

Thermohaline structure, ageostrophic vertical velocity fields and phytoplankton distribution and production in the northeast Atlantic subtropical front

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[1] Two oceanographic cruises were carried out in the Azores Current/Subtropical Front region in July 1997 and April 1999 to study the seasonal and mesoscale spatial variability in the relationship between the hydrodynamic characteristics of the water column and the distribution of nutrients, phytoplankton biomass, and production. Both the magnitude of chlorophyll-*a* values and primary production rates as well as their vertical distribution varied sharply associated with subtle changes in seasonal thermal stratification. Successive upwelling and downwelling regions were detected along the track of a cyclonic meander, with maximum ageostrophic vertical velocities of 3 m d^{-1} and -4 m d^{-1} , respectively, at 375 dbar. Relatively high nitrate concentrations ($>3.5 \mu\text{M}$) were found associated with denser waters at the center of the meander, where the deep chlorophyll maximum (DCM) uplifted ~ 20 dbar. Chlorophyll-*a* concentrations ranged from 0.1 to 0.4 mg m^{-3} , with slightly higher values ($>0.35 \text{ mg m}^{-3}$) at the northern side of the current. A significant relationship was not detected between the vertical ageostrophic velocity field and nitrate and chlorophyll-*a* distributions, which were significantly correlated with the depth of the 16°C isotherm. Vertical advective fluxes of nitrate across the base of the DCM were about 2 orders of magnitude higher than vertical diffusive nitrate transport (-6.6 to $3.7 \text{ mmol m}^{-2} \text{ d}^{-1}$ versus 0.01 to $0.07 \text{ mmol m}^{-2} \text{ d}^{-1}$). Diffusive nitrate fluxes only account for $<10\%$ of the total primary production rates measured in the region. *INDEX TERMS*: 4528 Oceanography: Physical: Fronts and jets; 4520 Oceanography: Physical: Eddies and mesoscale processes; 4568 Oceanography: Physical: Turbulence, diffusion, and mixing processes; 4845 Oceanography: Biological and Chemical: Nutrients and nutrient cycling; *KEYWORDS*: northeast Atlantic subtropical front, mesoscale variability, ageostrophic vertical circulation, vertical nutrients fluxes, phytoplankton biomass and production

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1. Introduction

[2] A relevant fraction of the oceanic kinetic energy resides in the mesoscale, 10 – 500 km, characterized by the internal Rossby radius of deformation where Coriolis and baroclinic pressure forces are balanced. It is in this scale that frontal systems become unstable and develop meander activity. Several observational [Pollard and Regier, 1992; Strass, 1994; Rudnick, 1996; Viúdez *et al.*, 1996; Shearman *et al.*, 1999] and modeling studies [Onken, 1992; Spall, 1995; Gomis *et al.*, 2001] have described the existence of

vigorous vertical velocities associated with the meandering of frontal jets. It has been theorized that this vertical water motion might play a key role not only in ocean circulation but also in the cycling of matter at global scales by entering nutrients into the photic layer and subsequent export of organic carbon to deep ocean waters (see review by Garçon *et al.* [2001]).

[3] Several studies have investigated the influence of vertical water circulation on ecosystem dynamics in the highly energetic western boundary currents [Flierl and Davis, 1993; Spall and Richard, 2000; Anderson and Robinson, 2001]. However, only a few authors have centered their attention on areas of relatively weak eddy kinetic energy [Dadou *et al.*, 1996]. The present investigation is focused on the Azores Current (AC), a distinct hydrodynamic feature located at 33°N – 35°N which flows eastward associated with the Subtropical Front (STF). The

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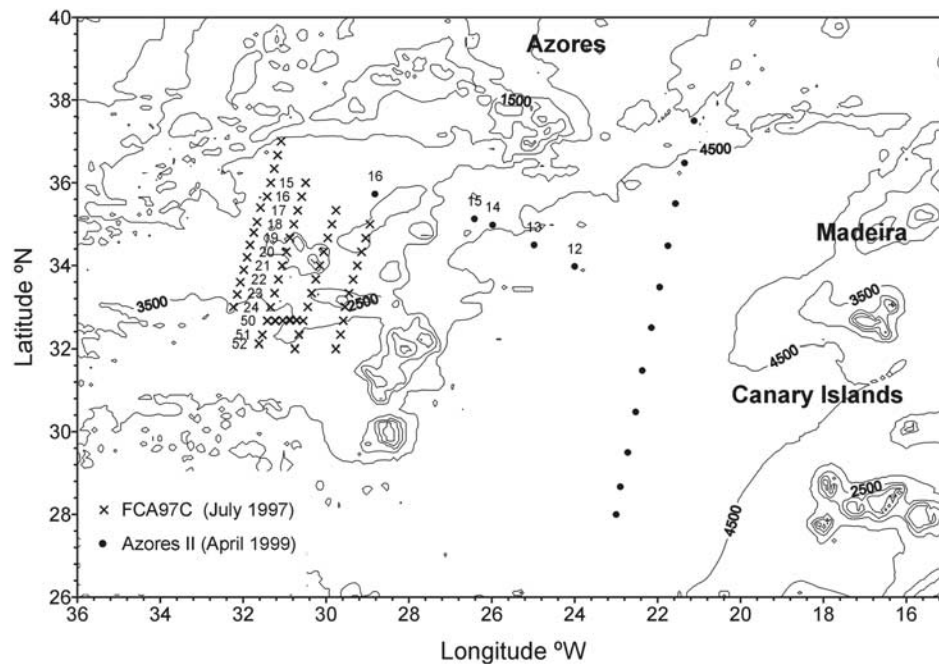


Figure 1. Stations visited at the AC/STF region during FCA97c (July 1997) and Azores II (April 1999) cruises. Station numbers of transects chosen to show vertical properties of water column are indicated. Numbers near isolines represent the depth of the bottom (in meters).

Azores Current/Subtropical System (AC/STF) constitute the north wall of the Northeast Atlantic Subtropical Gyral Province that separates warmer and saltier waters to the south from colder and less haline waters to the north [Gould, 1985; Longhurst, 1998]. A diverse mesoscale activity has been reported associated with the Subtropical Front, where meanders of the Azores Current occasionally develop into large, ~ 300 km in diameter, cold and warm core rings [Pingree *et al.*, 1996, 1999; Mouriño *et al.*, 2002, 2003].

[4] A high-resolution, cross-front sampling carried out with a Sea-Soar in March 1992 showed two distinct and isolated chlorophyll patches related to the northern and southern boundaries of the Subtropical Front, with values 2–3 times higher than at surrounding waters [Fernández and Pingree, 1996]. Primary production rates measured in the same study were about two-fold higher than those at neighboring areas not affected by mesoscale features. However, distinct biological responses were not always observed associated with the AC/STF system. Two oceanographic studies carried out in April and May 1981 showed little evidence for increased phytoplankton biomass associated with the Subtropical Front, and only patchiness of the deep chlorophyll maximum was observed associated with eddy-like features linked to the Azores Current [Fasham *et al.*, 1985].

[5] In this study, we compiled the information obtained in the Azores Current region during two oceanographic cruises carried out in July 1997 and April 1999 with the aim of (1) describing the relationship between the thermohaline properties of the water column and phytoplankton biomass and production at the Azores Current region in two distinct stratification conditions, (2) studying the spatial coupling between the ageostrophic vertical velocity and phytoplank-

ton biomass fields, and (3) quantifying the vertical input of nutrients into the photic layer by diffusive and advective processes, with the ultimate aim of exploring the impact of frontal thermohaline structure and hydrodynamics on phytoplankton distribution and production.

2. Methods

2.1. Hydrographic Sampling

[6] In summer 1997, from 19 July to 5 August, a high spatial resolution oceanographic survey (FCA97c) was carried out across the North Atlantic Subtropical Front on board RV *Arquipélago* (Figure 1), in order to characterize the meanders dynamic linked to the Azores Current. The general design and details of the observational strategy adopted for the FCA97c cruise were based on numerical simulations running a primitive equations model of the Azores Current [Alves, 1996]. The best design for a 3-dimensional mesoscale sampling is such that (1) the sampling area should be large enough to cover at least one wavelength and wide enough to cover meander amplitude; a minimum of four cross-sectional lines are required to cover a full wavelength; (2) the main axis jet must be as close as possible to the central sampling area; and (3) stations on a cross frontal line should be close enough to resolve frontal gradients. Bearing in mind these requirements, a total of 57 conductivity temperature depth (CTD) casts were carried out, and along-track acoustic Doppler current profiler (ADCP) data were collected. Individual sections were tested in almost real time to ensure cross sections of the mean path. Physical and chemical data collected during the 57 CTD casts were horizontally interpolated by an objective analysis method as described by Alves *et al.* [2002]. The second section (st. 15–52, see Figure 1) was used to describe vertical physical,

chemical, and biological characteristics of the water column in summer 1997.

[7] Two additional latitudinal sections across the meandering region of the AC/STF were sampled during the Azores II cruise, on board B.I.O. *Hesperides* from 8 to 28 April 1999. The second section (st. 12–16, see Figure 1) was chosen to show the vertical distribution of physical, chemical, and biological properties of the water column in spring 1999. Surface temperature and salinity was continuously monitored by means of a SBE-21 thermosalinograph. Expendable bathythermographs (XBT) were used extensively to obtain fine-scale temperature distributions. CTD pressures and XBT depths were calibrated and an appropriate correction was applied to make the CTD and XBT temperature data sets comparable (iso16°_XBT = iso16°_CTD + 20).

2.2. Dissolved Inorganic Nitrogen, Chlorophyll-*a*, and Primary Production

[8] CTD profiles were conducted with a Neil Brown mark III probe attached to a rosette equipped with 10-L Niskin bottles. CTD temperature and salinity sensors were calibrated using digital reversing thermometers and water samples drawn for salinity determinations. Water samples were collected on each CTD cast for the determination of dissolved inorganic nitrogen and chlorophyll-*a* concentrations, as well as for the measurement of primary production rates (Azores II cruise). Dissolved inorganic nitrogen was determined according to the method described by *Strickland and Parsons* [1972] (FCA97c) and by continuous flow analysis using a Technicon-Bran Luebbe AA II AutoAnalyzer as described by *Tréguer and Le Corre* [1975] (Azores II). Chlorophyll-*a* was determined fluorimetrically after filtration of seawater onto 0.2- μm polycarbonate filters and subsequent extraction in 90% acetone overnight. Chemically determined chlorophyll-*a* concentrations were used to calibrate the CTD fluorometer. Rates of size-fractionated carbon incorporation by phytoplankton were measured at selected stations during the Azores II cruise. Triplicate 70-mL acid-cleaned polypropylene bottles were filled with water collected from five or six depths corresponding to optical depths ranging from 100 to 1% of surface irradiance levels. Bottles were inoculated with 370 to 555 kBq (10–15 μCi) $\text{NaH}^{14}\text{CO}_3$ and immediately placed in an on-deck incubator cooled by surface waters for 7–11 hours. Samples were incubated at irradiances corresponding approximately to those experienced by the cells at the sampling depths. After the incubation period, samples were filtered at very low vacuum pressure (<50 mm Hg), and the filters were decontaminated by exposure to fumes of concentrated HCl for 12 hours. Radioactivity was determined by liquid scintillation on board (Azores II). Quenching corrections were performed using an external standard.

2.3. Vertical Nitrate Fluxes

[9] Vertical diffusive and advective nitrate fluxes were computed across the cyclonic meander studied during the FCA97c cruise.

2.4. Diffusive Fluxes

[10] Considering the important internal waves activity reported for this region [*Mouriño et al.*, 2001, 2002]

eddy diffusion coefficients were calculated by the formulation

$$K_z = \frac{\alpha}{N} \quad (\text{m}^2 \text{ s}^{-1}), \quad (1)$$

which assumes that mixing is mainly produced by internal waves [*Gargett*, 1984], where N is the Brunt Väisälä frequency, and α was set to $5.4 \times 10^{-4} \text{ cm}^2 \text{ s}^{-2}$ [*Mouriño et al.*, 2002]. The Brunt Väisälä frequency was derived from conductivity-temperature-depth (CTD) profiles according to the equation

$$N^2 = \left(\frac{g}{\rho_w}\right) \left(\frac{\partial \rho}{\partial z}\right) \quad (\text{s}^{-2}), \quad (2)$$

where g is the acceleration due to gravity (9.8 m s^{-2}), ρ_w is seawater density (1025 kg m^{-3}), and $\partial \rho / \partial z$ is the vertical potential density gradient. Diffusive nitrate fluxes were calculated from the product of the diffusion coefficients, K_z , estimated for each depth level (press interval 15 dbar) and the gradients of nitrate concentration.

2.5. Advective Fluxes

[11] The thermal wind balance (referenced to 1500 dbar) was calculated for the FCA97c cruise domain. On the basis of the temperature (T) and salinity (S) profiles, the dynamic height stream function was determined, objectively analyzed [see *Alves et al.*, 2002] and used to calculate the thermal wind vector. Using the same methodology as *Rudnick* [1996], the FCA97c cruise barotropic geostrophic stream function was calculated and added to the thermal wind to obtain the absolute geostrophic flow field in the area. The study of this flow demonstrated that the FCA97c cruise covered about one wavelength of the meandering Azores Current. This, together with an almost zonal Azores Current mean path, allowed us to produce mean zonal fields and to perform a zonal mean correlation analysis between the different quasi-geostrophic dynamical fields. The vertical velocity field was obtained assuming quasi-geostrophic dynamics and by deriving the w -equation in a way similar to *Hoskins et al.* [1978]. In the f plane, the resulting equation reads as follows:

$$\nabla_H^2 (N^2 w) + f^2 \frac{\partial^2 w}{\partial z^2} = -2 \vec{\nabla}_H \cdot \vec{Q}, \quad (3)$$

where N is the three-dimensional buoyancy frequency, f is the Coriolis parameter and the vector \vec{Q} can be expressed as

$$\vec{Q} = -\frac{g}{\rho_0} \left[\left(\frac{\partial \vec{v}_g}{\partial x} \cdot \vec{\nabla} \rho \right) \vec{e}_1 + \left(\frac{\partial \vec{v}_g}{\partial y} \cdot \vec{\nabla} \rho \right) \vec{e}_2 \right], \quad (4)$$

where $\vec{v}_g = (u_g, v_g)$ is the geostrophic vector, \vec{e}_1 and \vec{e}_2 stand for the unitary vectors in the east and north direction, and ρ is the density.

[12] The w -equation, which is a three-dimensional velocity elliptic equation in w , is forced by the divergence of the \vec{Q} vector. Using the previously calculated \vec{v}_g , N , and ρ fields for the FCA97C area and choosing appropriate boundary conditions, one can finally solve the above elliptic equation for

w . This was achieved numerically by using *Adams'* [1991] elliptic solver. Choosing boundary conditions of the Dirichlet type, as far as possible from the central frontal zone, with $w = 0$ for all of them (the elliptic nature of the equation gives confidence to such choice, since the solution within the domain should not be affected by the forcing at far boundaries), vertical velocity patterns which are in good agreement with previous numerical results described by *Alves and de Verdière* [1999] were obtained. Such agreement means that the meandering southern branch of the present current is developing according to the baroclinic instability patterns. Neumann boundary conditions were also tried without any significant change in the results. Advective nitrate fluxes were calculated from the product of the ageostrophic vertical velocity field and nitrate concentration for each depth level (press interval 15 dbar).

[13] Once the vertical velocity is calculated, the horizontal ageostrophy is readily obtained through the QG diagnostic relationships between the three-dimensional ageostrophy and the horizontal Q vector components [*Rudnick, 1996*]. From the ageostrophic and geostrophic parts of the flow field, the quasi-geostrophic flow is obtained.

3. Results

3.1. Seasonal Variability of Physical and Biological Fields in the AC/STF Region

[14] Figure 2 describes the thermohaline structure of the AC/STF region observed in July 1997 (FCA97c cruise, 32°N–37°N, 29.0°W–32.2°W). The Subtropical Front, located at about 32.5°N–33.5°N, appears as a meandering feature associated with a marked gradient in surface temperature and salinity ($\sim 1^\circ\text{C}$ and 0.4 psu, respectively) over spatial scales of ~ 100 km. The depth of the 16° isotherm deepened sharply southwards from 150 m to 275 m, as a consequence of the existence of different water masses on the northern and southern side of the front [*Pingree et al., 1996; Pollard et al., 1996; New et al., 2001*]. A relatively cold and less saline water mass was found at the meander trough, centered at $\sim 33.5^\circ\text{N}$, 30.5°W , associated to a slight shallowing (>25 dbar) of the depth of the 16°C isotherm. This uplifting of isotherms was not observed below 225 dbar (data not shown).

[15] A more extensive region of the northeast subtropical Atlantic was surveyed in April 1999 (Azores II cruise, 31°N–38°N, 20°W–32°W) (Figure 3). The thermohaline structure of the subtropical front was very similar to that previously described in July 1997. Sharp gradients in surface temperature and salinity ($\sim 2^\circ\text{C}$ and 0.3 psu, respectively) over spatial scales of ~ 200 km, as well as in the depth of the 16°C isotherm that deepened southward from 125 m to 250 m, delimited the position of the meandering Subtropical Front, located farther north (about 34°N–35°N) as compared to its position in summer 1997.

[16] The vertical distribution of temperature, sigma theta, geostrophic velocity, nitrate, and chlorophyll-*a* concentra-

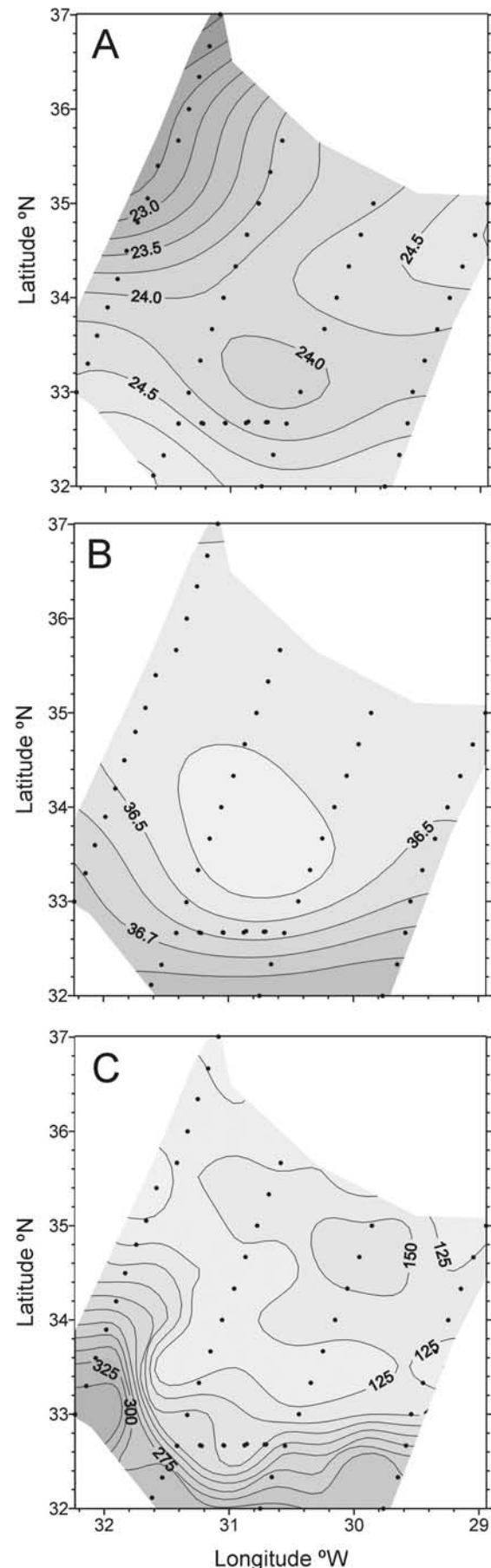


Figure 2. (a) Surface (15 dbar press, first level of the objective analysis) temperature ($^\circ\text{C}$), (b) salinity (psu), and (c) depth (m) of the 16°C isotherm in the frontal system AC/STF in July 1997. Circles represent CTD stations.

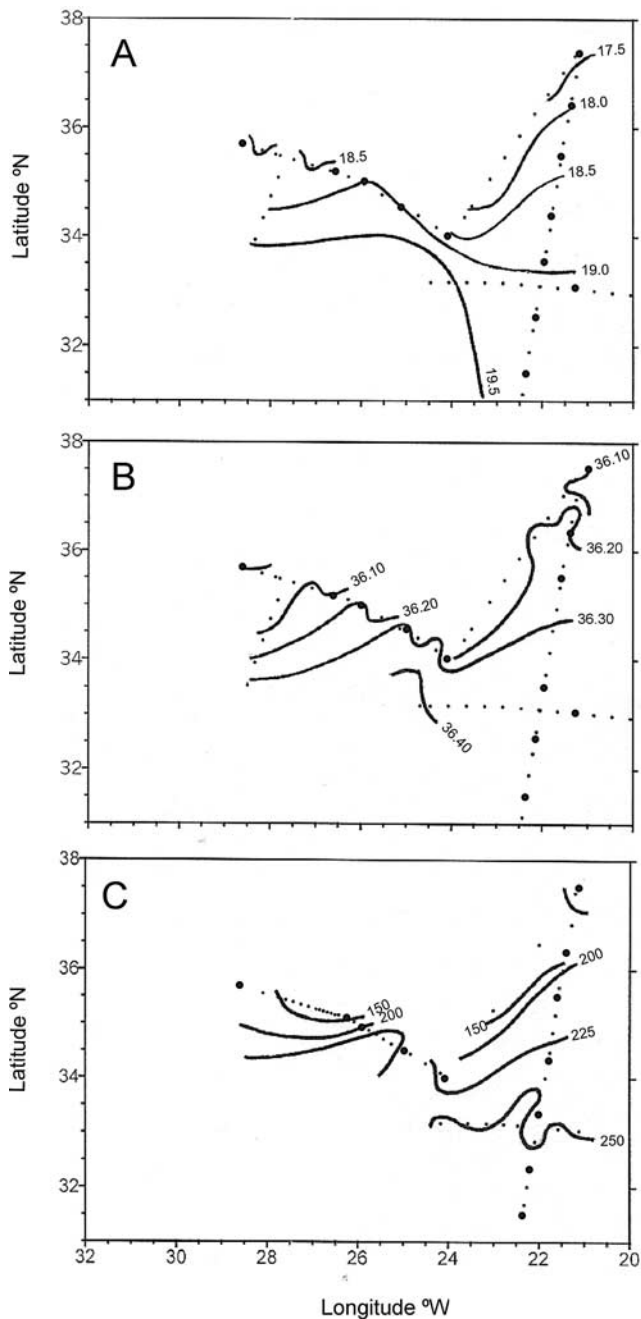


Figure 3. (a) Surface temperature ($^{\circ}\text{C}$), (b) salinity (psu), and (c) depth (m) of the 16°C isotherm in the northeast subtropical Atlantic in April 1999. Circles represent CTD stations. Dots represent interpolated positions of thermo-salinograph data (Figures 3a and 3b) and XBTs stations (Figure 3c).

tions across the Subtropical Front in July 1997 (st. 15 to st. 52) and April 1999 (st. 12 to st. 16) (see Figure 1) is shown in Figure 4. In July 1997, isotherms and isopycnals outcropped at approximately 33°N – 34°N , defining the position of the Subtropical Front. Geostrophic velocities calculated using a no-motion level of 1500 dbar showed the close association between the Subtropical Front and the Azores Current, with maximum geostrophic velocities ($>30\text{ cm s}^{-1}$) in the upper 50 dbar. The upper 70 dbar showed very low nitrate concen-

trations ($<1.0\text{ }\mu\text{M}$) with isolines uplifting associated with the position of the STF. The phytoplankton biomass distribution was characterized by the presence of a deep chlorophyll maximum, located at ~ 110 dbar in the southern end of the section, that shallowed northward reaching 85 dbar at 36°N . Chlorophyll-*a* concentrations $>0.20\text{ mg m}^{-3}$ were measured at the northern boundary of the subtropical front ($\sim 34^{\circ}\text{N}$) where the deep chlorophyll maximum was located at about 75 dbar. Vertical distributions of chlorophyll characterized by the existence of a deep chlorophyll maximum have been widely reported for the oligotrophic ocean [Gould, 1987] and in the studied region in particular [see, e.g., Fasham *et al.*, 1985; Maraño *et al.*, 2000].

[17] In April 1999, outcropping of isotherms and density surfaces defined the position of the STF at 35°N . Geostrophic velocities in the upper 75 dbar between st. 14 and 15 exceeded 12 cm s^{-1} . The upper 100 dbar of the water column was less stratified and relatively colder than in July 1997. Nitrate concentrations were lower than $1.0\text{ }\mu\text{M}$ in the upper 75 m, and a sharp horizontal nitrate gradient at subsurface layers was found across the Subtropical Front. Nitrate anomalies between the northern (st. 16) and southern (st. 13) side of the STF at 100 and 200 dbar were 1.54 and $6.68\text{ }\mu\text{M}$, respectively. The deep chlorophyll maximum, typically located at about 75 dbar, was slightly shallower and showed higher chlorophyll-*a* concentrations ($>0.25\text{ mg m}^{-3}$) at stations associated to the subtropical front (st. 14 and 15). A detailed description of phytoplankton biomass and production patterns in the region in April 1999 is given by Mouriño *et al.* [2001, 2002].

[18] A careful examination of the thermohaline distribution and horizontal and vertical velocity fields of the whole set of stations sampled by our group in the subtropical northeast Atlantic allowed us to select three stations located at the center of the subtropical front in March 1992 (st. 35, CD66 [Fernández and Pingree, 1996]), April 1999 (st. 15, Azores II), and July 1997 (st. 24, FCA97c) in order to study the seasonal pattern in the vertical distribution of temperature, chlorophyll-*a*, and primary production in this region (Figure 5). The thermal vertical distribution showed the existence of a homogeneous surface layer extended down to 110 dbar in March 1992 (vertical temperature gradient lower than $0.004^{\circ}\text{C dbar}^{-1}$), and 10 dbar in summer 1997. In April 1999, the surface homogeneous mixed layer extended down to ~ 115 dbar, similar to the mixed layer depth measured in March 1992; however, it was associated with a slightly higher thermal gradient ($<0.025^{\circ}\text{C dbar}^{-1}$). A shallow relatively high stratification layer was found at ~ 25 dbar. Both the magnitude of chlorophyll-*a* values and primary production rates as well as their vertical distribution varied sharply associated with subtle changes in thermal stratification. Thus, significant enhancement of phytoplankton biomass and production were observed associated with the lack of the seasonal stratification in March 1992, when chlorophyll *a* and primary production values were $30\text{ mg chl-}a\text{ m}^{-2}$ and $110\text{ mgC m}^{-2}\text{ h}^{-1}$, respectively, which contrast with the $13\text{ mg chl-}a\text{ m}^{-2}$ and $12\text{ mgC m}^{-2}\text{ h}^{-1}$ measured in April 1999 and the $15\text{ mg chl-}a\text{ m}^{-2}$ calculated in July 1997. The location of the chlorophyll *a* maximum deepened as stratification progressed. These results show that the thermal characteristics of the water column associated with the subtropical front are affected by an important

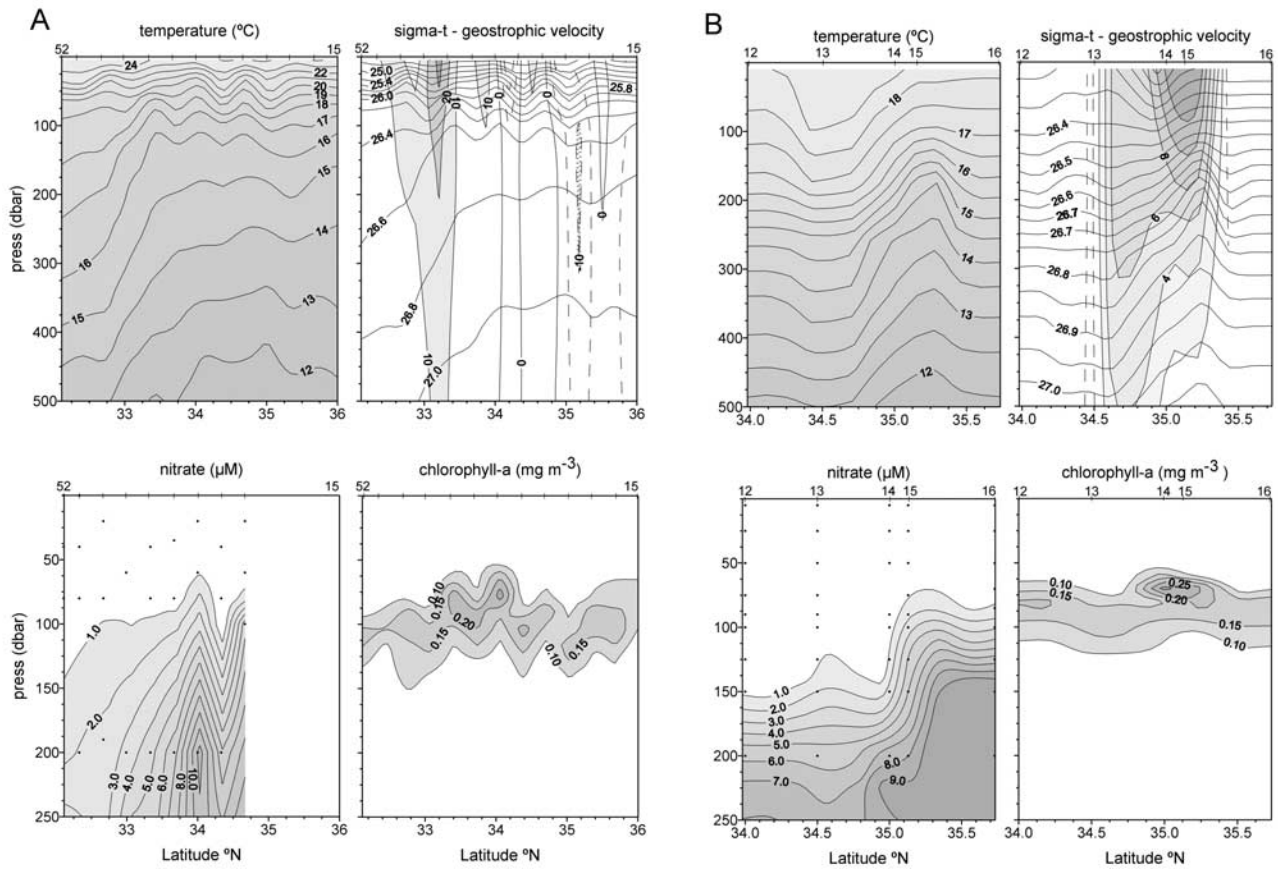


Figure 4. Vertical distribution of temperature (°C), sigma theta, and geostrophic velocity (cm s^{-1}) relative to 1500 dbar in the upper 500 dbar, and nitrate (μM) and chlorophyll-*a* (mg m^{-3}) in the upper 250 dbar across the Subtropical Front in (a) July 1997 (FCA97c) and (b) April 1999 (Azores II).

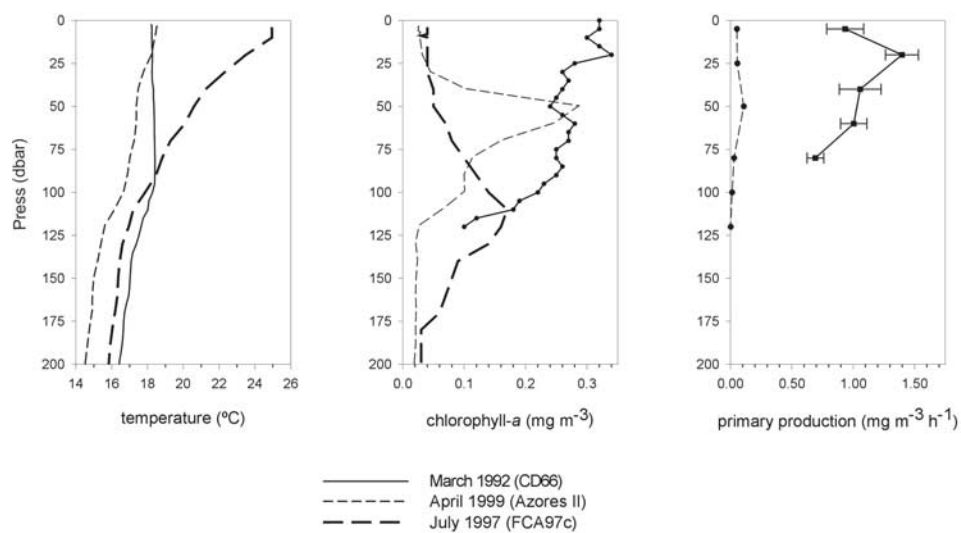


Figure 5. Vertical profiles of temperature (°C), chlorophyll-*a* (mg m^{-3}) and primary production ($\text{mg m}^{-3} \text{h}^{-1}$) at three stations located in the Subtropical Front studied in March 1992 (st. 35, CD66 cruise [Fernández and Pingree, 1996]), April 1999 (st. 15, Azores II cruise), and July 1997 (st. 24, FCA97C cruise). Error bars represent standard error between replicates ($n = 3$).

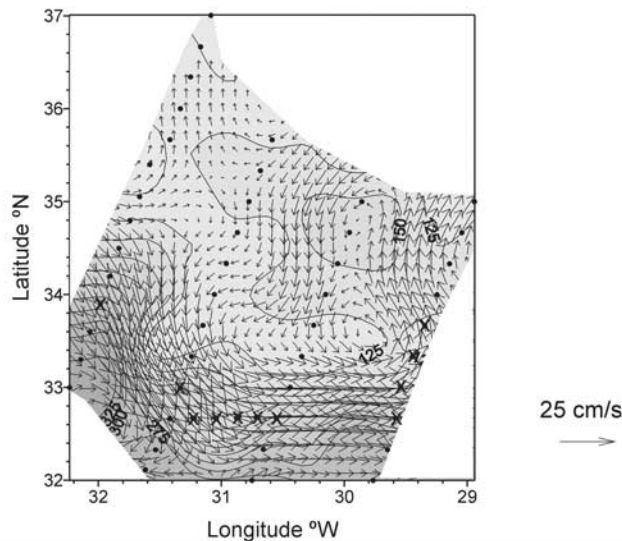


Figure 6. Depth (m) of the 16°C isotherm and surface quasigeostrophic velocities (cm s^{-1}) computed for the AC/STF region in July 1997. Circles represent CTD stations. Crosses represent stations selected along the AC axis. A 25 cm s^{-1} scale is shown at bottom right.

seasonal pattern responsible for significant episodic increases of phytoplankton biomass.

3.2. Three-Dimensional Mesoscale Dynamics of the AC/STF Region in July 1997

[19] Surface quasigeostrophic (QG) velocities computed during the FCA97c cruise reveal the pattern of circulation in the AC/STF region in July 1997 (Figure 6). The Azores Current flowed eastward with surface velocities higher than 30 cm s^{-1} . The relatively cold and fresher water described previously at 33.5°N , 30.5°W corresponds to the center of the cyclonic meander.

[20] Figure 7 shows the vertical velocity field at the mean depth of the base of the deep chlorophyll maximum (0.1 mg m^{-3}) in July 1997, 120 dbar, and at the layer where maximum vertical velocities were computed, 375 dbar. Successive upwelling and downwelling regions appear clearly correlated with the meandering horizontal front, with maximum vertical velocities of 3 m d^{-1} and -4 m d^{-1} , respectively. At 120 dbar, velocities were 50% lower than maximum values calculated at 375 dbar.

[21] The maximum values computed for FCA97c cruise are considerably lower than previous estimates reported by Rudnick [1996], who described maximum vertical velocities of 20 m d^{-1} at 200–300 m, and a tendency for downwelling (upwelling) on the northern (southern) side of the front. It is worth mentioning that maximum vertical ageostrophic velocities estimated in this study and by Rudnick [1996] were calculated for different water levels, 375 m and 200–300 m, respectively. Therefore it is expected that even larger differences would arise if a shallower level were considered in our study. Theoretically, in a growing baroclinic meander, horizontal divergence (upwelling) is expected upstream of the meander crest and horizontal convergence (downwelling) downstream [Onken, 1992]. The diagnosed ageostrophic vertical velocity field computed for July 1997 exhibited slight variations with the theoretical scheme. This

fact could be due to asymmetric variations in the curvature of the jet, the degree of maturity of the cyclonic meander [Alves and de Verdière, 1999], submesoscale processes [Pérez et al., 2003] and/or the interaction of the meandering

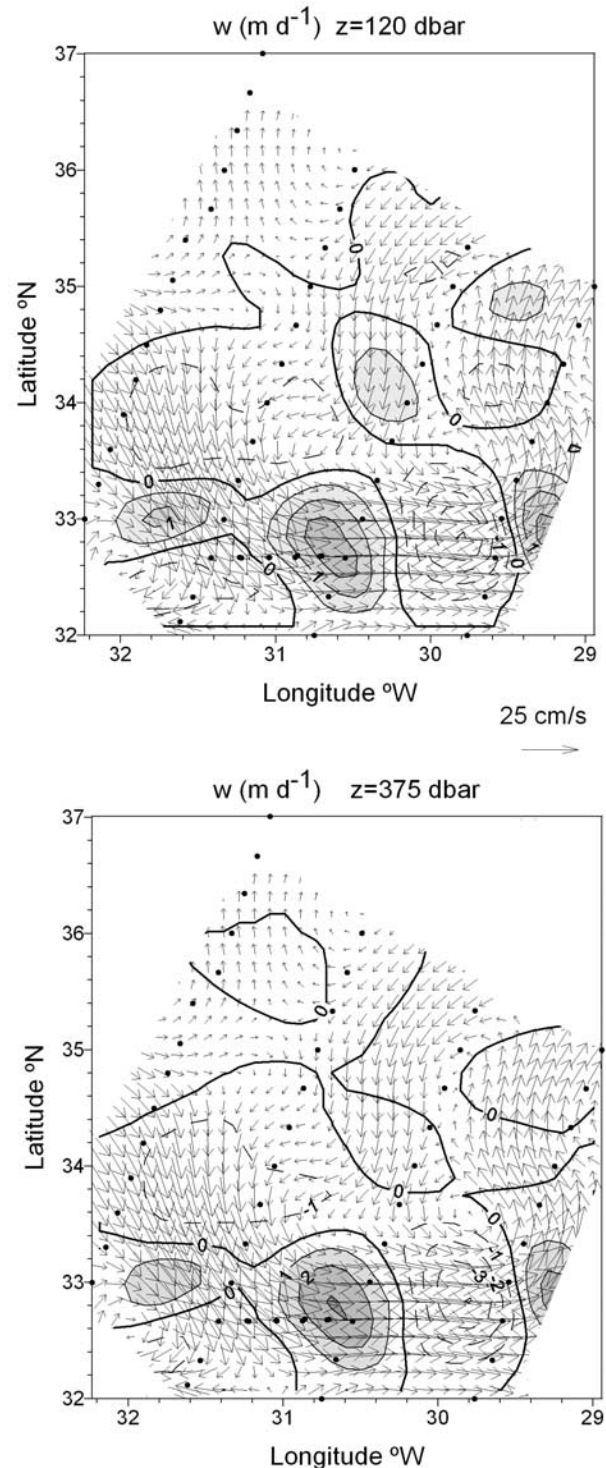


Figure 7. Vertical ageostrophic velocity (m d^{-1}) computed at 120 and 375 dbar for FCA97c cruise in July 1997. Circles represent CTD stations. Contour lines are plotted every 0.5 m d^{-1} (120 dbar) and 1 m d^{-1} (375 dbar). Shaded regions represent upward velocities. A 25 cm s^{-1} scale is shown at bottom right.

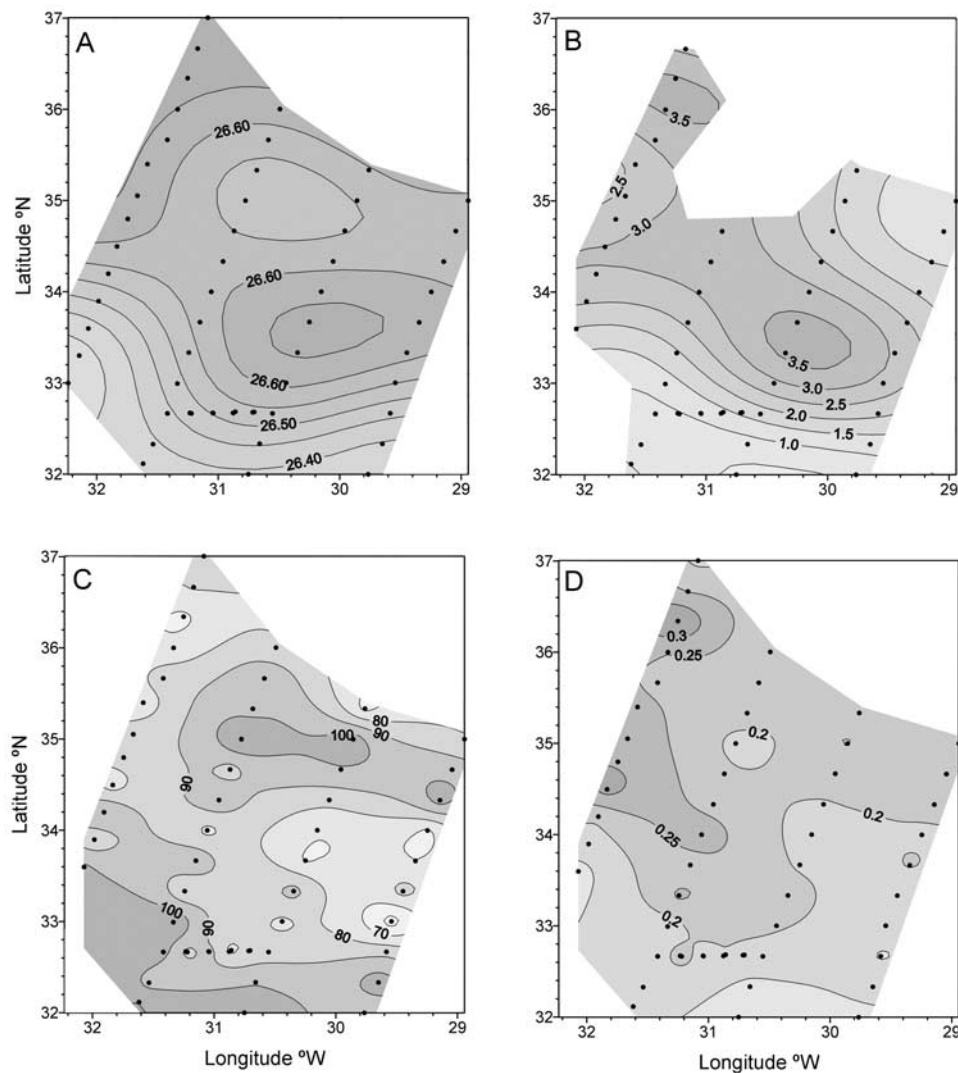


Figure 8. Horizontal distribution of (a) sigma theta and (b) nitrate concentration (μM) at 120 dbar, and (c) pressure (dbar) and (d) magnitude (mg m^{-3}) of the DCM across the cyclonic meander studied in July 1997. Circles represent CTD stations.

frontal system with the adjacent current field. We cannot discard that small methodological problems associated with data synopticity and/or data resolution modify the theoretical scheme previously described.

[22] Figure 8 shows the horizontal distribution of sigma theta and nitrate concentration at 120 dbar (averaged location of the deep chlorophyll maximum base), pressure, and magnitude of the deep chlorophyll maximum (DCM) during the FCA97c cruise. Relatively high nitrate concentrations ($>3.5 \mu\text{M}$) were found associated with denser waters at the center of the meander. A sharp nitrate gradient was clearly identified associated with the Azores Current, the nitrate anomaly between the northern and southern side of the AC being higher than $2 \mu\text{M}$. A similar scheme of nitrate distribution was reported at the center of a cyclonic meander in the Gulf Stream front in a modeling study carried out by *Anderson and Robinson* [2001], a pattern that was interpreted in terms of mixing at the base of the mixed layer due to horizontal inputs of upwelled water from the main current. The deep chlorophyll maximum typically located at 100 dbar uplifted ~ 20 dbar associated with the center of

the cyclonic meander. Chlorophyll-*a* values ranged from $0.1\text{--}0.4 \text{ mg m}^{-3}$, and only relatively enhanced chlorophyll-*a* concentrations ($>0.35 \text{ mg m}^{-3}$) were measured at the northern end of section 1 (36.3°N , 31.3°W).

[23] We explored the relationship between the thermohaline structure of the water column and nitrate and phytoplankton biomass distributions in all the domain previously described in July 1997. Significant correlations were found between the depth of the 16° isotherm and the depth of $1 \mu\text{M}$ nitrate concentration and magnitude of the chlorophyll maximum ($r = 0.64$, $p < 0.01$; $r = 0.64$, $p < 0.01$; respectively, Figure 9) and also the depth-integrated chlorophyll-*a* distribution ($r = 0.47$, $p < 0.01$; data not shown). However, statistically significant relationships between the vertical velocity field and nitrate and chlorophyll-*a* distributions were not observed ($r = 0.11$, $p = 0.50$; $r = -0.06$, $p = 0.68$; $r = -0.20$, $p = 0.20$; respectively). Nitrate and chlorophyll-*a* distributions primarily reflect the cross-frontal gradient, as indicated by significant correlations between the depth of the 16° isotherm and the depth of $1 \mu\text{M}$ nitrate concentration, magnitude of the chlorophyll maximum and depth-integrated

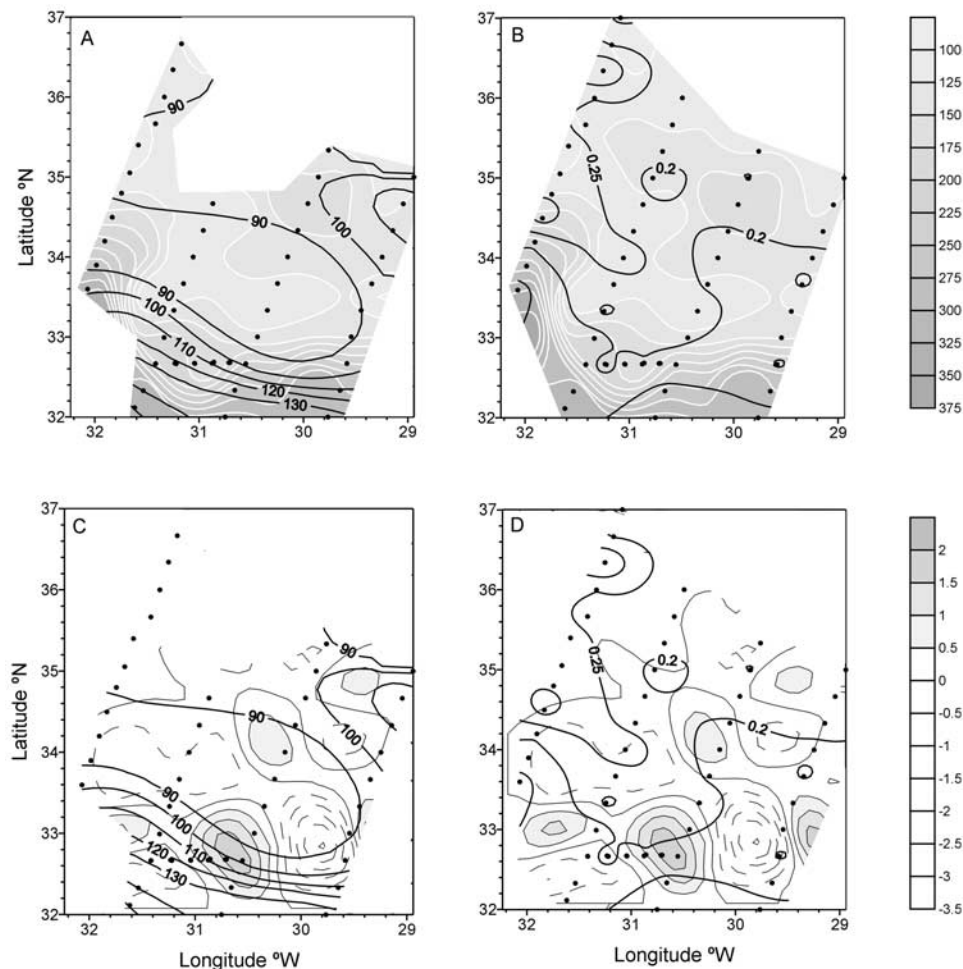


Figure 9. (tp) Horizontal distribution of depth of the 16° isotherm (m) and (a) depth of 1 μM nitrate concentration (M) and (b) magnitude of the chlorophyll maximum (mg m^{-3}). (bottom) Horizontal distribution of vertical ageostrophic velocity (m d^{-1}) at 120 dbar and (c) depth of 1 μM nitrate concentration (M) and (d) magnitude of the chlorophyll maximum (mg m^{-3}) across the cyclonic meander studied in July 1997. Top and bottom shading bars indicate the depth (m) of the 16° isotherm and vertical ageostrophic velocities (m d^{-1}), respectively. Circles represent CTD stations.

chlorophyll-*a*. A correlation analysis was performed between vertical velocity and depth-integrated phytoplankton biomass fields along the axis of the front (Figure 10). Eleven stations were chosen centered at the Azores Current, as defined by the surface quasi-geostrophic flow (see Figure 6). The lack of nutrient measurements in the longitudinal section along the axis of the current did not allow us to perform a similar analysis with the nitrate field. The statistical result of this analysis showed a weak negative correlation between both fields ($r = -0.12$, $p = 0.73$) that was slightly higher when phytoplankton biomass distribution was represented with a one-station spatial lag ($r = -0.46$, $p = 0.18$).

4. Discussion

[24] The results presented in this paper show the existence of a seasonal pattern in the AC/STF region that affects both the latitudinal excursions of the Azores Current axis and also the progressive shallowing of the mixed layer depth when summer thermal and haline stratification develops. The seasonal latitudinal displacement observed in the zonal axis

of the Azores Current agrees with previous observations carried out by *Stramma and Siedler* [1988]. These authors, using historical temperature-salinity data sets, described seasonal changes in the structure of the subtropical gyre in the eastern North Atlantic that displayed a shorter north-south extension in summer as compared to winter, and observed an $\sim 3^\circ$ southward shift of the zonal flow axis of the Azores Current in summer. Similar results were obtained from the mesoscale oceanic forecasting system SOPRANE [see *Mouriño et al.*, 2003]. However, studies carried out with Geosat altimeter data in the Azores-Madeira region did not find evidence for such a shift [*Le Traon and De Mey*, 1994]. We cannot discard that the latitudinal displacement observed in the zonal axis of the AC/STF system is partially due to the meandering of the current that was more accurately resolved in July 1997. The seasonal pattern described for the physical properties of the water column fits in well with the results provided by the model developed for the region by *Longhurst* [1998] that describes deepening of the mixed layer depth of ~ 100 m from summer to spring, similar to the results reported in this study.

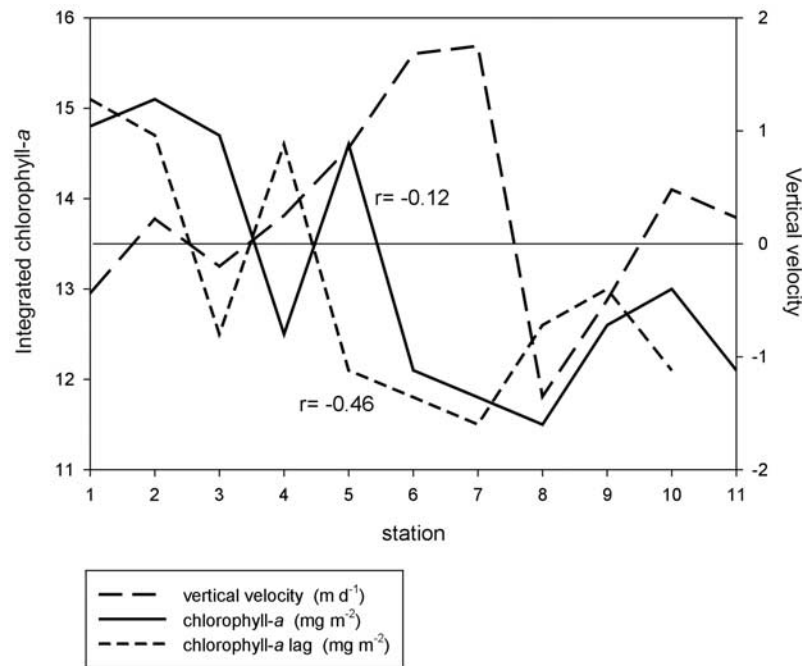


Figure 10. Vertical velocity (m d^{-1}), depth-integrated phytoplankton biomass (mg m^{-2}), and depth-integrated phytoplankton biomass one-station lag (mg m^{-2}) along 11 stations selected along the Azores Current axis.

[25] The seasonal variability observed in the thermohaline characteristics of the water column is known to induce significant variations in the biomass and carbon incorporation rates of primary producers in the region [Fernández and Pingree, 1996]. Although our results show that the stability of the water column in the upper 200 dbar in March 1992 ($<0.004^\circ\text{C dbar}^{-1}$ vertical gradient) was lower than April 1999 ($<0.025^\circ\text{C dbar}^{-1}$) (Figure 5), and that at least in part it could be due to interannual variability, it is expected that the enhanced phytoplankton biomass and production observed in March 1992 responds to optimal conditions for phytoplankton growth as a consequence of a seasonal episodic event between relatively intense winter vertical mixing and strong summer water column thermal stratification. Depth-integrated chlorophyll-*a* values described in this study for April 1999 (13 mg m^{-2}) compare well with the values previously reported by Fasham *et al.* [1985] at the same region in April 1981 (10 mg m^{-2}).

[26] The analysis performed in this study showed that the vertical velocity field was not statistically correlated with nitrate and chlorophyll-*a* distributions (Figure 9), and only a weak relationship was observed along the axis of the front when phytoplankton biomass distribution was represented with a one-station spatial lag (Figure 10).

[27] Generally, attempts to find relationships between vertical circulation and biological fields derive from modeling studies [Anderson and Robinson, 2001]. To our knowledge, the only significant empirical relationship between these variables in a frontal system has been reported recently by Rodríguez *et al.* [2001]. These authors found that phytoplankton size structure, a variable known to control cycling of organic matter in planktonic ecosystems [e.g., Legendre and Michaud, 1998] was significantly related to the magnitude of mesoscale vertical motion when these velocities lie

within the range -5 to 5 m d^{-1} , comparable to the maximum values computed for FCA97c cruise, -4 to 3 m d^{-1} .

[28] The study of physical and biological coupling of mesoscale dynamic in frontal systems has implicit several methodological limitations. A proper resolution of mesoscale dynamics requires time series of synoptic three-dimensional physical and biochemical measurements. However, oceanographic surveys must balance the number of observations needed to resolve mesoscale processes and the temporal extension of the investigation, which must be small compared to the displacement of mesoscale features. Significant errors in the accuracy of vertical velocity estimates arise from the necessary compromise between spatial resolution and synopticity of an oceanographic survey [Allen *et al.*, 2001]. These errors can be significantly reduced by adopting an adequate mesoscale sampling strategy and a posteriori corrections [Rixen *et al.*, 2001].

[29] The impact of mesoscale features on the biology of pelagic ecosystems will depend on the timescales of the physical processes involved as compared to those of the chemical and biological processes. Considering the surface velocity computed in the core of the current in July 1997 ($\sim 25 \text{ cm s}^{-1}$) and the distance between upwelling and downwelling zones ($\sim 100 \text{ km}$), we obtain a transit time between upwelling and downwelling regions of about 5 days which is within the range of doubling times estimates typically reported for subsurface phytoplankton populations of the oligotrophic North Atlantic subtropical gyre [e.g., Goericke and Welschmeyer, 1998].

[30] In addition to vertical motions associated with baroclinic mesoscale processes, phytoplankton communities will be affected by shorter temporal (internal waves [e.g., Mouriño *et al.*, 2002]) and spatial (sub-mesoscale processes [e.g., Lévy *et al.*, 2001; Martins and Richards, 2001;

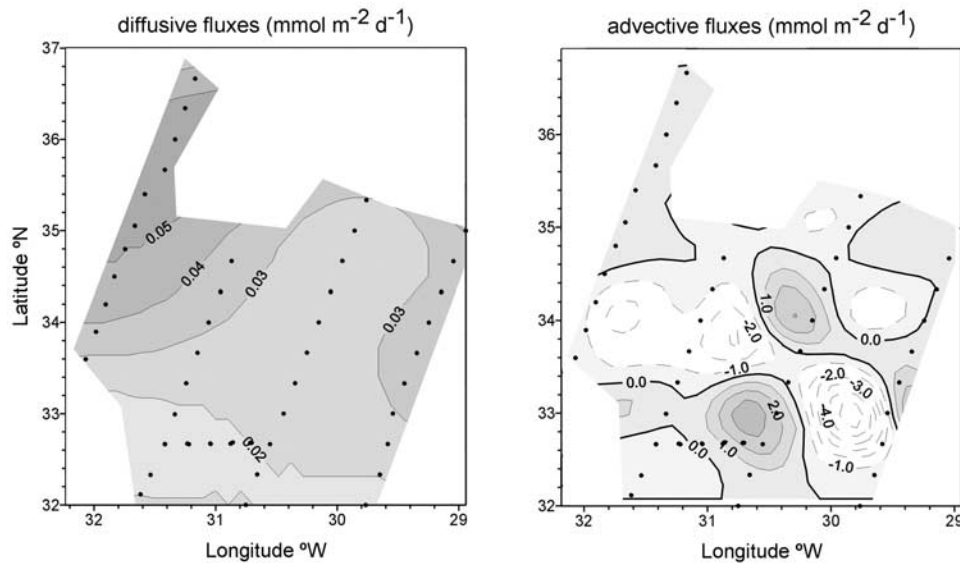


Figure 11. Vertical diffusive and advective fluxes ($\text{mmol m}^{-2} \text{d}^{-1}$) computed across the base of the deep chlorophyll maximum for the domain studied in the AC/STF system during the FCA97c cruise. Circles represent CTD stations.

Sánchez and Gil, 2004] scales. When in situ physical and biological measurements are carried out at the adequate space scales and timescales to fully describe mesoscale processes, the background mesoscale patterns will be superimposed on shorter temporal and spatial processes signatures intersected at the precise moment of the sampling. Both patterns produced by different processes and at different scales will appear combined, and it will be very difficult to separate both signatures without a follow-up method applied, with enough resolution, from the smallest to the largest scale. However, when in situ thermodynamic data are used to compute absolute geostrophy and the associated mesoscale ageostrophy, shorter temporal and spatial processes are filtered by the mathematical method. Therefore when we compare patterns of biological distributions (resulting from the combination of shorter temporal and spatial scale processes and mesoscale dynamics) with computed geostrophy and mesoscale ageostrophy fields (that filter out small-scale processes), the small-scale dynamics responsible, at least partially, for the nutrients and phytoplankton biomass distribution patterns will be missed, and so the calculated mesoscale vertical velocity field may appear partially uncorrelated with in situ biological fields.

[31] The results obtained in this investigation allowed us to estimate the relative contribution of vertical diffusive and advective nitrate fluxes through the cyclonic meander studied during the FCA97c cruise to the total amount of organic carbon synthesized photosynthetically in the northeast subtropical Atlantic region. Diffusive nitrate fluxes across the base of the DCM, calculated from the product of the estimated diffusion coefficients K_z ($6 \times 10^{-6} - 1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$) and the vertical gradients of nitrate concentration (0.02 and $0.08 \mu\text{M m}^{-1}$) (see section 2), ranged from 0.01 to $0.07 \text{ mmol m}^{-2} \text{ d}^{-1}$ (see Figure 11). These values are comparable to estimations previously reported for the same region [*Mouriño et al., 2002*]. Vertical upward advective nitrate fluxes computed from the product of the vertical velocity field (Figure 7), and nitrate concentration values

were about 2 orders of magnitude higher than vertical diffusive transport (-6.6 to $3.7 \text{ mmol m}^{-2} \text{ d}^{-1}$). Using the rates of nitrate input into the upper layer by both processes and assuming Redfield stoichiometric relationships and a f -ratio of 0.2 [see *Planas et al., 1999*], we estimated the maximum local phytoplankton production sustained by vertical diffusive ($28 \text{ mgC m}^{-2} \text{ d}^{-1}$) and advective ($1471 \text{ mgC m}^{-2} \text{ d}^{-1}$) nitrate transport. The averaged net primary production rate for the northeast subtropical Atlantic region reported by *Marañón et al. [2003]* was $264 \pm 69 \text{ mgC m}^{-2} \text{ d}^{-1}$, and *Teira et al. [2001]* estimated that the percentage of carbon flowing to the dissolved organic carbon pool in oligotrophic regions represents about 21% of total primary production (dissolved + particulate). The comparison of previously described vertical nitrate fluxes to the averaged total primary production rate estimated for the whole northeast subtropical Atlantic region (dissolved + particulate, $335 \pm 38 \text{ mgC m}^{-2} \text{ d}^{-1}$), a value presumably lower than the total primary production rate expected exclusively for the Subtropical frontal region, shows that the contribution of vertical diffusive nitrate fluxes to primary production estimations for the region would be less than 10%, whereas advective processes could locally sustain primary production rates four times higher than those measured in the region.

[32] Isolines of vertical ageostrophic velocity intersect the boundary of the domain studied in July 1997 (see Figure 7) which impede the computation of regional averages of the vertical velocities field. In addition, uncertainty in the amount of nutrient ultimately input into enhanced phytoplankton production and biomass [*Mouriño et al., 2002*] makes it difficult to establish the biological significance of the calculated nitrate fluxes in Figure 11. However, we estimated a value of 16 MtC yr^{-1} for the maximum net primary production associated with the STF, assuming that the maximum primary production rate measured at the STF in March 1992 ($1056 \text{ mgC m}^{-2} \text{ d}^{-1}$) remained constant during a two months period, and the surface occupied by the frontal system as 2.5

$\times 10^{11} \text{ m}^2$. This value represents a 5% increase over the annual net primary production estimated for the whole northeast Atlantic subtropical region, suggesting that the contribution of this feature is likely to be of low significance for the organic carbon deficit measured in this region [Duarte et al., 2001; González et al., 2001; Serret et al., 2001].

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