



Mesoscale contribution to the long-range offshore transport of organic carbon from the Canary Upwelling System to the open North Atlantic

Elisa Lovecchio¹, Nicolas Gruber¹, and Matthias Münnich¹ ¹ETH-Zürich, Universitätstrasse 16, 8092 Zürich, Switzerland *Correspondence to:* Elisa Lovecchio (elisa.lovecchio@usys.ethz.ch)

Abstract. Several studies in upwelling regions have suggested that mesoscale structures, such as eddies and filaments, contribute substantially to the long-range transport of the organic carbon from the nearshore region of production to the offshore region of remineralization. Yet this has not been demonstrated in a quantitative manner for the entire Canary Upwelling System (CanUS). Here, we fill this gap using the Regional Oceanic Modeling System (ROMS) coupled to a Nutrient, Phytoplankton,

- 5 Zooplankton, and Detritus (NPZD) ecosystem model. We run climatological simulations on an Atlantic telescopic grid with an eddy-resolving resolution in the CanUS. Using both a Reynolds flux decomposition and structure-identification algorithms, we quantify and characterize the organic carbon fluxes driven by filaments and eddies within the upper 100 m and put them in relationship to the total offshore transport. Our analyses reveal that both coastal filaments and eddies enhance the offshore flux of organic carbon, but that their contribution is very different. Upwelling filaments, with their high speeds and high organic
- 10 carbon concentrations, transport this carbon offshore in a very intense, but coastally-confined, manner, contributing nearly 80% to the total flux at 100 km offshore distance. The filament contribution tapers off quickly to near zero values at 1000 km distance, leading to a strong offshore flux divergence that is the main lateral source of organic carbon in the first 500 km offshore. Some of this divergence is also due to the filaments inducing a substantial vertical subduction of the organic carbon below 100 m. Owing to the temporal persistence and spatial recurrence of filaments, the filament transport largely constitutes
- 15 a time-mean flux and only to a limited degree represents a turbulent flux. At distances beyond 500 km from the coast, eddies dominate the mesoscale offshore transport. Although their contribution represents only 20 % of the total offshore flux and of its divergence, eddies, especially cyclones, transport organic carbon offshore to distances as great as 2000 km from the coast. The eddy transport largely represents a turbulent flux, but striations in this transport highlight the existence of typical formation spots and recurrent offshore propagation pathways. While they propagate slowly, eddies are an important organic carbon
- 20 reservoir for the open waters, since they contain on average a third of the offshore organic carbon, two third of which is found in cyclones. Our analysis confirms the importance of mesoscale processes for the offshore organic carbon transport and the fueling of the heterotrophic activity in the eastern subtropical North Atlantic, and highlights the need to consider the mesoscale flux in order to fully account for the three-dimensionality of the marine biological pump.





1 Introduction

The Canary Upwelling System (CanUS) is one of the four major Eastern Boundary Upwelling Systems (EBUS), i.e., coastal regions along the western boundaries of the continents characterized by equatorward winds inducing an offshore Ekman transport. This causes the upwelling of cold, nutrient-rich water in the nearshore region, fueling intense biological activity near

- 5 the coast (Chavez and Messié, 2009; Carr, 2002). This coastal upwelling is embedded within the equatorward flowing branch on the eastern side of the subtropical gyres, i.e., the relatively sluggish eastern boundary currents. Coastal shear and irregular topography, obstacles such as islands, and the density gradient generated by the upwelling of cold waters at the coast produce substantial variability in the flow of the coastal currents, giving rise to turbulence in the form of mesoscale fronts, filaments, eddies and other forms of mesoscale structures (Barton et al., 1998; Capet et al., 2013). This mesoscale variability modulates
- 10 the spatial distribution of tracers with an important impact on the biological activity (McGillicuddy, 2016; Mahadevan, 2014). Further, it is expected to have an important role in the offshore transport of the coastally-produced organic matter, fueling the biological activity of the oligotrophic open waters (Álvarez-Salgado, 2007; Sangrà, 2015; Pelegrí et al., 2005).

Coastal filaments are narrow (<50 km wide) structures that extend from the coast to several hundred kilometers into the open sea with rather large velocities (between 0.25 and 0.5 m s⁻¹), often recirculating the water in vortices at their extremity (Strub

- 15 et al., 1991). Offshore transport by filaments is typically accompanied by intense subduction, due to the high density of the cold upwelled waters (Mahadevan, 2014; Nagai et al., 2015). Filaments, with their high concentration of organic carbon (C_{org}), have been shown to export laterally about half of the coastal production from their region of origin (Gabric et al., 1993; Pelegrí et al., 2005; Arístegui et al., 2003). Locally, this transport can exceed the mean Ekman transport in the nearshore several times (Rossi et al., 2013; Álvarez-Salgado, 2007). The laterally exported C_{org}, part of it in the form of particulate organic carbon
- 20 (POC) and part of it in the form of dissolved organic carbon (DOC) (García-Muñoz et al., 2005), may accumulate then in the oligotrophic open ocean regions (Álvarez-Salgado, 2007), eventually fueling heterotrophic activity there. In addition to C_{org}, filaments are also responsible for the lateral export of chlorophyll, nutrients (Cravo et al., 2010) and living organisms (Brochier et al., 2014) to the open sea.

Long living mesoscale eddies generated by coastal instabilities, irregular topography and obstacles such as islands are responsible for the long-range transport of physical and biogeochemical properties (Stammer, 1998; Zhang et al., 2014; Amores et al., 2017). These non-linear structures propagate with velocities of a few centimeters per hour, about one order of magnitude slower than the filaments, while rotating much faster around their center (Chelton et al., 2007; Schütte et al., 2016a; Klocker and Abernathey, 2014). Stable eddies can live for several months up to years, and therefore propagate for hundreds or even thousands of km from their region of origin (Chelton et al., 2011), despite their low translational speed. They thus reach

30 substantially farther offshore than the filaments (Sangrà et al., 2009; Combes et al., 2013). Due to their non-linear character, eddies trap water and tracers in their core during their formation. Once the eddy is formed, the entrained tracers are nearly isolated from the surrounding environment, except for the vertical exchange (Karstensen et al., 2015). Through the initial trapping of tracers, and the subsequent upwelling/downwelling, mixing, and the interaction with the external forcings such as the wind (McGillicuddy, 2016; Gaube et al., 2015), mesoscale eddies produce important perturbations of the biogeochemical





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properties in the euphotic layer (Pelegrí et al., 2005; Gaube et al., 2014). This has strong impacts on the local biogeochemical fluxes and ecosystem (Baltar et al., 2009; Doblin et al., 2016; Rossi et al., 2008, 2009). Due to the long life span of the eddies, the isolation of their cores, and the substantial biogeochemical transformations, the tracer composition of the eddy center as well as the eddy community structure on many trophic levels may be substantially different from that of the surrounding waters (Löscher et al., 2015; Karstensen et al., 2015). As a result, the eddy can considerably modify the properties of the surrounding

waters when it releases its content upon its death (Mahadevan, 2014; Stramma et al., 2013).

Relative to the other EBUS, the CanUS has a moderate level of eddy activity (Lachkar and Gruber, 2011), but hosts some of the largest filaments (Ohde et al., 2015). Mesoscale activity within the CanUS differs substantially between the different subregions. This is a consequence of the complex circulation pattern that characterizes the region (Mackas et al., 2006; Sangrà,

- 10 2015). The Cape Verde frontal zone, along which the coastal Canary and Mauritanian currents are deflected offshore, defines a natural boundary for the flow of water masses and tracers in the region (Pelegrí and Peña-Izquierdo, 2015). This front separates the CanUS into a northern and a southern sector that differ in both biological activity, seasonality of the upwelling and circulation (Arístegui et al., 2009; Pelegrí and Benazzouz, 2015).
- Most of the coastal filaments in the CanUS are observed north of the Cape Verde front, generally associated with the 15 numerous capes that characterize this part of the CanUS (Arístegui et al., 2009; Pelegrí et al., 2005). The most prominent filament in the northern subregion is that associated with Cape Ghir. This quasi-permanent filament was estimated to export between 30 % and 60 % of the average annual primary production in its region of formation stretching offshore for at least 200 km (Santana-Falcón et al., 2016; García-Muñoz et al., 2005; Sangrà, 2015). South of Cape Ghir, numerous minor filaments with more variable origin are often found, among which the Cape Juby and Cape Bojador filaments stand out. These filaments
- 20 interact, feed into and wrap around numerous coastally generated eddies that often reach the Canary Archipelago, forming a filament-eddy coupled system (Barton et al., 2004; Garcia-Muñoz et al., 2004; Rodríguez et al., 2004). These nearshoregenerated eddies, together with the eddies shed by the Canary Archipelago through the destabilization of the flow of the Canary Current, form the so-called Canary Eddy Corridor, which has been demonstrated to strongly enhance primary production in the region due to the intense biological activity in the eddy cores (Barton et al., 1998; Arístegui et al., 1997). Eddies in the

25 Canary Eddy Corridor may live for more than a year, propagate far westward and thus drastically enhance the offshore reach of the coastally produced matter, with an estimated annual mean integrated transport of 1.3 Sv (Sangrà et al., 2009, 2007).

Bounding the northern and the southern CanUS subregions and originating in the region of formation of the Cape Verde front (21 °N), the giant Cape Blanc filament is the most intense upwelling filament of the system. In fact, it is one of the largest filaments among all EBUS, extending more than 700 km in the open waters in the winter season (Ohde et al., 2015). This

- 30 structure has been reported to export chlorophyll for about 400 km from the coast, and sinking POC up to 600 km offshore at intermediate depths of 400 m to 800 m (Fischer et al., 2009), accounting for a total lateral export of about 50 % of the newly produced particulate matter on the shelf (Gabric et al., 1993). The whole system of filaments that form along the northern CanUS sector from Cape Blanc (21 °N) and Cape Beddouza (33 °N) has been estimated to account for a total offshore flow of about 6 to 9 Sv (Barton et al., 2004), accounting for between 2.5 and 4.5 times the offshore carbon export driven by the Ekman
- 35 transport (Álvarez-Salgado, 2007).





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Fewer studies focused on the upwelling and mesoscale dynamics of the region south of the Cape Verde frontal zone. Here, filaments have a more transient nature compared to those generated in the northern CanUS sector (Arístegui et al., 2009). Most of the filaments in the southern sector are found between Cape Verde and Cape Blanc, they extend between 100 km to 200 km offshore and have a typical lifetime of a few weeks (Menna et al., 2016). Eddy-filament interaction such as the triggering of filament formation and the north-westward advection of entrained filament water by eddies have been documented (Meunier et al., 2012). Eddies in the southern CanUS tend to be generated mainly near the coast near some topographic hotspots, and

to move along distinct eddy corridors, having a major role in the westward transport of physical properties, with significant differences between cyclonic and anticyclonic eddies (Schütte et al., 2016a).

Given the complexity and the intermittency of the mesoscale dynamics, a quantification of the integrated mesoscale transport and of the relative contribution of eddies and filaments in upwelling regions is extremely challenging to achieve with observations alone. In response, most studies have employed results from model simulations. A comparative study of the CanUS and California Upwelling System (CalUS) addressed the role of the cross-shore eddy diffusivity in the redistribution of physical and biogeochemical properties, finding that systems with high eddy activity, such as the CalUS, are characterized by a much more dispersive environment and are therefore more likely to see also their coastal tracers concentrations eroded by the lat-

- 15 eral eddy mixing (Marchesiello and Estrade, 2006). Strengthening this claim, Nagai et al. (2015) demonstrated that mesoscale structures in the CalUS were largely driving the offshore transport of organic matter. Furthermore, model simulations for both the CalUS and CanUS also showed that eddies tend to reduce coastal production through the lateral export of the upwelled nutrients (Gruber et al., 2011; Lachkar and Gruber, 2011). Focusing on the CalUS and with the use of a passive tracer, Combes et al. (2013) have demonstrated that mesoscale eddies, and in particular cyclonic ones, exert a strong control on the horizontal
- 20 offshore transport. Combining a simple ecosystem model with modeled and observed velocity fields, the mesoscale transport in the Benguela Upwelling System was estimated to account for 30 %- 50 % of the total offshore flux (Hernández-Carrasco et al., 2014).

Despite these previous efforts, the long-range integrated mesoscale transport in the CanUS and its contribution to the total transport of C_{org} (Lovecchio et al., 2017) remains ill quantified. Here we aim to fill this gap using a fully coupled physical and biogeochemical model that we employed earlier to study the total offshore flux in this system. The model is configured on a full Atlantic basin grid with an eddy resolving resolution in the region of study that allows us to study the fluxes up to 2000 km offshore. Performing a Reynolds decomposition we present a quantification of the turbulent lateral and vertical transport of organic carbon as a whole; then, using a filament and eddy identification algorithms, we study the specific impact of filaments, cyclonic and anticyclonic eddies on the C_{org} budget and transport.

30 2 Methods

We employ the UCLA-ETH version of the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2005) coupled to the simple Nutrient Phytoplankton Zooplankton Detritus (NPZD) biogeochemical ecosystem model described by Gruber et al. (2006). The coupled model was run with the same grid, boundary conditions and climatological mean atmospheric





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forcings as those presented in Lovecchio et al. (2017). The employed Atlantic telescopic grid is curvilinear, covers the entire Atlantic, and has a strong grid refinement towards the north-western African coast (Figure 1). This setup allowed us to model the large-scale flow in the whole Atlantic basin, while maintaining an eddy resolving resolution of between 4.9 km and 20 km in the region of interest. The model was run for 53 years, of which the first 29 years are considered spinup and the last 24 years are used for the analyses. The output was saved in the form of bi-daily mean fields, a time resolution that allows us to identify the rapidly evolving mesoscale structures.



Figure 1. Model grid and CanUS domain superimposed on an instantaneous snapshot of Sea Surface Temperature [$^{\circ}$ C] from day 01/12/0030 of the run. (a) Atlantic telescopic grid showing every 20th grid line (solid lines) with isolines of grid resolution in km (dashed lines); the black square highlights the CanUS region used for the zoomed-in plot. (b) Zoom on the CanUS region including the names of the major capes and the boundaries of the regional and subregional domains used for the analyses. The western boundary (solid line) is located at 2000 km offshore distance, the northernmost and southernmost regional boundaries (solid lines) are set at 9.5°N and 32°N, respectively. The subregional boundaries (dashed lines) are located at 17°N and 24.5°N and divide the CanUS region into 3 subregions: southern, central and northern CanUS.

If F denotes the organic carbon flux vector, u the velocity vector and C_{org} the organic carbon concentration we have $F = uC_{org}$. To analyze this flux we performed a Reynolds decomposition, i.e., we split the flux into $F = \overline{F} + F'$, were the bar denotes time averaging according to the definition of the reference mean (see below) and the prime indicates turbulent deviations from this mean. To do so we first calculated the (time-varying) reference mean and turbulent contribution to the velocity vector \overline{u} and of the organic carbon concentrations \overline{C}_{org} at each time and determined the their turbulent values by subtraction $u' = \overline{u} - u$ and $C'_{org} = \overline{C}_{org} - C_{org}$. Throughout the entire analysis, our reference means are the climatological monthly means of velocities and concentrations as calculated from the 24 years of the run used for the analysis, and interpolated them to bi-daily fields. This choice allowed us to include both the seasonal and the monthly variations of the fields into the

15 mean fluxes, rather than into the turbulent component, while obtaining smooth mean bi-daily fields. We then decomposed the





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Corg fluxes at each time step, and calculated the long-term average mean and turbulent fluxes of Corg as in:

$$\langle oldsymbol{F}
angle = \left\langle \overline{oldsymbol{u}} \overline{oldsymbol{C}}_{\mathrm{org}}
ight
angle + \left\langle oldsymbol{u}' {f C}'_{\mathrm{org}}
ight
angle + r$$

(1)

where the angled brackets represent averaging over our analysis period. The first summand on the right hand side gives the average mean $\langle \overline{F} \rangle$, the second the average turbulent contribution $\langle F' \rangle$ to the overall flux. The last term $r = \langle \overline{u}C'_{org} \rangle + \langle u'\overline{C}_{org} \rangle$ term represents the sum of the residuals which we verified to be small, at least one order of magnitude or more smaller than the other terms.

To quantify the contribution of mesoscale eddies to the C_{org} budget and transport, we used a sea surface height (SSH) based eddy identification algorithm (Faghmous et al., 2015). According to this method, eddies are defined as the outermost closed SSH contour containing a single extreme (either maximum or minimum). Despite the geometrical, rather than physical,

- 10 definition of eddies and the restriction on the number of inner extremes, the algorithm was shown by Faghmous et al. (2015) to be able to retrieve 96 % of the eddies identified by domain experts. Our visual analysis of animations of the eddy contours and centers on the modeled SSH and horizontal velocity fields confirmed the good performance of the method. The algorithm was adapted to run on our curvilinear grid, allowing it to work with 2-dimensional longitude and latitude arrays and therefore to correctly weight with SSH the position of the eddy centers on our grid keeping into account the stretching and curvature of
- 15 the grid. Using this eddy identification method, we saved at each time step the position of all the eddy centers, the grid points covered by their areas and their signatures (cyclonic or anticyclonic). Eddies with a radius smaller than 15 km were filtered out to avoid noise in the nearshore high-resolution region.

To estimate the contribution of filaments to the mesoscale transport we developed an SST-based filament-identification algorithm. The filaments in question are upwelling filament generated at the CanUS coast which extend offshore the carrying

- cold upwelled water within them. First, the above reference mean SST field is coarsened onto a $2^{\circ} \times 2^{\circ}$ grid. Next the current SST anomalies (SSTA) are calculated by subtracting this mean SST from the current SST field. Any grid location were this SSTA is below a threshold of -0.3°C is marked as a potential location of a filament. Grids point of an identified eddy at that time are excluded from these potential filament locations. Finally each connected region of potential filament location that touches the coastline is declared a filament. Visual evaluation of our algorithm confirmed that the large majority of the filaments were
- 25 indeed captured by this method. The few false positives identifications were limited to the southern boundary of the CanUS. An example of one of the filament masks is given in the Appendix in Figure B1.

In the vertical direction, we assumed both eddies and filaments to have a prismatic volume, i.e., at each depth, k, they occupy the same horizontal i, j positions as those identified at the surface. We used these 3D masks to decompose the C_{org} concentration and the C_{org} fluxes into their filament, cyclonic, anticyclonic components. To calculate the C_{org} concentration

30 or concentration anomalies in the mesoscale structures, we multiplied these variables by the mask of interest at each time step and averaged the whole time series in time. To calculate the mesoscale components of the C_{org} fluxes, we multiplied C_{org} concentration and velocity fields at each time step by the mask of interest. We then multiplied the masked fields by each other step by step and averaged in time at the end. The non-filament/non-eddy (NF-NE) mask was calculated at each time step as





the difference between a matrix of ones and the sum of the filament and eddy masks, and was used for the calculation of the NF-NE flux components analogously to the eddy and filament masks.

We focus our analysis on the top 100 m, corresponding roughly to the average depth of the euphotic layer in the CanUS domain. This is largely motivated by our interest in the impact of the lateral redistribution of C_{org} in the biologically most active region of the ocean. We will demonstrate also that the conclusions we draw are not contradicted by a consideration of the fluxes throughout the entire watercolumn.

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3 Evaluation

Since the model setup used for the present study is the same as the one employed in Lovecchio et al. (2017), we refer to this previous publication for a detailed description of the model performance. We first summarize here the most important find-

- 10 ings, and then extend the evaluation to include aspects that are particular to this study, namely the model's representation of mesoscale processes. Physical variables such as sea surface height (SSH), sea surface temperature (SST), sea surface salinity (SSS) and mixed layer depth (MLD) are well represented by our model in the region of study, with correlations with observations of more than 0.85 in the annual mean. Relevant long-term mean biases in SST (~ +0.75 °C) and SSS (~ +0.4 g/kg) are found only in the sector of the CanUS located south of Cape Blanc (21 °N), where the modeled circulation is also too sluggish
- 15 compared to observations. Biological variables such as net primary production (NPP), chlorophyll (CHL) and POC are also well represented north of Cape Blanc and in its proximity, while south of this Cape they show too deep maxima. A Taylor diagram summarizing the evaluation of our modeled mean physical and biological fields can be found in the Appendix, Figure B2.
- Thanks to the model's high resolution, the magnitude of the Turbulent Kinetic Energy (TKE) as observed by AVISO is overall well captured by the model. Between the Canary and the Cape Verde archipelago, the modeled TKE pattern is the most similar to the one observed, indicating a very satisfactory representation of turbulence in this central sector of the CanUS. A similar observation results from the STD(SSH) comparison, which overall confirms our assessment of the ability of ROMS to represent turbulence in this zonal band. However, as expected from our assessment on the mean circulation, the TKE is underestimated south of Cape Blanc, especially in the proximity of the North Equatorial Counter Current and south of the
- 25 Cape Verde archipelago (Figure 2a,b). This is visible also in the evaluation of the SSH standard deviation (STD(SSH), Figure 2c,d). Similarly, at the north-western boundary of the CanUS the TKE associated to the incoming Azores Current is reduced. The underestimation of turbulence at the northern and southern CanUS boundaries can be due to the fact that both the Azores Current and the Northern Equatorial Counter Current are generated away from the north-western African coast, in regions in which the grid has a low resolution. On the eastern side of the northern CanUS, along the portion of the African coast located
- 30 north of Cape Blanc, and especially north of the Canary Archipelago, the modeled TKE is instead higher than observed. This region is the most populated by coastal upwelling filaments, which may be particularly intense in our model. However, in terms of the magnitude of STD(SSH) the overestimation of turbulence along the coast does not seem as pronounced as in terms of the TKE. The high aspect ratio of the filament structures, which often have a width of only a few tens of km, may also make







Figure 2. Comparison of (a) modeled ROMS and (b) observed AVISO Turbulent Kinetic Energy, TKE [cm²/s²]; Comparison of (c) modeled ROMS and (d) observed AVISO standard deviation of SSH, STD(SSH) [m]. Modeled velocities were calculated offline using geostrophy from modeled SSH and regridded on the AVISO DUACS 2014 product grid, 1/4 °resolution. TKE was calculated from bi-daily (ROMS) and daily (AVISO) turbulent velocities, defined as differences of the total fields from the monthly climatology interpolated to daily (AVISO) or bi-daily (ROMS) time resolution. A detailed description of the data used is provided in Appendix A: Datasets, Table A1.

them difficult to detect in the satellite product. The AVISO dataset, in fact, has a resolution of 1/4°(roughly corresponding to 25 km in our domain), way lower than our model grid, which is in the range of less than 8 km of grid spacing near the coast. Therefore, even though we evaluate the model data through a regridding onto the lower-resolution AVISO grid, the model may still resolve the turbulent flow on scales that are simply not detected by the remote sensors.

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To evaluate the ROMS eddy field, we ran the eddy-finding algorithm on both modeled and AVISO SSH. Since we did not regrid the two SSH fields, our results must be discussed taking into account differences in resolution between the model grid and that of the AVISO product, which has a resolution of 1/4 of degree. In particular, due to the fact that our the eddy-finding algorithm requires a minimum of 9 grid points to identify an eddy, the distribution of eddy radii (R) from AVISO drops for small R values. For this reason we have limited the comparison to big eddies ($R \ge 50$ km). The density of big eddy centroids







Figure 3. Comparison of the mean number of large eddy ($R \ge 50$ km) centroids from (a) modeled ROMS and (b) observed AVISO, binned to 1°x 1°bins. Comparison of the mean diameter [km] of large eddies ($R \ge 50$ km) from (c) modeled ROMS and (d) observed AVISO, binned to 1°x 1°bins.

(number of eddies per 1 degree bin) from model and observations show a very similar spatial pattern, even though the modeled density of large eddies is slightly biased low (Figure 3a,b). In the sector of the CanUS located between the Canary and the Cape Verde archipelagos, the modeled density of eddy centroids shows the closest match to the observations, in line with our previous findings. We also find a good agreement between the distribution of the modeled and observed large-eddy eddy

- 5 diameters (see Appendix: Figure B3b). The main differences in the pattern of eddies are found at the edges of the CanUS domain (both southern and northern boundaries), south-west of the Cape Verde archipelago, and around the Canary Islands. This goes along with our model struggling in these regions to reproduce the very big eddies with $\langle D \rangle > 300$ km (Figure 3c,d). The deficiencies at the southern and northern boundaries are associated with the onshore-flowing Azores Current and North Equatorial Counter Current, i.e., the eddies in these regions stem from outside our main region of interest, and also from a
- 10 region with relatively low resolution in our model. The eddy deficiency southwest of Cape Verde archipelago may be due to a





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northern shift of the modeled Cape Verde front, which results in the currents hitting the islands with a lower intensity, thereby generating fewer instabilities than observed. On top of this, the presence of land points (absent in the AVISO product) may hinder the identification of large eddies in the very proximity of the islands in our model. The latter effect may explain also the low bias in the density of large eddy centroids in the proximity of the Canary islands, since the model simulates the correct level of TKE in this region. This high level of TKE in the absence of large eddies stems from our model simulating a very high abundance of small eddies in the proximity of the Canary archipelago.



Figure 4. Statistics for all the modeled eddies with $R \ge 15$ km. (a) Modeled density of eddy centroids per day; (b) Modeled mean eddy diameter [km]; (c) Modeled Standard deviation of the eddy diameter [km]. All quantities have been averaged in 1deg x 1deg bins.

If we consider the whole modeled eddy population used for the analysis (R > 15 km), we find a strong offshore gradient in the density of eddy centroids, accompanied by an increasing mean eddy diameter in the offshore direction (Figure 4). In part, this is in line with the fact that smaller eddies tend to have a shorter lifetime, and hence may become less abundant as the coastally-produced eddies evolve and decay while they evolve and drift offshore (Chaigneau et al., 2008). In part, this may also be a model artifact stemming from our grid resolution decreasing with increasing distance from the north-western African

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coast. Thus, the model tends to suppress the small eddies in the open waters relative to the nearshore environments. In contrast with the lack of large eddies, small eddies are abundant found in the proximity of the Canary and Cape Verde archipelago.

Anticyclonic eddies (ACE) and cyclonic eddies (CE) in the CanUS differ marginally in terms of their statistical properties. ACE are slightly less abundant than CE throughout the CanUS, representing about 49% of the total eddy population, in

- 5 agreement with previous analyses (Schütte et al., 2016a). ACE and CE have a mean diameter of respectively 95 km and 86 km and occupy on average 15% and 10%, respectively, of the entire surface of the CanUS, summing to ~ 25 % of the total area, in line with the results of previous studies (Chaigneau et al., 2009). Both kinds of eddies reach a maximum area occupation at around 250 km offshore, i.e., in the range in which they are likely generated. With increasing distance, while the share of area occupied by CE remains pretty stable, ACE show a slow but persistent decline, which may be an indication of reduced stability
- 10 and shorter life span of this kind of eddies, with important consequences on their integrated offshore transport. A comparison of these trends with those derived from the AVISO daily eddy field shows overall an excellent level of agreement. Our model slightly underestimates the total surface occupied by CE (by 2.5 %) and by ACE (by 5 %), which results in a slight bias in favor of CE. But the offshore evolution of the surface occupation of the two types of eddies compares very favorably with the observed trends, giving us a substantial amount of confidence in terms of our analyses of eddy evolution (see Appendix: Figure B4).

4 Results

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4.1 Turbulence in the organic carbon field

At any moment, the pattern of C_{org} concentration is shaped by the interactions between the biological and physical processes that add, remove and redistribute the organic matter in the ocean. Due to the interplay of these processes, the concentration of C_{org} in the surroundings of the north-western African coast exhibits a complex pattern that combines a large-scale offshore gradient with smaller-scale anomalies visible as swirls, squirts and fronts that correlate strongly with the pattern of SSH and currents (Figure 5a,b). This highly variable pattern can be conceived as the superposition of a mean C_{org} field and of a turbulent deviation around it (Figure 5c,d). The turbulent component of this pattern, characterized by strong positive and negative anomalies, clearly evidences the important role of mesoscale eddies and filaments in the modulation of the C_{org} concentration. Thin and a short-lived filaments channel the carbon away from the coast, while slower, but persistent eddies create islands of enhanced or dampened C_{org} concentration that propagate toward the open ocean.

In the following, we will be employing two complementary approaches to quantify the relative role of these mesoscale variations to the total offshore transport of C_{org} . In the first "turbulence-based" approach, we will be using a Reynolds decomposition to separate these two components, while in the second "structure-based" approach, we will be using filament and eddy masks to quantify the specific contribution of these two kinds of mesoscale structures to the C_{org} transport.







Figure 5. Modeled 2-day mean variables for July 19-20 of year 33 of the simulation. (a) SSH [cm] (color shading) and currents u (vectors); (b) Total organic carbon stock ($\int C_{org}$) as well as its (c) mean ($\int \overline{C}_{org}$) and turbulent part ($\int C'_{org}$), respectively. The C_{org} is integrated throughout the entire watercolumn.

4.2 Mean and turbulent transport

The Reynolds decomposition of the advective fluxes of C_{org} in the top 100 m reveals that, while the time-mean flux dominates the total flux (see also: Lovecchio et al. (2017), Figure 11, Total organic carbon fluxes), the turbulent flux contributes substantially to the total fluxes and to their divergences in both lateral and vertical direction (Figure 6). In the zonal direction,

- 5 the turbulent transport strengthens the offshore transport of the C_{org} at every latitude with its persistently negative signature, visible also far into the open waters (Figure 6d). Its magnitude varies within the CanUS from a minimum of 5% to up to above 30 % of the mean lateral transport (Figure 7a,b), with the maximum relative contribution being reached at about 200 km from the coast and a slow decline in the offshore direction. In terms of its divergence (Figure 7a, insert), the turbulent component contributes about a third to the total zonal divergence, i.e., the amount of C_{org} released by the zonal flux on the way to the open
- 10 ocean, significantly enhancing the C_{org} stock.







Figure 6. Reynolds decomposition of the lateral and vertical advective fluxes of C_{org} into their average mean $\langle \overline{u}\overline{C}_{org} \rangle$ and average turbulent $\langle u'C'_{org} \rangle$ components, as defined in the methods section. Lateral fluxes are integrated in the first 100m depth, the vertical flux is sliced at 100m depth.

The contribution of the turbulent offshore flux is particularly important in the northern and southern CanUS. In the northern subregion (Figure 7c), the mean flux declines much faster than the turbulent flux in the offshore direction, allowing the latter to represent more than half of the total transport at distances exceeding 200 km from the coast. However, in terms of divergence, the turbulent contribution becomes important only at offshore distances of more than 500 km and then really dominant beyond

- 5 1500 km. In the southern subregion, the mean flux is, on average, directed onshore in the first 1000 km from the coast, while the turbulent flux opposes it, redirecting part of the C_{org} towards the open waters (Figure 7e). In terms of divergence, the turbulent flux opposes the mean fluxes, adding, rather than subtracting, C_{org} to the local budget with maximum rates of about 1/3 of the absolute value of the mean divergence between 100 km and 500 km offshore. In contrast, the central CanUS (Figure 7d) is characterized by a very intense mean offshore flux, likely connected to the far-reaching currents that create the Cape Verde
- 10 front. However, even in this region, the turbulent flux contributes up to 25% and always more than 5% to the total offshore flux of C_{org} , with a trend analogous to that for the CanUS as a whole. In the central subregion, the divergence of the turbulent offshore flux amounts to about 20% of the total, therefore still representing a non-trivial portion of the C_{org} released by the offshore flux.





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Figure 7. Magnitude of the mean and turbulent components of the offshore flux $[\text{GmolC yr}^{-1}]$: (a) Canary EBUS as a whole; (c) northern CanUS; (d) central CanUS; (e) southern CanUS. In all area plots: the black thick line is the total offshore flux, sum of mean and turbulent fluxes; fluxes are integrated in the first 100 m depth. Plot (b): only for the full EBUS we show the ratio of the magnitude of the turbulent/total offshore flux, integrated in the first 100 m and throughout the whole watercolumn. Inserts: ratio between the absolute value of the divergence of the turbulent component and that of the total flux, integrated in the first 100 m depth (black line) and over the full water-column (gray line). Per each offshore range, divergences are calculated as finite differences at the boundaries shown on the x-axis. Dots are red when both total and turbulent divergences are negative (fluxes remove C_{org}); dots have the same color of the line when both divergences are positive (fluxes add C_{org}). In the Southern subregion only: blue dots indicate that the divergence of the turbulent flux (positive) opposes the divergence of the mean flux (negative); the opposite is true for red dots with a blue contour.

The turbulent transport has an important role also in the meridional direction, as it opposes the mean flow and recirculates C_{org} against the direction of the mean currents, especially along the coast in correspondence to the intense Canary and Mauritanian currents, with a magnitude corresponding to about 20% of the mean flux (Figure 6b,e). But, perhaps, the most important contribution of the turbulent transport occurs in the vertical with the vertical component of the turbulent flux exceeding the magnitude of the mean fluxes (Figure 6c,f). This occurs especially in the nearshore northern and central CanUS, where the

turbulent vertical component at a depth of 100 m is strongly downwelling, opposing the mean upwelling at the coast. As a





result, the coastally-produced C_{org} gets subducted below the euphotic layer and potentially exported further offshore towards the center of the North Atlantic gyre.



Figure 8. Reynolds mean and turbulent components of the advective fluxes of C_{org} averaged along lines of equal distance from the coast in the whole CanUS. (a) Mean zonal advective flux; (b) Turbulent zonal advective flux; (c) Mean vertical advective flux; (d) Turbulent vertical advective flux.

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The vertical sections of the zonal transport of C_{org} (Figure 8a,b) reveal that, on average, this component is persistently directed offshore at every depth, and is most intense in the first 500 km from the coast. The turbulent component of this transport is characterized by a thin and shallow maximum confined to the top 100 m, with only a weak transport occurring below. The deepest extent is found in the first 500 km, reaching down as far 400 m. In contrast, the mean zonal flux tends to extend deeper, especially in the offshore region. Both the mean and the turbulent fluxes show an offshore deepening of the transport, likely as a consequence of the aforementioned vertical subduction and of the deepening of the production in response to the deepening of the nutricline (see also: Lovecchio et al. (2017), Figure B6, Vertical sections of the modeled POC). In the very nearshore, the mean transport at depths larger than 200 m is characterized by a weak onshore recirculation, a feature only

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very weakly seen in the turbulent transport.

Even though the vertical profiles of the mean and turbulent zonal fluxes differ, the regional pattern of the two components integrated in the first 100 m depth (Figure 6a,d) or from 100 m up to the bottom of the watercolumn (see Appendix: Figure B5) is very similar. An exception is the nearshore, where the onshore advection at depth in the mean transport, likely connected to

15 the presence of the upwelling cell, leads to a weakening of its negative signature. Nevertheless, the contribution of the turbulent





flux to the total divergence is about the same in the upper 100 m and across the whole water column (see Figure 7, inserts). We thus conclude that a focus on the transport in the top 100 m is well justified, and that the conclusions drawn from it are robust with regard to the selection of the vertical extent of the analysis.

- Switching to the vertical fluxes, the differences between the mean and turbulent flux components are even more pronounced (Figure 8c,d). Near the coast, the mean vertical advective transport is dominated, as expected, by the signature of the coastal upwelling. The different signature of the wind stress curl and consequent Ekman pumping offshore in the northern and southern CanUS results, on average in the CanUS, in a mixed signature of the vertical transport in the open waters. On the contrary, the turbulent component of the vertical advective flux of C_{org} is directed downward in all the subregions resulting in a negative signature for the whole CanUS. Also in this direction, the turbulent flux is particularly intense in the nearshore. However, in
- 10 opposition to what we have seen for the zonal flux, the turbulent vertical transport extends much deeper and more intensely than the mean transport, reaching 200 m depth everywhere and going deeper than 500 m in a range of more than 500 km from the coast.

4.3 From turbulent bursts of organic carbon to mesoscale anomalies

The important contribution of the offshore transport by turbulent anomalies can be classically visualized through the use of 15 Hovmoeller diagrams, which show how positive and negative anomalies of SSH' and C'_{org} are moving offshore (See appendix figure B6). This representation shows positive and negative signals of both C'_{org} integrated in the first 100 m and SSH' that propagate coherently from the coastline through the whole 2000 km offshore range in about 1.5 years, with a resulting mean propagation speed of about 4 cm s⁻¹. This speed corresponds closely to the typical speeds of the first baroclinic mode of Rossby waves at these latitudes (Klocker and Abernathey, 2014), suggesting an important role of coherent mesoscale eddies in

20 this offshore transport.

The mean correlation and covariance of SSH' with C'_{org} provide an additional link between the propagation of the turbulent anomalies and the mesoscale contribution to the long-range transport, as mesoscale structures are associated to both kinds of anomalies (Figure 9 a,b). The two anomalies are anti-correlated in most of our analysis domain, i.e., on average the concentration of C_{org} is enhanced when SSH'<0 (corresponding to CE) and dampened when SSH'>0 (ACE). Exceptions are found

in the surroundings of the incoming Azores and North Equatorial Counter Currents. The cross-product of SSH' and C'_{org} is particularly negative in the nearshore northern and central CanUS subregions (Figure 9b), where we find the most intense and recurrent upwelling filaments, by definition characterized by strongly negative SSH' (Cravo et al., 2010).

To better understand the nature of these correlations, we separately plot the anomalous C'_{org} content for the ACE and CE, respectively (Figure 9 c,d). Indeed, in most of the CanUS region, ACE and CE are responsible for a local decrease and increase

30 of the organic carbon concentration, respectively. This signature is typical of that expected from an eddy-induced vertical displacement of the nutricline (McGillicuddy, 2016). An additional contribution might stem from the trapping at the eddy formation in the proximity of the southward flowing Canary Current, which favors the formation of high C_{org} CE and low C_{org} ACE (Gaube et al., 2014).





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Figure 9. (a) Correlation and (b) covariance of the turbulent SSH anomalies (SSH') with the top 100 m organic carbon stock anomalies, i.e. $\int_{0}^{100\text{m}} C'_{\text{org}}$. Mean $\int_{0}^{100\text{m}} C'_{\text{org}}$ stock contained in (c) ACE and (b) CE, respectively.

Local deviations from the widespread negative correlation of SSH' and C'_{org} can also be explained in terms of eddy anomalies. The positive C'_{org} for ACE seen in the nearshore southern CanUS is likely a consequence of the northward flowing Mauritanian Current, which favors the trapping of carbon-rich coastal waters in ACE at the time of their formation. However, this signature is not sustained during the offshore propagation, likely owing to the reduced capacity of ACE to sustain new production, ultimately resulting in a mean negative signature. The reverse signature of C'_{org} within eddies at the northern CanUS boundary may be connected to the typical characteristics of the incoming large eddies formed in the Azores current (Gaube et al., 2014, Figure 1), leading to ACE with positive anomalies and CE with negative anomalies. In the offshore waters, ACE can also result in positive C'_{org} due to their aging, which causes a slowing down the rotation and eventually inverts the isopycnal tilting in their core (McGillicuddy, 2016).

10 The Hovmoeller diagrams of the eddy and filament associated C'_{org} , isolated with the use of the structure-identification masks, provide additional information regarding the propagation of the anomalies inside the mesoscale features (Figure 10), especially with regard to the differences between eddies and filaments. First, they reveal that the positive C'_{org} associated with







Figure 10. Hovmoeller diagrams of the top 100 m stock anomalies of C_{org} in the central CanUS subregion for (a) anticyclones (ACE), (b) cyclones (CE), (c) filaments (FIL). First 15 years of analysis data.

the filaments is, in absolute terms, at least twice as large as that associated with eddies. Second, while the eddy anomalies span the whole 2000 km of our offshore analysis domain, the filament anomalies typically reach only as far as about 500 km in offshore direction. Third, in terms of speed, the slope of the eddy trajectories corresponds to that seen for the turbulent anomalies discussed before (see Figure B6), while the filament anomalies are instead advected offshore with speeds that often

5 exceeds by several times those of the eddies. An analysis of the velocities in the first 100 m depth indicates on average zonal speeds of about 0.15 m s⁻¹ and 0.05 m s⁻¹ for filaments and eddies respectively, with no significant difference between ACE and CE.

4.4 Mesoscale contribution to the organic carbon stock

When contrasted to the total amount of C_{org} present in the upper 100 m, the fraction of C_{org} that is contained inside mesoscale structures differs drastically between filaments and eddies (Figure 11). On average, filaments contain most of the C_{org} in the first 200 km from the coast, but their contribution declines nearly exponentially with distance, reaching zero at about 700 km offshore. This trend is closely connected to the large aspect ratio of filaments, which extend offshore with a particularly narrow stream of typical widths of a few tens of km, and occupy therefore a small portion of the CanUS area. For this reason, in spite of their high C_{org} content (see Figure B6), they represent overall a small share of C_{org} in the offshore CanUS. On the contrary,

15 ACE and CE see a sharp increase of their C_{org} content in the first few hundreds km from the coast, where most of them are generated (see Appendix: Figure B4). On average, ACE and CE together contain about 30% of the total C_{org} in the top 100 m. The share of C_{org} found inside CE stays around 20 % at every distance beyond 200 km from the coast, with a weak increasing trend with increasing offshore distance. The opposite trend is observed in ACE, which have the highest share at about 200







Figure 11. Top 100 m organic carbon stock $(\int_{0}^{100m} C_{org})$ contained at different distances from the coast in filaments (FIL), cyclonic eddies (CE), anticyclonic eddies (ACE) and outside of the detected mesoscale structures (non-filament-non-eddy, NF-NE). The C_{org} is integrated in the first 100 m depth and across the horizontal extension of the domains for: (a) the Canary EBUS as a whole; (b) the northern CanUS; (c) the central CanUS; (d) the southern CanUS. Inserts: Percentage of the total organic carbon stock that is found within ACE, CE and FIL, by offshore distance; the FIL share of C_{org} in the first 50 km offshore is not plotted since their contribution in this range cannot be clearly identified.

km offshore, while at 1500 km distance they represent slightly less than 10% of the total C_{org} . This is due both to the faster decrease in the number of ACE offshore and to a decline in their C_{org} content.

In order to better understand the distinct C_{org} content of the three kinds of mesoscale structures, differences in their nutrient availability and biological production must also be discussed (Figure 12). In line with the previous discussion, filaments are

- 5 characterized by high nutrient concentrations and even higher production in the nearshore. Stronger differences emerge instead between the two kinds of eddies. While both kinds of eddies contain elevated amounts of inorganic nutrients at the time of their formation in the nearshore region, CE are characterized by an enhanced concentration also offshore. They account, on average, for more than 20% of the available nutrients in the open waters and their nutrient share rises to more than 25 % in the oligotrophic waters at distances beyond 1500 km from the coast. ACE, on the contrary, are characterized by a decline in the
- 10 nutrient stocks at every distance larger than 200 km offshore, accounting for less than 5% of the available nutrients in the open waters.







Figure 12. Inorganic nitrogen (Inorg.N) and Net Community Production (NCP) contained at different distances from the coast in filaments (FIL), cyclonic eddies (CE), anticyclonic eddies (ACE) and outside of the mesoscale structures (non-filament-non-eddy, NF-NE). Both quantities are integrated in the first 100 m depth and across the horizontal extension of the domains for: (a) the Canary EBUS as a whole; (b) the northern CanUS; (c) the central CanUS; (d) the southern CanUS. Inserts: Percentage of the total Inorg.N and NCP found within ACE, CE and FIL, by offshore distance; the FIL share of Inorg.N and NCP in the first 50 km offshore is not plotted since their contribution in this range cannot be clearly identified.

The elevated nutrient concentration in CE is due to several factors, including the input from below connected to the uplifting of the nutricline in their cores at the time of formation (McGillicuddy, 2016), the initial trapping of coastally upwelled waters (favored in the northern CanUS, as discussed above), the local remineralization of the organic matter and, possibly, the input from below through mixing and small scale advection. Given the initially high nutrient availability of these eddies, the offshore

5 drifting of the CE towards low-nutrient regions can result in a relative increase of the share of nutrients also without a large net resupply, simply through the efficient trapping and offshore transport of the reservoir. The elevated nutrient concentrations also allow CE to sustain their higher biological activity, and to compensate partially for the sinking losses of C_{org} to below the euphotic layer.

ACE, in contrast, tend to deepen the nutricline at formation leading to a lower initial nutrient concentration in their cores 10 relative to CE. The elevated nutrient concentration relative to the surrounding in the offshore regions most likely result from the initial trapping of upwelled waters (favored in the southern CanUS), local remineralization and possibly enhanced vertical mixing due to the deepening of the mixed layer in the core. As both the initial C_{org} and nutrient availability in ACE is lower than that of CE, ACE in the CanUS are characterized by lower rates of new and regenerated production and are therefore not as efficient in maintaining the initial C_{org} concentration, which is lost along their tracks through vertical export.

15 4.5 Filament and eddy transport of organic carbon

Having discussed the C_{org} content of each type of mesoscale structure, we can now compute the filament, eddy and non-filament/non-eddy (NF-NE) contribution to the offshore transport of C_{org} through the use of the structure identification algorithms, as described in the methods. These "structure-based" estimates of the transport by eddies and filaments (Figures





13,14) can then be compared to the "turbulence-based" estimate inferred from the Reynolds decomposition (Figures 6,7) both in terms of their respective patterns and in terms of their magnitude and divergence (see also Figure 15 for a summary). Figure 13a reveals that the magnitude and pattern of the NF-NE contribution to the zonal transport is rather comparable to the mean fluxes from the Reynolds decomposition. As was the case for the mean flux from the Reynolds decomposition, this component



Figure 13. Decomposition of the zonal advective transport of C_{org} into: (a) non-filament-non-eddy NF-NE, (b) filament FIL, (c) anticyclonic ACE and (d) cyclonic CE flux. Fluxes are integrated within the top 100m.

- 5 primarily reflects the regional pattern of the mean currents. An exception is the nearshore area where the intensity of the NF-NE transport is more modest, and also directed onshore (Figure 14). This is likely a consequence of our filament mask covering the nearshore few tens of km most of the time, as a result of which we tend to attribute most of the offshore transport for the first 50 km from the coast to filaments. As there is no clear definition of the boundaries of a filament on the shelf, we maintain a critical approach in the attribution of the transport to filaments or NF-NE flow in the first 50 km offshore.
- 10 The filament flux is coastally confined, especially compared to the other three components. However, an analysis of the integrated contribution of the four flux components at different distances from the coast shows us that the filament flux largely dominates the offshore export in the CanUS in the first few hundreds of km offshore both in terms of absolute magnitude and





in terms of its divergence (Figure 14 and Figure 15). The magnitude of the filament transport represents nearly 80% of the total transport at 100 km offshore; at offshore distances larger than about 500 km from the coast, the filament flux declines below the cumulative eddy offshore flux and reaches zero at about 1000 km offshore (Figure 14a,b). Between 100 km and 500 km from the shore, the divergence of the filament transport opposes that of the NF-NE transport, therefore exceeding the total

- 5 net amount of C_{org} added by the offshore flux and representing more than 120 % of its magnitude. Subregionally, filaments always add a substantial amount of C_{org} to the local stocks. The large magnitude of the filament transport in the nearshore reflects both their high C_{org} concentrations and the high zonal advective speeds. Also, despite their limited reach, filaments often shed long-living eddies, which are fed by them with large amounts of tracers; this coupling enhances the offshore reach of the coastal C_{org} initially transported by the filaments.
- Eddy fluxes (Figure 13c,d) are about five times smaller than the NF-NE fluxes, in analogy to the Reynolds turbulent transport when compared to the mean transport (see also Figure 15). Even though the magnitude of the eddy transport is small, in large part as a result of their limited drift speeds, eddies have a large offshore reach due to the their long-range propagation. Among the two eddy types, ACE have a minor role compared to CE in the offshore transport, with a less intense and less far-reaching contribution in the whole CanUS (Figure 14b). This is expected from their more modest C_{org} content and their offshore surface
- 15 decline (see Figure 11 and Figure B4), in part connected to their shorter life span. The striations that characterize the eddy offshore transport result probably from the existence of preferential regions of formation and propagation of the eddies. An excellent example is visible south of the Canary archipelago, where recurrent CE form near the coast (Barton et al., 2004) and drift offshore. Eddy striations are slightly deflected northward in the case of CE and southward in the case of ACE, as expected by the observed mean deflection of their trajectories (Chelton et al., 2011). In an integrated perspective, at offshore distances
- 20 larger than 200 km, ACE and CE together are responsible for about 20 % of the total offshore transport at every distance from the coast, with the CE transport accounting for several times as much as the ACE transport (Figure 14b). As is the case for the filaments, the divergence of the eddy transport enhances the C_{org} availability at every distance from the coast beyond the first 100 km offshore, contributing between 10 % and 20 % to the total divergence. A larger impact of the eddy flux divergence on the local C_{org} availability is detected in the northern subregion, where the NE-NF flux declines quickly offshore similarly to the
- 25 mean Reynolds flux; only in the southern CanUS eddies contribute, with a negative flux divergence, to the C_{org} sequestration between 500 km and 1000 km offshore.

Eddies and filaments have an important role also in the meridional and vertical redistribution of C_{org} (see Appendix: Figure B9 and Figure B10). In particular, ACE are responsible for the northward recirculation of C_{org} through the asymmetric stirring of the background gradient: due to their relatively fast decay that results in a slowing down of the clockwise rotation while

- 30 they move offshore, these eddies induce a net northward transport of C_{org} . CE, being more stable along their tracks, have a weaker effect on the net meridional transport. In the vertical direction, instead, eddies have a minor role in the C_{org} advection compared to the filaments, and their signature cannot be clearly distinguished from that of the NE-NF component, possibly due to the shallow distribution of C_{org} in the eddies. Filaments, on the contrary, are responsible a strong nearshore downwelling, which was previously captured by the turbulent component of the Reynolds fluxes (see Figure 6). The turbulent character
- 35 of the vertical filament transport can be attributed to irregular but intense bursts of downwelling within the structures. These







Figure 14. Magnitude of the non-filament-non-eddy (NF-NE), filament (FIL), anticyclonic (ACE), cyclonic (CE) components of the offshore flux [GmolC yr⁻¹]: (a) Canary EBUS as a whole; (c) northern CanUS; (d) central CanUS; (e) southern CanUS. In all area plots: the black thick line is the total offshore flux, sum of the 4 components; fluxes are integrated in the first 100 m depth. Plot (b): only for the full EBUS we show the ratio of the magnitude of the mesoscale/total offshore flux for FIL, ACE and CE. Inserts: ratio between the absolute value of the divergence of the filament or eddy (ACE+CE) component and that of the total flux within the 100 m. Per each offshore range, divergences are calculated as finite differences at the boundaries shown on the x-axis. Dots are red when total and mesoscale divergences are negative (fluxes remove C_{org}); dots are yellow if only the NF-NE divergence is negative; dots have the same color of the line when all divergences are positive (fluxes add C_{org}). For the southern subregion only: blue dots indicate that the total flux divergence is negative and opposes the mesoscale flux divergence; dots are red with a blue edge when the opposite is true.

structures advect below the euphotic layer a significant amount of C_{org} in the 200 km to 500 km from the coast, with the maximum distance reached in the region of the Cape Blanc filament. Turbulent subduction within upwelling filaments was previously observed both in models and in observations and is likely associated to the formation of convergence zones and frontal instabilities in the cold and dense structure (Nagai et al., 2015; Washburn et al., 1991). High vertical subduction speeds

5 combined with the elevated carbon concentrations can therefore result in very intense vertical advective export of C_{org} .







Figure 15. Comparison between the results of the turbulence-based and structure-based methods for the entire EBUS in the range of 100 km to 2000 km from the coast (offshore region) in which the divergence of the total offshore flux is always positive. Percent of the total offshore flux carried on by each flux component: (a) the turbulence-based method; (b) structure-based method. Percent of the total offshore flux divergence by each flux component: (c) the turbulence-based method; (d) structure-based method.

5 Discussion

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5.1 Turbulence and the mesoscale: insights from two complementary perspectives

Our analysis of the mesoscale transport in the CanUS is based on two different but complementary perspectives: a Reynolds decomposition of the fluxes into a mean and a turbulent component, and an independent decomposition of the total fluxes into an eddy, a filament and a non-filament-non-eddy component, in which we employ filament and eddy masks.

The filament zonal transport shows clear similarities with the nearshore mean zonal flux from the Reynolds decomposition, reflecting both its sign and its spatial structure. This implies that, even if the filaments may contribute to strengthen the turbulent transport in the nearshore, a relevant portion of the zonal filament transport has a mean character. This is not surprising, given





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that filaments tend to be recurrent features of the CanUS and are generally characterized by smooth and persistent flows during their lifetime (Navarro-Pérez and Barton, 1998; Arístegui et al., 2009). In a detailed study of the properties of a filament, Bettencourt et al. (2017) described the structure as a narrow corridor, in which the fluid progresses towards the offshore without deformation, i.e., with very little divergence of the trajectories along the path, confirming the non-turbulent character of the inner filament flow. Moreover, according to our filament detection algorithm, filaments are found in association with the major CanUS capes for more than 25% of the time, confirming their semi-permanent character (see Appendix: Figure B7).

Filaments dominate the mesoscale fluxes in the vertical direction, with an intense downwelling of organic matter to depths below 100 m occurring in the first 300 km in offshore distance. Even though these structures have a typical thickness of about 100 meters or less (Cravo et al., 2010), filament subduction well below their depths has been documented in observations

- 10 (Kadko et al., 1991; Brink, 1992; Barth et al., 2002; Peliz et al., 2004) and numerical studies (Nagai et al., 2015; Bettencourt et al., 2017). Differing from the zonal flux, the pattern of the vertical downwelling associated with filaments clearly resembles the turbulent component of the vertical Reynolds fluxes. Animations of the vertical velocities at 100 m depth show transitory and irregular hotspots of strong downwelling within the filaments, meaning that the vertical transport inside filaments is highly variable both due to horizontal movements of the downwelling cells and due to the intermittency of the process. With a
- 15 numerical study, Nagai et al. (2015) showed that this subduction happens primarily at the filament tip, therefore moving offshore during the filament formation and then oscillating laterally with the structure.

The eddy zonal transport resembles, for both kinds of eddies, the structure and magnitude of the turbulent Reynolds flux. Eddies are mostly transitory structures that drift while rotating around their axis and are characterized, through the course of their life, by oscillations both of the dimension of their radius and of their rotational speed (Sangrà et al., 2005). This high

20 variability explains why the lateral eddy transport mostly projects onto the turbulent transport. However, differing from the Reynolds turbulent flux, the CE and ACE zonal transports are also characterized by striations, which suggest the existence of recurrent regions of formation and preferential pathways for these eddies. This interpretation is supported by the fact that these striations show up in the time-mean Reynolds fluxes as well.

In addition to the differences arising from the time-averaging, there are other important differences between the "structurebased" and the "turbulence-based" results. Such differences may be caused, for example, by the existence of other forms of turbulence that we are not accounting for with our eddy and filament masks. One of these contributions could be that of offshore fronts and filaments between eddies, which evolve in time in close connection with the detected mesoscale field.

5.2 Comparison with previous work

Our results highlight the importance of the mesoscale transport in the lateral export of C_{org} from the north-western African 30 coast, and point to the importance of filaments and eddies as a source of carbon and nutrients for the offshore oligotrophic waters.

The filament C_{org} transport in the euphotic layer of the CanUS extends in our model up to 1000 km offshore, even though its intensity declines quickly offshore. This reach is larger than previous observations, which indicated about 700 km of maximum offshore extension for the giant Cape Blanc filament, as seen from satellite coastal zone color scanner (CZCS) radiometer





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images (Ohde et al., 2015). However, our analysis shows that the filament offshore transport reaches the largest offshore extension at a depth of 20 m to 30 m. A few filament transects from in-situ measurement also show that the filament lateral transport of biogeochemical tracers deepens below the surface at a depth of a few tens of meters moving away from the continental shelf (Cravo et al., 2010). This implies that the whole offshore range of reach of a filament may not be easily visible from surface chlorophyll images, with a likely underestimation of its range.

In terms of volume, our modeled mean filament offshore transport in the whole CanUS region amounts to about 2 Sv between 100 km and 200 km from the coast in the first 100 m depth (corresponding to $0.7 \text{ m}^2 \text{ s}^{-1}$), 3 Sv in the first 300 m depth which include most of the filament transport. A large fraction of this transport originates in the northern and central CanUS subregions. The intensity of our filament transport is lower than previous estimates of 6 to 9 Sv for the same subregions

- 10 (Barton et al., 2004), but it represents still a very large contribution to the offshore flux. As a term of comparison, the offshore Ekman transport per unit length in the CanUS ranges between $0.4 \text{ m}^2 \text{ s}^{-1}$ and $2 \text{ m}^2 \text{ s}^{-1}$ during the upwelling (Arístegui et al., 2009; Barton, 2001). Also, our quantification represents a climatological yearly average including the seasons of reduced filament activity, while observations are often done in periods of intense filament transport, possibly biasing high the estimates upscaled from relatively few observations. Even though typical zonal velocities observed inside modelled filaments (100 m
- 15 depth averages) are about 0.15 m s⁻¹, the flow often reaches speeds of about 0.3 m s⁻¹ and can peak at more than 0.5 m s⁻¹, in agreement with in situ observations (Pelegrí et al., 2005).

As highlighted in previous studies (Arístegui et al., 2009; Pelegrí et al., 2005), most of the filaments in the CanUS are found in the northern subregion. However, animations of S-CHLA, SST, as well as our filament mask, reveal also important filament activity south of Cape Blanc in winter and in April and May, in agreement with Menna et al. (2016). Even though these seasonal filaments are shorter (rarely extending beyond 200 km) and less persistent than the ones observed in the north, their

- 20 seasonal filaments are shorter (rarely extending beyond 200 km) and less persistent than the ones observed in the north, their high occurrence along the coast in the season of intense activity is particularly striking. The strong seasonality that characterizes these structures makes it difficult to appreciate their possibly intermittent impact on the local C_{org} budget in a climatological annual mean perspective such as the one adopted in the present paper. Dedicated studies and in situ observations may help to better understand these structures, which at the present moment are only partially characterized in the available literature.
- Modeled eddies are generated in the first 250 km from the coast, and very often interact with coastal filaments which feed them with tracers in a filament/eddy coupled system, as previously observed (Barton et al., 2004; Arístegui et al., 1997; Meunier et al., 2012). Our eddy translational velocities as well as the northward or southward deflection of the eddy tracks visible in the striations of the CE and ACE offshore transport are in agreement with the observations of global mesoscale eddy tracks (Chelton et al., 2011). In contrast to the coastally confined filament transport of C_{org} , the modeled eddy offshore flux extends
- 30 far into the open ocean up to the edge of our analysis domain, propagating offshore for several months (Sangrà et al., 2007). The integrated eddy offshore transport throughout the whole CanUS in the first 100 m depth ranges from 1 Sv at 200 km from the coast to 0.7 Sv offshore, with 80 % of the transport taking place in the northern and central subregions. This is a remarkable lateral flux comparable to that of other major currents in the region, such as the Canary Current (1.5 Sv to 3 Sv), the Canary Upwelling Current (1 Sv to 1.5 \pm 0.3 Sv) and the North Equatorial Current (0.5 Sv to 3 Sv) (Machín et al., 2006; Pelegrí and





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Peña-Izquierdo, 2015; Mason et al., 2011). In line with the results of Combes et al. (2013), we find that CE are responsible for large part of the offshore tracer transport, while ACE contribute in smaller measure to the flux.

The different impact of ACE and CE on the C_{org} concentration at each location of the CanUS is reflected in the correlation between SSH' and ΔC_{org} (Figure 9), which roughly agrees with the satellite-derived cross correlation of satellite SSH and surface chlorophyll for our region (Gaube et al., 2014, Figure 1a). Differences in the C_{org} concentration in the two kinds of eddies depend both on their C_{org} availability at the moment of formation, and on the evolution of the tracers during their life. Animations of the C_{org} field show that latitudinal differences in the ΔC_{org} found in ACE and CE at their formation can be attributed to the opposite direction of the meandering coastal current from which they are shed, combined with the offshore gradient in C_{org} (Gaube et al., 2014): this results in high C_{org} eddy-core concentrations at formations in northern CE and southern ACE.

Once formed, eddies account on average for about 30 % of the NCP at every distance from the coast, confirming their essential role in the increase of productivity, C_{org} and nutrients availability in the offshore regions (Sangrà et al., 2009). Several mechanisms have been proposed to explain this high eddy productivity (McGillicuddy, 2016). A dedicated study by Chenillat et al. (2015) suggests that trapping at formation and vertical pumping of nutrients fuel respectively regenerated and new

- 15 production in the core of a CE in the CalCS, with a shift towards the latter in the course of the eddy evolution. New production of C_{org} in ACE has been observed to be stimulated mostly at their peripheries by sporadic small scale upwelling, while, also in absence of wind-stress feedback, the ACE core can receive nutrients through deep mixing and upwelling connected to the eddy frictional decay (Lima et al., 2002; Zhang et al., 2001; Martin and Richards, 2001). In this sense, while the recycling and rejuvenation of the eddy C_{org} trapped at the origin can be thought as the effective offshore transport of coastally generated
- 20 material, the local uptake of both trapped and newly upwelled nutrients results in a net enhancement of the offshore production. A quantitative understanding of the evolution of tracers, remineralization and recycling along the eddy tracks in the CanUS requires, however, further analyses and likely must be addressed separately for the regions located north and south of the Cape Verde front.
- As highlighted in previous studies (Gruber et al., 2011; Lachkar and Gruber, 2011), the CanUS is characterized by a 25 mesoscale activity that, even though important, is not as intense as in other upwelling systems. Therefore, we expect mesoscale activity to have an even more substantial impact in other EBUS regions. In spite of the presence of one giant filament (the Cape Blanc filament) in the CanUS, filaments in the CalUS were observed to extend on average twice as far into the open ocean (Marchesiello and Estrade, 2006). Moreover, for the CalUS, the STD(SSH) and the cross-shore eddy diffusivity exceed by far those of the CanUS (Marchesiello and Estrade, 2006), and the number of observed eddies from satellite data is substantially
- 30 larger than the value that characterize the CanUS at most latitudes (Chaigneau et al., 2009). In the analysis presented by Nagai et al. (2015), the turbulent transport of C_{org} in the CalUS, obtained with a Reynolds decomposition, represents 20-25 % of the total offshore fluxes at the surface and is dominant further below. Thus, even though the level of mesoscale activity is substantially larger in the CalUS, the fractional transport by mesoscale processes is only slightly larger than in the CanUS. This might also be caused by the eddy/filament induced subduction of organic matter, which is particularly strong in the CalUS,
- 35 thus reducing the eddy-induced horizontal transport. A further quantification of the offshore transport by filaments and eddies





based on the identification of the mesoscale structures in other upwelling region may help to better clarify the importance of nearshore and offshore mesoscale fluxes.

5.3 Model limitations

As is the case for every model-based study, the impact of the inherent model limitations need to be clearly identified and put 5 into relationship with the results. The first set of shortcomings regards model biases; the second set regards potential limitations of the eddy and filament identification algorithms; in the end we discuss our lack of representation of the DOC pool.

As known from Lovecchio et al. (2017), our model underestimates the intensity of the flow in the southern CanUS subregion; concurrently, modeled POC shows a too-deep maximum in this CanUS sector compared to observations. The combination of these biases could result in an underestimation of the total offshore transport at these latitudes. For this reason, while we have

- 10 high confidence in our results regarding the lateral C_{org} transport in the northern and central CanUS, we maintain a critical position with regard to the results for the southern CanUS. The weaker circulation in the southern CanUS is reflected also in the underestimaton of the TKE at the same latitudes, especially along the coast and in the proximity of the Cape Verde archipelago (Figure 2). Even though the southern CanUS is known for having a modest filament activity and a reduced eddy activity compared to the northern CanUS (Arístegui et al., 2009; Chaigneau et al., 2009), our model enhances these zonal
- 15 differences. We may argue that the weakening of the mean circulation implies the weakening of the turbulent flow with a similar factor, possibly not affecting the ratio between the two contributions, which is of interest in the present analysis. Too large TKE and STD(SSH) compared to the AVISO satellite data is observed along the coast north of the Canary Islands

(north of 30 °N), and, in smaller measures, between the Canary Islands and Cape Blanc. This region is known to be characterized by intense filament activity and by the recurrent formation of small eddies and swirls. Even though it may be the case that

20 satellite data (provided on a 1/4 °resolution grid) does not have a sufficient resolution to resolve turbulence on these scales, we may still be modeling too intense filaments at these latitudes, possibly resulting in an overestimation of the filament transport in the northern CanUS.

In terms of eddies, our evaluation shows that the modeled large-eddy field ($R \ge 50$ km) is reduced by about 1/3 compared to the observations. However, differences in the performance of the eddy-finding algorithm, when applied to the ROMS and

- 25 AVISO grids, must be taken into account. Given the different resolution, the SSH-based algorithm may, on average, be able to find smaller closed SSH contours around a SSH maxima/minima in the higher-resolution Atlantic telescopic in comparison to the AVISO grid. Given the abundance of small and medium eddies in the modeled field and the positive results of the evaluation of the integrated area covered by ACE and CE in the model, we expect our integrated eddy transport to be close to the real value.
- 30 Given its formulation, our SSH-based eddy-finding algorithm does not distinguish between regular ACE and anticyclonic mode-water eddies (ACMEs), which are therefore included in our ACE budget and transport. These eddies have been especially observed in the southern CanUS subregion and are expected to represent about 20 % of the total ACE population at these latitudes (Schütte et al., 2016a). Given the observed high productivity of ACMEs compared to regular ACE (Schütte et al.,





2016b), including these eddies in the ACE budget likely increases the integrated ACE organic carbon availability and transport. Further analysis would be needed to correctly separate the ACMEs from the ACE contribution.

Our newly-developed SST-based filament detection algorithm was tested on our grid with satisfactory results, with the large majority of the filaments being detected on the base of SST and S-CHL images and very limited over-detection in the southern

- 5 CanUS. The algorithm performs particularly well in the zonal band located north of Cape Blanc, given the sharp offshore SST gradient; south of Cape Blanc detected filaments seem slightly shorter than what they appear to the human eye from a S-CHL figure, even though it is not always possible to univocally identify their offshore extent. Only during a few time steps we could see an over-detection of the extent of the filaments in the area surrounding the Cape Verde archipelago. Give this performance, we conclude that the our modeled filament transport is well represented by the filament-mask analysis.
- 10 Mesoscale structures and especially filaments are known to export large quantities of DOC, which can represent up to 70 % of the total C_{org} transported offshore (Santana-Falcón et al., 2016; García-Muñoz et al., 2005). However, only a small part of this exported DOC is biologically available for the offshore biological activity (Hansell et al., 2009). Our model does not include a DOC pool; however our small detritus pool behaves very similarly to a suspended POC pool given the very small sinking speed of 1 m day⁻¹. The possible repercussions of the lack of modeling of DOC in our model were already discussed by Lovecchio
- 15 et al. (2017), where we also presented the results of a sensitivity study, in which we tested the implications of modeling a purely suspended POC pool for our lateral export and the fueling of the biological activity. The results of this sensitivity experiment tell us that, even though the total offshore transport can increase as a result of the shallower POC distribution, the divergence of the transport remains basically unchanged, with no repercussion on the offshore NCP.

6 Summary and Synthesis

- 20 Through a Reynolds decomposition, we show that the turbulent component of the C_{org} zonal flux out of the coastal CanUS amounts, on average, from 5 % to above 30 % of the total zonal transport, extending out to 2000 km distance. This turbulent zonal flux is directed offshore at every latitude of the CanUS and its divergence represents 30 % of the total zonal flux divergence, fueling a large portion of the extra heterotrophy in the subtropical North Atlantic (Lovecchio et al., 2017). The turbulent zonal transport is mostly confined to the first 100 m depth, but it shows a subsurface intensification, owing to a strong turbulent
- vertical downwelling. The contribution of the turbulent zonal flux is particularly important in the northern and southern CanUS, where the mean transport either declines offshore (north) or sequestrates C_{org} on the way to the open sea (south). In the central CanUS, instead, the turbulent flux and its divergence strengthen an already intense mean offshore transport.

With the use of eddy and filaments masks we separate the contribution of mesoscale eddies and filaments to the availability and transport of C_{org} . Filaments channel offshore large amounts of C_{org} for a few hundreds of km from the coast with speeds

that reach up to 0.5 m s⁻¹; ACE and CE, instead, transport up to the middle of the North Atlantic gyre C_{org} at a speed of a few cm s⁻¹. Filaments contain most of the total C_{org} up to 200 km from the coast, but their contribution declines quickly offshore. Eddies, on the contrary, see a sharp increase of their C_{org} content in the first 200 km from the coast and contain, at every larger distance, about 30 % of the total available C_{org} , two thirds of which is found in CE.





Thanks to their high advective speeds, large C_{org} concentration and semi-permanent character, filaments dominate the nearshore zonal transport accounting for nearly 80 % of the total flux at 100 km offshore. The filament transport captures a large part of the mean Reynolds offshore transport near the coast, while vertically it is responsible for a strong turbulent vertical downwelling. The divergence of the filament offshore transport adds the majority of the extra C_{org} to the first few hun-

- 5 dreds km offshore, but the divergence drops off quickly, reaching zero at 1000 km. The eddy lateral transport, on the contrary, resembles in pattern and intensity the turbulent Reynolds offshore flux and accounts for about 20 % of the total zonal flux and total flux divergence. Eddies, which move slowly but contain about 30% of the C_{org} available offshore, add C_{org} to the offshore waters up to 2000 km from the coast; in particular CE are responsible for most of the offshore transport largely because of their elevated C_{org} concentration and longer lifetimes.
- 10 Overall, the mesoscale processes contribute to the offshore redistribution of the C_{org} from the CanUS shelf to the open waters through a combination of mean and turbulent transport. Filaments quickly export towards the open waters large amounts of carbon which is partially subducted, while eddies, generated mostly off the shelf, trap this carbon and convey it to the open waters, contributing substantially to the fueling of the net heterotrophy in the offshore water column (Giorgio and Duarte, 2002; Burd et al., 2010).

15 7 Conclusions

Our study in the CanUS confirms the important contribution of mesoscale processes to the offshore transport of C_{org} from the productive EBUS into the adjacent oligotrophic subtropical gyres. In particular, filaments drive the total offshore flux of C_{org} and its divergence in the nearshore, while eddies, especially cyclons, extend this transport up to the middle of the gyre. As a consequence, the divergence of the mesoscale transport allows extra vertical export out of the productive layer

- and strongly contributes to the shaping of the pattern of nearshore net autotrophy and offshore net heterotrophy of the water column (Lovecchio et al., 2017). Even though the CanUS has moderate levels of mesoscale variability in comparison with other EBUS, the mesoscale contribution to the transport and to the fueling of the offshore biological activity strongly dominates in the nearshore 500 km and amounts already to about 20% at larger offshore distances. This suggests that this mesoscale contribution may be even more crucial in other upwelling regions that have higher nearshore-generated mesoscale activity (Capet et al., 2013; Marchesiello and Estrade, 2006), such as the California Upwelling System (Nagai et al., 2015).
 - The key role of mesoscale processes in the lateral C_{org} transport has several consequences. First, it implies that coarse global models may be unable to account for a great part of this flux out of the upwelling regions, possibly failing at reproducing the offshore rates of deep respiration and at fully capturing the three-dimensionality of the biological pump. Second, remote sensing approaches may underestimate this offshore transport. On the one hand, this may be due to the time-limited sampling
- 30 owing to the frequent cloud cover preventing the detection of the chlorophyll and associated carbon content. On the other hand, because of our modeled filament transport deepening offshore up to a few tens of meters below the surface, i.e., below the detection level of satellites, leading to a potential underestimation of the actual offshore reach of filaments. Third, the relevant share of C_{org} found in the offshore region within mesoscale eddies, which are mostly laterally isolated structures (Chelton et al.,





2011; Karstensen et al., 2017; Stramma et al., 2013), also tells us that a fraction of the offshore biological activity is fueled discontinuously. In particular, both the transit of an eddy, which is associated with enhanced vertical export (Subha Anand et al., 2017; Waite et al., 2016), and the death of an eddy provide a discontinuous, but substantial, input of carbon for the oligotrophic waters.

5 While our study shows relevant levels of eddy productivity offshore, further analyses are needed to disentangle the pathway of new production and recycling of the C_{org} along long-lasting tracks of the northern and southern CanUS, and to understand the special role of mode water anticyclones in the budget and transport. Further studies can also help to better quantify the highly seasonal contribution of the many short filaments of the southern CanUS, of which little is known, and to investigate the role of the offshore transport of dissolved C_{org} , here not included in the model.





Appendix A: Datasets used for the model evaluation

| Data source | Ref. time | Resolution | Variables | Reference |
|--------------|-------------|-------------------|----------------------------------|-------------------------|
| Aviso DUACS | 1993-2012 | 0.25°x 0.25°grid | daily sea surface height, daily | Maheu et al. (2014) |
| 2014 | | | geostrophic velocities | |
| AVHRR | 1981-2014 | 0.25°x 0.25°grid | sea surface temperature | Reynolds et al. (2007) |
| CARS | 1955-2003 | 0.5°x 0.5°grid | sea surface salinity | Ridgway et al. (2002) |
| Aviso CMDT | 1993-1999 | 0.5°x 0.5°grid | sea surface height | Rio and Hernandez |
| Rio05 | | | | (2004) |
| Argo DT-0.2 | 1941-2008 | 2°x 2°grid | mixed layer depth | Montégut et al. (2004); |
| | | | | Argo (2000) |
| SeaWiFS | 1997-2010 | 9km grid | sea surface chlorophyll | NASA-OBPG (2010) |
| SeaWiFS VGPM | 1997-2010 | 9km grid | extrapolated net primary pro- | Behrenfeld and |
| | | | duction (NPP) | Falkowski (1997) |
| SeaWiFS CbPM | 1997-2010 | 9km grid | extrapolated net primary pro- | Westberry et al. (2008) |
| | | | duction (NPP) | |
| SeaWiFS POC | 1997-2010 | 9km grid | extrapolated surface particulate | NASA-OB.DAAC |
| | | | organic carbon (POC) | (2010) |
| AMT | (2004-2014) | in-situ [0m,200m] | particulate organic carbon | BODC-NERC (2014) |
| | | depth | | |
| Geotraces | (2010) | in-situ surface | particulate organic carbon | GEOTRACES (2010) |
| ANT | (2005) | in-situ [0m,200m] | particulate organic carbon | ANT (2005) |
| | | depth | | |

Table A1. Description of the datasets used for the model evaluation. CMDT: Combined Mean Dynamic Topography; AVHRR: AdvancedVery High Resolution Radiometer; CARS: CSIRO Atlas of Regional Seas; SeaWiFS: Sea-viewing Wide Field-of-view Sensor; WOD09:World Ocean Database 2009.





Appendix B: Supplementary figures



Figure B1. Example of the performance of the filament and eddy identification algorithms on 2-day mean fields. Subplot (a): red contours are warm-core anticyclonic eddies; blue contours are cold-core cyclonic eddies; yellow contour are coastal upwelling filaments. Subplot (b): sea surface temperature. Subplot (c): surface chlorophyll. The eddy identification algorithm is SSH-based, as in Faghmous et al. (2015). The filament identification algorithm is SST-based as described in the Methods section.







Figure B2. Taylor diagram for the Canary EBUS region of analysis as defined by the Budget boxes based on the 24 years climatologigal annual mean fields used in the present study. Used datasets - Sea Surface Temperature (SST): AVHRR, Sea Surface Salinity (SSS): CARS, Sea Surface Height (SSH): Aviso CMDT Rio05, Mixed Layer Depth (MLD): Argo DT-0.2, Chlorophyll (CHLA): SeaWiFS, Net Primary Production dataset 1 (NPP1): SeaWiFS VGPM, Net Primary Production dataset 2 (NPP2): SeaWiFS CbPM, Surface Particulate Organic Carbon (S-POC): SeaWiFS POC, Particulate Organic Carbon (POC): cruise POC data (AMT, ANT, Geotraces). A detailed description of the data used for the evaluation is provided in Appendix A: Datasets, Table A1.



Figure B3. Distribution of the eddy diameters [km] in the CanUS region as defined by the budget analysis boxes: (a) Propability density function (PDF) of the diameter of all the eddies from ROMS; (b) comparison of the PDFs limited to large eddies (R > 50 km) for the eddies from ROMS and AVISO.







Figure B4. Portion of the CanUS (EBUS) occupied by the eddies, by eddy type. (a) Modeled ROMS eddy field; (b) AVISO eddy field.



Figure B5. Reynolds decomposition of the lateral and vertical advective fluxes of C_{org} below 100 m into their average mean $\langle \overline{u}\overline{C}_{org} \rangle$ and average turbulent $\langle u'C'_{org} \rangle$ components, as defined in the methods section. Fluxes integrated from 100 m depth to the bottom of the water column. Colorscale corresponding to those of Figure 6 for a better comparison.







Figure B6. Hovmoeller diagram of the turbulent SSH anomalies (SSH') and top 100 m organic carbon stock C_{org} ($\int_{0}^{100m} C'_{org}$) for the central subregion of the CanUS. First 15 years of analysis data, bi-daily output. Their signature shows remarkable interannual variability despite the climatological forcing used for our simulation, highlighting the intrisic nature of turbulence and variability in the region.



Figure B7. Percentage of time occupied by filaments per grid pixel, according to our filament identification algorithm. The boundary corresponding to the first 50 km from the north-western African coast has been highlighted with a dashed yellow line. Regardless of the fact that this range of distances is often covered by the filament mask, alongshore currents are dominant in this region.







Figure B8. Spatial distribution of the 100m vertically integrated C_{org} [mmolC m⁻²] in: (a) non-filament-non-eddy (NF-NE) field, (b) filaments (FIL), (c) anticyclones (ACE), (d) cyclones (CE).







Figure B9. Decomposition of the meridional advective transport of C_{org} into: (a) non-filament-non-eddy (NF-NE) flux, (b) filament (FIL) flux, (c) anticyclonic (ACE) flux and (d) cyclonic (CE) flux. Fluxes [mmolC m⁻¹ s⁻¹] are integrated in the first 100m depth.







Figure B10. Decomposition of the vertical advective transport of C_{org} into: (a) non-filament-non-eddy (NF-NE) flux, (b) filament (FIL) flux, (c) anticyclonic (ACE) flux and (d) cyclonic (CE) flux. Fluxes [mmolC m⁻² s⁻¹] are sliced at a depth of 100m.





Author contributions. N.G. and E.L. conceived the study. E.L. and M.M. set up the experiment and improved the model. E.L. performed the analysis. All authors contributed to the interpretation of the results and to the writing of the manuscript. N.G. and M.M. supervised this study.

"The authors declare that they have no conflict of interest."

- 5 Acknowledgements. We would like to thank Martin Frischknecht for his valuable comments on the work and during the preparation of the manuscript, and Damian Loher for the technical support. We also thank Dr. Ivy Frenger for her fundamental help and suggestions that have substantially improved our analysis. This research was financially supported by the Swiss Federal Institute of Technology Zürich (ETH Zürich) and the Swiss National Science Foundation (Project CALNEX, grant No.149384). The simulations were performed at the HPC cluster of ETH Zürich, Euler, which is located in the Swiss Supercomputing Center (CSCS) in Lugano and operated by ETH
- 10 ITS Scientific IT Services in Zurich. Model output is available upon request. Please contact the corresponding author, Elisa Lovecchio (elisa.lovecchio@usys.ethz.ch), in that matter.





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