The Liguro-Provençal-Catalan current (NW Mediterranean) observed by Doppler profiling in the Balearic Sea*

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SUMMARY: For the first time a vessel-mounted Acoustic Doppler Current Profiler has allowed a general current survey on the continental slope off northeast Spain in spring 1989. The path of the Liguro-Provençal-Catalan current has been followed from 41° 40′ to 38° 45′ N. The structure of the current appears to be, in the northern part, an alongslope frontal jet 35 km wide and 250 m deep, with maximum velocities of 30 cm/s and a total flux of 1 Sv. In the southern part, the Gulf of Valencia, the current weakens and is partially detached from the slope and entrained in an anticyclonic gyre. Most of the flow feeds the return Balearic current and only a small part, 0.24 Sv, leaves the basin through the Eivissa sill.

Key words: General circulation, shelf/slope current, frontal jet, acoustic Doppler profiling, northwestern Mediterranean.

RESUMEN: LA CORRIENTE LIGURO-PROVENZAL-CATALANA (MEDITERRÁNEO NOROCCIDENTAL) OBSERVADA CON UN PERFILADOR DOPPLER EN EL MAR BALEAR. — Por primera vez un perfilador acústico por efecto Doppler, montado a bordo de un buque oceanográfico, ha permitido una observación general de las corrientes en el talud continental de la costa nororiental española durante la primavera de 1989. Se siguió el curso de la corriente Liguro-Provenzal-Catalana desde 41° 40′ hasta 38° 45′ N. La estructura de la corriente, en la parte norte, es la de un chorro frontal a lo largo del talud con un ancho de 35 km y una profundidad de 250 m. Las velocidades máximas son de 30 cm/s y el flujo total es de 1 Sv. En la parte sur, el golfo de Valencia, la corriente se debilita y se separa parcialmente del talud atrapada en un giro anticiclónico. La mayor parte del flujo pasa a alimentar la corriente Balear de retorno, y sólo una pequeña parte, 0,24 Sv, abandona la cuenca a través del canal de Ibiza.

Palabras clave: circulación general, corriente de talud/plataforma, chorro frontal, perfilador acústico por efecto Doppler, Mediterráneo noroccidental.

THE LIGURO-PROVENÇAL-CATALAN CURRENT

During recent years, an important increase of experimental work on the western Mediterranean circulation (e.g. WMCE CONSORTIUM, 1989) has modified the traditional picture of a wind-driven circulation described by OVCHINNIKOV (1966). High spatial resolution CTD data, tracked drifters, current meter moorings and satellite imagery indicate the existence of a complex current system with important spatial and temporal variability (MILLOT, 1987). Several driving mechanisms and processes, like deep water formation or frontal instabilities, may coexist and be responsible for the circulation patterns in the different sub-basins of the western Mediterranean. Considerable effort is now devoted by the international scientific community to understanding the role of these forcings and to the study of the circulation variability at different scales, mainly through the use of numerical modelling (EUROMODEL and MERMAIDS projects of the European MAST programme).

The northern part of the basin appears to be a

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dynamical entity. In this region the general circulation is dominated by a flow formed in the Ligurian Sea by the confluence of the East and West Corsican currents (ASTRALDI *et al.,* 1990), and progressing westwards controlled by the topography. The structure and variability of the Ligurian current has been studied in detail. The role of the accumulation of continental waters in the narrow shelf, and the formation of a shelf/slope density front, are considered to be fundamental to the existence of an intense and relatively stable current affected by strong seasonal flux variations (BETHOUX *et al.,* 1988). This current follows the continental slope along the coast of Provence and reaches the offshore region of the Gulf of Lions, where, although its structure has not been studied there in detail, it plays a key role in the process of dense water formation that takes place in winter in the region.

Downstream from the Gulf of Lions, the Catalan Sea (Fig. 1) is the end of the northwestern Mediterranean basin. Until the beginning of the 80s the circulation there, estimated from hydrographic data and geostrophic hypotheses, was described as a cyclonic gyre around one or more central domes (ALLAIN, 1960; FONT & MIRALLES, 1978). Results obtained from a study of deep water formation in the northern Catalan Sea (SALAT & FONT, 1987) indicated the presence of a geostrophic flow concentrated on the continental slope, that could be the continuation of a similar feature observed off the Gulf of Lions under the same seasonal situation (MAILLARD, 1974). FONT *et al.* (1988), after an analysis of an extensive set of hydrographic data, concluded that this was the

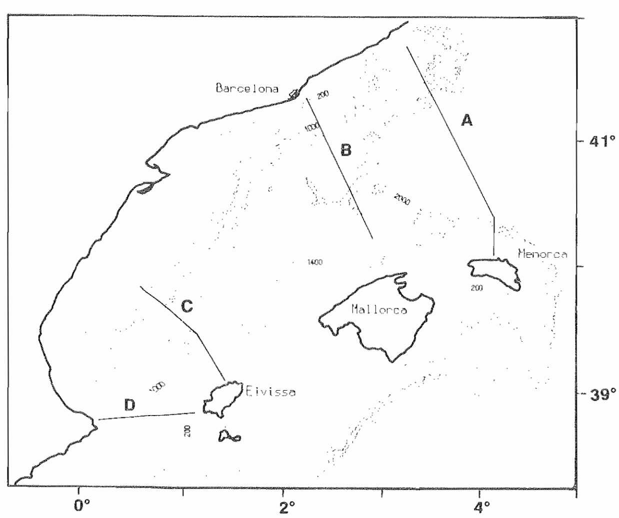


FIG. 1. — The Catalan Sea in the NW Mediterranean, with the ADCP sections measured in Spring 1989 (FRONTS-89 and FE89 cruises).

origin of a Catalan current linked to a permanent shelf/slope front, just like the Ligurian current at the other end of the northwestern basin. This Catalan current, together with a returning Balearic current in the Balearic islands shelf/slope area, appear to be the main characteristics of the regional circulation. LA VIOLETTE *et al.* (1990) have observed in satellite infrared images the year-round presence of a cool water plume, originated in the continental shelf of the Gulf of Lions, progressing along the continental slope of the Catalan Sea. This feature can be a good tracer of the alongslope current and of the evolution of mesoscale instabilities generated on it (TINTORÉ *et al.,* 1990).

In a document issued in 1988 by the Intergovernmental Oceanographic Commission of UNESCO, in preparation for an International Research Programme in the western Mediterranean to be developed in the next ten years (PRIMO), the entire northern part of the basin is considered to be involved in one important component of the general circulation. It is emphasized that this stream, for which the name "Liguro-Provençal-Catalan Current" is proposed, requires closer investigation, especially in its Provençal and Catalan sections. Direct current measurements in the Catalan Sea, of sufficient extent to characterize the structure of this flow, had never been done until now. Currentmeter data collected near the shelf break off the Ebro delta on several occasions during the last ten years (HAN & KOHLER, 1982; FONT *et al.,* 1990; NAVARRO, 1990) are consistent with the existence of a main southwestwards flow, but do not permit us to evaluate its cross-shore extension and consequently its hypothesized character of an alongslope current.

We present here the results of the first direct survey from an oceanographic vessel of this part of the Liguro-Provençal-Catalan current.

ACOUSTIC DOPPLER PROFILING IN SPRING 1989

The Acoustic Current Doppler Profiler (ADCP) is a sensor based on acoustic Doppler reflexion to remotely measure vertical profiles of three-dimensional water velocity. An ADCP (RD Instruments model RD-VM0150) was installed in the hull of the Spanish R/V "García del Cid" in March 1989. This model allows continuous relative current profiling down to 350 m in a maximum of 128 depth cells. Absolute velocities can be calculated through connection to the vessel's navigation system.

Two consecutive cruises were carried out aboard the R/V "García del Cid" in May-June 1989 in the Catalan Sea: FRONTS-89 ("Hydrodynamic effects on the distribution and physiology of planktonic communities in the Catalan Sea fronts" CICYT project MAR88-0252, P.I. M. Estrada) and FE89 ("Frontogenesis, secondary circulation and spatial variability in a density front" CICYT project PB86-0628, P.I. J. Font). On both cruises the ADCP recorded velocity data, averaged every 5 minutes to reduce the errors of the single profiles, uninterruptedly underway and during the fixed oceanographic stations, with a depth cell length of 8 m. Under these conditions the error in the horizontal velocity is expected to be 0.55 cm/s. Although a longer averaging period would allow better estimates of the large scale currents, it would also increase the risk of losing data due to individual erroneous pings. The velocities actually measured are not only related to the general circulation, but may include the effect of shorter period motions such as inertial currents. This can mainly affect the areas with weak circulation, but it is not decisive in the frontal zone, where inertial oscillations have not been observed to disrupt the alongshore current during similar seasonal conditions (SALAT *et al.,* 1989).

On 4 occasions (section B FRONTS-89 and sections A, C, D FE89) complete cross-shore sections intersected the supposed path of the Catalan current from 41° 40′ to 38° 45′ N (Fig. 1), and the corresponding ADCP velocities have been extracted from the total set of about 5000 velocity profiles.

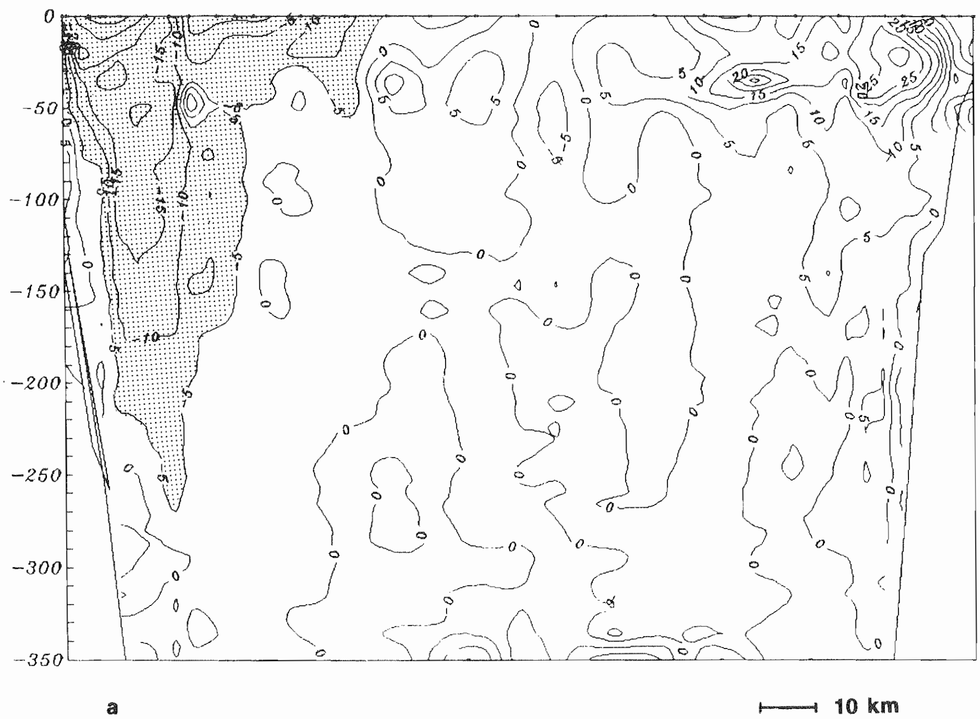
When the bottom depth was less than 450 m the Doppler shift of the sea bottom was clearly identified, and consequently it was possible to know the exact ship speed and transform relative water velocities measured by the ADCP into absolute values. In offshore areas, estimates of absolute velocities using ship positioning data lead to important errors. While the problem is being studied in detail, a reference level of 0 velocity has been used for the calculation of absolute values. A choice of 300 m as reference level gives a reasonably good agreement with the transition values (bottom tracking/reference level) in most cases. Geostrophic currents computed from FE89 cruise CTD data indicate, throughout the region, water speeds usually lower than 2 cm/s at 300 m with reference levels from 600 to 1000 m (GARCÍA, 1990).

An intercomparison experiment, ADCP (with bottom tracking) versus 3 Aanderaa RCM7 current meters, was done during FE89 cruise for 5 hours on June 1 near the shelf break. The mean differences in speed and direction for 10 minute averages were: 2.4 cm/s 3.4° (− 15 m), 2.0 cm/s 4.7° (− 50 m) and 4.4 cm/s 14.0° (− 100 m). By that time of the year, a surface mixed layer had developed in the region (30 m deep in the north and 15 m in the south). This could produce a seasonal disturbance in the spatial structure of the current in its upper part, since the top of the front was destroyed and the isopycnals were horizontal. The expected consequence would be a weakening of the surface alongshore velocities, the most intense in a situation of frontal adjustment (WANG, 1984). The presence of the thermocline could also be related to some velocity peaks that appear in most of the sections (Figs. 2 to 5), probably caused by the strongly sheared structure of the current at that level.

The vertical distribution of the alongslope velocity component in the northernmost section (A, Fig. 2a) shows a jet structure of the flow centered on the slope region, with a maximum velocity of 30 cm/s at the surface. If we characterize the limit of the jet by the 5 cm/s isoline, its width appears to be of the order of 40 km and its depth 250 m. The total alongslope southwestward flux, coincident with the cross-section direction which turns out to be almost exactly the direction of maximum flux, can be estimated at 1.02 Sv (1 Sv = 1 Sverdrup = 10^6 m^3/s). At the opposite end of the section, positive velocities indicate the presence of the northeastwards Balearic current, spread more offshore and less deep than the current in the peninsular slope.

Section B (Fig. 2b), 120 km wide from Barcelona to the center of the basin, again shows a well defined jet structure similar to that in section A. The space dimensions are the same, although the core velocities are not at the surface but centered about a depth of 50 m. The really low and variable velocity values offshore the jet in the whole section should be noticed. The alongslope character of the flow is well illustrated in figure 3, where the velocity vectors are clearly aligned with the isobaths and the highest values concentrated in the slope region.

Unfortunately, there were no complete ADCP sections across the slope until section C, 210 km downstream from section B. The zone in between includes the area of the Ebro delta, where sharp modifications in the bathymetry take place: widening of the continental shelf from 10 to 55 km and change of 75° in the slope isobaths (Fig. 1). This undoubtably has an effect on the local circulation, including a permanent upwelling of slope waters onto the shelf



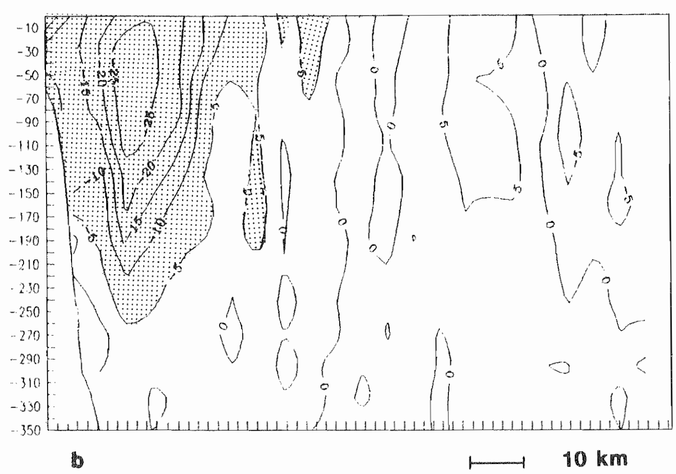


FIG. 2. — ADCP velocity distribution in cm/s across a) section A (FE89) and b) section B (FRONTS-89). Positive values are towards the NE and negative values towards the SW. The shaded area corresponds to the Catalan current.

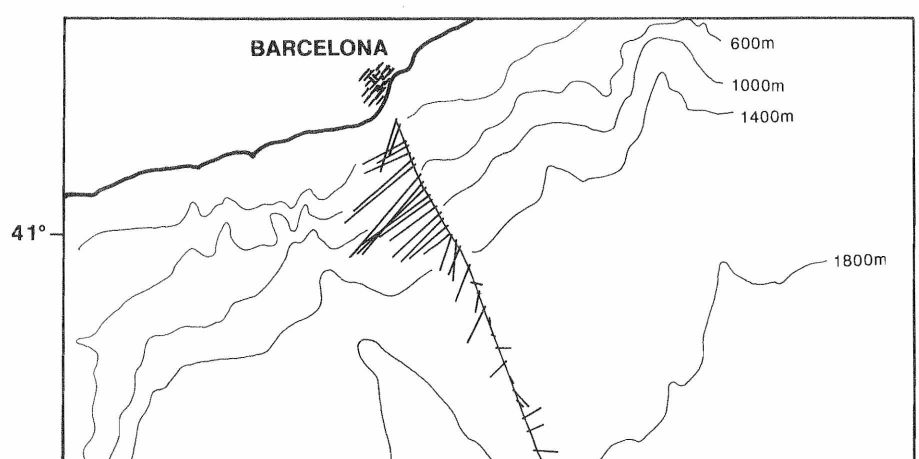


FIG. 3. — Horizontal distribution of the velocity vector in section B at the level of − 30 m.

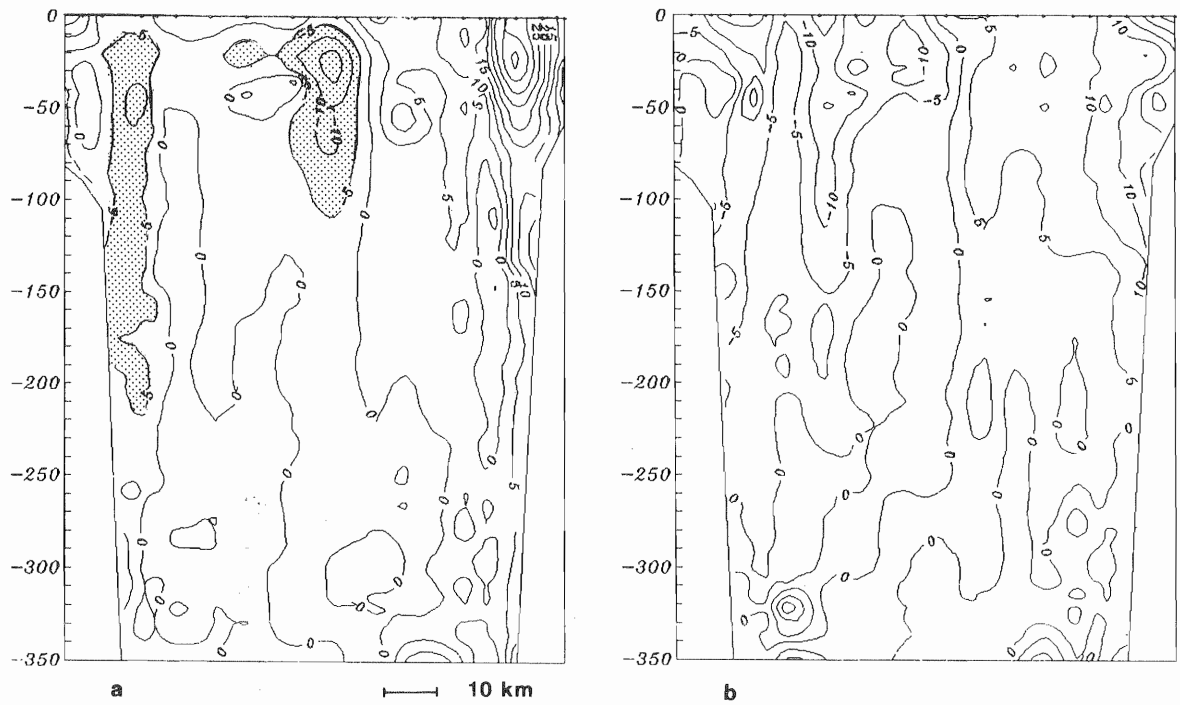


FIG. 4. — ADCP velocity distribution in cm/s measured during FE89 a) across section C (positive towards NE) and b) along section C (positive towards SE).

(FONT *et al.,* 1990). Nevertheless, the topographic constraint and the continued presence of the shelf/slope front south of the delta seem to be powerful enough to maintain the alongslope flow. Although ADCP data are not available there, a high horizontal resolution CTD section across the slope in June 1987 (40° 41′ N, SALAT *et al.,* 1989) indicates a geostrophic jet with a shape, space dimensions, core velocity values and location very close to those measured by the ADCP in sections A and B. The total flux was only 0.65 Sv.

Section C is located just before a sudden narrowing of the continental shelf and a marked change of isobaths direction in the southern part of the Gulf of Valencia (Fig. 1). The vertical distribution of alongslope velocities (Fig. 4a) shows an offshore spreading of the flow, that now occupies more than one half of the basin width and is almost in contact with the Balearic current. A remnant of the jet structure is observed on the slope, although it has much lower speeds than in the previous sections. Relatively high velocities are found in the center of the basin, but the total alongslope flux has decreased to 0.45 Sv, while the direction of maximum flux, 0.66 Sv, is towards the south. Figure 4b shows that the velocity component across the slope is highly significant in the whole section. Its flux in the peninsular side is of the same order as the alongslope flux. It should be mentioned that the central area is affected by important temporal variability in the upper levels: despite a clear trend to the south in the meridional velocity component, the east-west velocity can present opposite sign in successive 5 minutes averages.

A few ADCP profiles in the slope south of section C (not shown) indicate a clear reversal of the flow. It is directed to the ESE, following the isobaths but opposite to the direction of the current observed in the preceeding sections. Dynamic topographies calculated with CTD data (GARCÍA, 1990) indicate that, by the latitude of section C and coincident with the sharp topographic change, the current is detached from the slope and directed southeastward to the island of Eivissa. In the concavity formed in the southern part of the Gulf of Valencia (Fig. 1) an anticyclonic gyre is found between the detached current and the continental shelf. This anticyclonic gyre, which has been seen in infrared satellite images in the same place under similar seasonal conditions (e.g. May 1986, LA VIOLETTE *et al.,* 1990), appears to extend to at least 300 m and may be responsible for the disruption of the main alongslope flow. In the upper layer the detached flow partly feeds the return Balearic current that is formed in the northern shelf of Eivissa, while below 50-100 m the anticyclonic gyre

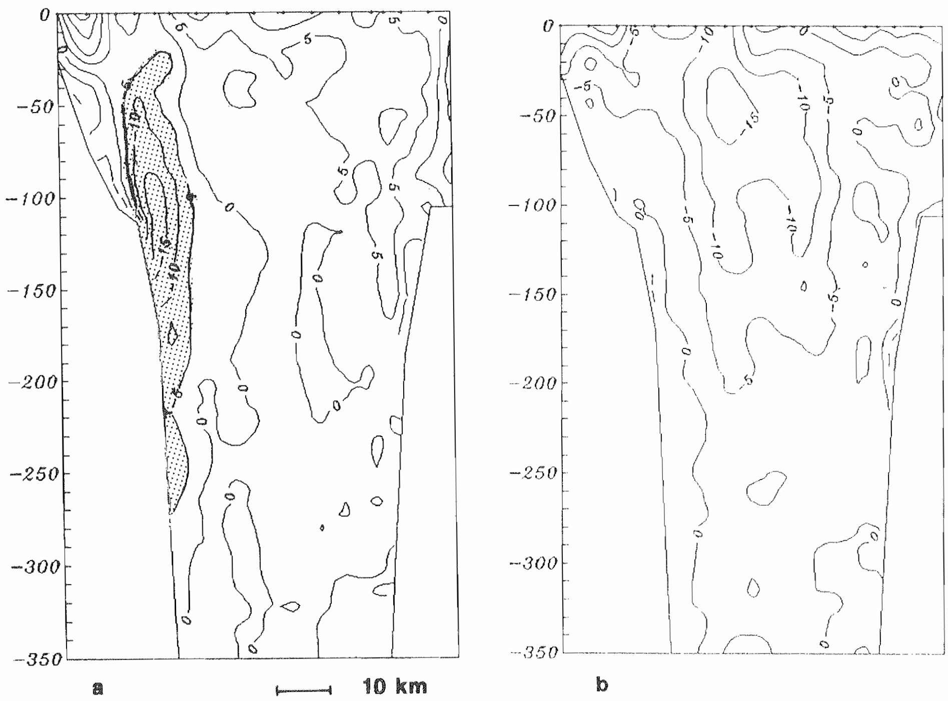


FIG. 5. — ADCP velocity distribution in cm/s measured during FE89 a) across section D (positive towards N) and b) along section D (positive towards E).

carries it again to the peninsular slope area by the latitude of section D.

In the southern sill (section D, Fig. 5a) the vertical distribution of alongslope ADCP velocities indicates that only a small part (0.24 Sv) of the flow that was following the continental shelf in the North leaves the basin. The jet structure that appeared in sections A and B can be seen again in the slope, but now centered at a depth of 100-150 m and with lower velocities. The distribution of the velocity component along the section (Fig. 5b) shows that important components to the West are present on the central part of the sill: in other words, there is a water inflow on the Balearic side and some of this water is entrained into the anticyclonic gyre situated just to the North.

DISCUSSION

This first ADCP current survey along the peninsular slope of the Balearic Sea in Spring 1989 has shown the frontal jet character of the general southwestwards circulation. An alongslope current 35 km wide and 250 m deep was present from the Gulf of Lions to the entrance of the Gulf of Valencia, centered over the 400 m isobath. It had maximum velocities of the order of 30 cm/s in the upper layer and its total flux was near 1 Sv.

A comparison with the total geostrophic water transport in the section that closes the Catalan Sea to the North (Fig. 6, GARCÍA, 1990), indicates that the flux of the jet we have observed (1.02 Sv according to the ADCP, 0.87 Sv from geostrophic computations) represents 95 % of the total inflow from the Liguro-Provençal basin, in only 20-25 % of the total length of the section. Consequently we can conclude that this inflow is formed mainly by a shelf/slope current, the Catalan current cited by FONT *et al.* (1988), whose characteristics are very close to those described for the Ligurian current. This is coherent with the existence of an unique stream, the Liguro-Provençal-Catalan current, in the entire northwestern Mediterranean basin.

Until now the existence of the Catalan current had been deduced from sets of data that only covered small parts of the region and at different periods. For the first time, we have been able to follow it along the entire continental slope of the region through very high horizontal resolution sampling in the cross-shore direction.

It should be recalled that the situation observed corresponds to a specific season, the beginning of the summer stratification, and that important changes might be found under different conditions. Although the structure of the flow is expected to be maintained for the whole year, as it happens with the density

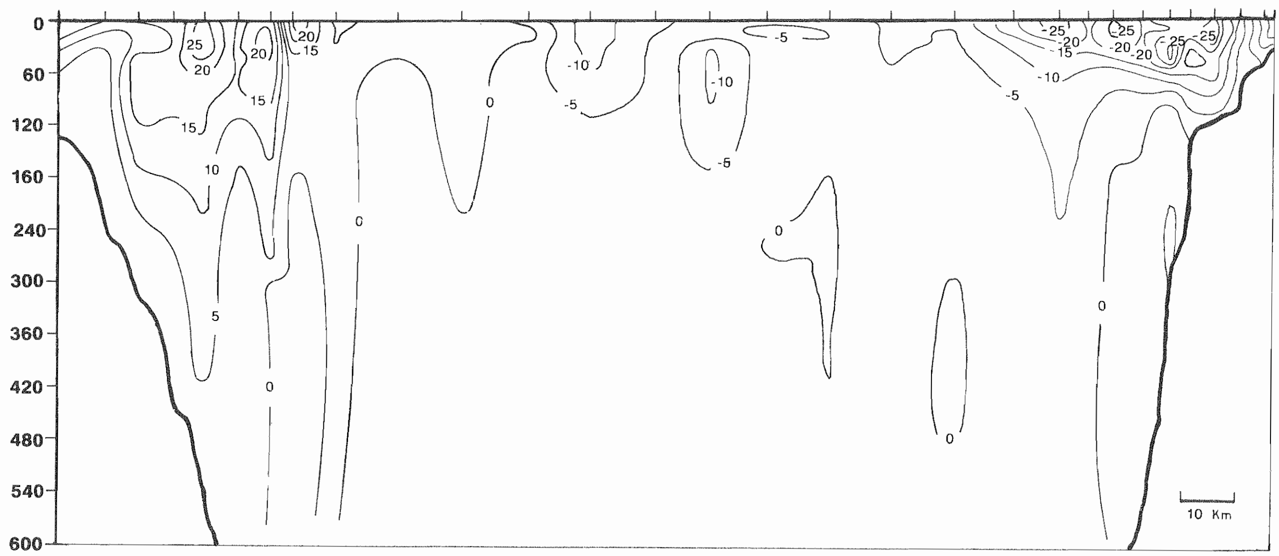


FIG. 6. — Geostrophic velocities in cm/s across section A computed with a reference level of 600 m. Positive values indicate inflow to the SW (from GARCÍA, 1990).

front, its intensity can vary considerably as it has been observed in the Ligurian Sea. In their analysis of geostrophic currents FONT *et al.* (1988) deduced that the influx from the Gulf of Lions could range from 1 Sv in summer to 2 Sv in winter. In spite of having few data, they estimated that the southern outflow, of the order of 1.5 Sv in winter, could decay dramatically in summer, linked to an increase of the flux of the return Balearic current. The current measured during our spring 1989 ADCP survey probably corresponds to the beginning of its weak season, a conclusion that agrees with a previous study of propagation of intermediate water across the Catalan Sea, where a change in thermohaline characteristics was found to occur in the Eivissa sill by May-June (FONT, 1987). It has to be confirmed whether the Catalan current in winter, together with a higher water transport, is more stable and maintains its alongslope structure even in the southern area.

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