Circulation of water masses through the Ibiza Channel

Ibiza Channel
Western Mediterranean
Water mass
Current
Circulation

Canal d'Ibiza
Méditerranée occidentale
Masse d'eau
Courant
Circulation

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ABSTRACT

An analysis of current velocity, temperature and salinity data collected between 15 November 1990 and 24 July 1991 in the Ibiza Channel has been made to illustrate the circulation of the different water masses within this area. At certain stages of early winter, outstanding intrusions of Modified Atlantic Water, lasting a few days, have been observed flowing northwards along the eastern part of the Channel. Western Mediterranean Intermediate Water appeared for the first time during the middle of February; from March onwards, the thickness of the layer of this water mass increased until it reached its greatest presence during early summer. Simultaneously, the amount of Levantine Intermediate Water decreased at the mooring site, being replaced by the MAW. Western Mediterranean Deep Water was detected flowing northwards by our deepest measuring device during June and July. This flow may be a seasonal feature of the circulation in the Channel, linked to the production of Deep Water.

RÉSUMÉ

Circulation des masses d'eau dans le canal d'Ibiza.

Le schéma de circulation des masses d'eau dans le canal d'Ibiza est établi à partir des données de courant, température et salinité enregistrées entre le 15 novembre 1990 et le 24 juillet 1991. Pendant certaines périodes du début de l'hiver, de très fortes intrusions intermittentes d'Eau Atlantique Modifiée portant vers le nord ont été observées dans l'est du canal. L'eau intermédiaire de la Méditerranée Occidentale est détectée pour la première fois à la mi-février; à partir de mars, l'épaisseur de cette couche d'eau augmente pour atteindre son maximum au début de l'été. En même temps l'Eau Intermédiaire Levantine observée sur le mouillage est remplacée progressivement par la précédente. Le flux d'eau profonde dirigé vers le nord est détecté par le courantomètre le plus profond (700 m) en juin et juillet. Cette caractéristique saisonnière de la circulation dans le canal pourrait être liée à la formation de l'eau profonde.

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INTRODUCTION

The Ibiza Channel is an important site in relation to the circulation of waters in the Western Mediterranean basin. It connects the Balearic (Catalan) Sea and the Gulf of Lions with the Algerian Basin (Fig. 1) by means of a wide (90 km) and relatively shallow passage (sill depth is 700 m). Its width is much greater than the first baroclinic deformation radius (about 6 km for the N(z) and $\sigma\zeta(z)$ profiles shown in Fig. 2). Thus, the combined effect of rotation and stratification is important for the circulation of water masses in this area; it can hold, or even generate, mesoscale eddies like that shown in Figure 6A, which has been plotted from hydrological data collected during the IBIZA1190 survey.

Different water masses are detected in this area. They include the Modified Atlantic Water (MAW), which originates from the inflowing Atlantic water that enters the Mediterranean Sea through the Strait of Gibraltar. The general path of this water is known, but it exhibits a poorly understood variability as it moves further into the Western Mediterranean Basin. When present in the Ibiza Channel, it can be detected flowing northwards along the eastern part of the channel. Another surface water is the Resident Mediterranean Surface Water (also known as Local Atlantic Water), which takes the form of a very modified Atlantic water due to its long residence time in the Mediterranean. This water, transported by the Ligurian Current, accelerates as it encounters the Spanish coast (Millot, 1987) and is deflected southwards following the continental slope. Part of it turns to the east and closes a large cyclonic gyre around the Balearic (Catalan) Sea. The remainder continues its path to the south along the western portion of the Channel. The meeting of these two different surface waters forms the so-called Balearic Front, often observed in the Ibiza Channel.

On the continental shelves north of the Channel, (Cataluña shelves and the gulfs of Lions and Valencia), the Western Mediterranean Intermediate Water (WIW) is formed in winter due to the cooling of surface waters caused by the very cold northerly winds. This water, easily identified by its absolute minimum of temperature, sinks below the above-mentioned surface waters to its equilibrium depths.

The Levantine Intermediate Water (LIW), which enters the Western Mediterranean Basin through the Strait of Sicily, arrives at the Ibiza Channel after completing a large cyclonic path following the continental European coast. It is found at intermediate depths (300 to 500 m), usually flowing southwards and moving more rapidly in winter (Font, 1987).

The last water mass to be observed in this area is the Western Mediterranean Deep Water (DW), formed in winter in a region around 42 N, 5 E in the Gulf of Lions. Underlying the LIW, it fills the deepest portion of the whole Western Mediterranean Basin to a depth which is not easy to specify because a DW-LIW interface cannot be satisfactorily

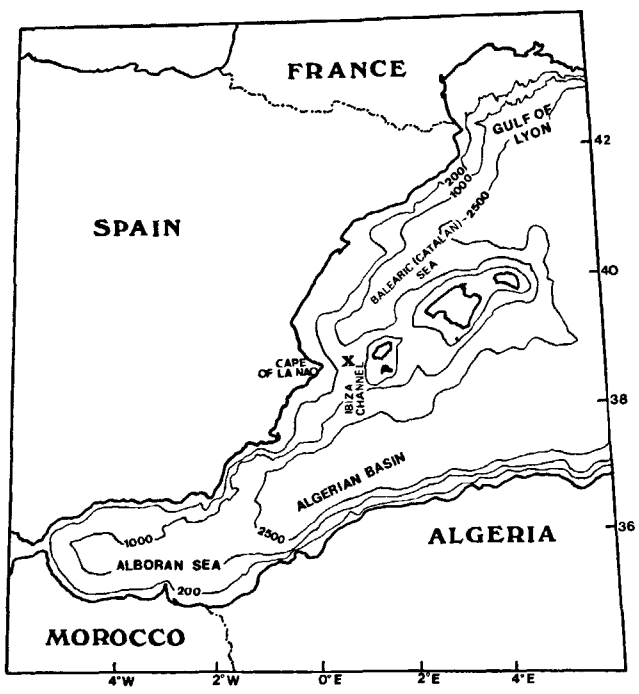

Figure 1

Map showing the location of the IBIZA CHANNEL and some of the topographic and geographic features of the zone. Different areas of the Western Mediterranean cited in the text have been labelled. The mooring site has also been marked with an "X".

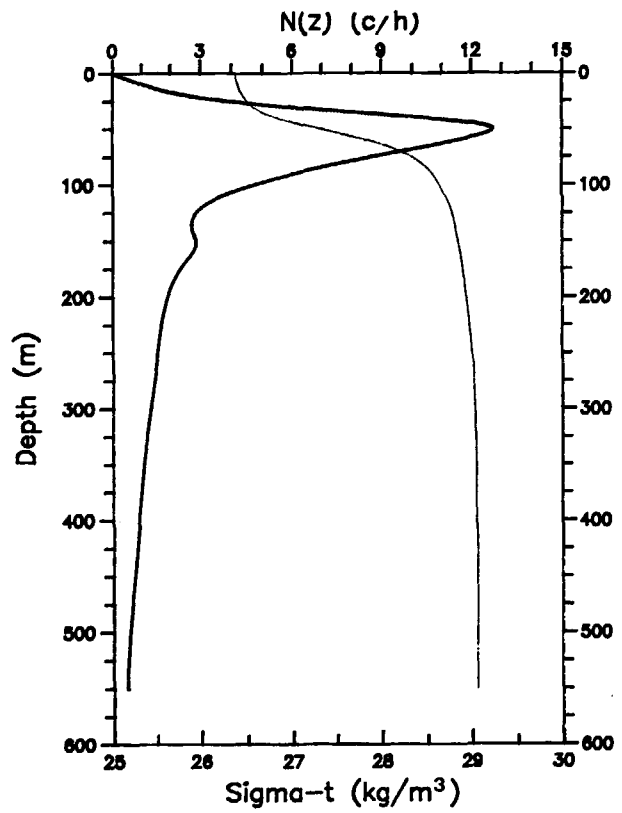

Figure 2

Profiles of sigma-t (thin line, lower scale) and N(z) (thick line upper scale) next to the mooring site during November 1990 (from data of IBIZA1190 hydrological survey).

defined. Moreover, this hypothetical interface will exhibit vertical oscillations which are both seasonal, following the cycles of DW production, and 'mesoscale' as it adjusts to the surface velocity field. For example, it will rise in the centre of cyclonic eddies and sink at their peripheries, changing its depth whilst these structures move. As a coarse reference, Stommel *et al.* (1973) situated the interface at a depth of 700 m in the Alboran Sea, and Lacombe *et al.* (1981), between 500 and 600 m in the Gulf of Lions. This depth is comparable to the sill depth; therefore, the sill may constitute a barrier that prevents this water from flowing through the Channel.

In the course of this paper, we shall discuss the seasonal features of the circulation of these water masses in the Ibiza Channel, as inferred from current velocity, temperature and conductivity data acquired at the site indicated on Figure 1. To begin with, in the next section, we shall present some results about the general circulation there (without considering the different water masses), deduced from elementary statistics and spectral analysis.

Data, method and preliminary results

On 15 November 1990 and during the IBIZA1190 hydrological survey, a mooring line was deployed at 38° 49.4 N, 0° 48.0 E by the *Instituto Español de Oceanografía* as an action of the **Dynamic study and biological production of the Ibiza Channel** project, which at the same time formed part of the **PRIMO-0** experiment. Data concerning horizontal current velocity, temperature and conductivity of water were taken at 30-minute intervals at six different depths by means of Aanderaa current-meters. The mooring line was removed for a few days in March to change the tapes and batteries of the instruments, whilst the IBIZA391 hydrological survey was being carried out. On 20 March 1991, the mooring line was deployed again at 38° 49.3 N, 0° 48.1 E and finally recovered in July. The close proximity of both locations allows us to consider them as a single site, which appears in Figure 1. More information about moorings can be seen in Table 1. Meteorological information (wind, atmospheric pressure) supplied by the *Instituto Meteorológico Nacional* and hydrological data from the IBIZA1190 and IBIZA391 surveys were also analysed, although the results concerning these hydrological data are presented in a different paper (López Jurado *et al.*, this issue).

All the time series were filtered to remove the effects of high frequency variability, especially inertial energy. The resulting horizontal currents are plotted in Figure 3. Our data set does not extend over an annual cycle. However, a seasonal variability is observed in this figure. Winter and early summer roughly coincide with our first (November to March) and second (April to July) mooring periods, respectively, and may be identified with them. Seasonality, often observed at different locations throughout the Western Mediterranean (Millot, 1987; Font, 1990; Astraldi *et al.*, 1990), affects not only the strength of the currents but also its vertical structure. During the first mooring, the horizontal speed did not decrease regularly from the surface to the bottom: around depth # 4, 265 m, an almost motionless layer appeared to exist, separating the two-layered flow observed in Figure 3A. The second mooring had a more 'barotropic' appearance and current speed was more uniform at the different depths.

Superposed on this low-frequency (seasonal) motion was the mesoscale variability (a period of 15-20 days) with similar energy values during both periods as shown in Figures 4A and 4B. On these, the mesoscale frequency band does not exhibit clearly differentiated spectral peaks, confirming the aleatory nature of these phenomena, associated with flow instabilities, eddies, filaments or similar features. In this respect, the Balearic Sea is a favourable place for their generation (La Violette *et al.*, 1990; Tintore *et al.*, 1990). They would have left the fan-shaped signatures observed in Figure 3 as they passed along the mooring site. A direct relationship between local atmospheric forcing and mesoscale motions was not found.

Table 2 summarizes elementary statistics of the data collected during each mooring. There are some similarities that must be emphasized. A minimum of mean current speed at intermediate depths was found again during mooring 2, although not as well differentiated as in mooring 1. Mesoscale variability, represented to some extent by the standard deviations, was also similar, as stated above. A curious behaviour is the counterclockwise (positive) rotation of the mean horizontal current as one looks up from the bottom observed in both periods (last column of Table 2). This rotation may be related to the vertical component of the velocity if the flow is assumed to be along isopycnals (U. $\nabla\rho = 0$, or $U_H \nabla_{H\rho} = -\partial w/\partial z$ subindex H stands for horizontal) and the thermal wind relation is used. Writing the horizontal current in polar form, $u = U_H \cos\theta$, $v = U_H \sin\theta$, θ being the polar angle positive counterclockwise and u and v as usually employed, after some manipulation we obtain the equation

$$w = -\frac{f}{N^2} U_H^2 \frac{\partial \theta}{\partial z}$$

Table 1

Current meter used in this study.

Mooring	Location	Depths		From	To
		#1:	90 m		
		#2:	115 m		
1	38° 49.4' N	#3:	165 m		
	0° 48.0' E	#4:	265 m	15-11-90	15-3-91
		#5:	465 m		
		#6:	715 m		
		#1:	100 m		
		#2:	125 m		
2	38° 49.3' N	#3:	200 m		
	0° 48.1' E	#4:	250 m	20-3-91	24-7-91
		#5:	450 m		
		#6:	700 m		

Table 2

Statistics for measured currents referred to a Cartesian frame with x,u pointing to the East, y, v to the North. Table *A(B) corresponds to first (second) mooring. Last two columns are modulus* $|\vec{u}|$ *and direction,* θ *of the velocity. Standard deviations* Δu *and* Δv *are greater than mean values* $\bar{u}$ *and* $\bar{v}$ *in agreement with Figure 3.*

(A)

DEPTH (m)	$\bar{u}$ (cm/s)	$\bar{v}$ (cm/s)	Δu (cm/s)	Δv (cm/s)	$\lvert\vec{u}\rvert$ (cm/s)	θ (°)
#1: 90	2.5	4.8	7.7	5.7	5.4	62
#2: 115	3.0	2.9	7.3	4.0	4.1	44
#3: 165	2.0	1.1	5.9	3.6	2.2	29
#4: 265	0.0	-0.4	3.4	2.4	0.4	-91
#5: 465	-1.9	-2.6	1.9	3.5	3.2	-125
#6: 715	-3.3	-0.9	3.5	3.9	3.5	-165

(B)

DEPTH (m)	$\bar{u}$ (cm/s)	$\bar{v}$ (cm/s)	Δu (cm/s)	Δv (cm/s)	$\lvert\vec{u}\rvert$ (cm/s)	θ (°)
#1: 100	1.3	0.2	4.8	4.1	1.3	10
#2: 125	0.9	-0.1	4.5	4.6	0.9	-9
#3: 200	0.5	-0.4	3.8	4.4	0.6	-43
#4: 250	-0.2	-0.8	2.5	4.0	0.8	-106
#5: 450	-1.2	-0.7	1.6	3.8	1.4	-151
#6: 700	-1.8	0.2	1.7	3.8	1.8	-187

Positive rotation of the current vector makes $\partial\theta/\partial z > 0$ and $w < 0$, *i.e.* the vertical component of the velocity directed downwards (on average). This result is compatible with a (mean) cyclonic circulation with its centre to the west of the mooring site, like that shown in Figure 6A: the mooring line should have been in the eastern part of a cyclonic gyre, in a positive vorticity region. This phenomenon, which may be a quasi-permanent oceanographic feature occupying preferentially the western half of the Ibiza Channel, is also compatible with the water mass circulation inferred from the data described below. Another interesting result is the findings of a net northeastward transport above the depth of minimum velocity and a southwestward transport below it. On the other hand, the seasonal variability observed when comparing Figures 3A and 3B is confirmed by the values on column #6.

Circulation of the water masses

To investigate the local variability of the water characteristics at the mooring site, T-S diagrams, such as those in Figure 5, have been used. These diagrams, together with the velocity time series given in Figure 3, are helpful in inferring the motions of the water masses and their seasonal variability. We shall comment consecutively on the observations concerning these different water masses.

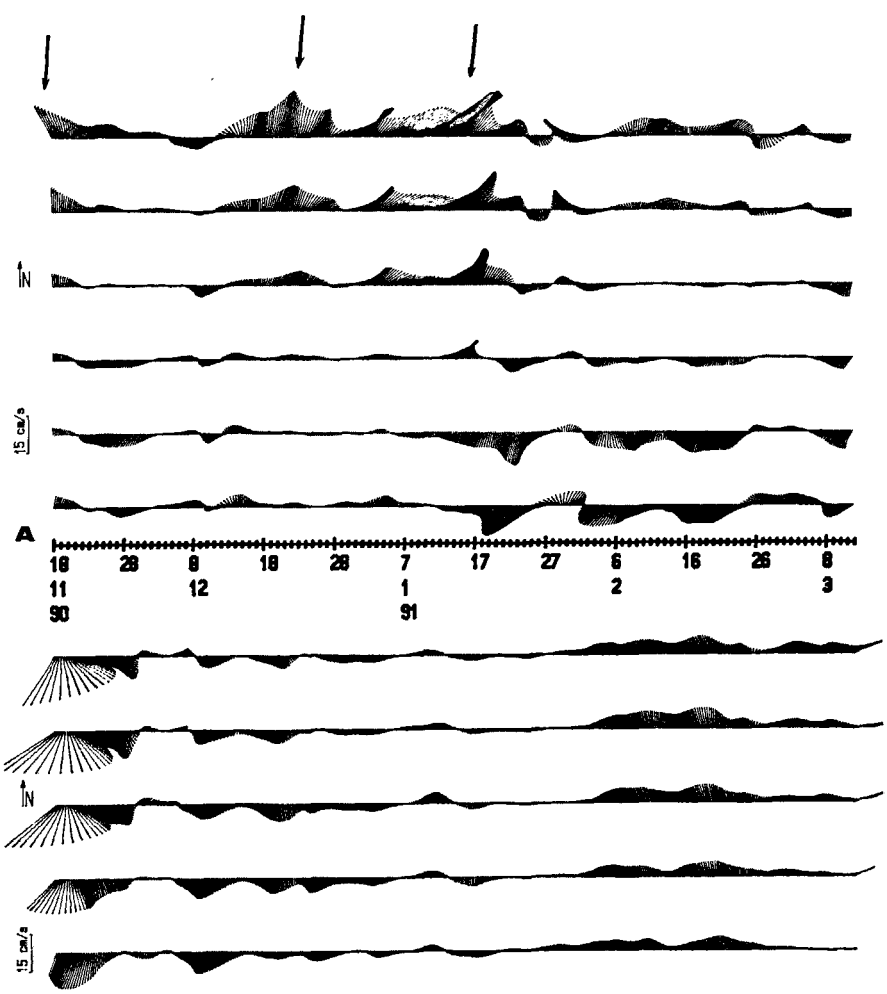

Figure 3

Stick diagram of the horizontal velocity at the different sampling depth during both mooring periods. Arrows on figure A (first period) point to the MAW intrusions discussed in the text. Note the different vertical structure of the horizontal velocity field in both periods.

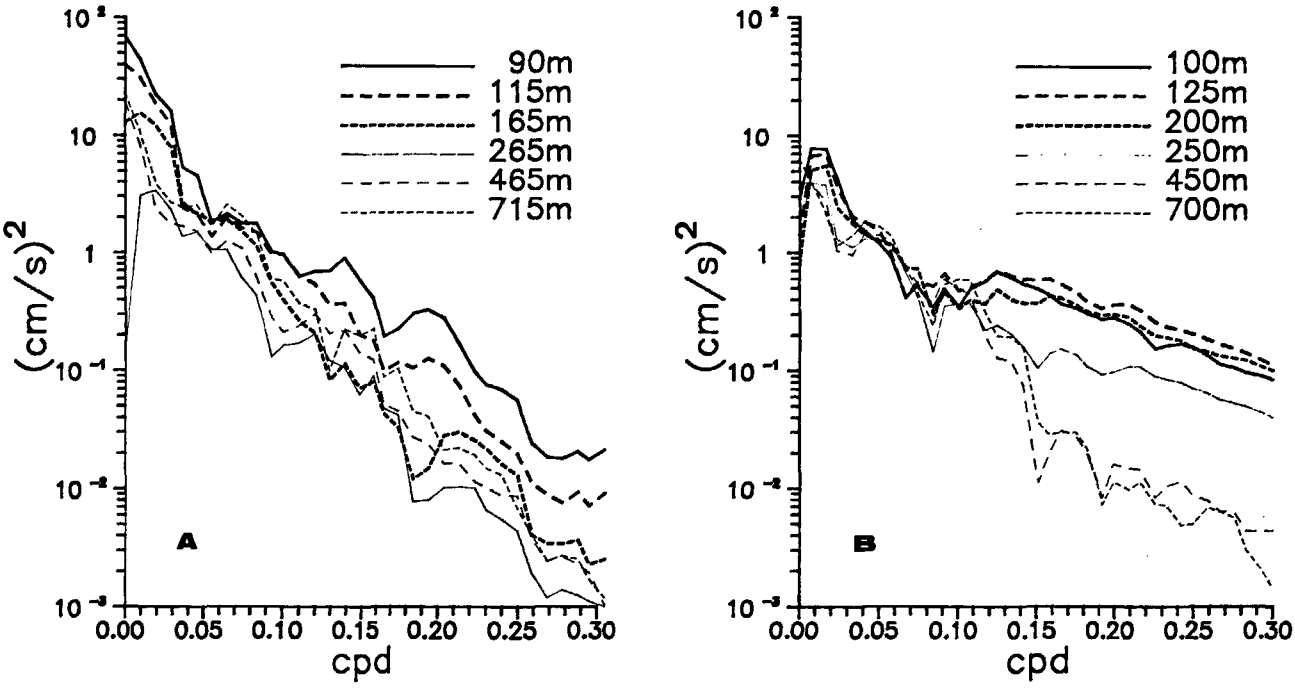

Figure 4

Velocity spectra (clockwise + anticlockwise) at each depth during the first, (Fig. A) and second (Fig. B) moorings. Different lines refer to different depths according to the label on the figures. The energy in the 'mesoscale' band (0.06-0.1 cpd) is similar in both periods but the energy of very low frequency motions is clearly greater during the first one.

The Modified Atlantic Water (MAW)

Even at the depth of the uppermost current-meter, the MAW appears rather mixed. Above this depth, the water will be fresher and will exhibit clearer MAW characteristics, that is, S < 37.5 PSU. The arrival of MAW at the Ibiza Channel produces a displacement of the points towards the upper-left corner in our diagrams, as shown in Figure 5A, for instance. From the beginning of mooring 1 until late January, the upper current-meters detected three perceptible intrusions of this water, marked by arrows in Figure 3A. The first was taking place when the IBIZA1190 hydrological survey was being carried out, and this permits us to know the synoptic conditions at the time and use them as reference to the other intrusions. Figure 6A shows the dynamic topography of the sea surface referred to 600 db; figure 6B shows the topography of the 37.5 PSU salinity surface, used to delimit the MAW; and Figure 6C shows the salinity at 30 m depth. The eastern half of the Channel was occupied by a vein of MAW entering from the south. Its western half sheltered a cyclonic gyre originating in the meeting of this water with Resident Mediterranean Water flowing southwards along the Spanish coast. The cape of La Nao influenced the formation of the gyre. The net transport of MAW to the north, according to geostrophic calculations, was 0.5 Sv.

During the other two intrusions, both the current speed and the thickness of the layer were greater than in November. Salinity values as low as 37.53 PSU were observed at 90 m depth during the second and most important intrusion. Vertical shear of the horizontal velocity, deduced from data of the upper current meters, gave $\partial v/\partial z > 0$, which implies $\partial \rho/\partial x < 0$ according to the thermal wind relation. Consequently, less dense water had to be east of the mooring site, a similar situation to that pertaining in November: MAW flowing northwards along the eastern part of the Channel. However, both the thickness layer and the flow speed suggest a larger transport than in November.

An obvious question arises: where did this water come from? Recirculation around a cyclonic gyre, such as that shown in Figure 6A, is not an acceptable answer, because water at the eastern side had purer MAW characteristics. The vein came from the south and it had to be related to what happened there. Figures 7A and 7B outline two possible ways in which the Atlantic Water can leave the Alboran Sea and enter the Algerian Basin. The first represents "normal" conditions: the inflowing water through the Strait of Gibraltar traces two large anticyclonic gyres in the basins of the Alboran Sea. The eastern gyre is bounded by the ALMERIA-ORAN Front which, at the same time, guides the Atlantic Water along the African coast to form the Algerian Current (Arnone *et al.*, 1990; Tintore *et al.*, 1988). The "anomalous" situation consists of either the absence of the eastern anticyclonic gyre or the presence of a very small gyre confined to a small area east of Cape Tres Forcas. The latter has been evidenced by hydrological surveys (Lanoix, 1974; Cano, 1977) and infrared imagery (Heburn and La Violette, 1987). When this situation prevails, the ALMERIA-ORAN Front must either be absent or, if present, must have a different orientation and intensity; the MAW that leaves the Alboran Sea would split into two veins, one leading to the east to form the Algerian Current, the other running to the north and eventually rea-

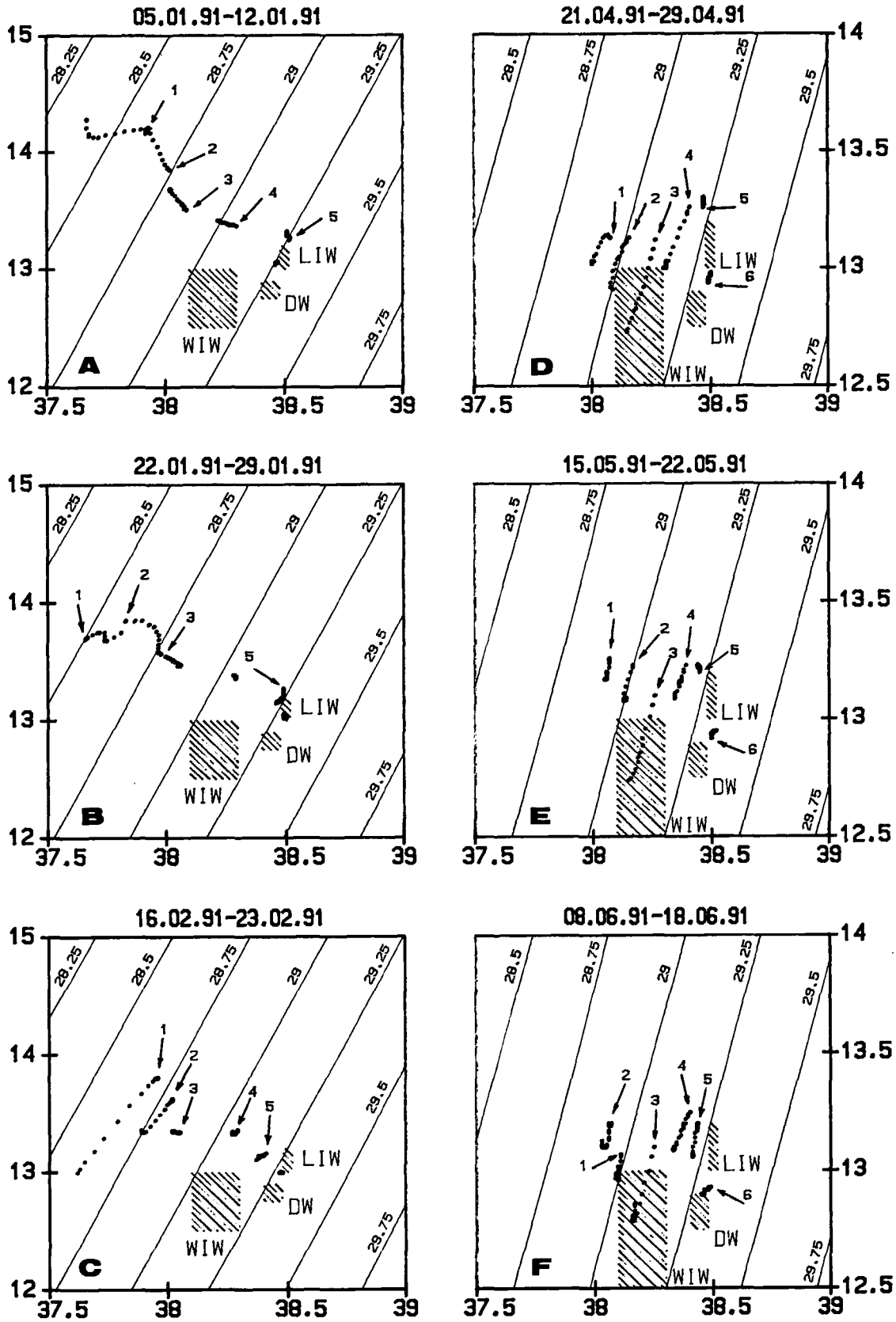

Figure 5

Selection of T-S diagrams showing time evolution of the water characteristics at the sampling depths which have been indicated by the small number beside the arrow. This points to the first T-S value of the represented period which appears at the top of the diagram. Two consecutive points are 12 hours apart (two points per day). Shaded areas mark the position of WIW, LIW and DW on the diagram according to the values that are usually found in the literature. Depending on the time of the year, WIW may have a lower value of salinity than these 'standard' ones, even as low as 37.6 PSU (diagram C): the temperature minimum is its more distinguishable feature. The MAW area does not appear as it lies beyond the upper-left corner; MAW intrusions in the upper surface layer may be monitored by point displacements toward this corner (diagram A). See text for more detail. (Note the different temperature scale in diagrams on the right).

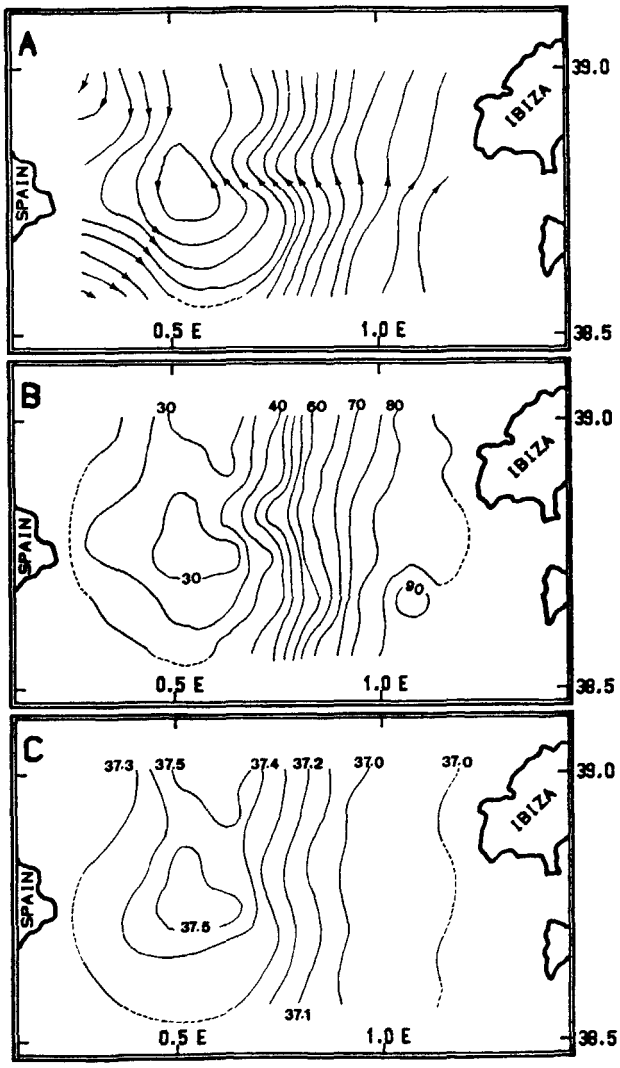

Figure 6

Some results from IBIZA1190 hydrological survey: A) Dynamic topography of sea surface referred to 600 db. Isolines interval is 1 dyn.cm. A cyclonic gyre occupies the western half of the Ibiza Channel, while a clear northward flow exists in its eastern part. B) Topography of S=37.5 PSU surface. The MAW thickness increases eastward and reaches up to 90 m near Ibiza island. C) Salinity map at 30 m depth. MAW characteristics are more prominent to the east and a salinity front is seen in the middle of the Channel. The whole of these figures confirms the intrusion of a vein of MAW coming from the south and flowing northwards along the eastern part of the Channel.

ching the Balearic Islands. This is the circulation pattern suggested by Allain (1960) and discussed in Hopkins (1985). Obviously, the first situation is not compatible with the observed intrusions of MAW from the south. Under "anomalous" conditions, the northern vein would describe meanders leading to variability of MAW flow through the Ibiza and other Balearic channels.

The northward MAW transport during these intrusions (0,5 Sv in November, probably higher values during the other two) would account for an important fraction of the estimated amount of Atlantic Water which leaves the Alboran Sea. Perkins and Pistek (1990) and Arnone *et al.* (1990) estimate from geostrophic calculations a transport of 0.5 Sv of MAW by the Algerian Current under conditions such as those shown in Figure 7A. (Their computation seems to be underestimated because of the lack of data in a strip twelve miles wide along the Algerian Coast.) In the absence of the eastern anticyclonic gyre, a slightly greater amount of MAW should exit from the Alboran Sea. Even so, the north vein could transport more than half the total amount of MAW, to the detriment of the Algerian Current. When the usual conditions are restored, the north vein would disappear, as would the MAW intrusions in the Ibiza Channel. Hydrological surveys carried out in June and July 1992 did not find MAW there (López Jurado *et al.*, this issue). It is interesting to note that, simultaneously with the arrivals or withdrawals of intense MAW flows, packets of internal inertial waves were detected. They were more energetic at 165 m (G. Lafuente and Cano, 1994), a depth that roughly coincided with the base of the baroclinic jet associated with the MAW intrusion.

The Levantine Intermediate Water (LIW)

The presence of LIW in the Ibiza Channel seemed to exhibit a seasonal behaviour conditioned by WIW formation. When the latter was not taking place (that is, during most of the first mooring period), the LIW occupied a considerable portion of the water column: it was detected by the two lower current meters during mooring 1 and part of mooring 2, flowing mainly to the south although short per-

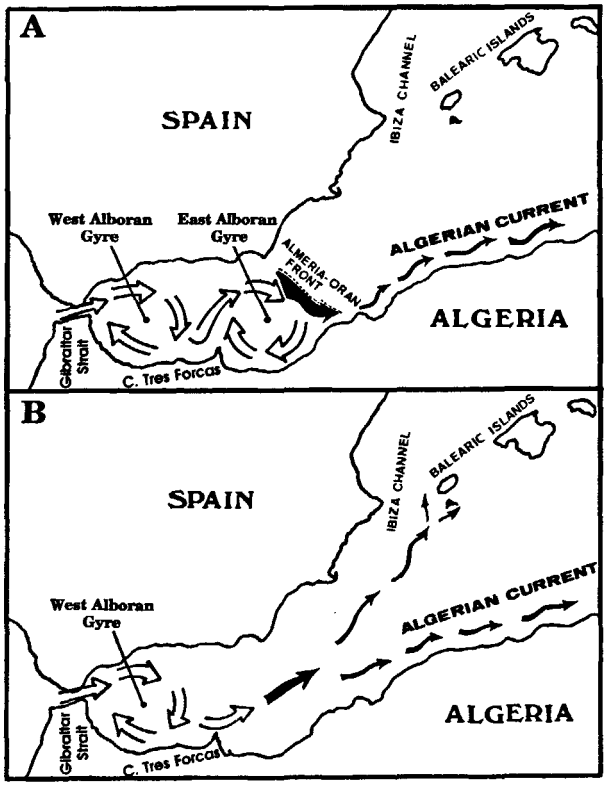

Figure 7

Likely paths of Atlantic Water in the Alboran Sea and Algerian Basin:
A. *"Normal" circulation (adapted from Tintore* et al., *1988).*
B. *"Anomalous" condition. (adapted from Hopkins, 1985, after Allain, 1960). See text for details.*

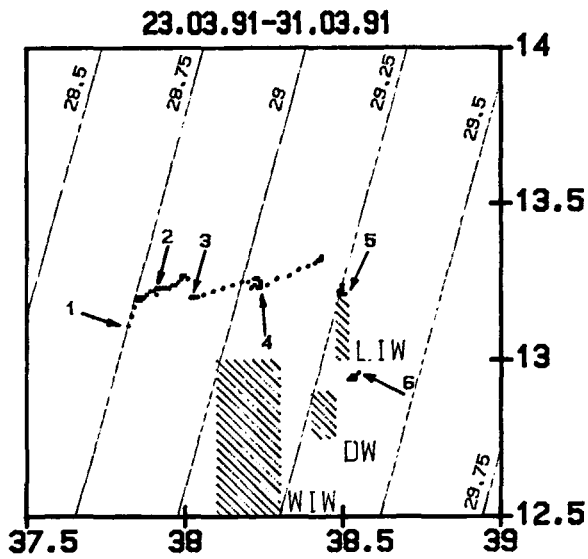

Figure 8

T-S diagram corresponding to the first days of the second mooring (see fig. 5 for explanations). Note the clear displacement of the T-S points in intermediate depths to the zone of LIW influence.

iods of weak flow to the north were also observed. These brief periods of flow reversal coincided with the first days of the MAW intrusions and could have been forced by them. After finishing the second one, an intensification of LIW flow to the southwest was recorded by the three lower current meters. The thermal wind relation applied to the velocity data collected by these instruments indicated denser water to the west of the channel and, therefore, a greater LIW transport along the Spanish Continental Slope, in agreement with the description of its circulation given in the literature (Font, 1987; Millot, 1987). However, the most pronounced intensification of LIW flow occurred at the beginning of mooring 2, (Fig. 3B). A strong flow to the southwest was observed at all depths, with current speeds exceeding 20 cm/s. The T-S diagram in Figure 8 shows the existence of water with strong LIW characteristics at depth #5 and a marked displacement of the T-S points corresponding to the four upper levels towards the zone of LIW influence. The points crossed σ_t = constant lines, indicating the occurrence of an energetic feature which affected the whole column of water. Strong internal inertial waves were also observed during this period (G. Lafuente and Cano, 1994). Unfortunately the data are insufficient to evaluate the transport of LIW to the south during these intensifications, but it must undoubtedly be quite important.

Once this flow intensification ceased (around 30 March), the water column became more homogeneous and the velocity field more barotropic. In fact, barotropicity was the rule during this second period (Fig. 3B). From the early days of April onwards, WIW appeared systematically at intermediate depths (as discussed in the following section), and seemed progressively to displace the LIW towards other areas (other inter-island channels) or to confine it to greater depths, or both. Velocities were weaker and the southward tendency of LIW disappeared. Periods of stagnancy alternated with periods of weak flow in both directions. From June onwards, a rather steady northward flow was established (Fig. 3B), but the T-S characteristics were closer to DW and to WIW than to LIW at the deepest current meter and at the remaining instruments, respectively (see Fig. 5F).

The Western Mediterranean Intermediate Water (WIW)

This water is identified by its absolute minimum of temperature, but its salinity varies within a wide margin. The values used to plot the shaded rectangles in figures 5*a* to 5*f* are only indicative: values lower than these must not be excluded. For example, Figure 5C shows the arrival of WIW fresher than usual and, therefore, lighter than other more saline WIW. Consequently, its equilibrium depth is around 90 m, shallower than that corresponding to the events represented in figures 5D and 5E ($\approx$ 200 m). Note the typical signature left by WIW arrivals in the T-S diagrams: points run parallel to σ_t = constant lines. This water may replace the pre-existing waters without the occurrence of energetic phenomena, as it had the same density.

The first appearance of WIW was recorded by the uppermost current meter by the middle of February and is illustrated in Figure 5C. Its strongest presence, however, was during the last half of mooring 2 and more specifically in June and July, when the five upper current meters were immersed in water bearing noticeable WIW features (Fig. 5F). Lopez Jurado (1990) states that summer is the season with a greater abundance of WIW in the Ibiza Channel; the results presented here agree with his conclusions.

Contrary to MAW and LIW motions, WIW did not flow in a single direction. By the end of April, a layer thicker than 150 m was observed flowing to the north at some 10 cm/s (Fig. 3B). During the last days of February, however, it flowed to the north at 90 m depth (figures 5C and 3A). A similar situation was observed between 15 and 20 May at a depth of 200 m (Fig. 5E and 3B). It is not possible to establish that the Ibiza Channel is a route for WIW into the Algerian Basin exclusively, despite the fact that this water was formed north of the channel. Recirculation of WIW around the Balearic Islands or in the Ibiza Channel itself seems to occur. Perkins and Pistek (1990) presented some evidence of clockwise WIW circulation around Menorca (the westernmost island of the Balearic archipelago) in summer 1986. It probably flowed from the Balearic Sea into the Algerian Basin and vice versa, disappearing progressively as a result of mixing with other water masses. In 1990, such disappearance occurred before November: the IBIZA1190 survey found no trace of this water and our moored current meters did not detect WIW until the second half of February 1991.

The role played by this water in the circulation through the Ibiza Channel and other channels between the Balearic Islands is not well known. The homogenization of the water column and the barotropic structure of the velocity field during the second mooring seemed to be closely related to the greater presence of WIW in the Channel. Judging from the data presented here, it controls the flow of the other water masses. LIW paths would be par-

ticularly affected in summer when WIW occupies most of the intermediate depths formerly occupied by LIW. This fact hampers its circulation along their usual paths and even may deflect it toward another channels. Lopez Jurado (1990) found some evidence of this deflection toward the Mallorca Channel (between Ibiza and Mallorca Islands) when analysing hydrological data collected in summer.

The Western Mediterranean Deep Water (DW)

The sill depth in the Ibiza Channel is 700 m. Thus, DW is not usually detected, or is found very near the bottom on both sides of the sill (López Jurado *et al.*, this issue). But from the first days of June onwards, a water of almost pure DW characteristics was detected by the deepest current meter (Fig. 5F), flowing to the north with a relatively constant speed of 5-6 cm/s (Fig. 3B). Perhaps this was not a fortuitous occasion but a seasonal feature of the water circulation through the Channel. As known, DW is mainly formed during February and March in the Gulf of Lions and then moves as a deep flow to the Algerian Basin. This production is not simultaneously compensated by an increased draining of DW through the Strait of Gibraltar, nor by an increased rate of mixing with the LIW above it. Thus, DW accumulates in the Algerian Basin and Alboran Sea, raising the interface. June is a propitious month for such an uprising to occur. If this seasonal lifting is accompanied by a favourable surface circulation (a large anticyclonic gyre in the Algerian Basin, the passage of erratic mesoscale anticyclonic eddies south of the Ibiza Channel or cyclonic circulation in the Channel itself for, example) the interface may exceed the sill depth. A pressure gradient to the north would be established and DW would flow in that direction through the Ibiza Channel, the deepest of the Balearic channels. The whole water column would follow this motion because of its homogeneity. The DW flow would become less and less probable as the DW reservoir in the Algerian Basin and Alboran Sea empties through the Strait of Gibraltar.

CONCLUSION

Although the data analysed in this paper do not extend over an annual cycle, they cover a period longer than eight months, which allows us to infer the existence of: a) some quasi-permanent features; b) a seasonal variability; and c) a mesoscale variability.

Quasi-permanent features comprise the existence of a layer of minimum speed at intermediate depths (see column #5 of Table 2), which, roughly speaking, separates a north or northeast flow from another to the south or southwest, (column #6) and a positive rotation of the horizontal velocity vector with "z" (column #7), which is compatible with cyclonic circulation west of the mooring line. A very simplified pattern of the mean circulation in the Channel emerges from these features: mean surface flow to the north or northeast, more intense at the eastern side (positive vorticity at the mooring site) and a (mean) southward deep flow. This fits in the pattern of general circulation of the Western Mediterranean as described by different authors (Hopkins, 1985; Millot, 1987; Font, 1987).

Seasonal variability is observed when comparing the vertical structure and mean values of the currents in Figures 3A and B. In winter, the speed of the current was greater than in early summer and a noticeable baroclinic flow was present during a considerable part of the first mooring period. The subsequent homogenization of the water column observed during the second period resulted in a much more barotropic shape of the velocity field. WIW played an important role in these phenomena: there was an obvious correlation between the strongest presence of this water and the change in the flow structure. A better understanding of the link between WIW formation and winter circulation through the Balearic Channels would be an interesting objective for future research. Another seasonal feature would be the northward flow of DW in the deeper layer observed from June onwards, which is postulated to be related to the cycles of DW formation.

Finally, the mesoscale variability, which mainly affects the upper layers, has a rather aleatory nature and is likely to be related to flow instabilities. The MAW intrusions are the most significative example of this variability, and may be linked to instabilities of the ALMERIA-ORAN Front, located to the south of the Ibiza Channel. Some intensifications of LIW flow have been also observed, although no hypotheses have been advanced concerning their origin. Perhaps they are related to the formation processes of the winter water masses, WIW and DW.

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