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Key Points:
- Organic carbon fluxes decreased at the coastal upwelling site CBeu (2003-2016). Both study sites show no signs of increasing upwelling
- We found a high temporal accordance of short-term peaks of biogenic silica and dust fluxes in winter to spring at the inner site CBeu
- The year 2005 is exceptional with a decoupling of coastal upwelling forced by NAO and particle fluxes

Correspondence to:
G. Fischer,
gerhard.fischer@uni-bremen.de

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Changes in the Dust-Influenced Biological Carbon Pump in the Canary Current System: Implications From a Coastal and an Offshore Sediment Trap Record Off Cape Blanc, Mauritania

G. Fischer[1,2], O. Romero[2], E. Toby[3], M. Iversen[4], B. Donner[2], G. Mollenhauer[4], N. Nowald[2], G. Ruhland[2], M. Klann[2], B. Hamady[5], and G. Wefer[2]

[1]Geosciences Department, University of Bremen, Bremen, Germany, [2]MARUM, Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany, [3]Senior Lecturer Emerita, Department of Statistics, Texas A&M University, College Station, TX, USA, [4]Alfred-Wegener Institute for Polar and Marine Research, Bremerhaven, Germany, [5]IMROP, Institut Mauritanien de Recherches Océanographiques et des Pêches, Nouadhibou, Mauritania

Abstract Long-term data characterizing the oceans' biological carbon pump are essential for understanding impacts of climate variability on marine ecosystems. The “Bakun upwelling intensification hypothesis” suggests intensified coastal upwelling due to a greater land-sea temperature gradient influenced by global warming. We present long time series of bathypelagic (approximately 1,200–3,600 m) particle fluxes from a coastal (CBeu: 2003–2016) and an offshore (CBmeso: 1988–2016) sediment trap setting located in the Canary Current upwelling. Organic carbon (C_{org}) and biogenic opal (BSi, diatoms) fluxes were twofold to threefold higher at the coastal upwelling site compared to the offshore site, respectively, and showed higher seasonality with flux maxima in spring. A relationship between winter and spring BSi fluxes to the North Atlantic Oscillation index was best expressed at the offshore site CBmeso. Lithogenic (dust) fluxes regularly peaked in winter when frequent low-altitude dust storms and deposition occurred, decreasing offshore by about threefold. We obtained a high temporal match of short-term peaks of BSi and dust fluxes in winter to spring at the inner site CBeu. We found synchronous flux variations at both sites and an anomalous year 2005, characterized by high BSi and C_{org} fluxes under a low North Atlantic Oscillation. C_{org} and BSi fluxes revealed a decreasing trend from 2006 to 2016 at the coastal site CBeu, pointing to coastal upwelling relaxation during the last two decades. The permanent offshore upwelling zone of the deflected Canary Current represented by the flux record of CBmeso showed no signs of increasing upwelling as well which contradicts the Bakun hypothesis.

1. Introduction

1.1. Biological Oceanography

Coastal upwelling systems such as the four major Eastern Boundary Upwelling systems (EBUEs; Fréon et al., 2009) have a high sensitivity to changes in the climate that regulates ocean stratification, upwelling, wind stress, dust supply, and basin wide circulation. Therefore, EBUEs are potential hotspots for observing climate change impacts on oceanic systems (Gruber, 2011; Garcìa-Reyes et al., 2015). The productivity dynamics of the EBUEs are mainly driven by the trade wind system, which is an important part of the global atmospheric circulation. Winds blowing parallel to the coast cause offshore Ekman transport and a replacement of warm coastal waters via upwelling by cold, nutrient- and CO_2-rich subsurface water masses close to the coast. Total primary production is relatively high (about 5% of the global marine production) especially given that the EBUEs comprise less than 1% of the total ocean area (Carr, 2002). Overall, the EBUEs contribute roughly 20% to the global fish catch (Fréon et al., 2009). Muller-Karger et al. (2005) argued that the oceanic biological carbon pump sequesters 40% of the carbon at continental margins.

Coastal upwelling under the influence of the NE trade winds system is well developed in the Canary Current (CC) EBUEs off NW Africa, in particular at certain upwelling filaments of which the Cape Blanc filament is the largest (Pelegrí et al., 2005). The “giant Cape Blanc filament” (Gabric et al., 1993; Van Camp et al., 1991) is a tongue of cold upwelled waters, spreading several hundreds of kilometers offshore. Upwelling filaments transport nutrient-rich coastal waters to the oligotrophic ocean (Àlvarez-Salgado et al., 2001) and are important transport pathways for particles (Karakas et al., 2006; Helmke et al., 2005; Figure 1). Coastal upwelling filaments form meandering structures that often form near large capes and specific bottom topography (Meunier et al., 2012). The Cape Blanc region is located in the southern part of the NW African upwelling where alongshore winds are strong all year long with some intensification in spring (Barton et al., 1998; Meunier et al., 2012). Our study sites are located at the southern rim of the permanent annual upwelling zone and the northern boundary of the Mauritanian-Senegalese seasonal upwelling zone (Cropper et al., 2014; Figure 1). Most of the year's productivity in EBUEs is assumed to be produced by rather short (daily to weekly) but massive blooms of mostly diatoms, coincident with cold-water upwelling events (Summerhayes et al., 1973).

Upwelling of cold and nutrient-rich subsurface waters causes high biological productivity in the CC-EBUEs although nutrient levels are rather low compared to the Peruvian upwelling (Summerhayes et al., 1973). The Cape Blanc area is situated north of the Cape Verde Frontal System (CVFS; Pelegrí et al., 2017; Zenk et al., 1991), which is a major open-ocean boundary, separating tropical from subtropical water masses (Figure 1). However, at the continental slope, a meridional exchange between both regions occurs with opposing along-slope flows of the Mauritania Current (MC) and the poleward undercurrent (PUC; Figure 1). The Cape Verde Frontal System separates the saltier and nutrient-poor North Atlantic Central Water (NACW) from the South ACW (SACW; Mittelstaedt, 1991). Both water masses are upwelled around the Cape Blanc area and mixed laterally while spreading offshore. It has been shown that macronutrient supply is the dominating regulating factor in the CC-EBUEs and iron limitation was found to be less important (Messié & Chavez, 2015). Site CBeu is within the coastal Ekman-driven upwelling, a narrow band on the shelf break, whereas CBmeso is located within the broader offshore upwelling region resulting from positive wind curl stress, leading to more local upward Ekman pumping (Pastor et al., 2013). However, both sites are connected by the lateral advection of water masses within the filament, of chlorophyll (Helmke et al., 2005) and sinking particles (Karakas et al., 2006). Site CBeu is more under the influence of the northward moving warm MC and the nutrient-rich SACW while site CBmeso is located approximately 220 km farther offshore in the southwestward deflected CC and experiences a higher contribution of the low-nutrient NACW as source water (Meunier et al., 2012; Figure 1).

1.2. Atmospheric Influences and Cape Blanc Wind Data

Mineral dust may impact on the efficiency of the biological carbon pump preferentially in two ways. First, due to the iron input (e.g., Jickells et al., 2005) and nutrient input to the surface waters (e.g., Mahowald et al., 2010) which appears to be less important in this region (Messié & Chavez, 2015; Neuer et al., 2004). Second, the biological carbon pump may be affected via the ballasting effect (Armstrong et al., 2002; Ittekkot, 1993; Klaas & Archer, 2002; Lutz et al., 2007; Van der Jagt et al., 2018) that leads to increased particle densities and settling rates (Ploug, Iversen, & Fischer, 2008; Iversen & Ploug, 2010). Ittekkot (1993) emphasized the role of episodic abiotic inputs, that is, of riverine lithogenic materials for the biological carbon pump, which result in increased deep sea carbon sequestration. Simulated dust events in mesocosms further underline the importance of ballast for organic carbon fluxes (e.g., Bressac et al., 2014). However, there is some debate about which ballast is most important for the biological carbon pump (Klaas & Archer, 2002; Thunell et al., 2007). Some authors even question the ballast hypothesis (e.g., Passow & de La Rocha, 2006) or favor a regional variability for the importance of dust for export fluxes (Iversen et al., 2010; Le Moigne et al., 2014; Wilson et al., 2012). In this paper, we only consider the role of mineral ballast for the biological carbon pump rather than the nutrient input from dust outbreaks or by lateral advection.

The interactions of organic-rich marine snow particles with mineral ballast, in particular the high dust availability in the NW African upwelling system, may result in a relatively high carbon sequestration flux compared to the other EBUEs (Fischer, Karakas, et al., 2009; Iversen et al., 2010; Van der Jagt et al., 2018). During winter and spring, dust is most frequently transported within the low-level NE trade winds to coastal Mauritania and deposited offshore above the sediment-trap sites (Bory & Newton, 2000; Friese et al., 2016; Ratmeyer, Fischer, et al., 1999, Ratmeyer, Balzer, et al., 1999; Stuut et al., 2005; Korte et al., 2017). In contrast, dust in summer, as seen in satellite aerosol optical depth, is transported primarily at higher altitudes (via the Saharan Air Layer, SAL, Carlson & Prospero, 1972) to the Americas (e.g., Prospero et al., 2010). Atmospheric dust loadings during fall are generally low (Knippertz & Todd, 2012). During summer, the

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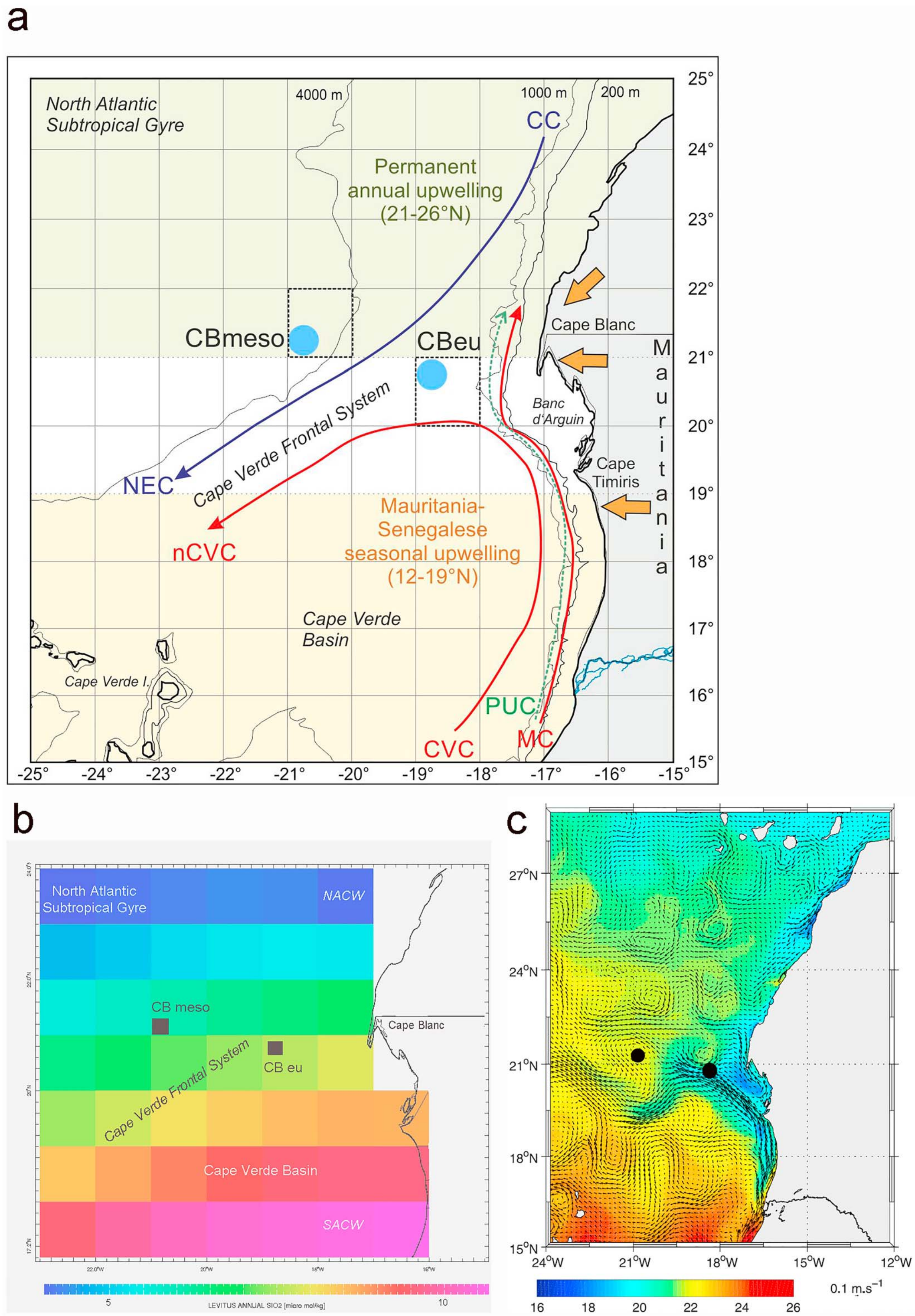

Figure 1. Description of the study area. (a) Major currents systems in the Cape Verde Basin and the Cape Blanc filament area (Pelegrí et al., 2017) and the CBmeso and CBeu study sites. High dust supply is indicated by orange arrows. Each 1° × 1° box at the sites (stippled) shows areas were additional web-based environmental data were used. (b) Dissolved silicate in 250-m water depth in the source waters of upwelling, indicating major influences of SACW on CBeu and NACW on CBmeso. (c) Major currents underlain by SST in spring (May) off NW Africa (modified from Karakas et al., 2006). CC = Canary Current; NEC = North Equatorial Current; MC = Mauritanian Current; CVC = Cape Verde Current (*n* = northern); PUC = Poleward Undercurrent.

Cape Blanc region is under the influence of the Intertropical Convergence Zone (ITCZ) or the Inter Tropical Front (Nicholson, 2013), which shift meridionally from ca. 12°N (winter) to 21° (summer), then approaching the study area. A clear coupling between atmospheric dust occurrence and deep-sea lithogenic fluxes is observed in the subtropical North Atlantic (Brust et al., 2011). The seasonally and regionally changing dust depositions may therefore have a direct impact on the efficiency of the biological pump, even on a small spatial scale as between the two sites studied here.

1.3. North Atlantic Climatic Variability, Global Change, and Potential Impacts on NW African Upwelling

The North Atlantic Oscillation (NAO) influences not only the intensity of the NW African coastal upwelling but also the supply of Saharan dust into the eastern North Atlantic (Chiapello et al., 2005). A positive phase of the NAO is associated with increased pressure of the Azores high and results in stronger trade winds along the NW African coast. Low frequency climate variability such as the Atlantic Multidecadal Oscillation (AMO) and the Atlantic Meridional Overturning Circulation (AMOC) may impact on the study area as well. Besides global warming and increased water column stratification, EBUEs are expected to change due to increasing wind and upwelling might intensify at least in certain regions (Bakun, 1990; Bakun et al., 2010, 2015; Cropper et al., 2014; Garcìa-Reyes et al., 2015). The Bakun upwelling intensification hypothesis (Cropper et al., 2014) suggests increasing coastal upwelling north of 20°N while decreasing upwelling happens in the Mauritanian-Senegalese seasonal upwelling zone. However, there is a considerable debate whether such wind field changes support Bakun's hypothesis (e.g., Garcìa-Reyes et al., 2015; Sydeman et al., 2014; Varela et al., 2015; Wang et al., 2015). Altogether, the response of climate change-driven increasing trade winds and stronger upwelling intensity on carbon export to the continental margin sediments are largely unknown and may vary regionally.

Satellite remote sensing has enabled oceanographers to monitor long-term changes in the surface ocean for decades. However, remote sensing cannot quantify carbon export and sequestration to the deep ocean. Export fluxes at continental margins are complicated by significant cross-shelf export of coastal chlorophyll and resuspended biogenic and nonbiogenic shelf material (e.g., Arístegui et al., 2004; Barton et al., 1998; Helmke et al., 2005; Karakas et al., 2006; Lovecchio et al., 2018; Pelegrí et al., 2005). As persistent upwelling occurs off Cape Blanc, this is a major hotspot for offshore advection of particles (Karakas et al., 2006; Lovecchio et al., 2017) but the fate of organic matter and the transport processes remain largely unresolved on regional and temporal scales. Van Camp et al. (1991), Pelegrí et al. (2005), and Gabric et al. (1993) estimated that offshore advection could cause a cross-shelf exchange of organic carbon of approximately 50% of the coastal new production. Similar advective processes occur at other EBUEs (e.g., Barth et al., 2002), suggesting that particle transport and sedimentation processes observed off Cape Blanc apply to other EBUEs. Finally, due to coastal increased upwelling and global climate change, an increase in lateral transport has to be considered for the EBUEs (Bakun et al., 2010, 2015; Garcìa-Reyes et al., 2015).

Long-term biological data from the ocean are essential for understanding climate change impacts on marine ecosystems (Doney et al., 2012; Ducklow et al., 2009). The longer the time scales of observations, the better to detect anthropogenic effects from substantial natural climate variability, for example, from the NAO. Here we report on the long-term variability of the particle fluxes and composition at the coastal eutrophic CBeu site (2003–2016) and the offshore mesotrophic CBmeso site (1988–2016; Figure 1), both located within the CC-EBUEs. We will focus on the record from the coastal upwelling at CBeu which is located close to the CVFS (Pelegrí et al., 2017; Zenk et al., 1991) and is influenced by the warm northward Mauritanian Current as well. CBeu is located in a highly dynamic coastal upwelling zone where carbon sinking in the water column and deposition to the seafloor is maximal, that is, at the slope depocenter. We will focus on the interaction of atmospheric dust as a major ballast mineral for marine snow aggregates (Van der Jagt et al., 2018) and study the marine carbon pump (BSi flux) over interannual to decadal timescales. In a second step, we integrate the flux records from site CBmeso, which have been reported on earlier (lower trap record from 1988 to 2012; Fischer et al., 2016). Meanwhile, we have extended the record by another 4 years at CBmeso (1988–2016) and here we include the upper trap time series offshore record at CBmeso as well. This will allow for a comparison to the synchronous fluxes at the eutrophic site CBeu over more than one decade. In addition, we are now able to provide a more detailed picture of the cross-shelf particle export of biogenic and nonbiogenic materials due to the longer record, mainly at the mesotrophic site (Table 1).

Table 1
Characterization of the Study Sites

Study sites seasons	Setting	Chlorophyll range and peaks mg/m^3	SST range °C	MLD range m	Major source water with silicate μM	Silicate in 250 m (mean) μM	Nitrate μM
							(Arìstegui et al., 2009)
CB Eutrophic	coastal upwelling	0–5 with peaks of 10–25	18–25	5–40	SACW ~10	~6.5	15–20
Winter–Spring			18–19	30–40			
Summer–Fall			24–25	5–10			
CB Mesotrophic	offshore wind-driven	0–1 rare peaks of up to 2	19–27	25–85	NACW ~4	~7.5	~9–15
Winter–Spring			19–22	55–85			
Summer–Fall			24–27	25–35			

NACW = North Atlantic Central Water
SACW = South Atlantic Central Water

2. Material and Methods

Particle fluxes were measured with deep-moored time series sediment trap arrays at CBmeso (upper and lower traps, approximately 1,300 and 3,600 m) and at CBeu (upper and lower traps, approximately 1,00 and 1,800 m). Kiel-AQUATEC (Kremling et al., 1996) and HONJO-type (McLANE) sediment traps with 20/40 sampling cups were employed. The mesotrophic site was located about 200 nautical miles (approximately 370 km) off Cape Blanc (approximately 21°15.N/20°45.W) in about 4,100-m water depth. The CBeu mooring (approximately 20°45.N/18°40.W) was around 80 nautical miles (approximately 150 km) offshore at the continental slope below the highly productive Cape Blanc filament (Mauritania) in about 2,750-m water depth. For the CBeu site, we show only the upper trap fluxes because the lower trap is only approximately 500-m deeper and hence, not comparable to CBmeso (Table 2 and 3). Sediment traps were deployed at bathypelagic depths except during the deployments of CBmeso-3 and 4. Current meter data (rotary and ACP) indicated a predominant southward flow with an average velocity of ca. 3 cm/s (with a range between 0 and 8 cm/s) in the lower NADW (deep CBmeso trap, 3,600 m) and about twice higher in the 1,200-m traps of CBmeso (upper NADW). During the CBeu deployments 6 and 7 (2008–2010; Nowald et al., 2015), ACP-derived currents varied between 1 and 10 cm/s (hence, mostly below the critical value of about 12 m/s when trapping efficiency may be reduced; Baker et al., 1988).

Preparation of the sampling cups, poisoning ($HgCl_2$) and storage of the collected samples were described in detail elsewhere (Fischer et al., 2016; Fischer & Wefer, 1991). Using freeze-dried wet ¼ or $^1/_5$ splits, the analysis of the <1-mm fraction for bulk (total mass), organic carbon, total nitrogen, carbonate, and biogenic opal (BSi = biogenic silica) followed Fischer and Wefer (1991). BSi fluxes were measured according to Müller and Schneider (1993), without including the variable water content of biogenic opal (around 5%–10%) in the calculation. The lithogenic (=nonbiogenic) flux was estimated as the difference between the total mass and the biogenic components (BSi, carbonate, and organic matter), whereby organic matter was derived from organic carbon using a multiplication factor of 2 (Hedges et al., 2002). We relate the lithogenic flux to dust-derived material (=mineral dust flux; Fischer et al., 2016). We did not correct fluxes for dissolution of particles in the supernatants of the sampling cups. In a study of the supernatants of the deployment CB-1, Fischer and Wefer (1991) found that the annual BSi fluxes were underestimated by only about 2.5% when correcting for elevated silicate concentrations in the supernatants.

The time resolutions of the sediment trap collections vary between 7.5 and 23 days (Tables 2 and 3). We determined average seasonal and yearly fluxes to evaluate the intra-annual and interannual variability of mass fluxes over the entire sampling periods. Seasons are determined by the switching of the sampling cups closest to the start of the astronomical seasons (Fischer et al., 2016). The mode of particle transport (vertical vs. lateral) is largely dependent on particle settling velocities (s.v.). For the estimation of s.v.

Table 2
Trap Data of CB eu

Mooring Name	LAT N	LONG W	Water depth m	Trap depth m	Sampling start	end	Samples × cup resolution days	Relevant references	Relevant cruise GeoB-no of recovery
CB eu-1	20°45.0′	18°42.0′	2,714	1,296	5 August 2003	5 April 2004	1 × 10.5, 19 × 15.5	Mollenhauer et al. (2015) and Romero and Fischer (2017)	POS 310/no GeoB
				1,876	5 August 2003	5 April 2004	1 × 10.5, 19 × 15.5		
CB eu-2	20°45.0′	18°42.0′	2,714	1,296	18 April 2004	20 July 2005	2 × 22, 18 × 23	Mollenhauer et al. (2015) and Romero and Fischer (2017)	M 65-2/GeoB 9630-2
				1,876	18 April 2004	20 July 2005	2 × 22, 18 × 23		
CB eu-3	20°45.5′	18°41.9′	2,693	1,277	25 July 2005	28 September 2006	20 × 21.5	Mollenhauer et al. (2015) and Romero and Fischer (2017)	POS 344/GeoB 11404-3
CB eu-4	20°45.7′	18°42.4′	2,705	1,256	28 October 2006	23 March 2007	1 × 3.5, 19 × 7.5	Mollenhauer et al. (2015) and Romero and Fischer (2017)	MSM 04b/GeoB 11835-2
				1,866	28 October 2006	23 March 2007	1 × 3.5, 19 × 7.5		
CB eu-5	20°44.9′	18°42.7′	2,709	1,263	28 March 2007	17 March 2008	2 × 6.5, 36 × 9.5	Nowald et al. (2015) and Romero and Fischer (2017)	POS 365-2/GeoB 12910-2
CB eu-6	20°45.1′	18°41.9′	2,699	1,263	26 April 2008	22 March 2009	2 × 3.5, 38 × 8.5	Nowald et al. (2015) and Romero and Fischer (2017)	MSM 11-2/GoeB 13612-1
CB eu-7	20°44.6′	18°42.7′	2,761	1,364	1 April 2009	28 February 2010	37 × 9	Romero and Fischer (2017)	POS 396/GeoB 14202-4
				1,923	1 April 2009	28 February 2010	18 × 18, 1 × 9.3		
CB eu-8	20°44.5'	18°42.8'	2,720	1,322	6 March 2010	27 August 2010	17 × 10, 1 × 4		MSM 18-1/GeoB 15703-2
				1,882	6 March 2010	10 April 2011	20 × 20		
CB eu-9	20°46.7′	18°44.1′	2,770	1,362	1 May 2011	21 January 2012	15 × 17, 1 × 10.5		POS 425/GeoB 16103-1
				1,883	1 May 2011	21 January 2012	15 × 17, 1 × 10.5		
CB eu-10	20°46.6′	18°44.2′	2,712	1,318	26 January 2012	26 January 2013	1 × 4, 1 × 7.1, 33 × 10.75		POS 445/GeoB 17108-3
				1,875	26 January 2012	26 January 2013	15 × 21.5, 1 × 50		
CB eu-11	20°46.4′	18°44.4′	2,800	1,299	29 January 2013	10 February 2014	17 × 21, 1 × 20.5		POS 464/GeoB 18006-2
				1,963	29 January 2013	10 February 2014	17 × 21, 1 × 20.5		
CB eu-12	20°46.4′	18°44.5′	2,750	1,249	14 February 2014	23 February 2015	1 × 12,5, 1 × 10.9, 18 × 19.5		POS 481/GeoB 19402-1
				1,913	14 February 2014	23 February 2015	1 × 12,5, 1 × 10.9, 18 × 19.5		
CB eu-13	20°53.0′	18°43.9′	2,739	1,346 1903	27 February 2015	18 February 2016	1 × 14, 19 × 18		POS 495(GeoB 20702-1

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Table 3
Trap data of CB meso

Mooring-Deployment	LAT N	LONG W	Water depth m	Trap depth m	Sampling start	end	Samples × cup resolution days	Relevant references	Relevant cruise/ GeoB-no of recovery
CB meso-1	20°45.3′	19°44.5′	3,646	2,195	22.03.88	08.03.89	13 × 27	Fischer et al. (1996, 2016) Müller and Fischer (2001)	Meteor 9/4/GeoB 1121-4
CB meso-2	21°08.7′	20°41.2′	4,092	3,502	15.03.89	24.03.90	22 × 17	Fischer et al. (1996, 2016) Müller and Fischer (2001)	Meteor 12/1/GeoB 1230-1
CB meso-3	21°08.3′	20°40.3′	4,094	730	08.04.90	30.04.91	18 × 21.5	Müller and Fischer (2001)	Polarstern ANT IX/4/no GeoB
				3,557	29.04.90	08.04.91	16 × 21.5	Fischer et al. (1996, 2016)	
CB meso-4	21°08.7′	20°41.2′	4,108	733	03.03.91	19.11.91	20 × 10	Müller and Fischer (2001)	Meteor 20/1/GeoB 1602-1
				3,562	03.03.91	19.11.91	20 × 10	Fischer et al. (1996, 2016)	
CB meso-5	21°08.6′	20°40.9′	4,119	3,587	06.06.94	27.08.94	19 × 4.33	Fischer et al. (2016)	Meteor 29/3/GeoB 2912-1
CB meso-6	21°15.0′	20°41.8′	4,137	771	02.09.94	25.10.95	20 × 22	Fischer et al. (2016)	Polarstern ANT XIII/1/no GeoB
CB meso-7	21°15.4′	20°41.8′	4,152	755	20.11.95	29.01.97	1 × 29, 11 × 22, 1 × 165		Meteor 38/1/GeoB 4302-7
				3,586	20.11.95	29.01.97	1 × 29, 18 × 22, 1 × 11	Fischer et al. (2016)	
CB meso-8	21°16.3′	20°41.5′	4,120	745	30.01.97	04.06.98	20 × 24.6	Fischer et al. (2016)	Meteor 41/4/GeoB 5210-2
CB meso-9	21°15.2′	20°42.4′	4,121	746	11.06.98	07.11.99	1 × 7.5, 18 × 27.5, 1 × 11.5		Meteor 46/1/GeoB 6103-3
				3,580	11.06.98	07.11.99	1 × 7.5, 18 × 27.5, 1 × 11.5	Helmke et al. (2005) and Fischer et al. (2016)	
CB meso-10	21°17.2′	20°44.1′	4,125	1,003	10.11.99	10.10.00	2 × 18, 1 × 297		Polarstern ANT XVIII/1/ no GeoB
				3,586	10.11.99	10.10.00	2 × 18, 1 × 297	Fischer et al. (2016)	
CB meso-11	21°16.8′	20°43.0′	4,113	1,003	11.10.00	30.03.01	20 × 8.5	Fischer et al. (2016)	Poseidon 272/GeoB 7401-1
CB meso-12	21°16.0′	20°46.5′	4,145	3,610	05.04.01	22.04.02	1 × 25.3, 12 × 19.3, 1 × 125	Fischer et al. (2016)	Meteor 53/1c/GeoB 7917-1
CB meso-13	21°16.8′	20°46.7′	4,131	1,228	23.04.02	08.05.03	20 × 19	Fischer, Reuter, et al. (2009)	Meteor 58/2b/GeoB 8628-1
				3,606	23.04.02	08.05.03	20 × 19	Fischer, Reuter, et al. (2009) Fischer and Karakas (2009)	
CB meso-14	21°17.2′	20°47.6′	4,162	1,246	31.05.03	05.04.04	20 × 15.5		Poseidon 310/no GeoB
CB meso-15	21°17.9′	20°47.8′	4,162	1,269	17.04.04	21.07.05	20 × 23		Meteor 65/2/no GeoB
				3,624	17.04.04	21.07.05	20 × 23	Fischer et al. (2016)	
CB meso-16	21°16.8′	20°47.8′	4,160	1,258	25.07.05	28.09.06	20 × 21.5		Poseidon 344/1/GeoB 11401-1
				3,633	25.07.05	28.09.06	20 × 21.5	Fischer et al. (2016)	
CB meso-17	21°16.4′	20.48.2′	4,152	1,204	24.10.06	25.03.07	20 × 7.5		Merian 04/b/GeoB 11833-1
				3,614	24.10.06	25.03.07	20 × 7.5	Fischer et al. (2016)	
CB meso-18	21°16.9′	20°48.1′	4,168	1,222	25.03.07	05.04.08	1 × 16, 19 × 19		Poseidon 365/2/GeoB 12907-1
				3,629	25.03.07	05.04.08	1 × 16, 19 × 19	Fischer et al. (2016)	
CB meso-19	21°16.2′	20°48.7′	4,155	1,209	22.04.08	02.04.09	1 × 11, 14 × 17, 1 × 96.5		
				3,617	22.04.08	22.03.09	1 × 11, 19 × 17	Fischer et al. (2016)	Merian 11/2/GeoB 13616-4
CB meso-20	21°15.6′	20°50.7′	4,170	1,224	03.04.09	26.02.10	1 × 16, 17 × 18, 1 × 7.5		Poseidon 396/GeoB 14201-3
CB meso-21	21°15.6′	20°50.9′	4,155	1,209	28.02.10	04.04.11	20 × 20		Merian 18/1/GeoB 15709-1
				3,617	28.02.10	04.04.11	20 × 20	Fischer et al. (2016)	
CB meso-22	21°16.1′	20°50.9′	4,160	1,214	05.05.11	11.01.12	1 × 262		Poseidon 425/GeoB 16101-1

Table 3
(continued)

Mooring-Deployment	LAT N	LONG W	Water depth m	Trap depth m	Sampling start	end	Samples × cup resolution days	Relevant references	Relevant cruise/GeoB-no of recovery
				3,622	05.05.11	11.01.12	15 × 17	Fischer et al. (2016)	
CB meso-23	21°15.8′	20°52.4′	4,154	1,218	20.01.12	22.01.13	17 × 21.6, 1 × 2.8		
				3,626	20.01.12	22.01.13	17 × 21.6, 1x2.8	Fischer et al. (2016)	Poseidon 445/GeoB 17102-5
CB meso-24	21°16.9′	20°50.6′	4,160	1,214	24.01.13	05.02.14	1 × 26, 16 × 21, 1 × 15.6		Poseidon 464/GeoB 18001-1
				3,622	24.01.13	05.02.14	1 × 378		
CB meso-25	21°17.8′	20°50.6′	4,160	3,622	07.02.14	12.02.15	19 × 19.5		Poseidon 481/GeoB 19401-1
CB meso-26	21°17.3′	20°52.0′	4,176	1,232	23.02.15	18.02.16	20 × 18		Poseidon 495/GeoB 20701-1

within the Cape Blanc filament over several years, we apply the benchmark method (Armstrong et al., 2009; Honjo, 1996) to the flux patterns of the upper and lower traps.

2.1. Additional Web Data

We extracted observational time series data sets from GIOVANNI (chlorophyll, SSTs = sea surface temperatures). For site CBeu, we used a 1° × 1° box from 20 to 21°N and 18 to 19°W (9-km resolution) to the southeast of the study site due to the main surface currents (Figure 1). For site CBmeso, we have similarly chosen a 1° × 1° box from 21 to 22°N and 20 to 21°W due to the prevailing SW directed surface currents (Figure 1). These selected boxes (= estimated particle catchment areas) are related to the findings about the statistical funnels areas (e.g., of Siegel & Deuser, 1997), which largely depend in particle sinking rates. As these rates are rather high off Cape Blanc, we assumed a catchment area (1° × 1° box) relatively close to the mooring positions under consideration of the main surface currents. For the estimation of the westward extension of the Cape Blanc filament with high chlorophyll standing stock (>1 mg/m^3), we used the seasonal MODIS ocean color of 9-km resolution and considered the 21°N latitude as reference to calculate the distance to Cape Blanc, Mauritania. Most important webpages used were as follows:

1. GIOVANNI (ocean color and SSTs): https://giovanni.gsfc.nasa.gov/giovanni/#service=TmAvMp&starttime=&endtime=&bbox=-19,20,-18,21
2. NAO (Hurrell et al., 1995) index based on station data of sea level pressure: http://climatedataguide.ucar.edu/guidance/hurrell-north-atlantic-oscillation-nao-index-station-based
3. NAO 1 (Gibraltar-Iceland sea level pressure) Jones et al. (1997): https://crudata.uea.ac.uk/cru/data/nao/

3. Results

3.1. Environmental Data and Organic Carbon and BSi in the Coastal Record CBeu From 2003 to 2016

Rather than using regional data sets (e.g., for NW Africa), we applied local wind data from Nouadhibou airport at Cape Blanc (Figure 2) as they might be more important for the local coastal upwelling at site CBeu located only approximately 150-km offshore. Daily wind velocities from Cape Blanc increase during winter, reach maxima during spring and show a clear tendency to lower values from 1988 to 2017. This is even better seen when applying the means of the spring season only (Figure 2c), the time of upwelling-favorable winds which should influence the trap site CBeu. Additionally, wind direction changes from more northwesterly to northerly directions during spring around 2005 (Figures 2b and 2c). During phases of weak winds at the turn of the year, a change of the directions from around 90° (easterly winds) before 2005 to 180° (southerly winds) after 2005 is observed (Figure 2b). The strong 1997–1999 ENSO event can be recognized by higher spring winds from more easterly directions; this event is seen in changing fluxes at site CBmeso as well (Fischer et al., 2016).

We observed coldest SSTs (approximately 19 °C) in winter and the highest during summer (approximately 25 °C). However, mean summer SSTs showed a shift between 2003 and 2005 (24.5 °C) and 2006 and 2015 (25.3 °C) toward higher SSTs (Figure 3a). Such a shift was not observed for the winter SSTs which remained almost constant at 19 °C (Figure 3a). This suggests the upwelling region off Cape Blanc has experienced increased seasonality in terms of

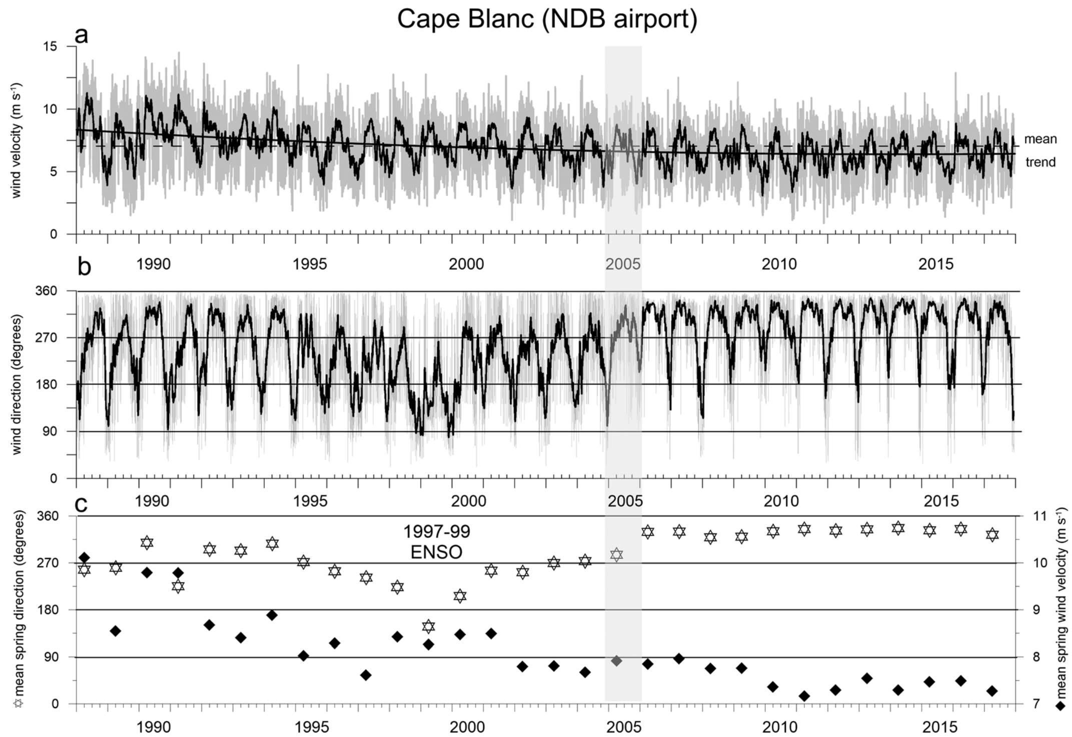

Figure 2. Daily wind velocity (a) and direction (b; shaded gray, with running average in thick black lines) and mean spring wind velocities and directions (c). Note the change in spring wind directions around 2005 (vertical grey bar) and the long-term decreasing trends in wind velocity (a, c).

SSTs since 2005. We generally observe an increase in surface chlorophyll with increasing SSTs (Figure 3a). This biomass pattern was reflected in the peak export of organic carbon (i.e., in 2005 and 2014) during spring. Deep carbon flux peaks were rarely observed in fall at CBeu except in December 2004 (almost 100 mg m^{-2} day^{-1}), although chlorophyll standing stock was low (Figure 3). This carbon pulse induced by the sedimentation of fast settling appendicularian fecal pellets (Ploug, Iversen, & Fischer, 2008) was the highest short-term carbon flux peak during the entire CBeu record (Figure 3c).

We observed high surface chlorophyll between 2005 and 2007 (around 15–25 mg Chl m^{-3}) and between 2011 and 2015 (approximately 10–20 mg Chl m^{-3}; Figure 3a). The organic carbon flux increased during the same period as well. However, we found no overall correlation between chlorophyll and the organic carbon fluxes. Organic carbon fluxes were highest in spring 2006 and decreased afterward until 2011. In summer 2013 and spring 2015, organic fluxes were extraordinary high again. These long-term trends are reflected in the extension of the Cape Blanc filament with a far westward extension in 2006 and 2014 (Figure 3b). Taking all the individual cup data for organic carbon fluxes, statistical evidence for an organic carbon flux decrease from 2003 to 2016 is obtained with a slope of −0.85 (p value = 0.028). However, the seasonal and annual means do not provide a statistical significant evidence for an organic carbon flux decrease.

BSi largely followed organic carbon fluxes (Table 4; R = 0.97–0.74) and correlation plots indicate comparable slopes and intercepts for all seasons. Similar to organic carbon (Figure 3c), highest seasonal BSi fluxes were observed in spring 2006, reaching ca. 65 mg m^{-2} day^{-1} (Figure 4a), where after the values decreased continuously until 2010–2011. Mean spring BSi values were related to the extent of the Cape Blanc filament (r = 0.72, N = 12). High summer BSi peaks occurred in 2003 and during a longer period in 2011 and 2013. Noticeably, high BSi fluxes in summer were found for the CBmeso offshore site in 2003 and 2010–2011 (Figure 4a). Correlations between the major biogenic and nonbiogenic components

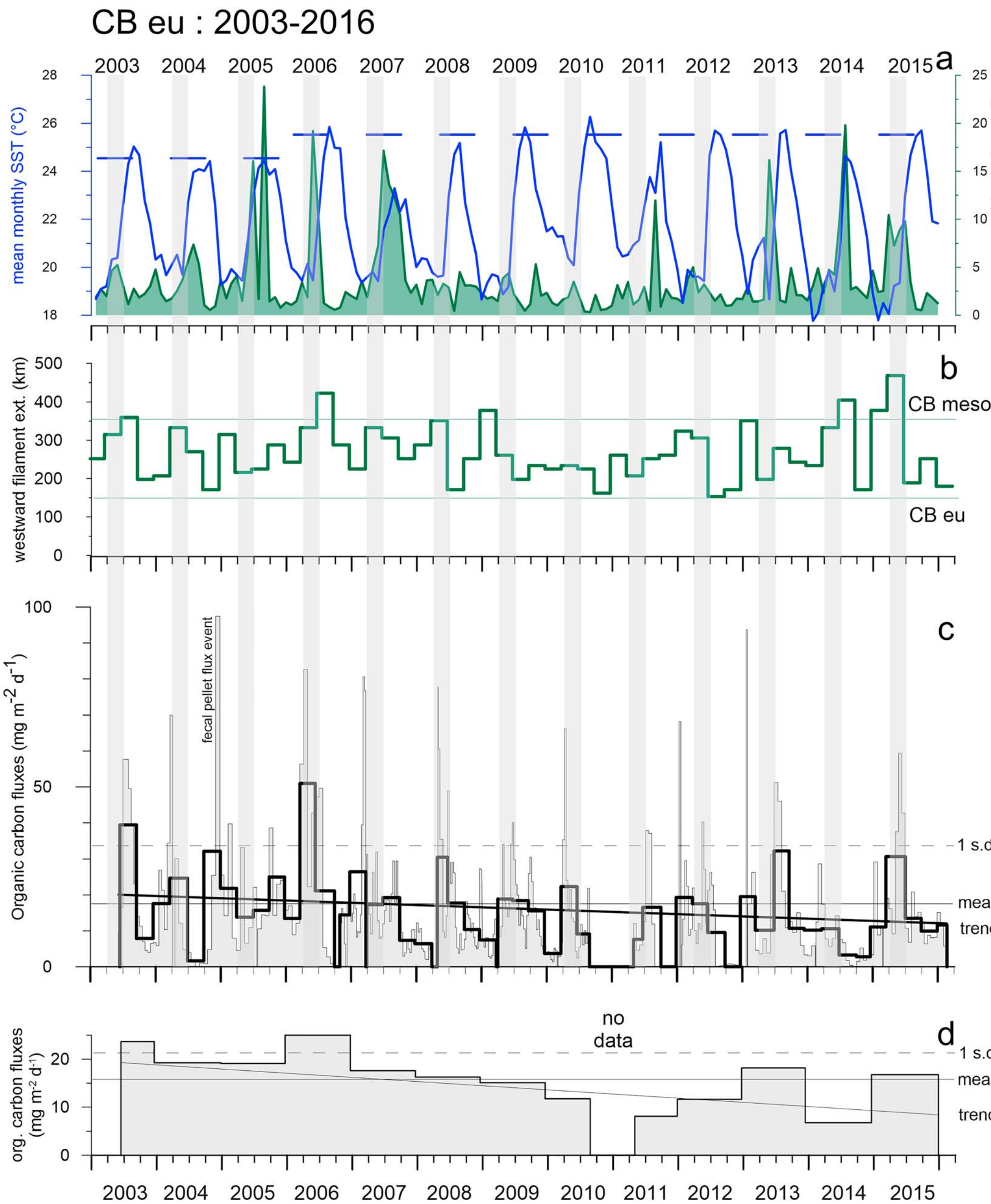

Figure 3. (a) Mean monthly SST and chlorophyll time-series from the CBeu box (GIOVANNI; see Figure 1). Note the change in mean summer SSTs since 2005 by almost 1 °C (vertical dashed line), (b) westward extension of the Cape Blanc filament at 21°N (Cape Blanc). (c, d) Mean daily carbon fluxes on daily, seasonal and annual scales with means, 1 standard deviations and trends. Note the decrease in carbon fluxes in c with a slope of −0.85 (line). The standard deviation of daily carbon fluxes is given for the identification of major carbon flux peaks in c.

revealed a close correlation between organic carbon and BSi to total carbonate and the lithogenic fraction (=dust-derived minerals; Table 4). Organic carbon and lithogenic fluxes correlated well during all seasons except during fall when dust deposition is generally low (Knippertz & Todd, 2012). During the spring bloom, total carbonate did not correlate strongly to organic carbon fluxes ($r = 0.54$, $N = 12$), possibly due to a significant contribution from foraminifera and pteropods to total carbonate flux (Fischer, Karakas, et al., 2009).

Table 4
Correlation of Organic Carbon to Bulk Flux Components

	CB eutrophic (upper trap) 1–13				CB mesotrophic (upper trap) 3–26					CB mesotrophic (lower trap) 1–26				
Organic carbon	winter	spring	summer	fall	organic carbon	winter	spring	summer	fall	organic carbon	winter	spring	summer	fall
BSi	**R = 0.74** N = 12 s = 2.7 I = −1.4	R = 0.94 N = 12 s = 2.8 I = 1.5	R = 0.93 N = 13 s = 2.3 I = −2.4	R = 0.97 N = 10 s = 2.2 I = −3.9	BSi	R = 0.85 N = 18 s = 1.1 I = −0.69	R = 0.69 N = 19 s = 1.3 I = −2.8 (Outlier 2015)	R = 0.74 N = 18 s = 0.78 I = 0.27	R = 0.81 N = 19 s = 0.91 I = −0.88	BSi	R = 0.80 N = 19 s = 1.2 I = 0.5	R = 0.75 N = 20 s = 2.4 I = −5.3	R = 0.75 N = 20 s = 1.3 I = −0.7	R = 0.83 N = 19 s = 1.7 I = −1.8
Carbonate	R = 0.87 N = 12 s = 7.8 I = 2.3	**R = 0.54** N = 12 s = 2.9 **I = 101.4**	**R = 0.70** N = 13 s = 3.8 **I = 47.4**	R = 0.89 N = 10 s = 6.8 I = 5.7	carbonate	R = 0.86 N = 18 s = 10.0 I = −5.5	R = 0.88 N = 19 s = 10.2 I = −0.03	**R = 0.56** N = 18 s = 6.0 **I = 35.4**	R = 0.87 N = 19 s = 8.3 I = 3.4	carbonate	**R = 0.66** N = 19 s = 7.7 I = 30.4	**R = 0.62** N = 20 s = 9.6 I = 23.4	**R = 0.25** N = 20 s = 4.3 I = 70.8	R = 0.80 N = 19 s = 11.5 I = 5.7
Lithogenic (=mineral dust)	**R = 0.75** N = 12 s = 7.7 I = −6.5	R = 0.88 N = 12 s = −5.4 I = −17.8	R = 0.89 N = 13 s = 3.8 I = 8.4	**R = 0.60** N = 10 s = 3.1 I = 32.1	lithogenic (=mineral dust)	R = 0.87 N = 18 s = 6.1 I = −7.8	R = 0.79 N = 19 s = 4.0 I=−3.0	R = 0.77 N = 18 s = 2.3 I = 7.2	R = 0.91 N = 18 s = 5.6 I = −7.7	lithogenic (=mineral dust)	R = 0.81 N = 19 s = 7.2 I = 3.8	R = 0.75 N = 20 s = 10.4 I = −14.3	**R = 0.56** N = 20 s = 4.7 I = 8.8	R = 0.78 N = 19 s = 9.5 I = −4.8

Note. Bold = not significant at the 99.9% confidence level.

3.2. Regional Flux Variability and Particle Composition Along the Cape Blanc Filament Transect

Total mass fluxes at the coastal site CBeu had peaks between 1,500 and 2,000 mg m^{-2} day^{-1} and were about 3 times higher compared to the upper CBmeso fluxes (peaks of up to about 500 mg m^{-2} day^{-1}; not shown). In Figure 4, the seasonal BSi and the corresponding lithogenic/dust fluxes at CBeu and CBmeso are given as daily means on the same timescale, indicating comparable long-term changes. The overall pattern of increasing BSi values from 2003 to 2005/2006, a later decrease with a minimum around 2010 and an increase in 2015 can be recognized at both sites. In winter 2005, high BSi fluxes were observed in both traps. The largest BSi flux and dust peaks were found in spring 2006 but only at the coastal site (Figure 4). Another prominent peak in BSi was found again in spring 2015 in both upper trap collections.

Seasonal means ±1 standard deviation revealed highest values of BSi for the spring seasons at CBeu (60 ± 40 mg m^{-2} day^{-1}; Figure 5) and highest dust fluxes in winter (approximately 104 ± 70 mg m^{-2} day^{-1}). Seasonality was lower farther offshore at CBmeso at both trap levels with slightly higher BSi values in winter (deep trap: 7.8 ± 4.3 mg m^{-2} day^{-1}; Fischer et al., 2016) and spring (upper: 6.9 ± 5.7 mg m^{-2} day^{-1}). During the winter–spring bloom, the upper mesotrophic trap showed a large standard deviation of 130% of the BSi fluxes (Figure 5), which was due to the highly variable extension of the filament on interannual timescales (Figure 3b). The lithogenic (dust) fluxes (mean 32 mg m^{-2} day^{-1}) showed highest standard deviations in winter at CBmeso when dust input was highest. The interannual variability of both dust and BSi fluxes at CBeu was lower compared to CBmeso, except in spring where the dust fluxes varied with 86% (Figure 5). The flux patterns contained fewer peaks in the deep CBmeso trap (Figures 4 and 5) which collected more material than the upper mesotrophic trap (Fischer, Reuter, et al., 2009). Interannual variability in the deep mesotrophic trap was lower compared to the other traps but was enhanced during the spring bloom for BSi fluxes (83%) and for the dust fluxes (64%). The increase of fluxes with depth at the mesotrophic site was highly variable. Carbonate and lithogenic fluxes clearly decreased in an offshore direction by approximately twofold and threefold, respectively. From the comparison of the upper and lower CBmeso trap fluxes, an additional source of particles from the more coastal area with higher production is obvious and can be modelled (Figure 6; Fischer, Reuter, et al., 2009; see chapter below).

The overall composition at the eutrophic site differed from the mesotrophic site mainly with respect to BSi which was mostly delivered by marine diatoms (Romero & Fischer, 2017). BSi was 14.4% of total mass (on

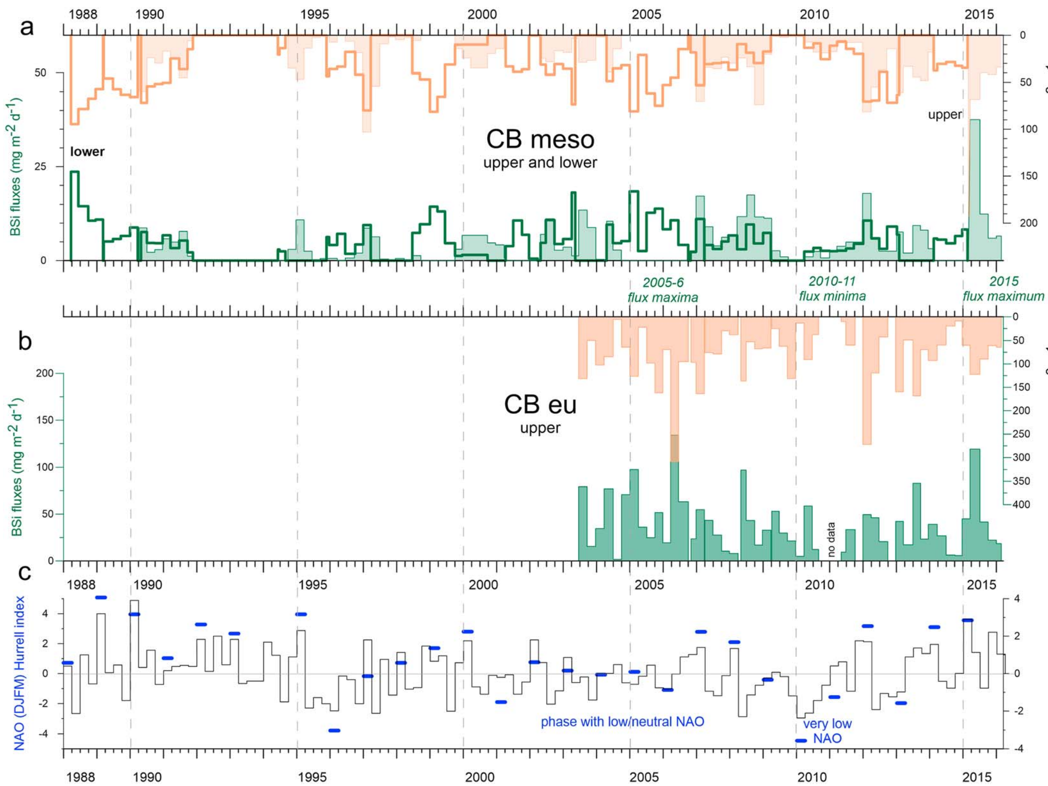

Figure 4. Seasonal daily BSi and dust fluxes at CBeu (b; upper) in comparison to the record of CB meso (a; upper and lower; thick line). Additionally, the NAO-DJFM Hurrell index is shown together with the NAO 1 (Gibraltar-Iceland). Note the low dust flux period from 2000 to 2004 at neutral NAO. BSi fluxes were highest in 2005–2006 despite a neutral NAO. All fluxes have a minimum around 2010–2011.

average), whereas it constituted only 4.7% at the upper mesotrophic trap level (Figure 6). Particles collected at CBeu contain slightly more lithogenic material (30.1%) and less carbonate (43.2%) of the total fluxes compared to CBmeso (Figure 6). In summary, we obtained an offshore shift toward more carbonate, less lithogenic, and lower BSi contribution to total mass fluxes.

3.3. Flux Changes With Depths and Lateral Advection of Particles

Mean annual fluxes at the offshore mesotrophic site (1988/1990 to 2016) in about 1,200- and 3,600-m water depth showed increasing total fluxes with depths (Figure 6). We used the lithogenic fluxes as a refractory and conservative flux tracer to address lateral advection processes on seasonal and interannual timescales and compared the upper and the lower mesotrophic CB traps. From earlier studies, we concluded that the upper eutrophic sediment trap site was within the transport path of particles moving offshore to the deeper mesotrophic trap (Fischer, Reuter, et al., 2009; Figure 6). For the lithogenic component at site CBmeso, an increase by approximately 18% with depth was found (Table 5) and carbonate fluxes increased as well. These increases were based on the long-term averages over the entire sampling periods. Even the BSi fluxes increased with depth by approximately 25%, whereas organic carbon and nitrogen fluxes decreased slightly. However, given the general undersaturation of nutrients in the water column (mainly with respect to silicate) and the resulting susceptibility of organic materials and biogenic opal to dissolution during sinking, we should expect distinct decreases of these components in the water column (Raguenau et al., 2000, 2006). Besides the lithogenic fluxes, the observed small changes with depths of nonrefractory components also point to a significant lateral flux contribution.

We found a change in the lateral contribution around 2005/2006 with high lateral fluxes before (approximately 114% increase of the lithogenic component) and a decrease in lateral contribution from 2006 onward (approximately 26%; Table 5). These relative changes with depth appear to be partly due to

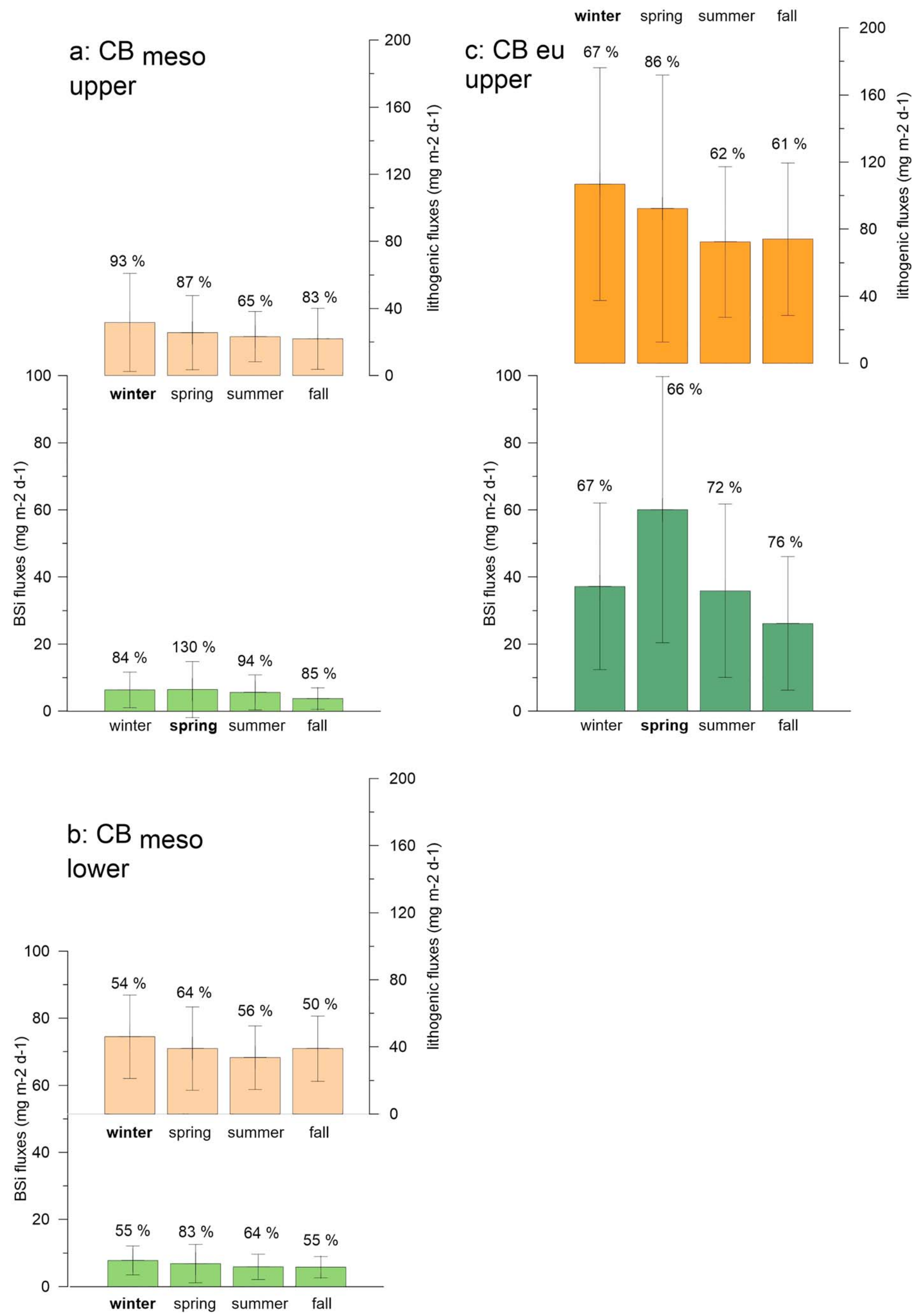

Figure 5. Mean seasonal BSi and dust fluxes at CBmeso (a, b) and CBeu (c) shown with the 1 standard deviation (SD). Highest interannual variability (SD) occurred at the upper offshore site CBmeso in winter (dust) and spring (BSi) due to the variable westward extension of the high chlorophyll filament (Figure 3b).

generally increasing fluxes in the upper mesotrophic traps. The average lithogenic fluxes of the lower traps were also higher before 2006 compared to 2006–2014. The flux changes with depth at the more coastal site CBeu were less clear. The upper and lower CBeu traps were only about 500 m apart, and it is therefore most likely that both traps received similar high amounts of material from the continental slope (Figure 6). Still, it is interesting to note that fluxes were lower at the deep CBeu traps compared to the upper ones before 2006 and that the opposite was observed after 2006 (Table 5). Therefore, this situation is contrary to the site CBmeso.

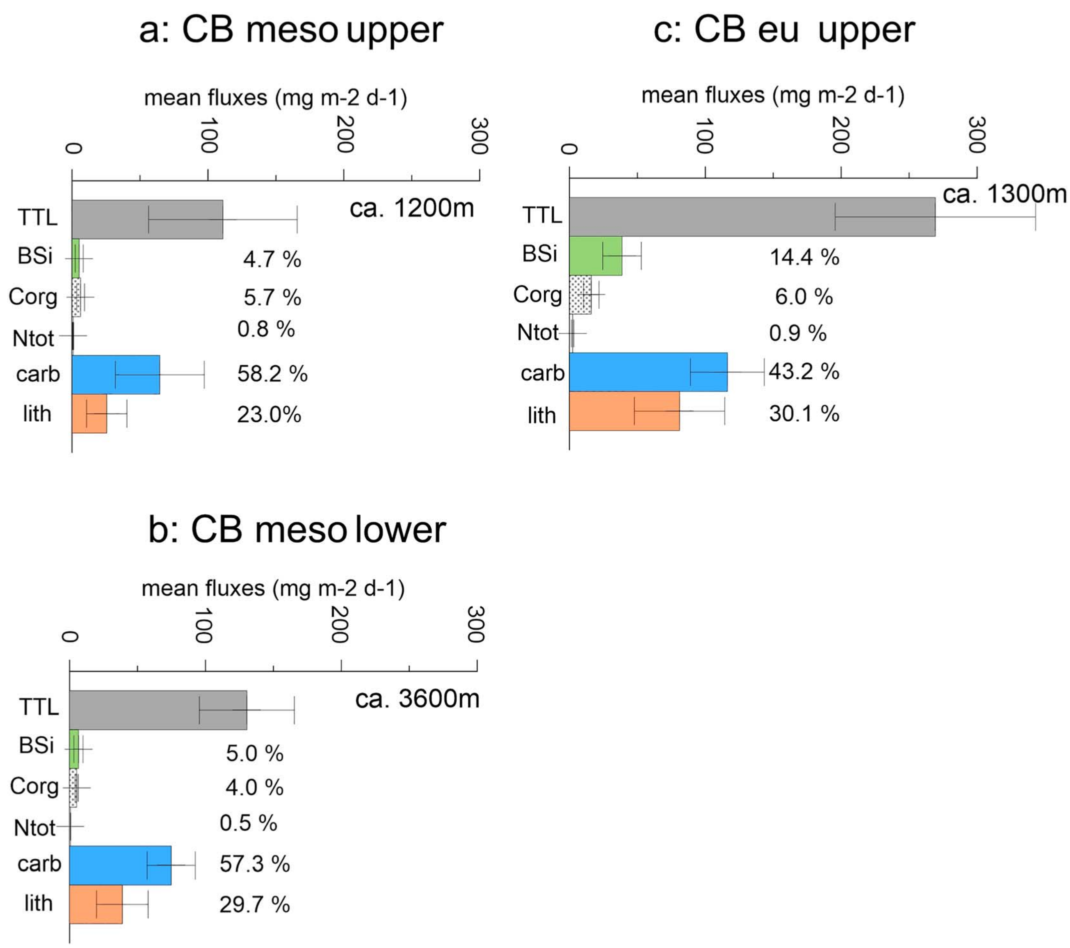

Figure 6. Mean total, BSi, organic carbon and lithogenic fluxes at CBmeso (a, b) and CBeu (c) with SD and mean percentages of composition (percentage of total fluxes), indicating a deep lateral flux component at CBmeso. However, lateral flux is highly variable between 1988 and 2016 (see text and Table 5).

4. Discussion

4.1. Short-Term Variability of the Dust-Influenced Biological Carbon Pump

Distinctive short-term peaks in BSi and lithogenic materials (dust) in the winter–spring season show a perfect temporal match (Figure 7). However, the relationship between the amplitudes of BSi and lithogenic components remains weak, suggesting complex interactions between the biological carbon pump and different types of ballast minerals (Le Moigne et al., 2014; Van der Jagt et al., 2018). BSi and organic carbon were highly correlated to the dust fluxes, except in fall when dust supply is rather low. This is due to numerous low altitude dust storms, in particular in winter and spring (Stuut et al., 2005), and dry dust deposition in the highly productive season due to gravitational settling in the atmosphere (Friese et al., 2016). The statistical analysis of winter and spring dust and BSi fluxes proved good relationships between CBeu and CBmeso (Figure 8), suggesting a ballasting of marine snow particles by mineral dust. In a combined study using optical particle characteristics and synchronous flux measurements between 2008 and 2010 at CBeu, Nowald et al. (2015) found that mass fluxes were not determined by changes of aggregate size but by the seasonally and interannually variable number of rather small (around 1 mm) but dense aggregates being ballasted with mineral dust. They could further demonstrate that an episodic event of Saharan dust input in September 2009 lead to the formation of a large number of comparably small particles (<1 mm) constituting the downward flux (Nowald et al., 2015). The records at CBeu imply a fast settling of rather small particles of around 0.5–1 mm in diameter, which argues against the general understanding of increasing settling rates with increasing particle sizes (McDonnell & Buesseler, 2010). Riley et al. (2012) claimed that fast settlers (s.v. = 350 m/d) are often ballasted and may account to explain the deep ocean fluxes, whereas slow sinkers may be remineralized in the water column.

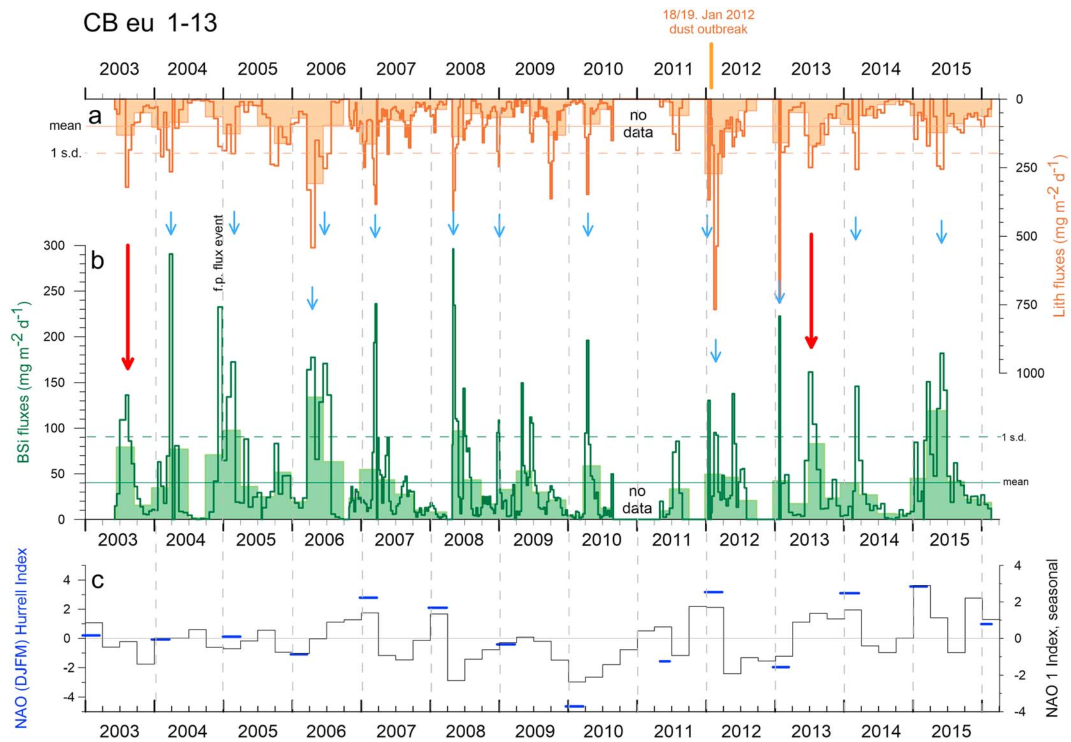

Figure 7. (a, b) High resolution record of BSi and lithogenic (=dust) fluxes at CBeu. Note the 1:1 correspondence in winter–spring over the entire record (blue arrows) and the summer peaks of BSi and dust only in 2003 and 2013 under low NAO conditions (c, red arrows) and wet summer dust deposition (northward ITCZ migration). An episodic appendicularian fecal pellet sedimentation event occurred in fall 2004 (Ploug, Iversen, & Fischer, 2008), corresponding to high BSi and carbon fluxes but no dust peak.

At the coastal site CBeu, pronounced summer/fall BSi flux peaks were observed mainly in 2003 and 2013 (Figure 7). These years were characterized by low wind velocities, a low or neutral NAO in winter, a higher northward propagation of the ITCZ (Inter Tropical Front; Nicholson, 2013) and positive Sahel precipitation indices (Becker et al., 2013). Therefore, we assume a wet deposition of Saharan dust in the surface ocean in both summers 2003 and 2013. Friese et al. (2016) used the occurrence of unsorted lithogenic particles (=large modal grain sizes) in the Cape Blanc sediment traps as an indicator for a wet precipitation of dust particles due to summer rains. They related distinct rain events to the modal grain sizes of dust particles intercepted by the traps. The distinct dust peaks in summer 2003 and 2013 were coincident with episodic BSi flux peaks (Figure 7). Atmospheric dust loadings in fall are generally low (Knippertz & Todd, 2012) which is reflected by the lowest seasonal dust fluxes in the entire Cape Blanc records, and a weaker relationship between BSi and the dust fluxes (Figure 4 and Table 4).

Fluxes may change on short timescales, even within days (e.g., Estapa et al., 2013; Summerhayes et al., 1973) as seen in studies in the Sargasso Sea, the North Pacific and the Cape Blanc study area as well (Iversen et al., unpublished data). Off Cape Blanc, the event scale of upwelling favorable winds is a few days and the total upper water column may be influenced within one day only (Pradhan et al., 2006; Postel, 1990). We therefore argue that the trap sampling resolution between 7.5 and 23 days (Table 2) may be still too low to resolve the natural variability of dust storm events and associated sinking blooms which sequester organic carbon. Thus, the flux peaks recorded with deep traps off Cape Blanc should be considered as a composite signal of several carbon flux events or pulses on daily or even diurnal timescales. Particle standing stocks captured on hourly timescales by high resolution optical systems in the surface waters off Cape Blanc in winter 2014 indicated a diurnal particle concentration variability (but not flux), perhaps due to day-night migration of zooplankton (Iversen, unpublished data; POS 464 cruise report). An episodic particle flux event with the highest carbon fluxes of the entire CBeu record in the fall season of 2004 (Figure 3) was due to the export and transfer of solely appendicularian fecal pellets. These very solid pellets constituted the entire mass of this sampling cup from fall 2004. They were sinking at measured rates of approximately 730 m/d and had a total

Table 5
Lateral Advection of Lithogenic Fluxes

CB Eutrophic	Period	Lith upper	Lith lower	Lower–upper	Lower/upper	% increase	CB Mesotrophic	Period	Lith upper	Lith lower	Lower–upper	Lower/upper	% increase
	years	g/m^2	g/m^2	g/m^2	ratio			years	g/m^2	g/m^2	g/m^2	ratio	
		~1,300 m	~1,900 m	~500 m					~1,200 m	~3,600 m	~2,400m		
	2003–2005	27.4	7.9	−19.5	0.3	***−71.3***		**1990–2005**	6.7	14.4	7.7	2.1	***113.9***
	2006–2015	25.5	37.0	11.3	1.5	***49.2***		**2006–2013**	14.5	10.7	−3.8	0.7	***−26.1***
	Total	25.9	30.4	4.4	1.2	23.1		Total	10.6	12.6	2.0	1.2	18.4

ballast content of approximately 80% (Ploug, Iversen, & Fischer, 2008). Organic carbon and BSi fluxes reached almost 100 and 230 mg m^{-2} day^{-1} in December 2004, respectively (Figures 3 and 7). This underscores the important effect of zooplankton "flux feeding" on carbon and BSi export on short timescales (McDonnell & Buesseler, 2010). The organic carbon and the BSi peak in fall 2004 did not correspond to any dust deposition/flux event (Figure 7), showing that this erratic/episodic peak was clearly stimulated by the occurrence and behavior of filter-feeding appendicularians.

A 2-day dust storm event in January 2012 (POS cruise 425 report) was documented in the deep flux record of CBeu as well (Figure 7). We were able to capture the settling particles with drifting traps at 100, 200, and 400 m in the twilight zone before and after the low altitude dust storm (Iversen, unpublished data). Threefold higher carbon fluxes and enhanced particle settling rates after the event were observed, leading to reduced organic carbon remineralization (Iversen, unpublished data).

We obtained statistically significant relationships between BSi and organic carbon fluxes during all seasons from the long-term deployments (Table 4). This could indicate that BSi may also have acted as an effective ballast mineral for the transfer of organic carbon to depth (e.g., Boyd & Trull, 2007). A significant relationship was observed between the organic carbon and BSi spring fluxes to the extension of the filament at 21°N with ($N = 12$, $R = 0.72$; not shown). BSi is mostly delivered by diatoms at CBeu (Romero & Fischer, 2017) and is widely used as an indicator of export productivity in the Mauritanian upwelling (Bradtmiller et al., 2015;

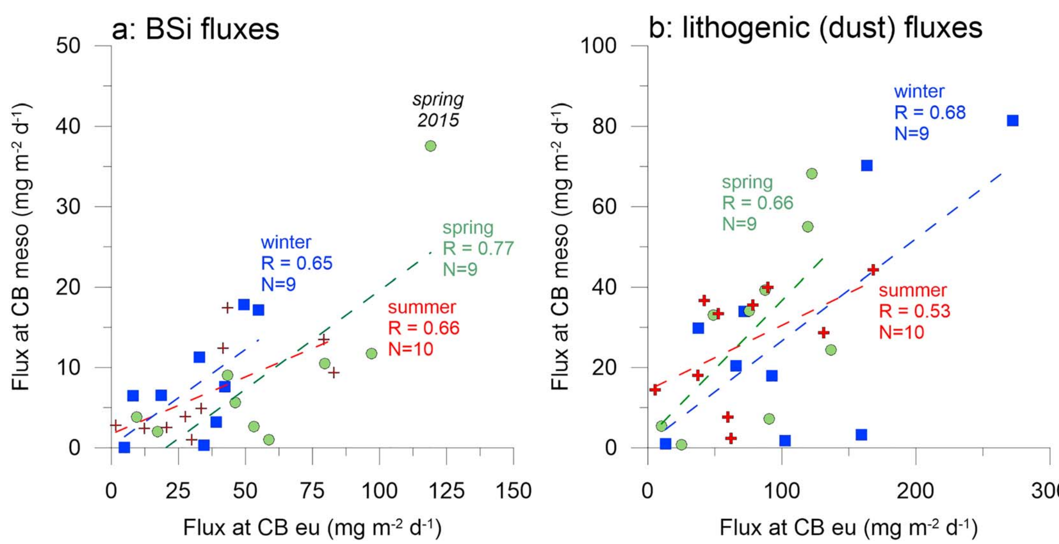

Figure 8. Relationships of seasonal BSi and dust fluxes between the two sites CBeu and CBmeso. Good correspondence is seen for winter (blue) and spring (green). Lower correlation is found for the summer dust fluxes (red) due to wet deposition which occurred preferentially at the coastal site CBeu.

Romero et al., 2008). Fischer et al. (2016) found a similar relationship between BSi fluxes and the entire size for the filament at site CBmeso.

4.2. Flux Changes Along the Cape Blanc Filament

Messié and Chavez (2015) argue that PP in the CC is mostly driven by macronutrients most of the year with silicate being more likely to regulate production than nitrate. Silicate supply via the NACW is lower than via the SACW source waters, the latter influencing the coastal CBeu site to a stronger degree (Figure 1). In general, the higher silicate availability (approximately 10 vs. 5 μM; Table 1) at the more coastal site as well as the higher Si:N ratios of the source waters (SACW vs. NACW and 0.6 vs. 0.3; Table 1) are reflected in approximately threefold higher BSi fluxes at the coastal CBeu compared to the offshore CB meso site (Figures 4 and 6). With respect to the most important flux ratios (Table 6), a clear distinction between the eu- and the mesotrophic locations can be observed. Overall higher C:N ratios farther offshore (C:N = 8.7 vs. 7.1 inshore) could indicate a higher degradation of primary produced material during offshore advection of particles within the filament (Helmke et al., 2005) and later settling to the traps.

Organic carbon fluxes decreased in an offshore direction from 16.1 to about 6.3 mg m^{-2} day^{-1} (Table 6). Furthermore, carbonate and lithogenic fluxes decreased approximately twofold and threefold from CBeu to CBmeso, respectively (Figure 6). Annual dust (=lithogenic) fluxes were almost 30 g m^{-2} $year^{-1}$ at the coastal site and 10 g m^{-2} $year^{-1}$ at the offshore site (Figure 9). Those values fall within the range of modelled dust deposition rates from satellite data (MODIS; Kaufman et al., 2005), assuming that all dust deposited at the surface ocean makes it down to bathypelagic depths. The offshore decrease in dust fluxes and grain size can be explained by gravitational settling of dust particles (Friese et al., 2016).

Carbonate is a mixture of primary (mainly coccolithophorids) and secondary producers (mainly foraminifera and pteropods) and their contribution to total carbonate is difficult to assess quantitatively. In a study conducted at the mesotrophic site, Fischer, Karakas, et al. (2009) showed that the contribution of major carbonate producers changes significantly on interannual timescales with coccolithophorids and planktonic foraminifera being the major contributors. However, at the eutrophic site influenced more by the MC which brings tropical waters into the study region, pteropods are important contributors as well and lead to higher carbonate fluxes, mainly in summer due to episodic peaks (Fischer et al., 2016). Flux peaks obtained for the upper CBeu trap were mostly reflected about 600-m deeper in the lower trap (data not shown). Major flux peaks in the CBeu record were also found in the deeper CBmeso traps (Figure 9), sometimes with a time lag due to the horizontal distance of about 120 nautical miles (approximately 220 km). This will be discussed in detail below.

Mean average organic carbon fluxes were 1.5–1.8 mg m^{-2} day^{-1} (approximately 4%–5% of total mass) at the oligotrophic EUMELI site off Cape Blanc and 5.3 to 20.2 mg m^{-2} day^{-1} (approximately 5%–20% of total mass) at the mesotrophic site (EUMELI program conducted from 1991 to 1994; Bory et al., 2001). Carbon fluxes of 20.2 mg m^{-2} day^{-1} in 1,000 m were in the same range as our mean carbon fluxes at the eutrophic site (Figure 3). However, the mesotrophic EUMELI site was located almost 2° farther to the south in the MRT-Senegalese upwelling zone and is therefore not directly comparable to site CBeu located at the southern end of the permanent upwelling zone (Cropper et al., 2014).

4.3. Particle Settling Rates and Cross-Shelf Particle Transport Processes

Increasing coastal winds, nutrients and productivity in the CC-EBUEs due to land heating and global change (Bakun hypothesis; Bakun, 1990, 2010) may at the same time increase offshore transport of water masses (Garcìa-Reyes et al., 2015; Lluch-Cota et al., 2014), chlorophyll and marine particles. Settling velocities of larger particles, that is, marine snow aggregates and fecal pellets are critical for the vertical and horizontal particle transport (Karakas et al., 2006), in particular in highly dynamic coastal upwelling areas. Calculated settling rates from sediment trap patterns with the so-called benchmark method (e.g., Honjo, 1996; Berelson, 2002; Fischer, Karakas, et al., 2009) are “signal propagation velocities” as emphasized by Armstrong et al. (2009). Armstrong et al. (2009) concluded that the settling velocities from the “benchmark method” are in agreement with other direct approaches (e.g., MedFlux data set).

BSi and diatom contribution to total fluxes is about threefold higher at CBeu compared to CBmeso, the latter site being dominated by coccolithophorids as major primary producers (Fischer, Karakas, et al., 2009). From

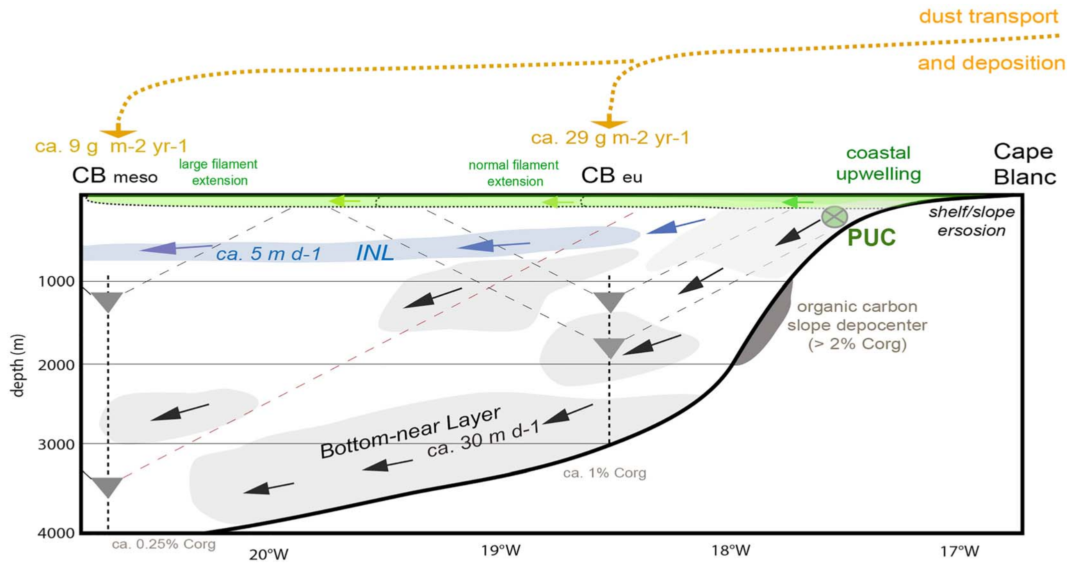

Figure 9. Schematic of major factors affecting particle transport processes to the sediment traps CBeu and CBmeso based on modelling (Karakas et al., 2006) and field data. Dust deposition estimated from the trap collections decreases about threefold in an offshore direction. In the uppermost surface layer, the variable westward extension of the Cape Blanc filament is shown (green). The Intermediate Nepheloid Layer (INL, blue) and the Bottom-near Layer (gray) are characterized by particle settling velocities (s.v.) of 5 and 30 m/day, respectively (modified after Karakas et al., 2006). Carbon contents (%) of the surface sediments are indicated together with the carbon depocenter on the slope. Note the overlapping collection funnels (Siegel & Deuser, 1997) of the deeper CBmeso and the CBeu trap (schematically, stippled grey lines). PUC = northward flowing Polar Undercurrent (Figure 1).

Table 6
Summary of Major Findings

Study site	Trap identification	Mean annual fluxes ± s.d.			Flux ratios				Mean s.v. ± s.d.	Mean lateral advection	Temporal and regional differences
Mean Depth	sampling duration	B Si	organic carbon	dust	C:N	BSi: Corg	BSi: Carb	C_{Corg}/ C_{Carb}		lithogenic flux	
		mg m^{-2} day^{-1}	mg m^{-2} day^{-1}	mg m^{-2} day^{-1}	molar				m per day		
CB eutrophic	CB eu 1-3	38.7 ± 14.2	16.1 ± 5.7	81 ± 33.3	7.95	2.41	0.33	1.15			close BSi-dust flux relationships
~1,300 m	2003–2016										long-term decrease of organic carbon and BSi
									75 ± 28		due to a decrease of coastal upwelling and warming
CB eutrophic	CB eu 1-3	34.6 ± 20.3	15.2 ± 5.6	94.3 ± 46.9	8.93	2.26	0.28	1.03		higher after 2005/2006	± similar flux patterns and absolute values
~1,800 m	2003–2016										compared to upper trap
CB mesotrophic	CB meso 3-26	5.3 ± 2.9	6.3 ± 2.9	25.6 ± 14.8	8.7	0.8	0.08	0.8			biological pump is mainly NAO-driven
~1,200 m	1990–2016										
									274 ± 134		
CB mesotrophic	CB meso 1-26	6.5 ± 3.4	5.2 ± 1.1	38.8 ± 19.0	8.9	1.3	0.09	0.6		higher before 2005/2006	lateral advection of particles from CB eu (upper)
~3,600 m	1988–2016										

Note. s.v. = settling velocities; s.d. = standard deviation.

experimental and field studies (e.g., Iversen & Ploug, 2010; Ploug, Iversen, Koski, et al., 2008), one might expect higher settling rates at CBmeso compared to CBeu due to the different ballast composition. Estimated rates using the benchmark method (Fischer & Karakas, 2009) indeed suggest higher rates farther offshore (mean s.v. = 274 ± 134 m/day) compared to CBeu (mean s.v. = 75 ± 28 m/day), where ballast is mainly composed of more carbonate and dust. The settling rates were slightly higher in summer–fall compared to the winter–spring season. At the eutrophic site with more BSi but almost similar dust contents in the collected particles, mean rates were almost fourfold lower with some seasonal variation. However, these estimations are largely dependent on the sampling resolution (between 7.5 and 23 days) and the depth difference between traps; the latter was only approximately 600 m at site CBeu which sets limits to our estimates of mean settling rates.

Following a 2-day dust storm event in 18–19 January 2012, fluxes of organic carbon, BSi and dust increased significantly approximately 20 days later in the CBeu trap in 1,00 m (Figure 4). We calculated a settling velocity of approximately 66 m/day that agrees with lower velocities in winter with an enhanced BSi production and export flux. This dust storm event in January 2012 was recorded from the upper CBmeso trap as well with an abrupt flux increase on February 19, resulting in settling velocities of approximately 40 m/day for the winter season. Higher dust availability can also be seen from elevated aerosol optical depth in winter 2012 (GIOVANNI time series; not shown).

Direct lab measurements of particle settling rates of carbonate-ballasted versus mixed carbonate/opal-ballasted organic aggregates show the same trend (Iversen & Ploug, 2010) as the "benchmark" estimations from the Cape Blanc flux records. Estimates from seasonal changing settling velocity at site CBmeso-13 (2002–2003; Fischer, Reuter, et al., 2009) show lower settling rates (approximately 65 m/day) during winter with more BSi and diatoms compared to summer with higher carbonate content (s.v. = ~250 m/day). Estimates of settling velocities derived from seasonal chlorophyll peaks in the surface transect off Cape Blanc with synchronous organic carbon fluxes in 3,580 m water depth at CBmeso (deployment CBmeso-9; 1998–1999; Helmke et al., 2005) offered a similar seasonal differentiation. In situ settling rates using a settling chamber with a camera system attached to a ROV were mostly between 10 and 150 m/day between 50 and 400 water depths at CBeu (Karakas et al., 2009). In summary, there is some indication that the settling rates of particles—although seasonally variable—are higher offshore at CBmeso compared to the coastal site CBeu. However, the reasons for this remain unclear. Individual settling events recorded with sediment traps, for example, fecal pellets produced by filtering appendicularians which constituted the entire flux in fall 2004 (Figure 7), provided settling rates of up to approximately 730 m/day (Ploug, Iversen, & Fischer, 2008). As flux variability is assumed to occur on daily and diurnal timescales (e.g., Estapa et al., 2013; Fischer et al., 1996), individual and regular settling events and their sinking rates as a function of particle characteristics (e.g., ballast composition) cannot be investigated with classical sediment trap techniques. Specially constructed sediment traps, partly combined with optical systems may help to elucidate the problem of seasonally and regionally variable particle settling velocities in the ocean in relation to particle characteristics (e.g., Armstrong et al., 2009; Peterson et al., 2005; Iversen et al., unpubl. data).

Offshore advective transport of waters carrying particles occurs within the surface layer in the filamental zone (Helmke et al., 2005) and in the subsurface and in deeper and bottom-near layers, partly in the form of plumes (Karakas et al., 2006). A significant relationship is obtained when plotting winter and spring fluxes of BSi for CBeu to CBmeso (deep trap; $R = 0.88–0.62$; Figure 8). This observation points to a lateral flux component within the already described bottom-near particle layer (Fischer, Karakas, et al., 2009). By comparing upper and lower seasonal flux patterns of the CBmeso-13 record, these authors estimated a lateral contribution of >63% organic carbon in winter–spring 2002–2003 (flux = 0.25 g C m^{-2}) to the deep CBmeso site. Fischer, Karakas, et al. (2009) concluded that there must be a repeated high lateral flux component during the productive winter-spring season. Additional evidence for this conclusion was the frequent optical observation of deeper, partly bottom-near particle layers and plumes, for the last time in 2006 (Nowald et al., 2006). These pronounced features can be observed in other coastal upwelling regions (e.g., Inthorn et al., 2006). Injection of carbon (2,400 t per event) from the shelf offshore in the meandering California Current jet was described in detail by Barth et al. (2002). They argued that chlorophyll-rich particles were forced downward along sloping density surfaces near the shelf break. This concept of a "particle injection pump" is discussed in a most recent publication by Boyd et al. (2019).

Using the mean upper trap carbon fluxes in approximately 1,200 m of 6.3 mg m^{-2} day^{-1} and the Martin-curve with $b = -0.858$ (Martin et al., 1987), we reach a value of approximately 2.4 mg m^{-2} day^{-1} for 3,600 m at deep CBmeso. Instead, we measure a mean deep ocean carbon flux of 5.2 mg m^{-2} day^{-1}, resulting in a lateral organic carbon flux estimate of approximately 2.8 mg m^{-2} day^{-1} (annually = ~1 g m^{-2} year^{-1}). We therefore assume that almost one half of the organic carbon at 3,600 m by CBmeso was derived from lateral supply from the coastal area (Karakas et al., 2006). This amount appears to be reasonable and is in accordance with other studies, for example, in the western and eastern North Atlantic (Gabric et al., 1993; Hwang et al., 2009; Lovecchio et al., 2017; McCave et al., 2001). BSi is remineralized at lower rates than organic carbon in the water column and is influenced by different physicochemical and biological factors in the ocean's environments as well (Ragueneau et al., 2006). At site CBmeso, long term mean annual BSi flux was 5.3 and 6.5 mg m^{-2} day^{-1} in 1,200 and 3,600 m, respectively, indicating a minimum lateral contribution of 20% when assuming that no dissolution of BSi occurred.

Considering the long-term records, lateral contribution appears to be changing around 2005/2006 at both study sites but in a different way. We found a high lateral contribution (up to a twofold increase of lithogenic fluxes with depths) between 1990 and 2005 at CBmeso (Table 5). Later on, fluxes were higher in the upper traps, suggesting reduced lateral advection at least within the particle layer supplying the deep mesotrophic site (Table 5). A compilation of flux changes with depth at CBeu revealed the reversed picture, with lower values at depth from 2003 to 2005 and ~50% higher lithogenic fluxes in the following years (Table 5). This overall pattern could suggest decreasing lateral advection of particles from the continental slope via the deep and bottom-near nepheloid layer (Fischer, Karakas, et al., 2009) to CBmeso (Figure 9). We speculate that the deep-water particle transport path changed vertically or that the rather small offshore westward particle transport path located between 19 and 21°N (Karakas et al., 2006) moved zonally. The shift of the particle transport path could be in a northward direction which would be consistent with a stronger influence of the warm MC, indicated by increasing SSTs from 2005 onward (Figure 3a). Thus, particles from the coastal upwelling may not have reached the deeper CBmeso traps after 2005. Instead, particles may have intercepted with the deeper CBeu traps situated in the depth range of the carbon depocenter or may have been deposited farther north of the CBeu site.

Romero and Fischer (2017) found a high number of small coastal benthic diatoms at CBeu (about one third of total diatom flux on average) derived from the inner shallow shelf starting around 2005/2006 onward to 2010. This might point to an intensification of the slope and shelf poleward undercurrents (e.g., PUC; Figures 1 and 9) probably related to circulation changes in this part of the coastal upwelling system. An intensification of the offshore transport of water masses (and particles) may occur due to global warming and increasing alongshore winds off NW Africa (Lluch-Cota et al., 2014) As discussed above, the changes in the flux patterns are accompanied by ocean warming (Figure 3a), pointing to an intensification of the northward flowing warm MC (Figure 1). This surface current might have transported benthic diatoms to the north and northwest reaching site CBeu. Coastal upwelling is centered at the inner shelf and the shelf edge. Over shelf and slope, compensatory subsurface waters flow poleward (PUC; Figure 1) beneath the SW flowing Canary Current (e.g., Arístegui et al., 2009). Mittelstaedt (1974) measured current velocities in the undercurrent at the slope (around 300–500 m) of as high as 30 cm/s which should result in a strong along slope northward transport of particles as observed at CBeu. Due to the rather shallow but wide shelf off Cape Blanc and the Banc d'Arguin (Figure 1) of around 100 m water depth, these undercurrents, slope currents and swells frequently cause a winnowing of fined-grained sediments and a redistribution of organic particles being produced over the shelf area to deeper environments (Figure 9).

A detailed description of particle transport along Intermediate Nepheloid Layers at the shelf break and upper slope and Bottom-near Layer on the Namibian margin is given by Inthorn et al. (2006). However, this study was mainly based on turbidity measurements and the observation and sampling of suspended particles, whereas our particle studies were focused primarily on larger particles (approximately >50 μm), being captured with particle cameras (Nowald et al., 2015). Inthorn et al. (2006) also mentioned massive sedimentation of fine-grained organic materials at the continental slope depocenter off Namibia, which is located at shallower depth compared to the NW African margin. Sediment dispersal from the shelf to the open ocean was investigated in detail during the OMEX project (e.g., McCave et al., 2001), indicating similar transport and sedimentation processes than at the Mauritanian slope.

4.4. Decadal-Scale Flux Variability, Atlantic Climate Forcings, and Climate Change

The coastal CBeu site located closer to the CVFS is influenced both by coastal upwelling within the CC driven trade wind system and the northward flowing MC that is strongest in summer during the monsoonal circulation. The strength of the CC is largely determined by the major driving force NAO over decadal timescales which can be seen in the flux variability to the deep ocean as well (CBmeso; Fischer et al., 2016). However, winter BSi fluxes and the winter NAO (December–March) at the coastal CBeu site revealed a less significant relationship ($R = 0.3$, $N = 12$) than at the offshore CBmeso site (upper traps: $R = 0.57$, $N = 18$; Figure 10). The year 2005 was unusual with an almost neutral NAO index, although with high BSi fluxes as seen for the deeper CBmeso trap samples (Figure 10c). Fischer et al. (2016) explained this with exceptional dust deposition events, stimulating the rapid transfer of biogenic matter during almost the entire year 2005 (see Friese et al., 2016). The year 2005 followed the longer dry period from 2001 to 2004 in the Sahel and Sahara and anomalously warm temperatures in the Eastern Atlantic (Alheit et al., 2014; Zeeberg et al., 2008). Chlorophyll was rather high at CBeu over a longer period in 2005 for the study box, whereas the size of the filament was relatively small (Figure 3). Friese et al. (2016) showed that in summer–fall 2005, modal grain sizes of lithogenic particles were maximum which points to wet deposition of dust. In contrast, grain sizes were minimum in winter-spring 2005 due to gravitational settling of dust. High dust deposition in winter 2005 was recorded at the sediment trap site Kiel 276 in the NE Atlantic close to Madeira (Brust et al., 2011) and in the NW Mediterranean with an impact on particulate carbon export (Ternon et al., 2010). These authors found a series of lithogenic flux events corresponding to high POC fluxes in the Mediterranean, which are supposed to be related to aggregation processes and ballasting rather than to nutrient fertilization. As emphasized by Bory et al. (2002), a high-frequency temporal coupling between atmospheric and oceanic fluxes is assumed to be primarily production-dependent. Due to an almost continuously high biomass and productivity in the permanent upwelling zone off Cape Blanc (Cropper et al. 2014), any supply of dust particles to the surface ocean may increase aggregate formation until a certain threshold or carrying capacity is reached (Van der Jagt et al., 2018) and particles settle to depth. Then, a coupled sedimentation of both biogenic and non-biogenic particles may be recorded in the traps (Fischer et al., 2016).

The CBeu time series showed a shift after 2005 with high fluxes of all components in 2006, followed by a rather continuous decrease until 2013 (Figures 4 and 11). This change was accompanied by a jump of almost 1 °C in satellite-derived mean summer SSTs (Figure 3a), indicating a relaxation of coastal upwelling off Cape Blanc and/or an increasing influence of the warm northward moving MC in the summer seasons after 2005. Statistically proven decreasing fluxes of organic carbon (slope −0.85; Figure 3) and the percentage decrease of organic carbon of the settling particles (Figure 11) suggests that the intensity of the coastal upwelling off Mauritania decreased. However, not only summer carbon fluxes showed a decreasing trend but the fluxes of the other seasons as well, indicated by the overall negative slopes (Figure 11; seasonal trends are not statistically significant). This could point to a relaxation of upwelling during the coastal upwelling season in winter–spring off Cape Blanc.

Using the diatoms as major primary producers and their fluxes from 2003 to 2010 at CBeu, Romero and Fischer (2017) suggested an increasing contribution of small coastal benthic diatoms starting in 2006. As these organisms are light-dependent, we assume that they originate from the inner shelf area of Cape Blanc, probably from a water depth of less than 50 m. These relatively small coastal species are less silicified and contain less carbon per cell than upwelling and offshore-living diatoms which could explain the decreasing fluxes of BSi and organic carbon and the relative changes in composition (Figures 3 and 11). In the GIOVANNI time series plots, increases CBeu cell(Figureell-358.9((Figur2374.9(eu)3)TjcChlorophyll and rze mened,. accompanied by a oy

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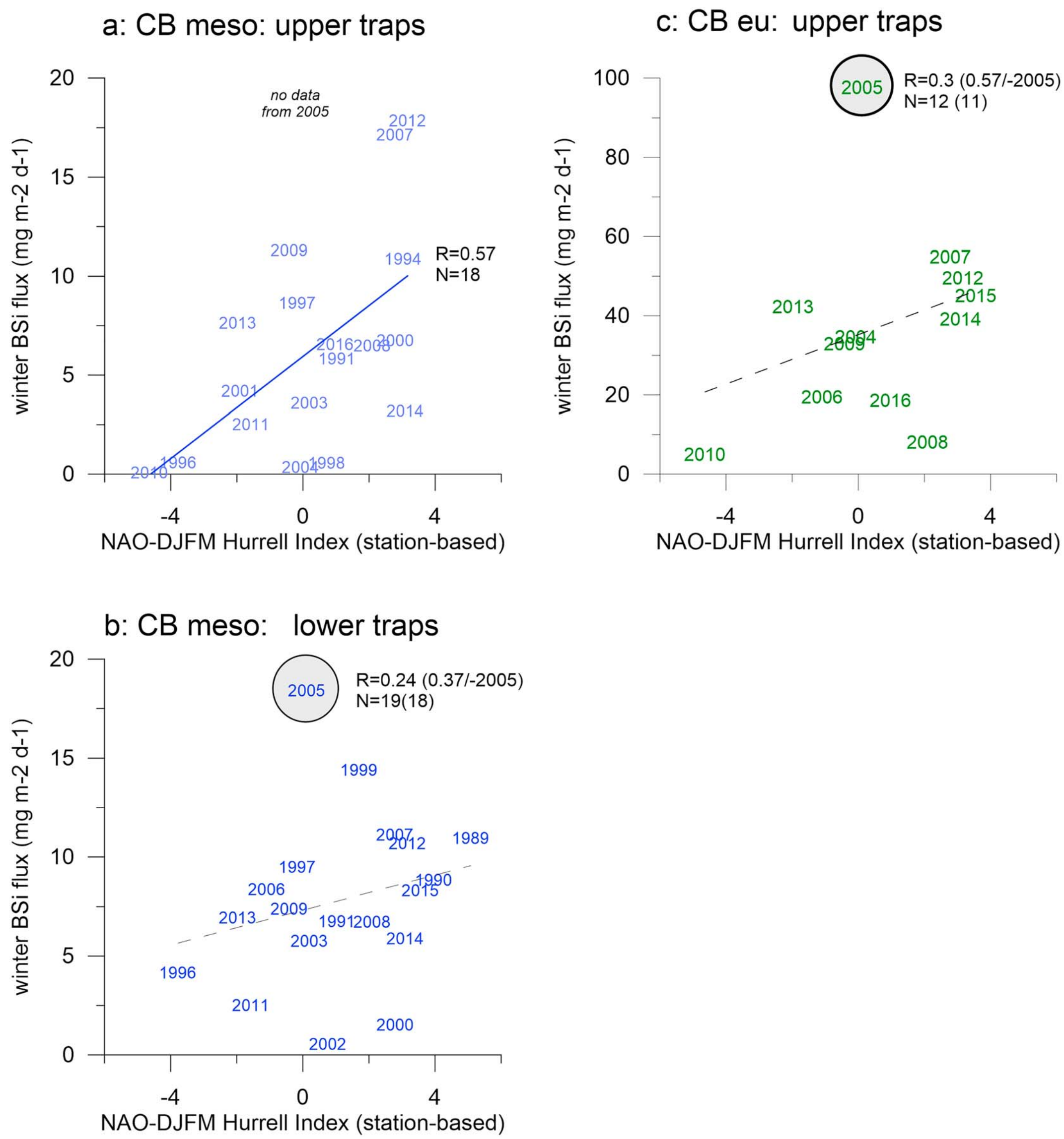

Figure 10. The DJFM-NAO index (Hurrell, 1995) versus the BSi fluxes at CBeu (c) and CBmeso (a, b). Note the higher correlation coefficient ($R = 0.57$; $N = 18$; significant at the 99% confidence level) at the upper offshore site (no data from 2005 available). The year 2005 is exceptional both at CBeu (upper) and CBmeso (lower) with high BSi fluxes combined with a neutral NAO.

benthic diatoms from the inner shelf to the CBeu traps (Romero & Fischer, 2017). Higher degradation of organic-rich particles may have been also due to ingestion by zooplankton which could result in elevated C:N ratios in the sinking material (e.g., Anderson, 1994).

Comparing the long-term trend of decreasing BSi and organic carbon fluxes from 2006 to 2014 at the coastal site CBeu to larger scale climatic forcings in the North Atlantic revealed no clear and convincing picture. A reconstruction of the time series of AMOC (Chen & Tung, 2018; Srokosz & Bryden, 2015) shows some correspondence to the decreasing fluxes with the extreme slowdown in 2009–2010 (Smeed et al., 2014; Srokosz & Bryden, 2015). The NAO was very low in 2009–2010 as well (Figure 4), as also seen in lowered wind speeds in winter in the CBeu box (GIOVANNI time series, not shown) and at Cape Blanc (Figure 2a). However, the general coupling between AMOC, AMO, and NAO are a matter of intense debate (Haine, 2016; Smeed et al., 2014). At present, it is unclear whether the proposed weakening trend of the AMOC over the past decade was part of a decadal variability or a persistent weakening (Haine, 2016; Jackson et al., 2016). Decreasing AMOC

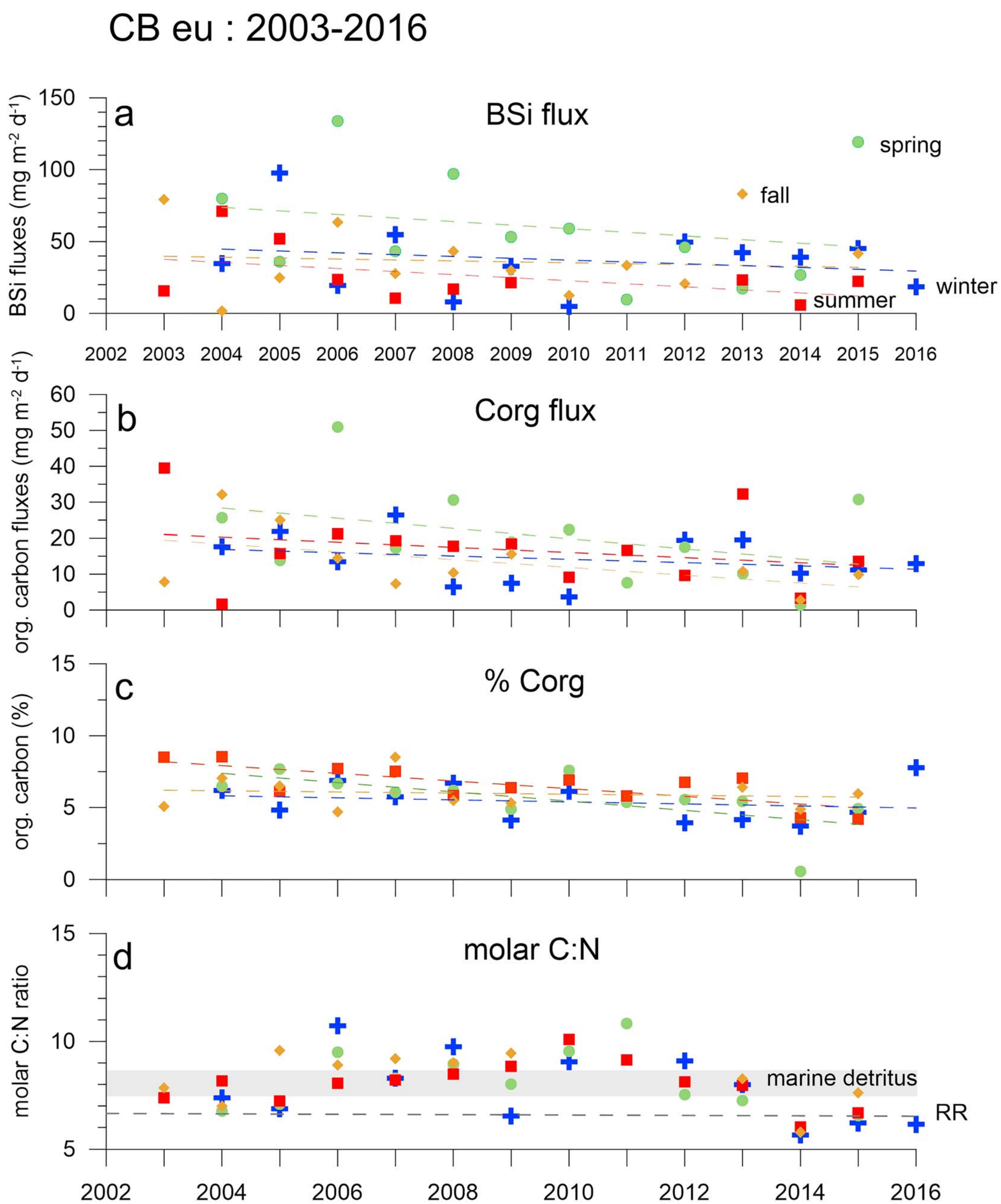

Figure 11. Long-term changes of seasonal BSi (a) and organic carbon fluxes (b), percentages of organic carbon (c), and the molar C:N ratios (d). Note the general long-term decrease of fluxes and composition. However, only the cup-to-cup carbon fluxes (Figure 3) reveal a statistically significant trend. C:N rations jumped to higher values from 2006 to 2012.

influences Ekman transport as well and might reduce the CC flow and decrease coastal upwelling in the trade wind region. Increasing summer SSTs after 2005 in the CBeu box (Figure 3) suggests upwelling relaxation and/or an increasing influence of the warm and northward flowing MC. The flux record at CBeu showed a minimum in 2010–2011, not in 2009–2010 as expected from the environmental data. Time series of the local wind field at Cape Blanc (Nouadhibou airport) suggests not increasing but decreasing winds, which agrees with a warming at the coastal CBeu site (Figure 3a) and at Cape Blanc (marine time series at Cansado, IMROP; M. Bambaye, personal communication, December 2017). These conditions match the decreasing carbon fluxes at site CBeu (Figures 3 and 11). A progressive warming and decreasing productivity over the last two decades was suggested for the CC-EBUEs as a whole (Arístegui et al., 2009), which would better match our flux records from the deep ocean sediment traps than the Bakun et al. (2010, 2015) scenario of coastal upwelling intensification. Barton et al. (2013) and Gómez-Letona et al. (2017) also found no evidence of increasing alongshore winds and productivity in the Canary Current System. However, one should keep in mind that the CC-EBUEs is characterized by various subsystems which could react differently to global warming (e.g., Arístegui et al., 2009; Garcìa-Reyes et al., 2015; Lathuilière et al., 2008; Sydeman et al., 2014). The California Current System, strongly influenced by ENSO, reveals a warming trend of surface waters for the past 100 years and an increase in the occurrence of harmful algal blooms since 1985 (Checkley & Barth, 2009). These authors pointed out that disentangling long term trends in winds, SST, and upwelling is still challenging. A long-term flux record from ~4,000 m from the California Current system (NE Pacific, 1989–2017) provides some indication of an increase of episodic POC flux events during the last decade (Smith et al., 2018).

5. Summary and Outlook

A comparison of the long-term flux records at a coastal (CBeu) and an offshore (CBmeso) upwelling site off Mauritania revealed the following major findings:

1. Organic carbon, BSi, and lithogenic (dust) fluxes were twofold to threefold higher at the coastal setting due to higher biomass, silicate (from SACW), and dust supply.
2. Winter and spring organic carbon and BSi fluxes showed a closer coupling to winter NAO at the offshore CBmeso site compared to CBeu.
3. A strong coupling between dust deposition/flux and the efficiency of the biological pump under both dry (winter-spring) and wet depositional conditions (summer) is found. Organic carbon was well correlated to BSi at the coastal site CBeu; individual BSi maxima revealed a peak-to-peak correlation to the dust fluxes in winter–spring (Figure 7). We propose that the ballasted organic-rich aggregates in the surface waters react immediately to any additional dust supply with aggregation followed by rapid sedimentation (Van der Jagt et al., 2018.),
4. Organic carbon fluxes and its relative contribution to total mass fluxes decreased from 2003 to 2016 at the coastal upwelling site CBeu during all seasons (Figures 3 and 11). This could point to decreasing coastal upwelling off Cape Blanc in winter–spring which disagrees with the Bakun coastal upwelling intensification hypothesis (Bakun, 1990),
5. Year 2005 was exceptional with a decoupling of coastal upwelling forced by NAO and particle fluxes at both CBeu and CBmeso (Figure 10). Following 2005, a change in the carbon cycle and/or particle transport indicated by a shift to higher molar C:N ratios by ~2 units at the coastal site was found. In addition, we observed a shift in the diatom composition to more coastal benthic species at site CBeu (Romero & Fischer, 2017). Therefore, we propose an intensification of lateral advection from the inner shelf area since 2005/2006 (Romero & Fischer, 2017).
6. We estimate a mean lateral contribution of organic to the deep offshore traps CBmeso of ~50% which is in accordance with other studies (e.g., Gabric et al., 1993; Hwang et al., 2009; McCave et al., 2001). Particle transport off Cape Blanc changed after 2005–2006, with a reduced advection to the deep CBmeso traps and an increase transport to the deep CBeu traps. This may be due to a northward shift of the particle export paths in the surface associated with the Cape Blanc filament and/or an intensification of the poleward undercurrents (PUC; Figure 1).
7. Estimated particle settling velocities were almost fourfold higher at the mesotrophic site (ballasted by carbonate and dust) compared to CBeu (ballasted mainly by BSi and dust). This is in accordance with lab and field studies (e.g., Iversen & Ploug, 2010).

The long-term decrease in carbon fluxes at CBeu might be part of a naturally forced climatic oscillation in the North Atlantic (decreasing NAO and/or AMOC) or due to global change. The flux records at both study sites, however, point to upwelling relaxation rather than to coastal upwelling intensification (Bakun, 1990, Bakun et al., 2010, 2015; Cropper et al., 2014). On the other hand, the flux data from the deeper CB traps suggest some change of lateral advection since 2005/2006 which might be due to circulation changes associated with global change and increasing alongshore winds (e.g., Lluch-Cota et al., 2014). Distinguishing between natural climate variabilities such as NAO and AMOC and trends due to global change (Haine, 2016), however, requires much longer time series of observations, in the order of 40 years (e.g., Henson et al., 2010). This is far from being available for most sediment trap sites. Other long-time series studies in the Atlantic Ocean, for example, at site BATS now come close to this long sampling period needed. However, BATS is an oligotrophic setting showing an increase in phyto- and meso-zooplankton in a comparable time period (1994–2010; Steinberg et al., 2012), which is opposite to what we are observing in the coastal upwelling off Mauritania.

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