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

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## ARTICLE INFO

## 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 $12.9 \pm 9.6 \, \mathrm{g \, m^{-2} \, d^{-1}}$ and $5.6 \pm 5.6 \, \mathrm{g \, m^{-2} \, d^{-1}}$ respectively), and comparatively lower fluxes ($3.6 \pm 4.1 \, \mathrm{g \, m^{-2} \, d^{-1}}$) 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 ($CaCO_3$), biogenic silica ($bSiO_2$)) 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 ($212 \, \mathrm{mg \, C \, m^{-2} \, d^{-1}}$) and considering an average primary production of $1013 \, \mathrm{mg \, C \, m^{-2} \, d^{-1}}$ from literature, we estimated that about 21% of the fixed carbon is vertically exported during the upwelling season.

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## 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.,

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
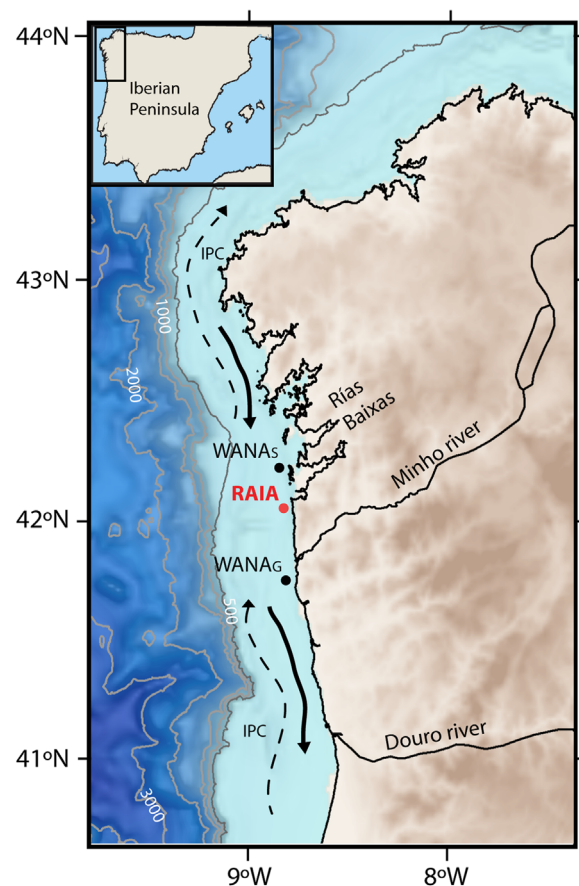


**Fig. 1.** Map of the NW Iberian Peninsula continental margin showing the position of the mooring line (RAIA) site and the WANA hindcast reanalysis points 3,027,034 (WANA$_S$ off Cape Silleiro) and 1,044,067 (WANA$_G$ off A Guarda) from which wave data were obtained. Circulation pattern along the margin 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
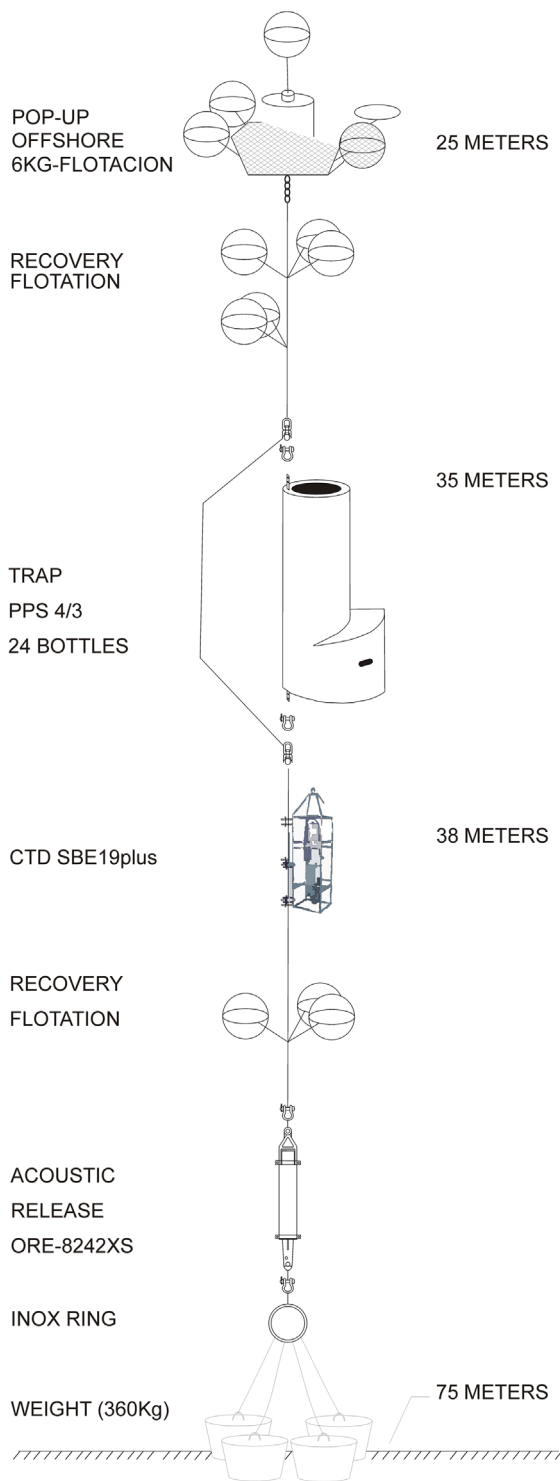
**Fig. 2.** Bottom-tethered mooring diagram deployed at the RAIA station showing main oceanographic instrumentation attached to the mooring line. The drawing is not to scale.

200 m³ s⁻¹) during summer (Dias et al., 2002; Otero et al., 2010).

### 2.2. Sampling strategy

A mooring line equipped with an automated Technicap PPS 4/3 sediment trap at 35 m of water depth and a CTD-SBE19 plus 2 m below the trap was used to monitored RAIA station from November 2008 to June 2012 (Fig. 2 and Table 1). Unfortunately some data were lost due to technical problems and bad weather

**Table 1**
Recorded days and sampling intervals of the mooring deployments at RAIA station.

| Period | Deployment | Recovery | Sampling interval (days) | Observations |
|---|---|---|---|---|
| I | 5 Nov 08 | 12 Feb 09 | 9 | Ok |
| II | 25 Mar 09 | 4 Jun 09 | 9 | Lost |
| III | 12 Jun 09 | 21 Sep 09 | 4–12 | Ok |
| IV | 24 Sep 09 | 11 Dec 09 | 9 | Ok |
| V | 28 Jan 10 | 27 Apr 10 | 9–12 | Ok |
| VI | 29 Jun 10 | 4 Dec 10 | 9 | Lost |
| VII | 26 Jan 11 | 28 Apr 11 | 7 | Ok |
| VIII | 10 Jun 11 | 14 Oct 11 | 7 | Ok |
| IX | 12 Jan 12 | 20 Jun 12 | 7 | Ok |

conditions (see Table 1). In addition, monthly cruises at RAIA station onboard R/V Mytilus were carried out in order to i) characterize the water column by conducting profiles for recording temperature and salinity (CTD-SBE25) and ii) collect discrete water column samples (5, 10, 20, 35, 50, 65 m) by means of an oceanographic rosette provided with $10-L$ PVC Niskin bottles for the determination of inorganic nutrients and chlorophyll $a$ (Chl $a$).

### 2.3. Physical forcing

Daily Ekman transport ($-Q_x$), an estimate of the volume of water upwelled per kilometre of coast, was calculated according to Bakun's (1973) method:

$$-Q_x = -((\rho_a C_D |V|)/(f\rho_{sw}))V_y.$$

where $\rho_a$ is the density of the air (1.22 kg m⁻³) at 15 °C, $C_D$ is an empirical dimensionless drag coefficient ($1.4 \ 10^{-3}$), f is the Coriolis parameter ($9.76 \ 10^{-5}$) at 42°N, $\rho_{sw}$ is the seawater density (1025 kg m⁻³) and $|V|$ and $V_y$ are the average daily module and northerly component of the geostrophic winds centred at 42°N, 10 °W, respectively. Average daily winds were estimated from surface atmospheric pressure fields (WXMAP atmospheric model) distributed by the US Navy Fleet Numerical Meteorological and Oceanographic Center (FNMOC) in Monterey, California (http://www.usno.navy.mil/FNMOC). Positive values show the predominance of northerly winds that induces upwelling on the shelf. On the contrary, negative values indicate the existence of downwelling processes. Minho and Douro river discharges were obtained from the web site https://github.com/PabloOtero/uptodate_rivers (Otero et al., 2010). Time series of wave data were done using the available data from WANA hindcast reanalysis points 3,027,034 (WANA_S: off Silleiro (42° 15′N; 9 °W)) and 1,044,067 (WANA_G: off A Guarda (41° 45′N; 9 °W)) (Fig. 1). Data were supplied by Puertos del Estado.

### 2.4. Water column data

Nutrient contents were determined by segmented flow analysis with Futura-Alliances autoanalyzers following Hansen and Grassoff (1983). The analytical error for nitrate is $\pm 0.05$ μM. For Chl $a$ concentration analyses, 250 mL water samples were filtered through GFF filters under low vacuum. The filters were placed in tubes and immediately stored in the dark at –20 °C for 24 h. Afterwards, 10 mL of 90% acetone were added to the tubes, placed in the refrigerator for 8 h, and the extracted fluorescence read before and after acidification (Chl $a$ corrected) using a Turner Designs fluorometer calibrated with pure Chl $a$ (Yentsch and Menzel, 1963). Chl $a$ measurement precision is $\pm 0.05$ μg L⁻¹.

### 2.5. Sediment trap processing and analytical methods

The Technicap PPS 4/3 sequential-sampling sediment trap used in this study has a cylindric–conical shape with a height/diameter

ratio of 1.7 and a collecting area of 0.05 m$^2$ (Heussner et al., 1990). In the laboratory, the rotary collector was cleaned with a detergent, soaked in HCl 0.5 N overnight, and rinsed several times with distilled water, and once on board, traps were rinsed with seawater. The receiving cups (250 mL) were filled with brine solution (5 psu in excess) to which 6 mL of saturated mercuric chloride solution was added to avoid the degradation of the collected particles and the disruption of swimmers (including all the organisms that do not fall gravitationally through the water column). Upon recovery, the receiving cups were stored in the dark at 2–4 °C until processing. Once in the laboratory, swimmers were removed from the samples by using fine tweezers under a dissecting microscope. Subsequently, samples were split into 5 aliquots using a high precision McLane WSD-10 sample divider. Each aliquot was rinsed with cold distilled water to remove the salts and then centrifuged to eliminate the supernatant. This procedure was repeated for three/four times to ensure that the sample was completely salt free. Aliquots were stored at $-80$ °C and freeze-dried.

Total mass was gravimetrically determined. After that, for major compound and isotopic analyses, samples were ground to a fine powder. For total and organic carbon (C$_{org}$) and nitrogen elemental composition analysis, 20 mg subsamples of dry sediment were used. Subsamples for organic carbon were firstly decarbonated with repeated additions of 10 μL of HCl 25%. Total and organic carbon and nitrogen were measured with a Perkin Elmer 2400 CNH analyser. The precision of the method is $\pm 0.3$ μ mol C L$^{-1}$ and $\pm 0.1$ μmol N L$^{-1}$, respectively.

Organic carbon isotopic ($\delta^{13}C_{org}$) analyses were performed over $\sim 15$ mg of decarbonated sample in silver capsules. Samples were measured by continuous flow isotope ratio mass spectrometry using a Thermo Finnigan MAT253 mass spectrometer coupled to an elemental analyser Carlo Erba EA1108 through a Conflo III interface. Organic carbon isotope composition is expressed as $\delta^{13}C_{org}$ parts per thousand (‰) relative to VPDB (Vienna Pee Dee Belemnite). Assuming that all the inorganic carbon was constituted by calcium carbonate (CaCO$_3$), the organic matter (OM) was calculated as [C$_{org} \times 1.87$] and the CaCO$_3$ content as [(total carbon–C$_{org}) \times 8.33$] (Fraga et al., 1998).

Biogenic opal (bSiO$_2$) content was analysed following Mortlock and Froelich (1989). The samples were treated with 2 M Na$_2$CO$_3$ for 5 h at 85 °C to extract the silica and then measured as dissolved silica by colorimetric reaction. The value of Si concentration was converted into bSiO$_2$ after multiplying it by a factor of 2.4 (Mortlock and Froelich, 1989).

The lithogenic fraction of each sediment trap sample was obtained by the difference between the total mass and the sum of the biogenic compounds (OM, CaCO$_3$ and bSiO$_2$).

### 2.5.1. Sediment trap collection efficiency

Sediment trap time series constitute the best way to study the variations of vertical particulate matter fluxes in the ocean. However, some studies point out that they may be subjected to some biases, depending on trap design, current velocity and characteristics of the settling particles. In this sense, Gardner et al. (1997) concluded that at current speeds less than 22 cm s$^{-1}$ vertical fluxes measured with cylindrical traps are not affected by horizontal currents. For the sampling period November 2008-May 2010, current speeds were registered by an upwards looking bottom mounted Doppler current profiler at RAIA location. Mean statistical parameters at 45 m water depth are presented in Table 2. Current velocities were lower than 22 cm s$^{-1}$ for 94%, 85% and 76% of the time during upwelling, poleward and winter mixing periods, respectively. Likewise, tilt calculated from examination of CTD pressure data mounted 2 m below the sediment trap also showed that the mooring line tilting was reduced, even during strong current episodes (Table 2). Thus, we assume that our

**Table 2**

Mean statistical parameters for ADCP current speeds registered at 45 m water depth and trap tilt angle obtained from CTD pressure data (November 2008–May 2010). S. D. refers to the standard deviation of the current speed. Unfortunately, data from June 2010 to June 2012 were not recorded.

| | Days | Average speed cm s$^{-1}$ (S. D.) | Maximum speed cm s$^{-1}$ | Speed $< 20$ cm s$^{-1}$ (%) | Tilt $< 5°$ (%) | Tilt $< 10°$ (%) |
|---|---|---|---|---|---|---|
| Upwelling | 198 | 10.5 (6.8) | 41.0 | 94 | 76 | 92 |
| Poleward | 183 | 13.3 (10.6) | 62.7 | 85 | 57 | 82 |
| Mixing | 63 | 15.4 (10.6) | 66.7 | 76 | 87 | 98 |

sediment trap was not affected by hydrodynamical biases during most of the time that it was deployed.

## 3. Results

### 3.1. Oceanographic conditions

Prevailing south-westerly winds (negative –Q$_x$ values) were registered from October to April-May causing strong downwelling conditions. (Fig. 3(a)). Such conditions were accompanied by strong SW storms responsible for significantly high wave heights (H$_S$) (up to 9.1 m) (Fig. 3(c)). Wave action lead to resuspension of bottom sediments as reflected by the significant increase in deep water column turbidity under stormy conditions (Fig. 4(e)). At the same time, intense Minho and Douro river discharges ($> 400$ m$^3$ s$^{-1}$), left their imprint as low salinity ($< 35.6$) and relatively high nitrate content water lens at sea surface (Fig. 4b, e).

Hydrographically, from late autumn (October) to early winter (January) downwelling conditions corresponded with the presence of the Iberian Poleward Current (IPC) in the region, as indicated by the anomalously warm (15–16 °C) and salty ($> 35.8$) waters with relatively low nutrient (2–4 μmol kg$^{-1}$) and Chl a
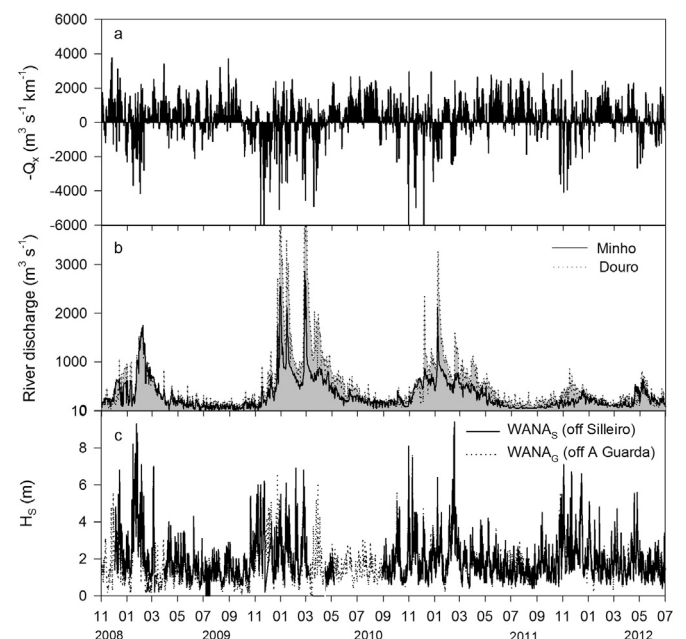


**Fig. 3.** Time-series of (a) upwelling index (-Q$_x$), (b) Minho and Douro river discharges and (c) significant wave height (H$_S$) obtained for propagation from the WANA$_S$ (off Silleiro) and WANA$_G$ (off A Guarda) points.
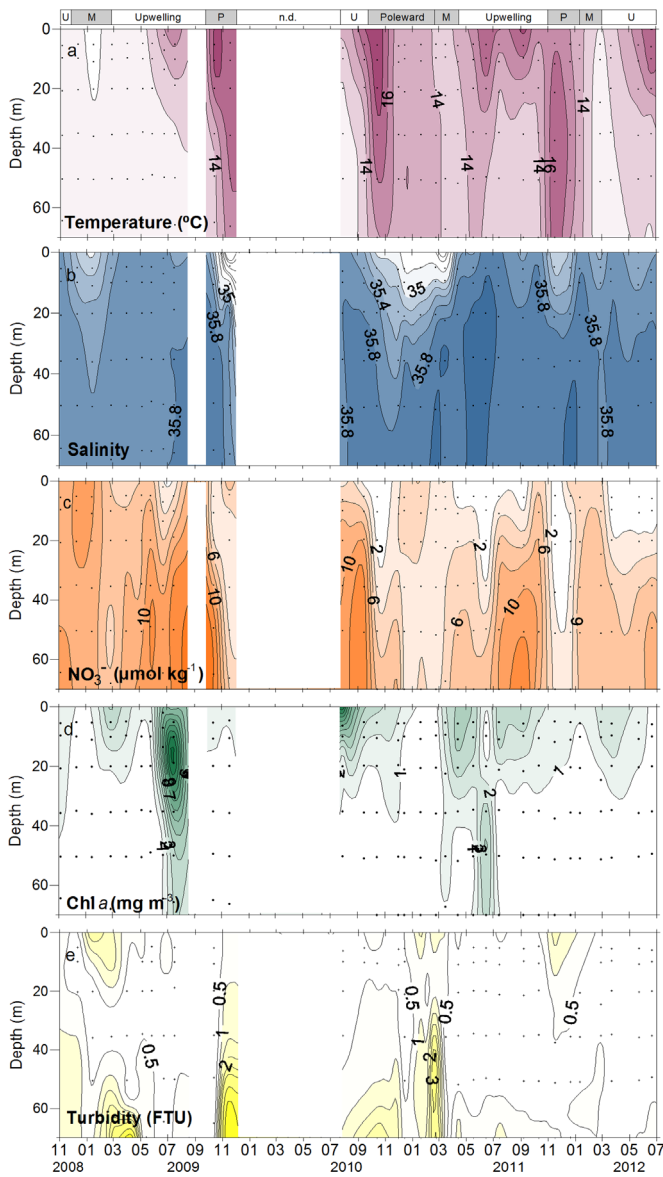
Fig. 4. Time-series of (a) temperature, (b) salinity), (c) nitrate ($NO_3^-$), (d) Chlorophyll $a$ (Chl $a$) and (e) turbidity concentrations registered at RAIA station. U: upwelling; P: Poleward; M: mixing; n.d.: no data.
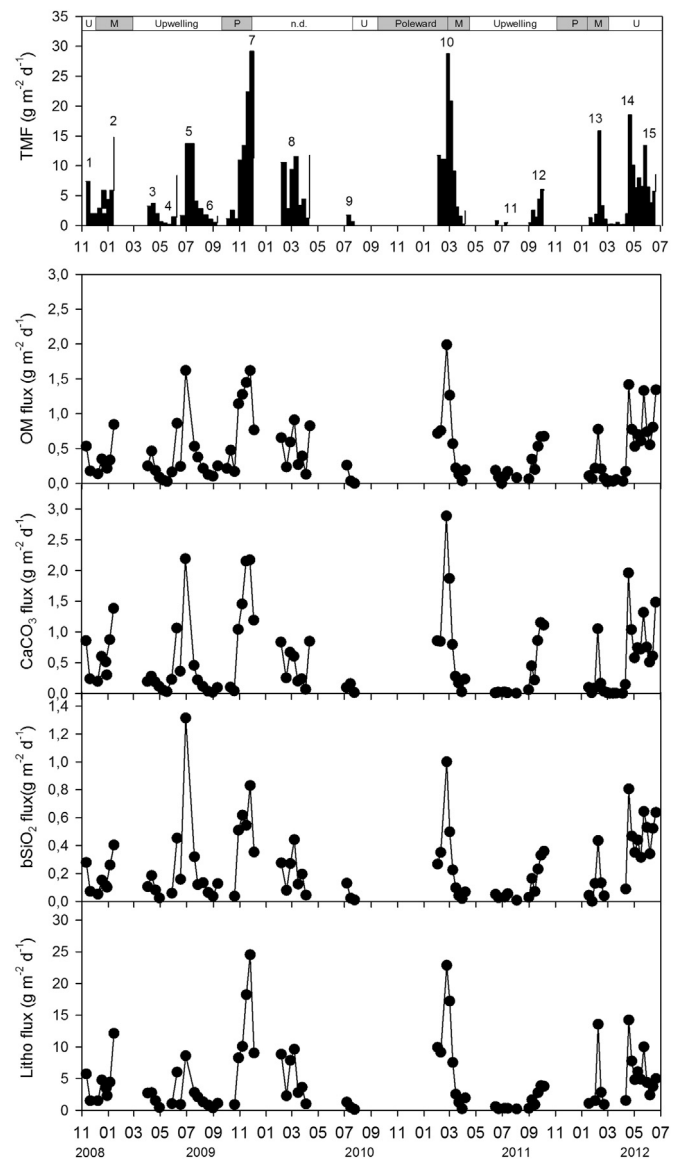


Fig. 5. Time-series of total (TMF) and major constituent (OM: organic matter; $CaCO_3$: calcium carbonate; $bSiO_2$: biogenic opal and Litho: Lithogenic) mass fluxes registered at RAIA station. U: upwelling; P: Poleward; M: mixing; n.d.: no data. Numbers are used to highlight main particle flux periods.

($< 1$ mg m$^{-3}$) contents (Fig. 4). Afterwards from January to March-April, the water column was thermally homogeneized ($\sim 14$ °C) and characterized by high nitrate levels (4–6 µmol kg$^{-1}$) due to the winter mixing and river runoff (Figs. 3(b), 4).

Subsequently, the transitional phase from winter to the up-welling season was marked by the spring bloom episode, as registered in March 2008, April 2011 and March 2012. During these spring transition periods, the development of sea surface thermal stratification due to incipient solar heating, jointly with the up-welled of nutrient rich subsurface waters, caused by the establishment of northerly winds, trigger the increase of Chl $a$ levels in the water column (Fig. 4). After that, between May and October a series of upwelling-relaxation cycles, as observed by –Q$_x$ temporal variability (Fig. 3(a)), promoted the upwelling of cold ($< 14$ °C) Eastern North Atlantic Central waters (ENACW) on the continental shelf, as the shoaling of the isotherms indicates (Figs. 3(a), 4(a)). This nutrient rich (10–12 µmol kg$^{-1}$) subsurface water mass favoured the development of Chl $a$ maxima, with concentrations as high as 9 mg m$^{-3}$, as registered in July 2009 (Fig. 4).

## 3.2. Magnitude and timing of fluxes

Time series of total mass fluxes (TMF) off Cape Silleiro revealed high values and significant seasonal and inter annual variability within the whole study period (Fig. 5). The highest fluxes ($12.9 \pm 9.6$ g m$^{-2}$ d$^{-1}$ and $5.6 \pm 5.6$ g m$^{-2}$ d$^{-1}$ for poleward and winter mixing, respectively) were always recorded during autumn – winter time, whereas during spring-summer upwelling periods TMF were comparatively low ($3.6 \pm 4.1$ g m$^{-2}$ d$^{-1}$), excluding the moderately intense deposition events in July 2009, September 2011 and June–July 2012, when values as high as 14 g m$^{-2}$ d$^{-1}$ were registered.

Temporal evolution of both biogenic (organic matter (OM), calcium carbonate ($CaCO_3$) and biogenic opal ($bSiO_2$)) and lithogenic fluxes presented similar trends, in agreement with TMF variability (Fig. 5). Fluxes of OM, $CaCO_3$ and $bSiO_2$ ranged around multi-year averages of $458 \pm 446$ mg m$^{-2}$ d$^{-1}$, $542 \pm 623$ mg m$^{-2}$ d$^{-1}$ and $263 \pm 254$ mg m$^{-2}$ d$^{-1}$, respectively, registering higher values during the poleward and winter mixing periods (Fig. 5 and Table 3).

**Table 3**
Total and seasonal (upwelling; poleward; mixing) mean (standard deviation) values of both total (TMF) and major compounds (OM: organic matter; CaCO$_3$: calcium carbonate; bSiO$_2$: biogenic opal and Litho: lithogenic) mass fluxes and percentages. Bio: total biogenic contribution (OM, CaCO$_3$ and bSiO$_2$). Organic carbon (C$_{org}$)/total nitrogen (TN) atomic ratio is also presented.

| | TMF (g m$^{-2}$ d$^{-1}$) | OM (%) | OM flux (mg m$^{-2}$ d$^{-1}$) | C$_{org}$/TN (mol: mol) | CaCO$_3$ (%) | CaCO$_3$ (mg m$^{-2}$ d$^{-1}$) | bSiO$_2$ (%) | bSiO$_2$ (mg m$^{-2}$ d$^{-1}$) | Bio (%) | Bio flux (g m$^{-2}$ d$^{-1}$) | Litho (%) | Litho flux (g m$^{-2}$ d$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Upwelling | 3.6 (4.1) | 13.2 (5.7) | 404 (400) | 8.9 (0.7) | 10.3 (5.9) | 441 (531) | 5.9 (2.0) | 245 (265) | 30 (7) | 1.2 (1.2) | 69.8 (7.0) | 2.9 (3.0) |
| Poleward | 12.9 (9.6) | 9.7 (4.8) | 935 (564) | 9.9 (0.8) | 8.0 (2.4) | 1235 (877) | 3.2 (0.8) | 479 (286) | 19.6 (3.4) | 2.9 (1.6) | 80.4 (3.4) | 12.2 (7.3) |
| Mixing | 5.6 (5.6) | 7.7 (2.1) | 366 (327) | 9.9 (0.8) | 7.8 (2.8) | 453 (474) | 3.5 (1.2) | 175 (147) | 18.9 (3.3) | 1.0 (0.9) | 80.9 (3.2) | 4.7 (4.7) |
| Total | 5.5 (6.3) | 10.9 (5.4) | 458 (446) | 9.3 (0.9) | 9.3 (4.9) | 542 (623) | 4.8 (2.0) | 263 (254) | 24.8 (8.3) | 1.4 (1.3) | 74.6 (7.8) | 4.7 (5.2) |
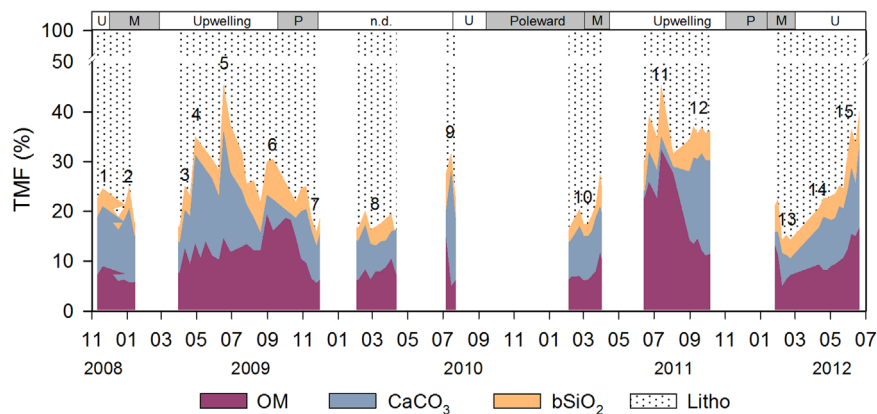


**Fig. 6.** Relative contributions (in percentage) of major compounds (OM: organic matter; CaCO$_3$: calcium carbonate; bSiO$_2$: biogenic opal and Litho: Lithogenic) to the total mass fluxes (TMF) of the settling material collected by the RAIA sediment trap. U: upwelling; P: Poleward; M: mixing; n.d.: no data. Numbers are used to highlight main particle flux periods.

In contrast, and except for the mass biodeposition events in July 2009, September 2011 and June-July 2012, minimum OM, CaCO$_3$ and bSiO$_2$ fluxes were linked to upwelling seasons, when values below 400 mg m$^{-2}$ d$^{-1}$ were recorded for the three major biological compounds. Time series of lithogenic fluxes ranged around a multi-year average of 4.7 ± 5.2 g m$^{-2}$ d$^{-1}$, showing clear seasonal contrasts. Two intense deposition events were recorded during November 2009 and February 2011 when fluxes were as high as 24 g m$^{-2}$ d$^{-1}$ and 23 g m$^{-2}$ d$^{-1}$, respectively (Fig. 5).

Relative contributions of major compounds to TMF are presented in Fig. 6 and Table 3. It is noteworthy that settling particulate material is mainly composed by lithogenic matter for the whole sampling period, with a mean percentage of 74.6 ± 7.8%. Seasonally, the relative contribution of the lithogenic fraction was higher during poleward and winter mixing periods than during upwelling seasons when biogenic compounds relatively increased their contribution. The percentage of OM to the settling material ranged around values of 13.2 ± 5.7% during upwelling periods. On the contrary, the contribution of OM was lower for the poleward and winter periods, ranging around mean values of 9.7 ± 4.8% and 7.7 ± 2.1%, respectively. Seasonal patterns for both %CaCO$_3$ and %bSiO$_2$, that ranged around multi-year averages of 9.3 ± 4.9% and 4.8 ± 2.0% respectively, were similar to temporal variability of % OM, with relative higher contributions during upwelling periods.

The organic carbon to total nitrogen (C$_{org}$/TN) atomic ratio of sinking particles also showed significant seasonal differences for the studied years, with values higher than 10 during lithogenic dominated autumn-winter events (peaks 2.7.8.10.13) and values lower than 9 for the most representative upwelling episodes (peaks 5,6,9,11,12,15; Fig. 7). Organic carbon (δ$^{13}$C$_{org}$) isotopic composition signal of the sinking particles ranged from −20.4‰ to −23.7‰ for

the upwelling and the winter season, respectively (Fig. 7).

## 4. Discussion

This work represents the first multi-year particle flux dataset obtained with time-sequential sediment traps within the NW Iberian continental margin. The few previous studies focused on vertical fluxes have only captured short periods of time and except for the work by Bode et al. (1998) off A Coruña and by Olli et al. (2001) off Cape Silleiro, all the published sediment trap data were obtained inside the adjacent Rías Baixas (Varela et al., 2004; Piedracoba et al., 2008; Alonso-Pérez et al., 2010, Zúñiga et al., 2011).

The magnitude and composition of total mass fluxes off Cape Silleiro presented abrupt changes for the entire time series and showed strong seasonal variability (Fig. 5). Major flux peaks occurring during highly hydrodynamic downwelling seasons were ruled by the lithogenic fraction. Comparatively lower fluxes with a relatively higher biogenic contribution dominated during less energetic upwelling periods (Figs. 2, 4, 5 and Table 3). These results indicate that the hydrodynamic conditions, modulated by the upwelling/downwelling seasons, have a major influence over the particulate material settling in this coastal upwelling system.

### 4.1. Downwelling season: the role of surface sediment resuspension and river inputs

During the poleward and winter mixing periods, south-westerly winds favoured downwelling of surface oceanic waters towards the continental shelf, confining coastal waters over the shelf and precluding exchange with the adjacent ocean (Castro et al.,
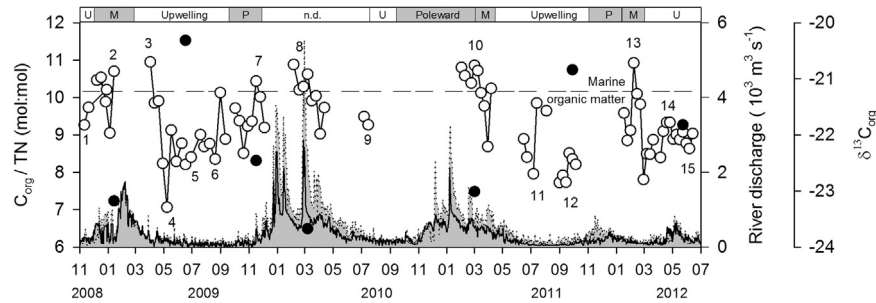
**Fig. 7.** Time-series of Minho (solid line) and Douro (dashed line) river discharges, and organic carbon ($C_{org}$)/total nitrogen (TN) atomic ratio (white dots) of the sinking particles collected by the RAIA sediment trap. Carbon isotopic ($\delta^{13}C_{org}$) signals (black dots) of several sediment trap samples are also presented. Lowest $\delta^{13}C_{org}$ signal ($-21.6‰$) characteristic of marine particulate organic matter in the adjacent Ría de Vigo (Filgueira and Castro, 2011) is marked by a dashed line in the figure. U: upwelling; P: Poleward; M: mixing; n.d.: no data. Numbers are used to highlight main particle flux periods.

1997, Álvarez-Salgado et al., 1997; Álvarez-Salgado et al., 2003). These studies have described how the shelf –ocean blocking effect caused by the presence of the Iberian Poleward Current hinders the offshore export of suspended particulate organic matter, and enhances its remineralization on the inner shelf. In fact, the higher amount of material collected into the sediment trap during the poleward and winter mixing periods (Fig. 4, Table 3) point to a prevalence of particulate matter sedimentation on the inner shelf over offshore horizontal transport, in response to this blocking mechanism of the coastal regime.

On the other hand, during these months we also observed high energy wave environment, with Hs > 5 m (Fig. 3), caused by intense SW storms (Oliveira et al., 2002; Villacieros-Robineau et al., in preparation). The waves associated with these stormy conditions produce high shear velocities, constituting the main forcing mechanisms of erosion and resuspension of surface sediments deposited at the inner shelf (van Weering et al., 2002, Villacieros-Robineau et al., in preparation). In this way, we observed how large amounts of particulate material has been resuspended into the water column during autumn and winter storms, as reflected by the significant increase in deep water column turbidity (Fig. 4 (e)). This explains the coupling between the massive lithogenic flux events (peaks 2, 7, 8, 10, 13) and the high wave heights registered at the Silleiro and A Guarda buoys (Fig. 8). During these high-energy episodes both lithogenic and biogenic fluxes achieved their maximum values revealing that not only lithogenic particles but also organic matter as well as silicious and calcareous shelled organisms were resuspended from surface sediments during the downwelling season.

Except for the high flux event of November 2009 (peak 7) and the period between November 2011 – March 2012, strong wave action has been accompanied by intense Minho and Douro river discharges (Fig. 3). The Minho and Douro flood events had a significant effect over the thermohaline structure of the water column through the formation of cold and low salinity water lens

(Fig. 4(b)), as previously studied by Otero et al. (2010). River discharges constitute an additional source of lithogenic and terrestrial organic matter to the sediment trap resulting from the bulk of sediment washed out from the rivers onto the continental shelf (Figs. 3, 6 and 7), as proposed by Dias et al. (2002). Thus, the marked co-occurrence and seasonality of these two factors, i.e. river discharges and sediment resuspension, clearly modulated the amount and quality of the material collected into the sediment trap during poleward and winter mixing periods.

The temporal evolution of $C_{org}$/TN ratio and $\delta^{13}C_{org}$ allowed an analysis of the quality of the settling material (Fig. 7). The $C_{org}$/TN ratios ($9.9 \pm 0.8$) during poleward and winter mixing periods, significantly higher than the classical Redfield ratio for marine plankton (6.7) (Redfield, 1958) pointed to more refractory organic matter being captured by our sediment trap. This fact is also corroborated by $\delta^{13}C_{org}$ displaying values clearly lighter ($-23.29 \pm 0.34‰$) than the typical pelagic organic matter end-member for the adjacent Rías Baixas ($-19.56 \pm 2.01‰$) (Filgueira and Castro, 2011). Moreover, $\delta^{13}C_{org}$ during these massive deposition events was similar to the $\delta^{13}C_{org}$ signal for surface sediments of the NW Iberian inner shelf found by Schmidt et al. (2010), suggesting that remobilization of underlying sediments during autumn and winter storm events may provide of more degraded organic matter to the settling material. At this point, one intriguing question comes from the fact that our carbon isotopic values may also be the result of a mixture between the marine $\delta^{13}C_{org}$ characteristic value and the lighter river terrestrial organic matter end-member ($-26.2‰$ for Minho river; from Schmidt et al. (2010)). The observed decrease of carbon isotopic composition of the sediment trap material could also be a direct evidence of how river flows may also leave their imprint in the particulate matter sinking at the inner shelf. From all these observations, we assume that even it is not possible to discern between organic matter from river inputs and surface sediment resuspension, there must be a large contribution of terrestrial organic carbon from these two
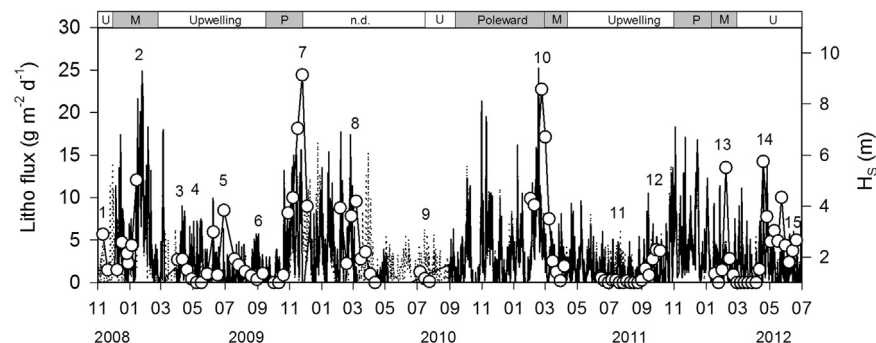


**Fig. 8.** Time-series of lithogenic fluxes (white dots) at RAIA station and significant wave height ($H_S$) at WANA$_S$ off Silleiro (solid line) and WANA$_G$ off A Guarda (dashed line) points. U: upwelling; P: Poleward; M: mixing; n.d.: no data. Numbers are used to highlight main particle flux periods.

sources in the trap material. Our results also corroborate previous physical and sedimentological studies that described this continental margin as a highly hydrodynamic region, where river discharges and winter storms play a key role in the distribution of fine sediment in the inner shelf (Vitorino et al., 2002; Schmidt et al., 2010).

### 4.2. Upwelling season: primary flux and carbon export

From March–April to September - October, northerly winds promote upwelling favourable conditions that lead to increases in primary production, reaching the highest annual values and representing about 63% of the total annual net primary production (Joint et al., 2001). The time series of Chl a off Cape Silleiro, as an estimate of phytoplankton biomass, followed this seasonal pattern (Fig. 4). Taking into account this high phytoplankton biomass, and the low wave energy conditions and negligible river discharges (Fig. 3) during this period, it could be expected to find high vertical biogenic fluxes. However, we observed a large variability in the biogenic fluxes during this season, mainly modulated by upwelling intensity (Fig. 9). It is well established that strong northerly winds may contribute to the oceanwards transport of a large fraction of the biogenic particles from the continental shelf by means of upwelling filaments formation (Suess, 1980; Walsh, 1981; Thunell, 1998; Olli et al., 2001). Off Cape Ghir, García-Muñoz et al. (2005) concluded that about 63% of the average annual primary production for the region is susceptible to be exported offshore via water filament formation. For the NW Iberian shelf, Alvarez-Salgado et al., (2001) estimated that the resultant organic carbon export by upwelling filaments may represent as much as 45% of the total annual primary production, including both dissolved and particulate organic carbon. The variability observed on the vertical fluxes of $C_{org}$ during the upwelling season seems to respond in this way, as shown in Fig. 9. During events 4, 6, 9 and 11, intense Ekman transport probably caused the formation of upwelling filaments,
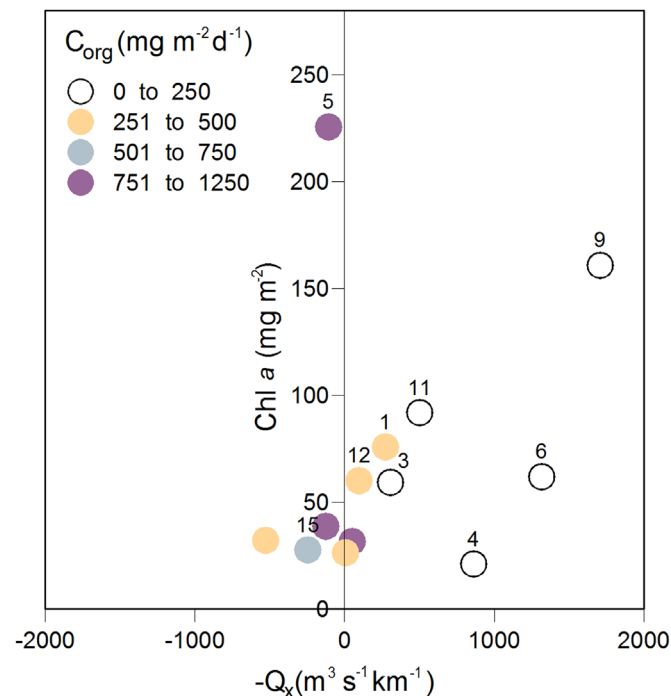
favouring the horizontal offshore export of the fixed organic carbon over vertical export, resulting in relatively low $C_{org}$ vertical fluxes. Under relatively low Ekman transport, the offshore export is not so favoured over the vertical one, registering high values of $C_{org}$ vertical fluxes as occurred for events 1, 5, 12 and 15. The highest $C_{org}$ vertical fluxes were reached in June – July 2009 (event 5) under a relaxation of northerly winds and high Chl a levels, leading to a $C_{org}$ vertical export as high as 866 mg C m$^{-2}$ d$^{-1}$.

If we consider the average net primary production value of 1013 mg C m$^{-2}$ d$^{-1}$ during the upwelling season reported by Joint et al. (2001) and take into account that the average $C_{org}$ flux from the sediment trap data for the upwelling season was 212 mg C m$^{-2}$ d$^{-1}$, we estimate that in seasonal terms about 21% of the primary production is vertically exported from the photic zone in this coastal upwelling area. This value is similar to the range of 14–26% obtained by Olli et al. (2001) from a lagrangian experiment carried out in the Iberian continental shelf during a summer upwelling season.

On the other hand, the time series of sediment trap material collected off Cape Silleiro also revealed that the contribution of biogenic material to total mass during upwelling season was on average (30 ± 7%), higher than during the downwelling (poleward: 20 ± 3%; mixing: 19 ± 3%) periods (Table 3). Besides, the lower $C_{org}$/TN ratio and the high carbon isotopic signal ($\delta^{13}C_{org} > -21‰$) corroborate that biogenic particle fluxes are derived from recently formed organic matter by primary producers (Fig. 7 and Table 3).

The high positive correlation between $C_{org}$ fluxes and both $CaCO_3$ and $bSiO_2$ fluxes (r=0.96 and r=0.96, respectively) during the upwelling season, higher than the correlation with lithogenic fluxes (r=0.90), also point to the overall control that both silicious (diatoms) and calcareous (coccolithopheres) phytoplankton communities exert over $C_{org}$ vertical export in the NW Iberian coastal upwelling system (Table 4). These correlation coefficients are very similar to those obtained for other upwelling-dominated continental margins (Thunell et al., 2007) and show that the ballast-ratio hypothesis (Armstrong et al., 2002; Francois et al., 2002) explained much of the variability of the organic carbon export during upwelling periods. The higher contribution of $CaCO_3$ to the vertical fluxes respect to $bSiO_2$ suggests that carbonate organisms (coccolithophores and foraminifera) must be abundant in the study area. Unfortunately there are no previous studies in the region to corroborate these results. Ecology of coccolithophores has been only studied further south in the Iberian margin where oceanographic conditions are more typically represented by subtropical waters masses influence (Moita et al., 2010; Guerreiro et al., 2013). Otherwise, the slope of the fitted lines point to $C_{org}$ preferentially co-sediment with $bSiO_2$ (Table 4) as occurred in diatom dominated production regimes, where a higher seasonality and a more event-driven export or pulsed sedimentation occurred (Berger and Wefer, 1990).

In summary, from our time series of downward particle fluxes we can conclude that ∼20% of the particulate $C_{org}$ attributed to primary production sinks on the continental shelf during the low



**Fig. 9.** Scatter plot of photic zone integrated chlorophyll a (Chl a) vs. Ekman transport (-$Q_x$) (same day as Chl a sampling). Dot color scale represents organic carbon ($C_{org}$) fluxes registered by the sediment trap including the day of Chl a sampling. Dot numbers are referred to $C_{org}$ flux events identified during upwelling periods (as referred in Fig. 5). Unfortunately, there were no Chl a data for event 14.

**Table 4**
Linear regression correlation coefficients for organic carbon ($C_{org}$) flux versus total mass (TMF), biomineral (calcium carbonate: $CaCO_3$ and biogenic opal: $bSiO_2$) and lithogenic (Litho) fluxes for the upwelling period. All correlation coefficients (r) are significat (P < 0.001). Regression line slope between the different compounds is also shown. Number of samples used for the linear regressions: 49.

|           | r    | Slope |
|-----------|------|-------|
| TMF       | 0.95 | 0.05  |
| $CaCO_3$  | 0.96 | 0.36  |
| $bSiO_2$  | 0.96 | 0.78  |
| Litho     | 0.90 | 0.06  |

hydrodynamic upwelling period. This means that a large fraction of particulate $C_{org}$ is susceptible to be recycled in the photic layer and/ or horizontally exported offshore. Under downwelling conditions (poleward/winter mixing periods) it has been proved that re-suspension of underlying sediments, associated to stormy conditions, and intense river discharges regulate the sedimentation processes. Further work is necessary in order to better determine more specific organic matter sources and transport pathways in this highly productive coastal upwelling system.

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## References

Alonso-Pérez, F., Ysebaert, T., Castro, C.G., 2010. Effects of suspended mussel culture on benthic-pelagic coupling in a coastal upwelling system (Ría de Vigo, NW Iberian Peninsula). J. Exp. Mar. Biol. Ecol. 382 (2), 96–107.

Álvarez-Salgado, X.A., Castro, C.G., Pérez, F.F., Fraga, F., 1997. Nutrient mineralization patterns in shelf waters of the Western Iberian upwelling. Cont. Shelf Res. 17 (10), 1247–1270.

Álvarez-Salgado, X.A., Doval, M.D., Pérez, F.F., 1999. Dissolved organic matter in shelf waters off the Ría DE Vigo (NW Iberian Upwelling System). J. Mar. Syst. 18, 383–3394.

Álvarez-Salgado, X.A., Doval, M.D., Borges, A.V., Joint, I., Frankignoulle, M., Woodward, E.M.S., Figueiras, F.G., 2001. Off-shelf fluxes of labile materials by an upwelling filament in the NW Iberian upwelling system. Prog. Oceanogr. 51, 321–337.

Álvarez-Salgado, X.A., Figueiras, F.G., Pérez, F.F., Groom, S., Nogueira, E., Borges, A.V., Chou, L., Castro, C.G., Moncoiffé, G., Ríos, A.F., Miller, A.E.J., Frankignoulle, M., Savidge, G., Wollast, R., 2003. The Portugal coastal counter current off NW Spain: new insights on its biogeochemical variability. Prog. Oceanogr. 56, 281–321.

Antia, A.N., Koeve, K., Fischer, G., Blanz, T., Shulz-Bull, D., Scholten, J., Neuer, S., Kremling, J., Kuss, R., Peinert, D., Hebbeln, D., Bathmann, U., Conte, M., Fehner, U., Zeitzschel, B., 2001. Basin-wide particulate carbon flux in the Atlantic Ocean: Regional export patterns and potential for atmospheric CO2 sequestration. Global Biogeochem. Cy. 15, 845–862.

Arístegui, J., Barton, E.D., Álvarez-Salgado, X.A., Santos, A.M.P., Figueiras, F.G., Kifani, S., Hernández-León, S., Mason, E., Machú, E., Demarcq, H., 2009. Sub-regional ecosystem variability in the Canary Current upwelling. Prog. Oceanogr. 83, 33–48.

Armstrong, R.A., Lee, C., Hedges, J.I., Honjo, S., Wakeham, S.G., 2002. A new mechanistic model for organic carbon fluxes in the ocean based on the quantitative association of OC with ballast minerals. Deep-Sea Res. II 49, 219–236.

Bakun, A., 1973. Coastal upwelling Indices, West Coast of North America, 1946–71. US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Seattle, WA.

Bauer, J., Cai, W.-J., Raymond, P.A., Bianchi, T.S., Hopkinson, C.S., Regnier, P.A., 2013. The changing carbon cycle of the coastal ocean. Nature 504, 61–70.

Berger, W., Wefer, G., 1990. Export production: seasonality and intermittency, and paleoceanographic implications. Palaeogeogr. Palaeoclim. Palaeoecol. 89, 245–254.

Biscaye, P.E., Anderson, R.F., 1994. Fluxes of particulate matter on the slope of the southern Middle Atlantic Bight: SEEP-II. Deep-Sea Res. 41 (2/3), 459–509.

Bode, A., Varela, M., Barquero, S., Alvarez-Osorio, M.T., Gonzalez, N., 1998. Preliminary studies on the export of organic matter during phytoplankton blooms off La Coruña (Northwestern Spain). J. Mar. Biol. 78 (1), 1–15.

Castro, C.G., Álvarez-Salgado, X.A., Figueiras, F.G., Pérez, F.F., Fraga, F., 1997. Transient hydrographic and chemical conditions affecting microplankton

populations in the coastal transitions zone of the Iberian upwelling system (NW Spain) in September 1986. J. Mar. Res. 55, 321–352.

Castro, C.G., Pérez, F.F., Álvarez-Salgado, X.A., Fraga, F., 2000. Coupling between thermohaline, chemical and biological fields during two contrasting upwelling events off the NW Iberian Peninsula. Cont. Shelf Res. 20, 189–210.

Castro, C.G., Nieto-Cid, M., Álvarez-Salgado, X.A., Pérez, F.F., 2006. Local remineralization patterns in the mesopelagic zone of the Eastern North Atlantic, Off the NW Iberian Peninsula. Deep-Sea Res. I 53, 1925–1940.

Chavez, F., Messié, M., Pennington, J.T., 2011. Marine primary production in relation to climate variability and change. Annu. Rev. Mar. Sci. 3, 227–260.

Dias, J.M.A., González, R., García, C., Díaz-del-Río, V., 2002. Sediment distribution patterns on the Galicia–Minho continental shelf. Prog. Oceanogr. 52 (2–4), 215–231.

Espinoza-Gonzalez, O., Figueiras, F.G., Crespo, B., Teixeira, I.G., Castro, C.G., 2012. Autotrophic and heterotrophic microbial plankton biomass in the NW Iberian upwelling: seasonal assessment of metabolic balance. Aquat. Microb. Ecol. 67, 77–89.

Figueiras, F.G., Ríos, A.F., 1993. Phytoplankton succession, red tides and the hydrographic regime in the Rías Bajas of Galicia. In: Smayda, T.J., Shimizu, Y. (Eds.), Toxic Phytoplankton Blooms in the Sea. Elsevier, New York, pp. 239–244.

Filgueira, R., Castro, B.G., 2011. Study of the trophic web of San Simón Bay (Ría de Vigo) by using stable isotopes. Cont. Shelf Res. 31, 476–487.

Fischer, G., Karakas, G., Blaas, M., Ratmeyer, V., Nowald, N., Schlitzer, P., Helmke, P., Davenport, R., Donner, B., Neuer, S., Wefer, G., 2009. Mineral ballast and particle settling rates in the coastal upwelling system off NW Africa and South Atlantic. Int. J. Earth Sci. 98, 281–298.

Fraga, F., 1981. Upwelling off the Galician coast, nothwest of Spain. In: Richards, F. (Ed.), Coastal Upwelling. American Geophysical Union, Washington, pp. 176–182.

Fraga, F., Ríos, A.F., Pérez, F.F., Figueiras, F.G., 1998. Theoretical limits of oxygen: carbon and oxygen:nitrogen ratios during photosynthesis and mineralisation of organic matter in the sea. Sci. Mar. 62 (1), 161–168.

Francois, R., Honjo, S., Krishfield, R., Manganini, S., 2002. Factors controlling the flux of organic carbon to the bathypelagic zone of the ocean. Glob. Biogeochem. Cy. 16 (4), 1087. http://dx.doi.org/10.1029/2001GB001722.

Gago, J., Gilcoto, M., Pérez, F.F., Ríos, A.F., 2003. Short-term variability of fCO2 in seawater and air–sea CO2 fluxes in a coastal upwelling system (Ría de Vigo, NW Spain). Mar. Chem. 80, 247–264.

García-Muñoz, M., Arístegui, J., Pelegrí, J.L., Antoranz, A., Ojeda, A., Torres, M., 2005. Exchange of carbon by an upwelling filament off Cape Guir (NW Africa). J. Mar. Syst. 54, 83–95.

Gardner, W.D., Biscaye, P.E., Richardson, M.J., 1997. A sediment trap experiment in the Vema Channel to evaluate the effect of horizontal particle fluxes on measured vertical fluxes. J. Mar. Res. 55, 995–1028.

Goñi, M.A., Aceves, H.L., Thunell, R.C., Tappa, E., Black, D., Astor, Y., Varela, R., Muller-Kager, F., 2003. Biogenic fluxes in the Cariaco Basin: a combined study of sinking particulates and underlying sediments. Deep Sea Res. I 50, 781–807.

Guerreiro, C., Oliveira, A., de Stigter, H., Cachao, M., Sá, C., Borges, C., Cros, L., Santos, A., Fortuño, J.M., Rodrigues, A., 2013. Late winter coccolithophore bloom off central Portugal in response to river discharge and upwelling. Cont. Shelf Res. 59, 65–83.

Hansen, H.P., Grassoff, K., 1983. Automated chemical analysis. In: Grasshoff, K., Ehrhadt, K., Kremling, K. (Eds.), Methods of Seawater Analysis. Verlag Chemie, Weinheim, pp. 347–395.

Haynes, R., Barton, E.D., 1990. A poleward flow along the Atlantic coast of the Iberian Peninsula. J. Geophys. Res. 95, 11425–11442.

Haynes, R., Barton, E.D., Pilling, I., 1993. Development, persistence, and variability of upwelling filaments off the Atlantic coast of the Iberian Peninsula. J. Geophys. Res. 98 (C12), 22681–22692.

Heussner, S., Ratti, C., Carbonne, J., 1990. The PPS 3 time-series sediment trap and the trap sample techniques used during the ECOMARGE experiment. Cont. Shelf Res. 10, 943–958.

Heussner, S., Durrieu du Madron, X., Calafat, A., Canals, M., Carbonne, J., Delsaut, N., Saragoni, G., 2006. Spatial and temporal variability of downward particle fluxes on a continental slope: Lessons from an 8-yr experiment in the Gulf of Lions (NW Mediterranean). Mar. Geol. 234, 63–92.

Honjo, S., Manganini, S.J., Krishfield, R.A., Francois, R., 2008. Particulate organic carbon fluxes to the ocean interior and factors controlling the biological pump: a synthesis of global sediment trap programs since 1983. Progr. Oceanogr. 76, 217–285.

JGOFS. Global Biogeochemistry and Global Change. IGBP Science No. 2., 2001. ISSN 1650–7770.

Joint, I., Inall, M., Torres, R., Figueiras, F.G., Álvarez-Salgado, X.A., Rees, A.P., Malcolm, E., Woodward, E.M.S., 2001. Two Lagrangian experiments in the Iberian Upwelling System: tracking an upwelling event and an off-shore filament. Prog. Oceanogr. 51, 221–248.

Liu, K.K., Atkinson, L., Quiñones, R., Talaue-McManus, L., 2010. Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis. Springer-Verlag, Berlin Heidelberg.

Lutz, M., Dunbar, R., Caldeira, K., 2002. Regional variability in the vertical flux of particulate organic carbon in the ocean interior. Glob. Biogeochem. Cy. 16 (3), 1–11.

Martin, J.H., Knauer, G.A., Karl, D.M., Broenkow, W.W., 1987. VERTEX: carbon cycling in the northeast Pacific. Deep-Sea Res. 34 (2), 267–285.

Moita, T.M., Silva, A., Palma, S., Vilarinho, M.G., 2010. The coccolithophore summer-autumn assemblage in the upwelling waters of Portugal: patterns of mesoscale distribution (1985–2005). Estuar. Coast Shelf S 87, 411–419.

Mortlock, R.A., Froelich, P.N., 1989. A simple method for the rapid determinations of

biogenic opal in pelagic marine sediments. Deep Sea Res. 36 (9), 1415–1426.

Muller-Karger, F.E., Varela, R., Thunell, R., Luersssen, R., Hu, C., Walsh, J.J., 2005. The importance of continental margins in the global carbon cycle. Geophys. Res. Lett. 31 (1), 1–4.

Oliveira, A., Rocha, F., Rodrigues, A., Jouanneau, J., Dias, A., Weber, O., Gomes, C., 2002. Clay minerals from the sedimentary cover from the Northwest Iberian shelf. Prog. Oceanogr. 52, 233–247.

Olli, K., Wexels Riser, C., Wassmann, P., Ratkova, T., Arashkevich, E., Pasternak, A., 2001. Vertical flux of biogenic matter during a Lagrangian study off the NW Spanish continental margin. Prog. Oceanogr. 51 (2–4), 443–466.

Otero, P., Ruiz-Villarreal, M., Peliz, A., Cabanas, J.M., 2010. Climatology and re-construction of runoff time series in northwest Iberia: influence in the shelf buoyancy budget off Ría de Vigo. Sci. Mar. 74 (2), 247–266.

Peña, M.A., Denman, K.L., Forber, J.R., Calvert, S.E., Thomson, R.E., 1996. Sinking particle fluxes from the euphotic zone over the continental slope of an eastern boundary current region. J. Mar. Res. 54, 1097–1122.

Piedracoba, S., Nieto-Cid, M., Teixeira, I.G., Garrido, J.L., Álvarez-Salgado, X.A., Rosón, G., Castro, C.G., Pérez, F.F., 2008. Physical–biological coupling in the coastal upwelling system of the Ría de Vigo (NW Spain). II: In vitro approach. Mar. Ecol. Prog. Ser. 353, 41–53.

Pilskaln, C.H., Paduan, J.B., Chavez, F.P., Anderson, R.Y., Berelson, W., 1996. Carbon export and regeneration in the coastal upwelling system of Monterey Bay, central California. J. Mar. Res. 54, 1149–1178.

Redfield, A.C., 1958. The biological control of chemical factors in the environment. Am. Sci. 46 (3), 205–221.

Schmidt, F., Hinrichs, K.U., Elvert, M., 2010. Sources, transport and partitioning of organic matter at a highly dynamic continental margin. Mar. Chem. 118, 37–55.

Suess, E., 1980. Particulate organic carbon flux in the oceans-surface productivity and oxygen utilization. Nature 288, 260–263.

Tenore, K.R., Alonso-Noval, M., Álvarez -Ossorio, M., Atkinson, L.P., Cabanas, J.M., Cal, R.M., Campos, H.J., Castillejo, F., Chesney, E.J., González, N., Hanson, R.B., McClain, C.R., Miranda, A., Roman, M.R., Sánchez, J., Santiago, G., Valdes, L., Varela, M., Yoder, J., 1995. Fisheries and oceanography off Galicia, NW Spain: mesoscale spatial and temporal changes in physical processes and resultant patterns of biological productivity. J. Geophys. Res. 100 (C6), 10943–10966.

Thunell, R.C., 1998. Particle fluxes in a coastal upwelling zone: sediment trap results from Santa Barbara Basin, California. Deep-Sea Res. II 45, 1863–1884.

Thunell, R., Benitez-Nelson, C., Varela, R., Astor, Y., Muller-Karger, F., 2007. Parti-culate organic carbon fluxes algong upwelling-dominated continental margins: rates and mechanisms. Glob. Biogeochem. Cy. 21, GB1022. http://dx.doi.org/10.1029/2006GB002793.

van Weering, T.C.E., Stigter, H.C., Boer, W., Haas, H., 2002. Recent sediment trans-port and accumulation on the NW Iberian margin. Prog. Oceanogr. 52, 349–371.

Varela, M., Prego, R., Pazos, Y., 2004. Vertical biogenic particle flux in a western Galician ria (NW Iberian Peninsula). Mar. Ecol. -Prog. Ser. 269, 17–32.

Vitorino, J., Oliveira, A., Jouanneau, J.M., Drago, T., 2002. Winter dynamics on the northern Portuguese shelf. Part 2: bottom boundary layers and sediment dis-persal. Progr. Oceanogr. 52 (2–4), 155–170.

Walsh, J.J., 1981. A carbon budget for overfishing off Peru. Nature 290, 300–304.

Wollast, R., 1998. Evaluation and Comparison of the Global Carbon Cycle in the Coastal Zone and in the Open Ocean in the Global Coastal Ocean. In: Brink, K.H., Robinson, A.R. (Eds.) John Wiley & Sons, Inc., pp. 213–252.

Wooster, W.S., Bakun, A., McLain, D.R., 1976. The seasonal upwelling cycle along the eastern boundary of the North Atlantic. J. Mar. Res. 34, 131–141.

Yentsch, C.S., Menzel, D.W., 1963. A method for the determination of phytoplankton chlorophyll and phaeophytin by fluorescence. Deep Sea Res. 10, 221–231.

Zúñiga, D., Alonso-Perez, F., Castro, C.G., Arbones, B., Figueiras, F., 2011. Seasonal contribution of living phytoplankton carbón to vertical fluxes in a coastal up-wellig system (Ría de Vigo, NW Spain). Cont. Shelf Res. 31, 414–424.