Limnol. Oceanogr., 52(3), 2007, 1287–1292

Contribution of upwelling filaments to offshore carbon export in the subtropical Northeast Atlantic Ocean

Abstract—Revisiting previously published data we show that upwelling filaments off Iberia and NW Africa export to the offshore system, largely as dissolved organic matter (DOM), from 35% to 58% of the net community production generated in the coastal upwelling systems. Transport by filaments accounts for 2.5 to 4.5 times the offshore carbon export driven by Ekman transport. The fate of this carbon is unknown, although conservative mass balance analysis in the subtropical Northeast Atlantic region suggests that <16% of the exported carbon may be respired in the coastal transition zone (CTZ). Thus, DOM exported by the filaments cannot fully account for the previously reported metabolic imbalance (i.e., net heterotrophy) of the surface waters of the CTZ. The remainder of exported organic matter is transported to and accumulated in the subtropical gyre, where high surface DOM concentrations have been reported. Since filaments are ubiquitous features in all coastal transition zone systems, they must represent a significant flux of carbon to the open ocean, which should be considered in global biogeochemical models.

Since the pioneering work of Flament et al. (1985), who first described the physical structure of an upwelling filament, marine biogeochemists have been concerned about the role played by these mesoscale structures in the exchange of materials between the productive shelf waters of coastal upwelling systems and the adjacent oligotrophic ocean. Ambitious coastal transition zone (CTZ) programs devoted to the study of upwelling filaments have been conducted off California (Brink and Cowles 1991), NW Africa (Barton et al. 1998), and Spain (Joint and Wassmann 2001). The significance of upwelling filaments in the seaward transport of chlorophyll and suspended particulate organic matter (POM) was demonstrated in the past using satellite-based estimates (Gabric et al. 1993) and modeling approaches (Gabric et al. 1996). However, the relevance of dissolved organic matter (DOM) transported by upwelling filaments was not considered until the work of Álvarez-Salgado et al. (2001). They found that the dissolved organic carbon excess (ΔDOC; in excess of DOC concentrations in the subsurface waters prior to upwelling) accumulated in surface waters of the NW Iberian continental shelf (42°–43°N) was equivalent to the suspended particulate organic carbon excess (ΔPOC) and that these excesses together represented 35% of the carbon net community production (NCP) during an upwelling event in August 1998. More recently, studies conducted in the Cape Guir (30°–31°N) and Cape Juby–Cape Bojador (26°–28°N) filaments off NW Africa indicated that ΔDOC in coastal surface waters represented ~90% of the organic matter exported to the adjacent ocean during a period of upwelling relaxation in September–October 1997 (García-Muñoz et al. 2005) and an intense upwelling period in August 1999 (García-Muñoz et al. 2004). Apart from these three studies on the eastern boundary of the North Atlantic, few studies have been conducted in coastal upwelling systems since the DOC measurement protocol was solved. Exceptions are the U.S. Joint Global Ocean Flux Study (JGOFS) program in the Oman coast of the northern Arabian Sea (18°–22°N; Hansell and Peltzer 1998) and the U.S. Global Ocean Ecosystem Dynamics (GLOBEC) program off the Oregon and Washington coast of North America (43°–47°N; Hill and Wheeler 2002), although these did not address the export of organic matter by upwelling filaments. The objective of this work is to demonstrate, using previously published data, that the hitherto unquantified off-shelf export of DOM through coastal upwelling filaments is an important flux to be included in carbon budgets of the global ocean.

Mass balance estimates—Quantifying the horizontal export of primary and net community production in the coastal upwelling system of Iberia–NW Africa to the adjacent oligotrophic ocean first requires assessment of ΔDOC, ΔPOC, and the inorganic carbon deficit (ΔC_T) in shelf-break surface waters by subtracting the DOC, POC, and C_T concentrations of the source upwelled water (average 100 to 200 m depth) from the DOC, POC, and C_T concentrations of the surface mixed layer, both at the shelf break. Assuming steady-state conditions, $-(\Delta DOC + \Delta POC)/\Delta C_T$ provides an estimate of the fraction of the NCP of the coastal upwelling system that is available for horizontal export by the filament.

Data for NW Iberia were taken from a seasonal study of the hydrographic variability at a fixed station in the base of the recurrent filament of 42°–43°N throughout 1995 (Álvarez-Salgado et al. 1999) and a Lagrangian study following an instrumented buoy along the core of the same filament in August 1998 (Álvarez-Salgado et al. 2001). In the case of the Cape Guir (García-Muñoz et al. 2005) and Cape Juby (García-Muñoz et al. 2004) studies, data were taken from cross-sections performed at the base of both filaments in September–October 1997 and August 1999,

Table 1. Compilation from published dissolved and suspended particulate organic carbon (DOC, POC) and total inorganic nitrogen (N_T) concentrations in upwelled (up; average of 100–200 m depth range) and surface outwelled (out; upper 50 m off Iberia and upper 100 m off NW Africa) waters of the study filaments at the shelf break; DOC and POC excesses (ΔDOC, ΔPOC) and inorganic carbon deficit (ΔC_T) in shelf-break surface waters; percentage of the exported organic material in the dissolved form (ΔDOC/[ΔDOC + ΔPOC]) and percentage of the new production that is exported off shelf ($-[\Delta DOC + \Delta POC]/\Delta C_T$); volume transport (VT) of shelf surface water and organic carbon flux (C flux) exported by the filaments (annual basis); area (A) of the shelf that is exported by each upwelling filament; primary production in that area (PP), and the percentage of PP exported by the filaments (−[ΔDOC + ΔPOC]/PP); filament : Ekman transport ratio (dimensionless).

		NW Iberia	NW Africa	
		42°–43°N	30°–31°N	26°–28°N
Period		Apr–Sep 1995	Sep–Oct 1997	Aug 1999
DOC (μmol L^{-1})	Up	63.0*	51.0†	60.0‡
	Out	78.6*	75.6†	90.0‡
POC (μmol L^{-1})	Up	1.4*	0.8†	1.7‡
	Out	10.1*	2.1†	6.0‡
N_T (μmol L^{-1})	Up	9.5*	10.0†	8.0‡
	Out	0.1*	0.1†	0.1‡
ΔDOC (μmol L^{-1})		15.6	24.6	30
ΔPOC (μmol L^{-1})		8.7	1.3	4.3
ΔC_T (μmol L^{-1})		−70	−74	−59
(ΔDOC)/(ΔDOC+ΔPOC)		64%	95%	87%
$-(\Delta DOC+\Delta POC)/\Delta C_T$		35%	35%	58%
VT (m^3 yr^{-1})		1.4×10^{12}§	9.9×10^{12}†	7.5×10^{12}‡
A (km^2)		3,400	6,660	13,400
C flux	(kg C yr^{-1})	4.1×10^{8}	3.1×10^{9}	3.1×10^{9}
	(g C m^{-2} yr^{-1})	120	460	230
PP (g C m^{-2} y^{-1})		630‖	750¶	750¶
(ΔDOC+ΔPOC)/PP		20%	60%	30%
Filament : Ekman transport ratio		2.5	4.4	2.4

* Álvarez-Salgado et al. (1999).
† García-Muñoz et al. (2005).
‡ García-Muñoz et al. (2004).
§ Álvarez-Salgado et al. (2001).
‖ Arístegui et al. (2006).
¶ Longhurst et al. (1995).

respectively. In all cases, DOC was determined with a Shimadzu TOC-5000 analyzer and POC with a Perkin Elmer 2400 CHN elemental analyzer. For the NW Iberia studies, DOC samples were filtered through precombusted Whatman GF/F filters, whereas in the NW Africa studies they were obtained by subtracting POC from the total organic carbon content of unfiltered samples directly injected in the Shimadzu TOC-5000 analyzer.

C_T data must be corrected for the precipitation/dissolution of calcareous structures and the CO_2 exchange with the atmosphere. Alternatively, the nitrate deficit (ΔNO_3^-) in shelf-break surface waters can be estimated and converted to ΔC_T using an appropriate C : N ratio: $\Delta C_T = (C : N) \times \Delta NO_3^-$. For a system that is not N-limited, C : N = 6.7 mol C mol N^{-1}, the classical Redfield ratio. On the contrary, in N-limited systems an excess carbohydrate production tends to produce higher C : N values. Low nitrate values (<0.1 μmol L^{-1}; Table 1) were recorded in shelf-break surface waters during the filament studies off NW Iberia (Álvarez-Salgado et al. 2001) and NW Africa (García-Muñoz et al. 2004, 2005). Although a C : N value of 8 ± 1 mol C mol N^{-1} was obtained during the filament study of the NW Iberian Peninsula (Álvarez-Salgado et al. 2001), 7.5 ± 1.0 mol C mol N^{-1} is a more appropriate value at the upwelling season timescale (Álvarez-Salgado et al. 1999). Total inorganic nitrogen data (N_T), measured by segmented flow analysis, were taken from the same sources as DOC and POC data.

The optimum solution is to calculate average ΔDOC, ΔPOC, and ΔN_T for the upwelling season. This is possible only for the NW Iberian upwelling system, where a seasonal cycle was sampled during 1995 (Álvarez-Salgado et al. 1999).

Table 1 summarizes the C and N concentrations of the source and exported waters and the calculated C excess/deficits in shelf-break surface waters obtained during the filament studies of NW Iberia (Álvarez-Salgado et al. 1999, 2001) and NW Africa (García-Muñoz et al. 2004, 2005). About 35% to 58% of the NCP of the coastal area is available for export to the adjacent oligotrophic ocean waters. The C and N data from NW Iberia represents the average seasonal cycle that integrates a sequence of upwelling events and, therefore, meets the steady-state condition. On the contrary, the Cape Juby and Cape Guir studies were sampled under strong upwelling (García-Muñoz et al. 2005) and upwelling relaxation (García-Muñoz et al. 2004) and they should be considered as upper and lower bounds of the fraction of the NCP that is available for horizontal export in NW Africa.

About 64% to 95% of the exported material is in the dissolved form. The variable contributions of DOC to the total organic carbon export is likely related to the increased POM sedimentation in the wider shelf off NW Africa, and less to other factors such as sampling under contrasting wind conditions. Although the filaments at Cape Juby and Cape Guir were sampled under contrasting wind conditions, the contribution of DOC to the total carbon export was not significantly different. In the Cape Juby study, high surface DOC concentrations (>80 μmol L^{-1}) were clearly associated with the filament system (see Fig. 5 in García-Muñoz et al. 2005). However, at Cape Guir, recirculation flows associated with the filament favored the presence of high (>80 μmol L^{-1}) surface concentrations of DOC also around the filament stations (see Fig. 4 in García-Muñoz et al. 2004).

Mass transport—For the three filaments studied, the water volume displaced by the upwelling filaments has been calculated on an annual basis. In each case, the offshore velocity observed directly in up to six transects was integrated over the cross-sectional area of the filament to obtain the total volume displaced offshore. For the Cape Juby filament, transects made in three different years during strong upwelling provided similar estimates (Barton et al., 1998, 2004), but off both Cape Guir and Iberia only a single realization was available during relaxations after strong events. Given the annual cycles of strong summer and weak (or absent) winter upwelling in the various locations, it is likely that the Cape Juby cases provide overestimates and the others underestimates of annual volume transports.

The resultant carbon fluxes, obtained by multiplying ΔDOC + ΔPOC by that volume, are 4.1 and 31 × 10^8 kg yr^{-1} C for the Iberian and NW African filaments, respectively (Table 1). The order of magnitude difference between the two regions is caused by the extension and intensity of the upwelling season. Offshore Ekman transport is an order of magnitude larger off NW Africa (Fig. 1) and upwelling occurs throughout the year, whereas off Iberia, upwelling occurs during half of the year (Barton et al. 1998; Joint and Wassmann 2001).

Dividing these carbon fluxes by the area of the shelf that supplies each upwelling filament allows determination of the fraction of the annual primary production that is exported to the adjacent ocean (20% to 60%; Table 1). The remarkable enhancement of the seaward export of coastal waters by the filament off Cape Guir is well known from satellite imagery (Van Camp et al. 1991). Our field data confirm that this filament exports 2–3 times more coastal primary production than the other filaments studied because of its larger dimensions.

Extrapolation of the carbon fluxes obtained at the three study sites to the entire Iberia–NW Africa coastal upwelling system from 15°N to 43°N requires estimating the total water volume displaced by the upwelling filaments. Offshore Ekman transport calculations provide a rough estimation of the volume of upwelled water per kilometer of coast. Therefore, to produce an integrated volume of upwelled water for the Iberia–NW Africa coastal upwelling system, long-term (1969–2004) monthly average Ekman transport values calculated from atmospheric pressure charts by the Pacific Fisheries Environmental Laboratory (web site http://las.pfeg.noaa.gov/) at six locations were used (Fig. 1). Average Ekman transports over the period of upwelling were calculated and transport over the latitude range of the system was integrated. Good fits to the latitudinal variation of mean transport are obtained to calculate the integral (Fig. 1). The total transport calculated was 2.75 Sv, or 0.25 Sv off Iberia and 2.50 Sv off NW Africa. Comparing the offshore Ekman transport (Fig. 1) with the filament transport (Table 1) at the three study sites, we obtain ratios of filament/Ekman transports ranging from 2.5 for 42°–43° N and 26°–28°N to 4.5 for 30°–31°N. Again, the importance of the Cape Guir filament is observed.

Filaments are often formed by the poleward limb of a meander in the alongshore flow that eventually returns the warmed filament water, with its carbon stocks, back to the shelf (Barton et al. 1998). Return flow is ignored for present purposes because the properties of the outflow are irreversibly modified by processes including vertical circulation in the filament, horizontal mixing with the surrounding oligotrophic waters, and sedimentation to the deep layers. So, taking into account the latitudinal differences in ΔDOC + ΔPOC, the offshore Ekman transport and the lower estimate of the filament/Ekman transport, a conservative estimation of the off-shelf carbon flux yields 2.3 × 10^9 kg yr^{-1} C off Iberia and 90 × 10^9 kg yr^{-1} C off NW Africa. Considering the area of influence of the upwelling filaments (2–3° [150–250 km] off Iberia and 3–10° [250–1000 km] off NW Africa [see the shadowed areas in Fig. 1]), these numbers translate to 60 g m^{-2} yr^{-1} C.

Fate of the exported carbon—What is the fate of the organic carbon exported by the filaments? Hydrographic sections across the North Atlantic indicate that DOC accumulates in the center of the subtropical gyre (Hansell 2002). Indeed, the average DOC level in the upper 50 m from 15°N to 30°N along ~25°W (occupation of CLIVAR section A16N in 2003, location indicated in Fig. 1, data available at http://cdiac.ornl.gov/oceans/ndp_085/NDP–085.html) is 70.2 ± 1.7 μmol L^{-1} (Table 2). Because the DOC exported by the upper 50 m of the NW Africa filaments is 82 ± 9 μmol L^{-1} (Table 2), 12 ± 9 μmol L^{-1} could be respired in the CTZ (see shadowed area in Fig. 1), under the assumption that filaments are a primary source of DOC to the upper 50 m of area of the gyre crossed by CLIVAR section A16N and that no DOC losses occur by mixing. A DOC decrease of 12 ± 9 μmol L^{-1} times a transport of 3.1 ± 0.3 Sv by the upper 50 m of the filaments (Table 2) yields a consumption of 14 ± 12 × 10^9 kg yr^{-1} C, i.e., about 16% of the ΔDOC + ΔPOC transported by the filaments off NW Africa.

Alternatively, the DOC exported by the filaments can be incorporated into the southward-flowing Canary Current (CC) , with subsequent westward transport within the North Equatorial Current (NEC) that detaches from the Africa coast at 15–10°N (Fig. 1). The CC forms from the Azores Current (volume transport [VT], 0.8 Sv; DOC, 63.4 ± 1.4 μmol L^{-1} [in the upper 50 m]; Table 2) and the

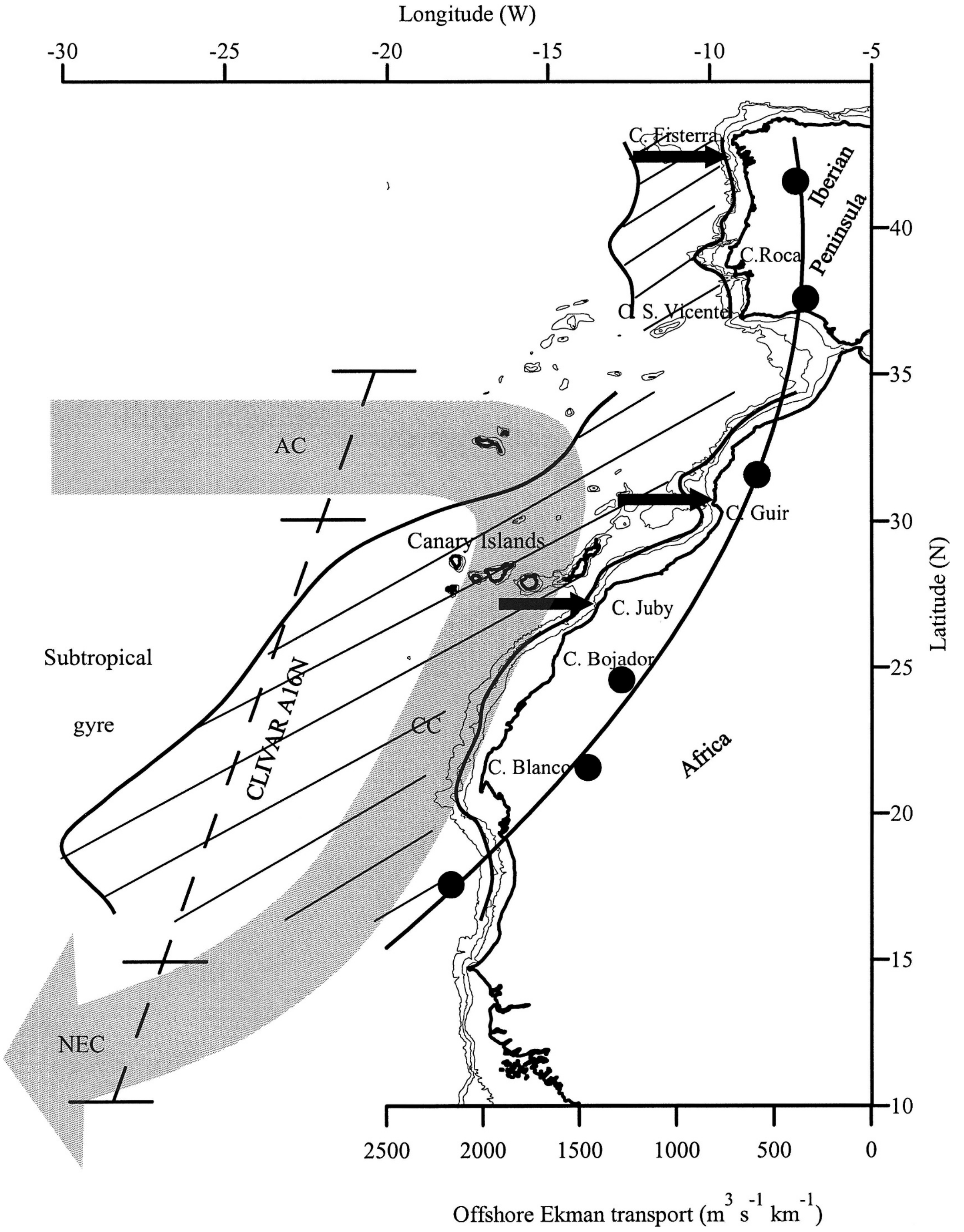

Fig. 1. Chart of the study area, the coastal upwelling system of Iberia–NW Africa from 15° to 43°N. The dark arrows show where process-oriented studies of carbon exchange by upwelling filaments were conducted. Filled circles are the upwelling season average offshore Ekman transport at the six selected sites, as calculated from atmospheric pressure charts by the Pacific Fisheries Environmental Laboratory (web site http://las.pfeg.noaa.gov/; see scale at the bottom axis). The solid line is the fit to the latitudinal variation of mean offshore Ekman transports. The hatched zone represents the area of influence of the coastal upwelling filaments in the adjacent oligotrophic ocean, i.e., the Coastal Transition Zone (CTZ). The dashed line is the track of CLIVAR line A16N, with data available at http://cdiac.ornl.gov/oceans/ndp_085/NDP–085.html. AC: Azores current; CC: Canary Current; NEC: North Equatorial Current.

filaments (VT, 3.13 Sv; DOC, 82 ± 9 μmol L^{-1} [in the upper 50 m]). Therefore, if this DOC is conservatively mixed, the CC may feed the NEC with 3.93 Sv of water with a DOC concentration of 78 ± 14 μmol L^{-1}. Since the average DOC concentration in the upper 50 m of the NEC between 10°N and 15°N is 73.9 ± 0.5 μmol L^{-1} (Table 2), no significant DOC respiration of 4 ± 14 μmol L^{-1} should occur in the CTZ, i.e., 7% ± 25% of the ΔDOC + ΔPOC

Table 2. DOC excesses (ΔDOC) and volumes transported (VT) by the Azores Current (AC), NW Africa upwelling filaments, and North Equatorial Current (NEC) in the upper 50 m of the study region. DOC in the AC, the subtropical gyre, and the NEC were taken from the CLIVAR section A16N (available at http://cdiac.ornl.gov/oceans/ndp_085/NDP–085.html). 1 Sv = 10^6 m^3 s^{-1}.

	Section A16N	DOC (0–50 m) (μmol L^{-1})	VT (0–50 m) (Sv)
Azores Current	30°–35°N	63.4±1.4	0.8±0.1*
Subtropical Gyre	30°–15°N	70.2±1.7	—
Filaments	Cape Juby & Guir	82.0±9.0	3.1±0.3†
NEC	15°–10°N	73.9±0.5	3.9±0.3‡

* Assuming 10 cm s^{-1} in the upper 50 m and a width of 150 km (Stramma, 1984) ±10% error.

† Assuming half of the Ekman transport of 2.5 Sv (see text) times a conservative filament:Ekman transport ratio of 2.5 (see Table 1) ±10% error.

‡ VT of the AC plus VT of the filaments.

transported by the filaments off NW Africa and practically all the DOC would be exported to the NEC. However, exported POC would probably sink and oxidize mostly in the mesopelagic layer (200–1000 m) of the CTZ. The average vertical export found in sediment traps within the CTZ of NW Africa is 4.8 g m^{-2} d^{-1} C and 12 g m^{-2} d^{-1} C if normalized to the 1000 and 200 m levels, respectively (Helmlke et al. 2005). These values are close to the expected POC export by filaments (9 g m^{-2} yr^{-1} C) assuming that 15% of the total export (60 g m^{-2} yr^{-1} C) is POC.

How does this horizontal export flux compare with the reported carbon (metabolic) imbalance of the CTZ region? On the basis of the annual primary production (PP) rates off NW Iberia (300 g m^{-2} yr^{-1} C; Joint et al. 2002) and NW Africa (325 g m^{-2} yr^{-1} C; Duarte et al. 2001), and the fitted regression equation relating PP and epipelagic community respiration (R) for the study area (Duarte et al. 2001; $\log PP/R = -3.9 + 1.12 \log PP$ in mg O_2 m^{-2} d^{-1}), and using an O_2/C photosynthetic and respiration quotient of 1, the carbon imbalance in the open ocean waters adjacent to Iberia–NW Africa must range from 60 to 90 g m^{-2} yr^{-1} C. Our conservative calculations of respiration of 7% to 16% of the carbon excess exported by the filaments (i.e., 4–10 g m^{-2} yr^{-1} C) would account for only 4% to 17% of the metabolic imbalance of the surface waters of the CTZ.

Our study suggests that upwelling filaments contribute to the offshore transport of NCP from coastal waters to the adjacent oligotrophic open ocean. Since upwelling filaments are found in all eastern boundary regions, as well as other coastal systems, their contribution to the overall organic matter flux to the open ocean must be relevant at a global scale. Quantification of these fluxes in other boundary regions merits consideration to constrain the carbon budget of the global ocean.

X. A. Álvarez–Salgado[1]
CSIC
Instituto de Investigacións Mariñas, Eduardo Cabello 6
36208 Vigo, Spain

J. Arístegui
Universidad de Las Palmas de Gran Canaria
35017 Las Palmas de Gran Canaria, Spain

E. D. Barton
CSIC
Instituto de Investigacións Mariñas, Eduardo Cabello 6
36208 Vigo, Spain

D. A. Hansell
University of Miami
Rosenstiel School of Marine and Atmospheric Science
4600 Rickenbacker Causeway
Miami, FL 33149

Acknowledgments

This work is a contribution to the European Network of Excellence for Ocean Ecosystems Analysis (EUROCEANS, contract 511106–2). D.A.H. was supported by the U.S. National Science Foundation (OCE–0223815). The valuable comments of two anonymous reviewers are acknowledged.

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[1] Corresponding author (xsalgado@iim.csic.es).

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Received: 10 July 2006
Accepted: 19 December 2006
Amended: 15 January 2007