

Dear Editor,

First of all we would like to thank you and the reviewers for the time and effort you spent on handling and reviewing the manuscript.

We have addressed all the questions and comments raised by the two reviewers and have listed our responses and edits on the manuscript point-by-point below (page & line numbers still refer to the initial submission). We also appended the marked-up manuscript at the end of this document in order to illustrate all the changes we did on the manuscript.

Throughout the manuscript we strengthened the linkages to the other papers of this special issue which contain more detailed information about this eddy that are not covered by this manuscript. Further, we strengthened the general description of the eddy characteristics by extending section 3.1 and renaming it to "Eddy Characteristics". In order to provide more evidence for the isolation and origin hypothesis we described mean water ages derived from transient tracer samples taken during the eddy survey. The water age analysis supports our interpretation of the water mass analysis based on temperature/salinity relations regarding the isolation and origin of the eddy.

Best regards,

B. Fiedler & Coauthors

1. Reviewer #1:

Review of Fiedler et al., Oxygen Utilization and Downward Carbon Flux in an Oxygen-Depleted Eddy in the Eastern Tropical North Atlantic.

bg-2016-23

General comments:

Reviewer Comment (RC)1_: *Boundary definition: The authors are rather vague about the definition of eddy boundaries (the lateral boundaries, but in particular the lower boundary of the eddy core), as well as the processes leading to exchanges, or lack thereof, across those boundaries. I would suggest the authors provide more details on eddy boundaries, the depth of the mixed layer, and the depth of euphotic zone, as well as provide a stronger case for rationalizing why eddy waters don't mix with the surrounding ocean waters. For example, is the depth of the euphotic zone (Dez) and mixed layer depth in the eddy core equal to the outside water? Or is Dez different due to higher light attenuation by particles?*

Author Comment (AC)1_: We agree that details about the physical boundaries of this eddy are not well described in this manuscript. However, we left this out on purpose as Karstensen et al. (2016, this special issue) are presenting an elaborate physical analysis of boundaries for this particular eddy. But we have to admit that this link was not made clear enough. Therefore we added a sentence to section 3.1:

“Isolation of this eddy was found to be caused by high eddy rotation speed and stratification and their joint impact on the propagation of internal waves (Karstensen et al., 2016, this special issue).”

We also edited two sentences in section 3.1 in order to explicitly mention the mixed layer depth in and outside the eddy.

“The upper bound of the eddy core is the mixed layer base at a depth of 70 m which has the same magnitude as the mixed layer outside the eddy (Karstensen et al., 2016, this special issue). A very sharp gradient exists between 70–77 m depth which amounts to 0.73 in salinity, 3.98°C in temperature and 165.8 $\mu\text{mol kg}^{-1}$ in dissolved oxygen.”

Unfortunately, light/PAR measurements failed during the surveys due to sensor problems. Thus, we can't give reliable information about the euphotic zone for this particular eddy. We removed speculative connections between the eddy core and the euphotic zone from the abstract and the conclusions.

RC2_: *Episodic events: Throughout the paper a steady state biogeochemical system is implied (or at least a slowly evolving biogeochemical state). Yet the physical processes that allow for these balances are episodic and submesoscale (e.g. evidence for the re-supply of nutrients into the upper layer is lacking, and yet required for the equilibrium biogeochemical state in the mixed layer). Is this vertical nutrient flux driven by interaction of eddies with the overlying wind field, Ekman pumping, or internal waves displacing isopycnals and mixing? How frequent are these episodic events?*

AC2_: This is indeed an important point. Unfortunately, these processes are extremely difficult to observe, even with the tools we applied during this study (autonomous glider, see Karstensen et al., 2016, this special issue). We disagree that evidence for re-supply of nutrients into the upper layer is lacking as we clearly found elevated nutrient concentrations in the surface during one of the two ship surveys (section 3.2, 2nd paragraph). Since methodological biases of these samples can be ruled out, this observation can only be explained by an upward vertical flux. Observations for chl-a also indicate elevated levels of phytoplankton towards the upper part of the mixed layer, likely being facilitated by upwelling of subsurface waters. Finally, Karstensen et al. (2016, this special issue) derived a physical concept which provides a mechanism for upwelling occurring at the rim of the eddy, followed by horizontal distribution. The process is mainly driven by

downward propagation of internal near inertial waves. Since details about this mechanism are described in Karstensen et al. (2016), we added a sentence in section 3.2 (2nd paragraph) in order to provide a link to that paper:

“As such, this finding is interpreted as being a signature of a vertical flux event. The physical mechanism is described in more detail in Karstensen et al. (2016, this special issue).”

Further, we cannot derive information about how intermittent/sporadic the upwelling is and we rephrased that to a more general statement on “upwelling processes”. The analysis of an oxygen float (Karstensen et al., 2015) showed that the respiration derived from 5 day oxygen profiles over a period of several month showed a surprisingly constant decrease which in turn suggests that particle sinking is also constant and probably also the upwelling to ensure a constant bloom. However, the finite duration of a bloom also applies a “running mean” to any intermittence of the upwelling. This is definitely a process that requires further attention.

RC3_: *Downward carbon flux - POC export: This seem to be the weakest part of the paper. The authors need to provide more details on physical and biological assumptions in the simple downward flux model, and whether its assumptions are valid in the eddy core. Is a steady state balance implied for model? A constant diffusivity? What about small non sinking POC export by eddy flow field subduction of surface waters with high POC concentrations? (See Mahadevan et al., 2015, Science). Consequently, the carbon flux model and Figure 8 may not make a meaningful contribution to the study.*

AC3_: The reviewer addresses the right issues if the applied model would have the intention to fully explain the total vertical carbon fluxes. We have to admit that the way we introduced the downward POC flux calculations might be a bit misleading and makes the reader to expect a more comprehensive model that also accounts for physical transportation processes such as diffusion or subduction. Our main intention, however, was to look whether observed carbon remineralization of sinking particles inside the core follows a classical Martin curve and how this amounts to an export of POC out of the euphotic zone over the lifetime of this eddy. In order to assess the magnitude of observed carbon remineralization compared to other ocean environments (e.g., open ocean ETNA, coastal upwelling, North Atlantic, eddies) we decided to translate our results to a mean daily POC flux. Our results suggest that the Martin curve fits well the carbon remineralization rates and thus sinking particles are likely to be the major driver for our observations. The 3-fold enhanced carbon export also matches very well with the independently determined production rates which were also enhanced by a factor of 3 (Löscher et al., 2015b).

Regarding the subduction of high POC waters as described in Omand et al. (2015) we think that this mechanism would not affect our POC calculations for two reasons: 1) Described subduction in Omand et al. occurs rather at the perimeter of the eddy and 2) the special physical conditions that characterizes an ACME would not allow for an intrusion of subducted (high POC) waters into the ACME core.

Finally, given that the core of the eddy is a transient system (oxygen consumption without reventilation) and only the limited number of observations in space and time we won't be able to come up with a more detailed approach.

Thus, we use a simplistic approach to observed change in biogeochemical water properties in order to give quantitative estimates of the POC flux and carbon export. For more sophisticated export flux models we lack information but this does not mean that carbon export can be fully explained by a Martin-type function. In general, however, the models fit our data well and is thus only used to extract quantitative information for further comparison. We therefore think that this section still make a meaningful contribution to the manuscript. In order to clarify this topic we edited the beginning of section 2.5 as follows: *“In order to estimate the amount of carbon exported from the euphotic zone as sinking POM we used CRRs to derive the shape of the vertical export flux curve for particulate organic carbon (POC). This approach assumes the absence of*

major physical transport processes between the mixed layer and the ACME core beneath except for sinking particles of POM which is generally being described by the established Martin Curve (Martin et al., 1987a):”

RC4_: *Significance (and a Budget): What is significance of 1 to 2 ACMEs generated every year that propagate into the open ETNA waters for biogeochemistry and ocean acidification of the region, or even the ocean basin? Is this a phenomenon that might be expected to occur elsewhere (does the study have much broader implications? To help address this it might be worth carrying out a budget/balance exercise to quantify, for example, whether the supply of nutrients exceeds export of nutrients, which leads to than increased productivity.*

AC4_: To estimate the significance of these eddies was also one of our main objectives of the “Eddy Hunt” project the special issue is concerned with. Besides a local impact, that is important for a process understanding, the larger scale impact, at least for the eastern tropical Atlantic is of interest. The occurrence of the dead-zone eddies was analyzed in a study submitted in parallel to ours (Schütte et al., 2016, this special issue). The authors analyzed satellite (SLA, SST) and in-situ oxygen and T/S profile data for the eastern tropical North Atlantic. They estimated that about 2 to 3 low oxygen eddies disperse in the region every year but because of the anomalous low oxygen they found an at least 6% contribution of these low-O₂ ACMEs in the maintenance of the shallow oxygen minimum zone (centered at about 70 m depth and about 250 m above the core OMZ). They conclude that their estimate is a conservative one since the detection of ACMEs from satellite data is challenging (because of a weak SLA signature of ACMEs) and the actual number of ACMEs is likely to be higher. We added a sentence at the end of the 2nd paragraph of the conclusion as follows:

“As revealed by Schütte et al. (2016) these ACMEs appear to play a small but significant role in maintaining the shallow OMZ in the ETNA.”

Probably related to the improvement of multidisciplinary autonomous and high resolution satellite-borne observing techniques, much attention has been devoted to investigating local processes in and large scale impact of ocean mesoscale eddies. Many studies have recently been published. What is specific for the ETNA region is the cold/fresh core of the eddies, an imprint from the coastal current and definitely different from the Pacific, where the coastal current carries warm/saline water. This could matter for the temporal evolution of the stratification and as such for the isolation (see Karstensen et al. 2016). For the purpose of this paper we limited our regional examples of other studies to the North Atlantic (McGillicuddy et al., 2007) and the South Pacific (Altabet et al., 2012).

Specific comments:

Abstract:

RC1: Page 1, Line 13: Define the extreme low oxygen environment.

AC1: Sentence edited: *“The occurrence of mesoscale eddies that develop suboxic environments at shallow depth (about 40 to 100 m) has recently been reported for the eastern tropical North Atlantic (ETNA).”*

RC2: Page 1, Line 22: Define the lower boundary of the euphotic zone.

AC2: Changes mentioned under AC1_, see above.

RC3: Page 1, Line 27: Define the lower boundary of the surface mixed layer. Is this shallower than the euphotic zone?

AC3: Information added as: “Vertical distributions of particulate and dissolved organic matter (POM, DOM) generally show elevated concentrations in the surface mixed layer (0 – 70 m), but particularly DOM also accumulates beneath the oxygen minimum.”

Direct observations of light attenuation are missing, see also AC1_.

RC4: Page 2, Line 1: an enhancement of apparent oxygen utilization rates: : at what depth?

AC4: We modified two sentences of the abstract to define the depth of the eddy core as follows:

“At the time of the survey the eddy core showed lowest oxygen concentrations of less than 5 $\mu\text{mol kg}^{-1}$ and a pH of approx. 7.6 at a depth of approx. 100 m.”

“Considering reference data from the upwelling region where these eddies are formed, we determined the oxygen consumption through remineralization of organic matter and found an enhancement of apparent oxygen utilization rates (aOUR, $0.26 \mu\text{mol kg}^{-1} \text{d}^{-1}$) inside the core by almost one order of magnitude when compared with typical values for the open North Atlantic.”

RC5: What is the significance of your findings for the biogeochemistry of ETNA?

AC5: As this study does not directly determine significance in a quantitative way we cannot define this in the abstract. However, we edited the last sentence of the abstract as follows: “The observations support the view that the oxygen depleted eddies can be viewed as isolated, westwards propagating upwelling systems of their own and thereby represent re-occurring alien biogeochemical environments in the ETNA.”

Introduction:

RC6: Page 2, Paragraph 2: A figure showing ETNA, OMZ, EBUS, CVFZ would be helpful. Maybe add on to Figure 1.

AC6: We appreciate this constructive comment from the reviewer and added some of the acronyms to Figure 1.

RC7: Page 3, Line 9: Define anticyclone mode-water eddies.

AC7: We followed this suggestion and added one sentence after the introduction of ACMEs: “The latter ones are characterized by a water lens of mode which is being formed by up- and downward-bent isopycnals towards the eddy center.”

RC8: What is the main objective of this paper?

AC8: We added one sentence to the last paragraph of the introduction: “Here, we present the first biogeochemical insights into low-oxygen ACMEs in the ETNA based on direct in situ sampling during two coordinated ship-based surveys. The main objective of this study is to reveal and quantify biogeochemical processes occurring inside a low-oxygen ACME in the ETNA.”

Methods:

RC9: Page 5, Line 8: At what depth were water samples collected?

AC9: Information added: “Water samples in the upper 500 m were collected with a rosette water sampling system...”

RC10: Page 6, Line 26: At what depth were the water samples for DO collected?

AC10: Niskin bottles during both cruises were closed following a certain depth grid. Only depths of Niskin bottles close to the eddy core/oxygen minimum were slightly adjusted in order to adequately resolve this part of the water column. All samples (for various parameters) were collected for each depth. Since sampling depths for each parameter can be also deduced from figures 4 – 6 we decided to not explicitly mention this information in the text.

RC11: Page 7, Line 10: same as above, define depth of DIC and TA samples.

AC11: see above (AC10).

RC12: Page 7, Lines 21-24, using which software?

AC12: We added this information to the text (and added the respective reference) as follows:
“Results from DIC and TA analysis were used to compute the remaining parameters of the marine carbonate system (pH, pCO₂ and Ω_{Ar}) using a MATLAB version of the CO₂SYS software (Van Heuven et al., 2011). Calculations were based on carbonic acid dissociation constants after Mehrbach et al. (1973) as refitted by Dickson and Millero (1987).”

RC13: Page 9, Line 4: Define apparent oxygen utilization rate.

AC13: We modified the respective section as follows: “Changes of oxygen and carbon due to remineralization of organic matter are being expressed as the apparent oxygen utilization rate (aOUR) and the carbon mineralization rate (CRR). In order to determine these rates not only the anomaly but also the age of the eddy, the time between formation on the shelf and the time the eddy surveys took place, needs to be known.”

Results and Discussion:

RC14: Page 10, Lines 15-20: This text is repetitious, and can be omitted.

AC14: We agree and removed this part from the manuscript.

RC15: Page 10, Lines 22-24: Specify depth.

AC15: Since the sentence describes the characteristics of ACMEs in the ETNA in general we can't specify a certain depth. However, we added the word “subsurface” to this sentence: “The Temperature-salinity (TS) characteristics of the subsurface core of ACMEs in the open ETNA (Schütte et al., in prep. for this issue; Karstensen et al., 2015) were found to be nearly unchanged, compared to coastal regions.”

RC16: Page 11, Line 20: (100m)- not clear if is this at 100m, or from 0 to 100m?

AC16: We slightly rephrased this sentence to avoid potential confusion: “In comparison to the reference profile from the Mauritanian Shelf we find a maximum oxygen decrease in the eddy core at a depth of 100 m of about 57.0 μmol kg⁻¹ to suboxic levels (<5 μmol kg⁻¹; Figure 3).”

RC17: Page 11, Lines 16-18 (sentence 2): move to after describing the results.

AC17: Thank you for this remark. We decided to fully delete this sentence as it is redundant with the second last sentence of this paragraph.

RC18: Page 11, Line 27: Why elevated nitrate, nitrite and phosphate but not silicate? Also, did you look into nitrate:phosphate ratio as evidence of denitrifying bacteria?

AC18: We interpret the depletion of silicate as a consequence of high abundance of diatoms in the surface mixed layer. From sediment trap data at CVOO (Fischer et al., 2015, this special issue) we know that diatoms were the dominant species during the passage of an ACME in 2010 at CVOO. Koeve (2004) also reported on high nitrate:silicate ratios in the North Atlantic and explains this with a different uptake ratios than the nitrate:silicate ratio of upwelled waters. We extended the discussion of surface nutrients as follows: “In contrast, silicate concentration remained low which could be explained by an enhanced abundance of diatoms in the mixed layer. Further, Fischer et al. (2016) reported on high opal concentrations in sediment traps at CVOO which were associated with the passage of a former ACME passing the observatory. High N:Si uptake ratios, also reported for the North Atlantic (Koeve, 2004), could explain observed nutrient concentrations.” We also looked into nitrate:phosphate ratios but couldn't find deviations pointing towards denitrification. However, genetic analysis of the microbial community clearly revealed active

denitrification in the core of the eddy. N:P ratios as well as the discussion on denitrification of this particular eddy are already published (Löscher et al., 2015).

RC19: Page 12, Lines 1-5: How often do these sporadic events occur? Are they wind induced, or due to passage of internal waves?

AC19: Please see above (AC2_).

RC20: Page 12, Lines 7-9: This sentence is a repetition from Methods and can be omitted.

AC20: We fully agree and omitted this sentence.

RC21: Page 12, Line 26: “phytoplankton communities are exposed to these acidified conditions”. How often? (the pH minimum is located just below the euphotic zone).

AC21: The reviewer is right in asking about abundance of phytoplankton in the core at this depth (beneath or close to the euphotic depth). However, here we wanted to give a general statement about acidified cores of ACMEs. Indeed, the particular ACME surveyed during this study has its core relatively deep. Other ACMEs may have more shallow cores which are located within the euphotic zone. Karstensen et al. (2015), for instance, observed an ACME in the same region in which the core reached up to even 40 m water depth which is very likely to be within the euphotic zone. In order to keep the respective sentence more general we slightly edited it as follows: “Absolute values of pH inside the eddy exceed these predictions and plankton communities inside shallow low-oxygen cores of ACMEs may get exposed to these acidified conditions.”

RC22: Page 13, Lines 25-29: is this consistent with your Chl-a observations?

AC22: This finding is consistent with discrete samples for chl-a which are presented in Löscher et al. (2015). Chl-a concentrations as illustrated in Figure 3 (most right panel) were derived from different fluorescence sensors mounted at the rosette water samplers during different cruises. Computation of chl-a concentrations were based on factory calibrations for each individual sensor. The fact that calibration of fluorescence data for the determination of chl-a concentration is not well developed and daylight quenching of fluorescence at the surface (Xing et al., 2012) biases this data as well, we doubt that absolute concentrations derived from fluorescence sensors are robust for a quantitative interpretation. We rather see these sensor measurements as a qualitative proxy that describes rather the vertical distribution of phytoplankton in the water column.

We added two sentences to the methods section as follows: “Additional sensors such as an oxygen sensor (SBE43, Seabird Electronics) and a two channel fluorometer (FLNTURT, WETLabs) were attached to the CTD. Note that factory-calibrated fluorometer data in this study can be only used as a qualitative proxy for phytoplankton distribution in the water column due to a lack of elaborate sensor calibrations.”

Conclusions:

RC23: Page 17, Line 30: “intense increase”: : specify where.

AC23: We added this information to the sentence as suggested: “Likewise, nutrient concentrations as well as $p\text{CO}_2$ levels showed a large increase within the eddy core which created significant anomalies when compared to ambient open-ocean ETNA conditions.”

RC24: Page 18, Line 9: Is the 3-fold increase in primary productivity consistent with your observed Chl-a?

AC24: Please refer to AC22.

RC25: Page 18, Lines 20-25: I would replace this text with a sentence on the significance of the 1 to 2 ACMEs generated every year that propagate into the open ETNA waters for biogeochemistry and ocean acidification of the area.

AC25: Thank you for this suggestion. However, please see AC4_ for details – as we decided to not replace this text with findings of Schütte et al. (2016), as at this part of the conclusions we explicitly want to look forward and give an outlook about open questions which need to be addressed by future studies. Instead, we added a sentence to the end of the second paragraph of the conclusions as follows: “As revealed by Schütte et al. (2016) these ACMEs appear to play a small but significant role in maintaining the shallow OMZ in the ETNA.”

Tables:

RC26: Table 1: Add: negative values correspond to: : : Are these average anomalies over some depth range?

AC26: We edited the caption as suggested: “Overview of detected concentration anomalies (Δ_{total}) within the ACME core ($\sigma_{\theta} = 26.35 \text{ kg m}^{-3} - 1000$) during the two surveys referenced against prevailing conditions at the shelf. Rate estimates are based on the lifetime of the ACME derived from satellite sea level anomaly data (ISL: 163 days, M105: 173 days). Values for the average shelf profile are given in order to illustrate local variability at the corresponding isopycnal ($= 26.35 \text{ kg m}^{-3} - 1000$). Negative values correspond to a decrease of the respective parameter over the lifetime of the ACME.”

Figures:

RC27: Figure 2: SACW missing?

AC27: We removed the dashed lines for water masses and decided to rather just labelling the two different branches according to a water mass analysis done by Schütte et al. (2015).

RC28: Figure 8: This figure and the associated carbon flux model (eqn 2) does not make a significant contribution to the paper as it stands. See general comment #3 above.

AC28: Please refer to AC3_.

2. Reviewer #2:

Review of Fiedler et al., Oxygen Utilization and Downward Carbon Flux in an Oxygen-Depleted Eddy in the Eastern Tropical North Atlantic.

bg-2016-23

General comments:

Reviewer Comment (RC)1_: *Reference Data Set: an assumption that needs to be strengthened*

The three Reference Data Sets used by the authors for the bgc fluxes calculations are from cruises that were conducted on the Mauritanian shelf around the second-half of July 2006, beginning of June 2010, and beginning of June 2014. The surveyed eddy is supposed to have formed on the Mauritanian shelf around June/July 2013. This can be inferred from the paper, but it's not explicitly stated. At page 8 lines 17-21 the authors explain how they reconstructed the region of origin of the eddy on the shelf on the base of statistical analysis of historical SLA, and how this region coincides with the location of the 3 Reference Data surveys. However, the eddy trajectory from SLA in "Figure 1" starts about two months later (Sept. 2013) at least 100km in the off-shore direction. The fact that the trajectory of this specific eddy was not retrieved on the shelf that may imply, for example, that the eddy boundaries of this eddy were not already well formed, therefore the eddy may have continued to trap water while leaving the shelf area of the Reference Data Sets, or may have been spun by a lateral filament. At page 11 lines 4-5 the authors underline the matching between the Temperature and Salinity of the eddy core when it was surveyed and the reference station measurements on the shelf. This supports the assumption of isolation of the eddy core from the shelf to the offshore waters. However, biogeochemical properties can be more variable than physical properties on both spatial and time scales, especially in active shelf regions. The authors write about the Reference Data Sets [page 8 lines 23-27] "in order to account for small scale variability [: :] an average profile for each investigated parameter was created [: :]. These mean profiles were assumed to represent typical initial conditions of ACMEs [: :]". Given the complex dynamics of the flow around the shelf edge, the time and spatial variability of biogeochemical processes, the timescale of sporadic upwelling events; given the fact that the eddy trajectory from SLA was not retrieved in the shelf region, and the complexity of the eddy formation process:

- 1. Can the choice of these Reference Data Sets be better justified? Are there no available data for the region in which the trajectory was actually retrieved in Sept. 2013?*
- 2. How do mean profiles account for small scale variability?*
- 3. Is it possible to exclude strong discontinuities (input of external water, sediment resuspension, interaction with other forming eddies, etc.) in the eddy evolution between the shelf region of the Reference Data Sets and beginning of the track in "Figure 1"?*
- 4. Several times in the article the authors refer to sporadic upwelling events fueling the high surface productivity in the eddy. How is the hypothesis of "production being boosted in the surface of the eddy by upwelling events" compatible with the hypothesis of "complete isolation of the eddy core" along the whole eddy lifetime? What is the spatial distribution of these upwelling events in the eddy?*

Author Comment (AC)1_:

We appreciate this comment and related thoughts about proper reconstruction of initial conditions of the surveyed ACME. We also see the need to constrain initial conditions of the eddy as good as possible as this directly affects derived rates for biogeochemical parameters. According to RC17 we decided to slightly reorganize the presentation and discussion of SLA results. We now introduced the SLA-derived trajectory already under 2.2 (reference data sets) and added some discussion on this under a more general eddy description section under 3 (results & discussion), as also proposed in RC2_.

We explicitly neglected SLA trajectory data closer to the shelf for two reasons: ACMEs only show a very minor sea level elevation of the eddy surface. This makes it very difficult to track these eddies. Furthermore, the high density of (short-lived) eddies and filaments close to the shore drastically impairs the reliability of the eddy tracking. Background noise impedes clear identification of individual eddies, in particular those with only minor signals (ACMEs). Schütte et al. (2016) performed an elaborate analysis of eddy statistics which clearly indicated this region as a release hotspot and states that this is related to a seasonal weakening of the coastal undercurrent along with coastal topographic features. Further, Thomsen et al. (2016) observed the initial formation of an ACME off Peru, which exactly took place at the shelf edge and thereby capturing hydrographic and biogeochemical conditions at this place. We cannot derive information about how intermittent/sporadic the upwelling is and rephrased that to a more general statement on “upwelling processes”. The analysis of an oxygen float showed that the respiration derived from 5 day oxygen profiles over a period of several months showed a surprisingly constant decrease which in turn suggests that particle sinking is also constant and thus upwelling. However, the duration of the blooms apply a running mean to any intermittence of the upwelling.

Answers to the 4 specific issues:

1. We only have a very few surveys near the Mauritanian shelf edge available which fall into boreal summer months and which also conducted biogeochemical samplings in that region. Data are also available for regions further offshore from the same expeditions. However, as we are confident that the origin of the eddy is located closer to the shelf edge, we would significantly bias our calculations if you choose the more offshore area as the starting conditions.
2. This sentence was not phrased correctly in the discussion paper. We rephrased it as follows: **“In order to neglect small-scale variability of water column properties within this area, an average profile for each investigated parameter was created by averaging on isopycnals but mapped back to depth via the mean depth/density profile.”**
3. Even though we were not able to have in situ observations of this particular eddy close to its origin we are confident that once the eddy has been created no further exchange of water masses between the inner and outer part took place. Usually, such eddies begin their lifetime with very stable conditions and slowly decay over their lifetime. Since we observed very stable conditions still after 6-7 months we don’t think that major fluxes occurred in the early days of this eddy. In addition to the water mass analysis we also added information (section 3.1) on mean water ages derived from transient tracer samplings in the eddy and in the EBUS region which corroborate this view: **“This hypothesis is further being corroborated by the calculation of mean water ages (using the transit time distribution – TTD – method) derived from transient tracer analysis (section 2.3). Mean water age in the core of the eddy ($\sigma\theta = 26.35 \text{ kg m}^{-3}$ -1000) was found to be 39 ± 5 years which matches very well mean water mass ages in the EBUS region on the same isopycnal (40 ± 5 ; (Tanhua and Liu, 2015). Usually, waters on this isopycnal at CVOO are much younger (6 ± 1) due to subducted waters originating in the North Atlantic subtropical gyre. This finding supports the isolation hypothesis as well as the assumed origin on the Mauritanian shelf of this particular eddy.”**
4. . Indeed the apparent contrariety between isolation on the one side and upwelling on the other side is a very interesting observation. We do not have a final answer to it but in Karstensen et al. (2016, “Upwelling and isolation in oxygen-depleted anticyclonic mode water eddies and implications for nitrate cycling”) we discuss a concept for the processes that interact on the submesoscale. In brief, the upwelling occurs at the rim of the eddy where the vertical shear in velocity is largest (enhanced by vertical propagating Near Inertial Internal Waves). The upwelling is thus expected to originate from shallow depth, say the upper 100m or so and should be rather constant. One part of the upwelled waters is “trapped” by eddy retention and is accessible for productivity across the eddy. While we speculated in the past that the isolation is related to the

eddy coherence further analysis reveals that the buoyancy frequency/stability maximum encompassing/defining the core is very efficient in isolating the core for mixing (e.g. shown in Sheen et al., 2015). Details are described in Karstensen et al. (2016). We added a sentence in section 3.2 (2nd paragraph) in order to provide a link to that paper: “As such, this finding is interpreted as being a signature of a vertical flux event related to submesoscale processes and stratification which on the one side isolate the core and prevent oxygen supply while in parallel support vertical nutrient flux at the eddy rim (see Karstensen et al., 2016, this special issue, for further details).”

RC2_: *Description of the surveyed eddy*

The authors do not provide a clear general description of the characteristics of the surveyed eddy, among which some basic details: date (month/year) and coordinates of the eddy when forming on the shelf; date and coordinates of the beginning of the track; date, coordinates, radius, shape and age of the eddy when surveyed. Some of these characteristics can be retrieved in different parts of the article explicitly or implicitly, but it is the work of the reader to collect them. I suggest presenting these characteristics in a dedicated paragraph where the eddy is introduced and described. As regard to “Figure 1”: it may be helpful to add a timescale of the eddy trajectory and to draw the eddy contours in the region of the cruises, to understand where the measurements were located with respect to the eddy center and boundaries. Most of the observations described in the chapter “3 Results Discussion” would be much easier to understand if a nice description of the vertical physical structure of the surveyed eddy was given.

AC2_: We appreciate this comment and provided a dedicated section that describes the eddy characteristics. In this section provide the requested information and incorporated section 3.1 (Hydrography) as well. The new section is entitled as “Eddy Characteristics”

Regarding Figure 1 we added a few dates along the trajectory for illustrating the timescale of the eddy propagation. However, we decided to not draw assumed eddy contours into the figure for the following reasons: 1) In reality the form factor of such an eddy is quite dynamic and a representing ellipse or circle would be a bit misleading, 2) the figure may become too busy and 3) this kind of illustration is already presented in two more papers as part of this special issue (Haus et al., 2016; Löscher et al., 2015a) and we want to avoid too many replicates. Finally, as our analysis mainly focuses on the comparison between the inner station, the CVOO reference station (far out of the eddy) and the shelf station (even further away) we don’t see an urgent need to include the potential size and shape of the eddy to this figure.

RC3_: *Description of the dedicated eddy surveys*

In paragraph “2.1 Eddy surveys” the number of samples that were collected during each cruise is not clear and some of the descriptions are confusing. As the 2 cruises are described as “first dedicated biogeochemical surveys” of the eddy the reader may expect to see some 2D biogeochemical sections and wonder what the spatial resolution of the samples is. However, it becomes clear later that the biogeochemical data analyzed in the article consist in only 2 bottle measurements per cruise, 1 per cruise referring to the eddy center. I suggest stating this clearly in the text. The CTD/UVP-only (no bgc) section M105 is introduced but never plotted or clearly discussed. At page 5 lines 19-24 the authors write that some stations supposed to be at a certain distance from the center of the eddy on the base of SLA “turned out probably more at the rim of the eddy than in the surrounding water representing typical background conditions”. What is the reason for this conclusion? Can this be elaborated more in depth to justify this sentence?

AC3_: We agree that we haven’t clearly pointed out that the biogeochemical component of these surveys only comprises hydrocast stations in- and outside this eddy. Since we mostly focus on the eddy center stations (one during M105 and another one during ISL_00314) we emphasized this in

the text as follows: “During both cruises hydrographic and biogeochemical data were sampled in the same eddy (Figure 1) although extensive biogeochemical samplings were performed only during single hydrocast stations at the eddy center.”

Since we don't show any data from the hydrographic section across the eddy (M105, see Hauss et al. 2016 or Löscher et al., 2015) we removed the short paragraph about this section and also removed the section from Fig1 in order to avoid confusion about this.

We also added some evidence for the location of the outside station in relation to the eddy center and rim as follows: “Based on the SLA data the “outside stations” during ISL and M105 were located 43 and 54 kilometers away from the supposed eddy center, respectively. However, ship-borne Acoustic Doppler Current Profiler data (ADCP; see Hauss et al., 2016) as well as SLA data (Löscher et al., 2015) suggest a radius of this eddy of approx. 50 - 55 km. This points out that these stations were more at the rim of the eddy than in the surrounding water representing typical background conditions.”

RC4_: *Quantitative results*

Some of the results presented in the sections from 3.1 to 3.4 are not well quantified. Data collected in the eddy center and data on the shelf or in the open Atlantic are often compared with not-well-defined or confusing terms. I strongly suggest giving to the descriptions a more quantitative flavor.

AC4_: We either stated these terms more precisely or added quantitative information wherever possible (see also AC35).

RC5_: *Style: English, typos*

The paper, apart for a few sections, is scattered with typos, misspellings and incorrect formulation of the English sentences. Sentences are often very convoluted and difficult to follow. The frequent use of bracketed subordinates makes the reading process even more complicated. I highly suggest a proof-reading of the paper for typos, grammar and syntax, as well as a simplification of the structure of the sentences and the limitation of the use of brackets to the very essential. Some errors are listed in the “Detailed comments” section.

AC5_: We followed the reviewer's recommendation by having had the paper proofread by a second native speaker. We removed bracketed subordinates wherever possible.

Specific comments:

RC1: Introduction: The section “Introduction” of the paper ends with a paragraph (from page 3 line 29, to page 4 line 10) that introduces the content of the article. However, it forgets to anticipate any section about consequences and conclusions of the present study. I suggest to strengthen this paragraph in this sense, anticipating to the reader the presence of relevant conclusions connected to the results.

AC1: We edited this paragraph as follows: “Here, we present the first biogeochemical insights into low-oxygen ACMEs in the ETNA based on direct in situ sampling during two coordinated ship-based surveys. The main objective of this study is to reveal and quantify biogeochemical processes occurring inside a low-oxygen ACME in the ETNA. This publication is part of a series that describes biological, chemical and physical oceanographic processes and their interaction inside these eddies. In this publication we first present the vertical hydrographic structure of a surveyed ACME and discuss nutrients concentrations and the marine carbonate system. All data are put into regional context by comparing ACME conditions with 1) ambient background conditions represented by CVOO and 2) the biogeochemical setting in the proximal EBUS off the West African coast, where the eddy originated from. Derived estimates for transformation rates of various key parameters and for carbon export rates within the surveyed ACME highly exceed known values for the ETNA and also other open-ocean regions.”

RC2: page 2 line 25: Eastern Tropical should be capitalized when defining acronym
AC2: We changed this as suggested.

RC3: page 3 lines 18-20: incorrect syntax, “that” should follow the name that it refers to (ACME)
AC3: Sentence corrected: “They found that about 2 to 3 ACMEs are generated each year at distinct regions in the EBUS and then propagate into the open ETNA waters.”

RC4: page 3 line 27: commas out of place
AC4: Sentence corrected: “Consequences for carbon cycling such as production and export as well as the impact on the ETNA OMZ also remain unclear.”

RC5: page 3 line 29: word “process” is redundant
AC5: Removed.

RC6: page 4 line 2: misspelling “describes”
AC6: Corrected.

RC7: page 4 lines 16-19: sentence beginning with brackets; confusing sentence, “in the ETNA” better after “in situ-data”, maybe the sentence should be divided in two parts
AC7: We corrected and rephrased the sentence as follows: “Schütte et al. (2016) analyzed satellite and corresponding in-situ data in the ETNA and found that on average about 20% of all anticyclones (10% of all eddies) are ACMEs that exhibit a pronounced low oxygen core.”

RC8: page 4 line 28: unnecessary brackets
AC8: Brackets removed.

RC9: page 5 line 8-10: data is a plural word, “were”, “do”
AC9: Corrected as suggested.

RC10: page 5 lines 11-12: if the quality of the measurements is lower then it’s half the accuracy (not double), the error doubles, the accuracy halves; numbers should go before the “for”
AC10: Corrected as suggested.

RC11: page 5 line 21: misspelling “turned”
AC11: Section will be rephrased according to AC3_.

RC12: page 6 line 10: sentence in brackets should actually be better illustrated and high-lightened since it’s an important piece of information for the whole paper
AC12: This was addressed by following also the suggestion in RC17. This information is now more emphasized right at the beginning of section 2.2:
“Based on satellite SLA data the formation location of the target eddy is reconstructed to be close to the shelf edge off Mauritania at approx. 18°N (Figure 1). This is further corroborated by an elaborate statistical analysis of historical SLA data (Schütte et al., 2015) which identified this region as one hotspot for the creation of anticyclonic mode water eddies (ACMEs).”

RC13: page 6 line 22: unnecessary brackets
AC13: Sentence split and rephrased as follows: “The observatory includes a ship-based sampling and a mooring program (Fischer et al., 2015; Karstensen et al., 2015). At the time of the ISL sampling CVOO was located about 167 kilometers south of the eddy survey location in an open-ocean setting.”

RC14: page 8 line 9: “by” not “from”

AC14: Corrected as suggested.

RC15: page 8 lines 9-12: unnecessary brackets; the vertical structure of the eddy is unclear: What is the depth of the euphotic zone and how does it compare with the depth of the eddy core? What is the depth of the mixed layer? Is primary production only taking place in the shallow mixed layer as it may be hypothesized from the chlorophyll plot, or is primary production also happening in the core? Is the core still in the euphotic zone? These points should be very well clarified also in the “Results” sections

AC15: Brackets removed.

Regarding the vertical structure of the eddy we provided this information in the “Eddy Characteristics” section following your suggestion made in RC2_. We also edited two sentences in section 3.1 (which was incorporated into the new section) in order to explicitly mention the mixed layer depth in and outside the eddy.

“The upper bound of the eddy core is the mixed layer base at a depth of 70 m which has the same magnitude as the mixed layer outside the eddy (Karstensen et al., 2016, this special issue). A very sharp gradient exists between 70–77 m depth which amounts to 0.73 in salinity, 3.98°C in temperature and 165.8 $\mu\text{mol kg}^{-1}$ in dissolved oxygen.”

Unfortunately, light/PAR measurements failed during the surveys due to sensor problems. Thus, we can’t give reliable information about the euphotic zone for this particular eddy. We removed speculative connections between the eddy core and the euphotic zone from the abstract and the conclusions.

Results for primary production rates are presented in Löscher et al., 2015 (Figure 7). Rates were found to be in accordance with discrete samples for chl-a. Unfortunately, no rates were determined for the depth of the eddy core.

RC16: page 8 line 13: misspelling “resembles”; I find it not so proper to say that this sporadic upwelling resembles coastal upwelling, it’s probably Ekman pumping, which does not require a coastal boundary to happen

AC16: It is true that coastal upwelling is maybe mostly an Ekman pumping problem, while for the eddies different upwelling models have been proposed. However, the effect of eddy-induced upwelling on the biogeochemistry is comparable to coastal upwelling regions (upward nutrient flux, enhanced surface productivity, etc.).

RC17: page 8, lines 17-31: this description should in part be moved to an eddy description section and in part be included in the 2.2 Reference Data Sets section

AC17: We appreciate this comment and moved most of this paragraph into section 2.2

RC18: page 8 lines 23-25: sentence is hardly understandable, “but” is incorrectly used

AC18: We split and rephrased this sentence as follows: “In order to neglect small-scale variability of water column properties within this area, an average profile for each investigated parameter was created. This was done by averaging parameters along isopycnal surfaces and then mapping back these values to the mean depth of each isopycnal surface.”

RC19: page 8 line 29: “en route”?

AC19: Sentence reworded as follows: “This reference data from the shelf was then used to determine the changes in biogeochemical parameters that occurred on the way from the formation to the survey area northwest of Cape Verde.”

RC20: page 9 lines 4-6: “remineralization”, not “mineralization”; words before acronyms should be capitalized; “age” doesn’t need quotation marks; very convoluted sentence, could be split in two parts

AC20: Sentence split and corrected as suggested: “Changes of oxygen and carbon due to remineralization of organic matter are being expressed as the Apparent Oxygen Utilization Rate (aOUR) and the Carbon Remineralization Rate (CRR). In order to determine these rates not only the anomaly but also the age of the eddy, the time between formation on the shelf and the time the eddy surveys took place, needs to be known.”

RC21: page 10 line 9: there should be a comma (not a dot) before “as”

AC21: Sentence changed as suggested.

RC22: page 10 line 24: misspelling “resemble”

AC22: Changed.

RC23: page 10 line 25: “predominating” not the right word, maybe “dominant”

AC23: Word changed to “dominant”.

RC24: page 10 lines 26-27: not sure if this sentence is needed. Either the paper includes a full description of the basin and relative water masses (eg, in the introduction) or it seems out of place; also: what is the typical TS signature of SACW that is also found in the core of the eddy? A reader may not be familiar with this water mass

AC24: We decided to mention NACW at this part of the paper as it directly emphasizes the observed anomaly. We incorporated this sentence into the sentence prior to it: “They resemble South Atlantic Central Water (SACW), the dominating upper layer water mass in the Mauritanian Upwelling region, whereas the region around CVOO is actually dominated by high salinity North Atlantic Central Waters (NACW; Pastor et al., 2008).”

RC25: page 11 line 8: I don’t understand “vertical contrast”, does it mean “gradient”?

AC25: Replaced by “gradient”.

RC26: page 11 line 11: “underway”?

AC26: “underway” was replaced by “Shipborne Sea Surface Temperature (SST)”

RC27: page 11 line 22: “minimal” not an adverb

AC27: Sentence changed as follows: “We expect the oxygen decrease from continuous respiration of the organic material that sinks out of the euphotic zone into an environment that is at most only slightly affected by lateral ventilation of the eddy waters.”

RC28: page 11 lines 25-26: “inside the ACME” seems to refer to the whole eddy, are these lines referring to remineralization that happens in the low-oxygen core?

AC28: We now write “ACME core” in order to avoid confusion.

RC29: page 12 line 25: clearly missing reference (!)

AC29: We added Schulz et al. (2013) who describe the range of pH values used for their mesocosm study.

RC30: page 13 line 5: paragraph on DIC should probably end here, not at line 3

AC30: Changed as suggested.

RC31: page 13 line 6-7: not quantitative, not clear, terms as “minor change” and “small but significant” should be defined

AC31: We will add the maximum value of change in TA beneath the eddy core as follows: “Here, only a small change of up to 17 $\mu\text{mol kg}^{-1}$ in TA inside the eddy core is found.” We further rephrased the following sentence as well: “This was expected as respiration processes may have a positive or negative effect on TA depending on the form of reactive nitrogen being released (Wolf-Gladrow et al., 2007).”

RC32: page 13 lines 17-18: “data not shown” used for drawing conclusion does not strengthen the paper, given the limited number of plots and their simplicity maybe some of the data could also be shown; same for the next “data not shown” in the paper

AC32: We decided to rather remove this sentence as the differences in correlations are very weak due to the very limited number of TA samples. Correlations pointing towards this direction but are clearly not robust. Regarding the following “data not shown” we decided to keep this statement as it is. It relates to POC samples collected during the remaining part of the M105 expedition south of Cape Verde. If we would include all this POC data into the subpanel it would make this plot too busy.

RC33: page 13 lines 20-32: all the detected small particles are assumed to be POM; this assumption is not explicitly stated even though it is at the base of the conclusions, I suggest to state and justify the assumption for this region. Are dust-deposition-derived particles irrelevant in this region/season?

AC33: The UVP is an optical instrument, thus we do not know the composition of the respective size classes of particles. However, although dust deposition is certainly an important factor in this region (also for ballasting of particles containing organic compounds), it seems unlikely that the marked increase in particles observed within the eddy is linked to a local dust event rather than the eddy itself. Particles larger than approximately 500 μm equivalent spherical diameter (for which the UVP stores the image information) mostly resemble “marine snow”-type aggregates (compare section across eddy and example images in Hauss et al. 2016, Fig 4a). While they may contain lithogenic material to some extent, it seems reasonable that they contribute to the POM (which was also measured independently by elemental analysis in discrete bottle samples) and provide the basis for water column respiration and carbon export flux (see also Fischer et al. 2015). We edited the first sentence of this section as follows: “We used data from the UVP to illustrate vertical distribution of small particles (60 – 530 μm) in the water column which we assume to primarily consist of POM but may also contain lithogenic material (Fischer et al., 2015).”

RC34: page 13 line 23: convoluted sentence

AC34: We suppose that actually the sentence in lines 21-23 was meant. Thus, we rephrased this sentence as follows: “During both surveys, particle abundances show a peak within the shallow OMZ slightly below the oxygen minimum (Figure 6).”

RC35: page 13 line 24 and 27: “significantly exceeds” and “much higher” not very quantitative

AC35: We changed this as follows: “This points at accumulated particles fueling microbial respiration in the core of the eddy. Furthermore, surface concentrations of particles exceed open-ocean conditions as found at CVOO by a factor of 2 to 3. This is in line with Löscher et al. (2015) who described a threefold higher primary production for surface waters inside the eddy as compared to the outside. In the Mauritanian shelf area particle concentrations are high throughout the water column (Figure 6).”

RC36: page 13 lines 30-31: “according to Hauss et al (2015)”, is this the same eddy?

AC36: Yes, it is.

RC37: page 17, lines 22-32: In the first paragraph of the conclusions the authors are very generic about their findings regarding the eddy bgc composition discussed in the sections from 3.1 to 3.4. Some of the results are not recalled (eg, particle, POM and DOM distribution). Since many interesting findings are discussed in the paper, I strongly suggest strengthening this part of the conclusion.

AC37: We agree and also see the need to improve this section. We extended this section in order to cover all relevant findings of this paper.

RC38: Figure 2: colorbar and legend seem to contradict each other: if orange points refer to ACME (M105), what do the blue points refer to? This choice of colormap is unhelpful, the color is mostly constant.

AC38: We agree that the legend is misleading due to the color. We changed this in a revised version of this figure and may also adjusted the colorbar.

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4. Marked-up Manuscript

Oxygen Utilization and Downward Carbon Flux in an Oxygen-Depleted Eddy in the Eastern Tropical North Atlantic

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Abstract

The occurrence of mesoscale eddies that develop ~~an extreme low oxygen~~suboxic environments at shallow depth (about 40 to 100 m) has recently been reported for the ~~e~~Eastern Tropical North Atlantic (ETNA). Their hydrographic structure suggests that the water mass inside the eddy is well isolated from ambient waters supporting the development of severe near-surface oxygen deficits. So far, hydrographic and biogeochemical characterization of these eddies was limited to a few autonomous surveys, ~~using with the use of~~ moorings, underwater gliders and profiling floats. In this study we present results from the first dedicated biogeochemical survey of one of these eddies conducted in March 2014 near the Cape Verde Ocean Observatory (CVOO). ~~At the time of~~During the survey the eddy core showed ~~lowest~~ oxygen concentrations ~~of less than~~low as 5 $\mu\text{mol kg}^{-1}$ ~~and with~~ a pH of ~~approx~~around 7.6 at ~~the lower boundary of the euphotic zone~~approximately 100 m depth. Correspondingly, the aragonite saturation level dropped to 1 at the same depth, thereby creating unfavorable conditions for calcifying organisms ~~at this shallow depth~~. To our knowledge, such enhanced acidity within near-surface waters has never been reported before for the open Atlantic Ocean. Vertical distributions of particulate and dissolved organic matter (POM, DOM), generally showed elevated concentrations in the surface mixed layer (0 – 70 m), ~~but particularly with~~ DOM also accumulating inges beneath the oxygen minimum.

1 ~~Considering~~ With the use of reference data from the upwelling region where these eddies are
2 formed, ~~we determined~~ the oxygen utilization rate was calculated by determining oxygen
3 consumption through the remineralization of organic matter. Inside the core, we found these
4 rates were almost one order of magnitude higher and found an enhancement of apparent
5 oxygen utilization rates (aOUR, $0.26 \mu\text{mol kg}^{-1} \text{d}^{-1}$) than by almost one order of magnitude
6 when compared with typical values for the open North Atlantic. Computed downward fluxes
7 for particulate organic carbon (POC), ~~at 100 m~~ were about around 0.19 to $0.23 \text{ g C m}^{-2} \text{d}^{-1}$ at
8 100 m depth, ~~which~~ clearly exceeding fluxes typical for an oligotrophic open ocean setting.
9 The observations support the view that the oxygen depleted eddies can be viewed as isolated,
10 westwards propagating upwelling systems ofas their own, thereby represent re-occurring alien
11 biogeochemical environments in the ETNA.

13 1 Introduction

14 New technological advances in ocean observation platforms, such as profiling floats, gliders,
15 and in sensors have greatly facilitated our knowledge about physical, chemical and biological
16 processes in the oceans, ~~and~~ particularly those occurring on small spatio-temporal scales
17 (Johnson et al., 2009; Roemmich et al., 2009). ~~In particular~~ Physical transport processes in
18 frontal regions and ~~in~~ mesoscale eddies have been found to generate biogeochemical
19 responses that are very different from the general background conditions (Baird et al., 2011;
20 Mahadevan, 2014; Stramma et al., 2013). A key process in driving the generation of
21 anomalies is the vertical flux of nutrients into the euphotic zone, ~~that~~ which enhances primary
22 productivity, a process that is of particular importance in usually oligotrophic environments
23 (Falkowski et al., 1991; McGillicuddy et al., 2007). Besides the locally generated response,
24 the westward propagation of mesoscale eddies introduce a horizontal (mainly zonal)
25 relocation of eddy properties. Satellite data and model studies show that eddies do play an
26 important role in the offshore transport of organic matter and nutrients from the eastern
27 Eastern boundary Boundary upwelling Upwelling systems Systems (EBUS) into the open
28 ocean. Considering their transport alone, eddies have been found to create a negative impact
29 on productivity in the EBUS regions because of their net nutrient export (Gruber et al., 2011;
30 Nagai et al., 2015; Rossi et al., 2009).

31 The Eastern ~~tropical~~ Tropical North Atlantic (ETNA) hosts an eastern boundary oxygen
32 minimum zone (OMZ), which is primarily created from sluggish ventilation (Luyten et al.,

1 1983) and high productivity in the EBUS along the West African coast. In its western part, the
2 ETNA is bounded by the Cape Verde ~~F~~frontal zone-Zone (CVFZ), separating the OMZ
3 regime from the wind driven and well ventilated North Atlantic subtropical gyre. In the south,
4 towards the equator, oxygen is supplied via zonal current bands (Stramma et al., 2005; Brandt
5 et al. 2015). The vertical oxygen distribution shows two distinct oxygen minima, an upper one
6 at about 75m depth and a deep OMZ core at about 400 m (Brandt et al., 2015; Karstensen et
7 al., 2008; Stramma et al., 2008b). On the large scale, the minimum oxygen concentrations in
8 the ETNA OMZ are just below $40 \mu\text{mol kg}^{-1}$ (Stramma et al., 2009) but an expansion of the
9 OMZ, both in terms of intensity and vertical extent, has been observed over periods of
10 decades (Stramma et al., 2008a). However, recently Karstensen et al. (2015) reported the
11 appearance of very low oxygen concentrations at very shallow depth, close to the mixed layer
12 base, ~~in~~within the ETNA. ~~This was observed during~~in a long term oxygen time series from a
13 mooring and profiling float at the Cape Verde Ocean Observatory (CVOO, cvo0.geomar.de),
14 ~~and from a profiling float~~. By making use of satellite derived sea level anomaly data, the
15 authors could associate the occurrence of the low oxygen events with cyclonic (CE), as well
16 as anticyclone mode-water eddies (ACMEs). The latter ones are characterized by a water lens
17 of mode which is being formed by up- and downward-bent isopycnals towards the eddy
18 center. Normal anticyclones did not show any low oxygen signatures. They also propose that
19 the oxygen minimum in CEs and ACMEs is not being exported from the eddy formation
20 region (along the west African coast), but created during the westward passage of the eddies
21 into the open ETNA.

22 Based on satellite data analysis, a statistical assessment of mesoscale eddies has been done for
23 the North Atlantic in general (Chelton et al., 2011), ~~in particular-as well as for~~ the ETNA ~~in~~
24 ~~particular~~ (Chaigneau et al., 2009; Schütte et al., 2015). However, (Schütte et al., 2016a,
25 2016b) ~~Schütte et al. (2015 & in prep. for this issue)~~ were the first to further differentiate
26 anticyclonically rotating eddies into “normal” anticyclones and ACMEs, by combining
27 satellite data (sea level anomalies, sea surface temperature) with in-situ data (CTD, profiling
28 floats, glider). They found that about ~~24~~ to ~~23~~ ACMEs ~~are-were~~ generated each year (at
29 distinct regions in the EBUS) ~~that-and then~~ propagate into the open ETNA waters.

30 An intense biogeochemical response in ACMEs has been reported for other ocean regions as
31 well. For instance, McGillicuddy et al. (2007) reported intense phytoplankton blooms in
32 ACMEs for the western North Atlantic, near Bermuda. They explained the phenomenon as

1 the result of a vertical nutrient flux driven by the interaction of the eddy with the overlying
2 wind field. Altabet et al. (2012) observed enhanced production of biogenic nitrogen (N₂)
3 inside an ACME in the generally suboxic conditions in the eastern South Pacific OMZ.
4 ~~Further, c~~Consequences for carbon cycling, such as production and export, as well as the
5 impact on the ETNA OMZ also remain unclear.

6 However, detailed ~~process~~ understanding of the physical and biogeochemical processes and
7 their linkages in eddies, in particular in the high productive ACMEs, is still scarce and one
8 reason is the difficulty in performing dedicated in-situ surveys of such eddies.

9 Here, we present ~~the first~~ biogeochemical insights into low-oxygen ACMEs in the ETNA
10 based on direct in situ sampling during two coordinated ship-based surveys. The main
11 objective of this study is to reveal and quantify biogeochemical processes occurring inside a
12 low-oxygen ACME in the ETNA. This publication is part of a series that describes biological,
13 chemical and physical oceanographic processes and their interaction in ~~low-oxygen ACMEs~~
14 ~~in the ETNA~~ side these eddies. In this ~~paper~~ publication we first present the vertical
15 hydrographic structure of a surveyed ACME and discuss nutrients concentrations and the
16 marine carbonate system. All the data are put into regional context by comparing ACME
17 conditions with 1) ambient background conditions represented by ~~the nearby Cape Verde~~
18 ~~Ocean Observatory time series site (CVOO)~~ and 2) the biogeochemical setting in the
19 proximal EBUS off the West African coast, where the eddy originated from. ~~We then~~
20 ~~provide~~ Derived estimates for transformation rates of various key parameters and ~~derive~~
21 ~~estimates~~ for carbon export rates within the surveyed ACME highly exceed known values
22 for the ETNA and also other open-ocean regions.

24 **2 Methods**

25 Mesoscale eddies can be detected and tracked from space (Chelton et al., 2011; Schütte et al.,
26 2015). However, only a few of such eddies develop an oxygen depleted core ~~and a, therefore~~
27 ~~targeted~~ surveys surveying an of oxygen-depleted mesoscale eddies in the ETNA (and
28 elsewhere) is somewhat challenging. Schütte et al. (2016) (~~Schütte et al., in prep. for this~~
29 ~~issue~~) analysed satellite and corresponding in-situ data in the ETNA and found that on
30 average about 20% of all anticyclones (10% of all eddies) are ACMEs ~~in the ETNA,~~
31 exhibiting a strong-pronounced low oxygen core. CEs also develop a low oxygen core but not
32 as low as ACMEs do.

1 In order to enable a targeted survey of the one particular ACME, the following strategy was
2 designed (“Eddy Hunt” project; Körtzinger et al., introduction to this special issue): we
3 combined satellite data (sea level anomaly, SLA, and sea surface temperature, SST) with
4 Argo float data in a near-real time mode. Although we did not had access to oxygen data in
5 near-real time, we knew from earlier observations (Karstensen et al., 2015) that low oxygen
6 ACMEs have a low salinity core. As such, detecting an eddy with high SLA and low SST
7 (~~note, normal anticyclones show high SST;~~ Schütte et al., 2015) and confirming low salinity
8 at shallow depth from opportunistic Argo float data, potential low-oxygen ACMEs were
9 detected. An ACME with a low oxygen core was discovered during a pre-survey using an
10 autonomous underwater glider, initiating ship surveys. A pre-survey (with an autonomous
11 underwater glider) of one such candidate ACME confirmed a low oxygen core and ship
12 surveys were initiated.

13 Here, we use ship data as well as data from a profiling float of a variety of biogeochemical
14 parameters in order to investigate the marine carbonate system functioning on low-oxygen
15 eddies. The following sections will provide a brief overview of samples collected during two
16 ship cruises and the applied analytical methods. Moreover, the general setting of the CVOO
17 ship time series, as well as data from hydrographic cruises and the profiling float will be
18 introduced.

19 2.1 Eddy Surveys

20 Dedicated eddy surveys were done during the RV Islandia cruise ISL_00314 (05 March – 07
21 March 2014; hereafter named ISL) and the RV Meteor cruise M105 (17 March to 18 March
22 2014; hereafter named M105). During both cruises hydrographic and biogeochemical data
23 were sampled ~~in~~on the same eddy (Figure 1), although extensive biogeochemical
24 samplings were performed only during single hydrocast stations at the eddy center. Water
25 samples in the upper 500 m were collected with a rosette water sampling system equipped
26 with a CTD (conductivity, temperature & depth), ~~and additional~~ Additional sensors such as an
27 oxygen sensor (SBE43, Seabird Electronics) and a two channel fluorometer (FLNTURT,
28 WETLabs) were attached to the CTD. Note that fluorometer data in this study will be used
29 only as a qualitative proxy and thus this data will be presented in arbitrary units only. Since
30 the CTD data during ISL_00314 ~~does~~ not meet all quality control measures following GO-
31 SHIP standards, we expect for the hydrographic data an accuracy of about ~~twice~~half the
32 GO_SHIP standard, which is 0.002°C for temperature ~~0.002°C~~, 0.004 for salinity ~~0.004~~ and

1 approx. 4 $\mu\text{mol kg}^{-1}$ for oxygen sensor data ~~approx. 4 $\mu\text{mol kg}^{-1}$ (note that M105 data fulfil~~
2 ~~these criteria).~~

3 Along with CTD casts, an underwater vision profiler 5 (UVP, Picheral et al., 2010) was
4 deployed during both cruises in order to quantify particle distribution in the water column (see
5 results in Hauss et al., 2015). During both cruises, CTD casts down to 600 m were ~~performed~~
6 ~~deployed, and trying attempting~~ to survey as close as possible to the eddy core (guided by the
7 near-real time satellite SLA maps). ~~This was also conducted and likewise~~ outside of the eddy
8 to be able to investigate the horizontal contrast of the eddy to the surrounding waters. Based
9 on the SLA data the “outside stations” during ISL and M105 were located 43 and 54
10 kilometres away from the supposed eddy centre, respectively. However, ship-borne Acoustic
11 Doppler Current Profiler data (ADCP; see Hauss et al., 2016) as well as SLA data (Löscher et
12 al., 2015) suggest a radius of this eddy of approx. 50 - 55 km. This points out~~It however tuned~~
13 ~~out~~ that these stations ~~where probably~~ more at the rim of the eddy, rather than in the
14 surrounding water representing typical background conditions. In order to compare the eddy
15 observations to the typical background conditions, we used data collected during M105 at the
16 CVOO time series station (see section 2.2).

17 ~~Additionally, a section across the eddy was performed during M105 that included multiple~~
18 ~~hydrocasts (CTD/UVP only, no bottle sampling) as well as current and backscatter profiles~~
19 ~~with the ship-borne Acoustic Doppler Current Profiler (ADCP) instrument and vertically~~
20 ~~stratified plankton net hauls (see results in Hauss et al., 2015).~~

21 For comparison, we also used data from an Argo profiling float (WMO no. 6900632) that got
22 trapped in a low-oxygen cyclonic eddy (Karstensen et al., 2015; Ohde et al., 2015). This float
23 was equipped with an oxygen sensor (AADI Aanderaa optode 3830) and a transmissometer
24 (CRV5, WETLabs). The given uncertainties of the float measurements were ± 2.4 dbar for
25 pressure, $\pm 0.002^\circ\text{C}$ for temperature and ± 0.01 for salinities, with an estimated uncertainty of
26 float-borne oxygen measurements at $\pm 3 \mu\text{mol kg}^{-1}$. The float was deployed in February 2008
27 at the Mauritanian shelf edge and propagated in a rather straight, west-northwest course, into
28 the open waters of the ETNA.

29 **2.2 Reference Data Sets**

30 Based on satellite SLA data the formation location of the target eddy is reconstructed to be
31 close to the shelf edge off Mauritania at approx. 18°N (Figure 1). This is further corroborated

1 by an elaborate statistical analysis of historical SLA data (Schütte et al., 2015), which
2 identified this region as one hotspot for the creation of anticyclonic mode water eddies
3 (ACMEs). Thus, ~~Data~~ data from former research expeditions in the ~~ETNA~~is region, conducted in
4 other research programs (e.g., SOPRAN, SOLAS, SFB 754), were used to put the results of
5 the dedicated eddy surveys into regional context. For the Mauritanian shelf area, ~~(Figure 1)~~
6 three cruises were identified that sampled the region during ~~that part of the year~~boreal
7 summer when eddies are typically created ~~(and so was the target eddy)~~ and released to the
8 open Atlantic Ocean (Schütte et al., 2015): RV Meteor cruise M68-3 (12 July – 6 August
9 2006) conducted a biogeochemical survey from the Mauritanian Upwelling region up to the
10 Cape Verde Archipelago, RV Poseidon cruise POS399/2 (31 May – 17 June 2010) which
11 operated in the same area and RV Meteor cruise M107 (29 May – 03 July 2014) focused on
12 benthic biogeochemical processes along the Mauritanian shelf edge. ~~Data from selected~~
13 ~~stations near the shelf edge from all three cruises were used as a reference for biogeochemical~~
14 ~~characteristics during the eddy formation.~~ We used the station data (CTD hydrocasts and
15 discrete water sampling) from these cruises which are within the area 17.45 °N to 18.55 °N
16 and -17.10 °E to -16.45 °E (Figure 1). In order to neglect small-scale variability of water
17 column properties within this area, an average profile for each investigated parameter was
18 created. This was done by averaging parameters along isopycnal surfaces and then mapping
19 back these values to the mean depth of each isopycnal surface. These mean profiles were
20 assumed to reflect typical initial conditions of ACMEs during formation in the Mauritanian
21 shelf area in boreal summer (Table 1).

22 Likewise, representative background conditions for the actual survey area northwest of the
23 Cape Verde Islands were estimated from data collected during M105 at the near-by CVOO
24 (17.58 °N, -24.28 °E, Figure 1). The observatory includes a ship-based sampling ~~program~~ and
25 a mooring program (Fischer et al., 2015; Karstensen et al., 2015). ~~and~~ ~~At the time of the ISL~~
26 ~~sampling CVOO is~~ was located about 167 kilometers south of the eddy survey location, ~~(at~~
27 ~~the time of the ISL sampling)~~ in an open-ocean setting. We used data of the CVOO sampling
28 during M105 as background conditions in order to illustrate local biogeochemical anomalies
29 caused by this ACME.

30 **2.3 Analytical Methods**

31 All discrete seawater samples collected for this study were analyzed for dissolved oxygen
32 after Hansen (2007) with manual end-point determination. Samples were stored dark after

1 sampling and fixation and were analyzed within 12h on board. Regular duplicate
2 measurements were used to ensure high precision of measurements (ISL: $0.27 \mu\text{mol kg}^{-1}$,
3 M105: $0.34 \mu\text{mol kg}^{-1}$). Oxygen bottle data were also used to calibrate the oxygen sensors
4 mounted on CTD instruments.

5 Samples for nutrients were analyzed with autoanalyzer systems following the general method
6 by Hansen and Koroleff (2007). Nutrient samples during ISL and M105 surveys were always
7 taken as triplicates, stored at $-20 \text{ }^{\circ}\text{C}$ immediately after sampling and were analyzed onshore
8 within 3 weeks (ISL) and 2 months (M105) after collection, ~~respectively~~. Obtained precisions
9 from regular triplicate measurements (in $\mu\text{mol kg}^{-1}$) for nutrient analyses were 0.08 (nitrate),
10 <0.01 (nitrite), 0.02 (phosphate), 0.04 (silicate) for ISL and 0.08 (nitrate), 0.02 (nitrite), 0.05
11 (phosphate) and 0.07 (silicate) for M105.

12 Samples for dissolved inorganic carbon (DIC) and total alkalinity (TA) were preserved and
13 stored for later onshore analysis, following procedures recommended by Dickson et al.
14 (2007). Briefly, 500 mL borosilicate glass bottles were filled air bubble-free with seawater
15 and then poisoned with 100 μL of saturated mercuric chloride solution. Samples were stored
16 at room temperature in the dark and, in case of later onshore analysis, shipped to GEOMAR
17 for analysis within 3 month after sampling. Preserved samples, as well as samples directly
18 analyzed onboard, were measured using automated high precision analyzing systems
19 performing a coulometric titration for DIC (SOMMA, Johnson et al. 1993) and a
20 potentiometric titration for TA (VINDTA, Mintrop et al. 2000). High quality of obtained
21 results was ensured by regular measurements of certified reference material (CRM, A.
22 Dickson, Scripps Institution of Oceanography, La Jolla, USA; Dickson, 2010) and duplicate
23 samples (TA: $1.30 \mu\text{mol kg}^{-1}$, DIC: $1.45 \mu\text{mol kg}^{-1}$). Results from DIC and TA analysis were
24 used to compute the remaining parameters of the marine carbonate system (pH, $p\text{CO}_2$ and
25 Ω_{Ar}) using a MATLAB version of the CO2SYS software (Van Heuven et al., 2011).
26 Calculations were based on carbonic acid dissociation constants after Mehrbach et al. (1973)
27 as refitted by Dickson and Millero (1987).

28 The transient tracers CFC-12 and SF6 were measured on-board M68/3 and M105 from
29 200 ml water samples using purge-and-trap, followed by a gas-chromatographic separation
30 and detection technique slightly modified from (Bullister and Wisegarver, (2008).

1 Samples for DOC/DON were collected into combusted (8 h, 500°C) glass ampules after
2 passing through combusted (5 h, 450°C) GFF filters and acidified by an addition of 80 µL of
3 80% phosphoric acid. The DOC was analysed with the high-temperature catalytic oxidation
4 method adapted after Sugimura and Suzuki (1988). Total dissolved nitrogen (TDN) was
5 determined simultaneously to DOC using a TNM-1 detector on Shimadzu analyser. DON
6 concentrations were further calculated by subtraction of measured total inorganic nitrogen
7 ($\text{NO}_3^- + \text{NO}_2^-$) from TDN. The calibrations and measurements are described in more detail in
8 Loginova et al. (2015) and Engel and Galgani (2015).

9 Filtration of seawater (1 L of seawater <150 m and 2 L >150 m depth) through a GFF filter
10 (0.8 µm pore size), was conducted during M105 in order to determine particulate fractions of
11 organic carbon and nitrogen. ~~with the Filters-filters were-being~~ stored frozen (-20 °C) until
12 analyses. In the lab, filters were exposed to fuming hydrochloric acid to remove inorganic
13 carbon, dried at 60°C for ~6 hours, wrapped in tin foil and processed in an Euro EA elemental
14 analyzer calibrated with an acetanilide standard.

15

16 2.4 Oxygen Utilization

17 Karstensen et al. (2015) suggested that the low-oxygen cores of the eddies were created ~~from~~
18 by an enhanced subsurface respiration due to high surface productivity. At the same time, and
19 subsequently sinking of particulate matter combined with ~~with-reduced-oxygen-supply (due-to~~
20 an efficient isolation of the core from surrounding waters hinders oxygen ventilation). The
21 high productivity is proposed to be driven by vertical nutrient flux into the euphotic zone, a
22 situation that ~~resamples-resembles~~ coastal upwelling regions. Therefore we compare our
23 results of the analysis of the eddy in spring 2014 (e.g., production and respiration of organic
24 matter and related export fluxes) with observations from the Mauritanian shelf (refer to
25 section 2.2).

26 ~~Based on satellite SLA data the formation location of the target eddy is reconstructed to be~~
27 ~~close to the shelf edge off Mauritania at approx. 18°N (Figure 1). This is further corroborated~~
28 ~~by an elaborate statistical analysis of historical SLA data (Schütte et al., 2015) which~~
29 ~~identified this region as one hotspot for the creation of anticyclonic mode water eddies~~
30 ~~(ACMEs). We used the station data (CTD hydrocasts and discrete water sampling) from the~~
31 ~~three cruises mentioned above which fall into the area 17.45 °N to 18.55 °N and 17.10 °E to~~

16.45 °E (Figure 1). ~~In order to account for small scale variability of water column properties within this area, an average profile for each investigated parameter was created by averaging on isopycnals but mapped back to depth via the mean depth/density profile. These mean profiles were assumed to reflect typical initial conditions of ACMEs during formation in the Mauritanian shelf area in boreal summer (Table 1).~~

This reference data from the shelf was then used to determine the changes in biogeochemical parameters that occurred en-route on the way from the formation to the survey area northwest of Cape Verde. Again, the anomalies were determined along isopycnals and mapped back to depth. We assumed that the core of the eddy was not significantly affected by either horizontal or vertical mixing, as-due to such ACMEs are-being known to host highly isolated water bodies due to their physical structure (Karstensen et al., 2015). This assumption allows us to derive estimates for biogeochemical rates being independent of mixing processes.

Changes of oxygen and carbon due to remineralization of organic matter are expressed as ~~In order to determine~~ the apparent ~~Apparent oxygen~~ Oxygen utilization ~~Utilization rate~~ Rate (aOUR) and the ~~carbon~~ Carbon Remineralization rate ~~Rate~~ (CRR). In order to determine these rates, not only the anomaly but also the “age” of the eddy, ~~that is~~ the time between formation on the shelf and the time the eddy surveys took place, needs to be known. The age was determined from the SLA tracking algorithm, that was also used to determine the area of origin (Schütte et al., in prep. for this issue; Figure 1). Biogeochemical rates were then estimated along multiple isopycnal surfaces between the shelf and the eddy interior as shown here for determination of CRRs:

$$CRR_i = \frac{DIC_{E,i} - DIC_{S,i}}{t_E - t_S} \quad (1)$$

where CRR_i is the carbon remineralization rate along the isopycnal surface i , $DIC_{E,i}$ the observed DIC concentration within the eddy on isopycnal i , $DIC_{S,i}$ the average DIC concentration on the shelf on isopycnal i , t_E the time of the eddy survey, and t_S the back-calculated time the eddy was created in the shelf area. The same approach was followed to determine rates for all other available biogeochemical variables as well.

Data from the Argo float trapped inside a CE in 2008 was processed as described in Karstensen et al. (2015). Corresponding CRRs were derived from aOURs by applying a Redfield stoichiometric ratio of $-O_2:C_{org} = 1.34 \pm 0.06$ (Körtzinger et al., 2001a), as no direct measurements of the carbonate system exist for this CE.

1 2.5 Carbon Export Flux

2 ~~In order to estimate the amount of carbon exported from the euphotic zone as sinking POM~~
3 ~~We used CRRs to estimate-derive~~ the shape of the vertical export flux curve for particulate
4 organic carbon (POC) ~~out of the euphotic zone. This approach assumes the absence of major~~
5 ~~physical transport processes between the mixed layer and the ACME core beneath, except for~~
6 ~~sinking particles of POM~~ which is generally being described by the established Martin Curve
7 (Martin et al., 1987a):

$$F(z) = F_{100} \cdot \left(\frac{z}{100}\right)^{-b} \quad (2)$$

8 where $F(z)$ is the POC flux at a given depth z , F_{100} the corresponding export flux at 100 m and
9 b a unitless fitting parameter that describes the shape of the curve.

10 F_{100} can be determined following an approach by Jenkins (1982) using a log-linear aOUR-
11 depth dependence which can be also described for CRR as follows:

$$\ln(\text{CRR}) = m \cdot z + c \quad (3)$$

12 where m is the slope and c the intercept of the linear regression of $\ln(\text{CRR})$ versus depth. An
13 estimate for F_{100} can be obtained by vertically integrating $F(z)$ from 100 m downward to a
14 maximum depth a :

$$F_{100} = \int_{100}^a \ln(\text{CRR}) dz = \int_{100}^a e^{(m \cdot z + c)} dz \quad (4)$$

15 The b parameter of the Martin equation (eq. (2)) can then be determined as the slope of the
16 linear regression of $\ln(\text{CRR})$ on $\ln(z)$.

17 The rates we derive from CRRs assume that the changes can exclusively be ascribed to the
18 biogeochemical processes and no major transport processes (ventilation) play a role. ~~As~~
19 such reported rates in this study are to be seen as lower order estimates. However, from the
20 comparison of the hydrographic properties in the eddy formation area and the survey area,
21 this assumption is plausible for the core of the eddy (see detailed discussion in section 3.1).

22

23 3 Results & Discussion

24 ~~In the following sections, we first examine the hydrographic (section 3.1) and biogeochemical~~
25 ~~setting (sections 3.2–3.4) of the surveyed ACME in a phenomenological sense. In order to~~
26 ~~better understand and interpret the biogeochemical anomalies found in the eddy core we~~

~~compare our results with observations that are representative for either the Mauritanian shelf region or the ambient open ocean conditions outside of the eddy. We then derive estimates for aOUR and carbon export rates from these data.~~

3.1 HydrographyEddy Characteristics

Based on SLA data analysis, the surveyed eddy was clearly identified for the first time in November 2013 near the Mauritanian shelf edge at 17.65 °N and 17.94 °W (Figure 1). Due to high density of filaments and other eddies closer to shore, a clear identification of this eddy further east could not be retrieved. However, based on the mean propagation velocity of this eddy it is assumed that the eddy has formed closer to shore already in September 2013. The observed diameter of this eddy was approx. 100 km (section 2.1), which is being corroborated with hydrographic observations in the water column (Karstensen et al., 2016). The eddy propagated west-northwestwards and was then surveyed 167 km north of CVOO, approx. 163 (ISL; 19.05 °N, 24.30 °W) and 173 (M105; 19.03 °N, 24.77 °W) days after its creation on the shelf, respectively.

The ~~TS~~ Temperature-salinity (TS) characteristics of the subsurface core of ACMEs in the open ETNA (Schütte et al., in prep. for this issue; Karstensen et al., 2015) were found to be nearly unchanged, compared to coastal regions. They ~~resemble~~ resemble South Atlantic Central Water (SACW), the predominating upper layer water mass in the Mauritanian Upwelling region, ~~whereas the region around CVOO is actually dominated~~ Towards the west and north, the influence of SACW decreases and is taken over by high salinity North Atlantic Central Waters (NACW;), the dominant water mass of the ventilated part of the North Atlantic subtropical gyre (Pastor et al., 2008). As expected for a low-oxygen eddy, the TS characteristic in the 2014 eddy core for the two surveys matched very well with the characteristic found from the Mauritanian shelf reference stations (Figure 2); ~~thereby~~ This underscores the isolation of the eddy against mixing processes with surrounding waters during its westward propagation from the shelf into the open. This hypothesis is further being corroborated by the calculation of mean water ages (using the transit time distribution – TTD – method) derived from transient tracer analysis (section 2.3). Mean water age in the core of the eddy ($\sigma_\theta = 26.35 \text{ kg m}^{-3} - 1000$) was found to be 39 ± 5 years, which matches very well mean water mass ages in the EBUS region on the same isopycnal (40 ± 5 ; (Tanhua and Liu, 2015)). Usually, waters on this isopycnal at CVOO are much younger (6 ± 1) due to subducted waters originating in the North Atlantic subtropical gyre. This finding supports the isolation

1 hypothesis as well as the assumed origin on the Mauritanian shelf of this particular eddy.
2 However, below the eddy core ($\sigma_\theta > \sim 26.6 \text{ kg m}^{-3} - 1000 \triangleq \sim 250 \text{ m}$) TS characteristics become
3 more variable and no indication for isolation is found. The upper bound of the eddy core is the
4 mixed layer base at a depth of 70 m which has the same magnitude as the mixed layer outside
5 the eddy (Karstensen et al., 2016, this special issue). A very sharp gradient exists between 70
6 – 77 m depth which amounts to 0.73 in salinity, 3.98°C in temperature and 165.8 $\mu\text{mol kg}^{-1}$
7 in dissolved oxygen.~~The upper bound of the eddy core is the mixed layer base, characterized~~
8 ~~by a very sharp gradient (between 70 – 77 m depth) in all parameters. The vertical contrast~~
9 ~~amounts to 0.73 in salinity, 3.98°C in temperature and 165.8 $\mu\text{mol kg}^{-1}$ in dissolved oxygen.~~
10 As expected from the satellite analysis of Schütte et al. (2015), the mixed layer temperature
11 ~~were was~~ found to differ significantly from outside-eddy conditions. Shipborne Sea Surface
12 Temperature (SST) Underway ~~measurements of temperature~~ recorded at 5 m depth during
13 M105 reveal colder temperatures within the eddy when compared to outside conditions. A full
14 description of the eddies' physical structure is given in (Karstensen et al., (2016).

15 **3.2 Oxygen and Nutrients**

16 Despite quasi-constant physical water mass properties over the course of the eddy's lifetime,
17 changes in biogeochemical variables are observed. ~~Continuing processes such as biological~~
18 ~~production in the euphotic zone and organic matter respiration within the low oxygen core as~~
19 ~~well as underneath drive significant changes in biogeochemical properties over time.~~ In
20 comparison to the reference profile from the Mauritanian Shelf, we find a maximum oxygen
21 decrease in the eddy core at a depth of (100 m) of about $57.0 \mu\text{mol kg}^{-1}$ to suboxic levels (< 5
22 $\mu\text{mol kg}^{-1}$; Figure 3). We expect the oxygen decrease from continuous respiration of the
23 organic material that sinks out of the euphotic zone into an environment that is at most only
24 ~~minimal~~ slightly affected by lateral ventilation ~~of the eddy waters~~. A more detailed
25 assessment of oxygen utilization is presented in section 3.5.

26 We observe elevated nutrient concentrations (nitrate, phosphate, silicate) inside the ACME
27 core which indicate the remineralization of organic matter (Figure 4). Nutrient data obtained
28 during the ISL survey showed also elevated concentrations for nitrate ($2.92 \mu\text{mol kg}^{-1}$), nitrite
29 ($0.08 \mu\text{mol kg}^{-1}$) and phosphate ($0.29 \mu\text{mol kg}^{-1}$) in the mixed layer of the eddy. In contrast,
30 silicate concentration remained low which could be explained by an enhanced abundance of
31 diatoms in the mixed layer. Furthermore, Fischer et al. (2016) reported on high opal
32 concentrations in sediment traps at CVOO, associated with the passage of a former ACME

1 passing the observatory. High N:Si uptake ratios, also reported for the North Atlantic (Koeve,
2 2004), could explain observed nutrient concentrations. Such—In general, elevated surface
3 nutrient concentrations are untypical for the oligotrophic waters of the open ETNA but can be
4 observed in the coastal upwelling region (Löscher et al., 2015). As such, this finding is
5 interpreted as being a signature of a vertical flux event related to submesoscale processes and
6 stratification, which on the one side isolate the core and prevent oxygen supply while in
7 parallel support vertical nutrient flux at the eddy rim (Karstensen et al., 2016).~~As such, we~~
8 ~~expect them to be a signature of a vertical flux event.~~ As these elevated surface concentrations
9 were not found during the M105 sampling we expect that the upwelling is intermittent and/or
10 maybe occurs only locally, confined to certain regions across the eddy. In any case, the
11 upwelled nutrients fuel surface production, which, in turn, draws down nutrient levels quickly
12 again. In an oligotrophic ocean setting, such an eddy with sporadic upwelling events creates a
13 ~~significant~~—strong anomaly when compared to ambient conditions. Consequences on carbon
14 cycling and sequestration are discussed in next sections in more detail.

15 **3.3 Carbonate System**

16 ~~By using the measured DIC and TA, the remaining two parameters of the marine carbon cycle~~
17 ~~(pH and $p\text{CO}_2$) as well as saturation levels for Aragonite (Ω_{Ar}) have been calculated following~~
18 ~~methods described in section 2.3.~~ In accordance with the oxygen decrease already discussed, a
19 clear respiration signal was also found in carbon parameters (Figure 5). Values for DIC (max.
20 $2258.8 \mu\text{mol kg}^{-1}$) and $p\text{CO}_2$ (max. $1163.9 \mu\text{atm}$) as well as for pH (min. 7.63) in the core of
21 the eddy deviate significantly from those observed in the reference profiles from the
22 Mauritanian Shelf region where the eddy was formed. Moreover, these values can be seen as
23 the highest or lowest end members for the open ETNA, respectively, thus creating an extreme
24 biogeochemical environment on the mesoscale. One parameter that illustrates this contrasting
25 environment very well is Ω_{Ar} which inside the eddy core dropped to 1.0 (i.e. the threshold
26 below which carbonate dissolution is thermodynamically favored; Figure 5). This value is
27 very much in contrast to the regional background conditions at CVOO₂ where $\Omega_{\text{Ar}}=1$ is found
28 below 2500 m depth and the typical Ω_{Ar} at 100 m depth is approx. 2.4.

29 The horizontal gradient of pH between inside and outside eddy conditions is up to 0.3 pH
30 units at a water depth of approx. 100 m. It is interesting to note that a pH of 7.63 is close to
31 values expected for future surface ocean conditions in the year 2100 (approx. pH of 7.8) as
32 predicted by models assuming a global high CO_2 emission scenario (Bopp et al., 2013).

1 Further, such low pH levels are used for example in artificial mesocosm experiments to
2 simulate these future conditions (~~REFERENCE!!!~~(Schulz et al., 2013)). Absolute values of
3 pH inside the eddy exceed these predictions and plankton communities inside shallow low-
4 oxygen the OMZ-cores of ACMEs may get-are exposed to these acidified conditions.
5 Vertically migrating zooplankton and nekton also encounter such a pronounced gradient
6 during migration (see Hauss et al., 2015).

7 Above the core, DIC concentrations in the surface mixed layer vary between the two eddy
8 surveys and CVOO. Slightly higher values were found during the ISL survey when compared
9 to the M105 survey. The same was found for nutrient concentrations (section 3.2), which
10 consistently points towards a very recent or even ongoing upwelling event encountered during
11 the ISL sampling. Episodic upwelling within ACMEs have been reported for other regions in
12 the past (McGillicuddy et al., 2007).

13 Below the eddy core at a depth of approx. 2500 m, the DIC anomaly disappears and
14 parameters fall back close to shelf background conditions (Figure 5).

15 A slightly different picture is found in profile data for TA. Here, only a ~~minor-small~~ change of
16 up to 17 $\mu\text{mol kg}^{-1}$ in TA inside the eddy core is found when compared to shelf conditions.
17 This was expected as respiration processes ~~have-may have~~ a positive or negative small-but
18 significant-effect on TA depending on the form of reactive nitrogen being released (Wolf-
19 Gladrow et al., 2007). However, the major difference at depth (increased values for TA inside
20 the core compared to shelf background) cannot be accounted for by respiration. One potential
21 reason for this pattern is calcium carbonate dissolution at depth. This explanation, however,
22 can be excluded since both Ω_{Ar} ~~are~~ is too high at these depths and aragonite dissolution would
23 also positively affect DIC concentrations (the increase of which can essentially be explained
24 by respiration). Thus, the more likely explanation is an intrusion of ambient NACW waters,
25 which, considering distinct TA-salinity relationships (Lee et al., 2006), would also affect TA
26 concentrations towards elevated levels. Indeed, vertical profiles for salinity (Figure 3) show
27 slightly higher salinity values beneath the eddy core. ~~Furthermore, TA salinity correlations~~
28 ~~show different patterns when comparing between the eddy core and underneath (data not~~
29 ~~shown) which also corroborates this interpretation.~~

1 3.4 Particles and Organic Matter

2 We used data from the UVP to illustrate vertical distribution of small particles (60 – 530 μm)
3 in the water column, which we assume to primarily consist of POM but may also contain
4 lithogenic material (Fischer et al., 2015). During both surveys, Particle-particle abundances
5 show a peak ~~at subsurface depth~~ within the shallow OMZ slightly below the oxygen
6 ~~minima observed during the ISL and M105 surveys~~ (Figure 6). This points at accumulated
7 particles fueling microbial respiration in the core of the eddy. Furthermore, surface
8 concentrations of particles ~~significantly~~ exceed open-ocean conditions as found at CVOO by a
9 factor of 2 to 3. This is in line with Löscher et al. (2015) who described a threefold higher
10 primary production for surface waters inside the eddy ~~as~~ compared to the outside. In the
11 Mauritanian shelf area particle concentrations are ~~much higher~~ throughout the water column
12 (Figure 6). Enhanced biological production as well as influence from nepheloid layers
13 (Fischer et al., 2009; Ohde et al., 2015) along the shelf edge most likely cause this high level
14 of particle abundance. According to Hauss et al. (2015) large aggregates (>500 μm equivalent
15 spherical diameter, UVP data) are 5-fold more abundant in the upper 600 m within the eddy
16 than in the usual open ocean situation in this region, suggesting a substantial increase in
17 export flux.

18 Discrete bottle samples for organic carbon (POC, DOC) and nitrogen (PON, DON) were
19 collected during the M105 survey only (Figure 6). Both POC and DOC concentrations are
20 elevated inside the eddy compared to concentrations found at CVOO. In particular, POC
21 shows a major peak in the surface mixed layer that exceeds not only concentrations at CVOO,
22 but also all other POC concentrations measured during the M105 cruise (including data
23 between Cape Verde and 7°N, data not shown). A similar picture was found for PON
24 concentrations. Again, these observations match very well with the findings by Löscher et al.,
25 (2015). Within the eddy core, only a very minor (positive) peak in POC (and PON) appears
26 which is located somewhat beneath the actual oxygen minimum of the core. Data below
27 250 m then matched well with background conditions again. Vertical profiles for DOC (and
28 DON) also show higher values in the surface as well as a distinct (positive) peak beneath the
29 oxygen minimum. In contrast to the particulate fraction, DOC (DON) concentrations at depth
30 exceed background conditions. The position of the small POM and the pronounced DOM
31 peaks beneath the actual oxygen minimum is confirmed by UVP particle data (one should
32 note that the depth of the UVP particle peak is slightly shallower than the associated discrete

1 sample). The obvious minimum in DOM exactly at the oxygen minimum (Figure 6) suggests
2 prolonged bacterial consumption of DOM at this depth. In other words, the drawdown of
3 POM and DOM by bacterial respiration can be already observed right beneath the
4 oxycline/mixed layer base at approx. 70 m depth and intensifies towards the core of the eddy
5 at approx. 98 m (during the M105 survey). Below the eddy core, along with POM and DOM
6 peaks, an accumulation of particles with low nucleic acids content was determined (Loginova,
7 pers. comm.). These particles might represent ruptured or dead bacterial cells. Therefore cell
8 mortality could induce a release of organic matter at this depth. However, the abrupt
9 accumulation of particulate matter (UVP profiles, and, to a lesser extent, discrete POM data)
10 and DOM somewhat beneath the core remains speculative so far.

11 **3.5 Oxygen Utilization & Carbon Export**

12 Based on the differences between the observed concentrations in the eddy and the reference
13 profiles in the Mauritanian upwelling region, the oxygen and DIC changes ~~and~~with
14 respective rates (section 2.4) were estimated (Figure 7). As outlined before, the data was
15 compared in density space in order to consider the large scale differences in the depth/density
16 relation that primarily reflects the difference in ocean dynamics (Figure 7, larger panels). As
17 outlined in section 2.4, the corresponding rates, presented here against depth (Figure 7,
18 smaller panel), were then calculated based on the estimated lifetime of the eddy (derived from
19 satellite data). Thus, examined rates represent mean rates over the lifetime of the eddy and do
20 not contain any information about their temporal evolution.

21 The dData show clear anomalies for all parameters within the eddy core which were most
22 pronounced at a depth of 98 m (M105) and 105 m (ISL),~~respectively~~. Rates for all parameters
23 are presented in Table 1. Below the eddy core, however, rates are vanishing and become
24 indistinguishable from the uncertainty introduced by the applied isopycnal approach. For
25 instance, the assumption of a well isolated water body holds true for the core of the eddy only,
26 but not necessarily for deeper parts of the eddy. Here, admixture of ambient waters becomes
27 more likely in agreement with the TS characteristic approaching the background signature
28 (Figure 2), which significantly alters water mass properties of this part of the eddy. As a
29 consequence of the non-isolation of the water underneath the core (below approx. 250 m)
30 rates can~~not~~ be derived using this approach and not further discussed. Similarly, rates can
31 also~~be~~ not be derived for the surface mixed layer where multiple processes modify the
32 parameter field (gas, heat and freshwater exchange).

1 The apparent oxygen utilization rate (aOUR) within the eddy peaks at $0.26 \mu\text{mol kg}^{-1} \text{d}^{-1}$
2 (M105 survey) in the oxygen minimum which corresponds to the $\sigma_{\theta} = 26.35$ isopycnal. This
3 aOUR is one of the highest values which have been reported so far for the ETNA. Karstensen
4 et al. (2008) derived large scale thermocline aOUR from transient tracer data and AOU values
5 and found a mean aOUR of $0.03 \mu\text{mol kg}^{-1} \text{d}^{-1}$ in the similar depth range (similar to other
6 estimates such as Jenkins 1982). However, from a low-oxygen CE a direct estimate based on
7 an Argo float that was trapped in an eddy revealed 3 to 5 times higher rates (Karstensen et al.,
8 2015). In the same study, an aOUR of $0.25 \mu\text{mol kg}^{-1} \text{d}^{-1}$ within another ACME was found
9 based on an approach similar to ours by comparing oxygen in the upwelling region with the
10 oxygen concentrations 7 months later. The smaller rates found in the cyclonic eddy might
11 indicate a less isolated core but could also be related to the steady mixed layer deepening in
12 the CE which may provide a diapycnal oxygen pathway. However, in summary aOUR within
13 | CEs₂ as well as ACMEs₂ significantly exceed typical rates in the ETNA.

14 Rate estimates for other biogeochemical parameters within the investigated ACME are also
15 exceptionally high (Table 1). We compared estimated rates with each other by looking at
16 stoichiometric ratios such as C:N, N:P and -O:C (data not shown). In fact, all ratios were
17 found to be close to, or not distinguishable from, the stoichiometry proposed by Redfield et al.
18 | (1963). This finding provides indication for a reliable assessment of biogeochemical rates₂
19 based on the assumptions that were made and on independent samples of multiple parameters
20 taken during two independent cruises.

21 The observed DIC increase rate within the eddy core can be referred to as the CRR resulting
22 from continued respiration of organic matter. As illustrated in Figure 5, the peak in DIC
23 coincides with the depth of the sharpest decrease of POM and DOM. This is to be expected,
24 as the CRR should equal the derivative of the vertical POC flux curve with respect to the
25 | depth. Following the approach of Jenkins (1982)₂, one can derive the vertical flux of POC
26 from aOUR or CRR values, respectively. Downward fluxes for POC can be seen as the major
27 export process of carbon out of the euphotic zone.

28 We used these CRRs within the eddy core for determination of the vertical POC flux at
29 different depths by means of a power law function (Martin et al., 1987b). Vertical integration
30 of the data between 100 m and 1000 m yielded estimates of the vertical POC flux at 100 m
31 during the ISL and M105 cruises of $0.19 (\pm 0.08)$ and $0.23 (\pm 0.15) \text{g C m}^{-2} \text{d}^{-1}$, respectively
32 | (Figure 8). These values are exceptionally high₂, both for the ETNA but also for other open-

1 ocean regions. Table 2 provides a brief overview of studies that determined POC fluxes at
2 different locations based on different methods. In the open ETNA, recently determined POC
3 fluxes at 100 m from floating sediment trap deployments (Wagner et al., pers. comm.) were
4 lower by a factor of approx. 3 than inside the ACME. Interestingly, the same authors revealed
5 POC fluxes at the Mauritanian shelf edge in the same magnitude as found inside the
6 investigated ACME. This supports the view that these ACMEs can be viewed as isolated,
7 westwards propagating upwelling systems as their own.

8 POC fluxes derived here generally show higher values than found in other open-ocean studies
9 but are comparable to values associated with a North Atlantic spring bloom event (Berelson,
10 2001). Moreover, POC fluxes for this ACME were also in line with estimates made for other
11 eddies, such as enhanced POC fluxes determined at the rim of a CE in the Western Pacific
12 (Shih et al., 2015) or inside a CE in the ETNA (Figure 8, derived from aOUR data in
13 Karstensen et al., 2015). In general, estimated POC fluxes for the surveyed ACME based on
14 the method described in section 2.5 may represent a rather conservative estimate as the aOUR
15 was derived based on the assumption of complete absence of vertical and horizontal
16 ventilation processes. Thus, any minor ventilation process affecting the eddy core would
17 cause our OURs and POC flux estimates to be biased low.

18 The corresponding b parameter of the Martin curve for the two ACME surveys are high (1.55
19 – 1.64, Figure 8) when compared with typical open-ocean values. High b values indicate steep
20 | and ~~thus~~therefore local flux attenuation in the upper layer which, in our case, could be
21 | explained by the vertical structure of the ACME with its well-isolated local core. Again, our
22 | findings for flux attenuation are comparable to those obtained during a North Atlantic bloom
23 | experiment (Berelson, 2001), but also to observations recently conducted in the North
24 | Atlantic subtropical gyre (Marsay et al., 2015). Controversial discussions in the scientific
25 | literature exist about different dependencies of the b parameter. For instance, Marsay et al.
26 | (2015) also compared POC flux determinations from four different sites in the North Atlantic
27 | with each other. They found a positive correlation between water temperature and the b
28 | parameter in the North Atlantic. Berelson (2001) proposed a linear relationship between the
29 | POC flux at 100 m and the b parameter which also matches with our data. In contrast, a few
30 | studies also suggest a dependency between the b -parameter and ambient oxygen
31 | concentrations with lower b -values found in low oxygen environments (Devol and Hartnett,
32 | 2001; Van Mooy et al., 2002). However, ~~Our~~ data do not reflect this relationship, ~~most likely~~

1 ~~due to physical processes inside the eddy such as local upwelling and redistribution of~~
2 ~~particulate matter which may alter the shape of the downward POC flux.~~ Since we are lacking
3 direct flux measurements and only had ~~ve~~ a very limited number of observations we ~~are~~ were
4 not able to appropriately de-convolve drivers of the derived POC flux attenuation profile
5 inside this ACME.

7 **4 Conclusions**

8 We performed two biogeochemical surveys within an ACME in the open ETNA off West
9 Africa near the CVOO time-series site. The core of this mesoscale eddy was found to host an
10 extreme biogeochemical environment just beneath the surface mixed layer. The concentration
11 of oxygen had dropped to suboxic levels (< 5 $\mu\text{mol kg}^{-1}$) as a consequence of severely
12 hindered vertical and horizontal ventilation of the core, along with continuing
13 remineralization during the eddy's lifetime. There is evidence that moderately elevated
14 nutrient concentrations in the top layer of the ACME are caused by ~~(episodic)~~ upwelling
15 events and fuel an enhanced surface primary productivity that moves with the ACME.
16 Likewise, nutrient concentrations as well as $p\text{CO}_2$ levels showed an ~~intense~~ large increase
17 within the eddy core, which created significant anomalies when compared to ambient open-
18 ocean ETNA conditions. Values of pH, for instance, indicate highly acidified waters (pH of
19 7.6) at the lower edge of the euphotic zone which corresponds to Ω_{Ar} values of 1. Particle
20 concentrations in the surface layer were found to exceed ambient waters up to three times,
21 which is in line with enhanced productivity in the surface layer (Löscher et al., 2015). The
22 core of the eddy was found to be degraded in DOM pointing towards enhanced bacterial
23 consumption of DOM. An accumulation of DOM was found closely below the O_2 minimum
24 most likely caused by a release of DOM from dead cells.

25 We also investigated magnitudes of biogeochemical processes occurring within the eddy
26 during its westward propagation, such as apparent oxygen utilization and carbon
27 remineralization, by comparing our survey data with conditions prevailing during the
28 ACME's initial state (Mauritanian shelf). Results showed mean aOURs over the lifetime of
29 the ACME that exceed typical rates in the open-ocean ETNA by an order of magnitude
30 (Karstensen et al., 2008). Resulting POC fluxes inside the ACME was also found to exceed
31 background fluxes in the oligotrophic ETNA by a factor of two to three, ~~and thus are therefore~~
32 comparable to meso- and eutrophic regions such as the Mauritanian upwelling region or the

1 subpolar North Atlantic spring bloom. This finding is also in line with a three-fold enhanced
2 primary productivity in the same ACME's surface layer derived from Löscher et al. (2015)
3 based on seawater incubations. Our results confirm that ACMEs in the ETNA can be seen as
4 open-ocean outposts that clearly exhibit their origin in the EBUS but through their continued
5 biogeochemical activity at the same time represent alien biogeochemical environments in a
6 subtropical ocean setting. As revealed by Schütte et al. (2016) these ACMEs appear to play a
7 small but significant role in maintaining the shallow OMZ in the ETNA.

8 The results of this study, however, are based on two independent surveys carried out at a
9 certain point of time in the lifetime of the ACME. ~~Thus, we~~We are not able to address
10 questions about the evolution and (non-) linearity of processes within the ACME throughout
11 its lifetime. Therefore, future surveys should resolve not only spatial structure but also
12 temporal evolution of biogeochemical processes at different life stages of these eddies.

13 In addition to this biogeochemical investigation, two other studies have documented the
14 impacts of this low-oxygen ACME on zooplankton and microbial communities (Hausse et al.,
15 2015; Löscher et al., 2015). There is empirical indication that future scenarios such as
16 deoxygenation and ocean acidification can also affect higher trophic species (Munday et al.,
17 2010; Stramma et al., 2012). Any possible influence of this ACME on higher trophic levels,
18 however, remains unknown and would require a different observational approach. The
19 discovered anomalies within this eddy can be seen as a large (50-100 km diameter) and
20 relatively long-lived (~1 year) mesocosm featuring the development of low-oxygen and low-
21 pH conditions in a completely unmanipulated natural environment. Hence, investigating the
22 full range of this mesocosm-ecosystem will provide useful data and may help to better
23 understand ecosystem responses to future ocean conditions.

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1 | Table 1 Overview of detected concentration anomalies (Δ_{total}) within the ACME core
2 | ($\sigma_{\theta} = 26.35 \text{ kg m}^{-3} - 1000$) during the two surveys referenced against prevailing conditions at
3 | the shelf. Rate estimates are based on the lifetime of the ACME derived from satellite sea
4 | level anomaly data (ISL: 163 days, M105: 173 days). Values for the average shelf profile are
5 | given in order to illustrate local variability at the corresponding isopycnal ($=26.35 \text{ kg m}^{-3} -$
6 | 1000). Negative values correspond to a decrease of the respective parameter over the lifetime
7 | of the ACME.

	ISL		M105		Shelf	
	05 – 07 March 14		17-18 March 14		June / July	
	Δ_{total} (unit)	Rate (unit d ⁻¹)	Δ_{total} (unit)	Rate (unit d ⁻¹)	Mean (unit)	SD (unit)
Salinity (psu)	-0.082	< 0.004	-0.054	< 0.002	35.588	0.124
Temp. (°C)	-0.280	-0.002	-0.184	-0.001	15.353	0.415
O ₂ (μmol kg ⁻¹)	-35.56	-0.22	-44.42	-0.26	48.95	8.88
NO ₃ ⁻ (μmol kg ⁻¹)	3.48	0.02	5.02	0.03	25.77	1.62
NO ₂ ⁻ (μmol kg ⁻¹)	-0.08	< -0.001	< -0.01	< 0.001	0.09	0.11
PO ₄ ³⁻ (μmol kg ⁻¹)	0.29	< 0.01	0.34	< 0.01	1.60	0.14
SIO ₂ (μmol kg ⁻¹)	2.05	0.01	2.52	0.01	6.73	1.27
DIC (μmol kg ⁻¹)	35.1	0.2	39.8	0.2	2218.7	1.4
TA (μmol kg ⁻¹)	-10.8	< 0.1	-12.3	< 0.1	2331.5	7.5
pCO ₂ μatm	268.68	1.65	332.67	1.92	827.93	28.15
pH	-0.12	< -0.01	-0.14	< -0.01	7.77	0.01
Ω _{Ar}	-0.38	< -0.01	-0.43	< -0.01	1.48	0.08

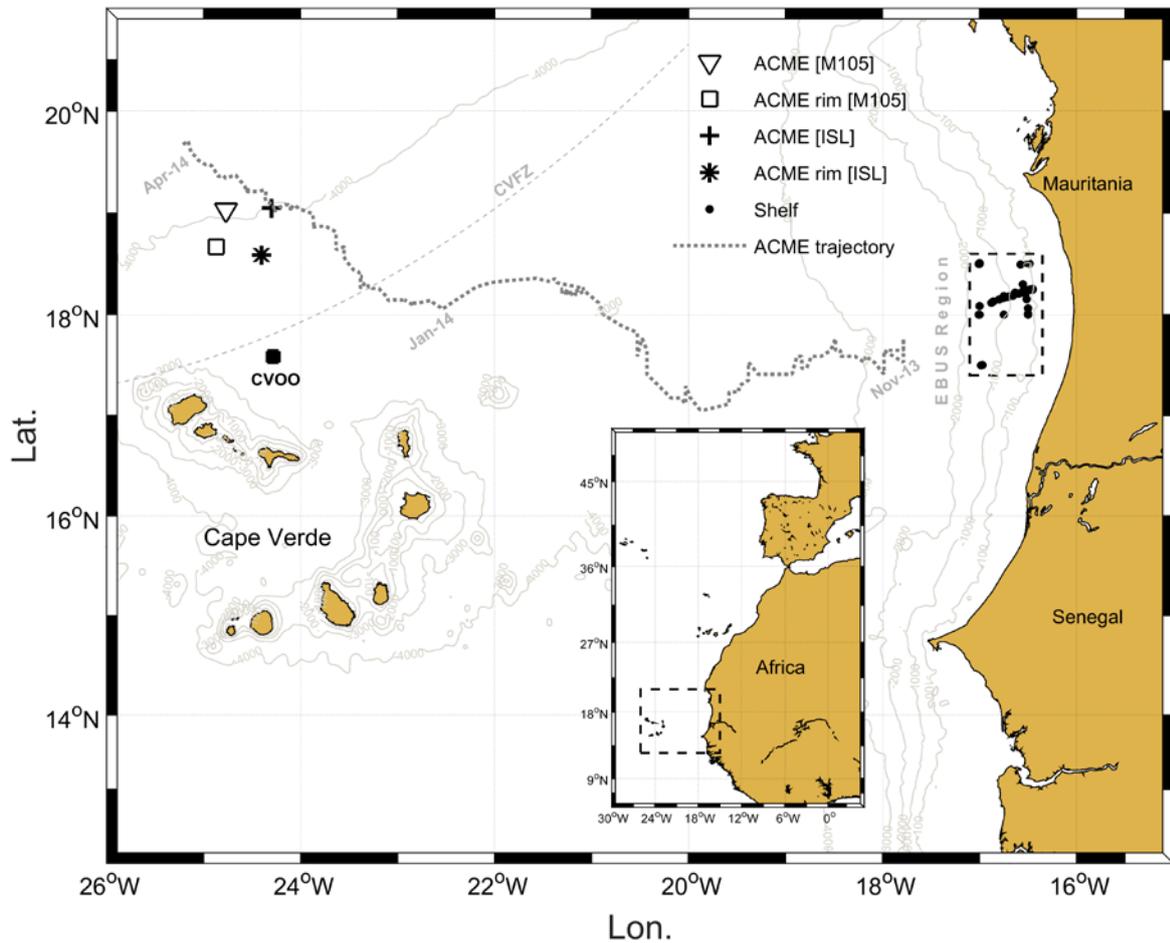
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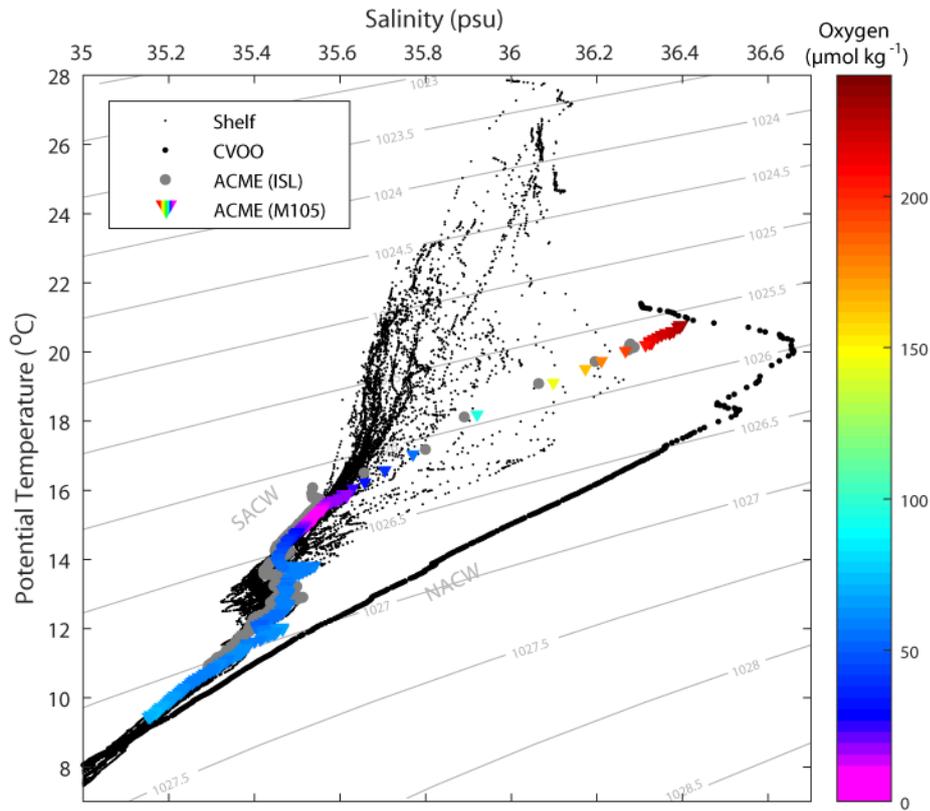
1 Table 2 Comparison of F_{100} values from the literature representing different ocean
 2 regions with the results of this study.

Region	F_{100} (g C m⁻² d⁻¹)	Method	Reference
ETNA (ACME)	0.19 – 0.23	aOUR	this study
ETNA (CE)	0.24	aOUR	this study (data from Karstensen et al. 2015)
West Pacific (CE)	0.13 – 0.19	Trap	Shih et al. 2015
ETNA (open ocean)	0.11	aOUR	Karstensen et al. 2008
N. Atl. (bloom)	0.29	Thorium, Trap	Berelson 2001
Arab. Sea	0.03 – 0.11	Thorium	Lee et al. 1998
N. Pac. Gyre (HOT)	0.03	Trap	Buesseler et al. 2007
N. Pac. (K2)	0.03 – 0.08	Trap	Buesseler et al. 2007
N. Atl. (Gyre)	0.02	Trap	Marsay et al. 2015
N. Atl. (Gyre)	0.15	aOUR	Jenkins 1982
NE Pac.	0.05	Trap	Martin et al. 1987b

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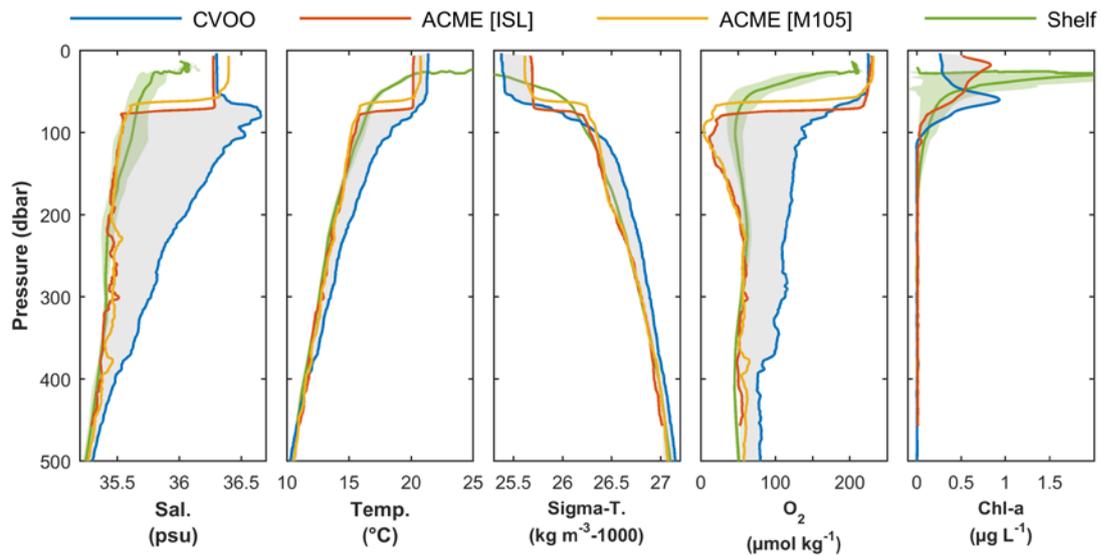


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 2 Figure 1 Map of the study area between the Mauritanian coast and the Cape Verde
 3 Archipelago. The ACME trajectory (dotted line) is based on satellite sea level anomaly data
 4 and starts off the Mauritanian shelf edge in Sept. 2013. In March 2014, the ACME was
 5 surveyed twice north of Cape Verde with two different research vessels: RV Islândia (ISL)
 6 and RV Meteor (M105). The area marked on the Mauritanian shelf (dashed line) represents
 7 the area where the ACME was most likely created and which serves as a reference for initial
 8 conditions within the eddy.



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 2 Figure 2 Temperature-Salinity (TS) diagram containing data from both eddy surveys
 3 (colored triangles and gray dots), the nearby CVOO station (large black dots) and
 4 accumulated CTD hydrocast data from multiple surveys on the shelf (small black dots).
 5 Dashed gray lines indicate typical Branches of NACW and SACW water masses signatures
 6 after Tomczak (1981) were labeled according to (Schütte et al., 2016b).

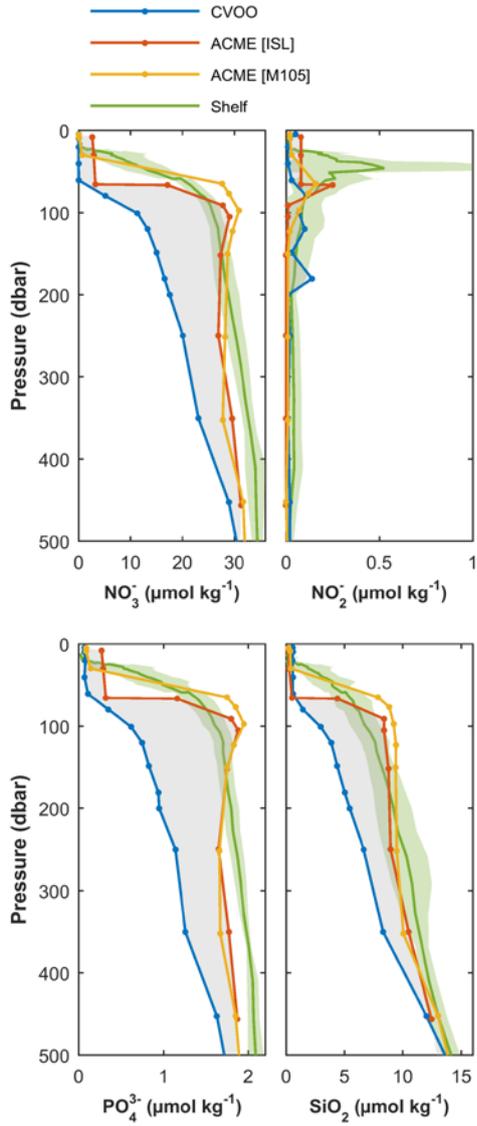
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 2 Figure 3 Vertical profiles for all parameters measured from sensors mounted on CTD rosette
 3 systems. Data from the nearby CVOO station (blue) represent local background conditions,
 4 the gray area emphasizes the local anomaly against the background introduced by the ACME
 5 (yellow and red) and the green curve represents mean initial conditions of the ACME at the
 6 shelf (light green indicates standard deviation of the mean profile). Note that not all surveys
 7 were carried out with the same sensor package.

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3 Figure 4 Discrete bottle data for nutrients from the different ACME surveys. The grey
4 shading illustrates the anomaly of the ACME (ISL) with respect to the regional background
5 situation (CVOO).

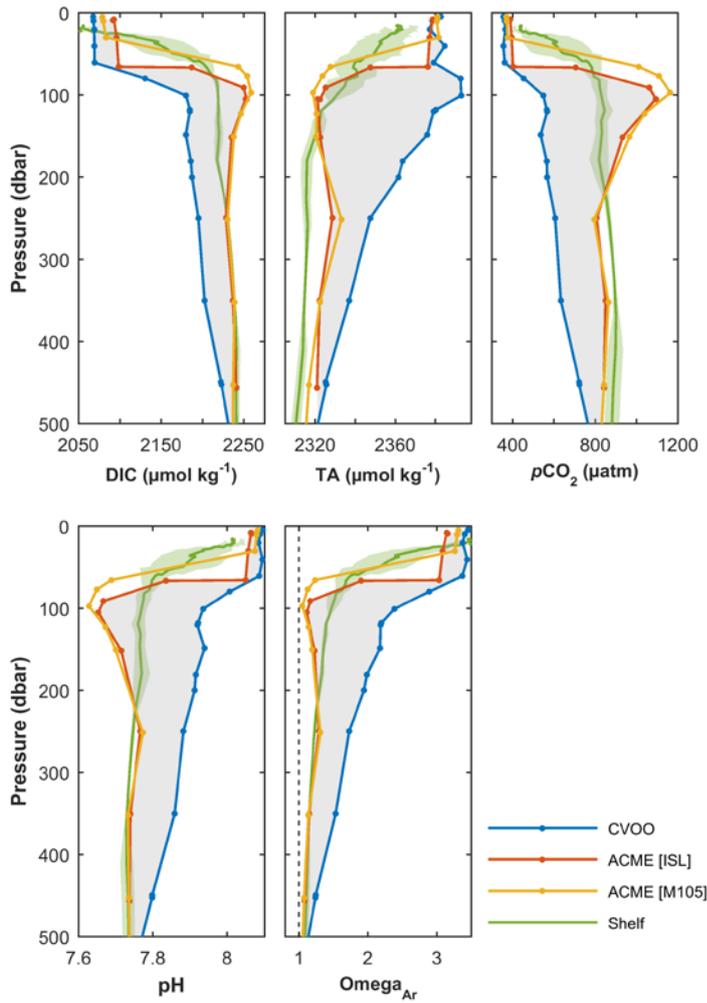
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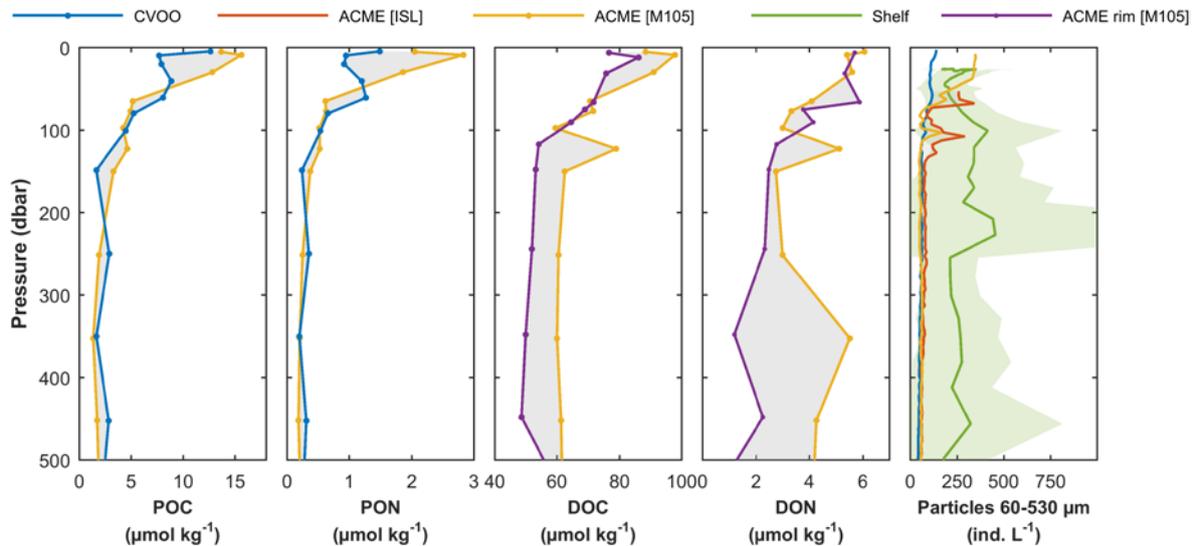
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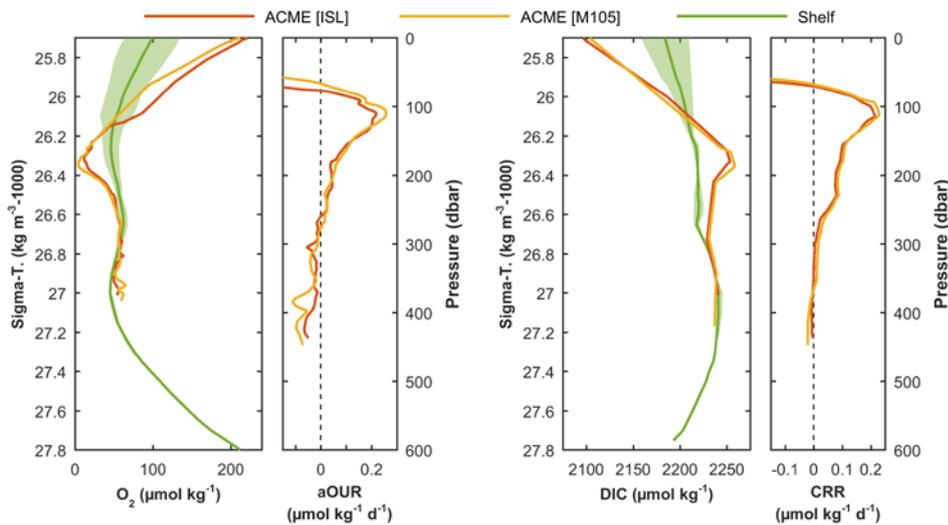
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Figure 5 Discrete bottle data for DIC and TA and calculated parameters of the carbonate system (pH, $p\text{CO}_2$ and Ω_{Ar}) from the different ACME surveys. The grey shading illustrates the anomaly of the ACME (ISL) with respect to the regional background situation (CVOO).



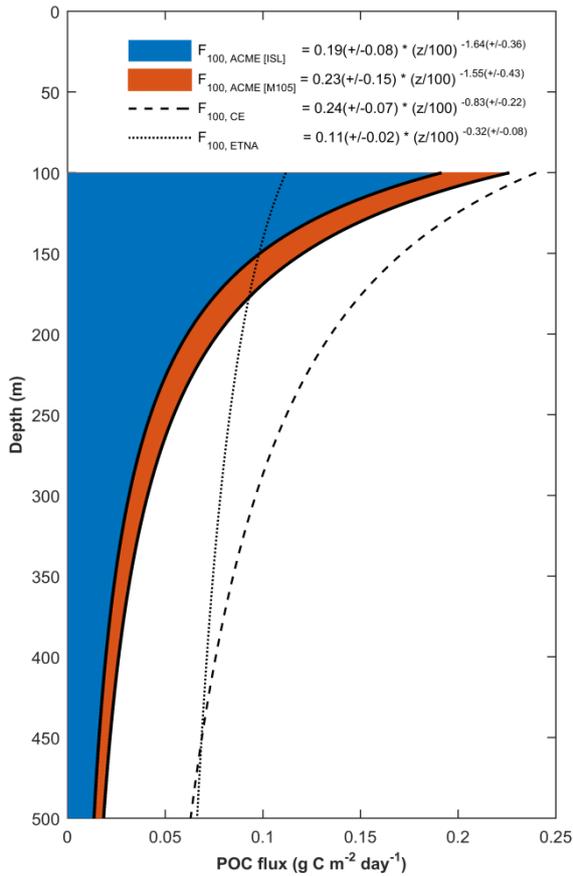
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 2 Figure 6 Vertical Distribution of particulate and dissolved organic matter (first 4 panels)
 3 based on discrete samples and particle density (60 – 530 µm) derived from high resolution
 4 UVP data (right panel). Note that no data at CVOO exist for DOC and DON, hence data from
 5 the eddy rim station is shown.

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 8 Figure 7 Estimated biogeochemical rates within the ACME as derived along isopycnals
 9 between the shelf (green) and the ACME at the time of the two surveys (red, yellow). This
 10 approach is illustrated for oxygen and DIC profile data (large panels). Corresponding aOUR
 11 and CRR are peaking in the core of the ACME (small panels). Note that the matching
 12 between shelf and ACME data was made in density space whereas the resulting rates are
 13 plotted in depth space.

1



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3 Figure 8 Derived downward POC fluxes based on a model after Martin et al. (1987b) for
4 the two ACME surveys (blue and red), a cyclonic eddy sampled by an Argo float (CE, dashed
5 line; Karstensen et al., 2015) and the general ETNA (Karstensen et al., 2008). Flux estimates
6 for the two ACME surveys are based on CRRs estimated from DIC sample data. For the CE,
7 aOURs derived from oxygen measurements on an Argo float were converted to CRRs by
8 applying a stoichiometric $-O_2:C$ ratio of 1.34 (Körtzinger et al., 2001b). Background POC
9 flux in the ETNA was estimated from large scale thermocline aOURs derived from transient
10 tracer data and AOU (Karstensen et al., 2008) followed by a stoichiometric conversion as
11 described above.