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Hydrographic conditions of the Ibiza Channel during November 1990, March 1991 and July 1992

Western Mediterranean
Water masses
Seasonal variability
Geostrophic currents
Transports

Méditerranée occidentale
Masse d'eau
Variabilité saisonnière
Courant géostrophique
Transport

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ABSTRACT

The hydrographic conditions of the Ibiza Channel were studied in successive surveys during November 1990, March 1991 and twice in July 1992. From a hydrographic viewpoint we must emphasize the importance of the intrusion of Modified Atlantic Water (MAW) with its associated front as a result of mesoscale processes, and the presence of the seasonal Winter Intermediate Water (WIW) which fills the entire width of the channel in the form of a layer between 300 or 400 m thick. This water mass affects the dynamics of the Ibiza Channel by a reduction in the exchange, hiding the seasonal characteristics of the Levantine Intermediate Water (LIW), which we consider to be one of the causes of the circulatory change in the channel. The combined action of the different water masses and their production cycles give rise to readjustments in density that could favour the presence of gradients on the continental slopes and Deep Water (DW) on the sill of the Channel. The geostrophic transports of the different water masses have been calculated.

RÉSUMÉ

Conditions hydrologiques dans le canal d'Ibiza en novembre 1990, mars 1991 et juillet 1992.

Les conditions hydrologiques dans le canal d'Ibiza ont été étudiés lors de campagnes effectuées en novembre 1990, mars 1991 et juillet 1992. L'entrée de l'Eau Atlantique Modifiée (MAW) et le front associé résultent de phénomènes à moyenne échelle. L'Eau Intermédiaire Hivernale (WIW), est présente sur toute la largeur du canal, dans une couche d'épaisseur comprise entre 300 et 400 mètres. L'effet de cette eau sur le régime dynamique du canal est une réduction des échanges, masquant les caractéristiques saisonnières de l'Eau Intermédiaire Levantine (LIW), ce qui est l'une des causes de la variation de la circulation dans le canal. L'action combinée des différentes masses d'eau et le cycle de leur formation conduisent à des réajustements de densité qui peuvent favoriser la présence des gradients sur le talus continental et celle d'eau profonde (DW) sur le seuil du canal. Les transports géostrophiques des différentes masses d'eau ont été calculés.

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INTRODUCTION

The target area of the present work is the Ibiza Channel, located between the Island of Ibiza and the Iberian Peninsula. The axis of this channel lies in a north-south direction and its width is some 47 nautical miles, having an appreciable shelf (10 miles) on both sides. Its central sector, with depths of more than 200 metres, extends for some 28 nautical miles. The sill depth is about 700 metres, while depths of 1000 metres are found both to the north and south of the sill.

The Balearic Islands separate two sub-basins within the Western Mediterranean: The Algerian basin, to the south of the islands, which is a receptor for Modified Atlantic Water (MAW); and the Catalan-Provençal basin, between the northern part of the islands and the Iberian Peninsula, which collects Local Atlantic Water (LAW), characterized by a long resident time in the Western Mediterranean that renders it somewhat colder and saltier. In a general sense, the Western Mediterranean circulation, as much at the surface as in the intermediate layers, can be considered cyclonic, the inference being that these northern waters flow towards the channels between the Balearic Islands, meeting with water coming from the Atlantic (Hopkins, 1985). For these reasons, the Ibiza Channel is a strategic place for studying the exchange of fluxes between the adjacent basins and the seasonal variability of the different water masses.

It follows from the above that the Atlantic Water inputs must have a seasonal component, which can be masked by the instability associated with the Almeria-Oran front (Millot, 1987) and by the mesoscale processes coming from the Algerian current. The intermediate waters that flow through the channels with a core of Levantine Water (LIW) circulate at depths between 200 and 700 m. The deep water formation process appears to affect this circulation and can thus produce an interruption in the Levantine flow (Font, 1987), giving rise to the appearance of a seasonal component in the circulation of this water. This seasonality is affected or to some extent camouflaged by the presence of another mass, Winter Intermediate Water (WIW) located above the LIW, which is totally seasonal (Katz, 1972) and present in this area from the end of winter until the beginning of autumn (López-Jurado, 1990). The Deep Water does not reach the sill of the Channel (700 m), appearing, in general, in depths greater than 800 metres to the north and south of the sill. The temperature and salinity values which characterize the different waters can be seen in Table 1.

Table 1

Characteristic values of temperature (Θ) and salinity (S) of the different water types and local values at the Ibiza Channel.

	Water masses	
	Water type*	Ibiza channel Local values
MAW	$15 < T < 18$ °C $36.15 < S < 36.5$ psu	$15 < T < 25$ °C $36.5 < S < 37.5$ psu
LIW	$14 < T < 15$ °C $38.7 < S < 38.8$ psu	$13 < T < 13.4$ °C $38.48 < S < 38.52$ psu
DW	$12.75 < T < 12.9$ °C $38.4 < S < 38.48$ psu	$12.75 < T < 12.9$ °C $38.4 < S < 38.48$ psu
WIW	$12.5 < T < 13$ °C $38.1 < S < 38.3$ psu	$12.5 < T < 13$ °C $37.6 < S < 38.3$ psu

* (Salat and Cruzado, 1981)

MATERIAL AND METHODS

As part of the project entitled "A dynamic and biological production (plankton) study of the Ibiza Channel", four hydrographic surveys were conducted, in November 1990, March 1991 and in early and mid-July 1992, by the Instituto Español de Oceanografía (IEO). In addition, a mooring with six current meters was deployed close to the sill from November 1990 to June 1991. The current meter analyses are presented by García Lafuente *et al.*, this issue. This project was developed within the framework of the "Programme Recherche Internationale en Méditerranée Occidentale" (PRIMO-0)

The first two surveys were carried out from *R/V F.P. Navarro* and the other two from *R/V Odón de Buen.* A network of 54 hydrographic stations, distributed in six sections of 9 stations each, with a 5-mile separation between stations, were covered in a period of less than five days during each survey. At all the stations within the network, measurements of conductivity, temperature and pressure were made (see Fig. 1).

These parameters were obtained with a Neil Brown, model Mark III (CTD) probe, during the IBIZA-1190 and IBIZA-0391 surveys, registering data at a predetermined velocity of 8 samples per second, descending at approximately 1 metre per second. The CTD measurements were calibrated by bottle samples which were analysed using a Guidline model 8400A salinometer. The precision of the measurements was 0.004 psu for salinity and 0.02 °C for temperature. During the IBIZA-0792a and IBIZA-0792b surveys a Seabird, model SBE-25 (CTD) probe was used, registering data at a predetermined velocity of 4 samples per second, descending at approximately 1 metre per second. The precision of the measurements was 0.008 psu for salinity and 0.005 °C for temperature. Data were edited at their original resolution and finally reduced to a 1-metre resolution for final analysis.

From the distribution of both salinity and temperature, the dynamic height anomalies of different isobaric surfaces relative to the 600 db have been calculated. Shallow stations were extended downward by appending below them the profile of dynamic height of the nearest deep stations. The average geostrophic transports during each survey have been calculated from the geostrophic velocities between adjoining stations of the same section and expressed in Sverdrups (1×10^6 m^3/s). The values corresponding to the transport of the distinct water masses and the net transports are shown in Tables 2 and 3. The criteria applied in order to differentiate the distinct water masses are shown in the column of local values in Table 1.

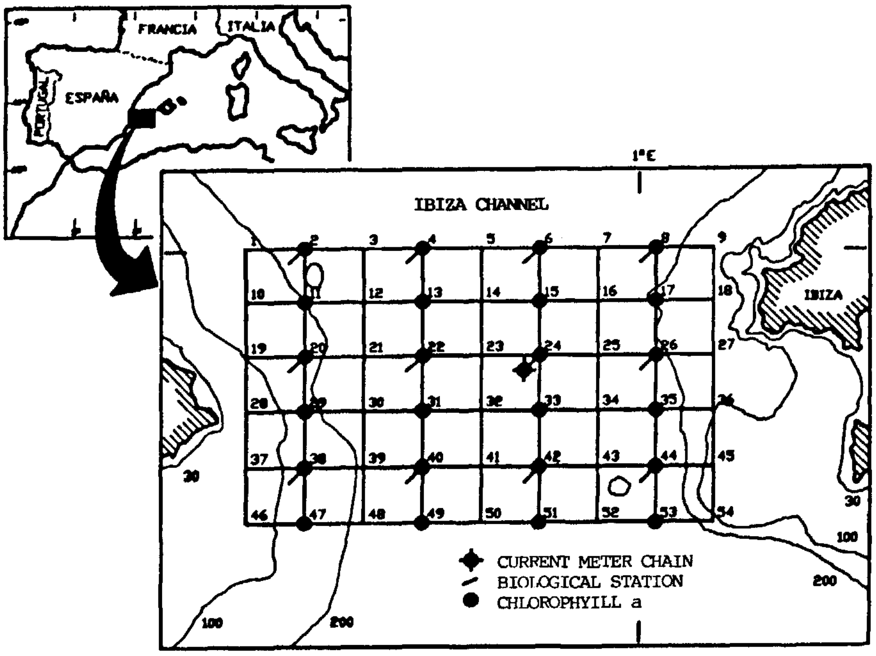


Figure 1

The location of the hydrological stations and mooring of the current meters.

RESULTS

The diagrams of temperature (Θ) and salinity (S) reveal the most outstanding characteristics of the four surveys: a notable seasonal variation in the distribution of these parameters and consequently a variation in the presence of the distinct water masses in the Channel (see Fig. 2 and 3).

Modified Atlantic Water (MAW)

This water has been found during each of the four surveys with slightly higher temperature and lower salinity than the Local Atlantic Water (LAW), the other surface water. The MAW is defined as having salinity less than 37.5 psu (Fig. 4). At its thickest, the MAW layer measured about 100 metres in the left corner (south-east) of the working area, close to the shore of the Ibiza island, in November 1990. In the first two surveys, salinity values slightly lower than 37 psu were observed in the area of the Channel.

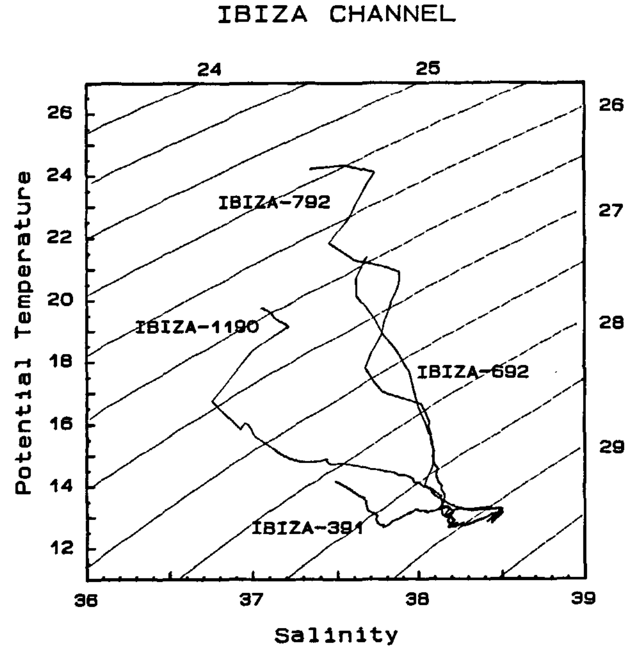


Figure 2

Diagrams of potential temperature and salinity showing profiles of a characteristic hydrographic station for each survey.

The dynamic topographies of the surface layer relative to 600 db shown in Figure 5, fit in with these distributions of salinity and reflect a northward circulation of MAW close to Ibiza and a southward flow displaying somewhat LAW characteristics near the coast of the Peninsula. The meeting of these waters results in the formation of an oceanic front whose intensity and position is variable, as the distribution of the distinct parameters in Figure 6 shows. The associated circulation of these fronts is complex and recirculations of these waters are often produced (Pinot *et al.*, 1994). The geostrophic calculations give maximum northward velocities of 30 cm/s and southward maximum velocities of 25 cm/s.

Winter Intermediate Water (WIW)

This seasonally-formed intermediate water is found in the Ibiza Channel just below the superficial water and above the LIW. It is characterized by a minimum temperature ($T < 13$ °C) and a wide range in salinity ($37.7 < S < 38.3$ psu). The salinity values of 37.7 psu seem to indicate that the formation of this water increases slowly and progressively as winter advances, being formed by convection due to the cooling of the surface in all northern parts of the Western Mediterranean including the Catalan coast (Salat and Font, 1987). The general circulation propagates its movement towards the Channel. The first WIW to arrive, less saline and more buoyant, was detected in March 1991, at between 40 and 100 metres depth, forming

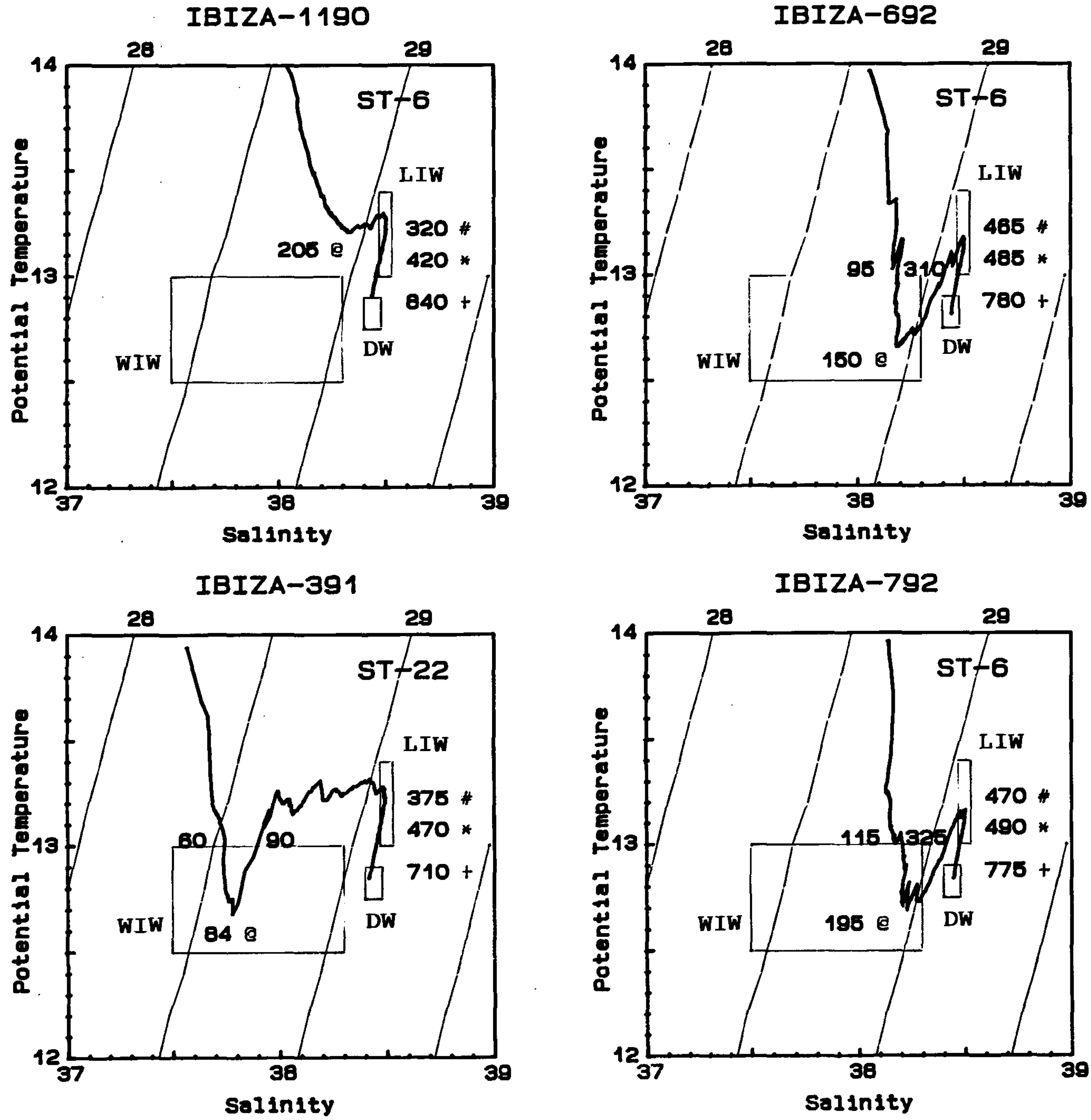


Figure 3a, b, c, d

Detail of the diagrams of previous potential temperature and salinity, in which the depths at the most significant points are shown. So, (#) LIW maximum of temperature, (*) LIW maximum of salinity, (+) depth at which DW was first recorded, (@) WIW minimum of temperature. Also, starting and finishing depths of WIW are shown in some graphics. The small frames correspond to the local values of these waters.

entrapped lenses, 10 to 30 metres thick, throughout the width of the Channel and lying between LAW without forming a continuous layer. The overlapping of the MAW above the LAW favours the sinking of these lenses, and therefore we found them deeper near the island of Ibiza. The registered values of temperature and salinity in these lenses were 12.68 °C and 37.7 psu, respectively.

Subsequently and during the surveys in July 1992, we again found these minima (Figs. 3c, 3d, 7c and 7d), with evolved general characteristics in comparison with those found previously: salinity was clearly higher, between 38.1 and 38.3 psu. The WIW then formed a continuous layer across the entire width of the Channel, separating the Superficial and Levantine Waters, with a thickness of some 300 metres. At the beginning of July (1992), this water was at a depth of between 65 and 365 metres, with a maximum thickness of 290 metres, absolute minimum temperature of 12.66 °C and salinity of 38.18 psu. Fifteen days later, we found it at between 80 and 380 metres depth

Figure 4a, b, c, d

Horizontal distribution of the depth at which the isohaline surface of 37.5 psu was found in the different surveys.

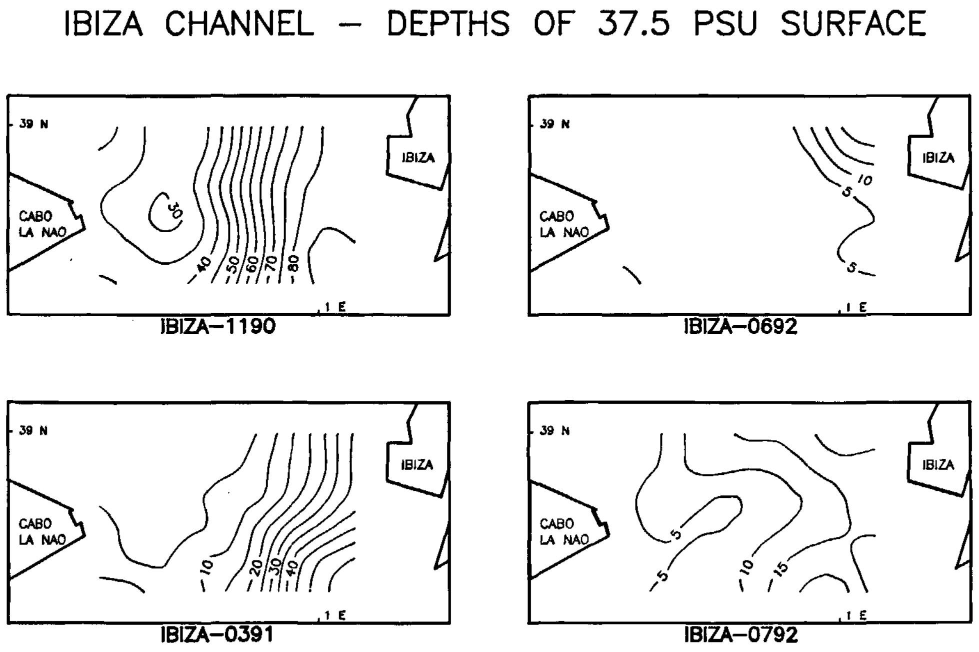
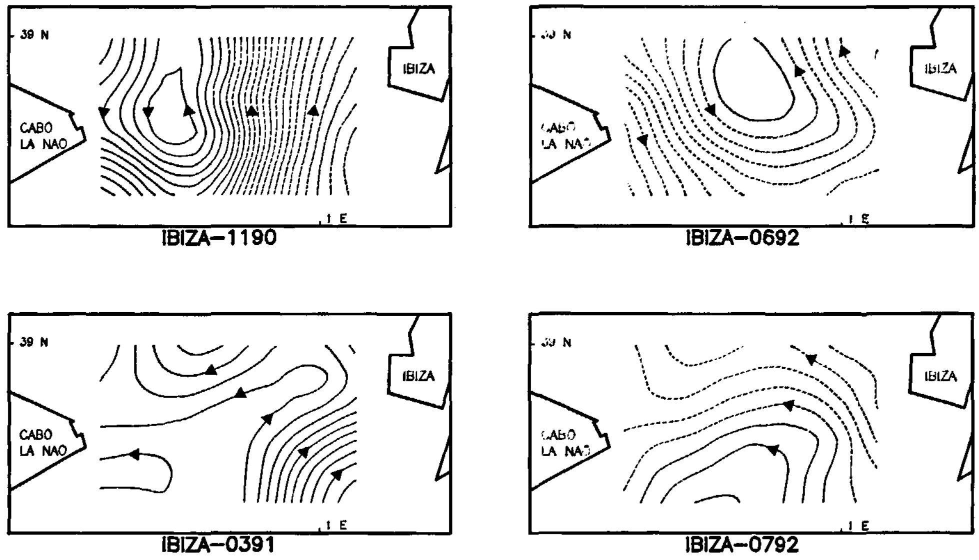


Figure 5a, b, c, d

Anomalies of dynamic heights corresponding to the surface of 0 db, relative to 600 db, at intervals between the isolines of 0.5 dyn cm. Arrows indicate the direction of the flow.



with a thickness of about 270 metres, a minimum temperature of 12.65 °C and a salinity of 38.19 psu.

The geostrophic velocities (relatives to 600 db) of this water oscillate between the average value for Atlantic Water (15 cm/s) and that for Levantine Water, a few cm/s, rapidly decreasing with depth. The maximum velocity of the WIW was noted during the March survey. The dynamic topography corresponding to these depths, during the surveys of March and July, denotes in general a southward motion, although recirculation of these waters may also occur (see Table 2 and García Lafuente *et al.*, this issue).

Levantine Intermediate Water (LIW)

This water coming from the Eastern Mediterranean is characterized by an absolute maximum of salinity and a relative maximum of temperature. During these surveys we have found it in the Channel at depths between 250 and 730 metres, with maximum salinity values slightly less than 38.52 psu (see Fig. 3). The potential temperature maximum within the layer oscillates between 13.39 and 13.22 °C, while the thickness varies between 240 and 320 metres. The core of maximum salinity (S > 38.5 psu) was found at between 400 and 450 metres depth, whilst the maximum temperature was above this. The difference in depth between the two maxima was more pronounced in the first two surveys than in the final two. Generally, the flow was southward in this layer, with weak geostrophic velocities, rarely exceeding a few cm/s, during the four surveys.

During the November survey, the core of LIW circulating southward through the Ibiza Channel on the continental slope off the Peninsula with maximum values of salinity of

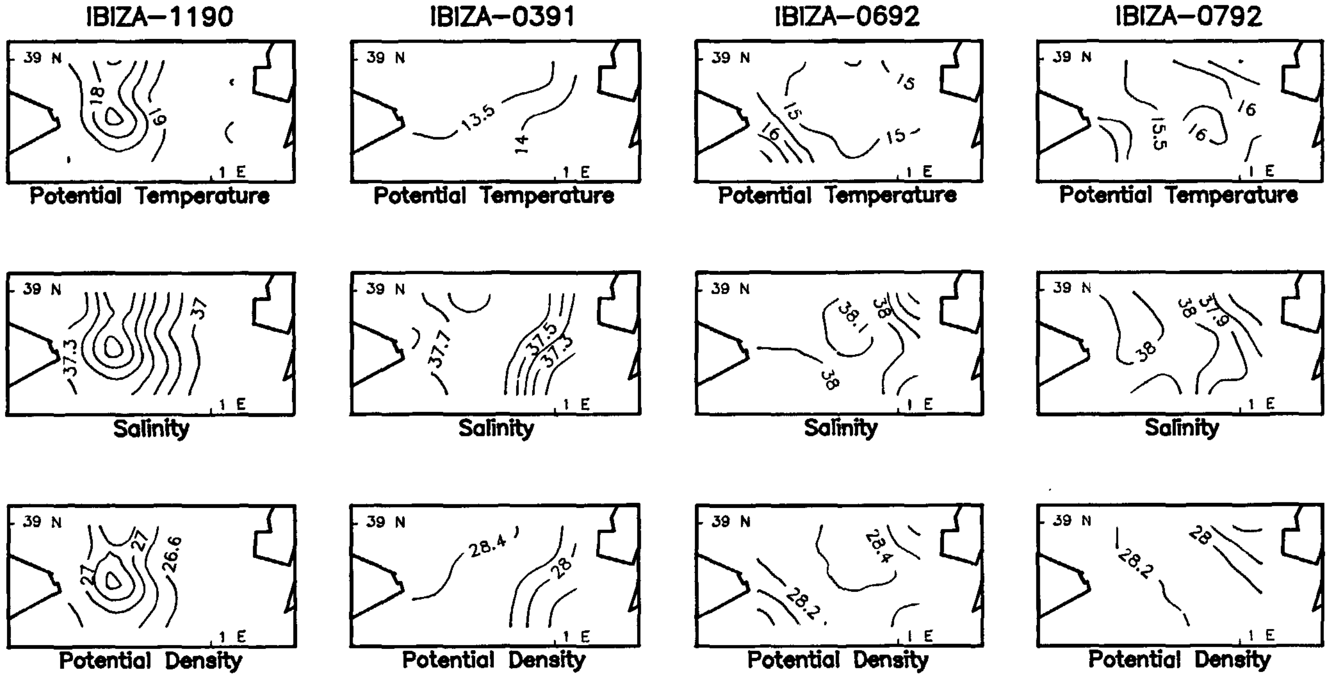


Figure 6a, b, c, d

Horizontal hydrographic sections, at a depth of 30 m, of potential temperature, salinity and potential sigma-t during the different surveys. These parameters have been indicated with intervals of 0.5 °C for temperature, 0.1 psu for salinity and 0.2 for sigma-t.

38.51 psu and potential temperature of 13.30 °C. In March 1991 the characteristics of this water changes slightly, maintaining a potential temperature maximum of 13.38 °C and with a decreasing salinity maximum (S = 38.50 psu). At this time, the core of LIW continued to circulate over the Peninsula's continental slope. In the two surveys of July 1992, the potential temperature maximum was reduced to 13.22 °C due to mixing with WIW, and the salinity increased to 38.51 psu. At this time, the LIW is displaced to the central part of the Channel.

Deep Water (DW)

This is usually found to the north and south of the sill of the Ibiza Channel at depths below 800 metres, with values of potential temperature less than 12.9 °C and salinity less than 38.46 psu. The minimum values of salinity (approximately 38.42 psu) were measured during November and March, which indicate a greater purity, and the maximum values (about 38.45 psu) in July, possibly due to greater contact and mixing with the LIW.

The arrival of these maximum values coincides with an elevation of the LIW-DW interface at the location of the deepest stations of the grid, where the orography of the Channel is considered to have little influence. This interface moved from a depth of 850 in March to 775 metres in July. Within the Channel, the DW is found in some isolated stations at a level somewhat less deep. For example, it was at 640 metres in November (St-33), 570 metres in March (St-16) and about 660 metres in July (St-22 and St-32) and, generally, over the slope off Ibiza. This circumstance, which we attribute to the combined effect of the circulation of WIW and LIW and to the production cycles of DW, would allow this water to cross the sill of the Channel (García Lafuente *et al.*, this issue).

Geostrophic transport

Results of the evaluated geostrophic transport are given in Tables 2 and 3. We have considered separately the northward ("plus" sign) and southward ("minus" sign) transport to illustrate the recirculation of water masses in the Channel. Table 2 shows the transport data of each of the different water masses mentioned above. The net transport of MAW was always to the north; its greatest value (+0.51 Sv) was found in November and almost no traces of it were found in the summer surveys. The LAW had a more continuous presence and flowed to the south, with a noticeable transport of – 0.17 Sv measured at the begining of July 1992 survey. The WIW transport increased from March to July to reach – 0.17 Sv in the latter month. On the other hand, the LIW flow showed neither great temporal variability, nor large values. No data to estimate DW transport are available; but this water has been detected at some hydrographic stations.

The whole net transports are presented in Table 3. The high value of +0.45 Sv measured in November 1990 was due to the large MAW transport at that time. Values on this table have great variations as a result of the seasonal or inter-annual variability of water circulation through the Ibiza Channel.

Table 2

Average transport of the different water masses at the Ibiza Channel. These values have been calculated by averaging the transports obtained at the six sections of each survey and are shown as Mean ± Standard Deviation, Sv. "Plus" and "minus" signs indicate north and south directions, respectively.

Water masses transport (Sv)		Surveys			
		IBZ-1190	IBZ-0391	IBZ-0792a	IBZ-0792b
	N	+0.68±0.10	+0.12±0.09	+0.00±0.01	+0.03±0.01
MAW	S	–0.17±0.26	–0.01±0.01	–0.00±0.00	–0.00±0.00
	Net	–0.51 Sv	–0.11 Sv	+0.00 Sv	–0.03 Sv
	N	+0.38±0.14	+0.33±0.26	+0.19±0.09	+0.17±0.07
LAW	S	–0.41±0.11	–0.38±0.26	–0.36±0.10	–0.24±0.05
	Net	–0.03 Sv	–0.05 Sv	+0.17 Sv	–0.07 Sv
	N	+0.00±0.00	+0.03±0.05	+0.14±0.10	+0.06±0.05
WIW	S	–0.00±0.00	–0.04±0.05	–0.20±0.09	–0.19±0.13
	Net	–0.00 Sv	–0.01 Sv	+0.06 Sv	–0.13 Sv
	N	+0.01±0.02	+0.01±0.01	+0.02±0.01	+0.01±0.01
LIW	S	–0.05±0.07	–0.02±0.02	–0.01±0.01	–0.02±0.00
	Net	–0.04 Sv	–0.01 Sv	+0.01 Sv	–0.01 Sv

Table 3

Net transport calculated from water masses transport on Table 2. "Plus" and "minus" signs indicate north and south directions, respectively.

	Net transport		
Survey	N	S	Net
IBZ-1190	+ 1.07	- 0.63	+ 0.44
IBZ-0391	+ 0.49	- 0.45	+ 0.04
IBZ-0792a	+ 0.35	- 0.57	- 0.22
IBZ-0792b	+ 0.27	- 0.45	- 0.18

DISCUSSION

The hydrological data collected during the four surveys point to the existence of a quasi-permanent cyclonic circulation in this area (see dynamic topographies on Figures 5). In November 1990, this circulation clearly defined a cyclonic gyre occupying the western half of the Channel (see Fig. 5a). It was greater and also well-defined at the beginning of July 1992, but this was not the situation during the other two surveys, when the gyre was absent, although the main circulation remained cyclonic. The relationship between the gyre definition and the relatively high values of the surface water net transport (MAW + LAW) is obvious if we compare Figures 5 and the net transport values of Table 2. The two phenomena are related.

Considering the results presented as indicative of seasonal evolution, we can conclude that winter is a favourable season for the presence of MAW in the Ibiza Channel. Moreover, its transport values exhibited large variations, +0.51 Sv in November versus +0.11 Sv in March, the two "winter" surveys. The former could be the result of an anomalous intrusion of MAW into the Channel, related to the instabilities of the Almería-Orán front (García Lafuente *et al.*, this issue). The other surface water, LAW, did not display great seasonal variations, although a small increase of southward transport was observed with the onset of summer.

The WIW formation area is not well delimited, but salinity values such as 37.7 psu indicate formation areas close to the Channel. Its initial stage of entrapped lenses within the LAW developed to establish a continuous layer across the entire width of the Channel, with a thickness large enough to affect the dynamics of the water motions, particularly the LIW flow, and to reduce the total transport through it. A gradual transition in the (Θ)-S characteristics of this water from March to July occurred, increasing its density and thereby decreasing its buoyancy. This is partially due to the arrival of northern WIW and to the orographic conditions of Valencia Gulf and the Ibiza Channel, which favour the retention and advective mixing of this water. Subsequently, it drains through the Channel during summer until the last traces of it disappear at the end of the autumn. However, this draining is not continuous. Periods of stagnacy and even reversal flow must not be discounted (García Lafuente *et al.*, this issue).

The changes shown by LIW in March and later in July must be related to WIW presence and DW formation processes. In July, the amount of WIW in the Channel was sufficient to displace the layer of LIW to the central part and reduce its thickness. This could be the cause of the appearance of the internal structure of Figures 7, which reveals a noticeable contrast in salinity at intermediate depths on both continental slopes, more pronounced on the

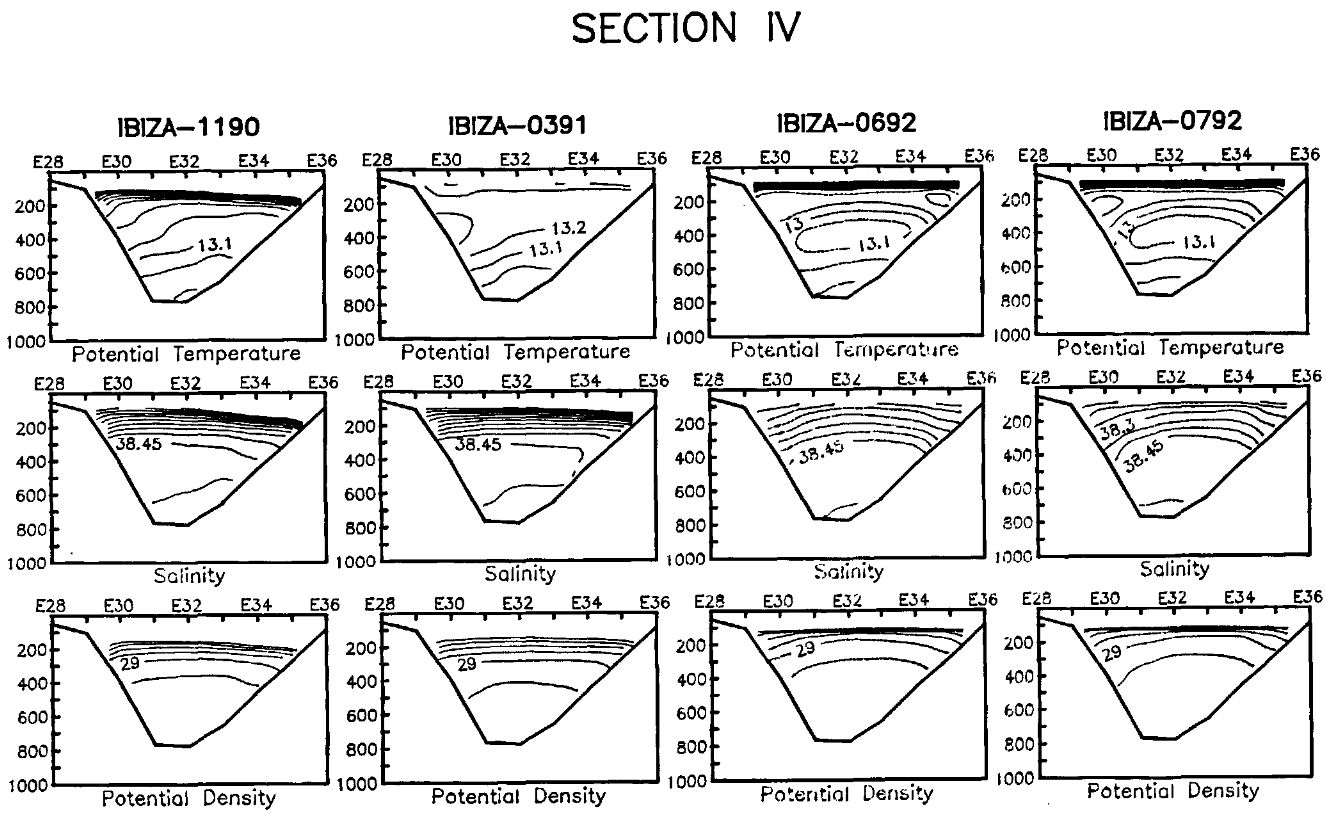


Figure 7a, b, c, d

Vertical distribution of potential temperature, salinity and sigma-t, during the four surveys, corresponding to section IV, in which the temperatures were represented in the range from 12.7 °C to 14 °C with an interval of 0.1 °C, the salinity in the range from 38 to 38.5 psu with an interval of 0.05 psu and Sigma-t in the range from 28.4 to 28.9 with an interval of 0.5.

Peninsula slope, which could be favoured by a large cyclonic recirculation of WIW in the Channel.

The DW-LIW interface uprising observed in July coincided with the theoretical time of lifting caused by the spreading of the new DW formed in winter. This uprising could have facilitated the flow of DW through the Channel, as observed during these surveys.

Transport data must be considered as indicative of a highly variable seasonal flow. In particular, the values found here during summer surveys are considerable smaller than –0.75 Sv as evaluated by Perkins and Pistek (1990) from hydrographic data taken in June, 1986. However, they are comparable to those given by García (1990), who evaluated +0.23 Sv for MAW and –0.19 Sv for LAW (+0.04 Sv, net surface transport) from data collected in June, 1989. Castellón *et al.* (1990) give –0.24 Sv for intermediate waters (LIW + WIW) from Doppler profiling data, taken during this same survey in June 1989. From this point of view, if we consider the net surface water transport (MAW + LAW) and the net intermediate water transport (WIW + LIW), a seasonal circulation pattern emerges. Thus, from Table 2 data we can observe that during winter surveys the net surface transport was northward, while the net intermediate transport was southward. Summer conditions were slightly different, with both net transports southwards and the net intermediate transport slightly increased. In an even broader sense, the whole transport through the Channel reverses from summer to winter, as Table 3 indicates.

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