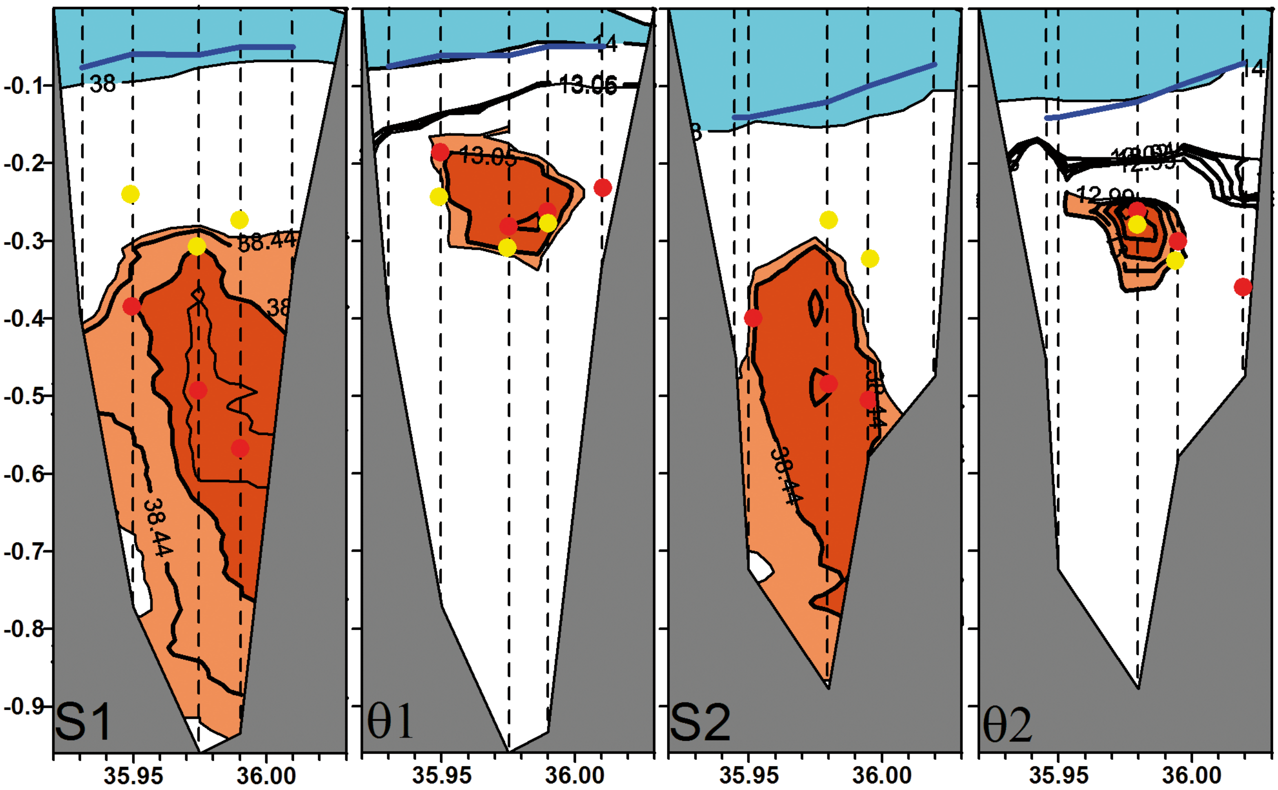

Fig. 3. – Adapted from Figure 11 of Millot (2009) and Figures 9 and 18 of Millot (submitted). θ and S sections near 5°30’ W during campaigns #1 and #2 of the 1986 Gibraltar Experiment GIBEX conducted in March-April and September-October, respectively; the CTD profiles are located by the dashed lines as a function of latitude (in °N) and depths are in km. The 14.0°C and 38.0 isolines roughly represent the interface between the AW (in cyan) inflow and the MW outflow; this interface is more accurately defined by the largest S(z) and σ(z) gradients that display the same cross-strait distribution (blue line). In the outflow, the relative θ maxima and absolute S maxima are marked by red dots, while the yellow dots locate the core (associated with a maximum of $d\sigma_\theta/dz$). The isolines that identify these maxima are plotted with thick (two-digit values) and thin (± 0.005 values) lines leading to specific ranges in orange: S1(38.435≤S<38.46), θ1(13.045≤θ<13.065), S2(38.435≤S<38.455), θ2(12.99≤θ<13.03). Using dark and light orange just differentiates higher from lower θ and S values

cesses will increase the heat and salt contents at these intermediate depths and these warm salty waters will spread sluggishly throughout the basin before either mixing with surrounding waters or being (re)involved in dense water formation processes until they finally escape through the Strait of Gibraltar. Also note that the yellow diagrams in the strait area correspond to the profiles displayed in Figure 3 (they were thus not selected as the diagrams in the other areas) and that they show some of the lowest θ minima (associated with WIW) available in the MEDATLAS data base for this specific area.

The series of θ-S diagrams in Figure 2 illustrates only partially the huge temporal variability in the θ and S characteristics that is encountered in any place in the sea. When considering this series, the overall impression one gets is that the sharpness of the “scorpion-tail” image more or less continuously smoothens downstream, which is consistent with LIW (in fact EIW) continuously mixing with surrounding waters. It is worth noting that all MWs (particularly LIW, which performs the longest transit in the sea), can be involved in so many intense processes that they develop complex and extremely variable signatures all along their courses. LIW certainly displays, shortly downstream from the zone where it originates, some clear seasonal variability, but it is illusory to look at Gibraltar in particular, for any original seasonal signal. It might be that in the eastern basin sharp peaks and straight mixing lines allow some characterization and delimitation of, for example, LIW. But from the Channel of Sicily downstream, mixing leads to a much smoothed peak and one is (we all have been!) tempted to assimilate the tangents to the diagrams at both the θ and S maxima with mixing lines, perversely leading us to use these maxima as some indication of the LIW thickness, without ever saying exactly how and why! Note that the variability of the waters encountered above and below LIW necessarily modifies the “scorpion-tail” shape. In particular it modifies the occurrence and immersion of the θ and S maxima, so that any definition of the LIW thickness based on these maxima will lead to values depending upon the variability of the surrounding waters. Whatever is the case, since there is plenty of space within the sea, defining the LIW thickness with the θ and S maxima (i.e. with an accuracy of a few hundred metres) does not induce major errors in the localization and route of LIW.

This is more difficult to accept in the Strait of Gibraltar because all other MWs (at least WIW, TDW/EMDW and WMDW) can be identified there, i.e. through a restricted section just a few hundred metres deep so, though accurately specifying the limits of each of them is difficult, if not impossible, such limits must be "specified" (either computed from data or postulated). The two diagrams shown at Gibraltar (in yellow, Figure 2) are those from the central profiles of the sections at 5.5°W that are displayed in Figure 3, namely at 39.975°N (35.98°N) during campaign #1 (2). Figure 3 first shows the AW-MW interface (blue line), which must actually be associated with the depth of the largest σ(z) gradient, which appears to be very similar to that of the largest S(z) gradient (both gradients cannot be inferred from the figure). Note that this interface can be satisfyingly associated with given isotherm (~14°C) and isohaline (~38) not only at 5.5°W but also in the whole eastern part of the strait, at least during the two valuable GIBEX campaigns that we have been analysing (Millot, in press). Now, one can wonder how specifying the interfaces between the various MWs, in particular those delineating LIW, has been done up to now and/or how this can/could be done more efficiently.

Considering that LIW is strictly limited by the θ and S maxima (red dots), this would leave significant room above and below LIW for the other MWs. However, the LIW core as defined by the maximum of $d\sigma_\theta/dz$ in between these maxima (yellow dots) would be much closer to the θ maximum than to the S one, which would be a strange feature for the core of a layer. In addition, the immersion of the θ maximum would imply that the MW lying between LIW and AW, which is actually WIW and has never been considered up to now as permanently outflowing, would occupy a fairly large percentage of the section. The immersion of the S maximum would also leave a significant place to the MWs below LIW, but TDW and/or WMDW would be as salty as most of the LIW, in particular roughly as salty as the LIW core on some profiles, which would be another strange feature. Another possibility is to consider that LIW is limited by fairly large values of the isothermals and isohalines that would be found both above and below the maxima (delimited in dark and light orange). As indicated by Figure 3, such large θ values always have a limited vertical extension and, though we cannot demonstrate whether or not they actually characterize the upper part of the LIW layer, they leave enough space for the WIW above since both waters outflow on the right hand side of the strait. However, again as indicated by Figure 3, the large S values regularly spread downwards. Associating "fairly large" S values (a feature that would not be easily specified) with LIW does not leave enough room for either TDW/EMDW or WMDW, which must outflow below and mainly on the left hand side of the strait. There are therefore objectively no arguments supporting a link between LIW and any characteristics of the S distribution below the S maximum, so we must ask how isohalines can be (could have been!) used to delimit the lower part of LIW! In order to seek a better understanding of the mixing processes and whether or not other criteria can allow LIW (and other similar intermediate waters) to be delimited, we performed the very simple calculations presented in the following section.

SIMULATION OF AN IW MIXING

For this exercise we performed very simple Microsoft Excel-based calculations, which should in no way be taken for a proper numerical simulation of LIW mixing processes.

As explained above, we are especially interested in the evolution of the LIW/EIW characteristics as a consequence of vertical mixing with the waters lying above and below. However, our results obviously apply to other warm salty intermediate waters, and (see the discussion) to cool fresh ones as well, even when these are entrained in open-sea and open-ocean eddies, being therefore structured as lenses or filaments. We will show that our results also apply to horizontal mixing of these intermediate waters when they flow along-slope while the case of open-sea/ocean lenses or filaments is different in this respect. Though we use θ and S numerical values that are typical of LIW and mainly deal with surrounding waters that can be found in the sea, we will also analyse cases that can be encountered in the world's ocean or could be encountered just in theory. For all these reasons, we prefer to deal with the case of a warm, salty intermediate water (IW) lying in between waters A (above) and B (below) and we start the mixing process with water types (identified by one single point in a θ-S diagram).

First we consider an IW of limited thickness between fairly thick A and B layers; the case of A, B and IW layers of the same thickness is also considered below. More precisely, we are currently looking at an IW layer of 9 depth units while both A and B have 50 depth units. We simulate the mixing just by averaging the θ and S vertical profiles (running mean over 7 depth units) at each time step t. These specific numbers of depth units (9, 50, 7) were chosen in order to have i) an easy location for the mixed value (7 is odd) and for the IW core (9 is odd), ii) the core of the IW layer (at depth level 55) still unmodified at time step one (9>7, more precisely level 5 in the IW layer (the core) >3, the number of levels in that layer modified by the mixing with either A or B at t=1), iii) a significant evolution of the profiles, hence a significant change in the location of the θ and S maxima, within a reasonable number of time steps (columns in our Excel file), and iv) the A and B layers not totally modified by mixing during the analysed period of time (to make the analysis as simple as possible). In Figure 4, number N=1 actually corresponds to the first time step (t=1) but, for practical reasons, the other numbers (N=2 to 5) correspond to time steps t=5(N-1). Note that it is only at the begin-

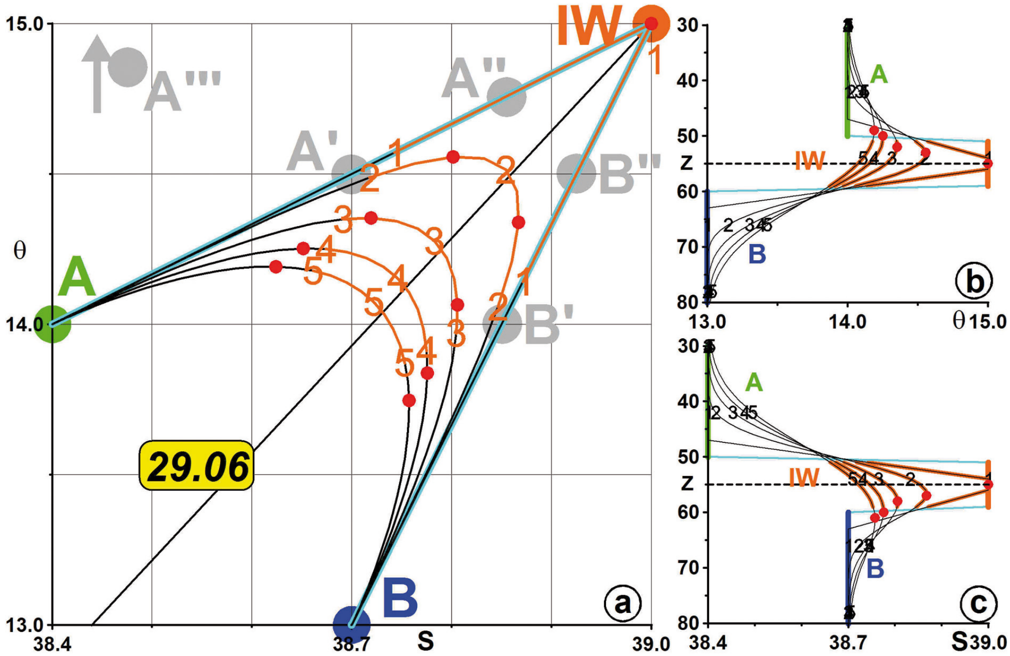

Fig. 4. – a) θ-S diagram for an IW layer (9 depths units; orange) between fairly thick (50 depth units) A (green) and B (blue) layers and unmixed values indicated by the large coloured points. Mixing lines between A and IW and between IW and B are indicated in cyan. For the 5 time steps shown here (N=1 to 5), the diagrams outside the IW layer are indicated by the black lines. The depth units corresponding to the initial upper level (51), core level (55) and lower level (59) of the IW layer are indicated by the N values in orange, hence the IW initial thickness by the orange lines; on these diagrams, it can be deduced that, for instance, the density in the middle of the IW layer remains near 29.06 kg m^{-3}. The θ and S maxima are indicated by the red dots. Waters identified in grey are considered in Figure 5. b,c) θ(z) and S(z) vertical profiles represented as in a), and A and B represented only over 20 depths units. Note that θ(z) and S(z) are symmetric with respect to depth unit 55 (dashed line). These profiles can be used to better analyse the θ-S diagrams in Figure 5.

ning of the mixing process, i.e. when the A-IW and B-IW gradients are still fairly large, that the mixing penetrates into the A and B layers by 3 depth units at each time step. Practically, two-digit numbers for the θ and S values are modified only over ~20 (~10) levels by ~1% (~10%) in the A and B layers at time step t=20 (N=5), which is fairly low as compared to the actual 60 levels (tx3). Though one can estimate the depth unit to a few tens of m (40-50 m), we are totally unable to quantify such a time step. Let us just emphasize that reducing the time step and/or the mixing intensity, i.e. reducing the number of averaged depth units (7), will not basically alter the results that are obtained from such simple calculations.

Figure 4a represents what we think is the more general case in the western basin (A≡WIW and B≡TDW/WMDW while IW≡LIW/EIW in the whole "Simulation" section), in the eastern part of the Channel of Sicily (A≡AW and B≡EMDW) and also, possibly, in the eastern basin (the solid grey diagram in the southern Ionian), i.e. with the water above (A) being fairly cool and the freshest, while the water below (B) is fairly fresh and the coolest. The specific θ and S values we have chosen, combined with the axes scales give the diagrams a fairly symmetrical shape; this symmetry has no specific importance and the diagrams in Figure 5 are plotted with the same scales. The diagrams show that, at t=1 (N=1), the IW core is still unmixed while the upper (lower) parts of the IW layer mix, along the classical mixing lines, with water A (B), so both the upper and lower parts of the IW layer are cooler and fresher than the core, as would be normally expected. Understanding the overall evolution of the IW characteristics during the other time steps (N=2 to 5) is made simple when one considers that the IW core (in this example) is always cooled more by B than by A, which is even more the case for the IW lower part, so the highest temperatures are found increasingly upwards. The same reasoning can apply for the freshening: the core is freshened more by A than by B, which is even more the case for the IW upper part, so the highest salinities are found increasingly downwards. Considering that, regardless of mixing, each layer must keep its initial thickness, the fundamental result which could have been easily intuited is the fact that the θ (S) maximum i) continuously crosses the A-IW (IW-B) initial interface and ii) continues moving regularly upwards (downwards). At the beginning of the mixing process, the θ and S maxima are still inside the initial IW layer: using them to delimit the layer thickness would give this layer an importance less than its reality. After a while, these maxima are outside the initial IW layer, which would give that layer an abnormally large thickness and hence a large importance not at all justified from a dynamical point of view. All these results are made more explicit by Figures 4b, c and do not therefore require major specific comments here.

Figure 5a shows the case of layers A, IW and B having the same thickness (limited to 9 depth units; names are thus AL and BL) and the same θ and S values as in the former case (Fig. 4a; hence A≡WIW, B≡TDW/WMDW, IW≡LIW/EIW). Results are similar up to N=3 since mixing is still progressing in the AL and BL layers. But then, the spread of heat (upwards) and salt (downwards) is limited by the AL and BL thicknesses so heat accumulates in the upper part of AL while salt accumulates in the lower part of BL. In this example, the θ and S maxima at time step N=5 have reached the last levels of layers AL (depth unit 1) and BL (depth unit 27).

Figure 5b shows the case of thick layers having the same S(B), hence named A' and B. This theoretical case (S(A')=S(B)), which is in fact representative of a more general case encountered in the sea with S(A')~S(B) and is not basically different from the former ones, is interesting since it leads to the IW core having specific values: being freshened in the same way from above and below, the core is always associated with the S maximum. More generally, freshening (in the IW layer) and salting (in the A' and B layers) being symmetric with respect to the IW core level, S profiles are symmetric with respect to this level. The IW layer is less cooled by A' than it is by A, so the θ maximum moves more rapidly upwards towards A' (Fig. 5b) than it moves upwards towards A (Fig. 4a). Figure 5c shows the symmetric case with waters A and B' having the same θ(A), which is another theoretical case representative of one commonly encountered (θ(A)~θ(B')), in particular in the deep ocean; similar reasoning explains why θ profiles are symmetric with respect to the IW core, which is thus associated with the θ maximum while the S maximum moves rapidly towards B' (saltier than B).

Figure 5d shows the case of water A" being warmer and saltier than water B, which is clearly the case for most profiles in the eastern basin if one considers that IW≡LIW alone (not EIW). Similarly, this case fits most profiles in the Tyrrhenian sub-basin as well if we consider some small θ minima above the peak. In this case, both the θ and the S maxima move upwards and out of the initial IW layer, leading to a total uncoupling between the initial IW layer and a layer that would be associated with the θ and S maxima. However, it is possible that maxima moving upwards out of the LIW layer could remain in the EIW layer, or these maxima may even move downwards in the EIW layer considering its potential to mix with AW and/or WIW above it! With water B" warmer and saltier than water A (Fig. 5e), similar results are obtained with both maxima moving downwards; such a situation is not encountered in the Mediterranean Sea but is a characteristic of the "scorpion-tail" in both the Antarctic Ocean and the Greenland Sea (e.g. Tchernia 1972).

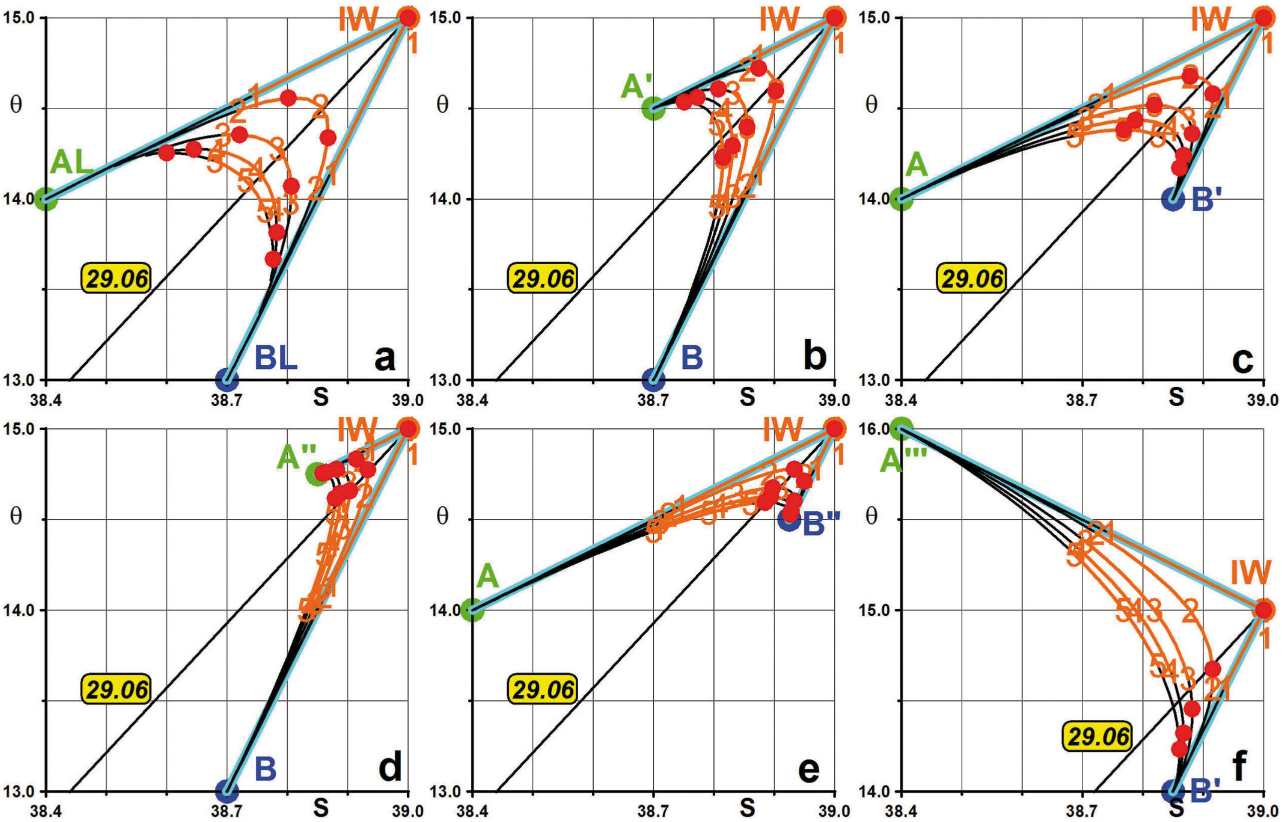

FIG. 5. – a) as in Figure 4a for layers A, B and IW of similar thickness (9 depth units), b) as in Figure 4a for layers A' and B, c) as in Figure 4a for layers A and B', d) as in Figure 4a for layers A'' and B, e) as in Figure 4a for layers A and B'', f) as in Figure 4a for layers A''' and B'.

Finally, Figure 5f shows the case in which water A''' is warmer and fresher than LIW, as often occurs in both the eastern basin and the Tyrrhenian sub-basin (see Fig. 2); in this case we have A'''≡AW and no WIW between the AW and the LIW. Because we considered θ values for A''' and B' that are symmetric as compared to the initial θ(IW), the IW core keeps that initial θ value; in general, there is no θ maximum while the S maximum rapidly evolves below in the B' layer. Though this case does not represent a "scorpion-tail" image, it is important because it is frequently encountered in most of the eastern basin and also because WIW is not found permanently everywhere in the western basin. This case also permits more general comment in the discussion.

DISCUSSION

Our primary concern in this paper is to deal with the LIW characteristics because we have been working for some time to develop our own view of the LIW circulation in the western basin as well as in the whole sea (Millot 1987a, 1999, Millot and Taupier-Letage 2005a). We have also performed specific experiments to demonstrate (Millot 1987b, Millot and Taupier-Letage 2005b) that LIW is entrained from Sardinia across the Algerian sub-basin by mesoscale anticyclonic eddies and not by a permanent westward-flowing vein, as was previously schematized (e.g. Wüst 1961). Such an entrainment is a feature that very probably applies to other eddies such as Ierapetra and Pelops in the eastern basin. We performed these analyses using both the classical "core method" and the fairly fuzzy assumptions that everybody has been using for a while, which are that the LIW upper and lower limits can be specified from the θ and S maxima. However, we never made any attempt to quantify LIW in any place of the sea, as we never believed that we could accomplish this objectively. Our recent work at Gibraltar (e.g. Millot 2009) combined with our aim to delimit each of the four MWs we claim being able to identify there (Millot, in press) led us to try to specify these assumptions and to perform the simple calculations presented herein.

However, though the warm salty LIW is the sole water that, to our knowledge, has been delimited using the θ and S maxima that characterize the so-called "scorpion-tail" image, other waters can be associated with this image. As we have long known (Tchernia 1972) this image is a characteristic of the deep stratification in both the Antarctic Ocean and the Greenland Sea. The same image also applies to numerous other water masses such as the North Atlantic Deep Water and each of the veins formed by the Mediterranean outflow in the Atlantic Ocean. Obviously, our analysis can be extended easily to fit the case of any intermediate water that is both cooler and fresher than the waters above and below it. This exercise would only require the reversal of the two axes and dealing with minima. An example in the sea would be the case, in the Ionian sub-basin, of the dense water formed in the Adriatic (AdDW) after having been uplifted by the dense water formed in the Aegean (AeDW) during the EMT. Other examples in the ocean would be the case of e.g. the Labrador Sea Water, at least just downstream from its formation area, the Antarctic Intermediate Water over the whole Atlantic Ocean and the North Atlantic Central Water in the west of the Strait of Gibraltar (Millot 2009, in press).

Our analysis focuses on vertical profiles just because most of the available observations (as profiles) are vertical ones. However, we could also have considered horizontal profiles. Indeed, since LIW and most other water masses as well (i.e. AW and the other intermediate MWs) are structured (according to us) as alongslope veins circulating counterclockwise within the sea, isopycnals there are sloping up offshore. Therefore, a horizontal profile at a given depth generally crosses, from the slope to the open sea, at first waters lighter than LIW (i.e. AW or WIW in the western basin), then LIW, and then waters denser than LIW (i.e. EMDW in the eastern basin, TDW and then WMDW in the western basin). Since the mixing of LIW with surrounding waters obviously occurs not only on the vertical but also on the horizontal plane, the same calculations would obviously apply to horizontal profiles.

The case of the LIW lenses and filaments entrained away from the slope by open-sea eddies (such as the Algerian ones and, very probably, Ierapetra and Pelops), and the case of open-ocean eddies (the Meddies) formed by the instability of an alongslope warm salty vein or series of veins (the Mediterranean outflow) is specific. While the vertical mixing is basically of a similar nature, the horizontal mixing is different. Indeed, isopycnals being essentially horizontal, the warm salty water mixes on the horizontal plane with fresher and cooler water that has the same density whatever the direction, so all mixing lines remain over time on the same segment of a θ-S diagram and no maxima can develop over time due to horizontal mixing.

To our knowledge, the idea that the θ and S maxima associated with the "scorpion-tail" image can delimit the warm and salty layer of IW that creates the image (using IW emphasizes the fact that the problem is more general than the LIW one) has never been checked—a fortiori demonstrated—by any theoretical simulation. Our very simple calculations (un-weighted moving averages) that deal initially with water types (defined by a point on a θ-S diagram) are aimed at motivating thinking and more sophisticated and accurate numerical simulations. As expected, these calculations show that it is only with a still unmixed IW core that a θ-S diagram displays straight mixing lines between IW and the waters above and below; but even though such lines might be somehow associated with interfaces, they do not provide any information about the IW thickness. As soon as its core starts mixing, IW is no more a water type, and different θ and S maxima appear, obviously with lower values, moving away and separately from their original position (at 15°C, 39). In the general case presented in Figures 4 and 5a (water A is the freshest and water B is the coolest), the θ and S maxima migrate upwards and downwards, respectively. They do this first within the initial IW layer and then within the initial layers above and below, but without displaying any specific behaviour when crossing the A-IW and B-IW initial interfaces. This migration occurs more or less rapidly according to the θ-S values and thicknesses of the A and B layers while, with some specific sets of θ and S values that generally correspond to cases encountered in the sea, both maxima can migrate either upwards (Fig. 5d) or downwards (Fig. 5e).

Though we have emphasized the links between some observed and calculated diagrams, we are obviously aware that natural variability is much larger than the simple cases that we have considered. This is especially the case in the upper layer and on time scales ranging from the season (in particular on θ) to a few hours or days (on both θ and S), as a consequence of fronts and eddies for instance. In contrast, the variability in the lower layer is much reduced on both seasonal and smaller time scales, this layer is always fresher and cooler than the IW layer and θ-S diagrams linking the two layers are fairly smooth. This makes the analysis of the maxima easier and more reliable for S than for θ and more reliable below than above the IW layer. And all theoretical cases that correspond to actual situations (in fact nearly all cases if one considers the comments about Figure 5d in Section 3) show that S (the more reliable parameter) always displays a maximum that moves downwards, first across the IW layer then in the lower layer (i.e. in the more simple and less variable part of the diagrams).

This downward spreading of the S maximum is supported by data analyses from such places as the Channel of Sicily and the Strait of Gibraltar, where there is limited space for any water outflowing. In the channel, our analysis emphasizes the fact that the S maximum has similar values all across it (while LIW mainly outflows in the east), being found at shallower depths in the west (consistently with the overall inclination of the isopycnals associated with an outflow of intermediate waters forcing the deep waters to overflow mainly in the west); we conclude that the S maximum should probably be in the EMDW layer and not in the LIW layer. Though EMDW then cascades in the southern Tyrrhenian and mixes with the MWs resident there to form TDW, the S maximum could probably be an "original characteristic" of TDW that should be maintained and even reinforced all across the western basin up to the Strait of Gibraltar. Indeed, whatever the variability of the upper waters (AW, WIW and LIW) will be in the western basin, mixing there will create another S maximum that will move downwards, possibly across the TDW layer and somehow merging with the TDW original one. This merging would help to explain why fairly large S values are found at fairly large depths that are much deeper than the LIW core in the Strait of Gibraltar. Here, as shown by Figure 3, one cannot demonstrate whether or not the θ maximum actually characterizes the upper part of the LIW layer. However, apart from any assumption, Figure 3 definitively demonstrates that the S maximum in particular cannot be used to delimit the lower part of the LIW layer. The Channel of Sicily and the Strait of Gibraltar are clearly the most suitable locations where dedicated observations as well as more sophisticated calculations and actual numerical simulations could be performed in order to check our hypothesis that the S maximum at least can be found at much greater depths than that of the LIW layer lower limit.

In order to fabricate some constructive ideas about the mechanism for specifying such a limit and initiating some thinking, let us make some general comments.

When considering the theoretical case of mixing between two and even three water types that are available in infinite amounts, any resulting mixed water can be precisely characterized in terms of percentages of this or that water type. Provided there is an agreement to infer an interface between two water types from some specific percentage (which should be 50%), such an interface could be precisely specified. When at least one water type is available in limited amounts, or in the case of mixing between two and even three water masses (defined by more or less large θ and S ranges), percentages can hardly be calculated precisely, and much less thicknesses.

Now, we also need to examine the commonly held notion that LIW "participates in the formation of both EMDW and WMDW". This notion implies implicitly that the amount of LIW decreases continuously along its course, so the LIW amount at Gibraltar (in particular) should be much lower than the initial LIW amount just downstream from its zone of formation in the Levantine region. Even without considering Figure 3 and the fact that LIW would still occupy a fairly large percentage of the strait section regardless of how it is delimited (from the θ and S maxima), this notion forgets the fact that "both EMDW and WMDW participate in the mixing of LIW", evidenced by the continuous smoothening of the "scorpion-tail" image. For instance, if a molecule of LIW (i.e. one that was initially a molecule of AW before sinking in the Levantine sub-basin) comes to sink in the deeper part of the western basin (then becoming a molecule of WMDW), other molecules of AW, or WIW, or TDW or WMDW that were resident in the Liguro-Provençal sub-basin have been entrained in the LIW flow and thus became molecules of LIW. Attempting to locally quantify a water amount from a specific set of measured parameters will thus always be fuzzy.

Another common misunderstanding concerns the future of a water mass once it has been created, for example, as an MW when identified at an intermediate or deep level by fairly large S values in particular. It is important to note that though MWs are not only saltier, but also cooler than AW, S is still a parameter of greater reliability than θ since i) it is directly related to the functioning of the sea (the "E-P-R" budget) contrary to the sensible heat for instance, and ii) S(AW) displays less seasonal variability than θ(AW). This idea is apparently supported by the historical bulk analyses that have assumed the conservation of salt in the sea, but not the conservation of heat. This assumption, relying on the conservation of salt, can only be accepted over fairly long time scales since S(AW) displays a huge yearly variability (Millot 2007). Therefore, what could be the future of such a MW? It cannot continuously mix with AW, which would consist in injecting salt in AW from which all MWs are formed, thus forming MWs that are saltier and saltier, and hence denser and denser over years. It cannot be entirely involved in the formation of another MW, just because it can be identified only if it occupies an area much larger than any zone of dense water formation, so such a total transformation can hardly be envisaged. Therefore, a MW can either strongly mix with other MWs to the point of being no longer identified or it can continue being identified although more and more mixed with surrounding MWs until it outflows through either the Channel of Sicily or the Strait of Gibraltar. In other words, if the MWs are more or less mixed together, then the salt amount of the MWs formed must equal the salt amount of the MWs outflowing (and overflowing), which is the only way to maintain a constant salt content in the sea. Because the MWs do not evaporate, the conservation of salt concept implies the conservation of volume, hence an outflow of all the MWs that have been formed, obviously over "fairly long time scales".

Therefore, in practical terms, the ability to accurately delimit any MW (as well as any water … anywhere!) is clearly impossible and dealing with water amounts might be possible only with the specification of postulates. For instance, one postulate could be that "once an MW, or a set of MWs that cannot be easily separated from each other near the place where they are formed, have been identified within the sea, then they must eventually outflow through either the Channel of Sicily or the Strait of Gibraltar; in other words, if a given MW represents N% of the MWs formed, it must still represent N% of the MWs outflowing". Such a postulate, which is far from the possibility of being validated experimentally, might first be tested with numerical simulations.

In the interim, when trying to specify what kind of data analysis could improve the use of the θ and S maxima, we can note that, according to both the available data set (as illustrated by Fig. 2) and our own simple calculations (Figs 4 and 5), the mixing of LIW with the waters above and below (with lighter and denser waters) does not necessarily lead to a marked change in the density associated with the "scorpion-tail" image. Suitable data, such as a continuous monitoring of the LIW core values alongslope south of Crete, are lacking but it is obvious that LIW (like any other MW) is formed year after year with variable characteristics. We do not have precise data or even ideas about either the speed of the LIW vein as a density current or the intensity of the mixing it encounters along its course. But it is conceivable that the LIW core could, more or less, maintain its initial potential density (near 29.05 $kg.m^{-3}$) in the formation area until the Channel of Sicily and even the Strait of Gibraltar.

Therefore, it could be postulated that the average potential density that is representative of some heat and salt content associated with a given MW (as well as with all MWs) would have to be maintained up to the Strait of Gibraltar since MWs do not evaporate and only mix together up to this point (beyond that point, mixing with AW of each of the MWs (Millot 2009, in press) is so intense that such postulates could no more be made). As an example, we have been analysing the 1985-1986 GIBEX data set and have found that defining LIW by any part of a given diagram that shows a "scorpion-tail" image in the density range 29.0-29.075 $kg\ m^{-3}$ gives LIW a reasonable amount and realistic distributions (Millot, in press). The same can be said for the other MWs associated with different characteristics/images (e.g. a θ minimum for WIW, a θ lower than a given value for WMDW, etc.). Valuable comparative studies between different places and/or during different seasons could be made for most of the MWs considering the density ranges associated with a characteristic image on a θ-S diagram. A proposal just considering the density range has already been made for LIW (range 28.95-29.10 $kg\ m^{-3}$) by e.g. Lascaratos and Nittis (1998).

However, actual numerical simulations must be performed that would require prior dedicated observations. For instance, mixing on the vertical (as well as on the horizontal) is certainly dependant on the density gradient and velocity shear … but to date, who is there who has ever tackled the problem in the Mediterranean Sea, a fortiori where the MWs are mainly circulating, which is alongslope in the northern part of the sea? Also, when considering the vertical shear, one must not only take into account the shear between overlying layers, but also the shear within one layer that one tends, more or less correctly, to associate with a core that would propagate faster than the outer part of the layer, thus providing a feed of new water larger in the core than out of it. In our opinion, if such a feeding were important, it would lead to sharper θ-S diagrams than the observed ones; because the latter are not so badly reproduced with our oversimplified assumptions, it might not be necessary, at least in the first step, to consider the complex problem of feeding.

Regardless of what new information becomes available in the future from more suitable data sets and numerical simulations, it seems to us at the present time that papers only describing LIW qualitatively with "its"/the θ and S maxima will just have to be read differently. Indeed, these maxima are actual features that just need to be decoupled from LIW itself because, in most cases, LIW in fact lies in between them. But quantitative conclusions obtained by those papers that deal with calculations involving LIW amounts in terms of percentages of volume, salt or heat contents will necessarily have to be reconsidered dramatically.

In this paper, we have argued that, once an MW has been identified in a basin (even if it can no longer be identified in either the Channel of Sicily or the Strait of Gibraltar), then it must be assumed to outflow and not to continuously increase the salt content in that basin. In a case in which several intermediate or deep MWs are formed in a single basin (which is especially the case of the eastern basin) but can no longer be differentiated when outflowing, then they must be defined in either the Channel of Sicily or the Strait of Gibraltar by a generic name. This has already been done for the deep waters outflowing from the eastern basin with the use of EMDW. Similarly, we would argue that, downstream from the Channel of Sicily where not only LIW but also at least CIW outflows, then the name of the intermediate waters that issue from the eastern basin must also be reconsidered. To remain consistent with the definition of WIW, the Western Intermediate Water (CIESM 2001), as has already been done for the deep waters (i.e. EMDW vs. WMDW even though the M is redundant since we are in the Mediterranean Sea), we suggest that the correct name for the intermediate waters outflowing from the eastern basin should not be LIW but should be the Eastern Intermediate Water (EIW).

Based on our knowledge of the sea characteristics, on our understanding of the sea functioning, on our experience of sea working conditions and on our feelings about the capabilities of the sensors we have and can develop, we believe that research in this area would benefit from at least two new approaches. One approach arises from the obvious fact that it will always be difficult, if not impossible after a while, to accurately delimit any water in any part of the sea by only looking at a set of measured parameters such as θ and S, just because of the permanent mixing of that water with surrounding waters. Postulating that any intermediate or deep water (or even set of waters) should keep their original heat and salt content regardless of whatever mixing they undergo along their course could allow the association, with that water or set of waters, of spatially integrated θ and S values, together with a given characteristic figure on a θ-S diagram and/or a given density range. Even though dedicated simulations have yet to be performed, it seems likely that this approach would at least allow quantitative comparisons to be made between contemporaneous data sets collected in different places of the sea. A second approach consists in extending to the Strait of Gibraltar the same concept that is now clearly accepted for the Channel of Sicily: namely that the eastern basin forms both intermediate and deep waters or sets of waters. The western basin also forms its own intermediate and deep waters in a zone that is not too far upstream from the strait and it could well be that these waters cannot entirely mix with those from the eastern basin before entering the strait. The challenge, though, could lie in trying to collect additional data and in performing dedicated simulations to check whether two intermediate and two deep waters or sets of waters can still be differentiated in the Strait of Gibraltar (as we claim) or not.

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