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Particle fluxes in the NW Iberian coastal upwelling system: Hydrodynamical and biological control

D. Zúñiga [a,d,*], N. Villacieros-Robineau [b], E. Salgueiro [c,e], F. Alonso-Pérez [a], G. Rosón [d], F. Abrantes [c,e], C.G. Castro [a]

[a] Consejo Superior de Investigaciones Científicas (CSIC), Instituto de Investigaciones Marinas (IIM), E-36208 Vigo, Spain
[b] Université Pierre et Marie Curie, Laboratoire d'Océanographie et du Clima, 75005 Paris, France
[c] Instituto Português do Mar e da Atmosfera (IPMA), Div. Geologia e Georecursos Marinhos, 1749–077 Lisbon, Portugal
[d] Universidad de Vigo, Departamento de Física Aplicada, Campus Lagoas-Marcosende, E-36310 Vigo, Spain
[e] CCMAR, Centre of Marine Sciences, Universidade do Algarve, Campus de Gambelas, 8005-139 Faro, Portugal

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ABSTRACT

To better understand sources and transport of particulate material in the NW Iberian coastal upwelling system, a mooring line dotted with an automated PPS 4/3 sediment trap was deployed off Cape Silleiro at the base of the photic zone. The samples were collected from November 2008 through June 2012 over sampling periods of 4–12 days.

Our study represents the first automated sediment trap database for the NW Iberian margin. The magnitude and composition of the settling material showed strong seasonal variability with the highest fluxes during the poleward and winter mixing periods (averages of $12.9 \pm 9.6\ g\ m^{-2}\ d^{-1}$ and $5.6 \pm 5.6\ g\ m^{-2}\ d^{-1}$ respectively), and comparatively lower fluxes ($3.6 \pm 4.1\ g\ m^{-2}\ d^{-1}$) for the upwelling season. Intensive deposition events registered during poleward and winter mixing periods were dominated by the lithogenic fraction ($80 \pm 3\%$). They were associated to high energy wave-driven resuspension processes, due to the occurrence of south-westerly storms, and intense riverine inputs of terrestrial material from Minho and Douro rivers.

On the other hand, during the spring - summer upwelling season, the share of biogenic compounds (organic matter, calcium carbonate (CaCO3), biogenic silica (bSiO2)) to downward fluxes was higher, reflecting an increase in pelagic sedimentation due to the seasonal intensification of primary production and negligible river inputs and wave-driven resuspended material. Otherwise, the large variations of biogenic settling particles were mainly modulated by upwelling intensity, which by means of upwelling filaments ultimately controlled the offshore transport of the organic carbon fixed by primary producers towards the adjacent ocean. Based on the average downward flux of organic carbon ($212\ mg\ C\ m^{-2}\ d^{-1}$) and considering an average primary production of $1013\ mg\ C\ m^{-2}\ d^{-1}$ from literature, we estimated that about 21% of the fixed carbon is vertically exported during the upwelling season.

1. Introduction

Continental margins, especially those affected by coastal upwelling are characterized by high primary production rates (Chavez et al., 2011; Bauer et al., 2013). These areas, representing the transition zone between the land and the open ocean are also strongly affected by seasonality of atmospheric regimes, which ultimately control additional terrestrial inputs to the system and convert these areas in regions of high particulate matter concentration. The identification of sources and transport pathways of particulate matter in these highly-productive coastal upwelling systems is essential to: (i) tackle particle flux transfer between the shelf and the deep ocean, and (ii) to discern which fraction of the particulate organic carbon may be attributed to primary production, a fundamental issue to be resolved in order to understand global ocean carbon cycling (Wollast, 1998; Muller-Karger et al., 2005; Liu et al., 2010).

Since the 80s, vertical particle fluxes have been largely studied, as they represent the missing link between the processes affecting particulate material at sea surface and their routes towards the deep ocean. Some global (e.g. JGOFS, 2001) and regional projects attempted to understand seasonal and inter annual organic carbon export rates in different ocean basins (Martin et al., 1987; Antia et al., 2001; Armstrong et al., 2002; Francois et al., 2002; Lutz et al.,

* Corresponding author at: Universidad de Vigo, Departamento de Física Aplicada, Campus Lagoas-Marcosende, E-36310 Vigo, Spain.
E-mail address: diana.zuniga@uvigo.es (D. Zúñiga).

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2002; Goñi et al., 2003; Honjo et al., 2008). Most of these studies have been focused on oceanic waters where the characteristics of particle fluxes are affected by the seasonality of large-scale oceanographic and biogeochemical processes, mainly linked to primary production annual cycle. Nevertheless, downward flux studies on continental margins where additional particle sources mask pelagic sedimentation showed how the particles export is greatly variable both in space and time. This large variability is mainly due to hydrodynamic processes such as waves and/or strong currents that favour resuspension of surface sediments (e.g. Biscaye and Anderson, 1994; Peña et al., 1996; Heussner et al., 2006). Besides, in highly productive coastal upwelling systems, sediment trap studies have evidenced a decoupling between primary production and particulate organic carbon flux at the base of the photic zone (e.g. Pilskaln et al., 1996; Thunell, 1998; Peña et al., 1996; Fischer et al., 2009). These authors proposed a variety of physical and biological factors determining the export rates of organic carbon during the upwelling season, emphasizing the role of particulate organic recycling rates and offshore advection of organic material.

The NW Iberian coast is located at the northern boundary of the unique upwelling regime in Europe, the Iberian-Canary Upwelling System (Fraga, 1981, Arístegui et al., 2009). This system has a particular set of physical and chemical characteristics, favouring blooms of phytoplankton that lead to high secondary production, maintaining large stocks of economically important exploitable species. Many biogeochemical aspects of the NW Iberian upwelling system have recently been studied, such as CO_2 spatial and temporal variability (Gago et al., 2003), biogeochemistry of the water column (Castro et al., 2000), dynamics of the dissolved organic matter (Álvarez-Salgado et al., 1999), phytoplankton community structure (Figueiras and Ríos, 1993; Espinoza-Gonzalez et al., 2012) and benthic – pelagic coupling (Alonso-Pérez et al., 2010). However, very few studies have been focused on the vertical sinking of organic material, covering short periods of time (<1 month) and by means of multitraps collector systems (Bode et al., 1998; Olli et al., 2001; Varela et al., 2004; Zúñiga et al., 2011).

In this context, this work focuses on the downward particle fluxes in the NW Iberian coastal upwelling system using the first long-term sequential sediment trap data collected in this region. Biogeochemical data for sediment trap samples are combined with oceanographic observations to examine how hydrodynamic and biological factors determine the seasonal variation of magnitude and geochemical composition of settling particulate material. This study will also help us to understand how this upwelling dominated continental shelf concentrate and/or export organic carbon to the open ocean.

2. Methods

2.1. Study area

Our station (RAIA) is located on the NW Iberian continental shelf off Cape Silleiro (42° 05′ N; 8° 56′ W) at 75 m water depth (Fig. 1). The wind regime in this coastal upwelling region shows a clear seasonal signal (Wooster et al., 1976). During spring - summer (April to September – October), the NW Iberian coast is characterized by prevailing northerly winds, that cause upwelling of cold and nutrient rich subsurface Eastern North Atlantic Central Water (ENACW) on the shelf and into the Rías Baixas, triggering the high primary production of the region (Fraga, 1981; Tenore et al., 1995). The establishment of northerly winds favour the formation of upwelling filaments (Haynes et al., 1993) that stretch offshore, potentially exporting organic matter to the adjacent ocean (Álvarez-Salgado et al., 2001). By contrast, during autumn – winter (October to March – April), south-westerly winds favour

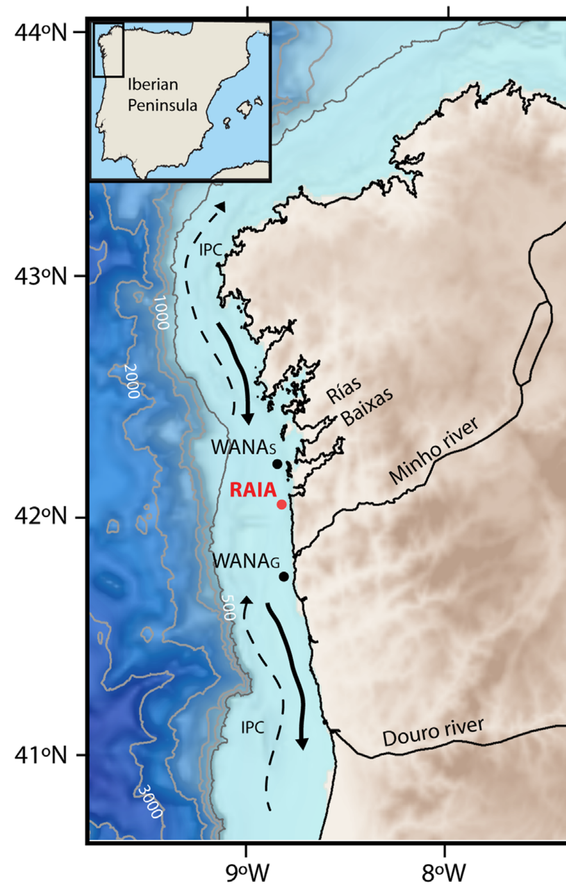

Fig. 1. Map of the NW Iberian Peninsula continental margin showing the position of the mooring line (RAIA) site and the WANA hindcast reanalysis points 3,027,034 ($WANA_S$ off Cape Silleiro) and 1,044,067 ($WANA_G$ off A Guarda) from which wave data were obtained. Circulation pattern along the margin is also presented. It includes the coastal current (solid line) moving southwards under upwelling favourable conditions, and the northward advection of southerly waters by the Iberian Poleward Current (IPC) (dashed line) dominating during downwelling periods.

coastal downwelling and the northward advection of warm, saline and nutrient-poor southerly waters conveyed by the Iberian Poleward Current (IPC) (Haynes and Barton, 1990; Castro et al., 1997). This poleward flow confines coastal waters over the shelf, precluding shelf-ocean exchange (Castro et al., 1997; Álvarez-Salgado et al., 2003; Schmidt et al., 2010). With the winter cooling (usually February - March), surface waters temperature drop and winter mixing occurs, resulting in a well homogenized mixed layer of cold and nutrient rich waters in the adjacent ocean (Álvarez–Salgado et al., 2003; Castro et al., 2006). On the other hand, these south-westerly winds during the autumn-winter promote significant wave heights exceeding 5 m 1.46% the time (mean annual conditions) and with a related peak period between 14 s and 18 s The highest values of maximum wave height measured in the area achieved 16.3 m. Such stormy conditions cause sediment remobilization on the continental shelf (Dias et al., 2002; Vitorino et al., 2002; Villacieros-Robineau (personal communication). This fact explains the characteristics of the bottom seafloor in the area of Cape Silleiro where surface sediments mainly consist in rocks and in minor proportion muddy sands (Dias et al., 2002). The NW Iberian continental shelf is also subject to river inputs, mainly from the Douro and Minho rivers. The annual average discharges are about 550 and 310 $m^3 s^{-1}$ for the Douro and Minho rivers respectively, and show strong seasonality. Maximum river inflows (up to 3850 $m^3 s^{-1}$ for Douro river and 1800 $m^3 s^{-1}$ for Minho river) occurred during winter months and minima (less than