Final Author Comments

"Characterization of "dead-zone" eddies in the tropical Northeast Atlantic Ocean"

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Dear Editor, dear Reviewer,

We would like to thank you for the overall positive evaluation of our manuscript. The constructive criticism, the very careful corrections and suggestions will surely help to improve the manuscript. In the following we address the remarks of the reviewer #1 in detail and how we intend to address the concerns in the manuscript. The comments by the reviewer are shown in normal text and our responses in italic.

Anonymous Referee #1

Summary

Schütte et al. use an extensive compilation of observation based data comprising of shipboard measurements, mooring data, Argo float profiles, glider data as well as satellite based products to characterize mesoscale activity in the Eastern Tropical North Atlantic (ETNA). In particular, their analysis focuses on cyclonic eddies (CE) and anticyclonic modewater eddies (ACMEs), the associated oxygen depletion within these mesoscale structures and their potential contribution to the pronounced low oxygen environment within the shadow zone in the ETNA with the subtropical gyre to the North and the equatorial region to the South. They find that almost all observations of low oxygen concentrations below a canonical value of 40 µmol/kg are co-located with either CEs or ACMEs that show negative oxygen anomalies which are most pronounced right beneath the mixed layer. These anomalies are attributed both to high productivity in the surface waters and the subsequent respiration of organic material as well as to the dynamically induced isolation of the mesoscale structures with respect to lateral oxygen resupply. The authors conclude that the investigated eddies *represent en essential part of the total consumption in the open ocean of the ETNA and partly contribute to the shallow low oxygen environment in the investigated region.*

1 General comments

The presented work extends and complements previous work carried out by the community and the authors. In particular, the compilation of different observation based and quality-controlled data sources that extend previous records allow the authors to draw conclusions on the general characteristics and oxygen depletion within CEs and ACMEs in the studied region that advances our scientific understanding of mesoscale structures and their contribution to the mean distribution of biogeochemical properties. Moreover, the work is generally well-written, well-structured and results are presented in a clear and concise way. In my opinion, this manuscript thus represents work that is well suited for publication within the scope of Biogeosciences. Nevertheless, of course, I would like to make some comments and suggestions that should be addressed before publication and hopefully help the authors to further improve their work.

- Thank you very much for this evaluation.

A) The use of the term "dead zone"

The authors use the term "dead zone" as a very prominent catchword throughout the whole manuscript. This term serves its purpose, but in my opinion, its use is not unproblematic. I think the use of this catchword is very colloquial and does not acknowledge our scientific understanding of hypoxic environments that still provide habitats to specifically adapted species. Thus, it might potentially lead to premature interpretations and misunderstandings. To avoid these challenges, my suggestion is that the authors concentrate on phrasings such as "anoxic" and "hypoxic" and do not use "dead zone" in this context. If this term is used, it needs to be motivated, most importantly, but also discussed in the introduction in a more differentiated manner and the difficulties involved with interpreting such a catchphrase need to be appropriately addressed. In addition to specifically adapted species making use of these environments, marine organisms experience a highly non-linear sensitivity to low oxygen concentration and thresholds for hypoxia vary greatly among marine taxa (Keeling et al. 2010, Vaquer-Sunyer and Duarte 2008). A more elaborate motivation and differentiated discussion of the term can for example be found in the introduction of the review paper by Keeling et al. (2010) (see References at the end).

- Thank you very much for pointing this out and reminding us to be more precise about the term "dead-zone" eddies. We totally agree with the reviewer that the use of the catchword “dead-zone” is problematic and imprecise. However, this term is chosen to be a major topic of the special issue and is consequently used in all of the associated manuscripts. We do not want to exclude us from that community and decided to use that term as well. In the understanding of the special issue a “dead-zone” is more a phenomenon than a certain concentration level and created by the variability in oxygen - in particular a "sudden" decrease ("sudden" with respect to life/adaption cycles of organisms). The "sudden" decrease in oxygen forces organisms to leave a region (if they are able to) or to die (the dead in "dead-zone"). This phenomenon is described for limnic and coastal systems and, as introduced in Karstensen et al. (2015), can occur in the open ocean in isolated eddies as well.

A more detailed discussion referring the used oxygen threshold in the manuscript and the mentioned paper by Keeling et al. (2010) is also given below (page 8 and line 24-30). However, we agree with the reviewer that a more differentiated introduction of the term “dead-zone” is certainly needed in our manuscript. We insert a paragraph in the introduction at page 2 line 28:

“The majority of organisms are insensitive to different oxygen levels as long as concentrations are high enough (Keeling et al. 2010). However, as soon as the oxygen falls below a certain critical threshold (which varies between different organisms) the most organisms suffer from a variety of stresses, which can lead to death if they are not able to migrate elsewhere and critical concentrations persists for too long (Gray et al. 2002, Keeling et al. 2010). It could be shown that the observed oxygen depleted eddy cores have profound impacts on microbial (Löscher et al. 2015) and metazoan (Hauss et al., 2016) communities. Furthermore the oxygen depleted cores of these eddies evolve in relatively “short” time scales ("short" with respect to time scales of life/adaption cycles of organisms), which resembles an environment similar to the “dead-zone” formation in coastal areas and lakes. Consequently, these oxygen depleted eddies have been termed “dead-zone” eddies (for a more detailed definition see also Karstensen et al., 2015).”

B) Quantification, Significance, Relevance and Implications

In my opinion, the presentation of some results in the current manuscript could be strengthened by clarifying certain paragraphs, putting results into a broader context and touch upon the relevance and potential implications of this work for other studies and concepts. Putting the results into a broader context can help a non-expert in mesoscale oxygen dynamics to better understand the relevance of this work. Reviewing some parts of the draft could add to the work presented here.

- Thank you very much for the assessment of our results. We worked through your following suggestions and tried in the complete manuscript to clarify some parts and to bring the results into a broader context to show the relevance and implication for other studies.

Even though this is a major comment, let me get a little bit more specific here, to better convey my request:

Page 1, Line 24:

"increased consumption within these eddies represents an essential part of the total consumption. . .". First of all, I think that this specific sentence of the abstract could benefit from some quantification. Second, in the discussion (Page 11, Line 18) you present the results from your budget analysis of the SOMZ oxygen consumption, stating that mesoscale structures contribute to about 6% of the observed low oxygen distribution. Even though this value is probably underestimating the total effect, as you argue in your work, 6% is not an essential part, in my opinion (please correct me if I misunderstood the line of argumentation). I think it's important that these paragraphs (abstract, discussion and conclusion) reflect each other and causal conclusions are drawn and described in a way that numbers and descriptions add up to the whole picture, even if this means being careful with catchwords such as "essential" or "significant". (Wouldn't a phrasing such as "the investigated contribution of mesoscale eddies only amounts to 6% of the observed low oxygen in the SOMZ. This value, though, is very likely to be underestimated due to..." also reflect the results but be more consistent when comparing the numerical and descriptive presentation?)

- That is right. We totally agree that the 6% are misleading as they suggest only a small impact of "dead-zone" eddies on the oxygen concentration in the ETNA region. The 6% are related to the absolute oxygen concentration (125 μmol kg^{-1}). More interesting is the impact of “dead-zone” eddies on the existence of the shallow OMZ. Hence, the oxygen anomaly due to “dead-zone” eddies should be related to the strength of the shallow OMZ, whereas the latter is defined as the difference between the profile neglecting the shallow OMZ and the actual profile, which is observed. Relating these values results in dead zone eddies being responsible for around 25% of the shallow OMZ. Thus we have eliminated the value of 6% throughout the manuscript and replaced it with the absolute contribution of the “dead-zone” eddies, which is a reduction of 7 µmol kg^{-1}.

Furthermore we changed the abstract at the position mentioned by the reviewer at page 1 line 24 from:

“The locally increased consumption within these eddies represents an essential part of the total consumption in the open tropical Northeast Atlantic Ocean and might be partly responsible for the formation of the shallow oxygen minimum zone.”

to

“The locally increased oxygen consumption within the eddy cores enhanced the total consumption in the in the open tropical Northeast Atlantic Ocean and might be partly responsible for the formation of the shallow oxygen minimum zone.”

Page 8, Lines 20-21:

“On average the oxygen concentration in the core of an isolated CE (ACME) decreases by about 0.10 (0.19) ± 0.12 (0.08) µmol kg^{-1} d^{-1}*.”*

Can these estimates of oxygen consumption be put into the context of other observations, studies or estimates? How do these values in general compare with available estimates of average oxygen consumption? Are the results presented in the order of magnitude that the authors expected them to be, or is the effect stronger/weaker than what the authors expected? The way the results are presented here makes it hard for the reader to understand the magnitude of the mesoscale effect. Providing more context and comparisons would really help here.

- These numbers are classified and discussed in the section *4. Discussion* at page 10 line 8 to 14:

"In combination with the eddy dynamics and its associated isolation of the CE (ACME) core, the oxygen content is decreasing on average by about 0.10 (0.19) ± 0.12 (0.08) µmol kg^{-1} d^{-1} in the ETNA. The apparent oxygen utilization rate (aOUR) is based on 504 oxygen measurements in CEs and ACMEs. It is in the range of recently published aOUR estimates for CEs (Karstensen et al., 2015) and ACMEs (Fiedler et al., 2016) based on single measurements in "dead-zone" eddies. An important point regarding the method to derive the aOURs is the initial coastal oxygen concentration, which is highly variable in coastal upwelling regions (Thomsen et al., 2015). "

But we agree that these numbers are difficult to be classified by the reader in the first place. We expand the sentence, at page 8 line 22, to give the reader a first idea about the magnitude of the aOUR estimates:

"On average the oxygen concentration in the core of an isolated CE (ACME) decreases by about 0.10 (0.19) ± 0.12 (0.08) µmol kg^{-1} d^{-1} which is in the range of recently published aOUR estimates for CEs (Karstensen et al., 2015) and ACMEs (Fiedler et al., 2016)."

Page 11, Lines 8-26: This is a very important part of your work. I think it could be strengthened by rephrasing some parts, putting the numbers into a broader context by providing comparisons that help the reader to better understand the magnitude of the discussed effects, and consistently present these findings in the abstract and conclusions (see comment above).

- We rephrased the mentioned paragraph, improved the structure and hopefully clarifying the description of the used budget estimation:

"Instead of describing the effect of the dead-zone eddies on the oxygen consumption we now consider a box model approach for the SOMZ. The basis of this box model is the mixing of higher oxygen waters (the background conditions) with lower oxygen waters (the "dead-zone" eddies). The average oxygen concentrations within the eddies in the considered depth range, i.e. 50 to 150 m depth, are 73 (66) µmol kg^{-1} for CEs (ACMEs). The average oxygen concentration of the background field averaged over the same depth range (between 50 and 150 m depth) derived from the MIMOC climatology (Schmidtko et al. (2013)) is 118 µmol kg^{-1}. This climatological value includes the contribution of low oxygen eddies. If we now consider the respective oxygen concentrations and volumes of the SOMZ and the eddies (multiplied by their frequency of occurrence per year), we are able to calculate the theoretical background oxygen concentration for the SOMZ without eddies to be 125 µmol kg^{-1}. Naturally due to the dispersion of negative oxygen anomalies, the oxygen concentrations in the SOMZ without eddies must be higher than the observed climatological values. Attributing the difference of these oxygen concentrations on the one hand in the SOMZ without eddies (125 µmol kg^{-1}) and on the other hand the observed climatological values in the SOMZ with eddies (118 µmol kg^{-1}), solely to the decrease induced by the dispersion of eddies, we find that a reduction of around 7 µmol kg^{-1} of the observed climatological oxygen concentration in the SOMZ box can be associated with the dispersion of eddies. Consequently, the oxygen consumption in this region is a mixture of the large-scale metabolism in the open ocean (Karstensen et al. 2008) and the enhanced metabolism in low oxygen eddies (Karstensen et al. 2016, Fiedler et al. 2015)."

I think this budget estimation is a central part of your work and very well motivated on page 2 (lines 39-40), thus, in my opinion, it should be mentioned in the conclusions and the abstract. Please note the technical comments below to correct errors in this paragraph that, unfortunately, hinder the clear communication of these results.

- That is right, we mention now the results in the abstract on page 1 and line 25:

"In a simple box model approach the investigated contribution to the observed low oxygen in the shallow oxygen minimum zone of "dead-zone" eddies is a reduction of the oxygen concentration of 7 µmol kg^{-1}."

And in the conclusion on page 12 and line 3:

"A simple box model approach on the basis of mixing ratios of high oxygen waters with low oxygen waters in the SOMZ reveals that a reduction of 7 µmol kg^{-1} of the observed oxygen in the shallow oxygen minimum zone is explainable due to the existence of "dead-zone" eddies. This value, though, is very likely to be underestimated due to difficulties in identifying and tracking of ACMEs."

Last but not least, your work naturally has implications for the nitrogen cycle. I am aware of some of the coauthors having submitted a manuscript on this issue as well (Karstensen et al. 2016). Nevertheless, I think it might help to at least mention some of the major implications for the nitrogen cycling within these mesoscale structures and the whole investigated region.

Interested readers of this work might expect the authors to at least touch upon this or refer to the relevant literature.

- That is correct, we insert a paragraph to give in the introduction some more details on the nitrogen cycle at page 2 line 28:

"The intense OMZ has profound impacts on microbial (Löscher et al. 2015) and metazoan (Hauss et al., 2016) communities. While denitrification is usually absent from the open tropical Atlantic, the detection of nirS gene transcripts (the key functional marker for denitrification) in an ACME potentially indicated nitrogen loss processes in the oxygen depleted eddy core (Löscher et al., 2015). However, the close-to-Redfield N:P stoichiometry in the same ACME (Fiedler et al., 2015), does not suggest a large-scale net loss of bioavailable nitrogen. In general, the relative magnitude of nutrient upwelling/primary productivity, nitrogen fixation and denitrification may vary between different eddies because of differences in the initial water mass in the eddies' core, the eddies' age and the external forcing (in particular wind stress and dust/iron input)."

2 Specific comments

A) Chosen threshold of 40 µmol/kg

Given a more differentiated discussion of the term "dead zone" (see comment above), can the authors elaborate on why they chose the specific threshold of 40 µmol/kg and whether and how they would expect their results to change when choosing, e.g. a higher threshold (e.g. 60 µmol/kg as mentioned in Keeling et al. 2010)? Would that significantly change the number of eddies considered as "low oxygen eddies" and thus increase the investigated sample or even strengthen the results?

- We wanted to highlight profiles with anomalous low oxygen concentrations. The minimal dissolved oxygen concentrations in the ETNA are in the range of 40-50 µmol kg^{-1}, thus the 40 µmol kg^{-1} threshold is chosen to clearly identify anomalous low oxygen concentrations. The number of profiles, probably near the coast or in the center of the OMZ, would increase if 60 µmol kg^{-1} were chosen as threshold. But the majority of the profiles would not be associated to mesoscale eddies, as the oxygen values (40-60 µmol kg^{-1}) are appearing in the large-scale oxygen distribution of the ETNA.

B) Physical contribution to the observed anomalies

In the abstract, the authors state that the most pronounced oxygen anomalies are found right beneath the mixed layer and that this signal has been attributed to a combination of high productivity in the eddies' surface waters and the isolation of their cores with respect to oxygen resupply. I do agree on this reasoning. However, I would like to mention an additional effect that has not been discussed in the manuscript and potentially plays a role here. The mere fact that the strongest anomalies are found at the base of the mixed layer hints at a pure physical contribution to the observed anomalies. Since density structures are shifted within the investigated eddies, this results in shifting the oxycline (i.e. shifting the isopycnals) and thus creating an oxygen anomaly that is of pure physical origin. If this is the case, can the author at least discuss the contribution of this mechanism on the observed concentrations, and if possible comment on the strength of this effect?

- That is a correct, a vertical displacement of isopycnals move lower oxygen concentrations closer to the mixed layer. First we rephrased the sentence in the introduction at page 3 line 10-11 from:

"At about 100 m depth, biogeochemical processes further increase the nutrient and oxygen anomalies with respect to the surrounding waters."

to

"At about 100 m depth, the elevated isopycnals in the eddies are associated to a displacement of the oxycline, which brings lower oxygen concentrations closer to the mixed layer. Here biogeochemical processes further increase the nutrient and oxygen anomalies with respect to the surrounding waters."

Further we investigated the contribution of the "physical" and "biogeochemical" part of the oxygen anomaly by comparing the oxygen anomaly derived on density surfaces against the oxygen anomaly derived on isobars (Figure 1).

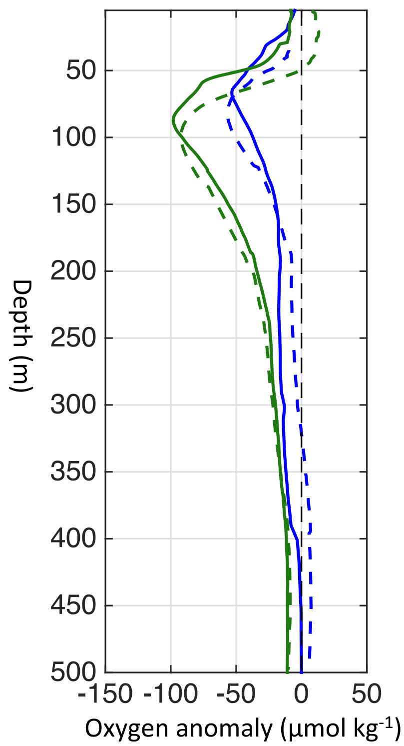

Figure 1: Mean Oxygen anomaly of ACMEs (green) and CEs (blue) derived on isopycnal surfaces (dashed lines) and isobars (continuous lines). The anomaly on isopycnal surfaces (dashed lines) are derived, by building an oxygen anomaly of each eddy type on density surfaces. Afterwards a transformation in pressure coordinates is done referenced to a mean density profile from outside the eddy.

Derived on isobars the oxygen anomaly in the upper eddy core is more pronounced compared to the anomaly derived on isopycnals, due to the upward bending of the density surfaces. However, the maximal absolute values of the anomaly are nearly the same. Therefore we conclude that the pure "physical" effect of shifting the oxycline is much smaller than the "biogeochemical" part in crating the oxygen anomaly.

C) Preconditioning through coastal environment

The presented apparent oxygen utilization rates range from about 0.1 (CEs) to 0.2 (ACMEs) µmol/kg/d. Even if the mesoscale structures are completely isolated and propagate offshore for, let's say, 2 months, this results in an oxygen decrease of only 12 µmol/kg compared to its initial oxygen concentration. It seems thus very challenging for this mechanism alone to cause "dead zone" eddies. I think it is important to note somewhere that not only do enhanced productivity in the mesoscale structures and their physical isolation cause these very low *oxygen eddies, but that there is a substantial contribution to the generation of these structures from the coastal environment, where most of them originate from. The above mentioned oxygen consumption alone would never be strong enough to result in a "dead zone" eddy, if it hadn't evolved from waters already low in oxygen along the upwelling region. I think this preconditioning is an important piece of the whole picture and should be briefly discussed somewhere.*

- Yes that is right, the preconditioning due to low oxygen values at the shelf of the formation region was poorly described in the manuscript before. The reviewer mentioned correct that the preconditioning is an important part in the developing of the open ocean "dead-zone" eddies. We plotted the Shipboard CTD section with the lowest oxygen at the shelf of Mauretania and Senegal we could find (figure 2).

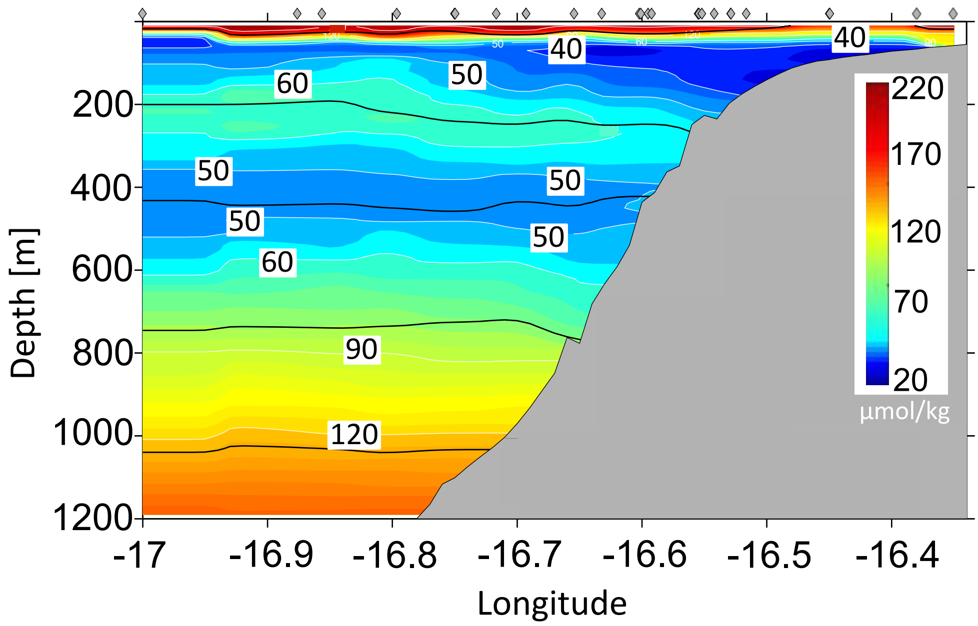

Figure 2: Oxygen in μmol kg^{-1} (color) section along 18°N on the Mauritanian shelf conducted from the RS Meteor cruise M107 in June 2014. Black lines represent density, grey diamonds at the top of the figure locate the positions of the individual CTD casts.

An oxygen minimum is found directly in the core depth of the "dead-zone" eddies between 50 to 150 m with a locally occurrence of minimal oxygen concentrations of around 30-35 μmol kg^{-1} very near to the shelf. Following the theory of the formation processes of ACMEs from McWilliams (1985) and D'Assaro (1988), these near-bottom shelf waters are most likely captured in the eddy cores. The isolated oxygen depleted eddy cores are thus a combination of already low oxygen concentrations from the beginning and the enhanced respiration associated to an oxygen loss with time. We added a paragraph at page 11 line 14 to discuss that in more detail:

“Regions with low oxygen concentrations around 30 µmol kg^{-1} in the depth range between 50-150 m could locally identified at the shelf off Northwest Africa. However, all observed CEs or ACMEs contain a negative oxygen anomaly, partly because they transport water with initial low oxygen concentrations from the coast into the open ocean and additionally because the oxygen consumption in the eddies is more intense then in the surrounding waters (Karstensen et al. 2015a, Fiedler et al. 2015).”

D) The use of the term “accuracy” (Page 4, Lines 13, 17, 20 and 25)

The use of the term “accuracy” in the discussed context on page 4 confused me. To my knowledge, this term refers to the closeness of a measurement to a standard or known value with “high accuracy” referring to “close measurements” and “low accuracy” describing rather poor measurement results. In general, one thus aims at high accuracies when observing natural phenomena and comparing to standard values. Here, the authors argue that the measurement methods have a rather high accuracy, but then state very low absolute values. Since the authors are describing measurement errors in the corresponding paragraph, I suggest they at least consider re-phrasing the sentences to ease the reader’s understanding (e.g. using the term measurement error). I am glad to learn something about the correct use of the term “accuracy”, in case I am wrong here.

- That is right. Accuracy refers the closeness of a measurement to a known reference value. In our case we do not know the exact reference value, thus the usage of the word accuracy is not correct in that context. We used, as suggested from the reviewer, the word “measurement error” instead. Changes are made on page 4, lines 13: 17, 20 and 25:

lines 13: “The resulting measurement error were ≤1.5 µmol kg^{-1}.”
lines 17: “We estimate their measurement error at <3 µmol kg^{-1}.”
lines 20: “The different manufacturers of Argo float oxygen sensors specify their measurement error at least better than 8 µmol kg^{-1} or 5%, whichever is larger.”
lines 25: “We thus estimate their measurement error to about 3 µmol kg^{-1}.”

E) Discussion of other mesoscale features (anticyclonic eddies)

On page 4 (line 30), the authors mention that their work also includes anticyclonic eddies. This eddy type is however not mentioned again. Even though I understand that the oxygen dynamics in eddies are strongly asymmetric between cyclonic and anticyclonic eddies, I wonder whether there is a compensating effect of anticyclonic eddies that stronger ventilate the water column. Could the authors elaborate on this, and maybe include a very brief comment on this in the manuscript?

- In this paper our main focus was to highlight sporadic profiles with very low oxygen concentrations between 50 to 150 m depth in the eastern tropical north Atlantic and that we could associate the profiles to CEs and ACMEs. We further tried to asses the number of such oxygen depleted eddies and the influence on the environment. Anticyclones play a minor role in the story. Furthermore, we think that the compensating effect of anticyclones is relatively small. The depression of isopycnals within anticyclones produces positive oxygen anomalies on depth levels, but on density surfaces these anomalies do not exist. To produce a compensating effect of anticyclones additional diapycnal processes are needed. Nevertheless we agree with the reviewer that during the decay of the eddy probably diapycnal processes are possible and therefore a compensation effect of anticyclones is not unlikely and should be mentioned and discussed in the paper.

First of all we delete the word anticyclone at page 4 line 30 as it is apparently confusing and unnecessary:

“To determine the characteristics of different eddy types from the assembled profiles, we separated them into CEs, ACMEs and the “surrounding area” not associated with eddy-like structures following the approach of Schütte et al. (2015). “

We further decided to discuss the influence on the oxygen budget of anticyclones on page 10 line 27:

“Anticyclonic rotating eddies with a low oxygen core are only observed for modewater type anticyclones (i.e. ACMEs), but not for “normal” anticyclonic eddies which do not show an oxygen depleted eddy core. Instead, the downward bending of isopycnals within “normal” anticyclones produces positive oxygen anomalies on depth levels, whereas on density surfaces these anomalies do not exist.”

and on page 12 line 26:

"In the contrary with additional diapycnal processes (for example during the decay of the eddy) a small compensating effect due to Anticyclones is expectable."

F) Figure 7 and Figure 9:

As I understand, Figure 7 depicts mean profiles of apparent oxygen utilization of all eddies derived from the corresponding initial and actual oxygen profiles assuming a linear oxygen consumption (correct me if I am wrong). According to the corresponding figure caption of Figure 9, this figure shows the same property (µmol/kg/yr instead of µmol/kg/d in Fig7). This confused me because the magnitude shown in these two figures does not compare well. Can the authors comment on the difference between the two figures, if necessary elaborate on the corresponding text (Page 11, Lines 2-4) to better differentiate between the two results and maybe adjust the figure captions to help the reader understand their difference?

- Thank you very much for this comment. We agree with the Reviewer that these pictures were confusing. Hopefully we could clarify some parts with the following explanation and changes in the figure captions. Figure 3 showing both of the mentioned pictures of the Reviewer.

Figure 3a shows the profiles of the apparent oxygen utilization rate of ACMEs and CEs per day in the ETNA region. It is calculated, as mentioned right by the reviewer, by using the propagation time of each eddy and an initial coastal oxygen profile and assuming a linear oxygen consumption (based on depth layers). It gives an indication of how much the oxygen concentration in isolated ACMEs and CEs cores in the ETNA region is reduced due to enhanced respiration.

Whereas figure 3b shows a budget term, namely the oxygen loss profile due to "dead-zone" eddies in the subarea "SOMZ" induced by the ACMEs and CEs on each ispopycnal (converted back to depth). The profiles are derived, by building an oxygen anomaly of each eddy type on density surfaces (O_2'). The derived anomalies are multiplied by the mean number of eddies dissipating in the SOMZ per year (n) and weighted by the area of the eddy compared to the total area of the SOMZ (A_{SOMZ} = triangle in Fig. 1a of the manuscript). Differences in the mean isopycnal layer thickness of each eddy type and the SOMZ are considered by multiplying the result with the ratio of the mean Brunt-Väisälä frequency (N^2) outside and inside the eddy, resulting in an apparent oxygen utilization rate per year (µmol kg^{-1} y^{-1}) due to "dead-zone" eddies in the SOMZ on density layers:

$$aOUR = nO_2' \frac{\pi r_{Eddy}^2 N_{SOMZ}^2}{A_{SOMZ} N_{Eddy}^2}$$

where r_{Eddy} is the mean radius of the eddies.

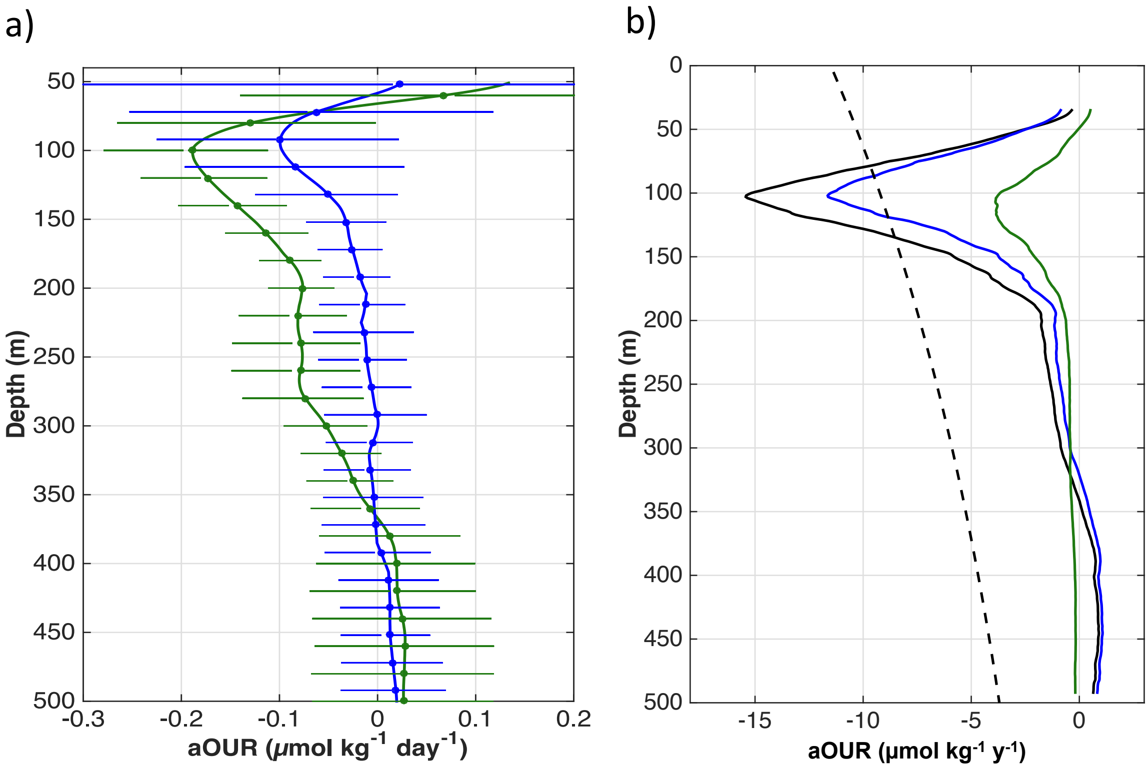

Figure 3: a) Depth profiles of a mean apparent oxygen utilization rate (aOUR, µmol kg^{-1} d^{-1}) within CEs (blue) and ACMEs (green) in the ETNA region with associated standard deviation (horizontal lines). **b)** Depth profile of apparent oxygen utilization rate (aOUR, µmol kg^{-1} y^{-1}) for the Atlantic as published from Karstensen et al. (2008) (dashed black line), the oxygen consumption profile due to "dead-zone" eddies in the SOMZ (solid black line) and the separation into CEs (blue) and ACMEs (green).

We changed the figure caption of figure 7 to:

"Depth profiles of a mean apparent oxygen utilization rate (aOUR, µmol kg^{-1} d^{-1}) within CEs (blue) and ACMEs (green) in the ETNA region with associated standard deviation (horizontal lines). Derived by using the propagation time of each eddy, an initial coastal oxygen profile and the assumption of linear oxygen consumption (based on depth layers)."

Furthermore we changed the figure caption of figure 9 to:

"Depth profile of the apparent oxygen utilization rate (aOUR, µmol kg^{-1} y^{-1}) for the Atlantic as published from Karstensen et al. (2008) (dashed black line). The oxygen consumption profile due to "dead-zone" eddies referenced for the SOMZ (solid black line) and the separation into CEs (blue) and ACMEs (green)."

3 Technical corrections and minor issues

What follows is a list of minor technicalities and other issues I noticed while reviewing. I kindly ask the authors to correct typos and misspellings, reply to my questions and at least consider suggestions and comments on the (re-)phrasing of some sentences that might help to improve the reader's understanding.

Page 1, Lines 24-25: consumption of what?

- We changed page 1 line 24-25 from:

"The locally increased consumption within these eddies represents an essential part of the total consumption in the open tropical Northeast Atlantic Ocean and might be partly responsible for the formation of the shallow oxygen minimum zone."

to

"The locally increased oxygen consumption within these eddies represents a part of the total oxygen consumption in the open tropical Northeast Atlantic Ocean and might be partly responsible for the formation of the shallow oxygen minimum zone."

Page 2, Line 28: consumption of what?

- We changed page 2 line 28 from:

"The ventilation and consumption processes of thermocline waters in the ETNA result in two separate oxygen minima (Fig. 1b): a shallow one with a core depth of about 80 m and a deep one at a core depth of about 450 m."

to

"The ventilation and oxygen consumption processes of thermocline waters in the ETNA result in two separate oxygen minima (Fig. 1b): a shallow one with a core depth of about 80 m and a deep one at a core depth of about 450 m."

Page 3, Line 4: The use of "However" in this sentence is rather confusing since it doesn't contrast to what has been said before. Suggestion: "Due to the absence of other ventilation pathways in this zone, the influence of "dead-zone" eddies on the shallow oxygen minimum budget may be important and a closer examination worth the effort."

- We changed page 2 line 28 from:

"However, due to the absence of other ventilation pathways, the influence of "dead-zone" eddies on the shallow oxygen minimum budget may be elevated and a closer examination worth the effort."

to

"Due to the absence of other ventilation pathways in this zone, the influence of "dead-zone" eddies on the shallow oxygen minimum budget may be important and a closer examination worth the effort."

Page 3, Lines 10-11: As mentioned above, the mere fact that the density structure changes within these structures might add a purely physical contribution to the observed anomalies. Thus, it is not only due to biogeochemical processes that the anomalies are strongest at 100m depth, but rather due to a combination of both a purely physical displacement of the oxycline and biogeochemical processes in the water column above. This sentence should be rephrased.

- We rephrased the sentence page 3 line 10-11 from:

"At about 100 m depth, biogeochemical processes further increase the nutrient and oxygen anomalies with respect to the surrounding waters."

to

"At about 100 m depth, the elevated isopycnals in the eddies are associated to a displacement of the oxycline. In combination with the biogeochemical processes they further increase the nutrient and oxygen anomalies with respect to the surrounding waters."

Page 3, Line 35: as THE last modification

- done

Page 4, Line 27: as A final result

- done

Page 4, Line 41: provided BY (phrasing of sentence is rather confusing)

- We rephrase the sentence Page 4, Line 41 from:

"Data of the SLA and of the geostrophic velocities, derived from the SLA and also provided from AVISO, for the period January 1998 to December 2014 were chosen."

to

"Geostrophic velocities anomalies also provided by AVISO were chosen analog to the SLA for the period January 1998 to December 2014."

Page 5, Line 7: data ARE considered (plural)

- done

Page 5, Line 9: provided BY the NASA. The data WERE

- done

Page 6, Line 1: Full stop missing (... propagation time is derived. We assume a mean. . .)

- done

Page 6, Line 6: less saline and colder water than surrounding water

- done

Page 6, Line 13: Depending on the status of isolation of the eddy, lateral mixing could take place (comma missing)

- done

Page 7, Line 13: At its closest, the eddy center was . . . (comma missing)

- done

Page 7, Line 18: blank space in unit missing

- done

Page 7, Line 22: westward PROPAGATING eddy

- done

Page 7, Line 37: data REVEAL (plural)

- done

Page 8, Lines 26-27: If Figures 8 really depict normalized radial distances (as I assume), I suggest this is mentioned not only in the text, but also in the figure caption. Maybe the axis labeling needs to be adjusted as well.

- That is correct, we add a sentence in the caption of figure 8 page 24, line 4-5:

"Oxygen anomalies derived by both methods are shown against the normalized radial distance."

The same comment goes for Figure 6.

In figure 6 we decided to use unscaled coordinates, because the majority of the selected low oxygen eddies was of similar size.

Page 9, Line 6: for THE ETNA

- done

Page 9, Line 20: As discussed in Schütte et al. (2015), in case . . . (comma missing)

- done

Page 10, Line 6: In the discussed context of eddy generation mechanisms, this formulation could be a little bit confusing, i.e. the word "generate" could be confused with eddy *generation. Suggestion: I assume the authors would like to say "However, both eddy regimes feature eddies which locally ESTABLISH open ocean upwelling systems with high productivity at the surface and enhanced respiration beneath the ML during their westward propagation."*

- We rephrased the sentence page 3 line 10-11 from:

"However, both eddy regimes feature eddies which generate during their westward propagation locally open ocean upwelling systems with high productivity at the surface and enhanced respiration beneath the ML."

to

"However, both eddy regimes feature eddies which locally establish open ocean upwelling systems with high productivity at the surface and enhanced respiration beneath the ML during their westward propagation."

Page 11, Line 2: each year are propagate from the upwelling system near the coast into the SOMZ and dissipate THERE.

- done

Page 11, Line 8-10: This sentence should be re-phrased.

- We rephrased these two sentences from:

"An equivalent view is, by investigating a simple mix ratio of higher with lower oxygen waters in a box model approach of the SOMZ. When averaging the oxygen concentrations of the eddies in the considered depth range, i.e. 50 to 150 m depth, a mean oxygen concentration of 73 (66) µmol kg^{-1} for CEs (ACMEs) is derived."

to

"Instead of describing the effect of the dead-zone eddies on the apparent oxygen conditions as an enhancement of the oxygen utilization as above is to consider a box model approach for the SOMZ. The basis of this box model approach is simply considering the mixing ratio of higher oxygen waters (the ambient conditions) with lower oxygen waters (the "dead-zone" eddies). The average oxygen concentrations within the eddies in the considered depth range, i.e. 50 to 150 m depth, are 73 (66) µmol kg^{-1} for CEs (ACMEs).”

Page 11, Lines 16-19: Lines 16-19 (Attributing the oxygen concentrations. . .) are lacking in clarity and don’t convey the intended message. Line 17 has an unnecessary parenthesis. Needs to be corrected and re-phrased.

- We rephrased these two sentences from:

“Attributing the difference of these values (oxygen concentration respiration without eddies (125 µmol kg^{-1}) and observed values with eddies (118 µmol kg^{-1}) solely decreased due to the dispersion of eddies, we find that around 6% of the observed oxygen concentrations in our box model can be associated to the dispersion of eddies.”

to

“Attributing the difference of these oxygen concentrations on the one hand the SOMZ without eddies (125 µmol kg^{-1}) and on the other hand the observed climatological values in the SOMZ with eddies (118 µmol kg^{-1}), solely to the decrease induced by the dispersion of eddies, we find that around 6% of the observed climatological oxygen concentration in the SOMZ box can be associated with the dispersion of eddies.”

Page 17, Line 7: Maybe a reference to Table 1 might be useful here for more information on M97.

- We repeated the information regarding M97 from table 1 in the figure caption of figure 1, page 17, line 7:

“The black crosses in **a)** indicate the position of the CTD stations taken during the research cruise M97 in boreal summer 2013, which are used to calculate the mean vertical oxygen profile shown in **b)**.”

Page 17, Line 9: around 80m depth (not plural)

- done

Page 18, Line 3: Map of THE ETNA

- done

Page 22, Line 4: b) CEs (use the introduced acronym)

- done

Page 22, Line 5: when compared TO the SLA and SST

- done

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