



Coupling between the Iberian basin — scale circulation and the Portugal boundary current system: a chemical study

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Abstract

The role played by the Portugal Current System in the ventilation of the different modes of Eastern North Atlantic Central Water (ENACW) is evaluated with data from a series of cruises carried out along the western coast of the Iberian Peninsula. Results show the Portugal Current, located west of 10.3°W, conveying fresh modes of recently ventilated ENACW of subpolar origin to the south. Within 70 km of the slope, the Portugal Coastal Countercurrent transports northwards low oxygen/high nutrient ENACW of subtropical origin. Downstream ventilation of ENACW of subtropical origin occurs by mixing or entrainment with offshore ventilated ENACW. We point to mesoscale eddies as the main mechanism for this downstream indirect ventilation, which reconciles opposing views from direct current measurements and hydrographic studies. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Circulation; Water masses; Ventilation; North Atlantic; Iberian Basin

1. Introduction

Northeast of the Azores Front there is a region of weak circulation bounded to the north by the North Atlantic Current (NAC), to the south by the Azores Current, to the east by Europe and to the west by the Mid-Atlantic Ridge (Maillard, 1986). Considering that the NAC and the Azores Current, respectively, bound the subpolar and subtropical gyres, then this weak circulation region is an intergyre zone (Pollard et al., 1996). The northern part of this zone (approximately north of 45°N) is characterised by strong winter convection, being the formation area of the Eastern North Atlantic Central Water Subpolar mode (ENACWsp), with density anomalies between 27.0 and 27.2

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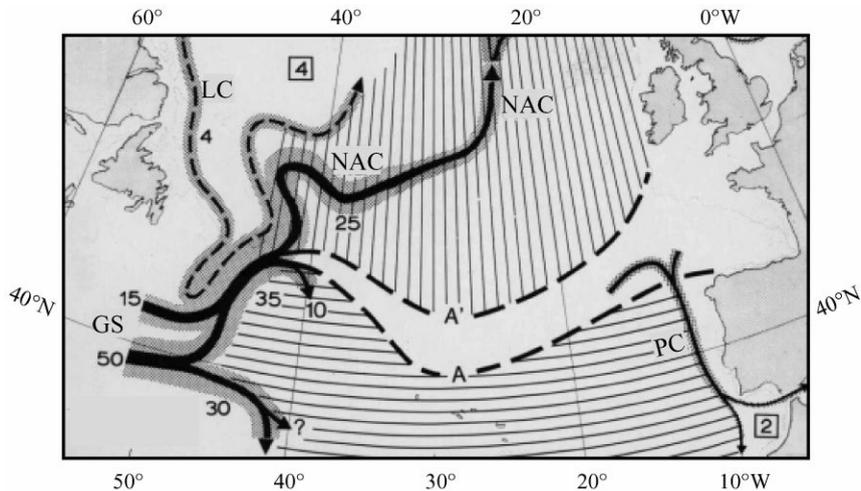


Fig. 1. Circulation in the upper layers of the northern North Atlantic as derived from drift experiments (adapted from Krauss, 1986). LC, Labrador Current; NAC, North Atlantic Current; GS, Gulf Stream; and PC, Portugal Current. Meridionally-ruled area, flow associated with the NAC toward the north. Zonally-ruled area, flow associated with the northern limb of the Subtropical Front. Numbers are transports in Sverdrups ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$).

(McCartney and Talley, 1982; Harvey, 1982; Paillet and Arhan, 1997). South of 45°N , a wedge of saline water ($S > 35.7$) is associated with the northern outcrop of the anticyclonic gyre (Pollard and Pu, 1985). In this region, the large-scale circulation is weak, eastward or southeastward. Krauss (1986) showed a similar pattern from surface current measurements (Fig. 1). He divided the intergyre region in to (i) a northern regime, where the NAC shows a broad west-wind drift (line A'), and (ii) a southern regime, where the subtropical gyre can expand (line A). The area between A and A' belongs alternately to the northern or southern regimes. The Portugal Current (PC) receives its water from this transition zone.

The geostrophic field from historical databases shows a weak southwestward flow from the southeastern side of the NAC (Helland-Hansen and Nansen, 1926; Dietrich, 1969; Wegner, 1973; Saunders, 1982). Current meter data indicate that the intergyre zone is also crossed by several southeastward branches of the NAC (Krauss, 1986). Both schemes show the equatorward PC as a characteristic feature of the upper circulation in the Iberian Basin with little seasonality in the dynamic field (Maillard, 1986). Within 70–80 km of shore a prevalent poleward flow ($\sim 200 \text{ m}$ deep) was described in autumn and early winter, conveying ENACW of subtropical origin ($S > 35.7$), ENACWst (Haynes and Barton, 1990; Pingree and Le Cann, 1990; Frouin et al., 1990; Castro et al., 1997). This poleward current, called the Portugal Coastal Countercurrent (PCCC) by Ambar and Fiúza (1994), is induced by geostrophic adjustment of the weak eastward oceanic flow driven by large-scale meridional baroclinic pressure gradient (Frouin et al., 1990), though it responds rapidly to the applied alongshore wind-stress (Haynes and Barton, 1990). During the upwelling season (from April–May to September–October), the PCCC vanishes because of the predominance of northerly winds. However, a subsurface poleward flowing Portugal Coastal Under Current (PCUC) centred at 100–200 m still transports ENACWst (Álvarez-Salgado et al., 1993; Castro

et al., 1994, 2000). Recently, Paillet and Mercier (1997) modeled these dynamic features by applying an inverse model for the Eastern North Atlantic. Mazé et al. (1997) described similar features in the volume transport of the Iberian Basin, with a poleward flow along the eastern boundary ($<10.5^{\circ}\text{W}$) and a weak southward flow in the open ocean ($>10.5^{\circ}\text{W}$).

Pollard and Pu (1985) estimated ventilation times from 7 to 20 years for ENACWsp in the Subtropical front on the basis of the downstream oxygen consumption, as this water mass is conveyed southward by the PC. On the other hand, according to the circulation scheme of the Portugal Current System, we should expect a downstream nutrient enrichment in ENACWst as it is transported northward by the PCCC. However, independent chemical determinations along this eastern boundary show a northward decrease (increase) of nutrient (oxygen) levels in ENACWst (Manríquez et al., 1976; Coste et al., 1986; Pérez et al., 1993).

The aim of this paper is to reconcile the above opposing dynamic and chemical features of ENACWst. We will first establish the Iberian basin-scale patterns of ENACW ventilation with observations collected during the *Bord-Est 3* cruise (Arhan et al., 1991). Then we will propose a possible mechanism of ENACWst ventilation based on data collected during cruises *MORENA I* (May 1993) and *GALICIA VI* (December 1983). A well-defined PCCC was observed along the slope of the Iberian Peninsula during these two latter cruises, and it was sampled in denser spatial detail.

2. Data set and methods

The *Bord-Est 3* (BE3) cruise was carried out from 9 to 26 May 1989 on board R/V ‘*Le Suroit*’. The cruise consisted of one meridional and three zonal transects off the Iberian peninsula (Fig. 2) between 36°N and 46°N (Arhan et al., 1991). The *MORENA I* cruise was performed on board R/V ‘*Cornide de Saavedra*’ from 10 to 26 May 1993 and consisted of 92 stations from 40°N to 43°N and from the coast to 11°W along 13 transects perpendicular to the western Iberian coast (Fig. 2). In both cruises a CTD-rosette sampler was used to measure temperature, salinity and pressure and collect samples for nutrients and oxygen analyses. Nutrients were determined by colorimetric methods with a Technicon autoanalyser. Nitrate was determined after reduction to nitrite in a Cd–Cu column (Mouriño and Fraga, 1985). The standard deviation for duplicate analyses was $0.05\ \mu\text{mol kg}^{-1}$, i.e. $\sim 0.5\%$ full scale. The classic Winkler method was used to measure dissolved oxygen concentrations. A Pt combined electrode was used to determine the end point of the titration with an accuracy of $0.5\ \mu\text{mol kg}^{-1}$. These data are available at the British Oceanographic Data Centre.

The *Galicia VI* cruise was executed from 1 to 12 December 1983 aboard R/V ‘*Garcia del Cid*’ at the time of the strong poleward flow observed by Frouin et al. (1990) along the continental slope of the Iberian Peninsula. It covers 8 zonal sections from 40°N to 47°N (Pérez et al., 1985). The southernmost transect of this cruise was selected for comparison with a similar section during the *MORENA I* cruise (Fig. 2). Casts of 51 PVC Niskin bottles with attached reversing thermometer frames were used during this cruise. Salinity was determined from conductivity measurements (UNESCO, 1985) with an AUTOSAL 8400 A. Oxygen and nutrient methods were the same as previously described for the *BE3* and *MORENA I* cruises. Potential temperature (θ) is used throughout this paper.

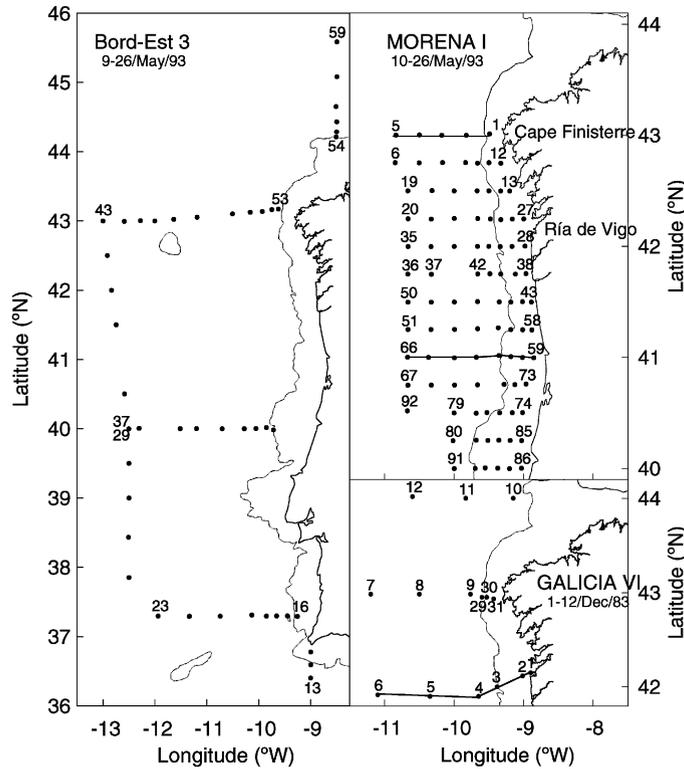


Fig. 2. Sampling grids during cruises *Bord-Est 3* (9 to 26 May 1989), *MORENA I* (12 to 26 May 1993) and *Galicía VI* (1 to 12 December 1983). The 1000 m isobath is shown. Black lines correspond to the zonal transects presented in Figs. 6, 7.

The geopotential anomaly at 120 dbar was computed relative to 2500 dbar. Water displacements at this reference level are very slow according to Mazé et al. (1997). For slope stations, where the water depth (Z) is shallower than the reference level, we extended the density profile from Z down to 2500 dbar considering the density profile of the nearest station in the Z –2500 dbar range. This is equivalent to considering that the velocity between the pair of deep and slope stations in the Z –2500 dbar range is zero.

The best fit between any pair of dependent (Y) and independent (X) variables was obtained by minimising

$$\sum_i [(X_i - \hat{X})^{w_x} \times (Y_i - \hat{Y})^{w_y}]^2,$$

where w_X and w_Y are weights for the independent and dependent variables with $w_X, w_Y > 0$ and $w_X + w_Y = 1$. \hat{X} and \hat{Y} are the average value of X and Y , the measured variables. The weight factors must be a function of the estimated experimental error (er_X, er_Y) compared to the standard deviation (SD_X, SD_Y) of X and Y . For a given pair of variables,

$$w_X = \left(\frac{er_X}{SD_X} \right) / \left(\frac{er_X}{SD_X} + \frac{er_Y}{SD_Y} \right).$$

In order to simplify the linear regression analysis, all possible cases were condensed into 2 categories or models: (I) $w_X = 0$, $w_Y = 1$; and (II) $w_X = w_Y = 0.5$ (Sokal and Rohlf, 1995). Model I was used when $w_Y \gg w_X$ as it occurs with any chemical variable vs. temperature or salinity. Model II was used when $w_X \approx w_Y$, i.e. when X and Y were chemical variables. Differences between models I and II increase as the correlation coefficient (r) decreases. The probability level of the regression is given by the p -level.

3. Results and discussion

3.1. ENACW variability at the scale of the Iberian Basin (BE3 observations)

Fig. 3a shows the θ/S diagram for water samples collected during the BE3 cruise in the depth range of central mode waters (100–500 m). ENACW observed during this cruise follows closely the reference lines defined by Ríos et al. (1992). However, oxygen and nitrate variability is somewhat more complex. For each zonal transect (37°N, 41°N and 43°N), and even for the meridional transect at 9°W, oxygen concentrations show a linear increase with temperature. However, a progressive shift with latitude is observed, presenting higher oxygen levels at higher latitudes for the same temperature (Fig. 3b). This trend parallels the decrease of oxygen saturation with increasing temperature and the southward increase of temperature for the upper layer of ENACW. Nitrate concentrations follow the opposite trend (Fig. 3c): nitrate levels decrease with increasing temperature. Likewise, there is also a marked meridional variability: for a given temperature, nitrate levels decrease northwards.

Due to the high correlation between salinity and temperature in the ENACW domain ($r > 0.97$, $p < 0.001$ for the three study cruises), the effect of ENACW modes mixing on the oxygen and nitrate variability can be adequately removed by linear regression with either salinity or temperature. Temperature is preferred because its range/precision ratio is 4-fold that of salinity. The linear regressions (Model I) for oxygen and nitrate with temperature for all samples corresponding to ENACW during cruise BD3 are:

$$\text{O}_2 (\pm 13) = 170 (\pm 8) + 4.7 (\pm 0.7)\theta \quad (1)$$

$(r = 0.40, n = 206, p < 0.001),$

$$\text{NO}_3^- (\pm 1) = 42 (\pm 1) - 2.7 (\pm 0.1)\theta \quad (2)$$

$(r = 0.86, n = 206, p < 0.001).$

The correlation between oxygen and nitrate anomalies (measured–calculated; Fig. 3d) is significant ($r^2 = 0.94$) with a slope $R_N (= -\Delta\text{O}_2 : \Delta\text{NO}_3)$ equal to 6.4 ± 0.2 ($n = 206$). Thus, about 94% of the oxygen and nitrate variability not fitted by mixing of ENACW modes can be explained by processes of remineralization of organic matter (ROM). However, the calculated slope is somewhat lower than the theoretical R_N value of 9.3 (Redfield et al., 1963; Anderson, 1995) and previous field determinations (Takahashi et al., 1985; Minster and Boulahdid, 1987; Fraga and Pérez, 1990; Castro et al., 1998). Castro (1997) showed that the low R_N values in the Iberian basin are due to the low preformed nitrate concentrations of ENACW_{sp}, related to the poleward intrusion of ENACW_{st}.

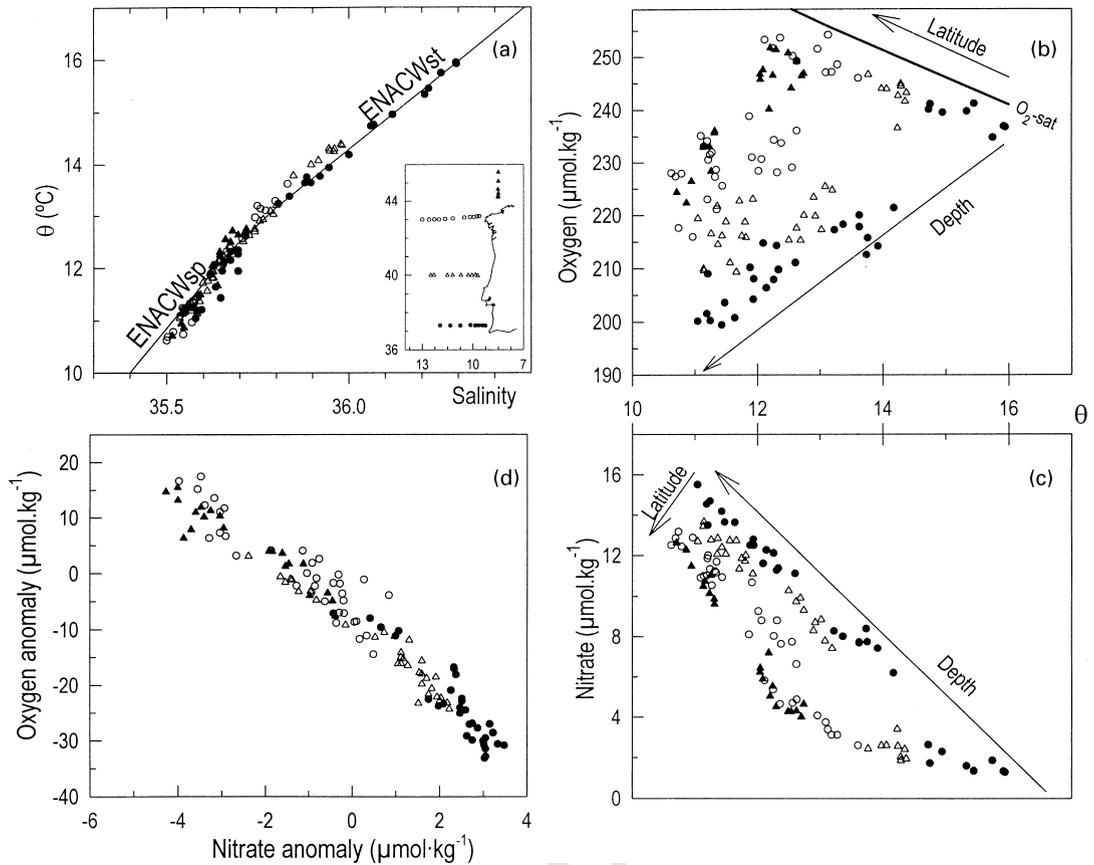


Fig. 3. The ENACW domain during cruise *Bord-Est 3* (9–26 May 1989). (a) θ - S diagram of ENACW samples showing the θ/S reference line of subtropical and subpolar ENACW modes by Ríos et al. (1992). (b) Oxygen vs. potential temperature plot, showing the latitudinal and vertical variability; the oxygen saturation line is also included. (c) Nitrate vs. potential temperature plot showing the latitudinal and vertical variability. (d) Oxygen (ΔO_2) vs. nitrate (ΔNO_3^-) anomalies. Temperature in $^{\circ}C$, and oxygen and nitrate in $\mu\text{mol kg}^{-1}$.

3.2. ENACW ventilation on the Portugal Current System

3.2.1. Thermohaline and geostrophic fields during a PCCC event

Southwesterly winds prevailed during the *MORENA I* cruise, with an average of 6.3 m s^{-1} and a maximum of 15 m s^{-1} , which favoured the development of the surface PCCC. Fig. 4 shows the horizontal distributions of θ , salinity, density anomaly and geopotential anomaly at 120 dbar. The upper limit of ENACW (identified by a shallow subsurface salinity maximum) all over the study area was between 75 and 105 dbar. ENACWst with $\theta > 13^{\circ}C$ (Fig. 4a) and $S > 35.75$ (Fig. 4b) occupied this horizon, except in the northwest corner (stns 3–5; Fig. 1). The distribution of thermohaline properties was meridional rather than zonal, opposite to the climatology of the Eastern North Atlantic (Maillard, 1986). The northward spreading of ENACWst is traced by temperature and salinity maxima that extend from $102^{\circ}W$ at $40.5^{\circ}N$ to $9.8^{\circ}W$ at $43^{\circ}N$ (dotted lines

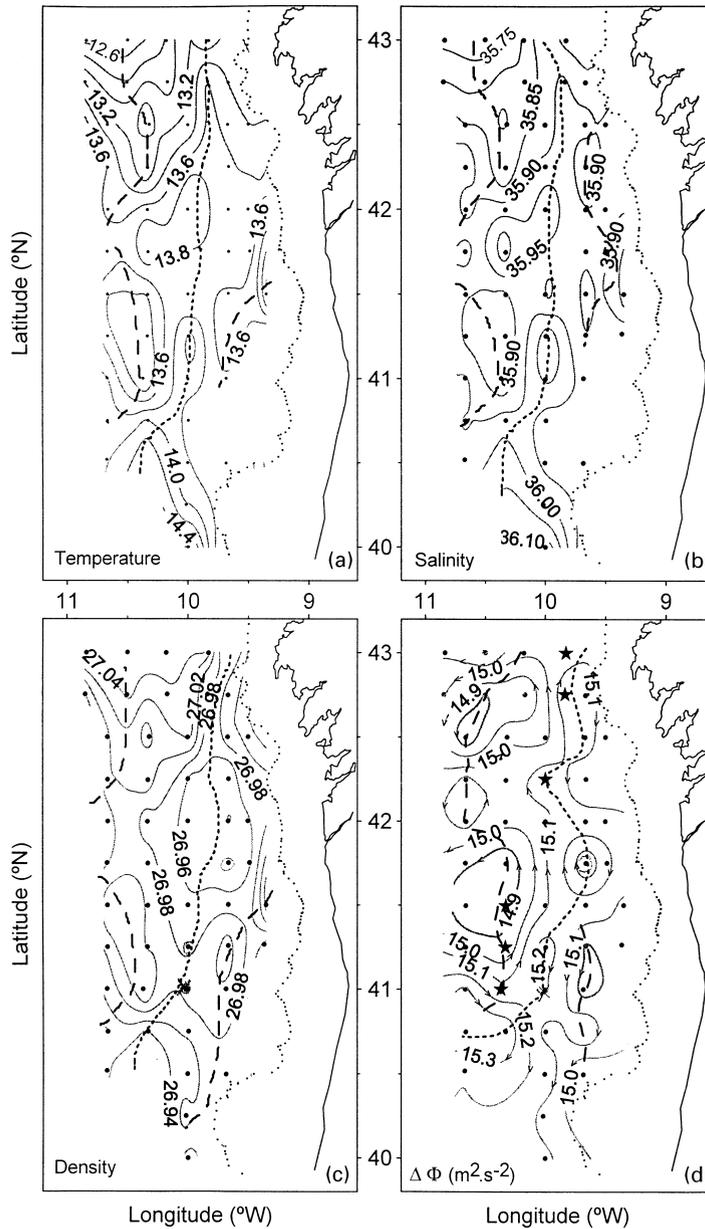


Fig. 4. Horizontal distributions at 120m depth of (a) potential temperature; (b) salinity; (c) density anomaly; and (d) geopotential anomaly relative to 700db during the MORENA I cruise (12–26 May 1993). Temperature in °C, density anomaly in kg m^{-3} and geopotential anomaly in $\text{m}^2 \text{s}^{-2}$. For temperature, salinity and geopotential anomaly, dotted and dashed lines correspond to maxima and minima, respectively. For density anomaly it is the opposite.

in Fig. 4). In the opposite direction, temperature and salinity minima stretched out from 43°N to nearly 41°N along 10.5°W (dashed lines in Fig. 4). However, there was a gap at the 41.8°N section associated with an eastward intrusion of saline and warm water during a short period (15–17 May) of strong southwesterly winds (15 m s^{-1}). Salinity and temperature minima observed at the shelf

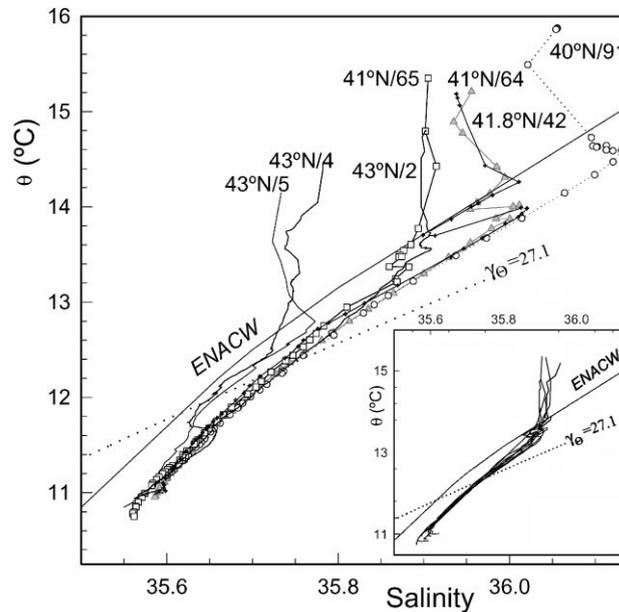


Fig. 5. θ - S profiles of some selected stations (see Fig. 1 for locations) during the *MORENA I* cruise (May 1993). The θ/S reference line of ENACW by Ríos et al. (1992) and the 27.1 kg m^{-3} isopycnal are also shown. The enclosed graph shows the θ/S profiles of station 2, 9, 22, 49, 52 and 65, which are labelled with stars in Fig. 4.

break suggest deepening in association with the convergence between the high salinity core of ENACWst on the slope and the fresher and cooler shelf waters. The density anomaly field (Fig. 4c) clearly shows the northward spreading of the lighter ENACWst between the shelf break and the ENACW located west of 10.3°W . The 120/2500 db geopotential anomaly field (Fig. 4d) shows alternating southward and northward geostrophic currents associated with the fronts between the warm and saline ENACWst wedge and (1) shelf waters, to the coast (east); and (2) cold and less saline modes of ENACWst, to the open ocean (west). It should be noticed that ENACWsp occupied the northwestern corner at this 120 db horizon.

The selected θ - S profiles in Fig. 5 also show the spatial variability of the water masses during the *MORENA I* cruise. It is worth noting that the θ/S relationships were shifted towards higher salinity or lower temperature compared with the ENACW reference line (Fiúza, 1984; Ríos et al., 1992) because of the strong salinity change in 1991 (Pérez et al., 1995; Pollard et al., 1996). The θ/S relationships for ENACW of stns 4 and 5 (43°N) were rather close to the ENACW reference line, and their salinity maxima were relatively fresh ($S < 35.72$). On the other hand, the θ - S profile of stn 91 covered the largest ENACW temperature and salinity ranges, with a salinity maximum as high as 36.14. For the rest of the stations, ENACW presented θ/S relationships between the extreme θ - S profiles of stns 5 and 91. Two specific θ - S profiles, at stn 65 (41°N , 10.32°W) and at stn 2 (43°N , 9.8°W), were practically coincident in the upper 150 m, although the stations were quite far apart (Fig. 2). The θ/S segment for ENACW at stn 65 was only slightly fresher or warmer than that of stn 2. In fact, stns 2, 9, 22, 49, 52 and 65, located along the northward-flowing geostrophic current (see stars in Fig. 4d) show very close θ - S profiles (Fig. 5). However, the θ - S profile of stn 64 was quite different from that of stn 65, whilst it was very similar to the θ - S profile at stns 42 (41.8°N , 9.8°W)

and 53 (not shown). It should be noticed that the line of maximum geopotential anomaly and minimum density linked stns 42, 53 and 64. Therefore, the analysis of water mass properties presented additional evidence of the northward spreading of the saline and warm ENACWst.

The hydrographic and dynamic fields during the *MORENA I* cruise differed from the large spatio-temporal average fields (Maillard, 1986). The observed mesoscale physical structure reflects a north-south exchange of water along two opposite paths. During the northward spreading of the warm and saline wedge of ENACWst along the slope of the Iberian margin, it mixes either with shelf waters to the east or with fresh and cold ENACW (either subpolar or subtropical) to the west.

3.2.2. Chemical fields during two contrasting PCCC events (*MORENA I* and *Galicía VI* observations)

The *BE3* data have clearly shown a northward decrease (increase) of ENACW nitrate (oxygen) levels for a given temperature (Fig. 3) at the Iberian basin scale. Therefore, the intense PCCC recorded during the *MORENA I* cruise (Figs. 4, 5) should transport northwards along the slope warm, low-oxygen and high-nutrient ENACWst, whereas the PC should transport southwards colder, high-oxygen and low-nutrient ENACW. After the first descriptions of the PCCC along the Iberian slope in autumn and winter (Haynes and Barton, 1990; Pingree and Le Cann, 1990; Frouin et al., 1990), Krauss' (1986) circulation cartoon (Fig. 1) was modified by Ellett (1993). He considered that, in light of the field observations, two opposite currents should constitute the Portugal Current System, but he did not go into any detail on their extension, coexistence or seasonality. Mazé et al. (1997) suggested a seasonal alternation of the PC and PCCC along the Iberian margin to explain the southward penetration of ENACWsp and the northward penetration of ENACWst. In the preceding section, we have shown how the PC and PCCC can coexist as suggested by Ambar and Fiúza (1994), leading to a quite intricate circulation pattern. In this section, we will demonstrate that mixing or entrainment of the contrasting water masses transported by the opposite flows produces a downstream modification of their chemical properties.

Following the same procedure as with the *BE3* data, the effect of mixing of ENACW modes on the oxygen and nitrate fields has been removed considering the anomalies of their respective linear regressions with temperature (Model I):

$$\text{O}_2(\pm 8) = 171(\pm 7) + 4.4(\pm 0.5)\theta \quad (3)$$

$(r = 0.43, n = 264, p < 0.001),$

$$\text{NO}_3^-(\pm 1) = 45.8(\pm 0.9) - 2.98(\pm 0.07)\theta \quad (4)$$

$(r = 0.93, n = 264, p < 0.001).$

The differences between the regressions for *BE3* and *MORENA I* are due to the different spatial coverages of the two cruises; the latitudinal range of *MORENA I* was 3°, about 1/3 the extension of *BE3*. Nitrate and oxygen anomalies for the *MORENA I* data are highly correlated ($r^2 = 0.76$) with a slope, $R_N (= -\Delta\text{O}_2 : \Delta\text{NO}_3)$, of 6.5 ± 0.2 ($n = 264$), which is not significantly different from the R_N ratio obtained with the *BE3* data. ROM explains ~76% of the nitrate and oxygen variability. This is lower than the percentage of explained variability for the *BE3* cruise, also because of the reduced spatial coverage of the *MORENA I* cruise.

Two zonal sections, along 43°N and 41°N, were selected to show the ventilation of ENACW (Fig. 6). Density was used to avoid changes due to vertical displacements of water masses. The salinity distribution along 43°N shows a saline wedge, with $S > 35.8$, over the slope (Fig. 6a). Less

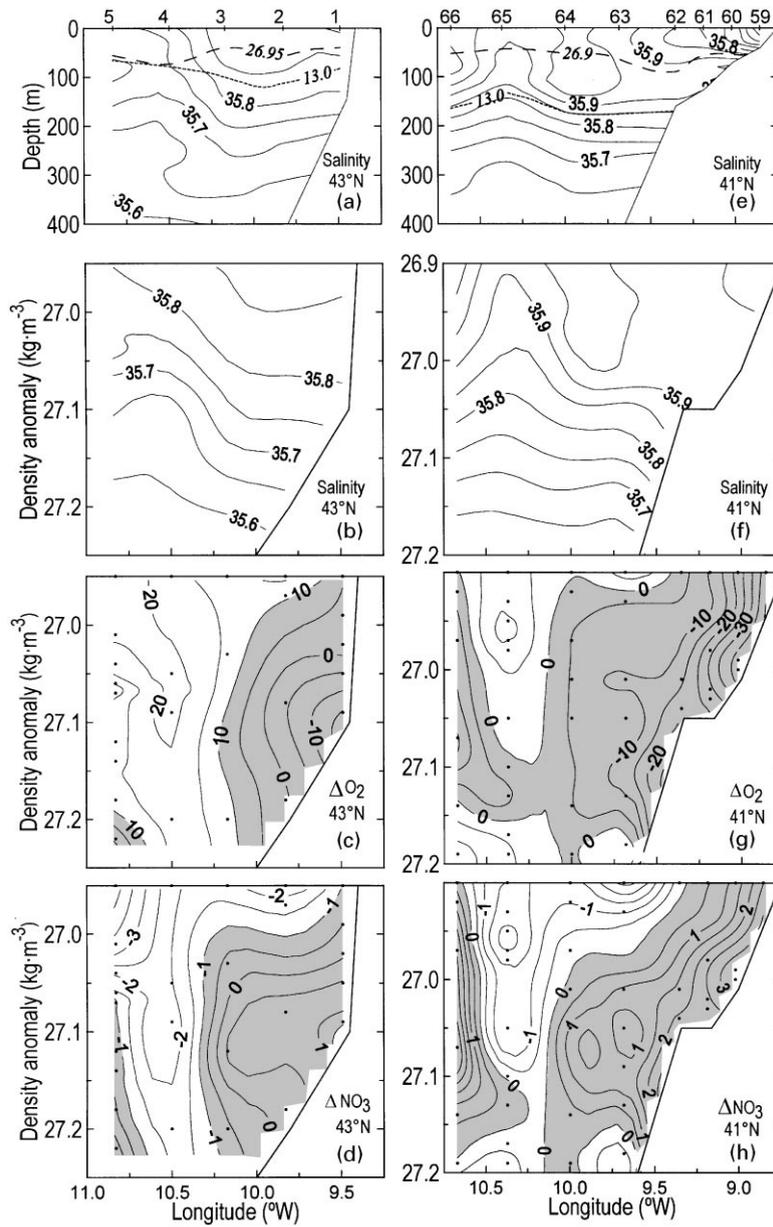


Fig. 6. Vertical distributions of salinity vs. depth (a,e); salinity (b,f), oxygen anomaly (c,g) and nitrate anomaly (d,h) vs. density anomaly along the zonal sections at 43°N and 41°N (see Fig. 1 for locations) during the *MORENA I* cruise (12–26 May 1993). Oxygen and nitrate anomalies in $\mu\text{mol kg}^{-1}$. Shaded areas indicate waters with high nutrient and low oxygen anomalies, which represent coarsely the PCCC domain. The isotherm 13°C and the isopycnals 26.95 kg m^{-3} (in a) and 26.9 kg m^{-3} (in e) are shown by dotted and dashed line, respectively.

saline ENACW was located west of 10.3°W with a distinct θ/S relationship (Fig. 5, stn. 5). At the 27.1 isopycnal level (about 200 m), a front between ENACWst and ENACWsp is clearly defined. Oxygen (Fig. 6b) and nitrate (Fig. 6c) anomalies closely mirror each other. The front is associated with the $10\ \mu\text{mol kg}^{-1}$ oxygen and $-1\ \mu\text{mol kg}^{-1}$ nitrate anomaly isopleths and separates ENACW with high oxygen and low nitrate levels to the west from ENACW with low oxygen and high nitrate over the slope. The lowest oxygen and highest nitrate anomalies are located on the shelf because of intense ROM processes (Álvarez-Salgado et al., 1997). Although the saline wedge that traces the poleward advection of ENACWst appears in the upper layers, the chemical fields depicted a deeper signature of the poleward current as well as the geostrophic velocity field (not shown).

The salinity distribution at 41°N clearly shows a front between stns 64 and 65 (Fig. 6d). The saline core extended from 10.2°W to the shelf-break with $S > 35.95$. In the upper layer, a salinity minimum was found at stn. 65. Below the upper layer, the salinity distribution showed a nearly constant vertical gradient without any frontal structure. The slight tilting of the isohalines indicates a minor salinity increase of ENACW to the slope. The nitrate (Fig. 6e) and oxygen (Fig. 6f) anomaly distributions also show good concordance. The lowest oxygen and highest nitrate anomalies are again located over the shelf, as along 43°N . The positive oxygen and negative nitrate anomalies centred at stn. 65 trace the southward penetration of recirculated ENACWst. On the other hand, the northward advection of ENACWst is characterised by negative oxygen and positive nitrate anomalies.

The 41°N section presents more negative oxygen and more positive nitrate anomalies than the 43°N section, following the large-scale pattern of increasing ventilation to the north (Pollard and Pu, 1985). The oxygen decrease and nitrate increase along the southward flowing branch of ENACW are in agreement with downstream ageing due to ROM. However, the nitrate decrease and oxygen increase in the northward flowing PCCC cannot be explained by downstream ageing due to the ROM processes, because one would expect a downstream nitrate increase or oxygen decrease parallel to mineralization. Mixing or entrainment with the southward flowing ventilated ENACW are the main responsible mechanisms for this oxygen increase and nutrient decrease of the ENACWst high salinity core as it flows northwards. The effect of mixing/entrainment on the chemical field is the same as direct ventilation when an isopycnal outcrops at sea surface, and we can consider it as a mechanism of indirect ventilation. Stn 2 (in the core of the PCCC at 43°N) showed higher oxygen and lower nitrate levels than stn 64 (in the core of the PCCC at 41°N), but lower oxygen and higher nitrate levels than stn 65, with a θ - S profile similar to stn 2. The northward geostrophic current band between 10 and 10.2°W seems to link stns 65 and 2 (Fig. 4d). However, the degree of ENACW ventilation is completely different. At 41°N , stn 65 is occupied by ventilated ENACW coming from the north. At 43°N , stn 2 clearly traces the PCCC transporting relatively aged ENACWst. A cyclonic circulation between both branches of ENACW could resolve this apparent contradiction. Two cyclonic eddies centred at 41.6° and 42.6°N can be observed in Fig. 4d. Stn. 65 is located in the southern limb of the cyclonic gyre centred at 41.6°N . Thus, ENACW at 41°N could be recirculated northward. These eddies are probably responsible for the property exchange between the poleward and the equatorward branches of ENACW. This mechanism could explain the continuous decrease of salinity and nutrient levels in the recurrently observed poleward slope current off the Iberian Peninsula (Haynes and Barton, 1990; Pérez et al., 1993; Pingree, 1994; Castro et al., 1997).

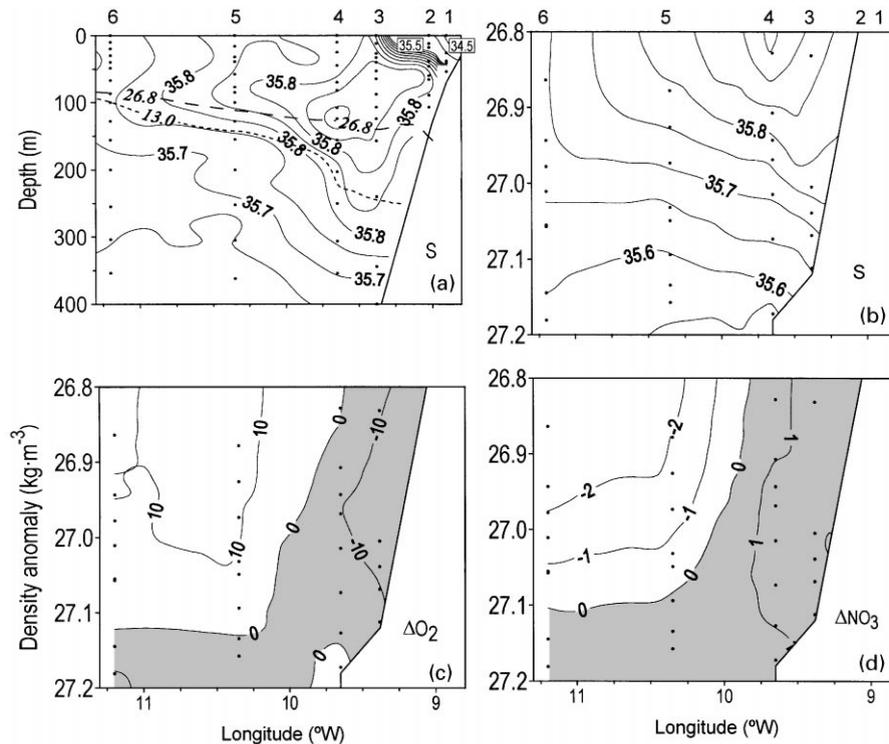


Fig. 7. Vertical distributions of salinity vs. depth (a); salinity (b), oxygen anomaly (c) and nitrate anomaly (d) vs. density anomaly along the 41.8°N zonal transect (see Fig. 1 for location) during the *Galicia VI* cruise (1 to 12 December 1983). Shaded areas represent waters with positive nutrient and negative oxygen anomaly. The isopycnal 26.8 kg m⁻³ and isotherm 13°C are shown in (a) by dashed and dotted line, respectively.

Therefore, the mesoscale observations during the spring cruise *MORENA I* indicate that the northward decrease of salinity and nutrients in the ENACW domain at the Iberian margin are due to water exchange between ENACWst in the poleward slope current and the surrounding fresh and ventilated ENACWsp. However, the most intense PCCC events are usually observed in late autumn and winter (Frouin et al., 1990; Haynes and Barton, 1990; Pingree and LeCann, 1990). Although all these observations were not complemented with oxygen and nutrient determinations, the Frouin et al. (1990) cruise *MEDPOR/2* (December 1983) was fortunately synoptic with the 41.8°N line of the *Galicia VI* cruise (Fig. 2). A detailed description of the physical setting at the time of the cruise was made by Frouin et al. (1990), supported by satellite imagery. Here we just describe the chemical setting of this strong autumn PCCC event, using the same procedure to calculate oxygen and nitrate anomalies used for cruises *BE3* and *MORENA I*.

Along 41.8°N, a clear high salinity core is quite apparent above 300 m depth, extending from the slope to 10.3°W (Fig. 7a). Frouin et al. (1990) found the same signature of the PCCC, estimating a geostrophic transport of 0.5 Sv along the same zonal transect. The PCCC also provoked a convergence toward the shelf break, with the corresponding isotherms deepening (not shown) and the confinement of the less saline continental waters toward the coast, as observed during the

MORENA I cruise. The haline field shows a clear front above the 27.0 isopycnal, between the core of saline ENACWst with $S > 35.8$ at stns 3 and 4 and the less saline ENACWsp at stn 6 located west of 10.3°W (Fig. 7b).

The corresponding nitrate (Fig. 7c) and oxygen (Fig. 7d) anomalies show good correlation ($r = 0.70$, $n = 42$, $p < 0.001$) with a slope R_N of 6.4 ± 0.1 , which is not significantly different from those calculated from *BE3* and *MORENA I* data. The PCCC transported northwards aged ENACWst, which is ventilated by mixing with the low nitrate/high oxygen ENACWsp flowing southward, west of 10.3°W (Frouin et al., 1990). Thus this autumn cruise also confirms the circulation pattern on this eastern boundary previously described for the spring cruise.

4. Conclusions

Poleward advection of ENACWst along the Iberian margin was first suggested by Fraga et al. (1982), who found a subsurface front between the subtropical and subpolar branches of ENACW off Cape Finisterre, 43°N (Fig. 1), and confirmed by Pérez et al. (1993). Ríos et al. (1992) and Álvarez-Salgado et al. (1993) noticed a year-round increase of ENACWst salinity off the Ría de Vigo, 42°N (Fig. 1), due to northward transport by the PCCC during the autumn, winter and spring, and by the PCUC during the summer. In the present work, the Portugal Current System was characterised chemically using data from cruises conducted under dominant southerly wind conditions (spring 1989 and 1993, autumn 1983). In such conditions, the Portugal Current (PC) transports southward fresh modes of well-ventilated ENACW west of 10.3°W (100–150 km off the Iberian margin). On the other hand, the PCCC moves as a high salinity core along the Iberian slope, transporting poorly-ventilated ENACWst. Exchange of ENACW between the PC and PCCC occurs, leading to a field of mesoscale cyclonic eddies superimposed on the classic large-scale zonal structure. As a result of this eddy-mediated exchange, ENACWsp is transported into the Subtropical Gyre, whereas aged ENACWst conveyed northward by the PCCC along the eastern boundary is indirectly ventilated with ENACWsp.

5. Uncited Reference

Fraga 1981; Reid and Mantyla, 1976.

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