

September 9th, 2023

Author Comments to Reviewer #1

We appreciate the encouragement and thoughtful comments. Below we provide point-to-point responses in red font.

The authors have presented an impressive analysis of interest to how global ocean oxygenation levels are changing. I believe that this study will be of broad interest for not only the detection of climate change, but also in motivating further community research activities. My recommendation is that the study be accepted for publication after only relatively small/minor changes that are detailed below.

Line 220:

Where the authors say "...that does not always capture the phasing of observed variability", can they say instead: "nature climate variability that in general does not reproduce the phasing of observed variability"?

We appreciate the suggestion. The sentence in L220 will be revised accordingly and it will flow much better.

Fig. 4b:

Can the authors point out how much larger these spurious signals (mapping error) are than Pinatubo etc.?

This is an excellent suggestion for comparison, giving an intuitive sense of mapping uncertainty. A recent modeling study (Fay et al., 2023) demonstrates that the effect of Pinatubo caused cooler SST and increased uptake of oxygen following the eruption in 1991. While the study was based on a single ESM large ensemble (CESM1-LENS), it showed over 80TmolO₂ increase in O₂ inventory within a few years, which is comparable to the amplitudes of the variability for both observation and models shown in Fig 4b. The manuscript will be revised around L245 on this point.

Given that the authors have collective familiarity and experience in working with large ensembles, even without doing any additional analysis, how would natural variability uncertainty measure up against any of the stories emphasized here?

We think that the contribution of natural variability is very likely important, but it is also difficult to quantify with the existing observations or a collection of single runs from the CMIP archive unfortunately. As suggested, the best approach would probably be to use multi-model large ensembles with adequate ensemble members of randomized natural climate variability.

The recent study mentioned above (Fay et al., 2023) indeed showed some evidence of the important contributions from natural variability seen as a spread in their Figure 2c. While it's based on a single model, it supports potentially crucial role of natural variability. We think this helps our concluding discussion and the source of uncertainties other than the sampling sparseness around Line 435.

And again without needing to perform additional analyses, it would be good if the authors can comment in a few sentences on the relative importance of anomalies in AOU versus O2SAT in determining the observed trend in O2 for the real ocean. As a related question, if globally extrapolation/mapping were to be performed using AOU and O2 separately on density horizons, would that make a difference? Or even if O2 itself were to be mapped on density surfaces, do the authors believe that this other aspect of mapping is an issue in producing spurious errors?

This paper has focused on mapping and the trends of total O₂ and it is good to refer to the two components, O2sat and AOU. Surface waters are relatively close to the saturation with overlying atmosphere. In general AOU is close to zero in the surface water, thus O2sat plays a dominant role at the surface. The importance of AOU increases with greater depth. If global mapping were to be performed separately for O2sat(S,T) and AOU, the mapping of O2sat would essentially reflect that of temperature with some minor contributions from salinity. Since temperature has been measured with much higher sampling rates, its mapping uncertainty would be significantly lower than that of O2/AOU.

On the second point, distributions of temperature, density and O2sat are known to covary. It would make sense to horizontally interpolate O2 (or AOU) and O2sat on density horizons for at least two reasons. First, temperature variation is much smaller on density surfaces than on z-levels, so the O2sat variation would be better constrained on isopycnals. Secondly, ocean transport in the interior ocean is primarily oriented along isopycnal surfaces, thus, it is very likely that the interpolation (smoothing) on isopycnal surfaces would reduce spurious errors. On the other hand, there could be technical difficulties. Winkler O2 measurements come from sparse bottle samples, and the sampling depths unlikely resolve the locations of the desired isopycnals. The calculation of inventory trends would also depend on the accuracy of isopycnal thickness. In the end, one would have to try and evaluate whether or not and how

much uncertainty can be reduced by mapping isopycnally. While it is beyond the scope of this study, we think it would be a promising topic for future study to compare O₂sat/AOU inventories calculated in depth and isopycnal coordinates and more importantly their impacts on uncertainty. The section 4 would be a good place to add this discussion around L435.

Minor editing points:

Throughout the text, the authors should replace “northern hemisphere” by “Northern Hemisphere”, I believe, to comply with the convention (same for the Southern Hemisphere)

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Also, I believe that “Earth system model” should be used instead of “Earth System Model”.

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 48: change to:

“WOD represents an international collaborative effort among...”

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Lines 56-57: change from “Without any measurements nearby...” to

“For regions without any nearby measurements...”

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 58: change to

“... the OI method will underestimate the declining trend...”

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 76: change "to valid the model" to

"For the evaluation of the model..."

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 175: change "reconstructed model output" to

"...reconstructions fr subsampled model output"

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 177: change "...outputs for the historical simulations to..." to

"...outputs for their historical simulations to..."

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 179: change "The bilinear" to "A bilinear"

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 181: Change "...as the observations" to "...as with the observations"

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 198: Change "...similar to previous studies..." to "...similar to those in previous studies..."

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 203: change "...in the south of Greenland" to "...to the south of Greenland"

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 330: change "There are two regions, the Subpolar and Subtropical..." to "There are two regions, namely the Subpolar and Subtropical..."

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 332: change "bracket the observation where some models" to "bracket the observations whereas some models..."

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 341: change "indicating that the OI method" to "indicating where the OI method"

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 386: replace "gap-filling method used" with "gap-filling method used with observations"

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 394: replace “least square sense assuming the Gaussian” with “least squares sense assuming a Gaussian...”

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Line 396: replace “wide-spread” with “widespread”

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

Lines 425-426: replace “at the spacial scales of 10-100km and timescales of several months” with

“With characteristic spatial scales of 10-100km and characteristic timescales...”

We appreciate the suggestion. If we are allowed to revise the manuscript, the text will be corrected accordingly.

This is the end of our responses. Thank you again for the thoughtful comments.