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4 The LIW characteristics: an astounding general misunderstanding!

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6 Claude Millot

7 Laboratoire d'Océanographie Physique Biogéochimique

8 Antenne LOPB-COM-CNRS de La Seyne/mer, BP 330, F-83150

9 f4eut@winlink.org and ailesetiles@gmail.com

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11 Abstract

12 The Levantine Intermediate Water (LIW) is the warmest and saltiest water resulting
13 from the dense water formation processes that occur in several zones of the Mediterranean
14 Sea. When LIW spreads away from the Levantine subbasin its core appears as a relatively
15 sharp peak on a temperature-salinity diagram. Then, while LIW is circulating and mixing with
16 surrounding waters, the peak smoothens, thus often leading to a temperature (salinity)
17 maximum above (below) the core. Both maxima have always been considered as LIW
18 characteristics in all papers (including ours) without, to our knowledge, having never been
19 analyzed theoretically. Simple computations demonstrate that i) these maxima are due more
20 to the waters above and below LIW than to LIW itself, so that they are evolving in variable
21 ways, and ii) these maxima generally tend to move out of the LIW layer, hence having given
22 to LIW an importance much larger than it actually has. We thus conclude that, theoretically,
23 these maxima cannot characterize LIW in any indubitable way. As inferred from data
24 collected at Gibraltar, nothing can be demonstrated for the θ maximum but, definitely, the S
25 maximum cannot be considered as a LIW characteristic. Characterizing LIW might be
26 possible only by associating, year after year, a specific density (near 29.06 kg.m^{-3}) with the
27 LIW core and a specific density range with the LIW thickness.

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30 1. Introduction

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32 The aim of this paper is to present a simple idea about the so-called "Levantine
33 Intermediate Water (LIW) characteristics", not to deal with these characteristics themselves.
34 If we are right, the results presented in all previously published papers (including ours) would
35 have to be questioned, in particular those papers dealing with LIW amounts, especially at
36 Gibraltar. We have thus found useless to cite contemporaneous papers dealing with the so-
37 called LIW characteristics and we just mainly cite those of ours papers that deal with the
38 functioning of the Mediterranean Sea, the LIW circulation in both the eastern and the western
39 basins and some general features at Gibraltar.

40 The water deficit in the Mediterranean Sea ($O(1\text{m/yr})$ due to evaporation exceeding
41 precipitation and river runoff) leads to an inflow of Atlantic Water (AW) that circulates as a
42 density current in the sea, hence alongslope counterclockwise (see Fig.1,2 of Millot and
43 Taupier-Letage, 2005a). AW thus circulates first in the southern parts of both the western and

1 the eastern basins, which are relatively arid regions off Africa, so that its salinity (S)
2 continuously increases eastwards all year long while its potential temperature (θ) fluctuates
3 seasonally. When arriving in the northern parts of both basins, wintertime air-sea interactions
4 with cold and dry air masses blown by violent northerlies mainly cool AW up to increasing its
5 density so much that it sinks through dense water formation processes in four major specific
6 zones (located in Fig.1), either in the open sea (convection) or on continental shelves
7 (cascading). Roughly, and a priori in any of these four zones, AW can be either only cooled,
8 hence forming intermediate waters, or it can be mixed with the waters below, hence forming
9 deep waters. Once formed, these Mediterranean Waters (MWs) spread from their formation
10 zones as density currents as long as they are not trapped in a specific basin or subbasin; in
11 such a case, which practically occurs only for the deep MWs, their upper part can outflow
12 only when uplifted by denser waters.

13 In fact, incoming AW is sucked towards these zones where dense waters tend to sink,
14 and it arrives there with different characteristics. For instance, AW arrives in the north of the
15 eastern basin with S values much larger than when it arrives in the north of the western basin,
16 just because of a longer stay in the southern arid regions off Africa. Then, in the eastern basin
17 and while flowing westwards after the Levantine subbasin (towards the two other zones of
18 dense water formation in the Aegean and the Adriatic), AW mixes with major freshwater
19 sources, such as the Black Sea or the Pô river, that reduce its salinity. Therefore, it is clearly
20 when arriving in the Levantine that S(AW) is the largest. Roughly, a direct consequence is
21 that wintertime cooling of such salty water does not need to be very intense to have it sinking,
22 which explains while LIW, the intermediate MW formed in the Levantine, is both salty and
23 warm. Another intermediate MW is formed in the Aegean subbasin (CIW, the Cretan
24 Intermediate Water; to our knowledge no intermediate MW has been said to be formed in the
25 Adriatic) but, maybe partly because it has less specific characteristics, it cannot be followed
26 easily. On the contrary, the Winter Intermediate Water (WIW, formed in the Liguro-
27 Provençal) is clearly identified at Gibraltar (just above LIW) by a θ relative minimum (Millot,
28 2009). Deep MWs mainly formed in the Aegean and the Adriatic are no more differentiated
29 when outflowing through the channel of Sicily (where they are generally called EMDW, the
30 Eastern Mediterranean Deep Water) before cascading in the Tyrrhenian, hence forming TDW
31 (the Tyrrhenian Dense Water, Millot (1999)) that will be identified together with WMDW
32 (the Western Mediterranean Deep Water formed in the Liguro-Provençal) at Gibraltar too.
33 Note that deep MW has already been reported to be possibly formed in the Levantine, but this
34 does not seem to be actually supported by the specialists of the place.

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36 2. The LIW characteristics

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38 It can thus be considered that both the eastern and the western basins form an
39 intermediate MW and a deep MW, all four MWs been almost easily identified at Gibraltar:
40 WIW (from the Liguro-Provençal), LIW (from the Levantine), EMDW/TDW (from both the
41 Aegean and the Adriatic) and WMDW (from the Liguro-Provençal). To better understand i)
42 the specificity given to LIW by its relatively large θ and S values, ii) its necessary implication
43 in the formation of all deep MWs as well as iii) its mixing with either AW or the other MWs,
44 let us first describe our own view of its circulation (Fig.1). This view was first presented for
45 the western basin in Millot (1987a,b), in total opposition to the pioneering view of Wüst
46 (1961) to which most other papers have continued referring for a while, at least till the late
47 90's. This view seems to be widely accepted nowadays (Schroeder et al., in press).

1 We illustrate here below the description of the LIW mixing and circulation with a
2 selection of θ -S diagrams (Fig.2) inferred from CTD profiles that can only provide a rough
3 idea of the LIW signature and cannot be linked to each others since they have been selected in
4 an almost particular way. We first selected in the MEDATLAS data base (MEDAR Group,
5 2002) areas of $\sim 1^\circ$ longitude by $\sim 1^\circ$ latitude covering the continental slope in some specific
6 areas indicated by the coloured triangles in Fig.1. We then extracted the available data and
7 selected the largest CTD files, i.e. the campaigns during which the largest number of data has
8 been collected, just hoping to find a larger choice of θ -S diagrams aimed at illustrating our
9 description; we thus chose data collected in different years. Some of these files obviously still
10 have numerous errors, others display strange (at least) values and we rejected others that
11 seemingly represent abnormal situations; most of our criteria are thus very subjective. The
12 MEDATLAS data base only contains in situ temperatures, so that we then had to compute θ
13 (and σ_θ , the potential density anomaly) before plotting θ -S diagrams, as well as $\theta(z)$ and $S(z)$,
14 and selecting profiles; since we have limited computational capacities, this represents for us a
15 relatively important work that we cannot perform in an exhaustive manner. We decided to
16 select two profiles per area, not to give an overview of the variability, which would have
17 necessitated a huge dedicated analysis, but just to prevent the reader from associating a
18 specific profile to a given area; we stopped our selection as soon as we found two
19 "convenient" profiles. For all these reasons, the θ -S diagrams in Fig.2 cannot be used for any
20 in depth analysis.

21 Before describing the LIW circulation and signature, let us just make a remark about
22 the nature of the AW and MWs density currents, their links with the dense water formation
23 zones and their implication in the functioning of the sea, all features that are important to
24 better understand the role of LIW and the consequences on its θ -S signature. Dense water is
25 formed where wintertime northerlies are blowing from the land to the sea, hence roughly in an
26 on-offshore direction, so that dense water should be mainly formed by convection in the
27 coastal zone (this is obviously the case for cascading). However, just because of geostrophic
28 adjustment, dense water tending to sink sucks surface water (AW) that tends to flow
29 cyclonically around the zone where dense water is sinking, hence in particular between that
30 zone and the coast. Because such a geostrophic adjustment, hence the dense water sinking,
31 has a time scale larger than one year, largest surface densities at the beginning of a given
32 winter are thus found offshore, which will then be where convection will preferentially occur.
33 But all other waters (AW and the MWs formed in other zones upstream) naturally tend to
34 flow alongslope, hence between the continental slope and this specific zone of convection, so
35 that at least a part of each of them will necessarily be involved in the formation of the deep
36 water in that specific zone. Another major consequence is that surface currents do not
37 necessarily surround the zones of convection, hence do not form the so-called "gyres". In
38 particular in the eastern basin, the Asia Minor Current (the AW westward flow along the
39 southern Turkish slope) is sucked not only towards the Levantine, but also towards the
40 Aegean and the Adriatic, so that it is only a part of it that will be involved in the LIW
41 formation and only a part of this part that will tend to flow cyclonically around its zone of
42 formation; whatever the case, the gyre that could thus be formed would be markedly
43 dissymmetric and much intense alongslope than offshore.

44 In its zone of formation of the Levantine (patch of several light grey profiles in Fig.2),
45 LIW can hardly be isolated from the waters above and below. We rely on papers such as e.g.
46 Theocharis et al. (1999) who say that it lies below AW, forming a 50-600-m thick layer with
47 θ in the range 14.70-16.95 $^\circ\text{C}$ and S in the range 38.85-39.15. In the following, we thus
48 assume nominal values for LIW in its formation zone of 15.0 $^\circ\text{C}$ and 39.0, which are then the
49 maximum values in most θ -S diagrams hereafter. Deep values there, as well as in the other

1 areas of the eastern basin, indicate EMDW. As for all other MWs, LIW first amasses in its
2 formation zone that must be considered as a reservoir that will be refurbished, year after year,
3 by slightly different water and from which LIW will continuously spread as a density current,
4 hence tending to form a vein flowing alongslope counterclockwise (Fig.1).

5 Part of it will penetrate through the deep Cretan straits into the Aegean and part of this
6 part will thus be involved in the formation of the Aegean Deep Water, the remainder
7 outflowing from the Aegean with more or less modified characteristics. The other part will
8 follow the continental slope south of Crete and it is there (red profiles in Fig.2) that
9 identifying LIW by a sharp peak is the easiest; however, note that i) the θ , S and σ_θ values
10 associated with the peak display a relatively large variability and ii) specifying a LIW
11 thickness is far from being obvious. Also note that a part of that part can be entrained offshore
12 by the Ierapetra and Pelops anticyclones that are generated every summer by the Etesians
13 before being released in the basin interior and forming a somehow background of non
14 circulating LIW (see similar comments for the Algerian subbasin). LIW flowing off the
15 Peloponnese (brown profiles) thus forms a recomposed vein that has already markedly
16 modified and variable characteristics but that can be recognized near $\sigma_\theta = 29.06 \text{ kg.m}^{-3}$ by an
17 almost truncated-peak shape; it might be there that the interfaces between LIW and the waters
18 above and below could be defined in the more accurate manner as relatively strait mixing
19 lines (see section 3).

20 The internal part of the LIW vein (the one closest to the slope) will then penetrate into
21 the Adriatic with consequences similar to those in the Aegean for the formation of the
22 Adriatic Deep Water, while its external part will skip the Adriatic so that LIW flowing off
23 southern Italy is still composed of parts having had different circuits, hence having different
24 characteristics and leading to a significant spatio-temporal variability. The orange profiles in
25 Fig.2 thus still indicate a relatively heterogeneous LIW and have a relatively sharp shape that
26 could make identification of LIW still not too difficult. Then LIW follows the slope around
27 Sicily where no dramatic processes occur, so that continuous mixing with surrounding waters
28 gives relatively smooth profiles in magenta (continuous lines) on the right hand side of the
29 channel (off Sicily) where LIW is mainly located. The initial peak near $14.5\text{-}15.0^\circ\text{C}$ and 38.9-
30 39.0 encountered south of Crete that was still identified in the northern Ionian by relatively
31 sharp shapes is now very smoothed and the LIW core can no more be located. Instead, the
32 sole identifiable characteristics of the diagrams are θ and S maxima, so that a link has always
33 been made between these maxima and the LIW vein. However, note that profiles on the left
34 hand side of the channel (off Tunisia, dashed magenta lines), have specific differences and
35 similarities. They are different in their upper part since LIW is not outflowing there but they
36 are similar in their lower part where they evidence EMDW since it is the water mainly
37 outflowing there, being pushed away from Sicily by LIW (Millot and Taupier-Letage, 2005a).
38 One conclusion is that EMDW is outflowing also on the right hand side of the channel below
39 LIW. But the other conclusion is that the S maximum, which appears all across the channel,
40 can hardly be associated with LIW.

41 Since the channel of Sicily is relatively wide and deep, LIW does not have to
42 markedly modify its immersion while crossing it and, contrary to EMDW, LIW does not
43 markedly cascade in the Tyrrhenian. Furthermore no major processes occur in that subbasin,
44 profiles are still relatively smooth and not very different from central Italy (violet) to southern
45 Sardinia (dark green) where most of the LIW vein flows while part of it crosses the channel of
46 Corsica. In the Tyrrhenian, LIW is generally located just below AW, which makes still
47 difficult if not impossible (as often in the eastern basin) the identification of a θ maximum
48 while an S maximum can always be identified. When entering the Algerian, LIW is eroded
49 from time to time by mesoscale Algerian eddies that are generated by instability processes off

1 Algeria and filaments are entrained in the subbasin interior; the dedicated study by Millot and
2 Taupier-Letage (2005b) is very demonstrative and could probably be directly applied to the
3 Ierapetra and Pelops regions. In the Ligurian (light green profiles), LIW starts flowing below
4 the locally-formed WIW, which is characterized by a relative θ minimum, so that a θ
5 maximum automatically reappears ... without providing any specific information about the
6 LIW upper limit. There and in the Provençal, LIW is involved in the formation of deep water
7 (WMDW) as it has been in both the Aegean and the Adriatic.

8 Roughly similar profiles just modified as a consequence of mixing are generally
9 encountered in the western Balearic (cyan), the northern Alboran up to the entrance of the
10 strait of Gibraltar (blue) as well as off western Algeria (grey). There, the smooth peak is due
11 to both some part of the LIW vein entrained away from the Spanish slope by AW when it
12 forms the Almeria-Oran jet, and to the filaments entrained offshore from southern Sardinia by
13 the Algerian eddies; even though data are lacking, we hypothesize that similar profiles should
14 be encountered for similar reasons in the south of the eastern basin. Now, it must be
15 emphasized that on the two cyan profiles we selected (by chance), the θ and S maxima spread
16 at depths of 290-360 m, but no more than 20 m apart. On the contrary, on one of the blue
17 profiles the maxima (at 330-380 m) are 10-40 m apart while, on the other, the maxima (at
18 370-510 m) are 100-120 m apart. Similar variability is observed for the grey profiles with
19 maxima (at 260-400 m) that are 140 m apart on one profile and maxima (at 340-420 m) that
20 are 50-80 m apart on the other profile. This just illustrates the huge temporal variability in
21 these characteristics that must be expected at any place in the sea. Be these characteristics
22 directly associated with LIW or not, the veins of all MWs, and in particular LIW that
23 performs the longest course in the sea, can be involved in so many dramatic processes that
24 they get a necessarily complex and extremely variable signature. At Gibraltar, it is thus
25 illusory to look for any original seasonal signal of LIW in particular.

26 The overall impression one gets when considering this series of θ -S diagrams is that,
27 apart from the Ionian where they display relatively sharp shapes that can probably be
28 assimilated with interfaces, hence giving a relatively accurate definition of the LIW core and
29 thickness, dramatic changes occur from the channel of Sicily. Mixing leads to a much
30 smoothed peak and one is (we all have been!) tempted to assimilate the tangents to the
31 diagrams at both the θ and S maxima with mixing lines, perversely leading to use these
32 maxima as some indication of the LIW thickness, never saying however exactly how and
33 why! Note that within the sea, the variability of the waters encountered above and below LIW
34 necessarily modifies the shape of the θ -S diagrams, in particular the occurrence and
35 immersion of the θ and S maxima. Therefore, any definition of the LIW thickness based on
36 these maxima will lead to values depending on the surrounding waters variability. Whatever
37 the case, and since "there is plenty of space" within the sea, defining the LIW thickness with
38 the θ and S maxima (i.e. with a few 100s metres accuracy) does not have major consequences.

39 This is more hardly acceptable at Gibraltar since all other MWs, i.e. (and at least)
40 WIW, TDW/EMDW and WMDW (see Millot, 2009, submitted), necessarily have to outflow
41 there, i.e. through a restricted section so that, even though specifying the limits of each of
42 them is not an easy task, such limits must be more accurately specified. Figure 3 shows that
43 the AW-MWs interface, which must actually be associated with the depth of the largest $\sigma(z)$
44 gradient that appears to be very similar to that of the largest S(z) gradient, can be satisfyingly
45 associated with given isotherm and isohaline in the eastern part of the strait, at least during the
46 two valuable GIBEX campaigns we have been analysing. Now, specifying the interfaces
47 between the various MWs, in particular those delineating LIW, has been done up to now from
48 the θ and S distributions only and one can wonder how this has been made. Considering that

1 LIW is limited by the θ and S maxima (red dots) leaves enough place above and below for the
2 other MWs. However, the immersion of the θ maximum implies that there is another MW
3 between LIW and AW, which is actually WIW that has never been considered up to now; and
4 the immersion of the S maximum implies that the MWs below (TDWd and/or WMDW) are
5 relatively salty. One can also consider the isothermals (isohalines) that define the intermediate
6 θ (absolute S) maximum in orange. The θ maximum has a relatively limited extension and,
7 even though we cannot demonstrate whether or not it actually characterizes the upper part of
8 the LIW layer, it leaves enough space for the WIW above, both waters outflowing on the right
9 hand side of the strait. However, the S maximum appears to regularly spread downwards,
10 which does not depend on the fact that S is an absolute maximum since one could have
11 expected a much variable S(z) gradient there, maximum values of that gradient hence possibly
12 delineating LIW. And associating "relatively large" (???) S values with LIW do leave enough
13 room for neither TDW/EMDW nor WMDW that have to outflow below and mainly on the
14 left hand side of the strait. Therefore, there are objectively no arguments supporting a link
15 between LIW and any characteristics of the S distribution below the S maximum so that one
16 wonders how isohalines can be (could have been!) used to delimit the LIW lower part! If
17 possible, other criteria have thus to be specified (see Millot, submitted). This analysis about
18 Gibraltar, together with the realization that we accepted, as a student, an idea without having
19 ever criticized it, motivated the study hereafter.

20

21 3. Simulation of the LIW mixing

22

23 Our simulation being made with Excel-type computations is as simple as possible.
24 Being especially interested by the evolution of the LIW characteristics as a consequence of
25 mixing with the surrounding waters, namely A (above) and B (below), we first consider a
26 LIW of limited thickness in between relatively thick A and B layers; but we also considered
27 A, B and LIW layers having the same thickness (see below). More precisely, we consider a
28 LIW layer of 9 depth units while both A and B have 50 depth units. We then simulate the
29 mixing just by averaging (running mean over 7 depth units), at each time step t, the θ and S
30 profiles. These specific numbers of depth units (9, 50, 7) were chosen in order to have i) an
31 easy location of the mixed value (7 is odd) and of the LIW core (9 is odd), ii) the core of the
32 LIW layer (at depth level 55) not modified yet at time step one ($9 > 7$, more precisely level 5 in
33 the LIW layer (the core) > 3 , the number of levels in that layer modified by the mixing with
34 either A or B at $t=1$), iii) a significant evolution of the profiles, hence a significant change in
35 the location of the θ and S maxima, within a reasonable number of time steps (columns in our
36 Excel file), iv) the A and B layers not totally modified by mixing during the analysed period
37 of time (to make the analysis as simple as possible). In Fig.4, number N=1 actually
38 corresponds to the first time step ($t=1$) but, for practical reasons, the other numbers (N=2-5)
39 correspond to time steps $t=5(N-1)$. Note that it is only at the beginning of the mixing process,
40 i.e. when the A-LIW and B-LIW gradients are still relatively large, that the mixing penetrates
41 in the A and B layers by 3 depth units at each time step. Practically, two-digit numbers for the
42 θ and S values are modified only over ~ 20 (~ 10) levels by $\sim 1\%$ ($\sim 10\%$) in the A and B layers
43 at time step $t=20$ (N=5) instead of 60 levels (tx3). Even though one can estimate the depth
44 unit to a few tens of m (40-50 m), we are totally unable to quantify such a time step. Let us
45 just emphasize that reducing the time step and/or the mixing intensity, i.e. reducing the
46 number of averaged depth units (7), will not change basically the results that are obtained
47 from computations as simple as possible.

1 Figure 4a represents what we think is the more general case in the western basin at
2 least, i.e. with the water above (A) being relatively cool and the freshest while the water
3 below (B) is relatively fresh and the coolest. The specific θ and S values we have chosen, as
4 well as the axes scales give to the diagrams a relatively symmetrical shape; this has no
5 specific importance and the diagrams in Fig.5 are plotted with the same scales. The diagrams
6 show that, at $t=1$ ($N=1$), the LIW core is still unmixed while the upper (lower) parts of the
7 LIW layer mix, along the classical mixing lines, with water A (B), so that both the upper and
8 lower parts of the LIW layer are cooler and fresher than the core. Understanding the overall
9 evolution of the LIW characteristics during the other time steps ($N=2,5$) is made simple when
10 considering that the LIW core, on this example, is always more cooled by B than by A, which
11 is even more the case for the LIW lower part, so that largest temperatures are found more and
12 more upwards. The same argument applies for the freshening: the core is more freshen by A
13 than by B, which is even more the case for the LIW upper part, so that largest salinities are
14 found more and more downwards. What appears (although this could have been easily
15 intuited) as a fundamental result is the fact that the θ (S) maximum i) "easily" crosses the A-
16 LIW (LIW-B) initial interface and ii) continues moving regularly upwards (downwards). It is
17 obviously essential to consider that, whatever the mixing, each layer, in particular LIW, must
18 keep its initial thickness; otherwise, this would give (has given!) to a water having specific
19 non-dynamical (θ and S) characteristics an importance not at all justified from a dynamical
20 point of view. All these results are made more explicit by Fig.4b,c.

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

28 Figure 5b shows the case of thick layers having the same S(B), hence named A' and B.
29 The LIW core being freshen in the same way from above and below, it is always associated
30 with the S maximum. More generally, freshening (in the LIW layer) and salting (in the A' and
31 B layers) being symmetric with respect to the LIW core level, S profiles are symmetric with
32 respect to this level. The LIW layer is much less cooled by A' than it is by A, so that the θ
33 maximum moves more rapidly upwards towards A' (Fig.5b) than it moves upwards towards A
34 (Fig.4a). Figure 5c shows the symmetric case with water A and water B' having the same
35 $\theta(A)$; with similar arguments, it appears that θ profiles are symmetric with respect to the LIW
36 core that is thus associated with the θ maximum while the S maximum moves rapidly towards
37 B' (saltier than B).

38 Figure 5d shows the case of water A'' warmer and saltier than water B; in such a case,
39 both the θ and the S maxima move upwards and out of the initial LIW layer leading to a total
40 uncoupling between the initial LIW layer and a layer that would be associated with the θ and
41 S maxima. With water B'' warmer and saltier than water A (Fig.5e), similar results are
42 obtained with both maxima moving downwards.

43 Finally, Fig.5f shows the case of water A''' warmer and fresher than LIW, as is often
44 the case in the eastern basin and the Tyrrhenian as well. Because of the values we considered
45 for A''' and B', the LIW core keeps the same θ ; in general, there is no θ maximum while the S
46 maximum rapidly evolves below in the B' layer.

47

4. Discussion

To our knowledge, the idea that the θ and S maxima, generally encountered in the Mediterranean Sea, especially in the western basin, were characteristics of the warm and salty LIW layer has never been checked, a fortiori demonstrated, by any theoretical simulation. The very simple one here presented thus aims at motivating reflexions and more sophisticated simulations.

We assume that everybody has had our own attitude. As a student, we got the LIW image of a "scorpion tail" on a θ -S diagram (Lacombe and Tchernia, 1960; Tchernia, 1972) that was continuously eroded due to mixing with the surrounding waters, leading to a smooth peak that could be characterized only by θ and S maxima. And, whatever the presentation given by our professors, we consider ourselves responsible for having accepted an idea without having criticized it enough.

According to our simple simulation, it appears that it is only with a core unmixed yet that straight mixing lines between LIW and the waters above and below can be associated with interfaces, hence can provide some information about the LIW thickness. Practically, this might be encountered only in the northern Ionian. But as soon as the core is mixed, hence in general as soon as a θ and S maxima appear such as in the channel of Sicily, they both migrate in general upwards and downwards, respectively, first within the initial LIW layer but then within the layers above and below. This occurs more or less rapidly according to the θ -S values and thickness of these surrounding layers and, with some specific sets of θ and S characteristics, both maxima can theoretically migrate either upwards or downwards.

Nothing can be demonstrated with the available data sets and for both the θ and S maxima in the sea since "there is plenty of space": defining a water thickness with some erroneous parameter does not have dramatic consequences. But at Gibraltar, initial amounts during the dense water formation processes must be retrieved, which can be easily validated due to the restricted section there. For instance, if LIW represents $\frac{1}{4}$ of all dense waters formed in the sea, it must still represent $\frac{1}{4}$ of the waters outflowing at Gibraltar. There, one cannot demonstrate whether or not the θ maximum actually characterizes the upper part of the LIW layer. But, definitely, associating the S maximum with LIW can no more be accepted. For the 1985-1986 GIBEX data set we have analysed, defining LIW by the density range $29.0-29.075 \text{ kg.m}^{-3}$ gives LIW a reasonable amount and realistic distributions on both sections and θ -S diagrams (Millot, submitted).

Surprisingly, mixing of LIW with the waters above and below, hence with lighter and denser waters, does not necessarily lead to a marked change in its initial density. We lack adequate data like a continuous monitoring of the core values south of Crete for instance but it is obvious that LIW is formed year after year, as any other Mediterranean Water, with variable characteristics. We do not have precise ideas about either the speed of the LIW vein as a density current or the intensity of the mixing it encounters all along its course. But, as suggested by our Fig.2, it might be that, overall, the LIW core could keep its initial density (near 29.06 kg.m^{-3}) for a while. We then could consider its thickness defined by straight mixing lines (sharp interfaces) as in the northern Ionian, and/or associated densities, and assume, as a first approximation, that this density range too is maintained all along its course in the whole sea.

Whatever the case and what will be found by more adequate studies and simulations, it seems to us that the major consequence is that all previous papers dealing in particular with the LIW amount have to be questioned. Those only describing LIW with "its"/the θ and S

1 maxima will just have to be read differently since these maxima are actual features and just
2 need to be decoupled from LIW itself. But conclusions obtained by those papers dealing with
3 computations involving LIW amounts in terms of percentages of volume, salt or heat contents
4 will necessarily have to be reconsidered.

5 To conclude, and even though we have been describing LIW in a wrong way in all our
6 papers during all our career, we are happy to have had the opportunity to demonstrate that
7 being critic is not necessarily a sign of aggressiveness but should be a major quality of all of
8 us!

9
10 Acknowledgements: I would like to thank "Mother Nature" for having provided me
11 with a brain never blindly relying on taught features, more or less fearing neither God nor
12 Man ... at least from a scientific point of view! Even though this does not facilitate friendly
13 relationships within the scientific community, I am sure this is the only attitude to have for
14 being scientifically honest and finally reaching ... "the Truth"!!

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8 9 Figures Captions.

10 Figure 1. This is essentially (manual drawing) Figure 3 of Millot and Taupier-Letage
11 (2005a); basic features in the western basin were already described by Millot (1987a-b, 1999)
12 and the thin line represents the 500-m isobath. LIW is necessarily involved in the convection
13 processes that occur in the Aegean, the Adriatic and the Liguro-Provençal subbasins. LIW can
14 be entrained offshore from its alongslope route by eddies such as Ierapetra (I), Pelops (P) and
15 the Algerian eddies (AE), leading to a signature of motionless LIW in the basins interior. The
16 parts of LIW that cannot outflow directly through the channel of Sicily and the strait of
17 Gibraltar continue circulating off Africa. The coloured triangles roughly locate the θ -S
18 diagrams in Figure 2.

19 Figure 2. θ -S diagrams selected as indicated in the text at places as indicated by the
20 coloured triangles in Fig.1. In the channel of Sicily, continuous (dashed) magenta diagrams
21 were collected on the right (left) hand side of the channel. The 29.06 kg.m^{-3} isopycnal is
22 indicated to roughly estimate the variation of the LIW core density all across the sea and with
23 a ± 0.02 interval to provide a density scale.

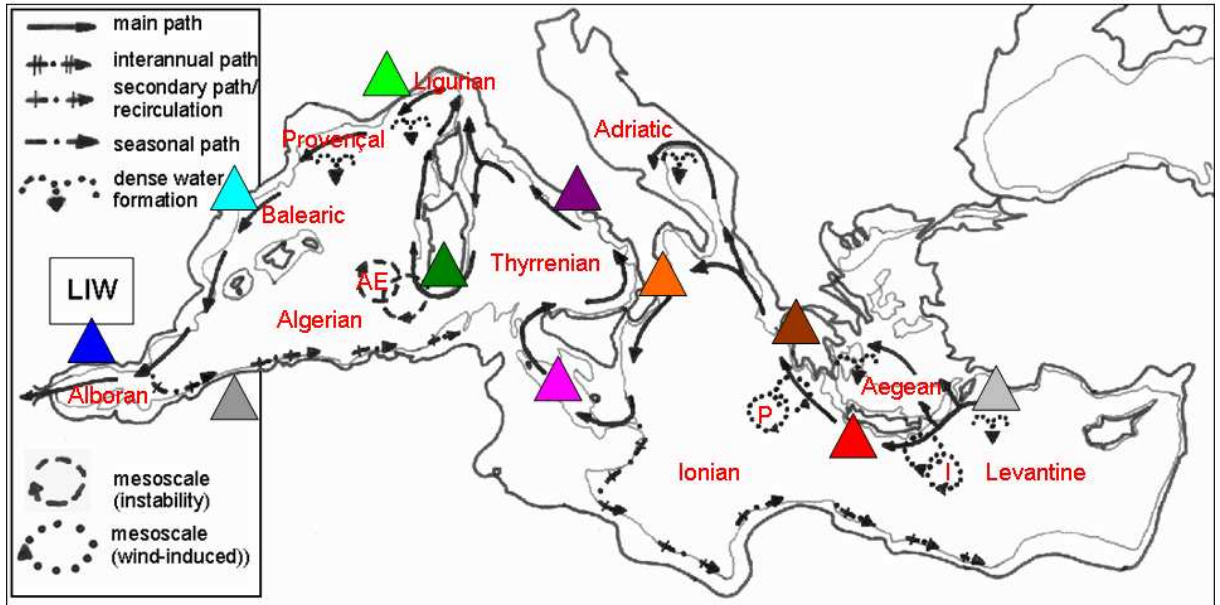
24 Figure 3. Adapted from Fig.11 of Millot (2009) and Fig.9,18 of Millot (submitted).
25 Temperature (θ) and salinity (S) sections near $5^{\circ}30'E$ during the campaigns #1 and #2 of the
26 1986 Gibraltar Experiment GIBEX conducted in March-April and September-October,
27 respectively; the CTD profiles are located by the dashed lines as a function of latitude (in $^{\circ}N$)
28 and depths are in km. The $14.0^{\circ}C$ and 38.0 isolines roughly represent the interface between
29 the AW (in cyan) inflow and the MWs outflow; this interface is more accurately defined (blue
30 line) by the largest $S(z)$ and $\sigma(z)$ gradients. In the outflow, the relative θ maxima and absolute
31 S maxima are marked by red dots; the isolines that identify these maxima are plotted with
32 thick (two-digit values) and thin (± 0.005 values) lines leading to specific ranges in orange:
33 $S1(38.435 \leq S < 38.46)$, $\theta1(13.045 \leq \theta < 13.065)$, $S2(38.435 \leq S < 38.455)$, $\theta2(12.99 \leq \theta < 13.03)$.

34 Figure 4. a) θ -S diagram for a LIW layer (9 depths units; orange) in between relatively
35 thick (50 depth units) A (green) and B (blue) layers and unmixed values indicated by the big
36 coloured points. Mixing lines between A and LIW, and between LIW and B are indicated in
37 cyan. For the 5 time steps here shown ($N=1,5$), the diagrams are indicated by the black lines.
38 The depth units corresponding to the initial upper level (51), core level (55) and lower level
39 (59) of the LIW layer are indicated by the N values in orange, hence the LIW initial thickness
40 by the orange lines; on these diagrams, it can be deduced that, for instance, the LIW core
41 density remains near 29.06 kg.m^{-3} . The θ and S maxima are indicated by the red dots. Waters
42 identified in grey are considered in Fig.5. b,c) $\theta(z)$ and $S(z)$ profiles represented as in a), and
43 A and B represented only over 20 depths units. Note that $\theta(z)$ and $S(z)$ are symmetric with
44 respect to depth unit 55 (dashed line). These profiles can be used to better describe the θ -S
45 diagrams in Fig.5.

46 Figure 5. a) as in Fig.4a for layers A, B and LIW of similar thickness (9 depth units),

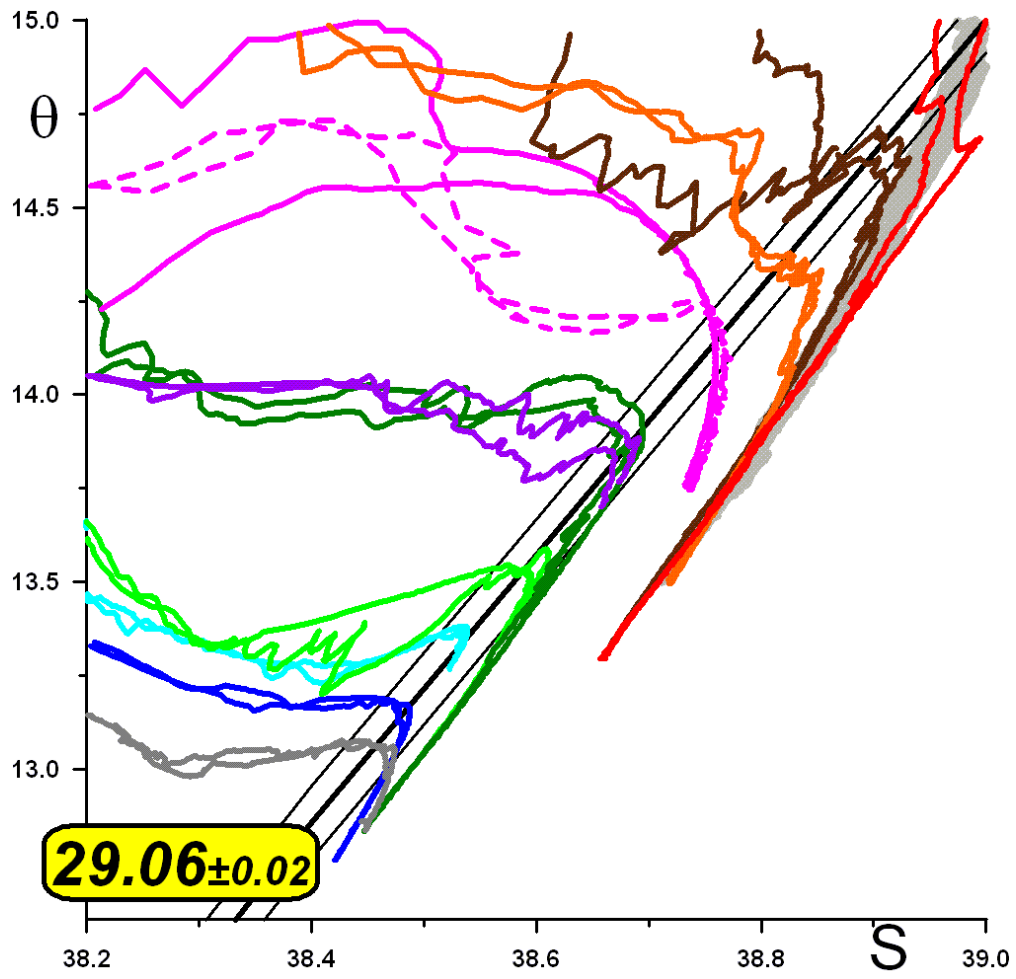
1 b) as in Fig.4a for layers A' and B, c) as in Fig.4a for layers A and B', d) as in Fig.4a for
2 layers A'' and B, e) as in Fig.4a for layers A and B'', f) as in Fig.4a for layers A''' and B'.

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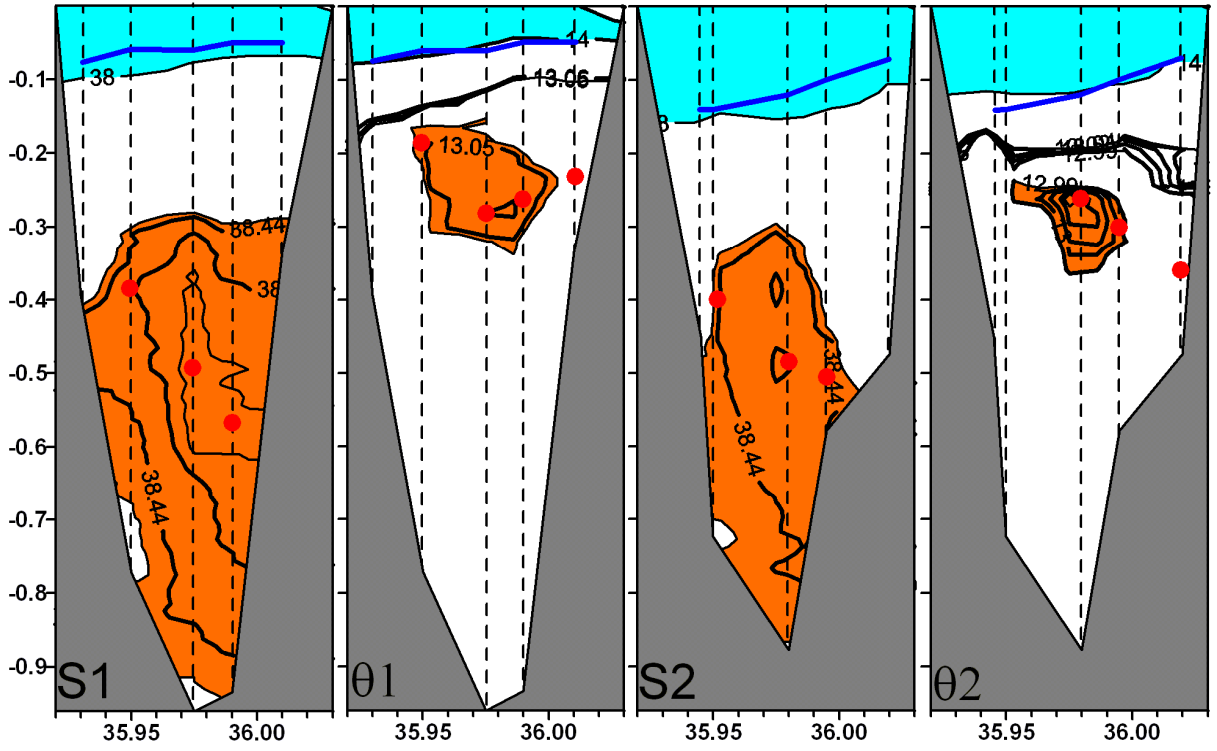
Fig.1



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Fig.2

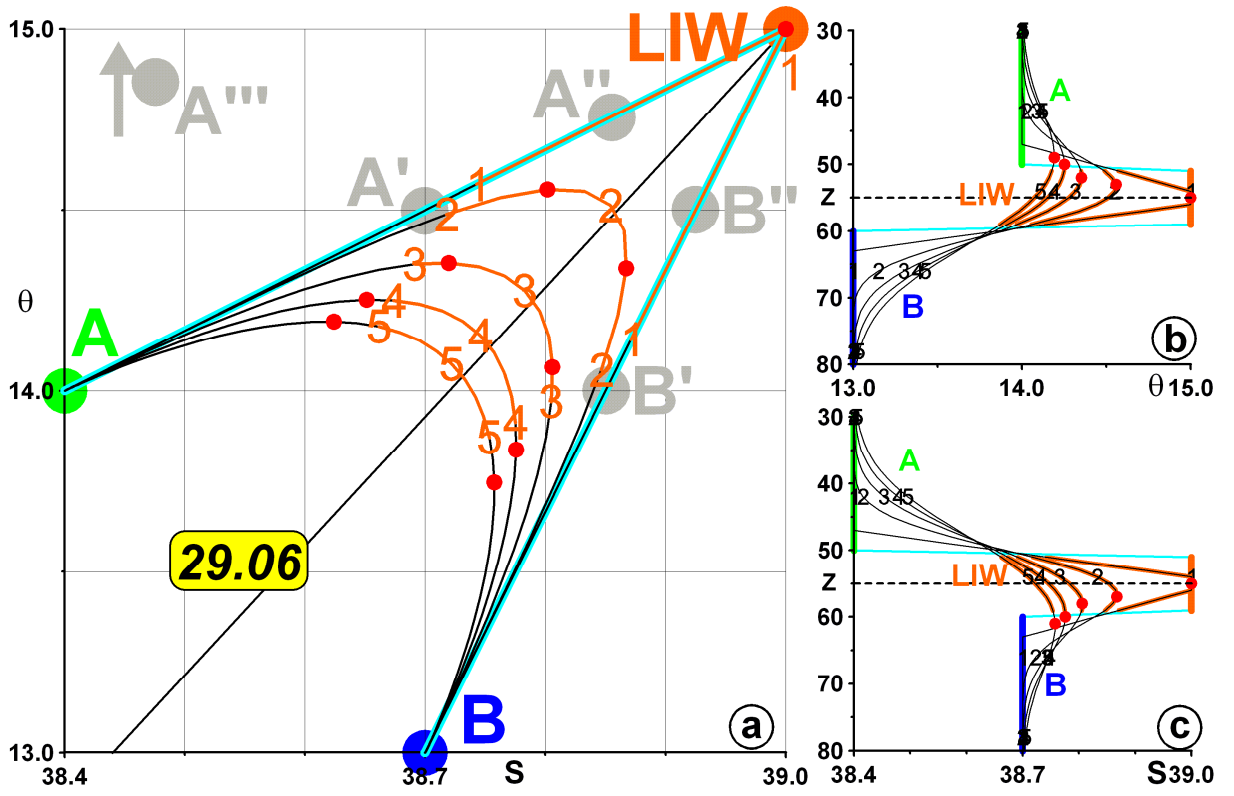
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Fig.3

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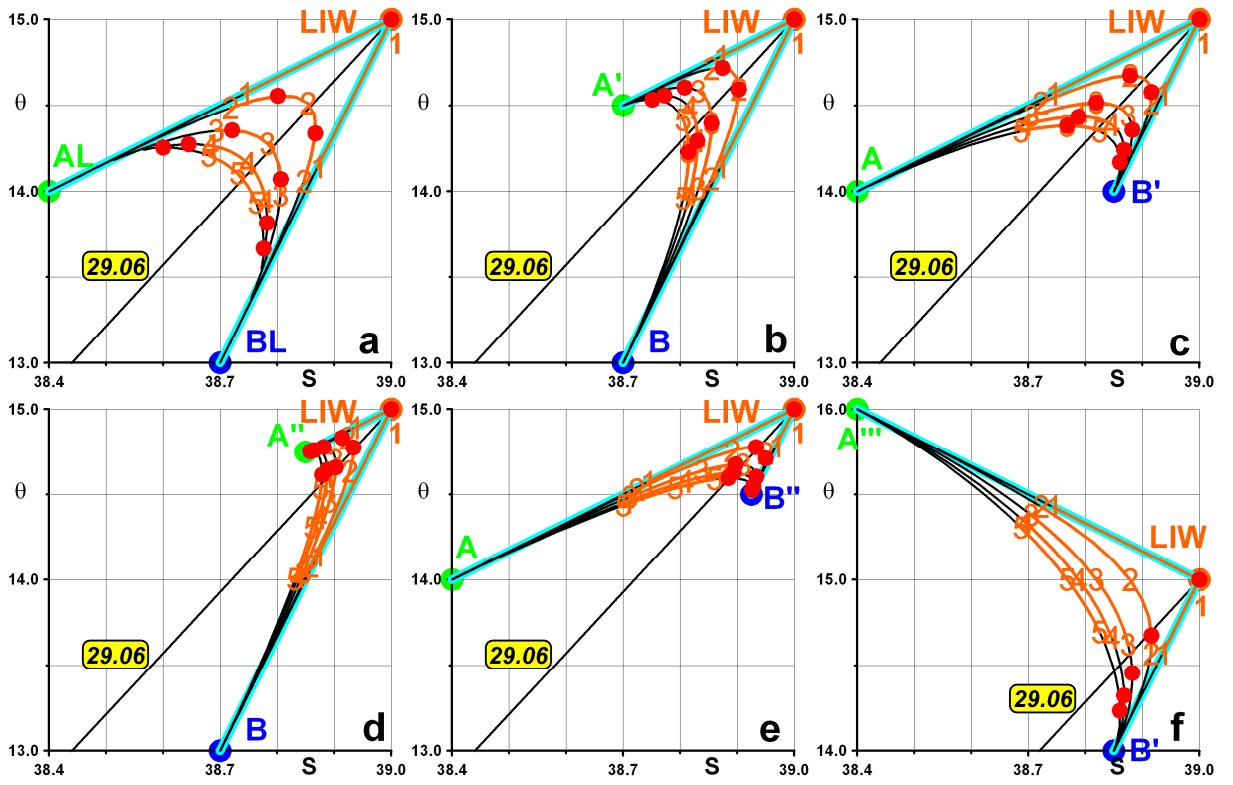


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Fig.4

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Fig.5