# Detailed response to reviewers comments

## Anonymous Referee #2

This article shows recent evidences of very low oxygen concentrations in the eastern tropical North Atlantic. The authors try to link these low levels of oxygen to mesoscale eddies but it is not very clear the message they really want to convey.

I consider this manuscript fits well within the scope of Biogeosciences. It deserves to be published after minor review once the relationship between the oxygen concentrations with mesoscale eddies is properly discussed including some hypothesis of potential mechanisms that may explain this connection.

We thank the reviewer#2 for the encouraging but also the critical words. We have revised our text and hope that the relationship between productivity in isolated eddies and oxygen consumption is now better accessible, including our hypothesis on the potential mechanisms behind it. We decided to combine the results and discussion into one paragraph that now connects the different pieces much better.

My specific comments are presented below:

1. Abstract: 'high productive cyclonic and anticyclonic-modewater eddies': this is not very clear to me. Not all eddies are productive,. . .. The impact of mesoscale eddies on biology is quite complex and should not be oversimplified. I refer the authors to some recent literature (see a non-exhaustive list at the end of the review).

We completely agree that the impact of mesoscale eddies on biology is quite complex – as such we reformulated the abstract and added further details about our hypothesis of isolation the resulting efficiency in net respiration in Paragraph 3.4. Moreover, we added a more comprehensive introduction on physical/biogeochemical interaction on the mesoscale. Thank you for suggesting the literature, which partly is included now.

*In particular we added:*
*A key process in the context of productivity is the vertical transport of nutrients into the euphotic zone. Different processes, operating on the sub-mesoscale, have been identified to be responsible for intense vertical velocities within eddies. However, the exact details are a topic that is under debate since more than a decade (see Klein and Lapeyre, 2009; Lévy et al., 2012; Gaube et al., 2014; Pascual et al., 2015, for further references). Also the trapping of surface waters by eddies should play a role (d'Ovidio et al., 2013). The data at hand does not allow to conclude on nutrient pathways within eddies nor can we estimate productivity. However, a bulk estimate for the vertical velocity across the eddies can be done, making use of an approach based on wind stress variations generated by wind/surface current shear (Martin and Richards, 2001; McGillicuddy et al., 2007; Pascual et al., 2015). In brief, on one side of the eddy, where the wind blows against the eddy rotation, the wind stress is elevated while the contrary happens at the opposite side. The resulting wind stress curl drive an Ekman flux divergence, which in turn is compensated by an upwelling in the case of anticyclonic surface*

*eddy rotation (McGillicuddy et al., 2007). Using typical wind (10 m s−1) and current speed (0.5 m s−1) across an eddy with diameter of 130 km (as observed for the CVOO2010 and CVOO2007 eddy), we estimate an upwelling of about 9 mmonth−1 corresponding to 65m over the 7 month – the time it takes the eddies to propagate from the formation region, off West Africa, to the CVOO site. However, controversy exists about the validity of this concept (Mahadevan et al., 2008; Eden and Dietze, 2009).*

2. Section 2.1: I have to admit that my background on oxygen concentrations in the Atlantic is limited but I think that there are some missing details in the paper that should be included. For example, please show in a figure the calibration between point observations and optode.

Probably the most important point is that, until our observation, minimal oxygen concentrations for the North Atlantic were only little below 40 microlmol per (GRL Stramma et al. 2008). We hope that the revised text makes this information more readily available.

*Relevant text:*
*The pelagic zones of the eastern tropical North Atlantic OMZ are considered to be "hypoxic", with minimal DO of hardly below 40 μmol kg−1 (Stramma et al., 2009; Karstensen et al., 2008). As such it is assumed that the DO levels pose on the regional ecosystem some limitation in biodiversity, primarily through avoidance and maybe an increased mortality (Vaquer-Sunyer and Duarte, 2008). The region is thus very much in contrast to the major OMZs in the eastern North and South Pacific Ocean and the northern Indian Ocean where DO concentrations pass all DO thresholds outlined above, and as such specifically adapted ecosystems must exists.*

We also re-wrote the sections on the oxygen calibrations procedures. As outlined in the text, the calibration of the moored optode is a multiple step process consisting of a "lab calibration" (zero oxygen forced water) and a calibration mounting the optode on a CTD, a single figure, as suggested ("…calibration between point observations and optode…") cannot be made. More details about the procedure can be found in Hahn et al. 2014 (now added as a citation).

*Text reads now:*
*For the first two deployments (period July 2006 to October 2009) we followed the recommendation of the manufacturer and did a calibration against zero oxygen concentration, by submerging the optodes into a sodium sulphite solution, and against saturated waters. For the following periods a more advanced technique was used, based on a number of calibration points at different temperatures and oxygen concentrations (Hahn et al., 2014). In brief, one set of calibration values were obtained from a comparison of oxygen data from an optopde attached to a CTD rosette and the accompanying CTD oxygen sensor (Sea-Bird Electronics 43 Clark electrode) calibrated itself using the Winkler titration method. This comparison was done by keeping the CTD over several minutes at a certain depth where a weak vertical oxygen gradient was seen. This procedure was done before and after the deployment of the respective optodes. In this way we obtained for each optode > 15 independent calibration points. In addition, a lab calibration at zero oxygen was done. All calibration points were used to derive a final calibration equation for one deployment of one certain optode. The chemically forced (and thus more precise) zero oxygen calibration was*

*weighted three times higher than the CTD/oxygen cast reference values. The difference between calibration point observations and calibrated optode suggests an overall rms error of 3µmolkg−1. Comparison of the chemically forced zero oxygen phase data and the phase readings at low oxygen concentrations suggests a higher accuracy at low DO concentrations of about 1 µmol kg−1. Pressure and salinity variability was corrected according to the AADI manual.*

3. Section 2.3: SLA acronym is not defined before. Certain points are omitted in this description. It should be mentioned what SLA product is used. Delayed time or real time? How many satellites are merged? What is the length of the time series? The eddy detection and tracking method depends of various parameters. I suggest to perform a sensitivity analysis to those parameters as well as the comparison to other methods (e.g. Chelton et al. 2011 –already cited in article- ; Halo et al. 2013; Nencioli et al. 2011).

Sorry for using an abbreviation before its proper introduction – this has been corrected now. We also added more details about the SLA data that we used in our study.

*Text reads now:*
*The delayed-time references product of merged sea-level anomaly (SLA) data (Version 2010) provided by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic) was used for tracking of the three eddies under discussion. The SSALTO/DUACS project constructs a merged satellite product projected on a 1/3 deg horizontal resolution Mercator grid every 7 days (e.g. Pascual et al., 2006, and references therein).*

Regarding methods, sensitivities, length of time series etc. it should be kept in mind that we are essentially talking about the tracking of three (3) eddies. For the three eddies we exactly knew for a certain period of time the position/time pair - as such it was simple to identify a single associated SLA on the respective SLA map associated with one of our eddies. This is not a very complex task and can be done even by eye (which we did when we started the work). However, at one stage we used automatic detection and the algorithm we used confirmed the findings obtained by visual tracking of the three eddies (shown in figure 1). Further explanations have been added to the text.

*Text reads now:*
*Initially we tracked the three eddies under discussion visually, by inspecting individual SLA maps. This was possible as we knew from the in-situ observations (mooring, float) the exact time and location of the appearance of a low DO eddies. By looking up subsequent SLA maps, the displacement of an identified SLA associated that was associated with the three eddies was charted and eddy tracks were constructed for the period before and after the in-situ observation (Fig. 1).*
*However, in addition we used an automatic detecting and tracking algorithm, based on the Okubo–Weiß method (Okubo, 1970). The method is robust and widely used to detect mesoscale eddies in satellite data as well as on numerical model output (Chelton et al., 2007; Sangrà et al., 2009; Souza et al., 2011). In brief, the method is based on quantifying the contribution of relative vorticity on the strain tensor, and an eddy is defined as a region of*

*negative W (vorticity dominates over strain) surrounded by a region of positive W (strain dominates over vorticity). One has to choose a threshold W0 and we used* $W0 = -2 \times 10^{-12}\ s^{-2}$ *for our eddy detection limit. Tracking was done by following the centre of individual W0 areas in SLA maps from 1 week (maximum 10 km) up to 3 weeks (maximum distance 60km). The automatic detection reproduced well the tracking that was obtained by the visual inspection method.*

4. Page 6: 'Anticyclonic . . ..': the authors should discuss about the potential governing processes that may explain the impact of anticyclonic modewater eddies on primary productivity.

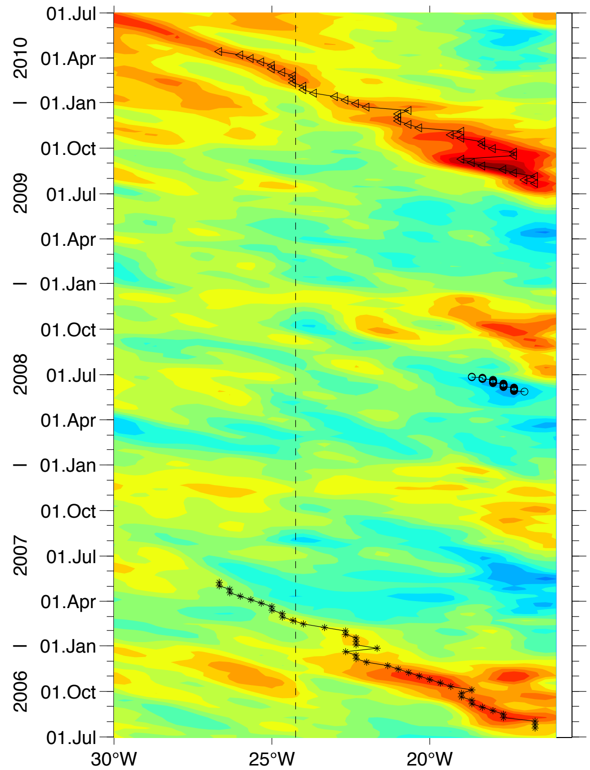
The basic idea and an estimate of the bulk vertical velocity using the apparently most frequently used concept (e.g. Martin and Richards 2001) is now added to the text. Moreover, we give an example for the possible mean upwelling in a dead-zone eddy based on this concept. However, it should be kept in mind that our observational data is insufficient to directly verify the upwelling or the associated transport pathways.

*Text reads now:*
*A key process in the context of productivity is the vertical transport of nutrients into the euphotic zone. Different processes, operating on the sub-mesoscale, have been identified to be responsible for intense vertical velocities within eddies. However, the exact details are a topic that is under debate since more than a decade (see Klein and Lapeyre, 2009; Lévy et al., 2012; Gaube et al., 2014; Pascual et al., 2015, for further references). The data at hand does not allow to conclude on nutrient pathways within eddies nor can we estimate productivity. However, a bulk estimate for the vertical velocity across the eddies can be done, making use of an approach based on wind stress variations generated by wind/surface current shear (Martin and Richards, 2001; McGillicuddy et al., 2007; Pascual et al., 2015). In brief, on one side of the eddy, where the wind blows against the eddy rotation, the wind stress is elevated while the contrary happens at the opposite side. The resulting wind stress curl drive an Ekman flux divergence, which in turn is compensated by an upwelling in the case of anticyclonic surface eddy rotation (McGillicuddy et al., 2007). Using typical wind (10* $m\ s^{-1}$*) and current speed (0.5* $m\ s^{-1}$*) across an eddy with diameter of 130 km (as observed for the CVOO2010 and CVOO2007 eddy), we estimate an upwelling of about 9* $m\,month^{-1}$ *corresponding to 65m over the 7 month – the time it takes the eddies to propagate from the formation region, off West Africa, to the CVOO site. However, controversy exists about the validity of this concept (Mahadevan et al., 2008; Eden and Dietze, 2009).*

5. Page 7: the amplitude of the eddy is rather low, almost at the limit of altimetry accuracy. I suggest showing a few maps of SLA to double check if this feature can be considered as an eddy or not. Have the authors compared the output of their eddy tracking code with the equivalent provided at http://cioss.coas.oregonstate.edu/eddies/?

This point is related to the referee comments point 3. Presumably it is resolved by making clear that we are talking about tracking of three eddies only. The three eddies where in-situ observational data is available – from the situ data we exactly knew that eddies existed but also we knew details about the dynamical character of the eddies (cyclonic or anticyclonic-modewater). The global eddy tracking presented on the website mentioned specifically tailored for global statistics and should cover a wide range of dynamical regimes. Apparently the algorithms are not optimal for eastern boundary regimes, as have been shown in recent papers (e.g. Capet al. 2014 and references therein). However, as said before, we are dealing only with a few eddies and could also simply inspect the SLA maps by eye and track the eddies in this way.

The hovmöller diagram along 18°N show the tracks

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6. Page 8: ‘geostrophic currents reflect only 10 to 20 %’. . .. I guess this is due to the smoothing that is applied to the altimeter maps and also to its low resolution. It could be useful looking at the formal error maps given by AVISO (I suppose the authors use this data provider), which may give some insights on the coverage of altimeter tracks in the area and period of study.

What is shown in Figure 3c (which is now Figure 3b as we added the temperature structure as requested by Reviewer 1) is the meridional flow where the upper part (approx. above 100 m) comes from direct observations of the flow using an acoustic current profiler and the part underneath is the geostrophic velocity derived from the density field and referenced to the observed currents at 75 m depth.
When using for the geostrophic flow instead of the ADCP current a layer of no motion at 1400m depth we get maximum swirl velocities of 20 cm/s (as such about half of the direct observations) but still located at about 70m depth.

The only point we wanted to make here is that the surface geostrophic current from SLA does not necessarily reflect the maximum swirl speed – which is of relevance when estimating the non-linearity (via an alpha) and as such the isolation.

*The text reads now:*
*The SLA across the eddy radius was rather weak, with an amplitude of only 1.5 (±1.5) cm (negative for the cyclone, positive for the anticyclones). Such a SLA anomaly translates to*

*maximum geostrophic surface currents of about 0.05–0.10ms−1, which is slow when compared with global eddies characteristics (Chelton et al., 2011; Risien and Chelton, 2008). However, this is not too much of a surprise as we knew, at least for the CVOO2007 and CVOO2010 eddies, from the in-situ velocity data that the maximum velocity was at subsurface, at about 70 m depth, and velocity rapidly decreased towards the surface (Fig. 3b). As such the maximum in SLA-derived surface geostrophic flow is only 10–20 % of the interior maximal swirl velocity directly observed with an Acoustic Doppler Current profiler (ADCP). We also used the density field derived from moored sensors and calculated a geostrophic velocity under the assumption of a layer of no motion at 1400m. This approach resampled the velocity structure fairly well and in particular the subsurface swirl velocity maximum at about 70 m depth.*

7. Page 8, first paragraph: In my opinion, this is a naive interpretation of the role played by eddies on oceanic productivity. Horizontal advection and trapping are relevant mechanisms for explaining those centers of maximum chlorophyll. Indeed, eddies may effectively redistribute phytoplankton horizontally, as they can transport properties in their cores for long periods of time (D'Ovidio et al., 2013, Capet et al., 2014). Other mechanisms such as internal dynamics (explained at a first order by Quasi-geostrophic approximation), and for instance Ekman pumping may contribute.

We have been adding a more comprehensive introduction on the potential mechanisms that contribute to the productivity in mesoscale eddies – making use of some of the suggested literature (and others). Unfortunately we cannot say much about productivity for our eddies, as we do not have the data at hand (except for a few Chl-a maps from ocean color).

*The text reads now:*
*A key process in the context of productivity is the vertical transport of nutrients into the euphotic zone. Different processes, operating on the sub-mesoscale, have been identified to be responsible for intense vertical velocities within eddies. However, the exact details are a topic that is under debate since more than a decade (see Klein and Lapeyre, 2009; Lévy et al., 2012; Gaube et al., 2014; Pascual et al., 2015, for further references). Also the trapping of surface waters by eddies should play a role (d'Ovidio et al., 2013). The data at hand does not allow to conclude on nutrient pathways within eddies nor can we estimate productivity. However, a bulk estimate for the vertical velocity across the eddies can be done, making use of an approach based on wind stress variations generated by wind/surface current shear (Martin and Richards, 2001; McGillicuddy et al., 2007; Pascual et al., 2015). In brief, on one side of the eddy, where the wind blows against the eddy rotation, the wind stress is elevated while the contrary happens at the opposite side. The resulting wind stress curl drive an Ekman flux divergence, which in turn is compensated by an upwelling in the case of anticyclonic surface eddy rotation (McGillicuddy et al., 2007). Using typical wind (10 m s−1) and current speed (0.5 m s−1) across an eddy with diameter of 130 km (as observed for the CVOO2010 and CVOO2007 eddy), we estimate an upwelling of about 9 mmonth−1 corresponding to 65m over the 7 month – the time it takes the eddies to propagate from the formation region, off West Africa, to the CVOO site. However, controversy exists about the validity of this concept (Mahadevan et al., 2008; Eden and Dietze, 2009).*

8. Page 8, 'proper reference velocity': this is not clear to me. Does it refer to the reference level needed to compute dynamic height? Please rephrase.

The problem is that we are not able to estimate in full the non-linearity parameter for the cyclonic eddy as we do not have direct velocity data available (as in the case of the two anticyclonic modewater eddies observed at the CVOO mooring). Moreover, this float was only profiling to 400m depth so no deep reference level (level of no motion) was available. However, we describe the vertical flow structure (should be independent from a reference level) and discuss it in relation to alpha.

*The text now reads:*
*For the Argo2008 survey of the cyclonic eddy no direct swirl velocity observation exists and as such α cannot be calculated. However, we used float profiles recorded before and after the float entered (May/June 2008) and left (March/April 2009) the eddy, and observed a fundamental change in the velocity shear profile – from a rotation with nearly constant velocity from just below the mixed-layer (30 m) to 400m depth (maximum observation depth) at the beginning of the survey to a profile with a distinct peak in swirl velocity at about 110 m depth at the end of the float survey. Such a change in the flow structure indicate that the maximum α moved to deeper levels. We can only speculate that this vertical movement of maximum α and associated local decrease of α allowed surrounding waters to enter the eddy core and ended the isolation (Fig. 4).*

9. Page 10, Discussion: 'While methods for . . . well established': I do not completely agree as there are important disparities between the outputs of different eddy trackers (e.g. Souza et al. 2011); 'details on vertical stratification'... some recent papers explore this issue (Zhang et al. 2013; Capet et al. 2014). 'Nevertheless, ... with floats': this sentence is not well formulated. Please rephrase.

This section is now move to the Conclusion section and reformulated. The statement about the methods is removed, our intention was to highlight the technical /observing system limitations to comprehensively detect and quantify the dead zone eddies.

*Text reads now:*
*In order to detect dead zone eddies from space, via SLA data, concurrent in-situ observations of the vertical structure of the water column is required. A combination of Argo float data and SLA data is a promising technique that have been already applied regionally (Southeast Pacific; Chaigneau et al., 2009) and globally (Zhang et al., 2013) but without a focus on detecting anticyclonic-modewater eddies or water mass anomalies in general. We did a preliminary analysis for the North Atlantic OMZ region, using SLA data and Argo float data, that revealed about 10% of the anticyclones are anticyclonic - modewater eddies (Florian Schütte, personal communication). However, still information about the oxygen distribution would be required to quantify the impact of the dead zone eddies on the large scale oxygen budget.*

10. Page 11, Conclusions: internal dynamics governed by QG dynamics might also be relevant and can have an impact on primary production (e.g. Pascual et al. 2015)

We rephrased the whole discussion on productivity, also adding the suggested reference in the Results and Discussion section (see also our response to point 7). Moreover, the conclusion section the point raised here is addressed in:

*High respiration rates were also found in anticyclonic-modewater eddies, but from measurements at one single depth only. From the few observations available, it seems that anticyclonic-modewater eddies may create more intense dead zones (DO close to zero) when compared with those in cyclonic eddies. Possibly this is related to higher productivity in connection with the eddy/wind interaction or other mechanisms (Martin and Richards, 2001; McGillicuddy et al., 2007; Chelton et al., 2011a; Gaube et al., 2014). Moreover the mixed-layer depth in anticyclonic-modewater eddies is very shallow and only a few 10s of meters, as such nutrients from below will be lifted far up into the euphotic zone.*