

# egusphere-2023-1049-manuscript-version2 Review

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**Title:** Multi-model comparison of trends and controls of near-bed oxygen concentration on the Northwest European Continental Shelf under climate change

This is my second review of this manuscript. On my first review I had recommended rejection mostly because a major conclusion was drawn from a correlation that was taken as if it was causal without justification. The authors have addressed this point fairly well in their response by clarifying that the water column equilibrates with atmospheric O<sub>2</sub> on short timescales mostly because of the strong mixing in the region, even if only seasonal. This is a key assumption and thus a welcome addition to the methods and the discussions. I would only argue that the main mechanism that degrades the causal link between O<sub>2</sub> and saturated O<sub>2</sub> is mixing of different waters (that can come from surface regions of different saturation states, e.g., near sea-ice or in upwelling regions) rather than the water age, although one could argue that age correlates well with mixing of diverse surface sources.

That being said, I think the manuscript in its current form requires major revisions before publication. The arguments are a little scattered and hard to follow, the decomposition methodology is a little confusing, there is a little too much information to digest in the form of complex spatial correlations (all of which have to be carefully inspected to determine if they represent causality or coincidence), the figures require improvements, and the main text remains filled with typos and incorrect capitalization/punctuation. Below I provide some major points and minor points for the authors to consider.

## Major points:

- The structure of the paper (mostly the results section) could be improved. I would recommend starting with the oxygen changes, which is the main focus of this study (i.e., move 3.3 to 3.1). Section 3.1 (Validation) could be relegated to an appendix or to Section 4 to discuss the reliability of the results. Section 3.2 ( $\Delta T$  and  $\Delta S$ ) could be placed later when these variables are invoked to explain different mechanisms and correlations. Section 3.4 (contributions to O<sub>2</sub> change) seems that it should include 3.5 (contributions from T and circulation) and 3.6 (contributions from biology). The following Section (3.7; Impact of abrupt changes in circulation) seems a little off-beat given that it is the only section supported by a time series (Fig. 10). Maybe the conclusions from Fig. 10 can be presented also in  $\Delta$ 's that match all the previous results/figures?
- I remain unconvinced that the decomposition of the authors of  $O_2 = O_2^{\text{sat}} \times SS$  is more useful than the traditional  $O_2 = O_2^{\text{sat}} - AOU$ . In the revised manuscript and to the other referees pointing to this in their first review, the authors responded that their method is different in that it focuses on change with respect to a reference period. However, this is entirely doable with AOU as well, simply through  $\Delta O_2 = \Delta O_2^{\text{sat}} - \Delta AOU$ . It thus appears that the SS decomposition only makes the paper unnecessarily convoluted.
- To reduce the number of panels, shorten the paper, and clarify which features/mechanisms are robust across models, maybe the authors could merge some panels, as is commonly done in CMIP studies? For example, Figure 4 in Busecke et al. (2022; doi: 10.1029/2021AV000470) uses dots to indicate where most of the models disagree on the sign of the 2000–2100 O<sub>2</sub> trend in the Pacific

OMZ. In a similar vein, to lend a helping hand to the reader, maybe the authors could use a distinct overlay/hash to indicate where they think the correlations are not to be understood as causal. Overall I think the paper would benefit from summarizing the Figures visually.

- Given that the authors focus on near-bed oxygen and thus benthic ecosystems, it might be good to consider changes in  $pO_2$  rather than  $O_2$  concentrations (as advocated by, e.g., Seibel (2011; doi:10.1242/jeb.049171) and Hofmann et al. (2011; doi:10.1016/j.dsr.2011.09.004)). Better yet might be to consider some metabolic index, e.g., such as the one by Deutsch et al. (2015; already cited by the authors), although that might arguably be out of the scope of this work. Importantly however, the authors should discuss the temperature dependence of the tolerance of benthic organisms to reduced  $O_2$  (e.g., Deutsch et al., 2020; doi:10.1038/s41586-020-2721-y), which might exacerbate the impact of deoxygenation on benthic ecosystems.

#### Minor points:

- "ecosystem" can be replaced by "biological" in many places for clarity.
- Many long multiple-idea sentences could be split up
- Avoid switching between "variables" and "parameters" if possible.
- Avoid the use of "common to X and Y" and instead maybe use "the same in X and Y"
- "Changes in  $\Delta X$ " is incorrect. It's either just " $\Delta X$ " or "changes in X".
- What exactly is the correlation shown in most figures? Over what is it computed? Over the time periods? Both other referees requested equations in the previous review but only some quite unclear text was added.
- Minus signs should be proper minus signs "-" if possible (instead of hyphens "-")
- Sentences starting without a capital letter should be fixed.
- Random capitals mid-sentence should be fixed.
- Typos persist in this revised version.

#### 1. Introduction:

- L65: What are example of sub-lethal effects? I think one could be vision loss (e.g., McCormick et al. (2017; doi:10.1098/rsta.2016.0322)) but maybe the authors had other effects in mind that they should explicitly list here.
- L70-74: Simplify to 2 significant digits and use the same unit (all in % or all in concentration) for clarity.

#### 2. Methods:

- Fig. 1: Add circulation arrows to guide the reader through the region dynamics if possible.
- L180: Explain what climate sensitivity means: After how many years of  $2\times pCO_2$  is the change in  $T$  given?
- L190: Explain what the version differences mean. What has changed between them?
- L191: Explain what do the functional types difference applies to and what these differences are.
- L206: the ocean color data product needs a reference.
- L209: What does "setting low parameter values" do? Which parameters?
- L209: What is "climatological" used for here? I think the authors mean "forced by climatological mean observations". Models can be deemed climatological too.
- L212: Space after dot is missing.

- L216: That the nitrogen deposition field was "downloaded 2011" is not useful. Give a reference instead.
- L216: Anything special or descriptive can be said about tidal forcing? Why two citations and no explanation?
- L219: Is the "zero-gradient scheme" what is commonly known as [Dirichlet boundary condition](#)? If so name it that way.
- L323–239: Rewrite nbias and nurmsd paragraph, which is currently obscure and repetitive. An equation for each term would not hurt, as suggested by the other referees before. Using equations and less text can be good for clarity and brevity.
- L244: The parenthetical is unclear: Enhanced stratification does not limit atmospheric oxygen uptake, at least not on the regional scale, and Changes in circulation include changes in lateral transport by definition.
- L249+: What about "works as an approximation" instead of just "works". Also, what about "saturated" instead of "relaxed": AOU assumes complete saturation. Assumptions about it are not "change a little" but they are "does not change" instead.
- Eqs. (1) and (2) are not useful in my opinion. Add an Equation for  $O_2 = SS \times O_2^{sat}$  instead, if you must. Related: Maybe I missed it, but how are  $O_2^{sat}$  and SS computed? Is  $O_2^{sat}$  an explicit tracer in the models? Is it computed directly from atmospheric  $pO_2$  and in situ  $T$  and  $S$ ?
- L269: The "discrete product rule" is not really a thing, although I guess it could be. (This is my fault for naming it that way, thinking it made sense as a comment. The "product rule" is a thing, but that's not what the authors are using.) Either way, this is basic calculus that does not need a name, so what about simply: "Oxygen change between  $t_0$  and  $t$  can be decomposed as follows:"
- L274: replace "being  $SS_t$ " with " $SS_t$  being"
- Remove Eqs. (4) to (6), and add braces below Eq. (3) terms instead.
- L297+: This false-positives part is a little obscure to me. Can the authors simplify it?
- L305: Replace " $O_2^{sat} / AOU$ " with " $O_2 = O_2^{sat} - AOU$ " to avoid confusion. ("/" can mean "divided by")
- L306: The difference with AOU is not "the reference period". See major point.
- Make it clear here that  $\Delta$ solubility captures most of the change in  $O_2^{sat}$  on the shelf because here intense vertical mixing dominates open ocean contributions.

### 3. Results

#### 1. Ensemble validation:

- So what? What is over/underestimated?
- Delegate to appendix or discussion.
- Fig. 2:
  - Colors would be welcome.
  - Add what is optimal/best in the caption. Is it (1,0), (0,0), or something else?
  - Use words and function names in parentheses in the caption.
  - Row labels are missing (I am guessing they are the 3 models)
  - Maybe bad suggestion: since these are normalized metrics, the axes could be shared and only be shown on the left for the y-axis of the left-most panels and the

bottom for the x-axis of the bottom-most panels (and the "cross" at (0,0) could be shown without the values for tick labels).

## 2. Changes in temperature and salinity

- Fig. 3:
  - (Also applies to most maps) permuting the layout would allow for bigger panels and avoid requiring the reader to zoom in.
  - (Also applies to most maps) units could be better placed near the colorbars rather than in the title.
  - (Also applies to most maps) Discrete colormaps and filled contours could help for humans to extract values and visualize fronts
  - Show past and future  $T$  and  $S$  too in appendix/supplement?

## 3. Near-bed oxygen current state and change

- Fig. 4:
  - Show future  $O_2$ ?
  - What are the red spots when zooming in?
  - Do the high hypoxia incidence coincide with the highest past  $O_2$  levels? Is this meaningful to discuss?
  - Is there no hotspot  $O_2$  decline for GFDL? What thresholds define hotspots?

## 4. Contributions to near-bed $O_2$

- L364: What is "negligible"? 10%? 1%? Less? It is important to be precise and quantify these terms because they are nonlinear (sometimes quadratic or worse), such that if they start gaining momentum as the climate changes, there is a chance they become dominant eventually.
- L376:  $\Delta SS_{O_2}$  notation unused elsewhere.
- Fig. 5: Colorbar tick labels of last column are rounded too aggressively.

## 5. Physical controls of $\Delta O_2$ : temperature and stratification

- L382: "Changes in  $\Delta O_{phy-ch}$ " does not work.
- Fig. 6: Why does the white turn gray for this figure?
- L397: missing punctuation before "de Boer"
- L401: Too many "is" in the sentence.
- L404: Replace "mediated" by "caused"

## 6. Biogeochemical controls of oxygen change: primary production and respiration

- L414: Not "all models":  $\Delta NPP$  looks to be positive for HADGEM (more strong red).

## 7. Impact of abrupt changes in circulation on the emergence of deoxygenation hotspots

- L452: What are "R" and "p"?
- Fig. 10: panel labels are not consistent with previous figures, which have no ending parenthesis, e.g., "a" vs "a)".

## 4. Discussion

- L465: Odd space
- L466: Move Holt et al. reference to just before the comma.
- L494: Remove "by critical hypoxia" (it is clear that you are talking about hypoxia for which you just defined the threshold)
- L493: "Oschlies" is misspelled.
- L533: Remove end of sentence: "testifying (...) in our ensemble" (redundant).

- L536: Capitalize RCP and define it (and cite appropriate reference)

## 5. Conclusions

- L571: There is no "World" in CMIP.