“Characterization of “dead-zone” eddies in the eastern tropical North Atlantic”

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Dear Editor,

We would like to thank you for the overall positive evaluation of our manuscript and your remarks, which will surely help to improve the manuscript. We try to strengthen the manuscript by clarifying some paragraphs (for example putting results into a broader context) in particular in the introduction and discussion. In the following we address your remarks and how we intend to address the concerns in the manuscript. After that we include the Final Author comments of the reviewer #1 and reviewer #2. At the end a marked-up version of the manuscript is attached.

Comments of Denis Gilbert

1.

P. 8, lines 20-21 of original manuscript: The confidence interval for the CE oxygen trend includes zero (0.10 ± 0.12). Given this, you cannot say that oxygen is decreasing within the CE. I propose that this sentence might be rephrased as “On average the oxygen concentration decreases by about 0.19 ± 0.08 µmol kg^{-1} *d*$^{-1}$ *in the core of an isolated ACME, but has no significant trend in the core of an isolated CE (0.10 ± 0.12 µmol kg*$^{-1}$ *d*$^{-1}$*)”.*

- Yes, that is true. We decided to take your suggested sentence and changed p: 9, lines 39-40 to “On average the oxygen concentration decreases by about 0.19 ± 0.08 µmol kg^{-1} d^{-1} in the core of an isolated ACME, but has no significant trend in the core of an isolated CE (0.10 ± 0.12 µmol kg^{-1} d^{-1})”.

2.

Referee # 1’s dislike of the term “dead-zone” is shared by many scientists because these low-oxygen waters are certainly not devoid of life. Given this, please make sure that double quotation marks always accompany the expression “dead-zone” in the final version of the manuscript, so that people understand this expression is a just a metaphor.

- We decide to substitute nearly all “dead-zones” within the manuscript through low-oxygen eddies. If we used the word “dead-zone” we always accompany the expression with double quotation marks.

3.

In your response to Referee # 1 (p.8, lines 24-26), you mention your rationale for picking a 40 µmol kg^{-1} *d*$^{-1}$

hypoxic threshold. Please include this rationale in the revised manuscript.

- We included the explanation why we choose 40 µmol µmol kg^{-1} as a threshold at two positions in the manuscript. P. 2. lines 8-9:

"Traditionally the ETNA is considered to be "hypoxic", with minimal oxygen concentrations of marginally below 40 µmol kg^{-1} (e.g. Stramma et al. (2009)) (Fig. 1a)."

and P. 27 lines 28-33:

"The pelagic zones of the ETNA are traditionally considered to be "hypoxic", with minimal oxygen concentrations of marginally below 40 µmol kg^{-1} (Brandt et al., 2015; Karstensen et al., 2008; Stramma et al., 2009). This is also true for the upper 200 m (Fig. 1). However, single oxygen profiles taken from various observing platforms (ships, moorings, gliders, floats) with oxygen concentrations in the range of severe hypoxia (< 20 µmol kg^{-1}) and even anoxia (~ 1 µmol kg^{-1}) conditions and consequently below the canonical value of 40 µmol kg^{-1} (Stramma et al., 2008) are found in a surprisingly high number (in total 180 profiles) in the ETNA."

4.

In your response to Referee # 1 (p.18, lines 10-11), I find this proposed new sentence confusing, especially this bit: "analog to the SLA".

- We rephrased the sentence, P.5 lines 17-18 to:

"The SLA and geostrophic velocity anomalies also provided by AVISO were chosen for the time period January 1998 to December 2014."

5.

In Figure 2 of the authors' reply to anonymous referee #1, please add text labels to the black isopycnal contour lines.

- Done.

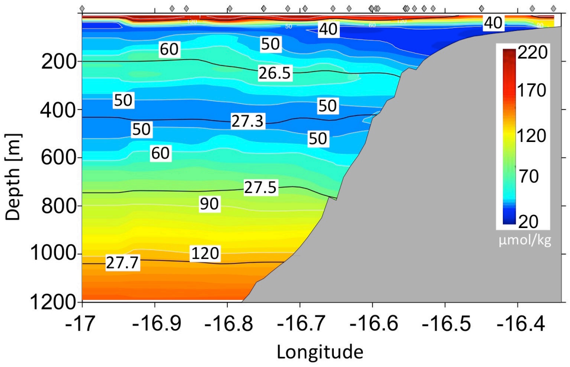

Figure 2: Oxygen in µmol kg^{-1} (color) section along 18°N on the Mauritanian shelf conducted from the RS Meteor cruise M107 in June 2014. Black lines represent density, grey diamonds at the top of the figure locate the positions of the individual CTD casts.

6.

The new Figure 1 included in your response to Referee # 2 presents useful additional information relative to Figure 6 of your original manuscript. You might like to consider producing a figure that would present SLA, SST, SSS and Chl a composites for cyclones, anticyclones and ACMEs, thus combining the information found in both of these figures.

- We decided not to show a figure, which includes Sea Surface Salinity (SSS) and the surface signatures from "normal" anticyclones because of several reasons: First, we published such a figure in Schütte et al., 2016 "Occurrence and characteristics of mesoscale eddies in the tropical northeastern Atlantic" (Figure 11). Second, we did not mention "normal" anticyclones in the manuscript and third we did not introduce or use SSS in the manuscript.

7.

On page 6 of your response to Referee # 2, you wrote that you changed figure 5 of the original manuscript by substituting the temperature with salinity. I suggest that in the revised manuscript, this particular figure should present both temperature and salinity panels in addition to meridional velocity and oxygen. Also, I must say that I preferred seeing the oxygen contours of the original figure 5, as they present more information than only oxygen concentration at a nominal depth of 120 m that you presented in Figure 2 or your response to Referee # 2.

- We changed the figure and now show velocity, salinity, temperature and oxygen. But we decide to not show the oxygen contours, because it is based only on one instrument in 120 m depth. In the original figure I assumed saturation at the surface and interpolated in between, but my Co-Authors mentioned that it is not correct to show contourlines based on only one measuring device.

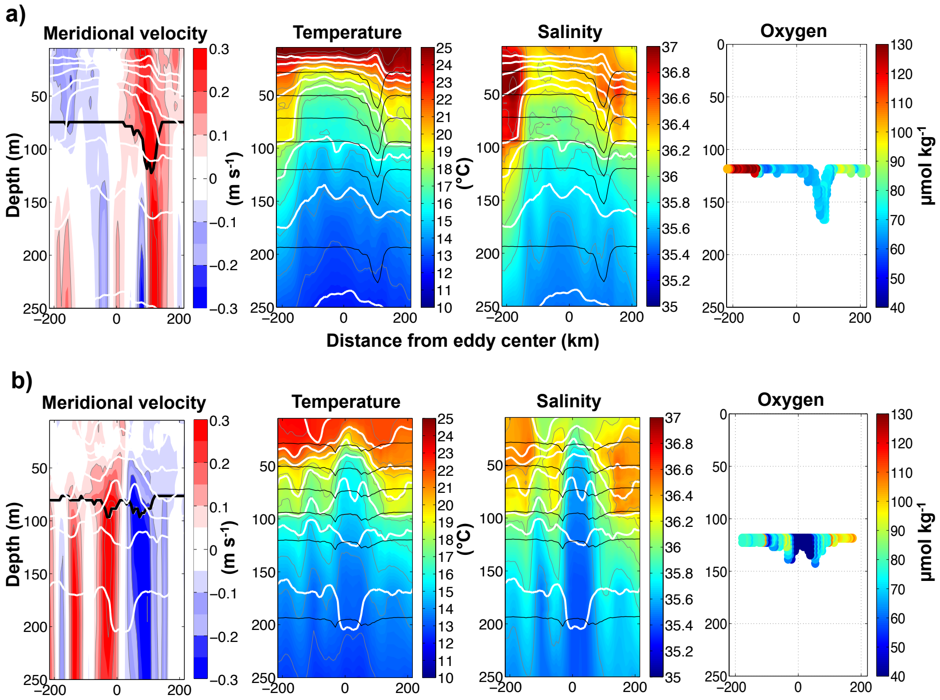

Figure 5: Meridional velocity, temperature, salinity and oxygen of an exemplary **a)** CE and **b)** ACME at the CVOO mooring. Both eddies passed the CVOO on a westward trajectory with the eddy center north of the mooring position (CE 20 km, ACME 13 km). The CE passed the CVOO from October to December 2006 and the ACME between January and March 2007. The thick black lines in the velocity plots indicate the position of an upward looking ADCP. Below that depth calculated geostrophic velocity is shown. The white lines represent density surfaces inside the eddies and the thin grey lines isolines of temperature and salinity, respectively. Thin black lines in the temperature and salinity plot mark the vertical position of the measuring devices. On the right time series of oxygen is shown from the one sensor available at nominal 120 m depth.

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).

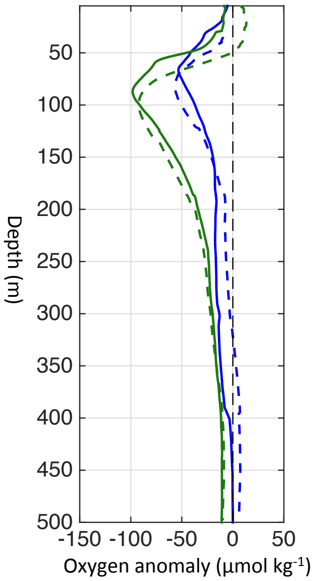

Figure 1: Mean Oxygen anomaly of ACMEs (green) and CEs (blue) derived on isopycnal surfaces (dashed lines) and isobars (continuous lines). The anomaly on isopycnal surfaces (dashed lines) are derived, by building an oxygen anomaly of each eddy type on density surfaces. Afterwards a transformation in 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).

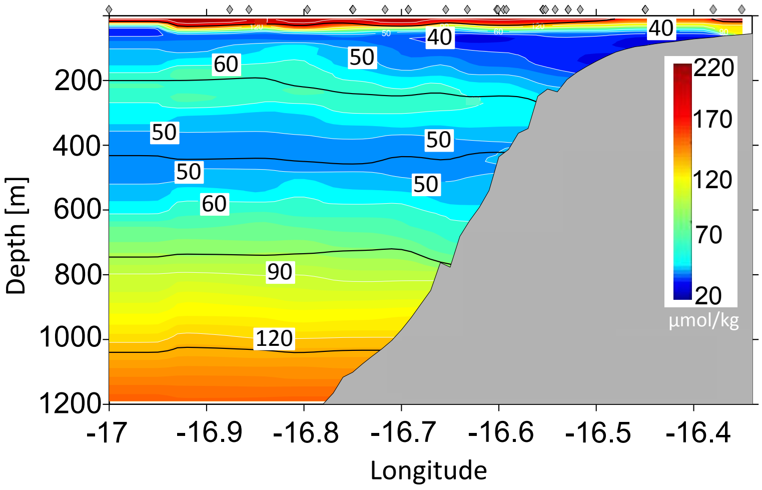

Figure 2: Oxygen in µmol kg^{-1} (color) section along 18°N on the Mauritanian shelf conducted from the RS Meteor cruise M107 in June 2014. Black lines represent density, grey diamonds at the top of the figure locate the positions of the individual CTD casts.

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.

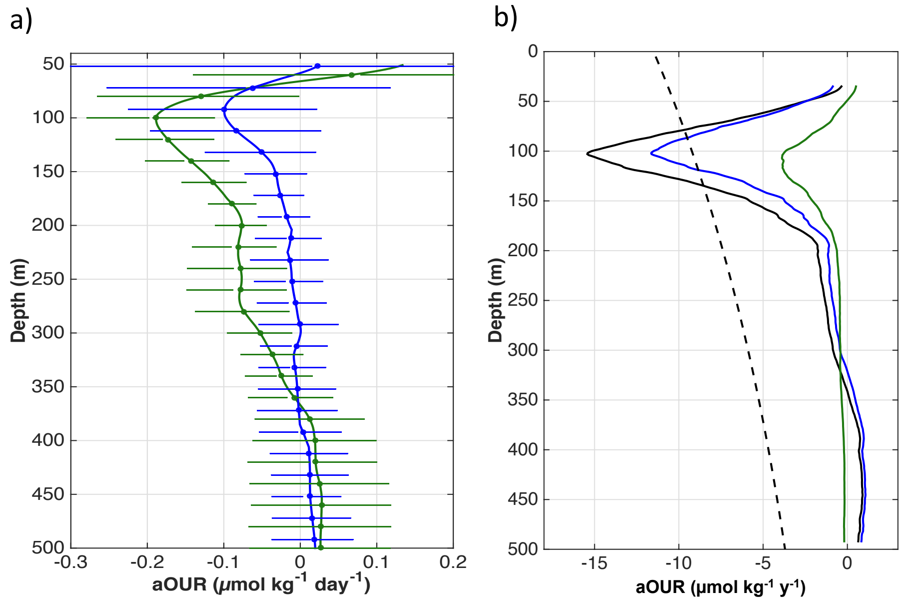

Figure 3: a) Depth profiles of a mean apparent oxygen utilization rate (aOUR, µmol kg^{-1} d^{-1}) within CEs (blue) and ACMEs (green) in the ETNA region with associated standard deviation (horizontal lines). **b)** Depth profile of apparent oxygen utilization rate (aOUR, µmol kg^{-1} y^{-1}) for the 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 re-phrased.

- 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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Anonymous Referee #2

Main Comments

Based on a set of data from different platforms, the authors analyze the impact of mesoscale eddies in the formation of the shallow oxygen minimum in the eastern tropical North Atlantic (which differs from the deepest minimum located below 400 m, that characterize the oxygen minimum zone of that region). Another central idea of the work is that the shallow oxygen minimum (~ 80 m depth) observed in some kind of eddies, is not due to the transport of waters with low oxygen carried by the eddies from the coastal regions, but is generated by the internal dynamics, particularly in cyclonic and subsurface anticyclonic eddies (or anticyclone modewater eddies). Within both types of eddies, the shallow isopycnal surfaces (located about 70-100 m depth) rise, favoring biological productivity near the surface (documented by positive chlorophyll anomalies estimated from satellite observations). The export of organic matter back into the subsurface would, thus, result in a relatively high rate of respiration leading to the formation of a shallow minimum of dissolved oxygen. Eddies effectively may "accumulate" this effect by transporting the water as they move.

I think the paper is an important contribution to the understanding of the dynamics of the biogeochemistry in the study region and highlights the effects of a special class of eddies (ACME), which is possibly relevant to other regions where the presence of subsurface anticyclonic eddies is frequent. The work is fairly well structured and in general, the argument is consistent and can be followed easily. It seems that the authors have done a good job and in my opinion is an important contribution to understanding the hydrography and the biogeochemistry in that region, and it is also a contribution on the role of mesoscale eddies in the ocean. However, there are two issues that seem to me that should be discussed:

- Thank you very much for this positive evaluation.

(1) Subsurface anticiclonic eddies may not have a proper manifestation in satellite altimetry. For example, contrasting Figure 5a for the cyclonic eddy and that for the ACME (Figure 5b), the latter has very small speed anomalies near the surface, and thus the sea level (and geostrophic velocity) anomalies should be small. This should be a relatively major problem if geostrophic velocities, based on altimetry, are used to identify, define the contours of these eddies and to position oxygen profiles.

- It is correct that ACMEs have a weak surface signature, which makes them more difficult to be detected and tracked by satellite altimetry compared to normal anticyclonic/cyclonic eddies. In the present analysis only eddies detected with a common Sea Level Anomaly (SLA) threshold are followed with the tracking algorithms. Resulting eddy composites of SLA, Sea Surface Temperature (SST) and Seas Surface Salinity (SSS) are shown in Figure 1. The weaker anomaly of ACMEs compared to the other types of eddies is apparent. However, as there should exist also ACMEs with weak or even no SLA signature, we expect that the frequency of occurrence of ACMEs is underestimated. We included a corresponding statement in the text.

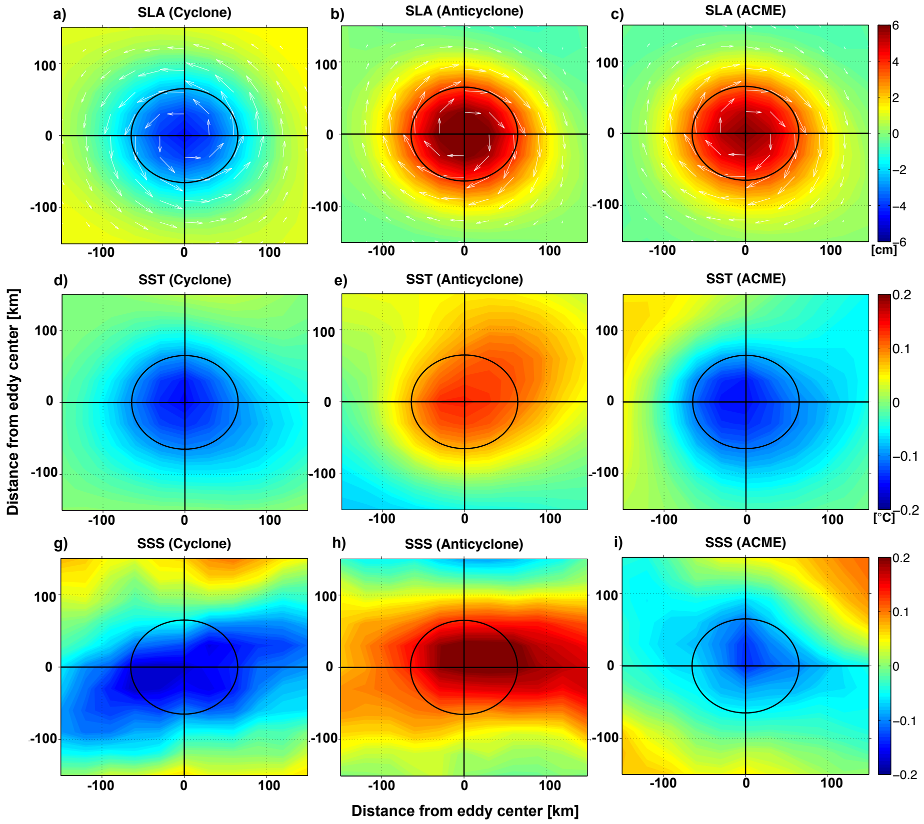

Figure 1: Sea Level Anomaly (SLA), Sea Surface Temperature (SST) and Sea Surface Salinity anomalies of the composite cyclone, anticyclone and ACME in the tropical Atlantic off northwest Africa. SLA (color) and the associated geostrophic velocity (white arrows) are shown for each eddy type in **a)**, **b)** and **c)**; SST anomaly in **d)**, **e)** and **f)**; and SSS anomaly in **g)**, **h)** and **i)**, respectively. The circles mark the mean eddy radius. Taken from Schütte et al. (2016).

We now added a sentence on page 10 line 23 that point out the weakness in the statistic assessment:

“As discussed in Schütte et al. (2016) we expect that the number of ACMEs is underestimated because of the possible existence of ACMEs with a weak surface signature in SLA data.”

(2) The authors argue that the water remains fairly isolated within eddies. Although several studies (based on observation, numerical modeling and theoretical models) have shown that this phenomenon is correct, this is generally true for high latitude or subtropical eddies. Eddies ability to trap and transport water could be lower in the more linear equatorial region. This should be an issue to consider, at least for the southern part of the study area, located south of 12° N.

- Thank you for the comment, this is a very interesting point. In general we where surprised to detect long lived low oxygen eddies in the region south of 12°N. At this stage we simply have to accept the fact that the low oxygen levels are present in these eddies and, as we see from the T/S characteristics, the water seems not to originate from the eastern boundary region as it is the case for eddies found further north. Following the trajectories it seems that the ACMEs are generated in the open ocean somewhere in the region between 5°N and 7°N. However, the eddies seem to be isolated long enough (and respiration is intense enough) to generate an oxygen depleted core during their westward propagation. Clearly, further studies on their generation mechanism and their characteristics are required.

We added one sentence to discuss less isolation in lower latitudes at page 10 line 17-19:

"The occurrence of oxygen depleted eddies south of 12°N is rather astonishing, as due to the smaller Coriolis parameter closer to the equator the southern eddies should be more short-lived and less isolated compared to eddies further north."

Another (positive) comment is that given the extensive data set used in the study, the authors present quantitative information and in some cases, allows them to estimate statistical errors based on the standard deviation. In general, dissolved oxygen data is relatively scarce in large areas of the open ocean, this work is undoubtedly also a contribution in this regard.

- As mentioned right by the reviewer the dissolved oxygen data is relatively scare and flawed with large errors (Argo-floats) in wide areas of the open ocean. Due to the combination of the shipboard, mooring, glider and Argo measurements a satisfying dataset in the eastern tropical Atlantic could be obtained. But this could only be done due to the extensive observation of the eastern tropical north Atlantic in the recent years (25 research cruises, 1 longtime mooring and several glider deployments).

Other minor comments

In the first paragraph of the introduction, the references to support some general sentences do not seem to me the most appropriate (for example, lines 6, 7 and 8). I do not mean that the argument is fallacious (magister dixit), but I think there are other studies that might have greater authority to support what is mentioned.

- That is correct. We include other references at page 2 line 6, 7 and 8:

Line 6:

"In particular, the eastern boundary current system close to the Northwest African coast is a region where northeasterly trade winds force coastal upwelling of cold, nutrient rich waters, resulting in high productivity (Bakun et al., 1990; Pauly and Christensen, 1995; Messié et al., 2009; Lachkar and Gruber, 2012) "

Line 7, 8:

”The ETNA region is characterized by a weak large-scale circulation (Mittelstaedt, 1991; Brandt et al., 2015), but pronounced mesoscale variability (here referred to as eddies) acting as a major transport process between coastal waters and the open ocean (Marchesiello et al., 2003; Correa-Ramirez et al., 2007; Capet et al., 2008a; Schütte et al., 2015; Thomsen et al., 2015; Nagai et al. 2015).”

P4. L 1-6. Time lag for optode sensors is rather long given important differences between glider dives and climbs. How were the optode data from gliders corrected. Page 4 lines 14-15 and 22-23. Aanderaa optodes were really calibrated (I mean to change the calibration constants) using CTD cast or the casts were used to estimate the accuracy of the optodes.

- We added more information on the time constant problem on page 4 line 23-24:

“All four autonomous gliders were equipped with Aanderaa optodes (3830) installed in the aft section of the devices. A recalibration of the Optode calibration coefficients were determined on dedicated CTD casts following the procedures of Hahn et al. (2014). These procedures also estimates and correct the delays caused by the slow optode response time (more detailed information can be found in Hahn et al. 2014; Thomsen et al., 2015).”

- The CTD casts are used to change the calibration constants of the Aanderaa optodes. We add one sentence at page 4 line 16 to give that information:

“Optode calibration coefficients were determined on dedicated CTD casts and additional calibrated in the laboratory with water featuring 0% air saturation before deployment and after recovery following the procedures described by Hahn et al. (2014): ”

P7. L24 (and 16). Salinity in the core of ACME is mentioned as an important variable, why did you decided not to show it.

- That is right. We changed figure 5 and substitute the temperature with salinity (see figure 2).

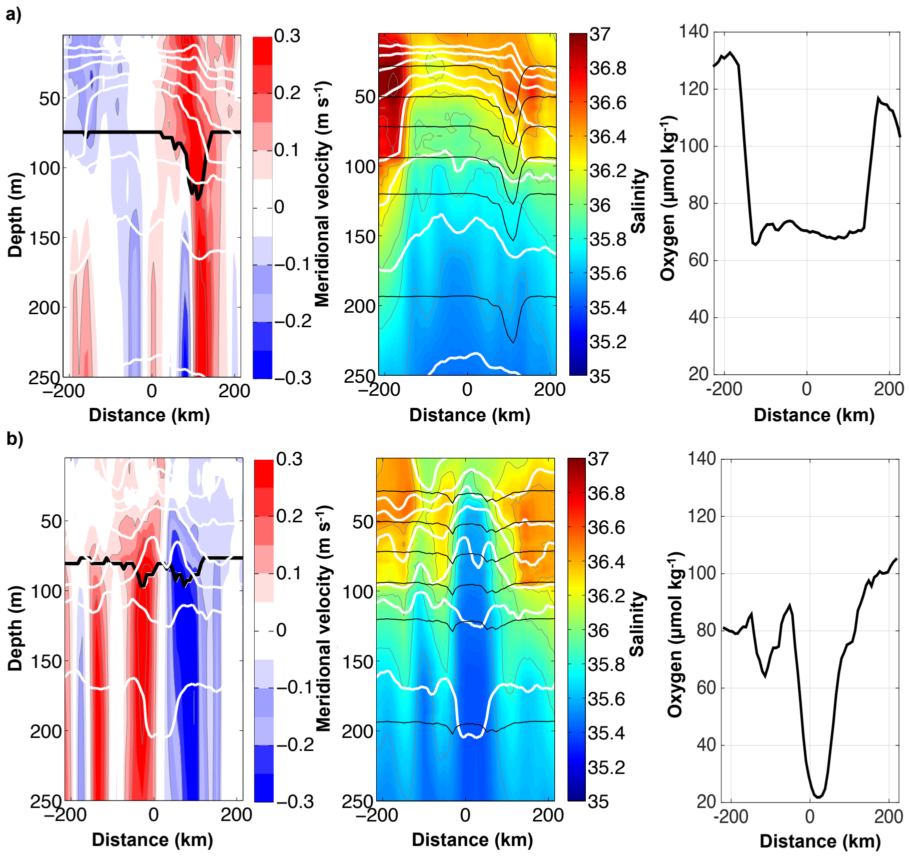

Figure 2: Meridional velocity, salinity and oxygen of an exemplary **a)** CE and **b)** ACME at the CVOO mooring. Both eddies passed the CVOO on a westward trajectory with the eddy center north of the mooring position (CE 20 km, ACME 13 km). The CE passed the CVOO from October to December 2006 and the ACME between January and March 2007. The thick black lines in the velocity plots indicate the position of an upward looking ADCP. Below that depth calculated geostrophic velocity is shown. The white lines represent density surfaces inside the eddies and the thin grey lines isolines of salinity. Thin black lines in the salinity plot mark the vertical position of the measuring devices. On the right time series of oxygen is shown from one sensor available at nominal 120 m depth.

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Characterization of “dead-zone” eddies in the eastern tropical North Atlantic

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Abstract

Localized open-ocean low–oxygen “dead-zones” in the eastern tropical North Atlantic are recently discovered ocean features that can develop in dynamically isolated water masses within cyclonic eddies (CE) and anticyclonic modewater eddies (ACME). Analysis of a comprehensive oxygen dataset obtained from gliders, moorings, research vessels and Argo floats reveals that “dead-zone” eddies are found in surprisingly high numbers and in a large area from about 4°N to 22°N, from the shelf at the eastern boundary to 38°W. In total, 173 profiles with oxygen concentrations below the minimum background concentration of 40 µmol kg^{-1} could be associated with 27 independent eddies (10 CEs; 17 ACMEs) over a period of 10 years. Lowest oxygen concentrations in CEs are less than 10 µmol kg^{-1} while in ACMEs even suboxic (< 1 µmol kg^{-1}) levels are observed. The oxygen minimum in the eddies is located at shallow depth from 50 to 150 m with a mean depth of 80 m. Compared to the surrounding waters, the mean oxygen anomaly in the core depth range (50 and 150 m) for CEs (ACMEs) is -38 (-79) µmol kg^{-1}. North of 12°N, the oxygen depleted eddies carry anomalously low salinity water of South Atlantic origin from the eastern boundary upwelling region into the open ocean. Here water mass properties and satellite eddy tracking both point to an eddy generation near the eastern boundary. In contrast, the oxygen depleted eddies south of 12°N carry weak hydrographic anomalies in their cores and seem to be generated in the open ocean away from the boundary. In both regions a decrease in oxygen from east to west is identified supporting the en-route creation of the low-oxygen core through a combination of high productivity in the eddy surface waters and an isolation of the eddy cores with respect to lateral oxygen supply. Indeed, eddies of both types feature a cold sea surface temperature anomaly and enhanced chlorophyll concentrations in their center. The low-oxygen core depth in the eddies aligns with the depth of the shallow oxygen minimum zone of the eastern tropical North Atlantic. Averaged over the whole area an oxygen reduction of 7 µmol kg^{-1} in the depth range of 50-150 m (peak reduction is 16 µmol kg^{-1} at 100 m depth) can be associated to the dispersion of the eddies. Thus the locally increased oxygen consumption within the eddy cores enhances the total oxygen consumption in the open eastern tropical North Atlantic Ocean and seem to be an important contributor to the formation of the shallow oxygen minimum zone.

Florian Schütte 8.9.16 10:24
Gelöscht: t…opical ... [1]

Florian Schütte 26.4.16 13:15
Gelöscht: …lbrechts- …niversität zu ... [2]

Florian Schütte 8.9.16 10:19
Gelöscht: N…rtheast…Atlantic are r ... [3]

1. Introduction

The eastern tropical North Atlantic (ETNA: 4°N to 22°N and from the shelf at the eastern boundary to 38°W, Fig. 1) off Northwest Africa is one of the biologically most productive areas of the global ocean (Chavez and Messié, 2009; Lachkar and Gruber, 2012). In particular, the eastern boundary current system close to the Northwest African coast is a region where northeasterly trade winds force coastal upwelling of cold, nutrient rich waters, resulting in high productivity (Bakun, 1990; Lachkar and Gruber, 2012; Messié et al., 2009; Pauly and Christensen, 1995). The ETNA is characterized by a weak large-scale circulation and instead dominated by mesoscale variability (here referred to as eddies) (Brandt et al., 2015; Mittelstaedt, 1991). Traditionally the ETNA is considered to be "hypoxic", with minimal oxygen concentrations of marginally below 40 µmol kg^{-1} (e.g. Stramma et al. (2009)) (Fig. 1a). The large-scale 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 (Brandt et al., 2015; Karstensen et al., 2008). The deep minimum is the core of the OMZ and is primarily created by sluggish ventilation of the respective isopycnals (Luyten et al., 1983; Wyrtki, 1962). It extends from the eastern boundary into the open ocean and is located in the so-called shadow zone of the ventilated thermocline, with the more energetic circulation of the subtropical gyre in the north and the equatorial region in the south (Karstensen et al., 2008; Luyten et al., 1983). The shallow oxygen minimum intensifies from the equator towards the north with minimal values near the coast at about 20°N (Brandt et al., 2015) (Fig. 1a). It is assumed that the shallow OMZ originates from enhanced biological productivity and an increased respiration associated with sinking particles in the water column (Brandt et al., 2015; Karstensen et al., 2008; Wyrtki, 1962).

The eddies act as a major transport agent between coastal waters and the open ocean (Schütte et al., 2016), which is a well-known process for all upwelling areas in the world oceans (Capet et al., 2008; Chaigneau et al., 2009; Correa-Ramirez et al., 2007; Marchesiello et al., 2003; Nagai et al., 2015; Schütte et al., 2016; Thomsen et al., 2015). In the ETNA, most eddies are generated near the eastern boundary, Rossby wave dynamics and the basin scale circulation force these eddies to propagate westwards (Schütte et al., 2016). Open ocean eddies with particularly high South Atlantic Central Water (SACW) fractions in their cores have been found far offshore in regions dominated by the much saltier North Atlantic Central Water (NACW) (Karstensen et al., 2015; Pastor et al., 2008). Weak lateral exchange across the eddy boundaries is most likely the reason for the isolation (Schütte et al., 2016). The impact of eddy transport on the coastal productivity (equivalent to other upwelling related properties) was investigated by Gruber et al. (2011), who were able to show that high (low) eddy driven transports of nutrient-rich water from the shelf into the open ocean results in lower (higher) biological production on the shelf. Besides acting as export agents for coastal waters and conservative tracers, coherent eddies have been reported to establish and maintain an isolated ecosystem changing non-conservative tracers with time (Altabet et al., 2012; Fiedler et al., 2016; Hauss et al., 2016; Karstensen et al., 2015; Löscher et al., 2015). Coherent/isolated mesoscale eddies can exist over periods of several months or even years (Chelton et al., 2011). During that time the biogeochemical conditions within these eddies can evolve very different to the surrounding water masses (Fiedler et al., 2016). Hypoxic to suboxic oxygen levels have been observed in cyclonic eddies (CEs) and anticyclonic modewater eddies (ACMEs) at shallow depth and just beneath the mixed layer (about 50 to 100 m) (Karstensen et al., 2015). The creation of the low-oxygen cores in the eddies have been attributed to the combination of several factors (Karstensen et al., 2015): high productivity in the surface waters of the eddy (Hauss et al., 2016; Löscher et al., 2015), enhanced respiration of sinking organic material at

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Florian Schütte 8.9.16 12:13
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Florian Schütte 5.9.16 14:30
Gelöscht: n

Florian Schütte 10.8.16 15:49
Gelöscht: (ETNA: 4°N to 22°N and from the shelf at the eastern boundary to 38°W, Fig. 1)

Florian Schütte 5.9.16 14:39
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Florian Schütte 10.8.16 15:41
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Florian Schütte 8.9.16 17:36
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Florian Schütte 8.9.16 18:50
[1] verschoben (Einfügung)

Florian Schütte 8.9.16 18:51
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Florian Schütte 8.9.16 18:51
Gelöscht: In the ETNA

Florian Schütte 8.9.16 18:51
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Florian Schütte 8.9.16 22:45
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Gelöscht: . ... [4]

Florian Schütte 8.9.16 12:20
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Gelöscht: in the ETNA

Florian Schütte 8.9.16 12:22
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Florian Schütte 8.9.16 16:55
Gelöscht: Enhanced vertical fluxes of nutrients and the dynamical isolation of the eddy interior from surrounding waters create very distinct

Florian Schütte 3.5.16 13:13
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Florian Schütte 8.9.16 16:56
Gelöscht: caused by a combination o ... [5]

Florian Schütte 8.9.16 16:57
Gelöscht: , just beneath the mixed layer

Florian Schütte 8.9.16 16:58
Gelöscht: has been

subsurface depth (Fiedler et al., 2016; Fischer et al., 2016) and an "isolation" of the eddy core from exchange with surrounding and better oxygenated water (Karstensen et al., 2016). The intermittent nature of the oxygen depletion and the combination of high respiration with sluggish oxygen transport resamples what is known as "dead-zone" in other aquatic system (lakes, shallow bays), and therefore the term "dead-zone eddies" has been introduced (Karstensen et al., 2015). So far the profound impacts on behaviour of microbial (Löscher et al., 2015) and metazoan (Hauss et al., 2016) communities has been documented inside the eddies. For example, the appearance of denitrifying bacteria, typically absent from the open tropical Atlantic, has been observed (Löscher et al., 2015) via the detection of nirS gene transcripts (the key functional marker for denitrification). However, the close-to-Redfield N:P stoichiometry in ACMEs in the ETNA (Fiedler et al., 2016), does not suggest a large-scale net loss of bioavailable nitrogen via denitrification. The key point in changing non-conservative tracers in the eddy cores is the physical-biological coupling, which is strongly linked to the vertical velocities of submesoscale physics, stimulating primary production (upward nutrient flux) in particular under oligotrophic conditions (Falkowski et al., 1991; Levy et al., 2001; McGillicuddy et al., 2007). The detailed understanding of the physical and biogeochemical processes and their linkage in eddies is still limited (Lévy et al., 2012). Consequently the relative magnitude of eddy-dependent vertical nutrient flux, primary productivity and associated enhanced oxygen consumption or nitrogen fixation/denitrification in the eddy cores and continuously the contribution to the large-scale oxygen or nutrient distribution is fairly unknown.

In order to further investigate the physical, biogeochemical and ecological structure of "dead-zone" eddies, an interdisciplinary field study was carried out in winter 2013/spring 2014 in the ETNA, north of Cape Verde, using dedicated ship, mooring and glider surveys supported by satellite and Argo float data. The analysis of the field study data revealed surprising results regarding eddy meta-genomics (Löscher et al., 2015), zooplankton communities (Hauss et al., 2016), carbon chemistry (Fiedler et al., 2016) and nitrogen cycling (Karstensen et al., 2016). Furthermore, analyses of particle flux time series, using sediment trap data from the Cape Verde Ocean Observatory (CVOO), were able to confirm the impact of highly productive "dead-zone" eddies on deep local export fluxes (Fischer et al., 2016). In this paper we investigate "dead-zone" eddies detected from sea level anomaly (SLA) and sea surface temperature (SST) data based on methods described by Schütte et al. (2016). We draw a connection between the enhanced consumption and associated low-oxygen concentration in eddy cores and the formation of the regional observed shallow oxygen minimum zone. To assess the influence of oxygen depleted eddies on the oxygen budget of the upper water column, a sub-region between the ventilation pathways of the subtropical gyre and the zonal current bands of the equatorial Atlantic was chosen and investigated in more detail. This region includes the most pronounced shallow oxygen minimum and is in the following referred to as shallow oxygen minimum zone (SOMZ, Fig. 1a). The probability of "dead-zone" eddy occurrence per year is more or less evenly distributed in the ETNA (Fig. 1a). Particularly in the SOMZ there seems to be neither a distinctly high nor an explicitly low "dead-zone" eddy occurrence. 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 determine the average characteristics of "dead-zone" eddies in the ETNA, addressing their hydrographic features as well as occurrence, distribution, generation and frequency. Based on oxygen anomalies and eddy coverage we estimate their contribution to the oxygen budget of the SOMZ. The paper is organized as follows. Section 2 addresses the different in-situ measurements, satellite products and methods we use. Our results are presented in section 3, discussed in section 4 and summarized in section 5.

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Gelöscht: conditions,.

Florian Schütte 8.9.16 17:07
Gelöscht: (Löscher et al., 2015)

Florian Schütte 11.8.16 10:26
Gelöscht: As such, these eddies resemble an environment similar to the "dead-zone" formation in coastal areas and lakes and therefore have been termed "dead-zone" eddies (Karstensen et al., 2015). ... [6]

Florian Schütte 8.9.16 18:31
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Florian Schütte 8.9.16 18:32
Gelöscht: anomalies

Florian Schütte 8.9.16 18:33
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Florian Schütte 8.9.16 23:38
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[1] nach oben verschoben: Most eddies are generated near the eastern boundary, Rossby wave dynamics and the basin scale circulation force these eddies to propagate westwards.

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Florian Schütte 8.9.16 18:31
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2. Data and methods

2.1 In-situ data acquisition

For our study we employ a quality-controlled database combining shipboard measurements, mooring data and Argo float profiles as well as autonomous glider data taken in the ETNA. For details on the structure and processing of the database see . For this study we extended the database in several ways. The region was expanded to now cover the region from 0° to 22° N and 13° W to 38° W (see Fig. 2). We then included data from five recent ship expeditions (RV Islandia ISL_00314, RV Meteor M105, M107, M116, M119), which sampled extensively within the survey region. Data from the two most recent deployment periods of the CVOO mooring from October 2012 to September 2015 as well as Argo float data for the years 2014 and 2015 were also included. Furthermore, oxygen measurements of all data sources were collected and integrated into the database. As the last modification of the database we included data from four autonomous gliders that were deployed in the region and sampled two ACMEs and one CE. Glider IFM11 (deployment ID: ifm11_depl01) was deployed on March 13, 2010. It covered the edge of an ACME on March 20 and recorded data in the upper 500 m. Glider IFM05 (deployment ID: ifm05_depl08) was deployed on June 13, 2013. It crossed a CE on July 26 and recorded data down to 1000 m depth. IFM12 (deployment ID: ifm12_depl02) was deployed on January 10, 2014 north of the Cape Verde island São Vicente and surveyed temperature, salinity and oxygen to 500 m depth. IFM13 (deployment ID: ifm13_depl01) was deployed on March 18, 2014 surveying temperature, salinity and oxygen to 700 m depth. IFM12 and IFM13 were able to sample three complete sections through an ACME. All glider data were internally recorded as a time series along the flight path, while for the analysis the data was interpolated onto a regular pressure grid of 1 dbar resolution (see also Thomsen et al., 2015). Gliders collect a large number of relatively closely spaced slanted profiles. To reduce the number of dependent measurements, we limited the number of glider profiles to one every 12 hours. All four autonomous gliders were equipped with Aanderaa optodes (3830) installed in the aft section of the devices. A recalibration of the Optode calibration coefficients were determined on dedicated CTD casts following the procedures of (Hahn et al., 2014). These procedures also estimates and correct the delays caused by the slow optode response time (more detailed information can be found in Hahn et al. (2014); Thomsen et al. (2015)). As gliders move through the water column the oxygen measurements are not as stable as those from moored optodes analyzed by Hahn et al. (2014). We thus estimate their measurement error to about 3 µmol kg^{-1}. The processing and quality control procedures for temperature and salinity data from shipboard measurements, mooring data and Argo floats has already been described by Schütte et al. (2016). The processing of the gliders' temperature and salinity measurements is described in Thomsen et al. (2015). Oxygen measurements of the shipboard surveys were collected with Seabird SBE 43 dissolved oxygen sensors attached to Seabird SBE 9plus or SBE 19 conductivity-temperature-depth (CTD) systems. Sampling and calibration followed the procedures detailed in the GO-SHIP manuals (Hood et al., 2010). The resulting measurement error were ≤1.5 µmol kg^{-1}. Within the CVOO moorings, a number of dissolved oxygen sensors (Aanderaa optodes type 3830) were used.

Calibration coefficients for moored optodes were determined on dedicated CTD casts and additional calibrated in the laboratory with water featuring 0% air saturation before deployment and after recovery following the procedures described by Hahn et al. (2014). We estimate their measurement error at <3 µmol kg^{-1}. For the few Argo floats equipped with oxygen sensors a full calibration is usually not available and only a visual inspection of the profiles was done before including the data into the database. 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. Note

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Florian Schütte 5.9.16 15:12
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Florian Schütte 5.9.16 15:12
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Florian Schütte 8.9.16 22:56
Gelöscht: 5

Florian Schütte 8.9.16 22:59
Gelöscht:

Florian Schütte 26.4.16 13:22
Gelöscht: accuracies

Florian Schütte 12.8.16 11:37
Gelöscht: The optodes were calibrated at dedicated CTD casts and in the laboratory with water featuring 0% air saturation before deployment and after recovery following the procedures described by Hahn et al. (2014).

Florian Schütte 26.4.16 13:22
Gelöscht: accuracies

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Florian Schütte 7.9.16 15:02
Gelöscht: after a strict visual control removing suspicious profiles.

Florian Schütte 26.4.16 13:22
Gelöscht: accuracy

that early optodes can be significantly outside of this accuracy range, showing offsets of 15-20 µmol kg^{-1}, in some cases even higher.

As a final result the assembled in-situ database of the ETNA contains 15059 independent profiles (Fig. 2). All profiles include temperature, salinity and pressure measurements while 38.5% of all profiles include oxygen measurements. The database is composed of 13% shipboard, 22.5% CVOO mooring, 63% Argo float and 1.5% glider profiles. 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. (2016).

Florian Schütte 12.8.16 11:39
Gelöscht: All four autonomous gliders were equipped with Aanderaa optodes which were calibrated on dedicated CTD casts following the procedures of Hahn et al. (2014). As gliders move through the water column the oxygen measurements are not as stable as those from moored optodes analyzed by Hahn et al. (2014). We thus estimate their accuracy to about 3 µmol kg^{-1}. ... [9]

2.2 Satellite data

We detected and tracked eddies following the procedures described in Schütte et al. (2016). In brief we used 19 years of the delayed-time "all-sat-merged" reference dataset of SLA (version 2014). The data is produced by Ssalto/Duacs and distributed by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic), with support from CNES [http://www.aviso.altimetry.fr/duac/]. We used the multi-mission product, which is mapped on a 1/4° x 1/4° Cartesian grid and has a temporal resolution of one day. The anomalies were computed with respect to a nineteen-year mean. The SLA and geostrophic velocity anomalies also provided by AVISO were chosen for the time period January 1998 to December 2014.

Florian Schütte 8.9.16 22:59
Gelöscht: 5…. In brief we used 19 y ... [10]

For SST the dataset "Microwave Infrared Fusion Sea Surface Temperature" from Remote Sensing Systems (www.remss.com) is used. It is a combination of all operational microwave (MW) radiometer SST measurements (TMI, AMSR-E, AMSR2, WindSat) and infrared (IR) SST measurements (Terra MODIS, Aqua MODIS). The dataset thus combines the advantages of the MW data (through-cloud capabilities) with the IR data (high spatial resolution). The SST values are corrected using a diurnal model to create a foundation SST that represents a 12-noon temperature (www.remss.com). Daily data with 9 km resolution from January 2002 to December 2014 are considered.

Florian Schütte 5.9.16 15:18
Gelöscht: Sea Surface Temperature ... [11]

For sea surface chlorophyll (Chl) data we use the MODIS/Aqua Level 3 product available at http://oceancolor.gsfc.nasa.gov provided by the NASA. The data were measured via IR and is therefore cloud cover dependent. Daily data mapped on a 4 km grid from January 2006 to December 2014 is selected.

Florian Schütte 5.9.16 15:19
Gelöscht: (Chl) …e use the MODIS ... [12]

2.3 Low-oxygen eddy detection and surface composites

Florian Schütte 8.9.16 23:48
Gelöscht: "Dead-zone"

In order to verify whether low oxygen concentrations (<40 µmol kg^{-1}) at shallow depth (above 200 m) are associated with eddies we applied a two step procedure. First, all available oxygen measurements of the combined in-situ datasets are used to identify negative oxygen anomalies with respect to the climatology. Next, the satellite data based eddy detection results (Schütte et al., 2016) were matched in space and time with the location of anomalously low-oxygen profiles. In this survey the locations of 173 of 180 low-oxygen profiles coincide with surface signatures of mesoscale eddies. Schütte et al. (2016) showed that ACMEs can be distinguished in the ETNA from "normal" anticyclonic eddies by considering the SST anomaly (cold in case of ACMEs) and sea surface salinity (SSS) anomaly (fresh in case of ACMEs) in parallel to the respective SLA anomaly. The satellite-based estimates of SLA and SST used in this study are obtained by subtracting low-pass filtered (cutoff wavelength of 15° longitude and 5° latitude) values from the original data to exclude large-scale variations and preserve only the mesoscale variability (see Schütte et al. (2016) for more detail). All eddy-like

Florian Schütte 5.9.16 15:20
Gelöscht: :…First, all available oxy ... [13]

structures with low-oxygen profiles are visually tracked in the filtered SLA (sometimes SST data) back- and forward in time in order to obtain eddy propagation trajectories. The surface composites of satellite-derived SLA, SST and Chl data consist of 150 km x 150 km snapshots around the obtained eddy centers. For construction of the composites the filtered SLA and SST is used as well.

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Gelöscht:

2.4 Reconstruction of oxygen concentrations in low-oxygen eddy cores

Florian Schütte 8.9.16 23:48
Gelöscht: "dead-zone"

About 30 % of the profiles from the combined in-situ dataset conducted in CEs or ACMEs do not have oxygen measurements available. However, we are only interested in oxygen measurements in isolated CE or ACME cores. These isolated eddy cores carry anomalously low salinity SACW of coastal origin, while the surrounding waters are characterized by an admixture of more saline NACW (Schütte et al., 2016) . All eddies that show a low salinity and cold core indicate that (I) they have been generated near the coast and (II) their core has been efficiently isolated from surrounding waters. The salinity-σ_θ diagram (Fig. 3a) of open ocean (west of 19°W) profiles shows a correlation between low salinity eddy cores and low oxygen concentrations. Moreover, it indicated that the oxygen content in the isolated eddies is decreasing from east to west. In order to compensate for missing oxygen measurements on many of the profiles we derive a salinity-oxygen relation but also considering the "age" of the eddy (time since the eddy left the eastern boundary) and a oxygen consumption rate within the eddy core. The oxygen consumption rate is estimated from the difference between the observed oxygen and a reference profile (the mean of all profiles east of 18°W in the eastern boundary region; Fig. 3a), the distance from the eastern boundary, and the propagation speed (3 km d^{-1}; see Schütte et al. (2016)). The mean eddy consumption rate is now the difference from the initial oxygen condition and the observed oxygen concentration in the eddy core divided by the eddy age (distance divided by propagation speed). For eddy profiles without oxygen measurements but SACW water mass characteristics (less saline and colder water than surrounding water) we can assume a strong isolation of the eddy and thus a lowering in oxygen. Using the coastal reference profile (Fig. 3), oxygen consumption rate and the distance from the coast an oxygen profile is reconstructed for all isolated CEs and ACMEs. To validate the method we reconstructed the oxygen profiles for the eddies with available oxygen measurements and compared them (Fig. 3b). On average an uncertainty of ± 12 (16) µmol kg^{-1} is associated with the reconstructed oxygen values (Fig. 3c) of CEs (ACMEs). Depending on the intensity of isolation of the eddy core, lateral mixing could have taken place, which is assumed to be zero in our method. However, this approach enables us to enlarge the oxygen dataset by 30%. We considered the reconstructed oxygen profiles only to estimate the mean structure of oxygen anomaly.

Florian Schütte 5.9.16 15:23
Gelöscht: in their cores… while the ... [14]

2.5 Mean vertical oxygen anomaly of low-oxygen eddies and their impact on the SOMZ

Florian Schütte 8.9.16 23:48
Gelöscht: "dead-zone"

To illustrate mean oxygen anomalies for CEs and ACMEs as a function of depth and radial distance, all oxygen profiles (observed and reconstructed) were sorted with respect to a normalized distance, which is defined as the actual distance of the profile from the eddy center divided by the radius of the eddy (the shape and thus the radius of the eddy are gained from the streamline with the strongest swirl velocity around a center of minimum geostrophic surface velocity). The oxygen profiles were grouped and averaged onto a grid of 0.1 increments between 0 and 1 of the normalized radial distance. Finally a running mean over three consecutive horizontal grid points was applied. A mean oxygen anomaly for the CEs and the ACMEs was constructed by the comparison with the oxygen concentrations in the surrounding waters. To illustrate the influence of the reconstructed oxygen values, the mean oxygen anomaly is also constructed based only on original measured oxygen values, both

Florian Schütte 12.8.16 15:15
Gelöscht: last closed contour of the geostrophic surface velocity…. The ox ... [15]

anomalies are shown for comparison.

An oxygen deficit profile due to "dead-zone" eddies in the SOMZ is derived by building an oxygen anomaly on density surfaces (O_2') separating CEs and ACMEs. 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). 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 (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.

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Gelöscht: of each eddy type

Florian Schütte 8.9.16 21:47
Gelöscht: per year

3. Results

3.1 Low-oxygen eddy observation from in-situ data

Several oxygen measurements in the ETNA with anomalously low oxygen concentrations, which is defined here as an oxygen concentration below 40 µmol kg^{-1} (Stramma et al., 2009) could be identified from Argo floats, ship surveys, glider missions and from the CVOO mooring (Fig. 4). In total, 27 independent eddies with oxygen values <40 µmol kg^{-1} in the upper 200 m were sampled with 173 profiles from 25 different platforms (Tab. 1). Almost all of the observed anomalous low oxygen values could be associated with mesoscale structures at the sea surface (CEs or ACMEs) from satellite data.

In-situ measurements for meridional velocity, temperature, salinity and oxygen of the CVOO mooring during the westward passage of one CE and one ACME with low oxygen concentrations are chosen to introduce the two different eddy types and their vertical structure based on temporally high resolution data (Fig. 5). From October 2006 to December 2006 (Fig. 5a), a CE passed the CVOO mooring position on a westward trajectory. At its closest, the eddy center was located about 20 km north of the mooring. The meridional velocities show a strong cyclonic rotation (first southward, later northward) with velocity maxima between the surface and 50 m depth at the edges of the eddy. In the core of the CE, the water mass was colder and less saline than the surrounding water, the mixed layer (ML) depth is reduced and the isopycnals are shifted upwards. The oxygen content of the eddy core was reduced by about 60 µmol kg^{-1} at 115 m depth (or at the isopycnal surface 26.61 kg m^{-3}) compared to surrounding waters, which have a mean (± 1 standard deviation) oxygen content of 113 (± 38) µmol kg^{-1} at around 150 m depth or 26.60 (± 0.32) kg m^{-3} during the mooring period between 2006 to 2014. Schütte et al. (2016) showed that around 52% of the eddies in the ETNA represents CEs. They have a marginal smaller radius, rotate faster and have a shorter lifetime compared to the anticyclonic eddies, which is also shown in other observational studies of Chaigneau et al. (2009), Chelton et al. (2011), and theoretically suggested by Cushman-Roisin et al. (1990).

From January 2007 to March 2007 (Fig. 5b), an ACME passed the CVOO mooring position. The core of the westward propagating eddy passed about 13 km north of the mooring. The velocity field shows strong subsurface anticyclonic rotation at the depth of the core, i.e. between 80-100 m. In contrast to "normal" anticyclonic eddies, the water mass in the core of an ACME is colder and less saline than the surrounding waters. The isopycnals above the core are elevated resulting in shallower MLs both resembling a cyclone. Beneath the core, the isopycnals are strongly depressed as in a normal anticyclone. Thus, dynamically this resembles a mode water anticyclone, an eddy type, which is well-known from local single observations in almost all ocean basins (globally: Kostianoy and Belkin (1989); Mcwilliams (1985) "submesoscale coherent vortices (SCV)"; in the North Atlantic: Riser et al. (1986); Zenk et al. (1991) and Bower et al. (1995); Richardson et al. (1989); Armi and Zenk (1984) "Meddies"; in the Mediterranean Sea: Taupier - Letage et al. (2003) "Leddies"; in the North Sea: Van Aken et al. (1987); in the Baltic Sea Zhurbas et al. (2004); in the Indian Ocean: Shapiro and Meschanov (1991) "Reddies"; in the North Pacific: Lukas and Santiago-Mandujano (2001); Molemaker et al. (2015) "Cuddies"; in the South Pacific: Stramma et al. (2013); Colas et al. (2012); Combes et al. (2015); Thomsen et al. (2016) and Nof et al. (2002) "Teddies"; in the Artic Dasaro (1988); Oliver et al. (2008)). For the majority of the observed mode-water type eddies the depressed isopycnals in deeper water mask the elevated isopycnals in the shallow water in terms of geostrophic velocity, resulting in an anticyclonic surface rotation, and a weak positive SLA (Gaube et al., 2014).

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Florian Schütte 7.9.16 16:30
Gelöscht: at shallow depth)

Florian Schütte 12.8.16 17:52
Gelöscht: show examples

Florian Schütte 12.8.16 17:52
Gelöscht: of the

Florian Schütte 12.8.16 17:52
Gelöscht: of the two different eddy types

Florian Schütte 8.9.16 21:50
Gelöscht: 65 km diameter

Florian Schütte 5.9.16 15:27
Gelöscht: CVOO

Florian Schütte 12.8.16 15:29
Gelöscht: (not shown)

Florian Schütte 6.9.16 15:36
Gelöscht: decreased

Florian Schütte 6.9.16 15:36
Gelöscht: with values

Florian Schütte 6.9.16 15:37
Gelöscht: round

Florian Schütte 5.9.16 15:28
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Florian Schütte 5.9.16 15:29
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Florian Schütte 5.9.16 15:29
Gelöscht: depth

Florian Schütte 5.9.16 15:29
Gelöscht: other typical

Florian Schütte 5.9.16 15:30
Gelöscht: eddy

Florian Schütte 5.9.16 15:30
Gelöscht: the

Florian Schütte 12.8.16 15:30
Gelöscht: (not shown)

Florian Schütte 8.9.16 23:46
Gelöscht: "

Florian Schütte 8.9.16 23:46
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In contrast to most of the ACMEs reported the CVOO ACME eddy core is located at very shallow depth just beneath the ML. The oxygen content in the eddy's core recorded from the CVOO mooring is strongly decreased with values around 19 µmol kg^{-1} at 123 m depth (or 26.50 kg m^{-3}) compared to the surrounding waters (113 (± 38) µmol kg^{-1}). Within the entire time series, the CVOO mooring recorded the passage of several ACMEs with even lower oxygen concentrations (for more information see Karstensen et al. (2015) or Table 1). Recent model studies suggest that ACMEs represent a non-negligible part of the worlds eddy field, particular in upwelling regions (Combes et al., 2015; Nagai et al., 2015). Schütte et al. (2016) could show, based on observational data that ACMEs represent around 9% of the eddy field in the ETNA. Their radii are in the order of the first baroclinic mode Rossby radius of deformation and their eddy cores are well isolated (Schütte et al., 2016).

3.2 Combining in-situ and satellite data for low-oxygen eddy detection in the ETNA

Combining the location and time of in-situ detection of low-oxygen eddies with the corresponding SLA satellite data reveal a clear link to the surface manifestation of mesoscale structures, CE and ACMEs likewise (Fig. 4). Composite surface signatures for SLA, SST and Chl from all anomalous low-oxygen eddies as identified in the in-situ dataset are shown in Figure 6. The ACME composites are based on 17 independent eddies and on 922 surface maps. The detected ACMEs are characterized by an elevation of SLA, which is associated with an anticyclonic rotation at the sea surface. The magnitude of the SLA displacement is moderate compared to normal anticyclones and CEs (Schütte et al., 2016) . More distinct differences to normal anticyclones are the cold-water anomaly and the elevated Chl concentrations in the eddy center of the ACMEs. Normal anticyclones are associated with elevated SST and reduced Chl concentrations. Through a combination of the different satellite products (SLA, SST, SSS) it is possible to determine "dead-zone" eddies from satellite data alone (further details of the ACME tracking and the average satellite surface signatures (SLA, SST, SSS) of all eddy types (CEs, anticyclones and ACMEs) identified in 19 years of satellite data in Schütte et al. (2016).

The composite mean surface signature for "dead-zone" CEs is based on 10 independent eddies and on 755 surface maps. The CEs are characterized by a negative SLA and SST anomaly. The observed negative SST anomaly of the "dead-zone" CEs is twice as large (core value CE: -0.12 (± 0.2) °C; core value ACME: -0.06 (± 0.2) °C) as the corresponding anomaly of the ACMEs. The Chl concentration in the eddy center is also higher for CEs compared to ACMEs (core value CE: 0.35 (± 0.22) log mg m^{-3}; core value ACME: 0.21 (± 0.17) log mg m^{-3}). Note, that we only considered the measured low-oxygen ACMEs and CEs from Table 1 to derive the composites.

Using the eddy-dependent surface signatures in SLA, SST and Chl the "dead-zone" eddies could be tracked and an eddy trajectory could be derived (e.g. Fig. 4). All detected eddies were propagating westward into the open ocean. North of 12°N, most of the eddies set off near the coast, whereas south of 12°N the eddies seem to be generated in the open ocean. Detected CEs have a tendency to deflect poleward on their way into the open ocean (Chelton et al., 2011), whereas ACMEs seem to have no meridional deflection. However, during their westward propagation the oxygen concentration within the "dead-zone" eddy cores decreases with time. Using the propagation time and an initial coastal oxygen profile (Fig. 3b) a mean apparent oxygen utilization rate per day could be derived for all sampled eddies (Fig. 7). On average the oxygen concentration decreases by about 0.19 ± 0.08 µmol kg^{-1} d^{-1} in the core of an isolated ACME, but has no significant trend in the core of an isolated CE (0.10 ± 0.12 µmol kg^{-1} d^{-1}). This is in the range of recently published aOUR estimates for single observations of

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Gelöscht: historical known mode water anticyclones,

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Gelöscht:) and therefore the oxygen concentration is reduced.

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Florian Schütte 8.9.16 21:53
Gelöscht: **"dead-zone"**

Florian Schütte 5.9.16 15:40
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Florian Schütte 5.9.16 15:41
Gelöscht: for ACMEs

Florian Schütte 5.9.16 15:42
Gelöscht:

Florian Schütte 15.8.16 11:39
Gelöscht: in the core of an isolated CE (ACME)

CEs (Karstensen et al., 2015) and ACMEs (Fiedler et al., 2016).

3.4 Mean oxygen anomalies from low-oxygen eddies in the ETNA

In Figure 8 we compare the mean oxygen anomalies based purely on observations with those based on the extended profile database including observed and reconstructed oxygen values (see section 2.4). It shows the mean oxygen anomalies against the surrounding water for CE (Fig. 8a) and ACME (Fig. 8b) versus depth and normalized radial distance. On the left side of each panel the anomaly is based on the observed and reconstructed oxygen values (736 oxygen profiles; 575 in CEs; 161 in ACMEs), whereas on the right side the anomaly is based only on the observed oxygen measurements (504 oxygen profiles; 395 in CEs; 109 in ACMEs). The distinct mean negative oxygen anomalies for CEs and ACMEs indicate the low oxygen concentrations in the core of both eddy types compared to the surrounding water. The strongest oxygen anomalies are located in the upper water column, just beneath the ML. CEs feature maximum negative anomalies of around -100 µmol kg^{-1} at around 70 m depth in the eddy core, with a slightly more pronounced oxygen anomaly when including the reconstructed values (left side of Fig.8) compared to the oxygen anomaly based purely on observation (right side of Fig. 8a). This is contrary for the ACME with stronger oxygen anomalies on the right part than on the left (Fig. 8b). Both methods deliver maximum negative anomalies of around -120 µmol kg^{-1} at around 100 m depth in the ACME core. At that depth, the diameter of the mean oxygen anomaly is about 100 km for ACMEs and 70 km for CEs (the eddy core is defined here as the area of oxygen anomalies <-40 µmol kg^{-1}). Beneath 150 m depth, magnitude and diameter of the oxygen anomalies decrease rapidly for both eddy types. Figure 8c is based on both, the in-situ and reconstructed oxygen values, and shows the horizontal mean oxygen anomaly profile of each eddy type against depth obtained by horizontally averaging the oxygen anomalies shown in Fig. 8a,b. The maximum anomalies are -100 µmol kg^{-1} at around 90 m for ACMEs and -55 µmol kg^{-1} at around 70 m for cyclones. Both eddy types have the highest oxygen variance directly beneath the ML (in the eddy core) or slightly above the eddy core. The oxygen anomaly (and associated variance) decreases rapidly with depth beneath the eddy core and is smaller than around -10 ± 10 µmol kg^{-1} beneath 350 m for both eddy types.

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Florian Schütte 5.9.16 15:44
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Florian Schütte 5.9.16 15:44
Gelöscht: in-situ

Florian Schütte 5.9.16 15:45
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Florian Schütte 6.9.16 10:42
Gelöscht: right part based only on observed oxygen concentrations (

4. Discussion

The pelagic zones of the ETNA are traditionally considered to be “hypoxic”, with minimal oxygen concentrations of marginally below 40 µmol kg^{-1} (Brandt et al., 2015; Karstensen et al., 2008; Stramma et al., 2009). This is also true for the upper 200 m (Fig. 1). However, single oxygen profiles taken from various observing platforms (ships, moorings, gliders, floats) with oxygen concentrations in the range of severe hypoxia (< 20 µmol kg^{-1}) and even anoxia (~ 1 µmol kg^{-1}) conditions and consequently below the canonical value of 40 µmol kg^{-1} (Stramma et al., 2008) are found in a surprisingly high number (in total 180 profiles) in the ETNA. In the current analysis we could associate observations of low-oxygen profiles with 27 independent mesoscale eddies (10 CEs and 17 ACMEs). Mesoscale eddies are defined as coherent, nonlinear structures with a lifetime of several weeks to more than a year and radii larger than the first baroclinic mode Rossby radius of deformation (Chelton et al., 2007). In reference to the surrounding water, the eddies carry a negative oxygen anomaly which is most pronounced right beneath the mixed layer. The oxygen anomaly is attributed to both, an elevated primary production in the surface layers of the eddies (documented by positive chlorophyll anomalies estimated from satellite observations, Fig. 6) and the subsequent respiration of organic material (Fiedler et al., 2016), and the dynamically induced isolation of the eddies with respect to lateral oxygen resupply (Fiedler et al., 2016;

Karstensen et al., 2015). In contrast to the transport of heat or salt with ocean eddies the oxygen anomaly intensified with time the eddy exists (eddy age). The oxygen depleted eddy cores are either associated to CEs or ACMEs. In the ETNA both eddy types have in common that in their center the mixed layer base rises towards shallow depth (50 to 100m) which in turn favor biological productivity in the euphotic zone (Falkowski et al., 1991; McGillicuddy et al., 1998). In addition, an enhanced vertical flux of nutrients within or at the periphery of the eddies due to submesoscale instabilities is expected to occur (Brannigan et al., 2015; Karstensen et al., 2016; Lévy et al., 2012; Martin and Richards, 2001; Omand et al., 2015).

As a consequence the eddies establish an specific ecosystem of high primary production, particle load and degradation processes, and even unexpected nitrogen loss processes (Löscher et al., 2015). The combination of high productivity and low oxygen supply resample the process of "dead zone" formation, know from other aquatic systems. As for other aquatic systems specific threats to the ecosystem of the eddies are observed such as the interruption of the diurnal migration of zooplankters (Hauss et al., 2016).

We observed low-oxygen cores only in ACMEs (also known as "submesoscale coherent vortices (SCV)" (Dasaro, 1988; Mcwilliams, 1985) or "intra-thermocline eddies" (Kostianoy and Belkin, 1989)) and CEs but not in normal anticyclonic rotating eddies. In fact the mixed layer base in normal anticyclonic eddies is deeper than the surroundings, bending downward towards the eddy center as a consequence of the anticyclonic rotation. Therefore the normal anticyclones create a positive oxygen anomalies when using depth levels as a reference. However, when using density surfaces as a reference the anomalies disappear. Moreover, normal anticyclonic eddies have been found to transport warm and salty anomalies (Schütte et al., 2016) along with the positive oxygen anomaly which is very different from the ACMEs (and CEs) with a low-oxygen core.

The ETNA is expected to have a rather low population of long-lived eddies (Chaigneau et al., 2009; Chelton et al., 2011), we could identify 234 CEs and 18 ACMEs per year in the ETNA with a radius > 45 km and a tracking time of more than 3 weeks. For the eddy detection we used an algorithm based on the combination of the Okubo-Weiß method and a modified version of the geometric approach from (Nencioli et al. (2010)) with an adjusted tracking for the ETNA (for more information see Schütte et al. (2016)). Schütte et al. (2016) found an eddy-type depended connection between SLA and SST (and SSS) signatures for the ETNA that allowed a detection (and subsequently closer examination) of ACMEs. Because of weaker SLA signatures, the tracking of ACMEs is rather difficult due to the small signal to noise ratio (not the case for the CEs) and automatic tracking algorithms may fail in many cases. Note, all tracks of ACMEs and CEs shown in Figure 4 were visually verified. Similar to what Schütte et al. (2016), did we derived "dead-zone" eddies surface composites for SST, SSS (not shown here) and Chl (Fig. ??). It revealed that the existence of an ACMEs is very associated with low SST (and SSS) but also with high Chl (see also single maps in Karstensen et al. 2015). Analyzing jointly SLA, SST and Chl maps we found that ACMEs represent a non-negligible part of the eddy field (32% normal anticyclones, 52% CEs, 9% ACMEs (Schütte et al., 2016)).

It has been shown (Fig. 4) that the low-oxygen eddies in the ETNA could be separated into two different regimes, north and south of 12°N. The eddies north of 12°N are generally generated along the coast and in particular close to the headlands along the coast. Schütte et al. (2016) suggested that CEs and normal anticyclones north of 12°N are mainly generated from instabilities of the northward directed alongshore Mauretania Current (MC), whereas the ACMEs are most likely generated by instabilities the Poleward Undercurrent (PUC). However, the detailed generation processes need to be further investigated. The low-oxygen eddies south of 12°N do not originate from a coastal boundary upwelling system. Following the

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Gelöscht: (Chelton et al., 2011; Zhang et al., 2013)

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Gelöscht: these eddies

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Gelöscht: boundary

Florian Schütte 15.8.16 10:22
Gelöscht: current.

Florian Schütte 26.4.16 16:11
Gelöscht: formation

Florian Schütte 8.9.16 20:10
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Florian Schütte 15.8.16 10:44
Gelöscht: southern

Florian Schütte 15.8.16 10:47
Gelöscht: do transport low-oxygen anomalies, but

trajectories it seems that the eddies are generated in the open ocean between 5°N and 7°N. In general, the occurrence of oxygen depleted eddies south of 12°N is rather astonishing, as due to the smaller Coriolis parameter closer to the equator the southern eddies should be more short-lived and less isolated compared to eddies further north. In addition, the generation mechanism of the southern eddies is not obvious. The eddy generation could be related to the presence of strong tropical instabilities in that region (Menkes et al., 2002; von Schuckmann et al., 2008). However, in particular the generation of ACMEs is complex and has been subject of scientific interest for several decades already (Dasaro, 1988; Mcwilliams, 1985). The low stratification of the eddy core cannot be explained by pure adiabatic vortex stretching alone as this mechanism will result in cyclonic vorticity, assuming that f dominates the relative vorticity. Accordingly, the low stratification in the eddy core must be the result of some kind of preconditioning induced by for example upwelling, deep convection (Oliver et al., 2008) or diapycnal mixing near the surface or close to boundaries (Dasaro, 1988) before eddy generation takes place (Mcwilliams, 1985). Dasaro (1988), Molemaker et al. (2015) and Thomsen et al. (2015) highlight the importance of flow separation associated with headlands and sharp topographical variations for the generation of ACMEs. This notion is supported by the fact that low potential vorticity signals are usually observed in the ACMEs (Dasaro, 1988; Mcwilliams, 1985; Molemaker et al., 2015; Thomas, 2008). The low potential vorticity values suggest that the eddy has been generated near the coast as - at least in the tropical latitudes - such low potential vorticity values are rarely observed in the open ocean. These theories seem to be well suitable for the ACME generation north of 12°N but do not entirely explain the occurrence of ACMEs south of 12°N. However, more research on this topic is required.

Because we expect "northern" and "southern" eddies to have different generation mechanisms and locations and because they have different characteristics we discuss them separately. The core of the eddies generated north of 12°N is characterized by less saline and cold SACW (Schütte et al., 2016) and thereby forms a strong hydrographic anomaly against the background field. On the contrary, the core of the eddies generated south of 12°N does not show any significant hydrographic anomalies. However, given the low-oxygen core in eddies in both regions we expect that the processes that create the "dead-zone", which is isolation and high productivity, are also present in both regimes. The oxygen content decrease on average by about 0.19 ± 0.08 µmol kg^{-1} d^{-1} in an ACME and by about 0.10 ± 0.12 µmol kg^{-1} d^{-1} in an CE, based on 504 oxygen measurements in CEs and ACMEs. Note, that these apparent oxygen utilization rates (aOUR) are in the range of recently published aOUR estimates for CEs (Karstensen et al., 2015) and ACMEs (Fiedler et al., 2016), which are based on single measurements in "dead-zone" eddies. In particular for CEs we take that as an indication that no significant trend in aOUR exists. An important point regarding the method and the associated inaccuracies in deriving the aOURs is the initial coastal oxygen concentration, which is highly variable in coastal upwelling regions (Thomsen et al., 2015). In addition one should mention that the relative magnitude of eddy dependent vertical nutrient flux, primary productivity and associated oxygen consumption or nitrogen fixation/denitrification in the eddy cores strongly varies between different eddies, because of differences in the initial water mass in the eddies' core, the eddies' age and isolation and the experienced external forcing (in particular wind stress and dust/iron input).

However, the mean oxygen profiles from the eastern boundary and inside of all CEs and ACMEs (Fig. 3b) indicate no pronounced oxygen difference beneath 250 m depth. The largest anomalies have been observed in the eddy cores at around 100 m depth (Fig. 8). As a result of the dynamic structure, the core water mass anomalies of the ACMEs are more pronounced than the one of the CE (Karstensen et al., 2016) and consequently the oxygen anomalies are stronger. This is supported by the differences in the oxygen anomaly

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Florian Schütte 8.9.16 20:16
Gelöscht: 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 (Karstensen et al., 2016). In combination with the eddy dynamics and its associated isolation of the CE (ACME) core,

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Florian Schütte 15.8.16 11:49
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Florian Schütte 15.8.16 11:50
Gelöscht: the ETNA

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Gelöscht: . The apparent oxygen utilization rate (aOUR) is

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Florian Schütte 6.9.16 10:53
Gelöscht: coast

based on the measured plus reconstructed and the measured oxygen values. The reconstruction of oxygen values assumes a complete isolation of the eddy core. The left side of Figure 8a, which includes the reconstructed oxygen values, features a larger oxygen anomaly than the right side based on measured oxygen values only. Consequently the CEs are probably not completely isolated and the evolving oxygen anomaly is affected by some lateral flux of oxygen. On the contrary, the oxygen anomaly of ACMEs (Fig. 8b) is smaller for the reconstruction than for the measured oxygen values. This suggest that the ACMEs are more effectively isolated resulting in enhanced apparent consumption in the ACME core. However, another source of error in the reconstructed oxygen values is the assumption of a linear decrease of oxygen with time. All observed CEs or ACMEs contain a negative oxygen anomaly, partly because they transport water with initial low oxygen concentrations and additionally because the oxygen consumption in the eddies is more intense then in the surrounding waters (Karstensen et al. 2015, Fiedler et al. 2016). Dasaro (1988), Molemaker et al. (2015) and Thomsen et al. (2015) argued that the core waters of ACME's generated near the coast originate to a large extent from the bottom boundary layer at the continental slopes. At the shelf off Northwest Africa occasionally low oxygen concentrations (around 30 µmol kg^{-1}) in the depth range between 50-150 m could locally identified (M. Dengler personal communication). Consequently it is certainly possible that the eddies have initially low oxygen concentrations in their cores. This is not the case for the short-lived southern eddies, which seem to be generated in the open ocean. It would suggest that, to achieve similarly strong negative oxygen anomalies, the oxygen consumption in the eddies south of 12°N must be even stronger than in the ACMEs further north. Pronounced productivity patterns in tropical instability waves and vortices have been reported in the past (Menkes et al., 2002), but were not connected to low-oxygen eddies before.

In the following, an estimate of the contribution of the negative oxygen anomalies of "dead-zone" eddies to the oxygen distribution of the SOMZ is presented. The satellite-based eddy tracking reveals that on average each year 14 (2) CEs (ACMEs) are propagating from the upwelling system near the coast into the SOMZ and dissipate there. By deriving the oxygen anomaly on density surfaces an oxygen loss profile due to "dead-zone" eddies in the SOMZ is derived (Fig. 9). Note that due to the lower oxygen values within the eddies compared to the surrounding waters in the SOMZ, the release of negative oxygen anomalies to the surrounding waters is equivalent to a local (eddy volume) enhancement of the oxygen utilization by -7.4 (-2.4) µmol kg^{-1} yr^{-1} for CEs (ACMEs) for the depth range of the shallow oxygen minimum in the SOMZ, i.e. 50 to 150 m depth. Instead of describing the effect of the dead-zone eddies on the oxygen consumption an equivalent view is to consider a box model approach for the SOMZ. The basis of this box model is the mixing of high-oxygen waters (the background conditions) with low-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

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Gelöscht: ue to the smaller Coriolis parameter closer to the equator the southern eddies should be more short-lived compared to eddies north of 12°N (Chelton et al., 2011). This

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Gelöscht: The SOMZ is located west of the boundary current coastal region, south of the subtropical gyre region and north of the zonal equatorial current bands. It covers the unventilated eastern boundary shadow zone and thereby is the region of the most pronounced shallow oxygen minimum (see Fig. 1a).

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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 an equivalent reduction of around 7 µmol kg^{-1} of the observed climatological oxygen concentration in the SOMZ box. To visualize that a depth profile of oxygen in the SOMZ without the dispersion of "dead-zone" eddies is equally derived and compared to the observed oxygen profile in the SOMZ (Fig. 9b). 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. 2016). Note, that a small compensating effect for example due to diapycnal oxygen fluxes in normal anticyclones can probably be expected. However, our estimates should be considered as a lower limit for the contribution of AMCEs because of the problem in detecting and tracking ACMEs (weak SLA anomaly) and because of the assumption of zero lateral ventilation within the eddies. Moreover, we identified a few occurrences of ACMEs based on shipboard ADCP as well as hydrographic measurements (e.g. during the research cruises of Ron Brown 2009 and Meteor 119) that did not have a significant SLA signature. In addition only eddies are considered which could be followed with tracking algorithms directly from the coast into the transition zone and having a radius greater than 45 km and a lifetime of more than 21 days.

Although a reduction of 7 µmol kg^{-1} seems to be small number one may note that the peak difference is a reduction of 16 µmol kg^{-1} at 100 m depth (Fig. 9), directly in the core depth of the shallow oxygen minimum zone in the ETNA. The additional respiration due to the presence of low-oxygen eddies can be important as well in numerical simulations, where up to now only the large scale consumption is taken into account. In turn it is important to investigate the eddy occurrence and eddy cycling in numerical simulation of the OMZs given they have a sufficient resolution.

Our results question the assumption that the oxygen consumption is determined by the metabolism of the large-scale community alone. The observations presented here suggest instead that also hot spots of locally enhanced consumption may possibly need to be considered in the future.

5. Conclusion

In this study, we investigated the vertical structure of oxygen depleted eddies in the ETNA based on satellite (a combination of SLA and SST) and in-situ oxygen and hydrography data (ship data, mooring data, profiling floats, underwater glider). We frequently detected oxygen concentrations below the canonical value of 40 µmol kg^{-1} within the ETNA that are associated with CEs and ACMEs. Lowest oxygen concentration in these eddies was observed at shallow depth, just underneath the mixed layer between 50 to 150 m. Both, CEs and ACMEs, are characterized by a positive Chl anomaly suggesting enhanced productivity in the eddy surface water. Respiration of the organic material, in combination with sluggish lateral oxygen fluxes across the eddy boundaries, most likely create the low-oxygen core. A process that resamples the creation of "dead-zones" but in the open ocean (Karstensen ??). Oxygen concentrations are found to decrease in the eddy cores during the westward propagation from their generation region along the West African coast into the open ocean. Our assessment reveals that 234 CEs (18 ACMEs) are generated each year (mostly on the eastern boundary) in the ETNA and can be tracked longer than 3 weeks (considered here as the time scale for coherent eddies). On average the oxygen concentration in the core of coherent CEs (ACMEs) decreases by about 0.10 (0.19) ± 0.12 (0.08) µmol kg^{-1} d^{-1}. Beside the eddies originating in generation regions along the West African coast, we observe low-oxygen eddies (primarily ACMEs) relatively close to the equator, south of 12°N. These eddies may

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Gelöscht: ... [16]

Florian Schütte 15.8.16 17:31
Gelöscht: The real amount of "dead-zone" eddies dissipate in the SOMZ is probably higher as only eddies which could be followed with tracking algorithms directly from the coast into the transition zone and have a greater radius than 45 km and a lifetime more than 21 days are considered.This …dd ... [17]

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Gelöscht: eddy types …re characte ... [19]

be generated from flow instability processes occurring during the formation of tropical instability waves. However, both types of eddies (north of 12°N and south of 12°N) contain their minimum oxygen concentration in the depth range where a shallow oxygen minimum is found in the ETNA. 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 mean reduction of around 7 µmol kg^{-1} (peak reduction is 16 µmol kg^{-1} at 100 m depth) of the observed oxygen in the shallow oxygen minimum zone is explainable due to the dispersion of "dead-zone" eddies. This value, though, is very likely underestimated due to difficulties in identifying and tracking of ACMEs. The additional consumption within these low-oxygen eddies represents a substantial part of the total consumption in the open ETNA and might be partly responsible for the formation and extend of the shallow oxygen minimum. Given the impact of ACMEs on the oxygen budget in the ETNA, a further distinction into the two types of anticyclonic eddies in global (Chelton et al., 2011; Zhang et al., 2013) as well as regional eddy assessments is necessary, particular in eastern boundary upwelling systems.

Data availability

The used satellite data SLA, SST and Chl can be freely downloaded at http://www.aviso.altimetry.fr/en/data/products, http://www.remss.com/measurements/sea-surface-temperature/ and http://oceancolor.gsfc.nasa.gov, respectively. The Argo float data is freely available at http://www.argodatamgt.org/Access-to-data/Argo-data-selection and the assembled shipboard measurements; shipboard CTD, glider and CVOO mooring data used in this paper are available at https://doi.pangaea.de/10.1594/PANGAEA.860778.

Acknowledgements

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The Argo data using in this study were collected and made freely available by the International Argo Program and the national programs that contribute to it. (http://www.argo.ucsd.edu, htpp://argo.jcommops.org). The Argo Program is part of the Global Ocean Observing System. The Ssalto/Duacs altimeterproducts were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (http://www.marine.copernicus.eu). The Microwave OI SST data are produced by Remote Sensing Systems and sponsored by National Oceanographic Partnership Program (NOPP), the NASA Earth Science Physical Oceanography Program, and the NASA MEaSUREs DISCOVER Project. Data are available at www.remss.com. The chlorophyll_a version 6 is a remote dataset from the NASA Ocean Biology Processing Group (OBPG). The

OBPG is the official NASA data center that archives and distributes ocean color data (http://oceancolor.gsfc.nasa.gov).

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Tables

Table 1: Available oxygen measurements below 40 µmol kg^{-1} in the ETNA. The * indicates recent observations which are not included in Fig. 4 due to not existent delayed time satellite products.

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	Time	**min O_2 between 0-200 m**	**Associated eddy type**
11 Ship-Cruises: **(81 profiles)**			
Meteor 68/3	Summer 2006	17	CE
L'Atalante GEOMAR 3	Winter 2008	25	ACME
Meteor 80/2	Winter 2009	32	ACME
Meteor 83/1	Winter 2010	20	ACME
Meteor 96	Spring 2013	38	ACME
Meteor 97	Summer 2013	28	ACME
Islandia	Spring 2014	10	ACME
Meteor 105	Spring 2014	4	ACME
Meteor 116	Spring 2015	17	ACME*
Meteor 119	Autumn 2015	30	ACME*
Maria S. Merian 49	Winter 2015	35	CE*
9 Argo floats: **(24 profiles)**			
6900632	Autumn 2008	14	CE
1900652	Winter 2008	26	ACME
1900650	Summer 2009	27	ACME
1901360	Autumn 2014	34	CE
1901361	Autumn 2014	21	CE
1901362	Autumn 2014	26	CE
1901363	Autumn 2014	37	CE
1901364	Autumn 2014	24	ACME
1901365	Autumn 2014	24	ACME
4 Gliders: **(32 profiles)**			
IFM 11	Spring 2010	19	ACME
IFM 05	Summer 2013	9	CE
IFM 12	Winter 2014	1	ACME
IFM 13	Spring 2014	1	ACME
9 CVOO events: **(36 profiles)**			
Optode at 127 m depth	Winter 2007	15	ACME
Optode at 79 m depth	Autumn 2008	38	CE
Optode at 54 m depth	Winter 2010	2	ACME
Optode at 53 m depth	Winter 2012	17	ACME

Optode at 53 m depth	Spring 2012	30	CE
Optode at 45 m depth	Summer 2013	29	ACME
Optode at 45 m depth	Winter 2013	9	CE
Optode at 43 m depth	Winter 2015	2	ACME*
Optode at 43 m depth	Summer 2015	6	ACME*
∑ 173 profiles			**∑ 27 different eddies**

Figures

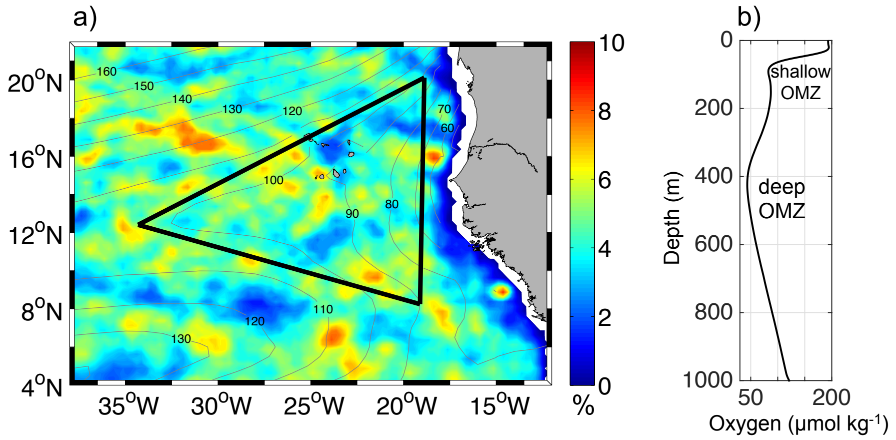
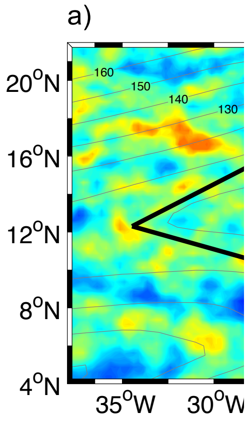


Figure 1: a) Map of the ETNA including contour lines of the oxygen minimum of the upper 200 m (in µmol kg^{-1}) as obtained from the MIMOC climatology (Schmidtko et al., 2013). The color indicates the percentage of "dead-zone" eddy coverage per year. The black triangle defines the SOMZ. **b)** mean vertical oxygen profile of all profiles within the SOMZ showing the shallow oxygen minimum centered around 80 m depth and the deep oxygen minimum centered at 450 m depth.

Florian Schütte 9.9.16 14:14



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Florian Schütte 15.8.16 20:28

Gelöscht: The black crosses indicate the position of the CTD stations of the research cruise M97, which are used to represent the vertical oxygen profile shown on the right.

Florian Schütte 20.4.16 18:05

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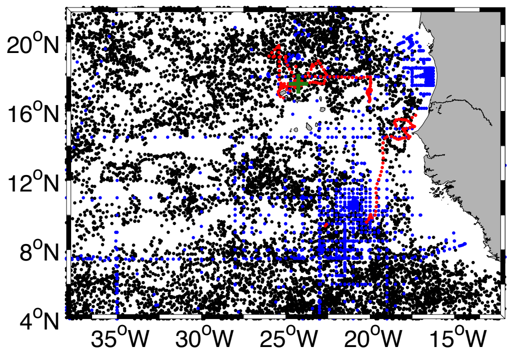

Figure 2: Map of the ETNA containing all available profiles between 1998 and 2014. The green cross marks the CVOO position, blue dots mark shipboard CTD stations, red dots mark the locations of glider profiles and black dots locations of Argo float profiles.

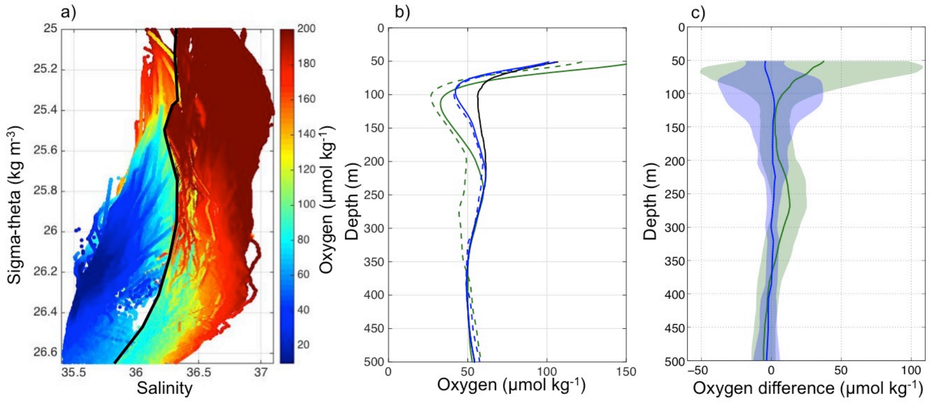

Figure 3: a) Salinity-σ_0 diagram with color indicating the oxygen concentrations. The black line separates the 173 profiles with minimum oxygen concentration of <40 µmol kg^{-1} (left side / more SACW characteristics) from profiles of the surrounding water (right side / more NACW characteristics), taken from the same devices shortly before and after the encounter with a low-oxygen eddy. **b)** Mean oxygen concentration versus depth of the coastal region (east of 18°W, solid black line), of all CEs (solid blue line) and all ACMEs (solid green line) with available oxygen measurements. The dashed line represents the reconstructed mean oxygen concentration for the same CEs (blue) and ACMEs (green). **c)** Difference between the reconstructed and measured oxygen concentrations in CEs (blue) and ACMEs (green) with associated standard deviation (shaded area).

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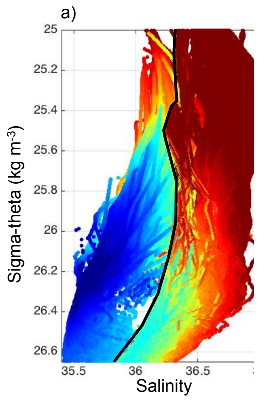

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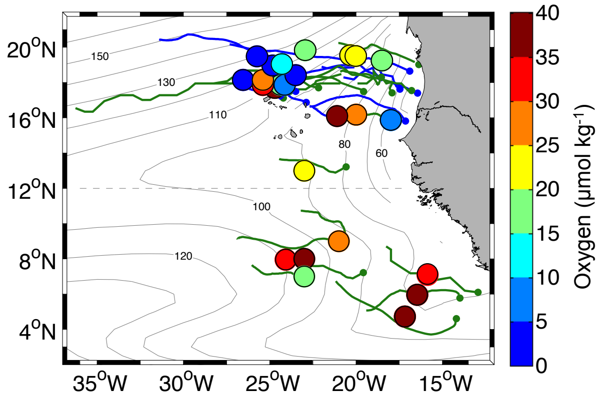

Figure 4: Minimum oxygen concentration (contour lines, µmol kg^{-1}) in the ETNA between the surface and 200 m depth as obtained from the MIMOC climatology (Schmidtko et al., 2013). Superimposed colored dots are all low-oxygen measurements (below 40 µmol kg^{-1} in the upper 200 m) which could be associated with eddy-like structures. The size of the dots represents a typical size of the mesoscale eddies. The associated trajectories of the eddies are shown in green for ACMEs and in blue for cyclones. The oxygen concentrations are from the combined dataset of shipboard, mooring, glider and Argo float measurements.

Florian Schütte 26.4.16 16:06

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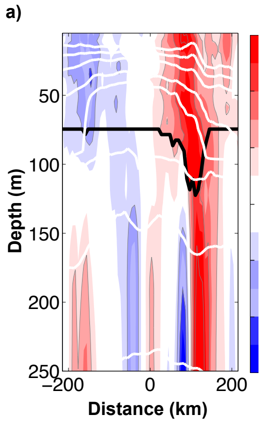
Florian Schütte 9.9.16 17:43



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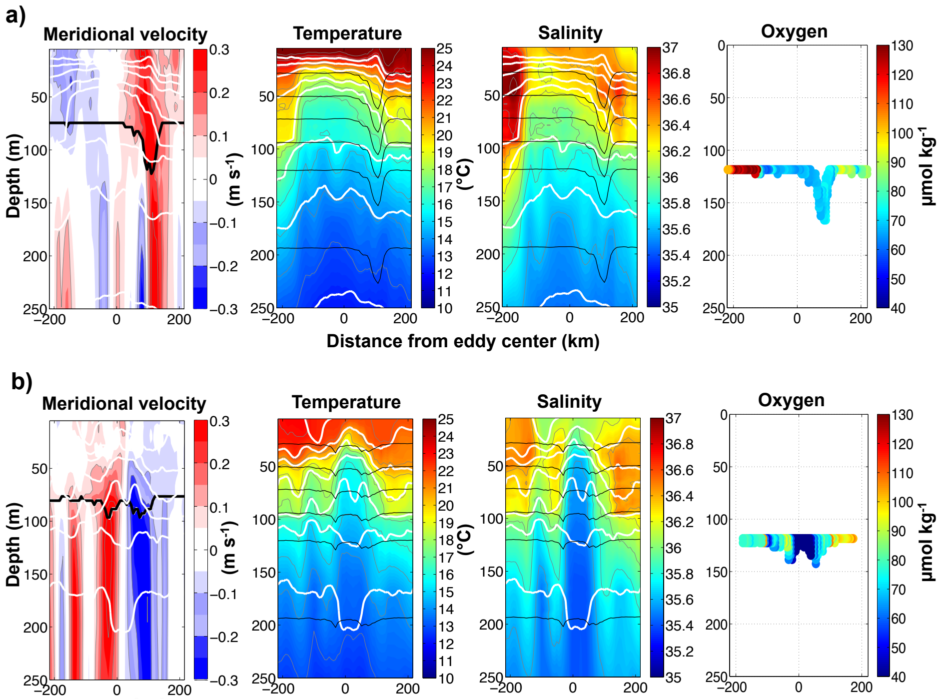
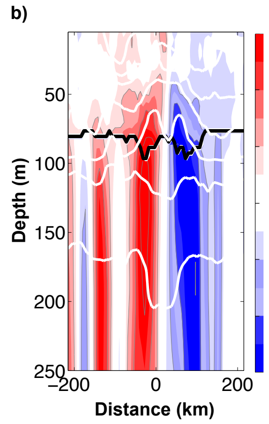


Figure 5: Meridional velocity, temperature, salinity and oxygen of an exemplary **a)** CE and **b)** ACME at the CVOO mooring. Both eddies passed the CVOO on a westward trajectory with the eddy center north of the mooring position (CE 20 km, ACME 13 km). The CE passed the CVOO from October to December 2006 and the ACME between January and March 2007. The thick black lines in the velocity plots indicate the position of an upward looking ADCP. Below that depth calculated geostrophic velocity is shown. The white lines represent density surfaces inside the eddies and the thin grey lines isolines of temperature and salinity, respectively. Thin black lines in the temperature and salinity plot mark the vertical position of the measuring devices. On the right time series of oxygen is shown from the one sensor available at nominal 120 m depth.

Florian Schütte 9.9.16 17:43



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Florian Schütte 9.9.16 17:44

Gelöscht: oxygen

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Gelöscht: oxygen

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Gelöscht: For the oxygen plot saturation at the surface is assumed and data is linearly interpolated between the measuring device and surface.

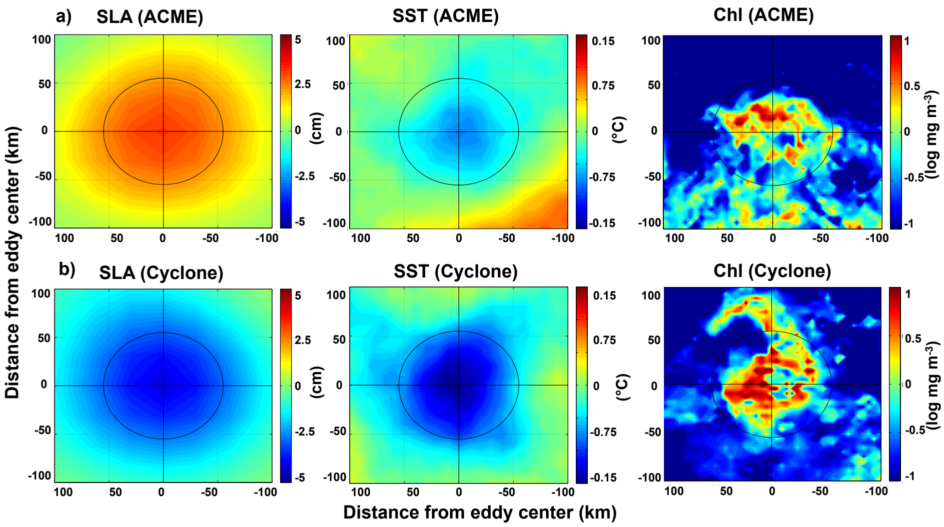

Figure 6: Composites of surface signature for SLA, SST and Chl from all detected low-oxygen eddies: **a)** ACMEs and **b)** CEs. The solid black cross marks the eddy center and the solid black circle the average radius. Due to significant cloud cover the number of Chl data are much less when compared to the SLA and SST data, thus there is more lateral structure.

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Gelöscht: “dead-zone”

Florian Schütte 20.4.16 18:06
Gelöscht: cyclones

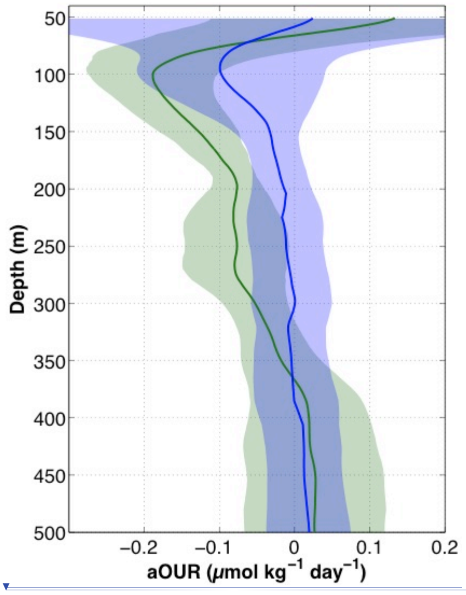

Figure 7: Depth profiles of a mean apparent oxygen utilization rate (aOUR, µmol kg^{-1} d^{-1}) within CEs (blue) and ACMEs (green) in the ETNA with associated standard deviation (shaded area). Derived by using the propagation time of each eddy, an initial coastal oxygen profile and the assumption of linear oxygen consumption (based on depth layers).

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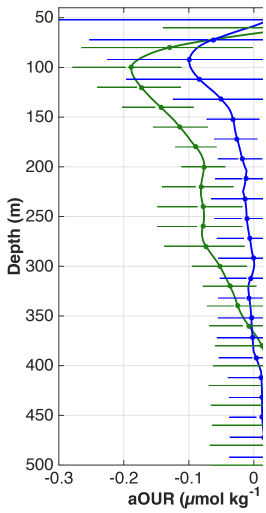

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Gelöscht: Depth profiles of a mean apparent oxygen utilization rate (aOUR, µmol kg^{-1} d^{-1}) within CEs (blue) and ACMEs (green) with associated standard deviation (horizontal lines).

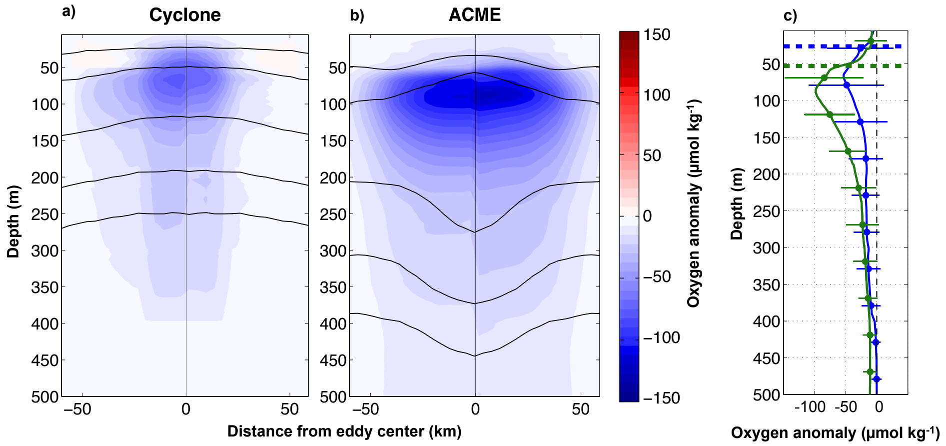

Figure 8: Vertical structure of oxygen from the composite **a)** CE and **b)** ACME in the ETNA presented as a half section across the eddies. The left side of both panels (-60 to 0 km) is based on reconstructed and measured oxygen profiles whereas the right side (0 to 60 km) is based on measured oxygen profiles only. Both methods are shown against the normalized radial distance. The grey lines represents the density surfaces inside the eddies. **c)** Mean profiles of the oxygen anomalies based on measured profiles only; green colors are associated to ACMEs and blue to CEs. Horizontal lines indicate the standard deviation of the oxygen anomaly at selected depths. The thick dashed lines indicates the mean ML within the different eddy types. The grey vertical dashed line represents zero oxygen.

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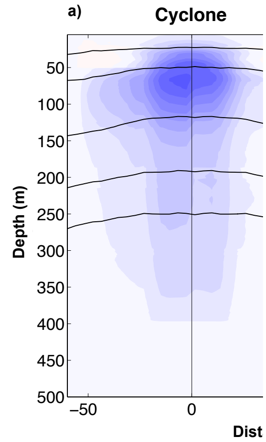

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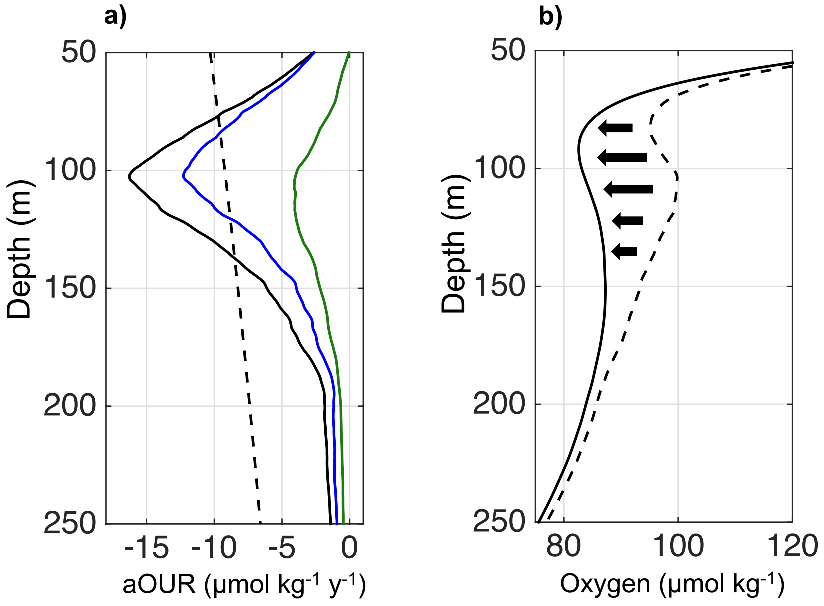

Figure 9: a) Depth profile of the apparent oxygen utilization rate (aOUR, µmol kg^{-1} y^{-1}) for the Atlantic as published from Karstensen et al. (2008) (dashed black line). The oxygen consumption profile due to low-oxygen eddies referenced for the SOMZ region (solid black line) and the separation into CEs (blue) and ACMEs (green). The solid black line in b) represents the observed mean vertical oxygen profile of all profiles within the SOMZ against depth, whereas the dashed black line represents the theoretical vertical oxygen profile in the SOMZ without the dispersion of low-oxygen eddies. Naturally due to the dispersion of negative oxygen anomalies, the observed values (black line) are lower than the theoretical oxygen concentrations in the SOMZ without eddies (dashed black line). The impact of the dispersion of low-oxygen eddies on the oxygen budget in the depth of the shallow oxygen minimum zone are also indicated by the thick black arrows.

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Gelöscht: 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).

Florian Schütte 9.9.16 18:09

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