Ligurian Sea: annual variation of the sea-surface thermal structure as detected by satellite NOAA 5

Remote sensing
Sea-surface temperature
Ligurian Sea

Télédétection
Température de surface
Mer Ligure

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Received 2/4/80, in revised form 19/5/80, accepted 22/5/80.

ABSTRACT

Examination of one hundred thermographies of the Ligurian Sea, obtained during the years 1975, 1977, 1978 and 1979 by the satellite NOAA 5, reveals the quasi-permanence, over a year, of a mean superficial cyclonic circulation, generally characterized by its thermal pattern. The large number of satellite images and the use of specific methods permit the description of the annual variations in the structure of the horizontal thermal gradients. Results are in close agreement with those provided by previous authors.

Oceanol. Acta, 1980, **3**, 4, 465-469.

RÉSUMÉ

Variation annuelle de la structure thermique horizontale superficielle en Mer Ligure d'après le satellite NOAA 5.

L'examen d'une centaine de thermographies de la Mer Ligure, obtenues par le satellite NOAA 5 en 1975, 1977, 1978 et 1979, montre la quasi-permanence annuelle du circuit cyclonique superficiel, généralement souligné par sa structure thermique. Le grand nombre d'images ainsi que l'utilisation des méthodes d'investigation spécifiques, permettent de décrire les variations de la structure des gradients thermiques à la surface de la mer durant l'année. Ces résultats concordent avec ceux des précédents auteurs.

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INTRODUCTION

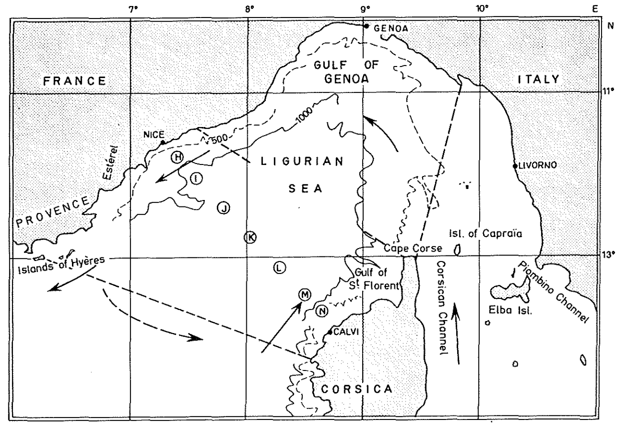
Mean superficial circulation in the Ligurian Sea has been studied over a long period (Bethoux, Prieur, 1978; Gostan, 1961, 1968; Hela, 1963; Lamy, 1976; Le Floch', Romanovsky, 1954; Le Pichon, Troadec, 1963 *a* and *b*; Stocchino, Testoni, 1977). Two superficial flows, coming from the South, pass along the Eastern and Western Corsican coasts and, after meeting offshore from Cape Corse, follow the continental coastlines in a cyclonic elongated loop, and then move through the outer Gulf of Lions (Fig. 1).

Along the Italian Riviera and Provence coasts, this flow is known as the Ligurian current. All earlier authors stress the high degree of permanency of this baroclinic superficial circulation throughout the year. Except during very cold winters, this pattern is underlined by the

Figure 1

Pattern of superficial circulation in Ligurian Sea. The dotted arrow indicates a possible seasonal branch of current.

Schéma de circulation superficielle en Mer Ligure. La flèche en tiretés indique la présence possible d'une branche de courant saisonnière.



cold and dense water to be found at the centre of the loop. Thus, it is generally possible to trace the Ligurian surface mean flow with the aid of infrared images from meteorological satellites.

SATELLITE DATA AND PROCESSING

Data from the radiometer VHRR of the NOAA 4 and 5 satellites are used. The VHRR spatial resolution is $\sim 1\,km^2$ at the nadir, and its radiometric resolution is 0.5 K at 300 K. Data processing includes the computation of equivalent temperatures, the smoothing of images with a bi-dimensional spatial filter, depending on the importance of local gradients with respect to noise; the plotting of thermographic maps, and geometric correction for the Earth's spin and the curvature of its surface (Albuisson, 1976).

The absolute values of temperature provided by the radiometer, even when using the best of atmospheric corrections, cannot be relied upon as sufficiently accurate; but relative sea-surface temperatures (SST) or horizontal thermal gradients may be determined in this area with an accuracy of 0.5°C for a 3 km resolution (Albuisson, Pontier, Wald, 1979). The satellite images may thus be considered as reliable in the study of horizontal thermal gradients and their spatial distribution. In order to make the images superposable ($\pm 1\,km^2$), they are geometrically corrected on the basis of known landmarks. Images are two-dimensional arrays, so we may compute for each geographical point the average in time of each image series, and focus our attention on local SST gradients. Because of the elimination of clouds, of variations in VHRR calibration, and of atmospheric effects on sea-surface radiance, these computations are not standard, but the attendant problems have been solved in the manner described in the Appendix below. Although the absolute values of *in situ* temperatures are unknown, we may draw location maps of mean surface isotherms in relative values. We can also compute for each geographical point the series variance of the local SST gradients, i.e. variations in the location of a mean isotherm (see Appendix). In Figures 2 and 4, which present mean structures, only those parts of the isotherm which are drawn in full line are highly stable in statistical terms; these are located with an accuracy of 3 km, which means that their location is identical throughout the time series, and that the spatial location variance is zero with respect to the weak accuracy of the relative SST measurements.

ANNUAL VARIATION IN THE PATTERN OF SST GRADIENTS

Examination of one hundred thermographies, obtained during the Summer of 1975, throughout 1977 and 1978, and in January 1979, and computed with the use of CTAMN facilities, first reveals the quasi-permanence throughout the year of the pattern of horizontal thermal gradients associated with the baroclinic cyclonic loop. The mean superficial circulation is fairly well reflected, except in February-March. During the other months,

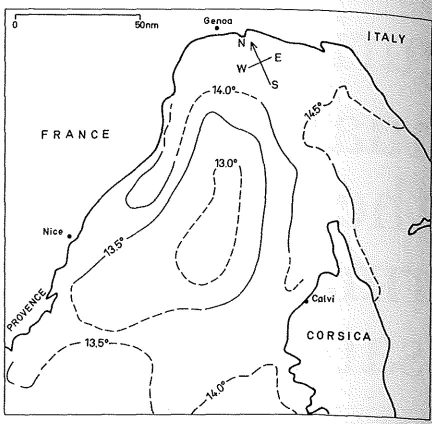


Figure 2

Mean horizontal thermal gradients pattern during December-January in the Ligurian Sea (see text for explanation).

Distribution spatiale moyenne des gradients horizontaux durant décembre-janvier dans la Mer Ligure (voir explications dans le texte).

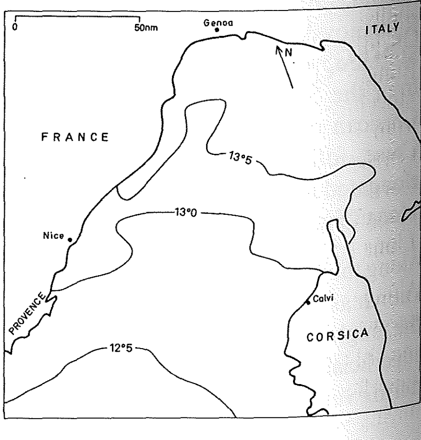
however, some morphological variations occur in the pattern of the SST gradients. These variations may be clearly shown by the use of image average and variance, as described above. Due to a lack of images, statistically significant results have only been computed for December-January, July and August. Despite the French Riviera's reputation for fine weather, the sky may be sufficiently overcast to prevent a fine observation of the Ligurian Sea during the Spring and Autumn, and, even in Summer, to prevent sufficiently long time-series for the tracking of a transient phenomenon. Nevertheless, variations are slow enough, during the Autumn, for this period, to be represented by a typical image. The evolution of the SST pattern is described below.

For December-January (Fig. 2), the mean is computed from a series of nine images. The eddy is well defined. The temperature values indicated are provided by an average of *in situ* data from Gostan (1968) and the Hydrokor cruises (1973, 1975). The 13.5°C isotherm is very stable in location, and these months are marked by an expansion of the cold centre (13°C isotherm). From December to February, acting like a welling spring, the cold core spreads further and further outwards, and reveals the importance of vertical movements during the Winter. Due to this expansion, and to the influence of cold air-masses descending from the Alps to the western part of the Ligurian Sea, the SST field in February-March presents a striped structure, with temperatures increasing from the South-West to the North-East. This structure is typified in Figure 3, which shows the disappearance of

Figure 3

Typical horizontal thermal gradients pattern during Winter (see text for explanation).

Distribution spatiale typique des gradients thermiques horizontaux en hiver (voir explications dans le texte).



the eddy. At this time, the thermographies provide no indication of the overall superficial flow, although the mean circulation remains identical throughout the year (Bethoux, Prieur, 1978; Gostan, 1961, 1968; Hela, 1963; Le Floch', Romanovsky, 1954; Stocchino, Testoni, 1977). The spatial distribution of SST depends not only on the mean superficial circulation, but is mainly linked to vertical movements and air cooling. During the three following months (April, May, June), the isotherms begin to bend to the South-West, and tend to lie parallel to the coasts. This process completed in late June, when the SST pattern is then an elongated loop with non-closed isotherms, very similar to the circulation scheme described above. This field is characterized in Figure 4 by

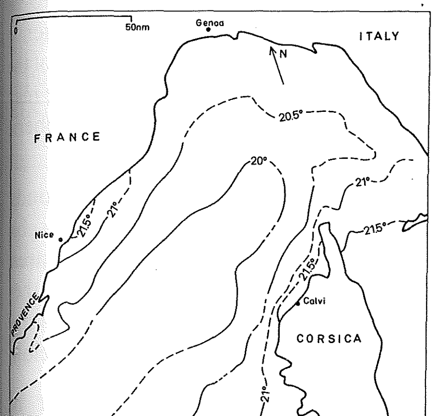


Figure 4
Ibid. Figure 2, *but for Summer.*
Ibid. figure 2, mais pour l'été.

a mean image, computed from a twenty-five-image series from July and August. Except for the two warmer cores along the French Riviera and north-west Corsica, the fields of the SST gradients during Summer and in December-January are similar. In comparing these two periods, we may observe the displacement of the mass centre of the cold core, which is some 20 km further to the South in Summer than in December-January. This may be related to the fact that westerly winds (Mistral) are more frequent in Summer than in December-January in this area (Darchen, De Bloch, 1968); but the hypothesis requires much finer statistics concerning wind stress. Another argument may be advanced on the basis of a number of single thermographies obtained during the Summer, while the Mistral is blowing strongly. These show that the isotherms towards Corsica have exactly the same locations as the Summer mean isotherms. A third argument is provided by the typical SST pattern in Autumn (September, October, November), characterized by a single thermography (Fig. 5). The SST gradient

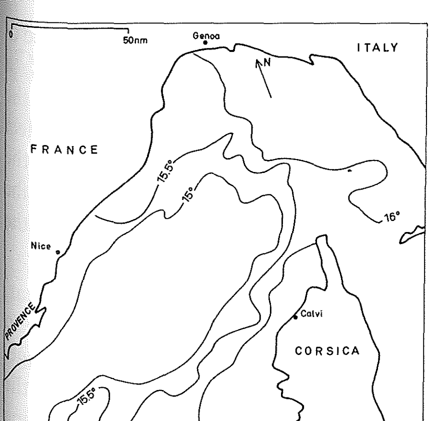


Figure 5
Ibid. Figure 3, *but for Autumn.*
Ibid. figure 3, mais pour l'automne.

field is similar to that in Summer, but the location of the mass-centre coincides with the pre-winter location. This may enforce the previous idea of a wind-effect, because of the very slight occurrence of Mistral during this period (Darchen, De Bloch, 1968).

COMPARISON WITH *IN SITU* DATA AND CURRENTS

We have used the *in situ* data from Gostan (1961, 1967) and the Hydrokor cruises (1973, 1975). These data were obtained in 1961, 1962 and 1963, and from 1969 to 1973, with one cruise every month along a line Nice-Calvi. Although our own data and the *in situ* temperature data do not cover the same years, the statistical comparison between our results, as presented above, and *in situ* thermal gradients data at the sea-surface and at a depth of 10 m, shows excellent agreement for all times of the year (Wald, 1980). Because our concern is only with the spatial distribution of the SST gradients, we compute the differences of SST between the stations located along the line Nice-Calvi and the central station (45 nautical miles off Nice), for both the *in situ* data and the average images, and then draw correlograms of these two series of thermal differences (an example is given in Figure 6). Most of the points of the correlograms lie along the line of slope unity which transects the origin. Excellent agreement is obtained between the *in situ* data and our own results.

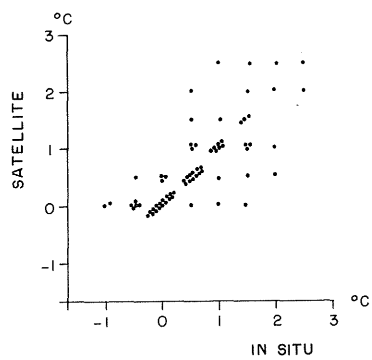


Figure 6
Statistical comparison, for Summer, between the differences of SST between the stations located along the line Nice-Calvi and the central station, for both the in-situ *data and the average images.*
Comparaison statistique, pour l'été, entre les différences thermiques superficielles entre les stations de la radiale Nice-Calvi et la station centrale pour les mesures *in situ* et celles tirées des images moyennes.

If thermographies permit a qualitative description of the mean superficial flow, the cold water being to the left as one looks in the downstream direction, we have been unable to establish a quantitative relationship between SST gradients and currents, computed with the dynamical method by Prieur (pers. comm.). Because of the great importance of salinity in this area, we cannot replace the horizontal density gradient by the horizontal temperature gradient in the thermohaline current relation. The fact that variations of salinity and temperature act together to weaken or strengthen the density, explains why the mean superficial flow in the Ligurian Sea may be described qualitatively with aid of thermographies.

CONCLUSION

This study underlines the importance of infrared measurements obtained from meteorological satellites. The two characteristics of these data, namely the quasi-instantaneous survey of vast areas and time-repetitivity, are fully utilized to initiate a climatological study of the Ligurian Sea. We have shown an evolution throughout the year of the SST gradient pattern, which may be described by the use of specific tools. Thermographies reflect the mean superficial flow in the Ligurian Sea, and are thus of assistance in the study of the dynamics of this area, at least from a qualitative point of view.

Acknowledgements

We are grateful to Pr. Lacombe and MMessrs. Bethoux, Crepon, Millot and Prieur for their useful comments.

This work was supported by the Centre National pour l'Exploitation des Océans (CNEXO) and the Centre National de la Recherche Scientifique (CNRS), with a grant from the École Nationale Supérieure des Mines in Paris.

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APPENDIX

This appendix describes the computation of the time-average of image-series and of the variance of local SST gradients.

Atmospheric absorption of sea-surface radiance may be characterized by two terms, τ and C : $T=\tau T_S + C$, where T is the measured SST from space, T_S the actual SST, τ the atmospheric infrared transmittance, and C a constant depending on atmospheric conditions. C may also include variations in the calibration of the VHRR.

Since Albuisson *et al.* (1979) have shown that, in the region under study, SST gradients measured by the VHRR and the *in situ* SST gradients are equal, the atmospheric infrared transmittance is considered to be unity. We are only concerned with local SST gradients; thus the term C disappears and the mean gradients of the actual SST and of the SST from space are equal. We may average images without knowledge of the atmospheric absorption.

However, two problems arise: border effect and clouds. The border effect is due to the fact that superposable images do not cover exactly the same geographical area. One image may represent the island of Elba, and another may not. This problem is, in fact, very similar to that due to the elimination of clouds, and will be dealt with below.

Some images present small clouds which must be removed in order to avoid bias in the interpretation of the average image. Because clouds are colder than the sea, we use a method of minimum accepted value. This is termed the threshold value, and depends on each image. We only take into account values greater than this threshold. But this leads to a further difficulty. Let us consider two images with thresholds S_1 and S_2, respectively, whose values at a geographical point A are a_1 and a_2, respectively, and b_1 and b_2, respectively, at all the other points. Let us also suppose that, for some reason or other (calibration, atmospheric absorption, etc.), the values of the first image are greater than those of the second, and that:

$$b_1 > S_1 \geqq a_1; \qquad b_2 = a_2 > S_2; \qquad b_1 > b_2.$$

Then, if X_A and X are the average values for A and the other points:

$$X_A = b_2; \qquad X = (b_1 + b_2)/2 > X_A.$$

The mean value in A is less than the actual mean value of the two images. The average image presents a discontinuity, which is only an artefact induced by the method of minimum accepted value. The border effect gives a similar discontinuity. Since no point outside the area covered by an image is taken into account, the border acts as a geographical threshold analogous to the thermal threshold.

One imagines that these discontinuities will disappear, provided that the values of different images are close to each other. This is achieved by rescaling. For each image, we effect a translation (change of origin) of values to the extent that the overall variation of the values from one image to another is slight. Rescaling does not involve any physical hypothesis, since we only study gradients.

The use of these methods may lead to erroneous results in the interpretation of the average image. The points of the average image do not have the same statistical value, because they represent a greater or smaller number of averaged values, according to whether these values are greater or smaller than their respective thresholds. It is thus necessary to know the number of estimators for each point of the average image.

To describe more precisely the image time-series, we also compute an image of the variance of the local SST gradients, which we define as follows:

$$V_A = \frac{1}{N_A} \sum_{i=1}^{N_A} (X^i_{A+d} - X^i_A - E(X_{A+d}) + E(X_A))^2,$$

where V_A: variance at point A; N_A: number of estimators at point A; X^i_A, X^i_{A+d}: values of A, $A+d$ in the i-th image; $E(X_A)$: mean value at point A.

This quantity V_A, which does not depend on rescaling, indicates the statistical accuracy of the mean gradient computed between points A and $A+d$. Otherwise it indicates the spatial accuracy of location of mean isotherms. We have set d equal to 5, but the choice of d-value will depend on the accuracy of the radiometer, the observed gradients, the hoped-for accuracy in the location of mean isotherms, and other factors. For the computation of the variance, we use the same thresholds as for averaging, and also apply the rescaling method. Because the points of the average image (or its variance) do not have the same statistical value, when computing the variance we apply a high value to all the points where the number of summed values is less than 75 % of the total number of images to be summed up. The image of the variance of the local SST gradients thus permits estimation of the accuracy of location of mean isotherms, and ensures the statistical credibility of the points of the average image.