Permanent features of the circulation in the Catalan Sea

Mediterranean Sea
Water masses
Circulation
Fronts
Mesoscale dynamics

Mer Méditerranée
Masses d'eau
Circulation
Fronts
Dynamique à moyenne échelle

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ABSTRACT

Through the analysis of hydrographic data collected during 16 cruises (1975-1985), we identify and describe the seasonal characteristics and the permanent features of the circulation in the Catalan Sea (North-Western Mediterranean). Two fronts follow the continental shelf break on the peninsular and Balearic sides, separating the central dense waters from the surrounding lighter waters of Atlantic and continental origins. One is mainly produced by strong salinity gradients (Catalan front) and the other by temperature gradients (Balearic front). Two currents are associated with these fronts : the southwest Catalan current and the northeast Balearic current. Strong vertical mesoscale motions have been observed on several occasions in the weakly stratified central area. An interpretation of these mesoscale phenomena is proposed in terms of cyclonic eddies generated by some kind of instability mechanism in the two frontal systems.

Oceanol. Acta, **1988.** Océanographie pélagique méditerranéenne, édité par H. J. Minas et P. Nival, 51-57.

RÉSUMÉ

Aspects permanents de la circulation dans la Mer Catalane

Nous avons identifié et décrit les caractéristiques permanentes de la circulation en Mer Catalane (Nord-Ouest de la Méditerranée) à partir de données hydrologiques acquises en 16 croisières (1975-1985). Deux fronts, qui séparent les eaux denses du centre du bassin des eaux plus légères d'origine continentale et atlantique, se trouvent sur la limite des plateaux continentaux ibérique et baléare. L'un est dû principalement au fort gradient de salinité (front catalan) et l'autre au gradient de température (front baléare). Il y a deux courants associés à ces fronts : le courant catalan vers le Sud-Ouest et le courant baléare vers le Nord-Est. Des mouvements verticaux intenses à méso-échelle ont été observés dans la région centrale peu stratifiée. Nous proposons une explication de ces phénomènes par des tourbillons cycloniques engendrés par instabilité des fronts.

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INTRODUCTION

The surface layer of the Catalan Sea (Northwestern Mediterranean) has a well-defined water mass structure, with significant changes in its horizontal distributions according to different seasonal conditions. Salat and Cruzado (1981) have described the water masses present in the surface layer :

A-Atlantic water, due to mixing of North Atlantic

Surface Water (15-17 °C, 36.15-36.50) with the local winter water.

M-Local Mediterranean water, formed locally in winter by cooling and evaporation, in a process similar to that which generates deep water, but confined to levels above the Levantine intermediate water. This characteristic winter water (12-12.8 °C, 38.1-38.3), modified seasonally by heating and mixing, forms the Local Surface Water.

C-Continental waters, fresh and cold (10-20 °C, 35.5-37), are formed near the mouth of the rivers (mainly the Rhône) and spread out following the continental coast driven by the dominant circulation.

The northern and western zones occupied by *C* present the lowest temperature values of the region (11 °C in winter, < 23° in summer) and low and very variable salinities. The maximum southward spread of *C* is produced at the end of spring (June) due to the considerable river runoff and the thinness of the layer above the thermocline.

The water mass *A*, which originates in the branches or eddies that leave the Algerian current to the North, has also low temperature and salinity values, but has a more distinct signature than *C* waters in the θ/S diagram (Fig. 1). It penetrates through the Balearic sills into the Catalan basin and covers an area that, depending on the surface circulation and the season, is of varying size, reaching a maximum in early summer. Through the eastern side of the region this water reaches the Liguro-Provençal basin, losing progressively its original characteristics.

The surface water in the central area can always be classified as *M* and is formed by warming and mixing with the sub-surface winter water. Its density is always higher than that of the surrounding waters, due to the permanent salinity maximum (never less than 37.8). The summer temperature also reaches the highest values in the basin ; in winter, it is lower than in the area occupied by *A*.

The Catalan Sea lies in the general cyclonic gyre of the thermohaline Western Mediterranean circulation.

The local cyclonic nature of the Catalan Sea circulation is consistent with the permanent presence of dense waters in the centre of the basin, surrounded by lighter waters of continental and Atlantic origin. This mechanism is more accentuated in winter, because the density gradients are increased by the action of the dominant strong, cold and dry northwesterly winds. In summer, the variable regime of light and local winds may break the circulation of the stratified upper layer into several non-permanent sub-gyres (Hopkins, 1985 ; Font, 1986).

Ovchinnikov (1966) evaluated the general circulation in the Mediterranean by geostrophic computations from data provided by 50 years of hydrographic observations, averaged in cells of one degree of latitude by one degree of longitude. He found a well-defined cyclonic structure that covers all the Balearic Sea, both in winter and summer, except for the region of the Algerian current in the South. This gyre is centered northeast of Menorca, at the limit between the Catalan Sea and the Liguro-Provençal basin, with a divergence line in its NE-SW axis from the Gulf of Genoa to Eivissa (Ibiza) and then to Cabo de Gata, at the entrance of the Alboran Sea.

There are, however, some features of the circulation in the Catalan Sea, at the mesoscale and synoptic levels, which do not appear distinctively in Ovchinnikov's calculations and which may be very important for the dynamics and ecology of the basin. For example, this circulation pattern keeps the flux of Atlantic water south and east of the Balearic islands, while water mass analysis and other geostrophic calculations (Allain, 1960 ; Font, Miralles, 1978) confirm an important inflow of Atlantic Water to the Catalan Sea through the Balearic sills, at least during the stratified conditions.

The aim of this study is to investigate the presence and evolution of these features through the analysis of the multiple observations carried out in the region by the Institut de Ciències del Mar de Barcelona.

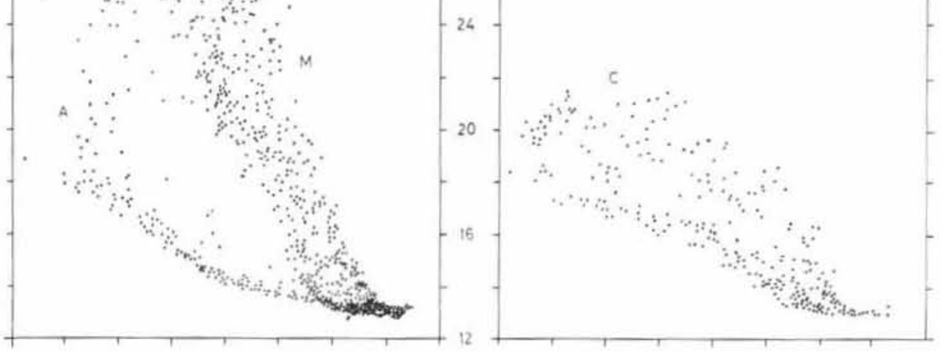

Figure 1

Summer θ/S diagrams in the Catalan Sea, corresponding to stations in the Balearic (A) and central (M) areas in July 1982 and to stations in the continental side (C) in July 1983.

Diagrammes θ/S d'été dans la Mer Catalane. Stations situées dans la zone baléare (*A*) et dans la zone centrale (*M*) en juillet 1982, et stations de la zone continentale (*C*) en juillet 1983.

MATERIAL AND METHODS

Hydrographic data of 16 cruises (1975-1985) carried out under different seasonal conditions and developed in the framework of several physical and biological research programmes have been used (Fig. 2). The location and relative distances between stations are not, in most cases, appropriate for the study of mesoscale phenomena, but the considerable amount of data collected have allowed us to clarify some aspects of the circulation.

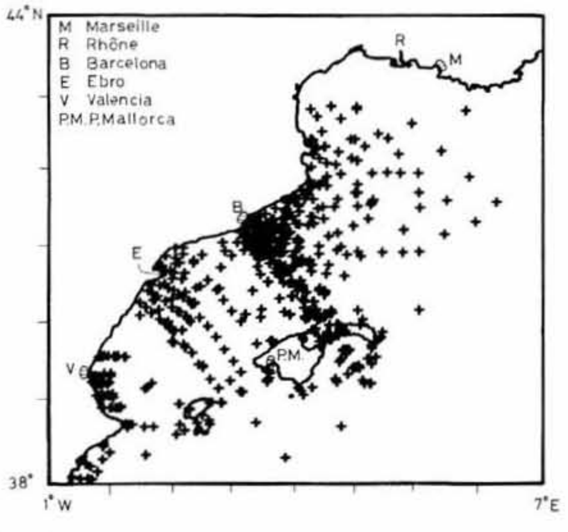

Figure 2
Situation of the almost 800 hydrographic stations in the Catalan Sea and surrounding waters used in this study.
Situation de près de 800 stations hydrologiques dans la Mer Catalane et eaux adjacentes utilisées dans cette étude.

Until 1982, measurements were obtained from traditional hydrographic stations with sampling bottles, reversing thermometers and manual salinity determinations. Since then, the data have been collected by CTD casts. In some of the cruises a TS surface continuous analysis was done. From these data we have drawn vertical sections of the different variables, θ/S diagrams to identify water masses, and have computed dynamical topographies with the reference level at 400 or 500 dbar.

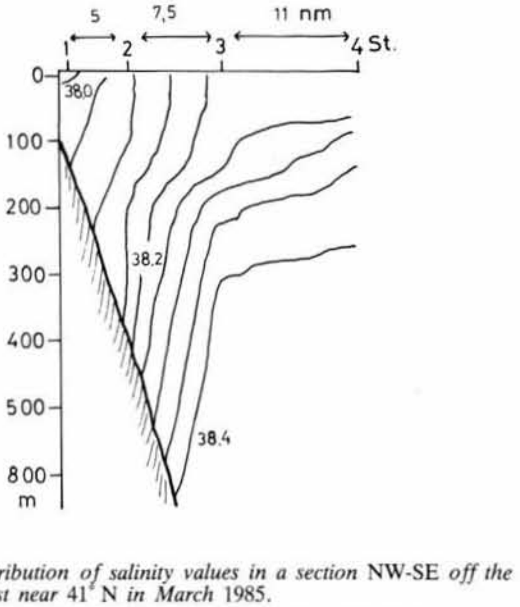

Figure 3
Vertical distribution of salinity values in a section NW-SE *off the Catalan coast near* 41° N *in March* 1985.
Distribution verticale de la salinité sur une section NO-SE au large de la côte catalane près de 41° N en mars 1985.

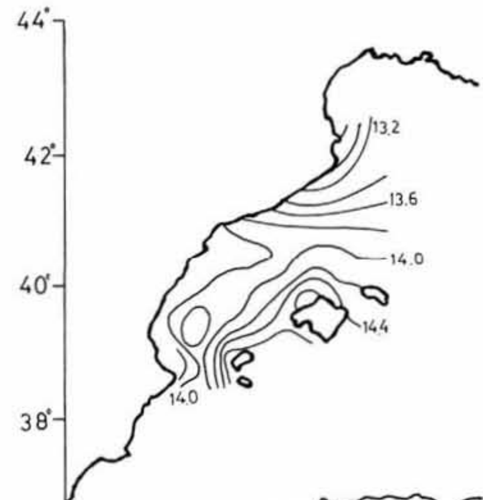

Figure 4
Horizontal distribution of surface temperature in the Catalan Sea in March 1977.
Distribution horizontale de la température de surface en Mer Catalane en mars 1977.

RESULTS

In the transition zones between the central and peripheral waters, two fronts have been detected from hydrographic data and confirmed by satellite observations : the Catalan front, approximately following the continental shelf-break of the Iberian peninsula, where the density gradient is primarily associated with salinity differences (Fig. 3), and the Balearic front, present along the Balearic continental shelf-break and in which the density gradient is mainly due to temperature differences (Fig. 4)

The structure of the Catalan front is fairly simple in winter from November to March. The water on the shelf is vertically homogeneous and salinity values range from 38.0 at the coast to 38.3 at the edge of the front. The 38.3 isohaline and the 29.0 isopycnal intersect the bottom at approximately 400 m while the surface signature of the front can be in a position ranging between 15 miles (March 1985, Fig. 3) and 30 miles offshore (November 1976, Vives, 1979). There is also a thermal front, acting in the same direction as the salinity front, and consequently enhancing the density gradients as shown in data from Salat *et al.* (1978).

During the summer period, the Catalan front is still present but it does not intersect the sea surface, due to the strong thermocline established over all the area. Isopycnals are then nearly vertical at depths of the order of 200 m but nearly horizontal when reaching 90 m because of the boundary action of the thermocline (Fig. 5). The vertical salinity gradient was 0.5 ‰ in 20 m in September 1975. The 29.0 isopycnal intersected the bottom between 250 and 300 m (20 miles offshore), during the summers of 1975 and 1976 (Salat *et al.*, 1978).

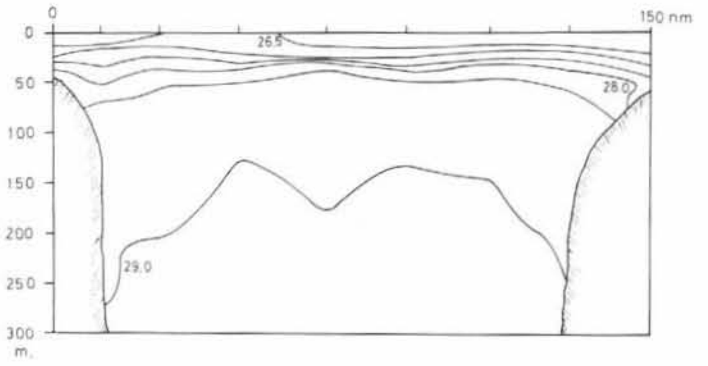

Figure 5

Vertical density distribution in a section NW-SE *in July* 1983.

Distribution verticale de la densité sur une section NO-SE en juillet 1983.

The Catalan front is therefore a permanent structure, and may be considered a shelf/slope front, similar to that present in winter in the Middle Atlantic bight (Houghton, Marra, 1983). Seasonal variations have been detected together with a high variability of its surface signature. More detailed data on the coastal zone are needed to study this front and its deep structure.

The Balearic front cannot be described in the same detail as the Catalan front because data available are more scarce. The vertical structure reveals a frontal zone well-defined in the surface layer but isolines bend to the horizontal as they deepen (Fig. 6). Below 300 m we find the vertical structure typical of the Western Mediterranean. The front separates an area

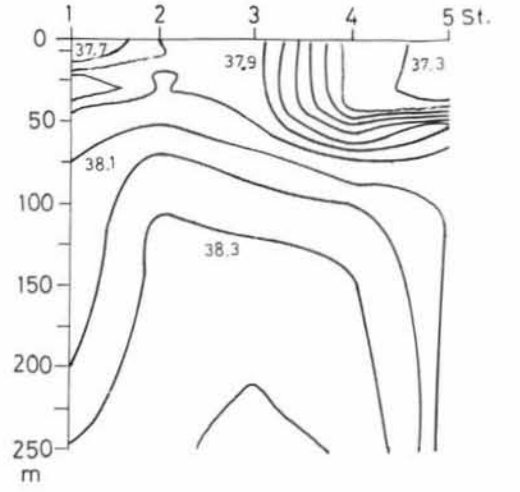

Figure 6

Vertical distribution of salinity values in a section NW-SE *from Barcelona to the Menorca Channel* (100 miles) *in October* 1976.

Distribution verticale de la salinité sur une section NO-SE de Barcelone au canal de Minorque (100 milles) en octobre 1976.

of weak stratification, on the centre of the basin, from a well-stratified area on the Balearic side.

Surface continuous analysis in some cruises and satellite observations show that this is a sinuous front and its position is more variable. It has the same characteristics as the Corsica front in the Ligurian Sea (Prieur, 1981) which can be considered as a continuation of the Balearic front, although there are not enough data to ensure continuity throughout the year.

Like the Catalan front, the Balearic front is a permanent feature of the basin as may be seen from infrared satellite images, each winter, when the thermal front reaches the sea surface (Philippe, Harang, 1982 ; Satmer, 1983-85). This front must be responsible for holding Atlantic waters off the Catalan coast ; in none of the hundreds of stations analysed west of the front the signature of Atlantic water appeared.

A common characteristic of the circulation patterns obtained from geostrophic calculations in all of the 16 cruises is the presence of a southwestward flux on the

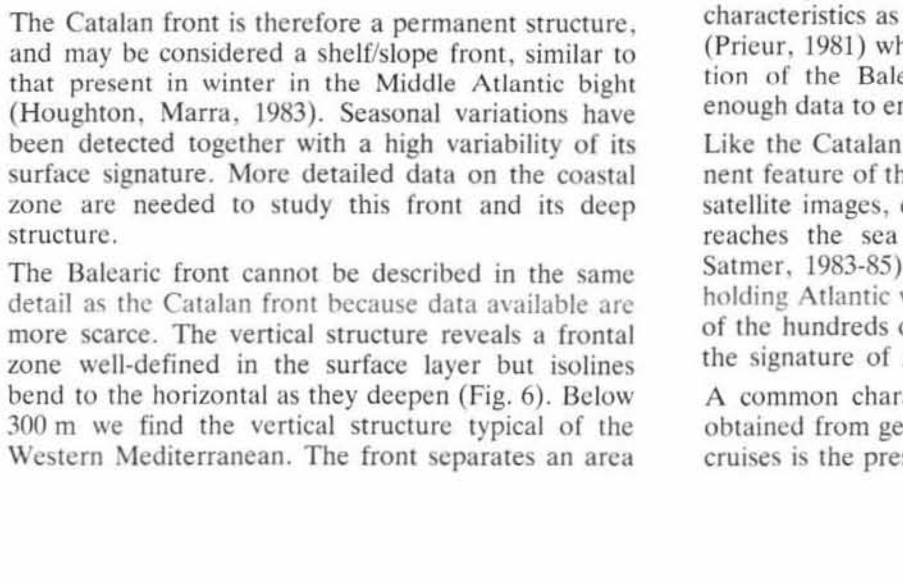

Figure 7

Lines separating the areas of Southwestward flux (continental side) and Northeastward flux (Balearic side), from several cruises under winter and summer conditions.

Lignes de séparation des flux vers le Sud-Ouest (près de la côte péninsulaire) et vers le Nord-Est (côte baléare) pour des croisières réalisées en hiver et en été.

continental side and a northeastward flux on the Balearic side. Besides the existence of some closed gyres, in almost all the dynamic topographies a line can be drawn separating the regions affected by the above-mentioned two fluxes. Figure 7 summarizes the situation of this line for 9 cruises carried out under winter conditions and 5 cruises during the stratified period. The discontinuities in the line are mainly due to the different cruise coverages rather than to real interruptions of the circulation schemes.

In winter the direction of this possible divergence line is SW to NE and it is located in the central part of the basin, both in surface and deeper levels, with a quite good agreement with Ovchinnikov's (1966) results. In summer a clear separation between both fluxes can only be seen in dynamic topographies below 50-100 dbar, since in the surface layer, above the thermocline, the topographies usually show irregular circulation patterns, according to the situation of a thin homogeneous layer affected by variable winds.

In cases where a good coverage of close stations permits, we can identify a well-defined current flowing southwestward, following the continental slope along the Catalan coast (Fig. 8). This current is associated

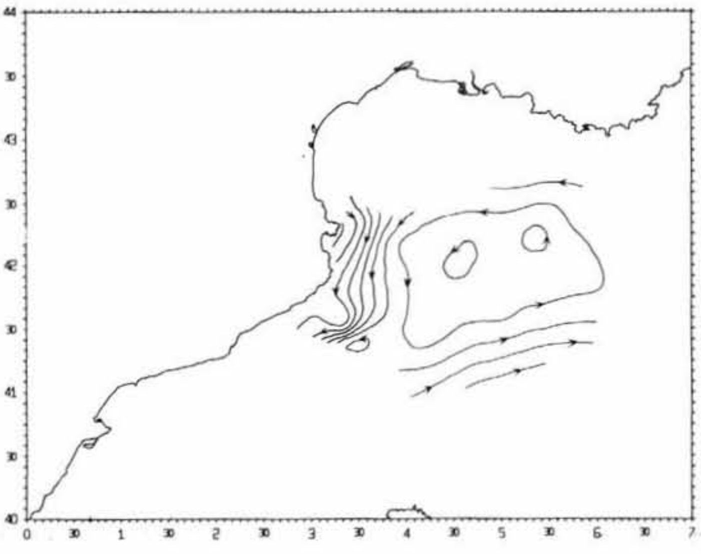

Figure 8

Dynamic topography, with 1 dyn cm *contour lines, of the surface of* 5 dbar *relative to* 500 dbar *in February-March* 1983.

Topographie dynamique (en cm dyn) de la surface de 5 dbar par rapport au niveau de 500 dbar en février-mars 1983.

with the Catalan front and is a continuation of the Liguro-Provençal current, drawing continental (Rhône) waters coming from the golfe du Lion. In winter it reaches mean surface velocities of 20 cm/s in its northern part. Its intensity decreases to the South and, near the Ebro river delta it partially penetrates to the wide continental shelf in the Gulf of Valencia (Font *et al.*, 1988). Around 39° 30′ N a branch is detached from the current and follows the Balearic continental slope to the East, while the rest of the current crosses the Eivissa sill and leaves the Catalan Sea. Below the surface layer, intermediate waters usually make their way south, and reach the southwest part of the Mediterranean (Font, 1986).

Detailed analysis of the stations along the continental slope (Font, 1987) shows that in winter the Levantine intermediate water (LIW) present in the Liguro-Provençal basin retains its θ/S values from 42° N to 38° 30′ N. This observation agrees with the circulation scheme proposed by Millot (1987) : the LIW reported in the Algerian basin is not due to a westward counter-current along the African coast but to the existence of cells trapped in anticyclonic eddies and, consequently the LIW present in the Alboran Sea has passed round the Northwest Mediterranean and crossed the Catalan Sea.

A second current can be identified in the Southern and Eastern parts of the Catalan Sea, moving northeast along the northern side of the Balearic islands. This Balearic current is likely fed by the incoming Atlantic waters and the eastward deflection of the Catalan current in the Gulf of Valencia. It shows considerable variability, with meanders and position changes associated with the Balearic front and the dynamics in the sills. Maximum surface velocities, 25 cm/s, are reached during the summer stratified period.

The calculated fluxes of the geostrophic currents give winter values of 1.5 to 2×10^6 m^3/s for the Catalan current in the North, 1×10^6 m^3/s in the Eivissa channel and 0.5×10^6 m^3/s for the eastward branch. In summer, the values are lower, about one half of the winter fluxes. The Balearic current has a geostrophic mean flux of 0.5×10^6 m^3/s, with minimum values of 0.3×10^6 m^3/s in winter and a maximum of 0.6×10^6 m^3/s in summer.

DISCUSSION AND CONCLUSIONS

Our results have produced a picture of the dynamic characteristics of the Catalan Sea : two permanent frontal zones on the coastal sides with the associated gravity currents (the Catalan to the SW and the Balearic to the NE), and a central zone of low horizontal motion where the vertical structure is weaker and conditions consequently more favourable to the development of vertical motions.

Vertical motion can tentatively be inferred from the hydrographic sections of several cruises. Figure 6 gives an example of the typical vertical structure found in a cross-shore section of 100 nautical miles from Barcelona to Mallorca. In the surface layer, the presence of the two fronts is expected to be theoretically related to convergence zones. Oxygen data from October 1976 (Vives, 1979) show relative maxima at stations 2 and 4 in Figure 6 (the estimated mean surface positions of the Catalan and the Balearic fronts) at approximately 50 m depth. Those two maxima could indicate the expected downward motion in the frontal zone.

Below 100 m, nitrate data (Vives, 1979) seem to show an upward motion in the central zone. This picture, sometimes referred to as a " doming " or a ridge has been described by Estrada (1985) and has been found approximately at the same geographical position over a period of 4 years (1982-85), in the stratified season.

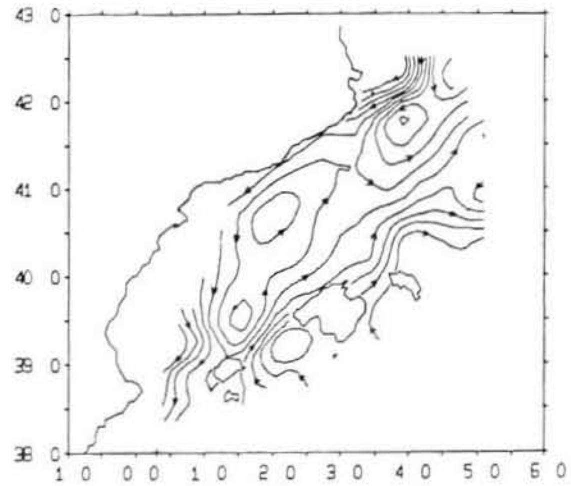

Figure 9

Cyclonic circulation shown by the dynamic topography, with 2.5 dyn cm *contour lines, of the surface level relative to* 500 dbar *in October-November* 1976.

Circulation cyclonique mise en évidence par la topographie dynamique (en 2,5 cm dyn) du niveau de surface par rapport au niveau de 500 dbar en octobre-novembre 1976.

This doming could be the signature of a slow upward motion associated with the apparently cyclonic circulation (Fig. 9). This upward motion seems to be confined to the region below 100 m because the density gradient, indicated by the 28.4 isopycnal (or 15 °C isotherm) acts as a barrier to the vertical motion, separating an upper layer characterized by the two frontal systems and a lower layer dominated by the general low-frequency circulation of the Catalan Sea. Figure 10 summarizes these basic features.

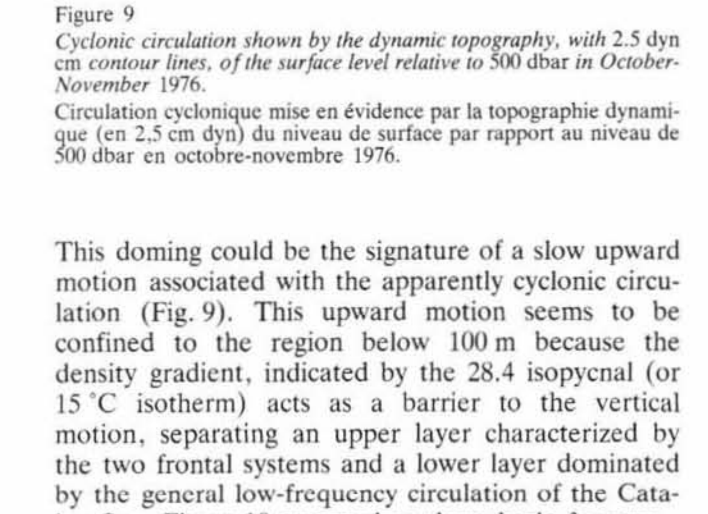

Figure 10

Idealized cross-shore representation of fronts and induced motions in the Catalan Sea in a section from Barcelona (left) to Mallorca (right). The deep limit of the summer stratified surface layer is indicated by the location of the 28.4 *isopycnal.*

Représentation au large des fronts et mouvements induits en Mer Catalane sur une section de Barcelone (gauche) à Majorque (droite). La limite profonde de la couche de surface en été est indiquée par la position de l'isopycne 28,4.

The permanent presence of this ridge of isopycnals along the axis of the Catalan Sea (the " divergence line " in Ovchinnikov, 1966) has been related to a biological frontal system which has an important role in primary production (Estrada, Margalef, 1988). But important non-permanent vertical motions, several orders of magnitude higher than those related to the geostrophic equilibrium described above, have also been reported in this central area.

Margalef (1985) discusses the importance of mesoscale distributions in the Western Mediterranean ecosystem and describes the existence of discontinuous upwelling cells in this zone of the Catalan Sea. Our own work on deep water formation shows that mesoscale cyclonic cells (~ 10 km diameter) develop along this line north of parallel 41° N during hard winter conditions (Salat, Font, 1987), and disappear after a period of about 3 days. These cells of high-density water (σ_t = 29.11) are the surface signature of " chimneys " of homogeneous water, where intense convective vertical motions, up to 10 cm/s (Gascard, 1973), take place during the process of water mixing, after a previous phase in which strong cyclonic eddies pump intermediate water to the surface.

A mechanism that can induce these closed cyclonic eddies, and hence upward motion, into the central area of the Catalan Sea is related to the existence of meanders in the fronts. The meandering shape of the Balearic front can be easily seen in satellite thermographs (Fig. 11). Although the horizontal spacing of

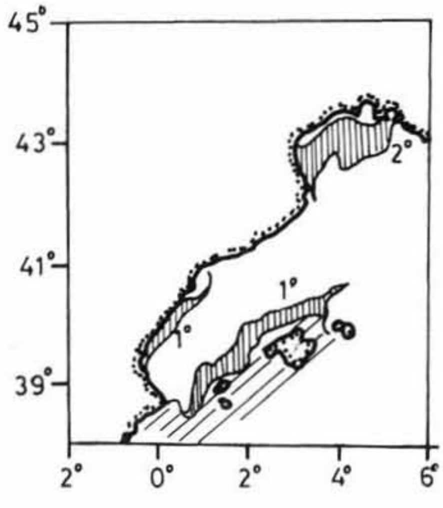

Figure 11

Surface thermal fronts in the Catalan Sea and the golfe du Lion from satellite infrared images in March 1984. *Numbers indicate maximum temperature gradient (degrees/*5 km*) between central waters and cooler (white) or warmer (dashed) surrounding waters (from Satmer, March* 1984*).*

Fronts thermiques en surface en Mer Catalane et dans le golfe du Lion en mars 1984 d'après les thermographies des radiomètres satellitaires. Les numéros indiquent le gradient maximum de température (degrés/5 km) entre les eaux centrales et les eaux adjacentes plus froides (blanc) ou plus chaudes (hachures) (d'après Satmer, mars 1984).

the stations of the different cruises we have analysed is too large for the study of these mesoscale features, we can propose a tentative interpretation of the phenomenon through a model based on long-period waves. This seems a reasonable assumption since the general circulation in the Northwest Mediterranean has been demonstrated to be mainly thermohaline and not wind-driven (Béthoux, Prieur, 1983).

Following Crépon *et al.* (1982), theoretical explanations in terms of large amplitude baroclinic waves can be sought. Baroclinic instability plays an important role in the formation of the mesoscale phenomena since the Catalan Sea can be considered as a baroclinically unstable area according to the criteria of Saunders (1973). The shape of the thermal front from satellite images is similar to that obtained by Saunders. He found that baroclinic instability occurs when $R^2 \ll D^2$, where R is the internal Rossby radius of deformation and D the width of the current. In the Catalan Sea, R is of the order of 10 km and both the northeastward Balearic current and the southwestward Catalan current have widths of the order of 50 km. So the area fills the conditions of baroclinical instability. Crépon *et al.* (1982) found a wavelength of 56 km for the most unstable waves in the Ligurian Sea, very similar to the wavelengths of the observed meanders in the Catalan Sea, 60 ± 20 km. Therefore large amplitude baroclinic waves could also explain the formation of meanders of the Catalan or Balearic front. These meanders would give rise to cyclonic and anticyclonic eddies with a diameter of the order of the internal Rossby radius of deformation. But according to potential vorticity arguments, only cyclonic eddies can develop offshore of the two fronts. Assuming no friction, potential vorticity is conserved during the motion of a barotropic fluid column. Assuming also a constant Coriolis parameter, if the depth increases, vorticity must also increase thus leading to an enhancement of the cyclonic motion and of the associated upward velocities. Therefore, eddies formed offshore the Balearic or the Catalan front will only persist if they are cyclonic. Strong upward velocities can arise in the upper layer for periods of a few days, as in the above mentioned case of deep water formation.

Acknowledgments

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