Ligurian current
General circulation
Wind-induced circulation
Remote sensing

Courant liguro-provençal
Circulation générale
Circulation induite par le vent
Télédétection

The effect of Mistral wind on the Ligurian current near Provence

C. Millot[a], L. Wald[b]
[a]Antenne du Laboratoire d'Océanographie Physique du Muséum National d'Histoire Naturelle, B.P. 2, 83501 La Seyne-sur-Mer, France.
[b]Centre de Télédétection et d'Analyse des Milieux Naturels de l'École des Mines, Sophia-Antipolis, 06560 Valbonne, France.

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ABSTRACT

The effect of the Mistral wind on the Ligurian current has been studied using the NOAA 5-VHRR imagery. A frontal zone separates the Ligurian current and colder water upwelled from the Gulf of Lions. It is found that the surface flow associated with the current, is halted by strong Westerly winds. When the wind drops, the frontal zone moves Westward at speeds up to 0.3 m.sec^{-1}. During a period of stratification, the Ligurian current in the surface layer tends to flow along the coasts of the Gulf of Lions.

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RÉSUMÉ

L'action du Mistral sur le courant liguro-provençal le long des côtes de Provence

L'effet du Mistral sur le courant liguro-provençal a été étudié à partir des images transmises par le VHRR du satellite NOAA 5. Une zone frontale sépare les eaux du courant liguro-provençal de celles, plus froides, qui sont associées aux upwellings du Golfe du Lion. On montre que le courant de surface est stoppé par de forts vents d'Ouest. Quand le vent cesse, la zone frontale se déplace vers l'Ouest avec des vitesses pouvant atteindre 30 cm.sec^{-1}. Lorsque le milieu est stratifié, le courant liguro-provençal dans la couche de surface a tendance à progresser le long de la côte, dans le Golfe du Lion.

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INTRODUCTION

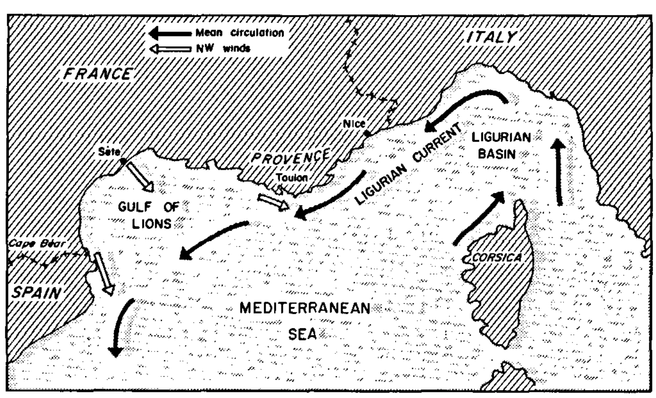
It is well known that the mean circulation in the North-Western Mediterranean Sea (Fig. 1) is cyclonic in the surface and intermediate layers (Lacombe, Tchernia, 1972). In the Ligurian Basin, the surface currents circulate in the same (cyclonic) sense as the prevailing winds. In the Gulf of Lions, however, the prevailing winds are from NW ($\sim$ 320° at Sète), and they diverge over the Ligurian Sea ($\sim$ 290° at Toulon), and over the Balearic Basin ($\sim$340° at Cape Béar). So, the mean surface current system is reinforced by the wind in the South-Western part of the Gulf, but resisted by the wind near the coast of Provence, in the vicinity of Toulon.

Off Nice, Bethoux and Prieur (1980) have found that the transport of the Ligurian current, between the surface and 200 m in depth, and from the coast to 80 km offshore, is of the order of the flows in the Straits of

Figure 1

The mean oceanic circulation is resisted by the N W winds near the coasts of Provence.

La circulation océanique moyenne est contrariée par les vents de NW le long des côtes de Provence.



Gibraltar (about 10^6 $m^3.sec^{-1}$). Depending on its vertical extent, which is probably affected by the seasonal thermocline, the inshore edge of the Ligurian current may be defined either by the coast or by the 100-200 m isobath, which is as far as 80 km offshore in the Gulf of Lions.

In the Gulf of Lions, there are insufficient observations to define the mean current pattern, but it is known (Millot, 1979) that there is a coastal upwelling which brings cold water to the surface. There is sometimes a rapid change in temperature, or a frontal zone, separating the Ligurian warmer current from the upwelled colder water from the Gulf of Lions; we have used satellite images of the Ligurian current and of this frontal zone to study the effect of strong adverse winds during the period July 17 to 25, 1977.

WIND OBSERVATIONS

Mean wind vectors were calculated from eight observations at a three-hour interval for each of the five stations (Bec de l'Aigle, Toulon, Porquerolles, Le Levant, Camarat). The averaging period was arranged to end at 09.00 UT, the approximate time at which the satellite was overhead (infrared data transmitted during the night were not recorded). During the period concerned, the Mistral wind was relatively high (Table):

Table

Three-hour wind measurements obtained between successive passages of the satellite, are vectorially summed to get daily mean speeds. The drop in wind speed on July 20, is significant at all the stations. In Toulon and other Eastern stations, the wind speed during the first part of the period is higher than during the second part.

Les mesures de vent obtenues toutes les 3 heures entre les passages successifs du satellite sont sommées vectoriellement pour obtenir des vitesses journalières moyennes. L'atténuation du 20 juillet est significative à toutes les stations. A Toulon et aux stations situées plus à l'Est, la vitesse du vent est plus élevée pendant la première partie du coup de vent que pendant la deuxième.

Day	Satellite view	Bec de l'Aigle	Toulon	Porquerolles	Le Levant	Camarat
15	–	4.5 285	2.1 251	3.1 246	2.1 286	1.5 222
16	–	8.9 306	4.0 283	4.7 260	3.4 280	1.3 287
17	X	8.0 296	6.6 284	8.4 260	7.3 285	3.8 237
18	X	8.5 278	7.4 289	9.0 260	10.0 276	5.1 218
19	X	7.8 306	5.3 283	8.0 242	8.8 277	4.9 225
20	–	7.0 293	4.6 276	5.6 233	4.0 280	1.4 32
21	X	11.9 307	5.5 288	6.6 259	7.0 283	2.6 189
22	X	11.8 336	5.1 300	5.9 256	5.5 292	5.8 212
23	X	1.9 119	.5 339	1.1 204	1.5 211	4.0 193
24	X	1.9 234	.3 255	1.7 232	2.8 281	3.0 195

the reported values are affected by the varying exposure of the anemometers, so the time variation and relative values are more indicative. The major variation consisted of two periods of strong to fresh wind separated by a relative lull, especially at the Eastern stations. The slackening of the wind on July 20, was associated with an overcast sky, which prevented satellite infra-red observations of the sea surface.

SATELLITE IMAGES

The NOAA 5-VHRR has a spatial resolution at the nadir of ~ 1 km^2, when its radiometric resolution is 0.5°K at 300°K. Data processing includes a smoothing of the images with a bidimensional filter, conditioned by the importance of local gradients with respect to noise, which increases the reliability of relative values (accuracy of 0.5°K for a 3 km resolution; Albuisson *et al.*, 1979). The set of observations lasts for about one week and *in situ* conditions (atmospheric absorption and atmosphe-

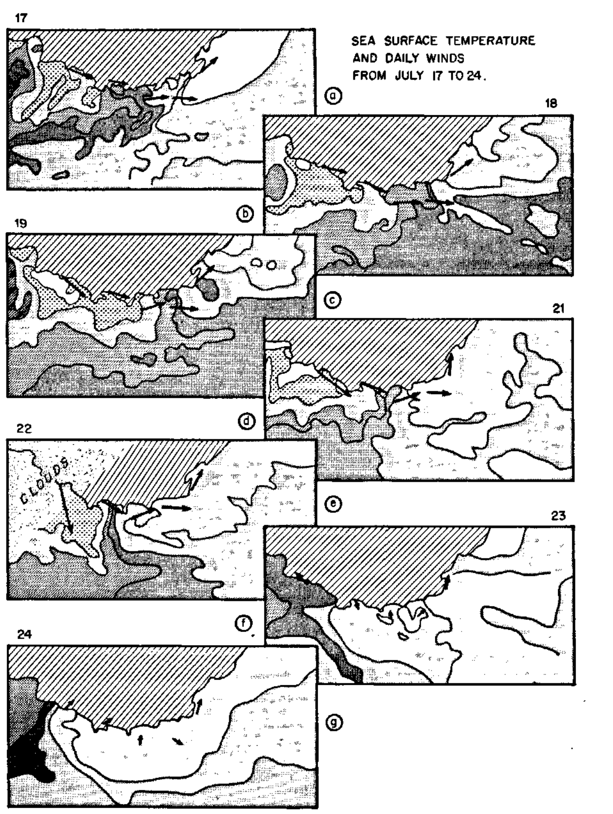


Figure 2

The wind and sea-surface temperature fields are drawn from July 17 to 24. Note the cyclonic rotation of the Mistral around the Provence coasts. With respect to offshore waters, the cooler ones observed in the Gulf of Lions are due to upwelling, and the warmer ones along the Eastern coasts of Provence are linked to the Ligurian current. The frontal structure (gradients of 1°C per some kilometres) is stationary from July 17 to 19, and then it moves Westwards along the coast. This is thought to be related to the lowering of the local wind stress.

La distribution spatiale du vent et de la température de surface est reportée du 17 au 24 juillet. On peut noter la rotation cyclonique du Mistral le long de la côte provençale. Par rapport aux eaux du large, les eaux plus froides observées dans le Golfe du Lion sont associées à des upwellings, et les eaux plus chaudes le long des côtes Est de la Provence sont celles du courant liguro-provençal. La structure frontale (gradients de 1°C pour quelques kilomètres) est stationnaire du 17 au 19, puis elle se déplace vers l'Ouest le long de la côte. Ceci est probablement relié à la baisse de la tension du vent local.

ric contents in H_2O, CO_2, O_3, roughness and emissivity of the sea surface, stratification of the upper layers, ...) are too variable to compare absolute values from one day to the other. Nevertheless, the induced errors are known to be sufficiently homogeneous, and they cannot significantly affect the large horizontal thermal gradients which are observed; when seen, clouds are not located in the vicinity of these gradients. This paper uses only the time and space distributions of the sea-surface temperature gradients, and then, the ± 0.25°K temperature intervals in Figure 2, *a* to *g*, are reliable.

During this period, the nearshore current was about 20 km wide, being characterized by water about 1°C warmer than that offshore. An interesting feature is the existence of strong alongshore gradients, with 2 to 4 isotherms perpendicular to the coast over a distance of about 10 km. This frontal structure represents the "head" of the Ligurian current, and gives information about its dynamics.

WIND-CURRENT INTERACTIONS

The daily mean wind vectors of the Table are superimposed on the satellite-derived temperature charts (note the cyclonic circulation of the Mistral around the coast of Provence).

On July 17, 18 and 19, the Westerly wind blows strongly (8-10 m. sec^{-1} at Le Levant) against the typical direction of the Ligurian current : during this time, the front is relatively stationary.

On July 20, the wind dropped (4 m.sec^{-1} at Le Levant): no infrared sensing of the sea-surface was possible; but on July 21, the front had propagated Westward to the Western edge of the Island of Porquerolles. The front continued to progress Westward from July 21 to 24, a period during which the wind in its vicinity fell from about 5 m.sec^{-1} to about 2 m.sec^{-1}. Stronger winds at the Bec de l'Aigle station occurred when the front was located in the vicinity of Toulon: they did not affect its Westward motion.

The speed of propagation of the frontal structure is difficult to specify because of the irregularities of the coastline. The daily speeds can be estimated along two lines roughly parallel to the coast of Provence (see Fig. 3), and it is found that the front was stationary from 09.00 July 17 to 09.00 July 19, moved at about 19 cm.sec^{-1} between 09.00 July 19 and 09.00 July 21, and at 19, 23 and 32 cm sec^{-1} in the succeeding 24-hour periods. So, during this specific event, the front was roughly stationary when the local wind speed was of about 8-9 m.sec^{-1}; it moved against the wind with a constant speed of about 20 cm.sec^{-1} when the wind decreased to about 5-6 m.sec^{-1}, and accelerated to 30 cm.sec^{-1} when the wind dropped. As a rule, the speed to the West seems to increase, as the wind from the West decreases; a surface current of about 30 cm.sec^{-1} would be expected from a surface wind of $\sim$10 m.sec^{-1}, and this is not inconsistent with the notion that strong local winds could halt the Westward progress of the surface outcrop of the Ligurian current. Detailed relations between the current flow and the wind stress, need an extensive knowledge of the meteorological and hydrological fields in the whole basin, and daily maps of the sea-surface temperature, do not allow more accurate studies than those here presented.

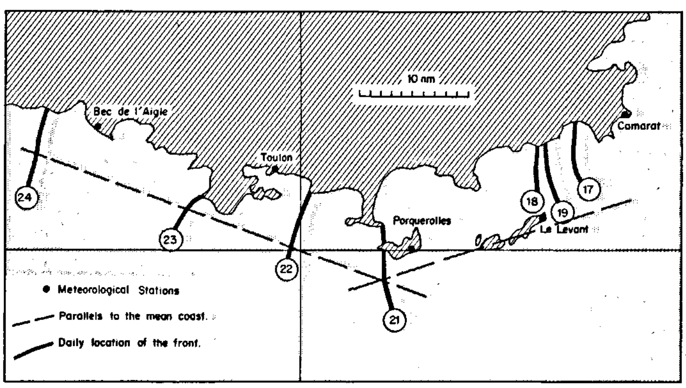


Figure 3

Mean locations of the front are indicated and daily speeds of propagation have been estimated along two lines parallel to the coast. Until July 19, the front is roughly stationary, thereafter it moves Westwards at speeds up to about 30 cm.sec^{-1}.

Les positions du front ont été reportées et son déplacement a été estimé le long de deux lignes parallèles à la côte. Jusqu'au 19 juillet le front est pratiquement immobile, puis sa vitesse de déplacement vers l'Ouest augmente jusqu'à des valeurs de l'ordre de 30 cm.s^{-1}.

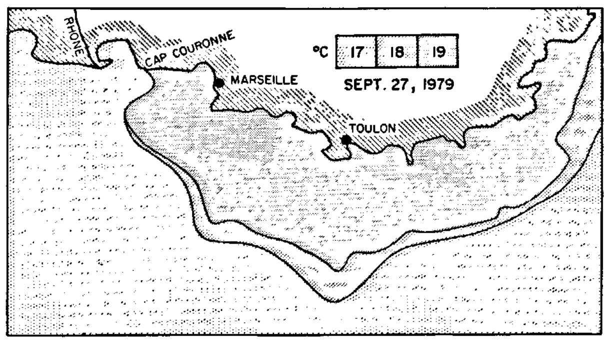


Figure 4

Although cloud-free images are few in late Summer and early fall, the view taken on September 27, 1979, suggests a circulation which is supported by in situ *current measurements: during this time, the lowering of the NW winds allows the Ligurian current to flow along the coast onto the continental shelf of the Gulf of Lions.*

Bien que les images sans nuages soient peu nombreuses vers la fin de l'été et le début de l'automne, la vue prise le 27 septembre 1979 suggère une circulation qui est confirmée par des mesures *in situ:* à cette époque, l'atténuation des vents de NW permet au courant liguro-provençal de progresser le long de la côte sur le plateau continental du Golfe du Lion.

The later temperature charts show that the Ligurian current tends to follow the shore as far as the Gulf of Lions. But by July 24, the warm water has not reached the continental slope off the Gulf, so it is not possible to say whether the flow would be limited by the continental slope or flow inshore along the coast. During July and August, North-Westerly winds are too frequent to allow the warm Ligurian current to penetrate onto the Gulf of Lions. In late summer, the NW component of the wind is small: *in situ* measurements obtained near the surface at about 20 km off the coast of Camargue (LION 77 experiment), strongly suggest that the Ligurian current flows onto the shelf. The lowering of NW winds is correlated with an increasing of the cloud-cover, and then when the current passes the Provence coasts, it is not easily observed from space: fortunatly, this has been possible on September 27, 1979, with the infrared scanner of Tiros N. Figure 4 represents the rough structure of the isotherms: it is clear that (1) the current follows the coastline and (2) it flows onto the shelf. Let us emphasize that, in the frontal zone, the radiometer never measures a sea surface temperature of 18 °C (mean value over a pixel): horizontal gradients in this area are expected to be very large; note that the outer edge of the current is well defined.

CONCLUSION

It is shown that some features of the Ligurian current can be studied, using satellite-derived temperatures as a tracer. On the occasion studied, there was a frontal region between the warm water of the Ligurian current and the cool water upwelled from the Gulf of Lions. In light winds periods, this frontal region propagated Westward (the normal direction of the Ligurian current), at up to 30 $cm.sec^{-1}$. But, with strong Westerlies, it does not progress. When the wind stops, the Ligurian current is found to flow along the coast, off Provence and then onto the continental shelf of the Gulf of Lions.

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