Distribution and transport of organic matter along a filament - eddy system
in the Canaries - NW Africa coastal transition zone region.

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Abstract

The distribution and transport of chlorophyll *a* (Chl*a*), particulate (POC) and dissolved (DOC) organic carbon, and the respiratory ETS activity of the microplankton community were studied along a filament-eddy system located in the transition zone between the NW Africa upwelling and Canary Islands waters. Two independent filaments (F1 and F2) stemming from the coastal jet, between Cape Juby and Cape Bojador, merged about 100 km offshore, turning southward and onshore forced by the circulation of a recurrent oceanic cyclonic eddy. In general, the coastal upwelling waters presented higher Chl*a*, but lower POC, DOC and ETS activity than filament waters. However, differences in organic carbon distribution and respiratory activity were observed among stations from the two filaments. The bio-chemical fields were strongly influenced by a complex sub-mesoscale hydrography resulting from the interaction of cyclonic and anticyclonic island eddies with the filaments. The combined F1+F2 filament system transported 97.1 kg s^{-1} of excess (non-refractory) total organic carbon (e-TOC), a value comparable to other published estimates from upwelling filaments in the NE Atlantic. About 90% of e-TOC was exported as DOC, since eddy re-circulation precluded the offshore transport of POC. Assuming that the calculated transport of e-TOC is representative of the annual average, the yearly offshore transport ($3.1 \times 10^9 \text{ kg C}$) would represent about 25% of the upwelling primary production of the region of study.

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1. Introduction

Coastal filaments are typical features associated with eastern boundary regions. They are near-surface structures, tens of kilometers in width, which may extend up to several hundred kilometres in length, connecting the coastal upwelling with the open sea (Tragana, Nestor & McDonald, 1980; Flament, Armi & Washburn, 1985; Kosro, Huyer, Ramp, Smith, Chavez, Cowles et al., 1991). Several studies have shown that upwelling filaments may play a key role in the transport of nutrients (Jones, Mooers, Rienecker, Stanton & Washburn, 1991), chlorophyll (Arístegui, Hernández-Guerra, Basterretxea, Montero, Wild, Sangrà et al., 1997; Basterretxea & Arístegui, 2000), zooplankton (Hernández-León, Portillo-Hahnefeld, Gómez, Rodríguez & Arístegui, 2002) and fish larvae (Rodríguez, Hernández-León & Barton, 2000) to the open ocean. In particular, it has been suggested that a large fraction of primary production generated

in the eutrophic coastal upwelling regions could be advected into the oligotrophic waters of the open ocean fuelling microbial respiration and affecting the metabolic balance of surface plankton communities (Álvarez-Salgado, Doval, Borges, Joint, Frankignoulle, Woodward & Figueiras, 2001; García-Muñoz, Pelegrí, Antoranz, Ojeda & Torres, 2004). This organic carbon would be transported either in particulate or dissolved form, depending on several factors, which affect the remineralization processes taking place during the offshore transport of the source water.

Although filaments are ubiquitous features in all upwelling regions, they are particularly abundant in the Canary Current region, because the strong eddy field south of the Canary Archipelago induces the development of numerous filaments when island-induced eddies interact with the offshore boundary of the coastal jet (Aristegui et al., 1997; Barton, Aristegui, Tett, Cantón, García-Braun, Hernández-León et al., 1998). Indeed, Kostianoy & Zatsepin (1996) observed up to 60 intermittent filaments in this region, along 1000 km of coastline, most of the filaments persisting all year round. Field data and satellite images of surface temperature and ocean colour suggest that these filaments may either re-circulate water back to the coastal jet, or exchange cold and high-chlorophyll water with open ocean eddies. The eddy-filament interactions, therefore, must be critical in determining the potential role of filaments in the transport of organic matter to the open ocean.

We present results here from a study carried out in a filament-eddy system between C. Juby and C. Bojador (NW Africa) during the second leg of the FAX'98 cruise (Barton, Aristegui, Tett & Navarro-Pérez, 2004). Two filaments, stemming from the coastal jet, merged about 100 km offshore and turned southward around the counter clockwise circulation of a recurrent cyclonic eddy in the trough between the African coast and the eastern islands (Barton et al., 1998; Navarro-Pérez & Barton, 1998). We have analyzed the vertical and horizontal distribution of the organic matter and microplankton respiratory activity along selected sections. We show that, superimposed on the coastal-open ocean gradients in these properties, a complex sub-mesoscale distribution is evident that results from eddy-filament interactions. We calculate the organic carbon transport along the two filaments, compare it with other published studies from the NE

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Atlantic, and discuss the potential role of filaments in the transport of excess particulate and dissolved organic carbon to the open ocean.

2. Material and methods

2.1. Sampling and hydrographic measurements

The FAX'99 cruise was conducted on board the BIO *Hespérides* from 6 to 26 August, 1999. Sea Surface Temperature (SST) images, derived from High Resolution Picture Transmission (HRPT) data, obtained in real time on board the ship, were used to select the survey grid. Sampling for this study was carried out during the second half of the cruise (from 13 to 26 August 1999).

A long hydrographic section (L) sampled the waters downstream of the Canaries Archipelago, and 8 shorter sections (lines 1 to 8) crossed several mesoscale features. Only the eastern sector of L and 6 of the 8 shorter lines (2, 4-8) were sampled for biology (Fig. 1a,b). Sections and mesoscale structures (eddies and filaments) were named as in Barton et al. (2004). Spacing between stations ranged from 2-5 km in the shorter sections to 20 km in L. At each station, conductivity, temperature and depth (CTD) were acquired down to 200 m with a SeaBird 9-11+ CTD, connected to Sea-Tech fluorometer and transmissometer systems, and mounted on a 24-bottle General Oceanics rosette sampler, equipped with 12 L Niskin bottles. Water samples for dissolved organic carbon (DOC), particulate organic carbon (POC), Chlorophyll *a* (Chl*a*), and microbial respiratory electron transport system (ETS) activity were collected from up to nine depths (5 to 200 m).

2.2. Geostrophic velocities and horizontal transport calculation

Horizontal advective fluxes across selected sections were estimated from geostrophic velocities obtained from density fields (see Barton et al., 2004 for the methodology). The velocity fields and the transported biological properties were interpolated onto a uniform grid overlying the sampling domain. The flux of each property was calculated

at each grid point as the product of the variable concentration and the estimated velocity. Net transport through filament cross-sections was calculated by integrating the flux over the filament sections down to both 100 and 200 m depth.

2.3. *Chlorophyll a*

Chlorophyll *a* (Chl*a*) was measured fluorimetrically with a Turner Designs bench fluorometer, previously calibrated with pure chlorophyll *a* (Sigma Co.; Holm-Hansen, Lorenzen, Holmes & Strickland, 1965). Samples of 500 ml of seawater were filtered through Whatman GF/F filters and preserved in liquid nitrogen until analysis. Pigments were extracted in cold acetone (90%) for 24 hours. For the final determination of Chl*a*, the acetone extracts were acidified, allowing chlorophyll and phaeopigments to be independently estimated.

2.4. *Particulate and dissolved organic carbon*

Samples for particulate organic carbon (POC) were collected in 1.5 liter polypropylene bottles and filtered at several depths onto pre-combusted (450°C, 5 hours) 25 mm Whatman GF/F filters. The filters were wrapped in pre-combusted aluminum foil and frozen at –20°C until processed. In the laboratory, the filters were thawed and dried overnight at 65°C, placed overnight in a desiccator saturated with HCl fumes, dried again at 65°C and packed in pre-combusted nickel sleeves. The carbon analyses were done on a Perkin Elmer-2400 CHN elemental analyzer (UNESCO, 1994)

Water for the analysis of total organic carbon (TOC) was dispensed directly from Niskin bottles into clean 10 ml glass ampoules (500°C, 12 hours). The samples were immediately acidified with 50 µl of 50% H₃PO₄ and stored at 2-4°C until analyzed (Sharp & Peltzer, 1993). TOC concentrations were measured using a Shimadzu TOC-5000 analyzer. At the beginning of each analysis run, the samples were sparged with CO₂ – free air for seven minutes to remove the inorganic carbon. The sample was then injected (three replicate injections of 100 µl) into a quartz tube with a platinum catalyst, and combusted at 680°C. TOC concentrations were determined from standard curves

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(30 to 200 $\mu\text{M C}$) of potassium hydrogen phthalate produced every day. TOC reference material prepared in the laboratory of Jonathan H. Sharp (University of Delaware) was analyzed every day to check the accuracy and precision of our instrument. We obtained an average concentration of $44.5 \pm 2.7 \mu\text{M C}$ ($n=31$) for the Deep Ocean reference material (Sargasso Sea deep water, 2600 m) and $0.21 \pm 0.53 \mu\text{M C}$ ($n=31$) for the Blank reference material, whose nominal values were $44.0 \pm 2.7 \mu\text{M C}$ and $0.0 \pm 1.5 \mu\text{M C}$ respectively. The dissolved organic carbon (DOC) was finally computed by subtracting POC from TOC.

2.5. ETS measurements

Depending on depth, 5 to 20 l of seawater were pre-filtered through a 200 μm mesh and poured into acid cleaned plastic carboys, before being filtered through 47 mm Whatman GF/F filters, at a low vacuum pressure ($<0.3 \text{ atm}$). The filters were immediately stored in liquid nitrogen until assayed in the laboratory (within a few weeks). ETS determinations were carried out according to the Kenner & Ahmed (1975) modification of the tetrazolium reduction technique proposed by Packard (1971) as described in Aristegui & Montero (1995). An incubation time of 20 min at 18°C was used. ETS activities measured at 18°C were converted to activities at *in situ* temperatures by using the Arrhenius equation. A mean activation energy of $16 \text{ kcal mole}^{-1}$ was used (Aristegui & Montero, 1995).

3. Results

3.1. Regional oceanographic setting

The waters downstream of the Canaries Archipelago presented a complex mesoscale hydrographic pattern during our study. SST images revealed the presence of 14 cyclonic and anticyclonic eddies as well as 4 upwelling filaments (Barton et al., 2004). The hydrographic conditions during the cruise coincided with an upwelling favourable period, although winds were weaker ($< 15 \text{ m s}^{-1}$) than in studies in the same season of previous years (Barton et al., 1998; Barton, Basterretxea, Flament, Mitchelson-Jacob,

Jones, Aristegui & Felix, 2000; Basterretxea, Barton, Tett, Sangrá, Navarro-Pérez & Aristegui, 2002). Figures 1a and b show the sampled sections superimposed on SST images; part of the eddy field, including two filaments and several eddies, is depicted.

The situation at the start of the cruise (6 August) was dominated by a large upwelling filament (F1) extending offshore from the NW African coast, between C. Juby and C. Bojador. At 15°W the filament turned southwest and subsequently shoreward around the recurrent cyclonic eddy (C7) locked on the trough between the African shelf and the eastern islands (Fig. 1a). About 10 days later (17 August; Fig. 1b), satellite images showed the development of a new upwelling filament (F2) originating north of C. Juby. Filaments F1 and F2 merged about 100 km offshore (15.1°W) and a large part of the joint flow re-circulated shoreward around C7. However, some of the water seemed to be partly entrained by an anticyclonic eddy (A6) developing south of Gran Canaria Island at the end of the cruise. North of F2, another anticyclonic eddy (A7) was located south of Fuerteventura Island, while two more counter-rotating eddies evolved between the two filaments: cyclonic eddy C8 and anticyclonic eddy A8, situated south of F2 and north of F1.

3.2. *Filament cross-sections*

Filaments F1 and F2 were shallow features (thickness 100-200 m) extending more than 150 km to the open ocean. Hence, vertical profiles were carried out down to 200m to study biological properties in the filament structure. In particular, we sampled seven vertical sections, crossing the two filaments at different positions. The first sampled section (L; Fig. 1a) extended zonally from the south of Gran Canaria (16°W) to the African coast (13.4°W). The other six sections were sampled sequentially from onshore to offshore (Fig 1b).

Section L (Fig. 1a) intersected filament F1 offshore near 27.3°N and 15.5°W in the return flow, crossed eddy C7 near its northern margin, and crossed F1 again near its root at 27.5°N, 14°W, before extending shoreward to the African shelf (Fig.2). The surface coastal upwelled waters (<19° C) presented the highest values in particulate organic

carbon (POC $>12 \mu\text{M}$), chlorophyll a (Chla $>3 \text{ mg m}^{-3}$), and respiratory activity (ETS $>3.5 \text{ mlO}_2 \text{ m}^{-3} \text{ h}^{-1}$), but among the lowest dissolved organic carbon concentrations (DOC $<80 \mu\text{M}$; Fig. 2). The surface signal of filament F1 was neatly traced (Fig. 2) by high POC concentrations ($>10 \mu\text{M}$) and low salinity values (<36.3 ; Barton et al., 2004) even in the return flow. Eddy C7 presented, in contrast, lower surface POC values, but relatively high Chla, suggesting that the doming effect of C7 enhanced primary production but did not favour the accumulation of POC in its core. DOC showed a patchy distribution, with the highest values in the margins between C7 and F1 affecting the water column to 200 m. Both Chla and ETS showed a decreasing offshore gradient, with the highest values in surface shelf waters. However, whereas the Chla maximum deepened offshore, the ETS maxima always remained in the upper 25m, indicating that microbial respiration was higher near the surface. Water in the 25-75m layer over the African shelf, presented some of the lowest values of ETS activity, coinciding with low DOC water.

Section 2 crossed the recently developed filament F2 (Fig.1b), which was identifiable by a slight uplift of temperature contours at $27.7\text{-}27.75^\circ\text{N}$ (Fig. 3). Subsurface maxima in Chla ($\sim 0.5 \text{ mg m}^{-3}$) and DOC ($105 \mu\text{M}$) were observed in the northern part of the filament, whereas subsurface maxima in POC ($>12 \mu\text{M}$) and ETS ($>1.5 \text{ mlO}_2 \text{ m}^{-3} \text{ h}^{-1}$) were identified at its southern boundary. Satellite images (Fig. 1b) show a small cyclonic eddy (C8), which Barton et al. (2004) found was re-circulating some of the F2 water south of section 2 back to the coast, and which may explain the higher POC concentrations and ETS activities in the southern sector of the filament.

Section 4, from C. Juby to Fuerteventura Island, intersected filament F2 and eddy A7 (Fig. 1b). Near the African coast, temperature contours upwelled to the surface, while at $13.8\text{-}14.2^\circ\text{W}$ isotherms deepened as result of convergence in the anticyclonic rotation of eddy A7 (Fig. 4). The African shelf waters presented the highest values in Chla ($\sim 4 \text{ mg m}^{-3}$), DOC ($>110 \mu\text{M}$), POC ($>8 \mu\text{M}$), and ETS ($\sim 9 \text{ mlO}_2 \text{ m}^{-3} \text{ h}^{-1}$). Filament F2 presented comparatively lower DOC, POC and ETS values than shelf waters, but relatively high Chla concentrations ($>2 \text{ mg m}^{-3}$), suggesting advection of water upwelled from an origin other than that of the shelf stations of this study. The boundary

region between A7 and F2 presented a clear signal of DOC accumulation down to 125 m, while relatively high ETS activity was observed in the core of A7 down to 150 m.

Section 5 extended southwestward from the northern position of section 2, crossing filaments F1 and F2 at 27.5°N and 27.7°N, respectively (Fig. 1b). According to Barton et al. (2004) filament F2 had weakened compared with a week before. Indeed, surface outcropping of isotherms was only apparent along filament F1, although the subsurface Chl a maxima ($>1 \text{ mg m}^{-3}$) were comparable in both filaments (Fig.5). Interestingly, F2 presented higher concentrations of POC than F1, whereas both filaments had surface maxima in DOC and ETS (Fig.5). This contrasting pattern (similar Chl a , but higher POC in F2) may be explained, as in section 2, by water re-circulation associated with eddy C8.

Section 6 ran northward to the southwest of Fuerteventura, intersecting F1 and F2 (Fig. 1b), which almost merged at 27.6-27.7°N (Fig. 6). F1 was evident at 27.6°N as a shallow breaking of surface isotherms. However, the geostrophic velocity maps (see Barton et al., 2004) show the offshore flow at a more southerly position. The discrepancy is probably due to weaker winds at section 6 and small scale eddying forcing re-circulation of water, as observed in the SST image of 17 August (Fig. 1b). Sub-surface maxima of Chl a observed at 27.7°N coincided with a strong offshore geostrophic flow, which was indicative of the presence of filament F2. At the northernmost position of the line, deeper POC, DOC and Chl a maxima coincided with a deepening of isotherms toward eddy A7. The highest integrated values of POC, DOC and ETS activity were found at stations south of F1, where filament water was forced to re-circulate by eddy C7 (see Fig. 1b)

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Section 7 ran parallel to line 6 about 50 km offshore, where satellite images from previous days showed F1 turning southward (Fig. 1a,b). However, continued weak winds and the increased distance offshore impeded the surface manifestation of both filaments during the time of sampling (Fig.7). Evidence of offshore geostrophic flow (Barton et al., 2004), coinciding with a subsurface maximum in Chl a , seemed to place the position of filament F2 at 27.8°N (Fig.7), while filament F1 would have been

located at a more southern position (27.65°N), out of the range of our sampling. POC and ETS showed values as high as at stations nearer to shore, but more homogeneously distributed in the 25-50 m depth layer.

Section 8 extended southwest to about 16°W, from the southernmost position of section 6 (Fig. 1b). The section crossed the southward path of the combined filaments (F1 + F2) between eddy A6, which had developed in the immediately previous days, and cyclone C7. The boundary between filament and anticyclone waters (27.55°N; Fig. 8) was marked by a strong increase in temperature, a decrease and deepening of the Chl a maximum, and an increase in water-column integrated POC; however, ETS showed no clear gradient (Fig. 8). The irregular vertical distribution of Chl a and POC at the eddy-filament boundary (27.55°N) could reflect entrainment of filament waters by eddy A6, as observed a few days later in SST satellite images.

3.3. Transport of organic matter and Chl a

The integrated (0-100 m, or down to the bottom at shallower stations) concentrations of Chl a , POC and DOC, and respiratory ETS activity are summarized in Table 1 for selected stations from the coastal upwelling and filament waters (Fig. 1b). In general, the coastal waters presented higher Chl a and lower POC and DOC values than filament waters, although differences were observed between the two filaments. In particular, F1 presented less POC than F2. The combined filament (F1+F2, Table 1) was characterized by lower POC and ETS activity than F1 and F2 before merging, but still presented high ETS and Chl a , suggesting that considerable non-refractory carbon was still transported by the filament along its offshore margin.

The net seaward transport of Chl a , POC and DOC by F1 and F2 was calculated across those sections oriented perpendicular to the filaments: section 4 for F2, section 5 for F1, and section 6 for F2 and F1. The fluxes were integrated down to both 200 m, the vertical extension of the filaments, and 100m, with the aim of comparing with other published studies (Álvarez-Salgado et al., 2001; García-Muñoz et al., 2004; Table 2). F2 at line 4 was about 3 times wider than F1 at line 5, and transported about 2 times more

Chl*a* and POC and 4 times more DOC than F1. At line 6, F2 was about 4 times wider than F1, and transported 4 times more Chl*a* and DOC, and 3 times more POC than the latter (Table 2). All this indicates that, during the time of the study, F2 contributed more than F1 to the offshore export of organic matter.

The transport of “excess total organic carbon” (e-TOC; i.e. the non-refractory organic carbon exported from the coast) was calculated for the upper 100 m at section 6 for filaments F1 and F2. The e-TOC (= e-POC + e-DOC) was computed by subtracting the average POC and DOC concentrations in filament waters (0-100 m) from the lowest concentrations of POC (1.7 mmol m^{-3}) and DOC (60 mmol m^{-3}) measured from the source upwelling waters, assumed to be mostly refractory carbon. The total flux of e-TOC in F1 + F2 at line 6 (97.1 kg s^{-1}) was obtained by multiplying the offshore geostrophic velocities by the e-TOC concentration at each depth in the filament cross-sections, and by the surface extension of the two filaments down to 100 m (1.9 km^2). To put this into a global context, with the aim of comparing with other published studies, the calculated flux can be expressed as $3.1 \times 10^9 \text{ kg C yr}^{-1}$, of which about 90% (90% for F1 and 92% for F2) was exported in dissolved form (Table 3).

4. Discussion

In some previous studies of this filament-eddy system (e.g. Arístegui et al., 1997; Barton et al., 1998), a single filament stretched from the African coast, between C. Juby and C. Bojador, towards the south of Gran Canaria. In others, (e.g. Barton et al., 2000; this study), two independent filaments (one closer to C. Juby and the other closer to C. Bojador) stemmed from the coastal jet, eventually merging into a single structure. The observed variability in the number of filaments and their structure is due to the interplay of the coastal jet with oceanic eddies formed downstream of the islands. The most permanent filament is the one found near C. Bojador (F1). It develops when the offshore boundary of the coastal upwelling interacts with a permanent cyclonic eddy (C7) locked in the trough between the African shelf and the islands (Barton et al., 1998). As has been observed previously (Basterretxea & Arístegui, 2000) and in our study, satellite images and field data indicate a large amount of filament water, with

relatively high chlorophyll content, may re-circulate back to the shelf, forced by the cyclonic rotation of eddy C7. A second filament, closer to C. Juby (F2), may at times develop due to entrainment of coastal upwelling water by an anticyclonic eddy spun up in the lee of Fuerteventura Island (A7), as observed during our cruise. This filament is less permanent than the C. Bojador one, since eddy A7 is intermittent. Yet, it may reinforce the offshore flux of organic matter to the Canary region. Indeed, ocean-colour images from different years and seasons show that both the C. Juby and C. Bojador filaments may transport high-chlorophyll waters from the coastal upwelling to the eastern Canary region (Aristegui et al., 1997; Pacheco & Hernández-Guerra, 1999).

Our study illustrates differences in the nature of organic matter transported by the two filaments, which may result from temporal changes in the intensity of the filament and the re-circulation processes along the filament structure. These differences are evident along lines 5 and 6 that crossed both filaments: F1 transported less POC and DOC than F2, but comparable amounts of Chl a , during the study. The counter-rotating eddies (A7 and C8) on either side of F2 and the high concentrations of organic carbon observed along the first section of the filament suggest that water entrainment due to re-circulation processes must be important. This is supported by the trajectories of three Argos drifters deployed south of F2, which performed several loops around C8 before being advected out of the eddy (Barton et al., 2004). Re-circulation would also affect F1 although to a lesser extent. Accordingly, most of the organic carbon was transported in dissolved form along the two filaments, favouring the development of microbial heterotrophic communities (Aristegui et al., 2004).

In a previous study, Basterretxea & Aristegui (2000) observed that the percentage of Chl a of size >2 μ dropped from ~80% in coastal waters to ~20% in offshore waters, reflecting a sharp change in the phytoplankton community structure, from a diatom – dominated community in the upwelling to a cyanobacteria-dominated community in offshore waters. Aristegui et al. (2004) observed a similar pattern of phytoplankton variability along F1 with an offshore shift from large to small phytoplankton cells, leading to a decreasing offshore gradient in autotrophic biomass. The smaller size structure of the phytoplankton community, dominated by pico- and nano-planktonic

autotrophic and heterotrophic cells, would favour the excretion and re-mineralization of dissolved organic carbon. Interestingly, no offshore gradient in the distribution of DOC was present, but rather DOC accumulated in the middle sections of the filaments. A detailed inspection of DOC distribution across filament sections shows that DOC concentrates in convergence zones, as in eddy-filament fronts (e.g. sections L and 4; Figs. 2, 4).

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The numerous eddies spun off from the islands have two important consequences for the coastal-open ocean transport of organic matter, which make this area unique amongst eastern boundary regions. First, eddies interact with the offshore extension of the coastal jet inducing the development of filaments. Second, eddies exchange water with filaments and with other eddies, either enhancing transport of organic matter offshore or re-circulating the organic matter back to the coastal upwelling. Indeed, Barton et al., 2004 reported that the three Lagrangian drifters deployed south of F2, provided robust evidence of coastal-offshore exchange of water. In particular, one of the drifters crossed the eddy field south of the Canary archipelago, following an overall westward trajectory by describing cyclonic loops until it left the influence of the islands. The secondary circulation of water forced by eddy rotation would in any case slow the offshore transport of organic matter and enhance re-mineralization processes. Our data show that most of the organic matter is transported in the dissolved form and that organic matter is accumulated mainly in the first half of the filament structure, because of effects from eddy circulation. In particular, the dipole C8-A8 eddy located between F1 and F2, re-circulated water back to the root of the filament over several weeks (Barton et al., 2004). Furthermore, eddy A7 in the lee of Fuerteventura, and the large and recurrent C7, contributed to re-circulation of water onshore from the two filaments, decreasing the coastal-ocean transport of particulate and dissolved material. The re-circulation of organic matter by all these eddies supports the high respiratory ETS activities, observed in the offshore portion of the filament (about twice the average value in the open ocean; Arístegui et al., 2003).

On the other hand, satellite images of ocean colour (van Camp, Nykjaer, Mittelstaedt & Schlittenhardt, 1991; Hernández-Guerra, Arístegui, Cantón & Nykjaer, 1993; Arístegui

et al., 1997) show that the C. Juby-C. Bojador eddy system may at times export large amounts of organic matter to the south of Gran Canaria. This suggests that re-circulation of filament water by eddies south of Fuerteventura, as occurred during our study, is not always the flow pattern. Cyclonic and anticyclonic eddies generated south of Gran Canaria may entrain high-chlorophyll water from filaments, enriching the western waters of the archipelago (Aristegui et al., 1997). Indeed, at the end of our cruise, there was strong evidence of entrainment of F1+F2 water by the anticyclone A6.

Most of the exchange of organic matter apparently would be in dissolved form.

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However, the frontal structure between filament and eddy waters presented integrated Chla values similar to F1 and F2 before merging (Table 1). Arístegui et al. (2004) observed that net community production was relatively high at this frontal region, presumably due to the shearing effect on the filament by the flank of the island.

Compared with other two-filament systems studied in the Northeast Atlantic (NW Iberia, Álvarez-Salgado et al., 2001; Cape Guir, García-Muñoz et al., 2004), the C. Juby-C. Bojador system presented stronger offshore flows (Barton et al., 2004). Hence, although the combined F1 + F2 cross-section at line 6 was about half as wide as the filament cross-sections in the other case studies, the overall annual transport of excess TOC (e-TOC) was higher than off NW Iberia and similar to the much wider C. Guir filament (Table 3). The NW Iberia filament was studied following a strong upwelling event, and about 50% of the e-TOC was exported as POC (Álvarez-Salgado et al., 2001; Table 3). The C. Guir filament was surveyed during a period of weak wind ($<2 \text{ m s}^{-1}$), unfavourable for upwelling, and most ($\sim 90\%$) of the e-TOC was exported as DOC (García-Muñoz et al., 2004; Table 3). In our study the winds, although rather variable ($5\text{-}15 \text{ m s}^{-1}$) and weaker than in other summer surveys, were upwelling-favourable, and the filaments extended offshore as in previous occasions. About 90% of e-TOC was exported as DOC (Table 3), since, as discussed above, eddy re-circulation decreased the offshore transport of POC.

In summary, the recurrence of the C. Juby-C. Bojador eddy-filament system, favoured by the presence of eddy C7 and island eddies spun up downstream of the eastern islands, contributes significantly to the transport of organic matter from the African

shelf to the Canary region. Assuming an average primary production of $2 \text{ g C m}^{-2} \text{ d}^{-1}$ (Longhurst, Sathyendranath, Platt & Caverhill, 1995; Pelegrí, Aristegui, Cana, González, Hernández-Guerra, Hernández-León et al., 2003) for the upwelling region between C. Juby and C. Bojador ($250 \text{ km length} \times 60 \text{ km width} = 15000 \text{ km}^2$), the total annual primary production for the studied region would be $11 \times 10^9 \text{ kg C}$. If we consider that the transport of e-TOC at section 6 (97.1 kg s^{-1}) is representative of an annual average, the yearly e-TOC offshore transport ($3.1 \times 10^9 \text{ kg C}$) would represent 28% of the primary production in the upwelling region. Nevertheless, the actual transport of organic matter to open ocean waters will depend both on the strength and persistence of the filament system, and the degree of re-circulation of water in the associated eddies. Paradoxically, eddy interactions may play a dual role, either increasing water and organic matter exchange by inducing filament generation, or decreasing the transport of labile organic matter by eddy re-circulation. Hence determining the nature and degree of these interactions is critical to quantifying the role of the filaments in their offshore transport of organic matter

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Table 1. Mean ($\pm$ SD) temperature (T, $^{\circ}$ C) and salinity (S), and integrated (0-47 m for station A, 0-35 m for B, and 0-100 m for C, D and E) values of dissolved organic carbon (DOC, mmol m^{-2}), particulate organic carbon (POC, mmol m^{-2}), chlorophyll *a* (Chl *a*, mg m^{-2}), and microplankton respiratory activity (ETS, $\text{mmol O}_2 \text{ m}^{-2} \text{ d}^{-1}$), for selected stations along coastal upwelling and filament waters (see Fig1 for positions).

n.d. = not determined

Eliminado: n

	Coastal		F1	F2	F1 + F2
	A	B	C	D	E
T	16.8 $\pm$ 1.1	17.2 $\pm$ 0.7	18.8 $\pm$ 1.7	19.3 $\pm$ 1.7	20.0 $\pm$ 2.4
S	36.25 $\pm$ 0.06	36.26 $\pm$ 0.05	36.40 $\pm$ 0.05	36.50 $\pm$ 0.10	36.49 $\pm$ 0.05
DOC	3286	3300	9389	8354	n.d
POC	338	451	634	899	574
Chl <i>a</i>	156	135	55	45	42
ETS	120	163	116	94	80

Table 2. Offshore transport (in Kg s⁻¹) of dissolved organic carbon (DOC), particulate organic carbon (POC) and chlorophyll *a* (Chl *a*), by filaments F1 and F2 across selected sections (see text for details). Depth = integration depth range (in m);

Extension = filament extension (in km) across sections. n.d. = not determined

Eliminado: K
Eliminado: n

	Section 4		Section 5		Section 6			
	F2		F1		F1		F2	
Extension	27.3		10.2		3.8		15.0	
Depth	100	200	100	200	100	200	100	200
DOC	714	826	116	204	88	136	344	506
POC	18.8	33.8	7.7	15.5	10.4	n.d.	28.8	n.d.
Chl <i>a</i>	0.28	0.46	0.16	0.17	0.05	0.05	0.17	0.21

Table 3. Comparison of estimated annual offshore transport of “excess total organic carbon” (e-TOC, in Kg yr^{-1}) by filaments F1 + F2 (computed at line 6), with other published studies from filaments in the NE Atlantic upwelling (see text for details). The filament cross-section area (in km^2) corresponded to a 100 m water column in the Cape Guir and Capes Juby/Bojador filaments, and to a 50 m water column in the NW Iberia filament. The e-TOC export was computed for 365 days/year for the C. Guir and C.s Juby/Bojador filaments, since these are recurrent features, but only for 150 days/year in NW Iberia system, corresponding to the upwelling period in this region.

	NW Iberia ¹	Cape Guir ²	Capes Juby-Bojador ³
Filament cross-section area	1.6	4.5	1.9
e-TOC export	3.5×10^8	3.1×10^9	3.1×10^9
% DOC export	50	90	90

¹Álvarez-Salgado et al. 2001

²García-Muñoz et al. 2004

³This study

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Figure 1.- (a) Station positions along section L superimposed on a sea-surface AVHRR temperature image of 7 August 1999. (b) Station positions along sections 2, 4-8 superimposed on SST image of 17 August 1999. F1, F2 = upwelling filaments; C7, C8 = cyclonic eddies; A6, A7 = anticyclonic eddies.

Figure 2.- Vertical plots of temperature (T , °C), chlorophyll a (Chl a , mg m^{-3}), microplankton respiratory activity (ETS, $\text{ml O}_2 \text{ m}^{-3} \text{ h}^{-1}$), dissolved organic carbon (DOC, μM), and particulate organic carbon (POC, μM), for section L. Black dots: stations. F1 and C7: position of filament 1 and cyclonic eddy C7

Figure 3.- Vertical plots of temperature (T , °C), chlorophyll a (Chl a , mg m^{-3}), microplankton respiratory activity (ETS, $\text{ml O}_2 \text{ m}^{-3} \text{ h}^{-1}$), dissolved organic carbon (DOC, μM), and particulate organic carbon (POC, μM), for section 2. Black dots: stations. F2: position of filament 2

Figure 4.- Vertical plots of temperature (T , °C), chlorophyll a (Chl a , mg m^{-3}), microplankton respiratory activity (ETS, $\text{ml O}_2 \text{ m}^{-3} \text{ h}^{-1}$), dissolved organic carbon (DOC, μM), and particulate organic carbon (POC, μM), for section 4. Black dots: stations. F2 and A7: position of filament 2 and anticyclonic eddy A7

Figure 5.- Vertical plots of temperature (T , °C), chlorophyll a (Chl a , mg m^{-3}), microplankton respiratory activity (ETS, $\text{ml O}_2 \text{ m}^{-3} \text{ h}^{-1}$), dissolved organic carbon (DOC, μM), and particulate organic carbon (POC, μM), for section 5. Black dots: stations. F1 and F2: position of filaments 1 and 2

Figure 6.- Vertical plots of temperature (T , °C), chlorophyll a (Chl a , mg m^{-3}), microplankton respiratory activity (ETS, $\text{ml O}_2 \text{ m}^{-3} \text{ h}^{-1}$), dissolved organic carbon (DOC, μM), and particulate organic carbon (POC, μM), for section 6. Black dots: stations. Black dots: stations. F1 and F2: position of filaments 1 and 2

Figure 7.- Vertical plots of temperature (T , °C), chlorophyll a (Chl a , mg m^{-3}), microplankton respiratory activity (ETS, $\text{ml O}_2 \text{ m}^{-3} \text{ h}^{-1}$), and particulate organic carbon (POC, μM), for section 7. Black dots: stations. F2: position of filament 2

Figure 8.- Vertical plots of temperature (T , °C), chlorophyll a (Chl a , mg m^{-3}), microplankton respiratory activity (ETS, $\text{ml O}_2 \text{ m}^{-3} \text{ h}^{-1}$), and particulate organic carbon (POC, μM), for section 8. Black dots: stations. F1 +F2: position of the merged filament