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# *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.

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Dear anonymous Reviewer II

We would like to thank referee 2 for the constructive comments, which have helped to considerably improve the manuscript. Detailed responses to referee #2's concerns are listed below. Respective changes are highlighted in bold in the accordingly-revised manuscript.

1. The main point of this study - that advection from the subtropics drives variability in



OMZ volume - is derived from an analysis that is not described clear enough in the text. The authors define a 'common' volume based on the extend of the suboxic waters, but I was not able to clearly determine the location of this volume from the text. Is it the full volume shown in Fig.5? Does it extend over the Equator? I recommend dedicating a separate section in the methods to describe (and maybe add a Figure) and show the volume. It would be particularly interesting to see how the volume evolves over time.

This is now added to the method section of the 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 margins In the present study, we analyse the dynamics of oxygen-poor waters in terms of the suboxic waters (SW). SW are defined here as waters with oxygen concentrations below 20 $\mu$mol/l . As shown in the 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 vary with time and due to ENSO fluctuations. Changes may also occur in the lateral limits of the OMZ. In order to remove the effect of volume changes on the calculation of the oxygen transport across the limits 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 extent are further limited by the SW meridional extent which is 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 750 km long from the onshore 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 (2-15oS) and subtropical/southern (15-28o S) margins.

The oxygen transport across the SW margins is calculated as:

F=U(x,y,z).O2 where U(x,y,z) is the velocity 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 cross the SW volume from the subtropical box (15-28°S). The oxygen fluxes from the equatorial region is accounted as a flux that cross the margins of the equatorial margin (2°S). The tropical waters enters the box from the region between 15-2°S.

2. Related to the above, the authors need to show clearly how the advective contributions were calculated across the surface of the SW volume. Presumably the tracer fluxes are split into x,y,z coordinates somehow (are they remapped on a z grid or are they left on the native sigma grid? The time averaging becomes crucial in these types of analyses (for an example see e.g. Bryan and Bachmann 2014) and needs to be mentioned in the paper. Do the authors quantify a diffusive tendency or does the divergence of the advective supply agree well with the total oxygen tendency in the volume?

The subsection showing how the oxygen fluxes across the OMZ margins were calculated is now added in the manuscript. See above comment.

The model output was analysed on the native sigma grid. Following your comment, we have interpolated the model output on a z grid in the analysis shown in the new version of the manuscript. The divergence of advective supply agrees well with the total oxygen tendency (Figure 1). In the offshore region, oxygen changes due to biogeochemical processes also contribute to the total oxygen tendency. Diffusion plays insignificant role in both onshore and offshore regions.

3. As mentioned by Reviewer \#1, the only quantity evaluated is the pure advective flux



of oxygen. The authors argue that the EUC is the main supply of oxygen in the mean state (but doesn't drive ENSO variability). If resolved perfectly in time, the advective supply of oxygen should vanish! Any exchange across the boundary would be driven by diffusion (see again Bryan and Bachmann for more details). If I would thus interpret the results as mostly driven by eddy diffusion (which is resolved in this setup and thus shows up as advective contribution). This would fit with the view in the literature that the poleward boundary of the OMZ is mostly ventilated by lateral diffusion (e.g. Gnanadesikan et al. 2013, Czeschel et al. 2010). It would be nice to attempt to decompose the advective transport into large and small scale components. At the very least these aspects need be discussed in more detail and also mentioned in the methods.

We agree with the reviewer that the mean advection across a mean oxygen isosurface vanishes. However, oxygen has internal tracer sources and sinks which changes its concentration within the volume. This oxygen-modified waters can be advected across mean surface. For our model results, the simulated oxygen advection appears to be higher than the diffusion terms (Figure 1). It would be indeed interesting to decompose the advective transport into large and small scale components. However, this is beyond the scope of this manuscript. Our goal here is to understand the pathways of oxygen supply into the ETSP OMZ.

4. Finally I think the visual presentation could be significantly improved. I had much trouble following the results section since I had to change Figures/pages all the time. I suggest to combine these timeseries into a larger single panel (perhaps smooth them to eliminate noise and make the ENSO signals more clear). An alternate suggestion would be to present these results as a normalized composite around El Ni\~no or La Ni\~na. There are some other aspects that can improve presentation, which I will describe below. Finally, I think a cartoon/schematic could help the reader grasp the concepts described when reading the paper.

The figure 6 and Figure 7 are now combined in a single panel. We have already applied

5 months moving average, as the El Niño SST anomaly index.

As pointed out by referee 3, and we agree, the composite around El Niño or La Niña may be biased by the short period of the simulation (e.g. El Niño signal will be influenced by the 97/98 strong event). In order to improve the visual aspect of the ENSO events, we now use patches with different colors to differentiate the events.

# Optional Style remarks For the sake of readability I suggest not to indicate the single plot elements [e.g.(see Figure.1, red line and grey patch)], but instead rely on clear figure legends.

In order to answer this optional comment, we have improved the figures representation.

Optional: I think the flow of the text could be improved by rearranging or combining the Results and discussion section. Instead of describing all results first and then interpreting the mechanisms in the discussion, I think it is better to discuss results as they are presented.

We have tried to improve the flow of the text, but still think that the results section should stand alone.

# Specific remarks

Text (line number indicated as "page.line") :

2.8 Yang et al, (2017) GBC could be relevant here.

We thank the reviewer for pointing out this relevant reference

Page 2, lines 7-9 now reads: ... have until recently received only limited attention (Llanillo et al., 2013; Mogollón and Calil, 2017; Yang et al., 2017; Espinoza-Morriberón et al., 2019) .

3.6 I am not familiar with sigma coordinates, but 32 levels seems like a low resolution given the high lateral resolution. Could the authors provide rough estimates how thick



grid cells are in the water column?

The 32 vertical levels allowed a minimum vertical resolution at the surface of about 1.25 m.

Page 3, lines 19-20 now reads:

The vertical levels allow a minimum vertical resolution at the surface of about 1.25 m, giving a reasonable representation of upper layer processes.

3.28 Are these products all publicly available? It would be nice to provide links or even better DOIs to the datasets

CTD and nutrients data from Meteor cruise M91 are available at: Https://doi.pangaea.de/10.1594/PANGAEA.817221 ttps://doi.pangaea.de/10.1594/PANGAEA.817174.

Page 11, line 19-20 now reads:

The Meteor M91 CTD data are available at https://doi.pangaea.de/10.1594/PANGAEA.81722 and the nutrient data at https://doi .pangaea.de/10.1594/PANGAEA.817174.

3.20 and following I think the authors could be more specific and show a difference or at least provide some numbers (e.g. the Root Mean Square difference). Is this agreement better than what one could expect from a coarse simulation or a typical coupled climate model (e.g. CMIP5)

Yes, the model results presented the coastal dynamics better than typical current coupled climate models, as it resolves the small scale processes that are not captured by the coarse resolution coupled-climate models. Difference between simulated and observed fields are now included in Figure 1 and Figure 2.

Page 4, line 23-25 now read:

Vertically, differences are observed close to the shore (Figure 2-f). This differences might be related to the boundaries conditions used in this configuration, which may not reproduce the observed local variability and/ or the difference between the model derived and real topography structure.

Page 4 line 31-32 now read:

The spatial distribution of the difference between the simulated and observed oxygen shows large discrepancies close to the coast (Figure 2-c). This is also the case in the vertical structure (Figure 2-i), where surface waters show significant differences with the observed fields. These discrepancy are probably related to the boundary conditions and surface forcing used in this simulation.

4.9 'Vertically, both simulated and observed temperatures decrease with depth'...it would really surprise me if that wouldn't be the case. Maybe remove?

Sentence removed

4.10 'presents' seems odd in this context.

presents replaced by shows

4.17-20 I do not see what the authors mean with this statement. Where do I see these differences?

These differences comes from NOAA and CROCO simulated Niño 1+2 and Niño 3 SST index (in new Figure 4). However, these differences are no longer visible in the new simulation in which we used longer spinup phase (20 years).

4.28-30 Could the authors explain why they chose this narrow range of 90-100m? How does this look for e.g. thickness of the SWL.

We have used here the simulated data in a depth between 90-100 m to fit with the observed oxygen used to validate the model. This depth range is not related to the SWL.



5.11 I suggest writing these statements out. These [statement(opposite) are linked to a(b)] are hard to read

Statements (now on page 6, line 17-19) now reads:

With fluctuations of SW volume, oxygen concentration within the SWL oscillates, increasing with a reduction of SW volume and decreasing with an expansion of SW volume...

5.18 and Fig. 4. I am again not sure what the volume is over which this was analyzed. Is it from the coast to either one of those black lines in Fig.5?

A definition of suboxic waters volume is now added to the method section of the manuscript. See first main comment for details.

5.19 The authors say: "This shows that enhanced oxygen supply reaches the core..." It is not clear to me if that means that the core OMZ is displaced (out of the control volume) or actually oxygenated.

The core OMZ is oxygenated. The sentence is now clarified.

Page 7 line 10 now reads:

This shows that enhanced oxygen supply reaches and oxygenates the core..

6.9-15 See above. I think this should be moved to the methods, but definitely needs more detail.

Changed accordingly.

6.17 How much do the results depend on SODAs ability to simulate a proper EUC response during ENSO if the EUC sets the mean oxygen ventilation? (Busecke et al. (2019), GRL and Coats and Karnauskas,(2018) Journal of Climate) might be relevant. Here I am very confused about the definition of the control volume. If there are separate offshore and onshore estimates, there must be one fixes boundary? In that case the

OMZ could simply move in or out of the volume. Pleas clarify as suggested above.

The control volume is now defined in the method section 2.3.

There is one fixed boundary which is the 250 km far from the coast that separates the onshore and offshore sub-volumes (see the second main comment).

No, the OMZ is never smaller than the control volume. But along the coast, the OMZ can extend further onshore during La Niña events, being larger than common volume.

In order to compare the present study with the previous studies and to to clarify the interpretation of the supply pathways, we now use a larger control volume which allows to fully investigate the oxygen pathways along the coastal and offshore region. .

6.34 This statement is just dropped and left there, even though I find it very interesting. This would mean that the OMZ is not only modulated by ENSO dynamics but also other internal variability?

It would be indeed interesting to understand the differences in oxygen transport during different El Niño events, which is more likely to be related to the boundary conditions and surface forcings used in this model configuration. However, the analyses of El Niños are beyond the scope of the present study.

7.9 The authors use pathways and directions like North, South etc. It would help to illustrate them in a schematic (see above comments)

A schematic (Figure 3) showing the dominant oxygen supply pathways during the early and late stage of an El Niño, as well as during La Niña events is now added to the revised manuscript

8.23 The introduction of the Atlantic seems to come out of nowhere. Since this is not part of the modeling experiment please move to discussion to avoid confusion.

Sentence removed



9.3-6 Not sure I follow this argument. Again a schematic would help.

A Figure 3 showing the dominant oxygen supply pathways during the early and late stage of an El Niño, as well as during La Niña events is now added into the revised manuscript.

10.2 Are the configurations of this particular experiment archived somewhere? Which version of the code was used? This needs to be expanded to provide reproducibility. I would prefer if the analysis code is archived (e.g. figshare or zenodo).

The data and the code is now at http://oceanrep.geomar.de/46565/

10.3 This seems insufficient to me. Can the authors archive key files (e.g. time-series data and data to produce maps) to a service like figshare or zenodo?

Key files are now at http://oceanrep.geomar.de/46565/

# Figures: - I would urge the authors to refrain from using the jet colormap. It is not perceptually uniform. **Fig.1**: - Please use a diverging colormap for velocities to make the sign shift clearer (see colorbrewer, palettable (https://jiffyclub.github.io/palettable/) and others for good colormaps depending on the software used) - c-f. Pleas unify the x coordinate, either degree or km - c-d. These appear to be 'squished' - Please indicate the section in the map in a/b

Changed accordingly. The x coordinate is now common for all vertical sections.

**Fig.2**: - Again x-labels are inconsistent - It might be beneficial to plot a difference instead of the total field (or overlay that as contour). With this coarse contour spacing its hard to see. - Again indicate section on map.

Changed accordingly. The x coordinate is now common for in all vertical sections.

**Fig.3**: - and following. Why do the authors use a barplot for the NINO3 index and lines for the other...this confused me. - The dashed lines are very hard to read. Pleas plot thicker.

NINO3 is now displayed as line as the other indices.

**Fig.5**: - Can the authors add the change of upper and lower boundary of the OMZ during these times? Would be interesting to see where the change comes from.

The upper and lower margins of the OMZ are now added into Figure 5.

Page 6, line 21-27 now read:

The vertical extent of these oxygen-poor waters varies geographically. The upper margin is located at shallower depths above the core region of the OMZ, at around 50 m depth, while along the equator and along the subtropical gyre the OMZ's upper margin is located at around 500 m depth (Figure 6-d). The opposite pattern is observed in the position of the lower margin, but the relative variations in the depth of the lower margin are weaker than those of the upper margin (Figure 6-g). Strong difference are present between the shelf and offshore regions, with SW lower margin dropping from around 50 m depth within the shelf to around 700 m depth at immediate offshore regions (Figure 6-g).

Page 7, line 4-7 now read:

This can also be seen from the spatial patterns of the OMZ dynamics during the strong 1997/1998 El Niño event (Figure 6-e,h). During this event, the upper margin of the SW (Figure 6-e) is deeper than the SW position during the normal condition (Figure 6-d). An exception is observed west of the Galápagos Islands, where the SW is absent in the normal condition.

Page 7, line 16-18 now read:

Contrary to the strong 1997/1998 El Niño event, the spatial structure of the upper margin of SW during the 1998/1999 strong La Niña appears deeper along the equator and shallower in the core region of the OMZ (Figure 6-f). Less pronounced changes occur in the position of the lower margin between El Niño (Figure 6-g) to La Niña (Figure 6-i) strong events



**Fig.6 7**: I think it would be great to combine these into less panels (as mentioned above).

Changed accordingly

References 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

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 caption:

Figure 1. Time series of oxygen budget components including (red) zonal advection, (blue) meridional advection, (black) vertical advection, (magenta) diffusion and (cyan) biogeochemistry source-sink. Data correspond to onshore (upper panel) and offshore region (lower panel). Red shading refers to El Nino conditions, green shading to La Nina conditions. The same time axis applies to both panels.

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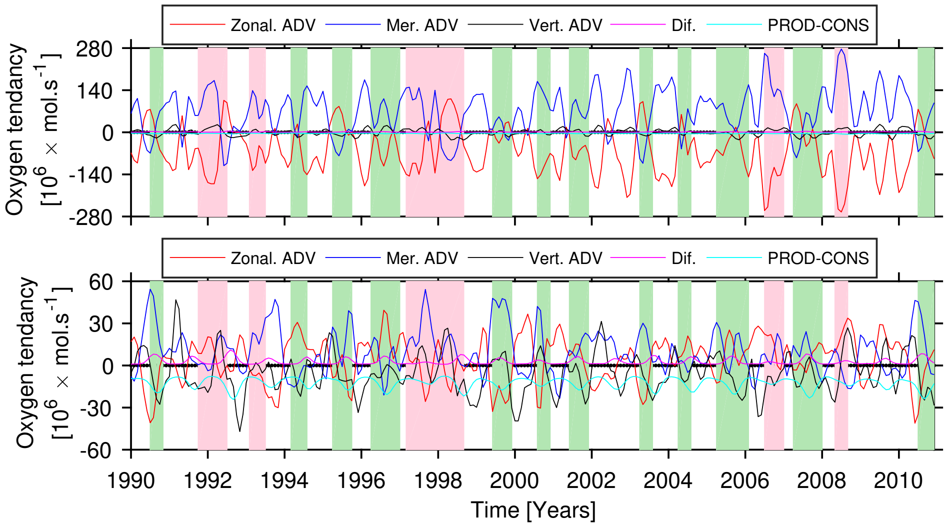
Zonal. ADV
Mer. ADV
Vert. ADV
Dif.
PROD-CONS
Oxygen tendancy
[10^6 × mol.s^-1]
280
140
0
-140
-280
60
30
0
-30
-60
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
Time [Years]

**Fig. 1.**