Journal of Marine Systems 154 (2016) 233–242

Contents lists available at ScienceDirect

Journal of Marine Systems

journal homepage: www.elsevier.com/locate/jmarsys

Coastal–offshore exchange of organic matter across the Cape Ghir filament (NW Africa) during moderate upwelling

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A R T I C L E   I N F O

Article history:
Received 18 June 2015
Received in revised form 12 October 2015
Accepted 14 October 2015
Available online 21 October 2015

Keywords:
Coastal–offshore transport
Upwelling filaments
Excess total organic carbon
Cape Ghir
NW Africa

A B S T R A C T

The net coastal–ocean export of particulate organic carbon (POC), dissolved organic carbon (DOC) and chlorophyll *a* is studied in August 2009 at the Cape Ghir filament, a recurrent feature located within the NW African upwelling system. The estimated flux of excess total organic carbon (the non-refractory pools of DOC and POC) is about 2.1×10^9 kg C y^{-1}. DOC represents ~70% of the excess organic carbon in August 2009, during moderate upwelling. Assuming that this flux is representative of the range within a typical year, the yearly offshore net transport of total organic carbon would represent at least 29% of the primary production in this area. Since the Cape Ghir filament may extend hundreds of kilometers offshore, the associated seaward flux of organic carbon would contribute to the high microbial respiration rates reported from the nearby oligotrophic open ocean region. Our results illustrate that, when considering the regional carbon budgets of eastern boundary regions, it is imperative to take account of the offshore transport of organic matter in the numerous and recurrent upwelling filaments.

1. Introduction

Eastern boundary upwelling systems (EBUS) account for the most productive coastal environments in the world's oceans (Carr, 2002), supporting more than 20% of the world marine fish global catch (FAO and Fisheries and Aquaculture Information and Statistics Service, 2005; Fréon et al., 2009; Pauly and Christensen, 1995), and contributing about 10% to total global primary production (Behrenfeld and Falkowski, 1997). EBUS comprise not only the areas on the continental shelf where coastal upwelling occurs, but also the adjacent open ocean, because water parcels and biogeochemical properties are exchanged through the coastal transition zone (CTZ), where mesoscale structures such as filaments and associated eddies are recurrent in time and space (e. g. Ikeda and Emery, 1984; Brink and Cowles, 1991; Gruber et al., 2006; Chaigneau et al., 2009; Nieto et al., 2012).

Upwelling filaments are upper layer structures, typically 50–150 m deep, and a few tens of kilometers wide, which may extend up to several hundred kilometers offshore, containing relatively cool and fresh waters from the nearby coastal upwelling (Brink, 1983; Brink and Cowles, 1991; Dewey et al., 1991; Flament et al., 1985; Lutjeharms et al., 1991). They are usually located in the vicinity of coastal irregularities associated with low-temperature and high-chlorophyll signals (Hagen et al., 1996), frequently observed through satellite imagery as cold tongues and meanders (Bernstein et al., 1977; Davenport et al., 2010; Haynes et al., 1993; Kostianoy and Zatsepin, 1996; Legeckis, 1978; Lutjeharms and Stockton, 1987; Van Camp et al., 1991). The recurrent activity of the upwelling filaments contributes significantly to the two-way exchange of both nutrients and organic matter between the eutrophic coastal upwelling system and the adjacent oligotrophic oceanic system (Álvarez-Salgado et al., 2007; Arístegui et al., 2009a; Gabric et al., 1993; García-Muñoz et al., 2005; Jones et al., 1991; Liu et al., 2000). Indeed, upwelling filaments have been observed to play a key role in transferring chlorophyll *a* (Chl *a*) (Álvarez-Salgado et al., 2001; Andrade and Barton, 2005a; Arístegui et al., 1997; Barth et al., 2002; Basterretxea and Arístegui, 2000; Kadko et al., 1991; Smyth et al., 2001), and organic matter (Fischer et al., 2000; García-Muñoz et al., 2004; García-Muñoz et al., 2005; Pilskaln et al., 1996) from the richer near-shore upwelling to the open ocean. Kostianoy and Zatsepin (1996) observed up to 60 intermittent filaments in the NW African region; along 1000 km of coastline (15–25°N), and estimated that these filaments could transport offshore around half of the upwelled waters in the coastal region. Filaments also contribute to coastal insular organic matter exchanges, such as at the Canary Islands

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http://dx.doi.org/10.1016/j.jmarsys.2015.10.008
0924-7963/

at 28°N (Brochier et al., 2011). Despite its relevance, the magnitude of this coast to open ocean transport of organic matter that is channeled by filaments has so far been poorly quantified at a global scale (Arístegui et al., 2009a; Wollast, 1998), and the potential impact of filaments in regional carbon budgets is largely unknown.

In the Cape Ghir area, located at ~31°N in the northwest African region, an upwelling filament has been recurrently observed year round in sea surface temperature (SST) and ocean color (Chl *a*) images (e.g., Arístegui et al., 2009b; Hernández-Guerra and Nykjaer, 1997; Hernández-Guerra et al., 1993; Van Camp et al., 1991). Although filaments appear in response to upwelling-favorable winds, hydrographic cruises have documented the presence of the filament off Cape Ghir (Hagen et al., 1996; Pelegrí et al., 2005a) even during periods of unfavorable winds, suggesting that the filament is more persistent than the upwelling itself (Pelegrí et al., 2005b). Since the transfer of chemical and biological properties through a filament is more effective than through wind-driven Ekman transport (Álvarez-Salgado et al., 2007; Barton et al., 1998; Navarro-Pérez and Barton, 1998; Strub et al., 1991), the Cape Ghir filament is thought to constitute an effective and continuous source of organic matter to the open ocean. Nevertheless, if the filament is associated with a meander of the alongshore jet, the flow of the return limb may act to return exported waters to the nearshore zone (Barton et al., 1998; Mooers and Robinson, 1984). In this case, the returning waters will have been warmed, modified by exchanges with surrounding waters and affected by processes such as sedimentation. Therefore there can still be a net export of material and properties associated with the filament. The effectiveness of the Cape Ghir filament as a net exporter is suggested by the occurrence of diatoms and foraminifera characteristic of the coastal upwelling in deep sediment traps hundreds of kilometers offshore of the cape (Abrantes et al., 2002).

Here we estimate the contribution of the two-way exchange of bio-available particulate (POC) and dissolved (DOC) organic carbon mediated by the filament off Cape Ghir during moderate upwelling. For this purpose we have used the data collected during an intensive survey carried out in August 2009 within the framework of the CAIBEX (Canaries–Iberian marine ecosystem Exchanges) project. The aim of the present study is to quantify the net export of excess total organic carbon (eTOC: ePOC + eDOC) that might support plankton metabolism in the adjacent open ocean area.

2. Materials and methods

2.1. Hydrography and seawater sampling

The CAIBEX-III interdisciplinary high-resolution survey was conducted aboard the R/V *Sarmiento de Gamboa* from 16 August to 5 September 2009 off Cape Ghir (Fig. 1a). Two transects were surveyed during the cruise. One transect perpendicular to the coast (transect P; stations labeled in blue in Fig. 2) at approximately 31°N. A second transect was made parallel to the coast a week after (transect T; stations labeled in red in Fig. 2) at the same latitude, across the most probable filament location as determined from analysis of the remotely sensed sea surface temperature (SST) field. Temperature, salinity and fluorescence data were recorded with a SeaBird 911 Plus CTD equipped with a Sea-Tech fluorometer, all mounted on a General Oceanics 24

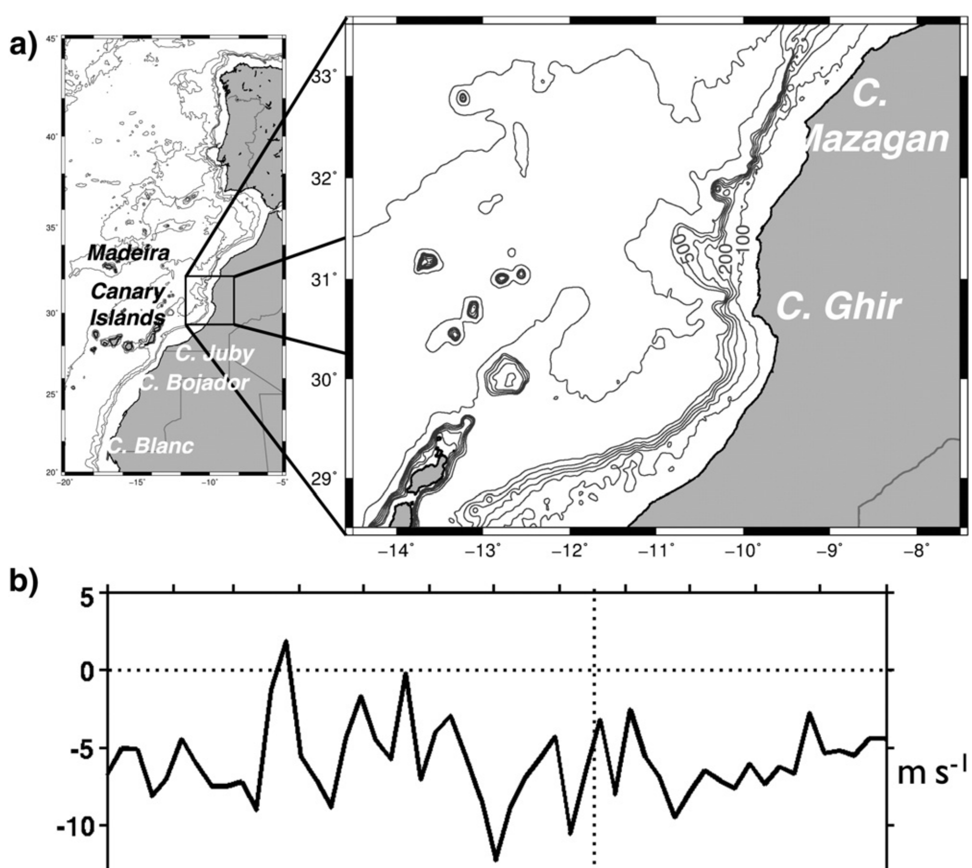

Fig. 1. (a) Northwest African upwelling region. The main capes and political boundaries are shown on the map. (b) Annual variation of the alongshore wind (m s^{-1}) in the region of interest. The data were derived from 3-day averages of the wind fields from January to December 2009. Vertical broken lines indicate the dates of the cruise.