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Wind induced upwellings in the Gulf of Lions

Coastal upwelling
Continental shelf
Gulf of Lions
Upwelling côtier
Plateau continental
Golfe du Lion

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ABSTRACT

Continental shelf dynamics have been observed since 1974 in the Gulf of Lions (North-Western Mediterranean Sea), with the principal aim of understanding the summer circulation in this region. From satellite infrared data, current meters, thermistor chains, and tidal gauge records, it appears that the major events occurring on the continental shelf take the form of wind-induced mesoscale phenomena. These phenomena, which are connected with strong and transient coastal upwellings, are generated by North-Westerly winds, the mistral and the tramontane, which are highly transient in speed, with a stable direction and a short lifetime. These specific features have enabled us to investigate the transient response of the sea on about ten such occasions per typical summer. The present paper clearly shows the importance of the coastline configuration for upwelling generation. Some hours after the onset of the wind, actual cool water source-points appear at the surface, along straight coastal segments some ten-twenty nautical miles in length. These cool areas then spread out, while warm waters remain in the vicinity of capes and small bays. Fundamental data from satellite observations are combined with *in situ* measurements to highlight the main features of wind-induced summer circulation. These features comprise high spatial and temporal variabilities of the current and temperature fields, together with complex advective circulations organized like cells around the upwelling areas.

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RÉSUMÉ

Upwellings dans le Golfe du Lion

Depuis 1974, des expériences ont été conduites sur le plateau continental du Golfe du Lion (Méditerranée nord-occidentale) dans le but de comprendre la dynamique d'été de cette région. Des vues infrarouge prises par satellite, et des mesures *in situ* du courant, de la température et de la pression sur le fond montrent que le vent induit des phénomènes d'échelle moyenne de grande amplitude sur le plateau continental. Ces phénomènes sont associés à des upwellings côtiers particulièrement intenses et transitoires. Ils sont engendrés par le mistral et la tramontane, vents de Nord-Ouest caractérisés par une augmentation très rapide de leur vitesse, une direction stable, une durée de vie de quelques jours. Ces particularités permettent d'étudier la réponse transitoire de la mer pendant environ dix coups de vent par été. Cette analyse montre clairement l'importance du dessin de la côte dans la genèse de l'upwelling et le développement particulièrement rapide de ce phénomène. Quelques heures après le début du coup de vent, de véritables points-sources d'eau froide apparaissent à la surface, le long de portions de côte rectilignes sur quelques dizaines de kilomètres. Ces zones froides s'étendent ensuite, pendant que des eaux plus chaudes persistent aux abords des caps et des baies. Les informations fondamentales obtenues par satellite sont confrontées aux observations *in situ* pour dresser un schéma cohérent de la circulation induite par le vent. Les caractères particuliers de cette dynamique sont une grande variabilité spatiale et temporelle des champs de courant et de température, et des circulations horizontales complexes organisées en cellules autour des zones d'upwelling.

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INTRODUCTION

Upwelling is a complex phenomenon involving many different space and time scales. Its study was initiated off the Oregon and North-West Africa coasts, where large vertical water motions occur in summer, under the influence of prevailing Northerly winds. The seasonal time-scale and the almost regular pattern of the coast may lead us to assume the validity of steady state approximations and two-dimensional models. These hypotheses remained permissible until accurate current measurements on the vertical plane (Joint-1 experiment) indicated that at the measurement point, offshore drift is not equal to the onshore flow. This suggests that coastal upwelling dynamics has a three-dimensional nature (Halpern *et al.*, 1977).

During the last decade, attention has been focused by aerial and satellite observations on the variability of coastal upwelling. Radiometry surveys of upwelled zones have revealed a variety of cool eddies of a scale of 20 to 100 km (Niiler, 1975); the response time to the wind is known to be of the order of hours (Stumpf *et al.*, 1977), while it appears, both from observation and theory that bottom topography, the shape of the coastline and transient forcings play an important role (Cannon, 1972; Pedlosky, 1974; Peffley *et al.*, 1976; Allen, 1976).

This paper presents a series of observations taken under stormy conditions in the Gulf of Lions (North-Western Mediterranean Sea).

Due to the fact that the prevailing winds (the mistral and the tramontane) are strong and highly transient, the upwelling is analysed through a succession of comparable events; the results may thus be considered representative.

Such an analysis, employed by Holladay and O'Brien (1975), emphasizes certain features of the mean sea surface temperature distribution which are not particularly apparent on each view (see p. 265). The space and time scales involved are short, as already mentioned, and upwelling appears to be strongly discontinuous in space. Relations between the upwelling locations and coastline segments of a length scale of the order of 10 nm are established.

Figure 1

The Gulf of Lions and the studied areas. The presence of clearly defined mountain masses influences the meteorology of this region.

Le Golfe du Lion et les zones étudiées. L'existence de massifs bien individualisés gouverne les conditions météorologiques dans cette région.

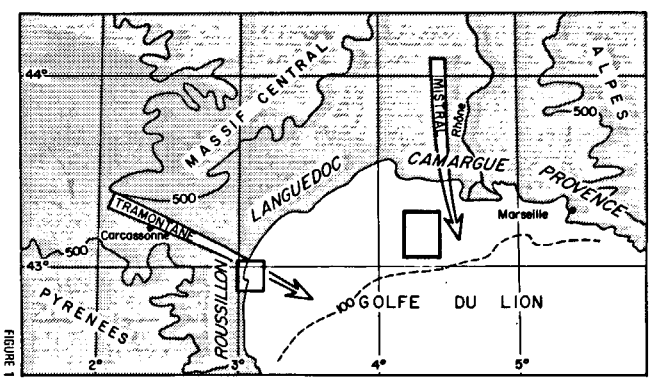


FIGURE 1

The main meteorological and oceanographical features of the studied area, the characteristics of the *in situ* experiments and a number of details concerning satellite information are presented below. The fundamental indications provided by satellite imagery and the main results obtained from the current and temperature sets of data are set out p. 264. In p. 270 the different results presented earlier are discussed. and relations between the various observations are established. All the *in situ* measurements are published in internal reports of the "Laboratoire d'Océanographie Physique du Muséum" (Campagnes du LOP).

THE SITE AND THE DATA

The meteorological regime

The Gulf of Lions is the most windy region of the entire Mediterranean Sea (Ascencio *et al.*, 1977). This basin is bounded along its North-West coasts by ranges of relatively high mountains interrupted by valleys (Fig. 1). Surrounding this near-semicircular gulf are the Pyrénées, the Massif Central and the Alps, separated by the ground-sill of Naurouze-Carcassonne and the Rhône valley.

Typical summer stormy conditions occur when a cold front is travelling across Europe, coming from the North-West. In general, a small depression appears to leeward of the Alps in the Ligurian basin or over the Pô plain (cyclogenesis phenomenon). This depression grows, absorbs the cold front into its own system, and the associated North-Westerly winds rush through the passes—the mistral in the Rhône valley and the tramontane over the Carcassonne region (Fig. 1). These North-Westerlies blow with stable characteristics, and the summer wind records presented in Figure 2 display some specific features of these storms. They occur, on average ten times during a typical summer, and last one to four days or more; the wind speed increases and decreases very quickly (Fig. 7). These characteristics permit the study of the transient stage of the sea during a large number of comparable events.

A vector averaging of the North-West storms during the summer of 1975 gives, for the mistral, approximate mean values of direction and speed of 330° and 6.6 m/s at Cap-Couronne, and 290° and 4.7 m/s at Toulon (Fig. 3). For the tramontane, values of 340° (9.2 m/s) are measured at Cap Bear and 315° (6.9 m/s) at Port-La-Nouvelle. Along the Languedoc coast, the wind at Sète is from 320° (6.6 m/s). We have no observations near Cap d'Agde and Cap de l'Espiguette. These measurements reveal a north-west mean flow in the central part of the Gulf of Lions (320° in Sète), spreading out over the adjacent Ligurian Sea (290° in Toulon) and the Balearic Basin (340° at Cap Bear).

We do not possess a great number of wind measurements between Port-La-Nouvelle and Sète, but during work at sea, we measured the very high spatial variability of the tramontane direction in this region. The wind was blowing with a mean speed of 25-30 knots, from 320° at 78-E and from 270° at 78-A (Fig. 3). There was thus a 50° difference between two points 25 nm (nautical

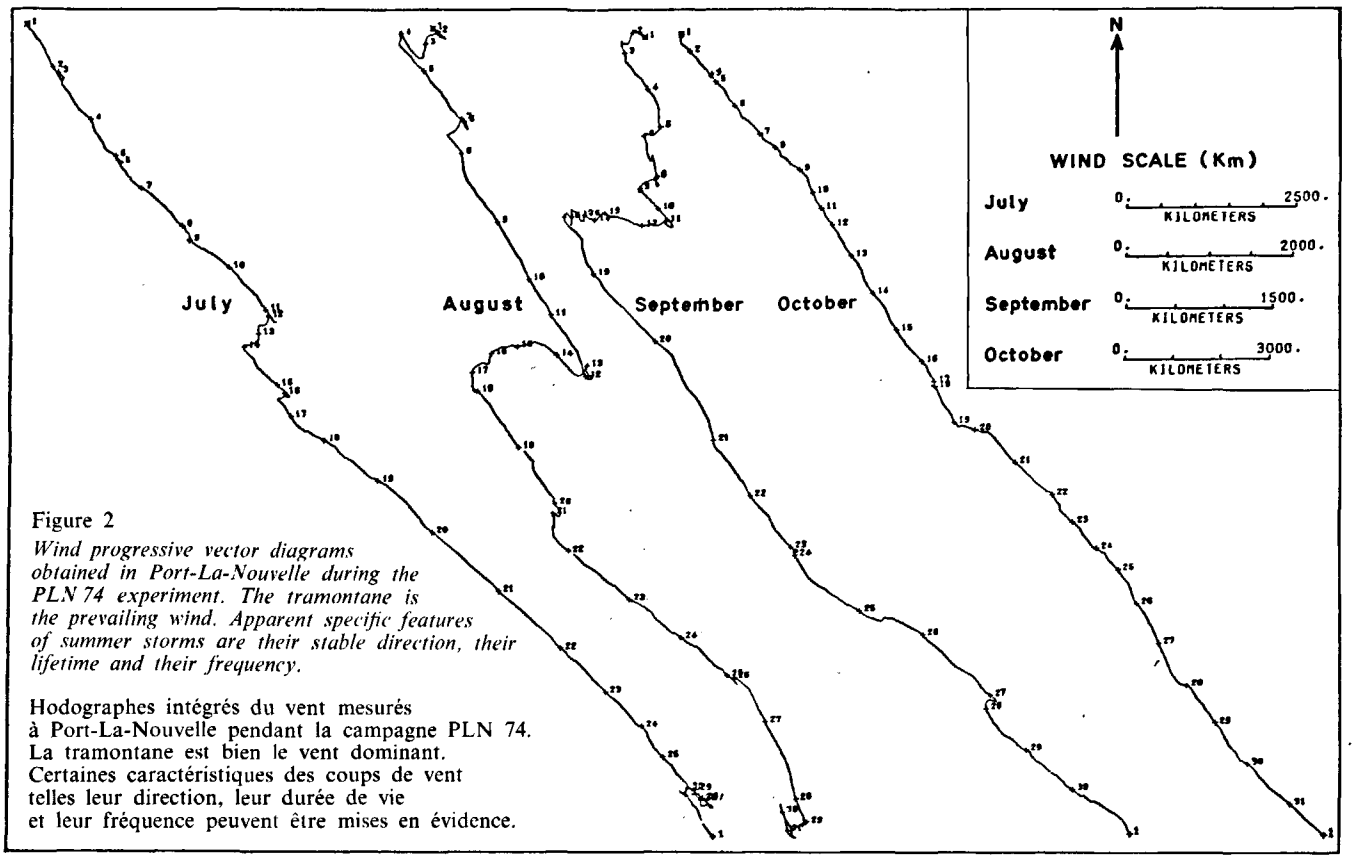


Figure 2
Wind progressive vector diagrams obtained in Port-La-Nouvelle during the PLN 74 experiment. The tramontane is the prevailing wind. Apparent specific features of summer storms are their stable direction, their lifetime and their frequency.

Hodographes intégrés du vent mesurés à Port-La-Nouvelle pendant la campagne PLN 74. La tramontane est bien le vent dominant. Certaines caractéristiques des coups de vent telles leur direction, leur durée de vie et leur fréquence peuvent être mises en évidence.

miles) apart, which supports the hypothesis that some local spreading of the tramontane occurs as a result of the funnel structure of the valley opening on the Gulf of Lions. The wind blows more westerly near Cap d'Agde than near Cap Leucate, and as we shall see later this constitutes an important parameter for the location of a particular upwelling.

The oceanographical regime

The important hydrological summer feature is the formation and deepening of a seasonal thermocline separating a bottom layer (minimum temperature value of about 13.5°C) from an upper layer with a mean temperature of about 20°C and surface values reaching maxima around 25°C. It is difficult to provide a mean temperature profile because of the high temporal and spatial variabilities of the meteorological, hydrological and dynamic conditions. However, one may obtain a rough idea of the stratification by assuming a thermocline 10 to 20 m thick, lying at about mid depth (10 to 50 m) on the greater part of the continental shelf (see Figs. 6, 8).

During periods longer than several days, the part of the circulation which does not appear to be induced by the wind is well defined only between mid-summer

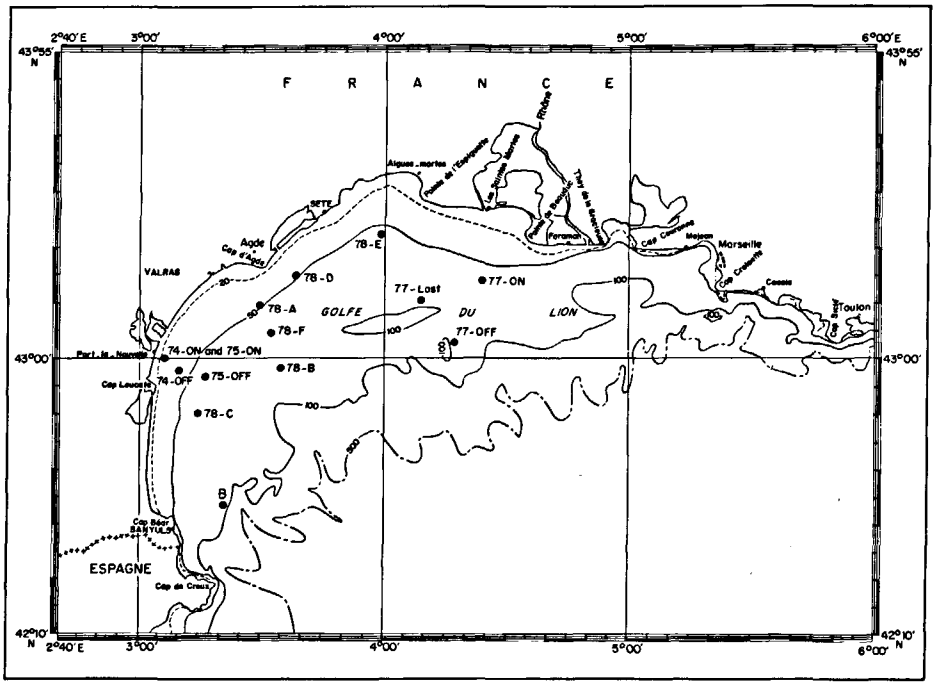


Figure 3
Topography and shoreline of the Gulf of Lions. The points referred to the PLN 74 and PLN 75 experiments represent the mean positions of mooring groups. The 77 and 78 mooring positions are identical with those occupied during the LION 77 and LION 78 experiments. Also indicated are the capes and towns mentioned in the text.

Bathymétrie du Golfe du Lion et points de mouillage. Les points se rapportant aux expériences PLN 74 et PLN 75 représentent des positions moyennes de groupes de mouillages. Pour les campagnes LION 77 et LION 78, les points reportés sont ceux de tous les mouillages mis en place. Les caps et les villes mentionnés dans le texte sont aussi indiqués.

and autumn. The surface layer is affected by an almost permanent current, flowing from North-East to South-West along the Gulf of Lions coasts. This current has been measured at 77-ON with a monthly mean Westward component of about 15 cm/s, and at 75-OFF with a monthly mean Southward component of about 20 cm/s. During September, this large surface transport, which has the coast on its right-hand side is correlated with the mean sea level at 75-ON, which is higher by about 10 cm than in July and early August. Such a current is never observed at 77-OFF, in the central part of the gulf.

This large geostrophic circulation is probably related to the Ligurian current, which flows South-Westward, at least during winter, along the Gulf of Lions continental slope, when its vertical extension is about 200-300 m. In summer, the thickness of this surface current is reduced by the thermocline, and it flows along the shallowest isobaths. Bottom mean circulation is less important in the 77 area than at 75-OFF, where a significant South-West flow occurs throughout the experiment. The tides have small amplitudes (a few centimeters), and the associated currents are too weak to be measured on the shelf.

The Port-La-Nouvelle experiments

A local experiment, hereafter referred to as PLN 74, was conducted from June to October 1974 between Port-La-Nouvelle and Cap Leucate on the Languedoc coast (Fig. 3). Equipment consisted of a four-mooring array centered in a 5 nm square zone, with one Aanderaa current meter located 5 m below the surface (hung under a surface float), and another located 5 m above the bottom on each mooring. The current meters were located on both sides of the thermocline, in order to define the motions of the surface and bottom layers. Because of the relatively small thickness of these sheets of water, they move like slabs (Gonella *et al.*, 1969), at least in the meso-scale frequency band. Analysis of the current and temperature measurements defines a near shore group of moorings (74-ON), and an offshore one (74-OFF). The first group is located 1.5 nm from the coast in 25 m water depth; the second is 4.5 nm offshore (40 m depth). During the experiment, bathythermograph records were obtained under different meteorological conditions.

A year later, the PLN 75 experiment was conducted in the same region and during the same season. Two mooring-points referred to as 75-ON and 75-OFF, were established at 1.5 and 9 nm offshore, at depths of 25 and 55 m (Fig. 3). At each point, in addition to sub-surface moorings with Aanderaa current meters located 5 m below the surface and 5 m above the bottom, we set two-leg moorings supporting thermistor chains ranging in depth from the surface (30 cm) to 20 or 50 m, together with a bottom pressure recorder. Hydrological casts were obtained during the experiment in the South-Western part of the gulf by another research group from the Arago Laboratory in Banyuls (Fig. 3).

The PLN 74 and PLN 75 records provided us with the first indications concerning the wind-induced upwelling phenomenon in the Gulf of Lions. But since there experiments were conducted with aims different from those of our present study, their location was not the best, as will be seen later.

The satellite data

The first infrared satellite views of the Gulf of Lions were collected in 1975 and analysed during 1976. These observations provide fundamental information concerning upwellings. A first obvious reason is that this phenomenon is characterized by surface temperature gradients which are easily measured with sufficient accuracy by infrared satellite radiometers. A second reason is that the air masses blown over the Gulf of Lions by the North-Westerlies lose moisture when they cross the mountains. Due to the foëhn effect, and at least in summer, the sky is generally cloud-free. Satellite observations are fundamental to the study of the upwelling phenomenon because of the high spatial variability of the sea motions in the Gulf of Lions, and the impossibility of obtaining a synoptic dense *in situ* array of moorings. The NOAA satellites are in sun-synchronous orbits (they cover the same area twice a day). The very high resolution radiometer (VHRR) is a scanning radiometer working in the 10.5-12.5 μm infrared band, with a pixel of about 1×1 km^2.

The LION 77 experiment

This experiment was specially addressed to the upwelling study and was conducted from early July to the end of September 1977. Recent publications on the effects of surface wave motions on current measurements (Halpern *et al.*, 1976; Beardsley *et al.*, 1977) led us to deepen the surface Aanderaa current meter. We conceived a low cost mooring system, called U type, similar to that described by Pillsbury *et al.* (1969) which proved quite reliable. Three sub-surface moorings with two current meters (at depths of 10 m beneath the surface and 5 m above the bottom), and one thermistor chain between them, were set in place on the continental shelf, in a region defined with the help of satellite imagery (Fig. 3). The mooring positions were chosen in order to obtain information on the circulation in different parts of an important upwelling. Unfortunately, only two of the three moorings were recovered, so that LION 77 is also a two mooring-point experiment : 77-ON is located at about 10 nm (65 m depth) off shore, and 77-OFF at about 25 nm (90 m depth) (Fig. 3).

THE OBSERVATIONS

The satellite data

The basic notions of wind-induced upwellings observed in the Gulf of Lions are provided by satellite imagery. The view presented in Figure 4 was obtained about one day after the onset of the wind, and provides a good idea of the temporal variability (a day earlier, the surface temperature was homogeneous). Since only one view per day is processed, and considering the time

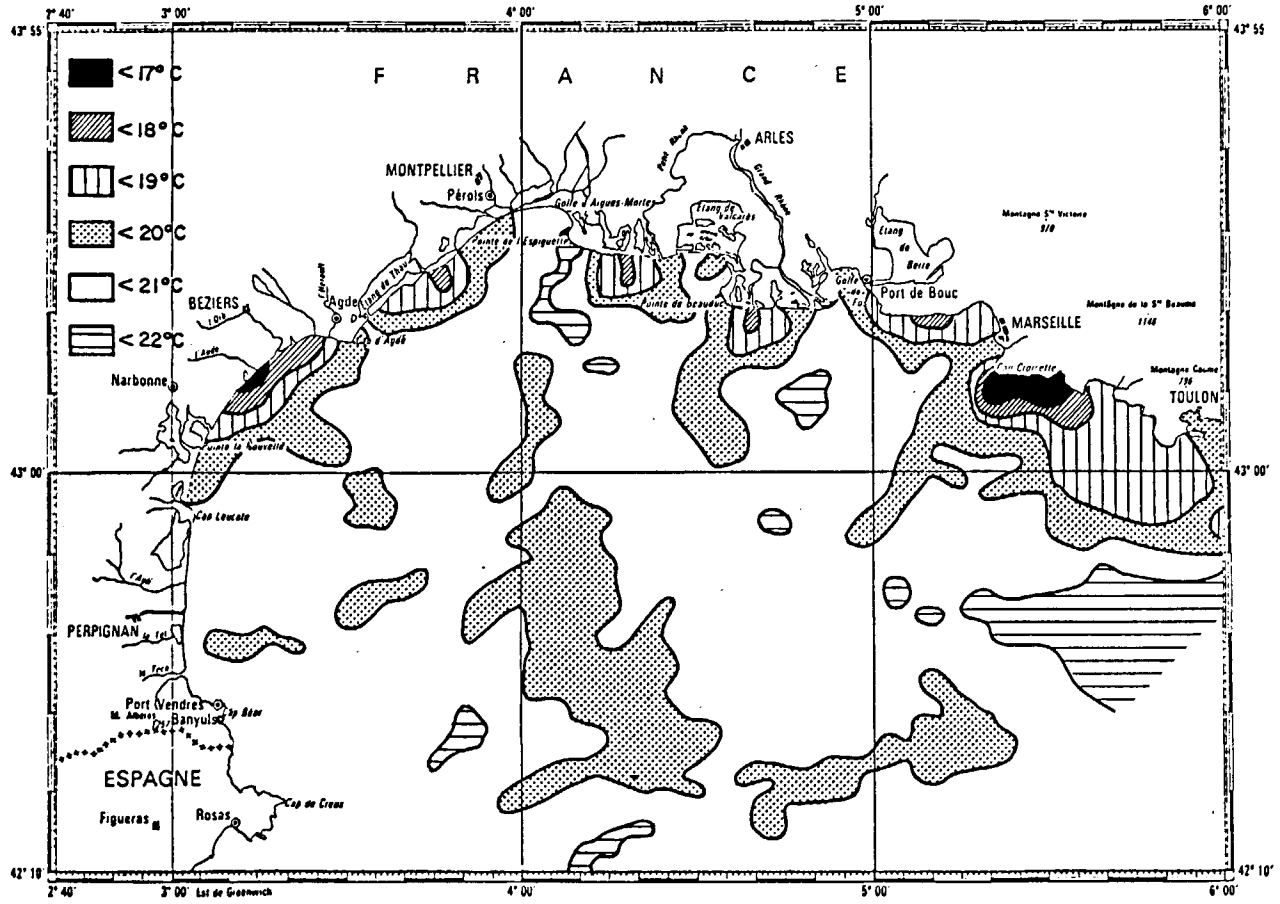


Figure 4

View obtained on 19 July 1975 at 19 h 00 (local time). The North-West has been blowing for about one day throughout the Gulf of Lions. Apparent in this view are all the classical features revealed by statistical analysis (Fig. 5).

Vue satellite obtenue le 19 juillet 1975 à 19 h (heure locale). Le mistral et la tramontane soufflent depuis 1 jour sur l'ensemble du Golfe du Lion. Cette vue présente des caractéristiques très proches de celles révélées par l'analyse statistique de la Figure 5.

scale of the wind and upwelling variations, the few sequences of satellite photos available during these events are not easily described in terms of evolution. During our analysis, we have endeavoured to obtain mean temperature values for each pixel during North-West wind events, and computer operations were processed. Eight photos obtained in July and August 1977 and 1978 were summed and the isolines reported in Figure 5 have some statistical significance, revealing as they do the rough structure of the wind-induced surface temperature distribution; but local gradients are smoothed. The map presented in Figure 5 provides an idea of the structure observed one or 2 days after the onset of the mistral and the tramontane, blowing with a mean speed of approximately 10 m/s over the greater part of the North-Western Mediterranean.

General features

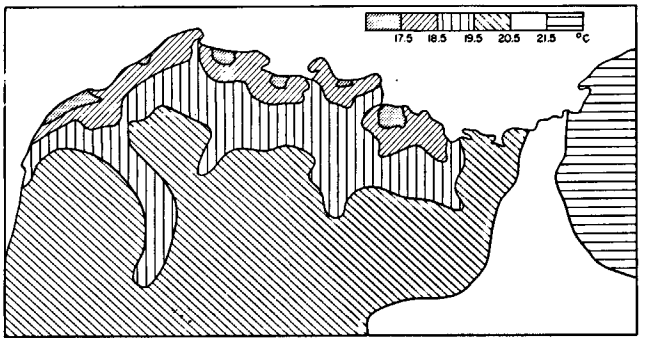
One of the most important surface features deduced from Figures 4 and 5 is the discrete distribution along the coast of cool areas; in other words, the phenomenon presents a high spatial variability. After about one day of wind, the sea surface temperature in the centre of these cool areas may have decreased by 5°C or more, which represents locally a high temporal variability.

If we bear in mind that the winds are blowing from the North-West, it is clear that these cool areas are mainly distributed along the Provence and Camargue coasts in such a way that an observer with his back to the wind has the sea mainly on the right side. Winds perpendicular to the coast and blowing out to sea, as in the Languedoc region, also create upwellings. In agreement with Coriolis acceleration and the coastal orientation with respect to the wind, no surface temperature gradient

Figure 5

Statistical wind induced temperature distribution. Eight different views were processed to obtain this wind-induced mean field, which is representative of the upwelling phenomenon one or two days after the onset of the wind. The rough structure of the temperature field is significant, but horizontal gradients are strongly smoothed by this analysis.

Distribution moyenne de la température de surface induite par le vent. Huit vues différentes ont été moyenées pour obtenir une image statistiquement significative du phénomène d'upwelling, 1 ou 2 jours après le début de vent. La structure générale du champ thermique est représentative mais les gradients horizontaux sont fortement atténués.



appears in the South-Western part of the gulf along the Roussillon coast. In this region, hydrological casts obtained before and after a storm clearly show the occurrence of mixing and downwelling phenomena (Fig. 6). On a large scale, North-West winds induce a displacement of warm surface waters from the left-hand side and leeward coasts to the coasts on the right-hand side and to the open sea.

On a smaller scale, the coastline forms a series of curves : segments 10 to 20 nm in length are separated by capes and small bays (Fig. 3). From South-West to North-East, these include : Cap Bear, Cap Leucate, Cap d'Agde, Golfe d'Aigues-Mortes and Pointe de l'Espiguette, Golfe des Saintes-Maries and Pointe de Beauduc, Golfe de Fos and They de la Gracieuse, rade de Marseille and Cap Croisette, Cap Sicié. It appears that upwellings in the Gulf of Lions spread out along straight coastal segments of the order of 10 nautical miles in length with an importance that is greater than in the vicinity of accidents of a smaller scale (Fig. 5). This is true for the first stages of upwelling development. But if the wind blows strongly for several days, the whole of the coastal boundary is submitted to a large upwelling, and low temperatures are measured along straight segments and around capes.

A very interesting comparison can be made between our Figures 5 and 8 *b* of Holladay and O'Brien's paper, with regard to the point-source structure of the upwelling (alongshore variability), and the fixed location of the upwelling centres. But the relation between this location and a particular geographical features is less clear off the Oregon coast than in the Gulf of Lions. In these two regions, however, upwelling centres are fixed and located nearshore. This is not the case off North-West Africa where they develop at the shelf edge and are associated with strong oceanic fronts (Tomczak, Miosga, 1976). As we shall see p. 266, the largest sea surface temperature gradients induced by the wind in the Gulf of Lions occur nearshore in specific areas, and are perpendicular to the coast. In the North-West Mediterranean Sea, satellite data do not reveal strong oceanic fronts associated with upwelling systems. It is to be noticed that the typical horizontal scale of the upwellings is of the order of the internal radius of deformation.

Satellite data are less effective in the analysis of the relaxation process after an upwelling event because the sky is in general more cloudy than during the North-West storms. A further reason is that the end of a storm is not as well defined as its onset by the wind speed evolution. Nevertheless, the coolest sea surface temperatures observed about 1 day after the end of the wind appear at the location of the upwelling centres (the upwellings vanish without moving). Warm waters are then advected alongshore from the North-East by the Ligurian current.

Turning to the possible relations between upwelling locations and bathymetry, we observe that the bottom slope at the edge of the Gulf of Lions continental shelf is steeper in the vicinity of capes than along straight segments and in bays (Fig. 3). Intuitively, we suppose that along a straight coast, the bottom water reaches the shoreline in an easier manner when the bottom slope is steep (the distance between the thermocline and the shoreline is short) than when it is smooth. We conclude, therefore, that the bottom influence is negligible on the shelf. Along the Provence coast, the shelf is reduced and cut by deep canyons, as in the Cassis area (Fig. 3). These topographical features and the wind direction with respect to the shore facilitate the extension of upwelling.

Specific features

Some hours after the onset of the wind, the new-born upwellings appear as surface source-points of cool water. At this stage, each source point is always located

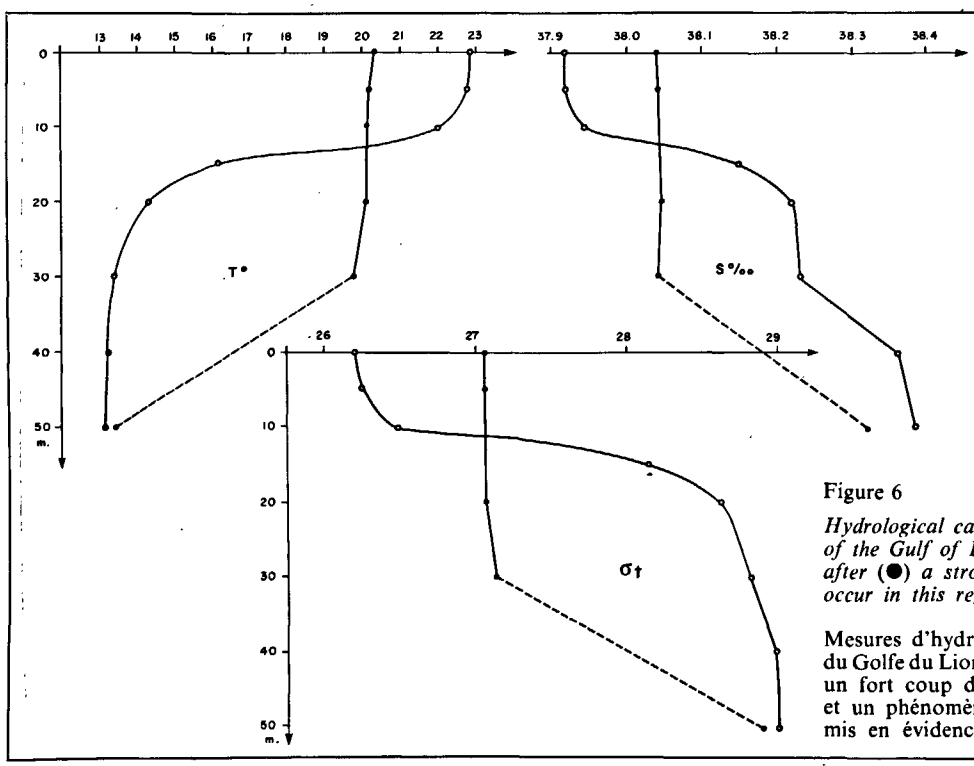


Figure 6

Hydrological casts obtained in the South-West part of the Gulf of Lions (PtB, Fig. 3), before (○) and after (●) a strong storm. Mixing and downwelling occur in this region.

Mesures d'hydrologie obtenues dans le Sud-Ouest du Golfe du Lion (PtB, Fig. 3), avant (○) et après (●) un fort coup de vent. Des processus de mélange et un phénomène de downwelling sont clairement mis en évidence dans cette région.

in the same coastal band of a length of some miles. These cool areas are identified by the names of the nearest town : hence from West to East, we refer to the upwellings of Valras and Sète along the Languedoc coast, those of Les-Saintes-Maries and Faraman, which belong to the Camargue system, and those of Méjean and Cassis at the Western end of the Provence coast. The specific features of each area are presented below, with reference to Figures 4 and 5.

• Valras : This is the most frequent upwelling and its surface temperature structure remains the steadtest under various wind conditions. As may be seen from Figure 2, the tramontane often blows in this region. This upwelling never extends beyond neither the Cap d'Agde nor the Cap Leucate; the coolest surface waters are always observed in the Northern part of the region. The tramontane direction in the Cap d'Agde area is more westerly (270°) than in Port-La-Nouvelle (315°) and Sète (320°) (see p. 262). In addition, changes in coastal orientation give a favourable angle between wind and shoreline for the upwelling generation near Valras. Surface isotherms always suggest that a cool water tongue has drifted seaward from the source point (Fig. 5). It should be noted that the PLN 75 moorings are in generally situated outside the central upwelling area. Some nautical miles North-East of Cap d'Agde, between the two cool areas of Valras and Sète, there is a singular region, often occupied by surface waters which are nearly as warm as those encountered in the open sea. Here, the surface isotherms are perpendicular to the shore. Similar zones appear in the vicinity of all capes and bays.

• Sète : This upwelling is weaker than the Valras one. Although frequently observed, it has a limited extension, small surface temperature gradients, and—more significantly—no tongue is drifted seaward. During wind events, the Pointe de l'Espiguette is occupied by warm waters with isotherms perpendicular to the coast. Associated with the Golfe d'Aigues-Mortes it forms the second singularly warm region.

• Camargue (Les-Saintes-Maries and Faraman) : The wind blows over the Camargue roughly in the same direction (330° at Cap Couronne) as in the Sète area (320°). In this region, however, the straight segments of the coastline lie in a West-to-East direction (instead of being oriented SW-NE as near Sète), and favour by Coriolis effect the formation of two strong upwellings. Although these two upwellings present some differences, they often form one system which constitutes an entity in the wind-induced circulation. The first upwelling is well located between the Pointe de l'Espiguette and the Saintes-Maries-de-la-Mer. The second upwelling generally presents larger surface temperature gradients. Well-bounded to the East by the Rhône delta, it often spreads westward. Sometimes before the fusion of these two upwellings but always later, a tongue of cool surface water is drifted seaward. The Golfe de Fos is characterized by isotherms perpendicular to the shore, and with the They de la Gracieuse (the cape to the east of the Rhône delta) they form another singular region.

• Méjean : This upwelling presents the same specific features as those of the Sète system, such as small surface temperature gradients, small extension and the absence of tongue. After the onset of the mistral, this upwelling spreads westward, but never reaches the South part of the Marseille Bay, to the East. Eastward from this area, Cap Croisette constitutes the fourth separating region, characterized by high alongshore temperature gradients between the neighbouring cool areas.

• Cassis : This upwelling is the largest and strongest of the series, but is observed less frequent than the others because the mistral does not occur as often in this region as in the Camargue. Only its Western limit is well defined by the Cap Croisette. Another important feature is the existence of two cool surface tongues, which extend from the central area in South-West-offshore and South-East-alongshore directions. Even during wind events, warm waters are often found close to the shore, West of Cap Sicié. The absence of continental shelf, the vicinity of deep canyons and the direction of the mistral, which is nearly parallel to the left-hand coast between Cap Croisette and Cap Sicié, are important characteristics to be noted.

The PLN 74 and PLN 75 main results

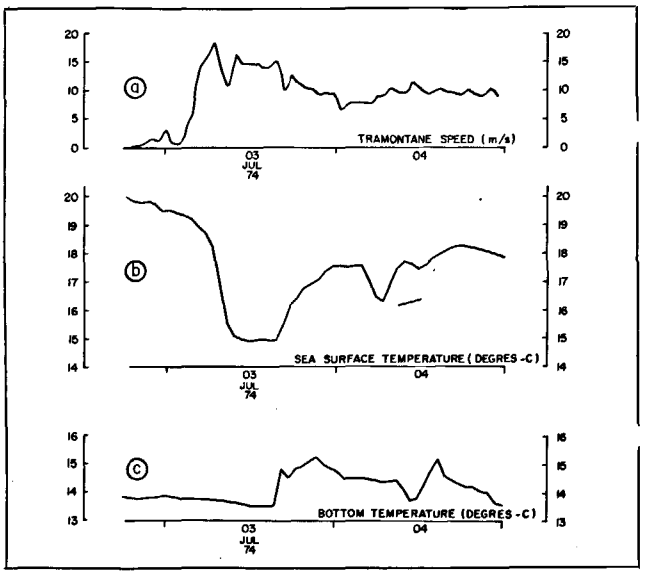
Temperature

The ON records show that the temperature decrease at a depth of 5 m below the surface and at a distance of 1.5 nm from the coast is observed between one and a few hours after the onset of the wind (Fig. 7). In other words, the sea stratification close to the coast is modified almost instantaneously by the wind action. At the beginning of a storm lasting some 24 hours, the temperature decrease at 5 m is sometimes of the order of

Figure 7

a: tramontane speed in PLN; b, c: temperature variations measured 5 m below the surface (b), and 5 m above the bottom (c) at 74-ON. Note the short delay between the wind onset and the sea response at 1.5 nm offshore. Subsequent temperature variations are due to internal inertial waves and nixing.

a : vitesse de la tramontane à PLN; *b, c* : évolution de la température à 5 m sous la surface (*b*), et à 5 m au-dessus du fond (*c*) à 74-ON. On peut remarquer la réponse particulièrement rapide du milieu à 1,5 mille au large. Ensuite les variations de la température sont dues à des ondes internes inertielles et au mélange sur la verticale.



1°C/1 hour, leading to variations of more than 5°C during the course of the day (Fig. 7). The bottom temperature subsequently increases in the coastal zone, as a result of mixing and of possible advective circulations. We should stress here that in view of the temporal variability of the wind, the spatial variability of the temperature distribution, the occurrence of large amplitude internal waves, and the small number of measurement points available, these two phenomena can only be separated with difficulty. Nevertheless, and due to the fact that the same bottom circulation is not systematically observed during the increase in bottom temperature, we may suppose that mixing constitutes the most important process.

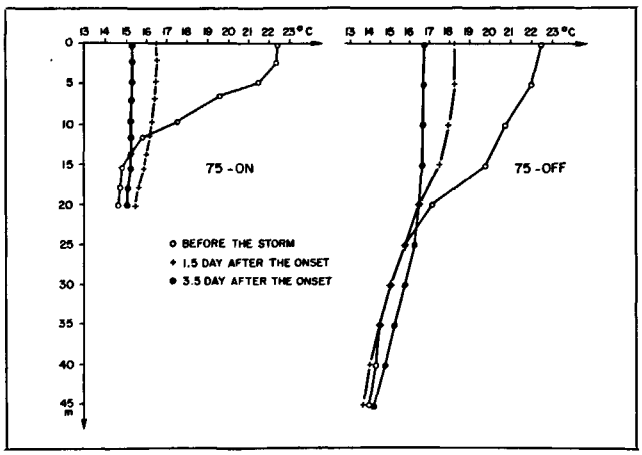
Upwelling is not generally observed at the 74-OFF and 75-OFF points. Some nautical miles offshore, the onset of the North-West wind is generally associated with mixing only. Consequently, the upwelling in the PLN area never extends beyond a few nautical miles from the coast. *In situ* observations are in accordance with satellite data on this point. Bathythermograph and towed surface thermistor measurements obtained during PLN 74 under tramontane conditions confirm this narrow coastal location of the upwelling near PLN, as well as the alongshore temperature gradient between Cap Leucate and Cap d'Agde.

These features are greatly modified when, as occurred during the PLN 75 experiment, the mistral and the tramontane are strongly blowing over the entire Gulf of Lions for a length period. For instance, at Port-La-Nouvelle during a 5-day period of strong winds with a mean speed of some 12 m/s, the temperature (Fig. 8) is quasi-homogeneous at 75-ON (about 15°C at the surface and close to the bottom) and at 75-OFF: at this mooring point a 3°C difference is measured between the surface (16.5°C) and the 50 m depth (13.5°C), when 10 m values are around 16.5°C. This was the first time that such low vertical gradients and local values were observed in this region during summer. The Valras upwelling grew rapidly, and extended Southward over the PLN studied area.

Figure 8

Vertical temperature profiles at different stages of the strong 75 wind event. These are mean profiles established over one inertial period, in order to filter out inertial internal waves.

Profils verticaux de la température à différents stades du fort coup de vent de l'été 1975. Ce sont des profils moyennés sur une période d'inertie afin d'éliminer l'effet des ondes internes inertielles.



Currents

Disregarding inertial oscillations due to the transient action of the wind, the current features observed in the PLN area under average tramontane conditions, both for the surface drift and for the associated bottom flow, are characterized by a weak intensity. Although the wind induced current is weak and sometimes masked by the thermohaline circulation, at the OFF points an Ekman southward drift is generally observed near the surface, and a northward flow near the bottom. This dynamic sea response to the wind sometimes occurs some hours after the onset of the wind (at the OFF points). This type of response is not regularly observed at the 74-ON and 75-ON mooring-points, where the coastal influence is very strong (little importance of inertial motions, straight or erratic progressive vector diagrams, etc.).

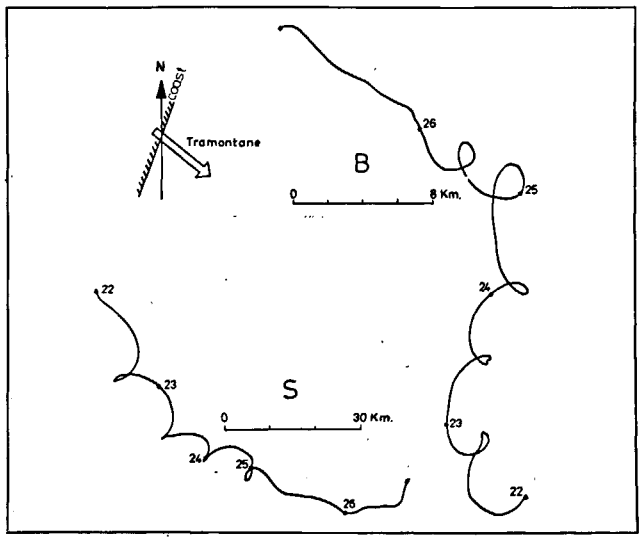
Associated with the very homogeneous temperature structure observed throughout the PLN area during the strong 75 tramontane event, the currents are very strong (Fig. 9). At the 75-OFF point, 5-day means of 20 cm/s seaward at 5 m below the surface, and 5 cm/s shoreward at 5 m above the bottom are measured in 55 m water depth. This 5-day mean shoreward flow of 5 cm/s is also found at 75-ON at 5 m above the bottom (25 m water depth); but the surface current at this point is mainly directed alongshore. Nevertheless, the seaward surface current at 75-ON (1.5 nm from the coast) is larger than 10 cm/s during one day.

We now turn to other observations deduced from the 74-ON group of moorings. The mean location of this group is 1.5 nm from the coast, but some moorings are near Port-La-Nouvelle, while one is near Cap Leucate, at a slightly deeper point and farther from the coast. From mid-summer to autumn, when the tramontane persists for a period longer than 3 or 4 days, the

Figure 9

Progressive vector diagrams obtained during the strong 75 wind event at 75-OFF (S: 5 m below the surface, B: 5 m above the bottom). Mean speeds are relatively large, and the directions lead to large on-offshore components.

Hodographes intégrés obtenus pendant le fort coup de vent de 1975 à 75-OFF (S = 5 m sous la surface, B = 5 au-dessus du fond). Les vitesses moyennes sont relativement importantes et les directions traduisent une circulation intense perpendiculairement à la côte.



ON moorings near PLN lie in a northward surface current, while the mooring near Cap Leucate remains in the surface Ekman drift (Millot, 1976). The same differences are observed between the 75-ON and 75-OFF mooring-points. This upwind current is measured near PLN with a 20-day mean value larger than 20 cm/s. If the tramontane is blowing strongly, the 74-ON moorings near PLN and near Cap Leucate are located in the northward current. A river plume at PLN is strongly deviated to the North under tramontane conditions (*in situ* and visual satellite observations). Current measurements reveals that the separation between the coastal northward flow and the southward Ekman drift is very sharp, and closely resembles a front associated with a large velocity gradient but no temperature gradient. The width and the intensity of the upwind current depend on the speed and duration of the tramontane. This current is observed at a distance of 1.5 nm from the coast, at the surface but also close to the bottom (at a depth of 20 m), when the homogeneous surface layer has a thickness of about 30 m near the coast.

The LION 77 experiment

Temperature

We shall now briefly describe the temperature variations induced by the four strongest wind events, corresponding to the progressive vector diagrams presented in Figure 10 (*a*, *b*).

Storm No. 1 has a 3-day mean wind speed of about 10 m/s. At the onset of the wind, the thermocline rises at 77-ON and falls at 77-OFF. 1 day later, it rises above the 10 m depth at 77-ON, but remains between 15 and 20 m at 77-OFF during the 2 other days. The temperature decrease is effective from surface to bottom at 77-ON (falling from 21.5°C to 17°C at 10 m), but is sensitive only in a 15 m surface layer at 77-OFF (where it decreases from 20.5°C to 18.5°C at 10 m).

Storm No. 2 occurs with a 2-day mean wind speed of about 12 m/s. The warm surface layer lies above the 10 m depth at the two mooring-points. At the onset of the wind, the 10 m temperature values are 17°C at 77-ON and 19°C at 77-OFF; decreases of about 1.5°C are then observed at the two locations. On the second day, the temperature at the 10 m-77-ON level is 15.5°C, which is nearly the bottom layer value.

Storm No. 3 has a 2-day mean wind speed of about 10 m/s. After 12 hours, the temperature decreases by 4°C (21 to 17°C) at 10 m-77-ON; but a 3°C increase (18 to 21°C) is measured at 15 m-77-OFF, while no variation occurs at 10 m-77-OFF. At 77-ON, the temperature decrease is sensitive only on the shallower records, and the main feature at the two points is the growth of large amplitude internal waves.

Storm No. 4 occurs with a 2-day mean speed of about 9 m/s. The temperature decreases from 19.5 to 16.5°C at 10 m-77-ON, and from 20.5 to 18°C at 10 m-77-OFF. In other words, cooling is effective in the surface layer and no variations are observed in the bottom layer.

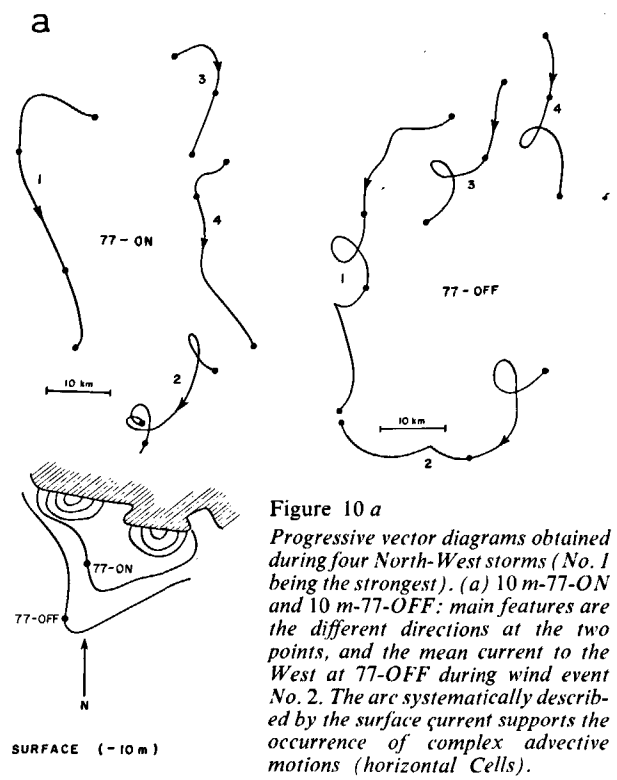


Figure 10 *a*
Progressive vector diagrams obtained during four North-West storms (No. 1 being the strongest). (a) 10 m-77-ON and 10 m-77-OFF: main features are the different directions at the two points, and the mean current to the West at 77-OFF during wind event No. 2. The arc systematically described by the surface current supports the occurrence of complex advective motions (horizontal Cells).

Hodographes intégrés obtenus pendant quatre coups de vent en 1977 (le n° 1 est le plus fort). 10 m-77-ON et 10 m-77-OFF : à noter que les directions sont toujours différentes entre les deux points, et que le courant moyen porte à l'ouest à 10 m-77-OFF pendant le coup de vent n° 2. L'arc de courbe systématiquement décrit par le courant de surface tend à prouver l'existence de mouvements d'advection complexes (cellules de circulation horizontales).

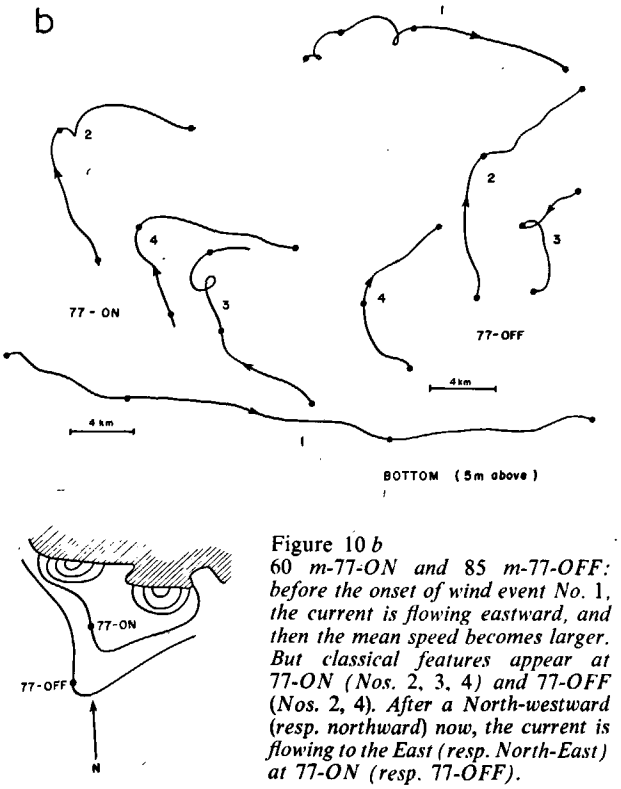


Figure 10 *b*
60 m-77-ON and 85 m-77-OFF: before the onset of wind event No. 1, the current is flowing eastward, and then the mean speed becomes larger. But classical features appear at 77-ON (Nos. 2, 3, 4) and 77-OFF (Nos. 2, 4). After a North-westward (resp. northward) now, the current is flowing to the East (resp. North-East) at 77-ON (resp. 77-OFF).

60 m-77-ON et 85 m-77-OFF : avant le début du coup de vent n° 1, le courant porte à l'est, et la vitesse moyenne se trouve alors augmentée. Par contre les enregistrements n° 2, 3, 4 à 77-ON et 2, 4 à 77-OFF révèlent des caractéristiques particulières. Le courant porte d'abord au Nord-Ouest (resp. Nord) puis vire à l'Est (resp. Nord-Est), à 77-ON (resp. 77-OFF).

During the relatively minor 77 wind events, the minimum temperature values measured at 10 m-77-ON are lower by about 1°C than those measured during a very strong storm at 10 m-75-OFF, although these two points are located at the same distance offshore.

Thus, at 77-ON an upwelling is observed during the two strongest storms, and a surface cooling during the two smallest ones. Only surface coolings or downwellings are observed at 77-OFF. These observations tend to confirm the limited extension of transient upwelling, properly so called (temperature decrease at all depths). But bottom waters, upwelled to the surface and mixed with warm waters, are drifted far from the shore.

Currents

The 77 current measurements show that wind induced motions are important at the two mooring points, both near the surface and close to the bottom. At a depth of 10 m below the surface (Fig. 10 *a*), wind-induced currents often reach 1-day mean values of about 20 cm/s in a seaward direction at points 77-ON and 77-OFF. Taking into account the deeper location of the 77 surface current meters and the relatively moderate winds during the summer concerned, we can compare the measured values with the PLN ones. It is clear that the LION 77 moorings are more often located in large seaward currents than the PLN ones (except during the one particularly strong wind event). Temperature observations show that bottom waters, upwelled to the surface at a nearshore location, are then drifted seaward. These surface flows of cool water are related to the tongues observed on satellite infrared views. The mean surface current direction throughout all the North-West events is set between S-SE and SW at 77-ON, and between South and West at 77-OFF. This difference is verified for each wind event and supports the hypothetical wind-induced anticyclonic surface gyre (p. 271). Analysis of the other periods shows that the surface current at 77-OFF is responsive even to the smallest wind events, but that this is not the case at 77-ON. It is thus certain that the current field is more homogeneous far offshore than nearshore. During the wind events, 1-day mean speeds ranging from 5 cm/s to more than 10 cm/s are commonly measured at the two 77 mooring points near the bottom (Fig. 10 *b*). In the PLN area, such values are obtained only during the 75 strong strom. But the most surprising feature of the progressive vector diagrams presented in Figure 10 *b* is the change of direction which occurs during the storms. The No. 1 wind event occurs when the bottom flow is directed eastward, along the isobaths. We only note an increase of the speed during the storm. The 77-ON records Nos. 2, 3, 4, show similar responses. The wind induced current, first directed North-westward, tends to flow in an eastward direction one day later. The same general features are observed at 77-OFF, except for No. 3. The current direction is generally North at the beginning of the wind, and then North-East. The variation of the direction is less important at 77-OFF than at 77-ON because of the bottom topography; the slope is sharp nearshore and almost zero in the central part of the continental shelf.

In summary, it is clear that the PLN and the LION 77 observations are very different. This fact is due to the array location which is roughly on the edge (PLN) or in front (LION 77) of a major (see below) upwelling.

DISCUSSION

Main effects of the coastline

On a large scale, both the infrared and *in situ* data confirm the occurrence of an Ekman drift to the South-West, to the right side of the North-West wind. Cool bottom waters are upwelled to the surface along the Provence, Camargue and Languedoc coasts, while downwelling is observed off Roussillon. By continuity, bottom currents are roughly directed from South-West to North-East.

On a smaller scale, it is clear that the upwelled waters do not appear homogeneously along the shore. Satellite data show that the upwellings are produced in certain specific areas, and never elsewhere. The cool areas are located along straight coastal segments, and the bottom topography does not play an important rôle (except near Cassis). We believe that the Gulf of Lions upwellings, and perhaps many other as well, are strongly dependent upon the shoreline geometry. The upwelling phenomenon is linked to an offshore drift of surface water. This seaward drift has a large spatial extension off a regular coastline well oriented with respect to the wind (as shown by theoretical models), because the drifting of all the surface particles results in the same phenomenon, i. e., the upwelling. This is not the case in the vicinity of an irregular coast, where different phenomena (for example up and downwelling) are induced in adjacent places. Due to large horizontal gradients, local circulations which reduce the extension of each phenomenon probably occur. This idea is to be tested with numerical models at the Laboratoire d'Océanographie Physique du Muséum.

Among the five upwellings found, three are important and two are secondary. The three major upwellings of Valras, Camargue and Cassis are characterized by a large extension, important surface temperature gradients, and large offshore surface transports from the upwelling centre associated with a tongue-shaped thermal structure (Figs. 4 and 5). On the other hand, the minor upwellings of Sète and Méjean are small in size, and never generate important seaward surface flows. The seaward transports indicated by satellite imagery are confirmed by *in situ* measurements. The mean surface current coincides with the axis of the cool surface tongue. The current does not flow along the isotherms (~ isopycns), and therefore is not purely geostrophic.

These wind induced transports are very strong, their mean speed being of the order of 20 cm/s at 10 m below the surface, some 10 nm from the upwelling centre. We have no current observations for the Cassis area, but

it is probable that the two tongues of this system are related to the same surface flow as those described here. Under North-West meteorological conditions, we observe four large seaward streams from the three upwelling centres. During the same period, no large seaward flow is generally observed, for instance, in the PLN area (on the South edge of the Valras upwelling). This means that the current field in the coastal zone is very unhomogeneous.

The five upwellings are separated from each other by four singular regions (Figs. 4 and 5), where steep alongshore temperature gradients are observed. All these regions are characterized by coastline irregularities (capes and bays), which inhibit a homogeneous drifting of surface waters. In these regions, the scale of the temperature gradients may be of the order of 1°C/nm. These values are the largest observed in the Gulf of Lions when the North-Westerlies are blowing, and are certainly associated with particular dynamic features.

Under average tramontane conditions, the current measured near the bottom in the PLN area is weak but significantly tending to the North. During the 75 strong storm, the current close to the bottom is shoreward. The LION 77 measurements reveal more complex features characterized by a shoreward motion (to the North) at the onset, and then by an Eastward flow. The mean bottom circulation is thus from South-West to North-East, and roughly along the isobaths. The 85 m-77-OFF current records (Fig. 10*b*) show that the wind-induced circulation is notable in the central part of the shelf.

Hypothetical horizontal cells

Due to the high temporal and spatial variabilities of all the parameters, an exact evaluation of the seaward flow is almost impossible, as an evaluation of the upward convection in the upwelling areas. Hela (1976) compiles all the published works concerning the vertical velocity of the upwelled waters and obtains a value of 10^{-4} m/s with a 10 m/s wind speed. Considering a 100 km^2 area for one upwelling centre needs a 10 cm/s horizontal current of 10 km wide, extending 10 m below the surface. These values are coherent, but require too many assumptions to support the assertion that wind-induced circulation occurs in vertical planes only.

Satellite information (Figs. 4 and 5) reveals the presence of large masses of warm surface waters which are not drifted seaward, at 10 to 20 nm offshore, between the cool tongues associated with the major upwellings.

Although their temperature is relatively homogeneous, some satellite views suggest a light shoreward and upwind displacement of these waters. The current observed near the surface at 77-OFF during wind event No. 2 (Fig. 10*a*) confirms this motion. Indeed, a westward flow cannot be considered as a classical Ekman drift. The rotation of the current between 77-ON and 77-OFF leads us to suppose that at a westward location, this surface flow is directed shoreward (to the North-West). The loss of the third 77 mooring was a severe blow to our investigations in this connection. GEK measurements and surface temperature records were made in the nearshore zone between Port-La-Nouvelle and Sète during the autumn of 1975, in order to define the characteristics of the coastal counter current, and specially the location of the current front (p. 270). The meteorological conditions encountered are not able to develop this phenomenon, but the Valras and Cap d'Agde limits are crossed some hours after the beginning of a tramontane storm. The temperature field is coherent with the summer satellite data. Although GEK was operating in bad conditions (nearshore, low depth, complex stratification), the analysis of the measurements indicates an homogeneous South-Eastward flow off the Valras region and a complex but mainly onshore flow off the Cap d'Agde area. At the time of these observations, we believed that the measures had no significance. But the lower temperature in the Valras area than off Cap d'Agde, the seaward surface flow from the cool area, and the knowledge from satellite imagery that they are normal features in this region, lead us to admit the existence of complex advective motions in the vicinity of the Cap d'Agde area.

We have described the coastal counter-current measured in the PLN area during the autumn, when the wind is blowing for a long time. During this season, the surface layer is homogeneous and the thermocline well defined at its yearly lowest position; in the Valras area, the surface temperature gradients are less important because the thermocline reaches the surface with greater difficulty; the satellite observations are less effective during autumn than during summer. *In situ* information concerning the occurrence of some coastal counter-currents are insufficient during summer, when the surface layer is less homogeneous and when the upwelling is clearly observed on infrared views. But the 74-ON and 75-ON progressive vector diagrams are very erratic during the July and August storms and certain northward flows occurring for some days during the wind action are similar to the well defined autumn coastal counter-current. The summer stratification perhaps leads to narrower coastal counter-currents than during the autumn. All these upwind flows reveal the existence of advective horizontal circulations associated with the upwellings.

The wind-induced currents are remarkable for their direction, strength and spatial variability. But they are not representative of the mean circulation in the Gulf, the main features of which are described in p. 263. In summer, North-westerlies blow during about 1 day out of 2 at Cap Bear (1/2.5 in Sète, 1/3 at Cap Couronne), but their strength is not always sufficient to modify the existing circulation. For instance, the net displacement over 3 months is of the order of 865 km and 360 km in the 260° and 210° direction at 10 m-77-ON and 10 m-77-OFF respectively; during this period, the total drift due to the four above-mentioned notable storms is of the order of 90 km and 114 km in the 180° and 210° direction at the nearshore and offshore 77 points respectively. Taking into account the low wind-induced currents generally observed in the PLN area, it is possible to say that the part of the total displacement which is due to the wind decreases from the central area of the

Gulf (77-OFF) to the nearshore zone in front of an upwelling system (77-ON) and to the nearshore zone on the edge of such a system (PLN points).

After the wind event, the relaxation process of the upwelling phenomenon occurs in two stages. During the first stage, we observe a disappearance of the upwellings due to advection of the neighbouring surface waters (described in front) to the upwellings centres. At this time the surface temperature in the Gulf of Lions is homogeneous but still lower than the values measured eastward. During the second stage, these warm waters are advected alongshore by the Ligurian current which is reestablished.

Summarization of the different observations presented here permits us to indicate the existence of complex wind-induced circulations (Fig. 11). Taking into account the Camargue upwelling, the seaward surface stream and the rotation of this flow to its right is measured. The presence of nondrifted warm waters at a westward location is known and, from satellite imagery, we are inclined to define a light upwind motion (to the North-West) of these masses. Surface water is not easily drifted away in the vicinity of Pointe de l'Espiguette and Cap d'Agde, where GEK data support shoreward motions. We thus believe that the seaward surface stream from the Camargue upwelling is not entirely a jet of bottom water. Surface waters are carried away from the vicinity of the straight coastal segments, and are partly replaced by the shoreward advection of warm surface waters towards the topographical singularities, leading to a horizontal surface gyre. Such a cell is suggested more clearly by the satellite data (Fig. 5) in the Southern part of the Valras upwelling than in the one above described and the coastal counter-current observed in the PLN area is supposed to form a branch of this cell; the circulation associated with the Cassis system appears to be more complex. More observations are required to confirm the existence of these cells.

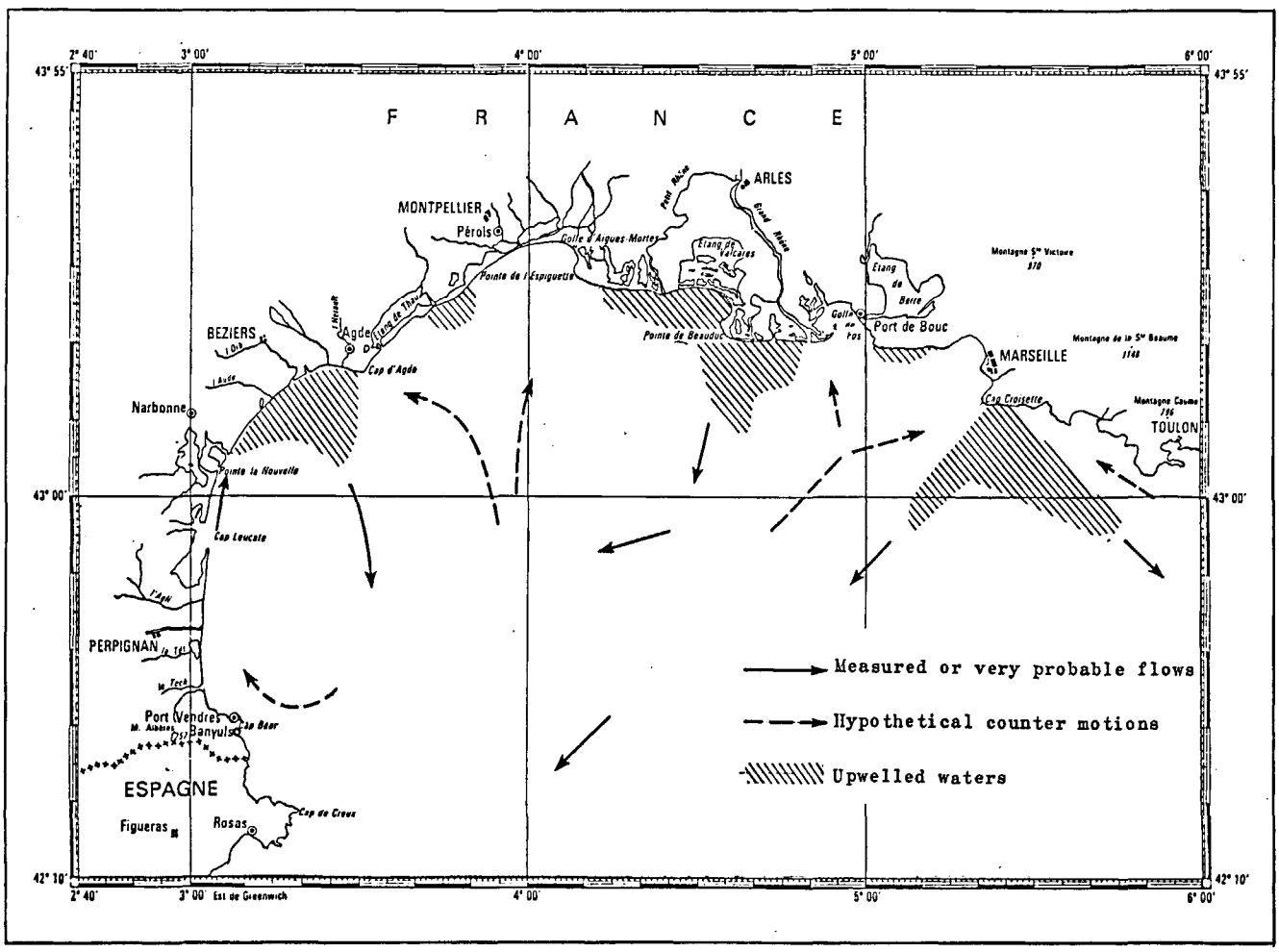
Bottom circulation (Fig. 12) is weaker than surface circulation and is less well defined. *In situ* measurements reveal a mean flow along the isobaths from South-West to North-East, with shoreward motions to the upwelling centres in their vicinity. But a large dependence upon bathymetry is probable in this connection.

CONCLUSION

Upwellings and mesoscale circulations induced by the North-Westerlies in the Gulf of Lions show very high spatial and temporal variabilities. The spatial extension of the upwellings (about 10 nm) is highly dependent upon the coastline and the wind orientations, and on

Figure 11
Sketch of wind-induced circulation at the surface drawn coherently with the infrared and in situ *data. The counter-circulations remain hypothetical.*

Schéma de la circulation de surface induite par le vent d'après l'analyse des vues satellites et des mesures *in situ*. Les transports contre le vent restent hypothétiques.



the duration of the storms (a few days). The same current and temperature features are observed during all the wind events, and compilation of a large quantity of infrared data reveals the fundamental and systematic rôle played by relatively small-scale coastline characteristics.

Upwellings spread out from actual source points located in the middle part of straight coastal segments, 10 to 20 nm in length. Some of these systems do not undergo an important development, while others generate large seaward surface transports. The upwelling of bottom waters is revealed far offshore by the tongue-shaped temperature field, and is supported by current measurements. Irregular coastline features such as capes and bays are, on the contrary, characterized by the presence of warm waters and steep alongshore temperature gradients (sometimes of the order of 1°C/1 nm). *In situ* measurements clearly reveal a very rapid response (of the order of one or a few hours) of the sea to the wind. At the onset of an upwelling event, surface temperature decreases near the coast are sometimes of the order of 1°C/hr. Certain observations support the occurrence of complex and unexpected horizontal circulations which are more or less imbricated with the upwelling systems, but these movements require confirmation through further *in situ* measurements.

Acknowledgements

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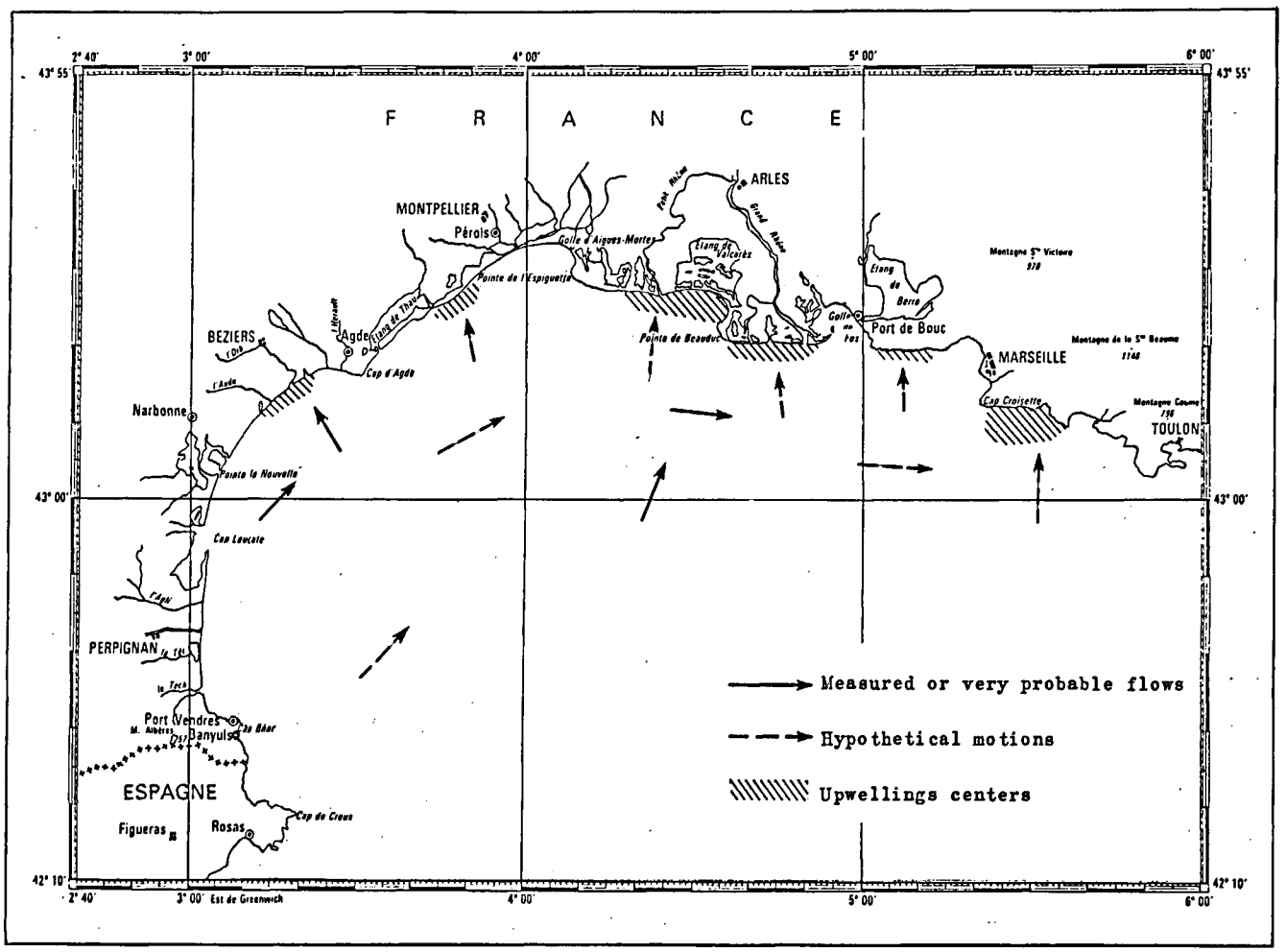
Figure 12

Sketch of the bottom induced circulation drawn from a number of current meter records. The mean flow is weak but mainly from South-West to North-East along the isobaths. The development of the upwellings depends on bottom advection to their centers. This shoreward motion was measured during the strong 75 wind event.

Schéma de la circulation induite par le vent dans la couche inférieure, d'après l'analyse des mesures *in situ*. Le courant moyen est faible et suit grossièrement les isobathes du Sud-Ouest vers le Nord-Est. Par principe, l'upwelling se traduit par un appel d'eau de fond vers la côte; un tel mouvement a été clairement observé pendant le fort coup de vent de 1975.



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