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Water masses off the Central Cantabrian Coast*

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SUMMARY. Four water masses have been recognized in the Central Cantabrian Sea (Bay of Biscay). Surface Water, Central Water, Mediterranean Water and Deep Water Mediterranean Water flowed at about 1000 m depth with a mean salinity value of 35 799 PSU and sigma-*t* between 27 58 and 27 59 The percentage of Mediterranean Water within this area was 39 The lower limit of Central Water was 500 m The upper limit was variable throughout the year In spring and autumn surface waters flowed in an eastern direction and Central Water characteristics were similar to those previously described for other Atlantic regions During summer, superficial currents flowed to the West A very homogeneous Central Water, Bay of Biscay Central Water (BBCW), was also found Two features were related to the main circulation pattern. intrusions of high salinity Central Water in spring and autumn, whereas in summer Central Water upwelled at coastal stations During summer, a stepwise thermocline developed between 20 and 50 m, as a consequence of intense surface heating This thermocline did not usually separate two well differentiated mixed layers Water of continental origin was distributed in a thin layer all over the study area during summer, whereas in spring and autumn it was found close to the coast Two different stratification processes were recognized: a mainly thermal stratification in summer, and coastal stratification caused by salinity gradients the rest of the year

Key words. water masses, seasonal changes, Central Cantabrian Sea, Bay of Biscay

RESUMEN. MASAS DE AGUA EN EL CANTÁBRICO CENTRAL. — Se distinguen cuatro masas de agua en el Cantábrico central: Agua Superficial, Agua Central, Agua Mediterránea y Agua Profunda El Agua Mediterránea circula alrededor de los 1000 metros de profundidad, con una salinidad media de 35,799 USP y un valor calculado de sigma-*t* de 27,58-27,59 El porcentaje de Agua Mediterránea en la zona de estudio es de 39 El Agua Central presenta su límite inferior asociado a un mínimo de salinidad situado a 500 metros, en tanto que el límite superior varía a lo largo del año En primavera y otoño las características del Agua Central se ajustan a las definidas en otras zonas del Atlántico, con intervalos de variación de 11 a 13 °C en la temperatura y 35,53 a 35,74 USP en la salinidad En verano el Agua Central es muy homogénea y encaja en la definición de ACGV (Agua Central del Golfo de Vizcaya) Asociados al régimen de corrientes, tienen lugar dos fenómenos: 1) Cuando la dirección de las corrientes es Este, en primavera y otoño, se detectan intrusiones de agua de elevada salinidad para esta zona y 2) en verano, cuando la dirección es Oeste se producen ascensos de Agua Central en las estaciones costeras Las corrientes superficiales determinan también la distribución del agua de origen continental En verano, se distribuye en forma de lámina muy delgada ocupando toda la zona de estudio, mientras que, en primavera y otoño, queda retenida contra la costa Por otra parte, el calentamiento de la zona superficial, en verano, da lugar a la aparición de una termoclina escalonada de 20 a 50 metros Esta termoclina no siempre separa una capa superior mezclada por el viento del Agua Central En consecuencia, se observan dos tipos de estratificación de la columna de agua: estratificación fundamentalmente térmica en verano y estratificación salina en las estaciones costeras durante el resto del año

Palabras clave. masas de agua, variación estacional, Cantábrico central, Golfo de Vizcaya

INTRODUCTION

The knowledge of water motion, both in vertical and horizontal direction, is necessary to understand biological processes occurring in a given oceanographic area

Hydrographic studies in Spanish waters of the Bay of Biscay are scarce and limited to small areas (FLOS, 1979; ARIAS *et al*, 1980; FRAGA *et al.*, 1982, RÍOS *et al.*, 1987) Several papers concerning a wider spatial scale have been published (FRUCHAUD-LAPARRA *et al.*, 1976; LE CORRE and TREGUER, 1976; TREGUER *et al.*, 1979) but they do not include the Spanish continental shelf

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Regional phenomena such as tidal fronts (FOGG *et al.*, 1985), shelf-break upwelling (PINGREE, 1979; DICKSON *et al.*, 1980) and coastal upwelling (DICKSON and HUGHES, 1981; BOTAS *et al.*, in press) contribute to most of the primary production in coastal waters of the Bay of Biscay.

An intensive description of deep water masses was not the main objective of this study. In this paper we describe the seasonal trends of water masses distribution in the upper layer (0-500 m), mainly those changes in the Central Water and the influence of water from continental origin on the development of water column stratification. Both processes were related to changes in the direction of surface currents. Most of the conclusions emerging from this study are not definitive, but new descriptive and experimental sampling designs can be performed on the basis of the results presented herein.

METHODS

Three transects perpendicular to the Central Cantabrian coast were sampled monthly during 1987 (Fig. 1). Water samples were taken at 0, 10, 20, 30, 40, 50, 75, 100, 125, 150, 200 and 250 m. At stations 13, 14, 24 and 25 deep water samples (300, 400, 500, 600, 700, 1500 and 1700 m) were taken every three months.

Water temperature was measured with Watanabe reversible thermometers attached to Niskin oceanographic bottles. Sampling depths were corrected using non-protected thermometers. Temperature data are referred as "in situ" temperature.

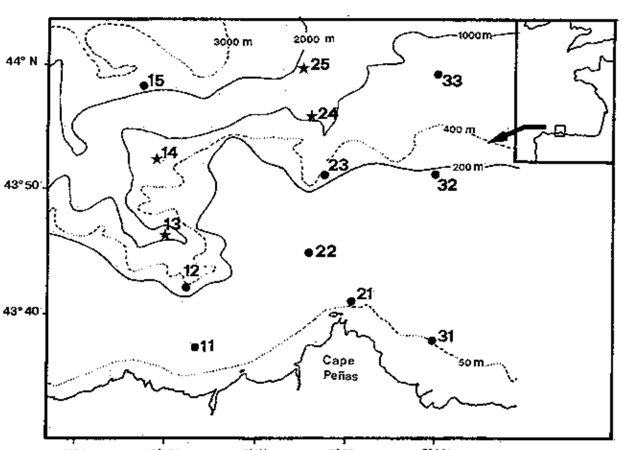


FIG. 1 — Map of the sampling locations. Asterisks represent the stations sampled up to 1700 m every three months.

Salinity was measured with a Watanabe MKIII induction salinometer calibrated with normal water (I.A.P.S.O.). Salinity in practical salinity units, was calculated using equation number 6 (UNESCO, 1984). Density was calculated from equation number 9 (UNESCO, 1984) and the values transformed to sigma-*t* as follows:

$$\text{Sigma-}t = (\varrho_{s,t,o} - 1) \times 100$$

where $\varrho_{s,t,o}$ is density at atmospheric pressure.

Dynamic topography maps were drawed from the dynamic heights calculated using the dynamic method. The reference level was 1000 m. This depth is recognized to be a lowmotion layer in this area (FRAGA, com. pers.)

The Brunt-Väisälä frequency was obtained as:

$$N^2 = (-g/\varrho) \times (\partial\varrho/\partial z) \quad \text{(PHILLIPS, 1966).}$$

Frecuency data are expressed as $N \times 10^2$.

The total volume of water from continental origin within the study area was calculated using the mean salinity value of the BBCW, 35.57 PSU (TREGUER, *et al.*, 1979) as the reference water. Underestimations of the amount of low-salinity water going into the ocean may occur in some months, because of the occasional presence of water with higher salinity than the BBCW.

RESULTS AND DISCUSSION

Figure 2 shows the T-S diagrams for all the samples grouped as follows: 2*a* (March, April, May), 2*b* (June, July, September) and 2*c* (January, October and December). Four water masses were distinguished:

— Surface water, originated from mixing between the upper layer and Central Water, were characterized by the highest temperature and the lowest salinity values.

— North Atlantic Central Water (NACW) (SVERDRUP *et al.*, 1942), with temperature values varying between 11 and 12.5 °C (Fig. 2*a*, 2*b* and 2*c*).

— Mediterranean Water (MW) (Fig. 2*a* and 2*b*). It was identified underneath the NACW region. Salinity increased continuously, reaching the maximum value around 1000 m depth.

— Points below 1000 m depth corresponded to mixing between MW and deep water

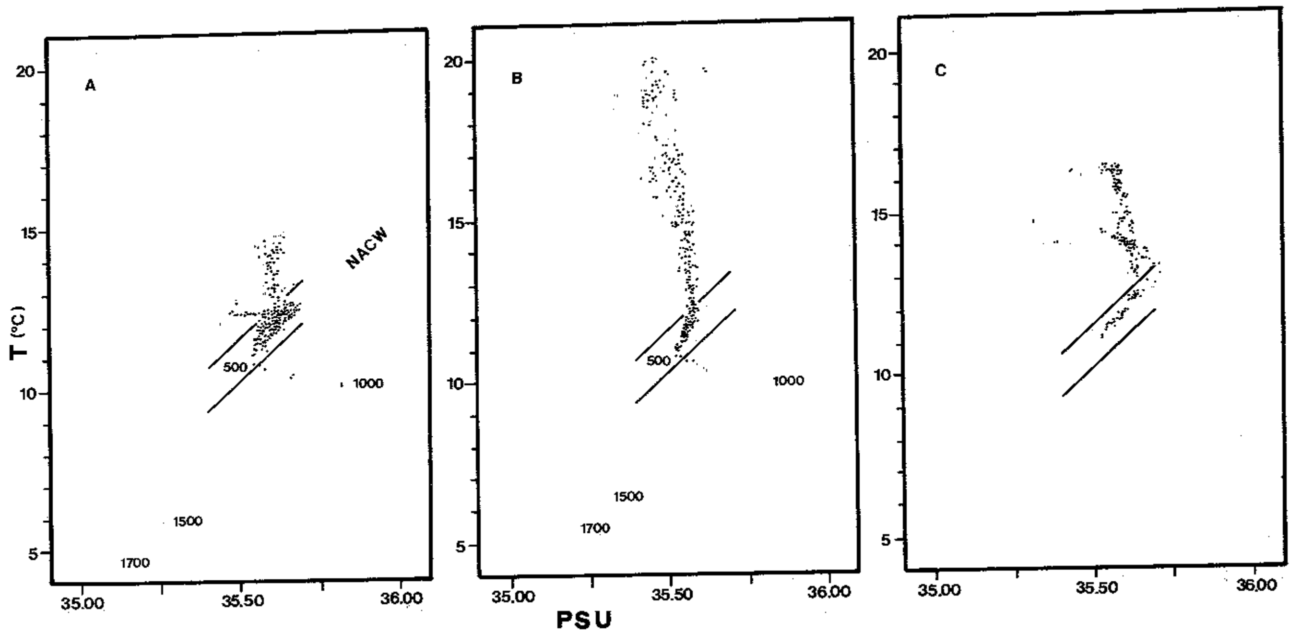


FIG 2 — Global T-S diagrams in spring (A), summer (B) and autumn (C) Steep lines represent NACW

Mediterranean Water

A salinity maximum was found at a depth of 1000 m. This is consistent with the mean depth at which MW flows in the Bay of Biscay (LE FLOCH, 1969) This salinity maximum exhibited small variability throughout the year. The lowest salinity within this water mass was measured in January at station 25 (35.799 PSU and 10 °C), whereas the highest value was found in April at station 24 (35.820 PSU and 10.1 °C). RÍOS *et al* (1987) had found higher salinity variations in this area (from 35.79 to 35.94 PSU) the year before In addition, LE FLOCH (1969) reported an eddy circulation of MW. Our results did not closely agree with those, but these differences can be attributed both to the reduced number of data we present and to the vertical sampling scale used

The sigma-*t* values calculated for the MW, ranged from 27.58 to 27.59, close to the mean value reported by LE FLOCH (1969) for the whole Biscay Bay basin (25.60).

The percentage of MW within the study area was calculated using the mixing triangle method (MAMAYEV, 1975). The reference values were T = 11.9 °C and S = 36.5 PSU (FRAGA *et al.*, 1982). The values defined by the deep salinity minimum were taken as reference values for Central Water, whereas the values reported by FRAGA *et al.* (1982), T = 3.4 °C and S = 34 89 PSU were used as reference values for deep water A percentage of MW of 39 % was found, in agreement with the data reported by RÍOS *et al.* (1987) in the same area.

Central Water

The lower limit of Central Water is characterized by a salinity minimum (FRAGA *et al.*, 1982) located around 400-500 m depth. The upper limit was not well-defined and varied throughout the year. During spring (Fig. 2*a*) and autumn (Fig. 2*c*) Central Water characteristics were similar to those described in other Atlantic areas (SVERDRUP et al., 1942; FRAGA *et al.*, 1982; EMERY & MEINCKE, 1986). Central

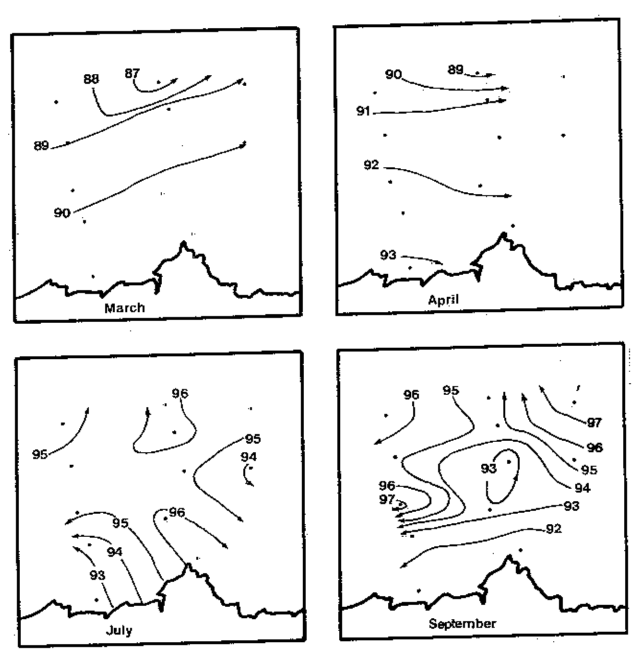


FIG 3 — Surface geopotential topography Height in dynamic centimetres. Reference level is 1000 m depth

Water temperature ranged between 11 and 13 °C, and salinity between 35.53 and 35.74 PSU.

TREGUER et al. (1979) and FRAGA et al. (1982) found a homogeneous water in this area, with salinity and temperature values ranging from 35.56 to 35.58 PSU and from 11 to 11.6 °C respectively. This water mass was identified as type G water of TREGUER *et al.* (1979) and BBCW of FRAGA *et al.* (1982). COOPER (1949) located its origin on the shelf of the Celtic Sea, where this water mass becomes colder during winter and sinks with intense mixing.

Figure 2*b* represents T-S diagrams for summer Central Water distributes in a very short portion of the Central Water straight line, according to the homogeneous characteristics of BBCW. The salinity and temperature values we measured within this water body was 35.53-35.58 PSU and 11-11.8 °C, respectively.

As pointed out by SVERDRUP *et al.* (1942), water masses characteristics within a given area depends on three different factors: latitude, isolation and water motion. If two of them remain constant, the variability observed in the water mass can be explained by the third factor. In the area studied latitude and isolation were constant and therefore, the Central Water variability can be explained in terms of water motion.

Surface water off the Central Cantabrian coast flowed to the west in summer, whereas during winter it flowed in the opposite direction (FRAGA *et al.*,

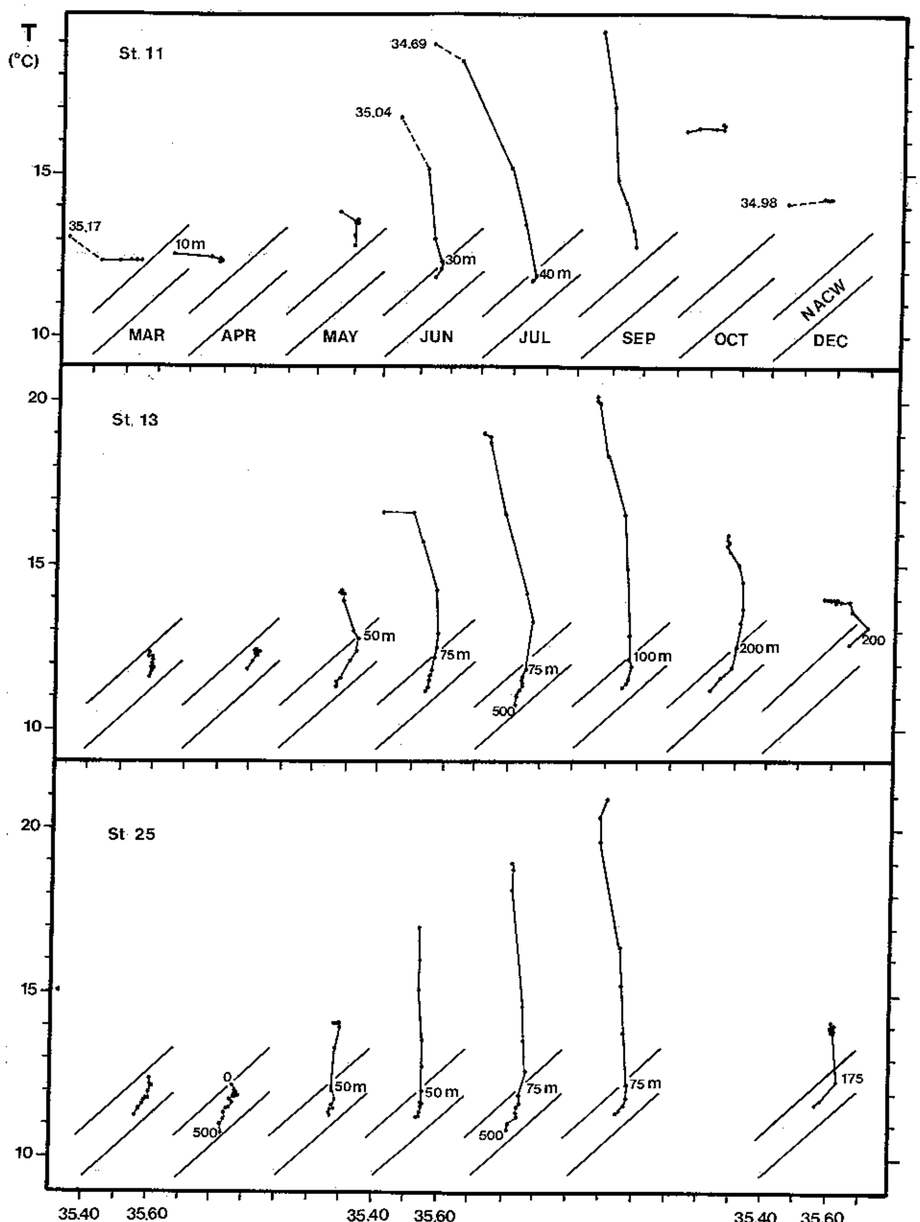


FIG 4. — T-S diagrams for the stations 11, 13 and 25 throughout the sampling period

1982; Ríos *et al.*, 1987). This was supported by the data of dynamic topography (Fig. 3). During spring an intrusion of high salinity water was originated by the movement of a surface current to the East (BOTAS *et al.*, 1988). Its origin was determined based on Central Water characteristics described by FRAGA *et al.* (1982) off the North coast of Galicia. Similar intrusions in surface waters of the Bay of Biscay have been also described by BARY (1963). They are responsible of the existence of the upper portion of the Central water straight line During summer surface currents flowed to the West, and as a consecuence, BBCW appeared in the area.

The vertical distribution of Central Water in different seasons can be described with the aid of T-S diagrams (Fig. 4). The upper portion of the NACW straight line appeared in spring and summer at the shelf-break station 13 and at the oceanic station 15. It was not found at the coastal station 11. Water from continental origin was responsible of the low salinity values observed at the surface layer (0-20 m) at the coastal station 11. During summer however, Central Water rose up to 30-40 m owing to northwest winds that prevailed during this season. At deeper stations, Central Water was always present, with the upper limit showing seasonal variations. In March and April, Central Water mixed with surface water and generated a homogeneous layer. Thoroughout the summer, the upper limit became deeper, reaching 75 m at the end of this season as a result of surface heating. In autumn, after a period of incomplete mixing, the upper limit reached the maximum depth, around 150-200 m.

Surface Water

Atmospheric changes and inputs of freshwater from rainfall or from continental origin are responsible of the high variability observed in surface water. In addition, the pattern of circulation and the Central Water, which appear underneath, can also modify the main characteristics of this water mass. In this

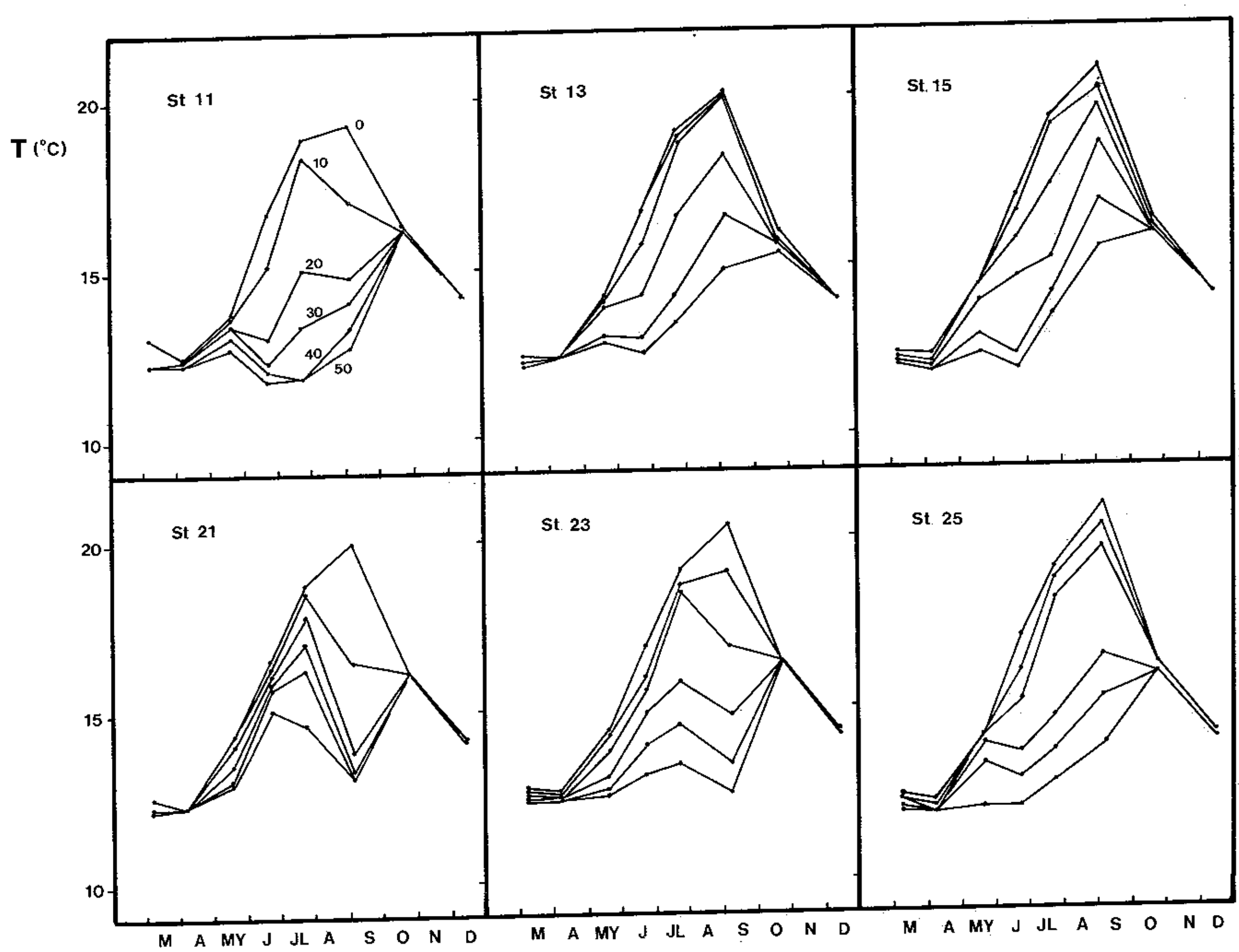


FIG 5 — Seasonal temperature variation between 0 and 50 m at the station 11, 13, 15, 21, 23 and 25 section we discuss the role of surface heating and river run-off in relation to the development of water column stratification.

Temperature distribution

Figure 5 shows how seasonal changes in solar energy flux modify water column structure close to the coast, at the shelf-break and at outer-shelf stations. During winter and early spring, water column temperature is homogeneous (Δ °C $m^{-1} \leq 0.01$). The minimum temperature was measured in April (12-12.5 °C). In May, surface heating was too high to be dissipated by mixing. Thus, a gradient was developed and consequently, heat flux downwards is reduced (PINGREE *et al.*, 1976). From May to July the upper layer temperature increased at a constant rate, reaching the maximum value in September (19.3-20.9 °C). At the layer below, temperature increased at a lower rate and a timelag with respect to the layer above was observed.

An abrupt decrease in temperature related to advection processes was detected in some occasions. Unless advection of cold water from deep layers occurred, a continous increase in temperature would take place due to diffusion (BOWDEN, 1983). Advection of cold water is more intense close to the coast in transect 1. As stations became deeper (13, 15 and 25) the decrease in temperature was less intense, and ocurred to a depth of 30 m in June. In September, cooling of surface water reached 10 m at stations 21 and 23. The maximum intensity of this phenomenon occurred at station 11 in June, when cold water was

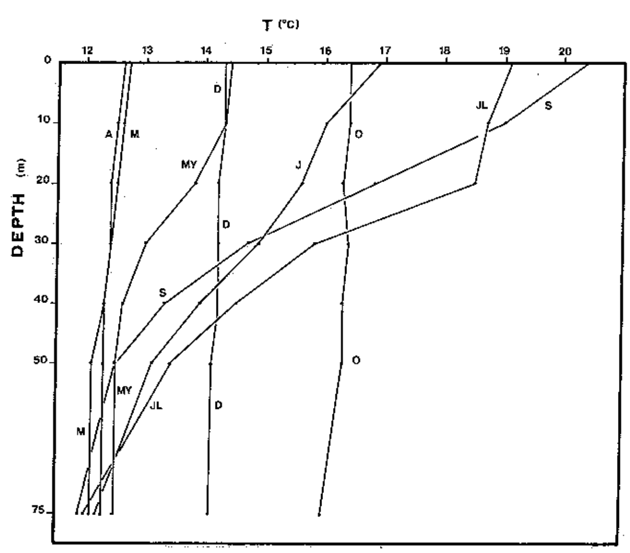


FIG 6. — Vertical distribution of temperature at the stations 23 during the sampling period

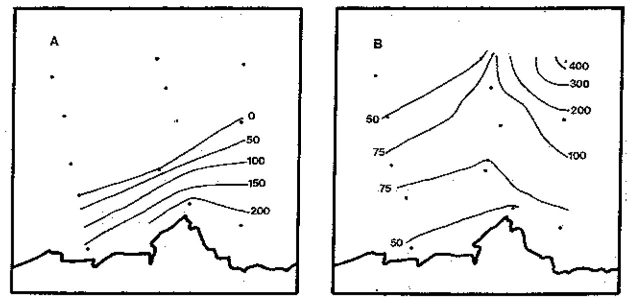
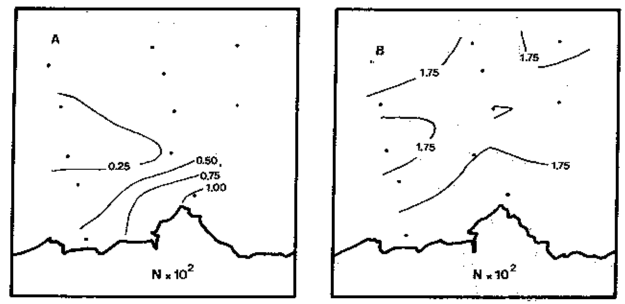


FIG 7 — Spatial distribution of water from continental origin during April (A) and September (B). Units are dm^3 m^{-2}



IG 8. 8 Spatial distribution of the Brunt-Väisälä frecuency calculated between 0 and 50 meters expressed as N × 10^2 Units are s^{-1}

located at 20 m. This event continued at lower intensity until September.

Both, the difference in surface temperature between coastal and offshore stations (1.8 °C) and the circulation pattern during summer (Fig. 3*c*), suggest a rise of Central Water that tends to balance the wind-driven transport of surface water. The advection process is probably reinforced by the topographic effect of Cape Peñas. From September, surface water began to become cooler. The decrease in temperature and early autumn storms broke up the thermocline, giving rise to thermal homogeneity in October.

The vertical distribution of temperature at station 23 throughout the year is shown in figure 6. The temperature gradient begun to develop in May, associated to a continuous decrease of 1.8 °C from 0 to 40 m. This gradiental situation increased during summer, reaching its maximum development in September when a difference of 7 °C between 0 and 50 m was detected. It is noteworthy that the thickness of the surface mixed layer was very small, usually less than 20 m.

Higher water column stability, was originated by thermal gradient. This is reflected in figure 8*b* where the Brunt Väisäla frequencies for September were plotted. Frequencies were high at all stations ($N = 1.75 \cdot 10^{-2}$).

Water from continental origin

Surface currents determine the distribution of low salinity water. During spring, surface water flowed to the East keeping low salinity water close to the coast (Fig. 7*a*). During summer, an inverse surface current direction, spread this water all over the study area in a thin layer and, at the same time, low salinity water from the inner part of the Bay of Biscay came into this region.

Water from continental origin, besides its role as carrier of nutrients into the marine photic layer, is of great importance in the development of water column stratification when there are not thermal gradients. This phenomenon can be observed in March and April when the vertical distribution of temperature was homogeneous but the distribution of the Brunt-Väisälä frequency exhibited a gradiental pattern which followed the distribution of low salinity water.

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