Ocean Science Discussions

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Reply on RC2

Henrike Schmidt et al.

Author comment on "Causes of uncertainties in the representation of the Arabian Sea oxygen minimum zone in CMIP5 models" by Henrike Schmidt et al., Ocean Sci. Discuss., https://doi.org/10.5194/os-2021-36-AC2, 2021

General Comments:

The authors present an interesting attempt to answer some of the uncertainties in the OMZ representation using the 10 CMIP5 model outputs. This is an important issue as the future prediction of OMZ shows a large inter-model spread which is a reflection of the current status of model OMZs. The models are first clustered into four bands based on vertical profiles of oxygen and then the models exhibiting most similarity with are observations are compared with other models in their water mass formation process — a representative of ventilation. The authors primarily attribute the uncertainties to a higher oxygen content in the southern ocean and the coarser model vertical resolution. However, quantitative assessment of the model discrepancies is not possible by just looking at model outputs, but I understand this is beyond the scope of the study.

The authors have communicated the scientific evidences with good clarity — outlining the scientific methods and results clearly — which is appreciable. The discussion section can be written a bit more orderly. Scientifically, there is very little discussion of the respiration part other than in the introduction section. Also, the methodology part could be a bit more explanatory to ensure transparency. Overall, the manuscript discusses a very important problem seen in nearly all the earth system models and is promising. I therefore, recommend the study alongside stating my serious concerns in detail below.

Reply to reviewer #2

We would like to thank the reviewer for taking the time and for providing constructive and very specific comments, which will help to improve the manuscript considerably. We will add more details to the methodologies and restructure the discussion part for more transparency. Also, we have carefully addressed the comments. The point-by-point responses to the specific comments follow below.

Specific Comments:

- One cause of deoxygenation is solubility which is highly sensitive to the temperature of the oceans — warmer the surface ocean, lesser the solubility of oxygen into the ocean. The representation of ASOMZ in the CMIP5 models will also be a function of ocean temperature in the surface ocean waters. The authors discuss ventilation and respiration to some extent — which I agree are the major causes of deoxygenation. However, I feel the solubility factor might also account to some of the OMZ difference seen among the models. How would the authors justify not looking at the solubility parameter while accounting for the uncertainty in CMIP5 models.

That is a good point that the reviewer mentions. We had a look at the temperature in the upper layers of the Arabian Sea and find slightly lower temperatures there in the models compared to the observations. We compute oxygen solubilities and analyse corresponding model-data differences and will add these findings to the revised manuscript.

- Discussion, Ln 15-24: The authors conclude that in their study there is no definite linkage found between the model resolution and the representation of OMZ — which to me is surprising. Fundamentally, the ASOMZ is located in what we call the shadow zone where ventilation occurs through mixing processes mainly caused by mesoscale eddies [Resplandy et al., 2012, Lachkar et al., 2016]. Increasing the model horizontal resolution should result in more mesoscale eddy activity hence allowing more ventilation (due to eddy mixing) and hence changing the OMZ. An absence of a linkage between the OMZ and model resolution highlights serious issues in the parameterization of subgrid scale processes in the models or the possibility that the increased model ventilation is being balanced by an increase in model respiration. I am not sure if you can conclude that increasing the horizontal resolution has no effect on the OMZ. Please explain your disagreement to my explanation, if any, and state your reasons for making such a conclusion.

Thanks for raising this point. In principle we agree with the reviewer. However, in all models considered in our study the sub grid processes are parameterized. Even those models that have a higher resolution are only eddy permitting. The comparison of these models shows that there is no improvement with resolution of the OMZ representation as long as all models are non eddy resolving. We agree with the reviewer that regional models eddy resolving resolutions definitely improve the representation of the OMZ. We will clarify this point in the discussion to avoid misunderstanding of our conclusions:

'Among the models considered here, we confirm the lack of an apparent correlation between model resolution and better representation of the OMZ in the IO, because we cannot establish a relationship between the oxygen clusters and the respective resolution of the models (Tab. 1 & 2). This is contradicting to what regional model studies show, that ventilation of the ASOMZ occurs through mixing processes mainly caused by mesoscale eddies (e.g. Resplandy et al., 2012; Lachkar et al., 2016). An increased horizontal resolution of the model should therefore lead to more mesoscale eddy activity, which allows for more ventilation and thus a change in the ASOMZ. However, we must take into account that all CMIP5 models are far from eddy resolving. As long as sub grid processes are parameterized an increase of the resolution seems to have no impact on the representation of the OMZ. Inclusion of mesoscale processes in the CMIP6

models resulted in moderate improvements in subsurface oxygen representation (Kwiatkowski et al., 2020).'

- Statement: "There is some evidence that these model flaws are related to a deficient representation of ventilation pathways in models. On this basis, it is hardly possible to say whether the models' biogeochemistry does have deficiencies that are associated with the oxygen representation"

Comment: OMZ is shaped majorly by respiration and ventilation. The study highlights the difference in model mixing of different water masses in the OMZ. However, arising from the fact that OMZ are located in the world's major upwelling zones — which depicts the importance of respiration in shaping OMZ — it is very possible that the model's biogeochemical component is highly (if not equally) responsible for the OMZ volume simulated in the models. Previous studies have addressed the weak representation of biophysical processes in the model, which lays a strong possibility of the deficiencies in the biogeochemical component thus, shaping the model's OMZ. Most of the burden here is placed on the physical parameterizations, whereas the biogeochemical part is a little under looked. Please justify.

You are right. The OMZ volume simulated in the models depends strongly on the models' biogeochemistry as well as the representation of circulation.

The focus of this paper, however, is placed on the physical processes. The underlying physical circulation has a large impact on the biogeochemical model components. Deficiencies of the physical circulation model can be compensated by over-tuning the biogeochemical model. This can be illustrated with the given example: If the upwelling strength in the model is deviating from the observations, this would strongly affect the nutrient supply in the AS and thus the phytoplankton growth that influences the respiration.

We have realised that there is an imbalance between the introduction and the discussion in the manuscript related to the consideration of biogeochemical processes and model uncertainties. We will clarify in the introduction that the focus lies on the physical model components. In addition, the discussion will focus more on the fact that the biogeochemical models also have uncertainties that can influence the OMZ representation.

- If you notice the core region of ASOMZ, then you would find almost all the models largely overestimating primary production in the region. This to me, suggests that large respiration should be occurring in the models. I suggest to check whether respiration is well represented in the models. This will confirm that the problem lies largely with the physical processes or biological processes.

We do not find any confirmation in the literature that almost all the models largely overestimate primary production in the ASOMZ region. Based on the historical data of the CMIP5 models, Bopp et al. (2013) shows that the multi model mean underestimates the NPP in the AS in the upper 600 m. In detail, Roxy et al. (2016) looked at the chlorophyll bloom. According to them, only three out of the here considered 10 models overestimate the chlorophyll bloom in the AS. Two of these models are from cluster HIGH and one belongs to cluster MEDIUM. Thus, we cannot confirm where the uncertainties come from.

- What clustering method is performed to identify the clusters. Please add some details about the clustering technique in the methods section of the manuscript.

As written in the methods section 3.2 we used the Hierarchical Agglomerative Cluster Analysis that was introduced by Johnson (1967). With this method we clustered the correlation between the vertical profiles in the Arabian Sea for oxygen and for salinity separately. We will add some more details in the revised manuscript:

'To reduce the high amount of data of the model output and detect similarities between the models and observations we grouped them with the Hierarchical Agglomerative Cluster Analysis (Johnson, 1967). Here, the correlation between the vertical oxygen profiles was used as the distance measure for the clusters. This means that profiles that are more similar to each other than to others are grouped together in a cluster.'

- There are 10 CMIP5 models used in the study. However, there are ~15-16 ESM models which participated in CMIP5. Please state your choice to choose these 10 models and leave the others.

We chose the 10 models from the CMIP5 models that provided oxygen data for the historical period. We will clarify that in the revised manuscript: "In this study we included all ESMs from the CMIP5 project (Taylor et al., 2012), where output of dissolved oxygen was available. The suit of ten model simulations includes …"

- What is the reason to choose the oxygen threshold value of 60 mircomol/litre?

Unfortunately this is a misunderstanding. We did not choose an oxygen threshold for the analysis but used averaged oxygen profiles in order to be able to compare the OMZs in a way that is as generally valid as possible. The thresholds that are mentioned in the text are used to make different statements, as the behaviour among the models show systematic differences when accounting a specific threshold. We will clarify this in the revised manuscript.

In addition, we add two vertical lines to Figure 4a for more clarity. With this modification, all thesholds that are mentioned in the text are included in Fig 4a.

- Use of T-S diagrams to resolve the water mass characteristics are not quite effective near the shelves. In such a case, how reliable are the estimates taken for the RSW and PGW water masses. Can this be the reason for the models showing large deficiencies in the RSW and PGW masses. What is the author's opinion?

This is a good point. As the formation regions are clearly defined by the geographical location, the T-S properties given here are exactly as simulated by the models. This does not mean that they are close to the observations. Coastal regions and shelf areas are not well resolved in the coarse resolution models. This might be one reason for the models showing deficiencies in the RSW and PGW water masses. We will include this point to the manuscript: …'A possible

reason for this offset in RSW and PGW could be the poor resolution of coastal regions and shelf areas in the coarse resolution models, which includes the shallow marginal seas.'

- Figure 4a: The authors have shown a vertical line of 50 micromol/litre. Why is this value pointed out when the threshold for hypoxia is considered as 60 in the rest of the study.

As mentioned in point 7 above, our analysis does not rely on a single threshold for oxygen. To avoid this misunderstanding in the revised manuscript, we clarified this in the text, as well as we modified Fig. 4. For details please see Point 7.

- It is advised to shorten the discussion section slightly. Nonetheless, it can be organized a bit more clearly.

Thank you for your advice, we will revise the discussion section.

- Summary, Ln 14-15: The authors suggest improved parameterizations of Persian gulf and Red sea water masses in the models. However, I am not confident if improvement in the parameterization of these water mass overflows into the OMZ region would significantly improve the OMZ. Instead, a more local process improvement would be inclusion of eddies into the parameterizations which would affect the ventilation. Please provide strong evidence supporting your solution put forward to the problem under question.

We agree with the reviewer that eddies might have a large impact on the OMZ. This important aspect will be added to the revised manuscript. However, upon the mismatches we find are in addition deficiencies in the representation of the RSW and PGW. To give a complete picture of potential error sources this needs to be mentioned as well.

- The authors discuss a very important problem using the available model outputs. However, using the model outputs it is very difficult to quantitatively separate the discrepancies in the physical and biogeochemical processes. It would be interesting to have a quantitative estimation of the model discrepancies in between the individual processes using some model experiments. I understand this is beyond the scope of this paper, but this can be mentioned as a future scope of the work undertaken.

Thank you for mentioning this point. This is indeed a future scope and we will mention it in the revised manuscript: …'Therefore, an important next step would be a quantitative estimate of the model discrepancies between the individual processes based on model sensitivity experiments.'

- The authors start the discussion section mentioning that all the models underestimate ASOMZ [as seen in Fig4a]. However, if we look at the vertical profile of oxygen in core region of OMZ [fig 5] we see that almost all the models have higher concentrations of oxygen. Is this possible that the models are overestimating oxygen in core region of OMZ? Please clarify.

You are absolutely right. Underestimating the oxygen minimum zone and higher than observed oxygen concentrations in the core region of the OMZ do not contradict each other. Looking at the OMZ volume or expansion as shown in Fig. 4 always needs a predefined oxygen threshold to define the OMZ. An underestimated OMZ thus means that the volume of water containing less oxygen than the threshold is smaller than in observations. Therefore, averaged profiles (Fig. 5) show higher oxygen values.

- It is advised to include how the water masses are calculated in the methods section.

We apologise that the description of the water mass calculation was not clear. We will rewrite and rephrase section 3.3 'Determination of water masses in models' to make our method comprehensible. We have included a preliminary revision of the chapter:

Red Sea Water and Persian Gulf Water (RSW and PGW) are geographically restricted in their formation regions. Figure 1a shows the formation region for RSW and PGW for which temperature and salinity ranges and mean values are determined (Table 2 and associated new figure).

In contrast to that Indian Central Water (ICW) is not geographically restricted in its formation regions. ICW is a mixed water mass and is characterised by a nearly linear temperature and salinity relation that is density-compensated (Tomczak, 1983) and can be identified in T-S diagrams. With this relation, we were able to define upper and lower temperature and salinity limits of ICW in observations and compared those values to respective values from literature values (see Tab. 2). ICW is formed on zonal oriented fronts in the tropical ocean sub-surface layers (Tomczak, 1983). Sprintall and Tomczak (1993) and Schott and McCreary (2001) described the geographical location of the formation region of ICW. Figure 1b shows the grid boxes where these T-S properties are found in the IO in WOA13 observations. These are in line with the description of the formation region as shown by Sprintall and Tomczak (1993) and Schott and McCreary (2001).nTo investigate the formation region of ICW in the models, we followed the same procedure as previously described for the observations. The linear temperature/salinity relation as given by the T-S diagrams of the individual models (Fig. S4) sets the upper and lower temperature and salinity limits (see also Table 2). Different to the observations and the literature, the resulting locations that determine the formation of the simulated ICW are not restricted to the subduction area of ICW. For consistency reasons, we therefore limit the formation region of ICW in the models to the subduction area of ICW as prescribed by Sprintall and Tomczac (1993) and Schott and McCreary (2001). We exclude grid boxes with similar T-S properties that are found outside the subduction region as well as those within the upper 200 m so that the oxygen content of subducted ICW is not affected by the well ventilated mixed layer. Figure S2 shows the respective area for each model and the deepest depth at each location, where the T-S properties are found.

Indian Ocean Deep Water (IODW) originates in the Southern Ocean, where it is

often referred to as Circumpolar Deep Water and Antarctic Bottom Water, before it travels northward into the deep IO and mixes along its way with the surrounding water masses. IODW is thus defined as the densest water mass in the IO north of 60 °S that is found below 1500 m depth (Talley et al., 2011).

Fig 1c shows the formation region of IODW derived from observations for which temperature and salinity limits are determined. IODW in the models is defined in the similar way as in observations. In the models the derived formation regions of IODW in the Southern Ocean differ from those we find in observations (Fig. S3).

The oxygen content of the water masses as listed in Table 2 (and shown in the corresponding Figure) is calculated, for each model and the observations, by the arithmetic mean of all grid boxes of the corresponding source waters.

Technical Corrections:

- Summary, Ln 10: "overestimate oxygen concentrations…." —> I think it should be underestimate.

Overestimate is right in this sentence. We say that the models overestimate the overall oxygen concentration in the Arabian Sea, which is right for our study (Fig. 5) as well as for the CMIP6 models (Seferian et al., 2020).

- Introduction, Ln 16-17: Provide references.

We will add the reference: 'The strong influence of the semi-annually changing monsoon winds on the circulation and resulting upwelling and subduction in the AS shapes the OMZ (Schott & McCreary, 2001; Schmidt et al., 2020).

- Discussion, Ln 16: "Recent studies analyzing…." —> Provide the references.

We will add the reference: 'Recent studies by Seferian et al. (2020) and Kwiatkowski et al. (2020) analysing CMIP5 and CMIP6 model data show that increasing the horizontal resolution does not overcome the major problems with respect to simulating oxygen in the open ocean.'

- It is advised to rephrase a few sentences in the discussion section as they are confusing.

We will go through the discussion section again and rephrase sentences that are hard to understand.

- Summary: Rephrase the first two sentences

We will rephrase the sentences: 'In this paper we compared 10 ESMs from the

CMIP5 historical experiment and analysed their representation of the modelled OMZs in the AS. We systematically grouped the models with a cluster analysis to recognize their similarities. By comparing the representation of water masses and mixing in the models with observations, we identified systematic weaknesses in the ESMs that lead to deficient oxygen concentrations in the AS in the northern IO.'