Biogeosciences Discuss.,
https://doi.org/10.5194/bg-2019-155-AC2, 2019

Interactive comment on "ENSO-driven fluctuations in oxygen supply and vertical extent of oxygen-poor waters in the oxygen minimum zone of the Eastern Tropical South Pacific" *by* Yonss Saranga José et al.

Yonss Saranga José et al.

yjose@geomar.de

Received and published: 5 December 2019

Dear anonymous Reviewer I

We would like to thank referee 1 for the constructive comments, which have allowed a considerable improvement of the manuscript. The most substantial point the referee stated concerned the common volume used in the calculation of oxygen transport. In revised version of the manuscript, we have used a more extensive volume, which also includes the onshore region. The respective analysis has been added to the revised

version of the manuscript and it further supports our conclusions.

1. In the paragraph at the bottom of page 5 and top of page 6, the authors directly link the modelled long-term vertical expansion of the SW layer to the observed long-term expansion of the OMZ (Stramma et al. 2008) without further discussion. While Figure 2a,b suggests that the average modelled oxygen distribution has moved away from the initial climatological conditions, the authors do not provide evidence, that the model is fully spun up after 10 years of climatological forcing, and that the trend in the hindcast is not an artefact of model drift.

Following this and the comment of reviewer 3, the trend analysis is removed from the revised manuscript. Moreover, we ran a simulation in which we used 20 years for the spin-up phase of the model and replaced the old simulation used in the analysis of the previous manuscript.

2. The concept of the common volume occupied by the SW within the 1990-2010 time period (page 6, lines 8-9) is crucial for the following analysis of ventilation pathways for the OMZ core. While this common volume seems to be constant over time, it remains unclear what shape this volume takes. Is it a cuboid with longitudinal and latitudinal lines as lateral boundaries and isobaths as upper and lower boundary? If not, i.e. if the boundaries of the common volume are slanted in space, how do you make the distinction between oxygen transports across the southern, northern, eastern, western, upper and lower boundary? Is it possible to plot the dimensions of the common volume? Further explanation is needed in order to convey the used methodology.

The common volume was defined as a volume in which SW (waters with oxygen below 20 μmol/l) are present all the time within the 1990-2010 time period and within 2-28°S in latitude and 69-90°W in longitude. This definition excludes the shelf region, which is oxygenated during EL Niño events. In order to compare the present results with the previous study by Espinoza-Morriberón et al. (2019), we replace the common volume by a constant volume extending horizontally from the coast to 1000 km offshore and from the equator to the southward mean extension of the OMZ (Figure 1). The southern and northern limits of the volume are further set by the meridional extent of the OMZ. The upper and lower margins of the constant volume are located at 50 m and 900 m depth, respectively. The common volume is further subdivided into onshore and offshore regions. The onshore region extends from the coast to 250 km offshore. The offshore region 750 km long from the onshore western margin (250km from the coast).

Following the above comment, a dedicated subsection explaining the methodology is now added in the method section of the revised manuscript.

Added in Material and methods section of the manuscript, Page 5 lines 25-34 and page 6 lines 1-11

2.3 Model output analysis

2.3.1 Calculation of oxygen transport across the SW marginsIn the present study, we analyse the dynamics of oxygen-poor waters in terms of suboxic waters (SW), defined here as waters with oxygen concentrations below 20 μmol/l. As shown in previous studies on the OMZ of the ETSP (Llanillo et al., 2013; Mogollón and Calil, 2017; Yang et al., 2017; Espinoza-Morriberón et al., 2019), the upper position of oxygen poor waters varies with time and due to ENSO fluctuations. Changes may also occur in the lateral margins of the OMZ. In order to remove the effect of volume changes on the calculation of the oxygen transport across the margins of the SW as well as on the oxygen demand of biogeochemical processes within this water body, we introduce here a constant volume spanning horizontally from the coast to 1000 km offshore and from 2oS to 28oS (Figure 4). The southern and northern limits of the volume are further set by the meridional extent of the temporal mean surface occupied by SW during the 1990-2010 time period (Figure 4). The upper and lower margins of the constant volume are located at 50 m and 900 m depth, respectively. The common volume is further subdivided into onshore and offshore regions. The onshore region extends from the coast to 250 km offshore. The offshore region extends up to 750 km westward from

the onshore region's western margin (250km from the coast). In order to distinguish the different oxygen supply pathways, we have subdivided the onshore and offshore common volume into equatorial or northern (2oS), tropical or western (2-15o S) and subtropical/southern (15-28o S) regions.

The oxygen transport across the SW margins is calculated as: F=U(x,y,z).O2

where U(x,y,z) is the velocity normal to the SW margins in zonal (x), meridional (y), and vertical (z) directions, O2 is the oxygen concentration. The oxygen transport across the southern margin is then estimated as a total flux that crosses the SW volume from the subtropical region (15-28°S). The oxygen fluxes from the equatorial region is accounted as a flux that crosses the margins of the northern margin (2°S). The tropical waters enter the SW region from the west between 15-2°S.

3. On page 6 beginning in the paragraph in line 16, the main ventilation pathways for the onshore and offshore region are discussed during normal conditions. The authors highlight the big role for the ventilation through the western margin with reference to the red lines in figures 6-a and 7-a. However, it is hard to see this large contribution in the mentioned plots. In addition, the contribution from other boundaries seems to be stronger than the transport through the western margin (e.g. the northern and southern margin). The discussion of the oxygen transport through the western margin remains also unclear in the following paragraph for the El Niño conditions.

We apologies for this misinterpretation and we completely agree with the reviewer's comment that there is no large contribution of western margin on the ventilation of OMZ. The sentence is corrected.

Sentence changed, now reads on page 7 lines 28-29: In normal conditions, the lateral transport into both onshore and offshore regions shows that, on average, oxygen supply occurs mainly from the southern and western margins.

4. On page 6, in lines 19 and 20, the transport of oxygen through the northern boundary

is described as an efficient pathway for oxygen supply for both the onshore and offshore region. However, there seems to be an inconsistency as on page 7, lines 5 and 6, the oxygen transport through the northern boundary of the onshore region is stated to be predominantly northward, corresponding to the positive values of the blue line in Figure 6-b. A clarifying note on which way the oxygen transport through the northern and eastern boundary are defined would be helpful.

We regret this confusion in the mechanisms involved in the SWL changes section. This is now clarified in the new version of the manuscript. Moreover, in order to simplify the interpretation of the oxygen fluxes across the open margins, positive oxygen transport indicates now injection and negative stands for outgoing fluxes.

Added on page 21, in caption of Figure 7: Positive values indicate oxygen supply and negative values illustrate oxygen loss.

5. In evaluating the mean state of the model the authors do not point out key differences between the observational datasets and the model output. As such, the mean oxygen distribution at 400 m depth in the ROMS-BioEBUS hindcast simulation shows almost anoxic conditions (O2 <5 μmol per litre) throughout the core OMZ, while the CARS dataset does not exhibit these low oxygen concentrations at 400m at all. A further difference not pointed out are the zonal surface mean currents modelled offshore at 22S, which is not featured in the observations.

The key differences between the observational datasets and the model output are now included in the manuscript

Added on page 4, lines 17-23:

Although the model represents correctly the circulation patterns, there are some discrepancies between simulated and altimetry-derived surface current in the offshore region. The simulated surface velocities show a well-defined westward current between 95-115oW which is not present in the observations. This discrepancy is likely to be

associated with the high viscosity applied in the vicinity of the open boundaries, which can block the outflow of the current along the boundary and generate a current recirculation. However, this problem appears to have negligible effect on the overall solution in the region of particular interest of this study.

Added on page 5 lines 3-8:

Oxygen-poor waters are present from 50 m to 700 m depth (Figure 4-c,d) and reach values below 5 μmol/l as shown in the vertical structure of observed concentrations (Czeschel et al., 2011, 2015). These low oxygen waters are not present in the CARS data (Figure 3-b). The absence of this poor-oxygen waters in CARS data is likely to be due to the bias in the Winkler titration method, which fails to detect lower oxygen concentrations such as those reported in the ETSP OMZ (Thomsen et al., 2016).

6. While appropriately putting the study in the context of previous observational studies, this study misses out on comparing the obtained results with the previous modelling studies and discussing the differences (i.e. Mogollón and Calil (2017), Yang et al. (2017) and Espinoza-Morriberón et al. (2019)). The discussion of the manuscript should include this aspect.

The results of this study are now compared with the previous modelling studies and we are discussing the differences.

Added on page 9, lines 23-32:

The increase of water column oxygen concentrations during El Niño events leads to a reduction of the SW volume as shown in previous modelling studies (Mogollón and Calil, 2017; Yang et al., 2017; Espinoza-Morriberón et al., 2019). The reduction of SW volume, which occurs not only in the onshore (Figure 5-a) but also in the offshore (Figure 5-b) regions of the ETSP OMZ, reflects the reduction of the most oxygen-poor waters (with concentrations below 5 μmol/l, Figure 5-c,d). Those changes respond to modification in the supply of oxygenated waters from the lateral margins and to a very limited extent from the vertical margins (Figure 7). This supports the results of Duteil et al. (2014a) and Duteil et al. (2014b), who found that lateral oxygen supply is the most effective way to oxygenate the core of suboxic waters. However, this result does not agree with the conclusion of Espinoza-Morriberón et al. (2019) who related the deepening of the OMZ to the passage of an intense remotely-forced downwelling coastal trapped wave.

2.2 Figures:

1. Fig. 1: A discrete color bar according to the contour levels would make a by eye comparison between model and observations easier. Are the x-axes for the panels c and d comparable to panels e and f

No, the axes for panels c and d are different from panels e and f. This is changed and the axes are now identical in the new version of the manuscript. Additionally, a discrete color bar according to the contour levels is now used.

2. Fig. 2: It would be helpful to have some labeled contour levels. From the provided color bar, it seems that the black contour levels in panel c and d mark the 10 umol per litre isoline instead of the 20 umol per litre isoline.

Indeed, the isoline in c and d was marking the 10 μmol/l isoline instead of the 20 μmol/l. We apologize for this inconsistency. This is now corrected in the revised manuscript.

3. Fig. 3: In the caption the model is referred to as CROCO, whereas the labelling is stating ROMS. This should be consistent. Furthermore, I find the color coding of the plot lines in panel a not to be intuitive, even though it is well labeled. Intuitively, I would compare the red with the magenta line and the grey bars with the black line.

Changes were made accordingly. ROMS is now replaced by CROCO in Figure 3 legend.

4. Fig. 4: It seems that the upper and lower margins presented in Figure 4-e and f represent the spatial average over the entire extent of SW in the onshore/offshore region.

What is the associated range of depths? Further, it might be helpful for readability to color the right y-axes and labels in panel e and f in red.

Yes, the upper and lower margins in Figure 4-e,f represent the spatial average over the entire extent of SW in the onshore/offshore region. The associated min (max) depths are 25.1 m (542.8 m) and 50.5 m (964.1 m) for onshore and offshore respectively.

Now page 6 line 23-24: On average, the associated minimum (maximum) OMZ depths are 25.1 m (542.8 m) and 50.5 m (964.1 m) for onshore and offshore respectively.

5. Fig. 5: In the caption the shown variables are described as “thickness of the suboxic waters [m] during (a) normal, (b) El Niño and (c) La Niña conditions.” While this implies some sort of composite distribution, the panels themselves state Normal (1998), El Niño (1997-1998) and La Niña (1998-1999), respectively. Clarify what is shown. Further state the shown variable and its units also in the figure (not just caption) for better understanding.

The figure caption shows now Normal (June-September 1998), El Niño (June 1997-May1998) and La Niña (September 1998 -February 1999) as in the figure. The units and the variable name are now shown in the figure. In addition, to make a comparison with previous studies straightforward, we use a Nino1+2 index for the identification of ENSO events.

Fig. 6: Clarify that positive values for northward and eastward transport indicate a loss of oxygen for the SW layer (see one of the major comments).

Positive transport now indicates oxygen supply and negative transport oxygen loss for all OMZ margins.

Added in old Fig 6 (Figure 7 in the new manuscript) Positive values indicate oxygen supply and negative values illustrate oxygen loss

3 Technical comments:

1. State what the model output time step is. Changes were made accordingly

Added in model configuration subsection, page 3 line 32: The model simulation covers the period from 1990 to 2010, in which the outputs were averaged every month.

2. page 4, line 28, be more precise on where the in-situ measurements come from: oxygen variability recorded at 90-100m at 12oS along the Peruvian coast

Now page 5 line 23-24: Changes were made accordingly. In situ measurements are described in more detail.

4 Typos and language suggestions:

1. page 2, line 8: remain

This sentence has changed to account for comment from Vincent Echevin.

2. page 2, line 32: nanophytoplankton or picophytoplankton

Now page 2 line 12:

Changes were made accordingly. Nanophytoplankton or picophytoplankton were explicitly mentioned in the description of small phytoplankton.

3. page 3, line 5: The model grid

Now page 3 line 19: Changes were made accordingly.

4. page 3, line 10: wind from the CCMP

Now page 3 line 25: Changes were made accordingly.

5. page 3, line 12: remote sensing systems

Now page 3 line 26: Changes were made accordingly. Sentence now reads "obtained from remote sensing systems and conventional..."

6. page 4, line 1: Peru Oceanic Current (POC)

Now page 4 line 15-16: Changes were made accordingly. Abbreviation POC is included

7. page 4, line 1: Peru Coastal Current (PCC)

Now page 4 line 15: Changes were made accordingly. Abbreviation PCC is included

8. page 4, line 6: extends along the equator

Now page 4 line 27: Changes were made accordingly. Sentence now reads: "The observed cold water tongue, which extends along the equator..."

9. page 5, line 3: defined here as waters

Changes were made accordingly. This sentence has moved to the Model output analysis section.

10. page 5, line 3: La Niña

Now page 6 line 14: Changes were made accordingly. Now reads: "La Niña . . ."

11. page 5, line 31: suggests

Now page 7 line 18: Changes were made accordingly. Now reads: " This intensification of suboxic conditions suggests..."

12. page 5, line 33: addition

The trend analysis is removed from the manuscript.

13. page 6, line 8: transport margins

This sentence is removed from the current manuscript version. The explanation of the calculation of oxygen transport across the OMZ margins is shown now in a dedicated subsection.

14. page 6, line 9: consists

Now page 7 line 26: Not applicable. Volume and margins definition were moved to methods section.

15. page 7, line 23: suggests

Now page 9 line 1: Changes were made accordingly. Now reads: “This suggests that...”

16. page 8, line 22: intermediate

Now page 10 line 4: Changes were made accordingly. Now reads: “... is one of the main routes for oxygen supply at intermediate layers...”

17. page 8, line 23: has also been reported

This sentence have been removed following the referee 2 comment.

18. page 8, line 25: supply varies

Now page 10 line 6: Changes were made accordingly. Now reads: “ Moreover, the intensity of the subtropical waters supply varies ...”

19. page 8, line 26: does not show any clear relation

Now page 10 line 1: Changes were made accordingly. Now reads: “... and does not show any clear relation with El Niño intensity...”

20. page 8, line 29: suggests

Now page 10 line 6: Changes were made accordingly. Now reads: “ The weakening of the oxygen supply suggests...”

21. page 8, line 33: The tropical pathway

Now page 10 line 12: Changes were made accordingly. Now reads: “The tropical pathway from the west becomes effective...”

22. page 9, line 1: suggests

Now page 10 line 8: Changes were made accordingly. Now reads: “ This pattern

suggests ...”

23. page 9, line 4: path

Now page 10 line 18: Changes were made accordingly. Now reads: “However, this path...”

24. page 9, line 9: pathway is an essential part

Now page 10 line 34: Not applicable

25. page 9, line 30: useful for the quantification

Now page 11 line 15: Changes were made accordingly. Now reads: “... can be useful for the quantification of nutrient budgets ...”

26. page 9, line 30: nutrient budgets

Now page 11 line 15: Changes were made accordingly. “... can be useful for the quantification of nutrient budgets ...”

27. page 14, caption Figure 1: Peru Oceanic Current

Now Figure 2: Changes were made accordingly. Peru Oceanic Current increased in Figure 1 caption

28. page 17, caption Figure 4: Figure 5-a (in line 1)

Now Figure 5: Not applicable

29. page 18, caption Figure 5: (c) La Niña conditions

Now Figure 6: Changes were made accordingly. Now reads: “... (c) La Niña ...”

30. page 19, caption Figure 6: as well as (d) oxygen consumption

This is not applicable in the new version of the manuscript. Old Figures 6 and 7 are merged following the suggestion of reviewer II. Oxygen consumption are shown in the new Figure 8.

31. page 19, caption Figure 6: Rephrase the second sentence

See the answer for point 30 above.

32. page 19, caption Figure 6: Figure 5

Not applicable.

33. page 20, caption Figure 7: The same as Figure 6

See the answer for point 30 above.

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, https://doi.org/10.1029/2010JC006565, 2011.

Czeschel, R., Stramma, L., Weller, R. A. and Fischer, T.: Circulation, eddies, oxygen, and nutrient changes in the eastern tropical South Pacific Ocean, Ocean Science, 11, https://doi.org/10.5194/os-11-455-2015, 2015.

Duteil, O., Schwarzkopf, F. U., Böning, C. W., and Oschlies A.: Major role of the equatorial current system in setting oxygen levels in the eastern tropical Atlantic Ocean: A high-resolution model study, Geophys. Res. Lett. 41, https://doi.org/10.1002/2013GL058888, 2014a.

Duteil, O., Böning, C. W., and Oschlies A.: Variability in subtropical-tropical cells drives oxygen levels in the tropical Pacific Ocean, Geophys. Res. Lett. 41, https://doi.org/10.1002/2014GL0617744, 2014b.

Espinoza-Morriberón, D., Echevin, V., Colas, F., Tam, J., Gutierrez, D., Graco,M., Ledesma, J., and Quispe-Ccalluari, C.: Oxygen Variability During ENSO in the Tropical South Eastern Pacific, Front. Mar. Sci, https://doi.org/10.3389/fmars.2018.00526,

2019.

Llanillo, J. P., Karstensen, J., Pelegri and Stramma, L.: Physical and biogeochemical forcing of oxygen and nitrate changes during El Niño/El Viejo and La Niña/La Vieja upper-ocean phases in the tropical eastern South Pacific along 86W, Biogeosciences, 10, https://doi.org/10.5194/bg-10-6339-2013, 2013.

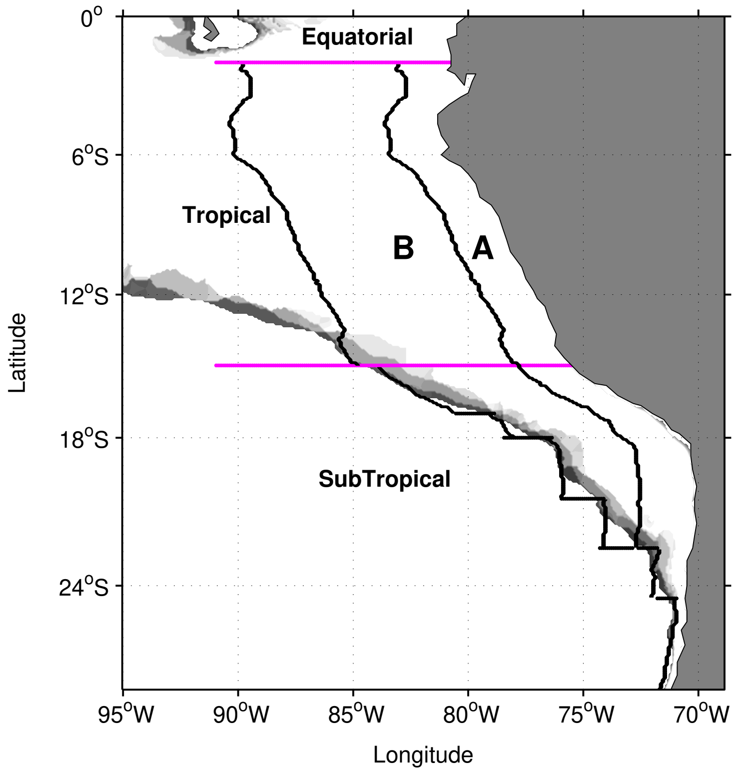
Mogollón R. and Calil, P. H.R: On the effects of ENSO on ocean biogeochemistry in the Northern Humboldt Current System (NHCS): A modeling study, J. of Marine Systems 172, https://doi.org/10.1016/j.jmarsys.2017.03.011, 2017

Thomsen, S., T. Kanzow, G. Krahmann, R. J. Greatbatch, M. Dengler, and G. Lavik, The formation of a subsurface anticyclonic eddy in the Peru-Chile Undercurrent and its impact on the near-coastal salinity, oxygen, and nutrient distributions, J. Geophys. Res. Oceans, 121, 476-501, https://doi.org/10.1002/2015JC010878, 2016.

Yang, S., Gruber, N., Long,M. C., and Vogt,M.: ENSO driven variability of denitrification and suboxia in the Eastern Tropical Pacific Ocean. Global Biogeochemical Cycles, 31, 1470-1487, https://doi.org/10.1002/2016GB005596, 2017

Figure 1. Schematic illustrating the lateral margins of the common volume (black lines) as well as the delimitation of action of different oxygen supply pathways (magenta lines). Gray shadow illustrate the southern limit of the mean OMZ. A represents the onshore region (250 km from the coast) and B indicates the offshore region (250-1000 km from the coast)

Interactive comment on Biogeosciences Discuss., https://doi.org/10.5194/bg-2019-155, 2019.



Equatorial
Tropical
B
A
SubTropical
0°
6°S
12°S
18°S
24°S
95°W
90°W
85°W
80°W
75°W
70°W
Latitude
Longitude

Fig. 1.