The Balearic current and volume transports in the Balearic basin

Circulation
Western Mediterranean
Balearic current
Hydrography
Volume transports

Circulation
Méditerranée Occidentale
Courant des Baléares
Hydrologie
Transport de masses d'eaux

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ABSTRACT

The Balearic basin is a semi-enclosed basin located in the western Mediterranean Sea, connecting the Gulf of Lions and the Alboran basin. While the characteristics and circulation of the water masses have been rather well established, the exchanges with adjacent basins, essential to our understanding of the circulation in the western Mediterranean and for validating outputs of general circulation models, have never been determined in detail. We present here the data from the FE-89 (June 1989) Spanish cruise, during which high-resolution CTD and ADCP measurements were performed on the open boundaries of the Balearic basin. The fluxes for all the boundaries were calculated in a quasi-synoptic fashion. The values found in the Ibiza and Mallorca channels contrast with those given by other authors. The cruise also allowed us to sample and determine the main characteristics of the Balearic front; the associated current flows SW to NE along the Balearic shelf, and the transport found is about 0.75 Sv. In contrast with the findings from previous analyses, these results suggest that the Balearic front is a permanent feature.

RÉSUMÉ

Le courant des Baléares et les flux d'eaux dans le bassin des Baléares.

Le bassin semi-fermé des Baléares se trouve en Méditerranée occidentale, entre le golfe du Lion et la mer d'Alboran. Les caractéristiques et la circulation des masses d'eau sont assez bien connues, mais les échanges avec les bassins adjacents n'ont jamais été déterminés dans le détail ; leur connaissance est pourtant essentielle pour expliquer la circulation dans la Méditerranée occidentale et pour valider les modèles de circulation générale. Ce travail présente les données de la campagne espagnole FE-89 (juin 1989) au cours de laquelle des mesures à haute résolution d'hydrologie CTD et de courantométrie ADCP ont été effectuées aux frontières ouvertes du bassin des Baléares. Les flux aux frontières ont été calculés par une méthode quasi-synoptique. Dans les canaux d'Ibiza et de Majorque, les valeurs trouvées contrastent avec celles données par d'autres auteurs. La campagne a permis également d'échantillonner et de déterminer les principales caractéristiques du front des Baléares ; le courant associé est orienté du SW vers le NE le long du plateau continental des Baléares, et le transport calculé est d'environ 0,75 Sv. Ces résultats suggèrent, moyennant quelques hypothèses supplémentaires, que le front des Baléares a un caractère permanent.

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INTRODUCTION

The circulation in the upper layer of the western Mediterranean is cyclonic, with significant sub-basin scale structures and forcings. Hopkins (1978) reviewed the dynamics of the Mediterranean system basins and made a systematic description of the main physical processes relevant to the general circulation, showing that the Alboran Sea and the Gulf of Lions are sites where the two main forcings in the western Mediterranean circulation – thermohaline forcing and wind stress – are well represented.

More recently, Millot (1987), proposing a scheme for the circulation of the Modified Atlantic Water (MAW) flowing in the upper 100-200 m of the entire basin, distinguished two main flows in the Mediterranean surface circulation. The north of the basin has a well defined current (the Liguro-Provenço-Catalan or Northern current); and the southern part, east of the Alboran Sea, has a strong eastward current characterized by high mesoscale variability (the Algerian current). Millot (1991) also described observations of large-scale anticyclonic eddies in the Algerian basin, pointing out the possibility that these eddies can eventually deflect northwards the main flow of MAW, thereby modifying the circulation in the Balearic basin. More recently still, Tziperman and Malanotte-Rizzoli (1991), who used an inverse method and obtained climatological seasonal maps of the upper and deeper circulation, found significant differences in the surface circulation. East of the Alboran Sea, the MAW forms two branches: an eastward current along the African coast and a "new" northeastward flow that enters the Balearic basin between the Island of Ibiza and the mainland. This circulation pattern appeared in all seasons, the currents being stronger in winter.

The first numerical models of the western Mediterranean stressed the importance of wind stress. The results of these numerical studies are in agreement with field observations in locations where local winds are particularly strong and essentially climatological winds, *e.g.* the Gulf of Lions (Heburn, 1987; Arnould *et al.*, 1988). More recently, large-scale numerical models have taken into account both wind stress and thermohaline forcing through the Strait of Gibraltar (Pinardi and Navarra, 1989; Beckers, 1992 ; Herbaut *et al.*, 1994). From these and some other local studies (Wang, 1990; Schott and Leaman, 1992; Beckers and Nihoul, 1992), it can be deduced that the Western Mediterranean is a semi-enclosed sea which in a relatively small area contains many different forcings with great variability at the basin and sub-basin scales.

In general, observational studies are essentially in agreement with numerical results. Although the latter are limited by a difficult choice of the initial conditions, the coarse grids and the forcings used, the large-scale pattern associated with the cyclonic circulation is obtained. However, the circulation in the Balearic basin is systematically absent from large-scale numerical simulations. It is important to note that this basin is essential to our understanding of the circulation between two key areas of the western Mediterranean, the Liguro-Provençal and the Alboran basins. As described by Font *et al.* (1988) and La Violette *et al.* (1990), the general circulation in the Balearic basin is mainly dominated by the existence of two quasi-permanent frontal structures. The associated currents flow along the islands and continental shelf/slope respectively, but the origin and dynamics of these flows remain poorly understood. García and Djenidi (1991), in a local numerical study of the Balearic Sea, demonstrated the sensitivity of the circulation to variations of inflow and outflow through the open boundaries: the circulation patterns were rendered very different by slight modifications to the fluxes at the boundaries.

Recent observational studies have shown that circulation in the Balearic Sea is also characterized by a high temporal and spatial variability. Wang *et al.* (1988) and Tintoré *et al.* (1990) described well developed mesoscale filaments and eddies in the shelf/slope region of the continental side. Font (1990) observed repeated several-day flow reversal in current-meter records at the shelf break. These are instabilities associated with a thermohaline front lying along the continental slope. Along the islands slope, Font *et al.* (1988) remarked the presence of a second thermohaline front (the Balearic front) and estimated the associated transport from a few hydrographic data. However, knowledge about the characteristics of this permanent frontal structure is incomplete. It has been observed systematically in several cruises and satellite thermographies (La Violette *et al.*, 1990; López *et al.*, 1994), but its variability and the associated flow have not been quantified. Recent observations (Pinot *et al.*, 1994) have shown cold eddies and warm filaments in the Balearic Sea, suggesting that the mesoscale variability has an important impact on the circulation of Mediterranean and MAW waters through this basin and thereby affects the circulation in the western Mediterranean basin.

The objectives of this study are to describe the main physical characteristics of the Balearic current, and to determine, with relatively high synopticity, the fluxes at all the boundaries of the Balearic basin.

The data presented here come from an intensive field experiment carried out in June 1989, using a Conductivity Temperature Depth probe (CTD), an Acoustic Doppler Current Profiler (ADCP) and radio-tracked drifters. The data-set allow us to describe the main physical characteristics of the Balearic current and to determine, with relatively high synopticity, the fluxes at all the boundaries of the Balearic basin. At the end, the results in the frame of the Western Mediterranean circulation are discussed.

THE FE-89 CRUISE DATA

The FE-89 cruise took place from 4 to 19 June 1989 on board the Spanish R/V *García del Cid*. The first part of the cruise focused on encompassing the Catalan Sea in several hydrographic sections, in order to estimate the water exchanges with the outer domain (Fig. 1). In the second part, a small zone along the slope of the Balearic islands was sampled in order to survey the mesoscale field of the Balearic current. Simultaneously, four surface drifters were released and radio-tracked over a period of six days.

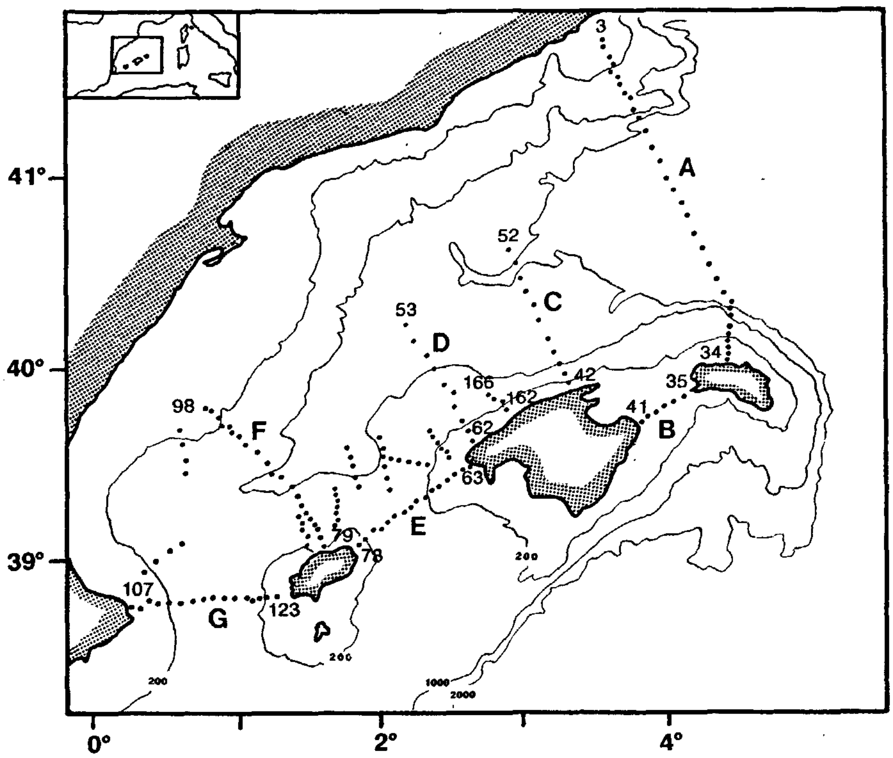

Figure 1

The Balearic Basin between the Spanish mainland and the Balearic Islands (western Mediterranean Sea). The markers represent the hydrographic CTD and ADCP casts made during the FE-89 cruise. The sections as referenced in the text are: A = Northern boundary, B = Menorca channel, E = Mallorca channel and G = Ibiza channel.

The CTD stations (Neil Brown Mark III probe) were set two nautical miles apart in the frontal regions, in order to obtain a much more detailed and complete description of the hydrographic structure than is provided in previous studies (*i.e.* Font *et al.*, 1988). In the vertical, the casts on the shelf and slope zones covered the water column near to the bottom. In the central zone, where bottom depths are about 1500-2000 m, the casts arrived generally to 1000 m depth, with a few stations as deep as 2000 m. The dynamic topographies were calculated using a level of no motion at 600 dbar. This level was specially chosen because it is sufficiently deep to capture the vertical structure of the currents in the basin and because the majority of the stations, including those on the island channels, extend to this depth. Over the slope, where a large topographic gradient occurs between two adjacent CTD stations, we have extrapolated the dynamic topographies using horizontal dynamic surfaces below the bottom. In order to determine the basin scale fluxes, we choose the large sections (Northern boundary, Mallorca and Ibiza channels and sections D, F, C, *see* Fig. 1) made during the first 10 days of the cruise. This is a short time scale to consider the data as quasi-synoptic and representative of the basin exchanges.

Direct current measurements were performed by means of a vessel-mounted ADCP (RD Instruments VM0150) system down to at least 350-400 m (integrated depth cell length of 8 m). The ADCP was designed to provide continuous as well as discrete sampling at the same locations as the CTD stations. In this case, ADCP profiles were averaged every 5 min. Whereas in shallow regions (less than 450 m), bottom tracking made it possible to know absolute water velocities, in deeper areas a reference level was needed, since navigational data were not sufficiently accurate for precise current determinations. We chose a level of no motion of 300 m, which is the deepest value always correctly recorded in the whole ADCP data set. This value give a reasonable match between bottom-tracked profiles and those where a reference level was needed: the differences found were always less than 5 cm/s (Castellón *et al.*, 1990). These data are often difficult to interpret because they can be affected by several mechanisms. While tides can be assumed not to be important in most regions of the western Mediterranean, inertial currents can on occasion be as intense as large-scale motions. Hence, the ADCP values may be affected, especially at the beginning of the stratified season. However, inertial oscillations have not been observed to disrupt the alongshore current on the continental slope except at the pycnocline level (Castellón *et al.*, 1990).

In order to determine the basin-scale fluxes, the data can be considered as quasi-synoptic since the cruise lasted only 15 days. However, because of the high temporal variability observed in the Balearic islands shelf/slope region we avoid using the complete data set. During the last five days of the cruise, several stations grouped in small sections were made in front of the Mallorca channel (*see* Fig. 1). Some of them were located near the position of stations made a week before (in sections D, E and F). The comparison between the vertical structures of neighbouring stations in space made one week later showed great differences in the upper 50 metres (García *et al.*, 1991).

OBSERVATIONS

Northern boundary (Section A)

Section A followed the boundary of the Balearic Sea with the south of the Gulf of Lions (*see* Fig. 1). The vertical hydrographic structure is typical of the western Mediterra-

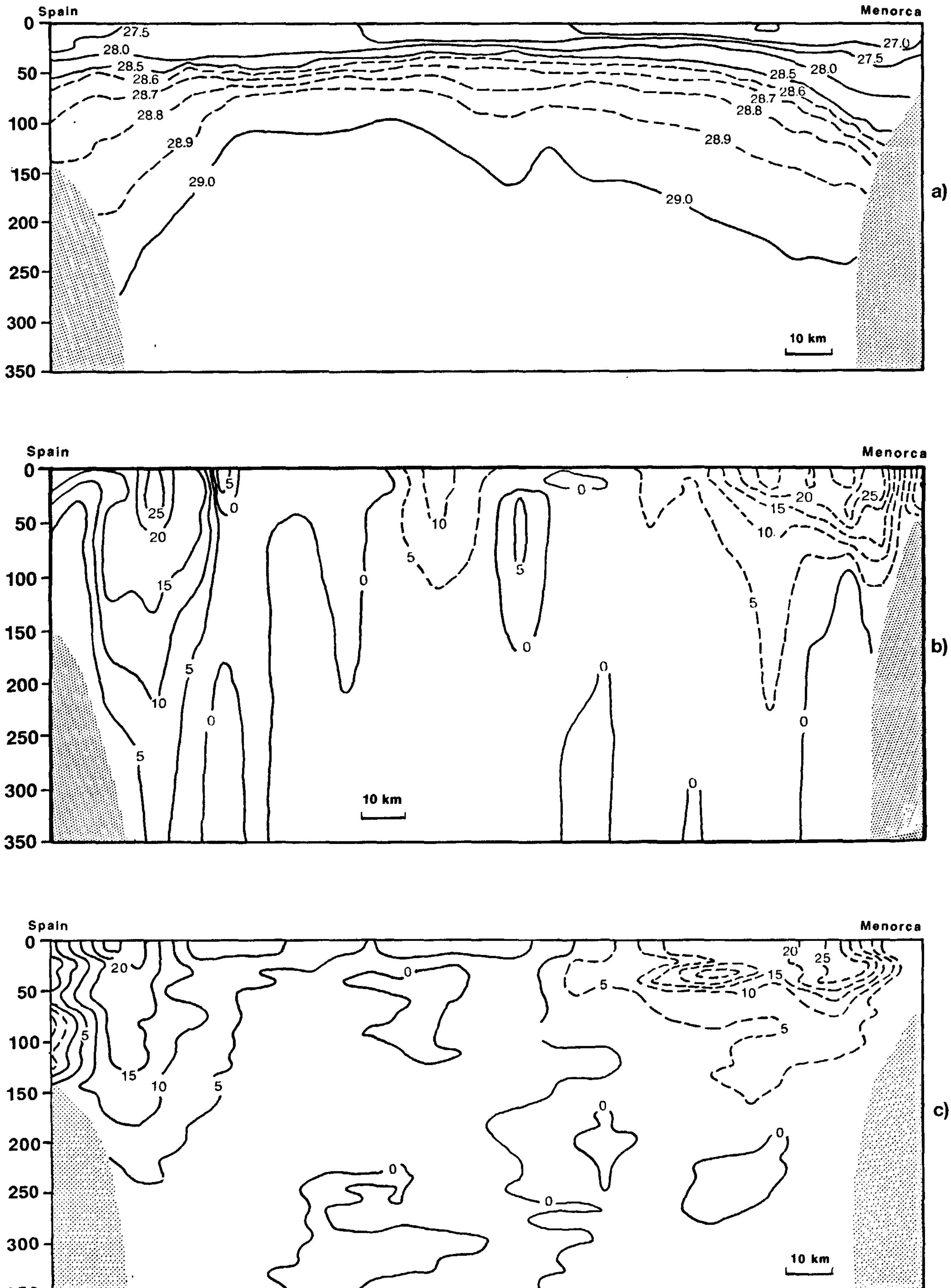

Figure 2

a) *Sigma-t,* b) *geostrophic currents and* c) *ADCP sections of the northern boundary.*

nean Sea at the beginning of the summer. There is a shallow mixed layer (first 30 m) with a sharp pycnocline separating an underlying weakly stratified zone (Fig. 2*a*). Two well-defined frontal structures on both sides of the section are worthy of note. On the continental margin (left-hand side of the picture), the front is formed by density changes between continental fresh waters (T ~ 14 °C, S ~ 38) and waters of the central basin (T ~ 13 °C, S ~ 38.3-38.4). Often identified as the Catalan front and constituting an extension of the Liguro-Provençal system (Millot, 1991), this is a shelf-break front, which is present all year round. On the eastern side, the differences between central waters and recent, less saline MAW (T ~ 15-16 °C, S ~ 37.2-37.5) characterize a second frontal structure usually identified as the Balearic front (Font *et al.*, 1988). The location of this second front is much more variable than that of the Catalan front and salinity would appear to be the most relevant tracer for its identification, especially in summer.

Both fronts seem to be associated with jet-like currents as may be seen in the vertical section of geostrophic currents (Fig. 2*b*). The Balearic front extends further offshore and is shallower than the Catalan front, and maximum velocities at the surface are of the order of 30 cm/s. Based on the 5 cm/s isoline as a boundary, the former reaches 100-150 m depth, while the latter reaches 250-300 m depth. The cross-section of the Doppler profiles is in fairly good agreement with the geostrophic computations (Figs. 2*b, c*). Both results show the same maximum velocities and spatial structure for the frontal currents. Finally, at the centre of the cross-section, neither the geostrophic velocities nor the ADCP measurements are significant, with velocities smaller than 5 cm/s.

Mallorca channel (Section E)

On the Mallorca sill (600 m depth), the vertical structure is well stratified (Figs. 3*a, b*). At the surface, the temperatures are typical of the summer season (22 °C) and the pycnocline defined between the isopycnals 26.4-27.2 is located at 10 m depth. The presence of MAW is evident from the low sigma-t values found in the first 60 m, as compared with other sections. Salinity ranges from 37.0 at the surface to 37.5 at 50-60 m depth, which is a feature common to the three Balearic channels. Geostrophic computations (Fig 3*b*) and ADCP records (Fig 3*c*) show a water inflow on the Ibiza side and a water outflow on the Mallorca side. While both sections agree in terms of velocity values, their spatial distributions differ slightly: the ADCP section is more irregular. On the Ibiza side, the incoming water has speeds of about 10-20 cm/s. On the other side, the outgoing water attains maximum speeds of 12 cm/s. The inflow extends over the upper 200 m and occupies the centre of the section area. This confirms what has often been suggested by satellite imagery (La Violette *et al.*, 1990; López *et al.*, 1994): the passage of recent MAW through the Mallorca and Ibiza channels.

Ibiza channel (Section G)

The hydrographic structure on the Ibiza sill (800 m depth) presents some differences relative to the Mallorca sill. The vertical structure is also stratified, with a small mixed layer (10 m depth) below the sea surface. However, the isopycnals below the mixed layer show a clear bending towards the Ibiza side (right-hand side of Fig. 4*a*) and towards the continental slope (left hand side) below 150 m. The water in the upper layers has features which are typical of recent MAW.

Geostrophic calculations show an incoming flux on the Ibiza side and an outgoing flux over the whole channel, particularly below 100 m depth (Fig. 4*b*). The inflow is mainly constrained in a layer of 200-250 m, which extends horizontally from Ibiza island (thicker) to the middle of the channel (thinner). Some areas of flux reversal are found between three or four casts over the continental slope. Here, the differences between the geostrophic and the ADCP sections are particularly relevant (Fig. 4*c*). On the continental side, the flow reversal present on the geostrophic section does not show up in the ADCP data. The velocities for the outflow are greater than those found in the geostrophic calculations. The ADCP data clearly show a subsurface core with velocities of about 15 cm/s (as compared with 8 cm/s for the geostrophic calculations). Castellón *et al.* (1990) reported (from ADCP measurements) strong along section velocity components over the same section, indicating strong interactions between the inflow and the outflow. In this area, particularly during the winter season, the formation and presence of mesoscale eddies and plumes, which could explain these reversal zones, have often been observed (López *et al.*, 1994; Pinot, 1995). The different bending of the isopycnals, together with the inflow-outflow structure, suggest the superposition of both fronts on the Ibiza sill, the Balearic frontal system occupying the upper 150 m, whith below it a trace of the Catalan front that can be observed on the continental slope, associated with an outflow core.

Sections FDC

The cross-sections F, D and C permit identification of the structure of the Balearic front. The three respective hydrographic cross-sections are very similar. The geostrophic computations shown here (Figs. 5*a, c*) clearly indicate that the associated current is still formed from Ibiza island (right-hand side of Fig. 5*a*). This current enlarges when it passing beside the Mallorca channel (50 km in section D, Fig. 5*b*), and again becomes narrow in the north (Fig. 5*b*), suggesting a meandering structure. The current boundary, as defined by the 5 cm/s isoline, is constrained in the three sections within a layer of approximately 200 m depth. Thus, our data set clearly indicates the presence of a well defined current, the Balearic current, flowing from the SW to NE with a maximum speed of about 30-40 cm/s.

FLUXES

The sections described above allow us to evaluate the volume transport between the Balearic basin and the adjacent western Mediterranean sub-basins. To do so, we consider it more adequate to calculate fluxes from the geostrophic

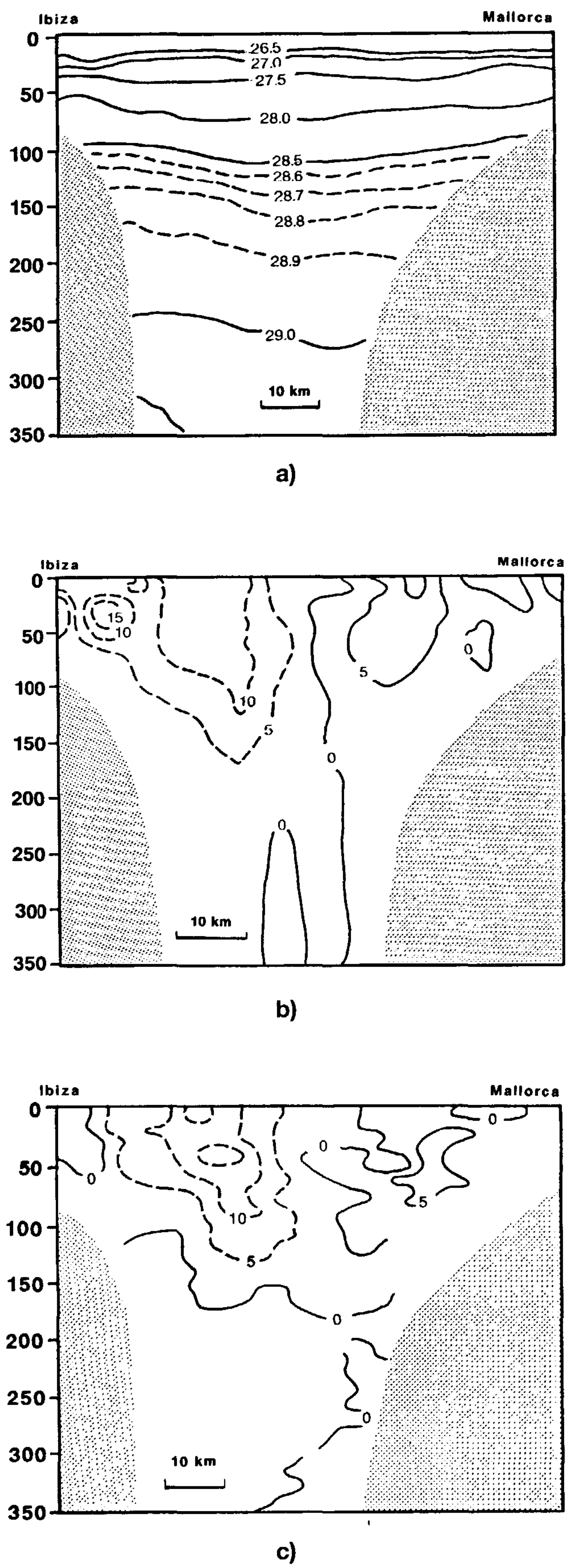

Figure 3

a) *Sigma-t*, b) *geostrophic currents and* c) *ADCP sections of the Mallorca channel.*

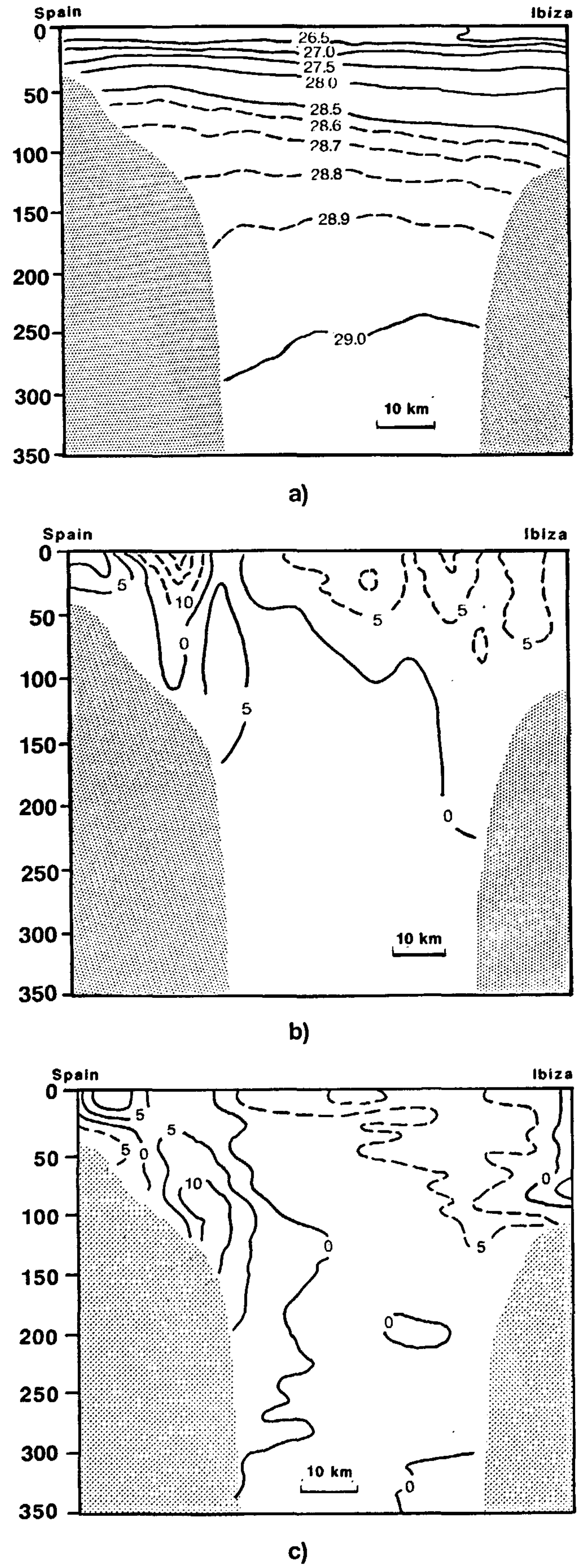

Figure 4

a) *Sigma-t*, b) *geostrophic currents and* c) *ADCP sections of the Ibiza channel.*

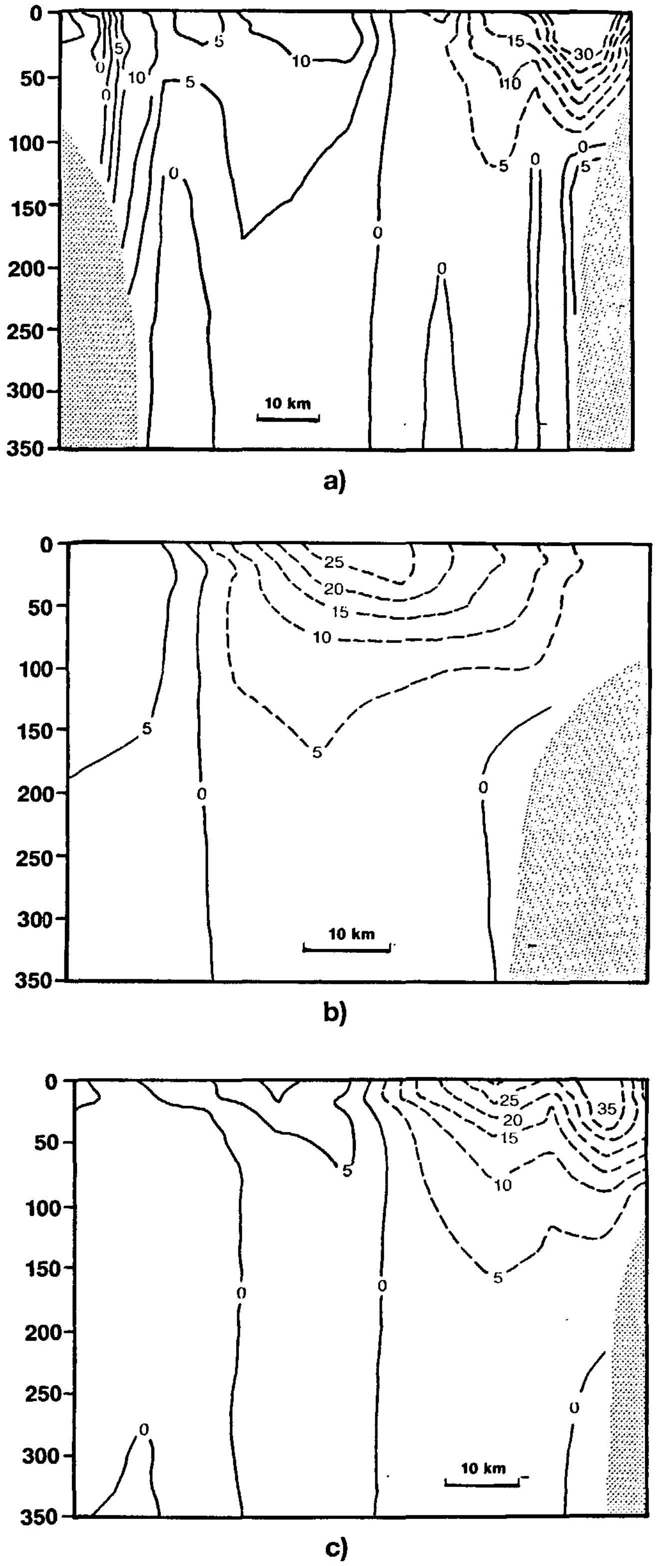

Figure 5

a) *Geostrophic currents of section* ***F*** *(cast 98-79),* b) ***D*** *(cast 53-62,* c) ***C*** *(cast 52-42).*

velocities, since ADCP measurements give instantaneous values which could be the product of a great variety of oceanic motions. High-frequency motions, such as internal waves, can be eliminated by averaging ADCP profiles over a reasonably wide time interval. But lower-frequency components – for instance, inertial oscillations – are much more difficult to filter out. Moreover, ADCP profiles have a coarse vertical resolution and a smaller vertical extent than the geostrophic profiles. Other errors due to the lack of synopticity or incomplete spatial coverage affect both data sources equally. Thus, we believe that fluxes calculated from geostrophic velocities, even if they only correctly represent baroclinic components, are in the present case accurate enough to estimate the magnitude of water fluxes.

In figures 6*a*, *c*, we summarize the fluxes calculated here, together with those given in previous works. The fluxes we have determined for the northern boundary are ~ 1 Sv for the Catalan front and ~ 0.75 Sv for the Balearic current. Between them, an outflow of ~ 0.3 Sv is found, occupying the centre of the cross-section. This flux is mainly due to small velocities values in a large area, and is associated with a recirculation of the Catalan current. The values obtained here, for both the Catalan and the Balearic currents, are higher than those provided by Font *et al.* (1988) for summer conditions and by Béthoux (1980) as annual budgets. The estimations made by Béthoux (1980) come from continuity arguments about the global balance in the western Mediterranean basin (Fig. 6*c*). In this sense, they are not as accurate and give only an order of magnitude. In Font *et al.* (1988), fluxes calculated geostrophically on the basis of several cruises (Fig. 6*b*) are lower than those found here (~ 0.75 Sv and ~ 0.5 Sv against ~ 1 Sv and ~ 0.75 Sv for both the Catalan and Balearic current respectively). Uncertainty in the determination of the fluxes can explain the differences, but interannual variability and the different sampling resolution used on the cruises must also be important. The resolution between casts in the case of the FE-89 cruise (2 miles in frontal regions) was accurate enough to sample the narrow veins of the currents.

Our most interesting results relate to the fluxes in the Mallorca and Ibiza channels, since this is the first occasion on which they have been precisely estimated. The inflow and outflow on the Ibiza sill are ~ 0.2 Sv. Traditionally, it has been considered that the Catalan current reaches the Ibiza channel and that most part of it flows towards the Alboran basin (*see*, for example, Font *et al.*, 1988; Millot, 1991). However, the outflow we have found is much lower as compared to the inflow associated with the Catalan current in the north. This imbalance shows that a recirculation of the Catalan current towards the Balearic islands, of the order of ~ 0.5 Sv, must exist. The same was found in winter, where Font *et al.* (1988) reported an inflow of ~ 1.5-2 Sv in the north and an outflow of ~ 1 Sv on the Ibiza sill. Perkins and Pistek (1990) found, from a cruise made during the same season as FE-89 (June 1986 and June 1989, respectively) an outflow in the Ibiza channel of ~ 0.75 Sv, which is considerably higher than the values found here. On the Mallorca sill, the exchanges correspond to an inflow of ~ 0.45 Sv and an outflow of ~ 0.15 Sv.

On the other hand, according to the geostrophic computations, the inflows and outflows for the Balearic current are unbalanced. If we add the inflow on the Ibiza sill, the net inflow in the Mallorca channel and the recirculation of the Catalan current, we obtain some ~ 0.25 Sv more than the ~ 0.75 Sv for the current outflow on the northern boundary. Moreover, the flux for the Balearic current computed for sections F, C and D is ~ 0.70 Sv, which suggests a continuity of the flow at least from Ibiza island. This is consistent if we only consider the Balearic current formed by the recirculation of the Catalan current (0.5 Sv) and the inflow of the Ibiza channel (0.2 Sv): the slight difference would be associated with the computation of the flow in the Ibiza channel, where the ADCP records show the flow to be essentially north-eastward (Castellón *et al.,* 1990). This scheme is also corroborated by the trajectories of four drifters released close to Ibiza island (Fig. 7), which moved to the north-east following the dynamic height contours. The average velocities for the drifters were about 30-40 cm/s, in close agreement with the geostrophic velocities. Thus, the continuity of the flow upstream and downstream from the Mallorca channel calls in question the geostrophic values obtained on this sill. Using ADCP measurements for flux computation, we found an almost total balance between the inflow and outflow in the upper 300 m.

CONCLUSIONS

In this paper we report the results of the FE-89 cruise. For the first time, the hydrographic structure of the boundaries enclosing the Balearic basin, with high horizontal resolution and relative synopticity, has been measured. Previous scarcity of data in the Mallorca and Ibiza channels gives special relevance to the results presented here. The vertical structure of the hydrographic sections is characteristic of the summer season in the western Mediterranean. We have computed geostrophic velocities and compared them with direct ADCP observations. The agreement is good in terms of magnitude and spatial structure on the northern boundary; but some differences have been found in the Mallorca and Ibiza channels which stresses the complex dynamics in those locations.

The hydrographic measurements indicate the presence of a current – the Balearic current – flowing along the Balearic islands and wider and shallower than the Catalan current. It is concentrated in a layer of 250 m, with maximum speeds of about 30-40 cm/s. The associated transport amounts to about 0.75 Sv. The Balearic current has been found to be formed from Ibiza island by an incoming flux of MAW through the Ibiza channel and the recirculation of old MAW from the Catalan current. It follows the Balearic shelf and quits the basin north of Menorca island. In this context, estimation of the fluxes through the Ibiza and Mallorca channels is crucial to the determination of the origin and variability of the Balearic current. The FE-89 cruise permitted us to compute both of them for the first time. In the Ibiza channel, the fluxes found are lower than those reported by other authors, which suggests a high variability in current dynamics. Traditionally, it has been supposed that the variability in the channel must be associated with seasonal changes. However, comparing our findings with other results obtained for the same seasonal period (June 1986), we believe that the variability in the Ibiza channel must be mostly associated with local mesoscale activity. While geostrophic computations give a net inflow through the Mallorca channel, the computations in the sections before and after the channel do not reveal any enhancement of the transport of the Balearic current. Moreover, ADCP measurements show that the inflow and the outflow practically

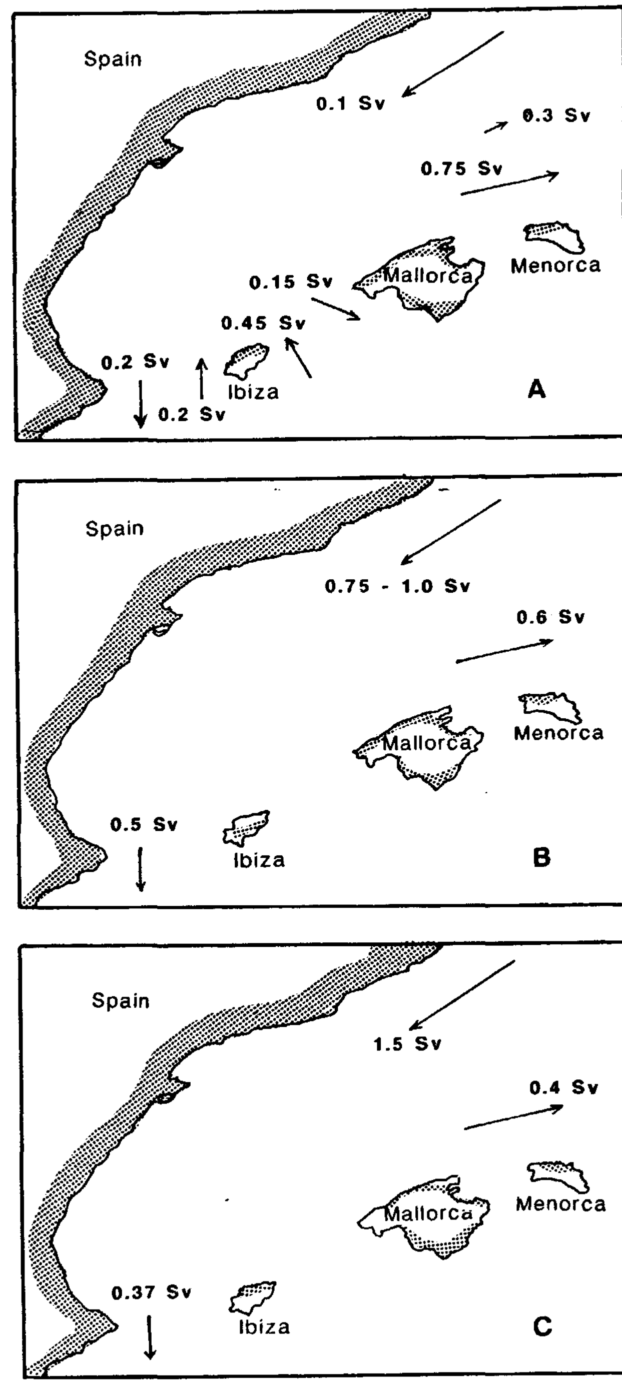

Figure 6

Water fluxes in the Balearic Basin. A) Fluxes from FE-89 data set, B) winter fluxes from Font et al. *(1988) and C) fluxes from Béthoux (1980).*

compensate each other. Thus, the estimation of the fluxes over both sills remains a delicate issue, and their improved quantification calls for careful experiments in the future.

The origin of the Balearic current must lie, as Millot (1991) suggested, in recent MAW driven by large eddies detached from the Algerian current through the Ibiza and Mallorca channels. In accordance with this hypothesis, the flow of MAW through the Balearic basin must be intermittent. On the other hand, the climatological maps obtained by Tziperman and Malanotte-Rizzoli (1991) showed the Balearic current to be one of the two branches of the Algerian current (*see* Figs. 4, 7). In this case, the flow of the Balearic current would instead appear to be a permanent feature, with a well defined structure, as the observations reported here have shown. Our data also indicate that there must exist a recirculation of old MAW from the Catalan current that can also contribute to the formation of the Balearic current. We would stress once again the importance of further studies designed to elucidate the variability of the MAW flux through the Mallorca and Ibiza channels. These are strategic sites for a better understanding of the link between the northern and the southern circulation in the western Mediterranean.

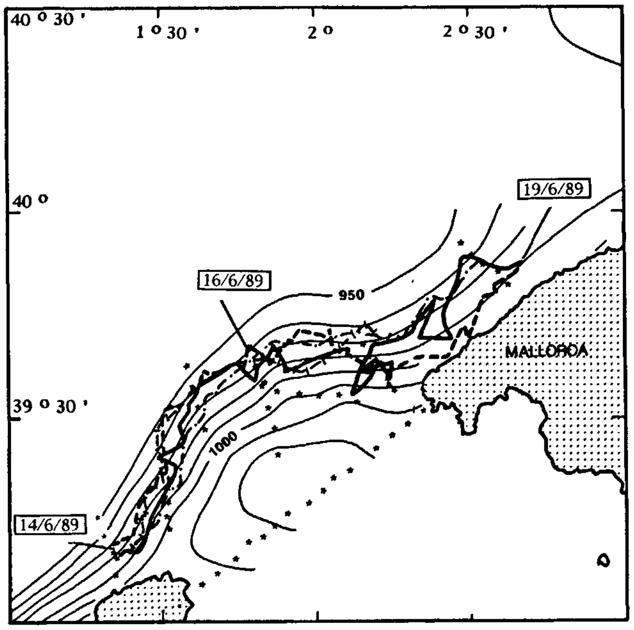

Figure 7

Surface drifters trajectories and surface dynamic contours with a reference level of 200 dbar.

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