JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. C12, 3383, doi:10.1029/2003JC001884, 2003

Significance of cyclonic SubTropical Oceanic Rings of Magnitude (STORM) eddies for the carbon budget of the euphotic layer in the subtropical northeast Atlantic

Beatriz Mouriño[1] and Emilio Fernández
Universidade de Vigo, Departamento de Ecoloxía e Bioloxía Animal, Campus Lagoas-Marcosende, Vigo, Spain

Helene Etienne, Fabrice Hernández, and Sylvie Giraud
Collecte Localisation Satellites, Ramonville St-Agne, France

Received 3 April 2003; revised 2 October 2003; accepted 15 October 2003; published 20 December 2003.

[1] The interannual and seasonal variability of cyclonic eddies budded from the Azores Current during the period 1993–1999 in the northeast subtropical Atlantic region (20°N–34°N; 19°W–35°W) was studied by using TOPEX/Poseidon and ERS-1/2 altimeter images, the operational ocean mesoscale forecasting system SOPRANE, and a mesoscale eddies automatic detection system. Seventeen cyclonic eddies were detected and monitored for time periods ranging from 50 to 360 days. They were characterized by mean westward velocity, amplitude, diameter, and eccentricity of about 2 km d^{-1}, 8 cm, 187 km and 0.7, respectively. The generation of cyclonic eddies was subjected to an important interannual variability, especially in 1995 when the activity of cyclonic eddies in the northeast Atlantic was more intense and associated with parallel changes in the eddy energy of the Azores Current. Seventy-five percent of the mesoscale features were generated throughout the October–February period. Significant relationships were found between the seasonal NAO index and both the annual eddy kinetic and potential energy in the Azores Current region and also the total annual area occupied by STORM eddies, calculated with a 1-year phase lag. The outcome of this study was used to estimate the contribution of STORM eddies to the organic carbon deficit measured in the northeast subtropical Atlantic. On average, these eddies accounted for <1% of the net community production in the region. *INDEX TERMS:* 4520 Oceanography: Physical: Eddies and mesoscale processes; 4806 Oceanography: Biological and Chemical: Carbon cycling; 1640 Global Change: Remote sensing; 4215 Oceanography: General: Climate and interannual variability (3309); *KEYWORDS:* mesoscale eddies, organic carbon deficit, subtropical northeast Atlantic

Citation: Mouriño, B., E. Fernández, H. Etienne, F. Hernández, and S. Giraud, Significance of cyclonic SubTropical Oceanic Rings of Magnitude (STORM) eddies for the carbon budget of the euphotic layer in the subtropical northeast Atlantic, *J. Geophys. Res.*, *108*(C12), 3383, doi:10.1029/2003JC001884, 2003.

1. Introduction

[2] Assuming steady state, the primary production fuelled by the input of new nutrients into the photic layer has to be balanced over long temporal and large spatial scales by the export of organic matter to the deep ocean. The processes that control the export of carbon to subsurface oceanic layers are critical for the biological pump mechanism [e.g., *Ducklow et al.*, 1995; *Sarmiento and Le Quéré*, 1996]. The f-ratio, originally defined by *Eppley and Peterson* [1979] as the ratio between new and total primary production, represents a quantitative measurement of the biological pump efficiency [*Ducklow et al.*, 2001]. On the other hand, the balance between microbial production and respiration determines the net community production. When production exceeds respiration, a net synthesis of organic carbon, available to be exported to higher trophic levels or to other ecosystems, occurs. By contrast, a negative balance involves a heterotrophic behavior that results in an organic carbon deficit. The information obtained from net community production and the f-ratio is comparable when large temporal and spatial scales are considered [*Quiñones and Platt*, 1991].

[3] Direct measurements of nutrient supply to oligotrophic surface waters have been considerably lower than indirect geochemical estimates for the northwest subtropical Atlantic [*Doney*, 1997]. In the northeast subtropical Atlantic, geochemical balances indicate that this region has a net heterotrophic behavior, that could result from the export of the dissolved organic matter from northern latitudes [*Álvarez et al.*, 2002]. This net heterotrophic behavior is not exclusively a characteristic of deep layers, having been observed repeatedly in the photic layer, that results in an organic carbon deficit [*Duarte et al.*, 2001; *González et al.*,

---

[1] Now at Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA.

0148-0227/03/2003JC001884$09.00

2001; *Teira et al.*, 2001; *Serret et al.*, 2001, 2002] whose magnitude is subjected to seasonal variability [*González et al.*, 2002]. The excess of oxidation rates with respect to production of organic matter characteristic of this region could be explained, at least partially, by episodic primary production increments associated with mesoscale features [e.g., *Angel and Fasham*, 1983; *Falkowski et al.*, 1991; *McGillicuddy et al.*, 1998; *Oschlies and Garçon*, 1998; *Siegel et al.*, 1999; *McNeil et al.*, 1999; *Uz et al.*, 2001].

[4] The eastern region of the subtropical North Atlantic is characterized by intense mesoscale activity, where meanders of the Azores Current, mesoscale eddies, and baroclinic Rossby waves result in a large diversity of ocean signals at many spatial and temporal scales [*Tokmakian and Challenor*, 1993; *Le Traon and De Mey*, 1994; *Pingree and Sinha*, 2001; *Mouriño et al.*, 2002]. Recent studies reported the possibility of tracking cyclonic eddies budded from the Azores Current, named SubTropical Oceanic Rings of Magnitude (STORM), by using altimeter data [*Pingree and Sinha*, 1998; *Pingree et al.*, 1999; *Pingree*, 2002].

[5] STORM eddies have been intensively investigated on two occasions. The westward motion of a ~400 km scale STORM eddy called Physalia was traced using drogued Argos buoys and subsurface Alace floats [*Pingree et al.*, 1996]. The STORM eddy rotated cyclonically (maximum swirl current ~50 cm s^{-1} at a radial distance of ~100 km) and moved westward (~3 km d^{-1}). Its azimuthal volume transport was 45 Sv and its temperature anomaly, a 200-m displacement upward, extended from 200 m depth to the seafloor (4 km depth). In April 1999, the STORM eddy Leticia was sampled to assess specifically the effect of these eddies upon the flux of dissolved inorganic nutrients into the upper mixed layer and to quantify the associated potential enhancement of phytoplankton biomass and/or primary production [*Mouriño et al.*, 2002]. Shallowing (~50 m) of the deep chlorophyll maximum (>0.3 mg m^{-3}) was observed at the eddy center associated with vertical displacements of the isotherms (>100 m) within the photic layer. Surface waters were nitrate depleted. A four-fold increase of integrated nitrate concentration in the photic layer (~115 dbar in April 1999) was detected inside Leticia (28 mmol m^{-2}) as compared to the external region (6 mmol m^{-2}) [see *Mouriño et al.*, 2002, Table 2]. Primary production rates were only slightly higher inside Leticia than in the surrounding waters [*Mouriño et al.*, 2002], and gross community production rates based on oxygen evolution measurements did not show noticeable increases associated with the eddy center [*González et al.*, 2001]. However, respiration rates were significantly lower inside than outside Leticia and hence, contrasting with the net heterotrophic metabolism measured in the northeast subtropical Atlantic, STORM Leticia showed a net autotrophic microbial O_2 balance [*González et al.*, 2001]. On the basis of these results, the last authors estimated that the organic carbon deficit measured in this region would be reduced between 14 and 52% by taking into account the effect of these mesoscale features. However, an accurate estimation of the residence time of STORM eddies in the region is needed if we aim to infer the significance of these features upon the carbon and nitrogen budgets of the northeast subtropical Atlantic region. Recently, *Pingree* [2002] described westward propagating disturbances at 32.5°N seen by altimeter for the period 1993–2000, and analyzed the interannual variability in flows and temperature climate. This study identified 14 or 15 negative sea level anomalies travel curves in the 8-year period considered and revealed an intensification of the structures in 1995 and 1999.

[6] In this study we used altimetry data collected during the period 1993–1999, model outputs from the operational forecasting system SOPRANE and an automatic detection system (see section 2) with the aim of objectively estimating the residence time and surface area of STORM eddies in the northeast subtropical Atlantic. These results were combined with the available sea-truth information on the thermohaline structure, nutrient levels, and biological rates at STORM eddies in order to estimate their contribution to the organic carbon deficit measured in the Northeast Atlantic Subtropical Gyre region (20°N–34°N; 19°N–35°W).

2. Methods

2.1. Maps of Sea Level Anomaly From TOPEX/Poseidon and ERS-1/2

[7] Using sea surface height (SSH) provided by the TOPEX/Poseidon (T/P), ERS-1, and ERS-2 satellites, more than 7 years (1992–2000) of sea level anomaly (SLA) maps were produced within the framework of the UE funded program Canary Islands Azores Gibraltar Observations (CANIGO). Several steps were necessary to obtain these maps [*Efthymiadis et al.*, 2002]. The data include: first, October 1992 to March 2000 SSH of T/P reprocessed Merged GDRs (GDR-M Version C), distributed by AVISO [*AVISO*, 1996]; then phase C (October 1992 to December 1993) and phase G (April 1995 to May 1996) ERS-1 SSH; and finally, June 1995 to March 2000 ERS-2 SSH from OPRs, distributed by *Centre ERS d'Archivage et de Traitement* (*CERSAT*) [1994, 1996]. The combination of T/P and ERS data dramatically improved the description of the Azores Current and its mesoscale dynamics [*Hernandez et al.*, 1995], and enhances the accuracy of the surface velocity estimates [*Le Traon and Dibarboure*, 1999]. In order to combine the 35-day repeat cycle ERS-1/2 data with the 9.95-day repeat cycle T/P data, the ERS-1/2 SSH were processed using, whenever possible, the same altimetric corrections, and a global crossover adjustment of ERS-1/2 arcs using the more accurate T/P data was performed, significantly reducing the ERS-1/2 large-scale uncertainties (i.e., orbit errors), and improving the consistency of the data sets [*Le Traon and Ogor*, 1998]. Third, T/P, ERS-1 and ERS-2 along-track SLAs were computed using a classical repeat-track analysis. The final merging was obtained by determining T/P and ERS-1/2 SLA maps on a weekly basis. An improved objective analysis technique was implemented [*Le Traon et al.*, 1998] to interpolate along-track SLAs on a regular grid spacing (0.2 × 0.2°) over the 40°W–6°W, 20°N–46°N area. Note that during the December 24, 1993, to March 24, 1995, period, maps were produced using T/P data only, since ERS-1 was operating in non-repeating geodetic phases. A detailed analysis of 10-day global SLA maps based on this improved interpolation technique is given by *Ducet et al.* [2000].

2.2. SOPRANE System

[8] SOPRANE is an integrated operational forecasting system based on a quasi-geostrophic baroclinic model

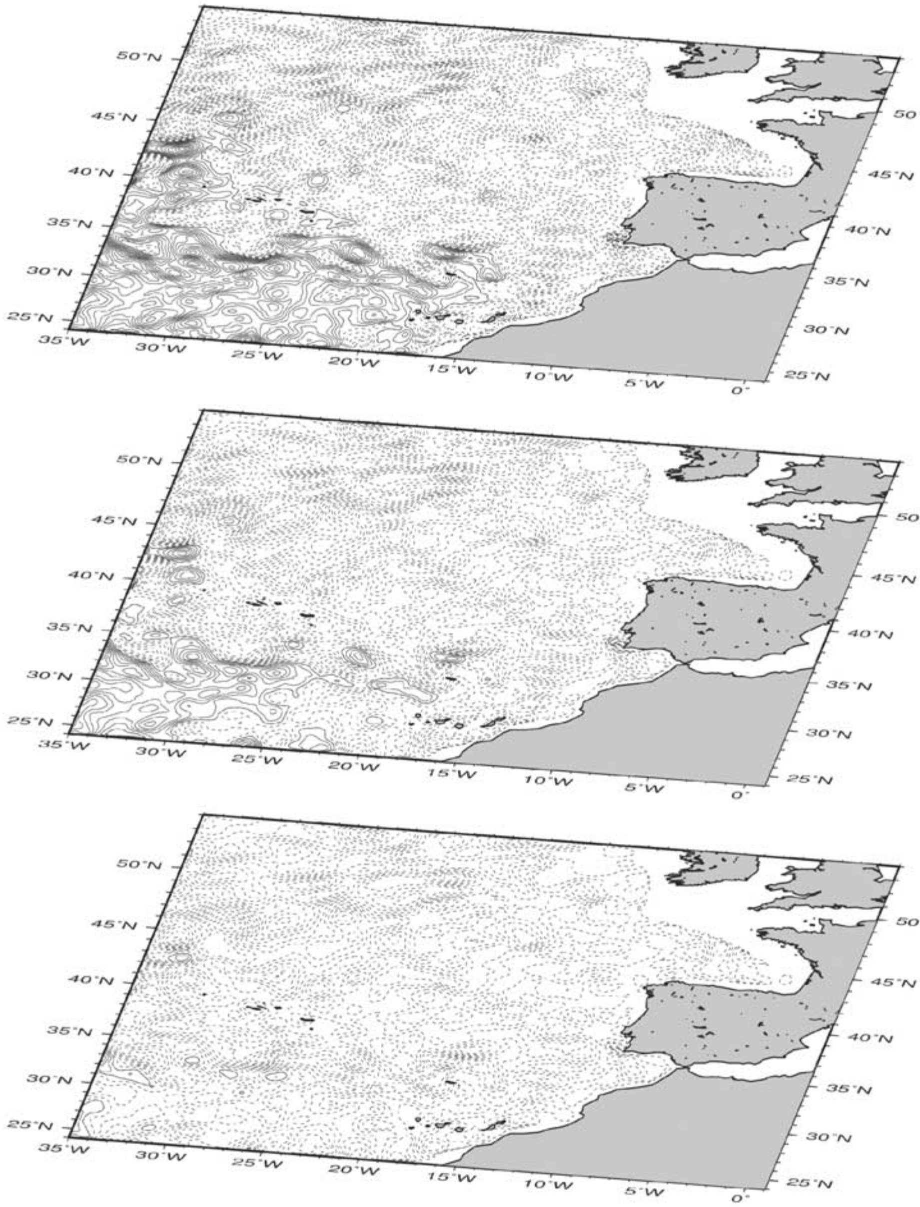


Figure 1. Snapshot (April 1999) of the northeast Atlantic circulation computed by the SOPRANE system at surface (layer 1), 200 m (layer 2), and 450 m (layer 3). Contour lines represent stream function values. The Azores Current appears as a tongue associated with high values of stream function between 30°N and 35°N, whose structure, clearly visible at the surface, can be observed with a progressively attenuated signal at deeper levels.

(10 layers, 1/10° horizontal resolution) assimilating fast delivery SLA data from TOPEX/Poseidon and ERS altimeters, derived from the *Blayo et al.* [1994] North Atlantic Quasi-Geostrophic model. The model coverage extends from 35°W to the European and African coasts and from 24°N to 54°N. The so-called "SOFA" assimilation [*De Mey and Benkiran*, 2000] is an optimal interpolation in a reduced space which assimilates the along-track data sequentially during 1-week assimilation cycles. Altimetric data constrain the model at the surface. Then the correction is propagated downward on the vertical using empirical orthogonal function (EOF). The results described below were obtained using reanalysis of the model. These model outputs are computed using a climatological wind stress, constant in time and historical altimetric data sets (see previous section). The resolution of the grid model allows eddies and meanders of the mean currents to be horizontally and vertically detected, providing a tridimensional description of the mesoscale dynamic in the model domain (Figure 1). Animations showing time sequences of the surface stream function forecasted by the model were used to detect and locate the motion and continuity of STORM eddies through the 1993–1999 time interval. Although STORM signatures can be followed for long distances, interactions between eddies and meanders of the main current occur, so it is not always possible to

determine whether an individual feature has followed the complete travel curve or if it has constituted a new feature after inputs of energy from other structures and meanders of the main current. Because the main goal of this research was to study the effect of isolated STORM cyclonic rings, differing from meander activity linked to the frontal system, on the carbon budget of the photic layer in the northeast subtropical Atlantic, we only considered features that presented a detectable sea level signature for either a timescale longer than 1 month or periods during which the features were manifested as clearly independent of the Azores Current. The travel curves of the STORM eddies, previously detected by SOPRANE animations, were constructed by using maps of sea level anomaly, similar to those presented by *Pingree et al.* [1999], but according to the criteria detailed above.

2.3. Energetic Analysis of the Azores Current Region

[9] The regional energy budget of the Azores Current frontal system was computed in the form of a Lorentz diagram [*Cronin and Watts*, 1996], using the results of the forecasting system SOPRANE in the upper layer (first 200 m). Energy values were spatially averaged over an area extending from 29°N to 38°N and 35°W to 1°W.

[10] The conversion terms between velocity and mass fields, and the coupling terms between mean and eddy fields are commented in the results section. As set by Reynolds axioms, each turbulent field X can be expressed as the sum of its mean part **X** and a residual term X′ corresponding to an eddy fluctuation.

[11] Eddy Kinetic Energy (EKE) in layer i was calculated by separating the velocity u_i in layer i into a temporal mean component **ui**, and a perturbation field u_i', according to the expression (by mass unit)

$$\mathrm{EKE_i} = \frac{1}{2}\left(\overline{u_i'^2} + \overline{v_i'^2}\right) = \frac{1}{2}\left[\overline{\left(-\frac{\partial \Psi_i'}{\partial y}\right)^2} + \overline{\left(\frac{\partial \Psi_i'}{\partial x}\right)^2}\right], \qquad (1)$$

where the overbar denotes the time average and $\boldsymbol{\Psi}_i = \boldsymbol{\Psi}_\mathbf{i} + \boldsymbol{\Psi}_i'$ is the stream function in the layer i. The Eddy Potential Energy (EPE) at the interface is expressed as

$$\mathrm{EPE}_{i+1/2} = -\frac{g}{2}\frac{\overline{\rho'^2}}{\partial\tilde{\rho}/\partial z} = -\frac{f_0^2\,\Delta h_{i+1/2}}{g'_{i+1/2}}\overline{\left(\frac{\partial \Psi'}{\partial z}\right)^2}. \qquad (2)$$

The subscript i+1/2 indicates variables at the interface between layer i and i+1, g is the acceleration due to gravity, and $g'_{i+1/2} = g(\rho_{i+1} - \rho_i)/\rho_0$ is the reduced gravity, with ρ_i density on the layer i and ρ_0 mean density of the seawater. $\Delta hi = (H_i + H_{i+1/2})/2$, with H_i depth of the layer i, f_0 is the Coriolis parameter evaluated at the central latitude, and ρ' is density perturbation from $\tilde{\rho}$, the global mean reference density at level z. In the following computation of energy, the mean fields **Ψ** and **u** are taken equal to the annual mean. In an open ocean domain, energy budget is not spatially closed, thus preventing us to fully interpret the temporal evolution of energy in terms of physical processes, especially because of the advection of energy across open boundaries. Moreover, in the case of an assimilating model, we have to take into account the weekly contribution of the state correction in the time evolution of the total energy, which is consequently not conserved.

2.4. Automatic Tool for Eddy-Tracking

[12] The SOPRANE system includes original software aiming at the automatic detection and tracking of eddy-like structures on time series of physical two-dimensional gridded fields (e.g., the QG model surface stream function). For this particular study, it has been applied from 1993 to 1999 to sea level anomaly high-resolution (SLA) (0.25°) mapped fields from the optimal interpolation of combined T/P and ERS-1/2 altimeter measurements.

[13] The detection method characterizes an eddy structure geometrically by a point that figures the center of the eddy and by a closed contour isoline that is the basis of the eddy. Thus the inner points bordered by this contour line belong to the eddy and determine its surface area. The deviation between the top value and the border iso-value of the field defines the amplitude of the eddy. Other geometrical parameters are computed, such as diameter and eccentricity of the elliptic fit.

[14] The detection algorithm explores for local extrema of the field using a five-points-wide spatial square window. Local extremum values/locations correspond to eddy center values/locations. The limit of the structure is found by dilatation from this central point via the first crossing of the zero-line of the computed gridded Laplacian field. When applied to a quasi-geostrophic stream function field, the Laplacian stands for the relative vorticity of the fluid. From the location of the changing sign of the Laplacian from the top, we deduce the field iso-value for the eddy borderline and, consequently, its amplitude. The eddy is selected when its amplitude is greater than a given threshold (here, 3 cm on SLA maps). The border value determines the shape of the structure at a finer resolution than the gridded field because the detection applies an interpolation method to locate the Laplacian zero-crossing line. The tracking algorithm consists in applying the detection algorithm to a time series of the same field: It selects among selected detected eddies (the ones whose center locates in a 1° neighborhood of the "previous" center using a 10-day time lag), the eddy that minimizes the distance between the two centers and between the two amplitudes within a given tolerance interval which is a function of the eddy amplitude. The tracking also takes into account a lifetime parameter which is set to 1 month in our application.

[15] We used this detection program to characterize the ocean meso-scale turbulence in the Azores region by geometrical parameters of the eddy-like structures (diameter, eccentricity, and amplitude), to track a given selected structure along its trajectory (path, propagation speed, lifetime), and to study the temporal evolution of its geometrical parameters. The size and intensity of detected eddies are quantified in terms of surface area and amplitude. This automatic detection is objective and complements the visual analyses.

2.5. Sea-Truth Measurements

[16] Sea-truth observations were conducted on cruise Azores II on board BIO Hespérides in April 1999, where an intensive sampling of the STORM eddy Leticia centered at 32.4°N–28.7°W was carried out (Figure 2) [*Mouriño et*

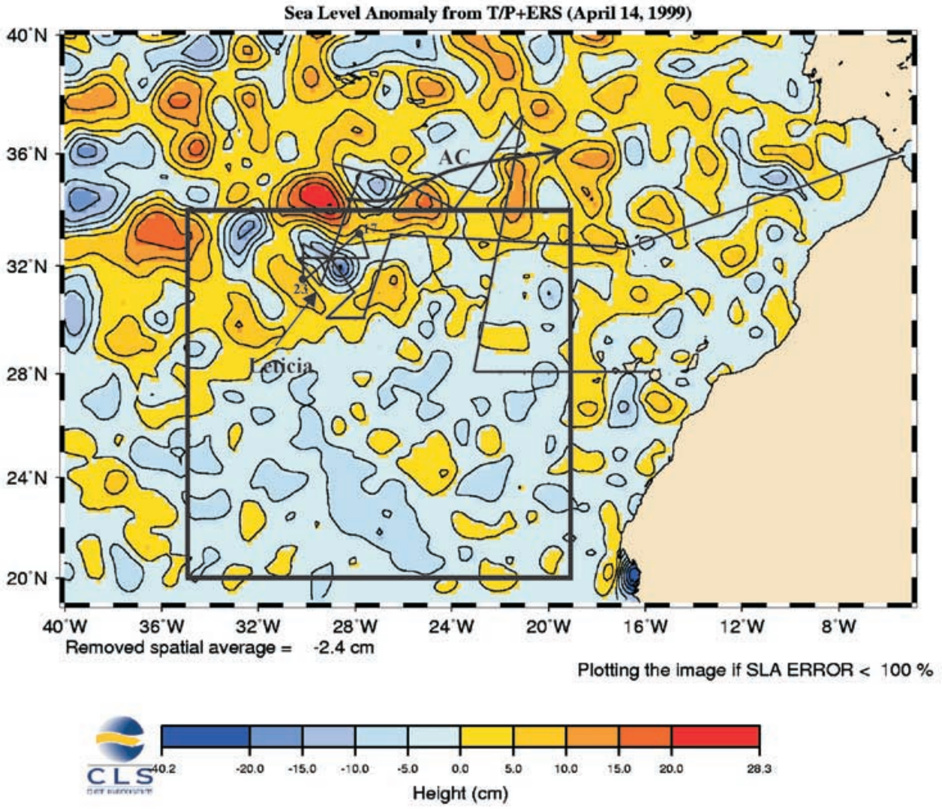


Figure 2. Map of merged T/P + ERS altimeter sea level anomalies (centimeter scale in color) for the northeast subtropical Atlantic (14 April 1999), corresponding to the Azores II cruise on board BIO *Hesperides* from Las Palmas (6 April) to Cartagena (3 May 1999) with cruise track superposed. The sea level depression at ~32.4°N–28.7°W is the signature of the STORM cyclonic eddy Leticia. The Eastern region of the subtropical North Atlantic considered in this study (20°N–34°N to 19°W–35°W) is framed. The main CTD section from station 17 (33.33°N–27.67°W) to station 23 (31.25°N–30.01°W) is indicated. AC is the Azores Current.

al., 2002]. Leticia had been previously detected by real-time SOPRANE maps and subsequently investigated during a mesoscale survey conducted with a conductivity-temperature-depth (CTD) Mark III probe mounted on a Rosette equipped with Niskin bottles and expendable bathythermograph (XBT) profiles. CTD temperature and salinity sensors were calibrated using digital reversing thermometers and water samples drawn for salinity determinations.

3. Results and Discussion

3.1. Mesoscale Activity in the Azores Current Region During the Azores-II Cruise

[17] Sea level anomalies determined from altimetry (T/P and ERS) corresponding to the northeast Atlantic region for April 1999 (Azores II cruise) are shown in Figure 2. The altimeter signal clearly manifested the existence of important mesoscale variability centered at ~34°N, linked to the Azores Current (AC). The STORM eddy Leticia, centered at 32.4°N–28.7°W was associated with an ~20-cm sea level depression, and presented a stretched shape with a scale influence of ~200 km. The sea surface height variability obtained from the altimeter reflected changes in the thermohaline structure of the water column. Figure 3 shows the vertical thermohaline structure of the STORM Leticia along the main CTD section sampled across the cyclonic eddy. Upward displacement of isolines >100 m over horizontal scales of ~100 km, extending from near surface (~100 dbar) to ~1500 dbar, is shown by the internal temperature, salinity, and sigma0 structure. The horizontal temperature, salinity, and sigma0 anomalies were higher than 1°C, 0.2 psu, and 0.2, respectively. Some stations showed fine-scale temperature-compensated salinity inversions, being therefore statically stable. Geostrophic velocities calculated across the main CTD section carried out in Leticia in April 1999 (see Figure 2) showed that the STORM eddy was spinning cyclonically with maximum geostrophic velocities >25 cm s^{-1} in the upper 200 m, 100 km away from the eddy center (Figure 4a). The geostrophic velocity field computed by SOPRANE system (Figure 4b) showed that the model reproduces adequately water column disturbances caused by mesoscale activity associated with the Azores Current. Small differences arise from the comparison with the velocity values obtained from in situ measurements, especially in the northern part of the eddy where the 10 cm s^{-1} isoline deepens to ~500 dbar versus ~700 dbar derived from the model results. Maximum geostrophic velocity values computed by SOPRANE system were slightly lower. The cross-section transport of the amount of water swirling cyclonically in Leticia calculated

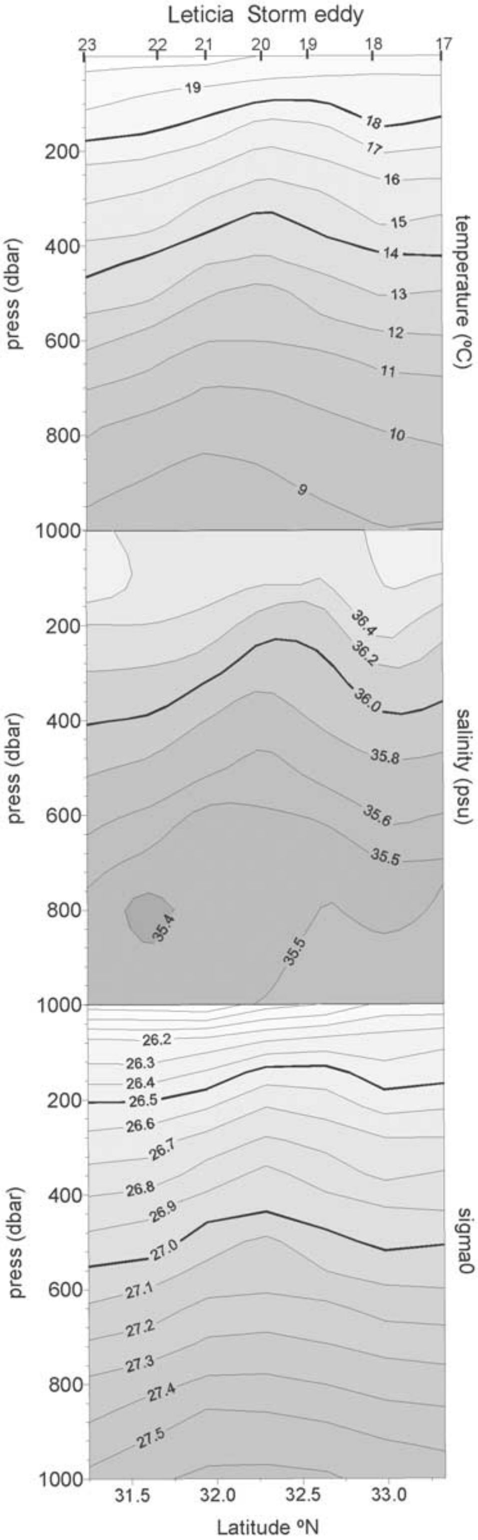


Figure 3. Vertical distribution of temperature (°C), salinity (psu), and σ_0 (kg m^{-3}) across the main CTD section sampled in Leticia (33.33°N–27.67°W; 31.25°N–30.01°W) in April 1999 during the Azores II cruise.

from hydrographic data was 7 Sv (relative to 1000 dbar, level of no motion) and 10 Sv (relative to 2000 dbar). It compares with 9 Sv (relative to 1150 dbar) and 11 Sv (relative to 2000 dbar) transports computed from SOPRANE system across a latitudinal section at 28.7°W. It is important to note that the two sections plotted in Figure 4 are not exactly comparable as the main CTD section (see Figure 2) is not strictly latitudinal. This difference could explain the slight disagreements observed between both estimations.

3.2. Storms Eddies Throughout the 1993–1999 Period

[18] The evolution of cyclonic eddies budded from the Azores Current in the northeast Atlantic was studied for the 1993–1999 period. Figure 5 shows travel curves of STORM eddies near 33°N, from 19°W to 35°W as determined by visual and automatic detection procedures (see section 2). Both methods differed, especially at the beginning and at the end of the detection periods when the interaction with meanders or other structures was conspicuous and the signature of the structures less obvious. Seventeen structures were identified. We have detected structures as far east as 19°W, but as described by *Pingree et al.* [1999], the long-lasting structures are formed farther west at ~26°W. *Pingree et al.* [1999, Figure 15] illustrated STORM travel curves near 33°N, from 24°W to 43°W over a 3.6-year period (JD 16,300–17,600). They described that two storms a year passed through a fixed point near 35°W and used ~6-year-long data records [*Pingree and Sinha*, 2001] to emphasize the wave-like properties. *Pingree* [2002] identified 14 or 15 negative sea level anomalies that were westward propagating at 32.5°N for the period 1993–2000. The comparison of the travel curves shown in Figure 5 and those plotted by *Pingree et al.* [1999] for the same time interval shows that our tracking periods were in general shorter and that some features tracked by *Pingree et al.* [1999] and *Pingree* [2002] were missing as a consequence of the different detection criteria adopted in both studies (see section 2).

[19] The analysis of SOPRANE model animations showed that the STORM eddy S97_1, originated in ~25.5°W at the end of February 1997, was reabsorbed by the current 3 months later. The meander resulting from this interaction broadened until reaching its maximum spatial extension in July 1997, when a high spatial resolution sampling was carried out during the FCA97c cruise (B. Mouriño et al., Thermohaline structure, ageostrophic vertical velocity fields, and phytoplankton distribution and production in the North East Atlantic subtropical front, submitted to *Journal of Geophysical Research*, 2003). Then, in November 1997, a new cyclonic feature was budded from the meander at 33.0°N–32.0°W. The sea level anomaly linked to this feature moved westward, being detectable but with a diminishing signal for about 3 months, when the anomaly disappeared in ~33.5°W. The evolution of this feature from the end of 1996 to the beginning of 1998 was represented by *Pingree et al.* [1999] as the track of the single STORM eddy S_4, illustrating the different criteria adopted in both studies. As we previously mentioned (see section 2), merging and splitting between eddies and meanders of the main current are continuously visualized, making it difficult to ascertain under the surface analysis if features formed after the occurrence of these interactions do or do not constitute a new STORM eddy. That is the case of STORM eddies S93_2 and S94_1.

[20] Table 1 summarizes several physical characteristics of the STORM eddies identified in the region 20°N–34°N

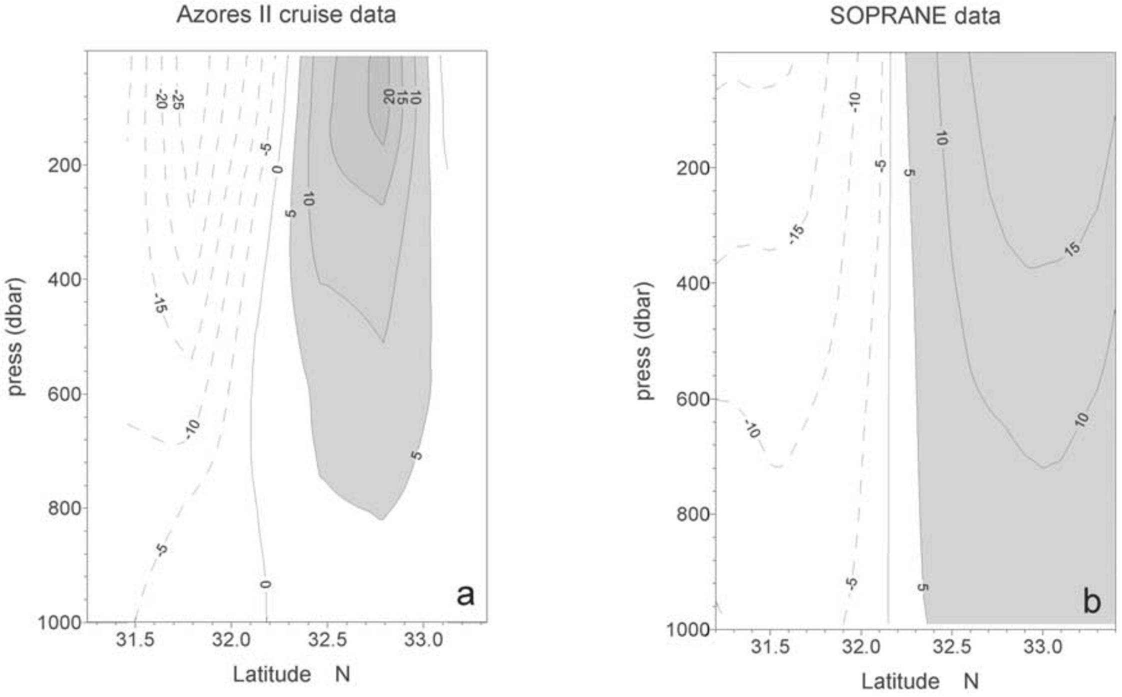


Figure 4. Vertical distribution of geostrophic velocity computed (a) from in situ measurements carried across the main CTD section sampled in Leticia (33.33°N–27.67°W; 31.25°N–30.01°W) relative to 2000 dbar and (b) from SOPRANE system across the 28.5°W longitudinal section.

to 19°W–35°W through the 1993–1999 period. The 17 cyclonic eddies were detected and monitored for time periods ranging from about 50 to 360 days. They were characterized by mean westward velocity, amplitude, diameter, and eccentricity of about 2 km d^{-1}, 8 cm, 187 km, and 0.7, respectively. Note that the values described in this table correspond to mean values estimated for all of the period when the cyclonic rings were tracked, whereas the 20 cm reported for Leticia STORM in Figure 2 represents the mean value for April 1999. Westward velocities, mean amplitudes, and diameters are comparable to previous direct observations carried out at STORM eddies [*Pingree et al.*, 1996, 1999] and to the mean diameter estimated for vortices of the eastern North Atlantic by *Paillet* [1999].

3.3. Interannual and Seasonal Variability

[21] The generation of STORM eddies was subjected to large interannual variability (Figure 5), particularly in 1995 and 1999 when their occurrence in the northeast Atlantic was more frequent. The annual number of observed STORM eddies ranged from six, in 1995, to two, in 1993 and 1997. We estimated the area occupied yearly by STORM eddies in the northeast Atlantic during the 1993–1999 time interval from the mean diameters and eccentricities computed automatically. The spatial coverage of STORM eddies increased from 1993 to 1995, when the maximum value (43,000 km^2) was estimated, then decreased progressively from 1996 to 1997 (6600 km^2) and finally increased again up to the 24,000 km^2 estimated for 1999. The annual surface occupied by STORM eddies represents less than 2% of the area covered by the northeast Atlantic region considered in this study (20°N–34°N to 19°W–35°W, $\sim 2.4 \times 10^6$ km^2). The animations derived from the SOPRANE model allowed the study of interannual variability both in geographical location and intensity of the Azores Current region during the 1993–1999 period. In 1995 the current developed a relatively intense meander activity, and moved southwestward with respect to its 1993 position, moving back in 1996 and northward in 1997. These shifts in the position of the Azores Current were followed by its overall recirculation system, south of 30°N–31°N. Previous studies reported ~2° latitudinal displacements of the Azores Current axis by using ~6 years of drogued buoy data [see *Pingree*, 1997, Figure 3].

[22] In order to characterize the physical processes involved in the variability of the area of interest, we computed selected terms from the energy budget in the form of a Lorentz scheme by using the SOPRANE system model outputs (Figure 6). BT (BC) is the Barotropic (Baroclinic) conversion rate between mean and turbulent velocity (respectively density) fields. Positive values of BT indicates that the mean flow feeds the eddy velocity field; that is, the mean current develops meanders. Negative BT values indicate that the eddy flow grows the mean current. In the same way, positive values of BC indicate that the mean stratification (large-scale density field) feeds the turbulent variations of the isopycnal inclination, and conversely if negative. Mean mass and velocity transfer energy (MMV) and eddy mass and velocity transfer energy (EMV) are, respectively, the coupling terms between mean potential energy (MPE) and mean kinetic energy (MKE) and between eddy potential energy (EPE) and eddy kinetic energy (EKE). They quantify the impact of density redistribution on the velocity fields. For example, a positive MMV value

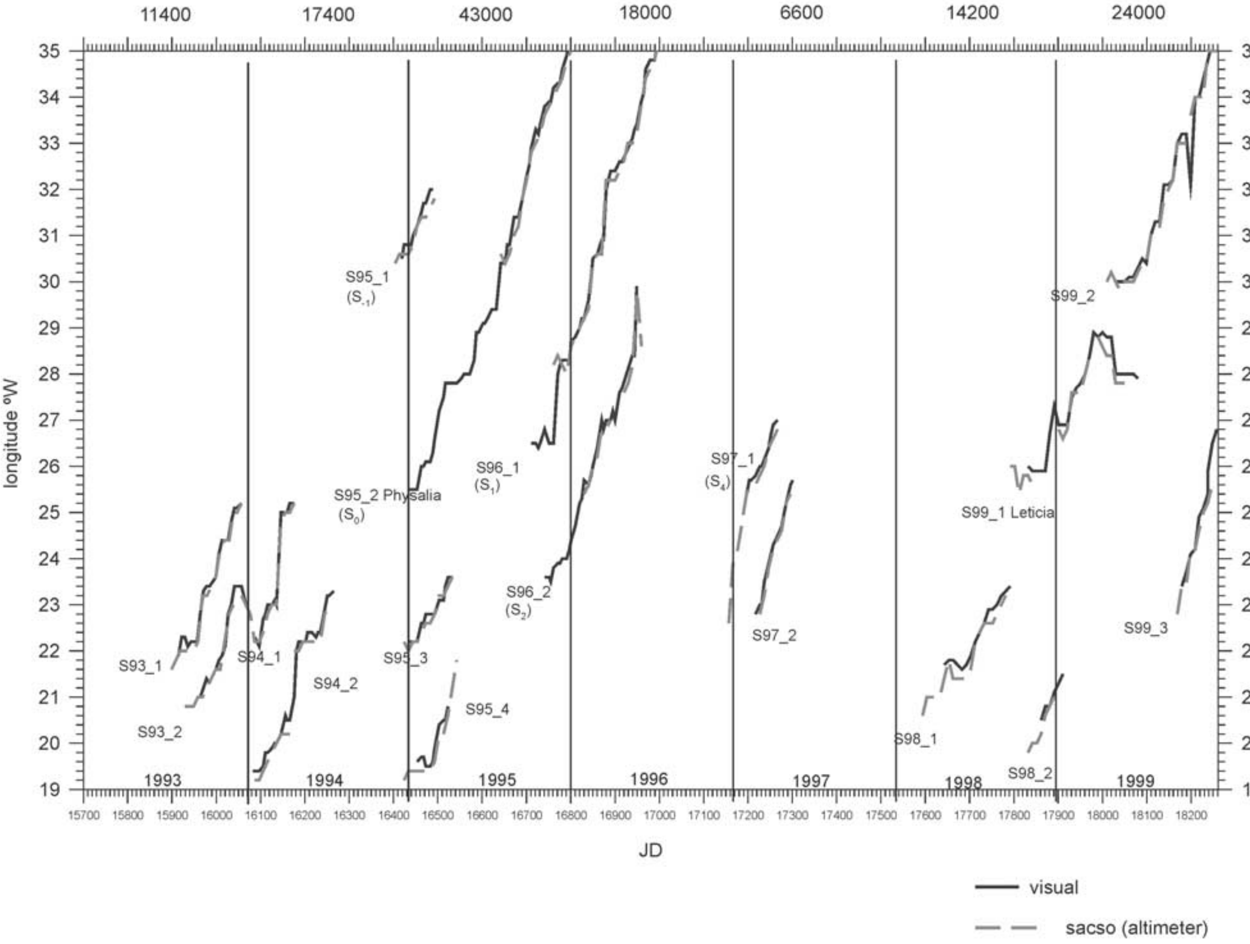


Figure 5. Travel curves of STORM eddies derived from joint visual and automatic detection methods in the subtropical northeast Atlantic (near 33°N, from 19°W to 35°W) for the 1993–1999 period (JD, Julian day). Names in brackets refer to labels previously used by *Pingree et al.* [1999]. Numbers on the top represent annual mean area (km^2) occupied by STORM eddies in the subtropical northeast Atlantic.

indicates upward heat transport (or a downward cooling) which implies a local pressure gradient and a change in the eddy flow. The data set and associated discussion of MPE have not been included in this study. EPE and EKE increased progressively from 1993 to 1995, when the maximum values for the period were calculated (75 cm^2 s^{-2} and 159 cm^2 s^{-2}, respectively). Eddy energies decreased from 1996 to 1998, then increased again in 1999. In 1995 the EKE tongue associated with the Azores Current showed a maximum meridional extension (from 31°N to 36°N), that was narrower in 1997 (from 32°N to 35°N). This year also showed increasing values of BT and coupling terms, whereas BC presented a value close to the 7-year average value. This indicates that the meanders were fed both by the mean flow and the eddy mass field (a tilt of the density surfaces could occur). EPE reached a maximum value in 1995 indicating that advection terms (data not shown) were important energy sources by this year. Strong baroclinic instability, indicated by the high $|BC|/|BT|$ ratio that characterized the Azores Current, decreased in 1995 and 1999, when the minimum values of this ratio were computed (78 and 52, respectively, versus 912 in 1993). This result indicates an increased barotropization of the frontal system in these years. The spatial coverage of STORM eddies (see Figure 5) was significantly correlated with both the annual EKE ($r = 0.92$, $p < 0.01$, where r is the correlation coefficient and p is the significance level) and EPE ($r = 0.86$, $p < 0.05$) in the Azores Current region.

[23] Figure 7 represents EKE and EPE values computed by SOPRANE system for October 1995 and April 1999, when hydrographic measurements were carried out at Physalia and Leticia STORM eddies. Both features showed higher eddy energy levels than the background. Maxima EPE values were located at the position of eddy centers, where the most intense isopycnal uplifting was observed, whereas maxima EKE values were found at eddy edges, where maximum velocity values stand. Physalia Storm eddy was associated with higher eddy energy levels than Leticia, being the variability observed higher in the EPE field (1267 and >3360 cm^2 s^{-2}, EKE and EPE values, were computed associated with Physalia STORM versus 580 and 1200 cm^2 s^{-2} values associated with Leticia STORM). Model-derived EKE values for Physalia STORM were higher than the 342 cm^2 s^{-2} KE estimation computed by *Pingree* [1997] from buoys tracks at 200 m depth.

[24] These results show that the Azores Current frontal system was subjected to a large degree of interannual

Table 1. Physical Characteristics of Storms Detected Through the 1993–1999 Period by Visual and Automatic Detection Methods[a]

	Visual			Automatic						
Storm	Tracked Period, days	Tracked Distance, km	West. Vel., km d^{-1}	Tracked Period, days	Tracked Distance, km	West. Vel., km d^{-1}	Mean Amplitude (s.e.), cm	Mean Diameter (s.e.), km	Mean Eccentricity (s.e.)	Mean Area (s.e.), $\times 10^3$ km^2
S93_1	142	314	2.2	158	343	2.1	6.8 ± 0.4	184 ± 12	0.63 ± 0.05	17 ± 1
S93_2	103 (93)	225	2.4	110	206	1.9	6.8 ± 0.6	187 ± 14	0.65 ± 0.03	17 ± 2
S94_1	89 (79)	292	3.7	119 (89)	283	3.1	8.1 ± 0.6	197 ± 8	0.67 ± 0.06	20 ± 1
S94_2	182	365	2.0	178	356	2.0	7.5 ± 0.6	209 ± 9	0.69 ± 0.04	23 ± 1
S95_1 $\mathbf{S_{-1}}$	70	141	2.0	90	131	1.5	14 ± 1	172 ± 4	0.66 ± 0.04	18 ± 1
S95_2 $\mathbf{S_0}$ **(Ph)**	356	890	2.5	158	412	2.6	13 ± 1	219 ± 16	0.76 ± 0.04	25 ± 3
S95_3	99	130	1.3	109	130	1.2	12.1 ± 0.7	222 ± 9	0.78 ± 0.04	29 ± 2
S95_4	70	112	1.6	119	244	1.6	7.3 ± 0.5	168 ± 6	0.78 ± 0.05	18 ± 1
S96_1 $\mathbf{S_1}$	282 (232)	802	3.5	234	641	2.7	7.8 ± 0.7	184 ± 11	0.72 ± 0.03	20 ± 2
S96_2 $\mathbf{S_2}$	208	603	2.9	110	286	2.6	4.6 ± 0.4	188 ± 10	0.61 ± 0.03	17 ± 1
S97_1 $\mathbf{S_4}$	70	149	2.1	110	391	3.6	10.2 ± 0.2	192 ± 6	0.70 ± 0.02	20 ± 1
S97_2	84	272	3.2	69	243	3.5	5.9 ± 0.3	155 ± 9	0.75 ± 0.03	14 ± 1
S98_1	149	241	1.3	188	241	1.3	10.5 ± 0.4	195 ± 7	0.76 ± 0.03	20 ± 1
S98_2	49	93	1.9	59	113	1.9	7.3 ± 0.6	166 ± 9	0.75 ± 0.05	17 ± 1
S99_1 **(L)**	248 (138)	280	2.0	258 (178)	318	1.8	8.4 ± 0.7	172 ± 10	0.73 ± 0.04	17 ± 2
S99_2	208	469	2.3	228 (198)	469	2.4	8.3 ± 0.8	210 ± 17	0.61 ± 0.03	21 ± 2
S99_3	79	317	4.0	79	261	3.3	5.0 ± 0.3	175 ± 11	0.65 ± 0.05	15 ± 1
Mean (s.e.)	146 ± 21	330 ± 57	2.4 ± 0.2	140 ± 15	298 ± 32	2.3 ± 0.2	8.4 ± 0.1	187 ± 5	0.70 ± 0.01	19 ± 1

[a] Numbers in brackets refer to westward displacement. Tracked distance indicates the spatial displacement of the observed eddies. Mean values correspond to the tracked period. Names in bold refer to labels previously used by *Pingree et al.* [1999]; s.e., standard error; Ph, Physalia Storm eddy; L, Leticia Storm eddy.

variability, with 1995 as the central year of this evolution, with maximum values of eddy energy and increasing number of meanders. *Pingree and Sinha* [2001] showed, using a 2000-day long SLA record, that the observed interannual variability was a consequence of the wave-like properties of the altimetric signal with periodicities of ~180 and ~200 days resulting in maximum amplitudes in 1995/1996/1997 at 35°W. The analysis of TOPEX/Poseidon and ERS altimeter data showed that the strong interannual variability observed in this study is not restricted to the Azores Current system, since it can be detected over the whole North Atlantic basin [*Efthymiadis et al.*, 2002]. This fact suggests that the origin of the observed variability could probably be related to large-scale events. In this regard, 1995, an unusually warm year at the global planetary scale particularly between 30°N and 40°N [*Stammer*, 1997], is also characterized by an inversion of the sign of the North Atlantic Oscillation (NAO) index, the dominant mode of atmospheric variability over the North Atlantic [*Hurrel*, 1995]. *Efthymiadis et al.* [2002] showed that meridional variations of the near-zonal Azores Current system were responsible for interannual large-scale meridional tilt of the sea surface that was correlated with large-scale wind stress changes in the northeast Atlantic, associated with the NAO. Sea level anomaly data constitute the only time-varying forcing term in the SOPRANE reanalysis used in this study. Indeed, the data assimilation scheme corrects weekly the model state and thus impacts the energy variations both in the inner domain and the lateral boundaries. Therefore the variability observed in the energy budget of the model probably results from changes in surface and lateral boundaries. *Pingree* [2002] showed that the North Atlantic Subtropical Gyre intensifies during periods of positive NAO index, and reported a 1-year lag of the ocean with respect to wind-forcing. This author suggested that the intensification of mesoscale activity observed in the region in 1995 and 1999 might result from increasing strength in the ocean response to positive NAO forcing. However, modeling experiments found that NAO-related changes in the distribution of eddy activity and eddy induced nitrate supply in the North Atlantic were negligible [*Oschlies*, 2001a]. In this study, we found a significant negative relationship between the seasonal NAO index estimated for the October–March period, when the most intense eddy generation activity was recorded, and annual EKE and EPE values in the Azores Current region. This correlation also stands between the NAO index and the total annual area occupied by STORM eddies calculated with a 1-year phase lag ($r = -0.89$, $p = 0.02$; $r = -0.93$, $p = 0.01$; $r = -0.99$, $p = 0.001$).

[25] The generation of STORM eddies showed a distinct seasonal pattern. Seventy-five percent of the features were generated in the October–February period (see Figure 5). This observation agrees with SOPRANE results showing increasing energy levels of the Azores Current during the winter period (data not shown), and with previous Geosat altimeter data studies reporting an increase in mesoscale variability of the Azores Current from summer to winter [*Tokmakian and Challenor*, 1993; *Le Traon and De Mey*, 1994]. However, these results contrast with previous investigations based on the analysis of historical hydrographic data [*Klein and Siedler*, 1989] which report increases of EPE during the summer period. This disagreement could be attributed to the effect of interannual variability. However, these authors observed a southward shift and a less meridian extension of the mean current in summer.

[26] We have shown that the SOPRANE system is a useful tool to characterize patterns of variability in the Azores Current frontal system region, and also explains interactions between the mean currents and the eddy fields via the $|BC|/|BT|$ ratio temporal evolution. Nevertheless, a

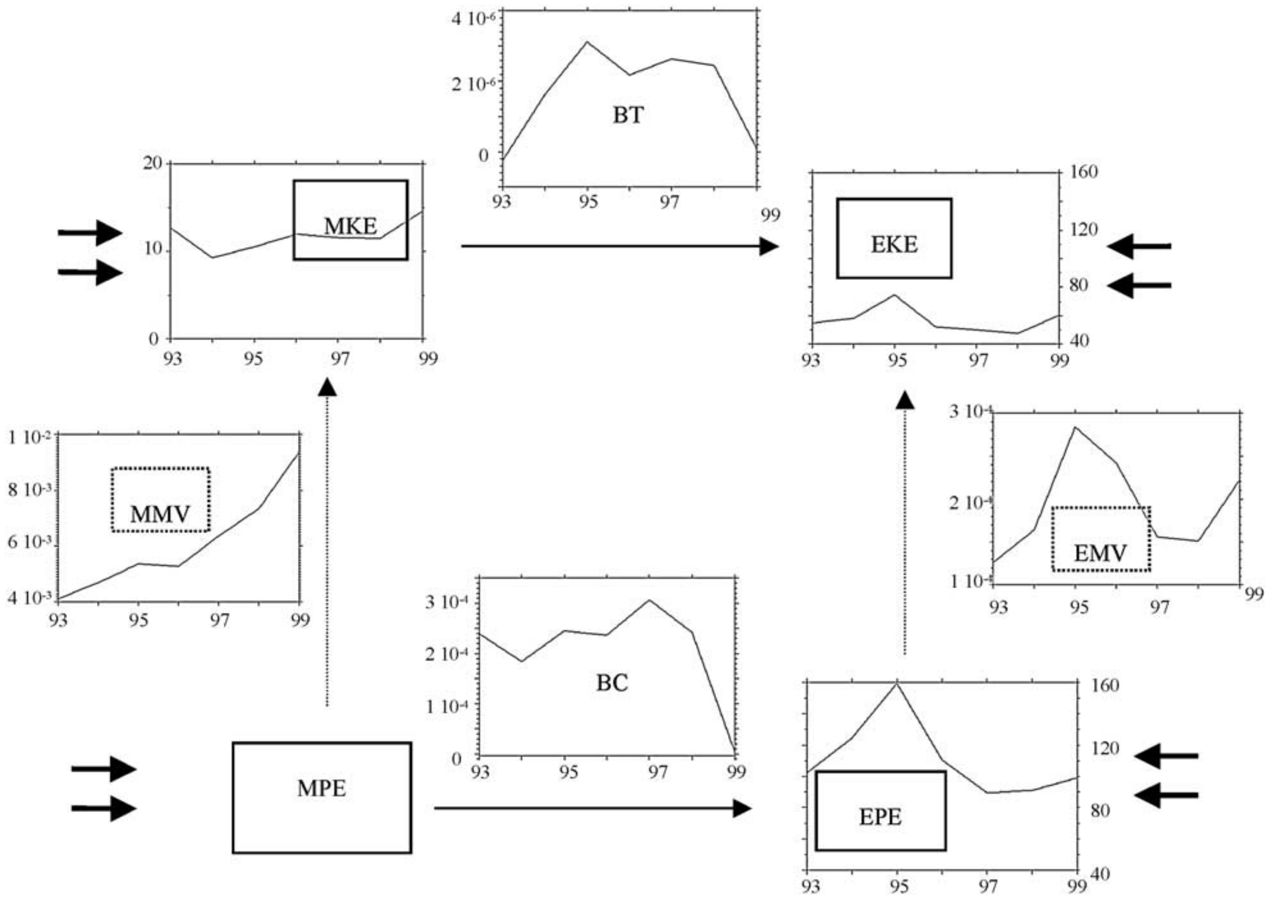


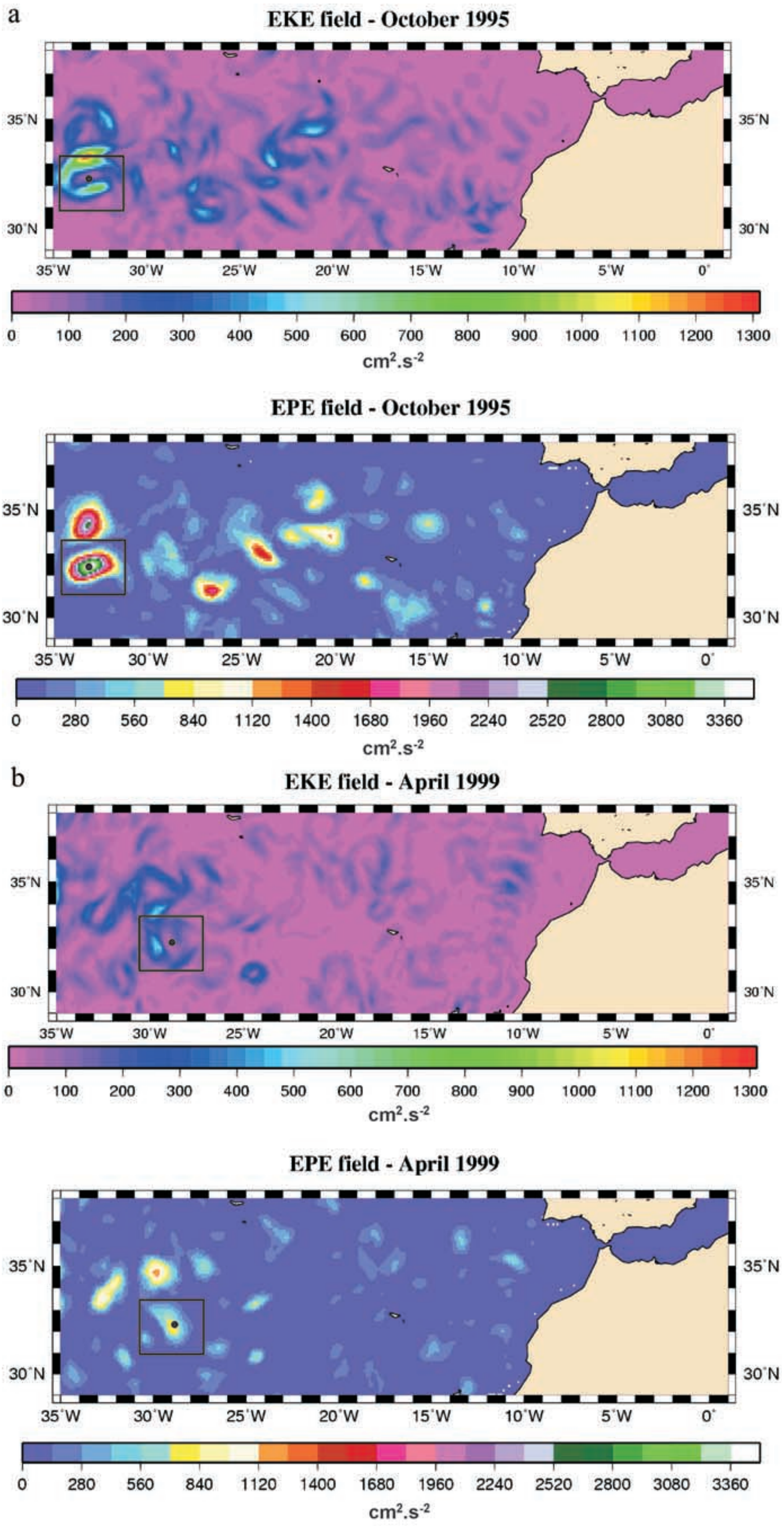
Figure 6. Lorentz diagram of the Azores Current energy budget computed from SOPRANE QG model stream function in the upper level (first 200 m). Energy values represent the spatial mean over an area extending from 29°N to 38°N and 35°W to 1°W. Thin arrows count for conversion terms between mean and eddy fields for velocity, BT (Barotrophic Term), and mass, BC (Baroclinic Term). Bold arrows account for advection terms by the mean, MKE (mean kinetic energy), and MPE (mean potential energy) and eddy, EKE (eddy kinetic energy), and EPE (eddy potential energy). Dotted arrows account for coupling terms between EMV (eddy mass and eddy velocity fields) and MMV (mean mass and mean velocity fields). Values are expressed in cm^2 s^{-2}.

full analysis of all the sources and sinks accountable for the different variability timescales observed in the region is not possible because of the presence of three open boundaries and the assimilation input of energy.

3.4. Contribution of Storm Eddies to Net Community Production in the Northeast Atlantic Subtropical Gyre Region

[27] A considerable body of knowledge has been built in the last 2 decades about the impact of mesoscale dynamics on the biochemical properties of the upper oceanic layer (see review by *Garçon et al.* [2001]). *Oschlies and Garçon* [1998] have estimated that mesoscale eddy activity could account for about one third of the total flux of nitrate into the euphotic zone in the subtropical North Atlantic Ocean, and *Siegel et al.* [1999] estimated the upward flux of nitrate associated with the dynamics of mesoscale eddies in the Sargasso Sea to be ~50% of the total nitrate flux into the photic zone, enough to balance the nutrient budget of the region. However, recent modeling experiments disagree on the relevance of eddy-pumping in surface nitrate depleted waters [*Oschlies*, 2001b; *McGillicuddy et al.*, 2003]. *González et al.* [2001] stressed the importance of mesoscale structures in the northeast subtropical Atlantic and estimated that the regional carbon deficit measured in this region [*Duarte et al.*, 2001; *González et al.*, 2001; *Teira et al.*,

Figure 7. (opposite) Mean EKE and EPE values (cm^2 s^{-2}) computed for (a) October 1995 (CD66 cruise [see *Pingree et al.*, 1996]), and (b) April 1999 (Azores II cruise [see *Mouriño et al.*, 2002]) from SOPRANE QG model stream function in the upper layer (first 200 m). Physalia and Leticia STORM eddies are framed. Dots represents eddies centers obtained from hydrographic cruise data, 32.33°N–33.33°W (Physalia STORM) and 32.4°N–28.7°W (Leticia STORM).


a
EKE field - October 1995
35°N
30°N
35°W 30°W 25°W 20°W 15°W 10°W 5°W 0°
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
cm².s⁻²
EPE field - October 1995
0 280 560 840 1120 1400 1680 1960 2240 2520 2800 3080 3360
cm².s⁻²
b
EKE field - April 1999
EPE field - April 1999

2001; *Serret et al.*, 2001, 2002] would be increased by 14 to 52% in the absence of the biological activity associated with the Subtropical Front and STORM eddies. These authors assumed that six STORM eddies budded from the Azores Current annually, that the lifetime of these structures was on average 1 year, and that their surface area ranged from $0.42-0.75 \times 10^{12}$ m^2. Our results, however, show that the generation and the activity of STORM eddies is subjected to a strong interannual and seasonal variability that affects the number of features generated, their lifetime, and the surface area occupied by these features. The number of features generated annually ranged from two to six (Figure 5), and the mean lifetime and surface area occupied were ~140 days and 0.2×10^{11} m^2 (see Table 1).

[28] *Mouriño et al.* [2002] showed that the increase of nitrate concentration in the photic layer measured inside Leticia did not translate into noticeable increases in phytoplankton biomass and primary production rates. Eddy diffusive flux of nitrate across the nitracline originated mainly by near-inertial waves explained less than 25% of the nitrogen required to sustain the estimated new production.

[29] According to the empirical model developed by *Serret et al.* [2002] to predict the net metabolism of the planktonic community starting from carbon incorporation rates measured in the Atlantic Ocean, the organic carbon deficit estimated for the Northeast Atlantic Subtropical Gyre from the model of primary production developed by *Longhurst* [1998] would be 388 mgC m^{-2} d^{-1}, which extrapolated to our study region would represent a carbon deficit of ~0.3GtC yr^{-1}. Assuming the averaged net production rate of 240 ± 204 mgC m^{-2} d^{-1} measured in Leticia as representative for STORM eddies and considering the mean surface area and the lifetime estimated automatically for each STORM eddy, we estimated that the annual net community production associated with the STORM eddies for the period 1993–1999 ranged from a minimum value of 0.58 MtC yr^{-1} in 1997 to 3.29 MtC yr^{-1} in 1995, indicating that the contribution of STORM eddies to the regional carbon deficit should be always lower than 1% (0.2–1%).

[30] Our results show that the contribution of STORM eddies to the net community production of the North Atlantic subtropical region was practically negligible. We are well aware that the main limitation of this estimate lies in the assumption that the net community production rate measured at STORM Leticia [*González et al.*, 2001] is representative of the actual magnitude of these rates in these mesoscale features. At present, we cannot ascertain the validity of this assumption because, unfortunately, these are the unique primary production data available for this type of eddies. These rates are likely to be relatively variable both in time and space, as could be deduced from the *Spall and Richards* [2000] numerical model outputs that show that the vertical input of nitrate only takes place during the initial stages of eddy formation. The short set of net community production measurements conducted within STORM Leticia showed a relatively high spatial variability [*González et al.*, 2001]. The detailed analysis of the available altimeter and hydrographic data indicated that during the Azores II cruise, we probably witnessed the decay stages of STORM eddy Leticia [*Mouriño et al.*, 2002]; that is, our measurements of primary production and net community production are likely to be at the lower end of the range of variability of these rates in STORM eddies. However, even if we assume a four-fold increase in the net community production rate characteristic of STORM eddies, which would represent a primary production rate considerably higher than the maximum rate of phytoplankton carbon incorporation derived from a seasonal model of primary production for the North Atlantic Subtropical Gyre Province (~490 mgC m^{-2} d^{-1}) [*Longhurst*, 1998], the contribution of these eddies to the total net primary production of the region would be only slightly enhanced by <4%. Recent net community production measurements reported for subtropical Atlantic regions indicate that the heterotrophic behavior of the photic layer described for the eastern boundary region of the North Atlantic subtropical gyral province is unlikely to be valid for the whole North Atlantic oligotrophic domain [*Serret et al.*, 2002]. Assuming that the selected northeast subtropical Atlantic region was two-fold smaller than the one considered in this study (~2.4×10^6 km^2), and the net community production rate characteristic of STORM eddies was four-fold higher than the rates we measured, the contribution of STORM eddies to the organic carbon deficit of the region would still be very low (<10%). Therefore, even if our net community production rates were severely underestimated and the extension of the northeast subtropical Atlantic heterotrophic domain largely overestimated, the conclusions arising from this investigation would not be significantly altered.

4. Conclusions

[31] • Seventeen cyclonic STORM eddies were observed through the 1993–1999 period in the Northeast Atlantic Subtropical Gyre region (20°N–34°N to 19°W–35°W). They were characterized by mean values of 2 cm s^{-1} for the westward velocity, 8 cm for the SLA amplitude, 187 km for the diameter, and 0.7 for the eccentricity.

[32] • The generation of STORM eddies was subjected to an important interannual variability, peaking in 1995 when the presence of STORM eddies in the Northeast Atlantic Subtropical Gyre was more important. The annual surface occupied by STORM represented less than 2% of the northeast Atlantic region considered in this study. Seventy-five percent of the mesoscale cyclonic features were generated in the October–February period.

[33] • Enhanced barotropization of the Azores current frontal system was observed in the SOPRANE model outputs in 1995 and 1999. Significant relationships were found between the seasonal NAO index and both the annual EKE and EPE in the Azores Current region and also the total annual area occupied by STORM eddies calculated with a 1-year phase lag.

[34] • The contribution of the STORM eddies to the regional carbon deficit measured in the subtropical northeast Atlantic was always lower than 1%.

[35] **Acknowledgments.** María José Pazó and Eva Teira (Universidade de Vigo) provided the chlorophyll-*a* and primary production data. Robin Pingree (University of Plymouth) and Bablu Sinha (Southampton Oceanographic Centre) contributed to the processing of physical data. Constructive comments by three anonymous reviewers helped to improve the manuscript. B. M. thanks D. McGillicuddy for helpful comments on an

earlier version of the manuscript. The authors would like to acknowledge the SHOM/CMO (Service Hydrographique et Océanograpique de la Marine/Centre Militaire d'Océanographie) for giving its authorization to use and publish the QG model results from the SOPRANE system and from the detection system in a scientific framework. We wish to thank the captain and crew of the BIO *Hesperides* for their valuable help at sea and to the UGBO personnel for excellent technical support. This work has been done by CLS under contract (98.87.064.00.470.29.25) with SHOM/CMO. This study was funded by the European Commission under the CANIGO contract MAS3CT960060 and CICYT. B. Mouriño was supported by a FPU fellowship from the Ministerio de Educación y Cultura (Spain).

References

Álvarez, M., H. K. Bryden, F. Pérez, A. Ríos, and G. Rosón, Physical and biochemical fluxes and net budgets in the subpolar and temperate North Atlantic, *J. Mar. Res.*, *60*, 191–226, 2002.

Angel, M. V., and M. J. R. Fasham, Eddies and biological processes, in *Eddies in Marine Science*, edited by A. Robinson, pp. 493–524, Springer-Verlag, New York, 1983.

AVISO, *AVISO Handbook for Merged TOPEX/Poseidon Products*, 3rd ed., 201 pp., Cent. Natl. d'Etudes Spatiales, Toulouse, France, 1996.

Blayo, E., J. Verron, and J. M. Molines, Assimilation of TOPEX/Poseidon altimeter data into a circulation model of the North Atlantic, *J. Geophys. Res.*, *99*, 24,691–24,705, 1994.

Centre ERS d'Archivage et de Traitement (CERSAT), ERS-1 altimeter products user manual, *C1-EX-MUT-A21-01-CN*, 52 pp., CERSAT/Ifremer, Brest, France, 1994.

Centre ERS d'Archivage et de Traitement (CERSAT), Altimeter and microwave radiometer ERS products user manual, *C2-MUT-A-01-IF*, 136 pp., CERSAT/Ifremer, Brest, France, 1996.

Cronin, M., and D. R. Watts, Eddy-mean flow interaction in the Gulf Stream at 68°W: 1. Eddy energetics, *J. Phys. Oceanogr.*, *26*, 2107–2131, 1996.

De Mey, P., and M. Benkiran, A multivariate reduced-order optimal interpolation method and its application in Mediterranean basin-scale circulation, in *Ocean Forecasting: Conceptual Basis and Application*, edited by N. Pinardi, Springer-Verlag, New York, 2000.

Doney, S. C., The ocean's productive deserts, *Nature*, *389*, 905–906, 1997.

Duarte, C. M., S. Agustí, J. Arístegui, N. González, and R. Anadón, Evidence for a heterotrophic subtropical northeast Atlantic, *Limnol. Oceanogr.*, *46*, 425–428, 2001.

Ducet, N., P.-Y. Le Traon, and G. Reverdin, Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and -2, *J. Geophys. Res.*, *105*, 19,477–19,498, 2000.

Ducklow, H. W., C. A. Carlson, R. N. Bates, A. H. Knap, and A. F. Michaels, Dissolved organic carbon as a component of the biological pump in the North Atlantic Ocean, *Philos. Trans. R. Soc. London, Ser. B*, *348*, 161–167, 1995.

Ducklow, H. W., D. K. Steinberg, and K. O. Buesseler, Upper ocean carbon export and the biological pump, *Oceanography*, *14*, 50–58, 2001.

Efthymiadis, D., F. Hernandez, and P.-Y. Le Traon, Large-scale sea level variations and associated atmospheric forcing in the subtropical north-east Atlantic Ocean, *Deep Sea Res., Part II*, *49*, 3957–3981, 2002.

Eppley, R. W., and B. J. Peterson, Particulate organic matter flux and planktonic new production in the deep ocean, *Nature*, *282*, 677–680, 1979.

Falkowski, P. G., D. Ziemann, Z. Kolber, and P. K Bienfang, Role of eddy pumping in enhancing primary production in the ocean, *Nature*, *352*, 55–58, 1991.

Garçon, V. C., A. Oschlies, S. C. Doney, D. McGillicuddy, and J. Waniek, The role of mesoscale variability on plankton dynamics in the North Atlantic, *Deep Sea Res., Part II*, *48*, 2199–2226, 2001.

González, N., R. Anadón, B. Mouriño, E. Fernández, B. Sinha, J. Escánez, and D. de Armas, The metabolic balance of the planktonic community in the N. Atlantic Subtropical Gyre: The role of mesoscale instabilities, *Limnol. Oceanogr.*, *46*, 946–952, 2001.

González, N., R. Anadón, and E. Marañón, Large-scale variability of planktonic net community metabolism in the Atlantic Ocean: Importance of temporal changes in oligotrophic subtropical waters, *Mar. Ecol. Prog. Ser.*, *233*, 21–30, 2002.

Hernandez, F., P.-Y. Le Traon, and R. Morrow, Mapping mesoscale variability of the Azores Current using TOPEX/Poseidon and ERS-1 altimetry, together with hydrographic and Lagrangian measurements, *J. Geophys. Res.*, *100*, 24,995–25,006, 1995.

Hurrel, J. W., Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation, *Science*, *269*, 676–679, 1995.

Klein, B., and G. Siedler, On the origin of the Azores Current, *J. Geophys. Res.*, *94*, 6159–6168, 1989.

Le Traon, P.-Y., and P. De Mey, The eddy field associated with the Azores Front east of the Mid-Atlantic Ridge as observed by the Geosat altimeter, *J. Geophys. Res.*, *99*, 9907–9923, 1994.

Le Traon, P.-Y., and G. Dibarboure, Mesoscale mapping capabilities of multi-satellite altimeter missions, *J. Atmos. Oceanic Technol.*, *16*(9), 1208–1223, 1999.

Le Traon, P.-Y., and F. Ogor, ERS-1/2 orbit improvement using TOPEX/POSEIDON: The 2-cm challenge, *J. Geophys. Res.*, *103*, 8045–8057, 1998.

Le Traon, P.-Y., F. Nadal, and N. Ducet, An improved mapping method of multisatellite altimeter data, *J. Atmos. Oceanic Technol.*, *15*(2), 522–534, 1998.

Longhurst, A., *Ecological Geography of the Sea*, Academic, San Diego, Calif., 1998.

McGilliccuddy, D. J., A. R. Robinson, D. A. Siegel, H. W. Jannasch, R. Johnson, T. D. Dickey, J. McNeil, A. F. Michaels, and A. H. Knap, Influence of mesoscale eddies of new production in the Sargasso Sea, *Nature*, *394*, 263–266, 1998.

McGilliccuddy, D. J., L. A. Anderson, S. C. Doney, and M. E. Maltrud, Eddy-driven sources and sinks of nutrients in the upper ocean: Results from a 0.1° resolution model of the North Atlantic, *Global Biogeochem. Cycles*, *17*(2), 1035, doi:10.1029/2002GB001987, 2003.

McNeil, J. D., H. W. Jannasch, T. Dickey, D. McGillicuddy, M. Brzezinski, and C. M. Sakamoto, New chemical, bio-optical and physical observations of upper ocean response to the passage of a mesoscale eddy off Bermuda, *J. Geophys. Res.*, *104*, 15,537–15,548, 1999.

Mouriño, B., E. Fernández, J. Escánez, D. de Armas, S. Giraud, B. Sinha, and R. D. Pingree, A SubTropical Oceanic Ring of Magnitude (STORM) in the Eastern North Atlantic: Physical, chemical and biological properties, *Deep Sea Res., Part II*, *49*, 4003–4021, 2002.

Oschlies, A., NAO-induced long-term changes in nutrient supply to the surface waters of the North Atlantic, *Geophys. Res. Lett.*, *28*(9), 1751–1754, 2001a.

Oschlies, A., Model-derived estimates of new production: New results point towards lower values, *Deep Sea Res., Part II*, *48*, 2173–2197, 2001b.

Oschlies, A., and V. Garçon, Eddy-induced enhancement of primary production in a model of the North Atlantic Ocean, *Nature*, *394*, 266–269, 1998.

Paillet, J., Central Water vortices in the Eastern North Atlantic, *J. Phys. Oceanogr.*, *29*, 2487–2503, 1999.

Pingree, R. D., The eastern subtropical gyre (North Atlantic): Flow rings recirculations structure and subduction, *J. Mar. Biol. Assoc. U. K.*, *77*, 573–624, 1997.

Pingree, R. D., Ocean structure and climate (Eastern North Atlantic): In situ measurement and remote sensing (altimeter), *J. Mar. Biol. Assoc. U. K.*, *82*, 681–707, 2002.

Pingree, R. D., and B. Sinha, Dynamic topography (ERS-1/2 and Seatruth) of subtropical ring (STORM 0) in the STORM corridor (32–34°N, eastern basin, North Atlantic Ocean), *J. Mar. Biol. Assoc. U. K.*, *78*, 351–376, 1998.

Pingree, R. D., and B. Sinha, Westward moving waves or eddies (*Storms*) on the Subtropical/Azores Front near 32.5°N? Interpretation of the Eulerian currents and temperature records at Moorings 155 (35.5°W) and 156 (34.4°W), *J. Mar. Syst.*, *29*, 239–276, 2001.

Pingree, R. D., B. Sinha, A. L. New, I. Waddington, R. N. Head, and L. V. Nechvolodov, Will deep subtropical ring 'STORM Physalia' cross the mid Atlantic Ridge and reach America?, *J. Mar. Biol. Assoc. U. K.*, *76*, 553–567, 1996.

Pingree, R. D., C. Garcia-Soto, and B. Sinha, Position and structure of the Subtropical/Azores Front region from combined Lagrangian and remote sensing (IR/altimeter/SeaWiFS) measurements, *J. Mar. Biol. Assoc. U. K.*, *79*, 769–792, 1999.

Quiñones, R. A., and T. Platt, The relationship between the f-ratio and the P:R ratio in the pelagic ecosystem, *Limnol. Oceanogr.*, *36*, 211–213, 1991.

Sarmiento, J. L., and C. Le Quéré, Oceanic carbon dioxide uptake in a model of century-scale global warming, *Science*, *274*, 1346–1350, 1996.

Serret, P., C. Robinson, E. Fernández, E. Teira, and G. Tilstone, Latitudinal variation of the balance between plankton photosynthesis and respiration in the E Atlantic Ocean, *Limnol. Oceanogr.*, *46*, 1642–1652, 2001.

Serret, P., E. Fernández, and C. Robinson, Biogeographic differences in the net ecosystem metabolism of the open ocean, *Ecology*, *83*(11), 3225–3234, 2002.

Siegel, D. A., D. J. McGillicuddy, and E. A. Fields, Mesoscale eddies, satellite altimetry, and new production in the Sargasso Sea, *J. Geophys. Res.*, *104*, 13,359–13,379, 1999.

Spall, S. A., and K. J. Richards, A numerical model of mesoscale frontal instabilities and plankton dynamics: I. Model formulation and initial experiment, *Deep Sea Res., Part I*, *47*, 1261–1301, 2000.

Stammer, D., Global characteristics of ocean variability estimated from regional TOPEX/POSEIDON altimeter measurements, *J. Phys. Oceanogr.*, *27*, 1743–1769, 1997.

Teira, E., M. J. Pazó, P. Serret, and E. Fernández, Dissolved organic carbon production by microbial populations in the Atlantic Ocean, *Limnol. Oceanogr.*, *46*, 1370–1377, 2001.

Tokmakian, R. T., and P. G. Challenor, Observations in the Canary Basin and the Azores frontal region using Geosat data, *J. Geophys. Res.*, *98*, 4761–4773, 1993.

Uz, B. M., J. A. Yoder, and V. Osychny, Pumping of nutrients to ocean surface waters by the action of propagating planetary waves, *Nature*, *409*, 597–600, 2001.

H. Etienne, F. Hernández, and S. Giraud, Collecte Localisation Satellites, 8-10, Rue Hermès, 31526 Ramonville St-Agne, France. (helene.etienne@mercator-ocean.fr; fabrice.hernandez@mercator-ocean.fr; sylvie.giraud@cls.fr)

E. Fernández, Universidade de Vigo, Departamento de Ecoloxía e Bioloxía Animal, Campus Lagoas-Marcosende, E-36200 Vigo, Spain. (esuarez@uvigo.es)

B. Mouriño, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Bigelow 404-MS 9, Woods Hole, MA 02543, USA. (bmourino@whoi.edu)