Interactive comment on “Physical and biogeochemical forcing of oxygen changes in the tropical eastern South Pacific along 86 ºW: 1993 versus 2009”
by P. J. Llanillo et al.

Reply to Anonymous Reviewer #1

We would like to sincerely thank Reviewer #1 for his/her constructive comments and useful suggestions. Next we reproduce the Reviewer’s comments (italics) followed by our response.

General comments
The paper by Llanillo et al. compares two cruises in the tropical eastern South Pacific, one in 1993 during a warm “El Nino” period and one in 2009 during a cold “La Nina” period. Using the extended OMP analysis, the authors explain the physical and biogeochemical forcing that are responsible for the oxygen changes observed during these two periods into a region well known as one of the most important OMZ. Nowadays is becoming of extreme importance to increase our knowledge about the oxygen changes in general, and in particular within these areas (the OMZs), since several studies have shown a consistent expansion of the OMZ and decrease of oxygen over the last decades.
The paper is well written, however I have some specific questions that I would like the authors to address.

Specific comments:
1) I can understand the choice of computing the changes along depth coordinates, since depth coordinates are more familiar for most of the readers. However, the authors should have done also the analysis on isopycnals coordinates. Isopycnals analysis tends to reduce the changes due to isopycnal heaves for all parameters (see for example Johnson and Gruber, 2007). Moreover, the discussion of the paper focuses on water mass mixing, and water tends to mix along isopycnals. It has been demonstrated that if you average along isobaric coordinates you may encounter into the problem of producing artificial water masses (see Lozier et al. 1994, Fratantoni and McCartney 2010, and how for example the WOCE hydrographic climatology has been gridded). I guess that performing

the difference of two hydrographic cruises that are interpolated along depth lever can bring to a similar problem.

The reviewer is completely right pointing out this issue so, in order to allow recognizing which changes are due to isopycnal heave and which ones might be due to other causes, we have repeated the analysis in density space. When looking at the results in density space (Figures 1 and 2) we can still appreciate the tongue of increasing AAIW flowing along shallower isopycnals, in good agreement with the warming (and density reduction) trends of the AAIW core in the eastern south Pacific (Schmidtko and Johnson, 2012). As this tongue replaces ESSW, it represents an increased advection of relatively oxygenated waters into the OMZ (26 < sigma-theta < 27) as proposed in our study (see figures below). Figure 1 is included in the revised manuscript as Figure 9B and Figure 2 will be shown in the Appendix to the revised manuscript.

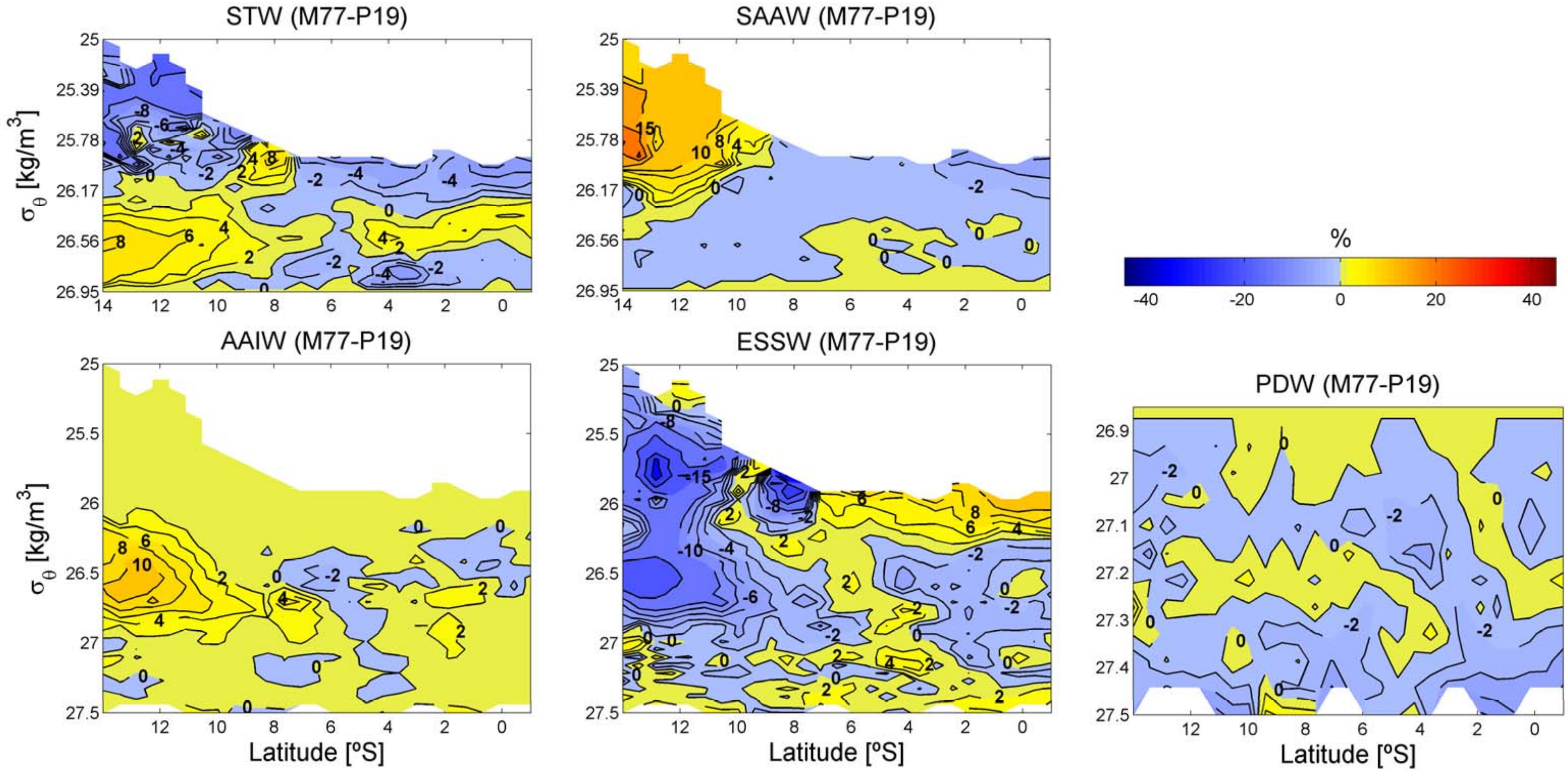


Fig. 1. Water mass changes (%) in density space between March 1993 and February 2009 (M77-P19) for SubtropicalWater (STW), SubantarcticWater (SAAW), Antarctic IntermediateWater (AAIW), Equatorial Subsurface Water (ESSW) and Pacific Deep Water (PDW).

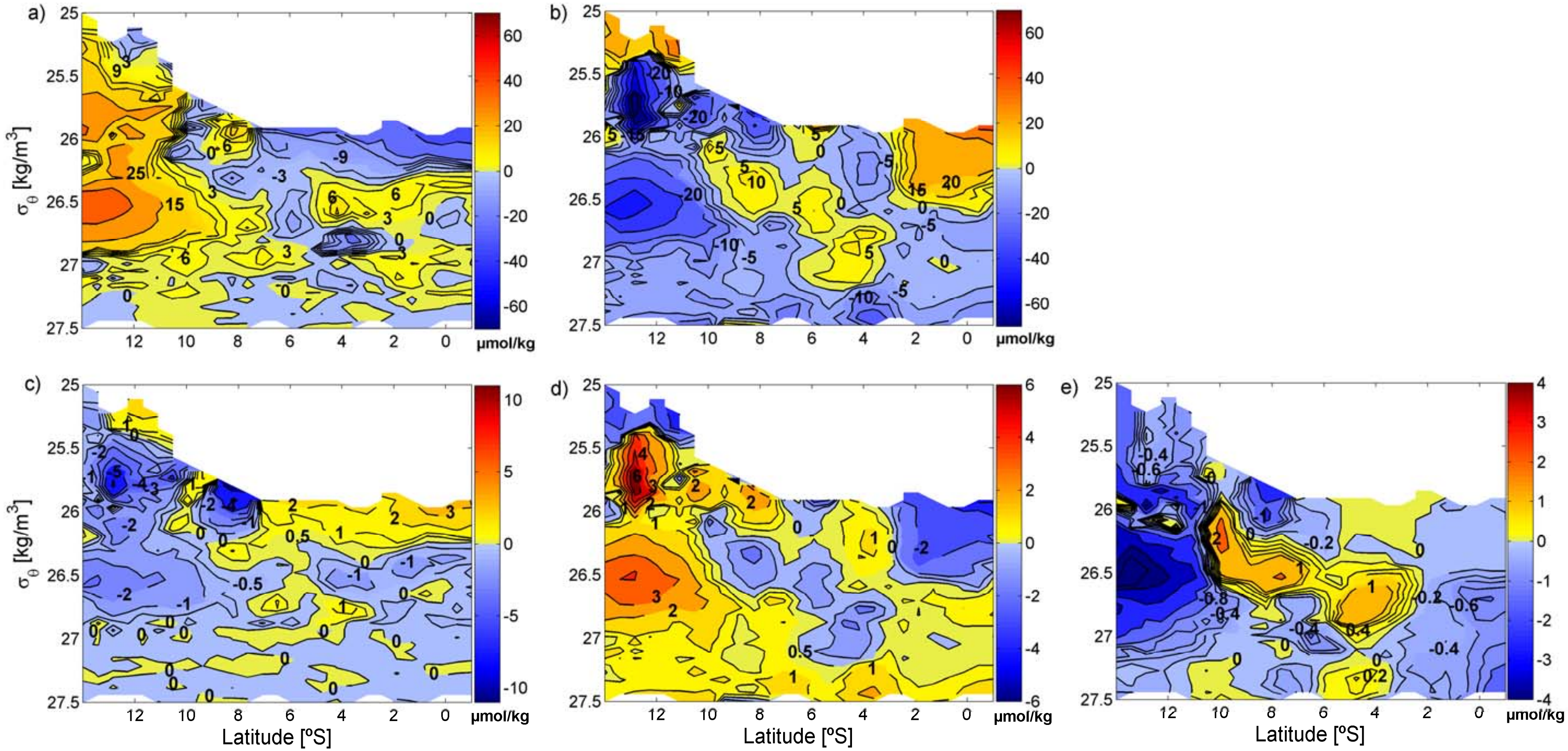


Fig. 2. OMP-derived changes in density space between March 1993 and February 2009 (M77-P19): (a) physical transport of oxygen, (b) respired oxygen, (c) physical transport of nitrate, (d) remineralized nitrate, and (e) denitrified nitrate.

2) P. 17588 from L. 16: I'm not completely sure whether the authors have done the interpolation before or after applying the OMP method. On my opinion the first option is not completely correct, it is better to do first the OMP and then interpolate the data. Indeed, the interpolation adds some artifact that you want to have as latest as possible in your results, even if, as the authors stated, the interpolated bottles data reproduces well the CTD data.

We first applied the OMP method to each data point and, afterwards, we objectively interpolated the data. We have rephrased that part in the manuscript to make that point clear.

3) Maybe I missed that but I don't see anywhere in the text the definition of the depth range of the OMZ, where is it laying in the region analyzed? Maybe a figure that shows the oxygen section from the two cruises would help.

According to Stramma et al. (2010) "there is no consensus on the oxygen thresholds defining an OMZ. When oxygen concentrations fall below ~60 to 120 µmol/kg (hypoxic conditions) important mobile macroorganisms are stressed or die." As it may be observed in the figure below, the whole section presents very low values of dissolved oxygen. Therefore, we decided to use the value of 20 µmol/kg as the boundary of the core of the OMZ, this value has also been used for this region by Stramma et al. (2013).

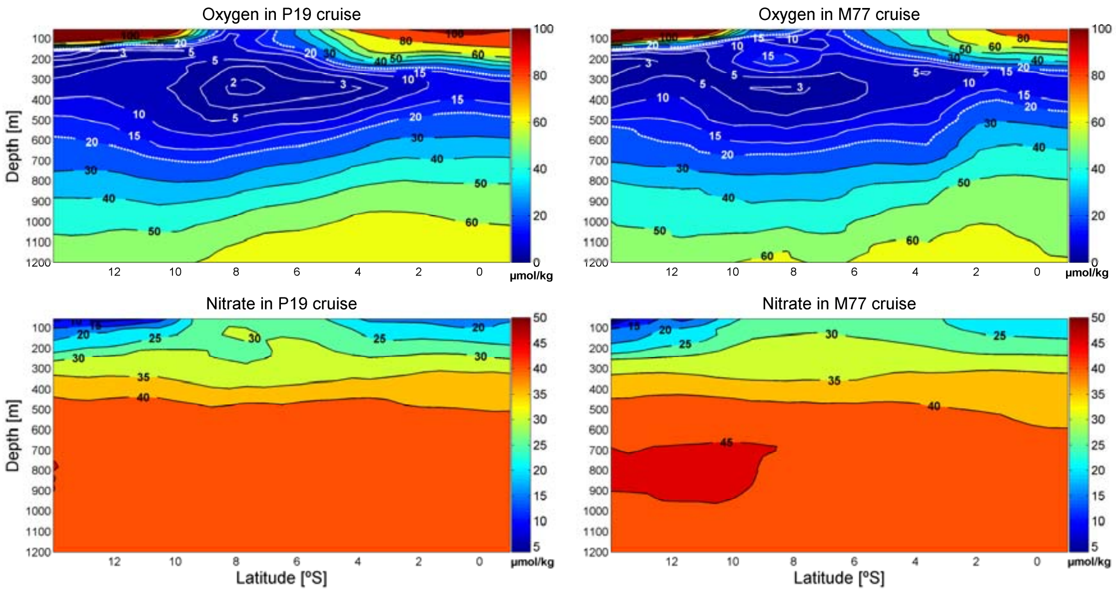


Fig. 3. Meridional section with measured oxygen (μmol kg^{-1}) and nitrate (μmol kg^{-1}) for March 1993 (P19) and February 2009 (M77). Following Stramma et al. (2013), we define the boundary of the OMZ core as the 20 μmol kg^{-1} oxygen isopleth (white dotted contour line).

4) What is the accuracy of the data? The authors should mention that in the data and methods. If you compute the changes in oxygen and nitrate all results that are lower than the accuracy should not be considered.

We will include this information in the manuscript. According to the WHP P19C cruise report, the accuracy of the sampled variables was:
CTD salinity = 0.002;
CTD oxygen = 0.03-0.04 ml/l (1.34-1.78 μmol/l);
Nitrate = 0.3-0.4 μmol/l;
Phosphate = 0.02-0.03 μmol/l;
Silicate = 1-2 μmol/l.
(Report available at http://sam.ucsd.edu/pacwoce/p19c/p19c_doc.txt)

According to the M77 cruise report, the accuracy for the sampled variables was:
CTD salinity = < 0.001;
CTD oxygen = 0.74 μmol/kg (or 0.72 μmol/l) (the accuracy for the oxygen titration was 0.244 μmol/l at values >5 μmol/kg);
Nitrate = 0.278 μmol/l;
Phosphate = 0.009 μmol/l;
Silicate = 0.180 μmol/l;

5) P. 17588 from L. 20: Which kind of data at the end it is used for your analysis? Interpolated bottle data for nutrients and CTD data for temperature, salinity and oxygen or only interpolated bottle data? This part should be better explained.

We used only interpolated bottle data for all parameters. We will make this clear in the revised manuscript.

6) P. 17590 from L. 3: As the authors wrote in this paragraph, the OMP analysis is based on the assumption that the source waters are time-invariant. What happens if the water mass changes over time? Do you have an estimation of the uncertainties or can you say something about how much your results would change if some of the water masses were subject to interannual or decadal changes?

Following the reviewer suggestion we have tested the influence of temporal changes of seawater properties in the source. For this purpose we have run a more complete series of sensitivity tests by perturbing simultaneously all the water types (end-members) in the source water mass matrix with Gaussian noise in a series of Monte Carlo experiments. We have examined what is the influence on the resulting water mixing fractions obtained after running the extended OMP analysis with the 'perturbed' source water mass matrix.

We have used the (largest) temporal trends in potential temperature (0.02 ºC/year) and salinity (-0.0005 psu/year) found in the formation region of AAIW in the eastern South Pacific (Schmidtko and Johnson, 2012) to estimate a standard error that would cover the temporal variability for each of these parameters from 1993 to 2009. We could not find in the literature temporal trends in potential temperature or salinity for the source regions of the rest of the water masses so we decided to use the AAIW salinity and potential temperature standard errors for all water masses. We are aware that the AAIW standard errors will probably represent overestimates for all other water masses (mainly for ESSW and PDW as they are defined below the sea surface). Therefore, all the results from these sensitivity tests (except for AAIW) must be understood as a 'worst case' scenario, mainly for ESSW and PDW. For nutrients and oxygen we have used the same standard errors calculated from the natural variability analysis (we calculated the standard error associated to each parameter by averaging the standard errors obtained for such parameter in each source region). These standard errors are then multiplied by Gaussian noise and the result is added to the original water type of the source water mass matrix (for each parameter) before applying the OMP.

All the sensitivity tests are run for each subsection for which we have resolved the extended OMP (four subsections: upper and lower analyses for both the P19 and M77 datasets). The mixing fractions obtained for each data point after each perturbed run were stored and a mean standard error was calculated for each mixing fraction from all the data points resolved with the OMP in each subsection.

Finally, a global-weighted mean standard error for each water mass mixing fraction is obtained (Table 1). The weighting applied takes into consideration the number of data points in each subsection analysed with the OMP method.

Mean standard error of the mixing fractions (%)	AAIW	ESSW	STW	SAAW	PDW
	2.42	7.64	5.08	5.25	4.45

Table 1. Mean standard errors in the water mass mixing fractions due to temporal changes in the water mass source regions, as obtained with the extended OMP analysis after running the sensitivity tests through a series of Monte Carlo simulations.

The global mean standard errors are quite low for AAIW (<3%) under conditions of both natural and temporal variability. This low variability gives us confidence in the results obtained and discussed in this paper. The worst results correspond to ESSW (9%) and PDW (5%). In the case of natural variability, this is probably due to the fact that we are using the averaged standard error (from all source regions) to characterize the natural variability of each parameter and the standard errors in potential temperature and salinity for ESSW and PDW are one or two orders of magnitude smaller than those of the remaining water masses (which were defined at the sea surface). In the case of temporal variability, these relatively larger values are probably related to the fact that we use standard errors that overestimate the temporal change of potential temperature and salinity for these water masses (as explained above).

7) P. 17590 from L. 14: It would be nice to have some estimation, like when the authors write in L. 14 "Characterized by a subsurface salinity maximum […]" how much is it this maximum? Or in L. 20, "Not to be confused with the salinity minimum of AAIW" which is about? Or, is the salinity around 34.0 the minimum of the SAAW? P. 17591 L. 7: "a broad silicate maximum": : :of?

This information will be included in the revised manuscript.

8) P. 17597: Similar to the previous comment. The authors have done a qualitative analysis about the changes observed in this region, but it would be nice to have also some quantitative analysis. For example, when the changes in the oxygen and nitrate contents are described, can you quantify a bit these changes? How much is the oxygen increase/decrease in _mol/kg and how much is the nitrate increase/decrease within the OMZ?

This information will be included in the revised manuscript.

9) L. 26 of P. 17599 until L. 4 of P. 17600: I am a bit puzzled about what it is described and what it is shown in Fig. 9. What I understood from the explanation, Fig. 9a represents the oxygen changes due to advection, Fig. 9b the oxygen changes due to respiration and so on. So if you observe an increase in the respired oxygen in Fig.9b, it means that the respiration rate is reduced since you have less oxygen advected in the region, which is available for the respiration. However, in P. 17600 L. 4, the authors wrote that in the upper 300 m there is a general decrease in the advected oxygen and gained in the advected nitrate (which I agree), but then it is said that this is accompanied by a reduction in the oxygen respired, while Fig. 9b shows an increase. Did you maybe mean that what is reduced is the respiration rate, since there is less oxygen available for the respiration, which reflects in the apparent gain of the oxygen in Fig. 9b?

Yes, that was our intention. We have rephrased it in the manuscript.

Also, P. 17599 L. 27, the authors said that a significant advective gain of oxygen is observed between 300 and 600 m depth. This is not completely true, since from Fig. 9a within that depth range the oxygen increases in the southern part but decreases in the northern part between 300 and 400 m. Then the authors said that this is partially compensated by an increase in the respiration rate (so reduction in the respired oxygen), but that again is not everywhere. First of all, I suggest describing the observed changes a bit more accurate, pointing to changes within particular regions in depth and along latitudes. Second to describe a bit better what the figures are really showing compare to what you are describing.

In the revised manuscript we will be more careful with these descriptions.

10) P. 17600 L. 19: Again the same problem as above but for the denitrified nitrate. You said that in the upper 250 m south of 10_S there is an increase in denitrification. If you look at Fig. 9e you observe negative denitrified nitrate. I guess again if you have an increase in the denitrification rate you observe a decrease in the denitrified nitrate. If this is what you mean, it is confusing to follow your argument when the direction of the changes plotted is on the opposite sign. So you should probably explain better what is shown in the figures, you could also for example invert the colorbar so that it follows the direction of your description.

This is exactly what we meant, with an increase in the denitrification signal we see an increased loss of nitrate, this is why this core appears as dark blue (negative colours) and this is also the reason why we have chosen this colour-bar, as negative values mean nitrate loss (due to greater denitrification activity). We will clarify this issue in the revised manuscript.

Regarding figures and tables, overall they are justified and clear. However I have some comment:

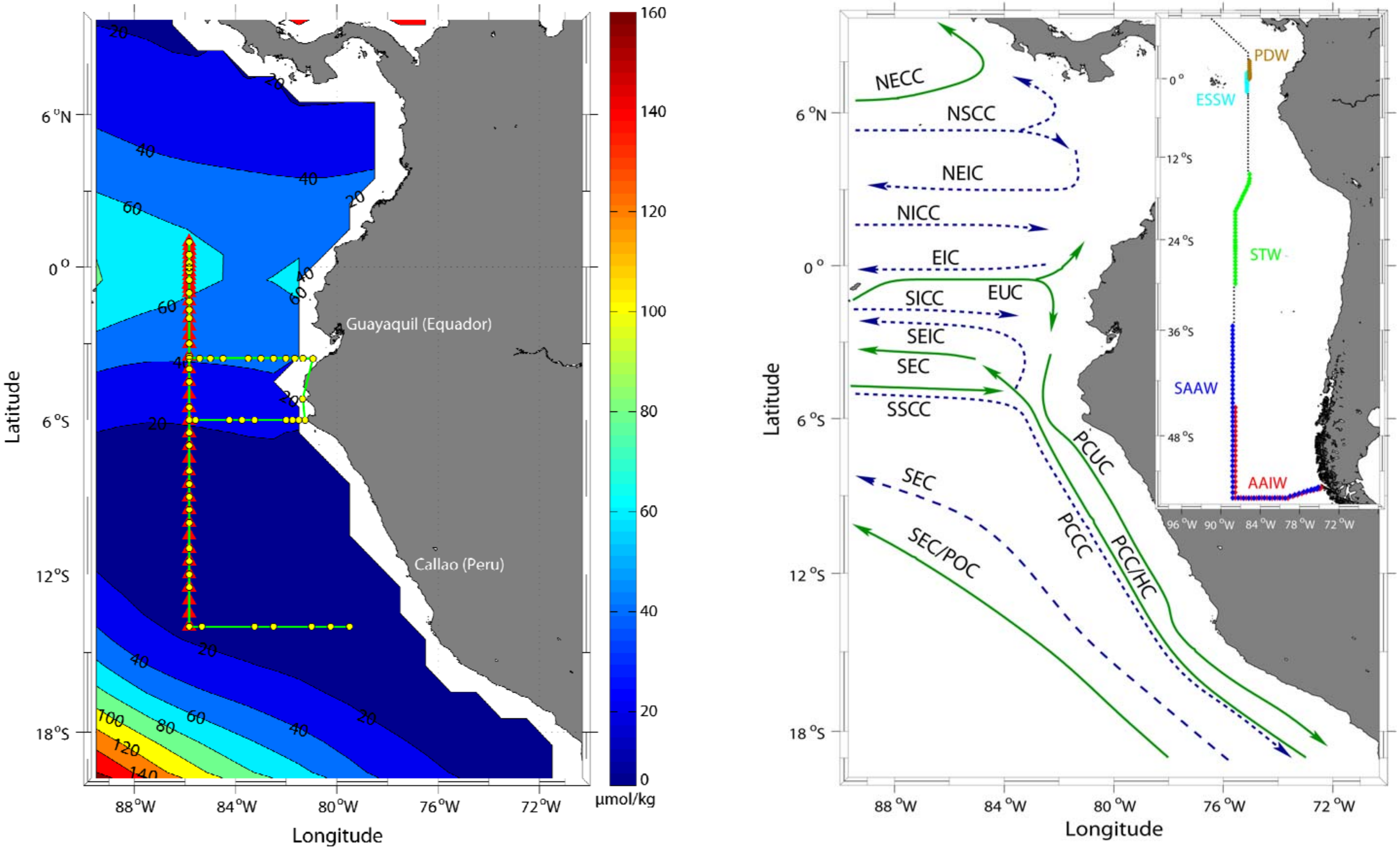
11) In table 1 the equation from Weiss (1970) it is used to calculate the oxygen saturation. This equation is obsolete, while a better equation is proposed by Garcia and Gordon (1992) based on the values of Benson and Krause. This equation has been used for calculating the oxygen saturation in well-known datasets like GLODAP and in the ATLAS09 (and all previous versions).

We have updated the values (Table 1 in the manuscript) following the equation proposed by Garcia and Gordon (1992). The table below shows the values used for the calculation:

Water mass	Pot. Temp. (ºC)	Salinity	Oxygen saturation
STW	20.8	35.52	221.55
SAAW	11	34.00	270.74
ESSW	10	34.80	275.00
AAIW	3.0	34	324.97
PDW	1.82	34.67	332.94

12) In Fig. 1 I suggest to make the line track of the Meteor cruise in white since black is not well visible with the dark blue color on the background. Also I would consider to add (maybe on the same figure on another panel if this one is already too crowded) a schematic of the water masses and currents in the region (with arrows for examples indicating the pathway of the water masses), since it will help the reader that is not familiar with the circulation in the Pacific Ocean, to identify all the water masses that are described in the paper.

We followed these suggestions but we have preferred to choose a green colour for the line track of the Meteor cruise as it is also visible over white background (zonal sections, Figure 1a in the manuscript). We will also include a new figure (Figure 1b in the manuscript) with a schematic of the main currents and source regions (along the P19 cruise track) were the water masses were defined.



160
140
120
100
80
60
40
20
0
µmol/kg
6 °N
0 °
6 °S
12°S
18°S
88°W
84°W
80°W
76°W
72°W
Latitude
Longitude
Guayaquil (Equador)
Callao (Peru)
NECC
NSCC
NEIC
NICC
EIC
EUC
SICC
SEIC
SEC
SSCC
PCUC
SEC
PCCC
PCC/HC
SEC/POC
PDW
ESSW
STW
SAAW
AAIW
12 °S
24 °S
36 °S
48 °S
96 °W
90 °W
84 °W
78 °W
72 °W

Figure 4
Circulation schematic (based on Kessler, 2006; Czeschel et al. 2011 and Grasse et al. 2012) for current bands in the upper 200 m (green lines) and 200 to 600 m (blue dashed lines), some current bands may cover both depth layers. The current bands shown are: NECC – North Equatorial Counter Current, NSCC – Northern Subsurface Counter Current, NEIC – North Equatorial Intermediate Current, NICC – North Intermediate Counter Current, EIC – Equatorial Intermediate Current, EUC – Equatorial Undercurrent, SICC – South Intermediate Counter Current, SEIC – South Equatorial Intermediate Current, SSCC – Southern Subsurface Counter Current, SEC – South Equatorial Current, POC – Peru Oceanic Current, PCCC – Peru Chile Counter Current, PCC/HC – Peru Chile or Humboldt Current and PCUC – Peru Chile Undercurrent. The inset shows the source regions (in the track of the P19 cruise) where the water masses (Table 1) were defined.

13) I would also consider inverting the order of Figs. 3, 4 and 5 since in the text the description of the figures starts with the 5 and continues with the 4 and then with the 3.

This will be done in the revised manuscript.

14) Fig. 6, why don't you use absolute values? It can be more intuitive for readers.

Because the purpose of our study (and accordingly our interpretation) was on the regional remineralization /respiration/ denitrification signals, therefore we do not try to over-interpret the results of this regional analysis. However, if our aim was to undertake an analysis of the global biogeochemical changes and water mass paths we would need a different set up for our study (using only true surface water masses, then discarding ESSW and PDW from our analysis as they are defined in subsurface and are themselves a mixture of other source water masses).

Technical comments:
15) P. 17588, L. 10: The cruise P19 also has bottle-data station. Specifying that you use bottle-data station only for the M77 cruise, seems to imply that other kind of data were used for the P19 cruise.

This will be corrected in the revised manuscript.

16) P. 17593, L. 25: ITCZ is not defined.

This will be defined in the revised manuscript.

17) P. 17594 from L. 5 on: Beside the suggestion to invert the order of Figs. 3, 4 and 5 (already mentioned in comment 13) I suggest also to refer to the figure the authors are describing in the text. For example: "SAAW has the highest percentage (>20%) in the western part of the 14_S transect (Fig. : : :)" and so on.

This will be corrected in the revised manuscript.

18) P. 17595, L. 1: "through" instead of "trough"

This will be corrected in the revised manuscript.

19) P. 17601, L. 11: remove "waters" after STW.

This will be corrected in the revised manuscript.

References:

Garcia, H. E. and L. I. Gordon, 1992. Oxygen solubility in seawater: Better fitting equations. Limnol. Oceanogr., 37, 1307-1312.

Fratantoni, P. S. and M. S. McCartney, 2010. Freshwater export from the Labrador Current to the North Atlantic Current at the tail of the Grand Banks of Newfoundland. Deep Sea Research I, 57, 258-283.

Johnson G. C. and N. Gruber, 2007, Decadal water mass variations along 20ºW in the northeastern Atlantic Ocean, Progress in Oceanography, 73, 277-295.

Lozier, M. S., M. S., McCartney, W. B., Owens, 1994, Anomalous anomalies in averaged hydrographic data. Journal of Physical Oceanography, 24, 2624-2638.

References:

Czeschel, R., Stramma, L., Schwarzkopf, F. U., Giese, B. S., Funk, A., and Karstensen, J.: Middepth circulation of the eastern tropical South Pacific and its link to the oxygen minimum zone, J Geophys Res, 116, 2011.

Grasse, P., Stichel, T., Stumpf, R., Stramma L. and M. Frank, M.: The distribution of neodymium isotopes and concentrations in the Eastern Equatorial Pacific: Water mass advection versus particle exchange, Earth and Planetary Science Letters, 353-354, 198-207, 2012.

Kessler, W. S.: The circulation of the eastern tropical Pacific: A review, Progr Oceanogr, 69, 181-217, 2006.

Stramma, L., Johnson, G. C., Firing, E., and Schmidtko, S.: Eastern Pacific oxygen minimum zones: supply paths and multidecadal changes, J Geophys Res, 115, C09011, 2010.

Stramma, L., Bange, H. W., Czeschel, R., Lorenzo, A., and Frank, M.: On the role of mesoscale eddies for the biological productivity and biogeochemistry in the eastern tropical Pacific Ocean off Peru, Biogeosciences Discuss., 10, 9179-9211, doi:10.5194/bgd-10-9179-2013, 2013.