From: OCEANOGRAPHY FROM SPACE
Edited by J.F.R. Gower
(Plenum Publishing Corporation, 1981)

INFRA-RED REMOTE SENSING IN THE GULF OF LIONS

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1. ABSTRACT

Spatial and temporal variabilities of the upwelling in the Gulf of Lions and some characteristics of the Ligurian current are studied by thermal infrared satellite imagery. Upwelling develops along straight coastal segments of some ten to twenty kilometers in length. On-offshore jets of cool water driven from major upwelling centers and unexpected circulations, are clearly detected from space. Off the coasts of Provence, the Ligurian current is halted by strong westerly winds. When the wind drops, the surface-layer current flows on to the continental shelf of the Gulf of Lions at speeds up to 30 cm/sec. These results suggest that, during summer at least, the upwelling and the surface-layer circulation mainly depend upon small- and meso-scale features of the coastline.

2. INTRODUCTION

Since 1975, infrared thermal images of the Northwestern Mediterranean have been provided by satellites (mainly NOAA 4, NOAA 5 and TIROS-N). This data set is of primary interest for studying the Gulf of Lions' summer dynamics because both the wind-induced phenomena and the general circulation are linked to specific sea surface temperature distributions. Information from remote sensing imagery is in agreement with in situ current and temperature measurements. Only large horizontal gradients of the sensed thermal field have been taken into account: the results cannot be influenced by errors such as atmospheric absorption. Details of satellit data processing used, including computation of temperature, smoothin and summation of a set of images, will be found in Millot and Wald (1980b). More details about meteorological and hydrological regimes of the Gulf of Lions, in situ experiments and specific features of upwelling, are found in Millot (1979). A more complete analysis of some of the characteristics of the Ligurian current which have been deduced from satellite data, is in press (Millot and Wald, 1980a).

The Gulf of Lions (Fig. 1) has a roughly semi-circular shape with a radius of about 100 km: the topography of the continental shelf is quite smooth. The Gulf is the windiest region of the entire Mediterranean Basin: strong (daily speeds range from 10 to 20 $m.s.^{-1}$) and transient northwesterlies are frequently blowing for 1 to 10 days all year round. During summer, the thermocline in the coastal zone lies at about mid-depth and separates a bottom layer (with a minimum temperature value of about 13.5 ^{o}C) from an upper layer with a mean temperature of about 20 ^{o}C and surface values reaching their maximum around 25 ^{o}C.

A cloud-free sky is generally observed during periods of wind and allows the study by remote sensing of wind-induced phenomena (i.e. upwelling and modifications of the general circulation). Wher the wind drops for a long time, the general circulation intensifies and the sky often gets clouded; nevertheless, the few available images clearly show some interesting typical features.

3. THE UPWELLING

Among the hundred views of the area in our hands, about half

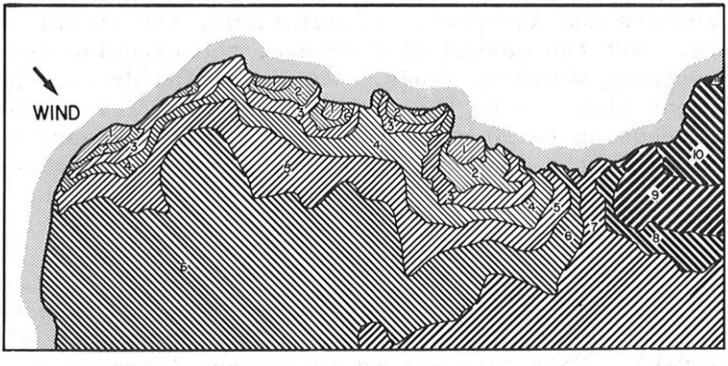

Fig. 1: The mean sea surface temperature distribution during upwelling in the Gulf of Lions, computed from the sum of 15 infrared satellite views. Isotherm interval is 0.5 ^{o}C. Note the six cold source-points (marked 1 or 2).

reveal the occurrence of upwelling. At a large scale, upwelling is intense where an observer with his back to the wind has the sea mainly on his right (along the coasts of Camargue and Provence); winds perpendicular to the coast (Languedoc) also create upwelling when no sea surface temperature gradient appears in the southwestern part of the Gulf (Roussillon). In some areas, the sea surface temperature may decrease by about 5°C in one day. At a small scale, upwelling appears to be very discontinuous, and actual source-points of cool water are clearly distinguishable. Six is the maximum number of upwelling centers, and we have collected fifteen views which reveal all these centers: the structure and the relative intensity of these sources vary from one view to the other and we have tried to reach a statistical aspect of the upwelling in the Gulf of Lions by summing these different views (Fig. 1).

If we consider that the coastline forms a series of curves (segments of 10 to 20 km in length separated by capes and small bays), it appears that upwelling spreads out first along straight segments and then in the vicinity of capes and bays. The largest sea surface temperature gradients (which may reach values up to 1°C per km) induced by the wind, occur nearshore in the vicinity of capes and bays and are directed alongshore; they are smoothed on the mean map because their location varies to a slight extent. Plumes of cool water moving seawards from some of the upwelling centers form strong on-offshore jets (daily speeds of the order of 40 $cm.s^{-1}$).

In many satellite images, the jet from the westernmost upwelling center is first directed seaward and then bends towards the south so to take up warmer water. Thus, it forms, off the Roussillon coast, an upwind current which is part of an anti-cyclonic wind induced eddy (Fig. 2). This upwind current in the surface layer has been confirmed by suitable in situ measurements; it does not appear in the mean map because the associated sea surface temperature features are weak and variable. Moorings have been set at suitable locations in order to test the ideas suggested by the infrared imagery. These two data sets are in very close agreement. To conclude, let us emphasize that only remote sensing from space has made possible the description of such large spatial and temporal variability of the upwelling.

4. THE LIGURIAN CURRENT

In the Ligurian Basin, the surface currents circulate in a cyclonic sense, as the prevailing winds do. In the Gulf of Lions, however, the prevailing winds are from the NW (~320° at Sète), but they diverge over the Ligurian Sea (~290° at Toulon) and over the Balearic Basin (~340° at Cape Béar). So, the mean current system is reinforced by the wind in the southwestern part of the Gulf, but resisted by the wind near the coast of Provence. In the

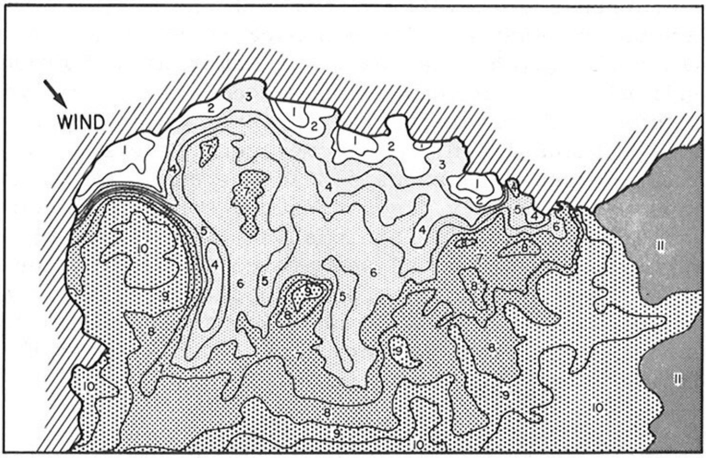

Fig. 2: Sea surface temperature distribution on 08/01/77, about one day after the onset of a NW storm. Isotherm interval is 0.5°C and grey interval is 1°C. The on-offshore jet is clearly visible.

vicinity of Toulon, westerlies blow about one day out of every three during the summer months, and then it is expected that in this area the Ligurian current in the surface layer depends to some extent on the local wind-stress. With respect to this phenomenon, the satellites provide two kinds of information.

First, we obtained a sequence of images at a day to day interval for about one week. Off the Provence coast, the Ligurian current which is about 20 km wide, is characterized by a frontal zone separating the warm water of the current from the upwelled colder water from the Gulf of Lions. This frontal structure (with a difference of about 2°C over a distance of 10 km) represents the 'head' of the current, and its displacement clearly depends on the local wind. The westward flow is halted by strong westerly winds, and when the wind drops the frontal zone moves at speeds up to 30 $cm.s^{-1}$; then, the current tends to flow along the coast of the Gulf of Lions.

The second feature revealed by infrared images concerns the location of the current when it reaches the continental shelf area. In situ measurements already obtained 30 km off Camargue, have led us to suppose that during long periods of gentle winds the Ligurian current penetrates into the Gulf: the Coriolis force and bottom topography mainly drive the surface-layer flow along the coast. The fact that in a period of stratification the Ligurian current follows the coasts of the Gulf of Lions, is proven by the satellite view taken on September 27, 1979 (Fig. 3). In this Figure, we note that the TIROS-N radiometer cannot define an intermediate temperature value in the frontal zone off Cape Couronne, which makes a

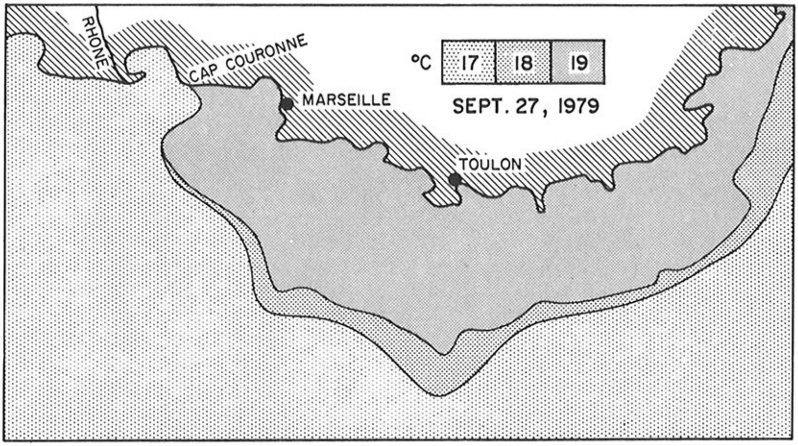

Fig. 3: This view shows that the Ligurian current tends to flow onto the continental shelf of the Gulf of Lions.

very high gradient. When the current penetrates into the Gulf, it is pushed away from the coasts by a new gust of NW winds; upwellings spread out and first cut up the warm mass of water; then mixing intensifies, but the water of the Ligurian current may be visible as far as off the continental shelf area. In general, a new frontal zone appears on the edge of the Gulf of Lions in the vicinity of Toulon.

5. CONCLUSION

Unexpected phenomena in the Gulf of Lions have been described from infrared satellite images. The spatial and temporal variability of both the upwelling and the Ligurian current is such that we would never have been able to reach this large amount of knowledge with in situ measurements. Moorings set at suitable locations give data which are in very close agreement with the ideas suggested by infrared imagery, and, inversely, phenomena expected from current-meter records have been confirmed by satellite views. The two data sets are both needed for the complete understanding of the observations.

REFERENCES

Millot, C., 1979, "Wind-induced Upwellings in the Gulf of Lions," Oceanol. Acta., 2, 3, 261-274.

Millot, C., Wald, L., 1980a, "The Effect of the Mistral Wind on the Ligurian Current Near Provence," In press, Oceanol. Acta., 3, 4.

Millot, C., Wald, L., 1980b, "Upwelling in the Gulf of Lions," IDOE International Symposium on Coastal Upwelling, Los Angeles, February 4-8, 1980.