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Surface circulation variability in the Balearic Basin

M. J. López García,[1] C. Millot,[2] J. Font,[3] and E. García-Ladona[4]

Abstract. The Balearic Basin is defined as a wide region of the western Mediterranean located in between the Liguro-Provençal and Algerian basins. The dynamics of the Liguro-Provençal Basin, in the north, is dominated by the dense water formation process associated with a permanent circulation along the continental slope: the Northern Current. The Algerian Basin, in the south, is dominated by intense mesoscale eddies and their interactions with the unstable Algerian Current. The Balearic Basin is a transition region between these two different dynamic regimes. It includes the Catalan Sea, located between the Balearic Islands and the Iberian peninsula, and the wide Gulf of Valencia in the south of this sea. Some new ideas about the surface circulation variability have been inferred from a series of NOAA satellite advanced very high resolution radiometer images, taken mainly from the autumn-winter period during 1981–1988, and also from various in situ data. The Northern Current, which flows southward along the Iberian peninsula slope, is covered in summer by a warm surface layer spreading over the whole Catalan Sea. This local warming creates one of the most intense thermal fronts in the western Mediterranean, the Pyrenees Front. Near the Balearic Islands, the flow through the sills of recent Atlantic water, partially deflected by anticyclonic eddies from the Algerian Current, creates the Balearic Front and contributes to its mesoscale variability. This variability appears to be much more intense than previously described. The Balearic Front is clearly recognized as the westward continuation of the North Balearic Front, already defined in the open sea as the northern limit of the recent Atlantic water reservoir. Finally, the Gulf of Valencia is frequently influenced by water entering from the Algerian Basin, which appears to be important in the disruption of the Northern Current and the formation of the Balearic Current, the geostrophic flow associated with the Balearic Front.

1. Introduction

The Balearic Basin is defined as a wide region of the western Mediterranean located in between the Liguro-Provençal Basin in the north and the Algerian Basin in the south. The dynamics of the Liguro-Provençal Basin is dominated by the dense water formation process that takes place in winter [*Programme de Recherche International en Méditerranée Occidentale* (PRIMO), 1989, 1991; *Astraldi et al.*, 1990; *Madec et al.*, 1991] associated with a permanent circulation along the continental slope: the Liguro-Provenço-Catalan or Northern Current [*Millot*, 1991]. In the south, the Algerian Basin is characterized by the presence of intense mesoscale eddies and their interactions with the unstable Algerian Current [*Millot*, 1987]. The Balearic Basin (Figure 1) is thus a transition zone between the region of dense water mass formation and the region dominated by mesoscale baroclinic instability. Consequently, it plays a key role for the general Mediterranean circulation since it connects the two different regimes that configure the western Mediterranean dynamics. It includes the Catalan Sea, located in between the Balearic Islands and the Iberian peninsula, and the wide Gulf of Valencia, stretching from the mouth of the Ebro to Cape La Nao, the southwestern extreme of the Balearic Basin. The arc of the Balearic Islands, with three sills of ≈ 100 m (Minorca, eastern), ≈ 600 m (Majorca, central) and ≈800 m (Ibiza, western) and the Gulf of Valencia, with its wide continental shelf, delimit the southern boundary of the region usually called the northwestern Mediterranean Sea.

Three major water masses are distributed in the western Mediterranean Sea. At the surface the incoming flow of Atlantic water through the Strait of Gibraltar progresses to the Alboran and Algerian regions and finally around the basin, where it constitutes the Modified Atlantic Water (MAW), a surface layer of 100–200 m. Down to about 800 m the more saline Levantine Intermediate Water (LIW) comes in from the eastern Mediterranean and partially mixes in the north of the sea with the MAW, giving rise to the Western Mediterranean Deep Water (WMDW) that fills the deepest part of the sea. "Recent" MAW originating in the Algerian Basin and "old" MAW recirculated by the Northern Current meet in the Balearic Basin.

Studies involving a large amount of hydrographic data [*Font et al.*, 1988] or satellite imagery [*La Violette et al.*, 1990] have described the main aspects of the circulation in the Catalan Sea. It is characterized by the presence of two permanent density fronts and currents, along the peninsular (Catalan) and insular (Balearic) continental slopes. The Catalan Front is a shelf/slope front marked mainly by a change in salinity. It separates the surface layer denser water

[1]Departament de Geografia, Universitat de València, Valencia, Spain.
[2]Centre d'Océanologie de Marseille, La Seyne, France.
[3]Institut de Ciències del Mar, Barcelona, Spain.
[4]Departament de Física, Universitat Autònoma de Barcelona, Bellaterra, Spain.

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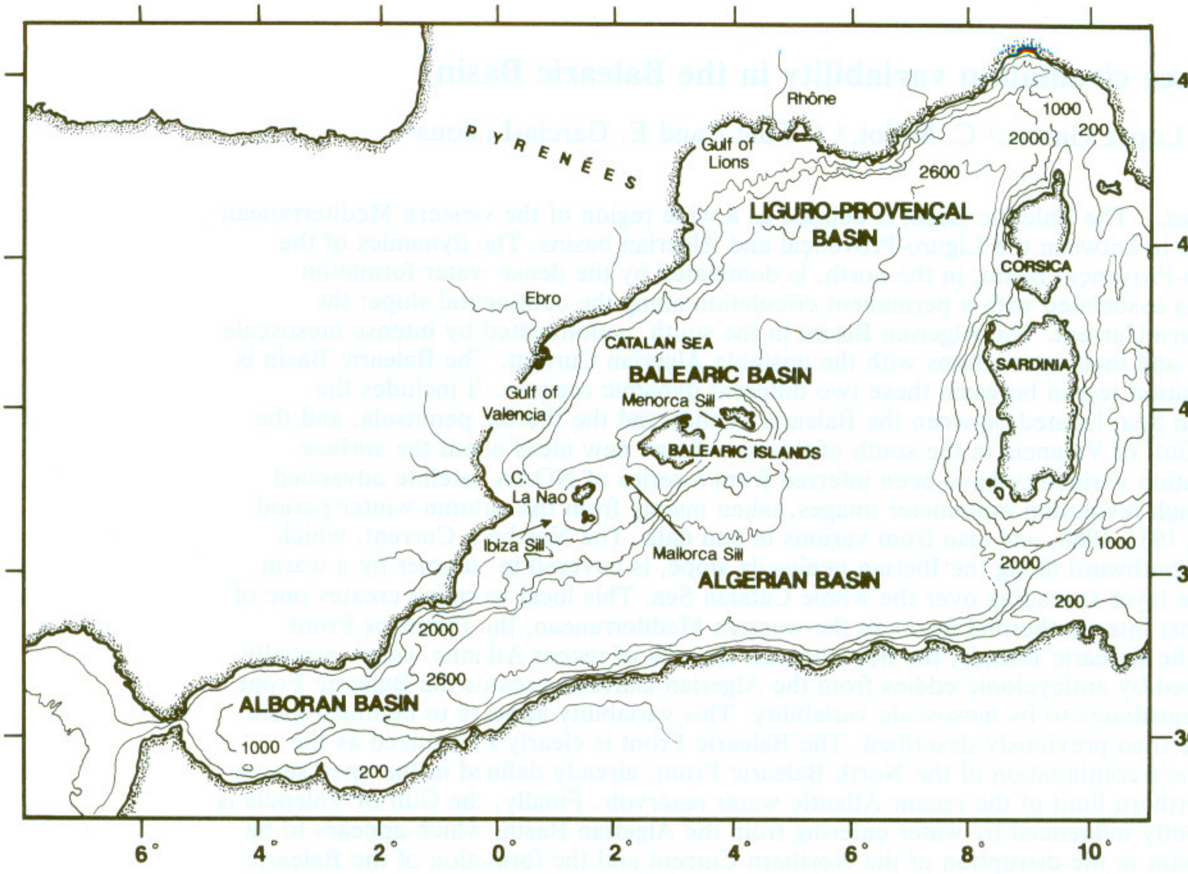


Figure 1. Location of the study area in the western Mediterranean.

(M in Figure 2), in the center of the Catalan Sea, from the water (C in Figure 2), transported by the Northern Current, that is fed in the Gulf of Lions and Catalan shelves by fresh continental water. This C water flows along the Iberian peninsula slope, with a mean surface velocity of about 20 cm/s, at least until the entrance of the Gulf of Valencia. The Catalan Front intersects the seabed at depths of nearly 400 m and intersects the surface at 15–20 km off the shelf break. In summer the surface heating stratifies the upper layer, and the density front does not reach the sea surface, but the isopycnal slope is still found below the thermocline. Acoustic Doppler current profile (ADCP) measurements across the slope have shown the mean current is alongslope and corresponds to the geostrophic adjustment in the area of the Catalan Front [*Castellón et al.*, 1990]. The Balearic Front has been associated with a northeastward Balearic Current, which has been less well described owing to the scarcity of available hydrographic data. It separates the old MAW located in the center of the Balearic Basin (M) from the lighter recent MAW (A in Figure 2) flowing from the south through the Balearic channels. Its vertical structure reveals a frontal zone well defined in the surface layer, with isolines bending to the horizontal on the southern side of the front at depths of 100–150 m [*Font et al.*, 1988]. The front is commonly observed in satellite thermography as a wavelike structure with a variable position along the northern side of the islands. These data show no evidence of lateral movement [*La Violette et al.*, 1990]. Figure 2 shows these main features as well as the three surface water masses (C, M, A) present in the region.

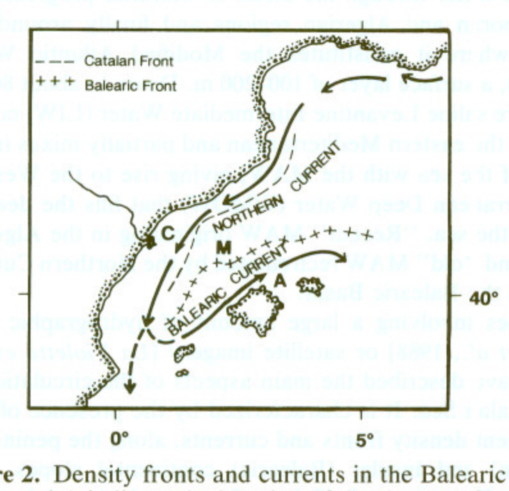


Figure 2. Density fronts and currents in the Balearic Basin. C, M, and A indicate the location of the three surface water masses present in the region.

Studies of the regional circulation have not paid a great deal of attention to the Gulf of Valencia shelf and slope area. However, because of its location this is an area of great importance for obtaining valuable information to complete our present knowledge of the Balearic Basin as well as the whole western Mediterranean circulation. It is in this region that the thermohaline forcing of the deep convection off the Gulf of Lions should close the cyclonic pattern of the general circulation in the whole western Mediterranean [*Millot*, 1987]. There are some interesting points which have not been resolved, such as the relationships between the aforementioned two fronts and currents off the Iberian coasts, the variability or branching of the Northern Current near the Ibiza Channel, the spatial and seasonal variability of the Balearic Front, and the extension of the MAW from the Algerian Basin to the Balearic Basin. The idea of a circulation scheme consisting of fairly well defined currents, such as in the north of the western Mediterranean Sea, is no longer acceptable anywhere else in the western basin owing to the dominance of instability processes affecting coastal currents, mesoscale phenomena, and seasonal variability [*Millot*, 1991].

The aim of this paper is to give a new insight into the variability of the surface circulation in the Balearic Basin, as observed from a multiyear set of infrared (IR) satellite images, with particular attention to the interaction with the Algerian Basin. The analysis of thermal gradients has often proved to be a useful tool for inferring surface circulation paths [e.g., *Legeckis*, 1978; *Champagne-Philippe and Harang*, 1982; *Deschamps et al.*, 1984; *Taupier-Letage and Millot*, 1988; *Le Vourch et al.*, 1992] and for providing valuable information when hydrological data are not available. Several sets of high-horizontal-resolution conductivity-temperature-depth (CTD) data have helped in the interpretation of IR images.

The work has been undertaken as part of the Euromodel, Hydrodynamic Modeling of the Western Mediterranean Basin, or project of the European Economic Community's EEC MAST1 program. This project investigates the processes and forcing mechanisms that drive the circulation in different regions of the western Mediterranean with special attention devoted to seasonal variability, the scale of the main driving process. The present study is part of the first phase of PRIMO, the International Research Program in the Western Mediterranean (supported by the Intergovernmental Oceanographic Commission of UNESCO and the International Commission for the Scientific Exploration of the Mediterranean Sea).

2. Material and Methods

The images used in this study were obtained by the advanced very high resolution radiometer (AVHRR) sensor on board the NOAA satellite series. This series, in operation since October 1978, consists of two satellites in complementary near-polar Sun-synchronous orbits, at an altitude of about 850 km. One crosses the equator at local solar times of approximately 0730 and 1930, and the other at 0230 and 1430, thus providing four images per day. The AVHRR sensor records radiation in five spectral channels, one in the visible domain (0.58–0.68 μm), one in the near-infrared (0.78–1.10 μm) and three in the thermal infrared centred at 3.7, 10.8, and 12 μm. The radiometer has a total field of view of 110.8° with 2048 samples per scan line, which gives a spatial resolution of 1.1×1.1 km^2 at nadir. The radiometric resolution of the thermal channels is 0.12 K at 300 K [*Fusco and Muirhead*, 1987]. Because of their temporal, spatial, and radiometric resolution, the NOAA satellites are the most suitable, at the present time, for determining sea surface temperature (SST) and studying surface circulation and thermal fronts at global and regional scales.

In order to obtain actual absolute SST values, satellite data must be corrected for emissivity effects and, more importantly, atmospheric attenuation. The calculation of the atmospheric correction is made by widely used techniques such as the multichannel method or the split-window method [*Deschamps and Phulpin*, 1980; *McClain et al.*, 1985], which produce absolute SST with a margin of error of less than 1 K [*Robinson et al.*, 1984]. However, the purpose of our study does not require atmospherically corrected images, since the use of maps of relative SST differences are enough for the observation of surface thermal patterns. We have produced relative SST maps with intervals of 0.2 K from AVHRR channel 4 (10.3–11.3 μm).

Our study is focused on the transition between the oceanographic seasons of autumn (October –December) and winter (January–March), because it is at this time that major changes in the thermohaline forcing and the induced circulation are expected. Several years have been studied in order to observe and characterize the main recurrent features. About 35, mainly nighttime, images from NOAA 6, 7, 8, 9, and 11, acquired during the autumns and winters of 1981–1988 were processed at the Centre d'Océanologie de Marseille. They were enhanced with color intervals of 0.2 K in order to highlight the most important thermal structures. The same color scale has been used for all the images with blue tones for lower temperatures and red for higher ones, but in different maps the same colors do not necessarily correspond to the same SST values. The images were also geometrically corrected onto a Mercator projection so that different images could be compared. Other sets of images already available from the Centre de Météorologie Spatiale de Lannion were also reviewed in order to complete the series under study.

3. Results and Discussion

A previous study of the spatial distribution and annual evolution of SST in the western Mediterranean Sea west of 6°E [*López García*, 1989] confirmed the specific nature, from a thermal view point, of the Gulf of Valencia, and more generally of the Balearic Basin. The study, based on the analysis of 4 years of weekly temperature maps from satellite data (SATMER, *Bulletin Mensuel de Renseignements Océanographiques Obtenus à Partir de Mesures Satéllitaires Météorologiques sur la Méditerrannée et l'Atlantique Nord-Est*, Direction de la Météorologie Nationale, Paris, 1984–1987) underlined the importance of the regional variations of SST (Figure 3). The Provençal Basin shows the lowest values in the whole area throughout the year, whereas the Algerian and Balearic basins present the highest values during the summer. The Alboran Basin, subjected to the permanent incoming flux of Atlantic water, shows the lowest annual amplitude, with high temperature in winter and values close to those of the Provençal Basin in summer. The Gulf of Valencia (Balearic Basin), which shows the highest annual thermal amplitude, with low values in winter similar to those observed in the Provençal Basin and high values in summer similar to those observed in the Algerian Basin, appears to have an intermediate nature.

The Recent Modified Atlantic Water

The Atlantic surface water flows into the Mediterranean Sea through the Strait of Gibraltar, presenting a warm thermal signature during the winter which is clearly recognizable in the thermal images [e.g. *Heburn and La Violette*,

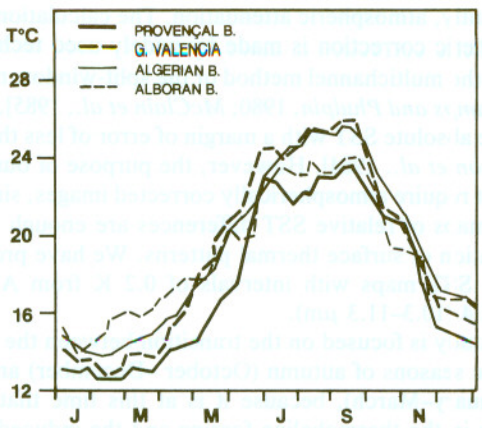


Figure 3. Annual evolution of sea surface temperature in four zones of the western Mediterranean Sea from satellite data.

1990], and then flows into the Algerian Basin, mostly via the Almeria-Oran jet [*Tintoré et al.*, 1988]. A stable current should flow eastward along the African slope and reach the Sardinian and Sicily channels, where it would partially continue along the northern Sicily coast and then return cyclonically through the rest of the western Mediterranean. It has been hypothesized from IR imagery that the Algerian Current, downstream 1°–2°E, could, however, become unstable and develop large meanders and eddies, which move eastward for months at a few km/day [*Millot*, 1985]; furthermore, stationary mesoscale eddies, whatever their relationship to these unstable eddies, could deflect the whole Algerian current seaward [*Taupier-Letage and Millot*, 1988]. Several numerical and physical models have been performed by the Euromodel group [*Chabert d'Hières et al.*, 1991; *Beckers and Nihoul*, 1992; *Mortier*, 1992] which account for the actual unstable behavior of the Algerian Current due to baroclinic instability. Eulerian and Lagrangian current measurements have clearly supported the actual role of mesoscale eddies in deflecting the Algerian Current seaward [*Millot*, 1991] and thus allowing the recent MAW to reach directly the Balearic channels.

This analysis is coherent with the series of images we have analyzed: it can be observed that warm water extends northward into the Balearic Basin and flows through the Balearic channels. As will be shown below, in winter this warm water can be identified as recent MAW originating in the Algerian Basin. Although the pattern of these inflows and the extensions to the north varies at different scales, some recurring features have been observed.

An inflow of warm water often passes through the Majorca Channel usually close to the western side of the island, and extends to varying degrees into the Catalan Sea; this can be clearly seen in the images of December 20, 1982, and January 17, 1983 (Plates 1a and 1c, respectively), as well as in the image of October 28, 1984 (Plate 2) and in the series of images during the winter of 1986–1987 (Plates 3a–3c). One particular feature observed in the image of December 13, 1986 (Plate 3a) is the formation of an anticyclonic eddy north of Majorca. The origin of this eddy could be related to the interaction between the local inflow of MAW through the eastern side of the Majorca Channel and the sharp western corner of the island of Majorca. The existence of such an eddy is consistent with the trajectory of a drifting buoy, drogued at 10 m, which was launched off Algeria in June 1986 and passed through the Majorca Channel in August 1986 (see *Millot* [1991] and Figure 4). It drifted northward close to Majorca before performing several anticyclonic loops north of the island and entering the interior of the Catalan Sea. On other occasions, however, the Majorca Channel presents an inflow by the west and an outflow by the east. Such a situation was observed in the density structure and by radio-tracking four surface drifting buoys during 6 days in June 1989 [*García-Ladona et al.*, 1991].

Another recurring feature is the presence of warm water, extending over the continental shelf of the Gulf of Valencia and apparently coming from the Ibiza Channel. This warm water is an almost permanent feature and usually forms an anticyclonic gyre, but it also can form a cyclonic gyre. An anticyclonic gyre on the continental shelf of the Gulf of Valencia could be inferred from the images during the winters of 1982–1983 (Plate 1) and 1986–1987 (Plate 3), along with February 1988. In the image of January 4, 1983 (Plate 1b), it seems that the circulation due to the anticyclonic gyre was superimposed on that due to an anticyclonic eddy located just within the Ibiza Channel. The structure of the latter is similar to the more intense eddy located about 100 km south-southeast, which indicates that these eddies might be due to instabilities of the Algerian Current that propagate northward. Plate 1 shows an eastward propagation of mesoscale features along the Algerian coast [*Millot*, 1985].

The existence of an anticyclonic gyre in the southern Gulf of Valencia has also been confirmed by in situ data. It was sampled in spring 1989 from an ADCP survey by *Castellon et al.* [1990]; they found that the gyre extended down to at least 300 m. This usual anticyclonic circulation pattern could coexist with a hydrographic structure in the Ibiza Channel corresponding to warm and fresh surface water flowing northward through the center and eastern sides of the sill [*García-Ladona*, 1990; *López-Jurado et al.*, 1991] and to water flowing southward through the western side and below the upper layer. During the stratified season, when the Northern Current is weakened [*Font et al.*, 1988], the upper 100–150 m of the southward flow could possibly detach from the slope and be deflected toward the Balearic Islands [*Castellón et al.*, 1990] where it can be incorporated into the Balearic Current as a deep component below the lighter incoming recent MAW [*Salat et al.*, 1992] (see Figure 2). Flux and velocity estimations indicate that the Balearic Current reaches its highest speeds (about 50 cm/s) during this stratified season [*Font et al.*, 1988; *García-Ladona*, 1990]. It seems that both topographic effects and these anticyclonic gyres can be responsible for the partial disruption of the Northern Current in the southern Gulf of Valencia.

Although anticyclonic gyres have been more frequently observed, a cyclonic gyre was detected in the autumn of 1984, as shown in Plate 2, where warm MAW seemed to flow through the Ibiza Channel, mainly on the island side and then deviated to the Iberian coast. Cyclonic patterns had been reported in other occasions from hydrographic observations [*Font*, 1986].

The Balearic Basin is the region where the greatest differences in the surface layer water are encountered. There is a natural tendency for the recent MAW deflected by the mesoscale Algerian eddies through the topographic barrier of the Balearic Islands to flow over the older denser water. This "overflow" takes place mainly on the east side of the Balearic channels and gives rise to the formation of the Balearic Front.

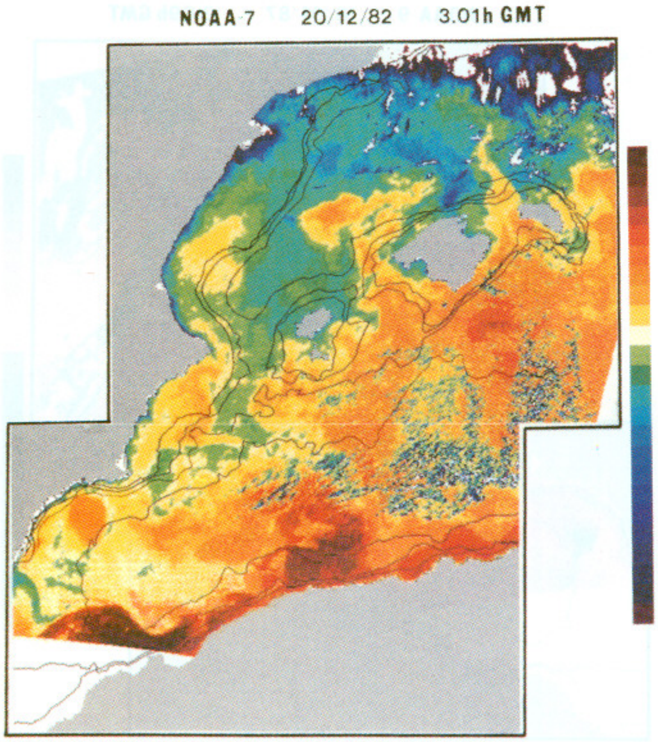


Plate 1a

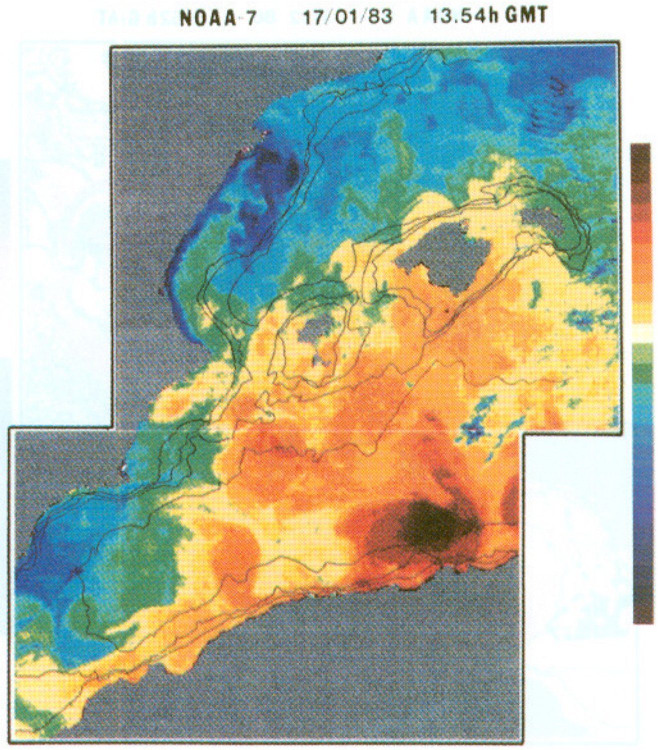


Plate 1c

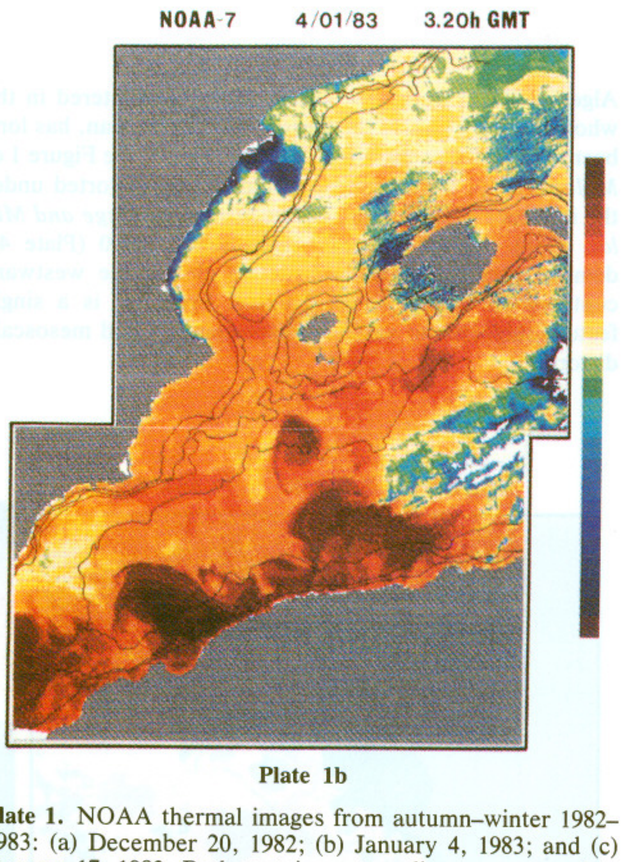


Plate 1b

Plate 1. NOAA thermal images from autumn–winter 1982–1983: (a) December 20, 1982; (b) January 4, 1983; and (c) January 17, 1983. Bathymetric contour lines correspond to 200, 500, 1000, and 2500 m.

The geostrophic adjustment of these two water masses causes a northeastward flow of the light water: the surface component of the Balearic Current. The variability of the circulation patterns found on the continental shelf of the southern Gulf of Valencia, where the Catalan and Balearic fronts are close to each other, could be related to the interactions between the intrusions of warm (recent) light MAW from the south and the cold (old) denser flow from the north.

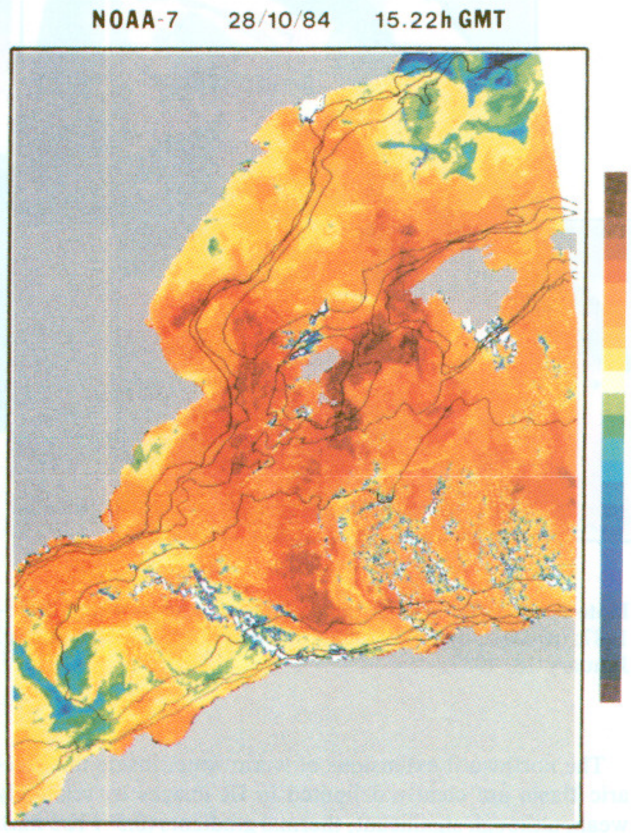


Plate 2. NOAA thermal image from October 28, 1984.

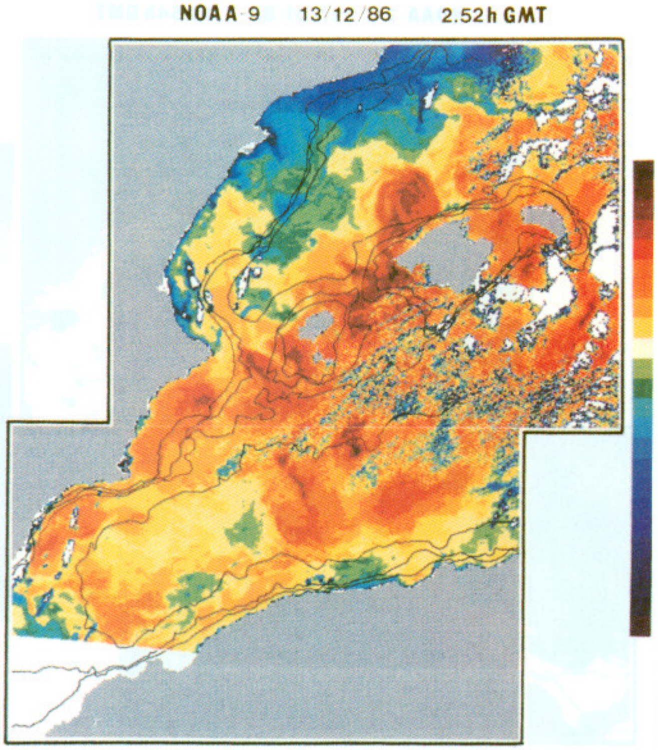


Plate 3a

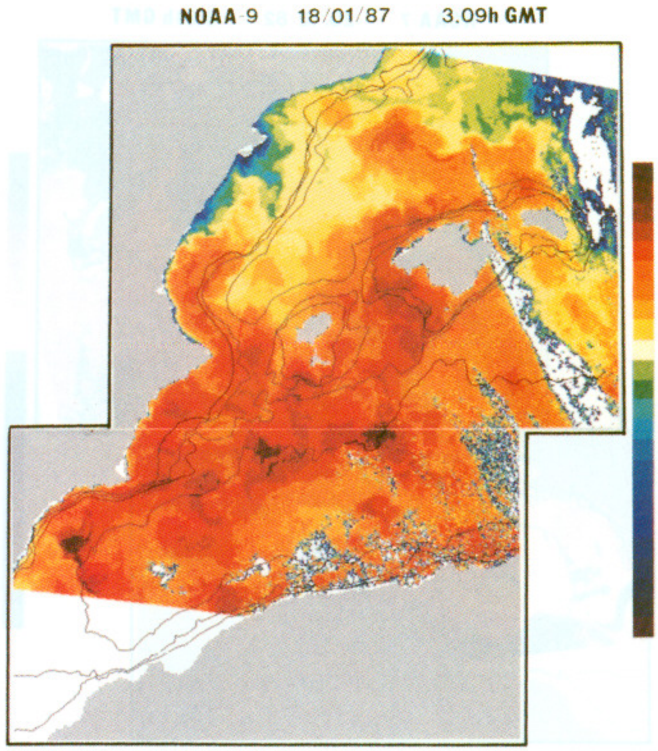


Plate 3c

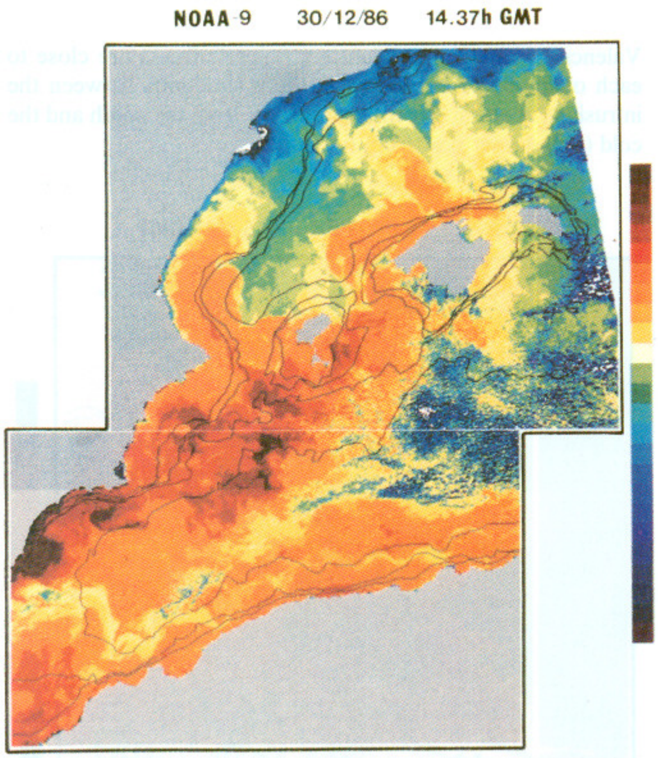


Plate 3b

Plate 3. NOAA thermal images from autumn–winter 1986–1987: (a) December 13, 1986; (b) December 30, 1986; and (c) January 18, 1987.

The northward extensions of warm water inside the Balearic Basin are clearly delimited in IR images by relatively weak, although significant, thermal gradients (0.5–1 K/5 km). Such a frontal structure, separating the recent MAW in the Algerian Basin from the surface water encountered in the whole northern part of the western Mediterranean, has long been recognized as the North Balearic Front (see Figure 1 of *Millot* [1987]), which can be tremendously distorted under the influence of mesoscale eddies [*Taupier-Letage and Millot*, 1988]. As the image of February 3, 1990 (Plate 4), demonstrates the Balearic Front is clearly the westward continuation of the North Balearic Front. It is a single feature subjected to seasonal displacements and mesoscale distortions.

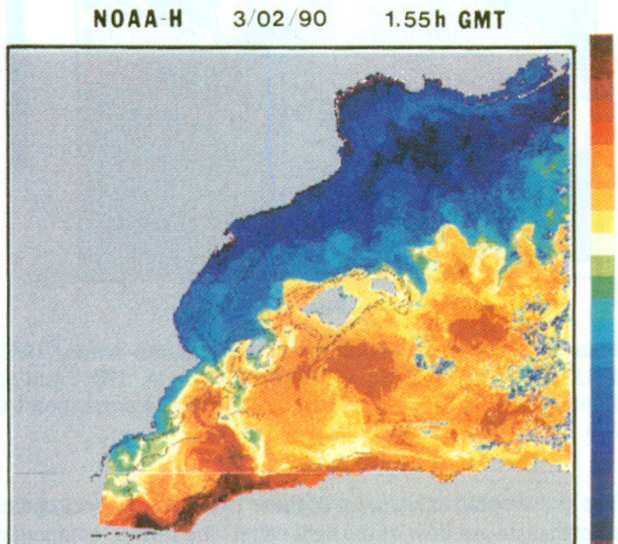


Plate 4. NOAA thermal image from February 3, 1990.

Seasonal Variability

In winter images (e.g., Plate 4) the thermal Balearic Front discussed in the preceding section is located close to the northern Balearic Islands shelf break. The tendency for the light MAW to spread northwards over the denser water formed in and north of the Balearic Basin in winter is strengthened in summer by the reduction in frequency and strength of the northwesterly winds and by the development of the seasonal stratification. Examples of very light water spreading above a shallow thermocline have been described close to the Catalan coast by *Castellón et al.* [1985] and *Masó and Tintoré* [1991]. *Font et al.* [1988] concluded from hydrological data that the northward spreading of recent MAW has a maximum at the beginning of the stratified season. In June 1989 the main salinity front was located about 50 km northwest of Minorca, and 50 km further seaward in the 15-m-thick upper mixed layer [*García-Ladona*, 1990].

In the northern part of the basin a surface thermal front is clearly observed in summer IR images between 41° and 42° N [*López García*, 1989]. This can be seen in the image of September 29, 1985 (Plate 5a), as the onshore-offshore frontal structure observed between the Gulf of Lions and the Balearic Basin. This surface front coincides with the southern limit (due to the barrier of the Pyrenees mountains) of the area affected by the strong and frequent northwesterly winds blowing in the Gulf of Lions [*Salat and Font*, 1987]. It is clear that the wind stress prevents the warm water from progressing northward, while in the north intense mixing produces a cooler and deeper mixed layer. The water trapped off the Spanish coast under cover of the Pyrenees can warm significantly, leading to the highest thermal gradients in the western Mediterranean in summer (see also *Le Vourch et al.* [1992]). In later summer and autumn the surface temperatures are relatively high so that small-scale and mesoscale meteorological, tropicallike, cyclones are often created. During the summer it is not possible to differentiate recent and old MAW with infrared images owing to the marked surface warming. The seasonal surface warming causes the surface signature of the Balearic density front to disappear, while an intense summer thermal front perpendicular to the coast, what we have called "the Pyrenees Front," is created.

Two possibilities could arise: either the recent MAW spreads in summer over the whole Balearic Basin, with the Pyrenees Front being the signature of the Balearic Front at its northernmost location, or the thermal homogenization south of the Pyrenees affects both old and recent MAW, and consequently the Balearic Front remains near to its winter position but hidden to AVHRR images by the surface mixed layer. Indeed, a very mixed surface layer is formed during spring over the whole Mediterranean Sea, giving rise to a two-layer stratification within the MAW layer itself. The mixed-layer dynamics are obviously more dependent on wind conditions than the remainder of the MAW below. It is well known that the Mediterranean summer surface flow is complex and variable owing to the diverse, small-scale wind regimes. Inertial motions, generated by gusts of wind, have been found to be one of the main seasonal characteristics in the region [*Font*, 1990], especially when the mixed layer is thin at the beginning of the stratified season. These phenomena lead to a smoothing of the SST gradients, and so IR information cannot reveal the circulation occurring in the whole MAW layer. For instance, the trajectory off Barcelona of the drifting buoy (Figure 4), which is initially shoreward and then seaward, more or less perpendicular to the Northern Current, clearly shows that in summer the mixed-layer displacements are quite erratic and disconnected from the major circulating phenomena.

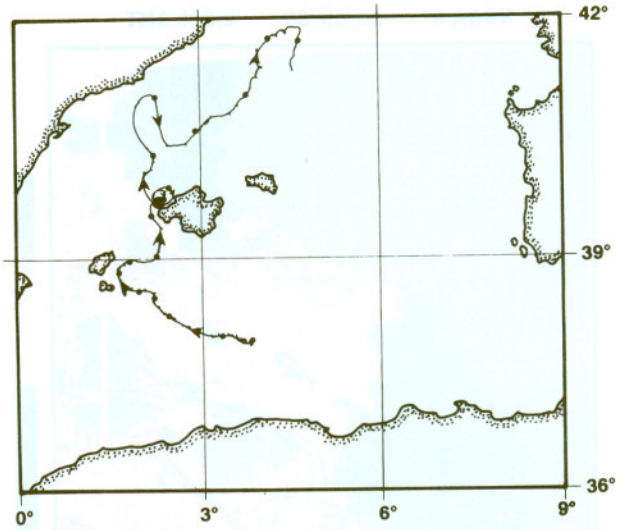


Figure 4. Trajectory of a drifting buoy in the Algerian and Balearic basins from July to September 1986 (Mediprod-5 experiment [*Millot*, 1991]. Dots indicate 5-day intervals.

Careful examinations of hundreds of hydrological casts in the Balearic Basin [*Salat and Cruzado*, 1981; *Font*, 1986] showed that water with TS characteristics of recent MAW can be found in the center of the Catalan Sea, especially near the surface at the beginning of the stratified season, but never reaching the limit of the Pyrenees Front. CTD data between Barcelona and Minorca collected in early November 1984 with a fully developed mixed layer (Figure 5) accounts for the occurrence of several thermal fronts located north of the salinity front, which marks fairly well the limit between recent and old MAW. In fact, this salinity front must be considered as the actual signature of the Balearic–North Balearic Front. The analysis of summer AVHRR images covering the whole Liguro-Provençal Basin sometimes shows traces of the actual North Balearic Front farther south than the marked temperature gradient that delimits the cold water of the Gulf of Lions [*Santoleri et al.*, 1992].

We have to conclude that the Balearic density front is at the surface a salinity front being accompanied by thermal differences during the winter season. It is clear that with respect to the specific problem of the northward spreading of MAW from the Algerian Basin, IR remote sensing is not efficient during the summer. A better understanding of this spreading can only be provided by CTD data collected from late spring to the autumn. The natural process of cooling in autumn, which gives rise to increased thermal contrasts at the surface, destroys the two-layer vertical structure, and by the end of December reveals, as can be seen in the image of December 28, 1983 (Plate 6, bottom panel), a marked frontal structure that was not visible at the end of the summer (see the image of October 3, 1983, in the top panel of Plate 6). This is the Balearic–North Balearic Front that plays a major role, like its counterpart the Catalan Front, in delineating the surface layer circulation in the Balearic Basin.

The transition between summer and winter conditions can be deduced from an analysis of the sequence of images in

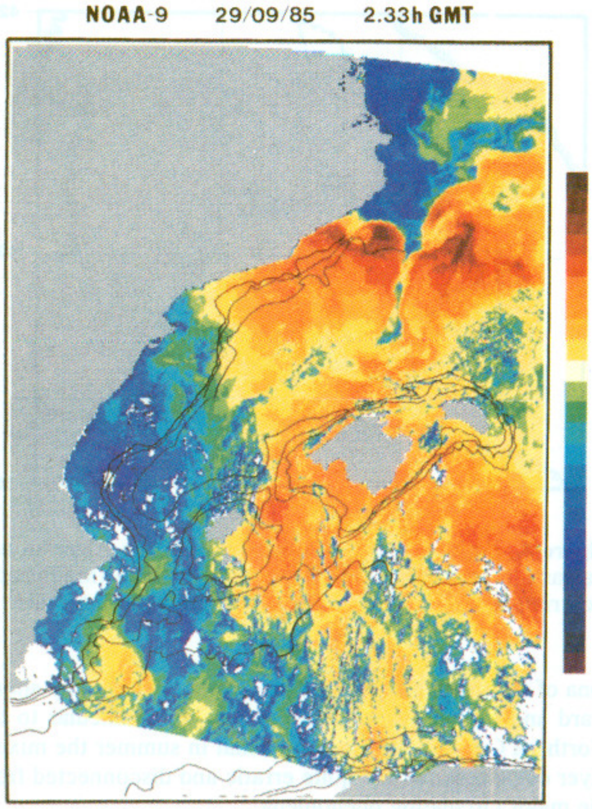


Plate 5a

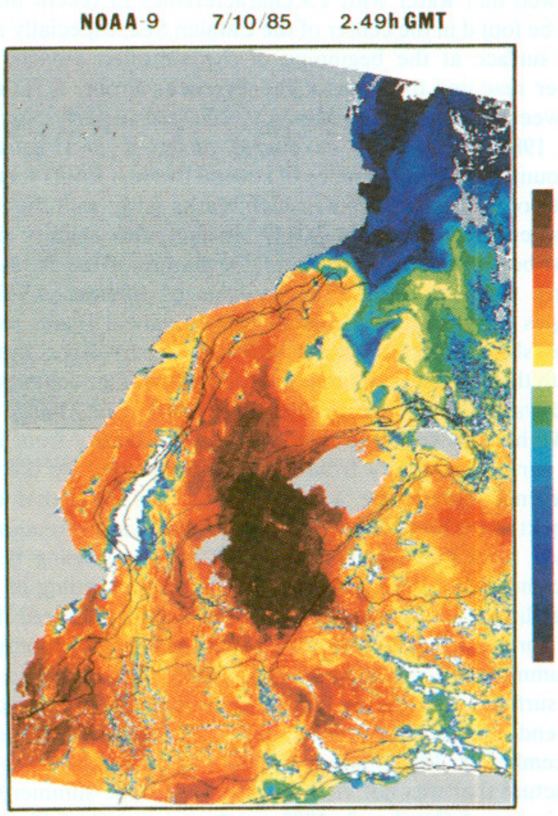


Plate 5b

Plate 5. NOAA thermal images from autumn 1985: (a) September 29, 1985; (b) October 7, 1985; and (c) December 20, 1985.

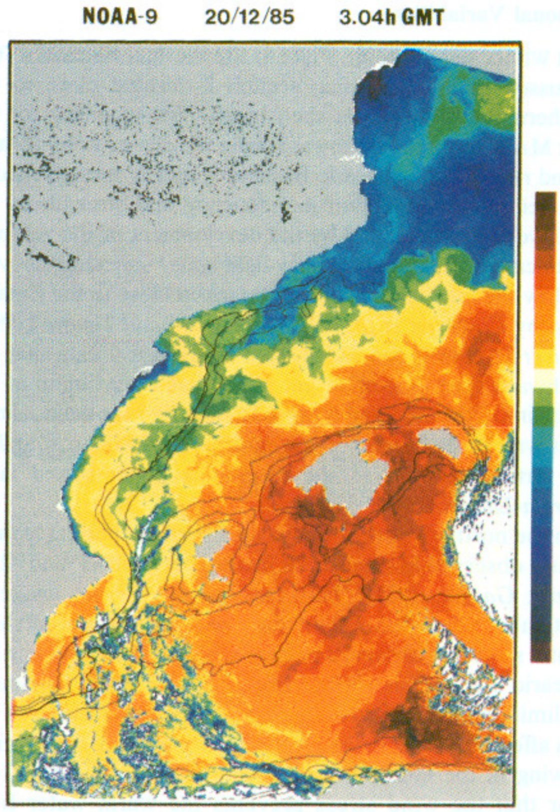
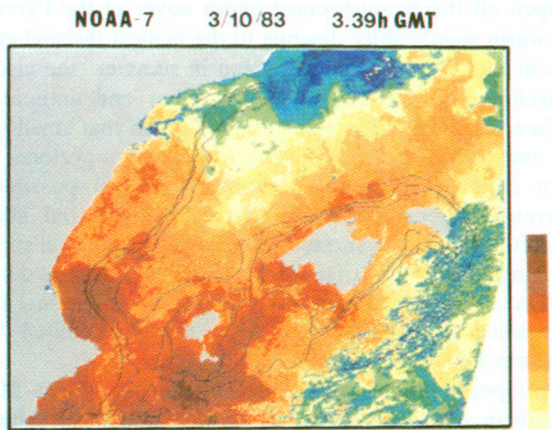


Plate 5c



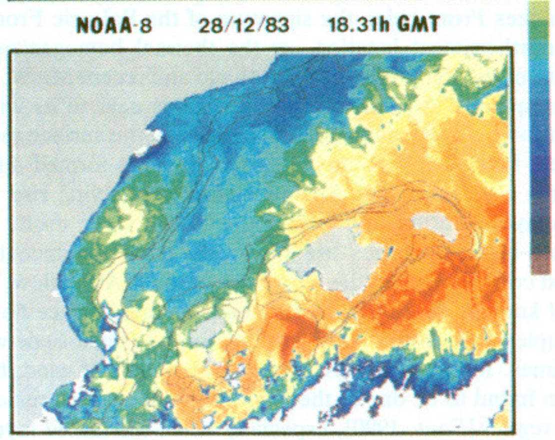


Plate 6. NOAA thermal images from autumn–winter 1983–1984: (top) October 3, 1983 and (bottom) December 28, 1983.

autumn–winter 1985 (Plate 5). Since current measurements in the Ligurian Sea, the Gulf of Lions and the Catalan Sea indicate that the Northern Current flows at least until 39°30′ N throughout the year along the continental slope [*Font*, 1990; *Font and Wang*, 1991], it is obvious that during the summer it flows beneath the surface warm water and perpendicular to the surface thermal front (the Pyrenees Front). Usually, owing to the relatively cool water from the Gulf of Lions that mixes with it, the Northern Current is easily traced in IR images along the slope in the Catalan Sea [*La Violette et al.*, 1990]. In the image of September 29, 1985 (Plate 5a), the Pyrenees Front appears clearly as strong thermal gradients perpendicular to the coast. One week later (Plate 5b) this structure is less marked, the thermal gradients are reduced, and cool water seems to progress southwards to the center of the Catalan Sea. Finally, in December (Plate 5c) it can be seen that the stratification of the surface layer

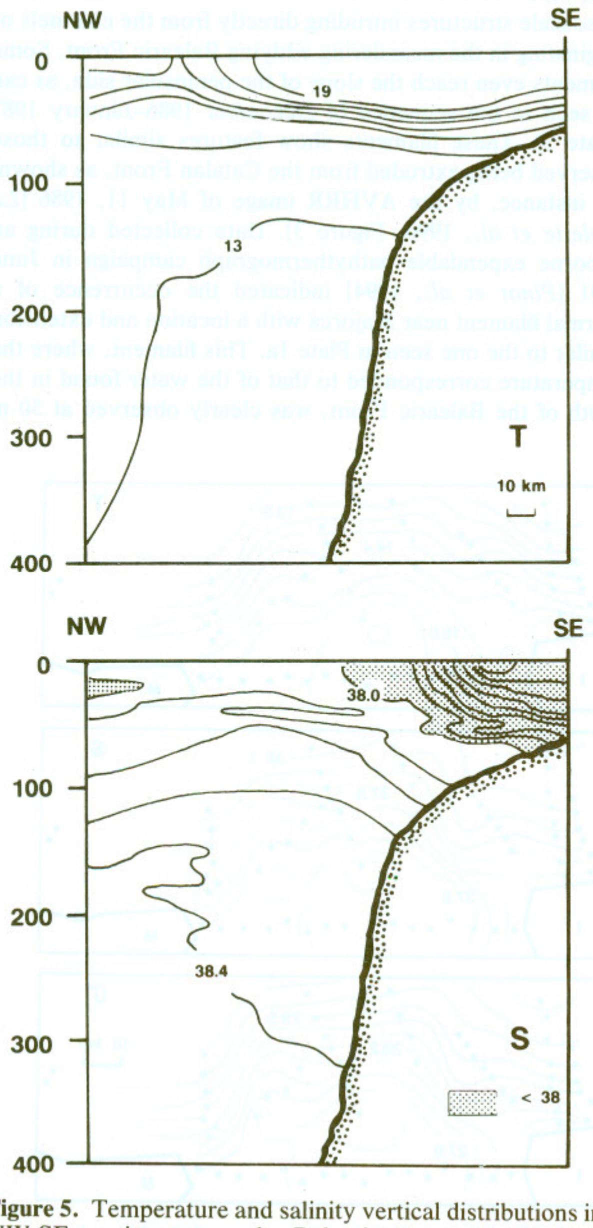


Figure 5. Temperature and salinity vertical distributions in a NW-SE section across the Balearic Front off Minorca in November 1984.

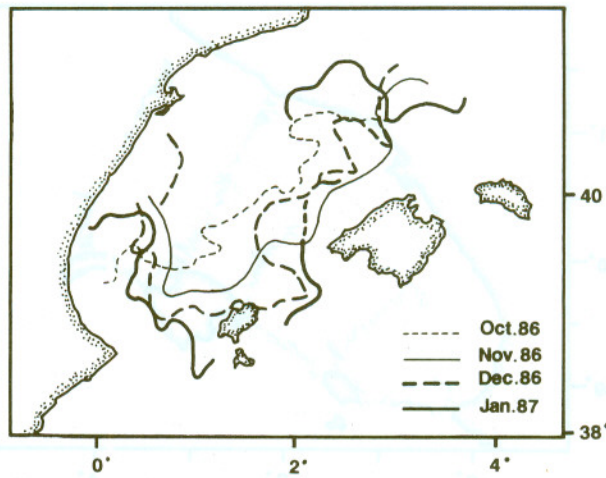


Figure 6. Synthesis of the different positions of the Balearic Front and thermal limits observed from the series of images of autumn–winter 1986–1987.

has been eroded by interactions with the atmosphere, and the mixing associated with the Northern Current gives it a distinct surface signature. This current is now visible flowing southwestward along the continental slope. Similar characteristics were also observed in autumn 1981, 1983 (Plate 6), and 1987.

The image of December 20, 1985 (Plate 5c), indicates strongly that the cold Northern Current follows the continental slope to the Ibiza Channel. In other images, mainly of the end of winter, cold water was observed lying over the whole continental shelf of the Gulf of Valencia. The image of February 3, 1990 (Plate 4), is a clear example of this situation due to the general winter cooling, especially intense over the shallow continental shelf.

Mesoscale Variability

Recent in situ studies have shown evidence that the Catalan Front contains important mesoscale variability [*Font and Wang*, 1991]. The occurrence of very energetic frontal features, like eddies and filaments, has been described in that area [*Wang et al.*, 1988; *Tintoré et al.*, 1990]. *La Violette et al.* [1990] have observed in IR images small eddies moving within the Catalan Front, while in the Balearic Front similar motion was not found in a series of successive images from spring 1986.

Although the existence of a lateral movement along the Balearic Front could not be deduced from our images, a latitudinal displacement was inferred from a series of 1986–1987 images (Plate 3). The different positions of the largest thermal gradients obtained from this set of images have been depicted in Figure 6. One can observe both the complex interactions in the southern Gulf of Valencia, probably accompanied by the latest stages of the surface mixed-layer erosion, and lateral displacements of the Balearic Front. These mesoscale displacements are clearly due to the advection of MAW from the Algerian Basin through the Balearic channels.

A high-resolution field study with CTD, ADCP, and surface drifters in June 1989, at the beginning of the stratified season, clearly associated a meandering front along the northern side of the Balearic Islands with the northeastward

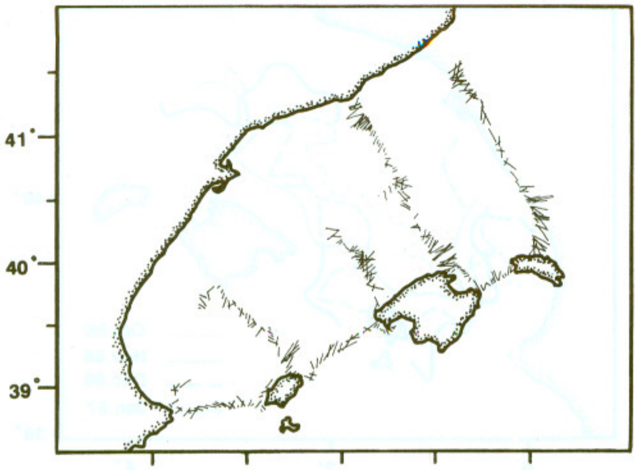


Figure 7. ADCP velocities at 30 m measured in May–June 1989. A reference level of no motion at 300 m has been used.

current in the upper layer [*García-Ladona et al.*, 1991]. Figure 7 presents ADCP velocities measured at 30 m during this cruise. A 15- to 30-m mixed layer covered all the region. Contemporaneous AVHRR images (not shown) give no evidence of a thermal signature of the Balearic Front, while on the peninsular side the cool plume associated with the Northern Current is clearly seen. The ADCP measurements allow identification of the Balearic Current from Ibiza to Minorca and even suggest its meandering shape. The position of the current indicated that the Balearic Front was situated along the insular slope but further seaward than its typical winter location (e.g., plate 4). The current had maximum speeds of 45 cm/s and a total flux of 0.75 Sv. A mean flux of 0.5 Sv had been previously estimated by *Font et al.*, [1988] from different data sets, and speeds of 50 cm/s have been observed in November 1984 with a drifting buoy north of Majorca [*Font*, 1986]. Figure 8 shows temperature, salinity, and density (σ_t) maps at 30 and 60 m depth between Ibiza and Majorca obtained during the June 1989 cruise. In addition to a general meander of some 80 km wavelength, related to the entrance of recent MAW through the channel as measured by ADCP, mesoscale thermal eddies can be observed at 30 m. This is just below the thermocline and consequently has nothing to do with diurnal heating or high-frequency motion in the mixed layer.

Given the origin of the Balearic Front, its season displacements can be masked by the mesoscale variability associated with the intrusions of recent MAW. An examination of our full set of autumn–winter images gives a lot of examples of mesoscale eddies and filaments generated in the Balearic frontal zone. Plates 1a, 1c, 2, 3a, 3b, and 3c show situations with cold water in the center of the Catalan Sea and warm mesoscale structures intruding directly from the channels or originating in the meandering-eddying Balearic Front. Some filaments even reach the slope of the peninsular side, as can be seen in the sequence of December 1986–January 1987 (Plate 3). These filaments show features similar to those observed being extruded from the Catalan Front, as shown, for instance, by the AVHRR image of May 11, 1986 [*La Violette et al.*, 1990, Figure 3]. Data collected during an airborne expendable bathythermograph campaign in June 1991 [*Pinot et al.*, 1994] indicated the occurrence of a thermal filament near Majorca with a location and extension similar to the one seen in Plate 1a. This filament, where the temperature corresponded to that of the water found in the south of the Balearic Front, was clearly observed at 50 m

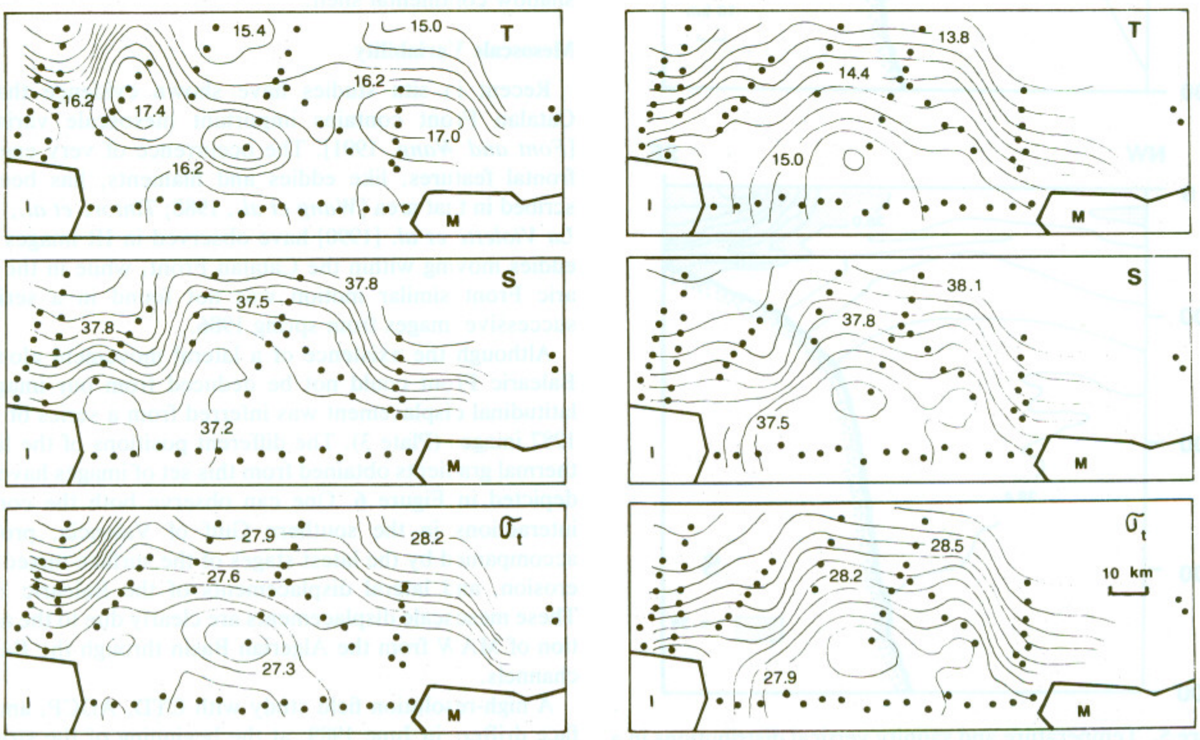


Figure 8. (top) horizontal distributions of temperature, (middle) salinity, and (bottom) σ_t at (left) 30 and (right) 60 m near the Majorca Channel in June 1989. Dots indicate station locations. I, Ibiza; M, Majorca.

and still detectable at 125 m. However, owing to the surface mixed layer, it was not detected above 20 m.

The importance of mesoscale variability has never been described in the Balearic Front, since it was considered to be less variable and have little motion compared with the Catalan Front [*La Violette et al.*, 1990]. We have observed that it has remarkable turbulent activity, with eddies usually larger than those traveling along the Catalan Front but that can only be observed in IR images when there is no surface mixed layer. Our images, which cover a region of the western Mediterranean from the Algerian coast in the south to near the Gulf of Lions in the north, show clearly that the Balearic Front is the northward extension of the eddy-dominated circulation regime of the Algerian Basin. The large anticyclonic Algerian eddies are deep enough for their eventual northward drift to be stopped by the topographic barrier of the Balearic Islands. We can conclude that the northward extension of recent MAW, and consequently the formation of the Balearic Front, is determined both by the presence of denser old MAW in the northwestern basin and the topography.

Finally, a different kind of mesoscale variability can also be observed over the continental shelf in the northern Gulf of Valencia. Relatively fresh and cold water of continental origin, mainly from the Rhône and Ebro rivers, spreads along the coast in the Catalan Sea [*Salat and Cruzado*, 1981]. This water is mixed with the old MAW transported by the Northern Current and gives rise to a specific water mass that occupies the surface layer over the continental shelf. It is separated from offshore waters by the along-slope Catalan Front.

A striking feature in most of the winter images is the presence of a cold area near the Ebro river delta. The fresh water of the Ebro discharge always has a low temperature in winter, causing its extension to be clearly visible. The whole series of IR images provides significant information about the spatial and temporal variabilities of the spreading of the Ebro runoff. A plume of cold water spreading seaward at the Ebro delta and a tongue of cold water south of it along the coast have been observed repeatedly. When the extension of the plume is relatively important, as in the winter of 1982–1983 (Plate 1), it can reach the edge of the continental shelf and then be deflected southward by the Northern Current, which in this season flows at the surface and prevents these waters from spreading seaward. The images during the winter of 1982–1983, a period of high discharge associated with heavy rains, demonstrate the importance of the Ebro runoff in surface circulation variability. The large volume of Ebro water in these images allows the evolution of the continental water to be analyzed.

4. Conclusions

The major features that characterize the surface layer circulation in the Balearic Basin during the autumn–winter period have been inferred from thermal satellite images. Plate 4 (February 3, 1990) exhibits virtually all of the circulation features described in this paper. Our study supports the observations already available and proposes new insights on the Balearic Basin hydrodynamics, leading to a coherent analysis of all the existing data sets concerning the circulation variability.

Our basic idea is that the Balearic Basin is an intermediate region that is widely open to the Liguro-Provençal Basin, where cold and dense waters are formed in winter, and that communicates through the sills of the Balearic Islands with the Algerian Basin, where relatively warm and light waters are amassed. There is a natural tendency for the latter waters, deflected by the mesoscale eddies, to intrude into the Catalan Sea and geostrophically adjust with the denser waters. The definition of the North Balearic Front as the northern limit of the waters recently entered into the Algerian Basin [*Millot*, 1987], applies to the Balearic Front as the limit of the intrusion of these waters into the Catalan Sea.

The Balearic Front, which is mainly a salinity front and does not have a sharp temperature gradient (< 1 K/5 km during winter), displays seasonal variations due to the interaction between the dynamics of the recent Modified Atlantic Water and the vertical structure of the waters occupying the Catalan Sea. As the stratified season progresses, a general warming takes place over the basin and horizontal thermal gradients tend to weaken. A strong thermal front (the Pyrenees Front) then appears, separating the warm waters in the Balearic Basin from the cold waters in the Gulf of Lions. During this period, satellite infrared images give inaccurate information on the circulation of the surface layer, since the main currents flow below the upper mixed layer. This is clearly illustrated with the Northern Current becoming progressively visible along the Iberian peninsula slope as the surface layer stratification is eroded during the autumn.

The instability processes affecting the flow of MAW along the Algerian coast give rise to the formation of eddies which can deflect recent MAW directly toward the Ibiza and Majorca channels. Intrusions of MAW have been observed to cross these channels, mainly on their eastern sides. They frequently form something like an eddy structure north off Majorca and also penetrate the continental shelf of the Gulf of Valencia, where they can contribute to the partial disruption of the Northern Current and form an anticyclonic, and at times cyclonic, gyre. The southern Gulf of Valencia and the Balearic Front are affected by important mesoscale variability. Eddies and large filaments have been observed extruding from the Balearic Front and crossing the Catalan Sea to the peninsular slope. These appear to be much more intense than previously described and show that the Balearic Front is the northern limit of the turbulent regime that dominates the Algerian Basin.

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J. Font, Institut de Ciències del Mar, CSIC, P. Nacional s/n, 08039 Barcelona, Spain.

E. García-Ladona, Departament de Física, Universitat Autònoma de Barcelona, 08139 Bellaterra, Spain.

M. J. López García, Departament de Geografia, Universitat de València, Apartado 22060, 46080 València, Spain.

C. Millot, Centre d'Océanologie de Marseille, B. P. 330, 83507 La Seyne, France.

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