Detailed response to reviewers comments

Anonymous Referee #1

The paper presents new observations of unexpected low oxygen concentrations in eddies of the eastern tropical North Atlantic Ocean. Observations are derived from the Cape Verde Ocean Observing mooring, from a RV Meteor survey and from an Argo float. The low oxygen zones are located below the mixed layer in the eddy euphotic zone. Evolution of the oxygen content suggests important net respiration that would explain the low oxygen content.

The study deals with new observations of major importance to understand the oxygen distribution in the eastern North Atlantic. Results are quite interesting. The paper should thus be published in Biogeosciences but the authors will need to significantly improve it. Some parts seem to have been written in a rush and others should be better synthetized. Discussion on differences between anticyclonic mode water eddies and cyclonic eddies is also unclear. A synthetic explanation of the DO low values should be given in the conclusion.

We thank the reviewer for encouraging but also critical words. We have revised the text and hope that the new version is not only better synthesizing our results but further addresses adequately the points were improvements have been suggested by this reviewer – namely a better (as far as it is possible based on the data at hand) discussion on possible differences between anticyclonic-modewater/intrathermocline eddies and cyclonic eddies. Note, we also extensively re-wrote the conclusion section.

Specific comments:

1. Abstract. I found the abstract poorly written. The sentence "a dynamic boundary. . ." makes no sense to me. Observation types are not presented.

We have re-written the abstract avoiding the dynamic boundary sentence and adding the in-situ observation platforms used in this study.

It reads now:
It is assumed that the strong velocity at the outer rim of the eddies hampers the transport of properties across the eddies boundary and as such isolates their cores. This is supported by a remarkable stable hydrographic structure of the eddies core over periods of several months.

2. Page 4 (section 2.1). CVOO meaning should be given the first time this acronym is used.

Thank you, we changed that.

3. Page 5 (section 2.2). pressure correction of 4%. Explanation needed.

Indeed, we added the respective reference (Tengberg et al 2006, Limnology & Oceanography)

Reads now:
a pressure correction was applied to the data (Tengberg et al., 2006) increasing the oxygen linear by 4 % per 100bar

4. Page 5 (section 2.3). SLA. Meaning. You should explain you are using altimeter data and describe them !

Thank you. We added the information requested.

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 degree horizontal resolution Mercator grid every 7 days (e.g. Pascual et al., 2006, and references therein).

5. Page 6. I found the discussion on the anticyclonic eddy vertical structure confusing. There is indeed a structure of downward/upward bended isopycnals at about 40 m (mode water eddy) but the eddy has a deep (> 400 m) velocity and salinity signature (the temperature structure should be given in figure 3).

Indeed, intrathermocline eddies or anticyclonic modewater eddies are characterized by a subsurface velocity maximum, but the anticyclonic rotation is found much deeper as well (see e.g. Kostianoy and Belkin 1989) as reflected in the structure of the density field. From a current meter record at about 600m depth we still clearly observe the eddy passage. Moreover, the geostrophic calculation (Figure 2) indicates that the eddy reaches down at least to 1400m depth. Nevertheless, the coherence parameter "alpha" indicate that the flow contrast is too weak at larger depths to significantly limit the exchange between eddy interior and surroundings.

More information about the velocity structure of the eddies has been added to the text, including a discussion on using different reference levels for the geostrophic calculations.
Note, we added the temperature section to figure 3 for completeness.

Reads now:
Further inspection of the temporal evolution of isopycnals (surfaces of constant water density) during the eddy passage indicated that a special type of anticyclonic eddy, a so called anticyclonic-modewater or intrathermocline eddy (Kostianoy and Belkin, 1989; McGillicuddy et al., 2007), crossed the mooring. Anticyclonic-modewater eddies can be identified from downward/upward bended isopycnals towards the eddy centre below/above a subsurface swirl velocity maximum. The transition between up and downward bended isopycnals form a lens (or mode) of a specific water mass which can be at all water depth. Prominent examples for intrathermocline eddies are so called "Meddies", which propagate at depth between 500 and 1500m and have been formed from instabilities of the Mediterranean outflow after entering the North Atlantic through the Strait of Gibraltar (Armi and Zenk, 1984). In our observations the mode is at much shallower depth, centred at about 70 m, and had a height of

about 50 m or so. It contained the most extreme low DO concentrations. Below this mode, the eddy had a structure of a typical anticyclone and reached deeper than 1400 m (not shown).

6. A discussion on vertical circulation associated to the different eddies should be given as it is related to the inputs of nutrients (to be added in the paragraph just before section 3.3).

The vertical transport in mesoscale eddies is a topic of past and current debate. From our observations we cannot conclude on details about the vertical circulation. However, we added more details on the concepts of vertical transport in cyclonic, anticyclonic, and modewater eddies. Moreover, we added a bulk upwelling estimate, following an Ekman divergence approach (e.g. Martin and Richards 2001) using typical wind and eddy rotation speeds and eddy diameter.

We added the information to paragraph 3.4 because we alos move the ocean color data to 3.4 now discussing al productivity and respiration issues in one Paragraph.

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). 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).

7. Page 7. There is no figure 4d !

Thank you, the reference to Figure 4d has been removed.

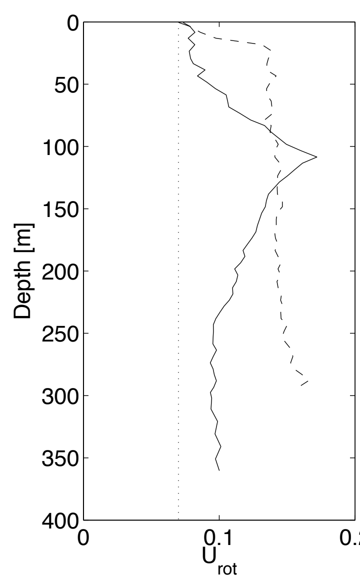
8. Page 7. Geostrophic surface currents of 5 to 10 cm/s (as derived from altimetry). Please check that similar results are obtained from your temperature and salinity observations (assuming a deep reference level).

In Figure 3c (which is now Figure 3b) we show the structure of the meridional flow. Information about how we referenced the geostrophic velocity in figure 3 is added in detail. In brief, the upper ocean (approx. above 100 m) is directly observed using an acoustic Doppler current profiler (ADCP). Below the geostrophic velocity is derived from the density field and referenced to the directly observed currents at 75 m depth. We also used 1400m as a level-of-no motion reference and it did not changed the structure of the flow with a maximum swirl velocity at a about 70m. We added this further information to 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). However, also used the density field from moored sensors and derived a velocity under the assumption of a layer of no motion at 1400m and which resampled the velcity structure fairly well, in particular also a subsurface swirl velocity maximum at about 70 m depth.

9. Page 9. First paragraph. A figure showing the evolution of the velocity structure is needed.

Unfortunately we do not have direct (ADCP) velocity observations for the Argo float. Here you should find a figure with the two geostrophic velocity profiles from the Argo float - derived from neighbouring profiles were the float was transiting in & out of the eddy – the broken one is at the beginning of the eddy survey, the solid line at the end. Note, the velocity is to be scaled with a reference velocity (here we set the surface velocity to zero, which is very likely not the case).
We do not think the figure will add more information than is written in the text and hope you agree.



The text reads now:
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).

10. Page 9. “which should be minimal given the constancy”. To be rephrased.

Has been rephrased.

The text reads now:

Moreover, the rates must be seen as a lower bound of the real respiration inside of the eddy, as we assume no supply of DO by vertical mixing or from outside the eddy. Nevertheless, remarkable constant hydrography of the eddy core over time (Fig. 4b for temperature) suggests that lateral exchange across the eddy rim with surrounding waters is small.

11. Page 10. So far not routinely measured.

The sentence was removed. The discussion section has been eliminated and merged with the results into one section “Results and Discussion”.

12. Page 11. This discussion should be related to your observations. What are the differences in intensity/lifetime and dead zones in your cyclonic and anticyclonic mode eddies?

The discussion and conclusion section have been intensively re-written. In particular we now discuss the cyclonic and anticyclonic modewater eddies in a much more coherent way.

Corresponding text reads now:

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 mechanism (Martin and Richards, 2001; McGillicuddy et al., 2007). 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.

13. Page 11. In principle open ocean dead zones . . . Explanation?

Thank you. Indeed some text was missing (a % in the latex file) – and now revived.

Reads now:

In principle open ocean dead zones in cyclonic and anticyclonic-modewater eddies could be created in all oceanic regions. Sufficient productivity, and particle sinking and remineralization, as well as non-linearity (and as such isolation) of the eddies, must be ensured for long enough periods of time. One other important control parameter is presumably the initial DO concentration. At the West African coast, were the eddies are created we report here, DO concentrations are around 40 to 70 μmol kg−1 in the depth level that will later be occupied by low DO waters. However, in the Pacific or the Indian Ocean coastal DO concentrations are lower and extremes in other biogeochemical parameters may be generated. Here, anomalous nitrogen isotope compositions (Altabet et al., 2012) or anomalous phytoplankton distributions (Morales et al., 2012) have been reported to exist in anticyclonic-modewater eddies in the past.