# The interaction between the Catalan and Balearic currents in the southern Catalan Sea

Northwestern Mediterranean
Ocean circulation
Water masses

Méditerranée Nord-Occidentale
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**Jordi SALAT**

Institut de Ciències del Mar, CSIC, P. Joan de Borbó s/n, 08039 Barcelona Spain.

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ABSTRACT

The Liguro-Provençal-Catalan current, associated with a permanent shelf/slope front, terminates near the Eivissa channel, in the southern part of the Catalan Sea. Also in this region, the North Balearic front is formed, associated with lighter waters of recent Atlantic origin. In May-June 1991, the oceanographic cruise FE'91 was carried out covering the region with CTD casts. The results of water mass analysis and geostrophic circulation are presented in this paper, and the interaction between the Catalan and North Balearic currents is described and discussed.

RÉSUMÉ

Interaction entre le courant Catalan et celui des Baléares dans le sud de la mer Catalane.

Le courant Liguro-Provençal-Catalan, associé au front permanent plateau continental-talus, arrive à son terme près du canal d'Eivissa, dans la partie sud du bassin Catalan. Là se forme le front nord - Baléares, associé à des eaux plus légères d'origine Atlantique récente. En mai-juin 1991, des sondages CTD ont été effectués dans toute la région au cours de la campagne FE' 91. Les résultats de l'analyse des masses d'eau et la circulation géostrophique sont présentés dans cet article ; l'interaction entre le courant Catalan et celui du nord des Baléares y est décrite et discutée.

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## INTRODUCTION

The continental coast of the Northwestern Mediterranean receives a major input of river runoff. This fresh water input must play an important role in maintaining a shelf/slope density front along the continental shelf break, with low salinity values on its coastal side. The circulation in this part of the Western Mediterranean is characterized by a current that follows the continental slope, in geostrophic equilibrium with the shelf/slope density front (Font *et al.*, 1988; Castellón *et al.*, 1990; Millot *et al.*, 1992). This current, the Liguro-Provençal-Catalan Current, is directed towards the west and south, according to the geostrophic equilibrium. Along the path of the current, from the Gulf of Genoa to the Gulf of València, the final significant fresh water supply comes from the Ebro river (Font *et al.*, 1990). The continental shelf in front of the Ebro mouth is wide (about 100 km) but ends abruptly about 100 km to the south, in the centre of the Gulf of València.

The shelf/slope front is quite well documented along the Catalan coast as far as the vicinity of the Ebro delta (Font *et al.*, 1988; Salat and Font, 1987; Wang *et al.*, 1988), but there are fewer observations southward, in the Gulf of València. Traditionally it was considered that the Catalan Current must follow the shelf break, entering the Gulf of València and continuing to the Eivissa channel. This theory would be consistent with the conservation of potential vorticity. However, observations of water outflow in the Eivissa channel have not confirmed this theory. Water balances over the Catalan basin (Garcia *et al.*, 1994) show that the volume of water flowing southward through the Eivissa channel is always smaller than the transport along the shelf break off the Catalan coast. Some eddies or ageostrophic features, like filaments, which export continental shelf waters to the open sea, have been observed in the region (Wang *et al.*, 1988), but it is difficult to attribute losses of 60-70 % of the current transport to those mechanisms alone.

On the northern side of the Balearic islands, there exists an eastward-flowing current known as the North Balearic Current (Font *et al.*, 1988; López-García *et al.*, 1994), which originates in the penetration of waters of recent Atlantic origin through the Eivissa and Mallorca channels. This water is characterized by a lower salinity and, usually, higher temperature than are found in the centre of the Catalan basin. A typical signature of the presence of this water is the North Balearic front which often appears in satellite thermographies (La Violette *et al.*, 1990). The North Balearic Current is also geostrophically balanced with a density front (Pinot *et al.*, 1994).

The traditional picture of the hydrography of the Catalan basin shows a central homogeneous part, lacking any characteristic defined motion, surrounded by waters of lower salinity whose circulation contours the shelf breaks of both the Continent and the Balearic Islands. This schematic picture has been presented in some papers (Font *et al.*, 1988; Castellón *et al.*, 1990), with the suggestion that part of the water transported by the Catalan Current recirculates and joins the North Balearic Current, closing a cyclonic gyre at basin scale. Vertical cross-sections of density in the central part of the basin always portray a doming of isopycnals, typical of cyclonic gyres (Allain, 1960; Estrada and Salat, 1989; Font *et al.*, 1988). This scheme, however, has not been completely confirmed because of the shortage of data concerning the southern region of the Catalan basin.

Water mass analyses of CTD data collected in several cruises in the region have always thrown into relief the different origin of low salinity waters on both sides of the basin. Waters of the continental side have lower salinity values, even at temperatures lower than 13 °C, while north Balearic waters have low salinity only at temperatures higher than 14°C (Salat and Font, 1987). These TS signatures are consistent with the continental influence of surface layer waters on the northern side of the basin and the Atlantic origin of the surface waters on the southern side (Salat and Cruzado, 1981; López-Jurado and Díaz del Rio, 1992). Given these findings, is it possible to state that part of the Catalan Current would close the cyclonic gyre and join the North Balearic Current? And, if recirculating water is not joining the North Balearic Current, where does it go?

In this paper we shall endeavour to provide a measure of reply to the above questions, using the results of the FE'91 cruise, which covered part of the southern Catalan basin with a regular grid of CTD stations. Unfortunately, there was not enough time during the cruise to cover the inner Gulf of València, but the set of data, in comparison with previous surveys, was still substantial.

## Data

The FE'91 cruise took place from 23 May to 2 June 1991, on board the *R/V Garcia del Cid*. The cruise, designed within the framework of the PRIMO circulation experiment as a part of the "Flotadors Errants" series, was intended to contribute to the knowledge of the mesoscale features associated with the circulation in the Western Mediterranean. During the cruise, a series of 158 CTD casts were performed in the southern part of the Catalan basin (Fig. 1). The cruise data set was completed with ADCP measurements and TS surface continuous analysis along the ship track. Samples for organic micropollutants and radioactive tracers were obtained at several points. A simultaneous synoptic coverage of AXBTs was performed

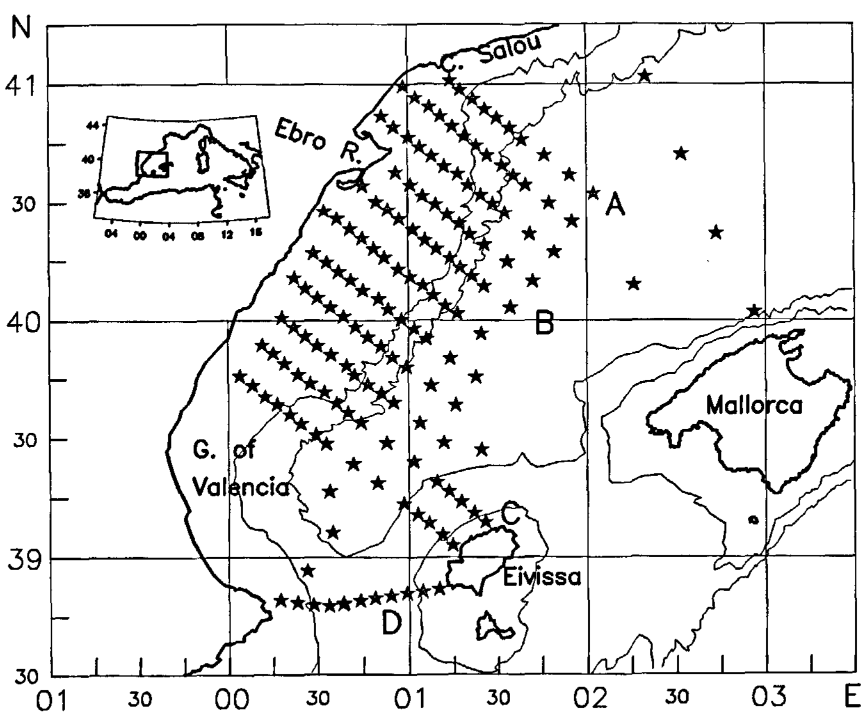



Figure 1

*Reference map of the Catalan sea, showing 200 and 1000 m isobaths. Position of CTD casts obtained in the FE'91 cruise are represented by stars. Lines A, B, C and D indicate the position of the vertical sections in Figures 6-9.*

on the eastern and southern sides of the basin, with some overlapping of the area covered by CTD casts. Some of the results of this operation have appeared in recent papers and presentations: Pinot *et al.* (1994), based mainly on the AXBT information; López-García *et al.* (1994), using miscellaneous data; Molero *et al.* (1994) and Sànchez-Cabeza (1995), using radioactive tracers for the Catalan current; Ballabrera-Poy *et al.* (1994), comparing ADCP results with geostrophic circulation. However, part of the information is still being processed, partially included in data reports or in various PhD theses. A preliminary description of the circulation, based on the complete results, was presented at the ICSEM meeting (Salat *et al.*, 1992) and a global report of the data collected during the cruise and the methodology used (Sànchez and Salat, 1995) will be available from the authors on request.

The results presented in this paper are essentially based on the information obtained from the CTD casts which, in most cases, is confirmed by the other sources of information. Dynamic topographies, geostrophic velocities and transport were calculated using a reference level of 600 m. This level was chosen as being deep enough to ensure the inclusion of the whole body of the shelf-slope current present along the continental slope. Dynamic heights at shallower stations, over the continental shelf, were extrapolated following lines of stations perpendicular to the shelf break (Fig. 1). This method is consistent with the presence of a shelf/slope front and the streamline patterns obtained over the shelf are similar to those using shallower reference levels.

## RESULTS

Dynamic topographies show that the shelf/slope current undergoes two important deflections (Fig. 2): The first appears at around 40° 30' N, 1° 40' E (point S in Fig. 2), where the slope orientation changes at the beginning of the wide continental shelf. The other deflection can be obser-

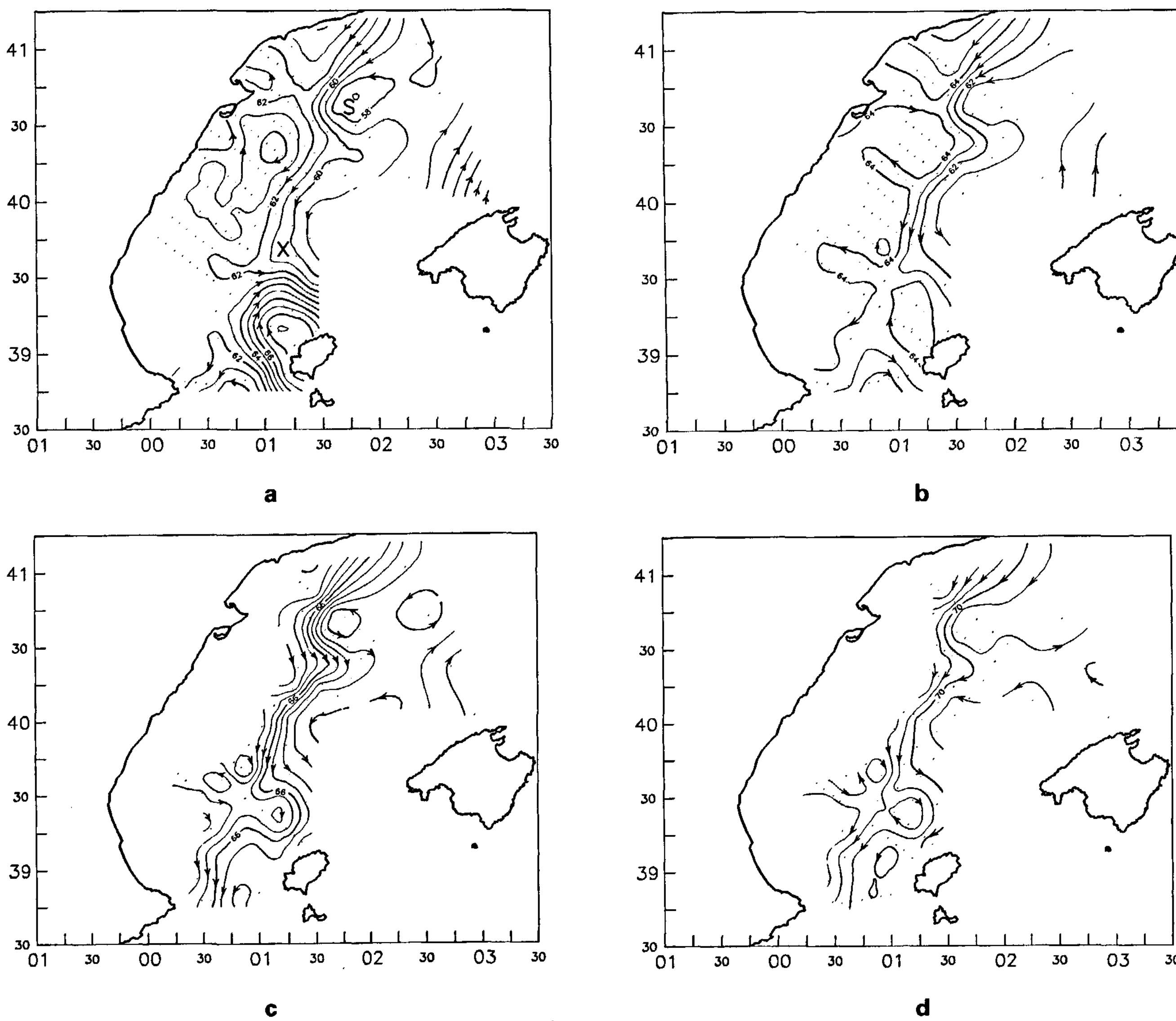



Figure 2

*Dynamic topographies, in dyn cm, at a) 10 m; b) 80 m; c) 130 m and d) 200 m, with a reference level of 600 m. the points S and X show the position of the two current deflection points cited in the text.*

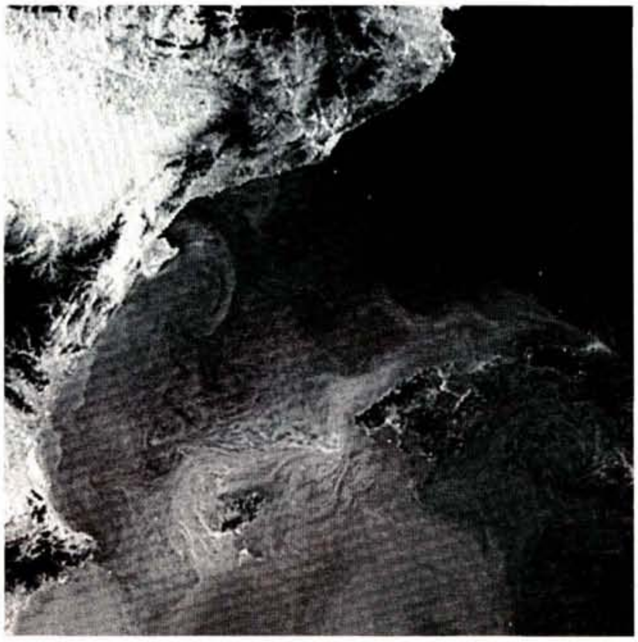


Figure 3

*Satellite infrared image ( 22 May 1991) of the region during the cruise.*

ved at around 39° 30' N, 1° E (point X in Fig. 2), near the end of the wide continental shelf. At this last point, the main current is definitively detached from the slope and only a residual attached flow continues towards the Gulf of València, and thence to the Eivissa channel.

The Ebro river discharge is located between the two points previously mentioned (S and X). The circulation there, over the wide shelf, is anticyclonic. It has been found to be dominated by local winds (Font, 1990) and by inertial oscillations (Salat *et al.*, 1992). Circulation of this kind acts as a trap for the Ebro river discharges (Fig. 2).

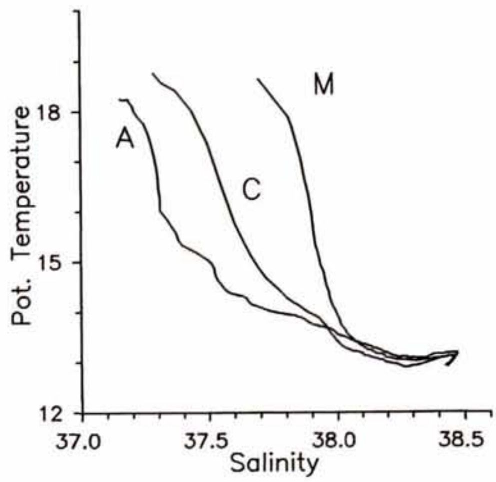
On the open-sea side of the main current, at the northern point (S), there is a clear signature of a cyclonic eddy that may divert, towards the open sea, part of the shelf/slope waters, and may also contribute to the propagation of filaments of shelf water, described in Wang *et al.* (1988), in this area.

In the southern part of the studied region, a well-defined anticyclonic eddy appears in the upper 100 m on the eastern side of the Eivissa channel (Fig. 2). A remarkable surface temperature front can be observed in satellite thermographies (Fig. 3) on the northern side of this eddy, where it contacts the deflected Catalan current at around 39° 30' N. This front has also been confirmed by the AXBT analysis (Pinot *et al.*, 1994) which, in addition, reveals its presence all along the northern side of the Balearic Islands, with some meanders and oscillations.

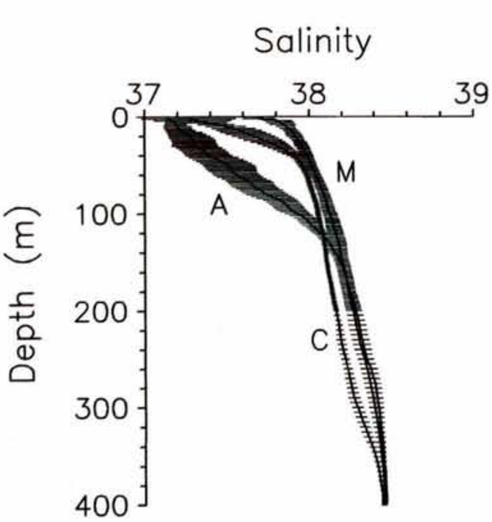
TS analysis of CTD data shows the presence of three water masses in the surface layer. Therefore, data of the casts have been classified in three groups (C, M, and A), according to the water mass analysis. Figure 4 presents the average TS diagram of each one of these three groups. The average (and 95 % confidence interval) vertical profiles of salinity are also shown in the figure because, in this case, salinity is an appropriate and useful indicator of the water mass. The spatial distribution of the three water masses is shown in Figure 5. Note that there is an agreement between this distribution and the dynamic height analysis (Fig. 2).

The vertical structure of water mass dynamics in the region is presented through a sequence of vertical sections of density and geostrophic velocity (Figs. 6-9), at the transects A, B, C and D, shown in Figure 1. At this point, it should be noted that the vertical structures of salinity and density are similar, which reaffirms that salinity distribution is dominant in the dynamics of the region.

The sequence of vertical sections presented in Figures 6 to 9 has been arranged from north to south, following the path of the shelf/slope current in order better to understand the evolution of the main flow. In the northern section (Fig. 6), a well-formed jet is associated with the shelf/slope front. The total estimated southwestward trans-




a




b

Figure 4

*Mean T/S diagrams of all the stations grouped according to the three different water masses present: A, Atlantic origin; C, Continental origin; and M, water of the centre of the basin. b) Mean vertical profiles of salinity of all the stations grouped as above (horizontal bars represent the 95 % confidence interval).*

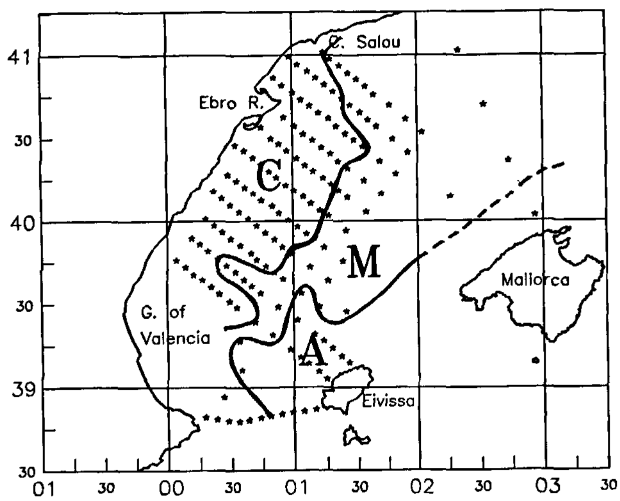



Figure 5

*Spatial distribution of the three water masses: A, C and M.*

port across this section, in the upper 400 m, amounts to 1.2 Sv. In the central section (Fig. 7), the structure is similar, while the continental shelf is much larger and occupied by lighter waters. The shelf/slope front is still important, as is the associated jet current, but southwestward transport estimated in the upper 400 m is 0.8 Sv, clearly lower than through the previous section. In the next section (Fig. 8), the continental shelf is again narrow, but here the main front is detached from the continental slope. Across this section two jets are directed to the southwest, one still attached to the continental slope and the other associated with the main density front, detached from the continental slope. At the surface layer, over the front, or even slightly more centred in the section, there is an important northward flow associated with low density waters of Atlantic origin, corresponding to the anticyclonic eddy found north of Eivissa (Fig. 2). The estimated total southward geostrophic transport through this section, in the upper 400 m, amounts to only 0.6 Sv, while the transport to the north is

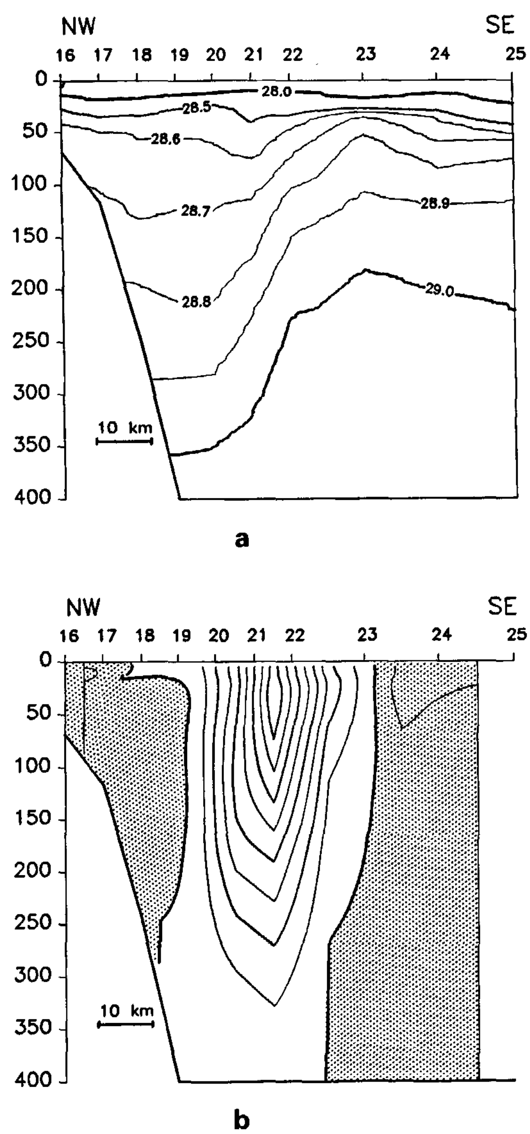



Figure 6

*Vertical sections of a) density and b) velocity across the section A (Fig. 1). Isotachs are drawn every 5 cm/s, and shaded region shows the flow directed to the NE.*

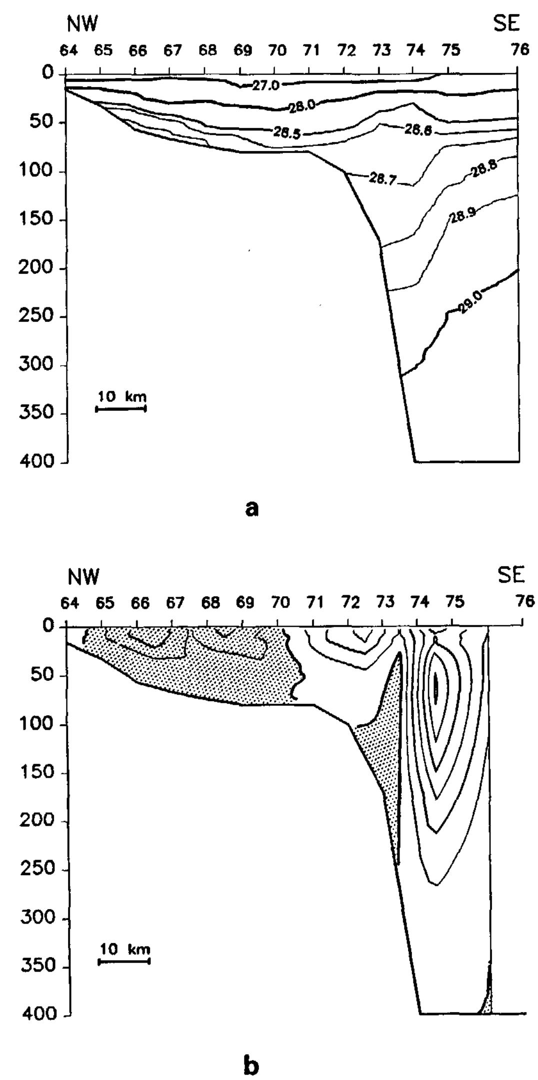



Figure 7

*Vertical sections of a) density and b) velocity across the section B (Fig. 1). Isotachs are drawn every 5 cm/s, and shaded region shows the flow directed to the NE.*

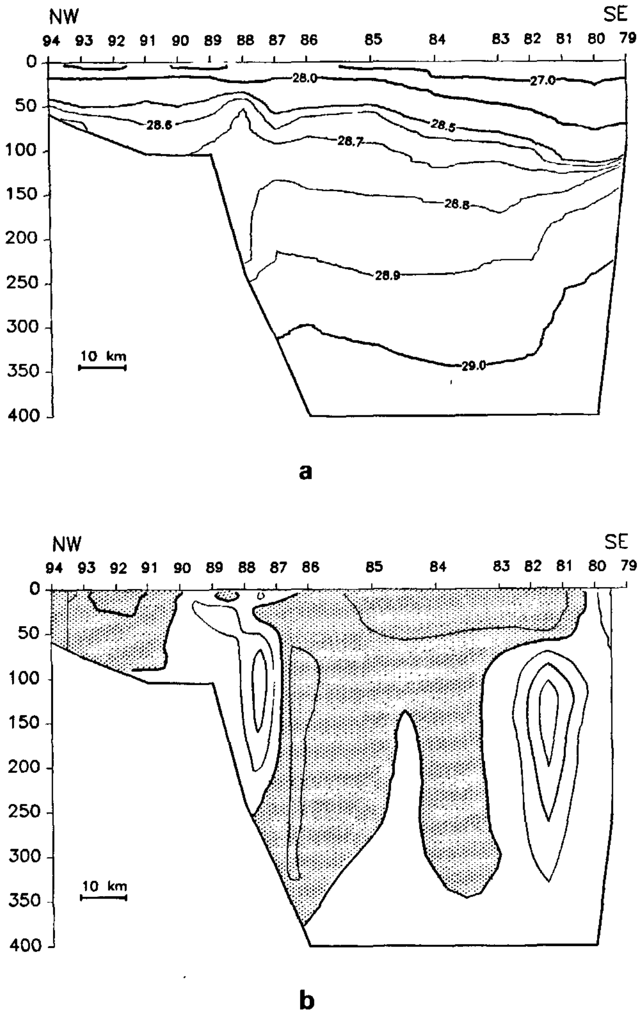



Figure 8

*Vertical sections of a) density and b) velocity across the section C (Fig. 1). Isotachs are drawn every 5 cm/s, and shaded region shows the flow directed to the NE.*

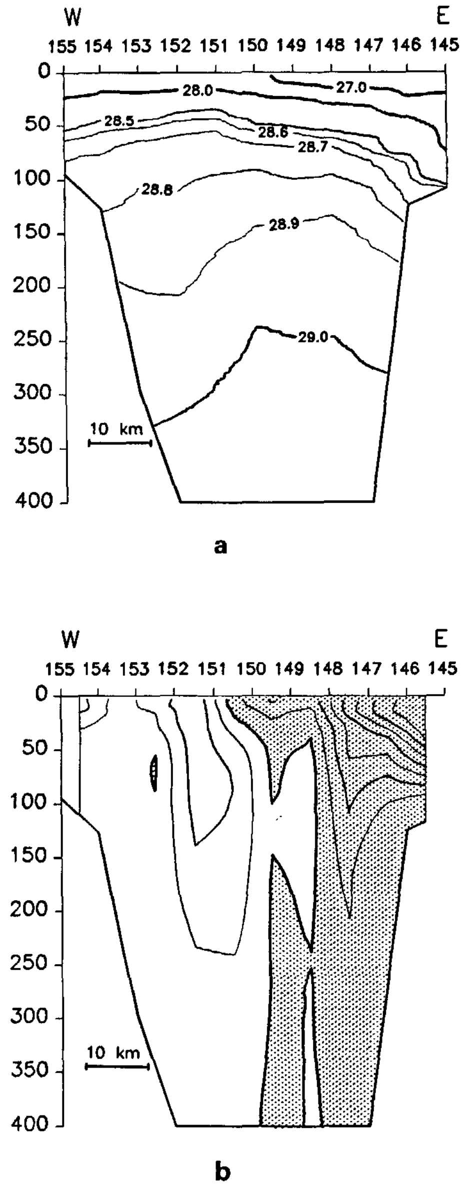



Figure 9

*Vertical sections of a) density and b) velocity across the section D (Fig. 1). Isotachs are drawn every 5 cm/s, and shaded region shows the flow directed to the N.*

of the same order, but restricted to the upper 120 m. Finally, in the last section, which corresponds to the Eivissa channel (Fig. 9), the flow to the south through the upper 400 m amounts to about 0.45 Sv, still lower than in the previous section, while the flow to the north is almost 0.6 Sv, similar to the previous section, and also restricted to the upper 120 m. Thus, there is a balance difference of 0.15 Sv (12 % of total input) in the upper 400 m, in the closed region between these two last sections. This difference may be partially due to ageostrophic flow and time-dependent fluctuations, and also to the errors inherent in the dynamic method.

Another interesting aspect found in the analysis of these sections (Figs. 6-9) is that the main jet current towards the south is deeper as it progresses in that direction. Whereas in the northern section (Fig. 6) the main jet is centred at a depth of around 30 m, in the southern section (Fig. 8) it is found at 100 m in the shelf break at the continental side and at 130 m near the Eivissa slope. As the surface waters in the south are lighter, the water coming from the north sinks and passes underneath.

The analysis of the current field observed by ADCP (Ballabrera *et al.*, 1994) shows a general agreement with the calculated geostrophic field. Some negative divergent areas were, however, found near points S and X, and positive areas in the central part of the basin, near the Ebro mouth and north of Eivissa.

## DISCUSSION

The Catalan shelf/slope density front is enhanced in the vicinity of the Ebro delta due to new continental inflow. Water on the wide continental shelf south of the Ebro delta is subjected to a strong continental influence. Like the associated jet current, the shelf/slope front splits into two fronts, at a level of $\sigma_t = 28.8$, near the point X (Fig. 2): one remains attached to the shelf break, and the other, only present below 130 m, crosses the basin to the Balearic continental slope, at Eivissa. In such conditions, water in the centre of the southern part of the Catalan basin, in the layer between 150 and 300 m, is nearly 0.2 kg/m$^3$ lighter than in the northern part. This would be consistent with the anticyclonic eddy proposed by Castellón *et al.* (1992) in the Gulf of València.

Thus, the general tendency of the circulation in the southern half of the basin appears to be dominated by the successive fragmentation of the Catalan current. These branches may be associated with changes in the orientation of the continental slope, due to the presence of a wide continental shelf just south of the Ebro delta, and the splitting of the shelf/slope front. The part of the main jet that is detached from the slope at each of the deviation points (S and X, Fig. 2) tends to go deeper, in consonance with negative divergence near these points (Ballabrera-Poy *et al.*, 1994).

CTD data collected during this cruise do not permit description of the destination of water that deviates in the northern point S. Analysis of the simultaneous AXBT measurements (Pinot et al, 1994) demonstrates that this water was trapped in a cyclonic eddy north of Mallorca. The other branch of the shelf/slope jet, deviated at point X, makes its way to the south following the Eivissa continental slope. Part of this flow, however, may also be trapped in another cyclonic eddy, also in agreement with the findings of the AXBT analysis (Pinot *et al.*, 1994).

On the southern and eastern sides of the basin, the intrusion of light waters coming from the south through the Eivissa and Mallorca channels is superposed at the surface layer forming the North Balearic Current. According to Pinot *et al.* (1994), this current displays important meandering and mesoscale activity. This activity can be associated with eddies in the Southwestern Mediterranean (Millot, 1987) that produce some kind of pulses of intrusion (López-García *et al.*, 1994), and also with the eddies marked by fragments detached from the Catalan current. The characteristic density front created by the intrusion of this lighter water apparently behaves as a shelf/slope front in the vicinity of the Eivissa channel. There are, however, several arguments against this theory. The waters forming the North Balearic current have salinity and density lower than in the centre of the basin, but the front has a limited extension in depth, restricted to 120-130 m. This depth is coherent with the recent Atlantic origin of these waters, but too shallow to be associated with the continental shelf break. Other arguments are: the observed presence of a detached part of the Catalan front at Eivissa slope; where the main North Balearic current is completely separated from this slope, the high mesoscale activity, which is not controlled by the topography; and the absence of local sources of continental waters.

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