Detailed response to guest editor and reviewers comments

We thank the guest editor Denis Gilbert and the two anonymous reviewers for evaluating the manuscript and providing constructive comments. We have revised and restructured the text over large parts, reworked the figures, and included (as requested by reviewer #2) one new figure. We redesigned Figure 8 (former 7) substantially. We hope that the new version of the manuscript is not only better synthesizing our results but further addresses adequately the points were improvements have been suggested. In the revision of the manuscript a more detailed discussion on potential mixing regions has been added by making use of the gradient Richardson number.

We now considered the erosion signal of the core that is clearly visible (see also a redesigned Fig. 4) but ignored in the previous submission. We did not include a ray trace model using our N2 and u,v shear (the application was suggested by the Reviewer#1 and taken up by the guest editor). The ray trace model (as in Sheen et al. 2015) will not provide any detail about potential mixing. In Sheen et al. (2015) mixing observations from Microstructure probes were available and the ray tracing helped to interpret the results. However, the mechanisms for mixing in Sheen et al. (2015) are speculative only. We do not even have direct mixing observations and as such not even a qualitative comparison beyond what is already presented in Sheen et al. can be expected. Sheen et al. (2015) note about the limitation of their model: *"We note that these simple ray tracing models are presented as a heuristic tool and are not intended to capture the full range of wave-mean flow interactions at play in such a complex system. For example, the models fail to account for the breakdown of the WKB analysis at critical layers [Booker and Bretherton, 1967; Jones, 1967], the consequences of using the WKB approximation in a background flow with relatively small horizontal length scales (O(10 km)) [Olbers, 1981; Whitt and Thomas, 2012], the assumption that the mean flow is 1-D and rectilinear [Bühler and McIntyre, 2005; Polzin, 2008], the potential for loss/gain of wave energy to the mean flow and/or a wave-induced effective viscosity [Booker and Bretherton, 1967; Muller, 1976; Polzin, 2010], the effect of f /N approaching 0.1 [e.g., Gerkema and Exarchou, 2008], the influence of the eddy rotation and the inclusion of the vorticity term in the ray tracing formulation [Kunze et al., 1995], and double diffusive processes."*

We think the Ri calculations are the maximum we could do to narrow down the potential mixing regions. Further studies with dedicated mixing experiments (e.g. MSS, dye experiments) in low oxygen eddies are required to provide observational ground truth which in turn can then be validated against e.g. ray tracing models.

Guest editors comments

Thank you for providing your constructive comments. Please find our response to your specific comments below:

Given that the eddy core described by Sheen et al. (2015) is located at a much greater depth (about 2000 m) than the 125 m deep core of the anticyclonic mode-water eddy (ACME) of your study, I believe that ray tracing specifically done for your study's ACME would help better determine the critical layer depth(s). See Referee # 1, Specific comment # 5;

We decided to not apply a ray trace model to our data for the reasons outlined in the summary section above – we hope that you agree to our conclusion.

Is vertical mixing really taking place mostly on the lateral edges of the eddy, as shown on your Fig. 7, rather than near the top of the eddy? Figure 4c of Sheen et al. (2015) shows enhanced mixing at the top of the eddy, at about the same depth (1500 m in their case) as where their critical layer scenario is located (their Fig. 5c).

Indeed, we revised that part of the manuscript substantially. By comparing the profiles and T/S diagrams from different life-stages of the eddy the impact of the "mixing", better "erosion", is clearly seen in the profiles and has not be adequately considered in the first submission. We redesigned Figure 4 that helps to discuss the temporal evolution in greater detail.

Anonymous Referee #1

General Comments

The present article presents a series of observational surveys relating the existence of an oxygen-deprived mesoscale eddy core in the North Atlantic to near-inertial wave dynamics and (maybe) large-scale Ekman transport. A sequence of observations and hypotheses are suggested to account for the fact that the eddy is mostly isolated from the outside waters, but not quite. I'm actually still confused about what stays in the eddy and what gets in and out, but amendments to the articles should remedy it. At least that's my take on it is but, but I am just a physical oceanographer and I don't spend much of my time thinking about biogeochemistry.

In general, the processing is well done, and the graphic depictions and the accompanying text show convincing signals, raising interesting scientific questions. I would be very happy if the authors left it at that, and maybe tried their hand at process guessing in a discussion section, with larger error bars around their allegations. But in my opinion, they stretch the

interpretation of their data way too far about how things are fluxed in and out of the eddy (or not), and how it explains the property structure inside of it. As far as I understand the article, they just see very interesting patterns, but are not able to prove many pieces of their model anyway. Either they are wrong, in which case this piece of text will fall into oblivion (although fig. 7 might unintentionally enjoy some form of posterity), or they are right, and the credit will go to whoever is able to prove this mechanism. Either way, I don't think they'll get citations for that part of the text. And I don't think that the article needs that to be publishable. Unless this model heavily relies on data published in other articles of their series, in which case they should consider publishing a separate article, because no-one has the time to read a whole series.

Considering that 12 co-authors could have proof-read it, the number of typos and English mistakes is rather large, even for non-native speakers. Not being a native English speaker myself, I have to let the editorial staff to correct these mistakes, but I have a list of my own if needed. Quite often, the authors prefer to use common words rather than field-specific terms ('normal eddy', 'erosion'), which would be fine if it didn't lead to ambiguities.

We thank the reviewer for the detailed and constructive comments. Based on the reviewer comments we hope that we were able to better (as far as it is possible based on the data at hand) discuss the physical (and biogeochemical) processes that are at work in the eddy.

Based on the data at hand we can describe the stratification, currents, and biogeochemical characteristic of the eddy, and its temporal evolution. We added now a more detailed analysis of mixing based on a gradient Richardson number approach. Moreover results published elsewhere are considered to interpret what we observe. The paper by Sheen et al. (2015) describes the possible Near Inertial Wave (NIW) propagation in and around a Modewater eddy (deep Southern Ocean eddy) based on observational (microstructure) data. Halle and Pinkel (2003) concluded that NIW propagation through a low stratified core impact the NIW energy density – the NIW propagation is very much increase in the low stratified core while in parallel the energy density decreases and thus mixing is supressed.

One part which was misinterpreted in the last version of the manuscript was related to the NIW propagation in regions where f_{eff}<f. Indeed NIW can propagate in region with f_{eff}<f (superinertial) such as for the core of an anticyclone. Here the NIW energy propagates downward. However, outside the eddy the horizontal velocity shear generates a region with f_{eff}>f (e.g. Halle and Pinkel 2003; their Fig. 16). Here, NIW generated in an f-region are forced to propagate downward when entering such a region until they are eventually reflected or loose energy by dissipation (critical layer). Enhanced mixing by shear instabilities from NIW currents that periodically enhance the background flow has been reported (Kawaguchi et al. 2016).

The comments about the quality of the writing are fully to the account of the lead author. In fact, the Guest Editor had kindly provided a proofread version that could have been used for initial publication – but unfortunately the file was "overlooked" by the lead author in the submission process. All comments have been considered in the revised version.

Specific Comments:

I will now switch to 'you' when referring to the authors.

1. P01L32: you and I seem to disagree on the specific definition of the submesoscale range. Some authors have it ranging from 1-10 km (10.1029/177GM04), some others have it ranging from 1-50 km or even 1-100 km (10.1038/ncomms7862), but everyone seems to agree on a key value of 10 km at mid-latitudes, and Ro, Ri = O(1) in general (which is perhaps the universally accepted definition). I'm fairly confident when I say that 1 km as an upper bound is too low, and 10 meters is too small, by a long shot. There has to be some influence of the Coriolis force, that I'm certain of.

A very valid comment – for the submesoscale range we followed the recent definition given by McWilliams (2016): "To be more quantitative, the approximate scale ranges for SMCs (*submesoscale currents*) are l=0.1–10km in the horizontal, h=0.01–1 km in the vertical, and hours-days in time (except for some submesoscale coherent vortices (SCVs) that can wander around in the vertical interior with lifetimes of years)."

1st paragraph of the intro: I'm not sure how useful this paragraph is.

This is true - we have shortened the paragraph, omitted the eddy detection sentences and restructured the paragraph.

P09, last paragraph (continued P10): I don't understand this. Why would the accumulation of NIW energy in high-N environments around an eddy shield it from mixing? If you accumulate NIWs anywhere, they tend to break, and bring mixing right at the door of the core. It sounds like planting wasp nests around one's house to prevent a wasp invasion. The whole article is confusing actually. I didn't understand it until way after, when you showed fig. 7.

We are sorry for the confusion. We take from this comment that the reviewer finally (fig. 8 – former fig. 7) understood the mechanism but not in the paragraph were it was described. As a consequence we re-wrote the paragraph (but also the introduction paragraph on lowering/increasing f around anticyclonic eddies and the impact on the propagation of NIW). It is also of important to mention that we wrongly interpreted the f_{eff} distribution. The lowering of the planetary vorticity in the core of ACME/AC creates superinertial NIW that propagate downward. In the $f_{eff} > f$ region at the transition zone between the eddy and the surrounding waters ("ridge region", Halle and Pinkel 2003) NIW energy propagates downward until reflected of dissipated (see e.g. Halle and Pinkel 2003; Fig. 16). This correction also required some modification in figure 8 (former Fig. 7) – which might be appreciated by this particular reviewer mentioning some concerns with the graphical realisation.

P10L4-12: I am not sure what this paragraph is about. My take on it: does mixing work differently for nutrients than it does for other quantities? But I'm still unsure of the answer.

Our intention was to discuss differences in surface signatures of nutrient upwelling (primary productivity) – is it more at the edge of an eddy or in the centre? The paragraph did not consider differences in mixing of different quantities. However, we re-wrote the paragraph.

P10L22-29: A bit of ray tracing would not add much work, and could greatly improve the credibility of your hypothesis.

We think that ray tracing that go beyond what has been already shown by Sheen et al. (2015) is outside of the scope of this manuscript. Instead we introduced the gradient Richardson number analysis on the individual CTD stations from the ships survey. The Ri analysis does support our conclusion about where the mixing is and why. Moreover, enhanced mixing at the N2 maximum in an ACME was also recently reported for an Arctic eddy (Kawaguchi et al. 2016) and that further support our interpretation of the data. What we actually miss in our observations is microstructure data that would help to quantify the mixing efficiency across an ACME – this data is to be collected in the future.

P11L14-26: my take from this paragraph: there is now an exchange pathway between the mixed layer and the core. Then what about everything you said in the preceding paragraphs? Is there a contradiction or is this a different issue?

The exchange is focussed at the mixed layer base (but only outward) and at the rim or edge of the eddy. There is no evidence from our data that support an exchange of the core (inward from the N^2 maxima) with the surrounding water. The term "erosion" should emphasize that the mixing is just towards the outside of the core - "outward" from the N2 maximum" and the core properties are largely unaffected. The term erosion has been used in the past in describing process that operate at the edge of warm core eddies (citation: "note that lateral intrusion and mixing on the sides of the eddy are contributing most to its erosion" Kroll, 1993).

P12L29-P13L15: Same problem as above. I don't find this paragraph very convincing. It is an interesting scenario, but fig. 7 is not substantiated by diffusive fluxes measurement/estimates. If Beal 2007 actually has something to say about it, you might want to use her article more, not cite her in passing. My suggestion is that this part be moved to the discussion section, with a much more honest depiction of how little you know about why

some properties are exchanged, and why some others aren't, and with a much more measured use of process-based interpretations (at least for the physical processes; I can't judge the chemistry part).

The new Ri analysis supports the mixing scenarios that are suggested by the property distributions. Analyses of microstructure observations that are interpreted as a result of NIW interaction with ACMEs (e.g. shallow ACME: Kawaguchi et al. 2016; deep ACME Sheen et al. 2015) have been published elsewhere. We followed your advice and move this part to the end of the paper.

P11L11-15: I thought I knew what flux was until I read these sentences. What do you mean by flux? Advective flux, diffusive flux? What do you mean by erosion? What does the phrase 'NO3-/oxygen from the eddy core is primarily outward' mean? Why would a flux necessarily transfer stuff from the outside? Are you talking about a mass flux, which in all rigour should be advective? Or a diffusive flux, in which case you may or may not be right depending on the concentration distribution? And what non-dimensional number quantifies the statement 'erosion rather than flux'?

We suspect you mean P13L11—15? The problem with a gradient flux considering an advective/ diffusive balance is that it would EXCHANGE properties – hence the core would be altered in its properties (e.g. Theta/S_A). What we actually observe is a remarkable constant T/S slope (and a decrease in oxygen over time – see figure below) but with a narrowing of the T/S range which indicate an erosion of the core above and below the eddy. The observations of a maximum in mixing efficiency at the N2 maximum by Sheen et al. (2015) and Kawaguchi et al. (2016), combined with the minimum in mixing efficiency in the core of the ACME (that is in-line with the NIW propagation pathways as simulated by Sheen et al. 2015 and Halle and Pinkel 2003) support an "erosion" scenario. With "erosion" we mean a transformation of the water at the N2 maximum into surrounding waters, which in turn drives a "shrinking" of the ACME core. We modified the text accordingly and added Figure 4.

P11L27-32 and figure 5b: are this paragraph and figure the only ones that actually lay out your case for an influence of Ekman transport on the ACME? If so, it is a very weak case, not enough to make it to the body of the article in my opinion, and certainly not enough to make it to the abstract, Once again, it could make it to the discussion section, in passing. Thomas 2005 considers a wildly different parameter regime by the way, I don't see how it can help you support your case without more calculations.

We agree and removed the paragraph.

P09L13: Could the low oxygen property have originated from the coast and simply have been

transported all the way to here? I know that you report a decrease from 8 to 3 micromoles/grams over the course of the experiment, but I don't know the error bars on these measurements. And as far as I can tell, you simply say at some point in the text that the signal looks real or something, but that's not quite the quantified statement, especially since so much hinges on it.

A very valid comment. We could show in the past (Karstensen et al. 2015, Fiedler et al. 2016, Schütte et al. 2016) that the low oxygen core did not originate from the coast. For example, direct observation of an Argo float with oxygen sensor that was trapped in a CE over a period of more than 7 month (Karstensen et al. 2015) from the upwelling region into the open North Atlantic showed a constant decrease in oxygen in the eddy core. Also from a number of direct observations of eddies that were surveyed shortly after they detached from the coast and many month later again (Karstensen et al. 2015, Fiedler et al. 2016, Schütte et al. 2016).

P14L23-25: 'The NIW concept (. . .) numerical models': it depends on which models you're talking about. Numerical process studies could resolve these sorts of scales (for a low-res version of what is achievable, see 10.1175/JPO-D-14- 0097.1; I am not an author, and I am not suggesting that you cite it), and could be the most obvious types of studies that could substantiate the viability of your hypotheses. So, I'd like this sentence to be rephrased in order to sound less like 'mission accomplished' and more like 'idealised process studies are needed'

Thank you for the comment. Of course there are models that do resolve the scales and hopefully the processes. We rephrased the sentence accordingly.

Technical Comments:

The Text has been modified throughout and it is difficult to identify the commented passages below. However, please be sure we applied the suggested changes BEFORE the text was re-written.

P01L14: extending from about 60 to 200 m depth and. . .? - done

P01L21: possibly -done

P02L03: 'has been conducted' => 'were conducted by Chaigneau. . .' - sentence removed

P02L10-13: you are describing a vertical stacking, or a baroclinic structure. Took me a while to figure out that it wasn't a radial shielding structure. And what do you mean by 'normal'?

Surface-intensified or barotropic? I don't see why one is more normal than the other anyway. I would also talk about ACEs rather than AEs, to be in line with ACMEs. And can't there be CMEs? – We rephrased the sentence and hope it is now clear that describe the stratification and the Mode. In the context of water masses the word "Mode" is often used for nearly homogenous properties such as for subtropical, or subpolar Mode Waters. We are not aware of a publication on "Cyclonic Modewater eddies" but would be happy to add a reference if the reviewer could provide one.

P02L26-29: something odd in that sentence. Perhaps the wrong verb ('explains') is used, or a comma is missing between 'ACME' and 'with', but something is odd. - We rephrased the sentence.

P03L04: 'Mesoscale eddies often have Ro close to 1' => 'Although usually characterised by Ro « 1, mesoscale eddies often feature local values of Ro closer to one'. See my Special Comment 1 though: you might disagree with me. – We rephrased the sentence accordingly.

P03L25-26: 'the modelled . . . eddy core.' If that's the message of the paragraph, it should be placed at the beginning. – We rephrased the whole paragraph.

P03L29: by rim, do you mean top/bottom or lateral rim or both? I would say edge or boundary actually. Rim sounds like lateral boundaries, which is what you might be referring to. – We rephrased the sentence

P04L15: 'and that' => 'which' – We rephrased the whole paragraph.

P04L26: 'but purely opportunistic': huh? I think you can delete anyway, no one is judging. - was deleted

P06L10: SA => S_A -changed

P07L16-17: 'During the last survey. . . 120 m': I actually see two minima, both at 120 m. Do you mean in the vertical again? - The sentence referred to the vertical and we modified the sentence.

P08L06: I don't see how the spiciness section shows the contrasting impact of Theta and S_A on isopycnals. I don't see Θ at all actually, and I don't remember the definition of spice. -Spiciness is constructed to be a variable that is most sensitive to isopycnal thermohaline variations, and least correlated with the density field (Flambert 2002). Because both, Theta and SA, contribute to density it is redundant to analyse them jointly along isopycnals. However, we decided to remove the spiciness discussion and added Theta section instead.

P08L13: ‘but separating the eddy surrounding water from. . .’ => ‘but well separates the eddy core from the surrounding waters’. –we rephrased the sentence

P08L16: in the stability ratio, what is the z index supposed to mean? Besides, you mix up θ and Θ here and in subsequent lines. –It is the vertical gradient/contribution. An explanation for z was now added to the text. Thank you for mentioning the problem with θ and Θ, which is related to using the word Equation editor or the symbol set.

P09L09: ‘but for the deeper levels more’ => ‘but more for the deeper levels’? - Changed accordingly

P09L30: ‘downward also’: missing word in-between? - Changed sentence

P09L31: a word on what a typical AE stratification is? - Sentence was removed (whole section rephrased)

P09L34: ‘and that also’ => ‘which also’ - Changed sentence

P10L4-5: ‘Having explained the isolation as..., it is tempting to...’ - Sentence was removed (whole section rephrased)

P10L06: what do you mean, ‘concept’? conceptual model? - Sentence was removed (whole section rephrased)

P11L14: ‘Only vertical propagation of internal waves does not generate mixing, but (...)’ => ’Vertical propagation of internal waves by itself does not generate mixing. In order to do so, . . .’ - Changed sentence

P11L15: I find it hard to conceive critical layer absorption not followed by KH. - That is true and we changed the sentence

P11L19-20: ‘Here the mean . . . vertical mixing’: I don’t understand this sentence. -Changed sentence: “Here the mean flow could gain energy from the NIW current that in turn could lead to energy dissipation because of the shear-instability (Kawaguchi et al. 2016)”

P12L25: Is the double minus in NO3- intentional? -Typo, Changed

P13L04: what’s PON? – It stands for “Particulate Organic Nitrogen” (which is nitrogen that is part of particles made out of organic substances) – we added the explanation.

Fig. 7: A few of my colleagues (not in this field) and I unanimously agree: this figure looks too

much like a particular piece of anatomy. We all suggest that you change the aspect ratio, make it less symmetric, and/or replace the blue and yellow lines by different lines. Once seen, it can't be unseen. Besides that, I thought oxygen was not transported in an out of the eddy (P14L15), so what's up with the yellow lines? I'd also like to see arrowheads on the blue and yellow lines, even if bi-directional (I don't think they would be). Finally, I'd like to see the huge converging arrows towards the centre of the eddy removed. I get it that some stuff is retained inside the eddy, but let's not forget that in a vortex, geostrophic or not, velocities are mostly azimuthal. I understand that this is meant to reinforce your point, but in the end, it is misleading. Or make them squiggly, which would evoke diffusion. - We changed the figure completely and hope it does not any longer displease peoples eyes. The low oxygen (high nitrate) waters are eroded from the core and introduced into the mixed layer. Here, low oxygen is brought back towards saturation by air/sea gas exchange – but this is not true for nitrate. The nitrate is taken up by phytoplankton and is reintroduced in the core via gravitational sinking of Particulate Organic Nitrogen (PON) into the core (new Fig 6 a). Back in the core, one certain nitrate molecule can be used multiple times for respiration of oxygen. This alters the AOU:NO3 ratio high.

Reference:

McWilliams JC: Submesoscale currents in the ocean. Proc. R. Soc. A 472: 20160117. http://dx.doi.org/10.1098/rspa.2016.0117, 2016.

Halle, C., and R. Pinkel: Internal wave variability in the Beaufort Sea during the winter of 1993/1994, J. Geophys. Res., 108(C7), 3210, doi:10.1029/2000JC000703, 2003.

Kawaguchi, Y., S. Nishino, J. Inoue, K. Maeno, H. Takeda, and K. Oshima: Enhanced diapycnal mixing due to near-inertial internal waves propagating through an anticyclonic eddy in the ice-free Chukchi Plateau. J. Phys. Oceanogr., 46, 2457-2481, doi:10.1175/JPO-D-15-0150.1, 2016.

Flament, P: A state variable for characterizing water masses and their diffusive stability: spiciness, Progress in Oceanography 54, 493–501, 2002.

Kroll, J.: The stability of an axially symmetric warm-core model eddy on a stratified ocean, Journal of Marine Research, 51, 273-292, 1993.

Anonymous Referee #2

GENERAL COMMENTS

This work is a contribution to a special issue about "dead-zone eddies" in the Eastern North Atlantic (ETNA) where 6 manuscripts are currently available, 3 already reviewed and published in BG and the rest in discussion form.
To be concise I consider Karstensen et al. (BGD, 2016) needs MAJOR REVISION, the reasons are exposed below. My main concern about this work is the lack of a clear focus on the hypothesis, results and discussion, is it about chemical or physical oceanography?

Another important consideration is that I needed to read carefully four manuscripts within the special issue to deeply understand the results and the discussion, the manuscript (ms) is full of typos or miss- references to the figures. It seems that the authors did not check the ms coherence before submitting, this is a very bad point for their reputation. Considering the amount of coauthors an effort should have been done to ease the reading of the ms and make it a stand- alone work.

Despite this I think the ms merits to be published after some improvements both in content and layout. I understand that it is somehow difficult to organize the wealth amount of data recorded by the different surveys and observing platforms deployed to characterize this intriguing new dead zones in the ETNA. In addition this paper is mostly about physical oceanography, and I am a chemical oceanographer, maybe the ms needs a third opinion.

We thank the reviewer for encouraging but also critical words. Indeed it is a problem to publish papers that address the interaction of physical and biogeochemical processes. To our opinion the Guest editor did a great job in selecting reviewers that, although addressing primarily points related to their own discipline (Reviewer 1 being a physical oceanographer, Reviewer 2 being a chemical Oceanographer), asked apparently “simple questions” on the others discipline which are often the trickiest to answer. As Reviewer 2 will see, we have revised the text and reordered the content over many parts. We reworked the figure and added one new figure that nicely shows the sinking of particles into the eddy core. We hope that the new version is now focussing to the point and thus is easier to read. We tried to simplify the physical and biogeochemical parts and reworked the summary figure (now Fig. 8). However, certain parts might be difficult to fully understand by one or the other disciplinary reader.

Indeed the many typos in the submitted version go fully to the account of the lead author. In fact, the Guest editor had kindly provided a proofread version that could have been used for publication – but unfortunately the file was “overlooked” by the lead author in the submission process.

A fundamental issue is the prime hypothesis of this ms which is finally resolved in Fig.7, the authors propose a physical mechanism to explain the isolation of the eddy core but also another one (near inertial waves, NIW, breaking) to explain the flux of nutrients to the upper mixed layer. As the authors say in the text the evidences to support the physical mechanisms

suffer from "not having concurrent hydrography and currents data and limited options for estimating balances" (P14, L3-4). On the biogeochemical side, the authors only support their "nitrogen cycling" hypothesis with nitrate and oxygen data from the glider surveys, but other measurements are available from typical CTD casts as described in Fiedler et al. (BGD 2016).

We added now a more detailed analysis of the potential mixing sites from a more „in depth“ analysis of the critical Richardson number. Moreover, a number of references are added that support the erosion concept (Halle and Pinkel 2003, Kawaguchi et al. 2016, Kroll 1993).

We added one figure that nicely shows the high particle load that “rains” into the eddy core (Fig. 6) and which further supports the idea that particle sinking and remineralization is one key process in creating the low oxygen core.

We also now added NO3/AOU data from the ship cruise that exactly show the same alteration of the AOU:NO3 ratio in the core.

SPECIFIC COMMENTS

Introduction
Although the intro is rather long, just the last three lines contain some references to the other ms related to the studied Anticyclonic Mode Water Eddies (ACME) within the same project and using the same observing platforms. I think a comprehensive summary of the different genomic, biological and biogeochemical aspects of the ACMEs should be given, also highlighting the contribution of the current ms.

We re-wrote and restructured the introduction. In particular the eddy detection part was removed (irrelevant for the present study). Details about the different genomic, biological and biogeochemical aspects of the particular ACME that we investigate here will be given in an overview article for the special issue (In preparation).

2. Data and methods
2.1. Glider survey
Maybe a word or reference about the interpolation method for the glider data would be interesting.
A linear interpolation was applied (now added to the text)

2.2 Glider sensor calibration
Page5, line 16. I would like to see some number about oxygen precision and accuracy, as done for nitrate (P6, L7-8). Although more details about this are surely given in Hahn et al 2014, please consider my demand.

The comparison between calibrated (by titration of oxygen samples) Clarke sensor on the CTD and the calibrated optode data suggests an overall (full oxygen range) RMS error of 3 µmol kg−1. However, for the chemically forced 0 µmol kg−1 oxygen an RMS error of 1 µmol kg−1 is expected. We added the information to the text.

2.3. Ship survey
I do not understand why not using the biogeochemical data gathered during M105, at least NO3, PO4, O2, particulate and dissolved organic matter, to sustain your biogeochemical interpretation of the results. More comments about this issue will be given in the corresponding section of the ms.
-As outlined under the specific points below, we primarily reference to the published figures in the accompanying articles. However, we added the AOU/NO3 data from the profiles taken un the eddy (ISL_000314).

3. Results and Discussion
3.1 Vertical Eddy Structure ”Biogeosciences” is not "Journal of Physical Oceanography" so my excuses for not understanding all the difficult terms in this section. As the aim of the ms is explaining the "fluxes of nitrate" into the mixed layer supporting the high primary production in the ACME, my opinion is that an effort should be done to make the ms more readable for the ocean biogeochemical community.
- The aim of the manuscript is to better understand mixing and isolation AND to reflect this back to the nitrogen cycling. We hope that the extensive rewriting of the manuscript has fixed this issue (also by summarizing the results in Figure 8 in a more transparent way).

P9L5-9. I checked (I read) Fiedler et al 2016 and I did not find any explanation about the translational velocity of the ACME, I found this information in Karstensen et al (BG 2015).
In section “3.1. Eddy Characteristics” Fielder et al. discuss the translation velocity. However, numbers are given in Karstensen et al. (2015) and Schütte et al. (2016). We changed accordingly.

3.2 Eddy core isolation and vertical fluxes. Please check the figure references in this section, it is a mess!! It was very hard to follow the result description and the final message to be conveyed.
The section has been completely rewritten and figures are re-done. We hope it is now easy to understand.

P9-L13 no reference to limnic systems is given in Karstensen et al (2015). -In the abstract of Karstensen et al. (2015) it says: “…create the “dead zone” inside the eddies, so far only reported for coastal areas or lakes.” – with “lakes” we anticipated limnic systems, but maybe that is incorrect?

P9-L19: the nonlinearity parameter is not defined or commented previously in this work but in Karstensen et al (2015). Please explain why alpha is important for the coherence of the eddy but it does not matter to explain isolation. -Eddies might be separated into linear waves (also called “Rossby Waves”) or in isolated, coherent structures. The non-linearity parameter is a measure to judge if the feature is a linear wave (translation speed and rotation speed are similar) or a coherent eddy (rotation speed much higher than translation) with a different dynamical regime. We refer in the text to the isolation of the core against lateral or vertical mixing – maybe shielding for mixing is a better formulation? The paragraph has been rewritten and a reference added (Chelton et al. 2011).

P10-L2-3. Weird phrase. – Indeed, but the paragraph has been completely rewritten and the sentence is removed.

P11. A mess with the figure references. Please just for the biogeochemist summarize where would NIW brake and induce mixing / fluxes in the eddy structure.
- We rephrased the sentences and hope that we provide with (new) Figure 8 a good overview about were exactly mixing occurs. We structured in three regions (I, II, III).

P11-L8-9. "no concurrent velocity and stratification section data exists" I do not understand, you have velocity and CTD casts from the ship so at least you have 8 stations. –We now exclusively use the CTD and ADCP shear data for estimating the gradient Richardson number (P11L8) and added information into Figure 4 (d, h).

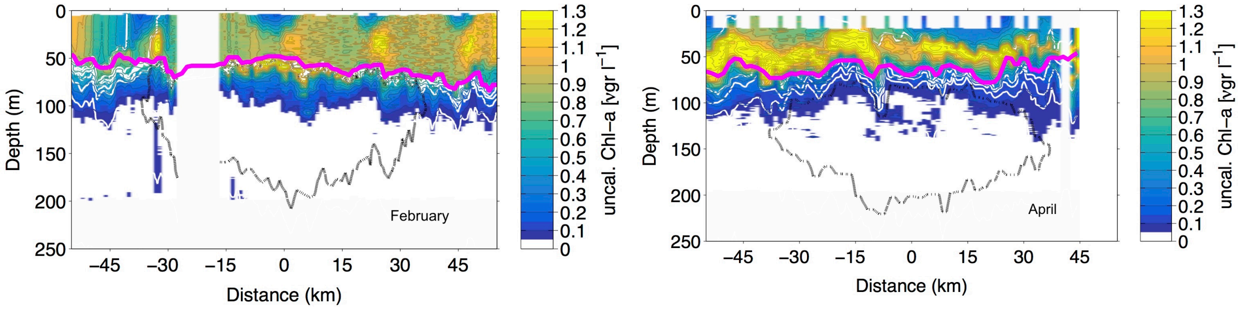
3.3 Nutrient budget.
This section should be entitled "nitrate budget"... but not even so... as no budget is estimated, a better title would be "nitrate cycling" .
- This is true and we changed that accordingly

My main concern about this section the rejection of using other biogeochemical data from the ship surveys within the ACMEs. For example why not using the M105 NO3 and AOU data in Fig 6c?, they crossed the eddy center as showed in Fig 2b.
– We added the data from ISL314 to the plot.

An evidence of denitrification would be a differential NO3:PO4 ratio.
- The NO3:PO4 ratio has been presented in Löscher et al. (2015) in Figure 3c and in Grundel et al. (in revision, Scientific Reports). It was determined in these papers that the nitrogen loss is in nanomol/kg range – while we talk about 4-6 micromol/kg.

After reading several times this section, the main question is how are the nutrients injected into the mixed layer to support primary production?. However no profile of chlorophyll is given (I found some info about this in Loscher et al. BG 2015) , I wonder if the gliders have at least a backscattering or fluorometer sensor.

- We added a new figure on turbidity that shows the particle sinking (turbidity) across the mixed layer base and deep into the low oxygen core. The fluorescence data we found not very instructive (see below). During the first occupation the high chlorophyll was more homogenous distributed across the mixed layer (but the quenching effect is therefore very pronounced). During the second occupation (IFM13) a clear subsurface Chl maximum relative well aligned with the mixed layer base is found (but the maximum is at about 10m shallower depth). We could add these plots to the Turbidity figure if the reviewer insists.



The biogeochemical info in Fiedler et al BGD 2016 in the shelf, CVOO and the eddies may help to explain the high primary production (PP), if eddies are formed in the shelf, they contain nutrients that are used and converted into organic matter (particulate and dissolved) that sinks and is remineralized in the eddy creating the O2 minimum. Is it enough the initial NO3 in the shelf to sustain PP in the eddy when it moves into the ETNA?. Does it really need an extra NO3 input?

- It is not a problem of the initial nutrient content in the eddy core but the processes that transport nutrients into the euphotic zone of the eddy. The process we propose alters fundamentally the NO3:AOU ratio because it is based on recycling of nutrients (but not of oxygen), which in turn is the results of the specifics of upwelling in the eddy.

We would not call that an “extra NO3” but a recycling that alters the AOU/NO3 ratio. Figure 4 in Fiedler et al. (2016) shows the profiles from the cruises as well as from the shelf. It can be seen that the shelf water are lower in NO3 (and higher in O2) than the waters in the eddy core. Moreover, in Karstensen et al. (2015) we could show that the low oxygen is generated en-route and not in the eddy at the time when it detaches from the coast.

It is very hard to understand a decoupled O2 and NO3 cycle if denitrification is not important. Please check the NO3:PO4 ratio. An anomalous O2:NO3 ratio could be related to the stochiometry of the organic matter remineralized both particulate and dissolved, please check the available data.

- As mentioned earlier, Löscher et al. (2015) (and in Grundle et al. in revision, Scientific Reports) determined the nitrogen loss by denitrification to be in the nanomolar range but the nitrate deficit is in the micromolar range.

We explain the decoupling from the specific mixing pattern of the eddy (erosion of the core) and the differences in what happens to oxygen and nitrate when reintroduced into the mixed layer (euphotic zone) of the eddy. Once in the mixed layer the pathways of the high NO3 and the low O2 water are different. The low O2 water will lower the oxygen content in the mixed layer (being now undersaturated in oxygen) but which is recharged by air/sea gas exchange. In contrast, the high NO3 water of the core will provide new nutrients to the mixed layer and in turn stimulate productivity. The nitrogen is incorporated into particles (as PON) in the productivity processes, which in turn sink out of the mixed layer and back into the core. Through this pathway, some of the upwelled nitrogen is re-entering the eddy core and is ready for driving new respiration via remineralization. Essentially the reintroduction of NO3 is a gravitational process and O2 does not participate in it.

4. Summary and conclusions

I suppose it would need to be rewritten depending on the results from section 3.3.

-We have rewritten the section 4 and hope to made the points now more clear.

I hope to have been helpful.

-Definitely – Thank you!

Upwelling and isolation in oxygen-depleted anticyclonic modewater eddies and implications for nitrate cycling

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Abstract. The temporal evolution of the physical and biogeochemical structure of an oxygen-depleted anticyclonic mode-water eddy is investigated over a two-month period using high-resolution glider and ship data. A weakly stratified eddy core (squared buoyancy frequency $N^2 \sim 0.1\cdot10^{-4}$ s^{-2}) at shallow depth is identified with a horizontal extend of about 70 km and bounded by maxima in N^2. The upper N^2 maximum (3-5·10^{-4} s^{-2}) coincides with the mixed layer base and the lower N^2 maximum (0.4·10^{-4} s^{-2}) is found at about 200 m depth in the eddy centre. The eddy core show a constant slope in temperature/salinity (T/S) characteristic over the 2 month but an erosion of the core progressively narrows down the T/S range. The eddy minimal oxygen concentrations decreased by about 5 µmol kg^{-1}, confirming earlier estimates of oxygen consumption in these eddies.

Separating the mesoscale and perturbation flow components reveal oscillating velocity finestructure (order 0.1 m/s) underneath the eddy and at its flanks. The velocity finestructure is organized in layers that align with layers in properties (salinity, temperature) but mostly cross through surface of constant density. The largest magnitude in velocity finestructure is seen between the surface and 140 m just outside the maximum mesoscale flow but also in a layer underneath the eddy centre, between 250 to 450 m. For both regions a cyclonic rotation of the velocity finestructure with depth suggest the vertical propagation of near-inertial wave (NIW) energy. Modification of the planetary vorticity by anticyclonic (eddy core) and cyclonic (eddy periphery) relative vorticity is most likely impacting the NIW energy propagation. Below the low oxygen core salt-finger type double diffusive layers are found that align with the velocity finestructure.

Apparent oxygen utilization (AOU) versus dissolved inorganic nitrate (NO_3^-) ratios are about twice as high (16) in the eddy core compared to surrounding waters (8.1). A large NO_3^- deficit of 4 to 6 µmol kg^{-1} is determined, rendering denitrification an unlikely explanation. Here it is hypothesized that the differences in local recycling of nitrogen and oxygen, as a result of the eddy dynamics, cause the shift in the AOU:NO_3^- ratio. High NO_3^- and low oxygen waters are eroded by mixing from the eddy core and entrain into the mixed layer. The nitrogen is reintroduced into the core by gravitational settling out of the euphotic zone. The low oxygen water equilibrates in the mixed layer by air/sea gas exchange and does not participate in the gravitational sinking.

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Introduction

Eddies are associated with a wide spectrum of dynamical processes operating on mesoscale (order 100 km) and submesoscale (order of 0.1 to 10 km) horizontal scales, but also down to molecular scale of three-dimensional turbulence (McWilliams 2016). The interaction of these processes creates transport patterns in and around eddies that provoke often very intense biogeochemical and biological feedback such as plankton blooms (Levy et al. 2012, Chelton et al. 2011).

The most simple way is classifying eddies by sense of rotation into cyclonic-rotating and anti-cyclonic rotating eddies (e.g. Chelton et al. 2011, Zhang et al. 2013). However, when considering the vertical stratification of eddies, a third group emerges that shows in a certain depth range a downward displacement of isopycnals towards the eddy centre, as observed in anticyclonic eddies (ACE), but an upward displacement of isopycnals in a depth range above, as observed in cyclonic eddies (CE). Because the depth interval between upward and downward displaced isopycnals creates a volume of homogenous properties, called a "mode", such hybrid eddies have been called anticyclonic modewater eddies (ACME) or intra-thermocline eddies (McWilliams 1985, D'Asaro 1988, Kostianoy and Belkin 1989, Thomas 2008). Modewater eddies occur not only in the thermocline but also in the deep ocean like for example Mediterranean Outflow lenses (Meddies) in the North Atlantic (Armi and Zenk 1984) or those associated with deep convection processes (e.g. Mediterranean Sea, Testor and Gascard 2006). Schütte et al. (2016a, 2016b) studied eddy occurrence in the thermocline of the tropical eastern North Atlantic considering CEs, ACEs, and ACMEs. They estimated that about 9% of all eddies (20% of all anticyclonic rotating eddies) in the eastern tropical North Atlantic are ACME. Zhang et al. (in press) found modewater eddies in all ocean basins and primarily in the upper 1000 m.

More than a decade ago a dedicated observational program was carried in the Sargasso Sea in the western North Atlantic in order to better understand the physical-biogeochemical interactions in mesoscale eddies. The studies revealed that in ACMEs particularly intense deep chlorophyll-a layers are found which align with a maximum concentrations of diatoms and maximum productivity (McGillicuddy et al. 2007). The high productivity was explained by the "eddy-wind interaction" concept (McGillicuddy et al. 2007; going back to a work from Dewar and Flierl, 1987) based on an Ekman divergence that is generated from the horizontal gradient in wind stress across anticyclonic rotating eddies. While the productivity is evident from observations the concept was questioned (Mahadevan et al. 2008). High-resolution ocean model simulations, comparing runs with or without eddy-wind interaction, reproduced only a marginal impact on ocean productivity (but a strong impact on physics; Eden and Dietze 2009). A tracer release experiment within an ACME revealed a vertical

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flux in the order of magnitude (several meters per day) as calculated based on the eddy-wind interaction concept (Ledwell et al. 2008).

Levy et al. (2012) summarized the submesoscale upwelling at fronts in general, not specifically for mesoscale eddies, and the impact on oceanic productivity. A key role is played by the vertical flux of nutrients into the euphotic zone, either by advection along outcropping isopycnals or by mixing. Moreover, eddies are retention regions (d'Ovidio et al. 2013) and the upwelled nutrients are kept in the eddy and utilized for new production (Condie and Condie, 2016).

In the tropical eastern North Atlantic ACMEs with very low oxygen concentrations in their cores have been observed (Karstensen et al. 2015). The generation of the low oxygen concentrations was linked to upwelling of nutrients and high productivity in the euphotic zone of the eddy followed by a remineralisation of the sinking organic matter and accompanied by respiration. The temperature and salinity characteristic of the eddy core was found unaltered even after many month of westward propagation of ACMEs indicating a well-isolated core. It was surprising to find a well isolated eddy core while in parallel enhanced vertical nutrient flux is required to maintain the productivity in the eddy.

A measure for the importance of local rotational effect relative to the Earth rotation is given by the Rossby number defined as $Ro = \frac{\zeta}{f}$, and where $\zeta = \frac{\partial v}{\partial x} - \frac{\partial v}{\partial y}$ is the vertical component of the relative vorticity (u, v are zonal and meridional velocities, respectively) and f the planetary vorticity. Planetary flows have small Ro, say up to ~0.2, but local rotational effects gain importance with Ro approaching 1, for example in eddies and fronts.

The horizontal velocity shear of mesoscale eddies create a negative (positive) ζ in anticyclonic (cyclonic) rotating eddies. The ζ modifies f to an "effective planetary vorticity" ($f_{eff} = f + \frac{\zeta}{2}$) (Kunze 1985, Lee and Niller 1998). Negative ζ of anticyclonic rotating eddies result in a $f_{eff} < f$ in their cores. In region outward from the maximum swirl velocity of the eddy, towards the surrounding waters, a positive ζ "ridge" is created and where $f_{eff} > f$ (e.g. Halle and Pinkel, 2003). The local modification of f has implications for the propagation of near inertial internal waves (NIWs): in the core of an anticyclonic rotating eddy ($f_{eff} > f$) the NIW become superinertial and their vertical propagation speed increase (Kunze et al. 1995). In the ridge region of any anticyclonic rotating eddy the NIW experience a reduction in vertical speed and they may reflect because $f_{eff} < f$. Downward propagation of NIWs may result in an accumulation of wave energy at some critical depth and eventually part of the energy is dissipated by buoyancy release through vertical mixing (Kunze 1985, Kunze et al. 1995, Whitt and Thomas 2013, 2017).

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In anticyclonic rotating eddies the downward propagation of wave energy in the $f_{eff} < f$ region has been observed and modelled (Kunze 1985, Gregg et al. 1986, Lee and Niller 1998, Koszalka et al. 2010, Joyce et al. 2013, Alford et al. 2016). Lee and Niiler (1998) simulated the NIW interaction with eddies (ACE, CE, ACME) and found vertical propagation of the NIW energy, the “inertial chimney”. In the case of an ACME with a low squared buoyancy frequency (N^2) layer they report on NIW energy accumulating below the eddy core and not inside as seen for ACE. This change in energy accumulation was attributed to the vertical stratification of the ACME, in particular the two N^2 maxima that shield the low stratified eddy core. Kunze et al. (1995) analysed NIW energy propagation in an ACE. Within a critical layer at the inner sides of the ACE and where the f_{eff} increases ≥1, the vertical propagation of NIWs is hampered and energy accumulates, the bulk is being released by turbulent mixing.

The vertical shear of the horizontal velocity that is generated by NIWs can eventually force overturning e.g. which approaching a critical layer (Kunze et al. 1995). The tendency of a stratified water column to become unstable through velocity shear $S = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2}$ can be estimated from the gradient Richardson number $Ri = N^2/S^2$. A $Ri < 1/4$ has been found a necessary condition for the shear to overcome the stratification and to generate overturning. However, Whitt et al. (submitted) measured enhanced dissipation was with shear probes along the Gulf Stream front in several regions where NIW shear produced $Ri < 1$.

Recent observational studies using microstructure shear probe data report enhanced mixing in a narrow depth range of a local, vertical N^2 maximum, above and below the low stratified ACME core (Sheen et al. 2015, Kawaguchi et al. 2016). By applying a internal wave ray trace model to the N^2 stability profile and vertical shear profile from outside and from inside of an ACME Sheen et al. (2015) could show that only a very limited range of incident angles of internal waves could propagate into the eddy core. Most NIWs encounter a critical layer above and below the eddy, the regions where they observed enhanced mixing. Halle and Pinkel (2003) analysed NIW interaction with eddies (owning a ACME vertical structure) in the Arctic and explained the low internal wave activity in the core as the result of an increase (order of magnitude) in wave group speed caused by low N^2 but which in turn lowering of wave energy density. Krahmann et al. (2008) reported observations of enhanced NIW energy in the vicinity of a Meddie. For Meddies signatures of thermohaline layering at the eddy periphery have often been observed and occurrence of critical layers identified that support the energy transfer from the mesoscale to the submesoscale (Hua et al. 2013).

In this paper we investigate the hydrography, currents, and biogeochemical characteristic of a low oxygen ACME and its temporal evolution. High-resolution underwater glider and ship data allow us to describe the eddy structure at submesoscale resolution. Characteristics of a low oxygen ACME found in the eastern tropical North Atlantic are provided. The paper is part of a series of publications that report

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on different genomic, biological and biogeochemical aspects of this eddy (Löscher et al. 2015, Hauss et al. 2016, Fiedler et al. 2016, Schütte et al. 2016b).

2. Data and Methods

Targeted eddy surveys are logistically challenging. Eddy locations can be identified using real-time satellite SLA data. To further differentiate a positive SLA (indicative for anticyclonic rotating eddies) into either an ACE or an ACME the SST anomaly across the eddy was additionally inspected, because ACMEs (ACEs) in the eastern tropical North Atlantic show a cold (warm) SST anomaly (Schütte et al. 2016a, Schütte et al. 2016b). For further evidence, Argo profile data were inspected to detect anomalously low temperature/salinity signatures also indicative of low oxygen ACMEs in the region (Karstensen et al. 2015, Schütte et al 2016b). In late December 2013 a candidate eddy was identified through this mechanism and in late January 2014 a pre-survey was initiated, making use of autonomous gliders. After confirmation that the candidate eddy was indeed a low oxygen ACME, two ship surveys (ISL_00314, M105; Fiedler et al. 2016) and further glider surveys followed.

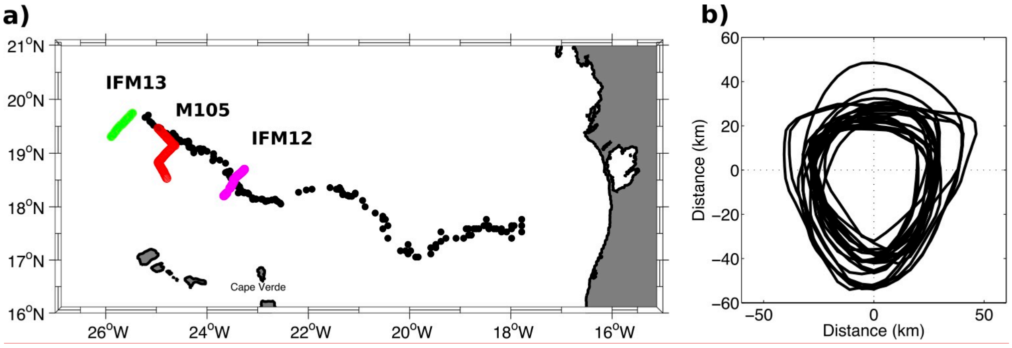

Figure 1: (a) Positions of Glider IFM12 (magenta) and IFM13 (green) surveys and the M105 ship survey (red dots). The Mauritanian Coast is on the east, the Cape Verde Islands in the south. The black dots represent the sea level anomaly (SLA) based estimate of the eddy trajectory (see e.g. Fiedler et al. 2016). (b) Last closed geostrophic contour from SLA during the IMF12 survey projected on the eddy centre.

2.1 Glider surveys

Data from the glider IFM12 (2nd deployment) and glider IFM13 (1st deployment) were used in this study (Fig. 1). Glider IFM12 surveyed temperature, salinity, and oxygen to a depth of 500 m as well as chlorophyll-a fluorescence and turbidity to 200 m depth. Glider IFM13 surveyed temperature, salinity, and oxygen to a depth of 700 m as well as chlorophyll-a fluorescence and turbidity to 200 m depth. Glider IFM13 was also equipped with a nitrate sensor that sampled to 700 m depth.

For one full eddy survey of glider IFM12 (Fig. 1) we combined data from February 3rd to 5th and from February 7th to 10th, 2014 because, due to technical problems, data were not recorded in between these

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periods. Glider IFM13 surveyed one full eddy section from April 3rd to 7th, 2014. All glider data were internally recorded as a time series along the flight path, while for the analysis the data was linear interpolated onto a regular pressure grid of 1 dbar resolution. For the purposes of this study we consider the originally slanted profiles as vertical profiles.

2.2 Glider Sensor Calibrations

Both gliders were equipped with a pumped CTD and no evidence for further time lag correction of the conductivity sensor was found. Oxygen was recorded with AADI Aanderaa optodes (model 3830). The optodes were calibrated in reference to SeaBird SBE43 sensors mounted on a regular ship-based CTD, which in turn were calibrated using Winkler titration of water samples (see Hahn et al. 2014). Considering the full oxygen range an RMS error of 3 μmol kg^{-1} is found. However, for calibrating at the chemically forced 0 μmol kg^{-1} oxygen the RMS error is smaller and about 1 μmol kg^{-1}. The calibration process also removes a large part of the effects of the slow optode response time via a reverse exponential filter (time constants were 21 and 23 seconds for IFM12 and IFM13, respectively). As there remained some spurious difference between down and up profiles we averaged up- and downcast profiles to further minimize the slow sensor response problem in high gradient regions, particular the mixed layer base. The optical (Wetlabs ECO-PUC) chlorophyll-a fluorescence (not used in our study) and turbidity data were not calibrated against bottle sample, only the factory calibration is applied. We subtracted a dark (black tape on sensor) offset value and the data is here given in relative units.

The nitrate (NO$_3^-$) measurements on glider IFM13 were collected using a Satlantic Deep SUNA sensor. The SUNA emits light pulses and measures spectra in the ultraviolet range of the electromagnetic spectrum. It derives the NO$_3^-$ concentration from the concentration-dependent absorption over a 1 cm long path through the sampled seawater. During the descents of the glider the sensor was programmed to collect bursts of 5 measurements every 20 seconds or about every 4 m in the upper 200 m and every 100 seconds or about every 20 m below 200 m. The sensor had been factory calibrated 8 months prior to the deployment. The spectral measurements of the SUNA were post-processed using Satlantic's SUNACom software, which implements a temperature and salinity dependent correction to the absorption (Sakamoto et al., 2009). The SUNA sensors' light source is subject to aging which results in an offset NO$_3^-$ concentration (Johnson et al., 2013). To determine the resulting offset, NO$_3^-$ concentrations measured on bottle samples by the standard wet-chemical method were compared against the SUNA-based concentrations. The glider recorded profiles close to the CVOO mooring observatory (see Fiedler et al. 2016) at the beginning and end of the mission. These we compared to the mean concentrations of ship samples taken in the vicinity of the CVOO location (Fiedler et al. 2016). In addition we compared glider measurements within the ACME to NO$_3^-$ samples from the ship surveys performed during the eddy experiment (see Löscher et al. 2015, Fiedler et al. 2016). The comparison

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showed on average no offset (0.0 ± 0.2 µmol kg^{-1}). However, near the surface the bottle measurements indicated NO$_3^-$ concentrations below 0.2 µmol kg^{-1} at CVOO, while the SUNA delivered values of about 1.8 µmol kg^{-1} possibly related to technical problems near the surface. We thus estimate the accuracy of the NO$_3^-$ measurements to be better than 2.5 µmol kg^{-1} with a precision of each value of about 0.5 µmol kg^{-1}.

All temperature and salinity data are reported in reference to TEOS-10 (IOC et al. 2010) and as such we report absolute salinity (S$_A$) and conservative temperature (Θ). Calculations of relevant properties (e.g. buoyancy frequency, oxygen saturation) were done using the TEOS-10 MATLAB toolbox (McDougall and Barker, 2011). We came across one problem related to the TEOS-10 thermodynamic framework when applied to nonlinear, coherent vortices. Because the vortices transfer properties nearly unaltered over large distances the application of a regional (observing location) correction for the determination of the S$_A$ (McDougall et al. 2012) seems questionable. In the case of the surveyed eddy the impact was tested by applying the ion composition correction from 17°W (eddy origin) and compared that with the correction at the observational position, more than 700 km to the west, and found a salinity difference of little less than 0.001 g kg^{-1}.

2.3 Ship survey

Data from two ship surveys have been used, surveying about 6 weeks after the first glider survey (and 3 weeks before the last glider survey) on the same eddy (Fig. 1), R/V Islandia cruise ISL_00314 performed sampling between the 5th and 7th March 2014 and R/V Meteor cruise M105 sampled on the 18th and 19th March 2014.. From M105 we make use of the CTD data and the water currents data recorded with a vessel mounted 75kHz Teledyne RDI Acoustic Doppler Current Profiler (ADCP). The data was recorded in 8 m depth cells and standard processing routines were applied to remove the ship speed and correcting the transducer alignment in the ship's hull. The final data was averaged in 15 min intervals. Only data recorded during steaming (defined as ship speed larger than 6 kn) is used for evaluating the currents structure of the eddy. It should be mentioned that the inner core of the eddy shows a gap in velocity records, which is caused by very low backscatter particle distribution (size about 1 to 2 cm) (see Hauss et al. 2016 for a more detailed analysis of the backscatter signal including net zooplankton catches). In order to provide a hydrography and oxygen framework for comparing ship currents and glider section data, we interpolated data from 8 deep (>600 m) CTD stations performed during the eddy survey, and estimated oxygen and density distributions across the eddy. Because only a few stations have been sampled (in the eddy and at the eddy edge) during RV Islandia ISL_00314 (Fiedler et al. 2016) we use this data only in our NO$_3^-$/oxygen analysis.

More information about other data acquired during M105 and ISL_00314 in the eddy is given elsewhere (Löscher et al. 2015, Hauss et al. 2016, Fiedler et al. 2016).

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3. Results and Discussion

3.1 Vertical Eddy Structure and its temporal evolution

In order to compare the vertical structure of the eddy from the three different surveys, all sections were referenced to “kilometre distance from the eddy core” as spatial coordinate, while the “centre” was selected based on visual inspection for the largest vertical extend of the low oxygen core defined by oxygen concentrations below 40 µmol kg^{-1}. In all three sections the core is found in the centre of the eddy (Fig. 2), extending over the depth range from the mixed layer base (50 to 70 m) down to about 200 m depth. The upper and lower boundary aligns with the curvature of isopycnals. Considering the whole section across the eddy it can be seen that towards the centre of the eddy the isopycnals show an upward bending in an upper layer (typically associated with cyclonic rotating eddies) and a downward bending below (associated with anticyclonic rotating eddies) which is characteristic for ACMEs.

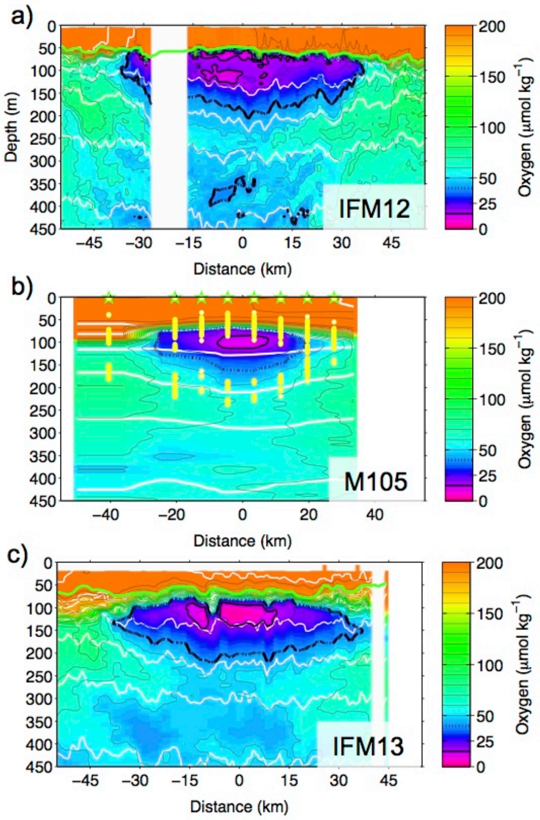

Figure 2: Oxygen distribution from the three eddy surveys (see Figure 1) in reference to distance (0 km is set at a subjectively selected eddy centre): a) Glider IFM12, b) ship M105, and c) glider IFM13. The 15 µM (40 µM) oxygen contour is indicated as a bold (broken) black line, selected density anomaly contours are shown as white lines ($\Delta\sigma = 0.2$ kg m^{-3}). The green line indicates the mixed layer base. The oxygen contour in b) was gridded based on the 8 CTD stations (locations indicated by green stars at

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0dbar) and mapped to a linear section in latitude, longitude. In b) the yellow dots indicate positions of local N^2 maxima in the CTD profiles.

During the first survey (IFM12), lowest oxygen concentrations of about 8 µmol kg^{-1} were observed in two vertically separated cores at about 80 m and 120 m depth, while in between the two cores, oxygen concentrations increased to about 15 µmol kg^{-1}. About 6 weeks later, during the M105 ship survey, lowest concentrations of about 5 µmol kg^{-1} were observed, centred at about 100 m depth and without a clear double minimum anymore, based on six CTD stations. During the last glider survey (IFM13), another three weeks after the ship survey, the minimum concentrations were < 3 µmol kg^{-1} and showed in the vertical a single minimum centred at about 120 m. The intensification of the minimum (by about 5 µmol kg^{-1} in 2 months) is assumed here to be a result of continues respiration without balancing lateral/vertical mixing oxygen supply. It is important to note that during the glider survey the eddy performed about one full rotation and hence we expect less impact of the spatial variability in our sampling of the core. Underneath the eddy core, and best seen in the 40 µmol kg^{-1} oxygen contour below 350 m at about 0 km (centre), an increase in oxygen over time is found indicating supply of oxygen from surrounding waters. Comparing the two glider surveys (Fig. 2) a broadening of the gradient zone at the upper boundary of the core is observed. Overall the upper boundary of the core during the first survey aligned tightly with the mixed layer base giving the core the shape of a plan convex lens, while the lens developed into a biconvex shape before the second glider survey (also seen in the ship survey Fig. 2b).

The SLA data analysis for the eddy (see Schütte et al. 2016b for details) suggests a formation in the Mauritanian upwelling region (Fig. 1). The composite of the outermost (“last”) closed geostrophic contour of the eddy (Fig. 1, right), revealed a diameter of about 60 km, which is in accordance with the dimensions of the vertical structures observed from the glider and the ship (Fig. 2 and 3). The eddy core is composed of a fresh and cold (Fig. 3a, b; Fig 4a) water mass that matches the characteristics of South Atlantic Central Water (SACW; Fiedler et al. 2016) and is a typical composition for low oxygen eddies in the eastern tropical North Atlantic (Karstensen et al. 2015, Schütte et al. 2016a, 2016b). The properties confirm that the ACME was formed in the coastal area off Mauritania, as suggested by the SLA analysis (Schütte et al. 2016b; Fig. 1, left). Layering of properties, as seen in oxygen (Fig. 3), is also observed in S_A and Θ (Fig. 4) underneath the eddy core. In the depth range between 160 to 250 m the layers are aligned with density contours and suggest isopycnal transport processes, while below that depth range, and at the edges of the eddy core the thermohaline intrusions cross density surfaces.

The low oxygen core of the ACME is well separated from the surrounding water through maxima in N^2 (Fig. 3c). The most stable conditions (N^2 about 3 to 5*10^{-4} s^{-2}; compare Fig. 4a) are found along the upper boundary of the core and aligned with the mixed layer base (changed from 50 to 70 m between

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IFM12 and IFM13, respectively). Θ (S_A) differences across the mixed layer base were large, about 5 to 6 K (0.7 – 1.0 gr kg^{-1}), but over time the mixed layer base widened from 8 m (glider IFM12 survey) to 16 m (M105 ship) and to 40 m (glider IFM13 survey) (Fig. 4a).

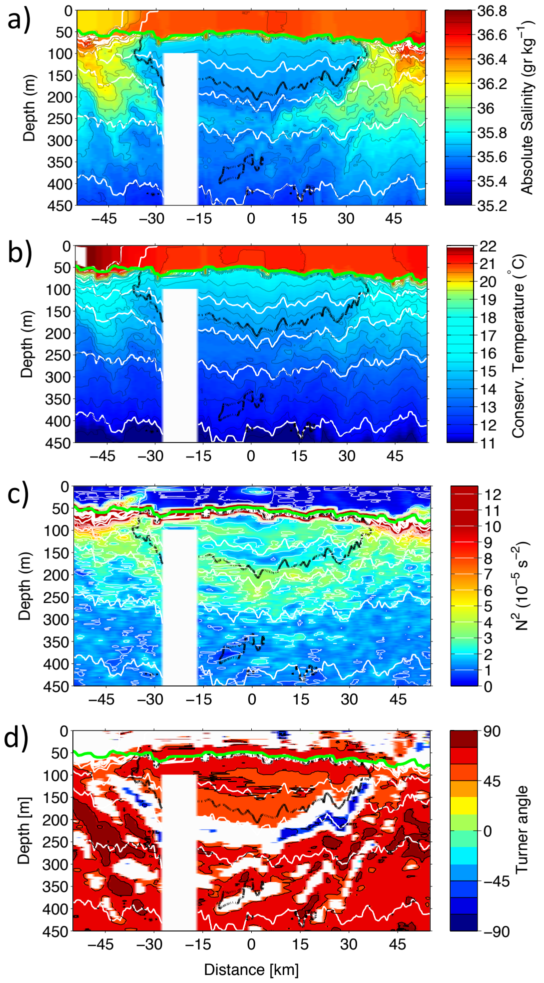

Figure 3: a) S_A, b) Θ, c) N^2, d) Turner angle (only segments |45 to 90| are shown) from IFM12 survey. The thick black broken line indicates the 40 µmol kg^{-1} oxygen concentration (see Fig. 2). The green line indicates the mixed layer base. Selected density anomaly contours are shown as white lines (Δσ=0.2 kg m^{-3}).

At the lower side of the ACME the N^2 maximum was an order of magnitude weaker (N^2 ~ 4*10^{-5} s^{-2}) but separates well the eddy core from the surrounding waters. The layering in properties is also seen in alternating patterns in N^2 at the rim and below the eddy. A possible driver for mixing in this region is

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Gelöscht: stability

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double diffusion and therefore the stability ratio $R_\rho = \frac{\alpha^\theta \Theta_z}{\beta^\theta (S_A)_z}$ (McDougall and Barker 2011) was calculated. R_ρ is the ratio of the vertical (z) gradient in Θ, weighted by the thermal expansion coefficient (α^Θ), over the vertical (z) gradient in S_A, weighted by the haline contraction coefficient (β^Θ) (Fig. 3d). For convenience R_ρ is converted here to a Turner angle (*Tu*) using the four-quadrant arctangent. For *Tu* between –45 to –90° the stratification is susceptible to salt finger type double diffusion, while *Tu* +45° to +90° indicate susceptibility for diffusive convection. Regions where most likely double diffusion occurs are found for *Tu* close to ±90°.

In the core of the eddy the *Tu* indicate a weak salt finger regime (*Tu* values close to +45°; Fig. 3d), however, no well developed thermohaline gradients exists and thus no enhanced vertical mixing by double diffusion is expected to take place here. In contrast, below the low oxygen core and along the thermohaline layering structures, the *Tu* patterns show values within the ±45° to ±90° range, even getting close to ±90°. At both edges (±15 to ±45 km) a band of diffusive convection is seen and here is where potentially water of the core exchanges/erodes (see below). The *Tu* pattern do not align with the tilting of the isopycnals but cross isopycnals. The thermohaline gradients are most likely created by intrusions of cold and saline SACW from the core, into the surrounding warm and salty water. The core itself shows a Θ/S_A characteristic of constant slope over time (Fig. 4c) and indicating weak mixing with surrounding water. The salinity offset between glider IFM12 and IFM13 is about –0.01 gr kg^{-1} which could indicate a weak exchange of the whole core (all densities) with surrounding water, but also is close to the expected accuracy of the salinity data. What clearly is evident is a shrinking of the core Θ/S_A range from 15.7°C/13.7°C to 15.2°C/13.9°C.

At the edge region of the eddy (Fig. 4e to g) the mixed layer base is wider and the gradient is less sharp (Fig. 4e) when compared with the centre of the eddy (Fig. 4a). No low N^2 core and thus not double N^2 maxima are found, but just one (much weaker N^2~10^{-4} s^{-2}) at the mixed layer base (Fig. 4 f) is found, at least for the ship (M105) and the second glider survey (IFM13). Overall the N^2 maxima are located deeper in the water column. The Θ/S_A diagram (Fig. 4g) shows more of the characteristic of the surrounding waters but thermohaline intrusions for temperatures below 13.8°C which have a water mass core moving along isopycnals.

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Gelöscht: (Fig. 3d). The $R_!$

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Gelöscht: $R_!$

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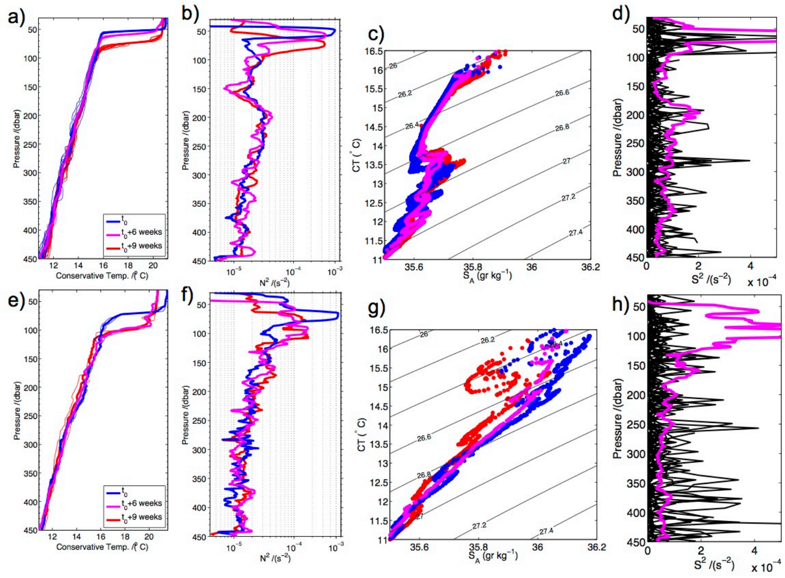

Figure 4: Eddy centre profiles for (a) Θ and (b) buoyancy frequency N^2, the (c) Θ/S_A diagram, and (d) vertical shear of horizontal velocities (S) squared. (e-h) as (a-d) but for selected profiles at the edge of the eddy. In d) and h) the magenta line indicates the magnitude of S^2 required to overcome the local stability ($4 \cdot N^2$).

The ADCP zonal velocity data from the M105 ship survey show a baroclinic, anticyclonic rotating flow, with a maximum swirl velocity of about 0.4 m s^{-1} at about 70 m depth and 30 km distance from the eddy centre (Fig. 5a). The maximum rotation speed (see as an approximation the meridional velocity section 5a) decreases nearly linearly to about 0.1 m s^{-1} at 380 m depth. Considering the translation speed of the eddy of 3 to 5 km day^{-1} (Schütte et al. 2016b), the nonlinearity parameter α, relating maximum swirl velocity to the translation speed, is much larger than 1 (about 6.5 to 11 in the depth level of the low oxygen core) and indicates a high coherence of the eddy (Chelton et al. 2011). At the depth of the maximum swirl velocity, and considering the eddy radius of 30 km, a full rotation would take about 5 days but more for the deeper levels.

To investigate the flow field we decompose the observed velocity (u, v) into a mean $(\bar{u}, \bar{v})$ and a fluctuating part (u', v') by applying a 120 m boxcar filter (longer filter length do not significantly change the results) to the observed profile data (here for the meridional velocity v, Fig. 5a, b, c):

$$v = \bar{v} + v'$$

The $\bar{v}$ field is here interpreted as the mesoscale or “subintertia” flow (Fig. 5b) and shows a baroclinic anticyclonic circulation with velocity maximum close to the surface at ±30 km in the eddy-relative

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Gelöscht: 45 m s^{-1} at about 100 m depth. The maximum rotation speed (approximately represented by the zonal section) decreases nearly linear to about 380 m depth where 0.1 m s^{-1} is reached. Alternating currents with about 80 to 100 m wavelength can be seen close to the eddy edges and more clearly seen after subtracting 120 m boxcar filtered profiles (Fig. 4 c). The local (at 19°N) inertial period is 36.7 h while the ADCP section was surveyed in 14 h (including station time) and only a moderate aliasing effects is expected in the sections. In contrast, the glider took more than 5 days (4 inertial periods) to complete the section (Fig. 3) and a mixture ... [324]

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coordinates. The fluctuating part (v'; Fig. 5c) is dominated by alternating currents with about 80 to 100 m wavelength. This layering of velocity finestructure resembles layering in properties (Fig. 2, 3) and indicate shear, most likely introduced by the propagation of NIWs (Joyce et al. 2013, Halle and Pinkel 2003). Largest v' currents are found in two regions: (i) in the upper 150 m in the vicinity of the mesoscale velocity maximum at the south-western side of the eddy and (ii) in the 250 to 450 m depth range below the core. We estimated the progressive vector diagram (PVD) of the v' fluctuating velocity components for the two regions and found cyclonic rotation, indicating the downward vertical energy propagation of NIWs (Leaman and Sanford 1975). However, for the region at the eddy edge (Reg. 1) the levels below 150 m depth show no rotation in the PVD, suggesting that the downward energy propagation does not continue which may suggest either reflecting or dissipation (e.g. Kunze et al. 1995).

From the velocity field the subinertia relative vorticity was calculated and subsequently the f_{eff} across the eddy (Fig. 5d). Within the core of the anticyclone ($\zeta < 0$) a $f_{eff} < f$ with *Ro* = –0.7 between 70 and 150 m is found. At the transition between eddy and surrounding waters ζ changes sign and a positive vorticity ridge ($f_{eff}/f > 1.3$) is observed. Likewise, a local increase in f_{eff} is seen underneath the core in the eddy centre. In both regions large amplitude v' (Fig. 5c) and u' (not shown) are observed as well as downward NIW energy propagation (from PVD; Fig. 5e).

An aliasing occurs trough the rotation of the inertial current vector during the survey time. Joyce et al. (2013) in their analysis of mid latitude NIW propagation (inertial period 19 h), applied a back rotation. However, at 19°N the inertial period is 36.7 h and the complete ADCP section was surveyed within 14 h (including station time). Because we primarily interpret station data, the aliasing effect should be small for the M105 data. In contrast, the glider sections took several days and many inertial periods and thus a mixture of time/space variability is mapped in the property fields (Fig. 3, Fig. 4). It is however interesting to note that still the velocity and property layering looks very similar and coherent across the different surveys suggesting that the processes that drive the layering are rather long-lasting over several month.

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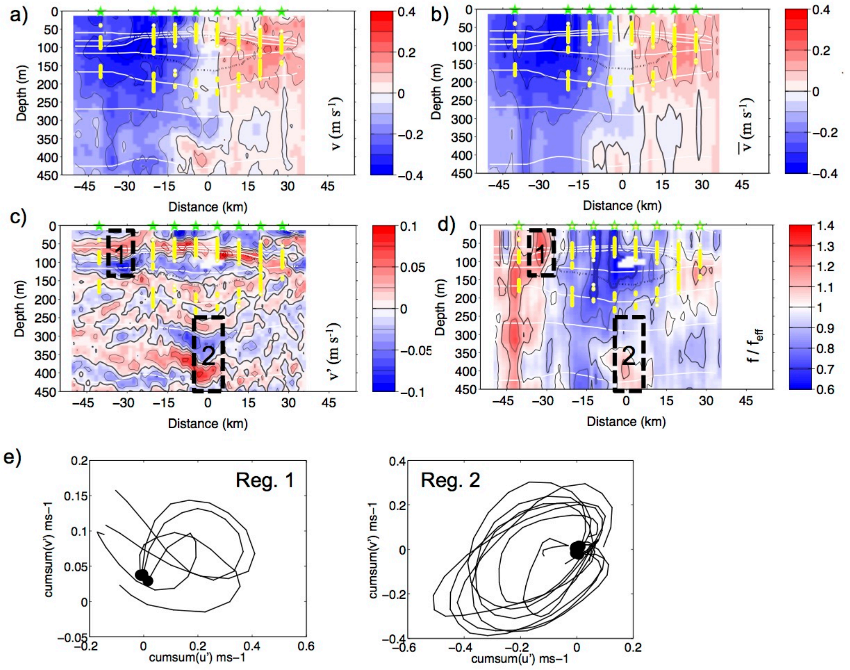

Figure 5: a) observed meridional velocity, b) boxcar filtered meridional velocity (applied over 150 m), c) difference between observed and boxcar filtered velocity. The thick black broken line indicates the 40 µmol kg^{-1} oxygen concentration, white contours are selected density anomaly contours ($\Delta\sigma$=0.2 kg m^{-3}) determined by gridding CTD profile data (see green stars at 0 dbar for station positions). The yellow dots indicate the N^2 maximum from CTD profile data. d) Ratio between local Coriolis parameter (f) and the effective Coriolis parameter (f_{eff}). e) Progressive vector diagram of v' for region 1 (250 to 450m depth) and 2 (20 to 140 m) (see c) and d)), black dots marks the shallowest depth

3.2 Eddy core isolation and vertical fluxes

Karstensen et al. (2015) proposed a concept for the formation of a low oxygen core in shallow ACME in the eastern tropical North Atlantic as a combination of isolating the eddy core against oxygen fluxes (primarily vertical) and high productivity and subsequent respiration of sinking organic material. The concept is in analogy to the formation of dead-zones in coastal and limnic systems and hence the name “dead zone eddies”. The key for high productivity is the transport of nutrients into euphotic zone in the eddy.

We identified three areas in the eddy where we further analysed vertical transport and mixing: (I) the eddy core, bounded by N^2 maxima with a low stratification in between. (II) The layering regime underneath the low oxygen core with alternating velocity shear and density compensated, mainly salt-finger supporting thermohaline intrusions. (III) The high velocity shear zones at the south-eastern edge of the eddy and underneath the eddy centre. We do not have direct mixing estimates (e.g.

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microstructure) but analyse the observed S^2, N^2 and Ri from the M105 ship survey data. Selected CTD N^2 profiles from the centre and the edge of the eddy are analysed in combination with ADCP fluctuation velocity (u', v') shear, estimated from 8 m bin data (Fig. 4d, h). To take the high frequency temporal fluctuations in the velocity data into account we show here the velocity shear in the vicinity of the CTD station, considering all ADCP data recorded 30 minutes before until 60 minutes after the CTD station started. Based on the existing (1 dbar) N^2 we calculated a S^2 that satisfied a $Ri < 1/4$ (magenta line in Fig. 4 d, h).

The vertical mixing/transport area I is the core. Here a strong contrast to surrounding water masses, either lateral as well as across the mixed layer base, is seen that clearly shows the isolation of the core (Fig. 4c). Moreover, the low and decreasing oxygen content and the stable Θ/S_A characteristic over a period of two months further indicate that during the 2 month period of observational data (Fig. 4). Low mixing in the core of ACMEs has been explained from direct observations before. Our observations do support that high mixing occurs at the N^2 maxima and that the core itself is a low mixing regime. The mixing to take place at the N^2 maximum is seen in a widening and deepening of the gradient zone at the mixed layer base in all sections and even stronger towards the edges of the eddy (Fig. 2, 3, 4a). Sheen et al. (2015) and Kawaguchi et al. (2016) observed enhanced mixing at the N^2 maximum and found wave/wave interaction as a likely process for the mixing. They argued that, because of the N^2 maximum around the core, but also because of the low N^2 in the core, less wave energy can enter the core and mixing in the core is low. Halle and Pinkel (2008) argued that, because of the low N^2 in the core, the NIW energy density was low and hence less energy is available for mixing. The consequence of vertical change from a high to a low mixing zone creates an "erosion" (outward directed mixing) of the core into the mixed layer. The erosion has implications for the oxygen and nutrient cycling as will be discussed below.

The vertical mixing/transport area II is the layering shear regime underneath the eddy (vertical transport area II) It is found that Ri approaches critical values (1/4) in layers of maximal NIW velocity induced shear and thus may indicate generation of instabilities in these layers. Below the eddy the S_A gradients (Fig. 3a) do align with the wave crests indicating the impact of intense strain, and thus a periodic intensification of S_A gradients which in turn could enhance the susceptibility to double diffusive mixing (Fig. 3d). Likewise the Θ/S_A diagram show clearly the existence of thermohaline intrusions oriented along isopycnals.

The vertical mixing/transport area III is were high v' shear is observed (Reg. 1 & Reg. 2 Fig. 5c,d). It is plausible to assume that a large fraction of the NIW energy that impact the eddy originate from wind stress fluctuations (D'Asaro 1985). The NIW energy propagation in the upper layer of the eddy (above the core) is downward, across the intense N^2 contours/mixed layer base and possibly driving enhanced mixing (e.g. by wave/wave interaction as in Sheen et al. 2015). The Ri (Fig. 4d, h) indicates that at the

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Gelöscht: at the eastern boundary, where the ACME was formed (Fiedler et al. 2016). The constancy of hydrographic properties over a period of about 7 month have

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mixed layer both, high shear and high N^2 is found. In the eddy core (Fig. 4d) N^2 is low but so is the shear. At the eddy edge (~ –32 km distance), in the transition between maximum swirl velocity and surrounding ocean, NIW energy is forced to propagate downward (see Fig. 4 b, d) because $f_{eff}/f > 1$ (Fig. 5b). The Ri distribution (Fig. 4h) for the M105 ship survey shows that N^2 is too high to be destabilized by the shear, at least at the location where the CTD profile was taken. However, we know that the NIWs have amplitude of more than 0.1 m s^{-1} and a vertical scale of about 70 to 90 m (Fig. 4d). This is similar to observations at mid-latitude fronts (e.g. Whitt et al. submitted; Kunze and Sanford 1984) were an inertial radius of about 2 km for a 0.1 m s^{-1} has been found and thus such a wave covers a good part of the eddy front. Moreover the magnitude of the fluctuation (0.1 m s^{-1}) associated with the NIW account for about 25% of maximum swirl velocity and in a region (about ~ –32 km, 50 to 120 m depth). The NIW phase velocity (v') is of similar magnitude as the swirl velocity and thus susceptible for critical layer formation (Kawaguchi et al. 2016). For a Gulf Stream warm core ring, Joyce et al. (2013) found most instabilities and mixing close to surface and where most horizontal shear in the baroclinic current is found (similar to our region 1; Fig. 5c,d). Evidence for vertical mixing to take place in this region is seen in upwelling of nitrate into the mixed layer/euphotic zone at about 100 m depth/distance of about –32 km (see below; Fig. 7b). Underneath the eddy the vertical propagation of superinertial waves across the anticyclonic eddy is seen (Kunze et al. 1995) but into a into a region where $f_{eff}/f > 1$ (Reg. 2 in Fig. 5c,d) and where Ri is getting critical, possibly related to a slowing of the energy propagation.

3.3 Nutrient cycling in the eddy

The productivity associated with the ACME requires the upward fluxes of nutrients into the euphotic zone. Schütte et al. (2016b) showed that the low oxygen ACME in the tropical eastern North Atlantic do have productivity maxima (indicated by enhanced ocean colour based Chlorophyll-a estimates) to be more concentrated at the rim of the eddies. This observation suggests that the vertical flux is also concentrated at the rim of the eddy. Indeed, when inspecting the glider section data (Fig. 3) we do find evidence for upwelling being concentrated at the rim, although the mixed layer base is characterized by very stable stratification and large gradients (e.g. 0.3 K m^{-1} in temperature). Considering the first glider oxygen section (IFM12, Fig. 2a), the upper of the two separate minima is found very close to the depth of the mixed layer base and indicate that any exchange across the mixed layer by mixing processes must be very small. The amount of particles might be approximated by the turbidity measurement from the glider (Fig. 6). While the first survey had very high turbidity several 10s of meters below the mixed layer base, the second glider survey showed much less particle load and indicating lower productivity across the eddy may related to a weakening of vertical flux.

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In order to interpret the low oxygen concentrations in terms of biogeochemical processes the bulk remineralization of oxygen and nitrate is determined. The apparent oxygen utilization (AOU, Fig. 7a) is defined as the difference between measured oxygen concentration and the oxygen concentration of a water parcel of the given Θ and S_A that is in equilibrium with air (Garcia and Gordon, 1992; 1993). AOU is an approximation for the total oxygen removal since a water parcel left the surface ocean. The low oxygen concentrations in the core of the eddy are equivalent to an AOU of about 240 µmol kg^{-1} (Fig 7a). Along with high AOU we also find very high NO_3^- concentrations with a maximum of about 30 µmol kg^{-1} (Fig. 7b). The corresponding AOU:NO_3^- ratio outside the core is 8.1 and thus close to the classical 8.625 Redfield ratio (138/16; Redfield et al. 1938). However, in the core an AOU:NO_3^- ratio of >16 is found.

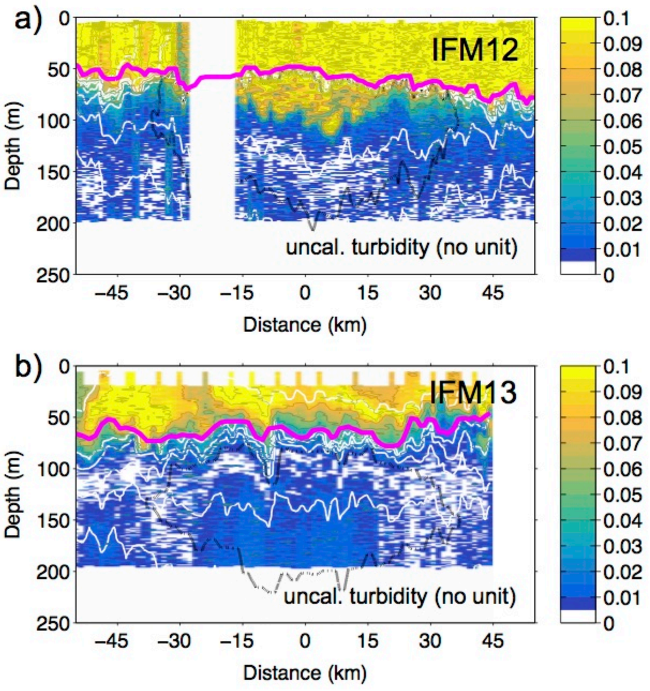

Figure 6: Uncalibrated turbidity data from (a) glider IFM12 survey and (b) glider IFM13 survey. The magenta line denoted the base of the mixed layer, the broken black line is the extend of the low oxygen core (oxygen <40µmol kg^{-1}).

This high ratio indicates that less NO_3^- is released during respiration (AOU increase) than expected for a remineralization process following a Redfieldian stoichiometry. By considering the remineralization outside the core (Fig. 7c) the respective NO_3^- deficit can be estimated to up to 4-6 µmol kg^{-1} for the highest AOU (NO_3^-) observations. By integrating NO_3^- and NO_3^--deficit over the core of the low

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oxygen eddy (defined here as the volume occupied by water with oxygen concentrations < 40 µmol kg^{-1}) we obtain an average AOU: NO$_3^-$ ratio of about 20:1.

One way to interpret this deficit is by NO$_3^-$ loss through denitrification processes. Loescher et al. (2015) and Grundle et al. (in revision) both found evidence for the onset of denitrification in the core of the ACME discussed here. Oxygen concentrations in the core are very low (about 3 µmol kg^{-1}) and

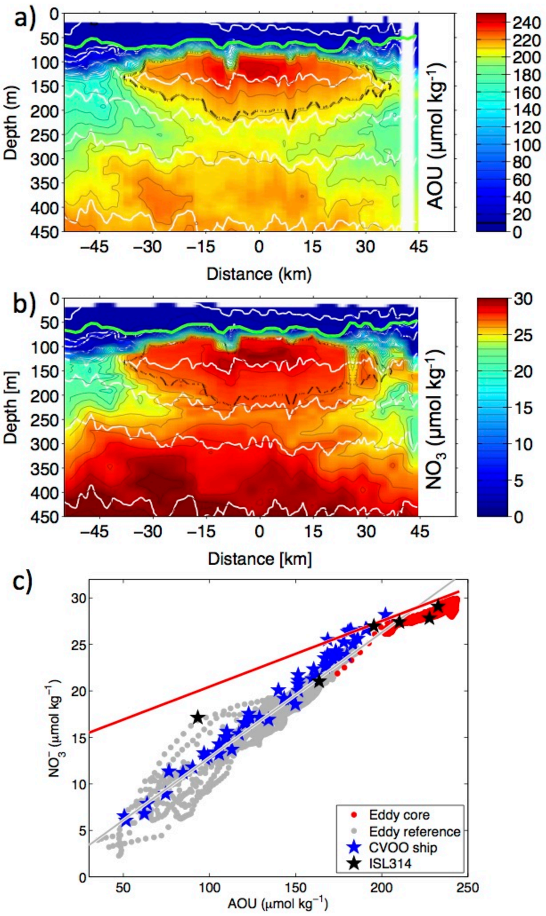

Figure 7: a) AOU and b) NO$_3^-$ from glider IFM13 survey. c) AOU versus NO$_3^-$ for the depth range 90 to 250 m depth – (red dots) glider IFM13 survey in the low oxygen core, (black dots) IFM13 glider survey close to CVOO, (blue stars) CVOO ship data and (black star) Islandia ISL_00314 eddy survey (see Fielder et al. 2016 for details on the surveys). Linear best fit to the glider data outside the eddy (grey line; slope 8.77) and inside core (redline; slope 0.56) are shown.

denitrification is possible. Evidence for denitrification in the core of the ACME was, however, demonstrated as being important for nitrosoxide (N$_2$O) cycling at the nanomolar range (Grundle et al. in

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revision, Scientific Reports), and not necessarily for overall NO_3^- losses which are measured in the micromolar range. Grundle et al. (in revision, Scientific Reports) showed by relating nitrogen and phosphorous cycling, that in the core of the ACME the NO_3^- losses were not detectable at the micromolar range. Thus, while denitrification may have played a minor role in causing the higher than expected AOU:NO_3^- ratio which we have calculated, it is unlikely that it contributed largely to the loss of 5% of all NO_3^- from the eddy as estimated based on the observed AOU:NO_3^- ratios.

Alternatively, but perhaps not exclusively, the NO_3^- recycling within the ACME could be the reason for the NO_3^- deficit. A high AOU:NO_3^- ratio could be explained through a decoupling of NO_3^- and oxygen recycling pathways in the eddy and details about the vertical transport pathways of nutrients (erosion of core). Based on the investigation of the possible vertical mixing/transport of nutrients (here NO_3^-) the erosion of the eddy core plays a key role. In this scenario NO_3^- molecules are used more than one time for the remineralization/respiration process and therefore the AOU increase without a balanced, in a Redfieldian sense, NO_3^- remineralization. Such a decoupling can be conceptualized as follows (Fig. 8, left): consider an upward flux of dissolved NO_3^- and oxygen in a given ratio with an amount of water that originates from the low oxygen core. The upward flux partitions when reaching the mixed layer, one part disperses in the open waters outside of the eddy, the other part is keep in the eddy by retention (D'Ovidio et al. 2013). The upwelled NO_3^- is utilized by autotrophs for primary production and thereby incorporated into particles as Particulate Organic Nitrogen (PON) while the corresponding oxygen production is re-ventilated by air/sea oxygen flux. The PON sinks out of the mixed layer/euphotic zone and into the core of the eddy were remineralization of organic matter releases quickly some of NO_3^- originating from the core waters. In contrast, the upwelling of oxygen-deficient waters will drive an oxygen flux from the atmosphere into the ocean in order to reach chemical equilibrium. But because the stoichiometric equivalent of oxygen is exchanged with the atmosphere and therefore not transported back into the core by gravitational settling of particles, as it is the case for nitrate (via PON), the respiration associated with the remineralization of the recycled nitrate will results in a net increase in AOU.

4 Summary and Conclusion

Here we present a first analysis of the temporal evolution of a low oxygen ACME in the eastern tropical North Atlantic from high-resolution multidisciplinary glider and ship survey data. The low oxygen eddy has a diameter of about 70 to 80 km and a maximum swirl velocity of 0.4 m s^{-1} close to the mixed layer base and can be considered typical for the region (Schütte et al. 2016a, 2016b). The eddy originated from the Mauritanian upwelling region (Schütte et al. 2016b; Fiedler et al. 2016) and had a distinct anomalously fresh and cold water mass in its low oxygen core. The core was located immediately below the mixed layer base (about 70 to 80 m) down to a depth of 200 to 250 m in its centre. The core

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showed minimum oxygen concentrations of 8 µmol kg^{-1} during the first glider survey (February 2014) and 3 µmol kg^{-1} during the second glider survey, 9 weeks later. Enhanced productivity was estimated for the eddy (Fiedler et al. 2016) implying a vertical flux of nutrient rich waters to the euphotic zone/mixed layer and is seen in high turbidity that reached during the first glider survey more than 50 m into the core (Fig. 6a).

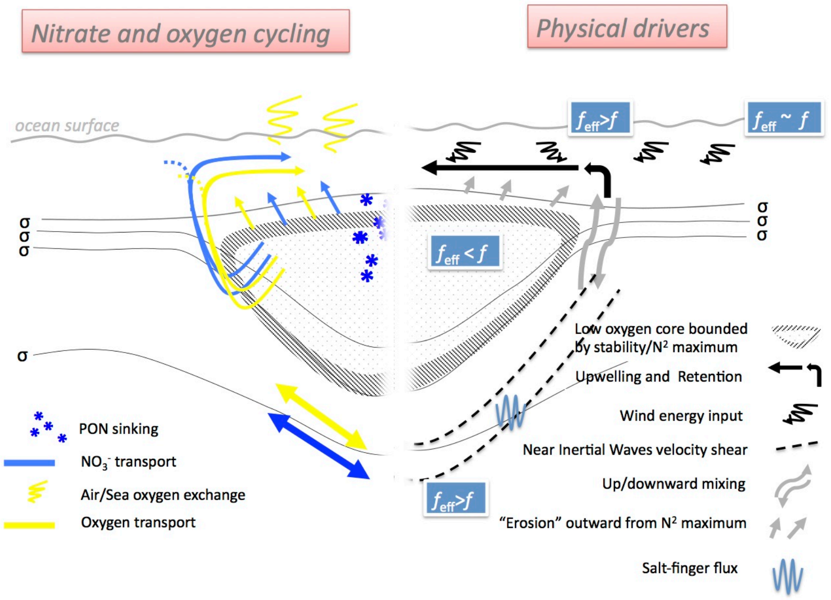

Figure 8: Conceptual view on the biogeochemical (left) and physical (right) processes responsible for creating a low oxygen ACME. The recycling of Nitrate is decoupled from the oxygen cycling through PON. The transport at the flanks and the isolation of the eddy core are linked to the energy propagation of NIW. Vertical flux (upwelling and downwelling) of nutrient rich/low oxygen waters occurs at the boundaries and at the mixed layer base (outward). Eddy retention keeps upwelling waters in the euphotic zone of the eddy. Shear from NIW velocity fluctuations create critical Ri underneath the eddy core with thermohaline anomalies that favour salt-finger type double diffusion.

A concept for the coexistence of an isolated, low oxygen core but surrounded by regions of enhanced mixing in an ACME was derived from analysis of observational data (Fig. 8). The eddy relative vorticity is negative in the core but positive at the transition outward from the swirl velocity maximum into the surrounding water ("positive vorticity ridges", Halle and Pinkel 2003). Distinct regions with $f_{eff} < f$ (core) and $f_{eff} > f$ (transition eddy/surrounding waters) are created by the mesoscale flow. The f_{eff}/f ratio has consequences on the vertical propagation of near NIW energy, as reported in numerous studies (e.g. Kunze 1985, Kunze et al. 1995, Sheen et al. 2015, Halle and Pinkel 2003). In

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general in $f_{eff} < f$ regions internal waves become superinertial and rapidly propagate downward. If these waves now propagate through a region of high vertical stratification (N^2 maxima at the upper and lower boundary of the core) they will have a high energy density while if the propagate through low vertical stratification (N^2 minimum in the core) they have low energy density. Numerical simulations (e.g. Koszalka et al. 2010) and observations (e.g. Sheen et al. 2015) report on high vertical mixing in region with strong stratification (and low mixing in low startfied regions). Our observations show low *Ri* at the N^2 maxima which suggests enhanced diapycnal mixing to occur here.

When the superinertial waves encounter a $f_{eff} > f$ region they will undergo a reduction in vertical speed and the waves may eventually reflect (e.g. Halle and Pinkel 2003) or dissipate (Kawaguchi et al. 2016). Indeed we observe critical *Ri* and a shear variance maximum in the velocity finestructure in these regions (Fig. 5, Reg. 1 & 2). The "Region 2", right below the centre of the eddy, coincides with where Lee and Niiler (1998) found a NIW energy maximum from their "inertial chimney" simulations of an ACME. Unfortunately we do not have a CTD profile in "Region 1" in the eddy edge region. Calculating *Ri* from the station further away from the eddy core (at about -40 km) no critical *Ri* are found (Fig 4, h). However, superinertial waves originating from the core should also reflect and/or dissipate here. Joyce et al. (2013) also derive NIW energy accumulation and a critical layer at the edge of an ACE (Gulf Stream warm core ring) at its mixed layer base.

Across the whole extend of the eddy, but below the low oxygen core, we observe velocity finestructure to align with salt-finger type double diffusion critical (*Tu* close to 90°) thermohaline finestructure. St. Laurent and Schmitt (1999) reported on an enhancement of mixing efficiency from the interaction between velocity shear and salt-finger type thermohaline anomalies.

A NIW and shear induced erosion of the core create an upward flux of nutrients (and other substances from the core) and which is supported by the NO_3^- observations. Once NO_3^- is in the mixed layer the eddy retention (D'Ovidio et al. 2013, Condie and Condie 2016) will trap a fraction of the upwelling waters. The AOU:NO_3^- ratio of the eddy core is altered high (16) when compared with the classical Redfield ratio (8.625) or the background ratio (8.1). We estimated the NO_3^- deficit for the eddy which is about 1:20 when referenced to the total NO_3^- content. Denitrification is one possible process but the significant nitrate loss of the core seems unrealistic to be explained by denitrification, given the minimal oxygen concentrations are more than 3 µmol kg^{-1}.

We consider it more likely that a local recycling of nitrogen but not oxygen takes place, driven by a combination of eddy dynamics and gravitational sinking. The NO_3^- eroded from the core enters the mixed layer and is incorporated in new production in the eddy euphotic layer. The nitrogen will then re-enters the core via gravitational sinking of PON. Such an isolated core is the rarely observed case of an isolated volume of water in the open ocean and which allows to study fundamental biogeochemical

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cycling processes in the absence of significant physical transport processes. A number of surprising biogeochemical cycling processes and ecosystem responses have been reported from the studies on eastern tropical North Atlantic low-oxygen eddies (Löscher et al. 2015, Hauss et al. 2016, Fiedler et al. 2016, Fischer et al. 2016, Schütte et al. 2016b, Grundle et al. in revision, Scientific Reports).

The NIW concept for the dynamical setting of the low oxygen ACME include different internal wave processes and a dynamical representation of ocean mixing – which are not routinely resolved by numerical models. A strategy for parameterizing these processes is required, for example Schütte et al. (2016b) report an increase in oxygen reduction by as high as 7 µmol kg^{-1} in the depth range of 50 to 150 m (peak reduction is 16 µmol kg^{-1} at 100 m depth) as a results of the high productivity and which is likely of great importance for creating the shallow oxygen minimum of the eastern tropical Atlantic. It has to be mentioned that the erosion processes at the mixed layer base should also operate in CEs and may explain the high productivity and low oxygen cores in CE in the eastern tropical North Atlantic (see Karstensen et al. 2015).

5 Data availability

The glider (IFM12 and IFM13) and shipboard (R/V Meteor expedition M105) data used in this paper are freely available at https://doi.pangaea.de/10.1594/PANGAEA.860781 (Karstensen et al., 2016).

Acknowledgment

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Gelöscht: 2016; Fischer et al. 2016, Grundle et al. in revision, Schütte et al. 2016). The NIW concept for the vertical flux outside the core but likewise the isolation of the ACME core that we presented here is based on internal wave processes that are not routinely resolved by numerical models. A strategy for parameterizing of these processes is however required considering the estimate by Schütte et al. (2016) who showed that the enhanced respiration in low oxygen eddies contribute about 20% to net respiration that creates the shallow oxygen minimum of the eastern tropical Atlantic.

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