Water exchanges in the Balearic channels

by

José Luis LOPEZ-JURADO[1], Jesús GARCIA LAFUENTE[2],
Jean-Michel PINOT[3] and Alberto ALVAREZ[3]

[1]*Instituto Español de Oceanografía, Centro Oceanográfico de Baleares, Palma, Spain.*
[2]*Departamento de Física, Universidad de Málaga, Málaga, Spain.*
[3]*Departamento de Física, Universidad de las Islas Baleares, Palma, Spain.*

ABSTRACT

This paper reviews the evidence gathered from recent observational and modeling studies of the circulation in the Balearic channels. Data obtained from hydrographic cruises and currentmeters moorings are used, together with results from simulations by a primitive equation numerical model. The analysis stresses the strong variability of the thermohaline properties and mass transports through these channels. This variability is mainly observed on the seasonal scale and mesoscale and appears as a result of the interaction between the different Western Mediterranean water masses that transit through the Balearic channels. The transports through these channels are also shown to exert a determinant control on the circulation in the adjacent Balearic and Algerian basins. Thus, the Balearic channels appear as a transition area where strong, highly variable, meridional exchanges take place between the north and the south of the Western Mediterranean.

RÉSUMÉ

Les résultats obtenus à partir de récentes observations et modélisations de la circulation dans les passages entre les Iles Baléares ont été synthétisés. Les données recueillies lors de campagnes hydrologiques et de mouillages de courantomètres ont été utilisées ainsi que les résultats de simulation par un modèle numérique aux équations primitives. Les analyses montrent qu'il existe une forte variabilité des propriétés thermohalines et des transports dans ces passages. Cette variabilité, principalement observée à l'échelle saisonnière et à méso-échelle, apparaît comme une conséquence des interactions entre les différentes masses d'eau de Méditerranée occidentale qui traversent les passages des Iles Baléares. On constate également que les transports au travers de ces passages exercent un contrôle déterminant sur la circulation dans les bassins baléare et algérien adjacents. Il apparaît donc que les passages entre les Iles Baléares forment une zone de transition où des échanges méridionaux intenses et fortement variables ont lieu entre le nord et le sud de la Méditerranée occidentale.

INTRODUCTION

The Balearic Sea is a sub-basin of the Western Mediterranean located between the Iberian peninsula and the Balearic Islands (Fig. 1). It is bounded to the north by the Gulf of Lions, characterized by strong atmospheric forcings, and to the south by the Algerian basin mainly forced by density gradients. As a consequence of the significant contrast between the dynamics of the northern and southern regions, the Balearic basin acts as a transition basin where strong adjustments occur. As such, it plays an important role in the general circulation of the Western Mediterranean.

Figure 1 – The Balearic Sea and its channels.

At first glance, the Balearic Islands act as a topographic barrier, aligned in the SW-NE direction, that isolates the Balearic Sea from the Algerian basin. However the existence of passages between the Balearic Islands allows meridional exchanges. These passages consist of two main channels, the Ibiza Channel (between Ibiza and the peninsula) and the Mallorca

Channel (between Ibiza and Mallorca), both characterized by significant widths (47 and 40 nautical miles respectively), large maximum depths (700 m and 600 m respectively) and relatively narrow shelves on each side (about 10 nautical miles). With such wide dimensions, these channels potentially allow substantial transport of mass, heat, salt, momentum and biogeochemical tracers accross them. Hence, the study of the Balearic channels is crucial to understand the interaction between the circulation in the southern and northern regions of the Western Mediterranean.

The aim of this paper is to review results obtained from recent observational and numerical experiments carried out in the 1990's and related to the study of the circulation in the Balearic channels and adjacent seas. Much attention is paid to the analysis of the flow variability through the channels and emphasis is placed on the role of the channels in the circulation of the Western Mediterranean at basin and sub-basin scales. The first section provides the background to the studies of the Balearic channels by describing some general results about the circulation in the Western Mediterranean off the Spanish coast. Section 2 concerns the description of hydrographic data collected during repeated extensive surveys in the Ibiza and Mallorca channels. Thermohaline properties are used to identify the different water masses which transit through the channels and characterize their dynamics and seasonal variability. In Section 3, continuous time series of currentmeter and T-S data are described in order to analyse the time variability of the flow and thermohaline properties through the Ibiza Channel. Section 4 deals with the summer circulation in the Balearic Sea inferred from a multivariate analysis of quasi-synoptic hydrographic and velocity data. Finally, in last section, the role of the Balearic channels in the general context of numerical modeling of the circulation in the Western Mediterranean is discussed.

GENERAL CIRCULATION

Historically, several Western Mediterranean water masses have been observed circulating through the Balearic channels or in the adjacent Balearic and Algerian basins. From a climatological data set, FONT *et al.* (1988) showed that the [0-300 m] layer in the Balearic Sea is generally occupied by Local Atlantic Waters (hereafter LAW). It is a very modified Atlantic water, advected by the general cyclonic circulation around the Western Mediterranean basin, relatively cold and salty. These waters flow southward along the peninsula slope, forming the Catalan current, and normally cross the Ibiza Channel although northward deflection of the flow before reaching the channel has been observed (CASTELLON *et al.*, 1990). In any case, the LAW transport is strongly dependent on the seasonal variability of the Catalan current, typically 2 Sv in winter versus 1 Sv in summer (FONT *et al.*, 1988).

Climatological data also indicated that the [0-150 m] layer in the eastern Balearic Sea is occupied by recent Modified Atlantic Waters (hereafter MAW) that enter the Balearic basin from the south through the Balearic channels (FONT *et al.*, 1988). The existence of a strong MAW inflow into the Balearic Sea was confirmed from analyses of CTD, ADCP and AXBT data (GARCIA *et al.*, 1994; PINOT *et al.*, 1994). MAW are formed by mixing between the fresh Atlantic waters which exit the Alboran Sea and the saltier Mediterranean waters present in the Algerian basin. However, the lack of observations does not allow to describe the MAW circulation in the Algerian basin nor to clarify the cause of the MAW inflow through the Balearic channels. Some observations suggest that large anticyclonic eddies associated with the Algerian current may advect MAW towards the channels (TAUPIER-LETAGE and MILLOT, 1988) while the results obtained from inversion of climatological data in the whole Mediterranean support the hypothesis of a permanent northern MAW branch at the exit of the Alboran Sea (TZIPERMAN and MALANOTTE-RIZZOLI, 1991).

At intermediate depths in the Balearic basin, FONT (1987) found Levantine Intermediate Waters (hereafter LIW) down to 700 m. These waters are formed by surface evaporation in the Eastern Mediterranean and are supposed to fill the Western Mediterranean describing a large cyclonic path along the northern Mediterranean coast which is characterized by deep salinity and temperature maxima. FONT (1987) suggested a southward path of LIW through the Balearic channels into the Algerian basin. Another intermediate water mass, called Winter Intermediate Waters (hereafter WIW), was described by SALAT and FONT (1987) who showed that these waters form in winter to the north of the Balearic Sea due to surface cooling. PERKINS and PISTECK (1992) showed that WIW can flow southward across the Ibiza Channel. Finally, Deep Waters (hereafter DW), which are formed in winter in the Gulf of Lions and the Ligurian Sea, occupy the whole bottom layer of the Western Mediterranean. Their path southward from the northern regions where they form is however poorly known.

HYDROGRAPHY OF THE IBIZA AND MALLORCA CHANNELS

While describing the main water masses present in the vicinity of the Balearic channels, none of the previous studies specifically focused on the channels. Furthermore, information about the variability of the circulation in the channels is lacking. In the period 1990-1993, the Balearic channels were intensively studied for the first time. In less than three years, seven hydrographic cruises were carried out in the Ibiza Channel and three in the Mallorca Channel with a Neil Brown SBE-25 CTD probe. Several cross-channel transects of 9 CTD casts were performed in both channels with a distance of 5 nautical miles between each station. Procedures for CTD calibration, hydrographic analyses and geostrophic calculations (based on a no motion level at 600 dbar) are described in LOPEZ-JURADO *et al.* (1995). Geostrophic transports integrated for each water mass are summarized in Table I. The new information gained from these analyses is described below with emphasis on the seasonal variability of the flow.

Surface waters

As expected, LAW ($S>37.5$ psu) are systematically found down to 300 m close to the peninsula coast in the Ibiza Channel, flowing southward into the Algerian basin with maximum southward geostrophic velocities of about 20 $cm.s^{-1}$. The southward LAW transport is very variable, ranging from 0.1 to 0.5 Sv. These fluctuations are likely related to the strong seasonal variability of the Liguro-Catalan current but also to the interaction with the other water masses present or not in the Ibiza Channel. In the Mallorca Channel, there is practically no southward LAW transport. Most of the sur-

Table I

Geostrophic transport (in Sv) of the different water masses in the Ibiza and Mallorca channels for the different surveys. "+/-" signs respectively indicate north and south directions. Note that significant errors are intrinsical to the computation of geostrophic transports in narrow passages. One of them is that a substantial part of the flow can be ignored over the shelf and close to the slope. Another one can be due the no motion level assumption at 600 m: an error of 5 cm.s-¹ in this level, which is realistic in a narrow channel where the flow is likely accelerated even at depth, gives an error of 0.2 Sv for a flow 20 km wide and 200 m deep.

WATER MASSES		**SURVEYS**									
TRANSPORT (Sv)		IBZ-1190	IBZ-0391	IBZ-0792a	IBZ-0792b	IBZ-0393	IBZ-0593	IBZ-0693	MCA-0393	MCA-0593	MCA-0693
MAW	N	+0.8	0.0	0.0	+0.1	+0.1	+0.2	+0.1	+0.7	+0.3	+0.3
	S	-0.1	0.0	0.0	0.0	0.0	0.0	0.0	-0.1	-0.1	-0.0
LAW	N	+0.4	+0.1	+0.3	+0.2	+0.1	+0.4	+0.3	+0.4	+0.1	+0.1
	S	-0.3	-0.3	-0.5	-0.3	-0.2	-0.1	-0.2	0.0	0.0	-0.0
WIW	N	0.0	0.0	+0.3	+0.2	+0.1	+0.1	+0.0	0.0	+0.1	+0.0
	S	0.0	0.0	-0.3	-0.2	-0.3	-0.4	-0.4	0.0	0.0	-0.1
NET	N	+1.2	+0.1	+0.6	+0.5	+0.3	+0.7	+0.4	+1.1	+0.5	+0.4
TRANSPORT	S	-0.4	-0.3	-0.8	-0.5	-0.5	-0.5	-0.6	-0.1	-0.1	-0.1
	Net	+0.8	-0.2	-0.2	0.0	-0.2	+0.2	-0.2	+1.0	+0.4	+0.3

veys reveal the existence of a quasi-permanent cyclonic circulation in the Ibiza Channel: even gyres involving recirculation in the channel itself can appear (Fig. 2).

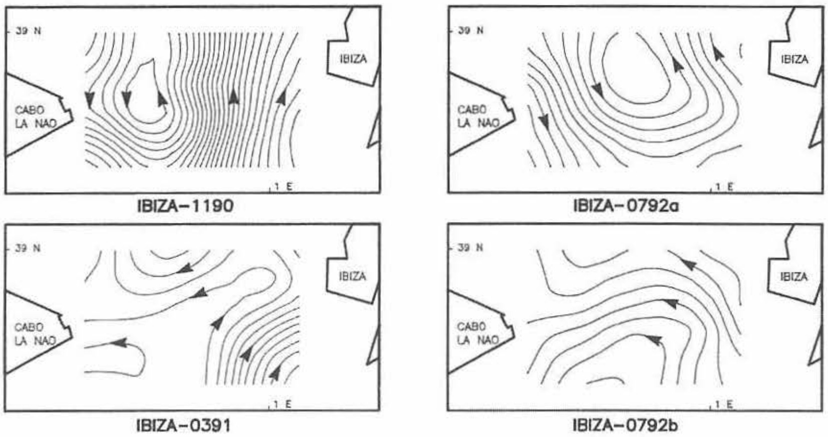

Figure 2 – Anomalies of dynamic height (relative to 600 dbar) at the surface, with contour interval of 0.5 dyn cm. Arrows indicate the direction of the flow (from LOPEZ-JURADO *et al.*, 1995).

MAW, characterized by a salinity lower than 37.5 psu, are systematically detected in both channels down to 150 m. As they enter the channels on the eastern side, MAW generate sharp density gradients with LAW so that narrow fronts are generally observed. Their spatio-temporal pattern is however highly variable. They are generally associated with energetic geostrophic frontal jets, typically 15 km wide and 150 m deep, with maximum velocities reaching 50 $cm.s^{-1}$ as was observed in March 1993 in the Mallorca Channel. Wider and weaker fronts are also found, associated with less deep and less energetic jets. These jets systematically involve northward transport over the eastern slope. The year-round presence of MAW in the Balearic channels supports the hypothesis of a northern MAW branch in the Algerian basin. However, data assess a strong seasonal variability of the northward MAW transport in the Balearic channels. The largest MAW inflows (0.8 Sv in the Ibiza Channel and 0.7 Sv in the Mallorca Channel) were observed in November 1990 and March 1993 respectively.

Intermediate waters

WIW are found mainly in the Ibiza Channel just below the surface waters and above the Levantine Intermediate Water. They are characterized by a temperature minimum ($T<13\,°C$) but exhibit a wide range of salinities ($37.7<S<38.3$ psu). However, as salinity values so low as 37.7 psu seem to indicate, WIW may also be partially formed in the Valencia Gulf where they could eventually mix with fresh continental waters of the Ebro river. An important result is that the presence of WIW in the channels exhibits a strong seasonal variability directly related to their progressive formation in the northern regions during winter. WIW are first detected in the channels in March, forming very thin lenses (20 m) entrapped within the LAW layer and extending over the whole width of the channels. The overlapping of light

MAW above LAW may favour the sinking of these lenses. During spring, these temperature minima evolve and salinity values are clearly higher, between 38.1 and 38.3 psu (Fig. 3). In late spring, WIW form a continuous layer which clearly separates the surface layer from LIW and fill the entire width of the Ibiza Channel. The thickness of this layer reaches values as high as 400 m. In November, no more WIW are found in the Ibiza Channel. This result seems to indicate that during summer and early autumn, WIW cross the channel and spread into the Algerian basin as suggested by KATZ (1972). Geostrophic velocities associated with WIW are lower than 15 $cm.s^{-1}$ and rapidly decrease with depth. On average, WIW flow southward – although recirculation may occur – and a maximum transport of 0.4 Sv was recorded in the Ibiza Channel in May-June 1993.

LIW form a continuous layer between 250 and 700 m in the Balearic channels. Cores of maximum salinity (38.50 psu) are found between 400 and 450 m, with potential temperatures between 13.2 and 13.4 °C (Fig. 3). Generally, LIW are observed close to the peninsula slope in the Ibiza Channel. In some cases however, LIW is found over the Mallorca slope. The associated geostrophic velocities are weak, rarely exceeding a few $cm.s^{-1}$, but this is strongly related to the no motion reference assumed at 600 dbar. Seasonal variations in the amount of LIW are observed, possibly in relation with fluctuations of the Liguro-Catalan current and DW formation processes (February-March) which may interrupt the inflow of LIW into the Balearic Sea. FONT (1987) suggests a period of three months for LIW to cross the Balearic Sea and reach the channels, with a speed about 5 $cm.s^{-1}$. Our cruise data show minimum salinity values in summer (July) and maximum in autumn (November). It is however not possible with the present data set to establish wether these differences are due to the interaction with DW formation or to the mixing with WIW. Furthermore, the progressive accumulation of WIW to the north of the channels and within the channels themselves increases the thickness of the WIW layer and reduces the section of the LIW layer constraining it to larger depths. It is also observed in the Ibiza Channel that the LIW core is detached from the continental slope and shifted towards the central part of the channel due to the presence of WIW above it (LOPEZ-JURADO *et al.*, 1995). The normal path of LIW is thus deflected towards the northern Balearic slope under the Balearic current as previously suggested by LOPEZ-JURADO (1990).

Deep waters

DW are found below LIW and can be detected at depths about 800 m to the north and south of the sills of the channels. Values of potential temperature less than 12.9 °C and salinity less than 38.46 psu are found. Within the channels, DW are surprisingly found at some isolated stations at shallower depths. Minimum values of DW salinity, about 38.42 psu, are measured in late autumn and winter, while maximum values are found in summer. This seasonal variability can be related to a greater mixing with the above LIW but also to cyclic DW formation events which would not be compensated by a simultaneous enhanced draining of DW through the Strait of Gibraltar into the Atlantic Ocean, nor by a greater rate of mixing with LIW. In this case, DW would accumulate in the Algerian basin and Alboran Sea, forcing the interface to rise. Summer seems a propitious time for this uprising to occur.

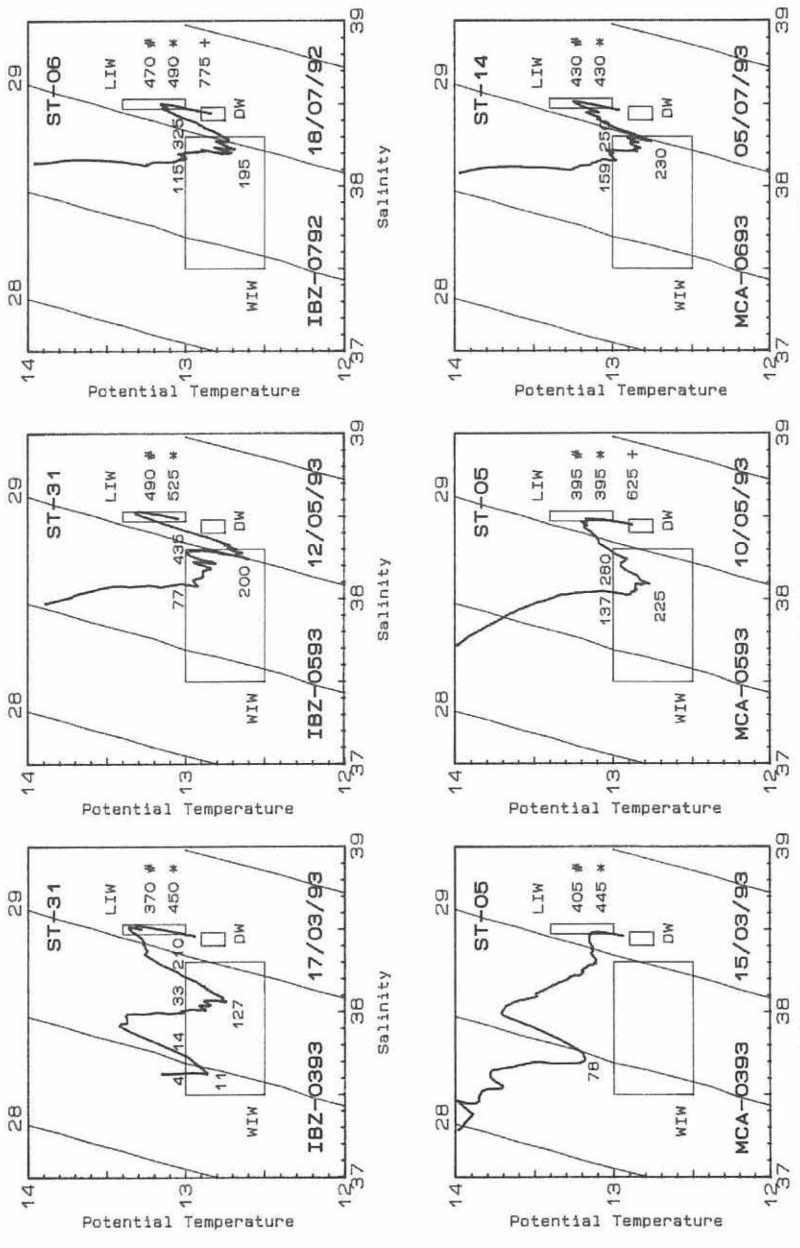

Figure 3 – T-S diagrams for several CTD stations in the Ibiza Channel. Depths at the most significant points are shown: (#) LIW maximum of temperature, (*) LIW maximum of salinity, (+) depth at which DW was first recorded. Also, starting and finishing depths of WIW (T<13 °C) are shown in some graphics. The small frames correspond to the local values of these waters.

FLOW VARIABILITY IN THE IBIZA CHANNEL

The scope of this section is to describe the low frequency flow variations through the Ibiza Channel, as inferred from currentmeter observations. These data help to make the link between the different circulation patterns observed during the repeated hydrographic surveys described above. Mooring observations also include temperature and salinity data, so that identification of water masses flowing at different depths can be easily made. By combining velocities and T-S measurements a good description of the variability of the year-round evolution of each water mass can be achieved. In general terms two different flow structures are found depending on the time of the year (GARCIA-LAFUENTE *et al.*, 1995): a two-layer baroclinic flow separated by an almost motionless layer at intermediate depths during winter (Fig. 4A), which gradually transforms into a barotropic flow in spring and early summer (Fig. 4B). Formation of WIW likely plays a key role in this transformation. Differences in the vertical structure of the flow seem to be the most noticeable seasonal characteristic of the circulation through the channel, but there are other features equally interesting.

MAW intrusions

In agreement with hydrographic data, mooring data show that autumn is a propitious time for the arrival of large amounts of MAW. Three intrusions are easily identified by a sudden increase of the flow speed in the upper layers (see arrows on Fig. 4A) simultaneously with displacements of T-S points corresponding to these layers toward the top-left corner (T-S diagram on Fig. 5A). The first intrusion (Fig. 4A) is rather well documented since it occurred in November 1990 when a hydrographic survey (IBIZA-1190) was being carried out. A northward MAW transport of +0.8 Sv was estimated from hydrographic measurements (Fig. 2 and Table I). The two other intrusions may involve higher transports (GARCIA-LAFUENTE *et al.*, 1995). All of them could be related to the circulation in the southern basin, principally to the variability of the Almeria-Oran front (see Fig. 6). An estimation of 1.8 Sv for the MAW transport out the Alboran Sea is given by VIUDEZ *et al.* (1995). Hence 0.8 Sv would represent practically one half of it. Thus, under the "anomalous" situation depicted on Figure 6B the north vein could account for one half or even more of the MAW leaving the Alboran basin, to the detriment of the Algerian current. Taking into account the lack of mooring data in the upper layer, the occurrence of smaller intrusions (*i.e.* not so deep-reaching) all year long cannot be discarded. However, the largest ones took place during autumn and early winter. This time of the year offers a great thermal contrast between LAW and inflowing MAW and, hence, may reinforce the opportunity of formation of a strong Almeria-Oran front. A decay of this front then (whose causes have to be investigated) would be followed by the release of a large amount of MAW to form the north vein which eventually would reach the Balearic channels as a jet.

Intermediate circulation: LIW and WIW

Only one of these intermediate water masses, LIW, is present all year long in the Balearic channels. The other, WIW, is of seasonal nature giving rise to a seasonal circulation at intermediate depths through the channels. When WIW are not present, LIW can flow freely following its usual path

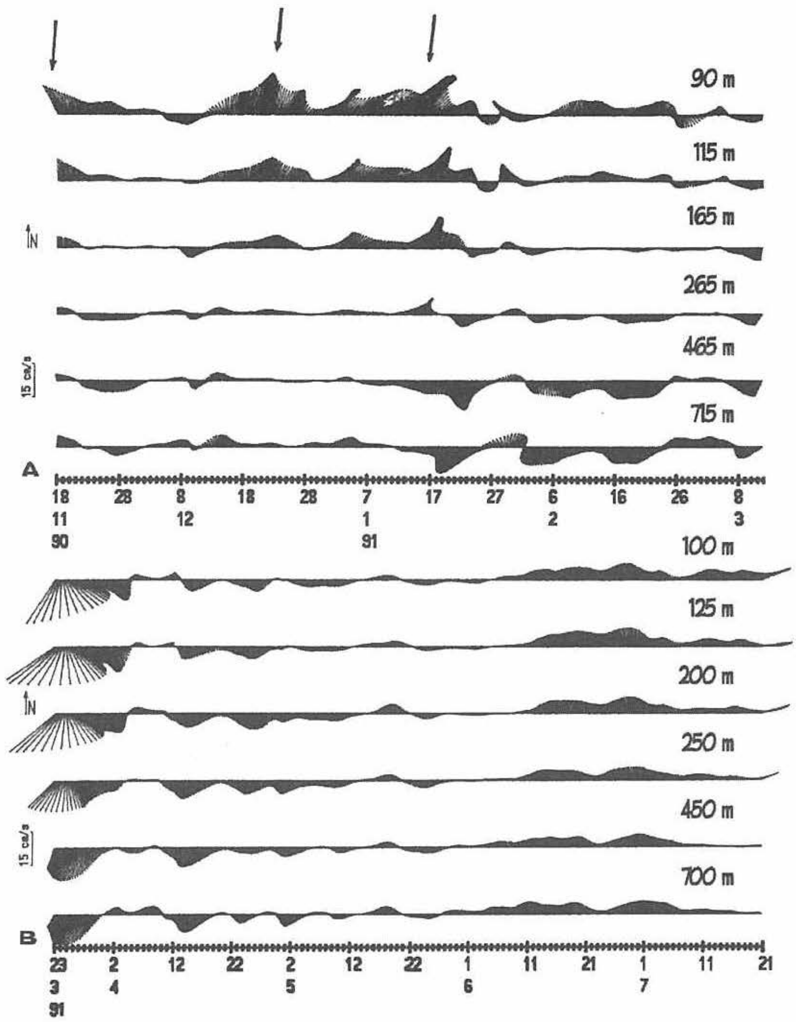

Figure 4 – Stick diagram of the horizontal velocity at the depths shown on the right side, during the periods seen on the abscisa axis. Arrows on Figure 4A indicate the MAW intrusions discussed in the text. Note the different vertical structure (baroclinic vs. barotropic) of the velocities in the different sampling periods (from GARCIA-LAFUENTE *et al.*, 1995).

toward the Alboran Sea as explained in the previous section. But the WIW layer interferes with the overall circulation through the Ibiza Channel. First appearance of WIW occurred by the middle of February; the water in question was fresher and less dense than in summer, placing it at an equilibrium depth of around 100 m (Fig. 5B) on top of the LIW layer, which remained largely unaffected by the WIW arrival at this time. On Figures 5D to 5F, from April to June, T-S characteristics, equilibrium depth and thickness of the WIW layer were similar to the values observed by PERKINS and PISTEK (1990). Their arrivals replaced gradually the LIW and affected its

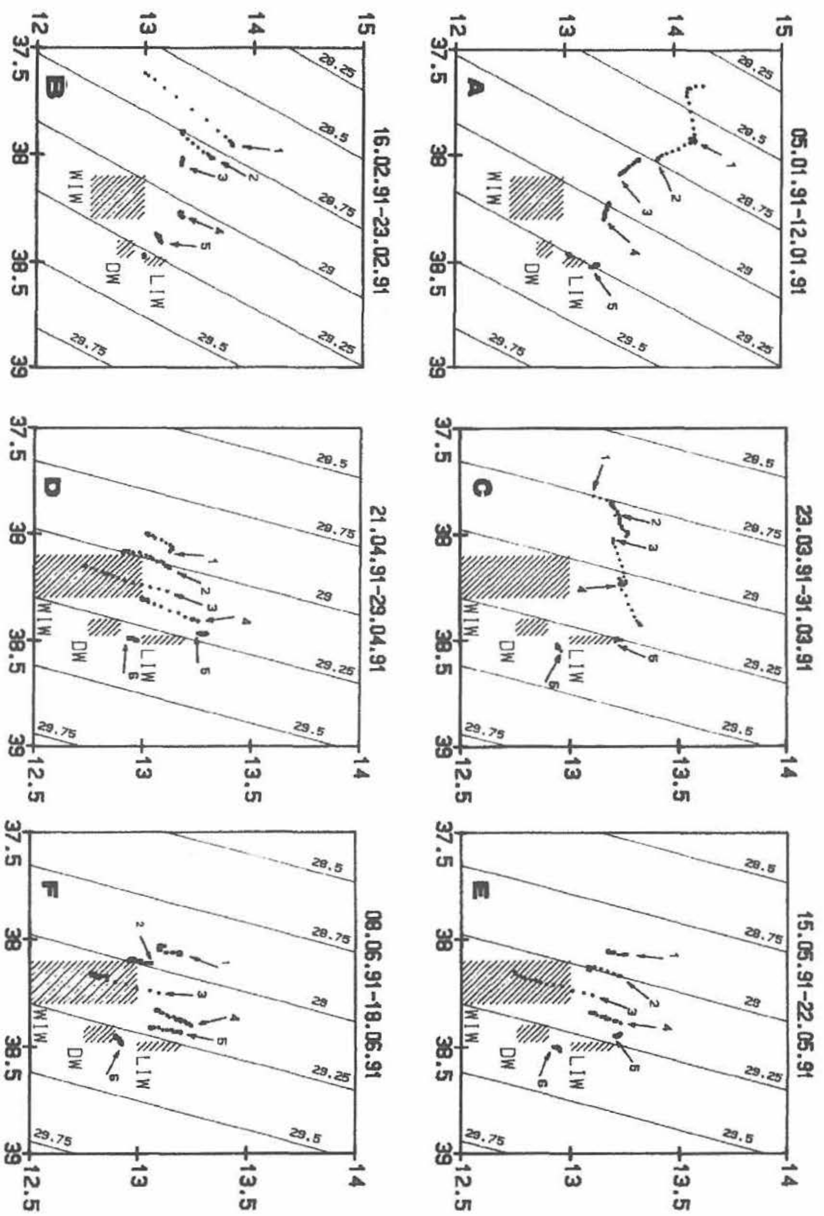

Figure 5 – T-S diagrams showing the "Eulerian" evolution of the water masses characteristics. The small numbers beside the arrows indicate the depth of the measurement in the same order that shown on Figure 4, and their tips mark the first T-S value of the represented period which appears on top of each diagram. Two consecutive points are twelve hours apart. Shaded areas indicate the position of WIW, LIW and DW on the T-S diagram according to their usual standards. MAW lie beyond the top left corner. Displacement of the points shows the local evolution of the water at a given depth (adapted from GARCIA-LAFUENTE *et al.*, 1995).

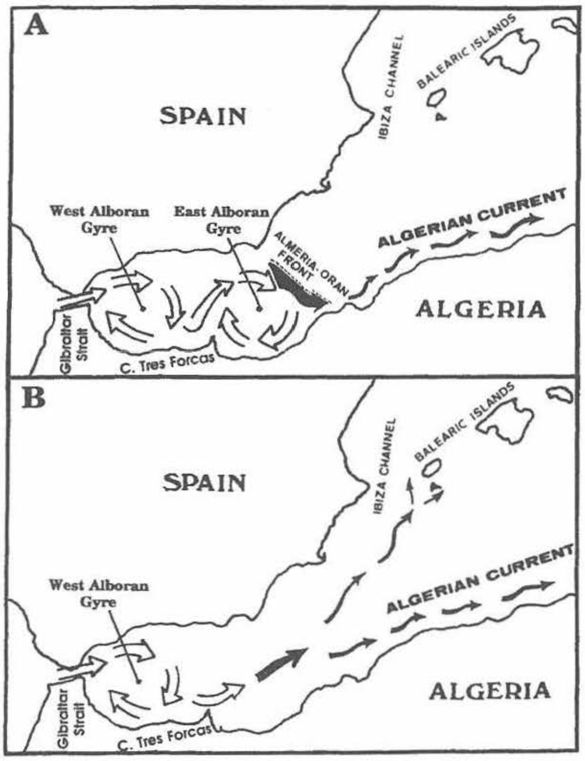

Figure 6 – Likely paths of Atlantic Waters (AW) in the Alboran Sea and Algerian basin. (A) "Normal" situation: AW describe two large anticyclonic gyres in the Alboran Sea. The eastern gyre is bounded by the Almeria-Oran front which, at the same time, guides AW along the African coast to form the Algerian current (TINTORE *et al.*, 1988). (B) "Anomalous" situation: The eastern gyre has disappeared or, if not, it is confined to a rather small area east of Cape Tres Forcas. MAW leaving the Alboran Sea splits in two veins, one to the east forming the Algerian current, the other flowing northward which eventually reaches the Balearic Islands (ALLAIN, 1960; HOPKINS, 1985). Under these conditions the Almeria-Oran front can not be present or must have a different orientation and strength. MAW intrusions in the Balearic channels are fully compatible with this "anomalous" situation.

circulation. Not much energy was involved in such replacements: points in T-S diagrams run parallel to lines of constant s_t when an arrival of WIW occurs (Fig. 5). As derived from hydrographic data, local replacements imply a LIW deflection from its usual path along the west side of the channel towards its eastern part, even towards the Mallorca Channel.

Moreover, WIW have an obvious influence on the homogenization of the water column and, hence, on the barotropic structure of the flow observed during spring and summer, times when their presence is particularly felt (Fig. 5F). Although on average they flow southward, as described previously, stagnancy and flow reversal periods do also occur. WIW progressively disappeared by mixing with other water masses and spreading through the channels into the Algerian basin. In 1990, WIW disappeared before November, as they were found during the IBIZA-1190 survey. One intringuing feature was the strong LIW intrusion observed in March 1991 (Fig.4B) which affected most of the water column (note the displacement of the points in the T-S diagrams of Fig. 5C towards the zone of LIW influence). Once the intrusion was over, the gradual replacement of LIW by WIW begun.

Deep circulation: DW

The depth of the interface between intermediate and deep waters in the Western Mediterranean Sea reported by STOMMEL *et al.* (1973) and LACOMBE *et al.* (1981) is comparable to the sill depth of Ibiza Channel (700 m). Although traces of DW appeared regularly on both sides of the sill during most of the CTD surveys carried out in the channels, it does not mean that DW are flowing from one side of the sill to the other. However, robust evidence for a deep flow comes from currentmeter observations. The deepest instrument (700 m) detected a weak DW flow to the north close to the sill from early June to July (Figs. 4B and 5F). It could be explained by the joint action of "new DW" accumulation in the Algerian basin and favourable mesoscale motions there able to lift the interface above the sill depth in the southern part of the channel, forcing this northward flow. If so, it would not be an unexpected feature but a seasonal (summer) characteristic of its circulation. Moreover, studies of bottom topography (CARTER *et al.*, 1972) pointed out the existence of sharp and narrow passes across the sill, which would favour such seasonal circulation of DW.

CIRCULATION IN THE BALEARIC SEA

The circulation in the Balearic Sea is largely controlled by the fluxes through the Balearic channels which form its southern boundary. Analyses of CTD and ADCP data (FONT *et al.*, 1988; CASTELLON *et al.*, 1990; GARCIA *et al.*, 1994) have shown that the circulation in the surface layer of the Balearic Sea is controlled by two quasi-permanent slope fronts: the Catalan front/current (0-400 m) located over the continental slope and the Balearic front/current (0-150 m) located over the insular slope. The Balearic front is due to the MAW inflow through the Balearic channels (see previous sections). It forms at the boundary between low salinity MAW and saltier LAW. The northward Balearic current advects MAW along the north-western coast of the Balearic Islands and the front is established over the slope. The Mallorca Channel plays an important role in the circulation of the southern Balearic Sea. The inflow or outflow of MAW through the Mallorca Channel can respectively enhance or decrease the northward Balearic current transport. Over the continental slope, the Catalan front is due to the salinity gradient between relatively fresh slope waters flowing from the Gulf of Lions in the surface layer and saltier open sea LAW. This front can be locally enhanced off the Ebro Delta due to river runoff onto the shelf.

Both the Balearic and Catalan currents are vertically sheared with maximum velocities about 30-40 $cm.s^{-1}$ at the surface. Several studies have emphasized a high mesoscale activity in the vicinity of both fronts (LA VIOLETTE *et al.*, 1990; PINOT *et al.*, 1994; LOPEZ-GARCIA *et al.*, 1994) consisting in the ocurrence of energetic gyres, meanders and filaments. These features with typical size of 40-50 km may arise from natural dynamical instability of the frontal currents. Such instabilities are characterized by cross-slope circulation which may have important consequences for the normally along-isobath oriented main flow in the channels. These instabilities may thus contribute to the high variability of circulation patterns observed in the Ibiza Channel.

The Catalan current does not systematically cross the Ibiza Channel. Objective analyses (PINOT *et al.*, 1995) have shown that an interaction between the Catalan and Balearic currents take place in the southern Balearic Sea, forcing the Catalan current to leave the slope and veer cyclonically offshore, back to the north (Fig. 7). This interaction may explain the weak southward transport observed at the same time through the Ibiza Channel. Apparently, two reasons can be given for the deviation of the Catalan current to the north. First of all, the existence of an energetic northward inflow of MAW through the Ibiza Channel at this time is likely to prevent any significant southward flux, at least in the upper layer (0-150 m). Second, a WIW gyre has also been observed to the north of the Ibiza Channel, which provokes the offshore shifting of the Catalan current at all depths (PINOT *et al.*, 1995). A slope-to-slope transect of temperature to the north of the Ibiza Channel (Fig. 8A) indicates that a large and cold WIW patch over 70 km

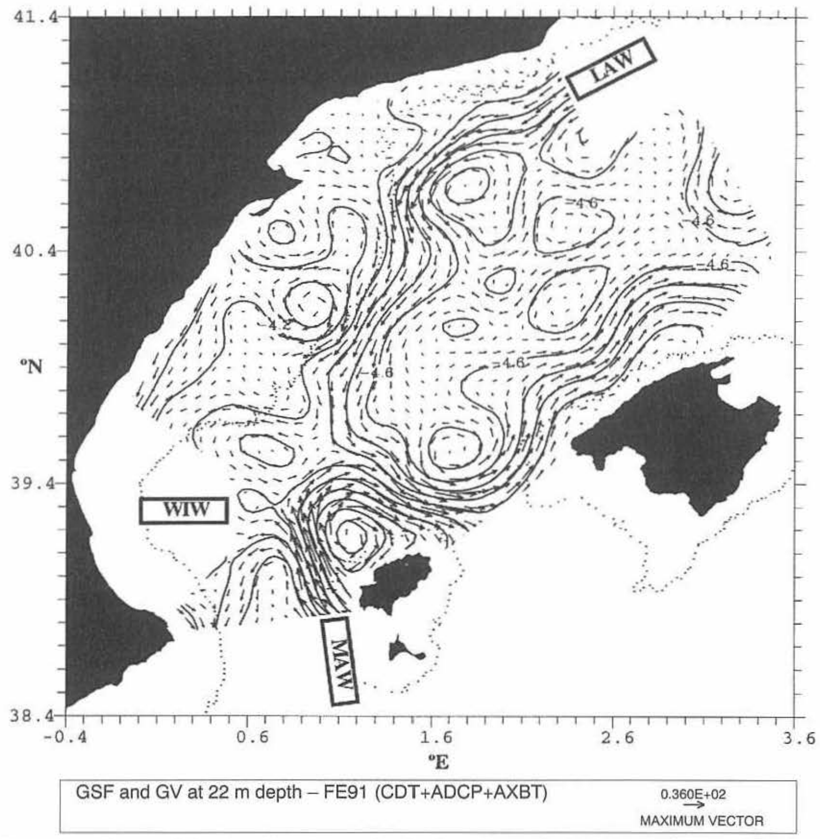

Figure 7 – Geostrophic streamfunction and velocity at 22 m depth inferred from multivariate objective analysis of CTD, ADCP and AXBT data collected during FE91 experiment (June 1991). Maximum velocity is 36 cm.s^{-1} (from PINOT *et al.*, 1995).

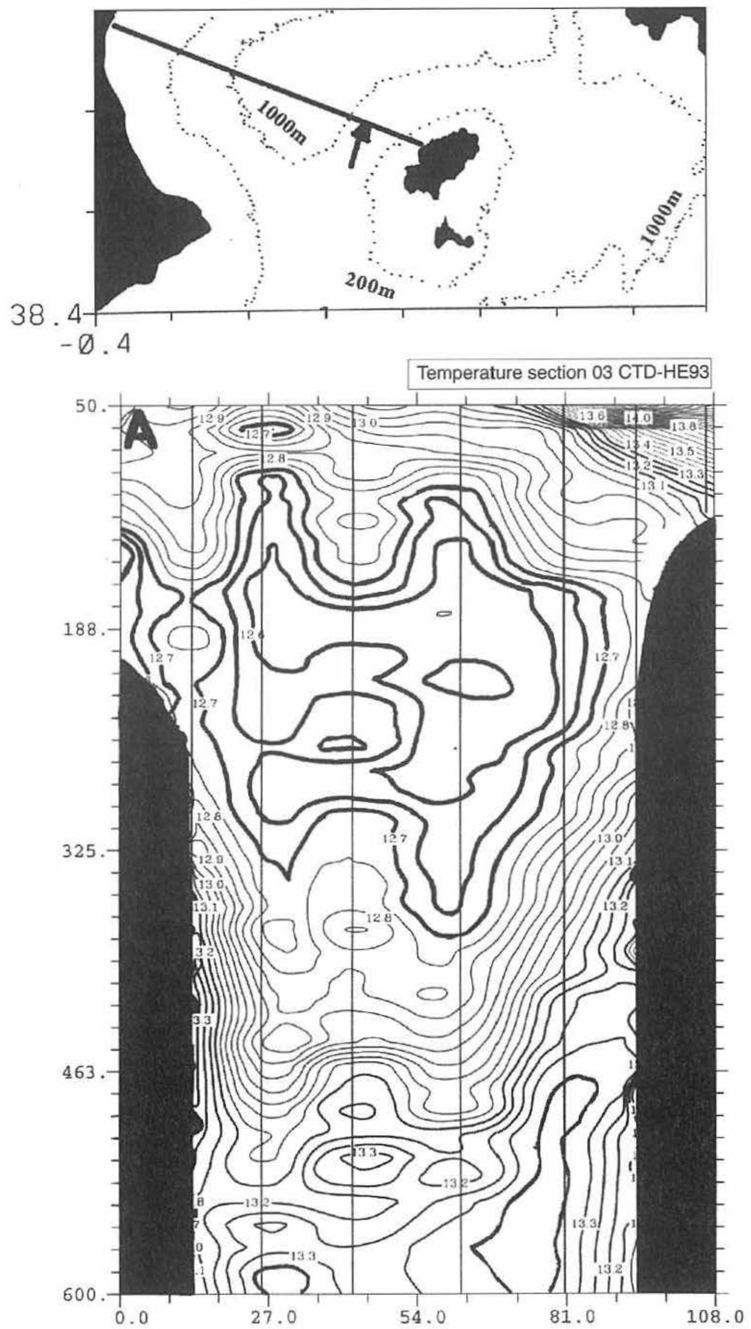

Figure 8A – Cross-basin vertical section between the peninsula slope (left) and the Ibiza slope (right) in June 93 : temperature.

wide that extends from 80 m down to 350 m, lays to the north of the Ibiza sill. However dynamics is controlled by salinity which is relatively low within this patch (Fig. 8B), inducing an anticyclonic circulation to the north of the Ibiza Channel. The morphology of the Balearic basin at this place may come into play for trapping WIW that would accumulate in the southern basin and slowly flow throughout the Ibiza Channel. It seems thus that WIW has significant implications for the exchanges through the Ibiza Channel which could temporarily be reduced or even blocked when WIW

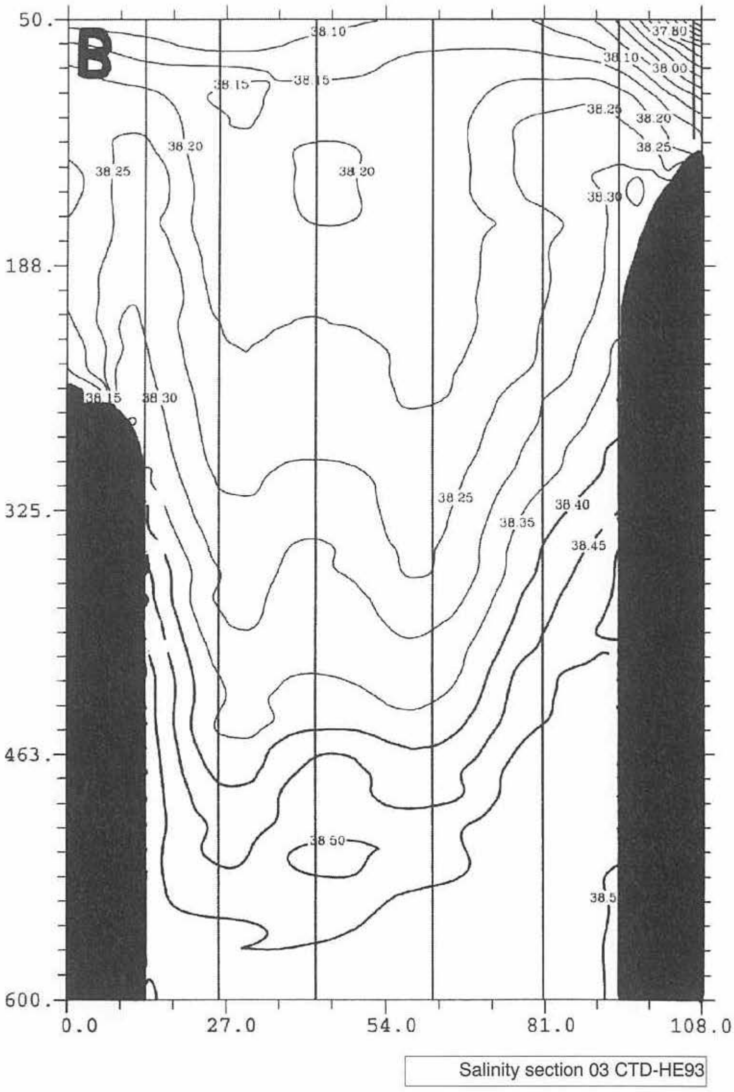

Figure 8B – Cross-basin vertical section between the peninsula slope (left) and the Ibiza slope (right) in June 93 : salinity.

accumulation is maximal. Results provided in previous sections indicate that a large amount of WIW is present in the Ibiza Channel during at least half the year, from late winter to late summer.

Recent extensive data sets collected in June 1989, June 1991 and June 1993 (GARCIA *et al.*, 1994; PINOT *et al.*, 1995) lead to the conclusion that there exists a real interannual periodicity in the exchanges through the Ibiza Channel. The map of geostrophic mass transport in June 1993 shown in Figure 9 can be considered representative of the summer circulation in the Balearic basin. It essentially shows the typical features of the summer circulation: the substantial northward MAW inflow (0.5 Sv) through the Ibiza Channel, the southward Catalan current transport of 0.9 Sv entering through the northern boundary, the offshore shift of the Catalan current in the southern basin and the weak southward outflow through the Ibiza Channel (0.2 Sv). Fluxes through the Mallorca Channel are also substantial in June 1993 but they seem to be associated with a cyclonic meander of the Balearic current over the sill between Ibiza and Mallorca. In June 1989, however, geostrophic transports provided the major inflow of MAW through the Mallorca Channel (GARCIA *et al.*, 1994).

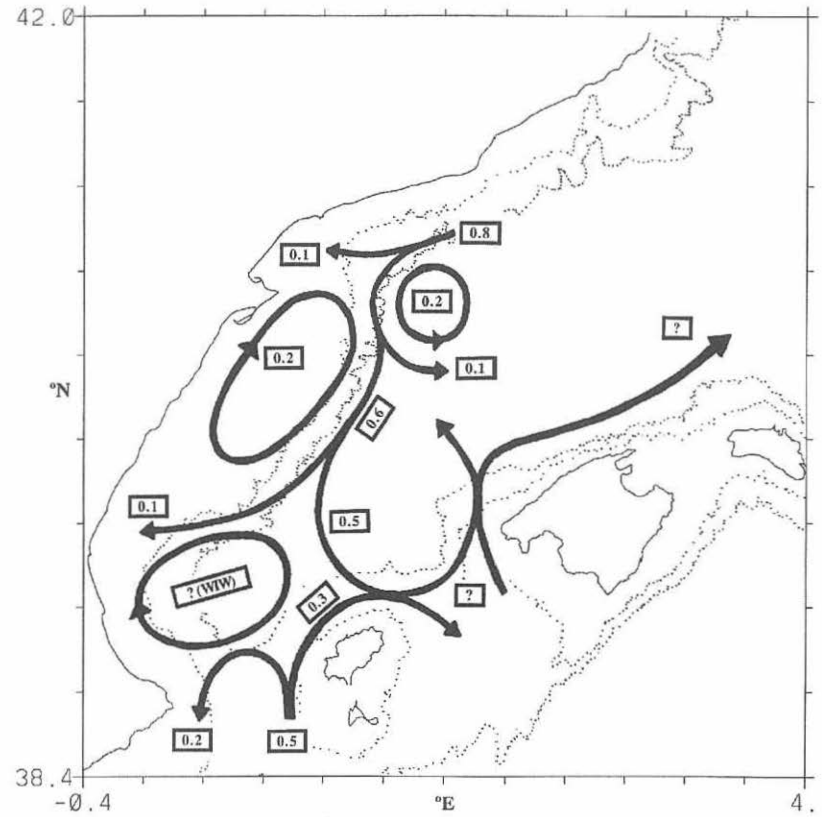

Figure 9 – Geostrophic transport (in Sv) integrated for the [0-400] m layer with a reference level at 600 m June 1993.

MODELING OF THE GENERAL CIRCULATION IN THE WESTERN MEDITERRANEAN

The primitive equation Modular Ocean Model (MOM) (BRYAN, 1969; SEMTNER, 1974; COX, 1984) was used to investigate general aspects of the feedback relation between the Balearic Sea circulation and the Western Mediterranean general circulation. To represent the Western Mediterranean, a 22 km resolution horizontal grid was designed and two reservoirs were included to simulate the Atlantic Ocean and the Eastern Mediterranean. 23 vertical layers ranging from 5 m to 2 760 m were used, based on the bathymetry of BECKERS (1992). Three islands were included: Corsica-Sardinia, Mallorca and Ibiza. The model was forced with monthly wind data from MAY (1982). Surface T and S forcings and initial data were taken from LEVITUS (1982). In the two reservoirs wind and surface forcings were not included while T and S fields were constantly relaxed to those of LEVITUS (1982) with a relaxation time of 60 days. Finally, the Neptune effect parametrization (HOLLOWAY, 1992) was implemented in order to capture some of the non-linear features of the eddy-topography interaction at small scales lost by the coarse resolution.

After 20 years of simulation, when an almost stationary state is reached, transports through the straits of Gibraltar and Sicily are 0.8 Sv and 1.1 Sv respectively, both of them very similar to the values derived from observations (BRYDEN *et al.*, 1988) and from salt balance estimations (BETHOUX, 1979). The obtained salinity field indicates the existence of a permanent branch of MAW in the Algerian basin towards the Balearic Sea. Note that the coarse horizontal resolution used does not allow the representation of mesoscale fluctuations like the Alboran gyres or Algerian instabilities. The associated inflow of MAW through the Ibiza Channel is practically constant (0.3 Sv) and generates the Balearic front, one of the most important features in the dynamics of the Balearic Sea. With a total depth of almost 200 m (Fig. 10), MAW follow the Balearic Islands slope in a north-east path and reach the north of Menorca. At this place, MAW flow eastward contributing to the generation of the northern Balearic front and the west Corsica current (Fig. 11). It is possible to infer from these results that any blocking mechanism of MAW which occurs in the Ibiza Channel induces important modifications on the circulation pattern in the north-western Mediterranean. In the Western Balearic Sea, model results show the existence of LAW flowing along the continental Spanish slope towards the Alboran Sea (Fig. 11). Complex interactions between this southward current and the northward MAW inflow can be inferred in the Ibiza Channel. As a result, part of the LAW crosses the Ibiza Channel and follows its path towards the Alboran Sea, while the other LAW are deflected northward towards the Balearic Island slope where they merge with MAW (Fig. 11). Again, model results indicate that processes in the Ibiza Channel may have an important role in the exit or recirculation of LAW and so may partially determine the balance between the Atlantic Ocean and the Western Mediterranean.

CONCLUSIONS

The results obtained from the study of the Balearic channels show that they are transition areas through which most of the Mediterranean water masses transit. The analysis of T-S properties and transports based on *in situ*

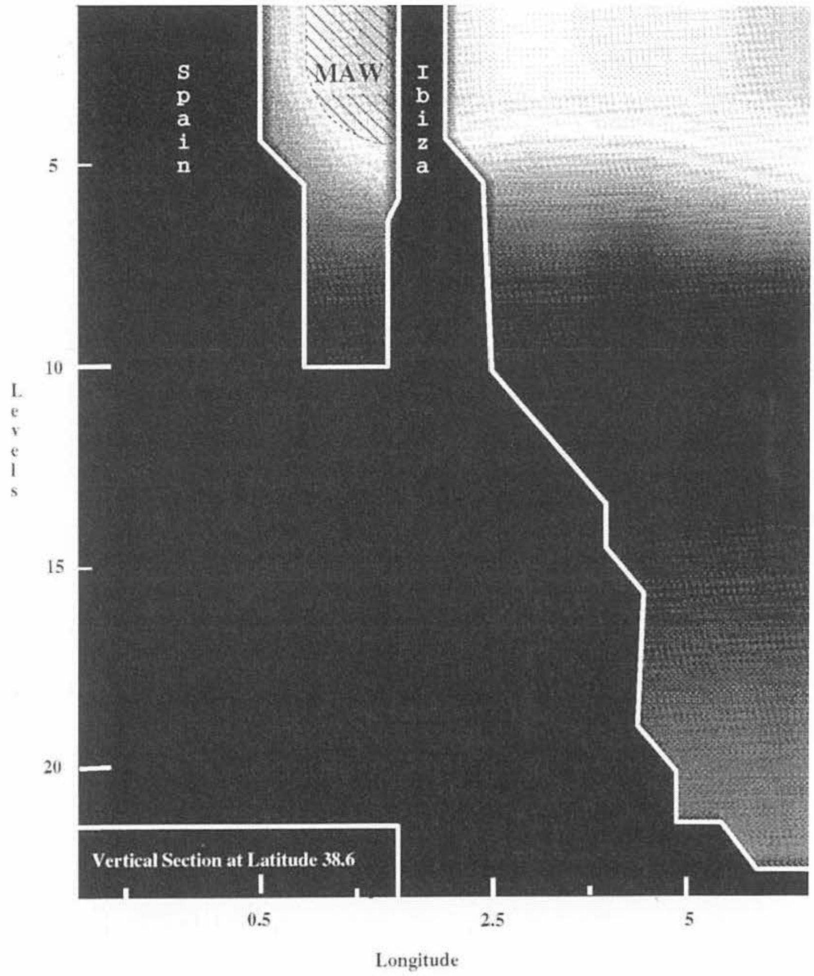

Figure 10 – Vertical zonal cross-section in the Ibiza Channel of the salinity field from the model output. Shaded area indicates the northward inflow of MAW into the Balearic Sea.

data indicates a highly variable flow regime through the channels, on both the seasonal scale and mesoscale. MAW are found almost systematically in the channels but mooring data indicate that this is the result of transient mesoscale pulses from the Algerian basin toward the Balearic basin. However, the strongest intrusions are detected in autumn and early winter indicating a possible seasonal variability of the northward MAW flow. WIW are found in the channels from winter to late summer. They likely accumulate to the north of the Ibiza Channel in winter and flow slowly southward during spring and summer. The southward LAW transport has also a high variability which is probably due to the seasonal variability of the Liguro-Catalan current and to the transient adjustments with MAW and WIW in the

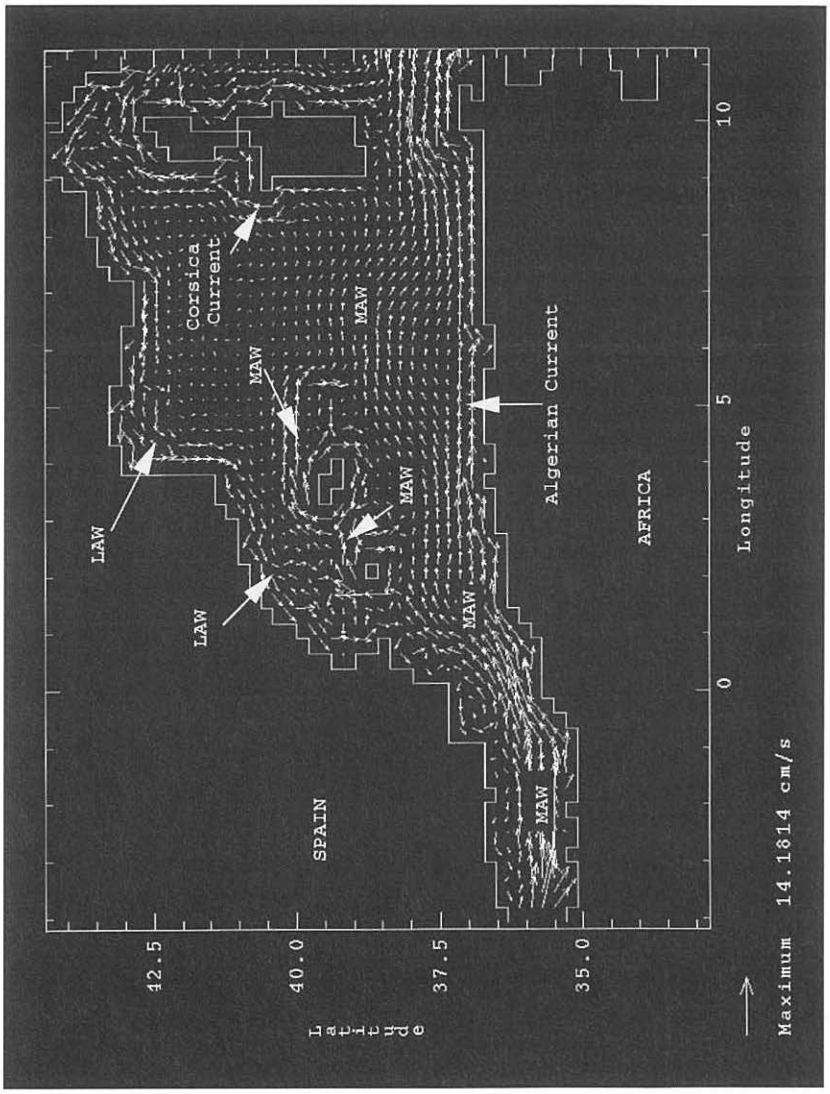

Figure 11 – Circulation in the surface layer (80 m) after 20 years of simulation.

channels. LIW circulation through the channels is also affected by WIW which partly occupy the intermediate layer.

This suggests that the dynamics of the exchanges through the Balearic channels can have major consequences for the general circulation in the Western Mediterranean. This is supported by the results obtained from a modeling study of the general circulation. The northward MAW inflow contributes to the Balearic current on the islands slope and to the north-eastward outflow off Menorca which may be partly responsible for the northern Balearic front. Also, model results show that the southward

Liguro-Catalan current can be deflected northward, before reaching the channels, and contribute to an enhanced north-eastward Balearic current. *In situ* data indicate that the presence of WIW to the north of the Ibiza Channel may enhance this deflection by blocking the southward LAW and LIW transport. Finally, this blocking of the southward LAW circulation, by affecting the dynamics of the Almeria front, may have major consequences on the MAW flow exiting the Alboran Sea.

Dynamical processes in the Algerian and Balearic basins are intimately related to strong water masses interactions in the Balearic channels. From this perspective, the Balearic channels can be considered as key places that fundamentally control the fluxes between the south and north of the Mediterranean. In this sense, future monitoring of the exchanges through these channels will provide invaluable knowledge for the understanding of the general circulation.

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