

Author's response

**"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, Matthias Münnich¹

¹ETH-Zürich, Universitätstrasse 16, 8092 Zürich, Switzerland

Dear Prof. Gerhard Herndl,
thank you very much for taking our manuscript into further consideration for publication on
Biogeosciences.

We have carefully revised our manuscript following your suggestions and the referees' comments.
We include below our point by point answer to the referees including (in blue) the relevant changes to the
manuscript for each point brought up by the referees, and a marked-up version of the manuscript.
A considerable part of our efforts have gone in the direction of shortening the overall length of the
manuscript and improve its readability, in compliance to the suggestions of the referees, while paying great
attention not to cut on the scientific content and message.
We have also prepared a dedicated supplement in order to better document the structure and performance
of our newly developed upwelling filament detection algorithm.

We look forward to your response.

Sincerely,

Elisa Lovecchio

Answer to Referee #1

We thank Referee #1 for the time spent on reviewing our manuscript and for his/her thoughtful comments on the pattern of the carbon fluxes and on the eddy influence on the organic carbon anomalies and fluxes, which have helped us to improve our manuscript. In order to address these comments, we have carried out further analysis with the aim to clarify some questions. We include below our detailed answers to the three major concerns raised by the Referee and to all the specific comments and describe the changes to the manuscript.

Answers to Major comments

MC1) Pattern of the meridional and vertical organic carbon fluxes

“One of these issues is that the mean vertical carbon flux presented in Figure 6c and 8c. There seems to be clear contrast between northern and southern regions separated at C. Blanc in plan view of the vertical carbon flux, which looks somewhat similar to the distribution of the mean meridional flux in Figure 6b. Also, in the vertical section, there is an upward flux at 60-70 m depths, right under and above the downward carbon fluxes. I’m puzzled by these mean vertical and meridional carbon flux distributions, and consider that this needs to be clarified.”

Answer to MC1

As stated by Referee #1 the pattern of the mean meridional and vertical organic carbon fluxes (Figure 6 of the manuscript) differs strongly between the regions north and south of the Cape Verde front, according to the subregional differences in the circulation of the Canary Upwelling System, which include a large-scale anticyclonic circulation north of the front and a cyclonic circulation to the south (Aristegui et al. 2009; Pelegrí and Benazzouz, 2015; Pelegrí and Peña-Izquierdo 2015). The mean signature of the wind stress curl (negative north of the front, positive south of the front) also induces a change of sign in the mean vertical fluxes at the front, as in Figure 6c (see also Lovecchio et al. 2017, Figure 11, and the in-depth discussion of the subregional differences in the Corg fluxes). In the present paper, we quickly refer to these differences in our introduction (page 3, lines 9-13). In order to clarify the drivers of the mean flux pattern, we have modified the first sentence of section 4.2 as follows:

“The time-mean fluxes from the Reynolds decomposition (Figure 5a-c) clearly reflect the regional circulation and the windstress curl pattern that characterizes the CanUS (Aristegui et al., 2009; Pelegrí and Peña-Izquierdo, 2015; Lovecchio et al., 2017). While these mean fluxes dominate the total fluxes (see also: Lovecchio et al. (2017), their Figure 11), the turbulent fluxes contribute substantially to the total fluxes and to their divergence (Figure 5d-f).”

Also the alongshore average section of the vertical advective flux (Figure 8c of the manuscript) reflects the subregional differences described above, showing a composition of positive (southern CanUS) and negative (northern CanUS) mean vertical advective fluxes of organic carbon. We refer to this in page 16, line 5-6 of the manuscript, as: “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.”. In order to better illustrate these differences we include in the present document the profile of the vertical advective flux calculated separately for the northern, central and southern CanUS (Figure 1). Furthermore we have modified the sentence mentioned above to:

“Offshore, the different sign of the wind stress curl (negative and positive, respectively) characterizing the latitudes located north and south of the Cape Verde front, results in an opposite sign of the time-mean vertical flux of organic carbon in the two zonal bands (see Figure 5c). These fluxes, averaged along the entire CanUS, give rise to an alternate pattern of upward and downward mean vertical transport.”

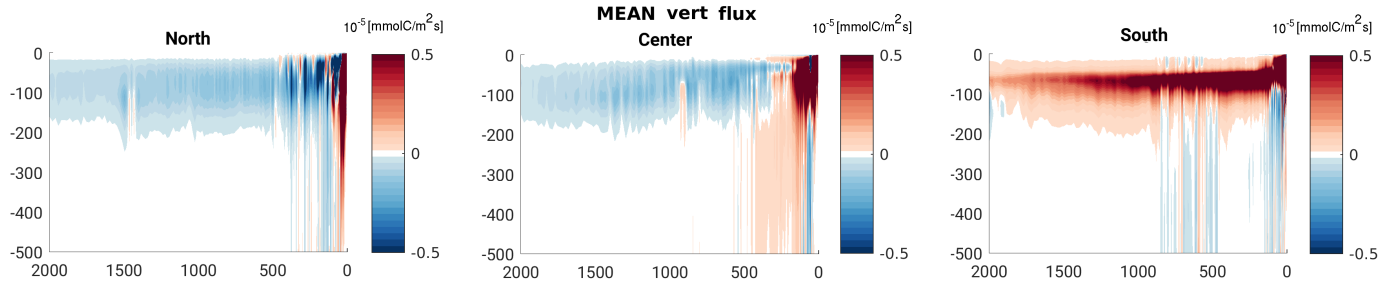


Figure 1: Alongshore average sections of the vertical advective fluxes of organic carbon for the three CanUS subregions, as defined in the manuscript. The change of signature in the vertical flux offshore is in agreement with the change of sign of the wind stress curl in correspondence of the Cape Verde front.

MC2) Analysis and discussion of the results of Reynolds decomposition and covariance

“In some part, although the authors tried to explain the resultant interesting patterns obtained by the Reynolds decomposition and structure based extraction of eddy and filament contributions, they are often stated without sufficient evidence and would make readers feel that they are rather speculative. For example, the high covariance between anticyclonic eddies and carbon anomaly in northern offshore, is explained by the upwelling induced by the anticyclonic eddy spin down, without any analysis.”

Answer to MC2

In order to address this comment we decided to make some changes in the Results section, keeping in mind also the suggestion of Referee #2 to shorten the manuscript where possible. We have therefore made the following changes:

- We agree with Referee #1 that there isn't enough evidence supporting the upwelling in ACE in the final stages of their life in the proximity of the Canary Archipelago (discussion of Figure 9).

Animations of the model output suggest that this positive C_{org} anomaly in ACE is rather associated with the extremely sharp offshore gradient in the average C_{org} concentrations at these latitudes. This gradient, resulting in very low C_{org} concentrations in the open waters, makes it possible for ACE formed near the coast to still contain on average more carbon than the open waters. Moreover, some of the ACE that cross these latitudes interact with filaments generated south of the Archipelago, which are particularly rich in C_{org} due to the north-south positive gradient in the tracer concentrations. We have revised the discussion of Figure 9 according to this analysis and have changed the paragraph on page 17, lines 1-9 as follows:

“Deviations from the negative correlation of SSH' and C_{org} ' can also be explained in terms of eddy anomalies. In the nearshore southern CanUS, the positive C_{org} ' in ACE might stem by the shedding of eddies from the northward flowing Mauritanian Current, which favors the trapping of C_{org} -rich coastal waters in ACE at the time of their formation. At the northern CanUS boundary, the signature of the eddy C_{org} ' is connected to the presence of incoming large eddies formed in the Azores current (Gaube et al., 2014, Figure 1), leading to ACE with positive C_{org} ' and CE with negative C_{org} '. Also in the offshore waters of the northern CanUS, ACE have a positive C_{org} '. This is possibly due to the sharp offshore gradient in C_{org} at these latitudes, where coastally generated ACE can carry the elevated C_{org} to the offshore waters even though they are generally not very efficient in doing so.”

- To further reduce the speculative elements in the discussion of our results, we have shortened section 4.4, limiting it to the discussion to the contribution of mesoscale activity to the organic carbon stock, while moving Figure 12 to the Appendix. This change to the manuscript is also listed in the answer to the general comment of Referee #2. The discussion of the nutrients concentrations and production in the eddies (page 20, lines 1-14) is now limited to the following sentence:

“Moreover, the two types of eddies are characterized by strong differences in their nutrient concentrations and in their production rates (see also Appendix: and Figure B8). This likely exacerbating the differences in C_{org} between CE and ACE, and especially for the long living ones.”

MC3) Manuscript structure: merging Summary and Synthesis with Conclusions

“To be concise, section 6 and 7 could be combined into one section.”

Answer to MC3

We have merged the Summary and conclusions into a single Conclusions section strongly limiting the summary, as most of the information is already highlighted in the abstract and discussion. Our new conclusions read as follows:

“Our study in the CanUS confirms that mesoscale processes contribute substantially to the long-range offshore transport of C_{org} through a combination of mean and turbulent transport. In particular, filaments drive the total offshore flux of C_{org} and its divergence in the nearshore, while far-reaching eddies, especially cyclones, extend this transport up to the middle of the gyre. 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 1000 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 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 also tells us that a fraction of the offshore biological activity is fueled discontinuously at the passage or death of such a structure. 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. 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} , not included in our model.”

Answers to specific comments

P2L13 *“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 (be-*

tween 0.25 and 0.5 m s⁻¹) ” Is this velocity in “with rather large velocities (between 0.25 and 0.5 m s⁻¹)”, propagation speed or current velocity?

Answer: This velocity refers to the current velocity found inside of the developed filaments. We clarified this modifying the sentence as follows: “Coastal filaments are narrow (<50 km wide) structures that extend from the coast to several hundred kilometers into the open sea and are characterized, in their interior, by rather large flow velocities (between 0.25 and 0.5 m s⁻¹).”

P2L15 “Offshore transport by filaments is typically accompanied by intense subduction, due to the high density of the cold upwelled waters” The subduction is intense in the cold filaments because frontogenesis at a cold filament generate two cell ageostrophic cross-frontal circulations, which work together to restratify the two fronts at the edge of the filament, and to narrow the width of the filament, producing the strong downwelling in the filament. This sentence seems not accurate, and I suggest that it should be modified with a reference of McWilliams et al. 2009, Cold filamentary intensification and oceanic surface convergence lines”.

Answer: We agree that this sentence is not clear. We have modified it as follows:

“Transport by filaments is typically accompanied by a deepening of the tracer fluxes in the offshore direction, due to the high density of the upwelled water (Cravo et al., 2010). This is also associated with intense downwelling induced by the generation of ageostrophic cross-frontal circulation at the edges of the filament (McWilliams et al., 2009; Nagai et al., 2015).”

P2L26 “These non-linear structures propagate with velocities of a few centimeters per hour, about one order of magnitude slower than the filaments . . .” “a few centimeters per hour” is 10 μ m s⁻¹, and should be too slow for the mesoscale eddy propagation speed.

Answer: Thank you. We corrected this typo with “a few centimeters per second”

P4L17 “CanUS also showed that eddies tend to reduce coastal production through the lateral export of the upwelled nutrients ” I think that the reduction is caused by both lateral and vertical nutrient transport.

Answer: Thank you, we have modified the sentence as follows:

“...CanUS also showed that eddies tend to reduce coastal production through the lateral export and subduction of the upwelled nutrients”

P5L8 “ $F = F + F'$, were ” Typo. “were” should be “where”.

Answer: Thank you, we have corrected this typo.

P6L4 “The last term $r = \langle u' \text{Corg} \rangle + \langle u \text{Corg} \rangle$ 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” The original rule of the Reynolds decomposition is that the mean of the fluctuation is zero, and the mean of the mean is the same mean, but the authors’ choice allows non-zero values for the former, as we as difference between the mean and the mean of the mean.

Is there any difference between the results using the original method, in which monthly average has just one value at each grid point for each month, and that with the authors’ method? If the difference is about 10%, which is the order of magnitude of r , then which method is better?

Answer: As Referee #1 states, our choice of the reference mean (climatological monthly means interpolated to 2-day steps) results in non-zero residuals in the long-term average fluxes obtained from the Reynolds decomposition. The Referee asks what would happen with the use of simple non-interpolated monthly averages, therefore an average that has a constant value for each month. As far as there is a time varying component in the reference mean (interpolated in time or not), the residuals of the decomposition will not be zero, as the long-term averaging of the components and the reference mean are calculated differently. The suggested non-interpolated monthly mean would give zero residuals only if we calculated the flux components separately for each month, obtaining

12 couples of plots for mean and turbulent fluxes, each with zero residuals. However, this level of detail goes beyond the purpose of the present study. Instead, the use of non-interpolated monthly means would result in large jumps in our time evolution of the turbulent deviations, with unrealistic discontinuities in the moment of transition between one month and the following one. Furthermore, the anomalies would have, on average, minimum values in the middle of the month and large values at the beginning and at the end of each month. We therefore consider our choice of reference mean a better choice than the use of non-interpolated monthly means. As stated in the manuscript (page 6, lines 5-6) the residuals of the Reynolds decomposition obtained with our choice of reference mean are at least one order of magnitude smaller ($<10\%$) than the smaller component between mean and turbulent fluxes in each direction of flow. In order to better document our results, we include the plots of the residual fluxes below (Figure 2).

To clarify this point, have modified the above-mentioned sentence as follows:

“The last term, $r = \langle u' \bar{C}_{org} \rangle + \langle \bar{u} C'_{org} \rangle$, represents the sum of the residuals, which arises from our use of a time-varying reference mean. We neglect this residual as it is at least one order of magnitude or more smaller than the other terms.”

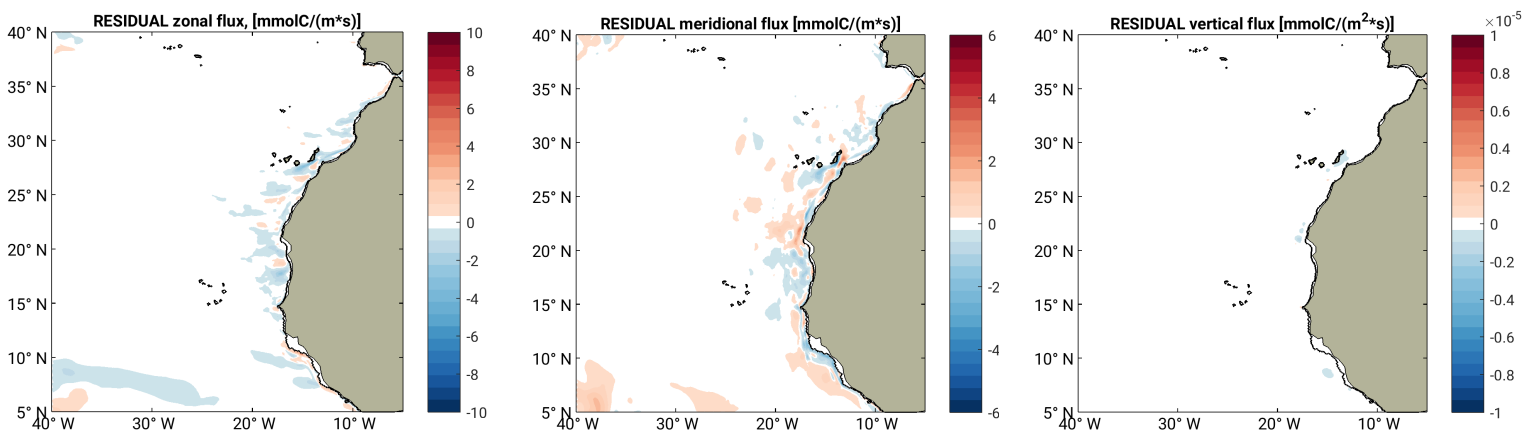


Figure 2: Residual fluxes of the Reynolds decomposition obtained using the time variable reference mean adopted in the manuscript, plotted on the same scales as the turbulent fluxes in each direction of the flow.

P6L20 “First, the above reference mean SST field. . .” This definition of the filament, does not include any shape criteria, and allows the region between straight upwelling front and the coast to be detected as a filament. Is it okay?

Answer: With the present question Referee #1 expresses two concerns regarding the filament mask: (a) the fact that the mask covers the nearshore upwelling band at most time steps, and (b) the lack of an explicit shape criteria for the filament identification. We address them separately.

(a) As stated, the filament mask often covers the nearshore upwelling band roughly corresponding to the first 50 km offshore. However, this does not affect our main results and conclusions significantly. In fact, the filament flux divergence in the nearshore is calculated taking differences between the flux at 100 km offshore (well defined filaments) and the flux at the coast (zero). In the discussion of the filament contribution to the tracer concentrations we avoid to show the filament tracer stock in the first 50 km (inserts of Figures 11, 12). We also do not refer to the nearshore fluxes (0-100 km offshore range) in our summary figure (Figure 15). For the remaining figures, we state that this potential limitation must be kept in mind (see also the discussion at p 21 lines 5-9 of the present manuscript). Operatively, it is actually difficult (if not impossible) to unequivocally identify the base of a filament, distinguishing it from the nearshore flow that feeds into the structure. Possible alternatives would be either to remove the first 50 km of the filament mask and attribute the flux to the NF-NE transport (resulting in discontinuous pattern in the fluxes), or somehow split this portion of the flux between filaments and NF-NE transport. We consider these

two methods more arbitrary than attributing the nearshore flux to the filament mask, while acknowledging the limitation in the manuscript.

(b) As regard to constraining the shape of the filaments, in the course of the analysis the filament mask was evaluated on the basis of both SST and surface Chlorophyll images (see Figure B1 for an example) with very satisfactory results and an extremely limited number of cases of overestimation of the filaments either in time or in space. Of the few cases identified, they were all confined to the southern CanUS latitudes. The coarsening of the reference-mean field before calculating the temperature anomalies and the choice of an appropriate threshold in temperature anomaly (see Methods, page 6, lines 18-25) assure in fact the identification of narrow cold structures. In order to provide a comprehensive description of the algorithm and of its sensitivity to the parameters, we have added a [supplement to the manuscript](#), which includes a technical description of the algorithm and of its properties, and an evaluation of the algorithm performance.

P7L21 *“representation of turbulence” should need “geostrophic” after “of”. The term “turbulence” throughout the manuscript sounds not adequate as it includes the meaning of three-dimensional microscale turbulence. The scale of the “turbulence” should be specified, or replace “turbulence” by “eddy”*

Answer: We have added “geostrophic” before “turbulence”.

P8L1 *“The AVISO datasets. . .”. The 1/4 degree is the resolution of the grid for mapping, the actual AVISO sea surface data’s resolution should be even coarser.*

Answer: Thank you for this comment, we now refer to the resolution of the AVISO grid

P11L2 *“small eddies are abundant found in the. . .” This should be “small eddies are abundantly found in the. . .” or “small eddies are abundant, and found in the. . .”*

Answer: Thank you, we have corrected this typo.

Figure 6c mean vertical flux *Why is the mean vertical flux directed upward in a fairly wide region in the southern part, and vice versa for the northern part? Is it vertical flux of omega flux, in which horizontal flux can contribute through the sloping grid bottom faces?*

Answer: The mean vertical flux is directed according to the regional signature of the wind stress curl, which is negative north of the Cape Verde front and positive south of the front (see also answer to MC1 for a further description of the flux pattern in the region). This results in a mean downward and upward flux respectively north and south of the front. In the nearshore the effect of the mean upwelling becomes evident, resulting in an intense upward flux in the nearshore northern and central CanUS. In the southern CanUS, where the upwelling intensity is on average weaker and the slope is especially wide (Aristegui et al. 2009), downwelling cells are also visible in the nearshore. The flux is not calculated with the omega velocity, but with the purely vertical component of the velocity. In order to further clarify this point, we have added in the Methods section, following the description of the Reynolds decomposition:

[“The vertical flux components were calculated using the purely vertical velocity from the model output”](#)

Figure 7e *What is the green color?*

Answer

We have added the following to the figure caption:

[“The green area shading results from the overlapping of opposing mean and turbulent flux contributions.”](#)

P16L4 *“Switching to the vertical fluxes, the differences between the mean and turbulent flux components are even more pronounced“ and Figure 8c. I’m puzzled by the mean*

vertical carbon flux. The bands of down-up-downwelling flux indicates the increase of carbon at 20 m and the decrease at 80 m depth on average, unless there is compensating lateral flux divergence. I don't understand how the Ekman pumping results in this structure.

Answer: Figure 8c shows the mean vertical component of the flux, averaged in the entire CanUS. As shown in Figure 6, the sign of the vertical component changes between northern and southern subregion. Therefore the mean plot shows a combination of downward organic carbon flux in the north and upward flux in the south. We refer to our answer to MC1 for a further explanation of the flux pattern, and for our proposed changes to the manuscript regarding this point.

P16L30 *"This signature is typical of that expected from an eddy-induced vertical displacement of the nutricline (McGillicuddy, 2016). " If this is the case, the eddy is linear Rossby waves, and not trapping to carry carbon when it propagates. I think eddy propagation speed c is a few centimeter per second, and velocity $u > 0.2$ m/s, so $u/c > 1$, suggesting that eddy is nonlinear, which can hold a large volume of water inside to travel together westward, which is the dominant signal discussed in this manuscript, rather than wave induced isopycnal displacement.*

Answer: Thank you for this comment. In the course of the manuscript revisions, this part has been shortened and the sentence is therefore not anymore in the final manuscript.

P17L7 *"In the offshore waters, ACE can also. . ." Is this mechanism same as the warm core eddy spin down, accompanied by weak upwelling at the center (e.g. Frictionally induced circulations and spin down of a warm core ring by Glenn R. Flierl and Richard P. Mied)? Do you have any evidence to support that this is the cause of positive C'_{org} within ACE?*

Answer: We thank Referee #1 for highlighting this passage and we refer to the answer to MC2 for our changes to the text.

P22L3 *"Between 100 km and 500 km from . . ." and Figure 15d The structure based estimate mean flux divergence between 100-500km is negative. Does it mean that the mean flux is removing the carbon from the shore? If so this makes sense, because Ekman transport from the coast should act to remove carbon from the shore. But the distance is somewhat too far from the coast. Why does it start from 100 km not 0 km? Also, in Figure 15, why does the Reynolds decomposition based mean flux divergence in 100-500 km show different results from the structure based results?*

Answer: In Figure 15d the blue area does not represent the mean flux but the non-filament-non-eddy (NF-NE) flux, which is different from a mean transport (Reynolds decomposition, Figure 15b). The two fluxes must not be confused, as they are defined differently and represent different processes. The mean Reynolds component of the flux refers to a mathematical definition of mean flux, as defined in the Methods section, which can include the contribution of recurrent structures. The NF-NE component is defined as everything which is not identified by our mesoscale structure identification masks and therefore does not include (for example) recurrent filaments. But it may include some turbulent transport which is not identified as an eddy or a filament (e.g., variable small-scale fronts offshore). For this reason, the Reynolds-decomposition-based divergence of the mean flux and the structure-identification-based NF-NE flux divergence should not be the same, but the divergence of the components must nevertheless sum to 100% of the total divergence. The plots in Figure 15 only refer to the offshore ranges of distances from 100km to 2000 km offshore, in which the divergence of the total offshore flux is positive and therefore receive organic carbon from the nearshore (see inserts of Figure 7a and Figure 14a, and the total offshore flux results previously presented in Lovecchio et al. 2017). Therefore, these plots have the aim of attributing the enhancement of the organic carbon availability offshore to the physical drivers. In the range of 0-100km offshore, instead, the divergence of the total offshore flux is negative,

removing organic carbon from the productive nearshore. We have clarified this point modifying the caption of Figure 15 as follows:

“Comparison between the results of the turbulence-based and structure-based methods for the entire EBUS in the range of 100km to 2000 km from the coast, where the divergence of the total offshore flux is positive, therefore resulting in an increase of the organic carbon availability (see also Lovecchio et al. 2017, Figure 10 for the divergence of the total offshore flux).”

The negative divergence of the NF-NE transport is determined by the fact that the non-mesoscale flux is weak at 100 km offshore, where most of the offshore transport is carried on by the filaments, while it intensifies moving towards 500 km from the coast.

We will clarify this point adding the following passage at the end of the first paragraph of section 4.5:

“An exception is the intensification of the NF-NE flux in the range between 100 km and 500 km, resulting in a negative offshore flux divergence (Figure 13).”

P22L12 “. . .offshore reach due to the their. . .” remove “the”.

Answer: Thank you for pointing out this typo, we have corrected it.

P22L19 “. . .mean deflection of their trajectories (Chelton et al., 2011)” The earlier study should be included “McWilliams and Flierl 1979: On the evolution of isolated, nonlinear vortices. Phys. Oceanogr., 1155–1182.”

Answer: Thank you for this suggestion, we have included this reference.

P22L28 “In particular, ACE are responsible for the northward . . . due to their relatively fast decay that results in a slowing down of the clockwise rotation while they move offshore, these eddies induce a net northward transport of C_{org} ” I don’t understand this explanation for the net northward carbon transport by ACE. Considering the positive carbon gradient in zonal direction with clockwise stirring, the southward transport should be stronger. How is this result related to Reynolds decomposed eddy meridional flux in Figure 6e?

Answer: The regional gradient in the organic carbon concentration is not only negative in the offshore direction (zonal gradient) but also positive southward, with a reduced zonal gradient at lower latitudes (Aristegui 2009, Demarq and Somoue 2015). ACE rotate clockwise and stir this gradient while moving offshore. In the nearshore, where the zonal gradient dominates, it is indeed possible to see a negative signature in the meridional ACE flux (Figure B9c). Away from the nearshore, where the meridional gradient and the ACE decay become relevant, the southern edge of the eddy stirs the organic carbon northward. The relatively fast decay of ACE also determines that in each point of the domain, on average, the western edge of a nearshore (therefore on average younger and more intense) ACE stirs the gradient northward, while the eastern edge of an offshore (older) ACE stirs it southward more slowly, resulting in a net northward meridional flux. In order to clarify this point, we have modified the sentence to read:

“In particular, ACE are responsible for the northward recirculation of the C_{org} through the asymmetric stirring of the background regional gradient. This is a consequence of the unique combination of an offshore negative gradient (strongest in the nearshore) and a southward positive gradient in C_{org} (Aristegui et al., 2009). Due to their relatively fast decay and the slowing down of the clockwise rotation while they move offshore, the ACE induce a net northward transport of C_{org} . This is because a younger and more energetic ACE stirs the C_{org} northward in the nearshore areas, while an older and weaker ACE stirs it southward in the offshore areas. CE, being more stable along their tracks, have a weaker effect on the net meridional transport.”

P22L31 “In the vertical direction. . .” I don’t understand why NE-NF vertical flux is the stronger than eddy components. Also do these vertical carbon fluxes reflect the lateral structure of the vertical flow itself or carbon distribution? For confirmation, the total

mean vertical flow at 100 m depth should be presented in appendix. The mean vertical flow should be largest at $\sim O(10^{-5} \text{ ms}^{-1})$ along the coast with the internal Rossby radius as the lateral width, which is very narrow compared to the model domain.

Answer: We thank Referee #1 for raising this interesting question, which points in the direction of our most recent analysis of the physical fluxes inside of the eddies, currently in development for a further dedicated publication. In order to address this question we therefore refer to our current understanding of the mesoscale eddy vertical fluxes according to our model results. Animations of the velocities inside of the eddies at each time step show dipolar or quadrupolar patterns in the vertical fluxes of well-formed stable eddies. These patterns average to a dipole in positive and negative vertical velocities in both composite cyclones and anticyclones at 100 m, in nice agreement with high-resolution observations of the mesoscale velocities in eddies (e.g., Barceló-Llull et al., 2017, JPO). The pattern of positive and negative vertical velocities averages nearly to zero throughout the eddy surface, therefore constituting a minor net contribution to the advective fluxes in well-developed eddies. As a consequence, the net eddy contribution to the vertical advective flux is mostly driven by the large scale forcing, and in particular by the pattern of the wind stress curl (see answer to MC1 for a detailed explanation of the vertical flux pattern in the region). Submesoscale fluxes are not explicitly resolved by our model due to the limited resolution of our grid in the offshore waters. The total vertical advective flux at 100 m is published in our previous publication on Biogeosciences “On the long range offshore transport of organic carbon from the Canary Upwelling System to the open North Atlantic”, and is visible in Figure 11c. In order to clarify this point, we modified these lines according to read:

“In the vertical, eddies have a minor role in the transport of C org compared to the filaments, and their signature cannot be clearly distinguished from that of the NE-NF transport. Inspections of the model output reveal (not shown) that mesoscale vertical velocities in well-developed eddies present a dipolar or quadrupolar pattern of upwelling and downwelling similar to the one observed by in-situ measurements (Barceló-Llull et al., 2017). This compensating nature of the vertical velocities results in a minor net contribution of these mesoscale structures to the vertical flux.”

P23L4 *The convergence at filament is revisited with the theory of frontogenesis by “McWilliams et al. 2009, Cold filamentary intensification and oceanic surface convergence lines”*

Answer: Thank you very much for this suggestion, we have added this reference to the manuscript.

P25L15 *“Nagai et al. (2015) showed that this subduction happens primarily at the filament tip. . .” Remove “tip” and insert “periphery of” before filament*

Answer: We have corrected the sentence accordingly.

Answer to Referee #2

We thank Referee #2 for the time spent on reviewing our manuscript and for his/her thoughtful comments about the length of the manuscript, the timescales of the turbulent variability, the filament detection algorithm and for the many specific comments which have helped us to improve our manuscript. We include below our detailed answers to the general comment about the writing and length and to all the specific comments and describe the proposed changes to the manuscript.

General comment

Length of the manuscript and writing

“...my only real concerns with this paper is its length. This contribution is significantly long (I acknowledge it contains many interesting results but some are a bit redundant) and the writing is slightly too didactic sometimes (it could often be more “to-the-point” and more condensed). For instance, it seems weird to have both “Summary and Synthesis” and “Conclusions” sections in the same article (although I enjoy the reading of both). I agree it has a lot of content (complex analyses & interesting well-supported results) but it may be “lost-at-sea” considering that, nowadays (and unfortunately), papers are more-and-more numerous and less-and-less read by the community. Their work could gain in visibility if they opt for shorter and/or separated contributions. I would suggest the authors to try reducing the length of the article (i) by focussing their analyses and the writing and (ii) maybe by keeping aside some content for another paper (especially the regional analyses over the three subsystems -keeping here only the whole CanUS- and the seasonality of the processes, cf. A comment below).”

Proposed solution

We thank Referee #2 for his/her evaluation of the manuscript. The length of the manuscript is indeed an issue and we will thrive to streamline and shorten it, to make it more accessible to the reader. In order to move in this direction, we have decided to combine the suggestions of Referee #1 (comments MC2, MC3, P17L7) and Referee #2 (this comment and specific comment SC6) and have made substantial changes to the manuscript in order to make it more concise. We list the changes below:

- 1 – We have shortened the Methods section by moving the (rather informal) description of the new filament detection algorithm to a dedicated [supplement to the manuscript](#), where we provide also an evaluation of the algorithm sensitivity and of its performance.
- 2 – We have moved the Evaluation section by moving Figure 4 to the Appendix, as it does not provide a comparison with the observations, and rephrased the section in order to remove a few repetitions in the discussion of the Figures.
- 3 – We have shortened the discussion of our results, while paying attention not to cut out on the scientific content. In particular, have merged subsection 4.3 and subsection 4.4 into a single subsection titled “From turbulent anomalies to the mesoscale contribution to the organic carbon stock” which serves as a transition between the discussion of the Reynolds decomposition and the discussion of our structure-based analysis. This allows us to present: velocities, C_{org} anomalies and C_{org} content of the mesoscale structures. With the purpose to ease the flow of the paper, have inverted the order of Figure 9 and Figure 10 and merged the first and last paragraph of the current subsection 4.3 into a single initial paragraph, followed by the discussion of the current Figure 9. We have cut part of the current subsection 4.4, limiting the discussion to the contribution of mesoscale activity to the organic carbon stock, in line with the focus of our paper. Figure 12 (mesoscale contribution to the nutrient stock and production) has been moved to the Appendix. This is also in line with the suggestion of Referee #1 to limit speculative discussion in the Results section.
- 4 – We have removed from our discussion the paragraph focusing on the processes regulating production and nutrient concentrations in the eddies according to previous literature (pg.27, ll.11-23), in order to maintain the focus on the organic carbon budget and transport.

5 - We have merged the Summary and conclusions into a single Conclusions section strongly limiting the summary, as most of the information is already highlighted in the abstract and discussion. Our new conclusions read as follows:

“Our study in the CanUS confirms that mesoscale processes contribute substantially to the long-range offshore transport of C_{org} through a combination of mean and turbulent transport. In particular, filaments drive the total offshore flux of C_{org} and its divergence in the nearshore, while far-reaching eddies, especially cyclones, extend this transport up to the middle of the gyre. 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 1000 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 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 also tells us that a fraction of the offshore biological activity is fueled discontinuously at the passage or death of such a structure. 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. 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} , not included in our model.”

6 - We have maintained the discussion of the subregional differences in the fluxes in the manuscript. These results provide essential information on the latitudinal differences in the flux contributions within the system, and can be of interest for studies that will focus on a specific portion of the CanUS. Moreover, they provide a term of comparison between our results and several previous studies which focused on a specific subregion.

Overall, the proposed changes have allowed us to shorten the manuscript core (from Abstract to Conclusions) by more than 10% of its length, i.e. from the initial 31 pages to 27 pages.

Answers to specific comments

SC1) Typing/English mistakes:

- 1) p 1 line 19: “anticyclonic” has been perhaps forgotten;
- 2) p 5 line11: delete “the”;

- 3) p 6 line 19: *filaments*;
- 4) p 9 line 4: delete “eddy”;
- 5) p 11 line 2: delete “abundant” or “found”;
- 6) p 11 line 25: delete “a”;
- 7) p 16 line 11: could it be “going deeper than 500 m within 500 km from the shore (or over 0-500 km offshore)”;
- 8) p 17 line 8: “which slow down the rotation...”;
- 9) p 18 line 14: should it refer to Fig. B7 and/or 8 instead of Fig. B6 there?;
- 10) p21 line 1: *estimateS*;
- 11) p 22 line 33: *responsible OF a*;
- 12) p 30 line 18: *cyclonEs*; etc..

Answer:

- 1) the sentence is actually complete as it refers to all types of eddies, and not anticyclonic eddies.
- 2) the paragraph was rephrased while revising the manuscript.
- 3) we have moved this paragraph to the supplement.
- 4) the entire paragraph was rephrased while revising the manuscript.
- 5) the entire paragraph was rephrased while revising the manuscript.
- 6) we have deleted “a” as in: “*Thin and short-lived filaments...*”.
- 7) the entire paragraph was rephrased while revising the manuscript.
- 8) we decided to remove this sentence.
- 9) thank you for pointing this out, yes it should be the plot B8 of the current manuscript version, we have corrected it accordingly.
- 10) we have corrected this typo.
- 11) the entire paragraph was rephrased while revising the manuscript.
- 12) thank you, we will correct the typo.

SC2) *Page 2 lines 9-10: there exist plenty of earlier references to support this statement, including some that are already cited, such as Rossi et al. 2008 and Gruber et al. 2011.*

Answer:

Thank you very much, we have added the references in this point.

SC3) *Page 2 lines 31-32 and page 30 lines 32-33 + page 31 lines 1-2: the “coherence” of eddies is still an open question to my mind; there is a bunch of papers around those questions, both from the observational and modelling point of views, and many situations (from very coherent to quite leaky) have been reported; so it seems no agreement has been reached yet. Please rewrite.*

Answer:

We agree with Referee #2 that significant progress still has to be made to understand the degree of isolation of mesoscale eddies from the surrounding environment.

We have rephrased the sentences as follows:

“Eddies trap water and tracers in their core during their formation. In stronger eddies, the degree of lateral isolation of the eddy core from the surrounding environment can be quite high, possibly resulting in the entrainment and long-range transport of trapped tracers at formation (Karstensen et al., 2015, 2017, Chelton et al., 2011).”

“Third, the relevant share of C org found in the offshore region within mesoscale eddies also tells us that a fraction of the offshore biological activity is fueled discontinuously at the passage or death of such a structure.”

SC4) *Page 4 line 11: in addition of in-situ observations and modelling studies, there also exist purely satellite studies (e.g. Capet et al. 2014, not yet cited) as well as merged modelling & satellite study (e.g. Hernandez-Carrasco et al. 2014, already cited). Capet et al. 2014. Implications of Refined Altimetry on Estimates of Mesoscale Activity and Eddy-Driven Offshore Transport in*

the Eastern Boundary Upwelling Systems, Geophysical Research Letters, 41 (21), 7602–7610, doi:10.1002/2014GL061770. It could also be cited at page 6 line 27-28 (assumption of “prismatic” volume) and page 30, line 25.

Answer:

We thank Referee #2 for the suggestions.

SC5) *Page 5 lines 12-15: the turbulent field (e.g. mesoscale activity) exhibits temporal variability, at monthly and especially seasonal time-scales. Why did you include the monthly/seasonal variability of the fields into the mean fluxes? I presume that this choice could impact your results about the “turbulence-based” methods, as well as when comparing it against the “structure-based” approach (has it been done similarly?). These additional analyses could be kept for future work anyway.*

Answer:

We agree with Referee #2 that the turbulent field exhibits a certain level of seasonal variability. However, seasonal changes in circulation and biological activity represent the dominant mode of temporal variability in the CanUS, both on the regional and on the subregional scale (Chavez and Messié, 2009, Mittelstaedt, 1991), i.e. on spatial scales that are larger than the mesoscale. For this reason, including the seasonal cycle into the turbulent field, for example using a climatological annual mean as a reference mean, would result in the turbulent deviations including strong signals that evolve on scales longer than the ones of interest for our study. In order to clarify this point, we have rephrased the sentence at page 5 lines 14-15 as follows:

“The time-varying reference means for the decomposition are computed from the climatological monthly means of velocities and concentrations calculated from the 24 years of the run used for the analysis, and then interpolated linearly to bi-daily fields. This choice allows us to avoid the inclusion of both the dominant seasonal variability (Chavez and Messié, 2009) and the recurrent monthly oscillations of the fields into the turbulent components. As a consequence, our turbulent fields represent only those signals that vary on timescales shorter than approximately one month.”

SC6) *Page 6 lines 18-20: Why is the reference mean SST field coarsened onto a 2x2° grid? This coarsening procedure is not applied to the snapshots, right? What could be the impact of a different coarsening? How was the threshold of -0,3°C defined? What is the sensitivity if your results to these threshold?*

Answer:

The coarsening of the reference field onto a 2x2 degree grid allows the algorithm to better recognize the upwelling filaments as connected structures in the 2-day output SST field. This procedure is not applied to the bi-daily mean field. While developing the algorithm we tested the sensitivity of our results to the coarsening and to the SST threshold.

In order to provide a comprehensive description of the algorithm and of its sensitivity to the parameters, we have added a **supplement to the manuscript** which includes a technical description of the algorithm and its properties, as well as an evaluation of its performance.

SC7) *Figures 3 and 4: for ease of understanding, please report in the caption that the unit of some panels is “number of eddies per 1 degree bin per day” (if I understood correctly).*

Answer:

Thank you for your suggestion, we have added it in the caption.

SC8) *According to their specific behaviours showed in Fig 7 inserts, it would be interesting to see the equivalent of Fig. 8 but for the different subsystems (to be kept for future work I suppose).*

Answer:

Thank you for your suggestion, we include below the subregional plots of the zonal flux of organic carbon as a term of comparison with Figure 7 and Figure 8 of the manuscript.

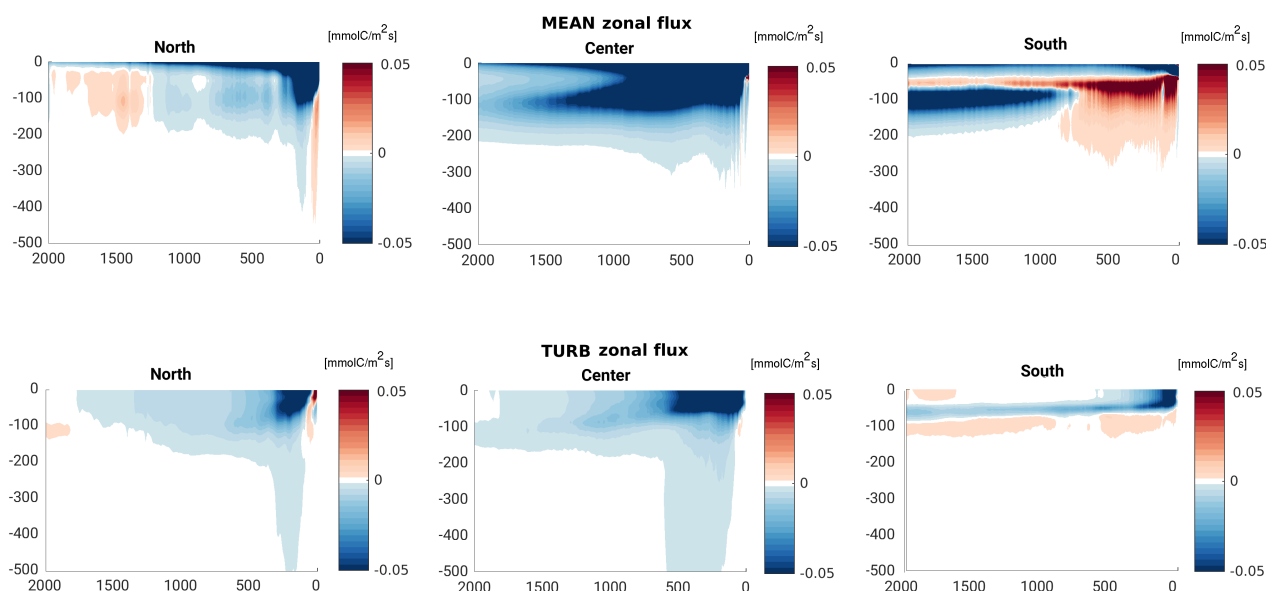


Figure re SC8: Reynolds mean and turbulent components of the zonal flux of Corg averaged along lines of equal distance from the coast in the three CanUS subregions, as defined in the manuscript.

SC9) Page 18 line 5-7: Were these velocities estimates taken from the Hovmöller plots of Fig. 10 or from a direct check of exemplary velocities modelled at the boundaries of those structures? If these propagation speeds (for each structure type) were derived from the Hovmöller of Fig. 10, are they in accord with those derived from Fig. B6?

Answer:

These velocities were calculated explicitly from the 2-day mean output.

SC10) Fig. 12: inconsistency between the caption and the plots displayed. I am also wondering if the explanations described lines 1-14 p 20 were obtained after having analysed the simulated fields of a few typical structures (if so, please show some figures in Appendix)? If not, I presume those lines of text are rather “discussion”, so that they should have more references and they could be transferred somewhere else.

Answer:

Thank you for pointing out this inconsistency, we have removed the reference to the subregions in this caption. Following this suggestion and the need to shorten the manuscript, we decided to shorten section 4.4, limiting the discussion to the contribution of mesoscale activity to the organic carbon stock, while moving Figure 12 to the Appendix. See our answer to the first comment (General comment) in this document for further details.

SC11) Page 21 line 10: I found that the expression “coastally confined” is a bit misleading to describe a process prominent over a region extending from the shores to more than 500 km offshore; maybe “shelf-confined”? (although the shelf might be even narrower than this...), else?

Answer:

Thank you for your suggestion, the entire paragraph was modified in the course of the revision of the manuscript.

SC12) Page 25 lines 7-11 and page 26 line 4: to further support those arguments, you could refer also to Rossi et al. 2013 (already cited) who documented (from in-situ observations in the Iberian Peninsula Upwelling) a filament of 50-60 m depth which experienced subduction when moving offshore (see their sect. 3.2.2 and 3.6).

Answer:

Thank you very much for this suggestion, we have added this reference.

SC13) *These “intermittent hotspots of downwelling” are puzzling; I wonder what mechanisms are involved and why are they so transitory?*

Answer:

Animations of our model output show small scale and highly variable hotspots of downwelling in the filaments, mostly concentrated to the first 100 km of offshore range. These hotspots evolve quickly and often drift laterally following the filament flow. This corresponds to the previous findings of Nagai et al. 2015, and suggests us that these small scale fluxes are associated to the formation and degradation of frontal regions at the edges of the filaments, which are associated by high strain in the horizontal flow. The formation of such small scale downwelling is also favored by the relatively high resolution of our grid in the nearshore, ranging between 8 and 5 km of grid spacing. We have rephrased the mentioned passage as follows:

“Animations of the vertical velocities at 100 m depth in the filaments show transitory and irregular hotspots of strong downwelling, which evolve quickly and often drift laterally following the filament flow. Therefore, 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 numerical study, Nagai et al. (2015) showed that this subduction happens primarily at the periphery of the filament due to the formation and degradation of frontal and high-strain regions at the filament edges.”

SC14) *Page 26 line 10: compilations of offshore transport due to upwelling filaments were also reported in Sanchez et al. 2008. Physical description of an upwelling filament west of Cape StVincent in late October 2004. Journal of Geophysical Research—Oceans, vol.113, C07044, <http://dx.doi.org/10.1029/2007JC004430>.*

Answer:

Thank you very much for your suggestion.

SC15) *Page 29 lines 3-9: why maps of chlorophyll are mentioned here? I thought that your structure detection algorithms were indeed applied to modelled SST*

Answer:

The filament detection algorithm was indeed developed only on the basis of SST, which is the only field used by the algorithm. To evaluate the performance of the the algorithm, the masks were also compared to images of modeled surface chlorophyll. Surface chlorophyll constitutes a good tracer for the identification of the streams of upwelled water and the choice was made also in analogy to the traditional methods of single filament identification (by hand) from satellite images, often based on surface chlorophyll signatures. However, in order to avoid confusion we have removed this detail from the discussion section:

“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 and very limited over-detection in the southern CanUS.”

Furthermore, we have included a dedicated **supplement to the manuscript** with the aim of providing a better description of the algorithm evaluation and of its performance.

Answer to Referee #3

We thank Referee #3 for the time spent on reviewing our manuscript and for his/her thoughtful comments on the representation of the organic carbon pool in our model. We include below our detailed answers to the Referee's major comment and to all the specific comments and describe the proposed changes to the manuscript.

Major comment

Representation of the C cycle in NPZD

I would also like to introduce a philosophical issue. The NPZD has difficulties to reproduce properly the C cycle in coastal upwelling zones for two reasons: ii) DOC is not properly included in the model; and ii) benthic nutrient mineralisation is not considered.

For the case of DOC, the authors have found a way to overcome the problem by introducing two POM pools (sinking and suspended) and considering DOC part of the suspended POC pool. It could work. In this regard, lateral Corg fluxes are reported without differentiating the pools considered (Phyto, Zoo, large POM, small POM + DOM). Are you reporting only small POM + DOM or also the other pools?

For the case of benthic mineralization, in EBUEs with wide continental shelves, as it the case of the NW Africa EBUE, 40-60% of the nutrients used for phytoplankton growth could come from the underlying sediments. Is this process included in the NPZD model in any way?

Answer

The organic carbon pool in the present NPZD model consists of four compartments, namely Phytoplankton, (PHY) Zooplankton (ZOO), Small Detritus (SDet) and Large Detritus (LDet). The presented Corg fluxes refer to the total organic carbon pool, therefore to the sum of the four modeled pools. Of these organic carbon types, only ZOO does not sink (see Gruber et al, 2006 for a complete set of parameters). The NPZD model does not include any dissolved organic carbon pool. In spite of this limitation, the modeled SDet, with its small sinking speed and large abundance, shares strong similarities with a suspended POC pool and, to some extent, with semi-labile DOC. A full discussion of the consequences of this representation of the organic carbon pool in our model is provided in Lovecchio et al., 2017, and in the BGC Discussion page of the same paper, especially the answer to the Major Comment 1 of Referee #1.

With regard to benthic remineralization: sediments in the NPZD model are not a sink for POM but act as a temporal buffer, meaning that all the POM that sinks into the sediments is slowly remineralized there back into inorganic constituents, which are then released immediately back into the bottom water. No burial of POM is considered in our model. Thus sediments are indeed a source of nutrients for the water column in our model. A clear drawback is our lack of consideration of benthic denitrification and other special processes altering the biogeochemistry of the sediments and of the overlying water column.

In order to better clarify this point, we have added this statement to the Methods section:

“For our analyses, the C_{org} pool is inferred from the explicitly modelled organic nitrogen pools through a constant stoichiometric ratio of C:N = 116:16. The following pools make up the total organic matter: a non-sinking zooplankton pool, a sinking phytoplankton pool, and two detritus pools, of which one is sinking fast, and one is sinking slowly. The biogeochemical model includes an explicit sediment layer at the bottom of each water column grid point. There, all deposited organic matter is remineralized slowly back to its inorganic constituents, which are then released back to overlying waters. Thus, the sediments act as a temporal buffer, but not as a net sink of any biogeochemical element. An important potential shortcoming is the lack of consideration of an explicit DOC pool. However, Lovecchio et al. (2017) demonstrated already that our slowly-sinking detritus pool acts akin to semi-labile DOC, so that our model captures important elements of

this pool as well. We refer to Lovecchio et al. (2017) for further discussions of the strengths and limitations of our modelling approach.”

Answers to specific comments

SC1) Page 1, line 4 – *I would not say that a model will be able to “demonstrate quantitatively” that eddies and filaments are exporting organic matter from the coast to the open ocean at the NW Africa EBUE scale. A numerical model is a tool that tries to approach as much as possible to reality, but it is (rather) imperfect.*

Answer:

We have rephrased this sentence as follows.

“Yet a comprehensive analysis of this mesoscale flux and of its impact in the entire Canary Upwelling System (CanUS) has not been provided.”

SC2) Page 5, caption of Figure 1 – *explain what is “01/12/0030” and change “9.5 ° N and 32 ° N” by “32 ° N and 9.5 ° N”.*

Answer:

We thank Referee #3 for this comment, but we think that it’s correct to list the latitudes in an increasing order. Day 01/12/0030 is the first day of the 12th month of the 30th year of simulation including spinup. We have rephrased this part of the caption as follows:

“from Dec. 1 of year 30 of the run (01/12/0030).”

SC3) Page 7, line 13 – *salinity is unit less*

Answer:

Thank you, we will correct this.

SC4) Page 9, line 1 – *It is a bit optimistic to state that the patterns of the model and the observations are “very similar”. I would say just “similar” or even “roughly similar”.*

Answer:

The entire paragraph was rephrased during the revision process.

SC5) Page 11, line 2 – *Please, erase “found”*

Answer:

The entire paragraph was rephrased during the revision process.

SC6) Page 11, line 18 – *Please, indicate what organic matter pools are included in C_{org} (Phyto?, Zoo?, large POM?, small POM + DOM?).*

Answer:

We have added a short description of the NPZD model following the first sentence of the methods, as proposed in the answer to the major comment. Please, refer to the answer to the Major Comment for further details on the actual changes to the manuscript.

SC7) Page 12, Figure 5 – Why Corg was integrated through the entire water column instead of just in the upper 100 m. No scale for current vectors has been added in panel (a).

Answer:

We have substituted the plots in Figure 5 with 100m-integrated organic carbon plots shown below in Figure 1.

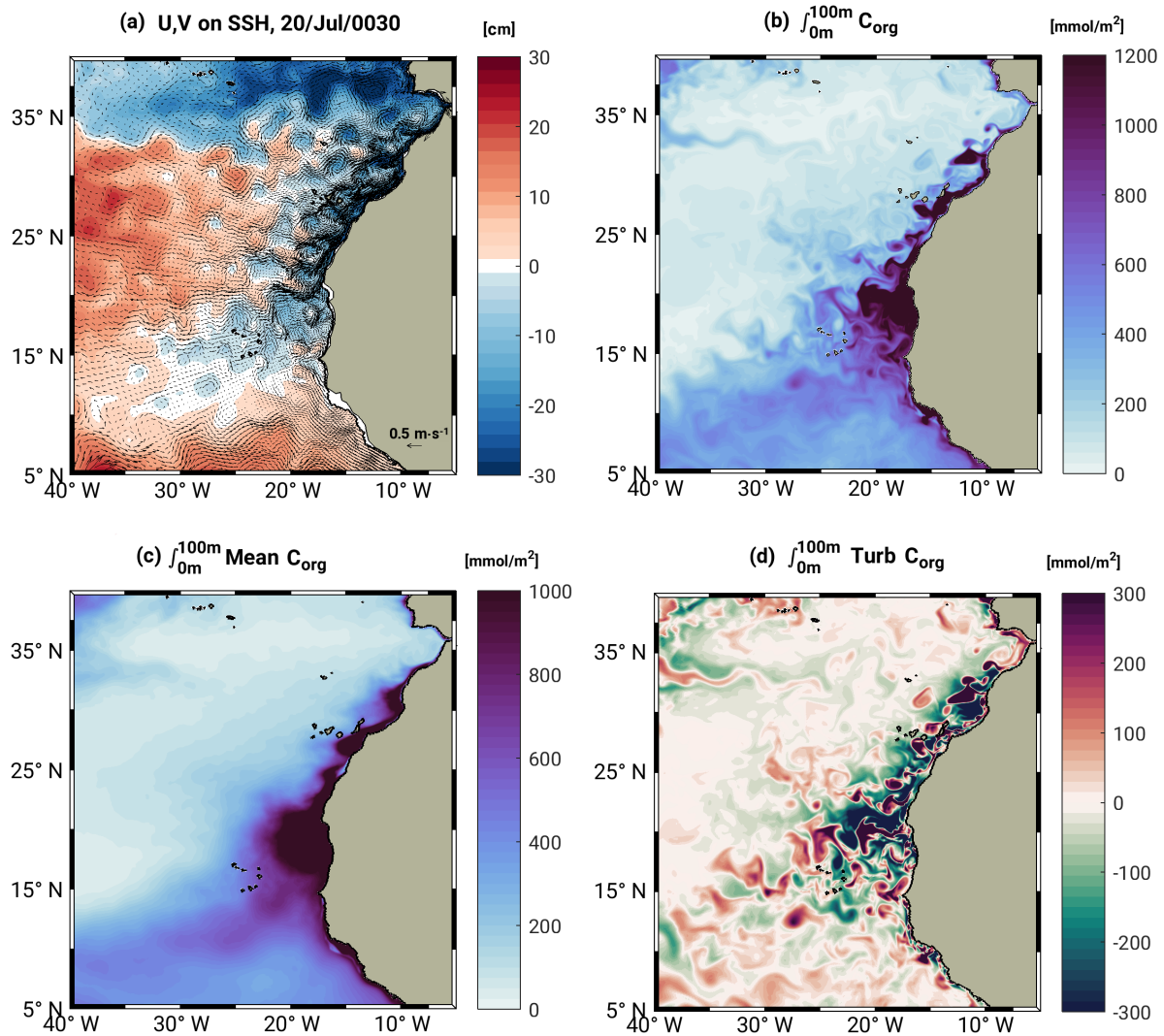


Figure 1: Modeled 2-day mean variables for July 20 of year 33 of the simulation. The Corg components are integrated throughout the first 100 m depth.

SC8) Page 20, Figure 12 – The footnote is not coherent with the figure.

Answer:

Thank you for pointing this out. We have corrected the caption removing the reference to the subregions.

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~~ a comprehensive analysis of this mesoscale flux and of its impact across the Canary Upwelling System (CanUS) ~~has not been provided~~. Here, we fill this gap using simulations with the Regional Oceanic Modeling System (ROMS) coupled to a Nutrient, Phytoplankton, 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~~ analysis reveals 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 carbon~~ concentrations, transport ~~this the organic~~ carbon offshore in a very intense, but coastally-confined, manner, contributing nearly 80% to the total flux of organic carbon at 100 km offshore ~~distance~~. The filament contribution tapers off quickly to near zero values at 1000 km ~~distance off the coast~~, leading to a strong offshore flux divergence that is the main lateral source of organic carbon in the ~~first 500 coastal waters up to 1000~~ 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 a time-mean flux ~~and only to a limited degree represents a turbulent flux, while the time-varying component, i.e., the turbulent flux, is comparatively small~~. 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 reservoir for the open waters, since they contain ~~on average, on average~~, a third of the ~~offshore organic carbon organic carbon in this region~~, 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~~ resolve the three-dimensionality of the marine ~~biological pump~~ organic carbon cycle.

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 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 generating instabilities that give rise to~~ mesoscale fronts, filaments, eddies and other forms of ~~mesoscale turbulent~~ structures (Bar-

ton et al., 1998; Capet et al., 2013). This ~~mesoscale variability~~ variability, especially that on the oceanic mesoscale (scales of ~20 km to ~200 km), modulates the spatial distribution of tracers with an important impact on the biological activity (~~McGillicuddy, 2016; Mahadevan, 2014~~) (McGillicuddy, 2016; Mahadevan, 2014; Rossi et al., 2008; Gruber et al., 2011). 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 and are characterized, in their interior, by rather large flow~~ velocities (between ~~0.25-0.1~~ and 0.5 m s⁻¹), often recirculating the water in vortices at their extremity (Strub et al., 1991). ~~Offshore transport~~ Transport by filaments is typically accompanied by ~~intense subduction~~ a deepening of the tracer fluxes in the offshore direction, due to the high density of the ~~cold upwelled waters (Mahadevan, 2014; Nagai et al., 2015)~~ upwelled water (Cravo et al., 2010). This is also associated with intense downwelling induced by the generation of ageostrophic cross-frontal circulation at the edges of the filament (C. et al., 2009; 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; Aristegui 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 (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 (Álvarez-Salgado, 2007). 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

substantially farther offshore than the filaments (Sangrà et al., 2009; Combes et al., 2013). ~~Due to their non-linear character, eddies~~ Eddies trap water and tracers in their core during their formation. ~~Once the eddy is formed, the entrained tracers are nearly isolated~~ In stronger eddies, the degree of lateral isolation of the eddy core from the surrounding environment ~~, except for the vertical exchange (Karstensen et al., 2015)~~ can be quite high, possibly resulting in the entrainment and long-range transport

5 of trapped tracers at formation (Chelton et al., 2011; 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~~ chlorophyll, phytoplankton biomass and all the other biogeochemical properties in the euphotic layer (Pelegrí et al., 2005; Gaube et al., 2014). This has strong impacts on the local biogeochemical fluxes and ecosystem composition (Baltar et al., 2009; Doblin et al., 2016; Rossi et al., 2008, 2009).

10 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).

15 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, 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

20 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 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

25 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 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; García-Muñoz et al., 2004; Rodríguez et al., 2004). These nearshore-

30 generated 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 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 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~~ transport of about 6 to 9 Sv (Barton et al., 2004), ~~accounting responsible~~ for between 2.5 and 4.5 times the offshore ~~carbon export-driven~~ C_{org} export carried by the Ekman transport (Álvarez-Salgado, 2007).

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 (Aristegui 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 lateral 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~~ C_{org} in this system. Furthermore, model simulations for both the CalUS and CanUS also showed that eddies tend to reduce coastal production through the lateral export and subduction of the upwelled nutrients, leading to a lower nearshore nutrient inventory (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 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 of biogeochemical tracers (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.

2 Methods

- 5 We employ the [same simulation results as used by Lovecchio et al. \(2017\) to study the time mean total offshore transport of \$C_{org}\$ in the CanUS. The model consists of the UCLA-ETH version of the Regional Ocean Modeling System \(ROMS\) \(Shchepetkin and McWilliams, 2005\) coupled to ~~the simple NutrientPhytoplankton-Zooplankton-a~~ \[Nutrient, Phytoplankton, Zooplankton, and Detritus \\(NPZD\\) biogeochemical ecosystem model described by Gruber et al. \\(2006\\). The coupled model was run with the same grid, boundary conditions and climatological mean atmospheric forcings as those presented in Lovecchio et al. \\(2017\\).\]\(#\)](#)
- 10 ~~The (Gruber et al., 2006). 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 [and track](#) the
- 15 rapidly evolving mesoscale structures.

For our analyses, the C_{org} pool is inferred from the explicitly modelled organic nitrogen pools through a constant stoichiometric ratio of C:N = 116:16. The following pools make up the total organic matter: a non-sinking zooplankton pool, a sinking phytoplankton pool, and two detritus pools, of which one is sinking fast, and one is sinking slowly. The biogeochemical model includes an explicit sediment layer at the bottom of each water column grid point. There, all deposited organic matter is

20 remineralized slowly back to its inorganic constituents, which are then released back to overlying waters. Thus, the sediments act as a temporal buffer, but not as a net sink of any biogeochemical element. An important potential shortcoming is the lack of consideration of an explicit DOC pool. However, Lovecchio et al. (2017) demonstrated already that our slowly-sinking detritus pool acts akin to semi-labile DOC, so that our model captures important elements of this pool as well. We refer to Lovecchio et al. (2017) for further discussions of the strengths and limitations of our modelling approach.

- 25 ~~If $\mathbf{F}$ denotes the~~ Using a Reynolds decomposition approach ("turbulence-based" approach), we separate the advective organic carbon flux ~~vector, $\mathbf{F} = \mathbf{u}C_{org}$, with $\mathbf{u}$ being the velocity vector and C_{org} the organic carbon concentration we have $\mathbf{F} = \mathbf{u}C_{org}$. To analyze this flux we performed a Reynolds decomposition, into a mean component ($\overline{\mathbf{F}}$) and into a time-varying ($\mathbf{F}'$), i.e., we split the flux into $\mathbf{F} = \overline{\mathbf{F}} + \mathbf{F}'$, where the bar denotes time averaging according to the definition of the reference mean (see below) and the prime indicates turbulent~~ turbulent component. The overbar denotes a time averaging operator, here
- 30 ~~chosen such that the reference mean of each field varies smoothly following the seasonal climatology. The prime indicates the temporal deviations from this mean. To do so we first calculated the (time-varying) reference mean and turbulent contribution to the velocity vector time-varying mean. The two components are computed by first calculating $\overline{\mathbf{u}}$ and of the organic carbon concentrations $\overline{C_{org}}$ at each time and determined the their turbulent values by subtraction $\mathbf{u}' = \overline{\mathbf{u}} - \mathbf{u}$ and $C'_{org} = \overline{C_{org}} - C_{org}$. Throughout~~

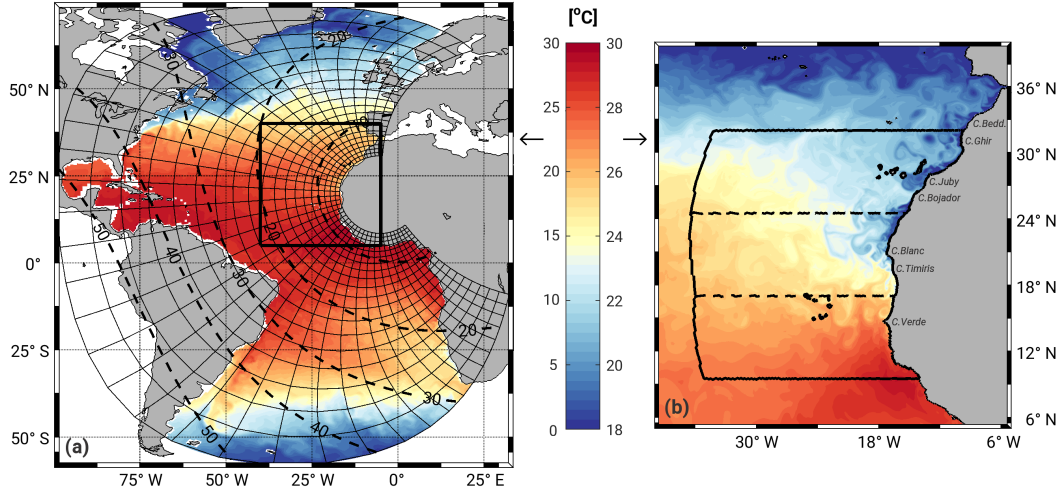


Figure 1. Model grid and CanUS domain superimposed on an instantaneous snapshot of Sea Surface Temperature [°C] from ~~day-Dec. 1 of~~ [year 30 of the run](#) (01/12/0030of the run). (a) Atlantic telescopic grid showing every 20th grid line (solid lines) with isolines of grid resolution in km (dashed 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.

~~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 mean fluxes, rather than into the turbulent component, while obtaining smooth mean bi-daily fields. We then decomposed the C_{org} fluxes at each time step, and calculated the-. We then~~
 5 ~~determine the temporal deviations by subtraction, i.e., $u' = \bar{u} - u$ and $C'_{org} = \bar{C}_{org} - C_{org}$. This permits us to decompose the long-term average mean and turbulent fluxes mean advective flux of C_{org} as in:~~ into three components, i.e.,

$$\langle F \rangle = \langle \bar{u} \bar{C}_{org} \rangle + \langle u' C'_{org} \rangle + r, \quad (1)$$

where the angled brackets ~~represent averaging indicate the average~~ over our analysis period. The first ~~summand term~~ on the right hand side ~~gives the represents the long-term average of the (time-varying) mean flux, i.e., $\langle \bar{F} \rangle$. The second term~~
 10 ~~represents the long-term average mean $\langle \bar{F} \rangle$, the second the average turbulent contribution $\langle F' \rangle$ to the overall flux. The last term, $r = \langle \bar{u} C'_{org} \rangle + \langle u' \bar{C}_{org} \rangle$ term-, represents the sum of the residuals~~ ~~which we verified to be small, which arises from our use of a time-varying reference mean. We neglect this residual as it is at least one order of magnitude or more smaller than the other terms. The time-varying reference means for the decomposition are computed from the climatological monthly means of velocities and concentrations calculated from the 24 years of the run used for the analysis, and then~~
 15 ~~interpolated linearly to bi-daily fields. This choice allows us to avoid the inclusion of both the dominant seasonal variability~~

(Chavez and Messié, 2009) and the recurrent monthly oscillations of the fields into the turbulent components. As a consequence, our turbulent fields represent only those signals that vary on timescales shorter than approximately one month. The vertical flux components were calculated using the purely vertical velocities from the model output.

To quantify the contribution of mesoscale eddies to the C_{org} budget and transport, we ~~used~~ use 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, definition of eddies and the restriction on the number of inner extremes, the~~ The algorithm was shown by Faghmous et al. (2015) to be able to retrieve about 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 the grid.~~ Using this eddy identification method, we ~~saved~~ save 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~~ are filtered out to avoid noise in the nearshore high-resolution region.

To estimate the contribution of filaments to the mesoscale transport ~~we developed an~~, we developed a new SST-based upwelling filament-identification algorithm. ~~The filaments in question are upwelling filament generated at the CanUS coast which extend offshore the carrying cold~~ This algorithm builds on several key characteristics of filaments, i.e., that they are generated near the coast, that they extend in a continuous manner offshore, and that they are distinctly colder than their environment, owing to them carrying recently 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 where 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 indeed captured by this method. The few false positives identifications were limited to the southern boundary of the CanUS.~~ A detailed description of the filament identification algorithm, including a discussion of its sensitivity to the parameters and an analysis of its performance in the system of interest is provided in the supplementary material. An example of ~~one of the filament masks is given in the Appendix in Figure B1~~ one of the filament masks is given in the Appendix in Figure B1.

We allocate all areas not covered by filaments and eddies to the non-filament/non-eddy (NF-NE) mask. As a consequence, this mask inherits the uncertainties and biases of the filament and eddy detections. For example, the filament detection method likely attributes a too large fraction of the nearshore 50 km to filaments, thus underestimating the contribution of the NF-NE transport in this very nearshore band. Unfortunately, we cannot easily correct for this likely bias, given the lack of a clear definition of the boundaries of a filament on the shelf. As a consequence, we disregard the results from the structure identification algorithms in the first 50 km.

In the vertical direction, we ~~assumed~~ assume 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~~ use these 3D masks to decompose the C_{org} concentration and the C_{org} fluxes into their filament, cyclonic, anticyclonic components ("structure-based" approach). To calculate the C_{org} concentration 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~~. The same procedure was followed for the computation of the fluxes. To calculate the mesoscale ~~and NF-NE~~ components of the C_{org} fluxes, we ~~multiplied~~ multiply C_{org} concentration and velocity fields ~~at each time step~~ by the mask of interest ~~. We then multiplied the masked at each time step, multiply the obtained 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, and finally average in time the obtained fluxes.~~

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 water column~~ Furthermore, this depth layer is responsible for the majority of the offshore transport, with a share of nearly 100 % of the total flux at 100 km offshore and ~80 % at 500 km offshore, where offshore transport is the most intense (Lovecchio et al., 2017).

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 findings, and then extend the evaluation to include aspects that are particular to this study, namely the model's representation of mesoscale processes. Physical~~ The extensive evaluations performed already by Lovecchio et al. (2017) revealed that the 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 ($\sim +0.75$ °C) and SSS ($\sim +0.4$ g/kg) are found only in the ~~sector of the CanUS located region~~ south of Cape Blanc (21° N), where the modeled circulation is ~~also~~ too sluggish 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. Correlations with the observed fields are always higher than 0.85 in the annual mean for physical variables and lay in the range of 0.6 to 0.88 for the relevant biological variables (see Appendix: Figure B2).~~

~~Thanks to~~ Extending these evaluations to include aspects that are particular to this study, namely the model's ~~high resolution, the magnitude~~ representation of turbulence and mesoscale processes, reveals also a good performance and a few weaknesses.

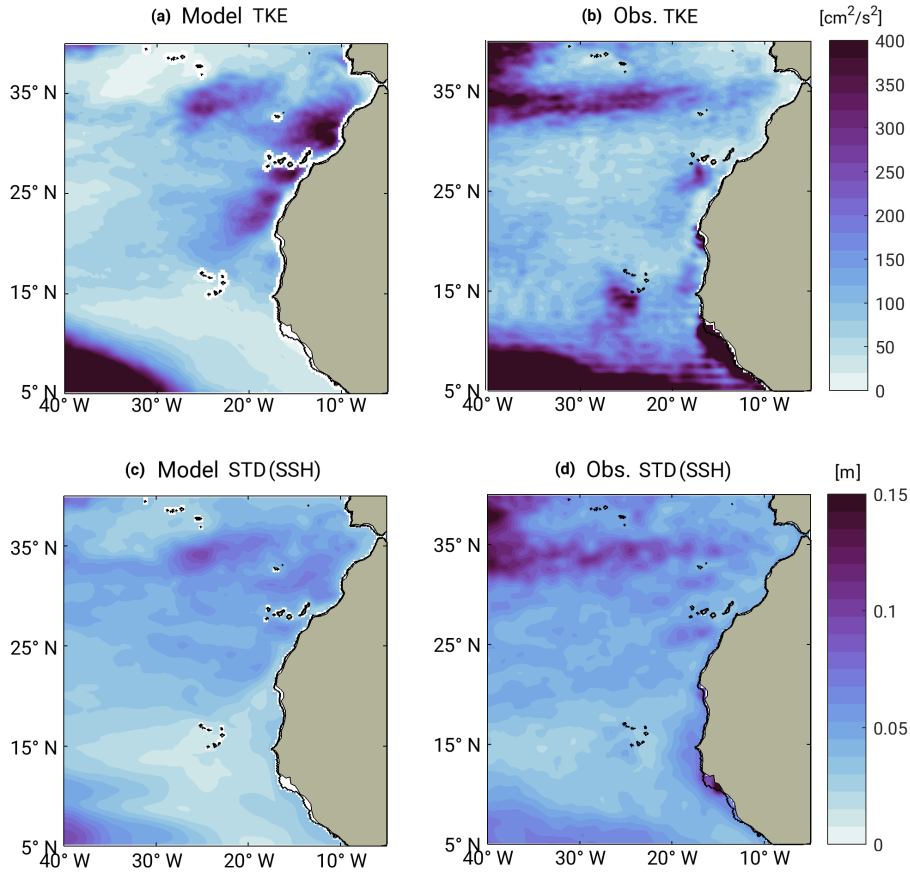


Figure 2. Comparison of (a) modeled ROMS and (b) observed AVISO Turbulent Kinetic Energy, TKE [cm^2/s^2]; Comparison of (c) modeled ROMS and (d) observed AVISO standard deviation of SSH, STD(SSH) [m]. Modeled velocities were calculated offline using geostrophy from modeled SSH and regridded on the AVISO DUACS 2014 product grid, $1/4^\circ$ 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.

The magnitudes of the Turbulent Kinetic Energy (TKE) and of the standard deviation of the sea-surface height (STD(SSH)) as observed by AVISO is (see Appendix, Table A1) are overall well captured by the model. ~~Between the Canary and the Cape Verde archipelago, the modeled TKE pattern is (Figure 2). This is especially the case in 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, corresponding to the region between the Canary and the Cape Verde archipelago.~~ However, as expected from our assessment ~~on of~~ the mean circulation, the ~~TKE is two quantities are~~ underestimated south of Cape Blanc, especially in the proximity of the North Equatorial Counter Current and south of the 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~~ with 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~~ smaller than observed. Both the Azores Current and the Northern Equatorial Counter Current are, in fact, generated away from the north-western African coast, ~~in regions in which the i.e., in regions where our~~ grid has a low resolution. ~~On the eastern side, hindering the formation of mesoscale variability.~~

5 Along the coast of the northern CanUS, ~~along the portion of the African coast located north of Cape Blanc,~~ and especially north of the Canary Archipelago, the modeled TKE ~~is instead and~~ STD(SSH) are actually higher than observed. This region is ~~the most highly~~ 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

10 ~~make them difficult to detect in the~~ only partially resolved by the employed 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.~~ Thus, it is conceivable that the TKE and STD(SSH) products are biased low in this region.

15 To evaluate the ~~ROMS eddy field~~ eddy field simulated by our model, 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~~ on their respective native grids. Given the AVISO grid resolution and the minimum threshold of 9 grid points to identify an eddy, the distribution of eddy radii (R) from AVISO

20 ~~drops for small R values. For this reason we have limited~~ We therefore limit the comparison to ~~big eddies ($R \geq 50\text{km}$)~~ eddies with a radius R of more than 50 km. The density of ~~big these "big"~~ "big" eddy centroids (number of eddies per 1 degree bin) from model and observations show a ~~very~~ similar spatial pattern, even though the modeled density of ~~large big~~ eddies is slightly biased low (Figure 3a,b). ~~In the sector of the CanUS located between the Canary and the Cape Verde archipelagos~~ line with our analyses of TKE and STD(SSH), the modeled density of big eddy centroids shows the closest match to the observations

25 ~~, in line with our previous findings. We also find a good agreement between the distribution of the modeled and observed large-eddy eddy diameters (see Appendix: Figure B3b). The main differences in the pattern of eddies in the central region of the CanUS, while the main differences~~ are found at the northern and southern edges of the CanUS domain (both southern and northern boundaries in correspondence of the Azores Current and North Equatorial Counter Current), 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

30 very big eddies with $\langle D \rangle > 300\text{km}$ (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~~ At the northern and southern boundaries, this deficiency could again be a consequence of the eddies originating from outside our main region of interest, ~~and also from a region with relatively low resolution in our model. The eddy deficiency i.e., from regions of low grid resolution. The lack of eddies~~ southwest of Cape Verde archipelago may be due to a northern shift of the modeled flow of

35 the Cape Verde front, which ~~results in the currents hitting the~~ hits the islands with a lower intensity, thereby generating fewer

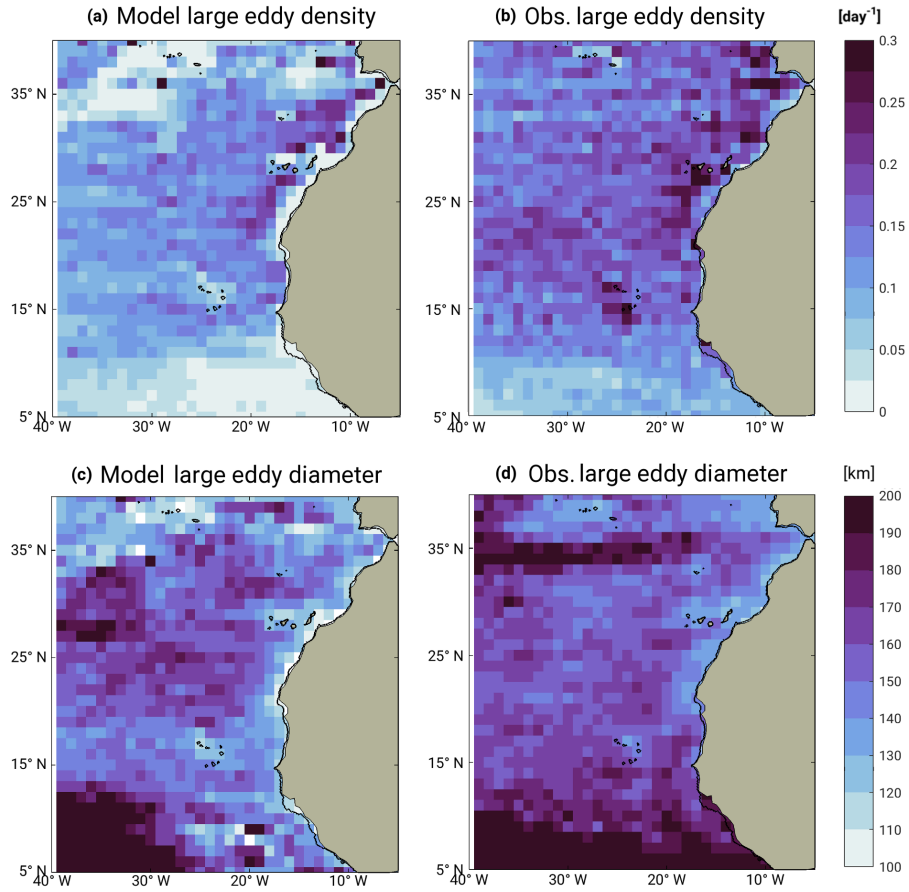


Figure 3. Comparison of the mean number of large eddy ($R \geq 50$ km) centroids from (a) modeled ROMS and (b) observed AVISO, binned to $1^\circ \times 1^\circ$ bins. Comparison of the mean diameter [km] of large eddies ($R \geq 50$ km) from (c) modeled ROMS and (d) observed AVISO, binned to $1^\circ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

instabilities, and hence eddies, than observed. On top of this, Also, in the proximity of both the Cape Verde archipelago and of the Canary Islands, 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. In the Canary Islands region, in fact, the high TKE in the absence of large eddies stems from our model simulating a very suggests a high abundance of small eddies in the proximity of the Canary archipelago. Statistics for all the modeled eddies with $R \geq 15$ 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 $1\text{deg} \times 1\text{deg}$ bins.

If we consider the whole modeled eddy population used for the analysis detected small eddies, as confirmed by our plot of the density of the entire eddy population ($R > 15$ km), we find a strong offshore gradient in the density of eddy centroids;

accompanied by an increasing mean eddy diameter in the offshore direction (used for the analysis (see Appendix: Figure B4). 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 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 agreement with previous analyses (Schütte et al., 2016a). ACE and CE have a mean diameter of respectively 95 km and 86 km and 100 ± 59 km and 90 ± 51 km with the distributions of the diameters peaking at around 45 km in both cases (see Appendix: Figure B3). The two types of eddies occupy on average, respectively, 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 where they are likely generated (see Appendix: Figure B5). With increasing distance, while the share of area occupied by CE remains pretty stable, ACE show while the share occupied by ACE shows a slow but persistent decline, which. The latter may be an indication of the reduced stability and shorter life span of this kind of eddies ACE, in line with the slight prevalence of CE over ACE detected in satellite-based studies for propagation distances of 2500 km (Chelton et al., 2011), with important consequences on their integrated role for 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 However, 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 B5).

4 Results

4.1 Turbulence in the organic carbon field

At any moment, the pattern of C_{org} concentration pattern 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 along 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 correspond closely with the pattern of SSH and currents (Figure 4a,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 4c,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-reduced C_{org} concentration that propagate toward the open ocean.

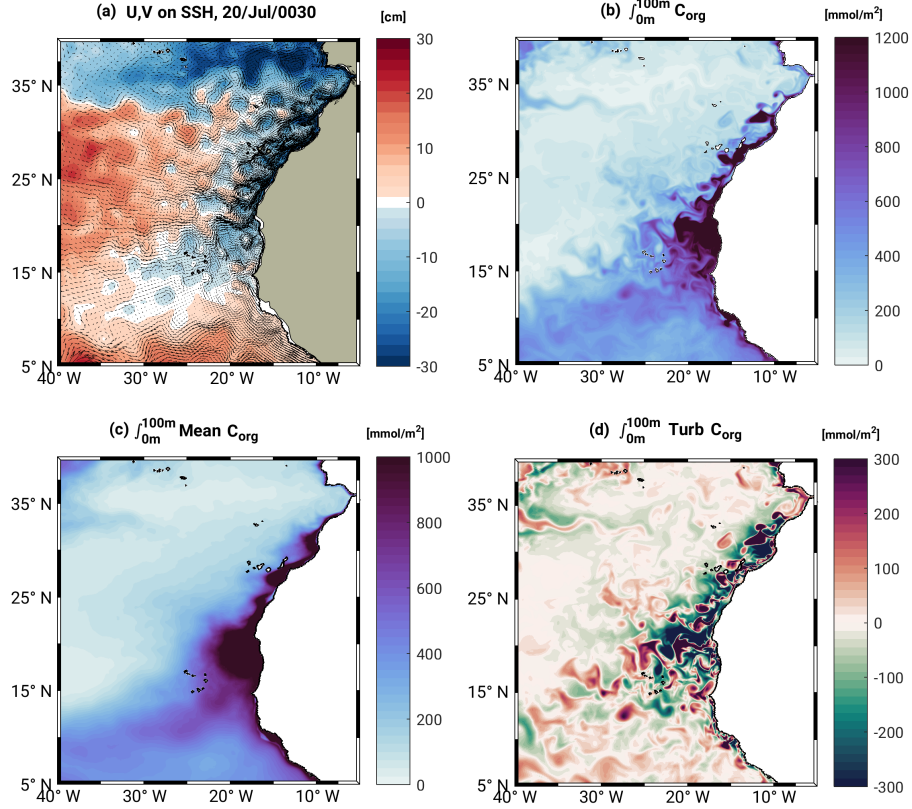


Figure 4. Modeled 2-day mean variables for July 19-20 of year 33 of the simulation. (a) SSH [cm] (color shading) and currents u (vectors); (b) Total organic carbon stock ($\int_0^{100m} C_{org}$) as well as its (c) mean ($\int_0^{100m} \bar{C}_{org}$) and turbulent part ($\int_0^{100m} C'_{org}$), respectively. The C_{org} is integrated throughout the entire water column first 100 m of depth.

In the following, we ~~will be employing~~ employ 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~~ use a Reynolds decomposition to separate these two components, while in the second "structure-based" approach, we ~~will be using~~ use filament and eddy masks to quantify the specific contribution of these two kinds of mesoscale structures to the C_{org} transport.

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~~ fluxes from the Reynolds decomposition (Figure 5a-c) clearly reflect the regional circulation and the wind stress curl pattern that characterizes the CanUS (Arístegui et al., 2009; Pelegrí and Peña-Izquierdo, 2015; Lovecchio et al., 2017).

While these mean fluxes dominate the total fluxes (see also: Lovecchio et al. (2017), their Figure 11, ~~Total organic carbon~~

fluxes), the turbulent ~~flux contributes~~ fluxes contribute substantially to the total fluxes and to their ~~divergences in both lateral and vertical direction~~ divergence (Figure 5d-f). In the zonal direction, the turbulent transport strengthens the offshore transport

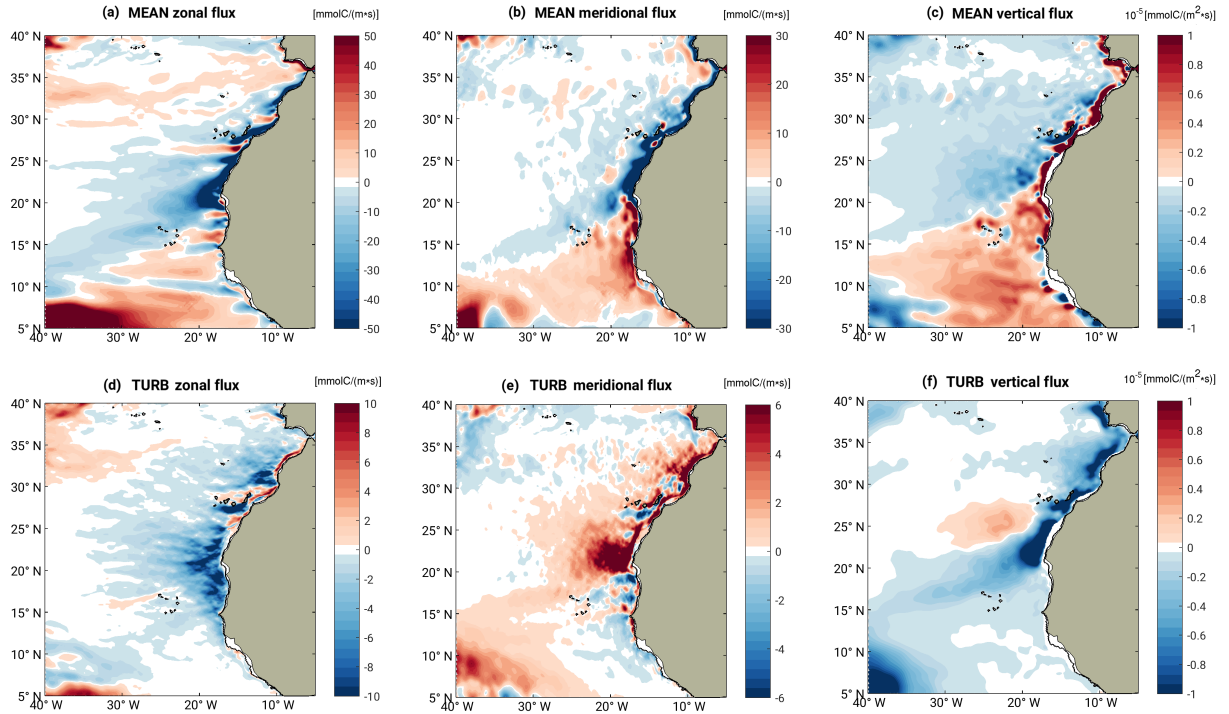


Figure 5. Reynolds decomposition of the lateral and vertical advective fluxes of C_{org} into their average mean $\langle \bar{u} \bar{C}_{org} \rangle$ and average turbulent $\langle u' C'_{org} \rangle$ components, as defined in the methods section. Lateral fluxes are integrated in the first 100m depth, the vertical flux is sliced at 100m depth.

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

10 The contribution of the turbulent offshore flux is particularly important in the northern and southern CanUS. In the northern subregion (Figure 6c), the mean flux declines much faster in offshore direction than the turbulent flux ~~in the offshore direction,~~ allowing the latter to represent, such that the latter is responsible for more than half of the total transport ~~at distances exceeding~~ in the region beyond 200 km ~~from the coast.~~ However, in terms of divergence, the turbulent contribution becomes important only ~~at offshore distances of more than~~ beyond 500 km and then really dominant beyond 1500 km. In the southern subregion,

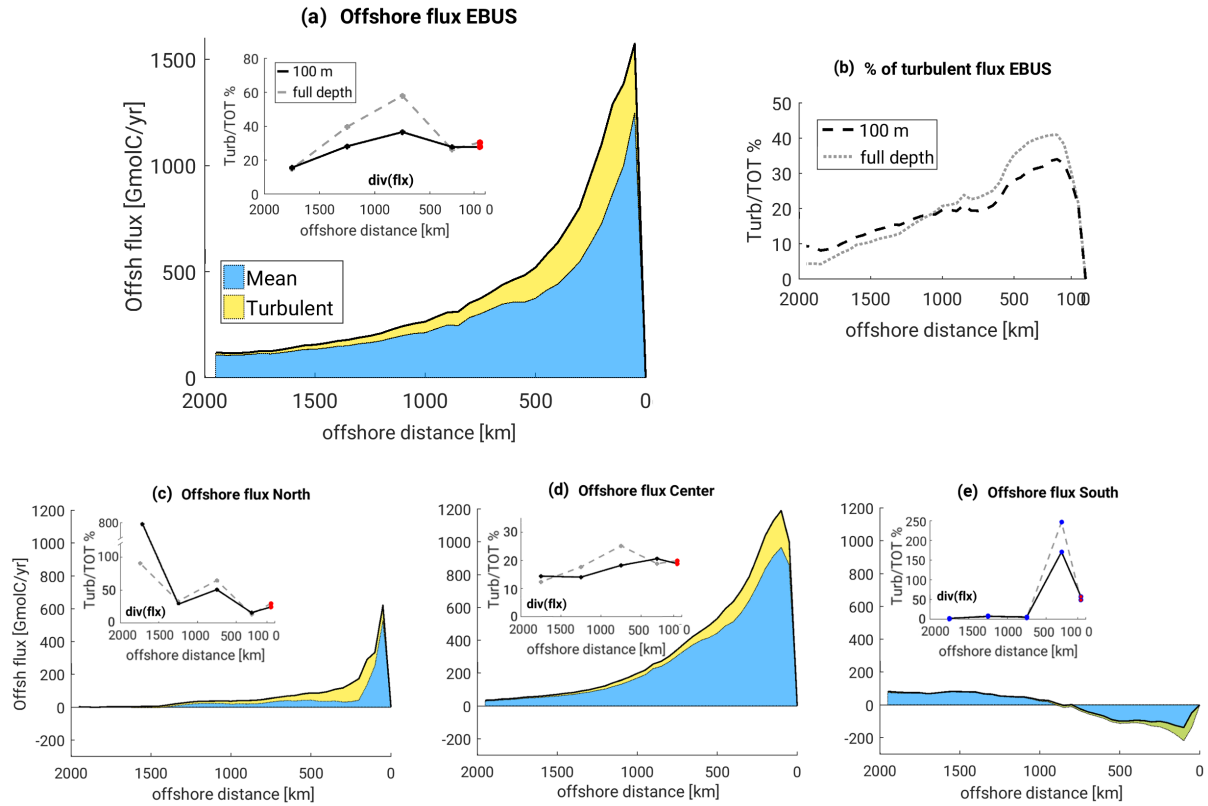


Figure 6. Magnitude of the mean and turbulent components of the offshore flux [GmolC yr^{-1}]: (a) Canary EBUS as a whole; (c) northern CanUS; (d) central CanUS; (e) southern CanUS. In all area plots: the black thick line is the total offshore flux, sum of mean and turbulent fluxes; fluxes are integrated 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 green area shading results from the overlapping of opposing mean and turbulent flux contributions.

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 6e). 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 6d) is characterized by a very intense mean offshore flux, likely connected to the far-reaching currents that create the Cape Verde 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.~~ The contribution 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 to the divergence is of similar magnitude.

- 5 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 (Figure 5b,e). This is especially the case~~ along the coast ~~in correspondence to the intense Canary and Mauritanian currents, with a magnitude corresponding to,~~ where the turbulent component reaches a magnitude of about 20% of the mean flux (Figure 5b,e). But, perhaps, the. The strongest turbulent meridional transports are associated with the Canary and Mauritanian currents.
- 10 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 5c,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.

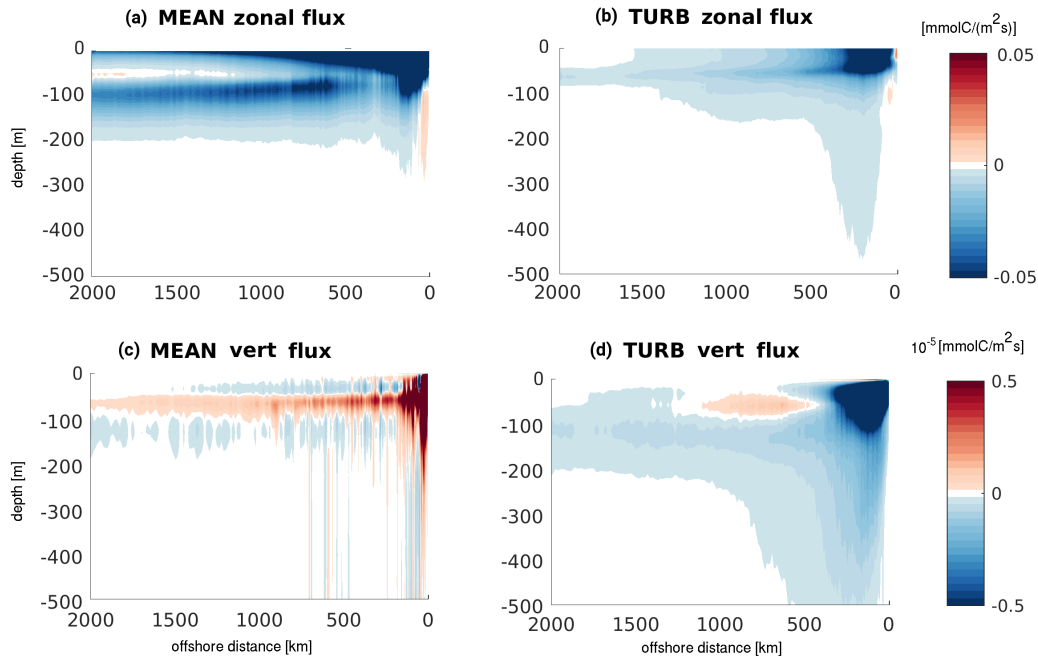


Figure 7. Reynolds mean and turbulent components of the advective fluxes of C_{org} averaged along lines of equal distance from the coast in the whole CanUS. (a) Mean zonal advective flux; (b) Turbulent zonal advective flux; (c) Mean vertical advective flux; (d) Turbulent vertical advective flux.

The vertical sections of the zonal transport of C_{org} (Figure 7a,b) reveal that, on average, this component is persistently directed-

Analyzing the offshore transport as a function of depth reveals that once averaged along the coast, the C_{org} is transported offshore at every depth, and is most intense in the first 500 km from the coast with the majority of this transport occurring in the top 100 m and almost none below 200 m (Figure 7a). The turbulent component of this zonal offshore transport is characterized by a thin and shallow maximum confined to the top 100 m, with only a weak little transport occurring below. The deepest extent is found in the first 500 km, reaching down as far 400 m. (Figure 7a). In contrast, the mean zonal flux tends to extend deeper, especially in the offshore region. Both the mean and the turbulent fluxes further offshore. Both flux components show an offshore deepening of the transport, likely as a consequence of the aforementioned vertical subduction and, but also because of the deepening of the production in response to the deepening of the nutrient line (see also: production (c.f., 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 very weakly seen in the turbulent transport.

Even though the vertical profiles of the mean and turbulent zonal fluxes differ, the strong near surface confinement of the offshore transport leads to a very low sensitivity of the results to the choice of integration depth, i.e., the regional pattern of the two components integrated in does not change substantially when the fluxes are integrated over the first 100 m depth (Figure 5a,d) or from 100 m up to the bottom of the water column (see Appendix: Figure B6) is very similar. An exception is the nearshore, where the onshore advection at depth in the mean transport, likely connected to 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 mean transport is directed onshore between about 100 m and across the whole water column (see Figure 6, 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 and 200 m, reflecting the presence of the upwelling cell.

Switching Compared to the vertical distribution of the zonal fluxes, the vertical fluxes show more pronounced differences between the mean and turbulent flux components are even more pronounced components (Figure 7c,d). Near the coast, the mean vertical advective transport is dominated, as expected, by the signature of the coastal upwelling. The different signature Offshore, the different sign 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. (negative and positive, respectively) characterizing the latitudes located north and south of the Cape Verde front, results in an opposite sign of the time-mean vertical flux of organic carbon in the two zonal bands (see Figure 5c). These fluxes, averaged along the entire CanUS, give rise to an alternate pattern of upward and downward mean vertical transport. 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, and particularly intense in the nearshore. However, in 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 more than 500 m in a range of more than within the first 500 km from the coast.

4.3 From turbulent ~~bursts of organic carbon anomalies~~ to the mesoscale ~~anomalies~~ contribution to the organic carbon stock

The important contribution of the offshore transport by turbulent anomalies can be ~~classically~~ visualized through the use of Hovmoeller diagrams, ~~which that~~ show how positive and negative anomalies of SSH, ~~i.e. SSH'~~ , and C'_{org} , ~~i.e. C'_{org}~~ , are moving offshore (See ~~appendix Appendix~~, figure B7). ~~This representation shows positive and negative signals of both C'_{org} integrated in the first 100 m and SSH' that~~ These signals propagate coherently from the coastline through the whole 2000 km offshore range in about 1.5 years, ~~with a resulting~~. Their mean propagation speed of ~~about 4 a few~~ $cm\ s^{-1}$. ~~This speed corresponds closely to the typical speeds of the~~ corresponds to that of first baroclinic mode of Rossby waves at these latitudes (Klocker and Abernathey, 2014), suggesting an important role of coherent mesoscale eddies in ~~this the turbulent~~ offshore transport. Analogous Hovmoeller diagrams can be plotted using the eddy and filament associated C'_{org} , isolated with the use of the

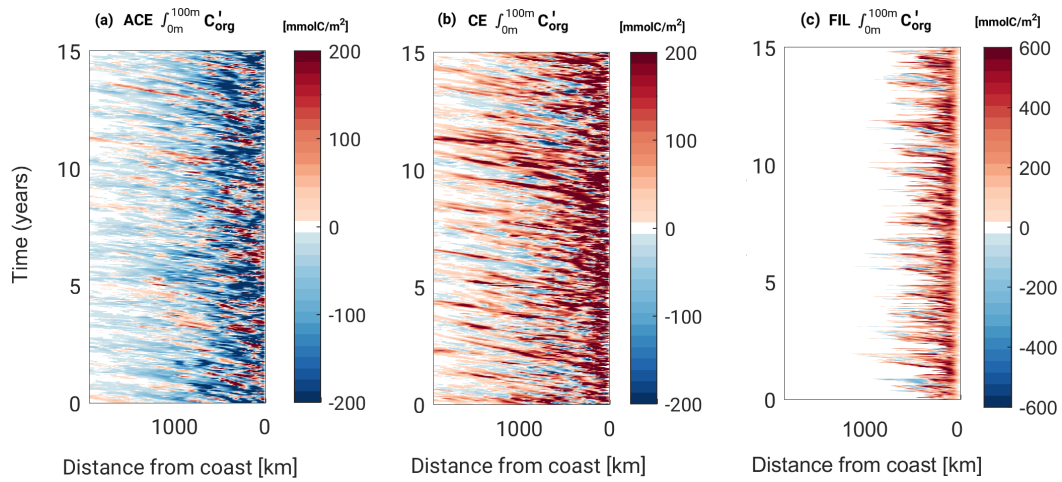


Figure 8. Hovmoeller diagrams of the top 100 m stock anomalies of C'_{org} in the central CanUS subregion for (a) anticyclones (ACE), (b) cyclones (CE), (c) filaments (FIL). First 15 years of analysis data.

structure-identification masks (Figure 8). These diagrams show that the propagation speed of the eddy anomalies is close to that of the above-mentioned turbulent anomalies, and highlight the opposing signature in the C'_{org} associated with ACE and CE. Filament anomalies, instead, show a different character: Both their magnitude and their advection speed generally exceeds by several times that of the eddy anomalies. Typical zonal velocities in the top 100 m of a filament are about $0.15\ m\ s^{-1}$, while the corresponding velocities for eddies are generally less than $0.05\ m\ s^{-1}$, with no significant difference between ACE and CE. But even though the filament transport is fast, it stays largely confined to the nearshore 500 km.

The mean correlation and ~~covariance of cross-products between SSH' with and 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~~. These anomalies (Figure 9 a,b). ~~The two anomalies~~ are anti-correlated in most of our analysis domain ~~(Figure 9 a,b)~~, i.e., on average the concentration of C'_{org} is enhanced when $SSH' < 0$ (corresponding to CE typically

associated to intense CE and filaments) and dampened when $SSH' > 0$ (associated to 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

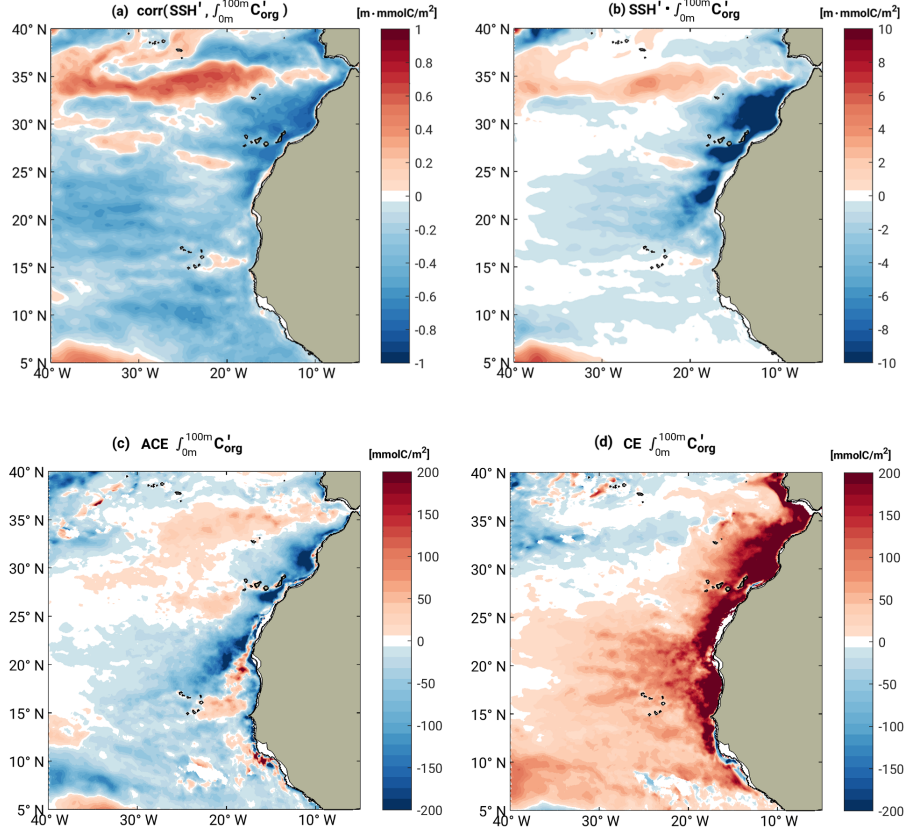


Figure 9. (a) Correlation and (b) covariance of the turbulent SSH anomalies (SSH') with the top 100 m organic carbon stock anomalies, i.e. $\int_0^{100m} C'_{org}$. Mean $\int_0^{100m} C'_{org}$ stock contained in (c) ACE and (b) CE, respectively.

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). (a) Correlation and (b) covariance of the turbulent SSH anomalies (SSH') with the top 100 m organic carbon stock anomalies, i.e. $\int_0^{100m} C'_{org}$. Mean $\int_0^{100m} C'_{org}$ stock contained in (c) ACE and (b) CE, respectively.

To better understand the nature of these correlations, we separately plot the anomalous C'_{org} content for the ACE and CE, respectively. The overall negative correlation between SSH' and C'_{org} stems indeed from ACE having, on average, a lower C_{org} content, and CE a higher one (Figure 9 c,d). Indeed, in most of the CanUS region, ACE and CE are responsible for a local decrease and increase of the organic carbon concentration, respectively. This signature is typical of that expected from an eddy-induced. Many potential mechanisms can contribute to this commonly made observation. These include a local vertical displacement of the nutricline (McGillieuddy, 2016). An additional contribution might stem from the trapping at the eddy at the

early stages of eddy intensification (McGillicuddy, 2016) and the trapping of the tracer anomalies at 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).

Local deviations from the widespread negative correlation of SSH' and C'_{org} can also be explained in terms of eddy anomalies. In the nearshore southern CanUS, the positive C'_{org} for ACE seen in ACE might stem by the shedding of eddies from the nearshore southern CanUS is likely a consequence of the northward flowing Mauritanian Current, which favors the trapping of carbon-rich C_{org} -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 At the northern CanUS boundary, the signature of the eddy C'_{org} within eddies at the northern CanUS boundary may be is connected to the typical characteristics of the presence of incoming large eddies formed in the Azores current (Gaube et al., 2014, Figure 1), leading to ACE with positive anomalies C'_{org} and CE with negative anomalies. In C'_{org} , Also in the offshore waters, ACE can also result in of the northern CanUS, ACE have a 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). This is possibly due to the sharp offshore gradient in C_{org} at these latitudes, where coastally generated ACE can carry the elevated C_{org} to the offshore waters even though they are generally not very efficient in doing so.

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 8), especially with regard to the differences between eddies and filaments. First, they reveal that the positive C'_{org} associated with 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 B7), while the filament anomalies are instead advected offshore with speeds that often exceeds by several times those of the eddies. An analysis of the velocities in the first Integrated across the top 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 the C_{org} stock that is contained inside mesoscale structures differs drastically between filaments and eddies (Figure 10). 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. On average, filaments contain are the mesoscale structure that contains most of the C_{org} in the first 200 km from the coast, but their offshore, representing between 20 % and 40 % of the total C_{org} share. Their contribution declines nearly

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.

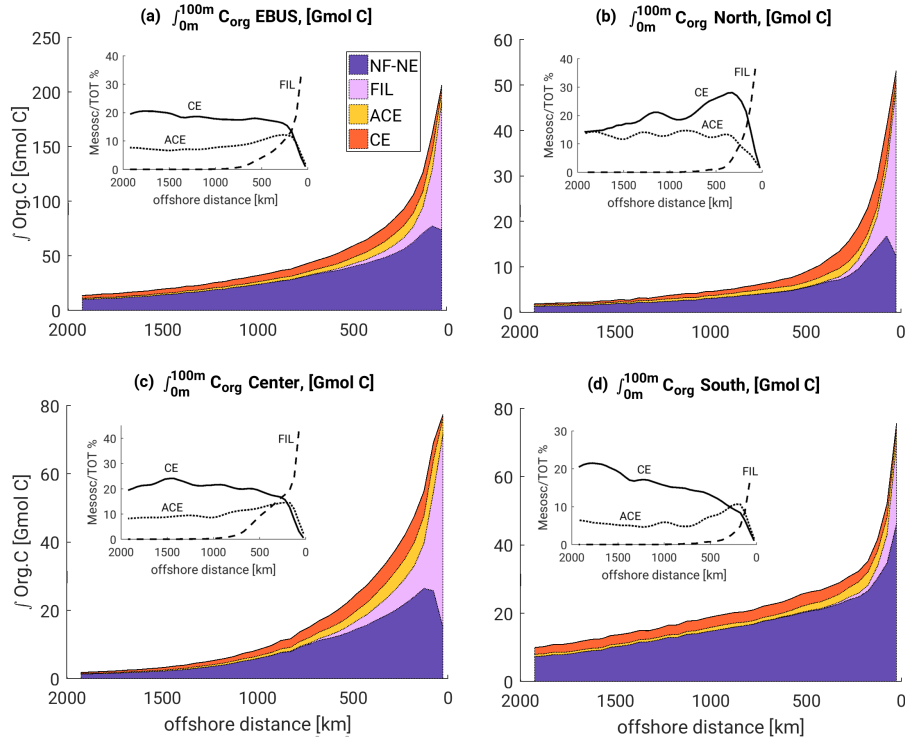


Figure 10. Top 100 m organic carbon stock ($\int_0^{100m} C_{org}$) contained in filaments (FIL), cyclonic eddies (CE), anticyclonic eddies (ACE) and outside of the detected mesoscale structures (NF-NE) by offshore distance. The $\int_0^{100m} C_{org}$ is integrated across the horizontal extension of: (a) the entire Canary EBUS; (b) the northern CanUS; (c) the central CanUS; (d) the southern CanUS. Inserts: Percentage of the total organic carbon stock found within ACE, CE and FIL, by offshore distance; the FIL share of C_{org} in the first 50 km offshore is not shown.

exponentially with distance, reaching nearly zero at about 700 km offshore. This trend-offshore decrease is closely connected to the large aspect ratio of filaments ,which that 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 B7), they represent overall a small share of C_{org} in the offshore CanUS. On the contrary, 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 B5). On average At offshore distances larger than 200 km offshore, ACE and CE together contain, on average, about 30% of the total C_{org} in the top 100 m. The share of C_{org} found inside CE stays, most of which is found in CE. The relative share of CE is around 20 % at every distance beyond 200 km from the coast, with a weak-increasing-trend-weakly increasing share with increasing offshore distance. This constitutes more than the portion of area occupied on average by CE (see Appendix: Figure B5), therefore indicating that CE constitute an important carbon reservoir for the open waters. The opposite trend is observed in ACE ,which that have the highest C_{org} share at about 200 km offshore, while at 1500 km distance they represent slightly less

than, they represent only around 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 B8). In line with the previous discussion, filaments are 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 Moreover, the two types of eddies 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 nutrient stocks at every distance larger than 200 km offshore, accounting for less than 5% of the available nutrients in the open waters. 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 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 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 strong differences in their nutrient concentrations and in their production rates (see also Appendix: and Figure B8). This likely exacerbating the differences in C_{org} between CE and ACE, 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 especially for the long living ones.

4.4 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 contribution to the total 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 11,12) can then be compared to the "turbulence-based" estimate inferred from the Reynolds decomposition (Figures 5,6) both in terms of their respective patterns and in terms of their magnitude and divergence (see also Figure 13 for a summary). Figure 11a 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. 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. As was the case for the mean flux from the Reynolds decomposition, this component primarily reflects the regional pattern of the mean currents. pattern of NF-NE component is primarily shaped by the mean surface currents. An exception is the nearshore area where the

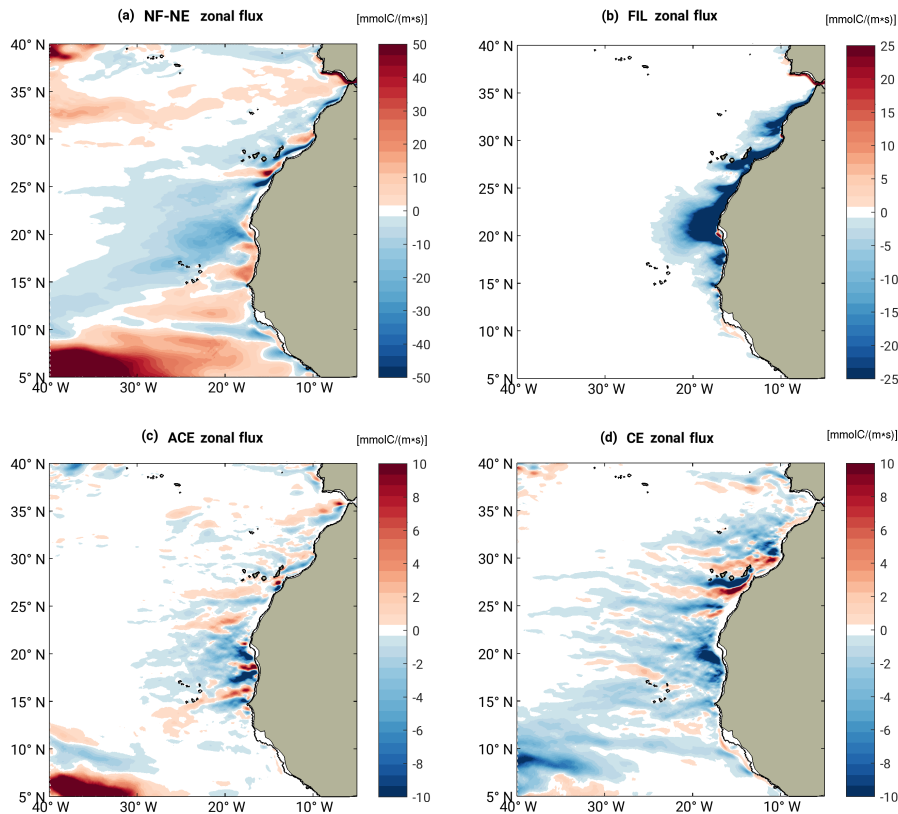


Figure 11. Decomposition of the zonal advective transport of C_{org} into: (a) non-filament-non-eddy NF-NE, (b) filament FIL, (c) anticyclonic ACE and (d) cyclonic CE flux. Fluxes are integrated within the top 100m.

intensity intensification of the NF-NE transport is more modest, and also directed onshore (Figure 12) flux in the range between 100 km and 500 km, resulting in a negative offshore flux divergence (Figure 13). 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 primarily the result of the transfer of C_{org} from the filament transport to the transport driven by NF-NE flow in the first. Only in the nearshore upwelling band (~ 50 km offshore) this negative divergence could also be a consequence of our likely underestimation of the NF-NE contribution (see methods).

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 first few hundred kilometers, both in terms of absolute magnitude and in terms of its divergence (Figure 12 and Figure 13). The magnitude of the filament transport represents b,d). In particular, at an offshore distance of 100 km, where the C_{org} offshore flux reaches its maximum magnitude, the filament flux accounts for 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, its contribution declines rapidly and reaches zero at about 1000 km offshore (Figure 12a,b). Between 100 km and 500 km from the shore, the horizontal (negative) divergence of the filament transport opposes that of the NF-NE transport, therefore exceeding the total net amount of exceeds the total (negative) divergence of the offshore C_{org} added by the offshore flux and $_{org}$ flux, 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 value. The difference is caused by the positive divergence of the nearshore reflects both NF-NE transport. Even though the filament flux decreases rapidly with offshore distance, its divergence still account for ~50% of the total divergence between 500 km and 1000 km offshore. Therefore, the filament transport constitutes overall the most important source of coastally-produced C_{org} in the first 1000 km, a consequence of their high C_{org} concentrations and as well as of the high zonal advective speeds. Also, despite their limited reach, Moreover, as filaments often shed long-living eddies, which are fed by them that travel eastward with large amounts of tracers; this coupling enhances the offshore reach of the coastal C_{org} initially transported by the filaments.

and nutrients embodied from the filaments, they extend their influence deep into the open ocean.

Eddy Across the whole domain, the eddy-associated fluxes (Figure 11c,d) are about five times smaller than the NF-NE fluxes, in analogy to the Reynolds turbulent transport when compared to the mean transport. This is similar to the ratio found for the Reynolds decomposition based separation between the turbulent and mean transports (see also Figure 13). Even though the magnitude of the eddy transport is small, in large part as a result of their limited drift speeds This is largely a consequence of the limited lateral drift speeds of eddies. But still, 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 The eddy-associated offshore transport is primarily carried by CE, with ACE playing a minor role (Figure 12b). This is expected from their more modest ACEs having a lower C_{org} content and their offshore

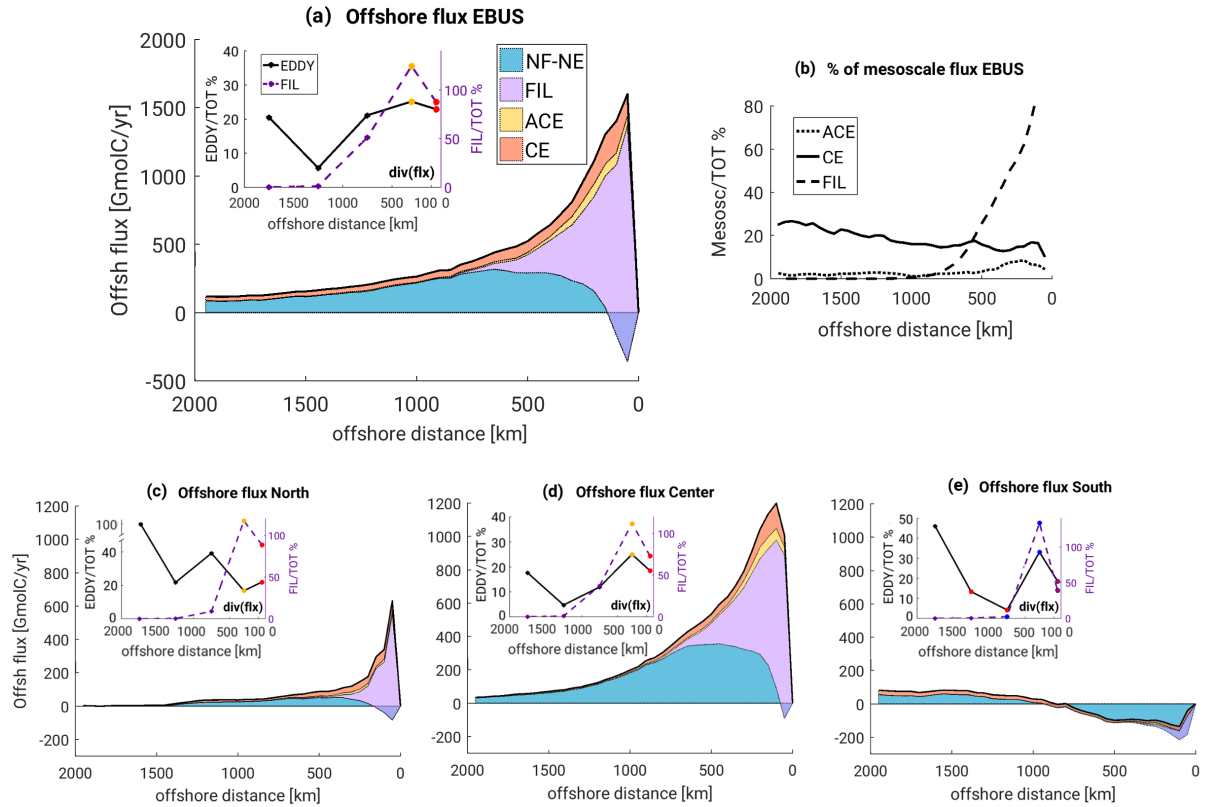


Figure 12. Magnitude of the non-filament-non-eddy (NF-NE), filament (FIL), anticyclonic (ACE), cyclonic (CE) components of the offshore flux [GmolC yr^{-1}]: (a) Canary EBUS as a whole; (c) northern CanUS; (d) central CanUS; (e) southern CanUS. In all area plots: the black thick line is the total offshore flux, sum of the 4 components; fluxes are integrated in the first 100 m depth. The purple area shading results from the overlapping of opposing NF-NE and filament flux contributions. 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.

~~surface decline a shorter life span, resulting also in an offshore decline of their surface area~~ (see Figure 10 and Figure B5), ~~in part connected to their shorter life span. The striations that characterize the~~

~~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~~
5 ~~drift offshore~~, reveals also distinct striations, e.g., near zonal bands of offshore transport next to bands of onshore transport.
~~Eddy~~ These eddy striations are slightly deflected northward in the case of CE and southward in the case of ACE, ~~as expected by~~

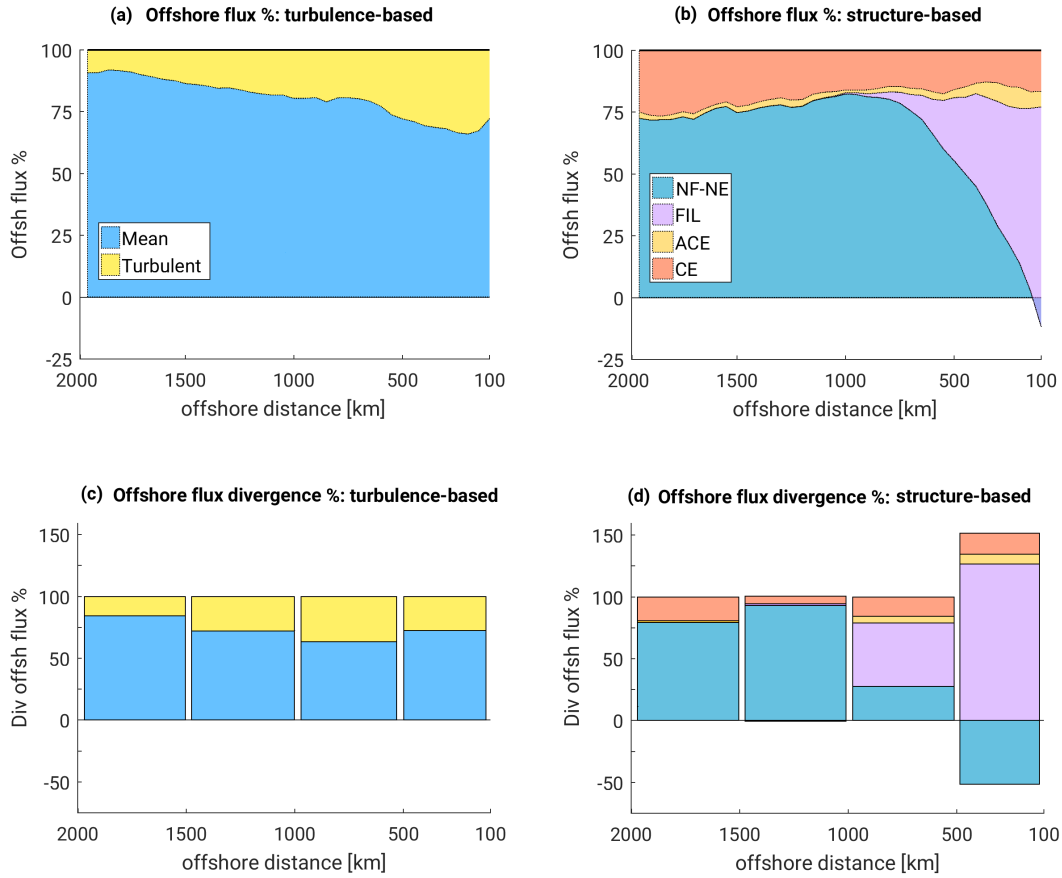


Figure 13. Comparison between the results of the turbulence-based and structure-based methods for the entire EBUS in the range of 100 km to 2000 km from the coast (~~offshore region~~ in which, where the divergence of the total offshore flux is ~~always~~-positive, therefore resulting in an increase of the organic carbon availability (see also Lovecchio et al. (2017), Figure 10 for a quantification of the divergence of the total offshore flux). 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.

consistent with the observed mean deflection of their trajectories (~~Chelton et al., 2011~~). In an integrated perspective, at offshore distances larger than 200 km, (~~Chelton et al., 2011; McWilliams and Flierl, 1979~~).

Integrated across the entire CanUS, ACE and CE together are responsible for about 20 % of the total offshore transport at every distance beyond the first 200 km from the coast, with the CE transport accounting for several times as much as the ACE transport (Figure 12b). 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~~ stock is found in the northern subregion, where the NE-NF flux declines quickly offshore ~~similarly to~~, similar to what is seen in the mean Reynolds flux; ~~only~~. Only in

the southern CanUS eddies contribute ~~with a negative flux divergence, to the~~ with a positive flux divergence to the removal of 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 B10 and Figure B11). In particular, ACE are responsible for the northward recirculation of the C_{org} through the asymmetric stirring of the background ~~gradient: due regional gradient~~. This is a consequence of the unique combination of an offshore negative gradient (strongest in the nearshore) and a southward positive gradient in C_{org} (Arístegui et al., 2009). Due to their relatively fast decay ~~that results in a and the~~ slowing down of the clockwise rotation while they move offshore, ~~these eddies the ACE~~ induce a net northward transport of C_{org} . This is because a younger and more energetic ACE stirs the C_{org} northward in the nearshore areas, while an older and weaker ACE stirs it southward in the offshore areas. 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 transport of 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~~ transport. Inspections of the model output reveal (not shown) that mesoscale vertical velocities in well-developed eddies present a dipolar or quadrupolar pattern of upwelling and downwelling similar to the one observed by in-situ measurements (Barceló-Llull et al., 2017). This compensating nature of the vertical velocities results in a minor net contribution of these mesoscale structures to the vertical flux. Filaments, on the contrary, are responsible for a strong nearshore downwelling, which ~~was previously is well~~ captured by the turbulent component of the Reynolds fluxes (see Figure 5). The ~~turbulent character of the vertical filament transport can be attributed to irregular but intense bursts of downwelling within the structures. These structures filaments~~ advect below the euphotic layer a significant amount of C_{org} in the range between 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; ?).~~ High vertical subduction speeds combined ~~with the elevated carbon concentrations can therefore result in very intense vertical advective export of C_{org} .~~

5 Discussion

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~~ 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~~ derived from the use of filament and eddy masks.

The In the nearshore areas, the filament zonal transport ~~shows clear similarities with the nearshore is very similar to the~~ mean zonal flux from the Reynolds decomposition, ~~reflecting both its~~ both with respect to 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 much~~ of the zonal filament transport has a mean-time-mean character. This is not surprising, given that filaments tend to be recurrent

and localized 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

5 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 B12).

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~~ away from the coast. Even though these structures have a typical thickness of about 100 meters or less (~~Cravo et al., 2010~~) (Cravo et al., 2010; Rossi et al., 2013), filament subduction well be-

10 low their depths has been documented in observations (~~Kadko et al., 1991; Brink, 1992; Barth et al., 2002; Peliz et al., 2004~~) (Kadko et al., numerical studies (Nagai et al., 2015; Bettencourt et al., 2017). Differing from (Nagai et al., 2015; Bettencourt et al., 2017; C. et al., 2009)

In contrast to 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 in the filaments show transitory and irregular hotspots of strong downwelling ~~within the filaments, meaning that,~~ which evolve quickly and often drift laterally

15 following the filament flow. Therefore, 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 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~~ periphery of the filament due to the formation and degradation of frontal and high-strain regions at the filament edges.

20 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 variability explains why the lateral eddy transport mostly projects onto the turbulent transport. However, ~~differing from the Reynolds turbulent flux, the~~ the CE and ACE zonal transports are also characterized by striations, which are not seen in the

25 turbulent fluxes from the Reynolds decomposition. These striations suggest the existence of recurrent regions of formation and preferential pathways for these 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. 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 "structure-based"~~

30 ~~and Further differences between the "turbulence-based" results. Such differences may~~ mesoscale and turbulent offshore flux components can 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-for~~ the lateral export of C_{org} from the north-western African coast, ~~and~~. ~~In particular, they~~ point to the importance of filaments and eddies as a source of organic carbon and nutrients for the offshore oligotrophic waters.

5 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 in 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-images-satellites~~ (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
10 filament lateral transport of biogeochemical tracers deepens below the surface ~~at a depth to depths~~ of a few tens of meters as the filament is moving away from the continental shelf (~~Cravo et al., 2010~~) (Cravo et al., 2010; Rossi et al., 2013). This implies that the ~~whole-offshore-range-of-total offshore~~ reach of a filament may not be ~~easily-visible-from-surface-chlorophyll-images; with-a-likely-visible-from-remotely-sensed-surface-chlorophyll-or-SST, resulting in a~~ underestimation of its range.

~~In-terms-of-volume, our~~ Our modeled mean filament offshore transport in the whole CanUS region amounts to about 2
15 Sv between 100 km and 200 km from the coast ~~in-the-first-and-integrated-over-the-top~~ 100 m depth (~~corresponding~~. This corresponds to $0.7 \text{ m}^2 \text{ s}^{-1}$ ~~); in transport per unit of length, which largely exceeds the estimated offshore Ekman transport per unit length in the CanUS, roughly 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). The filament transport increases to 3 Sv in-the-first-300-mdepth-which-include-most-of-the-filament-transport Sv if the top 300 m are considered. A large fraction of this transport originates in the northern and central CanUS subregions. ~~The-intensity-of our-filament-transport~~ Our intensity is lower than previous estimates of 6 to 9 Sv for the same subregions (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~~ One possible reason for our model's underestimation is the fact that it represents a climatological yearly average including the seasons of reduced filament activity, ~~while~~. In contrast, observations are often done in periods of
20 intense filament transport, possibly biasing high the estimates upscaled from relatively few observations. Even though typical zonal velocities observed inside modelled filaments (100 m 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~~ Consistent with 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~~
30 ~~important~~ our model simulates also a substantial amount of 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 high occurrence along the coast in the season of intense activity is particularly striking. ~~The-strong-seasonality-that-characterizes-these-structures~~ This strong seasonality makes it difficult to appreciate their possibly large, but 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 currently only partially characterized in the available literature.

Modeled eddies are Our modeled eddies are in great part 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 agree with observations of global mesoscale eddy tracks (Chelton et al., 2011). In contrast to the coastally confined filament transport of C_{org} , the The modeled eddy offshore flux extends 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 of the whole CanUS 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 ± 0.3 Sv) and the North Equatorial Current (0.5 Sv to 3 Sv) (Machín et al., 2006; Pelegrí and Peña-Izquierdo, 2015; Mason et al., 2011). In line with the results of Combes et al. (2013), we find that CE are responsible for a 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 negative correlation between SSH' and $\Delta C_{org} C'_{org}$ (Figure 9), which roughly agrees agrees roughly 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 $\Delta C_{org} C'_{org}$ 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 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 (McGillieuddy, 2016). A dedicated study by Chenillat et al. (2015) suggests that trapping at formation and vertical pumping of nutrients fuel respectively regenerated and new 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 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 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 in the CanUS, i.e., the~~ Cape Blanc filament) ~~in the CanUS~~, filaments in the ~~CalUS~~ California Upwelling System (CalUS) were observed to extend ~~on average, 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~~ exceeds by far that of the CanUS (~~Marchesiello and Estrade, 2006~~) (Marchesiello and Estrade, 2006; Lachkar and Gruber, 2011), and the number of observed eddies from satellite data is substantially larger than ~~the value that characterize~~ that found in 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, 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 across the different systems.

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 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 identified and discussed by~~ 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 high good 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 are more uncertain. The weaker circulation in the southern CanUS is reflected also in the underestimation 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 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 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.

5 In terms of eddies, our evaluation shows that the modeled large-eddy field ($R \geq 50$ km) is ~~reduced by about 1/3 compared to~~ the only about two thirds of that seen in observations. However, differences in the performance of the eddy-finding algorithm, when applied to the ROMS and 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
10 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.

~~Given its formulation, our SSH-based eddy-finding algorithm does~~ In our analysis, we do not distinguish between regular ACE and anticyclonic mode-water eddies (ACMEs), ~~which are therefore~~. As a result, the latter are included in our ACE budget and transport. These eddies have been ~~especially~~ observed in the southern CanUS subregion and ~~are expected to~~ may represent
15 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~~ analyses 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
20 majority of the filaments being detected ~~on the base of SST and S-CHL images and~~ and only a very limited over-detection in the southern CanUS. The algorithm performs particularly well in the zonal band located north of Cape Blanc, given the sharp offshore SST gradient; ~~However~~, 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, the~~ detected filaments appear generally shorter than a visual inspection might suggest. Only during a few time steps we could see
25 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. We refer to the supplement to the manuscript for more details and an accurate evaluation of the algorithm performance on our setup.

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
30 this exported DOC ~~is biologically available for the offshore biological activity~~ has a lability that contributes to a divergence, i.e., is being remineralized while it is being transported offshore (Hansell et al., 2009). Our model does not include a DOC pool; ~~however~~. However, our small detritus pool behaves very similarly to a suspended POC pool given ~~the~~ its 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 et al. (2017), where we also presented the results of a sensitivity study, in which we tested the implications
35 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~~ demonstrated 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~~ little repercussion on the offshore ~~NCP~~ productivity.

6 Summary and Synthesis

5 6 Conclusions

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 sequesters 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 hundreds 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.

Overall, Our study in the CanUS confirms that mesoscale processes contribute to the offshore redistribution of the substantially to the long-range offshore transport of 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).

~~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}

5 and its divergence in the nearshore, while far-reaching eddies, especially ~~eyelons~~cyclones, extend this transport up to the middle of the gyre. ~~As a consequence, the~~ 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

10 dominates in the nearshore ~~500-1000~~ 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

15 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 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

20 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 at the passage or death of such a structure. 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.

25 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~~our model.

Appendix A: Datasets used for the model evaluation

Data source	Ref. time	Resolution	Variables	Reference
Aviso DUACS 2014	1993-2012	0.25°x 0.25°grid	daily sea surface height, daily geostrophic velocities	Maheu et al. (2014)
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 Rio05	1993-1999	0.5°x 0.5°grid	sea surface height	Rio and Hernandez (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 production (NPP)	Behrenfeld and Falkowski (1997)
SeaWiFS CbPM	1997-2010	9km grid	extrapolated net primary production (NPP)	Westberry et al. (2008)
SeaWiFS POC	1997-2010	9km grid	extrapolated surface particulate organic carbon (POC)	NASA-OB.DAAC (2010)
AMT	(2004-2014)	in-situ [0m,200m] depth	particulate organic carbon	BODC-NERC (2014)
Geotraces	(2010)	in-situ surface	particulate organic carbon	GEOTRACES (2010)
ANT	(2005)	in-situ [0m,200m] depth	particulate organic carbon	ANT (2005)

Table A1. Description of the datasets used for the model evaluation. CMDT: Combined Mean Dynamic Topography; AVHRR: Advanced Very 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

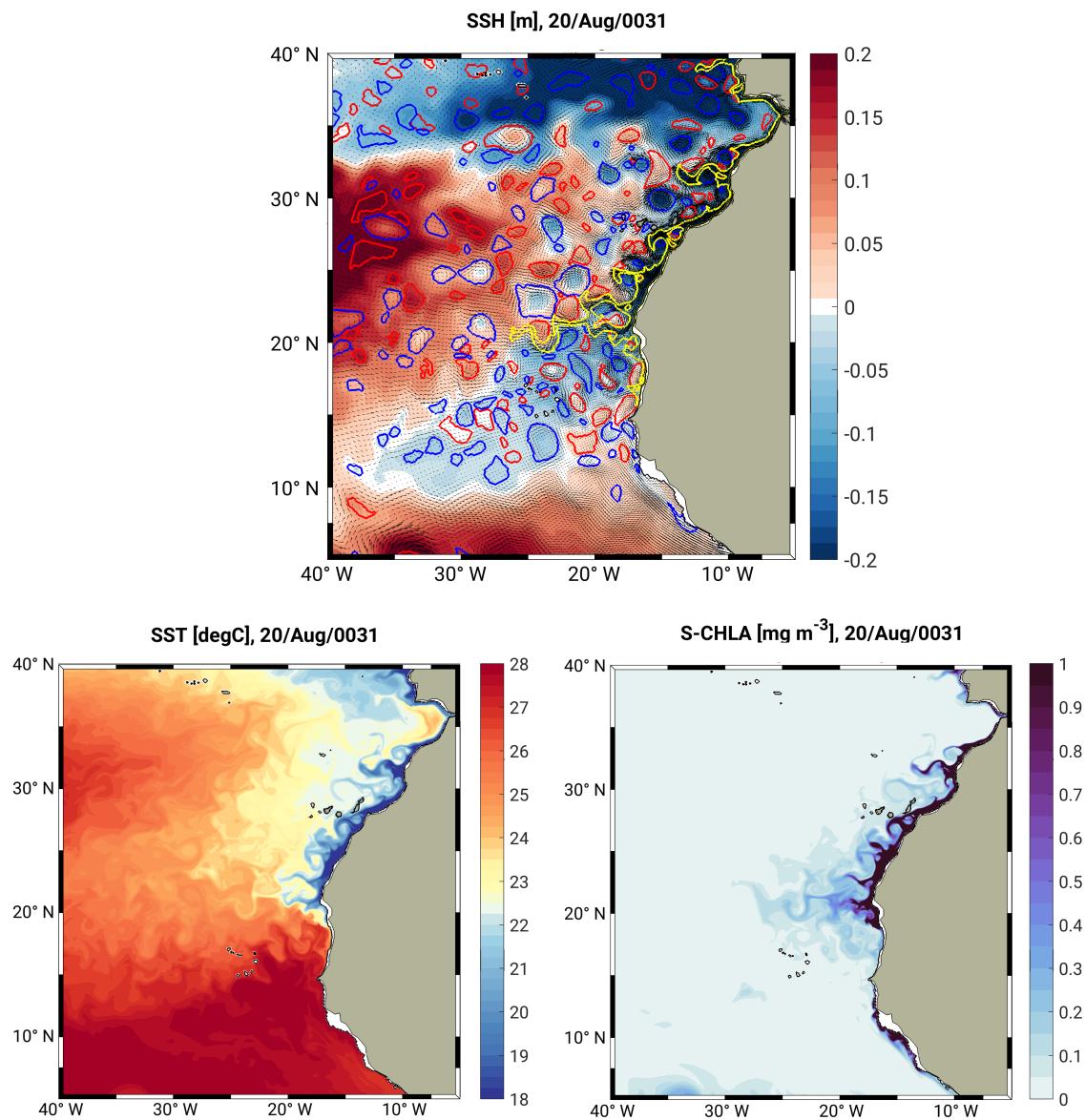


Figure B1. Example of the performance of the filament and eddy identification algorithms on 2-day mean fields. Subplot (a): red contours are warm-core anticyclonic eddies; blue contours are cold-core cyclonic eddies; yellow contour are coastal upwelling filaments. Subplot (b): sea surface temperature. 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.

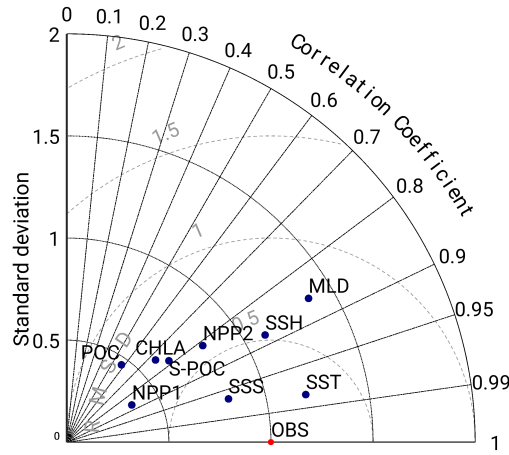


Figure B2. Taylor diagram for the Canary EBUS region of analysis as defined by the Budget boxes based on the 24 years climatological annual mean fields used in the present study. Used datasets - Sea Surface Temperature (SST): AVHRR, Sea Surface Salinity (SSS): CARS, Sea Surface Height (SSH): Aviso CMTD 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.

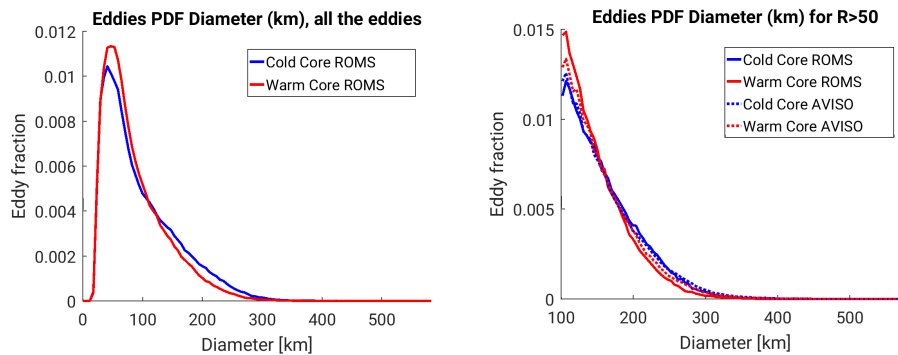


Figure B3. Distribution of the eddy diameters [km] in the CanUS region as defined by the budget analysis boxes: (a) Propability density function (PDF) of the diameter of all the eddies from ROMS; (b) comparison of the PDFs limited to large eddies ($R > 50$ km) for the eddies from ROMS and AVISO.

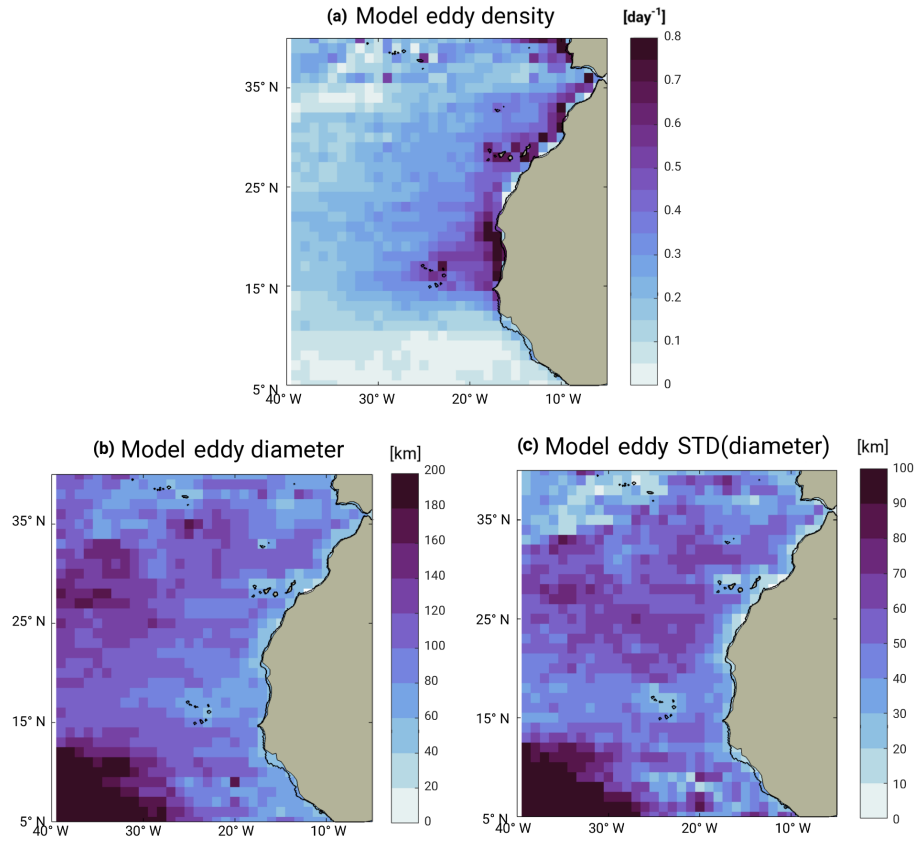


Figure B4. Statistics for all the modeled eddies with $R > 15$ km. (a) Modeled density of eddy centroids per day; (b) Modeled mean eddy diameter [km]; (c) Modeled Standard deviation of the eddy diameter [km]. All quantities have been averaged in $1\text{deg} \times 1\text{deg}$ bins.

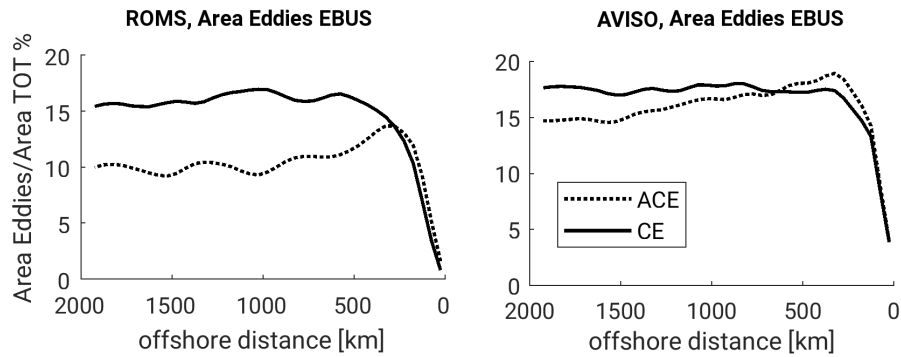


Figure B5. Portion of the CanUS (EBUS) occupied by the eddies, by eddy type. (a) Modeled ROMS eddy field; (b) AVISO eddy field.

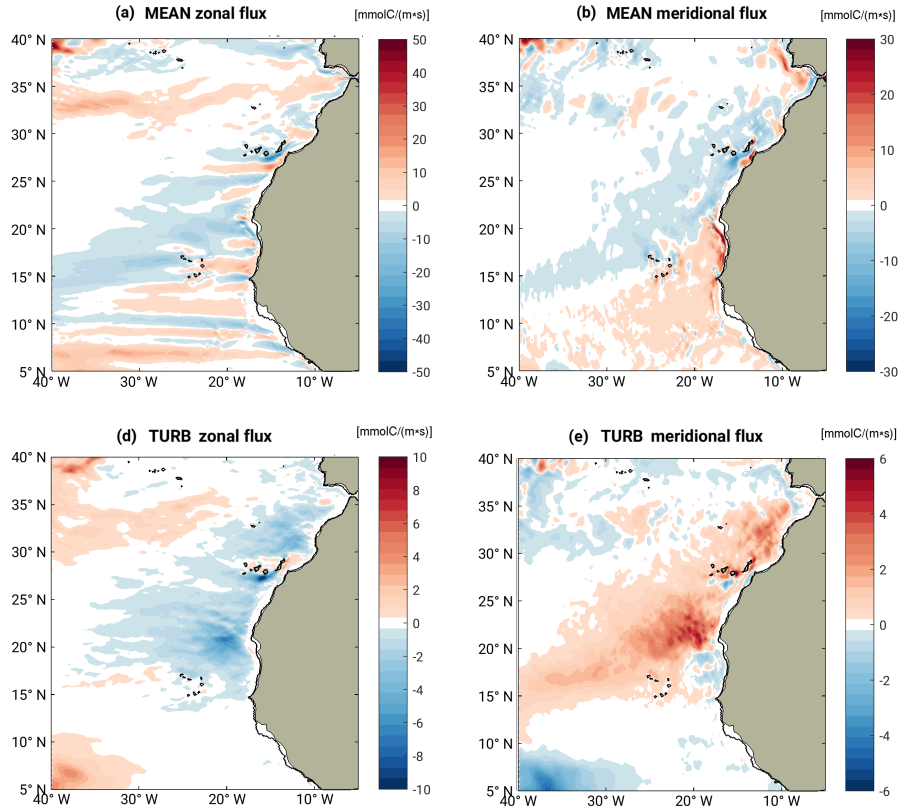


Figure B6. Reynolds decomposition of the lateral and vertical advective fluxes of C_{org} below 100 m into their average mean $\langle \overline{u} C_{org} \rangle$ and average turbulent $\langle u' C'_{org} \rangle$ components, as defined in the methods section. Fluxes integrated from 100 m depth to the bottom of the water column. Colorscale corresponding to those of Figure 5 for a better comparison.

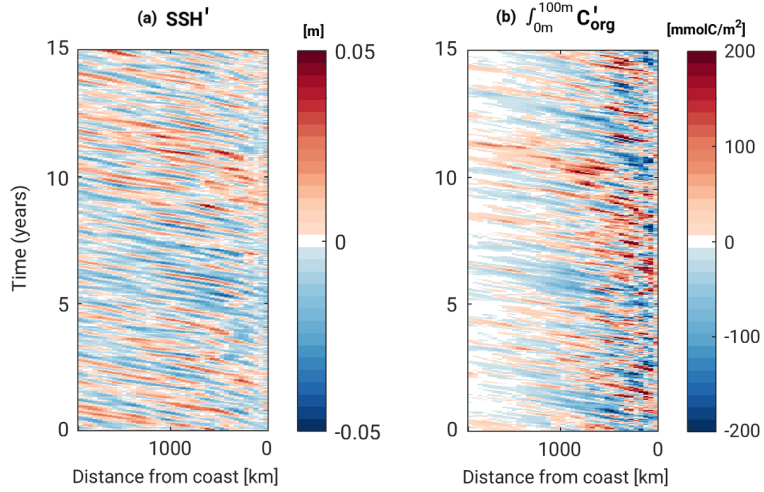


Figure B7. Hovmoeller diagram of the turbulent SSH anomalies (SSH') and top 100 m organic carbon stock C_{org} ($\int_0^{100m} C'_{org}$) for the central subregion of the CanUS. First 15 years of analysis data, bi-daily output. Their signature shows remarkable interannual variability despite the climatological forcing used for our simulation, highlighting the intrinsic nature of turbulence and variability in the region.

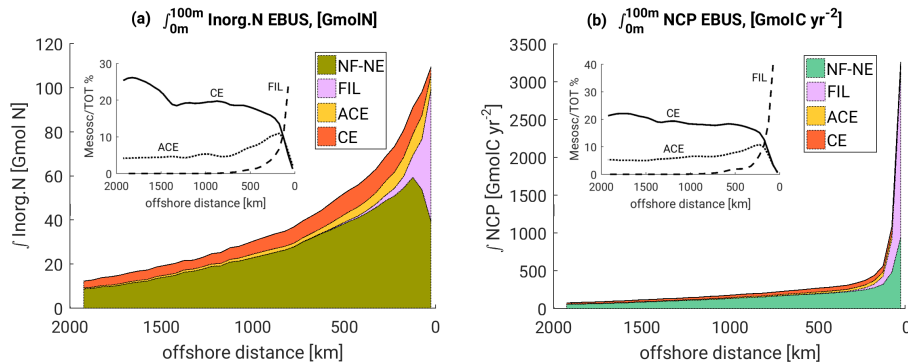


Figure B8. Percentage of time-occupied by Inorganic nitrogen ($Inorg.N$) and Net Community Production (NCP) contained at different distances from the coast in filaments per-grid-pixel (FIL), according to our filament identification algorithm, cyclonic eddies (CE), anticyclonic eddies (ACE) and outside of the mesoscale structures (non-filament-non-eddy, $NF-NE$). The boundary corresponding to Both quantities are integrated in the first 50 km from 100 m depth and across the north-western African coast has been highlighted with a dashed yellow line. Regardless horizontal extension of the fact that this range CanUS. Inserts: Percentage of distances is often covered by the filament mask total $Inorg.N$ and NCP found within ACE , alongshore currents are dominant 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 region range cannot be clearly identified.

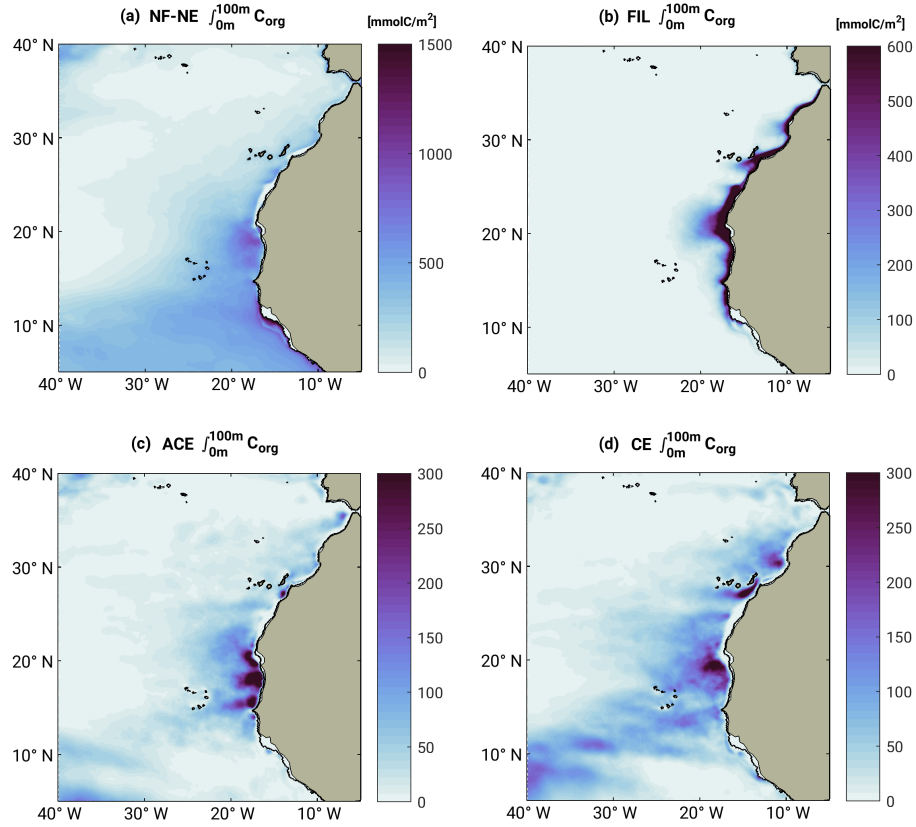


Figure B9. Spatial distribution of the 100m vertically integrated C_{org} [mmolC m⁻²] in: (a) non-filament-non-eddy (NF-NE) field, (b) filaments (FIL), (c) anticyclones (ACE), (d) cyclones (CE).

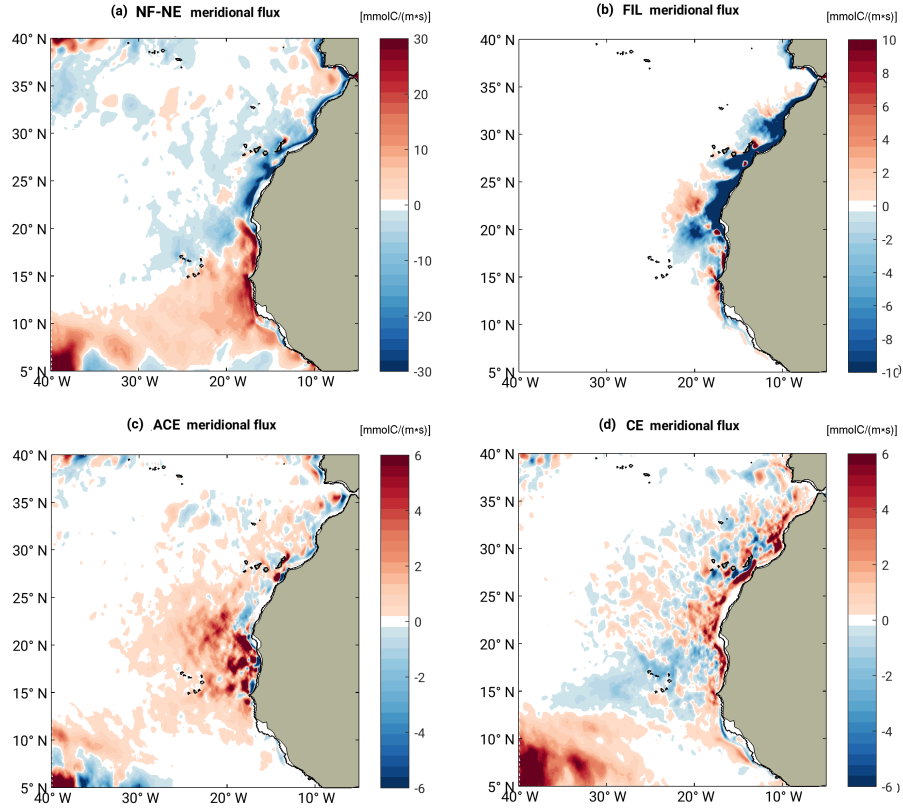


Figure B10. Decomposition of the meridional advective transport of C_{org} into: (a) non-filament-non-eddy (NF-NE) flux, (b) filament (FIL) flux, (c) anticyclonic (ACE) flux and (d) cyclonic (CE) flux. Fluxes $[\text{mmolC m}^{-1} \text{s}^{-1}]$ are integrated in the first 100m depth.

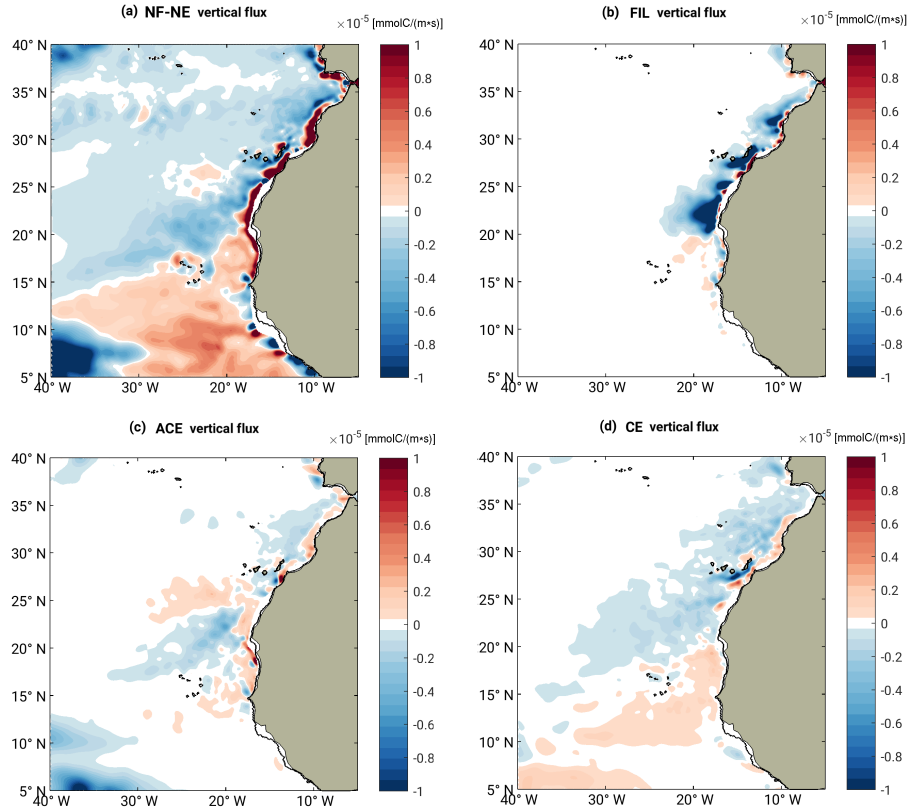


Figure B11. Decomposition of the vertical advective transport of C_{org} into: (a) non-filament-non-eddy (NF-NE) flux, (b) filament (FIL) flux, (c) anticyclonic (ACE) flux and (d) cyclonic (CE) flux. Fluxes $[\text{mmolC m}^{-2} \text{ s}^{-1}]$ are sliced at a depth of 100m.

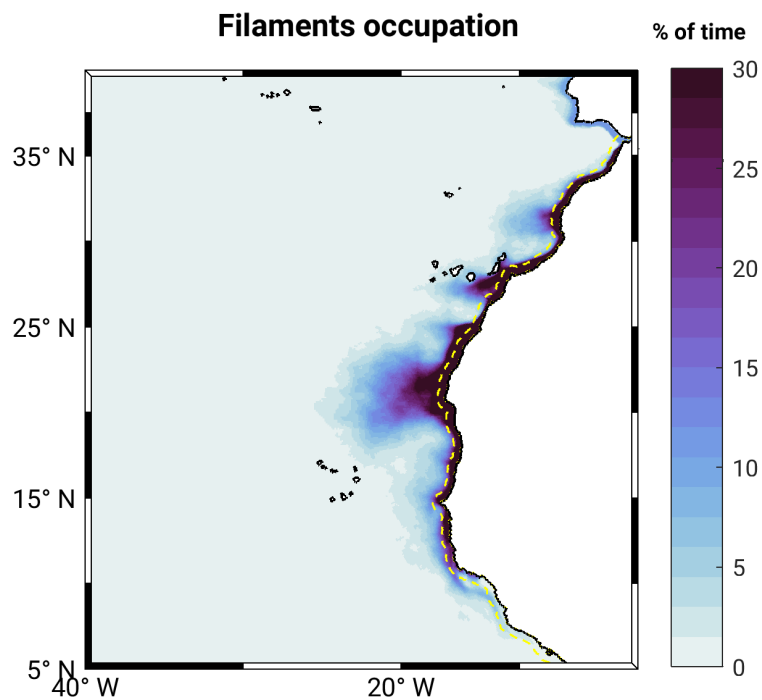


Figure B12. Percentage of the total time in which each grid node is occupied by a filament, according to our filament identification algorithm. The boundary corresponding to the first 50 km from the north-western African coast has been highlighted with a dashed yellow line. Regardless of the fact that this range of distances is often covered by the filament mask, alongshore currents are dominant in this region.

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."

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- 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.

References

- Álvarez-Salgado, X. A.: Contribution of upwelling filaments to offshore carbon export in the subtropical Northeast Atlantic Ocean, *Limnology and Oceanography*, 52, 1287–1292, doi:10.4319/lo.2007.52.3.1287, <http://dx.doi.org/10.4319/lo.2007.52.3.1287>, 2007.
- Amores, A., Melnichenko, O., and Maximenko, N.: Coherent mesoscale eddies in the North Atlantic subtropical gyre: 3-D structure and transport with application to the salinity maximum, *Journal of Geophysical Research: Oceans*, 122, 23–41, doi:10.1002/2016JC012256, <http://dx.doi.org/10.1002/2016JC012256>, 2017.
- ANT: Particulate organic carbon (POC), Tech. rep., <https://seabass.gsfc.nasa.gov/cruise/ant-xxiii-1>, (2005), ANT-XXIII-1, SIO Stramsky, (Accessed on 2017 at: <https://seabass.gsfc.nasa.gov/>), 2005.
- Argo: Argo float data and metadata, Tech. rep., Global Data Assembly Centre (Argo GDAC) SEANOE, <http://doi.org/10.17882/42182>, 2000.
- 10 Arístegui, J., Tett, P., Hernández-Guerra, A., Basterretxea, G., Montero, M., Wild, K., Sangrà, P., Hernández-Leon, S., Canton, M., García-Braun, J., Pacheco, M., and Barton, E.: The influence of island-generated eddies on chlorophyll distribution: a study of mesoscale variation around Gran Canaria, *Deep Sea Research Part I: Oceanographic Research Papers*, 44, 71 – 96, doi:[http://dx.doi.org/10.1016/S0967-0637\(96\)00093-3](http://dx.doi.org/10.1016/S0967-0637(96)00093-3), <http://www.sciencedirect.com/science/article/pii/S0967063796000933>, 1997.
- 15 Arístegui, J., Barton, E. D., Montero, M. F., nos, M. G.-M., and Escánez, J.: Organic carbon distribution and water column respiration in the NW African-Canaries Coastal Transition Zone, *Aquatic Microbial Ecology*, 33, 289–301, doi:10.3354/ame033289, 2003.
- Arístegui, J., Barton, E. D., Álvarez-Salgado, X. A., Santos, M. P., Figueiras, F. G., Kifani, S., Hernández-León, S., Mason, E., Machú, E., and Demarq, H.: Sub-regional ecosystem variability in the Canary Current upwelling, *Progress in Oceanography*, 83, 33–48, doi:<http://dx.doi.org/10.1016/j.pocean.2009.07.031>, 2009.
- 20 Baltar, F., Arístegui, J., Montero, M. F., Espino, M., Gasol, J. M., and Herndl, G. J.: Mesoscale variability modulates seasonal changes in the trophic structure of nano- and picoplankton communities across the NW Africa-Canary Islands transition zone, *Progress in Oceanography*, 83, 180 – 188, doi:<http://dx.doi.org/10.1016/j.pocean.2009.07.016>, <http://www.sciencedirect.com/science/article/pii/S0079661109000706>, eastern Boundary Upwelling Ecosystems: Integrative and Comparative Approaches, 2009.
- Barceló-Llull, B., Pallàs-Sanz, E., Sangrà, P., Martínez-Marrero, A., Estrada-Allis, S. N., and Arístegui, J.: Ageostrophic Secondary Circulation in a Subtropical Intrathermocline Eddy, *Journal of Physical Oceanography*, 47, 1107–1123, doi:10.1175/JPO-D-16-0235.1, <https://doi.org/10.1175/JPO-D-16-0235.1>, 2017.
- 25 Barth, J. A., Cowles, T. J., Kosro, P. M., Shearman, R. K., Huyer, A., and Smith, R. L.: Injection of carbon from the shelf to offshore beneath the euphotic zone in the California Current, *Journal of Geophysical Research: Oceans*, 107, 10–1–10–8, doi:10.1029/2001JC000956, <http://dx.doi.org/10.1029/2001JC000956>, 2002.
- Barton, E.: Canary and Portugal Currents, in: *Encyclopedia of Ocean Sciences*, edited by Steele, J., Turekian, K., and Thorpe, S., vol. 1, pp. 380–389, Academic Press, doi:10.1006/rwos.2001.0360, 2001.
- 30 Barton, E., Arístegui, J., Tett, P., Cantón, M., García-Braun, J., Hernández-León, S., Nykjaer, L., Almeida, C., Almunia, J., Ballesteros, S., Basterretxea, G., Escánez, J., García-Weill, L., Hernández-Guerra, A., López-Laatzén, F., Molina, R., Montero, M., Navarro-Pérez, E., Rodríguez, J., van Lenning, K., Vélez, H., and Wild, K.: The transition zone of the Canary Current upwelling region, *Progress in Oceanography*, 41, 455 – 504, doi:[https://doi.org/10.1016/S0079-6611\(98\)00023-8](https://doi.org/10.1016/S0079-6611(98)00023-8), <http://www.sciencedirect.com/science/article/pii/S0079661198000238>, 1998.
- 35

- Barton, E. D., Arístegui, J., Tett, P., and Navarro-Pérez, E.: Variability in the Canary Islands area of filament-eddy exchanges, *Progress in Oceanography*, 62, 71 – 94, doi:<http://dx.doi.org/10.1016/j.pocean.2004.07.003>, <http://www.sciencedirect.com/science/article/pii/S0079661104000928>, the Canary Islands Coastal Transition Zone - Upwelling, Eddies and Filaments, 2004.
- Behrenfeld, M. J. and Falkowski, P. G.: Photosynthetic rates derived from satellite-based chlorophyll concentration, *Limnology and Oceanography*, 42, 1–20, doi:10.4319/lo.1997.42.1.0001, seaWiFS VGPM available at: <http://orca.science.oregonstate.edu/1080.by.2160.monthly.hdf.vgpm.s.chl.a.sst.php>, Modis-Aqua VGPM available at: <http://orca.science.oregonstate.edu/1080.by.2160.monthly.hdf.vgpm.m.chl.m.sst.php>, 1997.
- Bettencourt, J. H., Rossi, V., Hernández-García, E., Marta-Almeida, M., and López, C.: Characterization of the structure and cross-shore transport properties of a coastal upwelling filament using three-dimensional finite-size Lyapunov exponents, *arXiv e-prints*, doi:arXiv:1707.09907, 2017.
- BODC-NERC, A.: Particulate organic carbon (POC) from Atlantic Meridional Transect (AMT), Tech. rep., Natural Environment Research Council, <http://www.amt-uk.org/Home>, (2004-2014), AMT 15-24, (Accessed on 2017 at: <https://seabass.gsfc.nasa.gov/>), 2014.
- Brink, K. H.: Cold-water filaments in the California Current system, *South African Journal of Marine Science*, 12, 53–60, doi:10.2989/02577619209504690, 1992.
- Brochier, T., Mason, E., Moyano, M., Berraho, A., Colas, F., Sangrá, P., Hernández-León, S., Ettahiri, O., and Lett, C.: Ichthyoplankton transport from the African coast to the Canary Islands, *Journal of Marine Systems*, 87, 109–122, 2014.
- Burd, A. B., Hansell, D. A., Steinberg, D. K., Anderson, T. R., Arístegui, J., Baltar, F., Beupré, S. R., Buesseler, K. O., DeHairs, F., Jackson, G. A., Kadko, D. C., Koppelman, R., Lampitt, R. S., Nagata, T., Reinthaler, T., Robinson, C., Robison, B. H., Tamburini, C., and Tanaka, T.: Assessing the apparent imbalance between geochemical and biochemical indicators of meso- and bathypelagic biological activity: What the @\$\$! is wrong with present calculations of carbon budgets?, *Deep Sea Research Part II: Topical Studies in Oceanography*, 57, 1557 – 1571, doi:<https://doi.org/10.1016/j.dsr2.2010.02.022>, <http://www.sciencedirect.com/science/article/pii/S0967064510000883>, ecological and Biogeochemical Interactions in the Dark Ocean, 2010.
- C., M. J., F., C., and J., M. M.: Cold filamentary intensification and oceanic surface convergence lines, *Geophysical Research Letters*, 36, doi:10.1029/2009GL039402, <https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2009GL039402>, 2009.
- Capet, X., Colas, F., McWilliams, J. C., Penven, P., and Marchesiello, P.: Eddies in Eastern Boundary Subtropical Upwelling Systems, pp. 131–147, *American Geophysical Union*, doi:10.1029/177GM10, <http://dx.doi.org/10.1029/177GM10>, 2013.
- Carr, M.-E.: Estimation of potential productivity in the Eastern Boundary Currents using remote sensing, *Deep-Sea Research II: Topical Studies in Oceanography*, 49, 59–80, doi:[http://dx.doi.org/10.1016/S0967-0645\(01\)00094-7](http://dx.doi.org/10.1016/S0967-0645(01)00094-7), 2002.
- Chaigneau, A., Gizolme, A., and Grados, C.: Mesoscale eddies off Peru in altimeter records: Identification algorithms and eddy spatio-temporal patterns, *Progress in Oceanography*, 79, 106 – 119, doi:<http://dx.doi.org/10.1016/j.pocean.2008.10.013>, <http://www.sciencedirect.com/science/article/pii/S0079661108001663>, the Northern Humboldt Current System: Ocean Dynamics, Ecosystem Processes, and Fisheries, 2008.
- Chaigneau, A., Eldin, G., and Dewitte, B.: Eddy activity in the four major upwelling systems from satellite altimetry (1992–2007), *Progress in Oceanography*, 83, 117 – 123, doi:<http://dx.doi.org/10.1016/j.pocean.2009.07.012>, <http://www.sciencedirect.com/science/article/pii/S0079661109001013>, eastern Boundary Upwelling Ecosystems: Integrative and Comparative Approaches, 2009.
- Chavez, F. P. and Messié, M.: A comparison of Eastern Boundary Upwelling Ecosystems, *Progress in Oceanography*, 83, 80–96, doi:<http://dx.doi.org/10.1016/j.pocean.2009.07.032>, 2009.

- Chelton, D. B., Schlax, M. G., Samelson, R. M., and de Szoeke, R. A.: Global observations of large oceanic eddies, *Geophysical Research Letters*, 34, n/a–n/a, doi:10.1029/2007GL030812, <http://dx.doi.org/10.1029/2007GL030812>, 115606, 2007.
- Chelton, D. B., Schlax, M. G., and Samelson, R. M.: Global observations of nonlinear mesoscale eddies, *Progress in Oceanography*, 91, 167 – 216, doi:<http://dx.doi.org/10.1016/j.pocean.2011.01.002>, <http://www.sciencedirect.com/science/article/pii/S0079661111000036>, 2011.
- 5 Chenillat, F., Franks, P. J. S., Rivière, P., Capet, X., Grima, N., and Blanke, B.: Plankton dynamics in a cyclonic eddy in the Southern California Current System, *Journal of Geophysical Research: Oceans*, 120, 5566–5588, doi:10.1002/2015JC010826, <http://dx.doi.org/10.1002/2015JC010826>, 2015.
- Combes, V., Chenillat, F., Di Lorenzo, E., Riviere, P., Ohman, M. D., and Bograd, S. J.: Cross-shore transport variability in the California Current: Ekman upwelling vs. eddy dynamics, *Progress in Oceanography*, 109, 78–89, doi:10.1016/j.pocean.2012.10.001, <GotoISI>:
10 //WOS:000315059200006, n/a, 2013.
- Cravo, A., Relvas, P., Cardeira, S., Rita, F., Madureira, M., and Sánchez, R.: An upwelling filament off southwest Iberia: Effect on the chlorophyll a and nutrient export, *Continental Shelf Research*, 30, 1601 – 1613, doi:<http://dx.doi.org/10.1016/j.csr.2010.06.007>, <http://www.sciencedirect.com/science/article/pii/S0278434310002001>, 2010.
- Doblin, M., Petrou, K., Sinutok, S., Seymour, J., Messer, L., Brown, M., Norman, L., Everett, J., McInnes, A., Ralph, P., Thompson, P., and
15 C.S., H.: Nutrient uplift in a cyclonic eddy increases diversity, primary productivity and iron demand of microbial communities relative to a western boundary current, *PeerJ*, 4, e1973, doi:<https://doi.org/10.7717/peerj.1973>, 2016.
- Faghmous, J. H., Frenger, I., Yao, Y., Warmka, R., Lindell, A., and Kumar, V.: A daily global mesoscale ocean eddy dataset from satellite altimetry, *Scientific Data*, 2, <http://dx.doi.org/10.1038/sdata.2015.28>, 2015.
- Fischer, G., Reuter, C., Karakas, G., Nowald, N., and Wefer, G.: Offshore advection of particles within the Cape
20 Blanc filament, Mauritania: Results from observational and modelling studies, *Progress in Oceanography*, 83, 322–330, doi:<http://dx.doi.org/10.1016/j.pocean.2009.07.023>, 2009.
- Gabric, A. J., Garcia, L., Camp, L. V., Nykjaer, L., Eifler, W., and Schrimpf, W.: Offshore export of shelf production in the Cape Blanc (Mauritania) giant filament as derived from coastal zone color scanner imagery, *Journal of Geophysical Research*, 98, 4697–4712, doi:10.1029/92JC01714, 1993.
- 25 García-Muñoz, M., Arístegui, J., Montero, M. F., and Barton, E. D.: Distribution and transport of organic matter along a filament-eddy system in the Canaries – NW Africa coastal transition zone region, *Progress in Oceanography*, 62, 115 – 129, doi:<http://dx.doi.org/10.1016/j.pocean.2004.07.005>, <http://www.sciencedirect.com/science/article/pii/S0079661104000941>, the Canary Islands Coastal Transition Zone - Upwelling, Eddies and Filaments, 2004.
- García-Muñoz, M., Arístegui, J., Pelegrí, J. L., Antoranz, A., Ojeda, A., and Torres, M.: Exchange of carbon by an upwelling filament off Cape
30 Ghir (NW Africa), *Journal of Marine Systems*, 54, 83 – 95, doi:<https://doi.org/10.1016/j.jmarsys.2004.07.005>, <http://www.sciencedirect.com/science/article/pii/S092479630400209X>, a general study of the Spanish North Atlantic boundaries: an interdisciplinary approach, 2005.
- Gaube, P., McGillicuddy, D. J., Chelton, D. B., Behrenfeld, M. J., and Strutton, P. G.: Regional variations in the influence of mesoscale eddies on near-surface chlorophyll, *Journal of Geophysical Research: Oceans*, 119, 8195–8220, doi:10.1002/2014JC010111, <http://dx.doi.org/10.1002/2014JC010111>, 2014.
- 35 Gaube, P., Chelton, D. B., Samelson, R. M., Schlax, M. G., and O’Neill, L. W.: Satellite Observations of Mesoscale Eddy-Induced Ekman Pumping, *Journal of Physical Oceanography*, 45, 104–132, doi:10.1175/JPO-D-14-0032.1, 2015.

- GEOTRACES: Particulate organic carbon (POC), Tech. rep., <http://www.bodc.ac.uk/geotraces/>, (2010), RV Knorr KN199-4, (Accessed on 2017 at: <https://seabass.gsfc.nasa.gov/>), 2010.
- Giorgio, P. A. D. and Duarte, C. M.: Respiration in the open ocean, *Nature*, 420, 379–384, doi:10.1038/nature01165, 2002.
- Gruber, N., Frenzel, H., Doney, S. C., Marchesiello, P., McWilliams, J. C., Oram, J. R., Plattner, G. K., and Stolzenbach, K. D.: Eddy-resolving simulation of plankton ecosystem dynamics in the California Current System, *Deep Sea Research I: Oceanographic Research Papers*, 53, 1483–1516, doi:<http://dx.doi.org/10.1016/j.dsr.2006.06.005>, 2006.
- Gruber, N., Lachkar, Z., Frenzel, H., Marchesiello, P., Münnich, M., McWilliams, J. C., Nagai, T., and Plattner, G.-K.: Eddy-induced reduction of biological production in eastern boundary upwelling systems, *Nature Geoscience*, 4, 787–792, doi:10.1038/ngeo1273, 2011.
- Hansell, D. A., Carlson, C. A., Repeta, D., and Schlitzer, R.: Dissolved Organic Matter in the Ocean: a controversy stimulates new insights, *Oceanography*, 22, 202 – 211, doi:10.5670/oceanog.2009.109, https://darchive.mblwhoilibrary.org/bitstream/handle/1912/3183/22-4_hansell.pdf?sequence=1, 2009.
- Hernández-Carrasco, I., Rossi, V., Hernández-García, E., Garçon, V., and López, C.: The reduction of plankton biomass induced by mesoscale stirring: A modeling study in the Benguela upwelling, *Deep Sea Research Part I: Oceanographic Research Papers*, 83, 65 – 80, doi:<http://dx.doi.org/10.1016/j.dsr.2013.09.003>, <http://www.sciencedirect.com/science/article/pii/S0967063713001878>, 2014.
- Kadko, D. C., Washburn, L., and Jones, B.: Evidence of subduction within cold filaments of the northern California Coastal Transition Zone, *Journal of Geophysical Research: Oceans*, 96, 14 909–14 926, doi:10.1029/91JC00885, <http://dx.doi.org/10.1029/91JC00885>, 1991.
- Karstensen, J., Fiedler, B., Schütte, F., Brandt, P., Körtzinger, A., Fischer, G., Zantopp, R., Hahn, J., Visbeck, M., and Wallace, D.: Open ocean dead zones in the tropical North Atlantic Ocean, *Biogeosciences*, 12, 2597–2605, doi:10.5194/bg-12-2597-2015, <http://www.biogeosciences.net/12/2597/2015/>, 2015.
- Karstensen, J., Schütte, F., Pietri, A., Krahmann, G., Fiedler, B., Grundle, D., Hauss, H., Körtzinger, A., Löscher, C. R., Testor, P., Vieira, N., and Visbeck, M.: Upwelling and isolation in oxygen-depleted anticyclonic modewater eddies and implications for nitrate cycling, *Biogeosciences*, 14, 2167–2181, doi:10.5194/bg-14-2167-2017, <https://www.biogeosciences.net/14/2167/2017/>, 2017.
- Klocker, A. and Abernathy, R.: Global Patterns of Mesoscale Eddy Properties and Diffusivities, *Journal of Physical Oceanography*, 44, 1030–1046, doi:10.1175/JPO-D-13-0159.1, <https://doi.org/10.1175/JPO-D-13-0159.1>, 2014.
- Lachkar, Z. and Gruber, N.: What controls biological production in coastal upwelling systems? Insights from a comparative modeling study, *Biogeosciences*, 8, 2961–2976, doi:10.5194/bg-8-2961-2011, 2011.
- Lima, I. D., Olson, D. B., and Doney, S. C.: Biological response to frontal dynamics and mesoscale variability in oligotrophic environments: Biological production and community structure, *Journal of Geophysical Research: Oceans*, 107, 25–1–25–21, doi:10.1029/2000JC000393, <http://dx.doi.org/10.1029/2000JC000393>, 2002.
- Löscher, C. R., Fischer, M. A., Neulinger, S. C., Fiedler, B., Philippi, M., Schütte, F., Singh, A., Hauss, H., Karstensen, J., Körtzinger, A., Künzel, S., and Schmitz, R. A.: Hidden biosphere in an oxygen-deficient Atlantic open-ocean eddy: future implications of ocean deoxygenation on primary production in the eastern tropical North Atlantic, *Biogeosciences*, 12, 7467–7482, doi:10.5194/bg-12-7467-2015, <https://www.biogeosciences.net/12/7467/2015/>, 2015.
- Lovecchio, E., Gruber, N., Münnich, M., and Lachkar, Z.: On the long-range offshore transport of organic carbon from the Canary Upwelling System to the open North Atlantic, *Biogeosciences*, 14, 3337–3369, doi:10.5194/bg-14-3337-2017, <https://www.biogeosciences.net/14/3337/2017/>, 2017.

- Machín, F., Hernández-Guerra, A., and Pelegrí, J.: Mass fluxes in the Canary Basin, *Progress in Oceanography*, 70, 416 – 447, doi:<http://dx.doi.org/10.1016/j.pocean.2006.03.019>, <http://www.sciencedirect.com/science/article/pii/S007966110600053X>, gabriel T. Csanady: Understanding the Physics of the Ocean, 2006.
- Mackas, D. L., Strub, P. T., Thomas, A., and Montecino, V.: Eastern ocean boundaries, pan-regional overview, in: *The Sea, Volume 14: The Global Coastal Ocean*, edited by Robinson, A. R. and Brink, K., chap. 2, Harvard University Press, 2006.
- Mahadevan, A.: Eddy effects on biogeochemistry, *Nature*, 506, 168–169, doi:10.1038/nature13048, 2014.
- Maheu, C., Pujol, M., and Faugère, Y.: Change of the Ssalto/Duacs reference period, Tech. rep., CNES, AVISO+, https://www.aviso.altimetry.fr/fileadmin/documents/newsstand/Newsletter/aviso_users_news09.pdf, a new version of SSALTO/Duacs products available in April 2014: <https://www.aviso.altimetry.fr/fileadmin/documents/data/duacs/Duacs2014.pdf>, 2014.
- 10 Marchesiello, P. and Estrade, P.: Eddy activity and mixing in upwelling systems: a comparative study of Northwest Africa and California regions, *International Journal of Earth Sciences*, 98, 299–308, doi:10.1007/s00531-007-0235-6, 2006.
- Martin, A. P. and Richards, K. J.: Mechanisms for vertical nutrient transport within a North Atlantic mesoscale eddy, *Deep Sea Research Part II: Topical Studies in Oceanography*, 48, 757 – 773, doi:[https://doi.org/10.1016/S0967-0645\(00\)00096-5](https://doi.org/10.1016/S0967-0645(00)00096-5), <http://www.sciencedirect.com/science/article/pii/S0967064500000965>, the Biological Oceanography of the north-east Atlantic-the PRIME study, 2001.
- 15 Mason, E., Colas, F., Molemaker, J., Shchepetkin, A. F., Troupin, C., McWilliams, J. C., and Sangrá, P.: Seasonal variability of the Canary Current: A numerical study, *Journal of Geophysical Research: Oceans*, 116, doi:10.1029/2010JC006665, <http://dx.doi.org/10.1029/2010JC006665>, c06001, 2011.
- McGillicuddy, D. J.: Mechanisms of Physical-Biological-Biogeochemical Interaction at the Oceanic Mesoscale, *Annual Review of Marine Science*, 8, 125–159, doi:10.1146/annurev-marine-010814-015606, 2016.
- 20 McWilliams, J. C. and Flierl, G. R.: On the Evolution of Isolated, Nonlinear Vortices, *Journal of Physical Oceanography*, 9, 1155–1182, doi:10.1175/1520-0485(1979)009<1155:OTEOIN>2.0.CO;2, [https://doi.org/10.1175/1520-0485\(1979\)009<1155:OTEOIN>2.0.CO;2](https://doi.org/10.1175/1520-0485(1979)009<1155:OTEOIN>2.0.CO;2), 1979.
- Menna, M., Faye, S., Poulain, P. M., Centurioni, L., Lazar, A., Gaye, A., Sow, B., and Dagorne, D.: Upwelling features off the coast of north-western Africa in 2009–2013, *Bollettino Di Geofisica Teorica Ed Applicata*, 57, 71–86, doi:10.4430/bgta0164, <GotoISI>://WOS:000387078600006, n/a, 2016.
- 25 Meunier, T., Barton, E. D., Barreiro, B., and Torres, R.: Upwelling filaments off Cap Blanc: Interaction of the NW African upwelling current and the Cape Verde frontal zone eddy field?, *Journal of Geophysical Research: Oceans*, 117, n/a–n/a, doi:10.1029/2012JC007905, <http://dx.doi.org/10.1029/2012JC007905>, c08031, 2012.
- Montégut, C. D. B., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, *Journal of Geophysical Research*, 109, C12 003, doi:10.1029/2004JC002378, 2004.
- 30 Nagai, T., Gruber, N., Frenzel, H., Lachkar, Z., McWilliams, J. C., and Plattner, G.-K.: Dominant role of eddies and filaments in the offshore transport of carbon and nutrients in the California Current System, *Journal of Geophysical Research*, 120, doi:10.1002/2015JC010889, 2015.
- NASA-OB.DAAC: SeaWiFS Level-3 Mapped Particulate Organic Carbon Data Version 2014, S19972442010273.3m_mc_chl_chlor_a_9km.nc, NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group, <http://oceandata.sci.gsfc.nasa.gov>, (1997–2010), doi:10.5067/ORBVIEWS/SEAWIFS/L3M/POC/2014 (Accessed on 2017), 2010.

- NASA-OBPG: SeaWiFS Data Level-3 Standard Mapped Image, S19972442010273.3m_mc_chl_chlor_a_9km.nc, NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group, <http://oceandata.sci.gsfc.nasa.gov> (Accessed on 2015), (1997-2010), 2010.
- Navarro-Pérez, E. and Barton, E. D.: The physical structure of an upwelling filament off the North-West African coast during August 1993, *South African Journal of Marine Science*, 19, 61–73, doi:10.2989/025776198784126827, 1998.
- Ohde, T., Fiedler, B., and Körtzinger, A.: Spatio-temporal distribution and transport of particulate matter in the eastern tropical North Atlantic observed by Argo floats, *Deep-Sea Research I*, 102, 26–42, doi:<http://dx.doi.org/10.1016/j.dsr.2015.04.007>, 2015.
- Pelegrí, J. L. and Benazzouz, A.: Coastal Upwelling off Northwest Africa, in: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*, edited by Váldes, L. and Déniz-González, I., chap. 3.4, IOC-UNESCO, - Technical Series 115, 2015.
- 10 Pelegrí, J. L. and Peña-Izquierdo, J.: Eastern Boundary Currents off Northwest Africa, in: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*, edited by Váldes, L. and Déniz-González, I., chap. 3.3, IOC-UNESCO, - Technical Series 115, 2015.
- Pelegrí, J. L., Arístegui, J., Cana, L., González-Dávila, M., Hernández-Guerra, A., Hernández-León, S., Montero, M. F., Sangrá, P., and Santana-Casiano, M.: Coupling between the open ocean and the coastal upwelling region off northwest Africa: water recirculation and offshore pumping of organic matter, *Journal of Marine Systems*, 54, 3–37, doi:<http://dx.doi.org/10.1016/j.jmarsys.2004.07.003>, 2005.
- 15 Peliz, A., Santos, A. M. P., Oliveira, P. B., and Dubert, J.: Extreme cross-shelf transport induced by eddy interactions southwest of Iberia in winter 2001, *Geophysical Research Letters*, 31, L08 301, doi:10.1029/2004GL019618, 2004.
- Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., and Schlax, M. G.: Daily High-Resolution-Blended analyses for sea surface temperature, *J. Climate*, 20, 5473–5496, doi:<http://dx.doi.org/10.1175/2007JCLI1824.1>, 2007.
- Ridgway, K. R., Dunn, J. R., and Wilkin, J. L.: Ocean interpolation by four-dimensional least squares: Application to the waters around Australia, *J. Atmos. Ocean*, 19, 1357–1375, doi:[http://dx.doi.org/10.1175/1520-0426\(2002\)019<1357:OIBFDW>2.0.CO;2](http://dx.doi.org/10.1175/1520-0426(2002)019<1357:OIBFDW>2.0.CO;2), 2002.
- 20 Rio, M.-H. and Hernandez, F.: A mean dynamic topography computed over the world ocean from altimetry, in situ measurements, and a geoid model, *J. Geophys. Res.*, 109, C12 032, doi:10.1029/2003JC002226, 2004.
- Rodríguez, J., Barton, E., Hernández-León, S., and Arístegui, J.: The influence of mesoscale physical processes on the larval fish community in the Canaries CTZ, in summer, *Progress in Oceanography*, 62, 171 – 188, doi:<http://dx.doi.org/10.1016/j.pocean.2004.07.006>, <http://www.sciencedirect.com/science/article/pii/S0079661104000953>, the Canary Islands Coastal Transition Zone - Upwelling, Eddies and Filaments, 2004.
- 25 Rossi, V., López, C., Sudre, J., Hernández-García, E., and Garçon, V.: Comparative study of mixing and biological activity of the Benguela and Canary upwelling systems, *Geophysical Research Letters*, 35, doi:10.1029/2008GL033610, <http://dx.doi.org/10.1029/2008GL033610>, 111602, 2008.
- 30 Rossi, V., López, C., Hernández-García, E., Sudre, J., Garçon, V., and Morel, Y.: Surface mixing and biological activity in the four Eastern Boundary Upwelling Systems, *Nonlinear Processes in Geophysics*, 16, 557–568, doi:10.5194/npg-16-557-2009, <https://www.nonlin-processes-geophys.net/16/557/2009/>, 2009.
- Rossi, V., Garçon, V., Tassel, J., Romagnan, J.-B., Stemmann, L., Jourdin, F., Morin, P., and Morel, Y.: Cross-shelf variability in the Iberian Peninsula Upwelling System: Impact of a mesoscale filament, *Continental Shelf Research*, 59, 97 – 114, doi:<https://doi.org/10.1016/j.csr.2013.04.008>, <http://www.sciencedirect.com/science/article/pii/S0278434313001088>, 2013.
- 35 Sangrà, P.: Canary Islands Eddies and Coastal Filaments off Northwest Africa, in: *Oceanographic and biological features in the Canary Current Large Marine Ecosystem*, edited by Váldes, L. and Déniz-González, I., chap. 3.5, pp. 105–114, IOC-UNESCO, - Technical Series 115, 2015.

- Sangrà, P., Pelegrí, J. L., Hernández-Guerra, A., Arregui, I., Martín, J. M., Marrero-Díaz, A., Martínez, A., Ratsimandresy, A. W., and Rodríguez-Santana, A.: Life history of an anticyclonic eddy, *Journal of Geophysical Research: Oceans*, 110, doi:10.1029/2004JC002526, <http://dx.doi.org/10.1029/2004JC002526>, c03021, 2005.
- Sangrà, P., Auladell, M., Marrero-Díaz, A., Pelegrí, J., Fraile-Nuez, E., Rodríguez-Santana, A., Martín, J., Mason, E., and Hernández-Guerra, A.: On the nature of oceanic eddies shed by the Island of Gran Canaria, *Deep Sea Research Part I: Oceanographic Research Papers*, 54, 687 – 709, doi:<http://dx.doi.org/10.1016/j.dsr.2007.02.004>, 2007.
- Sangrà, P., Pascual, A., Rodríguez-Santana, Á., F.Machín, Mason, E., McWilliams, J., Pelegrí, J., Dong, C., Rubio, A., Arístegui, J., Marrero-Díaz, Á., Hernández-Guerra, A., Martínez-Marrero, A., and Auladell, M.: The Canary Eddy Corridor: A major pathway for long-lived eddies in the subtropical North Atlantic, *Deep Sea Research I: Oceanographic Research Papers*, 56, 2100–2114, doi:<http://dx.doi.org/10.1016/j.dsr.2009.08.008>, 2009.
- Santana-Falcón, Y., Benavides, M., Sangrà, P., Mason, E., Barton, E. D., Orbi, A., and Arístegui, J.: Coastal–offshore exchange of organic matter across the Cape Ghir filament (NW Africa) during moderate upwelling, *Journal of Marine Systems*, 154, 233 – 242, doi:<http://dx.doi.org/10.1016/j.jmarsys.2015.10.008>, <http://www.sciencedirect.com/science/article/pii/S0924796315001669>, 2016.
- Schütte, F., Brandt, P., and Karstensen, J.: Occurrence and characteristics of mesoscale eddies in the tropical northeastern Atlantic Ocean, *Ocean Science*, 12, 663–685, doi:10.5194/os-12-663-2016, <https://www.ocean-sci.net/12/663/2016/>, 2016a.
- Schütte, F., Karstensen, J., Krahmann, G., Hauss, H., Fiedler, B., Brandt, P., Visbeck, M., and Körtzinger, A.: Characterization of “dead-zone” eddies in the eastern tropical North Atlantic, *Biogeosciences*, 13, 5865–5881, doi:10.5194/bg-13-5865-2016, <https://www.biogeosciences.net/13/5865/2016/>, 2016b.
- Shchepetkin, A. F. and McWilliams, J. C.: The regional oceanic modeling system (ROMS): a split-explicit, topographic-following-coordinate oceanic model, *Ocean Modeling*, 9, 347–404, doi:<http://dx.doi.org/10.1016/j.ocemod.2004.08.002>, 2005.
- Stammer, D.: On Eddy Characteristics, Eddy Transports, and Mean Flow Properties, *Journal of Physical Oceanography*, 28, 727–739, doi:10.1175/1520-0485(1998)028<0727:OECETA>2.0.CO;2, [https://doi.org/10.1175/1520-0485\(1998\)028<0727:OECETA>2.0.CO;2](https://doi.org/10.1175/1520-0485(1998)028<0727:OECETA>2.0.CO;2), 1998.
- Stramma, L., Bange, H. W., Czeschel, R., Lorenzo, A., and Frank, M.: On the role of mesoscale eddies for the biological productivity and biogeochemistry in the eastern tropical Pacific Ocean off Peru, *Biogeosciences*, 10, 7293–7306, doi:10.5194/bg-10-7293-2013, <http://www.biogeosciences.net/10/7293/2013/>, 2013.
- Strub, P. T., Kosro, P. M., and Huyer, A.: The nature of the cold filaments in the California Current system, *Journal of Geophysical Research: Oceans*, 96, 14 743–14 768, doi:10.1029/91JC01024, <http://dx.doi.org/10.1029/91JC01024>, 1991.
- Subha Anand, S., Rengarajan, R., Sarma, V. V. S. S., Sudheer, A. K., Bhushan, R., and Singh, S. K.: Spatial variability of upper ocean POC export in the Bay of Bengal and the Indian Ocean determined using particle-reactive ²³⁴Th, *Journal of Geophysical Research: Oceans*, 122, 3753–3770, doi:10.1002/2016JC012639, <http://dx.doi.org/10.1002/2016JC012639>, 2017.
- Waite, A. M., Stemmann, L., Guidi, L., Calil, P. H. R., Hogg, A. M. C., Feng, M., Thompson, P. A., Picheral, M., and Gorsky, G.: The wineglass effect shapes particle export to the deep ocean in mesoscale eddies, *Geophysical Research Letters*, 43, 9791–9800, doi:10.1002/2015GL066463, 2015GL066463, 2016.
- Washburn, L., Kadko, D. C., Jones, B. H., Hayward, T., Kosro, P. M., Stanton, T. P., Ramp, S., and Cowles, T.: Water mass subduction and the transport of phytoplankton in a coastal upwelling system, *Journal of Geophysical Research: Oceans*, 96, 14 927–14 945, doi:10.1029/91JC01145, <http://dx.doi.org/10.1029/91JC01145>, 1991.

Westberry, T., Behrenfeld, M. J., Siegel, D. A., and Boss, E.: Carbon-based primary productivity modeling with vertically resolved photoacclimation, *Global Biogeochemical Cycles*, 22, GB2024, doi:10.1029/2007GB003078, seaWiFS VGPM available at: <http://orca.science.oregonstate.edu/1080.by.2160.monthly.hdf.cbpm2.s.php>, 2008.

5 Zhang, J.-Z., Wanninkhof, R., and Lee, K.: Enhanced new production observed from the diurnal cycle of nitrate in an oligotrophic anticyclonic eddy, *Geophysical Research Letters*, 28, 1579–1582, doi:10.1029/2000GL012065, <http://dx.doi.org/10.1029/2000GL012065>, 2001.

Zhang, Z., Wang, W., and Qiu, B.: Oceanic mass transport by mesoscale eddies, *Science*, 345, 322–324, doi:10.1126/science.1252418, 2014.