SOME ASPECTS OF THE LIGURO-PROVENCAL FRONTAL ECOHYDRODYNAMICS

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INTRODUCTION

In the oligotrophic sea water, the biological production is mainly influenced by zones of discontinuity such as fronts and thermoclines. In the Mediterranean Sea, the front at the edge of the continental shelf separates general and coastal circulations, limiting lateral diffusion. The vertical motions associated with this front bring nutrients to the surface, increasing the biological productivity (PRIEUR, 1981). The produced biological material is exported off-shore perpendicularly to the front.

Since a few years, interdisciplinary studies have been led in the Corsican area of the Liguro-Provençal front by the University of Liège at STARESO Station (Calvi - Corsica).

These studies are integrated in an international program with the collaboration of L. PRIEUR (Station zoologique of Villefranche-sur-Mer, France).

General circulation

The dynamics of the Mediterranean Sea is mainly dominated by the general and the local atmospheric forcings. Due to the climatology of the Mediterranean area, the water balance is negative, the evaporation being more important than the precipitations and the river supply. In this concentration basin, the deficit is compensated for by an important water flux through the Gibraltar Strait (LACOMBE, 1973; BETHOUX, 1980)..

The Atlantic surface layer flows eastwards along the North African coast, forming the so called African current. In the Western part of the Mediterranean large cyclonic circulations are developed in the Thyrrhenian Sea and in the Liguro-Provençal basin (figure 1).

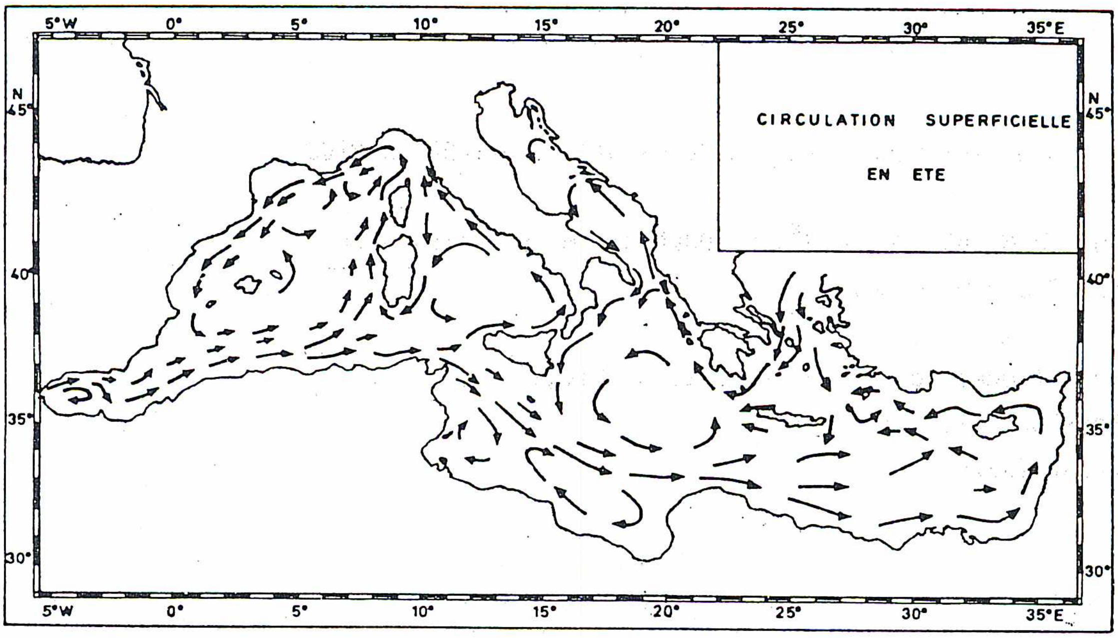

Fig. 1 : Summer superficial circulation (after SCHMIDT and NIELSEN)

The Summer heating of the surface layer leads to the formation of a seasonnal thermocline. During the winter, under the effect of dry and cold continental winds (Mistral, Tramontane, ...) and of the difference of temperature between air and sea, the evaporation and heat transfer from the sea to the air become very important. Hence the density of the surface layer increases, inducing a baroclinic instability. The consequent vertical mixing and convection give rise to deep waters. This phenomenon of deep water formation is observed in the North-West Mediterranean (GASCARD, 1978), in the Levantin basin and in the Adriatic Sea.

The water formed during the winter in the Levantin basin crosses the Sicilian Strait and spreads in the Western basin, describing cyclonic circulations of a so-called intermediate water.

So, the Mediterranean Sea seems to be a three layer system : a surface layer of Atlantic water (~ 0 - 100 m) cold and little saline, an intermediate levantine layer (~ 100 - 500 m) warmer and more salted and a typically mediterranean deep layer (under 600 m) colder and less salted. Above the summer thermocline, when it exists, the upper layer of the sea has higher temperature and salinity than the Atlantic water.

There is no doubt that this general scheme of circulation is highly perturbed and locally modified, at least in the surface layer, by the transient wind events.

From this general survey obtained by means of classical field measurements, one emphasizes the intense cyclonic gyre in the Liguro-Provençal basin carrying along surface and subsurface waters.

Since a few years, the new possibilities offered by the development of remote sensing techniques has allowed a better monitoring of oceanic phenomena like the frontal structures in the Western Mediterranean Sea.

The examination of a one year series of infrared thermographies provided by the Centre de Météorologie Spatiale (Lannion, France) shows for instance the seasonnal variability of the front separating the different water masses in the Liguro-Provençal basin (figure 2).

Spring images do not provide much information because of the weakness of the surface temperature gradients due to the strong mixing of the surface layer by the cold winds during the winter.

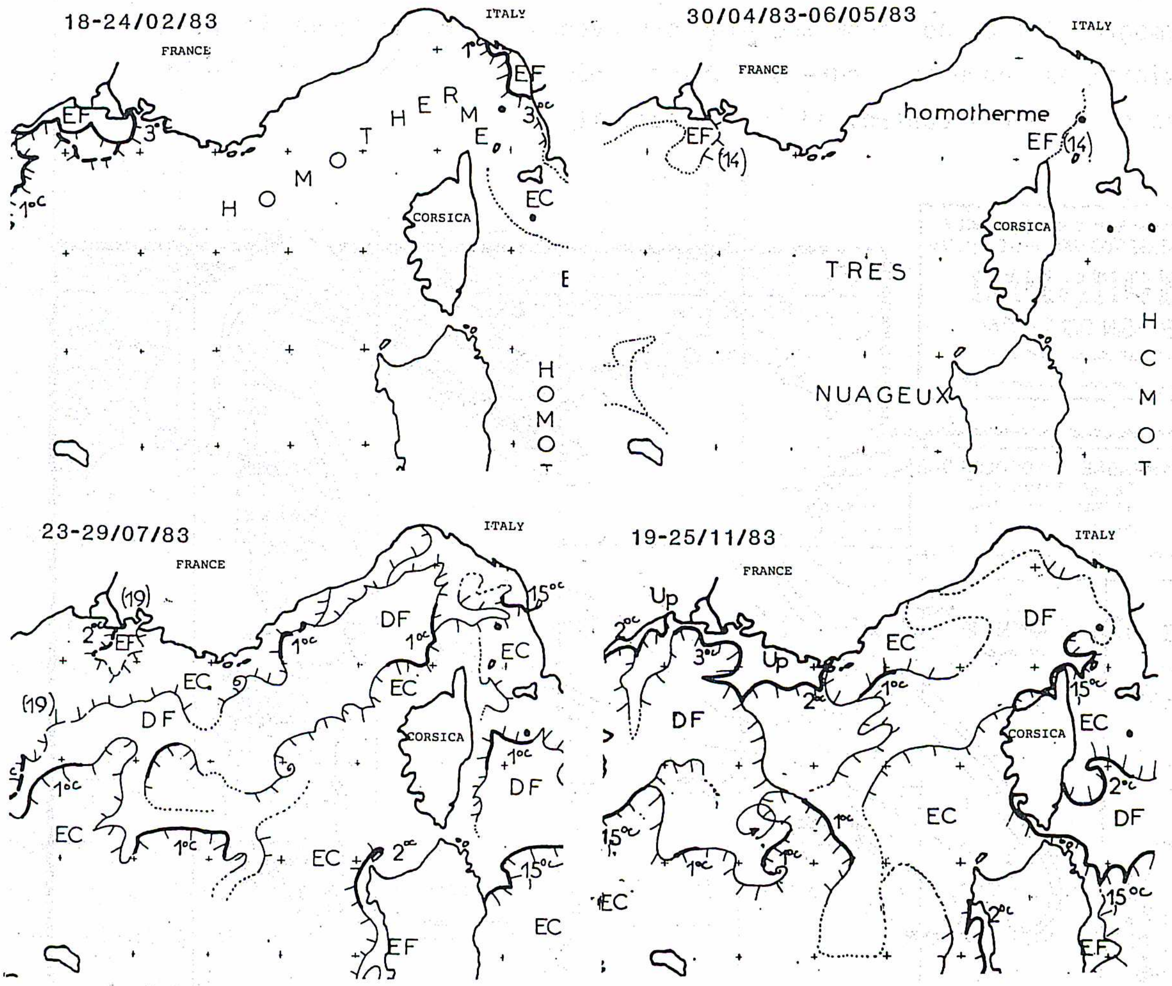

Fig. 2 : NOAA satellite infrared thermographies showing surface temperature gradient( )(from Centre de Météorologie spatiale, Lannion, France)

The heating of the surface water during the late spring progressively establishes a vertical stratification. The consequent seasonnal thermocline is affected by the water motions which disturb it, giving rise to horizontal temperature gradients visible form satellites in the form of more or less marked fronts. The most important front for us, in relation with the cyclonic circulation in the Liguro-Provençal basin, separates dense water of the cold core from the warm water running around it. The width of the warm water strip is variable, the front being sometimes firmly situated in the coastal zone, like it is the case off North Corsica from Calvi to Cape Corse. In spite of its variability in space and in time, the thermal front associated with this cyclonic loop is persistent throughout the summer and fall. However, during the autumn, it begins to weaken and to present instabilities.

The winter meteorological forcing removes the seasonnal thermocline and consequently the whole typical summer fronts. Then the winter and spring thermographies do not show the Liguro-Provençal gyre, although it is present in winter as shown in figure 3. During these seasons the density field appears as mainly controlled by the salinity.

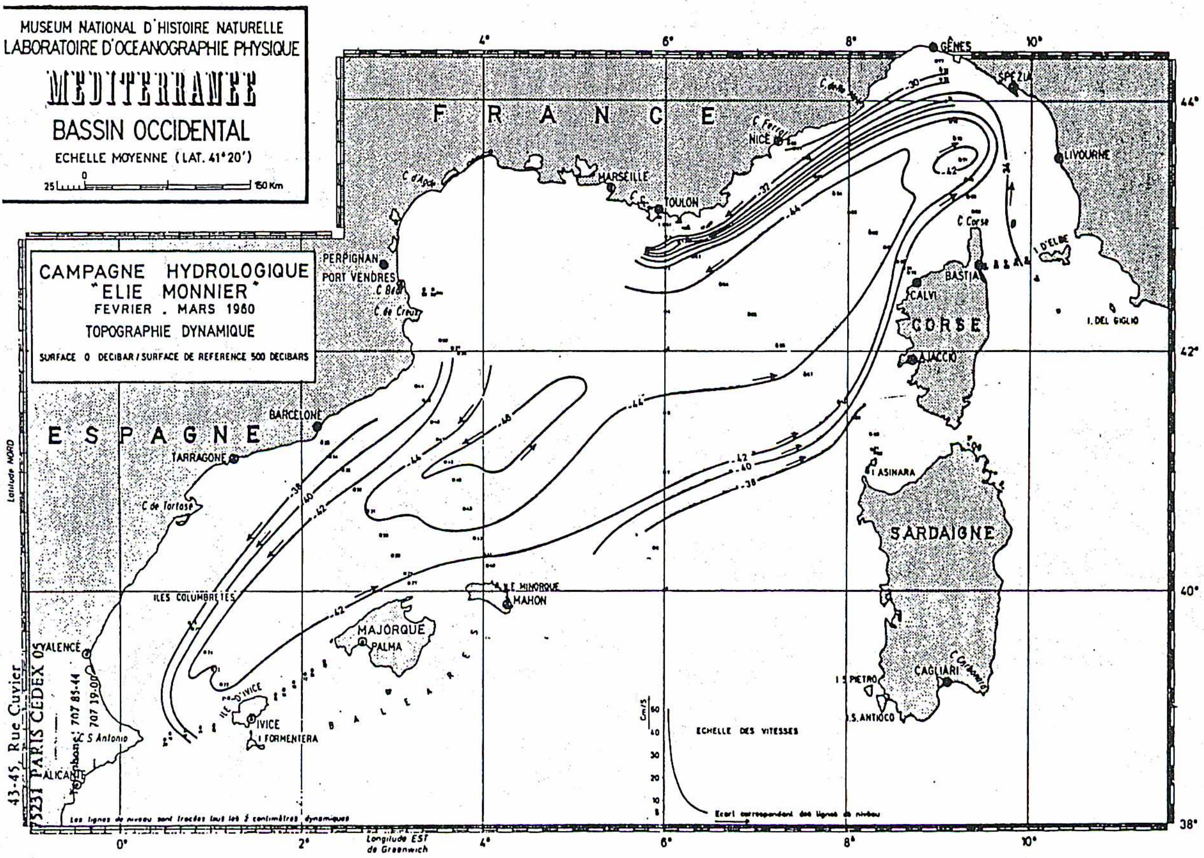

Fig. 3 : Dynamical topography in the North-West Mediterranean during the winter (from BOSCALS DE REAL).

Hydrological data

The study of hydrological data (temperature, salinity) collected in March, July and October 1984, during several oceanographic cruises across the Ligure-Provençal front (Corsican area), provides a more detailed picture of water masses distribution and seasonal fluctuations. These campaigns have been carried out on board of the "Recteur Dubuisson", the oceanographic ship of the University of Liège at Calvi (Corsica). Ten stations have been selected (figure 4) on the Calvi-Nice axis, from Calvi (station n°1) to 30 nautical miles offshore (station n°10).

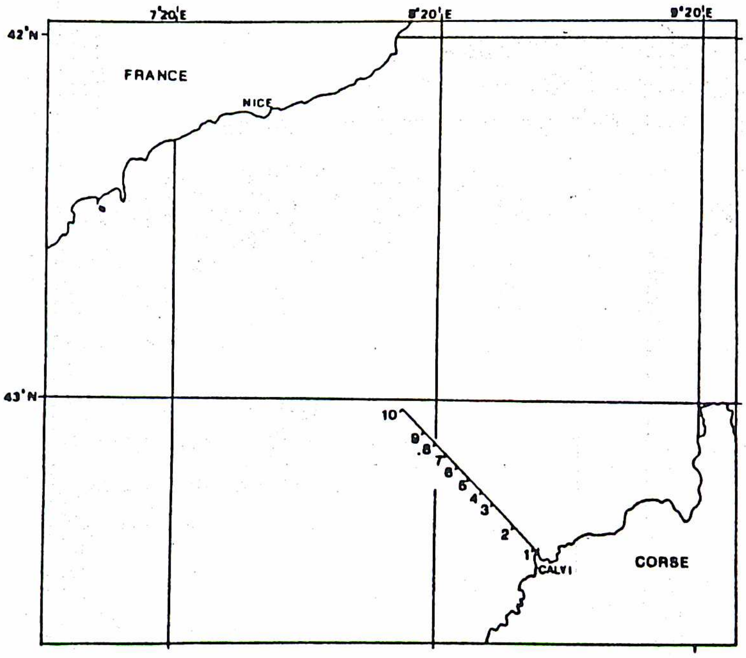

Fig. 4 : Position of sampling stations

Temperature and salinity measurements have been carried out at every ten stations, from the surface to 200 meters. The isotherms, isohalines and isopycnals distributions are presented.

In March, a strong gradient of salinity separates coastal waters ($S < 38.2$ °/oo) from offshore waters (figure 5A) ($S > 38.4$ °/oo). The distribution of isotherms shows that the upper layers are not really homothermal. Figure 5B shows that colder waters ($T \leq 12.9$°C) are merely situated beneath the haline gradient while warmer waters ($T > 12.9$°C) are situated above it, near the coast.

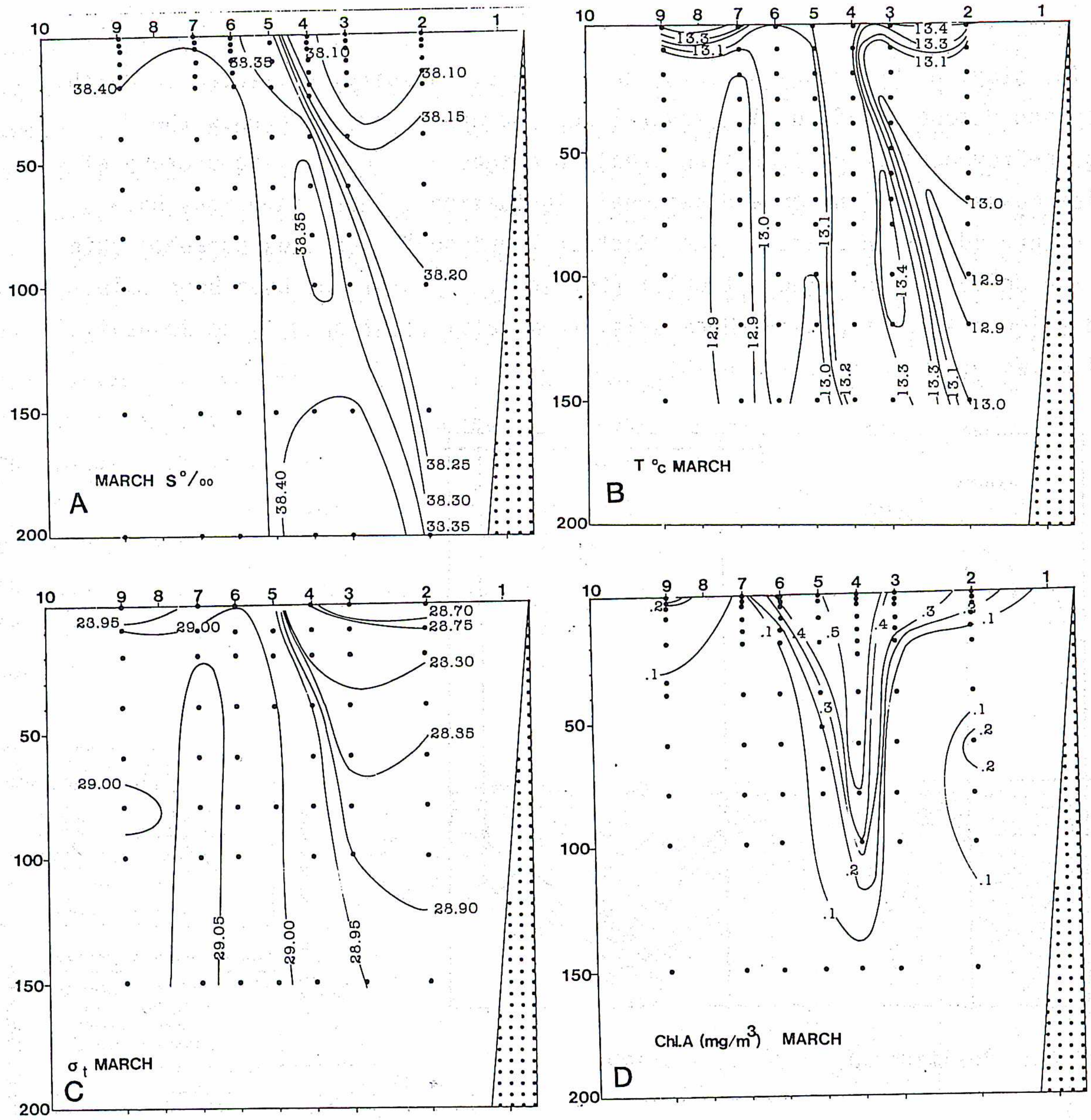

Fig. 5 : MARS 1984. Distribution of isohalines (A), isotherms (B), isopycnals (C) and chlorophyll A concentration (D) across Corsican front region from the coast (st 1) to 30 miles offshore (st 10) and from surface to 200 meters deep (HECQ et al, 1985).

Density distribution (figure 5C) shows that the thermohaline front separated two areas :

- Offshore stations with waters of high density, characteristic of Levantine origin; this region is unstratified and seems to be a divergence area,
- Onshore stations with less dense waters, characteristic of Atlantic origin. This region is little stratified with a tendance of convergence close to the gradient. In that period, the front crosses the sea surface about 15 miles off the coast and the isopycnals slant with a 1.6 % slope from the front area to the coast (HECQ et al, 1985).

In June, a vertical stratification is initiated (figure 6B) with the heating of upper layers. This vertical gradient of temperature masks the horizontal gradient at least in the 75 upper meters. From the point of view of the salinity (figure 6A), the haline gradient separating offshore and coastal waters in more important below 50 m than above. The density diagram (figure 6C) summarizes the water masses distribution. In the upper layer (from the surface to the 50 m depth), the distribution of isopycnals is approximately horizontal. Below 75 m, both a coastal stratified area and an offshore unstratified zone with high density values are still observed. This suggests that the divergence does not reach the surface but only affects the waters below the thermocline.

In October (figure 7), the distribution of isohalines is quite similar to the situation in June and two regions are separated by a frontal discontinuity. The increase of isothermal and isopycnal slope suggests the onset of a destabilization.

The "in situ" measurements confirm fairly well the existence of different water masses as described above.

The water situated between the front and the Corsican coast has the characteristics of an Atlantic water. The water situated beyond the front has the characteristics of an intermediate Levantine water.

In winter and at the begining of spring, salinity influences the most the slope of isopycnals (from offshore areas to the coast). In that period, divergences reach surface layers.

In contrary, during summer, surface temperature influences horizontal stratification of the upper layers and frontal divergences seem to reach only water layers below 100 meters.

In addition to the measurements of salinity and temperature, total alkalinity analyses have been carried out on the same samples. Total alkalinity is independent of biological processes as far as reactions involving carbonates exchanges are negligible (FRANKIGNOULLE and BOUQUEGNEAU, 1985)

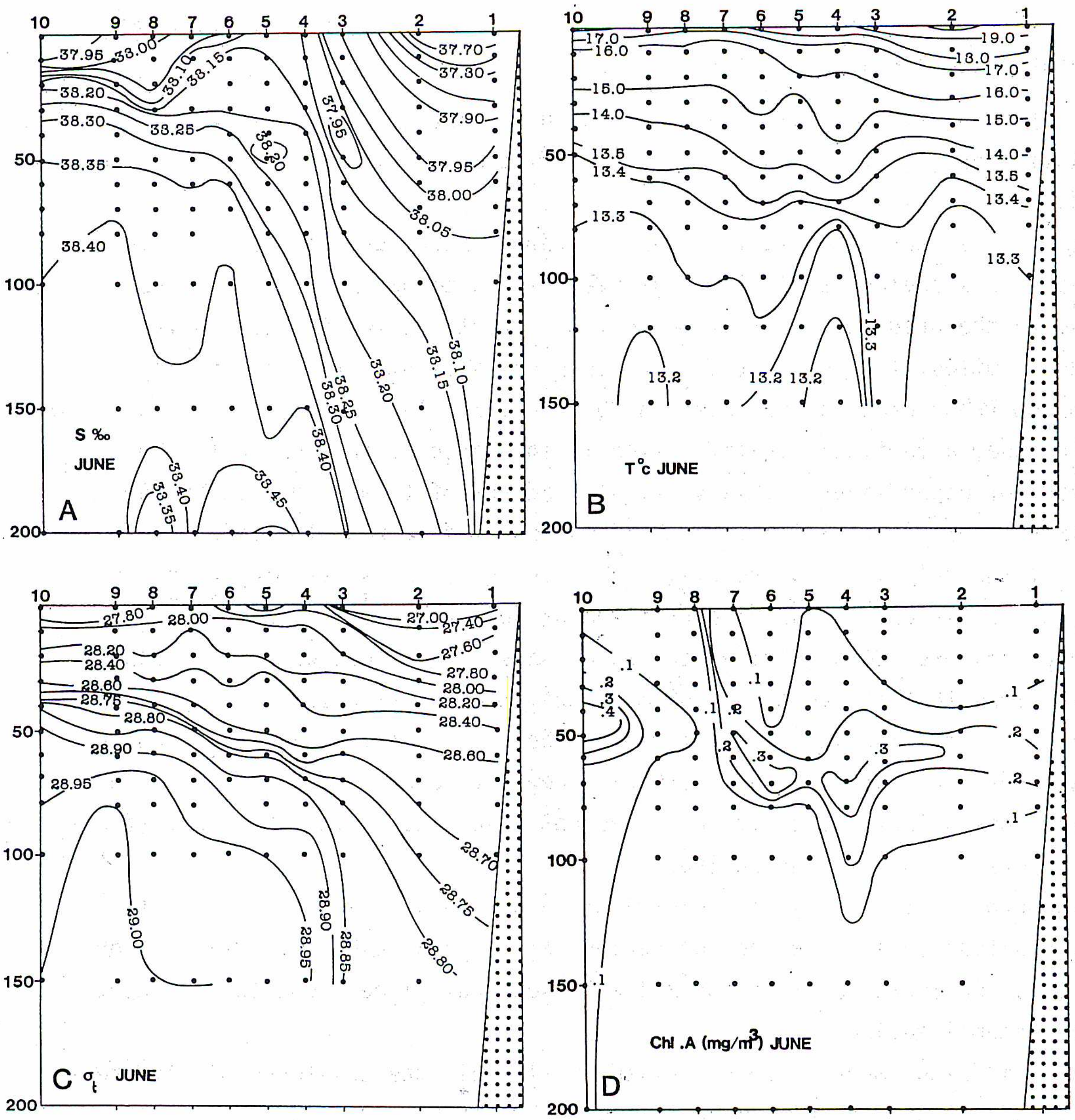

Fig. 6 : JUNE 1984. Distribution of isohalines (A), isotherms (B), isopycnals (C) and chloropyll A concentrations (D) across Corsican front region from the coast (st 1) to 30 miles offshore (st 10) and from surface to 200 meters deep (HECQ et al, 1985).

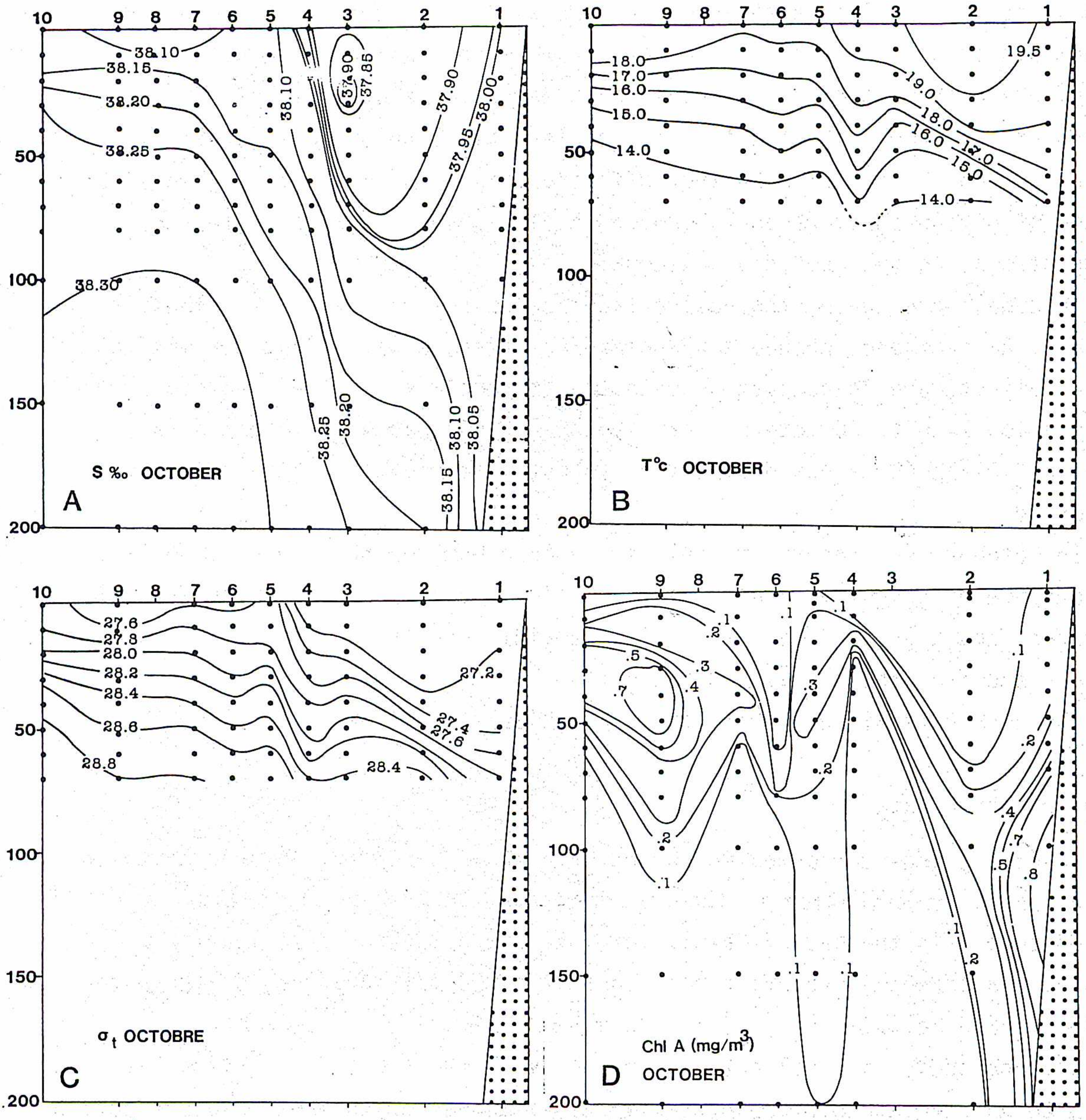

Fig. 7 : OCTOBER 1984. Distribution of isohalines (A), isotherms (B), isopycnals (C) and chlorophyll A concentrations (D) across Corsican front region from the coast (st 1) to 30 miles offshore (st 10) and from surface to 200 meters deep (HECQ et al, 1985).

and we believe that this parameter can be used to discuss the origin and movements of water masses : deep waters are more alkaline than surface ones.

Figure 8 shows the result obtained in March, June and October 1984. In March, the thermohaline front separates less alkaline onshore waters ($\leqslant$ 2.60 m Eq. L^{-1}) from alkaliner offshore ones ($\geqslant$ 2.65 m Eq. L^{-1}). A divergence of offshore waters and a convergence of onshore ones are clearly suggested along the isopycnal discontinuity.

In June, once again, the haline front separates more and less alkaline waters. A divergence phenomenon appears in offshore waters but the maxima of alkalinity are found just beneath the thermocline : there is a divergence at station 7 up to 50 meters where the pycnocline has been detected; at station 10, at 40 meters depth, the highest observed alkalinity value is observed.

In October, the waters are relatively more homogeneous and no important divergence or convergence are suggested. The frontal discontinuity is till apparent and a gradient of alkalinity remains both from coastal to offshore waters and from the surface to the bottom.

These results fit well with the other hydrological data described above.

Phytoplankton data

Investigations performed in spring have shown a spatial heterogeneity in chlorophyll distribution in the Ligurian Sea (JACQUES et al, 1973).

Moreover, in the Bay of Calvi, vertical phytoplankton distribution exhibits a seasonal evolution related to the thermal structure of the water column (HECQ et al, 1981, 1985; LEGENDRE, 1981).

Oceanographic data collected in the area of the front during 1984 have lead to an accurate picture of the spatio-temporal phytoplankton distribution.

The area investigated and the techniques have been described earlier. Chlorophyll A has been analysed on water collected at twelve different depths (from surface to 200 m) (according to STRICKLAND and PARSONS, 1968).

In March, chlorophyll A concentration (figure 5D) is important in the frontal area : more than 0.3 mgr. chl. A/m^3 from station 2 to station 6, where the amount of nutrients is high.

The maximal concentrations are recorded at station 4 ($>$ 0.5 mgr. chl. A/m^3). At this station, the living phytoplankton is found deeper than euphotic depth and the vertical distribution of chlorophyll A suggests a downwards transport of phytoplankton along isopycnals in the area of the front; e.g. at station 4, living chlorophyll content still reaches 0.4 mg/m^3 at 100 meters depth.

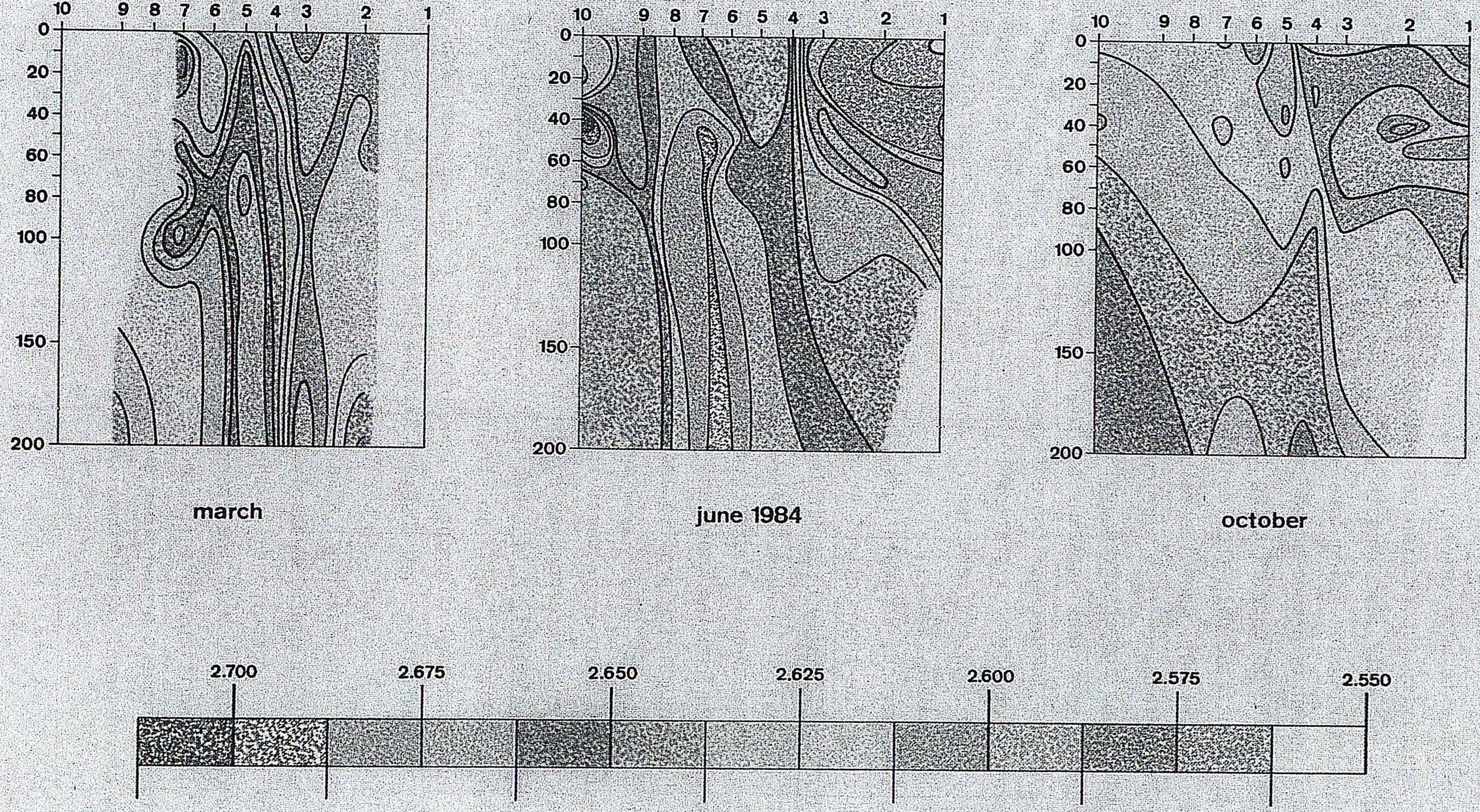

Fig. 8 : Distribution of alkalinity isolines across Corsican frontal region (number of stations.depth in meters) in March, June and October 1984. Alkalinity has been determined by electrochemical titration according to GRAN (1952)

During that period, the maximum of primary production is observed at the level of the front (figure 9) (from 0 to 25 m depth : 50 to 70 mg C m^{-3} D^{-1}) and is associated to high chlorophyll A concentrations. In the other hand primary productivity (production per unit biomass) reaches a maximum at the same stations but only just beneath the surface (200 mg C. mg chl A^{-1} B^{-1}). The biomass distribution being like a plume (figure 5D), we can conclude that phytoplankton is produced near the surface between stations 3 and 4 (LICOT, 1985), and is carried along the isopycnals, in relation with the convergence associated with the frontal system.

In June (figure 6D), when the value of the isopycnals slope is smaller than that found in March (0.5 % below the stratified layer) - maximal phytoplankton biomasses are observed just below the stratified layer (< 50 meters). The chlorophyll distribution seems to follow the general slope of isopycnals (σ_t 28.4 - 28.6). The highest concentrations (> 0.4 mgr. chl. A/m^3) are observed in the open sea at station 10, at 50 meter depth where alkalinity and density data show a divergence (figure 8) supplying an important nutrient concentration (LICOT, 1985).

During that period, accumulations of chlorophyll A are situated in the lowest level of the thermocline. At that level, the light intensity is reduced but sufficiently high nutrients concentrations are present.

Primary production in June is also maximum at the coast and offshore at the level of the seasonal thermocline. At the level of the haline front, primary production remains important (> 25 mg C^{-3} D^{-1}) despite a poor algal biomass. The productivity profile are quite different : coastal stations (1 - 3) with high productivity (800 - 1000 mg. C mg chl A^{-1}, D^{-1}) are separated from offshore stations of poor productivity (< 200 mg. C mg chl A^{-1} D^{-1}) by an horizontal gradient corresponding to the thermohaline front.

In October, a destabilization begins between 10 and 15 miles away from the coast (stations 3 to 5), while in offshore areas (stations 8 to 10), the distribution of maximal chlorophyll concentrations (> 0.7 mgr. chl A/m^3 at station 9) is similar to that observed in June. However, in the coastal area, chlorophyll A contents show a completely different pattern which is characteristic of that period : a maximum of chlorophyll A (> 0.8 mg chl A/m^3) is found below 100 m depth. Probably this accumulation of chlorophyll below the euphotic layer corresponds to the general trend of the coastal upper waters to destabilize. With the breakdown of the stratification, a return to the winter conditions is initiated.

In October, highest productions and productivities are found near the coast and at the level of thermohaline front.

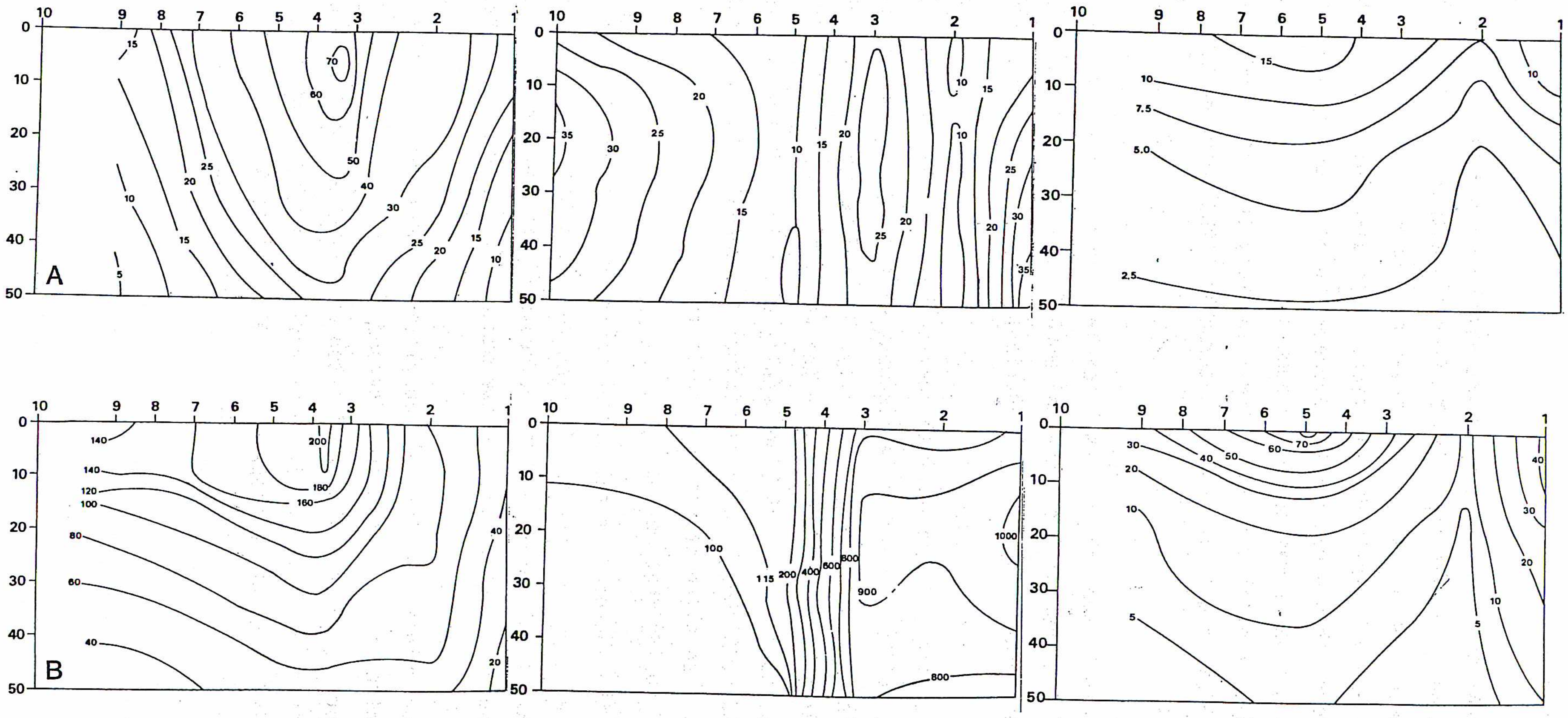

Fig. 9 : Distribution of primary production (mgC . m^{-3} . D^{-1}) (A) and primary productivity (mgC. mgChl A^{-1}.D^{-1}) (B) across Liguro-Provençal front in 1984 (LICOT, 1985).

CONCLUSIONS

Seasonal hydrological studies realized during 1984 show the presence of distinct water masses separated by fronts and thermoclines.

At these boundaries vertical movements occur as evidenced by temperature, salinity and alkalinity distributions. High alkalinity values characterize deep waters. This parameter has appeared to be an original and useful tool to study the water masses and movements.

The hydrological structures are relatively constant from year to year (LICOT, 1985) and their evolution throughout the year can be summarized as follows :

- In winter when the external forcing favours the mixing, an important haline front separates the coastal more stratified light pool from the waters of intermediate origin, nutrient-rich and undergoing high vertical mixing.

- In spring and summer, with surface heating a vertical stratification is induced, followed by the establishment of the seasonal thermocline, hence conducting to an increased stability. Hivernal water masses sink and the intermediate waters can not reach the surface. Destabilizing factors (such as winds, cold air masses) can locally generate divergences with rise of cold waters. Although vertical mixing is reduced by the presence of the thermocline, a shoaling of the isopycnals from the coast to the open sea is yet observed during that period.

- At the approach of the winter the thermal balance between the sea and the atmosphere reverses, leading to a destabilization of the water column and to the breakdown of the seasonal thermocline. Vertical mixing is enhanced and intermediate water masses can rise up to the sea-surface.

The description of the chlorophyllian pigments distribution in the upper layers along the transect is presented.

In spring, maxima of phytoplankton are found on the thermohaline front. In summer (June to October), chlorophyll maxima are situated below the stratified layer which slopes down from offshore to the coast.

The impact of frontal dynamics on primary production is well emphasized in our data.

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