Circulation in the Western Mediterranean Sea

Hydrodynamics
General circulation
Mediterranean Sea
Mesoscale phenomena

Hydrodynamique
Circulation générale
Mer Méditerranée
Phénomènes de moyenne échelle

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ABSTRACT

The beginning of the present decade saw a marked rekindling of scientific interest in the Mediterranean Sea; consequently, numerous cruises and theoretical studies have been undertaken. Most of these works refer to current charts which, although denoting a fairly good understanding of the circulation, are twenty years old (Ovchinnikov, 1966). Recent and valuable information has been obtained concerning the Western Basin, mainly from remote sensing and current measurements, and some aspects of the circulation can be either clarified or analysed in a new way. A synthetic analysis and schematic maps are proposed, emphasis being laid more on the mesoscale than on the seasonal variability of the circulation.

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RÉSUMÉ

La circulation en Méditerranée occidentale

Au début des années quatre-vingt, l'intérêt des scientifiques pour la Méditerranée renaît nettement; depuis, de nombreuses campagnes et études théoriques ont été entreprises. La plupart de ces travaux font référence à des cartes de courants qui, bien que traduisant une assez bonne compréhension de la circulation, ont vingt ans d'âge (Ovchinnikov, 1966). Or, des informations précieuses ont été récemment obtenues dans le bassin occidental, principalement à partir d'observations courantométriques et par télédétection, et certains aspects de la circulation peuvent être, soit clarifiés, soit interprétés de manière différente. Une analyse synthétique et des cartes schématiques sont proposées en mettant l'accent plus sur la variabilité à moyenne échelle que sur la variabilité saisonnière de la circulation.

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INTRODUCTION

The well-known charts of geostrophic currents computed by Ovchinnikov (1966), and that deduced from the core method by Wüst (1961) are based on mean seasonal temperature and salinity values obtained by averaging most of the available hydrological data. At places where the circulation is relatively well defined, such as in the Ligurian Sea, the computed current-paths are reliable. However, a survey of the whole satellite imagery clearly shows that in some other areas, such as the Algerian Basin, mesoscale phenomena are of major importance. Therefore, the combined analysis of measurements made in different years sometimes leads to a complete misunderstanding of the circulation.

Up to the 1970s, investigative studies were conducted throughout the Western Basin using a large sampling scale. Subsequent studies have been concerned with specific phenomena, such as deep water formation and continental shelf dynamics, occurring only in limited areas. Regional experiments prepared since the beginning of this decade, such as the Gibraltar Experiment and the Western Mediterranean Circulation Experiment, are in the process of completion, so that better understanding of the circulation in the Strait of Gibraltar and in the Algerian Basin may be expected; but data describing the circulation on the scale of the whole Western Basin are not much more numerous than twenty years ago.

Fortunately, the distribution of surface variables (mainly temperature), remotely sensed by satellites, can provide valuable information about the dynamics at relatively great depths. For instance, if *in situ* data on the structure of the Ligurian current are available off the Riviera and in the Catalonian Sea, and if remote data show that this current flows along the continental shelf of the Gulf of Lions, one can infer hydrodynamical features in the latter region. Likewise, it may be deduced, from arguments concerning the coherency of space- and time-scales, that large (100-200 km) eddies evidenced during over months on infrared images have a deep extent (several hundred of metres at least).

The Gulf of Lions and the Ligurian Sea are specific regions where direct measurements have shown that mesoscale currents display a marked seasonal variability. Therefore, the seasonal variation, in both strength and path, of the circulation itself cannot be easily defined. Moreover, data collected on a yearly time scale are very few and the energy of mesoscale motions was generally underestimated a few decades ago; emphasis will therefore be laid more on the mesoscale than on the seasonal variability of the circulation. We have used the values given by Béthoux (1980) for the mean fluxes through the Strait of Gibraltar (1.6 to 1.8 Sv) and across various sections in the Western Basin.

Some of our comments are deduced from a survey of numerous infrared images, a data set which is not—and will probably never be—published. Let us emphasize that local and regional studies based on infrared images could be done in a more extensive way than in the present case but it is not our purpose to complete accurately such studies. The aim of this paper is to analyse coherently most of the *in situ* and remotely sensed data available up to 1986 and to point out some key places where it seems easy to obtain valuable and definitive information about the circulation. Therefore, schematic maps are presented as new references for future works, with the obvious understanding that they will be certainly complemented quite shortly and, if necessary, corrected.

Water of Atlantic origin (Fig. 1)

The anticyclonic gyre described by Atlantic water in the Western Alboran Sea (5-3°W) is one of the most investigated phenomena in the whole Mediterranean Sea, and the subject of so many references that it would be difficult to give a list without serious omissions (*see* Preller, 1986, for an up-to-date review). Let us simply mention that the reasons for such a gyre, as for instance the orientation of the Strait of Gibraltar or the horizontal shear of the incoming current, are not definitively classified. It is now obvious from remotely sensed data that the Western Alboran gyre, although always anticyclonic, displays a large variability in extent, shape, strength and location at time scales from days to months.

The circulation in the Eastern Alboran Sea (3-1°W) is sometimes cyclonic, sometimes anticyclonic (Champagne-Philippe, Harang, 1982; Parrilla, Kinder, 1984). When cyclonic, the vein of Atlantic water follows the African continental slope and then, in the vicinity of ≈1°W, either forms a meander towards the Spanish coast (Lanoix, 1974) or keeps close to the African coast (Cheney, Doblar, 1982). The satellite imagery suggests that, most of the time, the circulation is anticyclonic with a well-defined vein flowing the Spanish coast and crossing from the Cape of Gata (≈2°W) to the vicinity of Oran in Algeria (≈1°W). The major part of the flow then progresses eastwards, while a minor part turns westwards, thus closing an anticyclonic gyre. On some occasions, the circulation might be more complex, with the flow of Atlantic water across the sea dividing into several branches.

In the Algerian Basin, namely between the Balearic Islands, Sardinia and Algeria, it has long been obvious that geostrophic currents display a large spatial variabi-

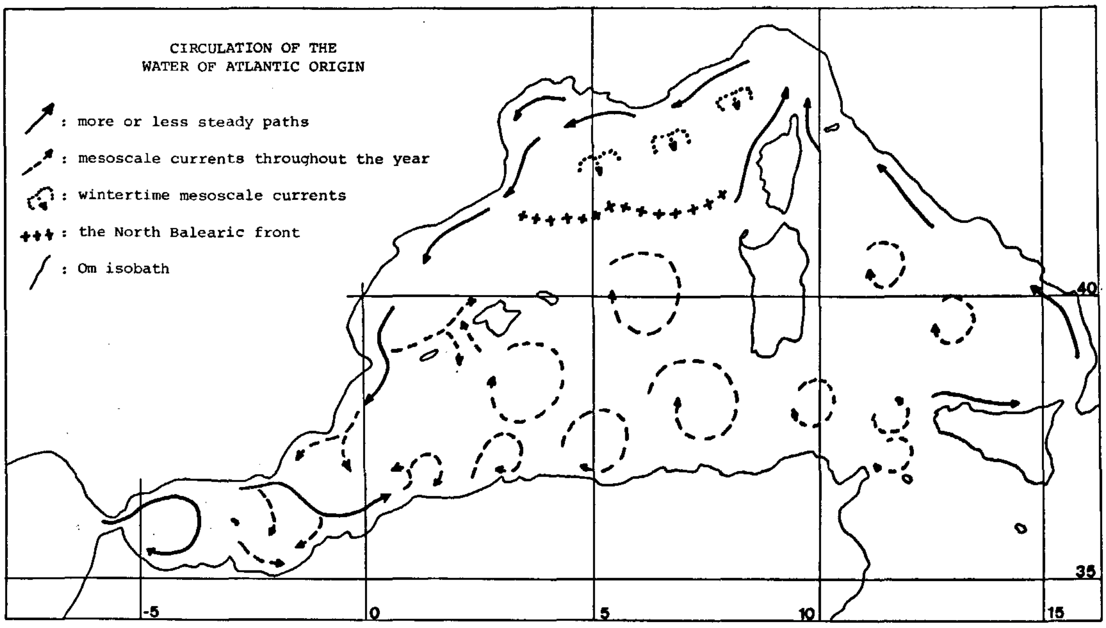

Figure 1
Circulation of water of Atlantic origin.

Circulation de l'eau d'origine atlantique.

lity (Lacombe, Tchernia, 1972). The infrared imagery has revealed the occurrence of anticyclonic eddies (diameter ≈ 100 km) in slow motion across the whole basin (Frouin, 1981; Champagne-Philippe, Harang, 1982; Deschamps *et al.*, 1984). A coherent analysis based on most of the infrared images collected since approximately 1978 and on the whole hydrological data set available in the Algerian Basin has recently been proposed, which accounts for a very large spatial and temporal variability of the circulation *per se* (Millot, 1985 *a*).

According to this analysis, it appears that the vein of Atlantic water is generally maintained along the coast near 0° and becomes unstable near 1-2°E. Eddies of both signs are generated that are advected by the mean current, but only anticyclonic eddies have been observed to increase in size. Eddies developing near the coast generate upwelling cells which are also advected (*i.e.* definitely not wind-induced) and have a sufficiently large space and time scale to be biologically productive (this feature is supported by the Coastal Zone Color Scanner images processed by Arnone and La Violette, 1986). As eddies extract more energy from the mean current they are advected more slowly, and may detach themselves from the coast and drift for several weeks in the open basin. A somewhat different situation was encountered in 1984: two very large eddies (≈ 200 km in diameter) were observed off the Algerian coast from June to at least October, the westernmost one diverting the vein of Atlantic water which was driven directly from the vicinity of Algiers (≈ 3°E) towards the Balearic Islands (Taupier-Letage, Millot, 1987). In any event, the Algerian Basin appears to be a reservoir in which water of Atlantic origin is amassed, thus forming a buffer zone which disconnects the flow of Atlantic water entering through the Strait of Gibraltar from the flow of Atlantic water (highly modified by upwelling and mixing phenomena) exiting from the basin through the Strait of Sardinia and into the Ligurian Sea.

The North Balearic front, which is the northern boundary of this reservoir, delineates the extent of the Atlantic layer, consequently revealing a frontal structure which is relatively superficial (≈ 200 m thick) and can be conceived without any large geostrophic current. This appears to be disturbed by mesoscale phenomena mainly originating elsewhere (Taupier-Letage, Millot, 1987) and it would be interesting to investigate whether a yearly shift of its location can be displayed according to the amount of Atlantic water filling the reservoir in the south and to the intensity of the deep water formation processes in the north.

The large (≈ 100 km in diameter) anticyclonic eddies observed as far east as 8-9°E (Garzoli, Maillard, 1979) probably result from the instability of the Algerian Current as described earlier. Therefore, at the entrance of the Strait of Sardinia, the eastward flow of Atlantic water is expected to be modulated by eddy-shaped sporadic events. As will be shown later, large anticyclonic eddies have a deep extent and, because the bottom depth there is significantly reduced, these eddies cannot propagate eastward of ≈ 9°E without large modifications of their structure. Thus, between Sardinia, Tunisia and Sicily, the turbulence in the surface layer undergoes a cascade to smaller scales; this is supported by the infrared imagery which shows numerous disorganized eddies a few tens of kilometres in diameter. About one-third of the surface flow enters the Tyrrhenian Sea, the other two-thirds spreading southwards through the Strait of Sicily.

Concerning the Tyrrhenian Sea, hydrological data are relatively scarce and only few dynamical phenomena have a marked thermal signature at the surface. Infrared images generally disclose the flow of Atlantic water entering the basin along the northern Sicilian coast and the cooling (without significant circulation) induced by the westerly winds off the Strait of Bonifacio. Along the continent, the curvature of the river plumes often reveals a northward circulation, a feature supported by *in situ* measurements near the coast at the entrance of the Ligurian Sea (Elliott, 1979; Astraldi, Manzella, 1983). Along the western side of the basin there is no clear indication about any kind of circulation. Off the southern coast of Sardinia, waters upwelled by strong northwesterlies are frequently encountered and a westward flow of surface waters is practically never evidenced by infrared data. Therefore, the water of Atlantic origin probably exits from the Tyrrhenian Sea mainly through the Corsican Channel, and the mean circulation in the middle of the basin is weak. In other respects, there may be noted in this basin a general heating of the surface waters due to the fact that meteorological conditions are not very severe.

Inside the reservoir of Atlantic water that constitutes the Algerian Basin, no steady current is likely to occur: the most intense currents are probably associated with the mesoscale eddies already described. In the vicinity of the upper right hand corner of this reservoir, namely in the sector defined by the North Balearic front and the coasts of Sardinia and Corsica, the surface water is drained towards the Ligurian Sea to form the Western Corsican Current. As first suggested by infrared images, instability processes affecting this current generate mainly anticyclonic eddies a few tens of kilometres in diameter (Wald, 1985). Such unstable events occur throughout the year (Taupier-Letage, Millot, 1986) and are limited in depth (Millot, 1987). Surface waters flowing northward on both sides of Corsica in roughly equivalent fluxes connect, interact in a turbulent way (Salusti, Santoleri, 1984) and mix together in the Gulf of Genoa to form the Ligurian Current. The eastern water is warmer and saltier than the western water, both being denser than pure Atlantic water.

Typical relative differences in density between the Ligurian Current and the Algerian Current are of the order of several 10^{-3}. Even if the flux of the former is roughly similar to that of the latter, their structure (width-depth ratio, speed distribution, *etc.*) is markedly different and thus the associated instability processes may be expected to be different, too. Indeed, the Ligurian current is mainly affected by meanders up to one hundred kilometres in wavelength (Viollier *et al.*, 1981; Crépon *et al.*, 1982) which are linked to large mesoscale currents at depth, mainly during winter (Taupier-

Letage, Millot, 1986). On one occasion, a cyclonic eddy was observed on the outer edge of this current in the Gulf of Lions (Caraux, Austin, 1984) but the most spectacular kind of unstable event induced by this current is the sporadic occurrence (observed only a few times in 1979 and 1981) of an authentic branch extending seawards from the coast of Provence as far as the Corsican coastal zone (unpublished data).

On the continental shelf of the Gulf of Lions, the circulation tends to be southwestwards, but strong and frequent northwesterlies induce intense and complex currents arranged around upwelling cells (Millot, 1979). While the Ligurian Current follows the continental slope along the coast of Provence and across the Gulf of Lions, its surface temperature is decreased by wind-induced homogenization and mixing with upwelled waters (Millot, Wald, 1980). The amount of water of Atlantic origin involved in the deep water formation processes occurring off the French coast is roughly one-fourth (the other three-fourths being Levantine intermediate water) the volume of water exiting from the Mediterranean Sea through the Strait of Gibraltar.

As shown by drifting buoy measurements (unpublished data), the Ligurian Current accelerates when it encounters the northeastern coast of Spain. Then, it flows along the continental slope in the northern (Font, Ballester, 1984) and southern part of the Catalonian Sea. Afterwards, a part of the surface flow is deflected toward the north-east by the Balearic Islands, the main branch probably remaining along the continent. Whatever the paths may be, this flow re-enters the reservoir of the Algerian Basin, leading to turbulent phenomena which are obviously very complex. Moreover, the Atlantic water flowing around the Western Mediterranean Basin comes under the influence of various mixing processes and meteorological effects which cause its temperature to fluctuate on the way—whereas its salinity increases continuously except in some areas where river outflow is important—and the Catalonian waters discharging into the Algerian reservoir cannot be distinguished easily by remotely sensed temperatures. Therefore, owing to very complex topographic features, dynamical processes and thermal signature of the water masses, the circulation in the surface layer around the Balearic Islands remains poorly defined.

Levantine intermediate water (Fig. 2)

In the latest and fairly reliable review of the description of the flow of Levantine intermediate water, Katz (1972) emphasized the discrepancies between the pioneer ideas of Nielsen (1912), assuming a buoyancy flow mainly constrained by the topography, and *in situ* observations, proving that high temperature and salinity values were sometimes measured in the middle of the Algerian Basin (a feature also noticed by Burkov *et al.*, 1979). The ambiguity of these two analyses has been dispelled (Millot, 1985 *a*) and, in accordance with the largest (Guibout, 1982) or most recent (Millot *et al.*, 1986) hydrological data sets, a coherent description of the circulation of the Levantine intermediate water in the whole Western Mediterranean can be put forward.

In the Tyrrhenian Sea, the highest temperature and salinity values are encountered in the peripheral zone but intermediate water obviously lies in the entire basin (Miller *et al.*, 1970). When crossing the Strait of Sicily, the flow of intermediate water is divided by a very complex topography and partly forced by the turbulent flow of surface water; such disturbances may account for some spreading of intermediate water seaward. But the thesis that the intermediate flow is mainly forced by buoyancy leads us to assume a path which is cyclonic as a whole. The Corsican Channel being neither wide nor deep enough to allow the draining of all the water coming into the basin, this water partly continues

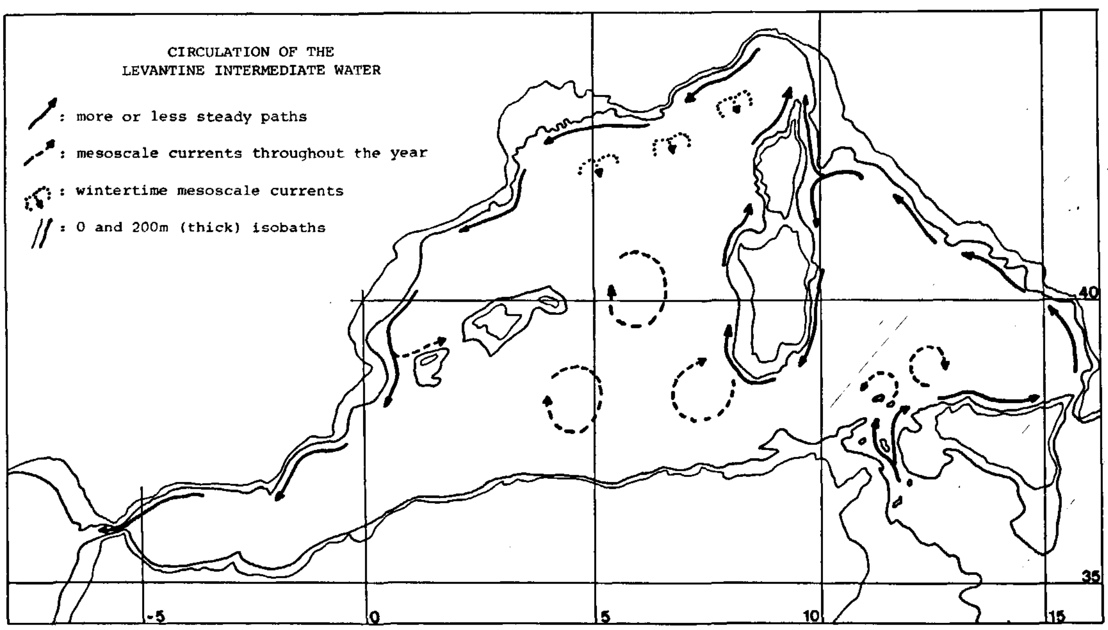

Figure 2
Circulation of Levantine intermediate water.
Circulation de l'eau intermédiaire.

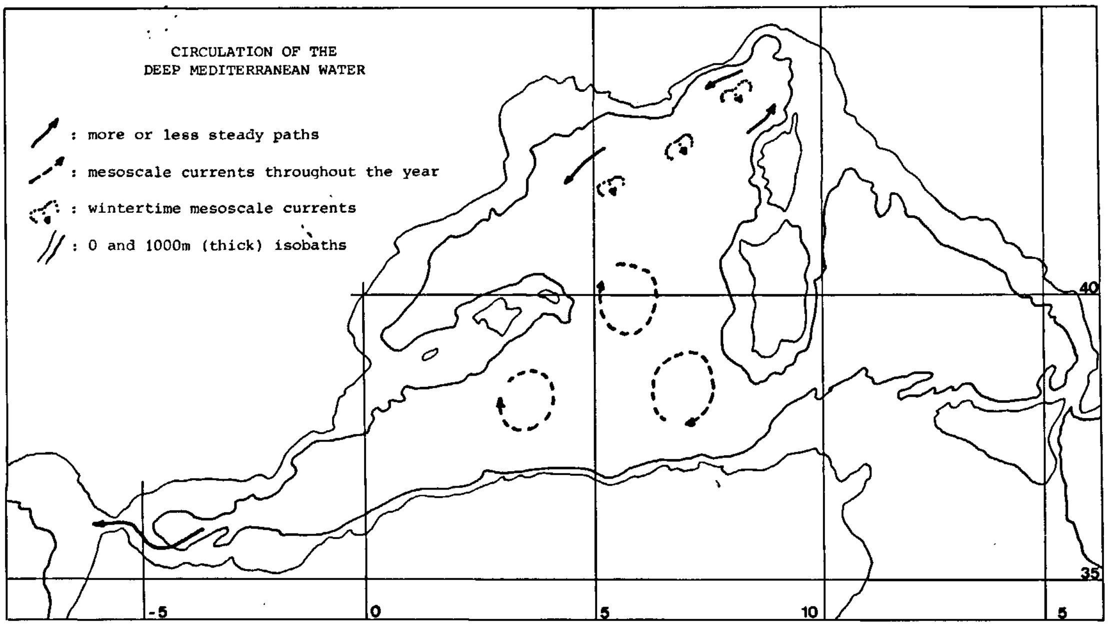

Figure 3
Circulation of deep Mediterranean water.
Circulation de l'eau profonde.

southward along the continental slope of Corsica and Sardinia.

Normally, and in a way similar to that of the Mediterranean water flowing northward in the Atlantic Ocean along the Iberian Peninsula, intermediate water exiting from the Tyrrhenian Sea through the Strait of Sardinia should proceed northward as a vein along the continental slope of Sardinia and Corsica. Now, when in the Algerian Basin, the intermediate water is exposed to the influence of the large anticyclonic eddies which can drift just along the continental slope of Sardinia (Millot, 1985 *a*). Indeed, these eddies are as deep as at least $\approx$1 000 m (Katz, 1972) and are clearly able to draw fragments of intermediate water seaward. Therefore, this water, when encountered in the middle of the Algerian Basin, is probably shaped as lenses or filaments trapped by the eddies and is not due to some branch of current proceeding westward along the coast of Algeria; these hypotheses are supported by the Médiprod 5 data (Millot *et al.*, 1986). Comparisons can probably be made between such intermediate lenses and isolated Mediterranean eddies observed in the open Atlantic Ocean (McDowel, Rossby, 1978).

The vein of intermediate water is clearly recognizable all around Sardinia and Corsica and along the continental slope of the Ligurian Sea and the Gulf of Lions (Miller *et al.*, 1970). An unknown amount of Levantine intermediate water is involved in the deep water formation processes. In the vicinity of the Balearic Islands, the path of the vein is not clearly defined. Indeed, there is no continuity between the sections occupied by Miller *et al.* (1970) around the islands; also, the warm and saline water found during the Médiprod 5 cruise was not close to the shelf and may have been carried there by eddies. In the Catalonian Sea, the vein probably flows mainly along the continental slope. This vein then goes on the western side of the Ibiza Island through a channel which is wide and deep enough to allow the draining of most of the flows; details may be found in Font (1987). It has been demonstrated (Bryden *et al.*, 1978; Gascard, Richez, 1985) that this vein clearly adheres to the Spanish continental slope in the Alboran Sea and in the Strait of Gibraltar. Therefore, the flow of Levantine intermediate water, although disturbed by various mesoscale phenomena, describes a steady path which is cyclonic along the continental slope off Italy, France and Spain; it appears to be mainly forced by buoyancy and it thus offers to numerical modellers a relatively simple and well-defined scenario.

Mediterranean deep water (Fig. 3)

Deep water formation processes are known to occur during winter in the Gulf of Lions (Gascard, 1978) and probably throughout the entire Liguro-Provençal Basin (Lacombe, 1984); a lower amount of deep water is also formed on the continental shelf of the Gulf of Lions (Fieux, 1974). A relatively large spatial and temporal variability of the hydrological characteristics near the bottom has recently been reported (Lacombe *et al.*, 1985).

As the residence time of this water mass is of the order of one century (Lacombe *et al.*, 1981), the average circulation from the Liguro-Provençal Basin towards the Strait of Gibraltar may be expected to be very weak. The few available records have been collected with Aanderaa current meters in the northern part of the sea. Two current meters were moored at 10 m above the bottom ($\approx$1 800 m) in the Gulf of Lions from August 1980 to March 1981 and nine moorings with current meters at 1 100 m were set in place in the Ligurian Sea from July 1981 to July 1982 over depths greater than 2 000 m. Both data sets reveal regional recirculations and a marked seasonal variability of the intensity of mesoscale currents with a quiet period from about June to December and a stormy one from January to about May.

During the quiet period, monthly-averaged currents in the Gulf of Lions were weak (3-4 cm/s), following the isobaths towards the southwest, and markedly disturbed by the occurrence of a several-day propagating wave (Millot, 1985*b*). During the same period in the Ligurian Sea, weaker (1-2 cm/s) but still significant monthly currents described a large asymmetrical cyclonic gyre (Taupier-Letage, Millot, 1986). During the stormy period, mesoscale currents (period $\approx$10-20 days, non-coherent 10-20 km apart, probably associated with deep water formation processes) were relatively intense and a cyclonic circulation was recognizable just along the continental slope in the Ligurian Sea. One-hour means reached $\approx$50 cm/s near the bottom in the Gulf of Lions (Millot, Monaco, 1984) and $\approx$25 cm/s probably down to the bottom in the Ligurian Sea while one-day means were sometimes as large as $\approx$30 and $\approx$25 cm/s, respectively.

Seasonal variability is probably not as marked in the Algerian Basin; however, some hydrological measurements down to $\approx$1 000 m (Katz, 1972) and the large space and time scale of the anticyclonic eddies (Millot, 1985*a*; Taupier-Letage, Millot, 1987) lead us to suppose that intense mesoscale currents may exist at depth throughout the year. The average flow of deep water probably skirts the Balearic Islands and is not significant in the Tyrrhenian Sea. At the entrance of the Strait of Gibraltar, this flow banks up along the continental slope of Morocco (Bryden *et al.*, 1978; Gascard, Richez, 1985).

DISCUSSION

We have gathered information about the circulation in the Western Mediterranean Sea from most of the papers available at present, and assembled it in the form of schematic charts. These do not differ basically from conventional charts, but we have tried to focus new attention on the role of mesoscale phenomena in explaining various aspects of the circulation of the three water masses at basin scale. This synthetic analysis and the schematic charts are necessarily partly based on assumptions; nevertheless, the latter may be tested with few hydrological measurements, specially in the Algerian Basin and in the vicinity of the Balearic Islands.

In the former region, several points will be clarified following complete analysis of the data from the Western Mediterranean Circulation Experiment (La Violette, 1985). At the present time, the non-occurrence of a vein of intermediate water adjacent to the Algerian continental slope has been definitively checked during the recent Médiprod 5 cruise. We have also studied the structure of young (*i.e.* coastal) and old (*i.e.* open-ocean) anticyclonic eddies with hydrological data and current measurements, and verified that the patches of intermediate water encountered far from the coast were clearly trapped by old eddies. In the vicinity of the Balearic Islands, the location of intermediate water may be easily investigated; afterwards, the different paths of water of Atlantic origin in this region will have to be identified. Let us also emphasize that real-time remote data provide very valuable information to guide all kinds of experiments conducted in the Mediterranean Sea.

While a more accurate description of the circulation is needed, this is not in itself sufficient for an understanding of the phenomenon. It is remarkable that the reasons for the circulation inside the Western Mediterranean Sea are not at present definitively known. Processes such as the stability of coastal currents and the growth of turbulent mesoscale eddies need to be analysed, and forcings such as the wind (Heburn, 1984; Saint-Guily, 1984) or the deep water formation (Crépon, Boukthir, 1986) must be classified. To this end, it is necessary to pursue data collection and analysis and then utilize models taking account of realistic forcings. Experiments at sea and theoretical works such as Medmodel (Lehucher *et al.*, 1986) may be expected to yield results in the very near future, and there can be no doubt that a definitive understanding of the major features of the circulation will be reached within a few years.

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