PERGAMON

Deep-Sea Research II 49 (2002) 4003–4021

DEEP-SEA RESEARCH
PART II

www.elsevier.com/locate/dsr2

A Subtropical Oceanic Ring of Magnitude (STORM) in the Eastern North Atlantic: physical, chemical and biological properties

Beatriz Mouriño[a,*], Emilio Fernández[a], José Escánez[b], Demetrio de Armas[b], Sylvie Giraud[c], Bablu Sinha[d], Robin Pingree[e]

[a] *Universidade de Vigo, Departamento de Ecoloxía e Bioloxía Animal, Campus Lagoas-Marcosende, E-36200 Vigo, Spain*
[b] *Instituto Español de Oceanografía, E-38120 Santa Cruz de Tenerife, Spain*
[c] *Collecte Localisation Satellites, 8-10, rue Hermès, 31526 Ramonville St-Agne, France*
[d] *Southampton Oceanography Centre, Southampton SO14 3ZH, UK*
[e] *The Laboratory, MBA Citadel Hill, Plymouth PL1 2PB, UK*

Received 15 September 2000; received in revised form 26 February 2001; accepted 5 June 2001

Abstract

A Subtropical Oceanic Ring of Magnitude (STORM) that budded from the Azores Current was studied in the Eastern North Atlantic Ocean in April 1999. The cyclonic eddy, called *Leticia*, was centred at ~32.4°N–28.7°W and extended across more than 200 km in an east–west direction. *Leticia* had been previously detected by means of TOPEX/POSEIDON altimetry data and further intensively investigated using expendable bathythermograph and conductivity–temperature–depth stations. The altimeter surface signature of the eddy revealed a ~20-cm sea-level depression, an upward displacement of the 16°C isotherm of ~125 m was linked to the eddy centre and Geostrophic transport of the amount of water swirling cyclonically was 7 Sv. The temperature, nitrate, and oxygen anomalies on the $\sigma_0 = 26.5$ isopycnal surface inside *Leticia* were −0.4°C, $-1\,\mu\text{mol}\,l^{-1}$, and $+0.3\,\text{ml}\,l^{-1}$, respectively, with respect to surrounding waters. Shallowing (>50 m) of the deep chlorophyll maximum ($>0.3\,\text{mg}\,\text{m}^{-3}$) was observed at the eddy centre associated with vertical displacements of the isotherms (>100 m) within the photic layer. Vertical excursions of the isopycnals and the deep chlorophyll maximum of more than 30 m were observed over temporal scales of a few (3–6) h. Integrated nitrate concentration over the photic layer was ~4-fold higher inside *Leticia* than outside, however, primary production rates were only slightly higher. Eddy diffusive fluxes across the nitracline, located ~30 m below the deep chlorophyll maximum, ranged from 0.02 to 0.10 mmol $NO_3\,m^{-2}\,d^{-1}$, and explained <25% of the nitrate required to sustain the estimated new production (0.24–0.48 mmol $NO_3\,m^{-2}\,d^{-1}$). © 2002 Elsevier Science Ltd. All rights reserved.

1. Introduction

Several observational (e.g., Angel and Fasham, 1983; Falkowski et al., 1991; McNeil et al., 1999) and modelling studies (e.g., McGillicuddy et al., 1995; McGillicuddy and Robinson, 1997) indicate that mesoscale features could play an important role in nutrient supply to the upper productive layer in subtropical nutrient-depleted regions. Recently, Oschlies and Garçon (1998) have estimated that mesoscale eddy activity could account for about one-third of the total flux of nitrate into

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*Corresponding author. Tel.: +34-986-814-087; fax: +34-986-812-556.

E-mail address: beame@uvigo.es (B. Mouriño).

PII: S0967-0645(02)00139-X

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 ca. 50% of the total nitrate flux into the photic zone, enough to balance the nutrient budget of the region. In a recent paper, Uz et al. (2001) showed that changes in sea-surface-height caused by the propagation of planetary waves were correlated with changes in surface chlorophyll-*a* concentration detected by satellite imagery. It was proposed that enhanced primary production as a result of nutrient pumping, a mechanism similar to that described in mesoscale eddies, might explain these observations.

Sea-truth observations carried out in the Subtropical Eastern North Atlantic throughout the past two decades (Käse and Siedler, 1982; Siedler et al., 1985; Gould, 1985; Pingree et al., 1996) and also investigations using remotely sensed data (Tokmakian and Challenor, 1993; Le Traon and De Mey, 1994; Pingree and Sinha, 1998; Pingree et al., 1999) demonstrated the presence of intense mesoscale activity linked to the Azores Current (AC). The AC is a branch of the Gulf Stream, associated with the North Atlantic Subtropical Front (STF) (Käse and Siedler, 1982; Gould, 1985). The core of the current, $\sim 150\,\mathrm{km}$ maximum width, penetrates to $>1000\,\mathrm{m}$, with a geostrophic transport of 7–12 Sv between 30° and 40°W (Gould, 1985; Sy, 1988; Klein and Siedler, 1989; Arhan et al., 1994; Pingree et al., 1999) and maximum velocities of up to $50\text{–}70\,\mathrm{cm\,s^{-1}}$. Two weaker countercurrents are situated on either side of the AC, with mean speeds ranging from 5 to $15\,\mathrm{cm\,s^{-1}}$, resulting in recirculation both north (anticlockwise circulation) and south (clockwise circulation) (Pingree, 1997). The AC jet tends to weaken eastwards, its flow may not even always be continuous, and develops large meanders that occasionally might develop into cold- and warm-core rings responsible for the exchange of properties across the Subtropical frontal system.

The physical characteristics of mesoscale rings at the Eastern North Atlantic region already have been described in the literature. Kort et al. (1983) observed the south-westward propagation of an anticyclonic feature in which the 15°C isotherm was depressed to as much as 430 m, and Gould (1985), using satellite-tracked drogued buoys, showed the existence of a closed-core eddy, $\sim 100\,\mathrm{km}$ in diameter, propagating westward at $2.2\,\mathrm{km\,d^{-1}}$ over a 200-day period. Pingree (1996) followed a Subtropical eddy with drogued buoys over a ~ 500-day period. This eddy appeared to receive its surface core-water properties during winter mixing south-west of the Canary Islands and then moved westward. Large cyclonic eddies (ca. 400 km diameter), which budded from the AC, named Subtropical Oceanic Rings of Magnitude (STORM), have been intensively investigated (Pingree et al., 1996, 1999; Pingree and Sinha, 1998). The westward motion of a 400-km scale *Storm* eddy *Physalia* was traced using drogued Argos buoys and subsurface Alace floats (Pingree et al., 1996). The *Storm* eddy rotated cyclonically (maximum swirl current $\sim 50\,\mathrm{cm\,s^{-1}}$ at a radial distance of $\sim 100\,\mathrm{km}$) and its temperature anomaly, a 200-m displacement upward, extended from 200 m depth to the sea floor (4 km depth). The azimuthal transport was 45 Sv, and the ring moved westward at $3\,\mathrm{km\,d^{-1}}$. Recent investigations reported the possibility of tracking *Storm* eddies by their altimeter signature using ERS satellite images (Pingree and Sinha, 1998).

It has been hypothesized that enhanced irradiance and nutrient levels at the base of the upper mixed layer associated with the doming of the seasonal thermocline observed at *Storms* might have a profound effect on phytoplankton production (Pingree et al., 1996). However, although the thermohaline and kinematic properties of *Storm* eddies have been intensively investigated throughout the last decade, their chemical and biological characteristics remain largely unknown.

To this aim, an oceanographic survey was conducted in the Subtropical NE Atlantic in April 1999 to assess specifically the effect of *Storms* upon the flux of dissolved inorganic nutrients into the upper mixed layer and the associated potential enhancement of phytoplankton biomass and/or production.

2. Methods

2.1. Cruise track and satellite data

Field observations were conducted on cruise Azores II onboard BIO Hesperides from 8th to 28th of April 1999. The cruise track (Fig. 1) was decided daily based on the information derived from expendable bathythermograph (XBT), conductivity-temperature-depth (CTD) data, and information provided by collecte localization satellites (CLS) from the operational ocean mesoscale forecasting system SOPRANE (see Alves et al., 2002). The system splits into several modules, dedicated to external data retrieval and processing (altimetry, meteorology, hydrology), quasi-geostrophic modelling with assimilation of altimetric data and derived oceanographic variables, and diagnostics helpful for the production of the Nowcast/Forecast Bulletins of the mesoscale ocean circulation in the Eastern North Atlantic. Details on the procedure to derive the altimeter signature and travel curves are described in Pingree and Sinha (1998) and Pingree et al. (1999). An animation showing time sequences of sea-level anomalies over a 400-day period in the AC/STF region was prepared and used to locate the movement and continuity of the eddy.

2.2. Hydrographic sampling

An intensive sampling was carried out in the *Storm* eddy, named *Leticia*, centred at 32.4°N–28.7°W. This mesoscale feature was compared with adjacent Subtropical stations not affected by large-scale eddy activity, (st. 23 and 34), and with a station representative of the AC/STF system (st. 14). CTD profiles were conducted with a Neil Brown mark III probe attached to a rosette

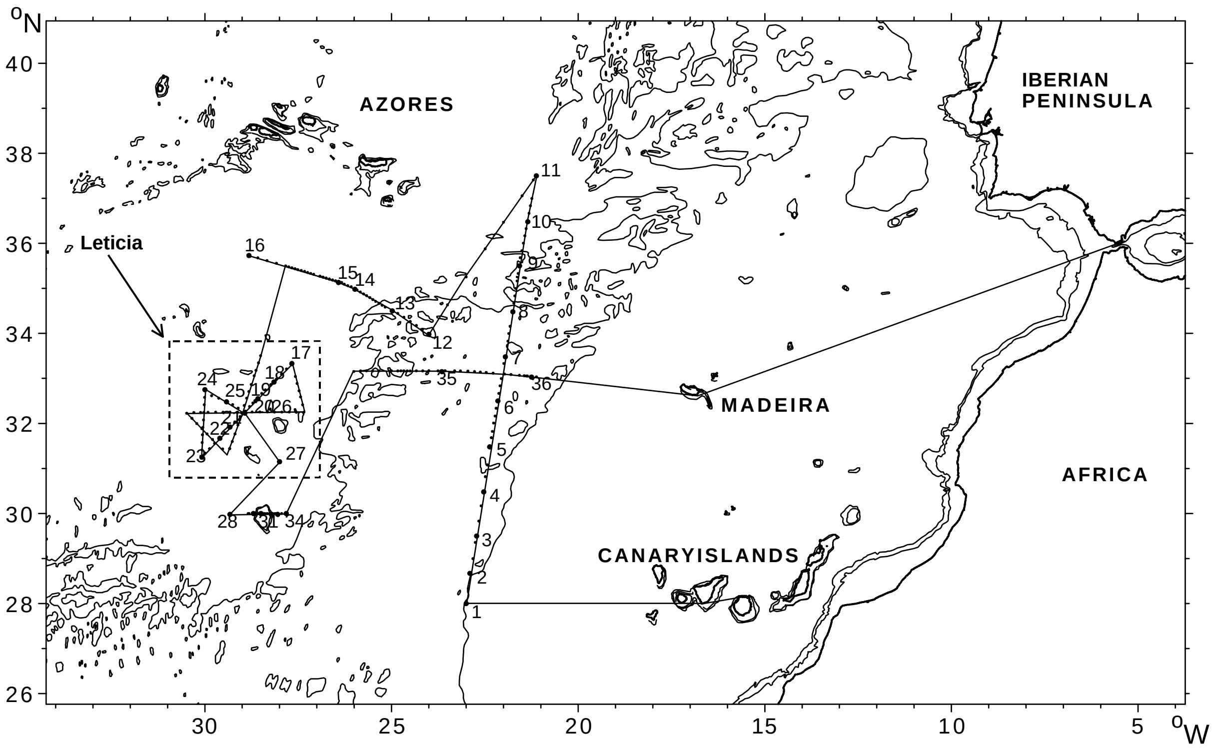


Fig. 1. Azores II cruise track in the northeast Atlantic Ocean from Las Palmas (6 April 1999) to Cartagena (3 May 1999) onboard BIO Hesperides. Circles represent CTD stations. CTD number is indicated. XBTs are shown by small dots.

equipped with Niskin bottles. CTD temperature and salinity sensors were calibrated using digital reversing thermometers and water samples drawn for salinity determinations. XBTs also were used extensively to obtain fine-scale temperature distributions. CTD pressures and XBT depths were calibrated, and an appropriate correction was applied in order to make the CTD and XBT temperature data sets comparable.

Samples were collected on each CTD cast for the determination of dissolved inorganic nitrogen, oxygen and chlorophyll-*a* concentrations as well as for the measurement of primary production rates. Dissolved inorganic nitrogen was determined by Continuous Flow Analysis using a Technicon—Bran Luebbe AA II AutoAnalyzer as described in Tréguer and Le Corre (1975). Nanomolar concentrations of Nitrate + Nitrite were measured as described by Oudot and Montel (1988). Dissolved oxygen was determined by the classical Winkler titration method according to WOCE methodology (Culberson, 1994) using the whole bottle with visual end-point titration using starch solution. The concentration of size-fractionated chlorophyll-*a* was measured with a SAFAS flx spectrofluorometer calibrated with a pure chlorophyll-*a* extract obtained by HPLC after filtration of seawater onto 0.2- and 2-μm polycarbonate filters, and further extraction with acetone 90% 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 cruise. Triplicate 70 ml acid-cleaned polypropylene bottles were filled with water from five or six depths corresponding to optical depths ranging from 100% to 0.1% of surface irradiance levels. Bottles were inoculated with 370–555 kBq (10–15 μCi) $NaH^{14}CO_3$ and immediately placed in an on-deck incubator cooled by surface waters for 7–11 h. 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) through the same type of filters mentioned for chlorophyll-*a* determinations. Filters were decontaminated by exposure to fumes of concentrated HCl for 12 h. Radioactivity was determined by liquid scintillation counting on board. Quenching corrections were performed using an external standard. Hourly production rates were converted into daily rates taking into account the daylight time periods and assuming that dark respiratory losses amount to 20% of the uptake of ^{14}C by photosynthesis (Marañón et al., 2000). New production was estimated from the rates of carbon incorporation by phytoplankton measured in this study and a f-ratio of 0.2 (see Planas et al., 1999), assuming Redfield stoichiometric relationships.

2.3. Diffusive nitrate flux

Eddy diffusion coefficients were calculated by the formulation

$$Kz = \alpha N^{-1},$$

that assumes that mixing is mainly produced by internal waves (Gargett, 1984), where N is the Brunt Väisälä frequency and α was set to $5.4 \times 10^{-4}\,\mathrm{cm}^2\,\mathrm{s}^{-2}$ in order to match the averaged Kz values estimated from a tracer-release experiment carried out in the same region by Ledwell et al. (1993). The Brunt Väisälä frequency was derived from CTD profiles over 10-dbar pressure intervals according to the equation

$$N^2 = -(g/\rho_\mathrm{w})(\partial\rho/\partial z) \quad (\mathrm{s}^{-2}),$$

where g is the acceleration due to gravity ($9.8\,\mathrm{m\,s}^{-2}$), ρ_w is seawater density ($1025\,\mathrm{kg\,m}^{-3}$), and $\partial\rho/\partial z$ is the vertical potential density gradient. Vertical nitrate fluxes across the nitracline were calculated from the product of the estimated diffusion coefficients Kz and the gradients of nitrate concentration across the nitracline, determined using linear interpolation.

3. Results

The altimeter surface signature corresponding to the Azores II survey with track superposed is shown in Fig. 2. The first two sections of the cruise (st. 1–11 and st. 12–16, see Fig. 1) were designed to

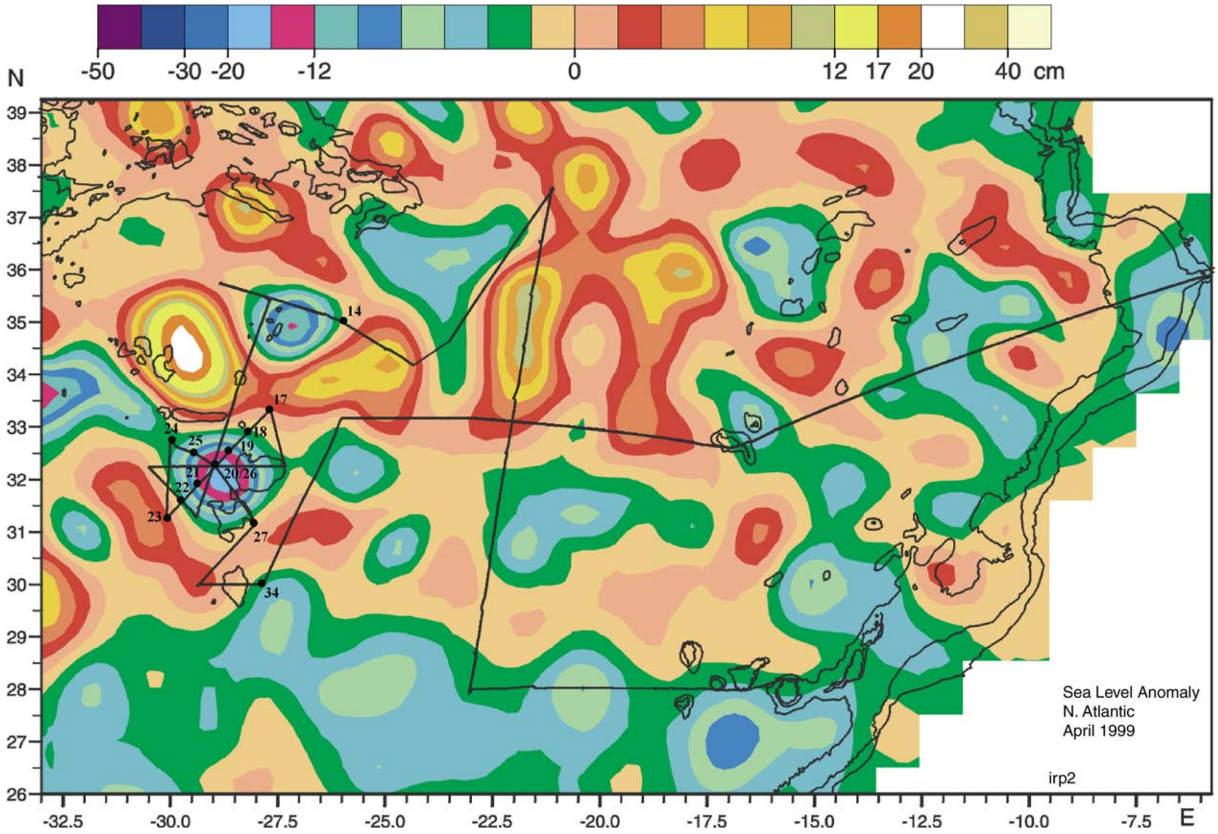


Fig. 2. Altimeter sea-level anomalies (cm scale in colour) for the NE Subtropical Atlantic (April 1999) corresponding to the Azores II cruise on board BIO Hesperides from Las Palmas (6 April 1999) to Cartagena (3 May 1999) with track superposed. CTD number is indicated. The circular purple/blue feature cut by ship's track at ~32.4°N–28.7°W is *Leticia Storm*.

cross the meandering region of the STF. An intensive sampling was carried out at the region centred at 32.4°N–28.7°W, where a ~20-cm sea-level depression with a large-scale influence of ~200 km had been detected. Then Hesperides steamed south towards the 30°N latitude and crossed the Great Meteor Tablemount (GMT). Finally, a zonal section was carried out along the *Storm corridor* (~32–34°N, Pingree and Sinha, 1998).

The CTD and XBT temperature data sets were combined to obtain the thermal structure of the region as shown in the spatial distribution of the depth of the 16° isotherm (Fig. 3). The AC appeared as a meandering region, located around 34–35°N, where the 16° isotherm deepened sharply southwards from 125 to 250 m, as a consequence of the existence of Eastern North Atlantic Central Water (ENACW) and Subtropical Water (STW) on the northern and southern side of the AC, respectively (Pingree et al., 1996; Pollard et al., 1996; New et al., 2001). Contours of the depth of the 16° isotherm showed an upward displacement of about 125 m associated with the *Leticia* centre, which appeared stretched and presented two domes at st. 19–20 and 24.

The position of the STF or AC is defined by a region of marked gradient of dynamic-height (from 1.10 to 1.18 dyn m) (Fig. 4A). A dynamic height anomaly of 0.14 dyn m, with respect to external stations (st. 23), was found at st. 19–20 and 24 inside *Leticia*, comparable to the sea-level anomaly (SLA) obtained using altimetry (~0.20 m, Fig. 2). The position of the centre of

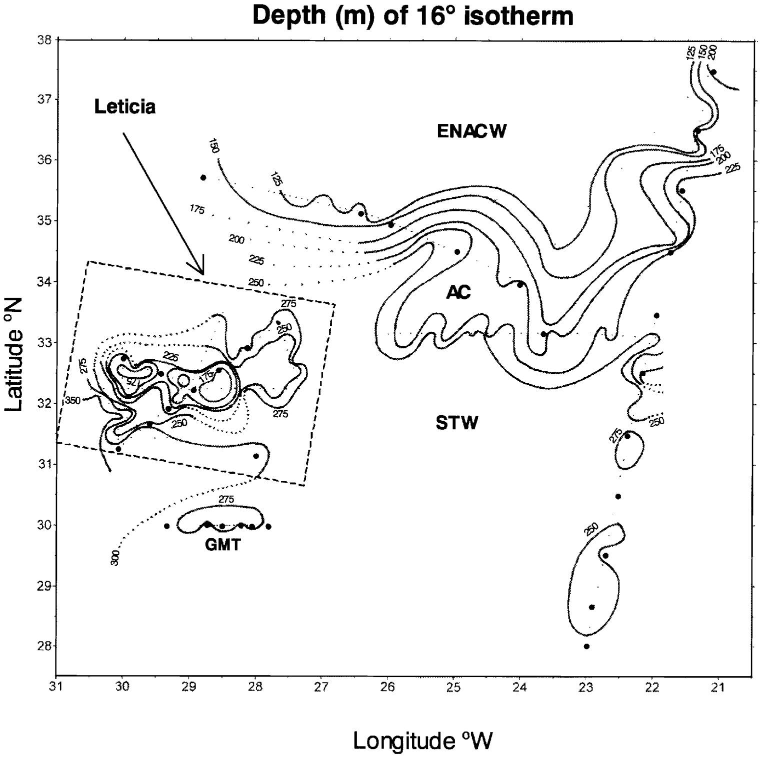


Fig. 3. Depth (m) of the 16° isotherm in April 1999 (AC, Azores Current; ENACW, Eastern North Atlantic Central Water; STW, Subtropical Water; GMT, Great Meteor Seamount). Large and small dots represent CTD and XBT stations, respectively. Discontinuous lines indicate low resolution of the data set.

Leticia derived from its thermohaline characteristics corresponds to the position of the altimeter depression (32.1°N–28.6°W) for mid-April. Geostrophic transports derived from CTD stations resolved the flow structure at the AC/STF region (Fig. 4B). The eastward flow of the AC was associated with a mean geostrophic transport of 7 Sv (relative to 1000 dbar) and 13 Sv (relative to 2000 dbar, data not shown), and an adjacent countercurrent linked to the main jet flowed along the ca. 37°N parallel. The mean transports calculated for the AC in this study are comparable but slightly higher than values previously reported (e.g., at 24.5°W, 5.1 Sv (relative to 1000 dbar) and 10 Sv (relative to 2000 dbar); Pingree et al., 1999). Adjacent westward counterflows have been described previously by Pingree (1997) using real measurement data, and by Cromwell et al. (1996) who found a persistent westward flow at a single position near 35.5°N–27.0°W using altimetry and CD66 CTD data (PML, 1992) The azimuthal transport of the amount of water swirling cyclonically (anticlockwise) in *Leticia* was 7 Sv (relative to 1000 dbar) and 10 Sv (relative to 2000 dbar), with two centres located at st. 20 (32.2°N–28.9°W) and st. 24 (32.8°N–30.0°W).

The distribution of properties in the STF region was examined on the $\sigma_0 = 26.5$ isopycnal surface (Fig. 5). This density level, the lowest isopycnal defining the surface layer subject to erosion, outcrops to the surface in the northern part of this region and reveals details of the near surface flow in the AC region. The $\sigma_0 = 26.5$ isopycnal was colder on the northern side of the AC, the temperature on a central streamline of the AC was 17.3°C (at $\sim$150 dbar), which compares with the value of 17.4°C found in 1992 (Pingree et al., 1999) and suggests no changes on climate of thermohaline structures from 1992. A marked oxygen front was found linked to the position of the STF.

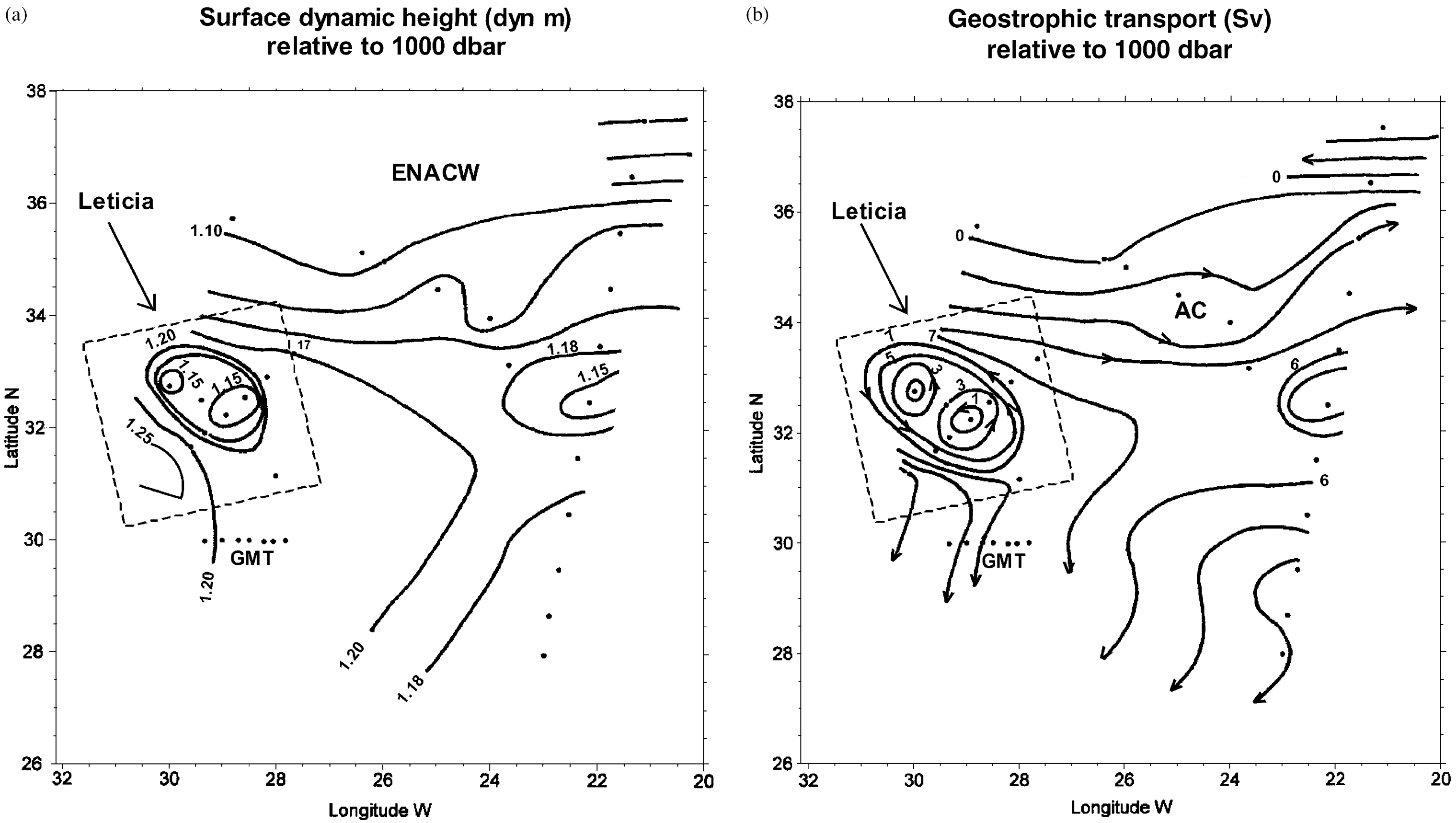


Fig. 4. Surface dynamic height (dyn m) (a) and geostrophic transport (Sv) (b) relative to 1000 dbar for the Azores II cruise in April 1999 (AC, Azores Current; ENACW, Eastern North Atlantic Central Water; STW, Subtropical Water; GMT, Great Meteor Seamount). Lines represent stream transport function and arrows direction of the flow. Dots represent CTD stations.

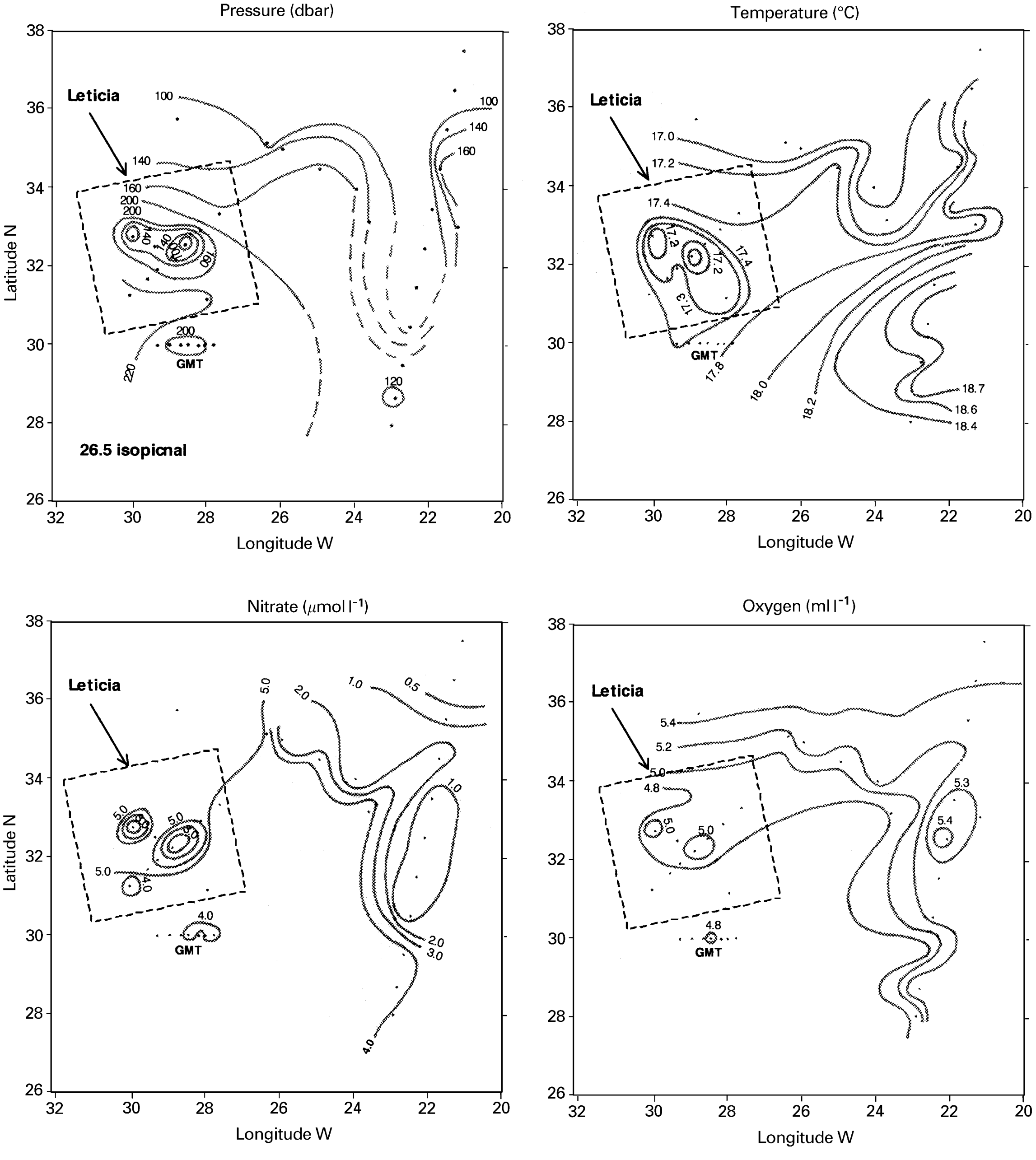


Fig. 5. Distribution of pressure (dbar), temperature (°C), nitrate concentration (μM) and dissolved oxygen concentration (ml l^{-1}) at the $\sigma_0 = 26.5$ isopycnal surface.

Temperature, nitrate and oxygen anomalies inside *Leticia* (st. 20) were −0.4°C, $-1\,\mu$mol l^{-1} and +0.3 ml l^{-1}, respectively, with respect to surrounding waters (st. 23).

The *T–S* diagrams of three stations located at *Leticia* domes (st. 19, 20 and 24), a Subtropical station not affected by eddy activity (st. 34), and a station located at the AC/STF system (st. 14) are

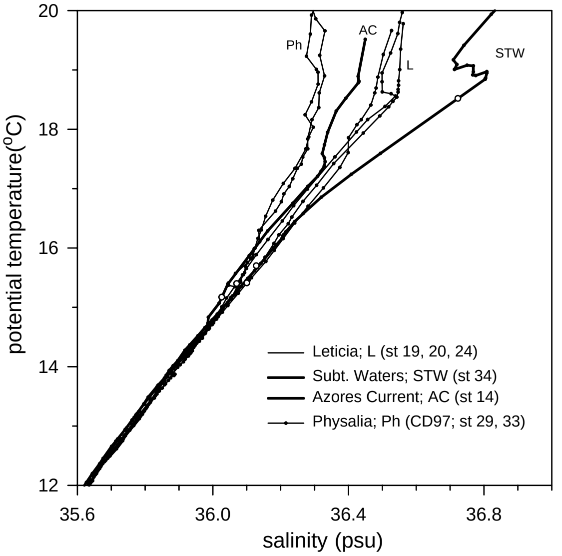


Fig. 6. *T–S* diagrams corresponding to *Leticia* (st. 19, 20 and 24), STWs (st. 34), AC (st. 14), and *Physalia Storm* (st. 29 and 33) described by Pingree et al. (1996). Curves are plotted every 10 m. Open circles represent 200 m depth.

compared in Fig. 6. The thermohaline properties of *Leticia* clearly differed from those of the Subtropical station, characterized by a water body of ~19°C and 36.75 psu in the upper 200 m, but were very similar to those of the AC/STF system. At deeper waters, thermohaline differences among *Leticia*, the STF and the Subtropical region were less pronounced.

A comparative study was carried out between the *Storm Physalia*, described by Pingree et al. (1996) and located at ca. 32.3°N–33.3°W, and *Leticia* (Table 1). The characteristics selected to represent both eddies have been chosen from a region near the eddy centre. *Leticia* showed lower geostrophic transport and maximum velocity and otherwise presented lower temperature, salinity and oxygen anomalies (with respect to eddy edges) on the $\sigma_0 = 26.5$ isopycnal surface. The thermohaline characteristics represented in the *T–S* diagram (Fig. 6) of *Leticia* and *Physalia* differed at the surface layer, probably due to the seasonality that affected the upper layers of *Physalia* in October and the higher contribution of fresh North Atlantic Central Water in the near surface region.

Analysis of the altimeter data archive allowed the study of the long-term evolution of *Leticia.* The position (longitude) against time (Julian Day, JD) of the SLA associated with the centre of the *Storm* eddy suggested continuity of structure from JD 17675 (24.05.98) to 18075 (28.06.99) over a period of ~400 days (Fig. 7). *Leticia* was first noticeable at 26.5°W, stayed for ca. 200 days between 26.5°W and 25.5°W, travelled westward at 2 cm s^{-1} as far as 28.5°W, and then moved back eastward, being detectable but with a diminishing signal for about 3 months after the survey. This eddy may have been slowed by eastward flow in the STF or AC system (Pingree and Sinha, 2001). *Leticia* was located near 25.5°W in August 1998, and some early evolution properties of this elongated eddy were observed on CANIGO Azores I cruise (See Fig. 3d in Doval et al., 2002). In August 1998 the *Leticia* altimeter signature of Fig. 2 was an elongated structure that spanned about 4° of longitude ~22–27°W near 33°N.

The vertical thermohaline structure of *Leticia* along the main CTD section (CTDs 17–23) is shown in Fig. 8. The internal temperature structure (also salinity and sigma0) of cyclonic eddy *Leticia* showed an upward displacement of isolines of more than 100 m over horizontal scales of ca. 100 km, extending from near surface (~100 dbar) to ca. 1500 dbar. The horizontal temperature, salinity and sigma0 anomalies exceeded 1°C, 0.2 psu and 0.2, respectively. Fine-scale inversions of salinity were found at some stations, but they were compensated for density by temperature and were therefore stable. The body of water was spinning cyclonically with maximum geostrophic velocities in the upper 200 m > 25 cm s^{-1}, 100 km away from the eddy centre.

Nitrate concentrations were lower than 0.5 μM at 100 m except at st. 19 and 22, where 1.76 and 0.84 μM were measured at this depth, respectively (Fig. 9). Nitrate anomalies between the centre of *Leticia* (st. 19) and waters outside the eddy (st. 23) at 150 and 200 m depth were 5.45 and 0.84 μM and 7.35 and 3.90 μM, respectively. Note that these differences result from the comparison of nitrate levels from the same depths, whereas in Fig. 5 is represented the distribution of nitrate concentration at a given isopycnal level. The depth of the

Table 1
Comparative characteristics of *Storm Leticia* and *Storm Physalia*, described by Pingree et al. (1996)

Property (units)	Near *Physalia* centre CTDs 29/33	At ~200 km distance CTDs 21/43	Near *Leticia* centre CTDs 19/20/26	At ~220 km distance CTDs 23/34
Observation data	October 1995		April 1999	
Extension (km)	~400		~200	
Maximum velocity ($\mathrm{cm\,s^{-1}}$) (radial distance)	~50 (100 km)		~25 (75 km)	
Geostrophic transport (Sv) (radial distance)	~40 (200 km)		~10 (75 km)	
Density σ_0 ($\mathrm{kg\,m^{-3}}$)	26.50	26.50	26.50	26.50
Pressure (dbar)	141	216	131	221
Salinity (psu)	36.171	36.449	36.288	36.437
Temperature (°C)	16.66	17.56	17.04	17.52
N, Brunt-Väisälä Frequency (cph)	4.4	2.3	3.9	2.6
Oxygen $\mathrm{ml\,l^{-1}}$	5.2	4.7	5.0	4.7
Nitrate (μM)	0.1[a]	3.4	2.9	3.9
Silicate (μM)	1.0	1.3	1.4	1.8
Rotation period (days)	13		14	
Ratio of semiminor/ semimajor axes, *b/a*	0.6		(1)[b]	
Relative vorticity ξ/f	0.166		0.133	
Absolute vorticity $f+\xi$ ($\times 10^{-4}\,\mathrm{s^{-1}}$)	0.892	0.765	0.882	0.754
Q, Potential vorticity ($\times 10^{-11}\,\mathrm{rad\,m^{-1}\,s^{-1}}$)	55	13	42	16
Property (units)	Near *Physalia* centre CTD 22	At ~200 km distance CTDs 21/43	Near *Leticia* centre CTDs 19/20/26	At ~220 km distance CTDs 23/34
Density σ_0 ($\mathrm{kg\,m^{-3}}$)	27.165	27.165	27.165	27.165
Pressure (dbar)	504	685	568	673
Salinity (psu)	35.535	35.565	35.538	35.541
Temperature (°C)	11.21	11.40	11.23	11.26
N, Brunt-Väisälä Frequency (cph)	1.9	1.9	2.1	2.1
Oxygen $\mathrm{ml\,l^{-1}}$	4.6	4.4	4.4	4.3
Nitrate (μM)	7.2	12.8	16.1	16.7
Silicate (μM)	6.1	7.4	7.6	8.4

[a] CTD 22.

[b] $R=1$ was assumed in order to use the expression $\xi/f = 4\pi/(\mathrm{T.f})$, a relative vorticity ξ/f value of 0.193 is obtained by using the true value of $R\sim0.4$.

photic layer (1% of surface irradiance) was shallower at stations located inside *Leticia* (105 m at st. 20) as compared to stations located outside (135 m at st. 23). Oxygen levels were generally higher inside than outside the eddy. Surface values were practically homogeneous in the upper 80 m ($>5.4\,\mathrm{ml\,l^{-1}}$), except at st. 20 and 21 where slightly higher values were measured ($>5.5\,\mathrm{ml\,l^{-1}}$). At deeper levels, isolines uplifted mainly at st. 22 and 19, showing a spatial distribution closely associated to that of nitrate. Enhanced oxygen concentrations ($4.9\,\mathrm{ml\,l^{-1}}$) were found at 300 m depth at st. 21.

Vertical excursions of the isotherms of ca. 80 m within the photic layer were observed associated with *Leticia* (Fig. 10). The deep chlorophyll maximum (DCM), typically located at ca. 100 m, uplifted ca. 50 m at the eddy centre in close relation to the vertical displacement of isotherms. Chlorophyll-*a* values measured at the DCM ranged from 0.1 to 0.4 mg m^{-3}, and no clear differences were found between the centre and the edge of *Leticia* (see e.g., st. 19 and 17 where >0.3 mg m^{-3} were measured). These results agree with previous studies that showed higher chlorophyll-*a* values at the DCM, and located at shallower depths, at the AC region and northwards (ca. 0.3 mg m^{-3} at 80–90 m), whereas they did not exceed 0.2 mg m^{-3} and occurred below 100 m in Subtropical latitudes below 33°N (Fernández and Pingree, 1996; Pingree et al., 1999). Small phytoplankton (<2 μm) always accounted for $>60\%$ of total chlorophyll-*a* biomass in the upper 120 m. Their contribution exceeded 70% at the DCM. Significant differences in phytoplankton size-structure between eddy *Leticia* and waters outside the cyclonic structure were not found. The concentration of surface chlorophyll-*a* in the region of the *Storm Leticia*, derived from SeaWiFS data, shows a distinct seasonal pattern with chlorophyll values ranging from ca. 0.07 mg m^{-3} in summer to ca. 0.20 mg m^{-3} in late winter (Fig. 11). A similar seasonal trend has been reported for 30.0°N; 28.5°W (see Fig. 12 in Mouriño et al., 2001). Maximum rates of primary production were measured at subsurface layers either inside or outside *Leticia*, with typical values ranging from 0.05 to 0.25 mgC m^{-3} h^{-1} (Fig. 12). The vertical position of the primary production maximum coincided with the depth of the DCM. Depth-integrated phytoplankton carbon incorporation rates measured inside the eddy were slightly higher (17 mgC m^{-2} h^{-1} at st. 20) than

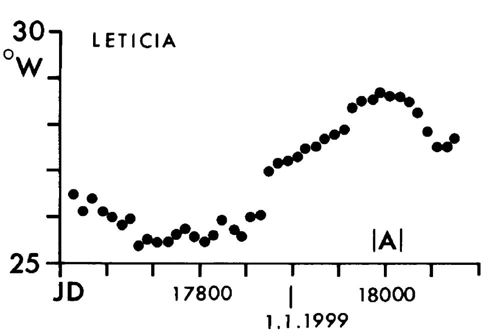


Fig. 7. SLA travel graph of *Leticia* showing movements near 33°N. Time is in Julian Days (1950), JD, and 1st January 1999 is marked. The window, A, indicates April 1999 when the sea survey was carried out (Azores II).

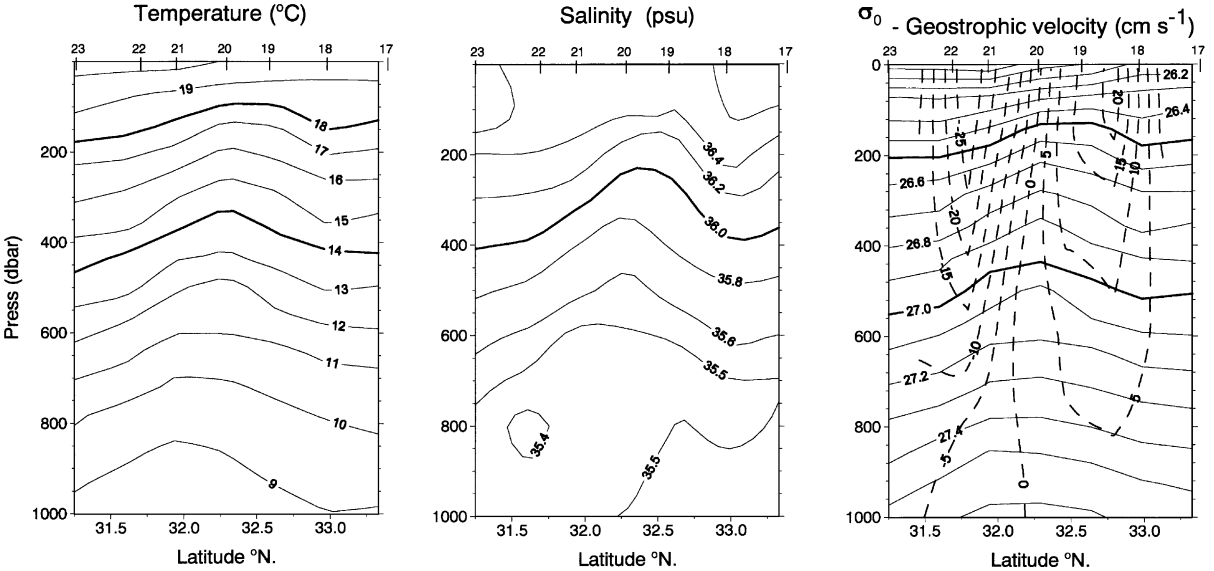


Fig. 8. Vertical distribution of temperature (°C), salinity (psu), σ_0 (kg m^{-3}), and geostrophic velocity (cm s^{-1}) relative to 2000 dbar across *Leticia* in the upper 1000 m.

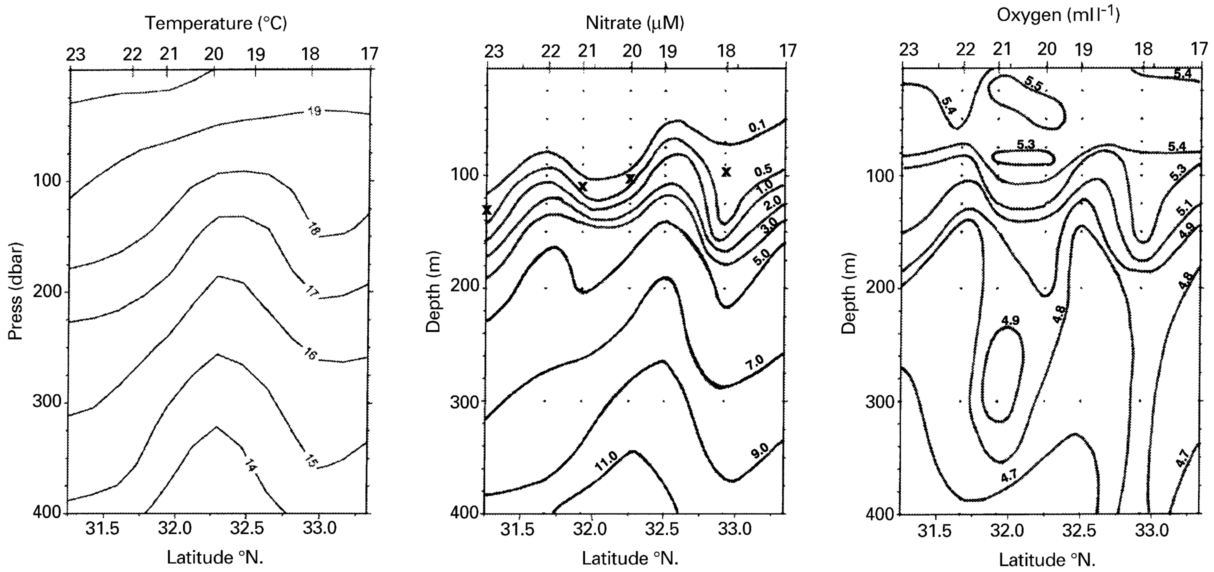


Fig. 9. Vertical distribution of temperature (°C), nitrate concentration (μM) and dissolved oxygen concentration (ml l^{-1}) across *Leticia* in the upper 400 m. Crosses represent the photic-layer depth (1% of surface irradiance).

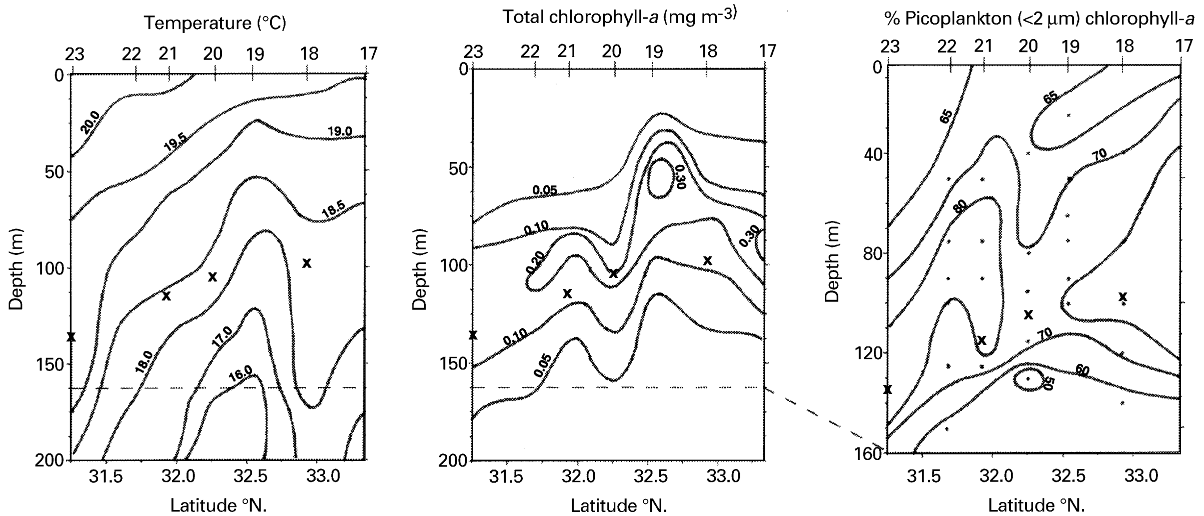


Fig. 10. Vertical distribution of temperature (°C), chlorophyll-*a* concentration (mg m^{-3}) and percentage of <2 μm chlorophyll-*a* across *Leticia* in the upper 200 m. Crosses represent the photic-layer depth (1% of surface irradiance).

outside *Leticia* (14 mgC m^{-2} h^{-1} at st. 23) (Table 2). Unfortunately, primary production rates could not be determined at st. 19, where the more intense uplifting of isotherms was detected. The relative contribution of the different phytoplankton size-classes to total carbon incorporation rates was not significantly different inside *Leticia* as compared to waters outside the eddy.

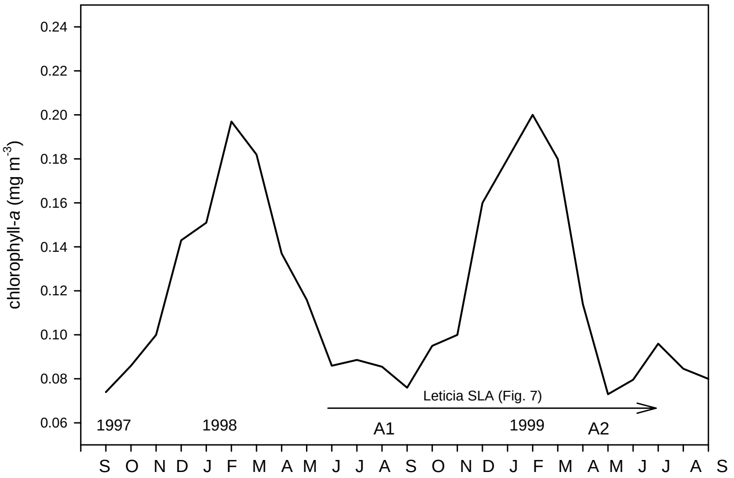


Fig. 11. Seasonal cycle of SeaWiFS chlorophyll-*a* (mg m^{-3}) of the *Storm* corridor (~33°N) at the mean position of *Leticia* (~27°W). Altimeter was used to identify a mean continuous SLA (*Leticia* evolution) which showed partial continuity from April 1998 to July 1999 (see Fig. 7). A1, Azores I cruise; A2, Azores II cruise.

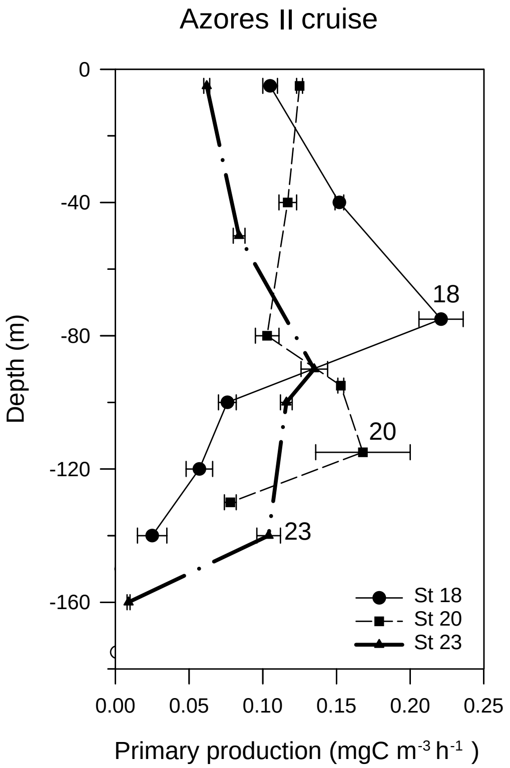


Fig. 12. Vertical profiles of primary production (mgC m^{-3} h^{-1}) at stations located inside and outside *Leticia*. Error bars represent standard error between replicates ($n = 3$).

Table 2 summarizes some physical, chemical and biological characteristics of stations located in the *Leticia* centre (C), influenced by the eddy-induced uplifting of isopycnals but not located at the eddy centre (I), in Subtropical waters (STW), outside Leticia but not in Subtropical waters (O) and in the AC.

At selected stations, more than one CTD cast was deployed in order to draw water samples at the timing adequate for the determination of different variables studied. This sampling strategy allowed us to study the short-term (hourly scale) variability of the thermohaline structure of the water column by comparing the different vertical profiles obtained for each station (Fig. 13). The interpretation of these results from a temporal perspective assumes that the fraction of the observed changes explained by the effect of water displacements was negligible. Upward isopycnal displacements of more than 30 m were observed both inside (st. 18 and 20) and outside (st. 23) *Leticia* over temporal scales of a few (3–6) h (time between profiles). Linked to isopycnal vertical displacement, excursions of the deep chlorophyll-*a* maximum of the same magnitude were found. Slight differences arise in the thermal structure of these stations when the results from Figs. 8–10 are compared (e.g., at st. 23 the 19°C isotherm was located at 115 and 175 m in Figs. 9 and 10, respectively). This results from the use of deep CTD casts for the study of physical and chemical fields (Figs. 8 and 9) and shallow casts for the analysis of biological variables (Fig. 10).

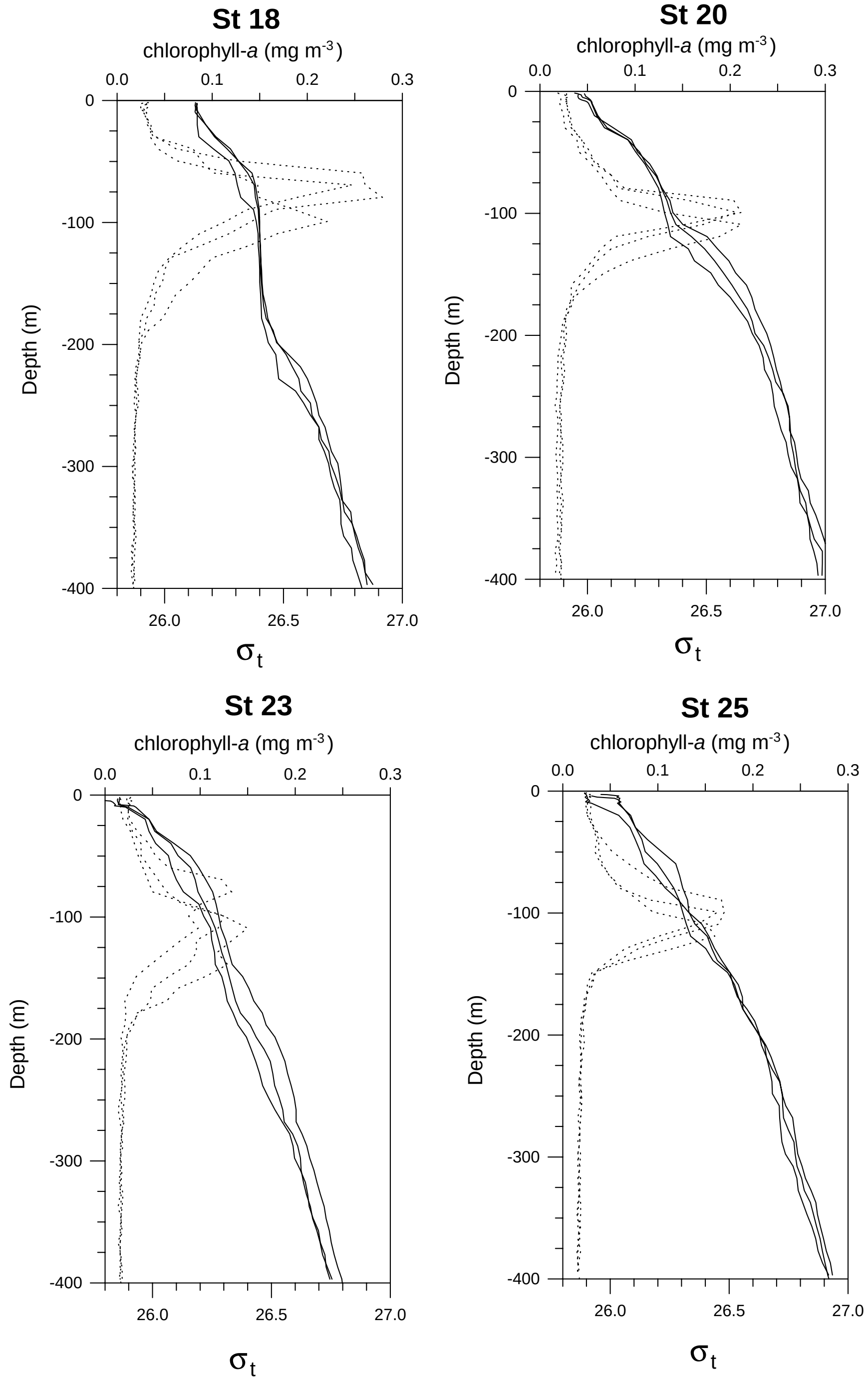
Table 2
Values of selected physical, chemical and biological variables at stations located in the *Leticia* centre (C), influenced by the eddy-uplifting but not located at the eddy centre (I), STW, outside *Leticia* but not in subtropical waters (O), and in the AC

Variables	Stations										
	17 (O)	18 (I)	19 (C)	20–26 (C)	21 (I)	22 (I)	23 (STW)	24 (C)	25 (I)	27 (STW)	14 (AC)	34 (STW)
Depth 16°C isotherm	253	277	175	176	253	299	343	198	219	315	178	305
Integrated nitrate 0–115 m (mmol m^{-2})	27	14	74	28	8	33	6	13	28	—	9	19
Nitrate phosphate ratio 0–115 m	6.6	5.2	10.3	5.8	3.3	9.6	3.0	5.4	7.1	—	3.5	9.8
Nitrate silicate ratio 0–115 m	0.6	0.2	0.8	0.5	0.1	0.4	0.1	0.2	0.6	—	0.3	0.2
Oxygen anomaly 0–150 (mmol m^{-2})	197	963	−540	457	1108	−4.1	1098	863	535	—	1602	−0.3
Integrated chlorophyll-*a* 0–150 m (mg m^{-2})	18	15	20	12	11	12	10	13	11	13	15	13
Percentage picoplankton 0–150 m (<2 μm) chlorophyll-*a*	77	72	72	67	76	74	73	76	73	—	74	72
Integrated primary production 0–150 m (mgC m^{-2} h^{-1})	—	18	—	17	—	—	14	—	9	—	—	13
Percentage picoplankton 0–150 m (<2 μm) primary production	—	69	—	56	—	—	56	—	57	—	—	52

4. Discussion

The results presented in this study clearly demonstrated that *Leticia* was a *Storm* eddy. The study of satellite images showed that the birth of *Leticia* took place at ~26°W (Fig. 7), close to where *Storms* or their initial perturbations are generally apparent (Pingree et al., 1999), and remained for more than 1 year in the *Storm corridor* (~32–34°N, Pingree and Sinha, 1998). The thermohaline characteristics of *Leticia* centre were very similar to those at the core of the AC and differed from those of the Subtropical region, characterized by the presence of STW in the upper 200 m. The sea-surface anomaly observed in *Leticia* (~20 cm) and the corresponding internal isotherm displacement (~125 m) show that surface elevation changes of +1 cm can be interpreted as changes of ~–6 m for the deeper ocean temperature structure (~-600 times magnification), similar to the results obtained by Pingree and Sinha (1998). The altimeter signal of *Leticia* disappeared approximately 3 months after the cruise, indicating that we were witnessing the decay stages of this *Storm*. The elongated shape of the ring and the existence of two centres (Fig. 3) suggest an unstable structure. The anomaly of the studied properties on the $\sigma_0 = 26.5$ isopycnal surface inside and outside eddy was in general lower in *Leticia* compared to the *Storm Physalia* studied by Pingree et al. (1996) (see Table 1). The lower gradient, specially in properties such as potential vorticity that was almost 2-fold lower in *Leticia*, and also the lower geostrophic transport and maximum velocity are indicative of a less-energetic water body.

The biological effects of mesoscale eddies in the NW Atlantic ocean have been intensively investigated, mainly in the Sargasso Sea and Gulf Stream. A warm-core Gulf Stream ring formed


St 18

St 20

St 23

St 25

Fig. 13. Short-term temporal variability of σ_t and chlorophyll-*a* profiles collected every 3–6 h at stations located inside and outside *Leticia*.

in late February 1982 was studied by Hitchcock et al. (1985) and Gould and Fryxell (1988a, b). Phytoplankton biomass and carbon productivity rates inside the ring did not differ from external waters, albeit the ring showed marked differences in phytoplankton species composition. The chlorophyll-*a* concentration (1.4 mg m^{-3}) associated with a mesoscale eddy advected across the Bermuda Testbed Mooring was the highest recorded during the US JGOFS Bermuda Atlantic Time Series Study program (McNeil et al., 1999). Siegel et al. (1999) estimated that the eddy pumping in the Sargasso Sea results in a flux of 0.24 ± 0.10 mol N m^{-2} yr^{-1}, which balances previous geochemical estimates of annual new production for that region.

However, the effects of STORMs on the productive layer of the ocean remains unknown. The results presented in this study show enhanced concentrations of dissolved inorganic nutrients linked to isopycnal uplifting at the eddy centre. Integrated nitrate concentration over the photic layer (~115 m for April 1999) measured at st. 20–26 (*Leticia* centre) was ~4-fold higher than at st. 23 (external waters) (see Table 2). This increase did not translate into notable increases in phytoplankton biomass and primary production rates (12 mg chl-*a* m^{-2} and 17 mgC m^{-2} h^{-1} were measured at st. 20–26 versus 10 mg chl-*a* m^{-2} and 14 mgC m^{-2} h^{-1} at st. 23). Depth-integrated primary production rates measured during the cruise (9–18 mgC m^{-2} h^{-1}) lie within the range of values estimated using a data set sampled during three cruises carried out from September 1995 to October 1996 in the Subtropical NE Atlantic, approximately along the 20°W section (Marañón et al., 2000). However, they are considerably lower than the carbon incorporation rates reported by Fernández and Pingree (1996) for the spring season in the same region where *Leticia* was surveyed. Gross community production rates based on oxygen evolution measurements did not show notable increases associated with the eddy centre (González et al., 2001). However, respiration rates were significantly lower inside than outside *Leticia*, and so the net oxygen production balance was positive inside *Leticia* and negative at the external stations.

The oxygen anomaly ($\Delta[O_2]$, the excess over saturation that summarizes the recent history of community metabolism (e.g., Keeling et al., 1993)) calculated across *Leticia*, did not show enhanced biological activity from the oxygen mass balance (see Table 2). It is important to bear in mind that, by the time of the cruise, *Leticia* was a low-energetic water body, and it is expected that the effects of mesoscale hydrographic structures on biological activity are dependent on age (Karrasch et al., 1996).

Vertical sections across *Leticia* (Figs. 9 and 10) showed that the DCM was located ~30 m above the nitracline, and therefore the nitrate introduced into the photic layer was largely unavailable for phytoplankton growth. It has been hypothesized that the slow diffusion of nutrients across isopycnal boundaries may be enhanced by breaking internal waves which would increase turbulent mixing (e.g., Gargett and Holloway, 1984; Denman and Powell, 1984). Large-amplitude near-inertial waves have been reported along frontal regions in the ocean (Weller, 1982, 1985; Kunze and Sanford, 1984; Salat et al., 1992), and recently Krauss (1999) proposed that internal tides can be produced by the interaction of surface tides and eddy fields. Granata et al. (1995) reported high subsurface chlorophyll concentrations coincident with near-inertial frequencies waves packets in a large mesoscale feature in the Sargasso Sea, and hypothesized that mixing associated with shear instabilities stimulated new production. High-temporal-resolution measurements carried out in a mesoscale eddy advected across the Bermuda Testbed Mooring site over a 30-day period revealed that inertial pumping could represent an important mechanism for lifting nitrate farther into the photic layer than would occur solely by isothermal lifting linked to the eddy (McNeil et al., 1999). Our results showed that the Eastern North Atlantic was subjected to short-term temporal variability causing isopycnal displacements of more than 30 m both inside (st. 18 and 20) and outside (st. 23) *Leticia* over temporal scales of a few (3–6) h, and associated excursions of the deep chlorophyll-*a* maximum of the same magnitude (Fig. 13). Temperature variance of near-inertial frequency were found at 700 m depth in a 530 d mooring record showing the crossing of three *Storms* (Pingree and Sinha, 1998). These high-frequency oscillations represented about 20–30% of the total upward doming of the thermal structure associated with the *Storms*. Similar variances were found at 250 m depth at four *Storms* (Pingree and Sinha, 2001), and vertical oscillations of the thermocline of higher amplitude were measured at the Great Meteor Seamount, located at 30°N–28.5°W (Mouriño et al., 2001). A high temporal and spatial variability of primary-production rates, and also spatial uncoupling of biomass and primary production maxima, could be expected as a result of these vertical oscillations, as cells would be subjected to large changes in irradiance and nutrient levels over short time periods (Armstrong and La Fond, 1966; Pingree and Mardell, 1981, Mouriño et al., 2001). The eddy diffusive flux of nitrate across the nitracline originated mainly by internal waves was calculated from the product of the estimated diffusion coefficients Kz (7×10^{-6}–$4 \times 10^{-5}\,\mathrm{m^2\,s^{-1}}$) and the gradients of nitrate concentration across the nitracline (0.023–0.072 $\mu\mathrm{M\,m^{-1}}$) (see methods) to determine the fraction of new primary production accounted by diffusive processes. The estimated fluxes ranged from 0.02 to 0.10 $\mathrm{mmol\,m^{-2}\,d^{-1}}$. These rates, which were similar to those reported for the same region (Planas et al., 1999), explained $<25\%$ of the nitrogen required to sustain the estimated new production (0.24–0.48 $\mathrm{mmol\,m^{-2}\,d^{-1}}$), and therefore, other mechanisms, apart from diffusion, might be largely involved in the input of dissolved inorganic nitrogen into the productive layer.

In this paper we have described the importance of *Storm* eddies in introducing cool, nutrient-rich waters into the euphotic layer. However, more research needs to be conducted to accurately ascertain the effect of these eddies on primary production rates. Specifically, intensive knowledge is needed on (a) the residence time of *Storm* eddies in the region, (b) the duration and intensity of isopycnal doming above the euphotic layer, (c) non-diffusive upward fluxes of nitrate across the pycnocline, and (d) the effect of short-term oscillations of the pycnocline upon the nutrient and irradiance regimes experienced by subsurface phytoplankton populations, if we aim to understand the significance of *Storm* eddies upon the carbon and nitrogen budgets of the NE Subtropical region. In this connection, future comprehensive observational activities combining mooring deployments, Lagrangian surveys, direct turbulence observations, and remote sensing are clearly needed.

Acknowledgements

We thank the captain and crew of the BIO Hesperides for their valuable help at sea and to the UGBO personal for excellent technical support. María José Pazó and Eva Teira (Universidade de Vigo) provided the chlorophyll-*a* and primary production data. Light measurements were conducted by Eduardo Pérez (Universidad de Málaga). We are indebted to Leticia Viesca who inspired the naming of the *Storm* eddy sampled in this survey. Comments by two anonymous referees improved an earlier version of the manuscript. The altimeter studies were supported with ESA A02 UK 121 and ENVISAT UK Grant A03 158. The authors would like to acknowledge the SHM/CMO (Service Hydrographique et Oceanograpique de la Marine/Centre Militaire d'Oceanographie) for giving its authorization to use and publish the QG model results from the SOPRANE system in a scientific framework. This work has been done by CLS under contract (number 98.87.064.00.470.29.25) with SHOM/CMO. B. Mouriño was supported by a PFPU fellowship from the Ministerio de Educación y Cultura (Spain). This study was funded by the European Commission under the CANIGO contract MAS3CT960060 and CICYT.

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