Hydrographic conditions associated with the relaxation of an upwelling event off the Galician coast (NW Spain)

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Abstract. During the GALICIA-XI cruise from May 10 to May 14, 1991, the relaxation of a previous strong upwelling event took place along the Galician coast caused by a shift in the position of the Azores High. The coldest temperatures and highest nitrate levels were found near the coast corresponding to the advection of subsurface waters, particularly of Eastern North Atlantic Water (ENAW). On the basis of thermohaline properties, ENAW of polar (ENAW_p) and tropical (ENAW_t) origin are distinguished. The highest salinity values found correspond to a saline wedge of ENAW_t located off the west coast of Galicia. The relaxation of upwelling produced a shoreward migration of surface water from oceanic stations which came into contact with upwelled Eastern North Atlantic Water from the coastal stations to form a convergence front 28 km off the coast. Meanwhile, the saline wedge displaced towards both the north and the shore which is favored by the compression of the upwelling system to a narrow coastal strip outwardly limited by the convergence zone.

Introduction

Along the eastern boundaries of oceans, coastal upwelling occurs due to the action of equatorward winds. Accordingly, intensity and spatio-temporal variability of coastal upwelling events are coupled to fluctuations of winds. Wind fluctuations are driven primarily by the atmospheric pressure although they can be substantially modified in the coastal atmospheric boundary layer [Halliwell and Allen, 1987].

Similar seasonal latitudinal migration of upwelling are described along the northeastern boundaries of Pacific and Atlantic oceans. Coastal upwelling off the western coast of United States, from 25°N to 50°N, presents significant alongshore variations [Huyer, 1983]. South of 40°N, favorable upwelling winds dominate all the year. Halliwell and Allen [1987] find large equatorward winds between Cape Mendocino (40°N) and Point Conception (35°N) in summer 1981 and 1982. In winter, winds point northward (southward) to the north (south) of 40°N. Off Oregon, upwelling season corresponds to summer. Here upwelling events occur during relatively short periods of upwelling favorable winds. Cold sea surface temperatures, indicative of coastal upwelling, are found near the coast from 35°N to 40°N during all year [Huyer, 1983]. Off southern Baja California, absence of cold coastal water is described in spite of favorable upwelling winds domain all year. Concerning the eastern North Atlantic, Wooster *et al.* [1976] have examined seasonal variations in sea surface temperature and trade winds and their relation to upwelling phenomena in the region between Cabo Finisterre (43°N, 9°W) and Sierra Leone (7.5°N, 13°W). Upwelling seasons occur along this boundary according to the seasonal north-south displacement of the trade belt. South of 20°N upwelling arises from January through May, between 20°N and 25°N it occurs throughout the year. Further north, off the Iberian Peninsula, it occurs from June through October [Fraga, 1981; Fiúza *et al.*, 1982; Fiúza, 1983].

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Paper number 93JC02735.

0148-0227/94/93JC-02735\$05.00

The Galician coast, between 42°N and 44°N, is included in the latter regime. Although the main cause of the upwelling is the predominance of northerly winds during these months, the Galician coastline and the properties of the subsurface waters also affect it. For example, Blanton *et al.* [1984] predict the existence of topographically intensified upwelling in the vicinity of Cabo Finisterre (Figure 1). Along the western coast the presence of embayments or rias (Rías Baixas) also enhances it. The high primary production in this region depends on this upwelling [Fraga, 1981] and the circulation pattern close to the Rías Baixas, which acts as a nutrient salt trap [Fraga and Margalef, 1979]. These factors enable the rias to support the highest world extraction of edible mussels [Blanton *et al.*, 1987].

Fraga [1981] describes the presence of two different subsurface water masses along the Galician coast. The subsurface water to the west is typical North Atlantic Central Water (NACW) with TS properties given by $S = 35.586 + 0.116(t-11)$. The subsurface water to the north is highly modified NACW, referred to as Biscay Bay Central Water (BBCW) by the author, with TS properties described by $S = 35.565 + 0.096(t-11)$. This water has a smaller salinity range centered at 35.57 psu (practical salinity unit). Both water masses are similar to the Eastern North Atlantic Water (ENAW) according to Fiúza [1984]. Fiúza divides ENAW into two components. The first component has TS properties following the line connecting 10°C, 35.40 psu and 12.20°C, 35.66 psu and is essentially the ENAW described by Harvey [1982]. Its origin is in the Celtic Sea north of 46°N. Ríos *et al.* [1992] designate it as Subpolar Eastern North Atlantic Water (ENAW_p). The second component has TS properties following the line connecting 13.15°C, 35.80 psu and 18.50°C, 36.75 psu. These two segments are joined by a curve which has ranges of temperature and salinity (12.50° - 12.825°C and 35.70 - 35.75 psu) that coincide with the NACW defined by Helland-Hansen and Nansen [1926]. Ríos *et al.* [1992] gave the name Subtropical Eastern North Atlantic Water (ENAW_t) to the ENAW with temperature and salinity higher than 12.2°C and 35.66 psu, respectively. ENAW_t is formed to the north of the Azores Current at approximately 40°N.

The ENAW_t moves partly northeastward, and forms a subsurface front with ENAW_p which moves southward, between

Figure 1. Schematic coarse view of ENAW distribution including the regions of formation of ENAW_P and ENAW_T [Rios *et al.*, 1992].

43°N and 44°N [Rios *et al.*, 1992]. The zone of the most intense convergence is situated in the vicinity of Cabo Finisterre [Fruchaud-Laparra *et al.*, 1976; Fraga *et al.*, 1982] where strong upwelling takes place during spring and summer.

Surface currents are more influenced by atmospheric forcing (i.e., position and strength of the Azores high). According to Fraga *et al.* [1982], surface water flows along the Galician coast from northeast to south during summer. Flow in the opposite direction is often observed in other seasons. Swallow *et al.* [1977] found a northward surface current in the upper 1500 m along the western coast in January. Blanton *et al.* [1984] describe a complex circulation pattern with predominantly northward currents during April 1981.

This paper describes the hydrographic and chemical conditions present along the Galician coast in early May 1991. Horizontal distributions of temperature and nitrate reveal the upwelling of subsurface waters. The thermohaline properties of the water masses off Galicia, especially of ENAW, are considered. Salinity and sigma- t profiles have been studied in order to establish the displacements of the different water masses.

Materials and Methods

From May 10 to May 14, 1991, the GALICIA-XI cruise was run on R/V *Investigador-S*. The region studied is from 42°N to 44°N and from 7°W to 11°W. Thirty-nine stations were sampled along eight transects perpendicular to the coastline (Figure 2).

At stations indicated by a square in Figure 2 a continuous recording of salinity, temperature and pressure was obtained by a conductivity-temperature-depth (CTD) 9 SBE incorporated into a rosette sampler. Subsamples of salinity, nutrients and chlorophyll *a* were taken with 1.7 dm³ polyvinyl chloride Niskin bottles, placed around the rosette, at 0, 10, 20, 30, 40, 50, 75,

100, 125, 150, 200, 250, 300, 350 and 400 m depth. At stations indicated by a circle in Figure 2, only a continuous recording of salinity, temperature and pressure was obtained by a CTD 25 SBE.

Salinity was calculated using equation (6) of UNESCO [1981] from conductivity measurements with an AUTOSAL 8400A calibrated with "Copenhagen Standard Water." Nutrient concentrations were determined by Technicon AAII SFA systems, according to Hansen and Grasshoff [1983], with some improvements [Mouriño and Fraga, 1985; Alvarez-Salgado *et al.*, 1992]. Chlorophyll *a* was measured after 90% acetone extraction in a 10,000 R Turner fluorometer.

Upwelling index, I_w , was calculated at 43°N, 11°W (150 km off Cabo Finisterre) in accordance with Bakun's [1973] method using the geostrophic winds deduced from surface pressure charts (3 times per day). The vectors are multiplied by 0.7 and cyclonically rotated by 15° to estimate the surface wind velocity. Wind stress is computed from the equation

$$\bar{\tau} = \rho_a C_d |\bar{v}| v_N$$

where $\bar{\tau}$ is the southward stress, ρ_a is air density (1.22 kg m⁻³), C_d is an empirical drag coefficient (1.3×10⁻³ following Hidy [1972]), $\bar{v}$ is wind speed over the sea surface and v_N the north component of $\bar{v}$. I_w was finally obtained dividing $\bar{\tau}$ by the Coriolis parameter f (9.946×10⁻⁵ s⁻¹ in our case) giving an estimation of the surface water flow per kilometer of coast to the offshore.

Dynamic topography of sea surface relative to 300 m was calculated using the Helland-Hansen [1934] method. This reference level was chosen because the circulation at this depth is very weak according to Frouin *et al.* [1990]. Due to some shallower stations over the shelf an extrapolation of specific

Figure 2. Galician coast with 100-, 200-, and 2000- m isobaths and the survey stations during GALICIA-XI cruise. Circles represent stations surveyed with CTD 25 SBE where only TS profiles were obtained; squares represent stations surveyed with CTD 9 SBE incorporated into a rosette sampler. Aliquots for salinity, nutrients and chlorophyll *a* measurements were collected.

volume anomaly is made. For shallower stations, an imaginary water mass is substituted for the section from the bottom to the reference level. This imaginary water mass is considered to be the water column between the depths of the next oceanic station [Rudnev and Palii, 1966]. Consequently, results derived from this method must be interpreted with caution, but general trends can be distinguished.

Results

Wind Conditions

It is observed from surface pressure charts that at the beginning of May, after a period of calm, the Azores high was centered on 47°N, 18°W and strong northerly winds ($13 \pm 2 \text{ m s}^{-1}$) were blowing over the Galician coast. However, on May 5 a cold front appeared north of 46°N and the high moved southwestward and reached 38°N, 28°W on May 10.

Consequently, the strength of the winds decreased. Following this date, during the period of the cruise, the high returned northeastward (about 52°N, 17°W) and due to a low, centered over the south of the Iberian Peninsula, wind direction shifted from northeast. The wind component from north to south thus averaged $9 \pm 2 \text{ m s}^{-1}$.

The average value of the north-south component, computed with the geostrophic wind, is $6.1 \pm 0.9 \text{ m s}^{-1}$. Ship observations indicate the predominance of northeastern winds during the cruise, with a north-south component of $7.0 \pm 0.1 \text{ m s}^{-1}$, which is not significantly different from the former.

These prevailing winds generated an important offshore Ekman transport and an equatorward geostrophic current. In fact, the upwelling indices between May 1 and May 5 were very high for this time of the year (average value of $1386 \text{ m}^3 \text{ s}^{-1} (\text{km coast})^{-1}$, Figure 3). The days that followed, from May 6 to May 14, it diminished to an average value of

Figure 3. Daily average upwelling index versus time calculated for 43°N 11°W (150 km off Cabo Finisterre) for the period April 26 to May 20.

$769 \text{ m}^3 \text{ s}^{-1} (\text{km coast})^{-1}$. Therefore according to these indices, at the beginning of May an intense wind-driven upwelling took place which weakened during the cruise. In any case these values are not only larger than the monthly average for May 1966-1989 at the same point, $217 \text{ m}^3 \text{ s}^{-1} (\text{km coast})^{-1}$ but also larger than the greatest values given by *Lavin et al.* [1991] for the upwelling season during 1966-1989. *Da Silva* [1992] also finds the most intense upwelling winds off northern Portugal occurred during early May 1987 with an average wind stress of 0.07 Pa .

Hydrography Along the Galician Coast

The GALICIA-XI cruise provides a general picture of the hydrographic conditions present at the beginning of the upwelling season. The horizontal distribution of surface temperature (Figure 4a) shows a very small range, from 12° to 14°C . These low temperatures suggest that the surface heating due to irradiance is still relatively low. Consequently, the thermohaline properties of the surface layer are not very different from those during the recent winter mixing. In spite of this, the lowest temperatures are found close to the coast. The largest cross-shelf temperature gradient (2°C in 40 km) is located off the mouth of Río Miño and there is a temperature minimum of 12.2°C in the vicinity of Cabo Finisterre. A similar distribution of temperature is also observed at 50 m depth (Figure 4b). However, between the Islas Sisargas and the Cabo Ortegal the 50-m temperature across the shelf ranges from 12°C at the coast to 12.6°C offshore while surface temperature is practically constant at 12.9°C . This shoreward decrease of temperature at 50 m suggests an upwelling of colder subsurface waters.

Charts of nitrate concentration at surface and at 50 m depth are illustrated in Figures 5a and 5b and show the effect of vertical advection of nutrient rich subsurface waters. As can be expected, the colder areas are the most nutrient rich. The surface nitrate concentration is practically nil except in front of Cabo Finisterre and the mouths of Ría de Muros and Río Miño, where there are maxima of 7, 8 and $3 \mu\text{mol kg}^{-1}$, respectively. The 50-m nitrate distribution depicts the same pattern as temperature, showing the extension of upwelling along the northern coast (Northeast of the Islas Sisargas) in contrast to the surface where depletion of nutrient salts is almost complete. Therefore the horizontal distributions of temperature and nitrate reveal a stronger upwelling along the western than along the

Figure 4. Horizontal distribution of temperature at (a) surface and (b) 50 m depth.

Figure 5. Horizontal distribution of nitrate at (a) surface, and (b) 50 m depth.

northern coast with maxima located in front of Cabo Finisterre and the mouths of the Ría de Muros and the Río Miño.

Dynamic topography of the sea surface relative to 300 m (Figure 6) indicates the presence of an equatorward geostrophic current roughly parallel to the coast except at transect 1 (see Figure 2) where it flows primarily in the shoreward direction. Therefore the dynamic topography chart also suggests coastal

upwelling following the temperature and nitrate horizontal charts. The highest velocities (8.6 cm s^{-1}) are observed near the Cabo Finisterre where upwelling is very intense. However, it is important to remark that this structure is complicated by the presence of convergence zones at the north and south of the cape centered close to stations 23 and 73, respectively. In contrast, a

Figure 6. Dynamic topography chart of the sea surface relative to 300 dbar in dynamic centimeters.

Figure 7. Horizontal distribution of chlorophyll *a* at surface ($10^{-6} \text{ kg m}^{-3}$).

divergence off Rio Miño seems to be the cause of the upwelling there.

Finally, the surface chlorophyll *a* chart (Figure 7) illustrates the presence of larger phytoplankton populations along the western than along the northern coast. The enhancement of estuarine circulation due to upwelling provokes the high biomass accumulation off the Rías Baixas. This moves as a "tongue" drawn by the equatorward surface circulation over the shelf (Figure 6).

Characterization of the Upwelled Water

In Figure 8 a TS diagram for all water samples collected is shown. The clustering of points along a straight line between a minimum of 35.55 psu and a maximum of 35.84 psu (solid squares) stands out clearly. This segment represents the ENAW. Over this line, there is a great dispersion of points (open squares) which belong to the surface layer. Samples corresponding to the mixing of proper surface water with ENAW are also included. Triangles represent samples of the mixture of ENAW and Mediterranean Water (MW), whose core is about 1200 m depth at our latitudes [Fraga *et al.*, 1982]. Their salinities range from 35.63 to 35.75 psu and temperatures from 11.1° to 11.7°C.

Starting from the samples of ENAW the following straight thermohaline relationship was established for the upwelled water:

$$S = 35.553 (\pm 0.016) + 0.125 (\pm 0.004) (t-11)$$

$$n = 104 \quad r^2 = 0.92$$

This agrees with the linear regression given by Fraga [1981] for ENAW during the GALICIA-III cruise in June 1976:

$$S = 35.525 + 0.125 (t-11)$$

Figure 8. TS diagram for all water samples collected. Surface data (open squares), ENAW data (solid squares) and ENAW-MW mixing data (triangles).

Although the TS diagram of all samples reveals the water masses existing along the Galician coast from surface to 400 m depth, a more detailed study is only possible using the continuous CTD sampling. The TS profiles of every station, grouped by transects, are shown in Figure 9. Line I represents ENAW by Fiúza [1984] and line II is the typical NACW that upwells in front of the Rías Baixas by Fraga *et al.* [1982].

The main differences are found between coastal (X1 and X2) and oceanic (X3 to X5) stations. At oceanic stations ENAW is clearly delineated by a salinity maximum in the upper boundary and a minimum in the lower boundary with large temperature and salinity ranges observed between maxima and minima (0.8°C and 0.1 psu, respectively). The anomalously high salinities at stations 55, 74 and 84 suggest the presence of a saline wedge of new ENAW. At the coastal stations, ENAW has a small range of temperature 0.3°C and salinity 0.04 psu. At the salinity maximum, associated with the upper boundary of this water mass, the water is colder and less saline at coastal stations than at oceanic stations. For example, along transect 2, the salinity maximum at station 23, classified as oceanic, is 0.092 psu more saline and 0.841°C warmer than at station 22, classified as coastal. Nevertheless, at some stations, 21, 21M, 31, 62, 71 and 72, this salinity maximum is not so sharp. Over the shelf, a strong mixing of the upper layer of ENAW and surface water occurs; consequently, there is a great modification of the upper boundary of the ENAW. For transects 2, 3 and 4 the ocean-coast transition is located at stations 22M, 33 and 43, respectively, as the TS profiles suggest. There is a significant difference between the TS at station 22M and the adjacent stations. At station 22M, there is a nearly constant salinity of 35.68 psu profile from 80 m to the bottom. At stations 33 and 43 the TS slope is bigger than those of oceanic stations.

Furthermore, ENAW along the western coast is slightly different from that along the northern coast. According to depth and geographical position, this subsurface water is better characterized by either the ENAW by Fiúza (line I) or NACW by Fraga (line II). Thus north of Cabo Finisterre (transects 1-4), the thermohaline properties of ENAW correspond with Fraga's NACW (line II). South of Finisterre, at oceanic stations, the deepest ENAW fits with the Fiúza's subpolar ENAW and the upper ENAW is close to NACW by Fraga although it is slightly more saline.

Along the northern coast, the mixing between ENAW and MW occurs above 340 m depth. In contrast, along the western coast this mixing is present below 400 m depth. Fraga *et al.* [1982] in June 1976 found a minimum about 400 m along the Galician coast reaching the lowest depth at 300 m, off the Cabo Estaca de Bares. At station 33, there is a vertical mixing of ENAW and the water below so strong that it displaces the TS slope in relation to station 34.

Evolution of Upwelling: Distribution of ENAW

To describe the distribution of ENAW and to consequently clarify the dynamic process that led to the hydrographic situation found, it is necessary to analyze the cross sections of salinity and sigma-t of every radial transect. In Figure 10 these cross sections are shown; the dotted curve represents the upper layer of ENAW.

The isopycnals in transects 1, 5, 6 and 8 tend to slope upward toward the coast, indicative of coastal upwelling. Only at transect 5, off Cabo Finisterre, however, do the isopycnals outcrop at the surface. The salinity maximum also tends to slope

Figure 9. TS profiles for every station grouped by transect. Line I represents ENAW by Friúza [1984] and line II typical NACW according to Fraga *et al.* [1982]. In every graphic, the vertical line corresponding to the upper limit of ENAW_p is marked by H.

upward toward the coast in these cross sections, reflecting the upwelling of ENAW. However, at stations 14, 82, 82M and 84 there are subsurface salinity maxima above the ENAW upper limit which are also observed in the TS diagrams (Figure 9).

At transects 2, 3, 4 and 7, there is a clear slope of the isopycnals at the coastal stations suggestive of upwelling, but at intermediate stations on these transects, depressed isopycnals occur which cannot be explained in terms of coastal upwelling. The isopycnal depression is clearly observed at transect 2. The isopycnal of 27.12 goes down from 50 m at station 24 to 200 m at station 22M and rises again to 75 m at station 21. The ENAW trapped over the continental shelf, because of this deepening, shows a modified salinity maximum corresponding to its upper boundary (stations 21, 31, 71 and 72). This modification is due to mixing with surface water. In some cases this salinity maximum is so modified that it has not been considered strictly ENAW, as at station 42. At the oceanic stations 23, 23M, 44M, 45, 73 and 73M, this maximum evolved to form a subsurface salinity maxima due to mixing with less saline water as can also be seen in the TS diagrams (Figure 9). The upper limit of ENAW corresponds with the deepest salinity maximum (indicated by the dotted curve in Figure 10).

The distribution of the ENAW upper limit depth (Figure 11) also indicates the advection of this subsurface water mass against the coast, reaching closest to the surface in front of Cabo Finisterre and the mouths of the Ría de Muros and the Río Miño. This corresponds to the colder temperatures and higher nutrient concentrations found in these three zones (see Figures 4a and 5a). The upper boundary of ENAW is deepest about 28 km off the coast (Figure 11). Along the coast, the deepest level of the ENAW upper boundary is located at stations 23 and 73, coinciding with zones of greatest convergence (Figure 6).

Finally, the penetration of a warm and poor nutrient saline wedge of ENAW from the southwest occurs. This saline intrusion is located at stations 84, 74 and 55, as was also observed on the respective TS profiles (Figure 9), between 64 and 127 m depth. This wedge extends toward the shore and northeast. The horizontal distribution of salinity for the ENAW upper limit (Figure 12a) shows a salinity maximum of 35.8 psu at station 55. This core gets diluted northeastward, decreasing to 35.69 psu at station 23. The lowest levels of nitrate along the western coast for the ENAW upper layer coincide with the presence of this saline intrusion (Figure 12b). Thus there is an increasing gradient of nitrate shoreward, from 2 to 10 $\mu\text{mol kg}^{-1}$.

Figure 9. (continued)

Discussion

Water mass dynamics in the upper layer (0-200 m depth) off the Galician coast are strongly influenced by wind variability, which depends on the location, position and strength of the Azores high. Northerly winds drive coastal upwelling from June through October [Wooster *et al.*, 1976].

In this study, due to the southwestward-northeastward oscillation in the Azores high during May 1991, a succession of wind stress-relaxation pulses was observed. Therefore there were two upwelling events with wind stress anomalously high (Figure 3) comparing to average values given by Lavin *et al.* [1991] for the same area during the period 1966-1989. These average values are between those found in Oregon and northwest Africa [Smith, 1981; Lentz, 1992]. These two upwelling events, at about May 3 and May 17, were separated by a relaxation centered at May 10. This fortnightly succession of upwelling events has been found by other authors [McClain *et al.*, 1986]. The cruise, from May 10 to May 14, coincided with the relaxation period. However, the imprint of the strong upwelling on May 3 still remained in the water column during the cruise.

Surface water circulation, calculated by dynamic topography, responds to the predominant northerly winds. Consequently, an equatorward geostrophic current is observed along the coast which becomes weaker seaward (Figure 6). Fraga [1981] describes a similar pattern for the summer of 1975 and also

found that the highest velocities occur around Cabo Finisterre (7.5 cm s^{-1}). These high velocities are associated with an intense upwelling confirmed by the colder temperatures and higher nitrate concentrations observed (Figures 4 and 5). Data from González *et al.* [1984] in June 1979, Mouriño *et al.* [1985] between July and August 1984, Fraga *et al.* [1987] between September and October 1986 and Cabanas *et al.* [1988] in July 1987 also show a prominent upwelling at the cape. Fraga *et al.* [1982] suggest that this intense upwelling is due to a permanent subsurface front between BBCW and typical NACW. During GALICIA-XI cruise the subsurface front was not found as the TS profiles indicate. Although along the northern coast, ENAW shows slightly different thermohaline properties to those of the ENAW on the western coast, these differences are not as large as those found by Fraga *et al.* [1982]. North of Finisterre, ENAW also shows a large range in salinity and temperature values and not a strong salinity homogeneity as BBCW found by Fraga *et al.* [1982]. According to the conservation of vorticity, [Arthur, 1965], Blanton *et al.*, [1984] justify theoretically this enhancement due to the topographic effect of the Cabo Finisterre. They also suggest that the existence of a cyclonic eddy should enhance upwelling off the Ría de Arousa. This prediction is supported by cold temperatures and high nitrate levels observed at these locations during GALICIA-XI cruise. Also McClain *et al.* [1986] using sea surface temperature satellite images found the same zones of more intense upwelling

These three zones of strong upwelling are located along the

western coast. Northeast of the Islas Sisargas, upwelling is relatively weak. Temperature and nitrate horizontal charts at 50 m depth (Figures 4b and 5b) show this advection of subsurface waters along the whole coast, while at the surface (Figures 4a and 5a) it is only detectable south of the Islas Sisargas. According to the theoretical circulation model along the Galician coast established by McClain *et al.* [1986], upwelling on the north coast is not only favored by northerly winds but also by a greater variety of wind directions compared with the western

Figure 10. (continued)

coast. The northerly winds enhance the upwelling along the western coast.

The chlorophyll *a* chart at the surface (Figure 7) follows this circulation pattern. The high primary production within the rias is exported offshore by the upwelling favorable winds and then is advected southward by the equatorward flow. Both geostrophic surface current and biomass accumulation over the shelf have the same origin: the northerly wind stress.

Just like dynamic topography, density and salinity profiles show convergence zones located over the edge of the shelf approximately 28 km off the coast. The highest convergences are

found in the proximities of stations 23 and 73 (Figure 6). This convergence zone, which coincides with the line of maximum depth of the ENAW upper limit, separates oceanic and coastal water (Figure 11). The ENAW present close to the bottom near the coast is located at about 200 m depth at more oceanic stations where the upper limit of this water mass is only about 150 m depth (Figure 11).

McClain *et al.* [1986] describe a similar situation during April 1982 along the western coast: advection of subsurface water near the shore and convergence located 20 km off the coast. The convergence is due to a current system parallel to the

Figure 11. Depth of ENAW upper limit. Dotted curve indicates the maximum depth of this upper limit.

coast: a southward coastal jet adjacent to a northward flowing current. A negative wind stress curl associated with a cold front caused this coastal circulation response. Similar convergences are found in another upwelling areas. *Mittelstaedt* [1983] describes a very similar situation along the northwest African

coast, between 16° and 26°N, during upwelling season. At this zone, there is a southward drift current and an adjacent surface countercurrent offshore. This countercurrent is the surface manifestation of a northward undercurrent. This northward current is caused by the meridional large-scale pressure gradient in the eastern Atlantic. The boundary between the surface currents tends to be a convergence located along the shelf edge, above 50 km offshore. When upwelling favoring winds are strong, the countercurrent is weak of a few centimeters per second within the surface layer. When there is a weakening of the northerly winds that lasts a few days, this countercurrent advances shoreward and covers the entire column over the shelf, interrupting coastal upwelling.

In our case the presence of a cold front on May 5 provoked the displacement from northeast to southwest of the Azores high. Associated with this displacement, wind stress did not cause a strong circulation pattern as that found by *McClain et al.* [1986] but only the weakening of the equatorward geostrophic current offshore (Figure 6), while close to the coast this current was still intense.

The change in position of the Azores high seems to be responsible for the relaxation of the strong upwelling event on May 3. In addition, it is necessary to take into account that the response time of coastal circulation to wind stress is about 3 days [*McClain et al.*, 1986]. Thus the hydrographic situation found during GALICIA-XI cruise is explained by this upwelling relaxation.

The strong upwelling event of May 3 caused the advection of offshore subsurface waters, at about 200 m depth offshore, toward the coast. Afterwards during the cruise, there was a relaxation of this event. At oceanic stations, the upwelled water returned shoreward, while at coastal stations the equatorward surface circulation and the offshore Ekman transport were still maintained. Consequently, surface waters from coastal stations

Figure 12. Distribution of (a) salinity and (b) nitrate for the ENAW upper limit.

Figure 13. Simple scheme of the convergence front due to the relaxation of upwelling. Arrows show water circulation pattern.

were strongly mixed with the oceanic ones, leading to the convergence front 28 km off the coast (Figure 11) as the isopycnal deepening at halfway stations indicate (Figure 10). The most pronounced convergences at transects 2, 3, 4 and 7 are probably due to topographic effects. In Figure 13 a simple scheme of this upwelling-relaxation pattern is shown for transect 7.

The ENAW that advected, because of previous intense upwelling, were trapped at coastal stations suffering strong mixing with the surface water which modified the salinity maximum of the ENAW upper limit (Figures 9 and 10). However, the deepest upwelled ENAW preserves its thermohaline properties. It is probable that this core remained as a northward undercurrent over the shelf and restricted the vertical mixing with the rest of the water column that displaced equatorward [Hart and Currie, 1960].

This dynamics of upwelling favors the penetration of a warm, poor nutrient saline wedge of ENAW from the southwest. This wedge spreads northward following the convergence zone. Only Otto [1975] describes the presence of a saline wedge along the Galician coast during spring.

Response of upwelling system to slackening of winds have been described for other areas. The response is strongly influenced by irregularities of the coastline and bathymetry as well as by variations of oceanic currents. Coste *et al.* [1986] found a similar situation for summer 1981 along the Portuguese coast: a relaxation of an upwelling event, and the shoreward displacement of a warmer and saltier surface water body. Halpern [1976] studied an upwelling event that occurred between July 7 to July 19, 1973, off Oregon latitudinally adjacent to Galicia and with a similar regime of winds [Huyer, 1983; Halliwell and Allen, 1987; Kosro *et al.*, 1991]. The relaxation of wind stress from 0.5 Pa to -0.1 Pa caused the return of lighter (warmer) surface water shoreward; and a movement of the front, formed during previous strong upwelling, closer to the shore. They did not find convergence zones. Stevenson *et al.* [1974] for the same area describe the formation of a convergence at the beginning of the decay phase of an upwelling cycle during 1972. Abbott and Zion [1985], off northern California, found an ocean response to the weakening of winds during upwelling on July 1981 very similar to the situation described in this work, with wind relaxation, upwelling zone constrained to the coast; and warmer water advanced shoreward.

Analysis of hydrographic conditions and currents found during GALICIA-XI cruise has lead to a complete view of

physical processes during the relaxation of an upwelling episode in early May off the Galician coast. Further studies of chemical and biological conditions are necessary in order to relate biological and physical processes.

Acknowledgments. Support for this work came from the EEC project MAST PL-890021 and CICYT grant MAR88-0245. We thank all the participants in the GALICIA-XI cruise and the crew for their help. We thank F. Fraga for providing his valuable critical comments, Ramón Penín for his help in the preparation of the figures, and Gavin Tilstone for his English correction.

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(Received May 26, 1992; revised August 20, 1993; accepted August 20, 1993)