Hydrodynamics
Ligurian Sea
General circulation
Mesoscale
Variability

Hydrodynamique
Mer Ligure
Circulation générale
Moyenne échelle
Variabilité

General hydrodynamical features in the Ligurian Sea inferred from the DYOME experiment

Isabelle TAUPIER-LETAGE, Claude MILLOT
Laboratoire d'Océanographie Physique du Museum National d'Histoire Naturelle, Antenne de Toulon, BP 330, 83507 La Seyne-sur-Mer, France.

Received 28/6/85, in revised form 4/12/85, accepted 10/12/85,

ABSTRACT

The major purpose of the DYOME experiment was to study the mesoscale variability of two coastal currents, the Ligurian Current in the north and the Western Corsican Current in the south; these currents are affected by meanders and eddies respectively. A network of thirty current meters was set in place for about one year and was complemented with hydrology, drifting buoys and infrared images. It appears that in the north the intense mesoscale activity is limited to the winter season and has a large vertical extent, while in the south it is quasi-permanent and mainly restricted to the surface layers. In the vicinity of these two currents, the structure of the mesoscale phenomena is sometimes clearly baroclinic. In the central and weakly stratified zone where typical speeds are only a few cm/s during the rest of the year, mesoscale currents in winter are clearly barotropic and may reach ≈ 20 cm/s at depths ranging from 100 to at least 1100 m. The marked seasonal variations of the mesoscale activity in the northern and central zones of the Ligurian Sea corroborate earlier observations in the Gulf of Lions. Indeed, the DYOME experiment clearly confirms that, in December-January, intense mesoscale phenomena first develop in the northern Ligurian Sea. At the same time, the structure of the Ligurian Current markedly changes, mainly with isotachs becoming steeper. One major source of the deep mesoscale phenomena might therefore be this coastal current through instability processes. These phenomena, which grow 1-2 months before the classical February-March period of deep water formation, play a significant role in the homogenization of the water masses, the most homogeneous zone being located near the outer edge of the Ligurian Current,

Oceanol. Acta, 1986, **9**, 2, 119-131.

RÉSUMÉ

Caractères généraux de l'hydrodynamisme en Mer Ligure d'après le programme DYOME

Le principal objectif de l'expérience DYOME était l'étude de la variabilité moyenne échelle de deux courants côtiers, le courant liguro-provençal au Nord et le courant ouest-Corse au Sud, courants qui sont perturbés respectivement par des méandres et par des tourbillons. Un réseau de trente courantomètres, mis en place pendant environ un an, a été complété avec de l'hydrologie, des bouées dérivantes et des images infrarouge. Il apparaît qu'au Nord l'activité moyenne échelle se développe principalement en hiver, se faisant sentir très profondément, alors qu'au Sud elle est quasi permanente et concentrée dans les couches superficielles. Au voisinage de ces deux courants les phénomènes de moyenne échelle ont une structure parfois nettement barocline. Dans la zone centrale peu stratifiée, où les vitesses caractéristiques ne sont que de quelques centimètres par seconde le reste de l'année, on observe en hiver des courants moyenne échelle de ≈ 20 cm/s nettement barotropes, à des profondeurs comprises entre 100 et au moins 1100 m. La variabilité saisonnière très marquée de l'activité moyenne échelle dans les zones du nord et du centre de la Mer Ligure confirme des observations antérieures dans le Golfe du Lion. En effet, l'expérience DYOME prouve clairement qu'entre décembre et janvier d'intenses phénomènes de moyenne échelle se développent d'abord dans la partie nord de la Mer Ligure. En même temps, la structure du courant liguro-provençal change nettement, avec surtout des isotaches devenant plus pentues. Une des sources principales de ces phénomènes pourrait donc être ce courant côtier par l'intermédiaire de processus d'instabilité. Ces phénomènes, qui se développent 1 à 2 mois avant février-mars, période classique de formation de l'eau profonde, jouent un rôle important dans l'homogénéisation des masses d'eau, la zone la plus homogène étant localisée sur le bord externe du courant liguro-provençal,

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INTRODUCTION

The major large-scale hydrodynamical feature in the Liguro-Provençal Basin is a well-defined cyclonic circulation in a coastal zone a few tens of nautical miles (nm) wide (Fig. 1). Waters flowing northwards on both sides of Corsica (the Western and the Eastern Corsican currents) join and form the Ligurian current. This current remains close to the coast of Provence and then flows along the continental shelf break across the Gulf of Lions. The cyclonic paths described in the Ligurian Sea and in the Gulf of Lions are associated with doming hydrological structures. Various data sets were available in 1981 in the whole area. They were:

Current measurements

In the Ligurian Sea, some information was available for the Italian coast but very little concerned offshore seasonal and mesoscale variabilities.

In the Gulf of Lions, a considerable number of experiments had been conducted with a specific interest for the convective processes occurring in winter (Gascard, 1978); most of the current measurements devoted to

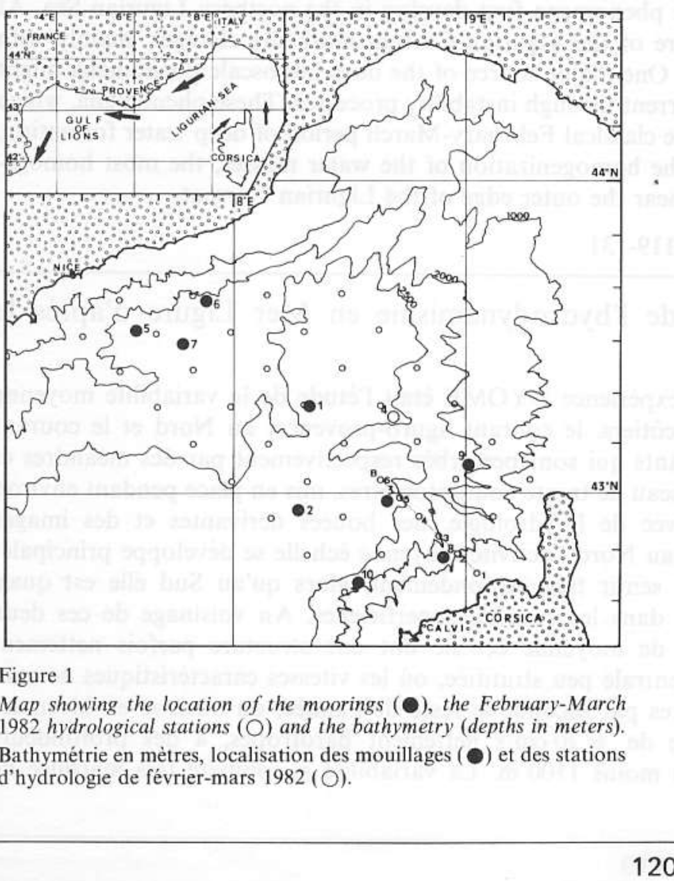


Figure 1

Map showing the location of the moorings (●), the February-March 1982 hydrological stations (○) and the bathymetry (depths in meters).

Bathymétrie en mètres, localisation des mouillages (●) et des stations d'hydrologie de février-mars 1982 (○).

these studies were limited in both space (the weakly stratified area) and time (February-March) or were only recorded near the surface. Long time series (May-November 1976 and February-August 1977 at 800 m; November 1976-May 1977 at 75 m), collected in the vicinity of 42°N, 05°E with other intents, displayed some mesoscale activity but the seasonal variability was not well marked. Similar conclusions arose from the analysis of scarce current measurements collected on the continental slope in the central part of the Gulf of Lions.

The sole evidence for seasonal variations of the mesoscale activity was given by two sets of records collected in 1980-1981, at 10 m above the bottom ($\approx$ 1 800 m), in the vicinity of 42°10'N, 04°50'E; in this central and weakly stratified zone, the large-scale currents were a few cm/s. From August to late December, smooth and regular variations ascribed to a several-day propagating wave were observed (Millot, 1985); then the mesoscale activity suddenly increased and remained intense (1-hour means up to 48 cm/s; 4-day means of $\approx$ 30 cm/s) from January to at least March (Millot, Monaco, 1984).

Hydrological data

During the last twenty years, numerous cruises have been conducted in the Ligurian Sea and it is well known that three water masses are encountered there. The surface water ($\approx$ 0-200 m) of Atlantic origin and the intermediate water (down to $\approx$ 800 m) which comes from the Sicilian Strait, enter the Ligurian Sea from both sides of Corsica. The western and eastern currents join together, interact in a turbulent way (Salusti, Santoleri, 1984) and flow westwards along the continental slope of Provence; the deep water is also expected to describe a cyclonic path (De Maio *et al.*, 1974). According to Bethoux *et al.* (1982), the surface water and the intermediate water have mean fluxes (resp. $\approx 22.10^{12}$ m^3/year and $\approx 6.10^{12}$ m^3/year) equal on both sides of Corsica, which means that the flux along the coast of Provence is twice these values and roughly as large as the flux coming in at Gibraltar. Correlatively, the hydrological structure between Nice and Calvi, as first shown by Hela (1963), is asymmetrical.

There is no consensus about the seasonal variability of the general circulation inferred from the hydrological data sets. According to Gostan (1967), a seasonal variability is expected only if wintertime meteorological conditions are extremely severe. Santoleri *et al.* (1983) and Bethoux *et al.* (1982) agree on a marked increase of the surface and intermediate fluxes during the fall season in the Corsican Channel and along the coast of Provence (the flux of the Western Corsican Current is shown to be almost constant). Ovchinnikov (1966) and Lacombe and Tchernia (1972) assume that the general circulation weakens during summertime. Relationships between seasonal variability and atmospheric pressure have been investigated by Gasparini and Manzella (1985) in terms of barotropic planetary waves.

Satellite imagery

A statistical analysis of sea surface temperatures (Wald, 1980) shows that in summer there is a continuity between the cool central zones of the Ligurian Sea and the Gulf of Lions, while in winter a closed circulation and a northwards displacement of the cooler waters are suggested in the former region.

This imagery also shows that the mesoscale phenomena in the northern and southern halves of the Ligurian Sea are markedly different. Indeed, Wald (1985) has shown that numerous eddies are observed and that most of them are located off the north-western coast of Corsica; they are 20-50 km in diameter and three out of four are anticyclonic. In the northern half of the sea, such eddies (measuring a few tens of kilometres) are practically never observed and only small-scale ones (a few kilometres) have been reported (Marullo *et al.*, 1985). On the other hand, the Ligurian current commonly displays meanders, the wavelengths of which range from a few tens to about one hundred kilometers. These meanders have been described by Viollier *et al.* (1980) and by Crépon *et al.* (1982) from images collected in March (visible) and December (infrared), respectively. These features indicate that the Ligurian Current and the Western Corsican Current are both affected by instability processes but the differences between the resulting mesoscale phenomena suggest that the two currents have different hydrodynamical structures.

The DYOME (Meso-Scale Ocean Dynamics) experiment

It was conducted in 1981-1982, within the framework of the MEDALPEX program to investigate the mesoscale phenomena which disturb the general circulation in the Ligurian Sea. With the available instrumentation (33 Aanderaa current meters and 10 acoustic releases) ten subsurface moorings were set in place in July 1981 for a one-year experiment. Points were positioned in the central (1, 2, 3, 4, 7) and coastal (10, 8, 9, 6, 5) zones at places where the bathymetry was relatively smooth. Various problems were encountered with the moorings, including drift due to intense barotropic currents and cutting by sharks. Electrical or mechanical failure of all the relases compelled us to dredge for the moorings. Indications about the immersion and the duration of the 30 records which were recovered are reported in Table 1. A linear relationship between rotor revolutions and current speed has been used with a threshold value of 1.5 cm/s. The 1-hour time series were passed through

Table 1
Characteristics of the current records.
Caractéristiques des enregistrements de courants.

Point/nominal depth (real depth of the upper meter)	Observations
1/100 (95) 1/250 1/350 1/500 1/1 100	The mooring drifted in February-March; from mid-March the real depth was reduced by ≈ 60 m. It was recovered in early June at 13 nm north-westwards.
2/100 (105) 2/350 2/1 100	The speed values at 100 m are not reliable after May 6
3/100 (100) 3/350 3/1 100	
4	Not recovered
5/100 (125) 5/350 5/1 100	
6/100 (130) 6/105 6/350 6/1 100	The mooring was cut at ≈ 400 m on May 13 by a shark (teeth were inserted in the rope) and the upper part was recovered while drifting by the Marine Nationale.
7/100 (200) 7/350 7/1 100	Just after launch the mooring slided down by ≈ 100 m; it slided down again in early March by ≈ 30 m more but was recovered at less than a few hundred meters from the lauching position. Speed values at 100 m are not reliable after May 20.
8/100 (120) 8/350 8/1 100	
9/100 (115) 9/350 9/1 100	
10/100 (145) 10/350 10/1 100	The speed values at 100 m are not reliable.

a 36-hour filter, in order to filter out the inertial motions, and resampled daily. The time-scale of the recorded mesoscale events is visibly a few weeks. Therefore, we have quantified the mesoscale activity by the variance $(1/2(\sigma_E{}^2+\sigma_N{}^2))$ over 20-day periods and a characteristic amplitude of the mesoscale currents by the 4-day vector averages; the general circulation direction is deduced from progressive vector diagrams and large-scale (mean) currents are the 20-day vector-averages (Tab. 2).

Two kinds of hydrological networks were also carried out: 1) in July 1981 and February-March 1982 (DYOME 1 and 2 cruises), at the locations indicated in Figure 1 (10 nm spacing) and along specific sections off Nice and off the north-western coast of Corsica (5 nm spacing), and 2) since October 1981, at 6 stations equally spaced (5 nm) between 3 and 28 nm off Nice with a two-week period (PROS 6 experiment; L. Prieur, pers. comm., 1984). In addition, three drifting buoys drogued at ≈ 10 m and Argos-positioned were launched and some infrared images collected during the experiment have been analysed. During the MEDALPEX program various data sets were collected in the Ligurian Sea (mainly on the continental shelf)

Table 2

Mean speed values in cm/s as computed from the 20-day vector averages. The start dates of the 20-day periods are indicated. Results obtained with a 10-day lag have not been listed.

Vitesses moyennes sur 20 jours en cm/s. La date de début de la période est indiquée (les résultats obtenus avec un décalage de 10 jours ne sont pas représentés).

	27/7	16/8	5/9	25/9	15/10	4/11	24/11	14/12	3/1	23/1	12/2	4/3	24/3	13/4	3/5	23/5	12/6	2/7	22/7	11/8
1/100	3.8	4.4	3.6	0.9	3.5	0.8	4.1	0.9	9.5	2.1	4.2	7.3	6.7	8.1	3.6	5.6				
1/350	2.9	2.7	2.1	0.7	3.0	0.6	2.6	1.4	4.9	2.3	5.4	7.6	3.0	8.6	2.8	4.0				
1/1 100	2.2	1.9	1.4	1.0	2.2	0.0	2.0	0.3	1.3	2.3	5.4	6.4	2.7	7.9	2.1	3.6				
2/100	2.1	5.0	1.9	2.8	5.9	1.0	0.7	2.2	5.5	2.2	7.4	13.2	1.9	3.8	3.2	1.1	0.5	0.9	1.3	
2/350	1.8	3.8	1.7	2.6	3.7	0.8	1.5	0.8	4.1	3.3	8.6	13.3	2.5	4.5	3.2	6.1	1.1	1.8	2.4	
2/1 100	2.6	2.6	1.8	2.6	3.0	1.1	1.9	0.9	3.0	3.5	8.6	13.3	3.6	6.3	3.6	5.4	1.4	1.7		
3/100	5.9	8.7	4.0	5.9	7.1	7.7	3.7	2.8	5.6	6.3	12.3	8.8	6.5	4.2	4.8	1.2	7.6	6.4	1.2	1.3
3/350	1.9	3.7	1.1	2.6	2.0	1.7	0.2	0.8	2.9	2.5	7.8	6.4	4.7	3.3	4.0	2.3	4.4	2.1	0.7	0.9
3/1 100	1.1	2.6	1.4	1.2	0.3	0.9	2.7	1.3	1.6	1.2	6.6	7.1	3.5	2.6	3.4	1.8	2.1	2.3	1.3	
5/100	9.2	15.8	14.8	14.2	12.0	19.8	17.5	14.1	20.2	17.9	8.5	10.9	9.0	6.2	17.4	18.3	12.8			
5/350	4.1	5.7	4.4	5.2	5.4	6.7	5.6	5.8	9.5	7.3	4.1	2.6	1.7	2.7	5.9	1.8	2.2			
5/1 100	2.4	1.5	0.9	1.2	1.9	0.7	1.0	2.1	3.8	4.7	3.5	0.2	0.5	3.1	4.3	0.7	3.3			
6/100	10.0	11.4	13.5	10.8	13.2	17.9	16.3	13.4	21.4	15.6	7.6	15.6	9.2	10.2						
6/350	4.2	4.6	5.4	4.2	5.8	6.9	6.1	5.6	10.0	5.3	2.3	5.0	4.5	5.3						
6/1 100	2.3	2.2	2.2	1.7	2.3	2.0	1.7	2.1	4.2	2.1	1.8	2.3	3.7	2.9	2.7	0.4	2.3			
7/100	1.2	1.9	2.0	1.9	2.4	3.7	6.4	2.7	4.4	2.3	8.7	5.4	2.5	4.3	0.7	1.2	1.0			
7/350	0.9	1.2	1.1	1.2	1.2	2.7	3.6	2.1	2.0	1.6	8.8	5.8	2.4	3.4	1.2	2.0	0.2			
7/1 100	0.5	1.0	1.2	1.3	1.0	2.6	2.2	3.3	0.1	2.0	7.1	7.0	2.4	2.7	1.5	1.9	0.2			
8/100	4.3	4.9	6.1	7.8	4.9	4.8	5.3	12.1	13.2	10.3	8.2	5.1	8.6	18.0	11.2	4.6	2.1			
8/350	3.6	3.9	3.6	3.0	1.8	3.2	1.4	4.8	2.8	6.1	2.6	0.8	5.8	11.2	10.6	9.0	6.1			
8/1 100	0.8	0.8	0.4	1.3																
9/100	9.5	8.1	14.0	10.8	11.9	10.6	13.7	13.7												
9/350	4.6	5.2	6.2	5.2	6.4	4.3	6.4	6.8	7.4	8.5	5.2	6.1	7.7	5.7	4.6	3.8	4.0	2.6	4.4	5.3
9/1 100	1.5	0.9	1.7	1.9	1.3	0.7	1.0	1.7	2.6	1.9	0.8	0.6	3.3	0.9	3.0	0.2	0.8	1.3	1.2	
10/350	7.5	6.9	5.4	7.4	4.7	6.7	6.3	5.9	9.8	9.5	8.2	9.1	7.1	6.8	7.3	7.7	6.8	4.9	4.7	7.5
10/1 100	3.6	3.1	2.1	2.7	1.4	2.8	2.4	1.8	4.3	3.6	3.4	2.8	1.8	1.2	2.9	1.2	1.9	5.5	1.8	

by Italian colleagues but possible relationships with our data have not been investigated.

In this paper, our aim is to describe some general hydrodynamical features in the Ligurian Sea as, for instance, the variations with space and time of the mesoscale activity. A more detailed analysis of the mesoscale motions will be addressed in a forthcoming paper. The observations collected in 1981-1982 are presented in section 2 and a discussion is made in section 3.

OBSERVATIONS

Although the description of each current meter recording may make somewhat heavy reading, it is thought to be necessary for a complete understanding.

Point 1 (Fig. 2)

From July to December the mesoscale activity was weak. A large increase of this activity appeared from

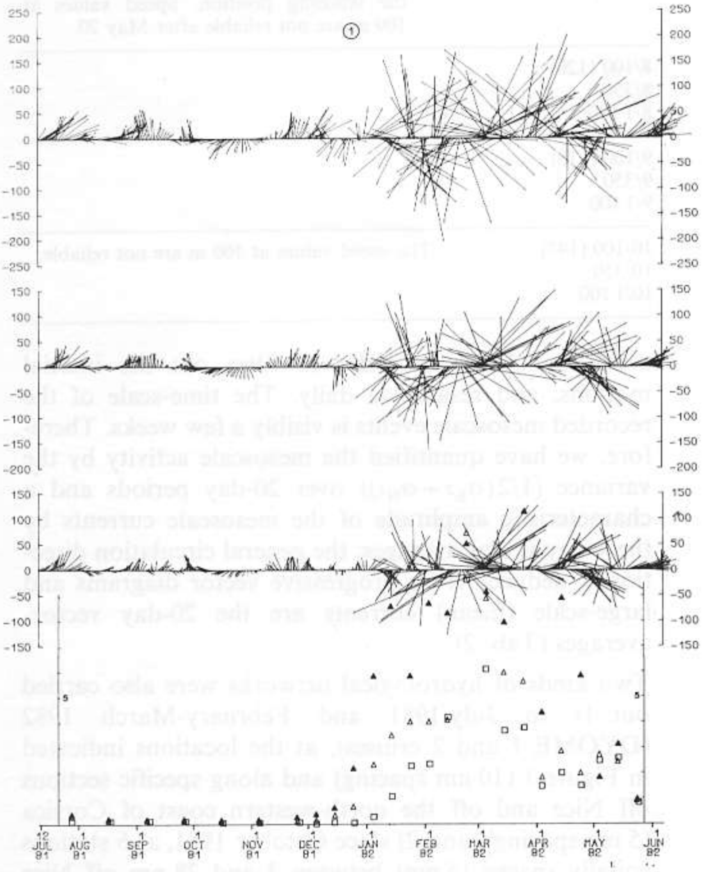


Figure 2

Point 1. Stick diagrams at 100 m (upper), 350 m (middle) and 1 100 m (lower); values in mm/s and north pointing upwards. The variances at 100 m (▲), 350 m (△) and 1 100 m (□) are plotted one point out of two when low and similar; values in 10^3 mm^2/s^2.

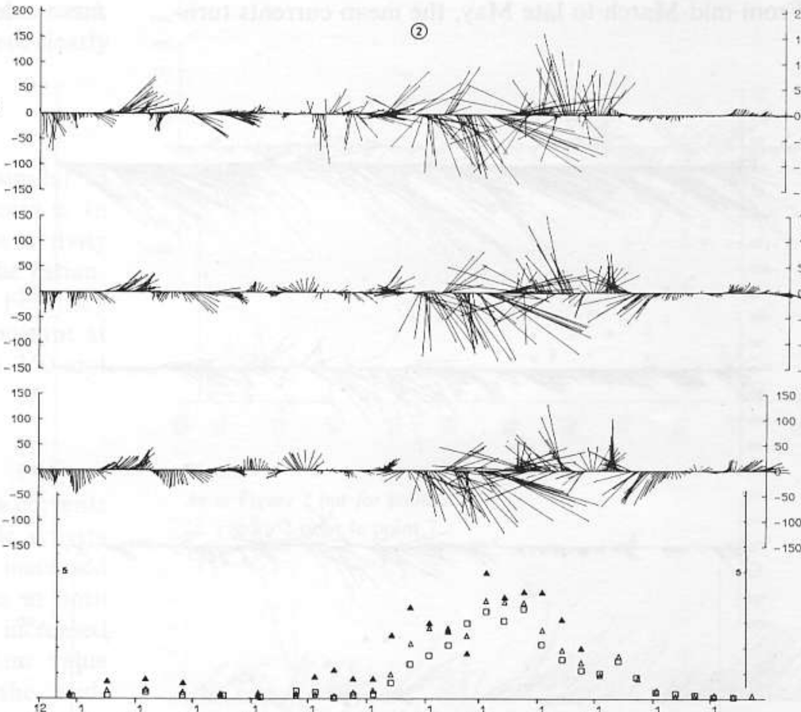
Point 1. Stick diagrammes à 100 m (en haut), à 350 m (au milieu), et 1 100 m (en bas); vitesses en mm/s, nord vers le haut. Les variances à 100 m (▲), 350 m (△), et 1 100 m (□) ne sont reportées qu'une fois sur deux lorsque faibles et du même ordre; valeurs en 10^3 mm^2/s^2.

late December, first near the surface and then at greater depths; in January, a noticeable mesoscale event with large vertical shear was observed. The mesoscale motions were then clearly barotropic and speeds reached 15-20 cm/s over the whole depth, leading to a drift of the mooring until mid-March; it was recovered at ≈ 13 nm north-westwards, the immersion of the meters being reduced by ≈ 60 m. Intense barotropic mesoscale currents (≈ 10 cm/s) were observed until May, although there was a tendency to attenuation. During both the quiet and stormy periods, the large-scale currents were a few cm/s and roughly towards NE.

Point 2 (Fig. 3)

A mesoscale activity as weak as at point 1 was observed from July to early January with mean currents (a few cm/s) towards SE. The activity then increased and mesoscale currents of ≈ 20 cm/s were observed at all depths; on the whole, this activity during the stormy period was barotropic and reached a maximum intensity in March. Up to mid-March, the mean currents were still towards SE with the largest values

Figure 3
As in Figure 2 but for point 2.
Id. Figure 2 pour le point 2.



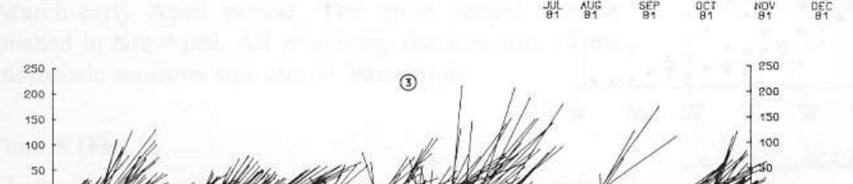


Figure 4
As in Figure 2 but for point 3.
Id. Figure 2 pour le point 3.

($\approx$ 13 cm/s) at all depths in early March. The general circulation reversed in mid-March at 350 and 1 100 m while veering northwards at 100 m, and then it turned back towards SE at all depths from mid-May.

Point 3 (Fig. 4)

During the quiet period (from July to November-February) the mean currents were towards NE at 100 m (5-10 cm/s) and 350 m (a few cm/s) while being $\approx$ 0 at 1 100 m. At all depths, the general circulation continued towards NE until mid-March and the largest mean currents were respectively $\approx$ 12, 8 and 7 cm/s. From mid-March to late May, the mean currents turned southwards (a few cm/s) while a relatively intense mesoscale event was observed. From early June, the characteristics of the first quiet period were observed again. The mesoscale phenomena appeared baroclinic during the quiet period and barotropic during the stormy period.

Point 5 (Fig. 5)

The quiet (with respect to the mesoscale activity) period lasted up to mid-December with SW mean currents at all depths ($\approx$ 10-20, 4-7 and a few cm/s resp.). The mesoscale activity increased at all depths in late

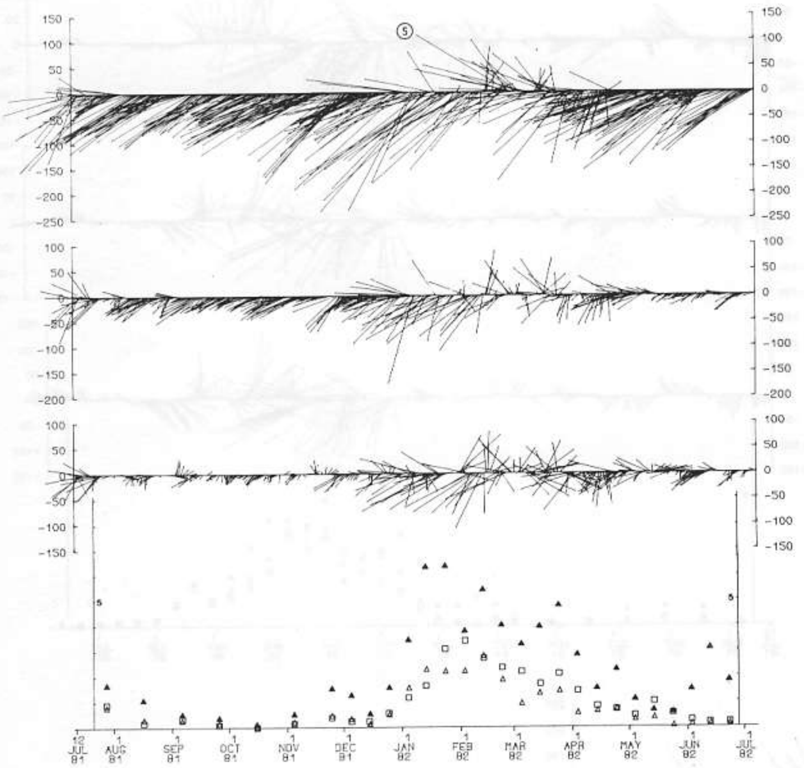


Figure 5
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Id. Figure 2 pour le point 5.

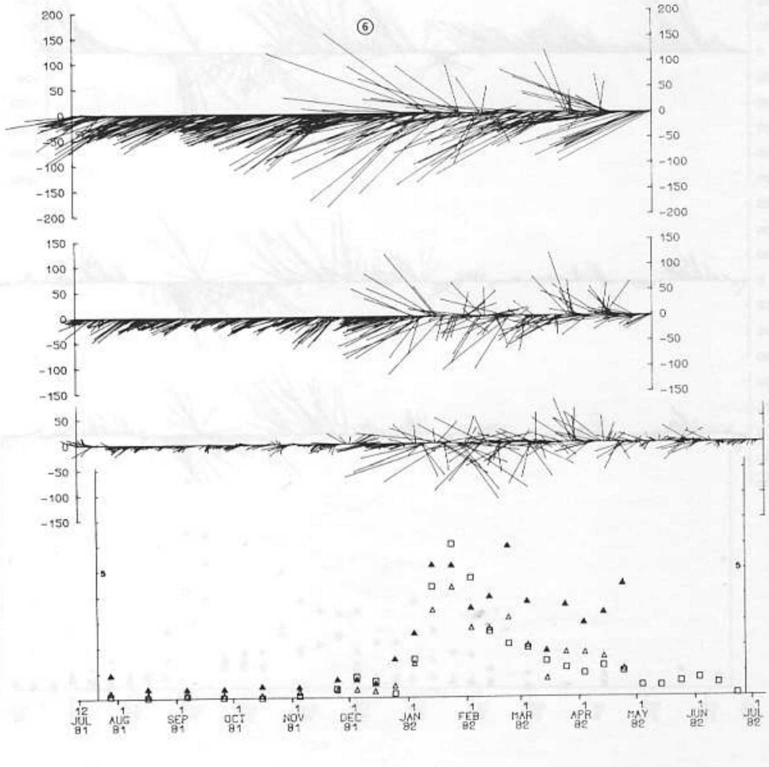

Figure 6
As in Figure 2 but for point 6.
Id. Figure 2 pour le point 6.

December-early January, with the largest values at 100 m and similar values at 350 and 1 100 m; the mean currents reached their maxima in January (≈ 20, 9 and 5 cm/s, resp.). From February to April, the mean currents significantly decreased at 100 m leading to frequent reversals now affecting the smaller depths as well. The mesoscale activity continuously weakened at all depths but values at 1 100 m were always larger than at 350 m. The quiet period began in May. Due to the large values and vertical shear of the mean currents, the vertical structure of the mesoscale phenomena could not be easily defined; during the quiet period, large phase lags were fairly often encountered, while during the stormy period some events were clearly barotropic.

Point 6 (Fig. 6)

Large-scale and mesoscale features roughly similar to those noticed at point 5 were observed at point 6. In late December-early January, the mesoscale activity increased at all depths; in January-February, the variances at 1 100 m were the largest ones. From February to April, the mesoscale activity remained important at 100 m while decreasing with similar values at 350 and 1 100 m.

Point 7 (Fig. 7)

Up to the end end of December, the large-scale currents (a few cm/s) were westwards and the mesoscale activity was very weak at all depths. This activity increased from January to mid-April with larger values at both 450 and 1 200 m; the large-scale currents increased during the stormy period with the maximum value (10.5 cm/s) measured at 1 200 m during the mid-March-early April period. The quiet period re-established in late April. All year long, the structure of the mesoscale motions was clearly barotropic.

Point 8 (Fig. 8)

The seasonal variability encountered at the other points did not occur. The NE large-scale currents commonly ranged from 5 to 13 cm/s at 100 m and from 2 to 6 cm/s at 350 m, except in April-May when values increased to ≈ 18 and 11 cm/s respectively. Unlike points 1 to 7, the mesoscale motions at point 8 were characterized by a permanent occurrence and a moderate amplitude; large vertical phase lags were frequently observed throughout the year.

Point 9 (Fig. 9)

The NNE mean currents (8-15 cm/s at 100 m, 3-9 cm/s at 350 m and a few cm/s at 1 100 m) were larger than at point 8. At 350 m, the mesoscale activity was as large as at point 8 and did not display a marked seasonal variability either, while at 1 100 m, the mesoscale activity increased in March-April. A northward deviation of the large-scale currents was observed from mid-March to mid-May at 350 and 1 100 m. Large vertical phase lags were fairly often noticed; in March-April, the mesoscale currents looked incoherent between 350 and 1 100 m.

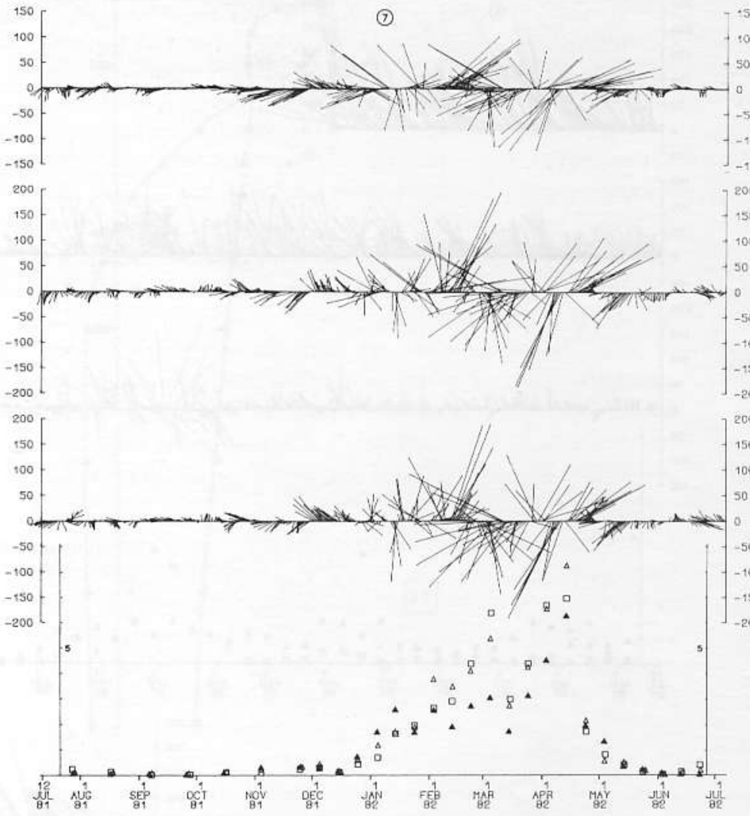

Figure 7
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Id. Figure 2 pour le point 7.

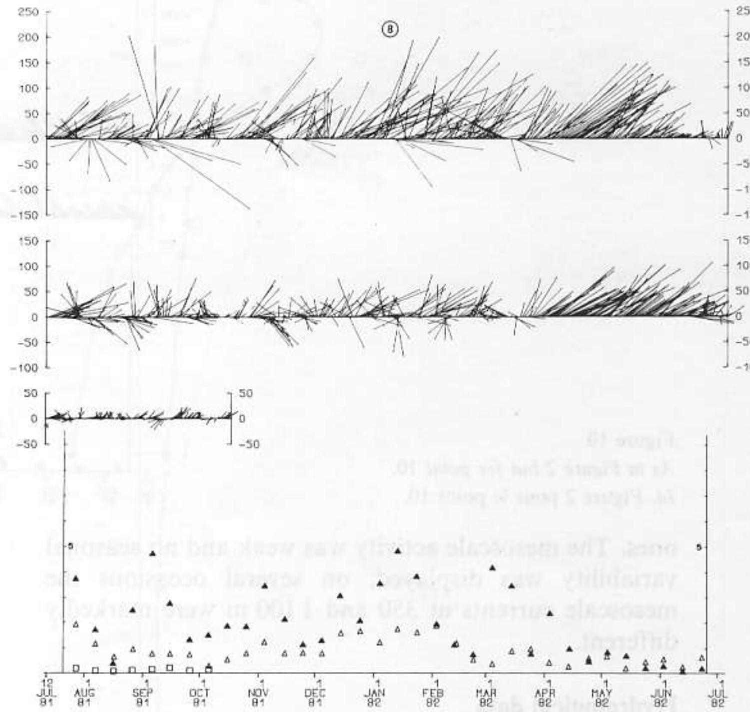


Figure 8
As in Figure 2 but for point 8.
Id. Figure 2 pour le point 8.

Point 10 (Fig. 10)

The flow was NE at all depths and the large-scale currents at 350 (5-10 cm/s) and 1 100 (2-4 cm/s) were the most regular and, on a yearly average, the strongest

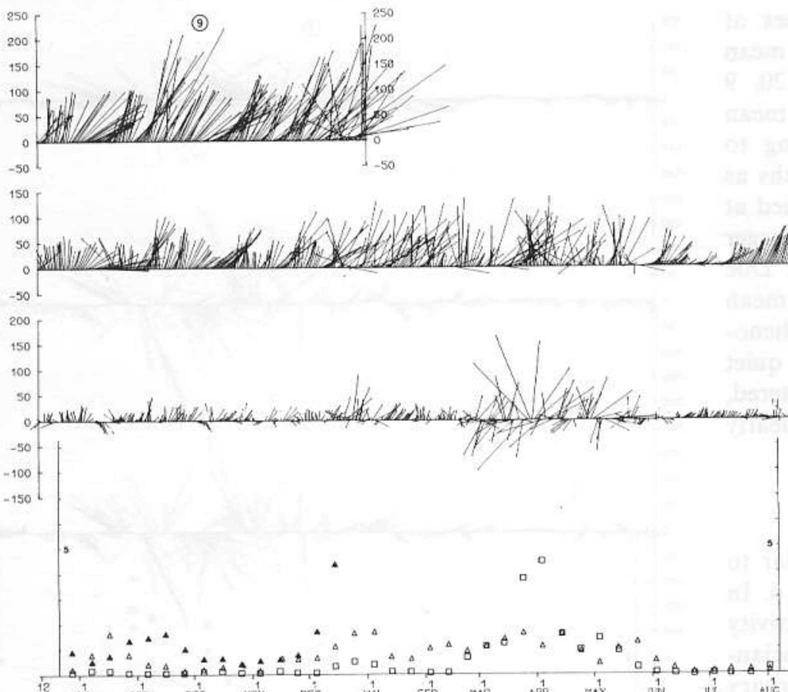


Figure 9
As in Figure 2 but for point 9.
Id. Figure 2 pour le point 9.

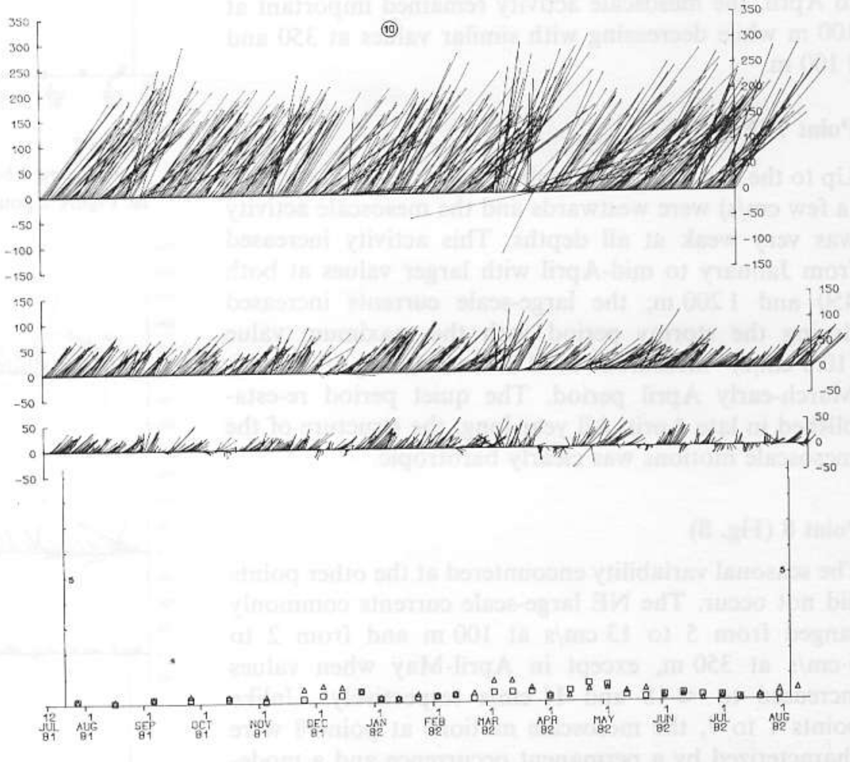


Figure 10
As in Figure 2 but for point 10.
Id. Figure 2 pour le point 10.

ones. The mesoscale activity was weak and no seasonal variability was displayed; on several occasions the mesoscale currents at 350 and 1 100 m were markedly different.

Hydrological data

We have found agreements between the main features observed during the DYOME 2 and PROS 6 experiments and the statistics computed with larger space and time scale by Nyffeler *et al.* (1980).

The statistical data along the Nice-Calvi section (10 nm spacing in the coastal zones, 30 nm in the central zone) show that differences exist throughout the year between the Continental and Corsican coastal currents (Fig. 11). The northern flux is about twice the southern one, and, due to both the freshwater discharge from the Italian peninsula and the warm water issued from the Tyrrhenian Sea, densities are lower in the north. These features lead to steeper isopycnals and isotachs and to larger horizontal density gradients in the north; the edge of the Ligurian current, at 10-20 nm offshore, is therefore well defined.

The CTD casts collected in February-March 1982 gave results in agreement with the statistical data. The denser surface waters were encountered at ≈ 20 nm off the northern coast; for instance, at the most homogeneous station which was in the vicinity of point 7 between Nice and Calvi, values of salinity, potential temperature and density between 0 m and 1 950 m ranged from 38.432 to 38.469 ppt, from 12.764 to 12.926°C and from 29.103 to 29.118 respectively. The hydrological

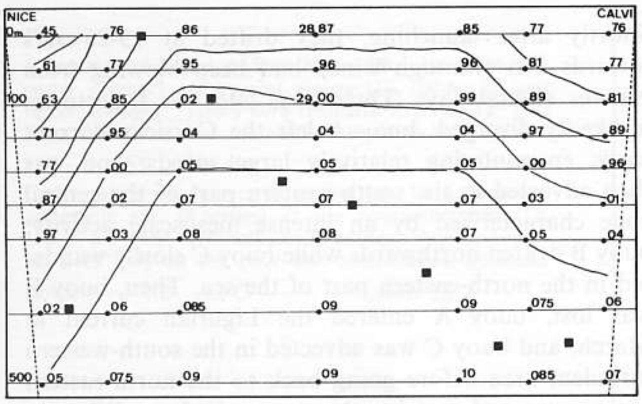


Figure 11
Statistical density values between Nice and Calvi in March (from Nyffeler et al., *1980). Immersion of the 29.10 isopycnal during the February-March 1982 cruise (■).*
Valeurs statistiques des densités entre Nice et Calvi en mars (d'après Nyffeler *et al.*, 1980). Immersion de l'isopycne 29.10 pendant la campagne de février-mars 1982 (■).

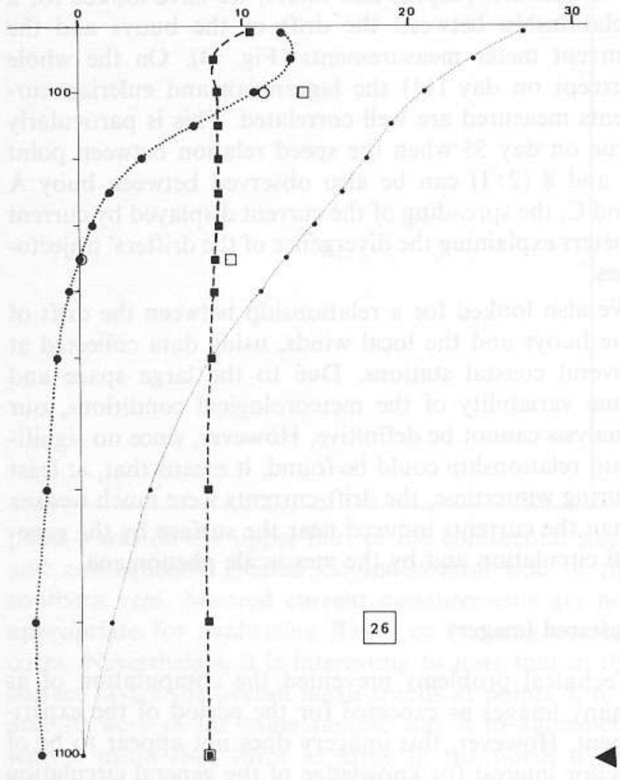
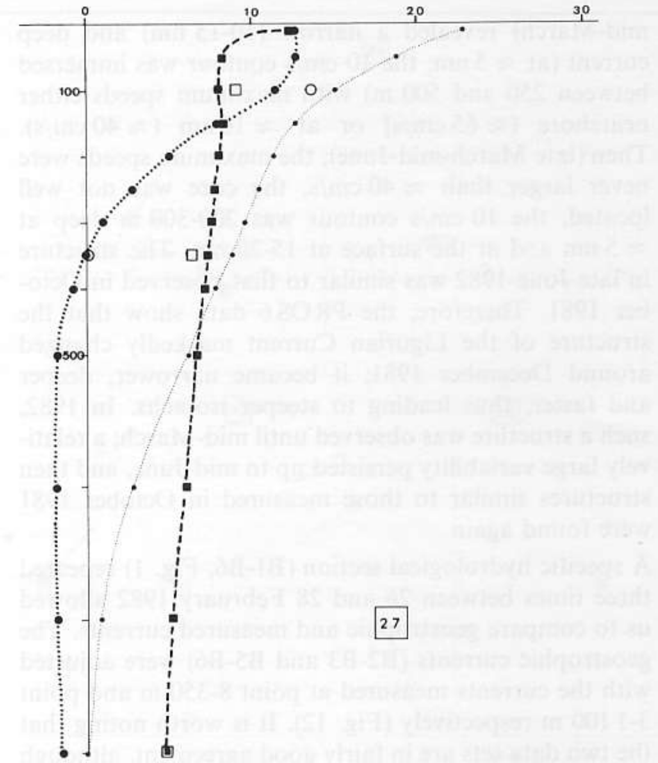
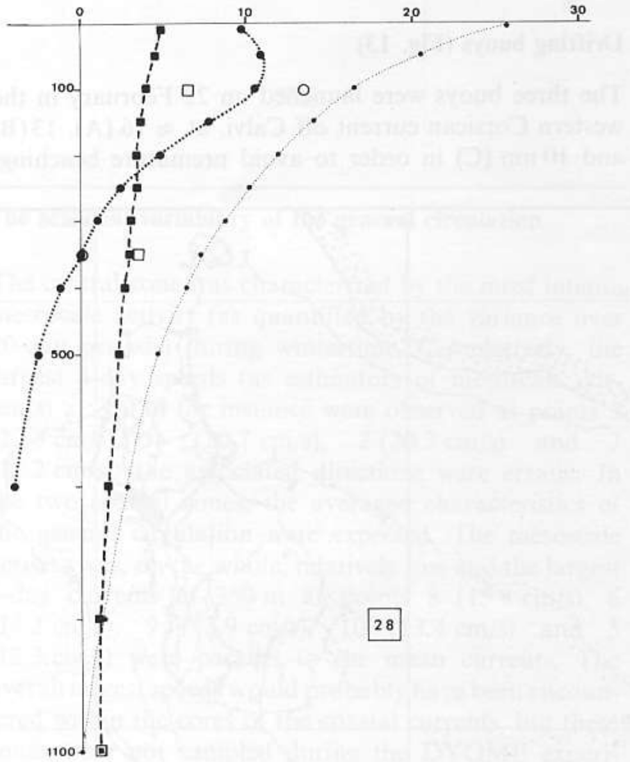


Figure 12
Geostrophic currents (B2-B3 . . . ● . . ., B5-B6 - - - ■ - - -) adjusted with the normal component of the 36-hour vector average of the mooring 8 (○) at 350 m and 3 (□) at 1 100 m. The maximum speed profile (B3-B4 . . . ● . . .) could not be adjusted. 26 *day Feb. 26, 1982, speeds in cm/s, depths in m.*
Courants géostrophiques (B5-B6 - - - ■ - - - et B2-B3 - - - ● - - -) recalés avec la composante normale du vecteur moyenné sur 36 heures au point 3 (□) à 1 100 m et au point 8 (○) à 350 m. Le profil de vitesse maximale (B3-B4 . . . ● . . .) n'a pas pu être recalé. 26 jour 26/2/1982, vitesses en cm/s, immersions en m.

structure between the continental and Corsican coasts was well represented by the 29.10 isopycnal which sloped down from the outer edge of the Ligurian Current at rates of ≈ 2 % northwards and ≈ 0.4 % southwards (Fig. 11); similar features were displayed in the whole studied area.

The PROS 6 data provided information twice a month on the variations of the Ligurian current in 1981-1982.





The autumn sections (October-early November) depicted isotachs regularly sloping down (the 10 cm/s contour intersected the surface at 20-25 nm and was 100-200 m deep at ≈ 5 nm offshore) with maximum speeds of ≈ 50 cm/s nearshore. From mid-November to mid-December, the core of the current (≈ 40 cm/s) was at 10-15 nm, while the 10 cm/s contour intersected the surface at ≈ 20 nm. The later sections (January to mid-March) revealed a narrow (10-15 nm) and deep current (at ≈ 5 nm; the 10 cm/s contour was immersed between 250 and 500 m) with maximum speeds either nearshore (≈ 65 cm/s) or at ≈ 10 nm (≈ 40 cm/s). Then (late March-mid-June), the maximum speeds were never larger than ≈ 40 cm/s, the core was not well located, the 10 cm/s contour was 200-300 m deep at ≈ 5 nm and at the surface at 15-20 nm. The structure in late June 1982 was similar to that observed in October 1981. Therefore, the PROS 6 data show that the structure of the Ligurian Current markedly changed around December 1981; it became narrower, deeper and faster, thus leading to steeper isotachs. In 1982, such a structure was observed until mid-March; a relatively large variability persisted up to mid-June, and then structures similar to those measured in October 1981 were found again.

A specific hydrological section (B1-B6, Fig. 1) repeated three times between 26 and 28 February 1982 allowed us to compare geostrophic and measured currents. The geostrophic currents (B2-B3 and B5-B6) were adjusted with the currents measured at point 8-350 m and point 3-1 100 m respectively (Fig. 12). It is worth noting that the two data sets are in fairly good agreement, although the variability of the currents was relatively large at point 3. This exercise suggests that in the central zone and during wintertime, in particular, geostrophic calculations should not be carried out without direct current measurements.

Drifting buoys (Fig. 13)

The three buoys were launched on 22 February in the western Corsican current off Calvi, at ≈ 16 (A), 13 (B) and 10 nm (C) in order to avoid premature beaching.

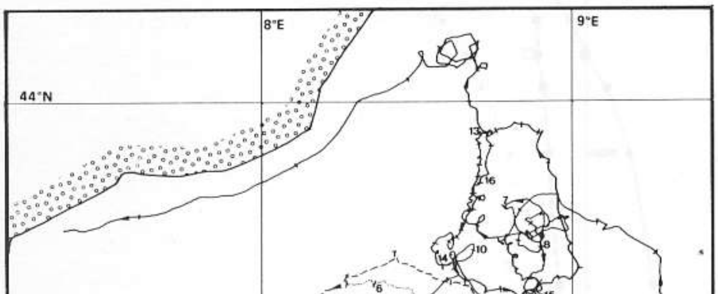


Figure 13
Trajectories of the drifting buoys (days are marked with ticks and numbered in tens of Julian days).
Trajectoires des bouées dérivantes (les jours sont repérés par des tirets et numérotés en dizaines de jours juliens).

Shortly after launching, they drifted at 15-25 cm/s towards NE although winds had been blowing from NE for several days. Three days later the trajectories markedly diverged: buoy A left the Corsican current early, encountering relatively large speeds, and was then advected in the south-western part of the central zone characterized by an intense mesoscale activity; buoy B drifted northwards while buoy C slowly wandered in the north-eastern part of the sea. Then, buoy B was lost, buoy A entered the Ligurian current in March, and buoy C was advected in the south-western turbulent area before going back to the north-eastern quieter one and entering the current in June. When in the Ligurian current, buoys A and C drifted in a direction parallel to the coast, the trajectory of A supporting the fact that this current was at least ≈ 20 nm wide around mid-March.

Although there was some discrepancies between the two data sets (depths and filters) we have looked for a relationship between the drift of the buoys and the current meter measurements (Fig. 14). On the whole (except on day 111) the lagrangian and eulerian currents measured are well correlated. This is particularly true on day 55 when the speed relation between point 3 and 8 (2:1) can be also observed between buoy A and C, the spreading of the current displayed by current meters explaining the divergence of the drifters' trajectories.

We also looked for a relationship between the drift of the buoys and the local winds, using data collected at several coastal stations. Due to the large space and time variability of the meteorological conditions, our analysis cannot be definitive. However, since no significant relationship could be found, it means that, at least during wintertime, the drift-currents were much weaker than the currents induced near the surface by the general circulation and by the mesoscale phenomena.

Infrared imagery

Technical problems prevented the computation of as many images as expected for the period of the experiment. However, this imagery does not appear to be of major interest for knowledge of the general circulation itself. The surface waters that issue from the Tyrrhenian Sea are always warmer than those advected by the western Corsican current, and the Ligurian current, which results from their mixing, has intermediate temperature values; it follows that the width of the two currents, for instance, cannot be accurately compared. On the other hand, and as expected, this imagery clearly confirms that, at least during summer, the mesoscale variability of the surface layers is larger in the southern part of the Ligurian Sea.

DISCUSSION

The asymmetry of the large-scale hydrodynamical features

Points 5 and 6 in the north, 9 and 10 in the south, were located roughly at the same distance offshore and clearly within the two veins of the general circulation;

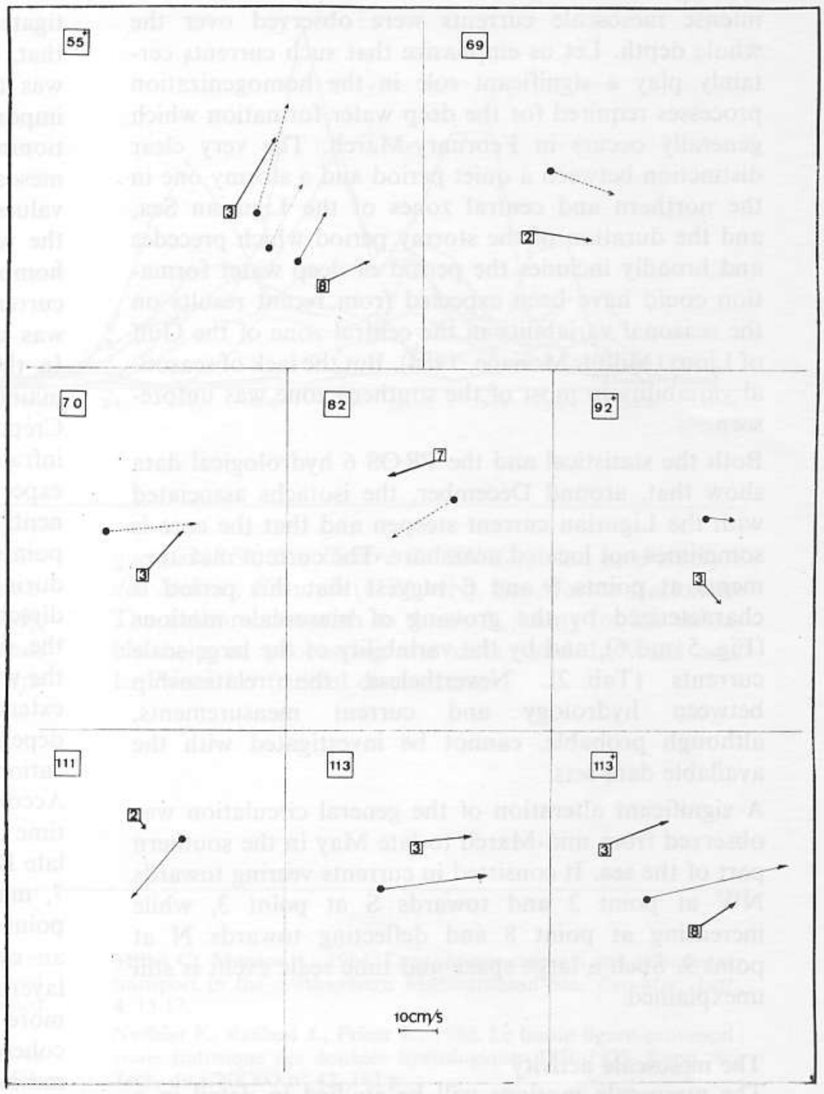


Figure 14
Comparison between drifting buoys (●, 10 m, 24-hour vector average) and current meters (□, 100 m, 36-hour vector average). Vectors were computed either at 12^H (+) or at 00^H for a best comparison. Buoy A----, B....., C———, 55 julian day.
Comparaison des bouées dérivantes (●, 10 m, moyenne vectorielle sur 24 heures) et des courantomètres (□, 100 m, moyenne vectorielle sur 36 heures). Vecteurs reportés à 12^h (+) ou 00^h pour une comparaison optimale. Bouée A----, B....., C———, jour julien 55.

point 8 was on the upper part of the continental slope and consequently located on the coastal side of the southern vein. Moored current measurements are not appropriate for evaluating fluxes or locating current cores. Nevertheless, it is interesting to note that in the surface layers the overall mean speeds at points 5, 6, 9 and 10 were in the same ranges; this is in agreement with a mean flux twice as large in the north if the Ligurian current is narrower, deeper and faster than the western Corsican current.

In the central zone the mean currents were, at least during the quiet period, W at point 7 and NE-SE at points 1, 2, 3, thus suggesting a large-scale cyclonic gyre roughly centered between points 1 and 7. In February-March 1982, nearly homogeneous waters were encountered near the outer edge of the Ligurian Current (around point 7) and isopycnals were sloping six times steeper in the north; this is in agreement with the pioneer work of Hela (1963), with the statistics of hydrological data (Nyffeler *et al.*, 1980), and with the satellite imagery which displays sea surface temperatures that are cooler in this region (Wald, 1980).

Therefore the large-scale hydrodynamical features in the Ligurian Sea are markedly asymmetrical. Let us emphasize that the general circulation is significant at 1 100 m in the coastal zones; it is cyclonic and in the order of a few cm/s.

The seasonal variability of the general circulation

The central zone was characterized by the most intense mesoscale activity (as quantified by the variance over 20-day periods) during wintertime. Correlatively, the largest 4-day speeds (as estimators of mesoscale currents) at 350 m for instance were observed at points 3 (22.5 cm/s), 1 (20.7 cm/s), 2 (20.3 cm/s) and 7 (18.2 cm/s); the associated directions were erratic. In the two coastal zones, the averaged characteristics of the general circulation were expected. The mesoscale activity was, on the whole, relatively low and the largest 4-day currents at 350 m at points 8 (15.8 cm/s), 6 (15.2 cm/s), 9 (13.9 cm/s), 10 (13.4 cm/s) and 5 (12.3 cm/s) were parallel to the mean currents. The overall largest speeds would probably have been encountered within the cores of the coastal currents, but these zones were not sampled during the DYOME experiment (this will be done in 1985).

The seasonal variability was not marked in the south (8, 9 (350 m) and 10), but two periods of time were clearly displayed by the northern (points 5 and 6), the central (points 1, 2, 3 and 7) and one southern (9 (1 100 m)) records. The quiet period, from summertime to December-February, was characterized by the relatively small amplitude of mesoscale motions. During the stormy period, from late December to May, intense mesoscale currents were observed over the whole depth. Let us emphasize that such currents certainly play a significant role in the homogenization processes required for the deep water formation which generally occurs in February-March. The very clear distinction between a quiet period and a stormy one in the northern and central zones of the Ligurian Sea, and the duration of the stormy period which precedes and broadly includes the period of deep water formation could have been expected from recent results on the seasonal variability in the central zone of the Gulf of Lions (Millot, Monaco, 1984). But the lack of seasonal variability in most of the southern zone was unforeseen.

Both the statistical and the PROS 6 hydrological data show that, around December, the isotachs associated with the Ligurian current steepen and that the core is sometimes not located nearshore. The current measurements at points 5 and 6 suggest that this period is characterized by the growing of mesoscale motions (Fig. 5 and 6), and by the variability of the large-scale currents (Tab. 2). Nevertheless, the relationship between hydrology and current measurements, although probable, cannot be investigated with the available data sets.

A significant alteration of the general circulation was observed from mid-March to late May in the southern part of the sea. It consisted in currents veering towards NW at point 2 and towards S at point 3, while increasing at point 8 and deflecting towards N at point 9. Such a large space and time scale event is still unexplained.

The mesoscale activity

The mesoscale motions will be studied in detail in a forthcoming paper but several features are immediately noteworthy.

The vertical structure of the mesoscale motions between 100 and 1 100 m accounts for marked differences between the central and peripheral zones. In the central zone it is mainly barotropic. In the peripheral zone it could not be definitively classified with the present analysis; mesoscale events are generally recognizable over the whole depth, but vertical phase lags can be very large.

In the southern part of the Ligurian Sea, intense mesoscale eddies were expected during summertime from the infrared satellite imagery. This could be related to the fact that during this period the mesoscale activity at points 8 and 9 in the surface layers (100 and 350 m), and to a lesser extent at point 3 (100 m) and 10 (350 m), was relatively large. However, in this zone, several other features were unexpected: at points 8 and 9, the mesoscale activity during summertime was the largest of all and it was permanent all year long, though at point 10 the deeper records (350 and 1 100 m) at least were characterized by relatively low values of mesoscale activity.

The central zone (points 1, 2, and to a lesser extent 3 and 7) was expected to be weakly stratified during wintertime, thus leading to deep water formation in February-March. This phenomenon could not be investigated with the available data sets but we have shown that, during the winter-spring period, the central zone was the area of the strongest mesoscale activity, an important element for the description of the preconditioning phase (December-January). These barotropic mesoscale events were associated with the largest speed values, and intense currents probably occurred over the whole depth. This was specially true in the most homogeneous zone along the outer edge of the Ligurian current where the mesoscale activity at 450 and 1 200 m was larger than at 200 m (point 7).

In the northern zone, mesoscale meanders, although mainly studied during wintertime (Viollier *et al.*, 1980; Crépon *et al.*, 1982), are depicted all year long by the infrared imagery. The mesoscale activity was therefore expected to be relatively large and more or less permanent; on the contrary, this activity clearly displays at points 5 and 6 a seasonal variation with largest values during wintertime. Therefore, it seems that there is no direct relationship between the meanders observed at the surface and the mesoscale activity observed over the whole depth. This is probably linked to the vertical extent of the mesoscale phenomena which may be dependent upon the stratification, the lesser the stratification, the deeper the phenomena.

According to the 1 100 m recordings, the beginning time of the stormy period evolved from north to south: late December at points 5 and 6, early January at point 7, mid January at points 1 and 2, early February at point 3, and late February at point 9 (Fig. 15). Such an evolution is not clearly displayed in the surface layers probably because the mass and current fields are more heterogeneous horizontally. The lack of spatial coherency and the large frequency spectrum of the mesoscale currents during this period account for small turbulent events. We hypothesize that this mesoscale turbulent activity is created mainly by the Ligurian current and gradually reaches the central zone. The processes involved might be instabilities of the Ligurian current. Indeed, the deep extent, the narrow width and, more especially, the steep isotachs of this coastal current during wintertime lead to a structure which may be more adequate to create deep mesoscale events. The western Corsican current probably prevents these events from reaching the Corsican coasts.

Three zones, southern, central and northern, have been schematically defined, but in fact, the general hydrodynamical features evolved continuously. Points 8 and 10 were in the western Corsican current; there, the mesoscale activity was moderate and displayed no marked seasonal variations. Point 9 was also in this current but large mesoscale events, originated in the north, reached the deeper layers in late winter. Point 3 was on the edge of this current during the quiet period and in the central zone during the stormy one. Points 1 and 2 were in the central zone characterized by weak mean currents and marked seasonal variations of the mesoscale activity. Point 7 was on the edge of the Ligurian Current during the quiet period and in the most homogeneous area during the stormy one. Points 5 and 6 were in the current; there, the mesoscale activity was weak during the quiet period and relatively large during the stormy one.

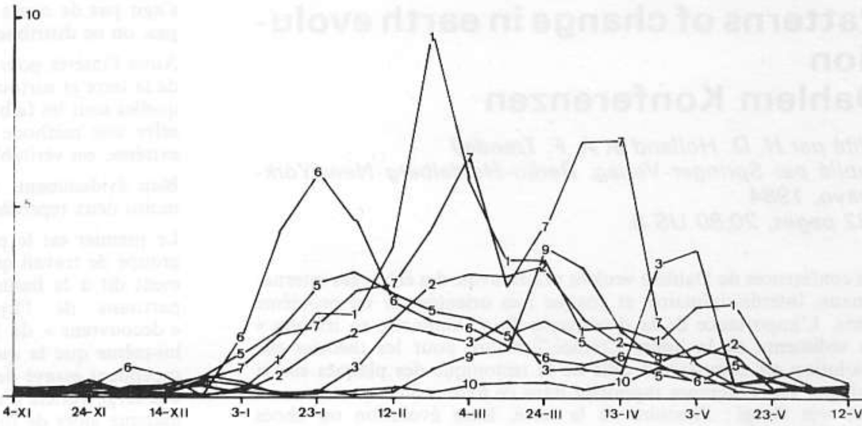


Figure 15
Mesoscale activity at 1 100 m during the stormy period (10^3 mm^2/s^2).
Activité moyenne échelle à 1 100 m pendant la période agitée (10^3 mm^2/s^2).

Acknowledgements

The collection and processing of the various data sets were made possible with the support of several organizations: the *Centre d'Essais de la Méditerranée* (CEM), the *Centre National pour l'Exploitation des Océans* (CNEXO), the *Centre National de la Recherche Scientifique* (CNRS), the *Centre de Télédétection et d'Analyse des Milieux Naturels* (CTAMN), the *Marine Nationale.* The authors also wish to thank A. Lamy for his valuable help in processing the data, and L. Wald and L. Prieur for fruitful discussions.

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