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Interactive comment on "Diapycnal oxygen supply to the tropical North Atlantic oxygen minimum zone" *by* T. Fischer et al.

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Reply to Reviewer #2

Thank you very much for your helpful comments. Our replies follow after each of the comments.

Manuscript number bg-2012-470: "Diapycnal oxygen supply to the tropical North Atlantic oxygen minimum zone", by Fischer et al. In this paper, the authors investigate the diapycnal process as a possible mechanism for the replenishment of consumed oxygen in the OMZ of the tropical North Atlantic Ocean. For that, they used different sources of data from CTD measurements, microstructure profiles, tracer release experiment and shipboard acoustic current measurements. The diapycnal diffusivity is estimated by

3 methods and two of these methods are independent. Finally, they estimate that the diapycnal process contributes about 1/3 of the total demand in oxygen using an oxygen budget. This paper is well presented. The calculations and hypothesis of this work are generally well discussed. This study is of importance for the actual challenging questions on the OMZs and its supply via physical processes. It fits perfectly in this special issue on OMZs. However, the authors have to better replace their study in the context of the previous studies on this topic and within the challenging question on OMZs. For example, what new information does this study bring to the general community working on the OMZ topic? So I recommend the publication of this paper after revision and satisfying answers to the following questions. Detailed comments:

1) P14292: Lines 13-15: In this abstract, as well as in the following of the paper, could the authors explain in more details the link between diapycnal diffusion, isopycnal diffusion, eddies, horizontal/vertical advection? What physical processes drive this diapycnal mixing in this studied area? it's a general comment on this paper.

Answer: We change the abstract in P14292 L1-6 and now mention the other supply component, isopycnal supply, to complement the diapycnal supply. It now reads: "The replenishment of consumed oxygen in the open ocean oxygen minimum zone (OMZ) off Northwest Africa is accomplished by oxygen transport across and along density surfaces, i.e. diapycnal and isopycnal oxygen supply. Here the diapycnal oxygen supply is investigated using a large observational set of oxygen profiles and diapycnal mixing data from years 2008 to 2010."

Also we add to the abstract: (P14292 L9) "The average diapycnal diffusivity in the study area which is predominantly caused by turbulence is 1x10ˆ-5 m2s-1, with lower and upper 95% confidence limits of 0.8x10ˆ-5 m2s-1 and 1.4x10ˆ-5 m2s-1."

In the introduction (P14293 L10) we now detail that both, diapycnal and isopycnal transport of oxygen can be achieved by advection and diffusion, where diffusion includes eddy diffusion and molecular diffusion. Other processes can be fit to this classification depending on scales, e.g. double diffusive convection would be part of diapycnal eddy diffusion on the OMZ scale.

Open ocean diapycnal mixing is usually driven by breaking of internal waves. Double diffusion can also lead to elevated mixing. To clarify this we add to the introduction: "In the open ocean away from topographic features, diapycnal mixing is often sustained by breaking internal waves and can be enhanced by double diffusion [Staquet and Sommeria 2002, St.Laurent and Schmitt 1999]." Additionally, in the discussion section, we discuss the contribution of processes responsible for mixing in the study region.

2) P14292-P14294: Introduction: The authors have to replace their study within the previous studies on diapycnal mixing, especially for the OMZs. Also if this kind of study is new, they have to tell it and explain it (see my general comment).

Answer: We add some details of the results of Banyte et al. [2012] and Brandt et al. [2010] (P14294 L13) to the introduction, now stating that "Diapycnal mixing was determined by a tracer release experiment in the oxycline above the core of the tropical North Atlantic OMZ and was found to be larger than expected with respect to the hypothesis of reduced internal wave energy conversion in the vicinity of the equator [Banyte et al. 2012]. In an idealized framework of an advection-diffusion model fit to observations, Brandt et al. [2010] quantified the contributions of physical processes replenishing oxygen to OMZs by assuming a diapycnal diffusivity and an oxygen curvature at a given isopycnal surface. However, diapycnal oxygen flux has not yet been quantified from observations of oxygen and diapycnal mixing in any of the OMZs in the ocean."

See also answer to question 1 of reviewer #1 for studies on diapycnal mixing to infer fluxes for different tracers.

3) P14293: Lines 10-11: In the introduction, at this stage, it is not obvious why the divergence of the flux (diapycnal and isopycnal) is the quantity to study. Please, explain it in the introduction or keep this detail for section 3.1 where you explain it.

Answer: We refrain from referring to flux divergence in the introduction and instead rephrase P14293L10 to "In steady state there must be a balance between consumption rate, isopycnal supply and diapycnal supply."

4) P14295: Line 13: Could the authors specify the increase of volume as well as the decrease in oxygen minimum concentrations for the deep OMZ (450m) compared to the shallow OMZ (100 m)?

Answer: We expand in the paper from P14295 L9 on: "The shallow minimum with a thickness of about 50m is pronounced in 80 to 90% of the oxygen profiles. Profiles lacking a shallow oxygen minimum were found to be scattered throughout the study area, with a tendency to become more frequent towards the southern part of the OMZ. The deep oxygen minimum at a depth range of about 300m to 700m exists in all profiles from the region and shows core concentrations of typically 40 to 60 μmol kg-1. These minimum concentrations are on average 40 μmol kg-1 lower than the core concentrations of the shallow minimum. In the following we will only study the deeper, more voluminous and more intense oxygen minimum."

5) P14295: Line 22: Could the authors explain why they chose 60 micromol kg-1 as the threshold to define the OMZ? In other studies, different values are used to define the OMZ limit.

Answer: We rephrase and add a sentence at P14295 L23: "The reason for this choice is that the region encompassed by the 60 μmol kg-1 isoline includes as much as possible of the low oxygen region of the tropical Northeast Atlantic, while it excludes adjacent regimes which are better ventilated, particularly those associated with the eastward flow of the NECC/NEUC in the South and with the subtropical gyre at Cape Verde front in the North. Furthermore, 60 μmol kg-1 can be considered as a limit to hypoxia for marine animals [Diaz 2001, Vaquer-Sunyer and Duarte 2008, Ekau et al. 2010, Keeling et al. 2010]."

6) P14297: Line 5: “approximate estimates had to be used”, Could the authors explain

here the assumption made? If I understand correctly, the oxygen diffusivity is assumed equal to the mass diffusivity estimated in this study? The authors have to discuss this assumption in the Results and discussions section. They have also to notice in their paper that the notation “K” stands for the mass diffusivity “Krho” in the following of the paper, except for KTRE which is the diffusivity of a passive tracer.

Answer: After rethinking the nomenclature, it seemed best to let K be the diffusivity that we are aiming at, Koxygen. All other flavors of K get a specifying index and are accordingly renamed throughout the paper.

We clarify and rephrase from P14297 L5 onwards: "If not stated else, K throughout the paper is Koxygen, the one this study aims at. Other meanings of K will be indicated by indices, which may specify the technique to obtain K (KTRE, KMSS/ADCP) or the property the specific K is valid for (e.g. Ktracer, Krho) or the mechanism that caused K (Kturb from mechanical turbulence, KDD from double diffusive enhancement). In this study three different measurement methods are used to obtain approximate estimates of Koxygen. 1) The diapycnal spreading of a tracer during GUTRE (Sect. 3.4) delivered KTRE, which is an estimate for both Ktracer and Koxygen, if dissolved oxygen behaves similar to the tracer, which is assumed here. 2) Measurements of the strength of mechanical turbulence by using a microstructure profiler (Sect. 3.5) delivered an estimate of the diapycnal diffusivity of mass Krho. Krho can serve as an estimate for Koxygen if a) turbulent diffusivity is much greater than molecular diffusivities and b) double diffusion is negligible [St. Laurent and Schmitt 1999, Ferrari and Polzin 2005]. 3) Velocity profiles from vessel mounted Acoustic Doppler Current Profilers (vmADCP) delivered estimates of vertical shear spectra (Sect. 3.6) which served to parameterize Krho. As this parameterization (Appendix A) is based on the measured microstructure profiles, the use of vmADCP measurements is not an independent method, but it helps in substantially enhancing the database."

We further discuss the validity of the assumptions in the 'results and discussion' section in subsection 4.1: The average <K>MSS/ADCP = 1x10ˆ-5 m2 s-1 as an estimate

for <K>rho is much larger than the molecular diffusivity of heat (∼10ˆ-7 m2 s-1) and the molecular diffusivity of solutes (∼10ˆ-9 m2 s-1). Thus, concerning the one part of eddy diffusivity which is caused by mechanical turbulence, <K>oxygen,turb should be undistinguishable from <K>rho,turb. Double diffusion could enhance the diffusivity: Koxygen = Koxygen,turb+Koxygen,DD. Assuming that dissolved oxygen behaves as a tracer similar to salt, we estimate the double diffusive enhancement following the technique of St.Laurent and Schmitt [1999] to be on the order of 1x10ˆ-6 in the depth range 150m to 500m. That means <K>oxygen might be 10% larger than <K>MSS/ADCP, which is an insignificant difference in the range of uncertainties. Nonetheless such double diffusive enhancement would reduce the difference of <K>oxygen as estimated from <K>MSS/ADCP to the observed <K>TRE.

7) P14297 Lines 21-22: why not using the mmol/m3 as units for oxygen? If so, the water density will not be needed anymore in this equation. P14297 Line 26: same question, I do not understand why you do not use mmol/m3/yr as units for the diapycnal flux divergence. Please, change a-1 to yr-1 as well as in the whole paper.

Answer: We would like to keep concentrations based on weight, so that concentration remains constant for a material water parcel. We admit that only small changes in numerical values would occur by using concentrations based on volume, but the concentration in mmol m-3 would be susceptible to changes in say temperature, even if no change in the number of oxygen molecules and water molecules occurred.

We replace a-1 by yr-1 throughout the manuscript.

8) P14298: Lines 7-8: How is the decorrelation scale of 0.5° determined?

Answer: We used a semivariogramme including all 400 diffusivity values calculated from our data, and assumed horizontal isotropy. As the diffusivities were determined from data collected during ship transects, some temporal influence on the semivariogramme cannot be ruled out. However, we expect that the true spatial decorrelation scale could only be larger than the estimated value, as temporal variability adds to the spatial variability. So we keep to the reported decorrelation scale of 0.5° as a conservative estimate.

We add some wording to the appropriate sentence stating "For the objective mapping, the decorrelation scale was determined by a semivariogramme to be 0.5°.

9) P14298: Lines 12-21 Section 3.2: It seems a lot of data are available for this study for 3 different years: 2008, 2009, 2010. Is there a possibility to estimate the diapycnal diffusivity for each year? and study the variability of this diffusivity over the 3 years? What is the minimum number of data necessary to estimate this diffusivity?

Answer: Thank you for these helpful proposals, we add according passages to the 'results and discussion' section.

Comparing the estimated diapycnal diffusivity <K>MSS/ADCP for Nov. 2008, Nov/Dec 2009 and Oct 2010 (from essentially one cruise per year) we get 0.9x10ˆ-5 m2 s-1 [0.7 1.1]x10ˆ-5 m2 s-1 (95% confidence limits) 0.95x10ˆ-5 m2 s-1 [0.75 1.15]x10ˆ-5 m2 s-1 and 1.05x10ˆ-5 m2 s-1 [0.85 1.3]x10ˆ-5 m2 s-1. The <K>MSS,ADCP estimates do not vary significantly between the three years. However each value only represents a month of survey during the last quarter of the according year, so a seasonal bias cannot be ruled out. We further use the dataset of 400 KMSS,ADCP values to investigate the influence of the number of randomly chosen diffusivity data on the resulting uncertainty, after using the same processing as used for the entire dataset (see Figure 1 at the end of this reply). 100 measurements (each consisting of either 3 MSS-profiles or an ADCP recording during about a 1 hour CTD cast) seem to be a reasonable number for an efficient estimate of <K>. Thinking further, we expect the analogous minimum necessary number of measurements larger, if the aim is estimating the diapycnal flux profile, because the natural variability of oxygen profiles adds to the uncertainty.

10) P14298: Lines 21-24: same question for the seasonal variability. As 110 additional oxygen profiles are available for other months February, March and April for 2008, is it possible to use these profiles to estimate the oxygen diapycnal supply for example

in April 2008 and compare it with the oxygen diapycnal supply in November 2008. I assume you will have to use the same diapycnal diffusivity estimated in November 2008 or over the whole period 2008-2010?

Answer: The coverage of the analysis box with the spring of 2008 oxygen data is poor and there are no simultaneous measurements of K. So seasonal variability estimation we deem outside the scope of the paper.

11) P14299: Lines 24-25, explain how this typical instrument noise is estimated? (refers to the oxygen sensor instrument noise)

Answer: We report the 95% percentile of the signal residuals, after removing the slowly varying signal. This is well possible, because the time constant of the oxygen sensor and the timescale of the noise are well separated.

12) P14301: Line 2, How are the results impacted by this choice of gamma value?

Answer: K, diapycnal flux, and diapycnal flux divergence are directly proportional to gamma. We think that 0.2 is a sensible choice for the study area, based on the current knowledge. The comparison of resulting <K> from MSS/ADCP and TRE indicates no contradiction. We cannot give a proper 95% confidence interval for gamma, though.

13) P14303 : Line 14: replace 'gradc" by the appropriate mathematical sign (as for page 14297) as well as in the following of the paper.

Answer: Corrected as suggested.

14) P14303: end of section 3.4, it will be nice to compare the precision of these two estimated diffusivities KTRE and KMSS/ADCP.

Answer: The precisions of <K>TRE and <K>MSS/ADCP are not only a function of the methods, but also highly dependent on the effort of data sampling. That is why we would rather not discuss the precision in the methods part, but leave the evaluation and comparison of the uncertainty of the <K> estimates to section 4.1, where the result for <K>MSS/ADCP is presented and the result for <K>TRE is reported. With the given amount of MSS/ADCP data collected (400 stations) and tracer profiles measured (also about 400 profiles), both methods lead to comparable precisions.

15) P14303-14305 section 4.1: Is there a spatial variability of K in the studied area based on the measurements?

Answer: We provide a map and a distribution of the measured K values (Fig. 2a and Fig. 2b at the end of this reply). The reasons for the spatial patterns are at the present stage rather speculative (possibly bottom topography), and will be subject of further study.

16) P14305-14306: Is there another way to estimate the isopycnal oxygen flux and compare it with the estimation made in this study using the budget equation?

Answer: This requires an in-depth analysis of the lateral eddy diffusivity as well as of advection by varying and time-mean current field, which is far beyond the scope of the present manuscript. Particularly the quantification of the isopycnal advective contribution is a difficult task as not much is known about the general pattern of the time-mean flow in the tropical Atlantic at intermediate depths.

For a very rough estimate of the magnitude of isopycnal diffusive supply we could use an isopycnal diffusivity of 500 m2 s-1 [e.g. Banyte et al. 2013, submitted] and a typical curvature of our measured oxygen field on isopycnals within the deep OMZ of 10ˆ-10 μmol kg-1 m-2, and come to an estimate of 2 μmol kg-1 yr-1. This value is in the range of the expected isopycnal supply (isopycnal diffusion plus advection) within the deep OMZ. Brandt et al. [2010] obtained in an idealized framework of a zonal flow from the western boundary into the OMZ consistent estimates for the isopycnal eddy supply. Depending on the assumed strength of the zonal flow, they derived an isopycnal eddy supply of 0.5 to 0.9 μmol kg-1 yr-1 when using an isopycnal K of 200 m2 s-1 and an isopycnal advective supply varying between 0 and 2 μmol kg-1 yr-1.

17) P14308 : Lines 3-11: As explained in the paper, consumption profiles are diverse and uncertain, so why do the authors just use one estimate? Could the authors use two others estimates for the consumption profiles (min and max) to evaluate the influence of the consumption uncertainty on their results (isopycnal oxygen supply)?

Answer: Consumption profiles are diverse globally ([Feely et al. 2004] for the Pacific), but for our study region, there is only the one estimate available that we use. We have no criteria what a min and max consumption profile for the study region might be, except the uncertainty estimates of the given profile.

We change the misleading wording in P14308 L3 to: "Reported consumption rate profiles vary throughout the global oceans and are uncertain [Keeling et al. 2010], ..." and P14308 L8 to: "This profile is the only one reported specifically for the Northwest African OMZ. It is used here, with consumption rate in μmol kg-1 yr-1 estimated from -0.5+12 exp(-0.0021 z) with z depth in meters."

18) P14309: Line 20. Please, explain in one or two sentences why this diapycnal mixing in the study region is high. It's due to which processes?

Answer: At the present stage of knowledge we can only state, as at the end of section 4.1, that this is coincident with an observed intensified internal wave field and rough bottom topography. We add "The exact reasons for the higher than expected level of diapycnal mixing are subject to further study." after P14309 L20.

19) P14310: Lines 13-14, add a reference for the acoustic evidence of strong migrant activity.

Answer: It is experience from our own vmADCP observations during the survey cruises. We rephrase the sentence to make this clear: "The local impact of the latter process on the OMZ is unknown, but collected acoustic data during the survey cruises showed strong migrant activity. The acoustic backscatter records suggest enhanced oxygen consumption at about 300m and diminished oxygen consumption at about 200m depth."

20) P14310: Lines 18-29 and P14311 : Lines 1-3: See my first comment (abstract). The link between diapycnal diffusion, isopycnal diffusion, eddies, horizontal/vertical advection is not clear. So could the authors explain it in their paper?

Answer: We now clarify the principal link in the introduction (see answer to first comment). Furthermore we precise the terms used in the conclusions (P14310 L18): "Concerning the shape of the deduced isopycnal supply profile (Fig. 7), there is a sharp decline of isopycnal oxygen supply at the depth of the deep oxycline. This contrast in isopycnal oxygen supply could basically originate in isopycnal eddy diffusion and/or isopycnal advection. However, several potential explanations for the sharp contrast seem improbable: ..."

21) P14310: Could the authors comment their results in the context of OMZs study? Does this study bring new information to the community? For example could we use this estimated diapycnal diffusivity in modeling study to improve the modeled OMZ? (see my general comment).

Answer: In our view, the new and useful information consists of 1) the recognition that diapycnal mixing is one of the major controlling processes for this OMZ's formation and maintenance and will have to be taken into account when exploring the controlling processes of other OMZs, 2) the estimates of vertical structure of supply components to the Northwest African OMZ, which also lay the base for further research into this OMZ's oxygen budget 3) progress in understanding via which pathways this OMZ is supplied and what could cause its relatively high oxygen level compared to other OMZs, 4) potential use of the estimated <K> as one constraint to improve the modeling of the Northwest African OMZ, and to improve model predictions of future oxygen trends, which can depend very sensitively on chosen diapycnal diffusivity [Duteil and Oschlies 2011], 5) methodological and statistical information useful for the planning or data processing for similar studies in other OMZs or for monitoring.

We add this information to the conclusions. Further we expand the introduction at P14294 L11, referring stronger to the importance of constraining diapycnal diffusivity to allow better model predictions, and referring stronger to the scarceness of knowledge about OMZ controlling processes.

22) Fig1: -Put the different currents (NEC, NECC/NEUC),

Ok.

23) -Change WOA 77/60 for WOA 77/67 ?

Answer: The isoline 77 μmol kg-1 from the World Ocean Atlas 2009, which encircles our 60 μmol kg-1 observations, is what we intended to address here. We rephrase this to "The WOA 77 line is used here to define the extent of the OMZ".

24) Fig4: -Add an explanation for K, especially the boxes and the vertical black bars within the boxes in the legend - Add the deep oxycline and the deep OMZ core on this plot as in Fig7.

Ok.

25) Fig7. Add the Central Waters on this plot.

Ok.

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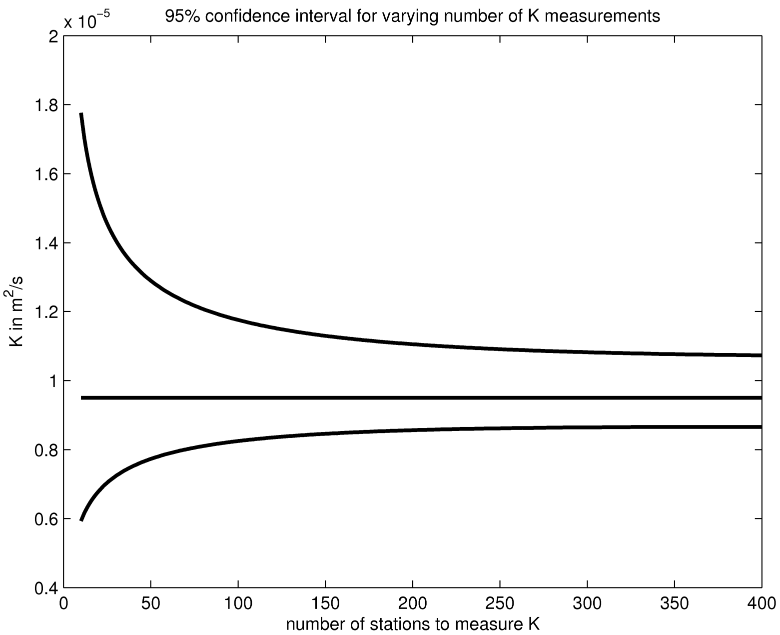

Fig. 1. 95% confidence limits for the estimated average diapycnal diffusivity for the study area, as a function of number of available datapoints. Assumed that data are distributed randomly in the study area

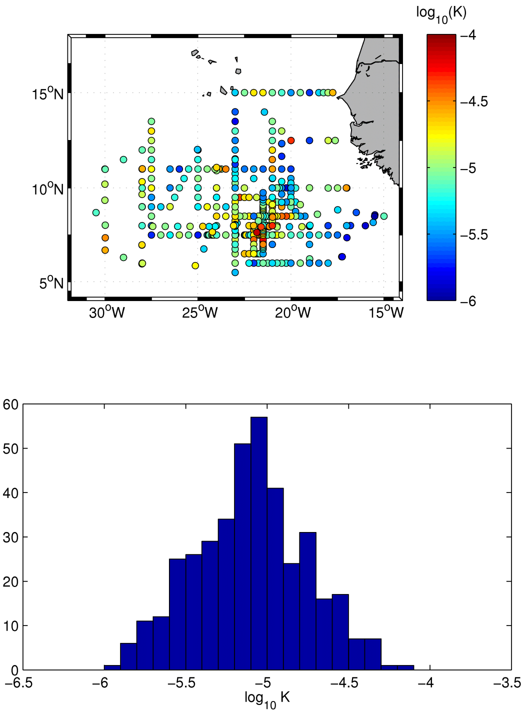

Fig. 2. Upper panel: Map of observed diapycnal diffusivities in the study area. Lower panel: According histogramme of diapycnal diffusivity data