

A Persistent Upwelling off the Central Cantabrian Coast (Bay of Biscay)

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North Atlantic Central Waters were detected near the surface in some locations off the Central Cantabrian Coast (Bay of Biscay). This feature suggests an upwelling process taking place in the season of the thermal stratification which is persistent throughout the summer. The exact mechanism of formation is unknown but the wind driven currents are probably the main force. The prevailing winds off the Cantabrian coast are northeast during summer, generating westward superficial currents that produce an Eckman transport offshore. Factors such as shape of the coast and slope topography maybe modulators. Although the upwelling was subsuperficial, our results suggest that cold and nutrient rich waters reached the surface previously.

The biomass distribution of phytoplankton varied according to the upwelling and different populations could be recognized. In stations not affected by upwelling phytoplankton occurred mainly on top of the thermocline, whereas in those affected by upwelled waters it was concentrated near the surface. The mean size and composition of the populations were also different, and two distinct types could be recognized and related to nutrient concentrations.

Introduction

The literature available regarding coastal oceanography of the Cantabrian Sea (Bay of Biscay) is scarce and does not give sufficient information on the seasonal trends in physical, chemical and biological parameters. Treguer *et al.* (1979) and Fraga *et al.* (1982) pointed out the homogeneity and distinctive characteristics of the North Atlantic Central Water in this area. The general pattern of circulation is not coupled to the North Atlantic current, the mean current velocity being very small (Maillard, 1986). In addition, diverse cyclonic and anticyclonic eddies seem to be the principal features of the surface circulation (Howe & Tait, 1967; Pingree, 1979; Dickson & Hughes, 1981).

Regional phenomena could be more important concerning biological productivity than general circulation. Tidal mixing fronts enhanced primary productivity in some shallow-seas (see Fogg *et al.* 1985) and, moreover, slope upwellings have been described along the edge of the Armorican shelf (Pingree, 1979; Dickson *et al.*, 1980).

Dickson and Hughes (1981) suggested coastal upwelling near Cape Peñas explained the presence of surface cold water detected by satellite imagery. Also, recent studies carried

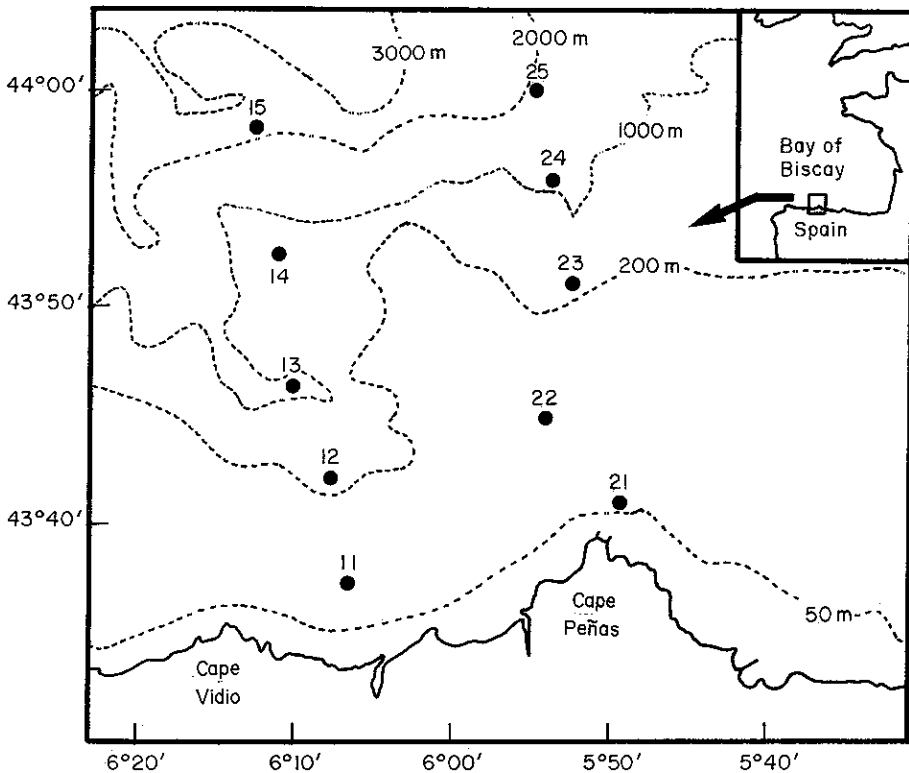


Figure 1 Map of the sampling locations

out by Rios *et al.* (1987) showed a narrow fringe of surface cold water along the western Cantabrian coast during summer.

The aim of this paper is to describe the temporal variations in chemical and biological parameters of the coast off Cape Peñas, and to evaluate the biological consequences of the summer Cape Peñas upwelling reported by Dickson and Hughes (1981) and Rios *et al.* (1987).

Materials and methods

Three cruises were run aboard the *R/V Noega* in Spanish waters of the Central Cantabrian Sea from 23 June to 4 September 1987. Ten stations, located along two transects perpendicular to the coast, were studied monthly at depths down to 1700 m (Figure 1).

Five litre Niskin bottles equipped with reversible thermometers were used. Salinity was measured with an inductive salinometer Watanabe (Mark III). Nutrient samples were prefiltered onto a 200 μm mesh and stored deep frozen -20°C until analysis in the laboratory. Nutrient concentrations were determined using an Autoanalyzer Technicon AAI. The methods for nutrient analysis are described in Grasshoff *et al.* (1983).

Surface currents were calculated by the dynamic method (Fomin, 1964), with 1000 m depth considered as a no motion layer in this area (Fraga, pers. comm.). Results derived from this method must be interpreted with caution, but general trends can be distinguished.

TABLE 1 Limits of the particle size-classes measured by the Coulter Counter (R)

Class	ESD* inferior (μm)	ESD superior	Mean volume (μm^3)
SC2	2.68	3.38	11.32
SC3	3.38	4.25	22.65
SC4	4.25	5.36	45.29
SC5	5.36	6.75	90.58
SC6	6.75	8.50	181.16
SC7	8.50	10.71	362.32
SC8	10.71	13.50	724.64
SC9	13.50	17.01	1449.28
SC10	17.01	21.43	2898.56
SC11	21.43	27.00	11594.24
SC12	27.00	34.02	23188.48
SC13	34.02	42.86	46376.96
SC14	42.86	54.00	92753.92
SC15	54.00	68.04	185507.84
SC16	68.04	85.72	371015.68

*ESD, equivalent spherical diameter

Water samples (250 ml) were filtered through Whatman GF/C glass fibre filters and chlorophyll *a* concentrations were determined by fluorometric analysis (Yentsch & Menzel, 1963; Holm-Hansen *et al.* 1965). Phytoplankton cells were identified and counted using the sedimentation technique. Seston was analysed with a Coulter Counter TALL, setting and calibrating the apparatus to particles in the size range of 3 to 80 μm of equivalent spherical diameter (ESD). The limits of the considered size classes are given in Table 1).

Results

Hydrographic parameters

Three water masses were identified in the zone (Figure 2). The surface waters were the most variable and they presented the lowest values of salinity and highest of temperature. The North Atlantic Central Water (NACW) appeared with some modified characteristics (Figure 2). Fraga *et al.* (1982) named this water Biscay Bay Central Water (BBCW) and defined its typical range of salinities between 35.54 and 35.58‰, and temperatures from 10.9 to 12.0 °C. The BBCW was mixed with the Mediterranean Water (MW) to a depth of approximately 1000 m.

Surface currents in July and September are shown in Figure 3. In July, an offshore current could be detected in transect 1, whereas in transect 2 surface waters moved towards the coast. In September, a general westward trend in the superficial currents in both transects could be recognized.

The main variations occurred near the coast. In June, the surface waters of Station 11 had the lowest salinity values (Figure 4). In addition, the subsuperficial waters of Station 11 were different, with the BBCW at 40 m depth while in Station 12 that water type appeared at 75 m. The distribution of temperature, sigma-*t* and nitrate (Figure 5) indicate the stratification of the surface waters except at Station 21 where homogeneity between 10 and 40 m prevailed. The isopleths of the variables for section 1 showed an undulated shape and an upward trend near the coast. In contrast, the slope of the sigma-*t* lines for section 2

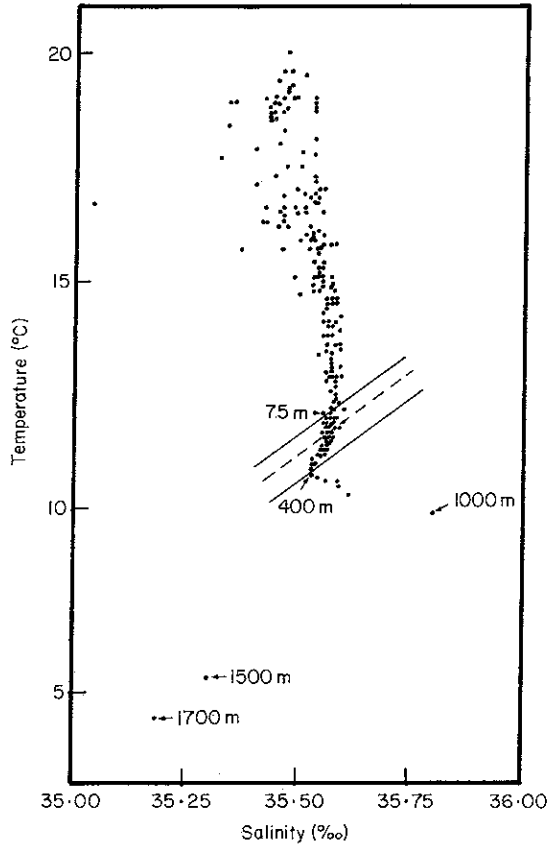


Figure 2. Global T-S diagram. Steep lines represent the range of North Atlantic Central Water

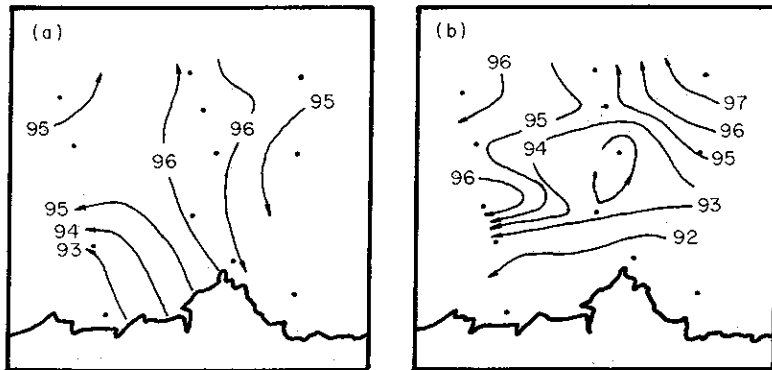


Figure 3. Geopotential topography in (a) July and (b) September. Height in dynamic centimeters

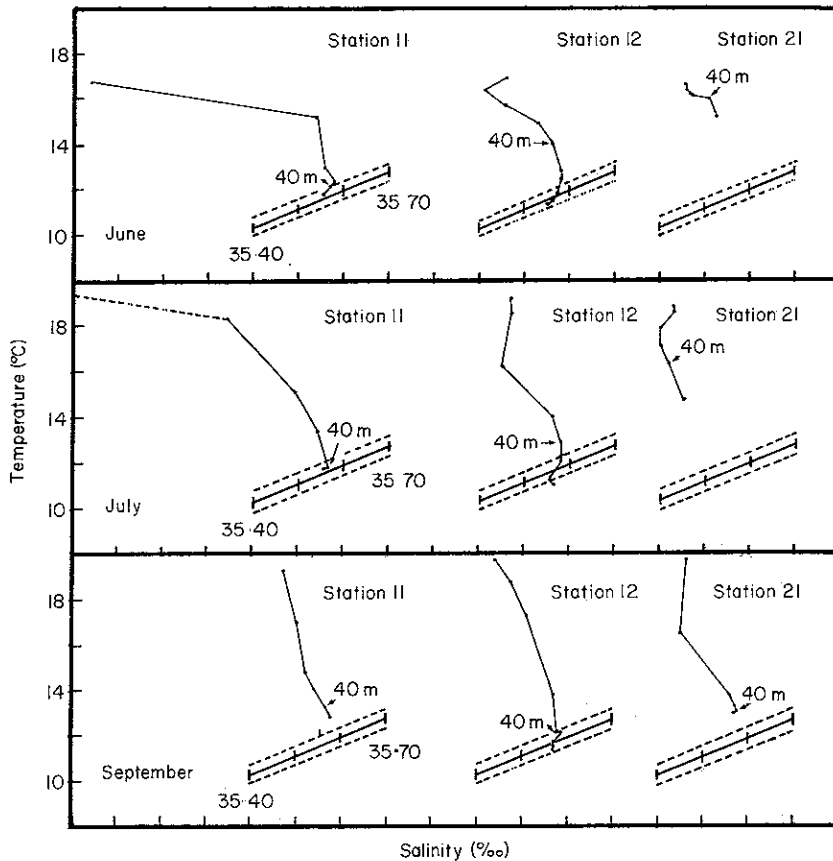


Figure 4. T-S diagram for the stations affected by upwelling. Dashed lines represent the range of NACW. Sampling depths are 0, 10, 20, 30, 40, 50, 75, 100 and 125 m

was in the opposite direction, showing downwelling of surface waters. The nitracline did not follow the fluctuations of a singular σ_t line. It was related to a different σ_t value depending on the proximity to the coast, from 26.25 nearshore to 26.75 offshore.

As the summer progressed the coastal surface waters became less saline and warmer (Figure 4). The distribution of variables in June and July was quite similar, although an undulated shape could not be detected in transect 1 (Figure 6). It is also noteworthy that marked stratification and a 15–20 m wind-driven mixed layer occurred at all the stations except the upwelled Station 11.

In September, the influence of continental water on the surface was negligible (Figure 4). Both transects showed similar characteristics with cold water below 30 m at Stations 11, 12, 21 and 22. Surface nitrate concentration was higher in section 2. At the stations with no upwelling, the nitracline became deeper (Figure 7).

Biological parameters

Deep chlorophyll maxima (DCM) were found in June at all stations between 30 and 40 m deep, except at the innermost stations on the two shelf sections (Figure 8a). In transect 1 isopleths showed a shorewards gradient.

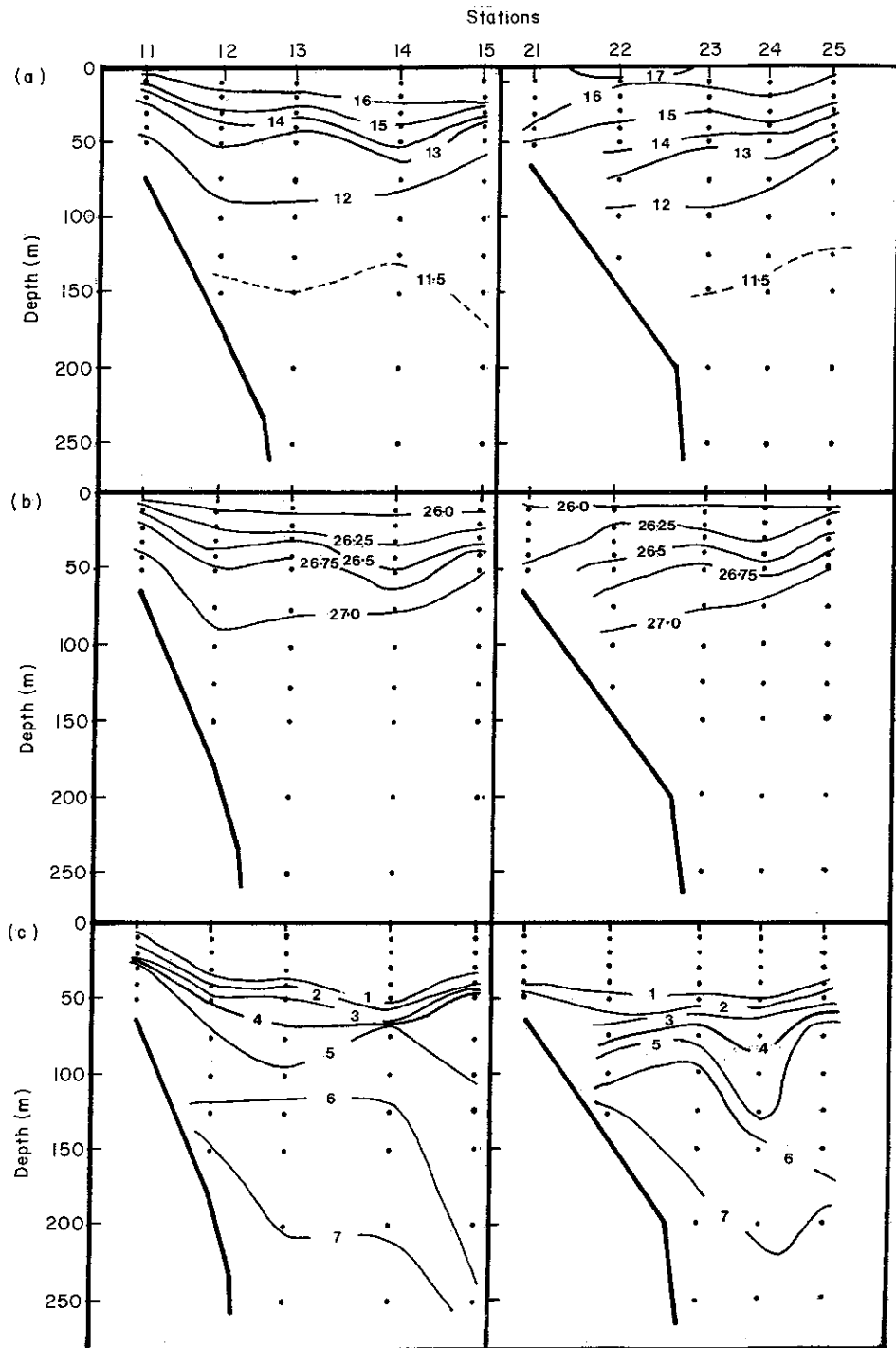


Figure 5. Vertical distribution of (a) temperature ($^{\circ}\text{C}$), (b) $\sigma\text{-}t$ and (c) nitrate concentration ($\mu\text{mol kg}^{-1}$) in June

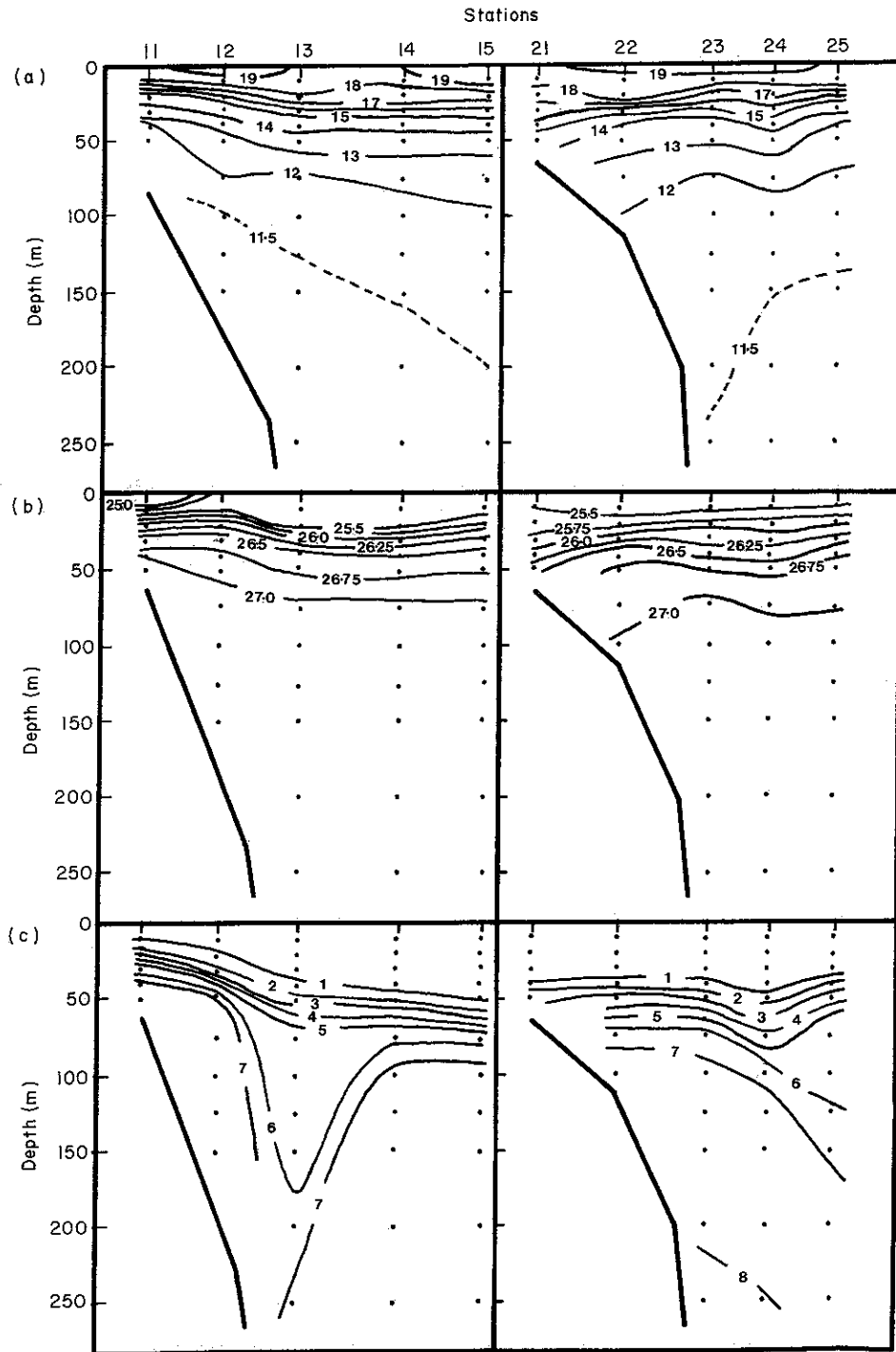


Figure 6. Vertical distribution of (a) temperature ($^{\circ}\text{C}$), (b) sigma- t , and (c) nitrate concentration ($\mu\text{mol kg}^{-1}$) in July

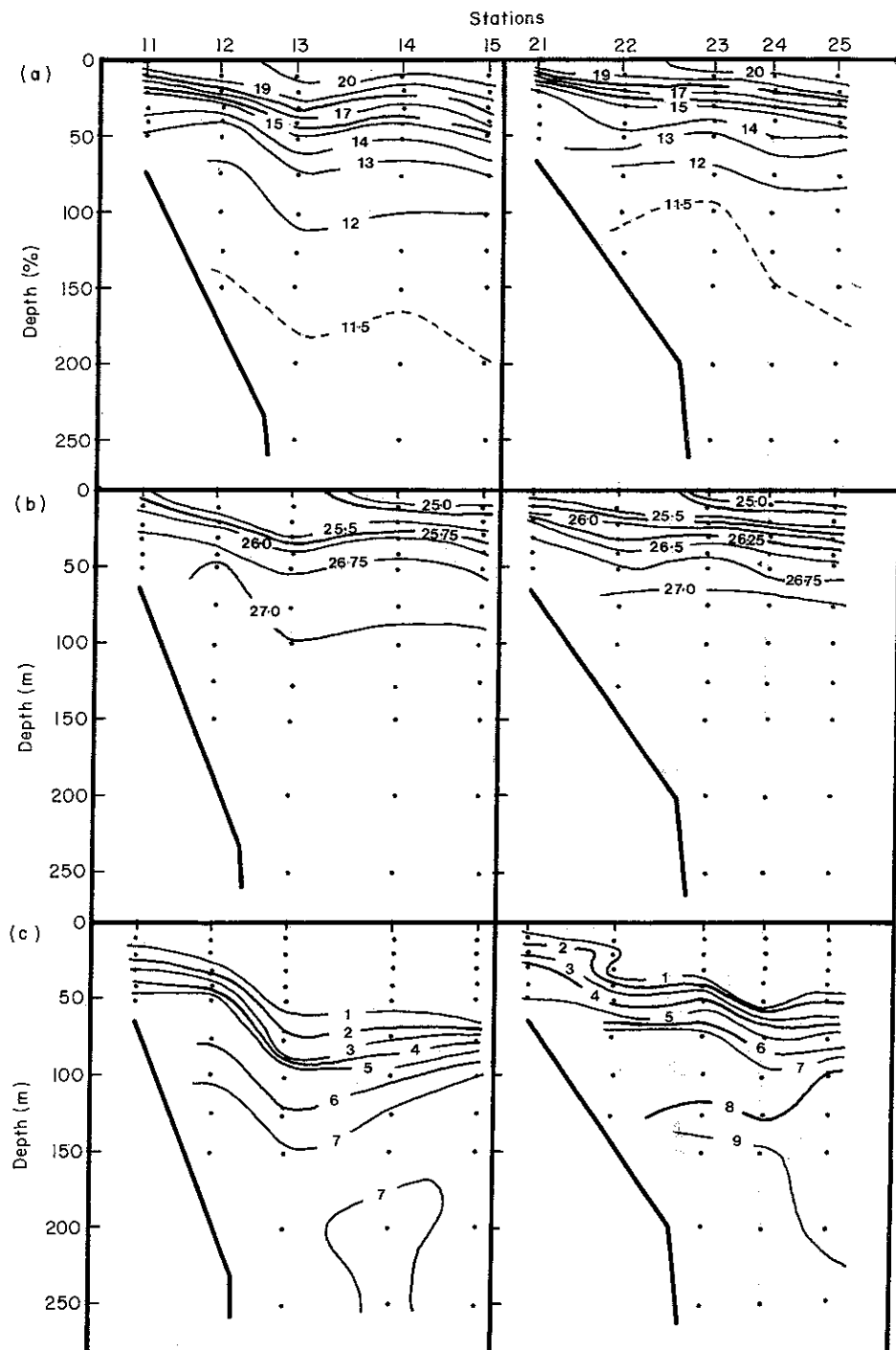


Figure 7. Vertical distribution of (a) temperature ($^{\circ}\text{C}$), (b) $\sigma\text{-}t$ and (c) nitrate concentration ($\mu\text{mol kg}^{-1}$) in September

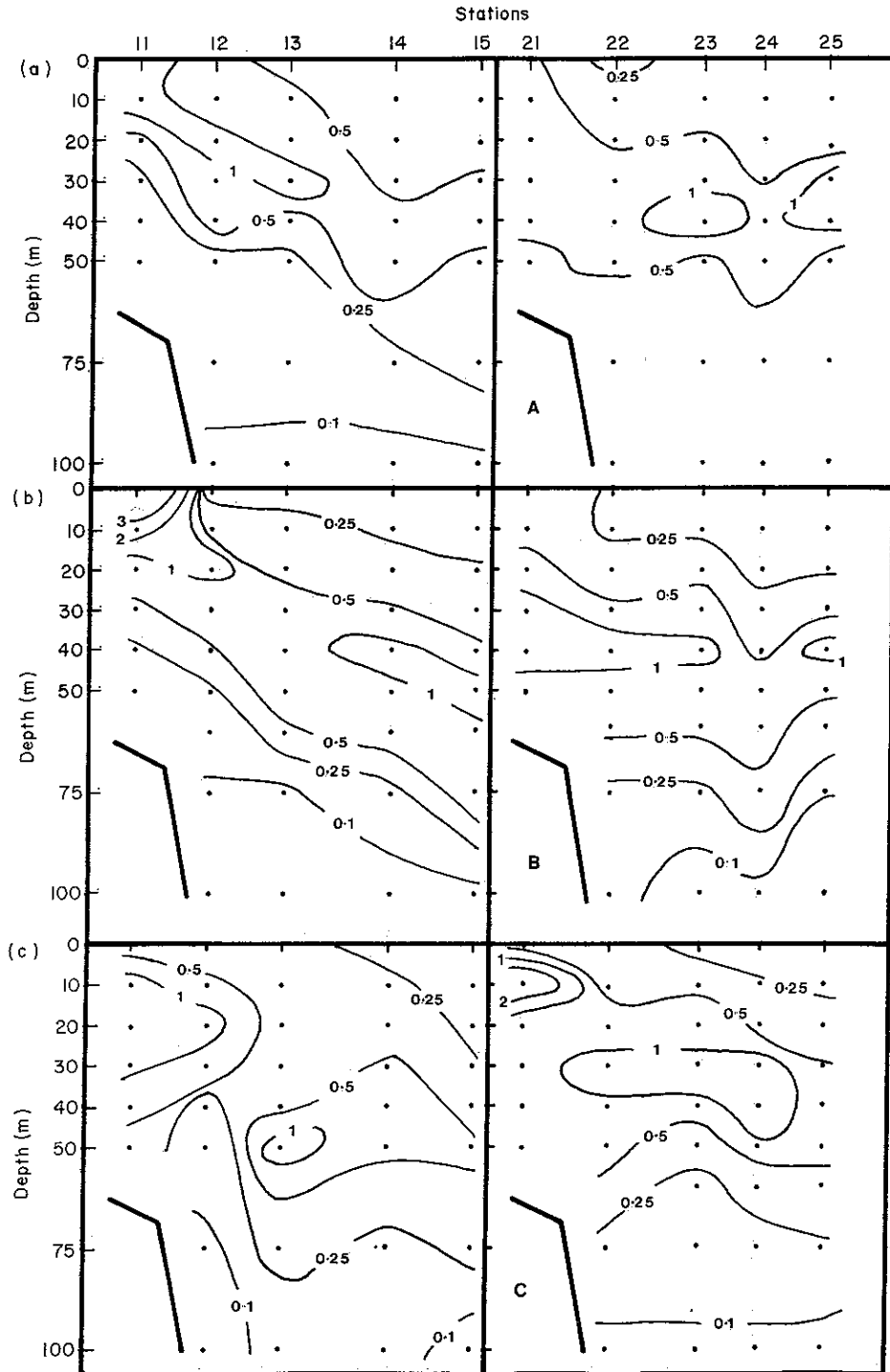


Figure 8. Vertical distribution of chlorophyll-a concentration ($\mu\text{g.l}^{-1}$) in June (a), July (b) and September (c)

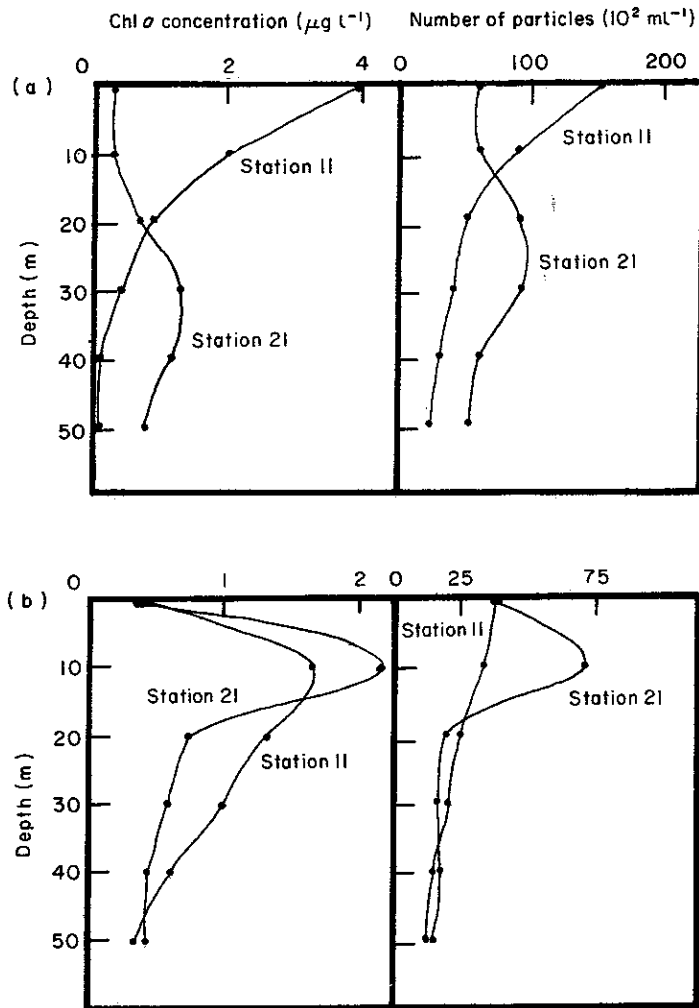


Figure 9. Vertical profiles of chlorophyll (a) concentration and number of particles at the Stations 11 and 21 in (a) July and (b) September

In July, chlorophyll distribution in the euphotic zone varied inversely with temperature. DCM were found at all stations except Station 11 (Figure 8b), nevertheless surface waters with high phytoplankton biomass ($4 \mu\text{g Chl-a l}^{-1}$) were located close to the coast. Clear differences appear in the shapes of the profiles of the variables from Stations 11 and 21 (Figure 9a). The profile for Station 21 was sigmoidal with maximum values at the bottom of the mixing layer, whereas an exponential decrease occurred at Station 11. In Figure 10, particle size distribution of the chlorophyll maximum at upwelled stations were compared with the same depth at nonupwelled stations in July and September. Particle size distribution at the surface from Station 21 (Figure 10) was more uniform than that of Station 11, where two modes could be distinguished at 7 and 21 μ mean ESD. This is in agreement with phytoplankton composition. Diatoms formed the bulk of the phytoplankton in this high biomass area, being *Bacteriastrum hyalinum*, *Nitzschia* c.f. *delicatissima*, *Nitzschia longissima*, *Leptocylindrus danicus*, species of the genus *Chaetoceros* and the

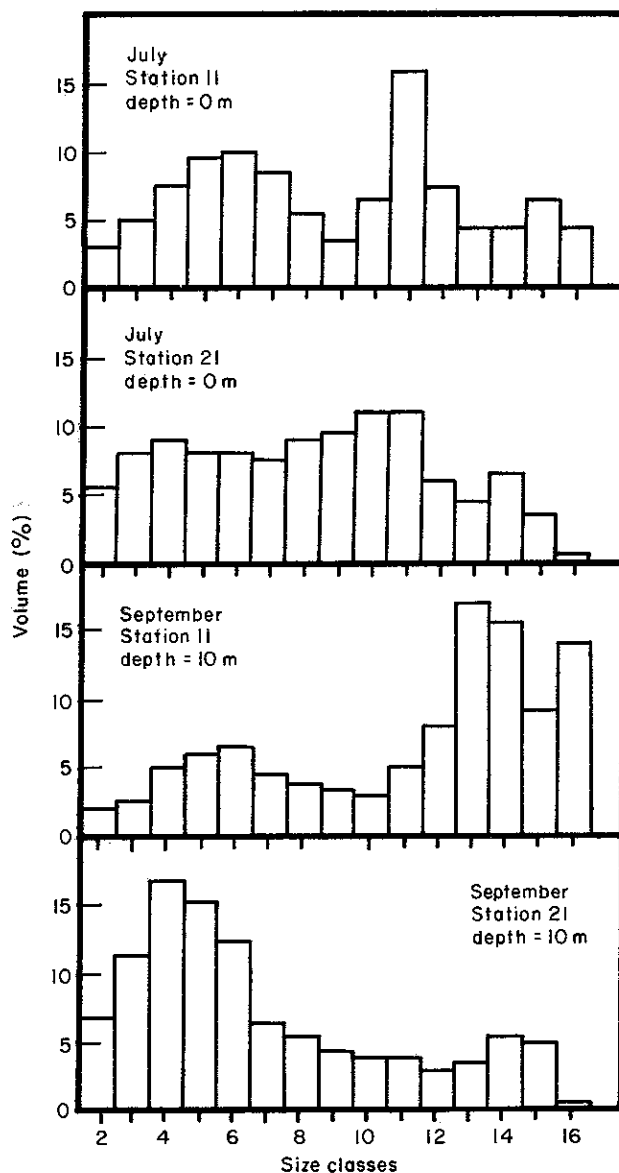


Figure 10. Particle size distributions observed at the stations 11 and 21 in July and September. The depths represented correspond to the chlorophyll maximum of the upwelled station.

small dinoflagellate *Cachonina nesi*, as well as microflagellates which predominated in the samples. The total cell number was higher than $250 \text{ cells ml}^{-1}$ (Table 2). These chlorophyll maxima were associated with the upwelling of nutrient-rich water described above. At the nonupwelled station (Station 21) the deep chlorophyll maximum was located at a depth of 30 m, and small dinoflagellates and microflagellates accounted for a high percentage of the total number of cells (63 cells ml^{-1}) (Table 2).

In September maximum phytoplankton biomass was found between 30 and 40 m at all stations except at those coastal stations where the DCM was located at 10 m. A high

TABLE 2. Cell number (cells ml⁻¹) of the most abundant species at the Stations 11 and 12 in July and September. The depths represented correspond to the chlorophyll maximum of the upwelled station

Species	July (depths, m)				September (depths, m)			
	Station 11		Station 21		Station 11		Station 21	
	0	30	0	30	0	10	0	10
Bacillariophyceae:								
<i>Bacteriastrium hyalinum</i>	41.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0
<i>Chaetoceros decipiens</i>	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Chaetoceros</i> spp.	2.8	0.3	0.0	1.6	0.0	0.0	0.0	0.1
<i>Chaetoceros</i> spp. small	4.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Hemiaulus hauckii</i>	0.0	0.0	0.0	0.0	0.2	0.0	0.3	0.1
<i>Leptocylindrus damicus</i>	12.4	0.4	0.1	4.3	0.0	0.3	0.0	0.7
<i>Nitzschia</i> c.f. <i>delicatissima</i>	31.8	2.1	0.0	2.0	0.8	0.9	0.0	0.0
<i>Nitzschia longissima</i>	13.2	0.7	0.0	1.5	0.0	0.0	0.0	0.0
<i>Rhizosolenia fragilissima</i>	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Small unidentified diatoms	1.2	0.9	0.0	0.0	0.0	1.2	0.0	0.0
Other diatoms	0.3	0.0	0.0	0.2	0.0	0.6	0.0	1.2
Dinophyceae:								
<i>Cachonina niei</i>	30.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
<i>Ceratium furca</i>	0.0	0.0	0.0	0.0	0.1	0.2	0.1	0.1
<i>Oxitoxum variabilis</i>	0.0	0.0	0.3	0.6	0.0	0.0	0.0	0.0
<i>Prorocentrum balticum</i>	3.6	0.0	0.9	0.0	0.0	0.0	0.0	0.0
<i>Prorocentrum micans</i>	0.4	0.0	0.1	0.1	0.0	0.0	0.0	0.0
Small naked dinoflagellates	15.6	1.2	6.0	22.8	3.6	3.6	1.8	6.0
Other dinoflagellates	0.4	0.0	0.4	1.4	0.7	1.9	0.6	1.2
Flagellata:								
Microflagellates	105.6	2.7	7.2	33.6	10.8	16.2	12.0	44.4
Total cell number	263.9	8.3	15.1	68.1	16.2	24.9	14.7	53.9

phytoplankton biomass concentration of 2.24 µg Chl-a l⁻¹ was measured at station 21 (Figure 8c). These features were in accordance with a change of position of the upwelling. Related with this event, Station 21 showed low phytoplankton biomass below 20 m. The depth profiles of chlorophyll and particle number for Station 11 and 21 were quite similar in shape, although subsurface particle maximum at Station 21 could not be detected. Particle size distributions at 10 m showed main peaks at 4 µm mean ESD for Station 21 and 34 µm ESD for Station 11 (Figure 9). Microflagellates and small naked dinoflagellates were the most abundant groups of the phytoplankton at Station 21, whereas at Station 11 population density was lower (Table 2) and the dominant cells were microflagellates, some medium-sized diatoms (*Nitzschia* 'delicatissima-like'), small diatoms and large flocs of detritus.

Discussion

The results presented here indicate that BBCW upwelled waters pushed up the seasonal thermocline off the Central Cantabrian coast. The vertical displacement of cold water detected was from 75 m to 30 m in depth, but Rios *et al.* (1987) found cold water (14.63 °C)

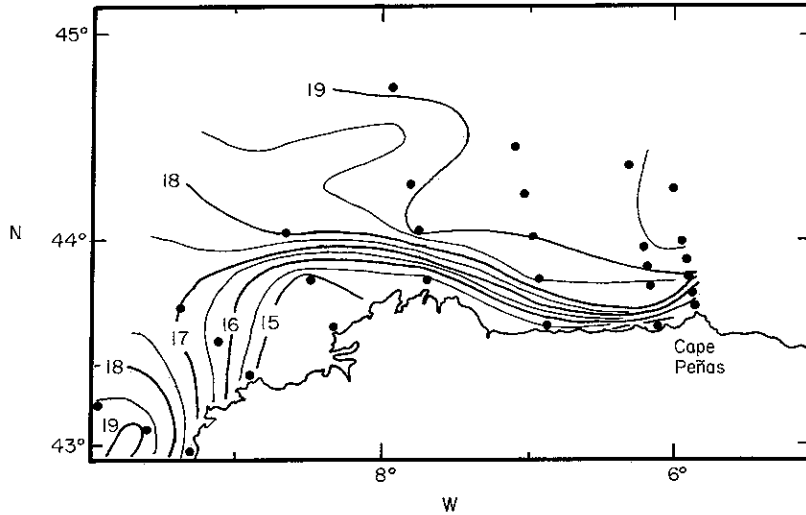


Figure 11. Surface temperatures off the northwest coast of Spain in September 1986. (from Rios *et al.*, 1987)

reaching the surface the former summer (Figure 11). The exact mechanism of the upwelling is unknown but wind driven currents probably provide the main force, small variations in speed and direction having special importance. The prevailing winds off the Cantabrian coast are northeast in summer, generating westward superficial currents running parallel to the coast and producing an Eckman transport of surface waters offshore.

The vertical motion of water may be enhanced by the shape of the coast, the main feature being Cape Peñas. The slope topography and several types of internal waves (Killworth, 1978) may act as modifying factors of these vertical motions: This may be the case in transect 1 where the phenomenon occurred with greater intensity than in transect 2. In transect 1, the existing deep and narrow submarine canyon could have several associated currents, as suggested by Shepard *et al.* (1978) for some coastal canyons. The shelf which is narrower than in other Western European regions (e.g. the Celtic Sea), differentiates the described upwelling from the one occurring at the Armorican Shelf. In our case, no evidence of the phenomenon was found at the shelf break, as theory (Hill & Johnson, 1974; Heaps, 1980) and thermal observations (Pingree, 1979; Dickson & Hughes, 1981) suggest for the Armorican upwelling.

Cold upwelled water has previously been detected at the surface (Dickson & Hughes, 1981; Rios *et al.*, 1987) but this is not reflected in our results. In spite of this, there is some indirect evidence of a previous presence of nutrient rich water near the sea surface at Station 11 in July. During July, the thermocline was located between 10 and 20 m depth, and the existing nitrate concentrations at the surface were too low to sustain the phytoplanktonic biomass ($30.4 \text{ mg Chl-a m}^{-2}$) in a column of 10 m depth. Using a value of $0.02 \text{ mol nitrate g}^{-1} \text{ Chl-a h}^{-1}$ for the nitrate uptake (Harrison *et al.*, 1983), the requirements of the present phytoplankton in the upper mixed layer were estimated as $0.608 \text{ mmol nitrate m}^{-2} \text{ h}^{-1}$. The amount of nitrate in this water column was $5.4 \text{ mmol nitrate m}^{-2}$, only sufficient to maintain the population for approximately 9 h. Furthermore, we estimated the upward transport of nitrate from below the thermocline using

the procedure of McCarthy and Carpenter (1983), and estimating the vertical eddy diffusivity coefficient (K_z) from the empirical formula of Anderson (1978). The calculated $K_z = 0.013 \text{ m}^2 \text{ h}^{-1}$, and the gradient of $3.21 \text{ mmol nitrate m}^{-4}$ gives an influx of $0.042 \text{ mmol nitrate m}^{-2} \text{ h}^{-1}$, so only 6.9% of the nitrate consumed by the phytoplankton would be supplied by vertical diffusion. It is well documented that active growth and subsequent bloom of diatoms occur based on new production and therefore on oxidized forms of nitrogen. Thus, the observed populations may be the result of the time lag in the response of the phytoplankton to high nutrient concentrations in the surface waters, now almost depleted. Regeneration processes may therefore actually support the phytoplankton, as in other upwelling areas (Treguer & Le Corre, 1979).

Some of the biological processes related to the upwelling are reflected in the particle size spectra and the dominant species of phytoplankton. According to the described phases and life forms in other areas (Margalef, 1978; Varela & Costas, 1987), Station 11, in July, appears as the phase after a period of intense upwelling and mixing, having medium and large size cells adapted to high nutrient concentration and also small and motile cells, more characteristic in nutrient poor waters. The characteristics of this phase are consistent with stage IV of the general model of Jones *et al.* (1983) and MacIsaac *et al.* (1985). Moreover, the low intensity of the upwelling in September in Station 21 excluded the large cells but not the small ones. By contrast, Station 11 had large diatoms due to the presence of small nutrient-regenerating microplankton. The phytoplankton response should depend on the initial nutrient concentrations (Codispoti, 1983) and the nutrient regeneration rates but the persistence and the processes involved in the studied upwelling remain unknown.

As far as we know the upwelling off the Cantabrian coast occurs throughout the summer, affecting with different intensity distinct coastal zones at both sides of Cape Peñas. In this area, upwelled and nonupwelled waters interfaced. A more detailed study will be necessary on the physical mechanism involved in this upwelling, as well as the geographical distribution of the process.

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