Variability of the northern current off Marseilles, western Mediterranean Sea, from February to June 1992

Northern Current
Variability
Gulf of Lions
Hydrology
Flux

Courant Nord
Variabilité
Golfe du Lion
Hydrologie
Flux

Pascal CONAN and Claude MILLOT

Centre d'Océanologie de Marseille, Faculté des Sciences de Luminy, Case 901, 13288 Marseille cedex 9.

Received 11/04/94, in revised form 26/01/95, accepted 30/01/95.

ABSTRACT

A hydrological transect was performed on seven occasions from February to June 1992 in the coastal zone off Marseilles, a region of the western Mediterranean Sea where such data were not yet available. This lack of information is surprising, especially if one considers the large amount of data already collected both further seawards and in neighbouring regions such as the Ligurian and the Catalan Seas. The time interval between the transects (one week to one month) does not permit a distinction between mesoscale and seasonal variations, but the fine space interval between the casts (3-4 km) and the length of the transect (~45 km) provide significant information on the characteristics of the Northern Current (NC) when it penetrates into the Gulf of Lions, and on those of the Modified Atlantic Water (MAW), the Winter Intermediate Water (WIW), and the Levantine Intermediate Water (LIW).

Large mesoscale meanders of the NC have been evidenced; within the space of one week, its core can be found at a distance of more than 35 km or less than 20 km, while the LIW vein can be shifted by more than 10 km seawards from its mean location close to the slope. This also accounts for the fact that the NC was, in general, relatively deep (5 cm/s at 400-500 m), with surface speeds up to 30-50 cm/s continuously decreasing with depth. Its transport displayed a specific variation: low (~0.7 Sv) in late February-early March, it increased up to 1.75 Sv in April-May and decreased to ~0.5 Sv in June. Although significant, such a seasonal variation differs from that encountered in the Ligurian Sea (the maximum occurs earlier in the winter), but is not inconsistent with what is predicted from numerical models with regard to the rim current associated with the formation of the Western Mediterranean Deep Water (WMDW).

A mechanism for the formation of WIW is proposed which can occur more or less everywhere in the western Mediterranean Sea, throughout the general circuit of MAW. It is clear that MAW, cooled and homogenized in winter during gusts of northwesterly winds, is rapidly overlaid, when the wind ceases, by warmer MAW that is preserved from such strong interactions in neighbouring places; this cool MAW will subsequently be recognized as WIW and characterized by a temperature minimum with respect to both MAW above and LIW below.

It is confirmed that the general circuit of LIW in the whole sea is cyclonic along the continental slope, and it is shown that the variations of both its distribution and hydrological characteristics there are clearly dependent on the formation of WMDW. At that time, LIW spreads seawards along the isopycnals while its temperature and salinity maxima are low due to intense mixing; it then re-structures itself as a vein flowing westwards along the slope while its maximum values continuously increase, due to lower and lower mixing.

RÉSUMÉ

Variabilité du Courant Nord, au large de Marseille (Méditerranée Nord occidentale) entre février et juin 1992.

Une section hydrologique a été réalisée sept fois entre février et juin 1992 dans la zone côtière au large de Marseille, qui est une région de la Méditerranée occidentale où de telles données n'étaient pas disponibles. Ce manque d'informations est surprenant, d'autant que de nombreuses données ont déjà été collectées plus au large et dans des régions voisines comme la mer Ligure et la mer Catalane. L'intervalle de temps entre les sections (une semaine à un mois) ne permet pas de séparer les variabilités saisonnière et à moyenne échelle, mais le faible espacement des stations (3-4 km) et la longueur de la section (~45 km) permettent d'obtenir des informations significatives sur les caractéristiques du Courant Nord (NC), quand il pénètre dans le Golfe du Lion, et sur celles de l'eau modifiée d'origine atlantique (MAW), de l'eau intermédiaire d'hiver (WIW), et de l'eau levantine intermédiaire (LIW).

Le NC peut décrire des méandres de moyenne échelle de grande amplitude; en une semaine, son cœur peut être trouvé à plus de 35 km ou à moins de 20 km, tandis que la veine de LIW peut être déplacée vers le large de plus de 10 km par rapport à sa position moyenne le long de la pente. Ceci traduit aussi le fait que le NC était, en général, relativement profond (5 cm/s à 400-500 m) avec des vitesses en surface jusqu'à 30-50 cm/s décroissant continuement en profondeur. Son transport a décrit une variation particulière : il a été faible (~0,7 Sv) fin février-début mars, il a augmenté jusqu'à 1,75 Sv en avril-mai puis a décru jusqu'à ~0,5 Sv en juin. Si elle est significative, une telle variation saisonnière est différente de ce qui se produit en mer Ligure (le maximum a lieu plus tôt dans l'hiver), mais pas incompatible avec ce que prédisent les modèles numériques sur le courant de bord associé à la formation de l'eau profonde de la Méditerranée occidentale (WMDW).

On propose un mécanisme pour la formation de WIW qui pourrait se produire plus ou moins n'importe où en Méditerranée occidentale, le long du circuit de MAW. Il est clair que MAW, refroidie et mélangée en hiver pendant les coups de vent de nord-ouest, est rapidement recouverte, lorsque le vent cesse, par de la MAW préservée d'aussi fortes interactions dans des endroits proches; cette MAW froide sera ensuite reconnue comme WIW et caractérisée par un minimum de température par rapport à MAW au-dessus et LIW au-dessous.

On confirme que le circuit général de LIW dans l'ensemble de la mer est bien cyclonique le long de la pente continentale et on montre que les variations de sa répartition et de ses caractéristiques dans la région sont clairement dépendantes de la formation de WMDW. À cette époque, LIW se répand vers le large le long des isopycnes tandis que ses maxima de température et de salinité sont faibles sous l'effet d'un mélange intense; puis elle se re-structure comme une veine s'écoulant vers l'ouest le long de la pente tandis que ses valeurs maximales augmentent continuement, sous l'effet d'un mélange de plus en plus réduit.

Oceanologica Acta, 1995, **18**, 2, 193-205.

INTRODUCTION

All water masses in the northern part of the western Mediterranean Sea are expected to flow mainly cyclonically along the continental slope (Millot, 1987, 1991). It is well known that the Modified Atlantic Water (MAW) flows northwards on both sides of Corsica; the Western and the Eastern Corsican Currents join in the Ligurian Sea and form the Northern Current (NC), previously called the Liguro-Provenço-Catalan Current and recognized as an entity as far as the Catalan Sea (Lopez-Garcia *et al.*, 1994). It is less easily recognized that a similar circuit is followed by the Levantine Intermediate Water (LIW), as the part which has flowed from the Tyrrhenian Sea through the Corsican Channel joins the part which has skirted Sardinia and Corsica (Millot, 1987). Nevertheless, a synthetic account of the location of LIW, mainly along the slope, as well as its mesoscale and seasonal variabilities, is provided by Albérola *et al.* (1995) in the Ligurian Sea, Durrieu de Madron *et al.* (1990) in the Gulf of Lions and Font (1987) in the Catalan Sea. Most of the Winter Intermediate Water (WIW), recognized between MAW and LIW and mainly formed in the whole area (Lacombe and Tchernia, 1971), is thus expected to flow cyclonically, as well. This along-slope circulation of the surface and intermediate waters surrounds an offshore and less stratified zone where the Western Mediterranean Deep Water (WMDW) is formed in winter; no general circulation is evidenced in the interior of the zone (Taupier-Letage and Millot, 1986), but at depth

– and this is a generally unknown feature – WMDW clearly flows cyclonically along the continental slope, too (Millot, 1994).

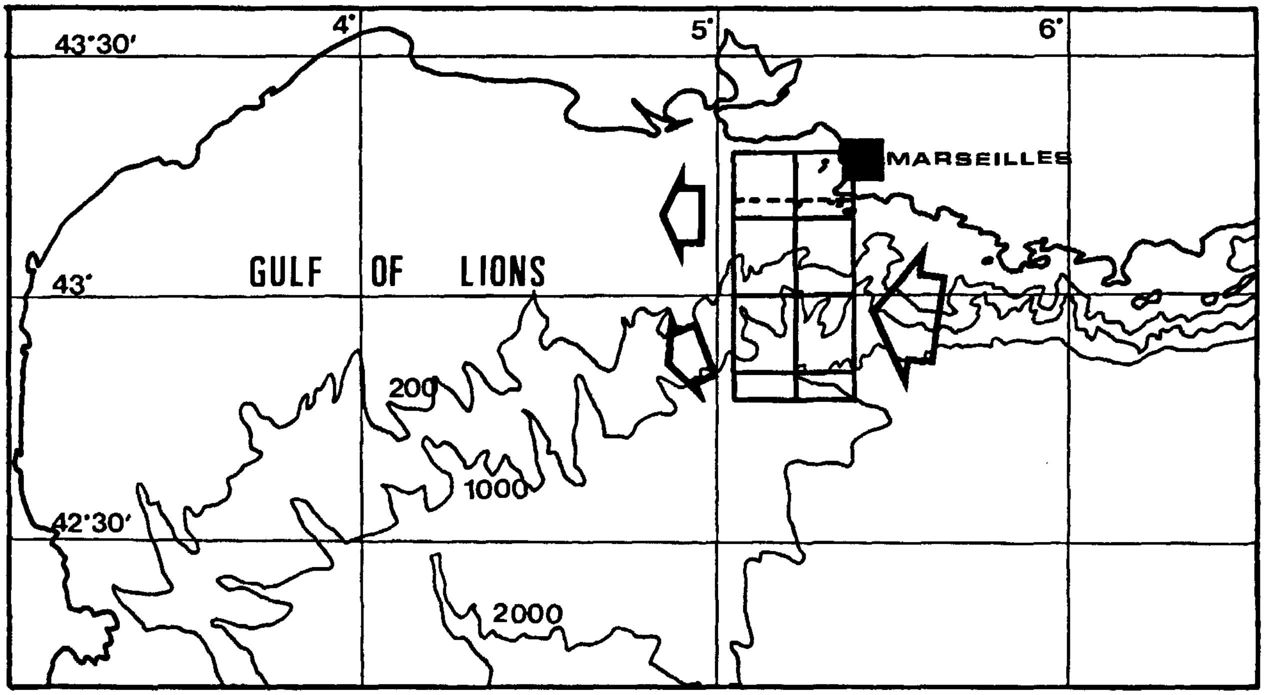
As all these water masses mix together and entrain each other, it is difficult from both a hydrological and a dynamic point of view clearly to identify the sole flow of MAW, *i.e.* the NC (Northern Current) *stricto sensu*. Practically, and as argued later, it can be considered that the NC transports MAW (sometimes down to 300-400 m close to the slope), LIW (down to 600-700 m) and WMDW (down to the bottom), with a relatively thin layer of Winter Intermediate Water (WIW) between MAW and LIW; these waters are characterized respectively by low salinities (MAW), and relatively high temperatures (WIW), and relatively high temperatures and salinities (LIW).

The more recent hypotheses put forward by Astraldi and Gasparini (1992) to explain the general circulation in the northern part of the sea consider that the Eastern Corsican Current should mainly result from the density differences between the Tyrrhenian Sea and the Gulf of Lions (as well as probably the Ligurian Sea), and thus be maximum in early winter, while the Western Corsican Current should mainly result from the geostrophic adjustment (rim current) to the formation of WMDW (as first hypothesized by Crépon and Boukthir, 1987 and thereafter detailed by Madec *et al.*, 1991), and thus be maximum in late winter. These hypotheses concerning the seasonal variations of the circulation are coherent with the various hydrological and dynamic data sets collected in the Ligurian Sea over a number of decades (see, among others, Nyffeler *et al.*, 1980; Béthoux *et al.*, 1982, 1988; Taupier-Letage and Millot, 1986; Astraldi *et al.*, 1990; Astraldi and Gasparini, 1992; Sammari *et al.*, 1995; Albérola *et al.*, 1995), as well as for some ten years past in the Catalan Sea (see Font, 1987; Font *et al.*, 1988).

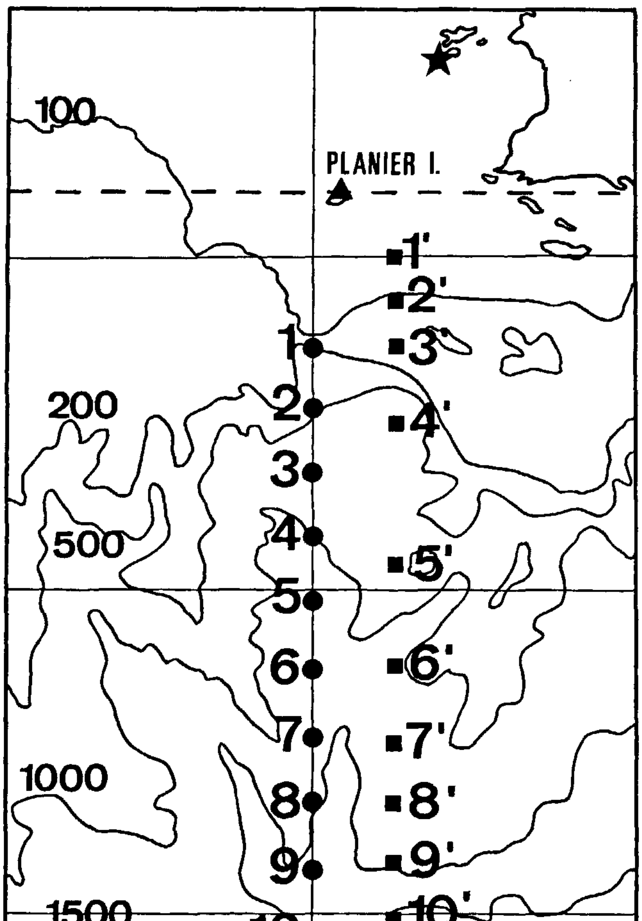
But few convenient hydrological data sets have been collected up to now along the intermediate circuit of the NC, *i.e.* in the coastal zone of the Gulf of Lions, apart from the rare ones analysed by Furnestin (1960) or Minas (1968). At present, only few current time series are available (unpublished data). Basic features of the water masses associated with the NC have been described by Lacombe and Tchernia (1971), from bottle measurements collected at 6° E in January-March 1963, and by Durrieu de Madron *et al.* (1990); from a one-week CTD campaign in November-December 1986. The former paper emphasizes the fact that LIW can be markedly displaced, both on a vertical plane and towards the central zone, in association with the WMDW formation. It also hypothesizes that WIW is mainly formed according to a virtual shelf process, thus sinking from the central zone along the isopycnals. The latter paper provides clear evidence of the mixing of LIW during its course along the slope in the Gulf of Lions. From a dynamic point of view, the major features concerning the geostrophic currents are similar to those described below and to those evidenced in the Ligurian Sea. Basically, the above-mentioned references tell us that this current there is 30-50 km wide, with most of the isopycnals sloping down towards the coast. It is characterized by a flux of the order of 2.0 Sv according to the authors (with the exception of Lacombe and Tchernia, 1971, who reported surprisingly large values up to 4.7 Sv) in winter, and by speeds of several tens of cm/s at its core and a few cm/s at a few hundreds of metres continuously decreasing down to the bottom. Mainly in winter, the NC becomes baroclinically unstable and forms mesoscale meanders, measuring several tens of km in both amplitude and wavelength and propagating at about 10 km/day, which generate a barotropic turbulence spreading seawards over a period of months. But other kinds of mesoscale phenomena resembling eddies (Caraux and Austin, 1984) or tongues (Millot, 1991) have been evidenced by satellite imagery during the other seasons within or close to our studied area. These mesoscale phenomena can bias the analysis of any kind of hydrological data set.

Against this background, and within the framework of the *Programme National d'Océanographie Côtière (PNOC)*, a hydrological survey of the NC along a north-south transect off Marseilles has been initiated (Fig. 1). This is a crucial location in the Gulf of Lions, as the NC is expected to interact strongly with the semicircular continental shelf nearby and to the west. The deeper part of the current will obviously continue to follow the continental slope southwestwards, while the circuit of the upper part is less clear (Durrieu de Madron *et al.*, 1990; Millot, 1990). As demonstrated by drifting buoy trajectories, infrared images and current measurements collected close to the surface over isobaths ranging from 200 to 1000 m in the central part of the gulf (most of these data being unpublished), some of the surface water, or surface water on some occasions, also follows the continental slope. Other infrared images (Millot and Wald, 1980) and current measurements on the shelf (Lamy and Millot, 1979) show that some or all of the upper part of the current, on certain occasions, penetrates along the coast over the shelf. In order better to understand the interactions between the NC and the continental shelf, as well as the effects of the upwelling phenomena on the mean hydrological characteristics (Millot, 1978), numerical models are at present under way (S. Deleville, personal communication) which need *in situ* data to be initialized and validated.

Monitoring the NC at the entrance of the Gulf of Lions was called for anywhere between ~5 and 6° E. The studied area, chosen for various logistic reasons, is less convenient than somewhat further to the east, due to the presence of some deep canyons (*e.g.* in the vicinity of 5° 25′-30′ E) and ridges (around 5° 15′-20′ E), and of a continental shelf which is beginning to widen (Fig. 1). Although we had requested operations at least twice a month, severe meteorological conditions, which are typical of the Gulf of Lions, and ship availability permitted only the realization of seven transects, separated by periods ranging from one week to one month, on 25 February, 6 March, 20 March, 7 April, 4 May, 15 May and 11 June (the survey has been re-initiated and is still continuing). During the first two transects, stations s1′-s10′ were occupied, but this proved not to be appropriate for geostrophic current computation as several stations were insufficiently deep; from then onwards, we occupied stations s1-s12, which are mostly over depths greater than 700 m (Fig. 1). The chosen spacing between the stations was as small as possible (3-4 km) so that a tran-



a



b

Figure 1

The studied area (b) is located at the entrance, with respect to the general circulation of the water masses (arrows), of the Gulf of Lions (a) in the northern part of the western Mediterranean Sea. Transects 1-2 (resp. 3-7) correspond to stations s1'-s10' at ~5° 16' E (resp. s1-s12 at ~5° 13' E). Distances from the coast are referred to the parallel (43° 12' N) of Planier island (▲) while meteorological data were collected on Pomègues island (★).

sect of ~45 km (from an effective coastline chosen as 43° 12′ N, the parallel of Planier island) could be performed in a single day with ships measuring 15-20 m in length (RV *Antedon* and *Korotneff*). We used a Seabird CTD (type SBE 19) whose accuracies are ~± 0.01 °C in temperature, ~± 0.01 mS/cm in conductivity and ~± 1 dbar in pressure, and precisions (resolutions and repetitivities) about ten times better (the sensors we used for the first time were calibrated about six months before the experiment).

It is important to note that working with such small ships in winter in such a difficult region implies that all transects have been performed with relatively calm winds, *i.e.* at least a few days after the most severe meteorological conditions. As has been known for a long time (see for instance Medoc group, 1970) and verified by numerous experiments, the entire water column in the central part of the Gulf of Lions (reached at the southern end of the transect) comes to be completely homogeneous in the deep winter; but it is now also known that surface water recovers this homogeneous state within a few days following the end of any gust of wind (Schott and Leaman, 1991). As further argued below, cool and dry air masses swept by strong winds can lead to the homogenization of the whole layer of MAW all along our transect but, here too, the spatial variability of the topography and the wind field (on both sides of ~6° E) allows less mixed MAW (sheltered east of ~6° E) rapidly to overlay the strongly mixed and cooled MAW west of ~6° E. In other words, most of our data sets correspond to relatively stratified conditions.

The aim of this paper is principally to provide more information on the distribution and characteristics of MAW, WIW and LIW, as well as on the structure and transport of the NC at the entrance of the Gulf of Lions. The various transects are described and some simple analyses are made; other analyses involving several transects as well as a general discussion of the results are presented; and a summary is provided.

THE TRANSECTS

Temperature and conductivity profiles are often systematically separated in depth between the upcast and downcast. The causes are lags in temperature and conductivity sensor response and hysteresis in the pressure measurements. These can be compensated by shifting temperature and conductivity relative to pressure. The best diagnostic of a proper alignment is the elimination of salinity spikes that coincide with very sharp temperature steps. Because the SBE 19 probe uses a temperature sensor with a relatively slow time constant, we choose an advance temperature relative to pressure of +0.5 second. The flushing rate of the conductivity cell depends on drop speed. As we respect a regular downspeed of ~2 metres per second, the advance of conductivity relative to temperature seems to be appropriate with –0.1 second to minimize the salinity spikes.

The situations depicted on 25 February by the potential temperature (Θ), salinity (S) and potential density (σ_Θ) profiles (Fig. 2) is rather specific. Due to the wintertime cooling and mixing which has been under way for several weeks throughout the region, MAW is cool and homogeneous (Θ = 12.75-12.9 °C, S = 38.1-38.2) while WIW can be clearly evidenced by Θ sometimes as low as 12.71-12.72 °C in the greater part of a 20-30 km coastal band. Comparatively, LIW is characterized by large maxima (Θ = 13.42 °C, S = 38.53) due to the fact that it has not yet been involved in the formation of WMDW which will occur later. A striking feature is that the core of LIW, immersed some 400-500 m seawards from s7′ (~35 km), is not located, as is usually the case, close to the continental slope; equally specific is the fact that the isolines corresponding to the lower part of the vein are nearly horizontal. This might be linked either to a deflection of the LIW vein by the ridge depicted by the 500 m isobath just upstream of the transect (Fig. 1), or to the occurrence of mesoscale phenomena. The slope of the σ_Θ = 29.06 isoline, chosen as representative of the dynamic structure at depth, is smooth with immersions lower than 550 and 350 m at ~15 and 40 km, respectively; note that most of the isopycnals display such a smooth slope.

Another very specific feature is that the core of the NC is found further seawards than 35 km, with surface velocities larger than 30 cm/s. There, it is deep (400-450 m, understood as the deepest immersion of the 5 cm/s isotach) and its inner boundary (understood as the location of the 5 cm/s isotach at the surface) is at a considerable distance (25-30 km). Let us emphasize that the 5 cm/s isotach has been chosen only for convenience; but the relatively smooth gradient, in this velocity range, accounts for the difficulty in delimiting the NC in depth, while the spatial homogeneity of the velocity field accounts for the significance of the computations. It is clear that the entire current has not been sampled, so that the transport of ~0.7 Sv com-

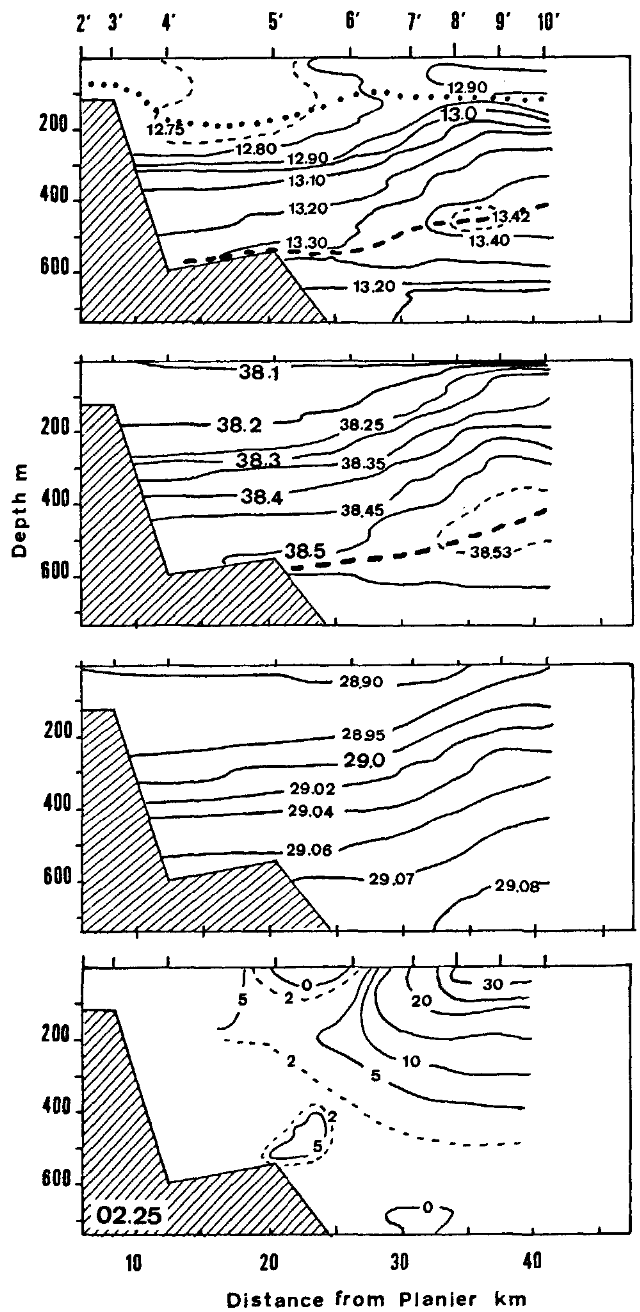


Figure 2

Distribution of the potential temperature, salinity, density, and geostrophic velocity (from top to bottom) on 25 February. The location of the temperature minimum associated with WIW (dotted line) as well as that of the relative temperature maximun and salinity maximum associated with LIW (dashed lines) are also indicated.

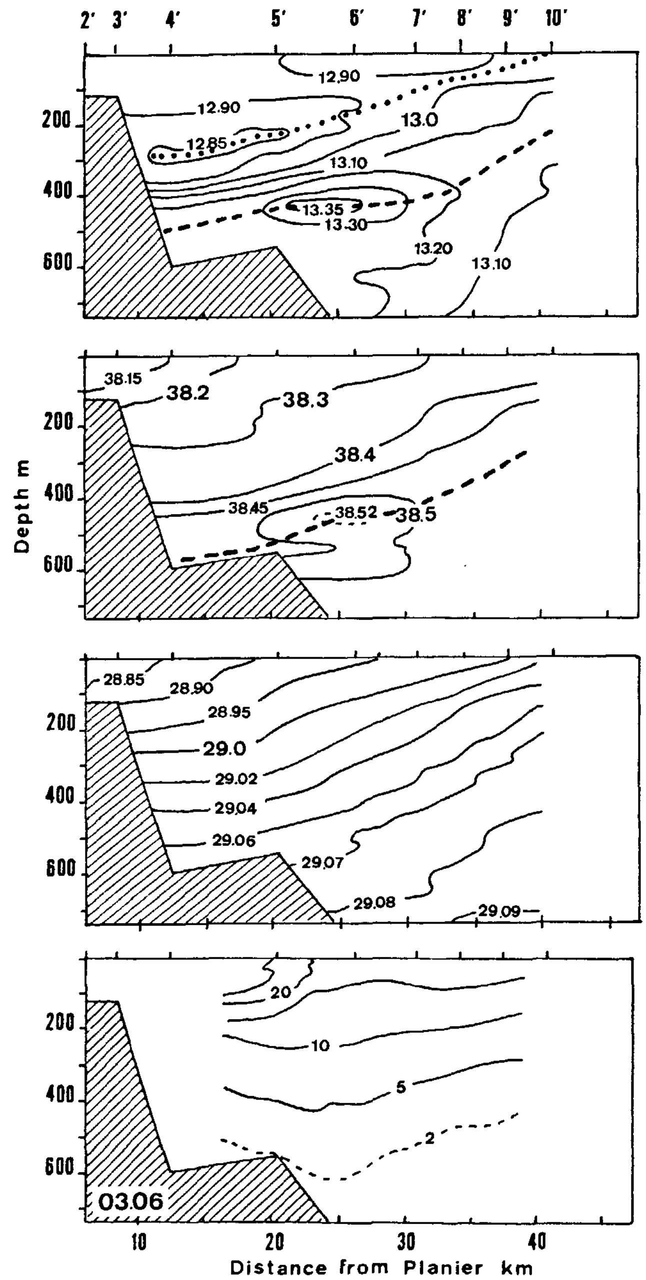


Figure 3

As in Figure 2 but for 6 March.

puted over the complete transect and the whole depth is underestimated.

Some of the features encountered on 6 March (Fig. 3) are similar, while others are different. MAW is still cool and homogeneous (Θ ~12.90 °C, S = 38.20-38.30) and WIW is still evidenced by Θ sometimes lower than 12.85 °C. But the core of LIW (Θ ~13.35 °C, S ~38.52), still immersed at 400-500 m, is now found at only 20-30 km, which corresponds to a classical distance with respect to the continental slope, account also being taken of the possible influence of the ridge upstream. The marked rise and steepness of all the isopycnals is also noteworthy; even if deep (400-450 m) and wide (more than 40 km), the NC has its core located at less than 20 km with velocities larger than 25 cm/s; here too, the entire current has not been sampled, so that the transport of ~0.7 Sv computed over the complete transect is underestimated.

The marked differences between the hydrodynamic features encountered on 25 February and 6 March constitute a very demonstrative example of the amplitude of the mesoscale phenomena figured out by meanders involving not only the MAW layer (the NC *stricto sensu*) but also the LIW layer. Over a period of a single week, the core of the NC (velocities larger than 25-30 cm/s at the surface) can be found at more than 35 km or at less than 20 km, while the core of the LIW vein can be either located along the continental slope or shifted seawards by more than 10 km, roughly below the surface core. These features are coherent with those observed in the Ligurian Sea; they clearly demonstrate that one week is definitely too large a sampling interval to describe the NC correctly. They also tell us that it is nearly impossible clearly to delimit the NC in depth.

On 20 March (Fig. 4), dramatic changes have occurred from a hydrological point of view. MAW is now warmer (Θ = 13.00-13.10 °C) and saltier (S = 38.20-38.30), while the reverse pertains for LIW (maxima of Θ = 13.24 °C, S ~38.49), which certainly accounts for some significant mixing between the two water masses. But, as the surface densities (σ_Θ = 28.85) are lower than previously, advection must be taken into account, which will provide a very demonstrative example of the formation of WIW.

In fact, it is easy to assume that cooling and mixing, especially intense in the Gulf of Lions (from 11 to 16 March, where northwesterly winds at the Pomègues meteorological station (Fig. 1) reached daily means of ~15 m/s in association with minimum temperatures of ~6 °C), have led to the formation of well mixed (Θ < 13.00 and even 12.95 °C, S ~38.30, σ_Θ ~28.95) surface water there. Then, MAW, continuously tending to flow from the Ligurian Sea (east of ~6° E) where meteorological conditions are less severe so that its temperature is relatively high, has overrun this relatively cool water, which will be recognized from now as WIW (Θ sometimes < 12.95 °C). Note that WIW is not signed in S as the MAW/LIW stratification leads to a monotonous salinity gradient.

Such a process for the formation of WIW probably occurs, albeit less markedly, more or less everywhere (see Benzohra and Millot, 1995) as the wintertime surface temperatures in the western Mediterranean Sea are lower than in the Atlantic Ocean; consequently, there is a monotonous temperature gradient along the mean MAW cyclonic circuit, and cool water will be continuously overlaid by warmer water. Let us specify that the change from mixed (MAW completely transformed into WIW) to stratified (new MAW over WIW) conditions, at this specific location (at the entrance of the Gulf of Lions where intense mixing and wind-induced upwelling occur) and in winter, is related directly to the gusts of northwesterly winds whose time scale ranges from a few to several days. As demonstrated by Millot and Wald (1980) in summer, surface water transported by the NC is kept west of ~6° E when the mistral strongly blows; when the wind ceases, this warm water progresses westwards at several tens (~30 during a specific

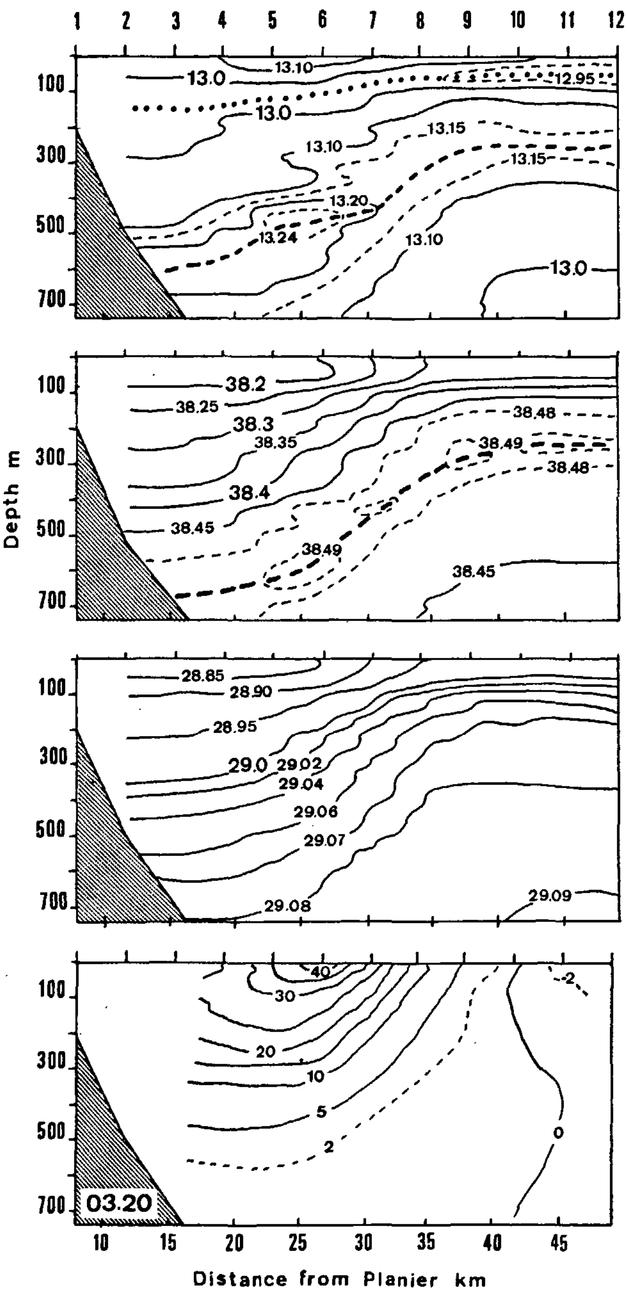


Figure 4

As in Figure 2 but for 20 March.

event) of km/day, so that the interval of a few days between successive gusts is sufficient for this warm water (MAW) to overflow the cool and mixed (WIW) water (as observed on 20 March, *i.e.* four days after the end of the gust). Such a process is different from that described by Lacombe and Tchernia (1971), who assumed that WIW is only formed in the central zone and then sinks along the isopycnals, *i.e.* towards the coast between MAW and LIW. One can also consider that WIW can be formed on the continental shelf, as already demonstrated in the Gulf of Lions (Fieux, 1974).

Another interesting feature depicted by Figure 4 is the extremely wide spreading of LIW seawards (Θ > 13.15 °C, S > 38.48), clearly along the isopycnals (σ_Θ = 29.06-29.08). A core is weakly evidenced at 20-25 km from the slope in Θ (relative maximum of ~0.9 °C), but not in S. The similarity between the general shape of the various isolines (*i.e.* their parallelism) is noteworthy, especially when comparing this figure with the others, and clearly accounts for an on-offshore movement of LIW. The vein is found at relatively large depths (~700 m) close to the slope, but it clearly extends at relatively low depths (200-300 m) at a distance of more than 40 km seawards. Correlatively, the marked sinuosity of the isopycnals is also to be emphasized: the 29.06 isoline reaches its deepest (~550 m at s1) and shallowest (< 150 m at ~40 km) immersions, with the largest slope at ~30 km. The current is deep (450-500 m) and narrow (35-40 km); velocities reach ~40 cm/s in the core (at 25-30 km, which does not correspond to the lowest densities) and the transport is ~1.4 Sv; these values (and the following ones) are roughly similar to those measured during this season in the Ligurian Sea (Albérola *et al.*, 1995).

About two weeks later, on 7 April (Fig. 5), significant changes have occurred for both MAW and LIW, but in a different manner. Mainly due to a one-week gust of northwesterly wind (daily means up to 15 m/s and minimum temperature of ~5 °C) in late March, mixing and cooling have occurred near the surface (Θ minima are now < 12.90 °C), as well as advection of new MAW (S < 38.10, σ_Θ< 28.75). But this new MAW is relatively cool (Θ < 13.10 °C), so that the layer of WIW (Θ < 13.10 °C) is heterogeneous and not easily defined. The major changes concern LIW which is now concentrated as a vein along the continental slope and is characterized by a well defined core (Θ > 13.40 °C, S > 38.52) at 300-500 m and ~25 km, which is not very close to the slope. But LIW, as a whole, is located along this slope; the isopycnals are no longer parallel to the other isolines seawards from 30-35 km, so that LIW no longer displays on-offshore movements and is maintained along the slope by the Coriolis force. The 29.06 isopycnal is less curved than previously (< 550 m at s2-s3 and 150-200 m at ~45 km). As a consequence of these different variations, the MAW/LIW density gradient has increased and the slope of the interface has been reduced; the current is deeper (~400 m) and wider (~40 km); maximum velocities have reached ~50 cm/s; the core is still found at 25-30 km (which corresponds to the lowest salinities and densities); and the transport reaches an overall maximum of ~1.8 Sv.

On 4 May (Fig. 6) as well as on 15 May (Fig. 7), which display some similar features, the seasonal thermocline begins to be established in the upper part of the MAW layer with Θ > 14.00-16.00 °C, S < 38.10 and σ_Θ< 28.50. The layer of WIW can be evidenced mainly in the coastal zone as far as 25-30 km, temperatures there having increased to Θ ~13.10-13.2 °C. The maxima associated with LIW have values (Θ ~13.30-13.35 °C, S ~38.52) similar to those measured more than one month before; but these maxima are encountered closer to the slope and the vein is thinner, reflected in a major difference between Figure 5 and Figures 6-7 as regards LIW.

But there are some marked differences between Figure 6 (the following aspects of which are similar to Figure 5) and

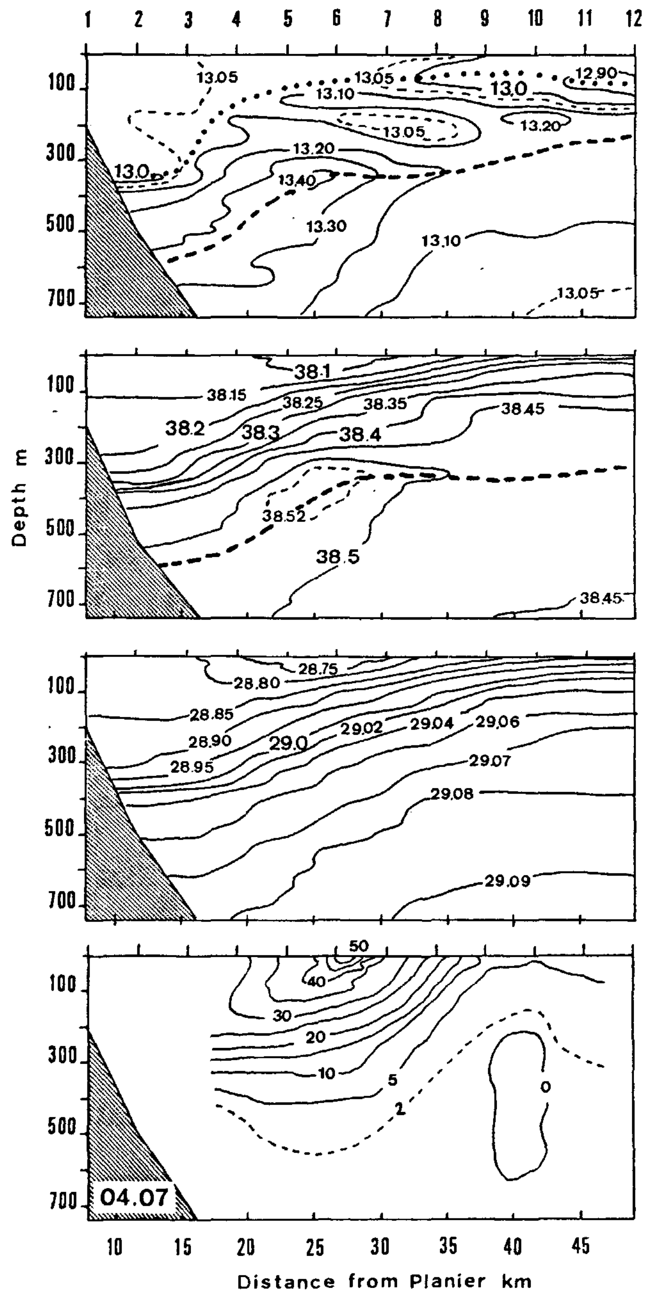


Figure 5

As in Figure 2 but for 7 April.

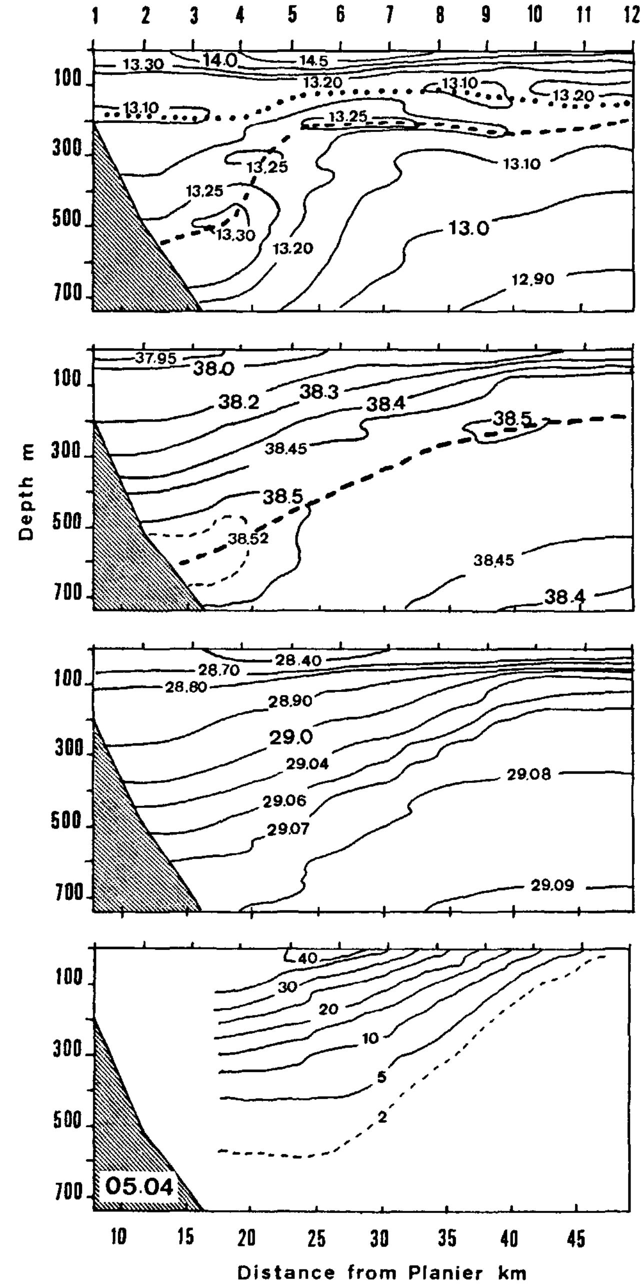


Figure 6

As in Figure 2 but for 4 May.

Figure 7 concerning the immersions of, for instance, the isolines Θ = 13.30 °C and S = 38.50 close to the bottom, which have risen by ~200 m from 4 to 15 May; correlatively, the immersion of the isoline σ_Θ= 29.06 has risen by ~100 m. In association with the lifting of the LIW vein between these two dates, the isopycnals delimiting the MAW/LIW interface have flattened. The current is a little shallower (< 400 m); and wider (40-45 km); maximum velocities only reach ~45 cm/s and are encountered below the seasonal thermocline; the core is closer to the coast (at 20-25 km which corresponds to the lowest densities); and the transport has fallen from ~1.6 to ~1.2 Sv. Correlatively, the deep isopycnals (29.08-29.09), which displayed a similar structure up to 4 May, are found closer to the slope on 15 May.

One month later, on 11 June (Fig. 8), the seasonal thermocline is now well established with Θ up to ~18.00 °C, S < 38.00 and σ_Θ < 28.00 everywhere. The layer of WIW can still be evidenced only in the coastal zone as far as ~35 km with Θ now lower than 13.30 °C. The maxima associated with LIW have values (Θ ~13.38 °C, S ~38.54) slightly larger than those previously measured; they are located somewhat further seawards and the vein is wider. Even if the whole LIW layer, as well as the σ_Θ = 29.06 isoline, are a little deeper than on 15 May (Fig. 7), they are not as deep as on 4 May (Fig. 6) and earlier. Therefore, the bending of the isopycnals has lessened, which accounts for marked changes in the structure of the current; it is now extremely shallow (< 300 m) and wide (> 45 km), maxi-

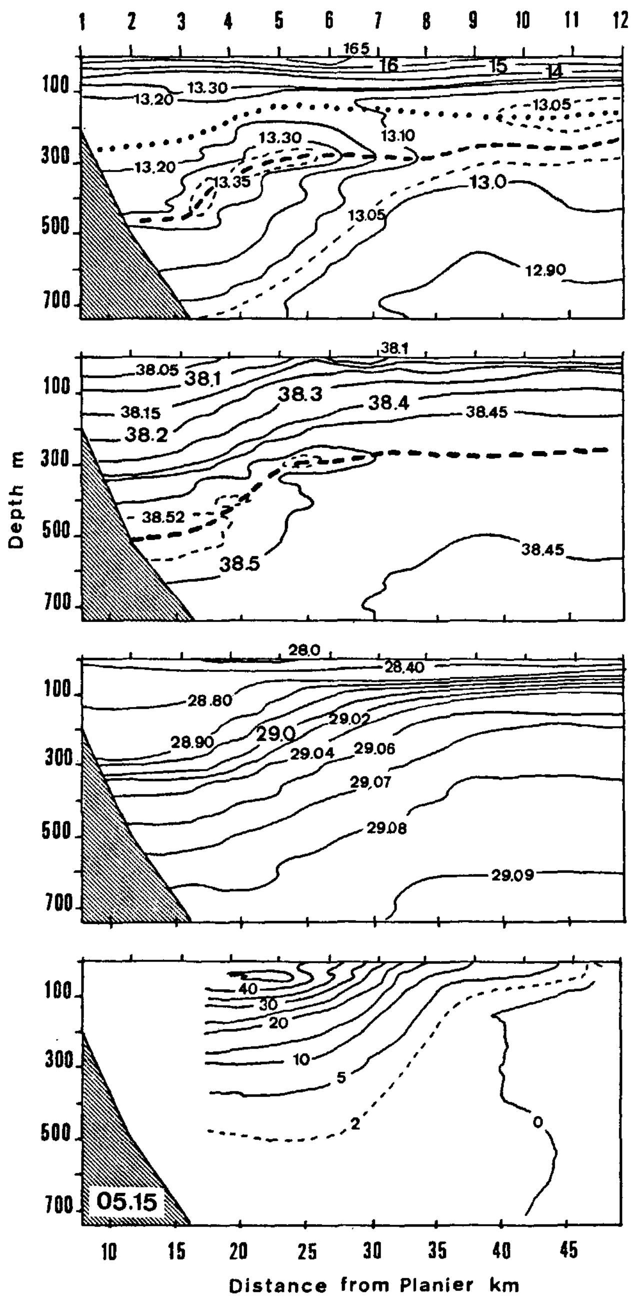


Figure 7

As in Figure 2 but for 15 May.

mum velocities only reach ~30 cm/s at 25-30 km. Even if most of the current has been sampled, it appears that its transport has declined dramatically to ~0.5 Sv.

DISCUSSION

As already stated in the introduction, and clearly demonstrated by the analysis of the transects, principally on 25 February/6 March but also on 4/15 May, sampling intervals as short as one week throw into relief, even if they do not permit resolution of, the mesoscale variability. It will therefore be difficult definitely to distinguish between the mesoscale and seasonal variabilities. Nevertheless, on the basis of our data set and quite simple arguments, some reasonable working hypotheses can be advanced.

A relatively solid hypothesis concerning the formation of WIW, widely discussed in the previous section, is based on the assumption that more or less everywhere in the western Mediterranean Sea and especially in the Gulf of Lions, expected to be a very convenient location, MAW cooled and homogeneized in winter during gusts of northwesterly winds will be overlaid by warmer MAW and subsequently recognized for some considerable long time as WIW. Correlatively, the stratification of the MAW layer and the lowest temperatures encountered in winter are heavily dependent on the meteorological conditions: for instance, while the temperature minima slightly increased during March, values in early April after a relatively cold wind event were lower than in late March. Such an overlaying incident can be very rapid, as in our studied area, due to the marked discontinuity at ~6° E in both the topographic and meteorological fields. The proposed mechanism is very different from a local warming of the surface layers which cannot be so rapid and intense in winter, and which cannot explain the sudden occurrence of relatively fresh water. As soon as the seasonal thermocline forms and deepens, WIW is protected from any exchanges with the atmosphere and is only modified by interactions with the warmer MAW and LIW layers, so that a temperature minimum can be found more or less everywhere and throughout the year long in the sea. This process (WIW formed locally and overlaid by MAW) is basically different from both the shelf process (WIW formed on the shelf which sinks seawards) and from the virtual shelf process (WIW formed in the central zone which sinks towards the coast). Now, the cooling of MAW will be more intense where its thickness is minimum, *i.e.* both on the shelf and near the central zone. Because marked temperature minima were encountered during the various transects either close to the coast (12.85 °C on 6 March) or in the central zone (12.95 °C on 20 March, 12.90 °C on 7 April, 13.05 °C on 15 May) or more or less everywhere (12.75° C on 25 February, 13.10 °C on 4 May), all these processes can probably occur more or less simultaneously.

A second reasonable hypothesis concerns the LIW vein which seemingly displays significant seasonal variations in both its hydrological characteristics and shape. Up to early March, which roughly corresponds to the preconditioning phase of the WMDW formation (see Medoc Group, 1970), LIW had relatively large maximum values (13.35-13.42 °C, 38.52-38.53); it was structured as a vein, even if markedly displaced in an on-offshore direction, as a consequence of the strong instabilities, shaped by mesoscale meanders, which disturb the NC in winter (see Taupier-Letage and Millot, 1986 and Albérola *et al.*, 1995). Very reduced maxima (13.24 °C, 38.49) were then observed in the winter (late March), when the vein spread seawards and formed a relatively continuous layer; at that time, which usually corresponds to that of the formation of WMDW in which LIW is known to be directly involved, it was especially deep along the slope and shallow at the end of the transect. In early April and early May, when the WMDW formation usually stops, LIW was found to be

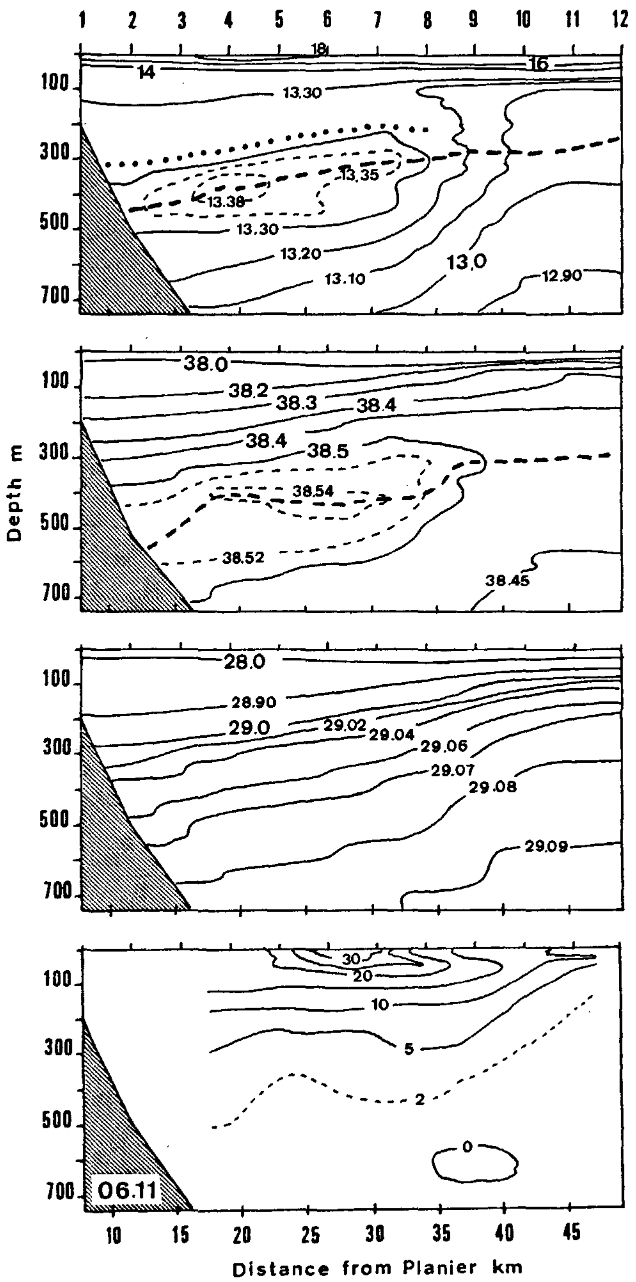


Figure 8

As in Figure 2 but for 11 June.

concentrated again along the slope, still at a relatively large depth, with maxima up to 13.30-13.40 °C and 38.52. In mid-May and mid-June, LIW was observed with roughly the same structure, but at a mean depth lower by ~100 m, and with relatively large maxima of 13.35-13.38 °C and 38.52-38.54, which are similar to those observed in mid-winter. Throughout the studied period, the geostrophic speeds at the LIW core level are significant (ranging from one or two to ~5 cm/s). Intuitively, one may assume such a variation with time of the T and S maxima to be due to a varying mixing of LIW with the surrounding waters. This is clearly supported by the analysis of the difference between the depths of the T and S maxima, which results from the fact that the water above (WIW) is cooler and the water below (WMDW) fresher than LIW. When considering, for each transect, the stations closest to the LIW core, these differences, which normally vary from a few metres to a few tens of metres, increase to a hundred metres or so on 20 March, so that the largest differences correspond to the lowest T and S maxima and account for intense mixing. Therefore, LIW is for most of the time structured as a vein along the slope with maxima of 13.35-13.42 °C and 38.52-38.54, (which is consistent with the values reported by Durrieu de Madron *et al.*, 1990), except in the deep winter when it forms a layer, markedly sloping up and spreading seawards, obviously mixed with surrounding waters (13.24 °C, 38.49) and involved in the WMDW formation (see also Lacombe and Tchernia, 1971). Note that, off Nice and not during the same year, the maximum values were a slightly larger (~13.55-13.60 °C and 38.58, Albérola *et al.*, 1995), which is coherent with the general mixing of LIW expected all along its cyclonic course in the western Mediterranean Sea (Millot, 1987). In the Catalan Sea, the maxima are coherently somewhat lower, and display seasonal variations with a weakening occurring a few months later (Font, 1987); this delay probably corresponds to the time of propagation from one place to the other.

The fact that the LIW core is often found close to the slope, even at a point located a few kilometres downstream from a marked ridge, means that LIW closely follows the slope up to this specific point, and certainly throughout its circuit in the western Mediterranean Sea. It is markedly displaced seawards only under the influence of intense mesoscale phenomena such as meanders of the NC. The variations with depth of the LIW vein/layer are certainly dependent on those of the NC *stricto sensu* (the flow of MAW-WIW). But, as shown from all the geostrophic computations, the variations with depth of the speed are always smooth, so that is is impossible to delimit the NC dynamically in depth. Moreover, speeds of 5 cm/s are encountered during all the transects at depths of ~400 m or more, except during the final transect when this isotach was at ~300 m; whether this difference is due to mesoscale or seasonal variations cannot be proved (even if we are inclined to favour the latter explanation). Note that this variation in depth of the 5 cm/s isotach (rising on 13 June) is relatively simultaneous with that of the LIW vein (rising on 15 May and 13 June).

The core of the NC (speeds larger than 30 cm/s and even reaching 50 cm/s on some occasions) is generally encountered at the surface, except on 15 May when it was immersed at ~50 m. This core is generally located at a distance of 20-30 km, except during the first two transects when it was either further seawards or shorewards; note that these two transects were made a little to the east of the others, even if we believe that this difference in location is not significant. Setting aside these two transects, which were relatively short and did not cross the entire NC, it appears that the outer edge of this current, as defined for instance by the location of the 5 cm/s speed at the surface, is roughly found further and further seawards from one transect to the other (see Fig. 2 to 8). Another interesting representation of the NC variability is given in the three-dimensional plot in Figure 9 which shows the distribution in an on-offshore direction of the integrated transport; in general, the largest integrated transport corresponds to the core of the current.

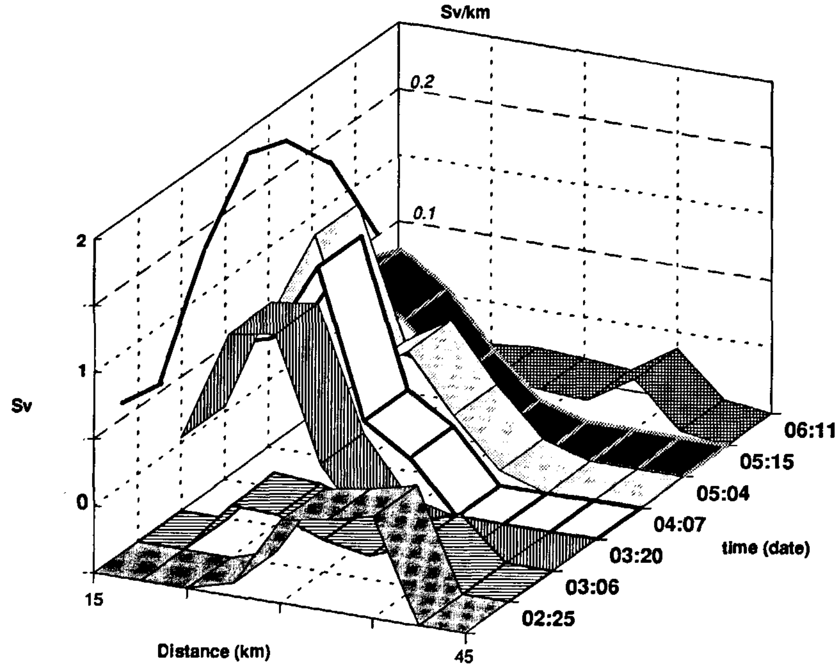


Figure 9

Distribution in the on-offshore direction (in km from the parallel of Planier island on the Ox axis, see Fig. 1), during the seven transects (along the Oy time axis), of the vertically integrated transport (in Sv/km on the right-hand scale of the Oz axis). The total transport is also reported (Oz, in Sv on the left-hand scale).

Figure 9 shows that the current is close to the coast when its transport is large (from late March to mid-May), while it is markedly spread seawards when its transport is low (June). Here again, we cannot estimate the importance of the mesoscale variability, even if we believe this spreading to be representative of a seasonal evolution.

The dynamic characteristics in the studied area are entirely associated, as previously argued, with the NC. In order to throw greater light on possible seasonal variations of these characteristics, let us roughly analyse at 100, 300, 500 and 700 m, and from time to time, the location of some specific isopycnals (Fig. 10). It is important to note that the spacing between the isopycnals is representative of on-offshore density gradients and thus partially indicative of the isopycnal inclination and of the geostrophic velocity. We do not consider the first two transects, during which relatively large mesoscale phenomena have been clearly evidenced. During the four following transects, most of the isopycnals are located at roughly the same distance from the coast and are close to one another; such a distribution corresponds to a narrow and intense NC. During the final transect, the spacings between the curves in Figure 10 generally increase, which corresponds to a less intense current, and these curves diverge, *i.e.* the isopycnals closest to the coast generally move shorewards while the others move seawards. Therefore, one can think in general terms of a density field roughly pivoting in a plane perpendicular to the NC, which is coherent with the seaward spreading of this current already described.

Let us now consider the total transport during each transect (Fig. 9). As the first two transects did not cross the entire NC, their associated transports are significantly underestimated; and as they are characterized by low speeds, it is likely that actual values of the transports are low (they can be doubled without any modification of the following analysis). In any case, and even if (i) the confidence intervals on the first two values are relatively large; (ii) it is clear that a (minor) part of the transport of the NC is always

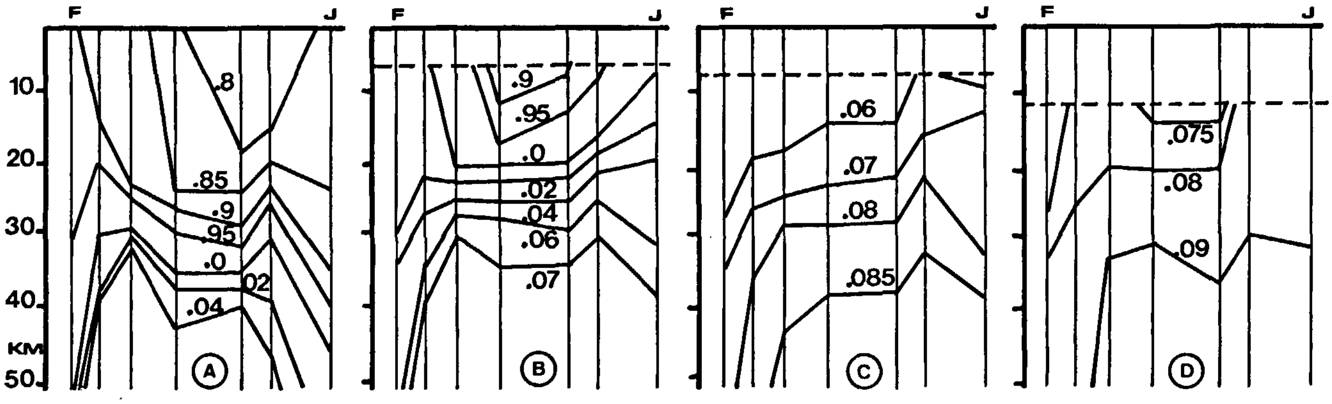


Figure 10

Location in the on-offshore direction (in km from the parallel of Planier island, see Fig.1), during the seven transects (from February to June) of some specific isopycnals, between 28.80 and 29.09, at depths of 100 (A), 300 (B), 500 (C) and 700 (D) metres.

missed close to the coast; and (iii) the mesoscale variability cannot be definitely estimated, it is likely that some gross features in Figure 9 might be taken into consideration. Basically, the transport increased up to early April-early May and then continuously decreased, and the maximum values (1.70-1.75 Sv) are consistent with those (~1.6 Sv) computed from similar transects by Albérola *et al.* (1995), as well as from broader ones by Béthoux *et al.* (1982, 1988).

If representative of some actual seasonality, such a variation of the transport of the NC with a maximum in early spring is very different from events in the Corsican Channel, where the maximum is observed in early winter, as well as along western Corsica, where the maximum is observed in late winter (Astraldi *et al.*, 1990; Astraldi and Gasparini, 1992) and off Nice, where the maximum occurs during a relatively long winter period (Albérola *et al.*, 1995). Let us also emphasize that our studied area is very close to the zone where most of the WMDW is formed and that, according to Crépon and Boukthir (1987), Madec *et al.* (1991), the associated rim current should be maximum in late winter. Coherently, a transport off Marseilles seemingly (transports have not been estimated during the same years) larger than off Nice (the difference between the computed values must probably be increased as the total transport is underestimated off Marseilles and rather well estimated off Nice, due to a wider continental shelf at the former location) might be due to some part of the rim current (running mainly around the sole Gulf of Lions) which did not flow off Nice. Therefore, taking into account obvious inaccuracies in both the observations and the models, and thus merging late winter and early spring, we arrive at a relatively important result: assuming that dense water formation is a major forcing of the NC should really constitute a promising working hypothesis.

SUMMARY

The lack of information in the coastal zone off Marseilles is very surprising, especially if one considers the large amount of data already collected both further seawards, in the central part of the Gulf of Lions, and in neighbouring places such as the Ligurian and the Catalan Seas. The time interval between the transects we performed on seven occasions from February to June 1992 was longer (ranging from one week to one month) than desired, preventing us from definitely separating the mesoscale variations from the seasonal ones which are believed to attain similar amplitudes. But the fine space interval between the casts (3-4 km) and the length of the transect (~45 km) provide significant information on the characteristics of the NC, and on those of the water masses encountered down to ~700 m, *i.e.* MAW, WIW and LIW.

In the first place, extremely large mesoscale meanders of the NC have been evidenced; within a single week, the core of the NC in the upper part of the MAW layer can be found at a distance of more than 35 km or less than 20 km, while the LIW vein can be shifted by more than 10 km seawards from its mean location close to the slope. Apart from these obvious mesoscale variations, a general feature is that, from all but the final transect, the current is relatively deep (the 5 cm/s isotach is at 400-500 m) with surface velocities up to 30-50 cm/s within its core continuously decreasing with depth. Although this has to be supported by a larger amount of data, the variation of the transport from one transect to another was specific: it was low (~0.7 Sv) in late February-early March, increasing up to 1.75 Sv in April-May and decreasing to ~0.5 Sv in June. If significant, such a seasonal variation is relatively different from what is encountered in the Ligurian Sea (the maximum occurs earlier in the winter) but not inconsistent with what is predicted from numerical models concerning the rim current associated with the formation of WMDW, which mainly occurs in late winter just seawards from our studied area. In any case, the NC, defined *stricto sensu* as the flow of MAW, has a large vertical extension (it actually transports also LIW and WMDW) and is characterized by relatively smooth vertical velocity gradients.

One other major result concerns the formation of WIW. It is clear that MAW, cooled and homogenized in winter during gusts of northwesterly winds which are especially strong in the Gulf of Lions, is rapidly overlaid, when the wind ceases, by warmer MAW that is prevented from such strong interaction in a neighbouring place, mainly east of ~6° E; then, thin water will be recognized as WIW and characterized by a temperature minimum with respect to both MAW above and LIW below. As meteorological conditions vary markedly in both time and space everywhere in the sea all along the general cyclonic circuit of MAW, the formation of WIW is probably ubiquitous, and a temperature minimum can be found all year round in the whole sea. It is also shown that LIW displays variations in both its distribution and hydrological characteristics that are clearly dependent on the formation of WMDW. At that time, LIW spreads seawards along the isopycnals while its temperature and salinity maxima are low due to intense mixing; it then re-structures itself as a vein flowing westwards along the slope while its maximum values continuously increase, due to lower and lower mixing.

Acknowledgments

This work is a contribution to and benefited from the logistic support of the *Programme National d'Océanographie Côtière (PNOC)*. It is part of the EUROMODEL contribution to MAST-2 supported by DGXII-CEE under grant MAST-CT 920041. We warmly thank M. Leveau for his continuous support, as well as P. Raimbault and I. Taupier-Letage for their contribution to the data analysis and M.-C. Bonin for her help in drawing the profiles. A first version of this paper has been improved by enlightened comments by L. Prieur, to whom we are also grateful.

REFERENCES

Albérola C., C. Millot and J. Font (1995). On the seasonal and mesoscale variabilities of the Northern Current during the PRIMO-0 experiment in the western Mediterranean Sea. *Oceanologica Acta* **18**, 163-192.

Astraldi M. and G.P. Gasparini (1992). Seasonal characteristics of the circulation in the western Mediterranean basin and their relationships with the atmospheric-climatic conditions. *J. Geophys. Res.* **97**, 9531-9540.

Astraldi M., J.P. Gasparini, J.M.R. Manzella and T.S. Hopkins (1990). Temporal variability of currents in the eastern Ligurian Sea. *J. Geophys. Res.* **95**, 1515-1522.

Benzohra M. and C. Millot (1995). Hydrodynamics of an open-sea algerian eddy. *Deep Sea Res.* in press.

Béthoux J.P., L. Prieur and F. Nyffeler (1982). The water circulation in the north-western Mediterranean Sea, its relations with wind and atmospheric pressure. In "Hydrodynamics of Semi-Enclosed Seas", J.C.J. Nihoul ed., Elsevier, 129-142.

Béthoux J.P., L. Prieur and J.H. Bong (1988). Le Courant Ligure au large de Nice. In «Océanographie pélagique Méditerranéenne», H.J. Minas and P. Nival ed. *Oceanologica Acta* n. sp. **9**, 59-67.

Caraux D. and R.W. Austin (1984). Multispectral satellite remote sensing of an oceanic cyclone in the northwestern Mediterranean. *Int. J. Remote Sens.* **5**, 855-860.

Crépon M. and M. Boukthir (1987). Effect of deep water formation on the circulation of the Ligurian Basin. *Annal. Geophys.* **5B**, 43-48.

Durrieu de Madron X., F. Nyffeler and C.H. Godet (1990). Hydrographic structure and nepheloid spatial distribution in the Gulf of Lions continental margin. *Cont. Shelf Res.* **10** (9-11), 915-929.

Fieux M. (1974). Formation d'eau dense sur le plateau continental du Golfe du Lion. Colloq. Internat. du CNRS sur la formation des eaux océaniques profondes, **215**, 165-189.

Font J. (1987). The path of the Levantine Intermediate Water to the Alboran sea. *Deep-Sea Res.* **34**, 1745-1755.

Font J., J. Salat and J. Tintore (1988). Permanent features of the circulation of the Catalan Sea. In «Océanographie pélagique Méditerranéenne», H.J. Minas and P. Nival ed. *Oceanologica Acta* n. sp. **9**, 51-57.

Furnestin J. (1960). Hydrologie de la Méditerranée occidentale (Golfe du Lion, Mer Catalane, Mer d'Alboran, Corse orientale). *Rev. Trav. Inst. Pêch. Mar.* **24**, 5-119.

Lacombe H. and P. Tchernia (1971). Caractères hydrologiques et circulation des eaux en Méditerranée. In "The Mediterranean Sea", D.J. Stanley ed. Dowden Hutchinson and Ross, Stroudsberg, 26-36.

Lamy A. and C. Millot (1979). LION 78: Rapport de présentation des mesures. Int. rep. LOP-MNHN, 79, 249 p.

Lopez-Garcia M., C. Millot and J. Font (1994). Surface circulation variability in the Balearic Basin. *J. Geophys. Res.* **99** (C2), 3285-3296.

Madec G., M. Chartier and M. Crépon (1991). The effect of thermohaline forcing variability on deep water formation in the western Mediterranean: a high-resolution three-dimensional study. *Dyn. Atmos. Oceans* **15**, 301-332.

Medoc Group (1970). Observation of formation of deep water in the Mediterranean Sea, 1969. *Nature* **227**, 1037-1040.

Millot C. (1978). Wind-induced upwellings in the Gulf of Lions. *Oceanologica Acta* **2**, 261-274.

Millot C. (1987). Circulation in the western Mediterranean Sea. *Oceanologica Acta* **10**, 143-149.

Millot C. (1990). The Gulf of Lion's hydrodynamics. *Cont. Shelf Res.* **10**, 885-894.

Millot C. (1991). Mesoscale and seasonal variabilities of the circulation in the western Mediterranean. *Dyn. Atmos. Oceans* **15**, 179-214.

Millot C. (1994). Models and data: a synergetic approach in the western Mediterranean Sea. In «Ocean Processes in Climate Dynamics: Global and Mediterranean Examples», P. Malanotte-Rizzoli and A.R. Robinson ed. Kluwer, 407-425.

Millot C. and L. Wald (1980). The effect of the Mistral wind on the Ligurian Current near Provence. *Oceanologica Acta* **3**, 399-402.

Minas H.J. (1968). Recherches sur la production organique primaire dans le bassin méditerranéen nord-occidental. Rapports avec les phénomènes hydrologiques. Thèse de Doctorat d'Etat, Université d'Aix-Marseille II, 228 p.

Nyffeler F., J. Raillard and L. Prieur (1980). Le bassin liguro-provençal: étude statistique des données hydrologiques 1950-1973. Rapp. Sci. Tech. CNEXO, 42, 163 p.

Sammari C., C. Millot and L. Prieur (1995). Some aspects of the seasonal and mesoscale variabilities of the Northern Current inferred from the Prolig-2 and Pros-6 experiments. *Deep Sea Res.* in press.

Schott F. and K. Leaman (1991). Observations with moored acoustic doppler current profilers in the convection regime in the Gulf of Lions. *J. Phys. Oceanogr.* **21**, 1991.

Taupier-Letage I., C. Millot 1986. General hydrodynamical features in the Ligurian Sea inferred from the DYOME experiment. *Oceanologica Acta* **9**, 119-131.