Review of egusphere-2026-304

Reviewer: Benoît Pasquier

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Summary of the Manuscript

This short manuscript by Wolfgang Koeve and Ivy Frenger offers a valuable analysis of the pertinence and accuracy of apparent oxygen utilisation (AOU) for quantifying the biological contribution to current and future oxygen levels in the ocean. For context, AOU ≡ $O_2^{sat}(T,S)$ – O_2 is an approximation of the accumulated oxygen consumption by bacteria as water transits in the ocean interior. AOU is thus an approximation of true oxygen utilisation (TOU), which is defined as the exact amount of oxygen consumed along the same transit. However, AOU has more practical utility than TOU because AOU only requires O_2, temperature, and salinity. As such, AOU can effectively be "observed" in situ, as opposed to TOU, which requires a model that precisely tracks O_2 consumption. But AOU also has caveats. In particular, its uncertainties are rarely quantified, so that cautious oceanographers rightfully worry about its accuracy and whether it can be used reliably (Ito et al., 2004). Nevertheless, the authors argue that part of these uncertainties are useful as they unintentionally capture biological effects that TOU does not, and thus that AOU is a better metric for quantifying the biological contributions to O_2 levels and future changes. The authors argue that the part of the uncertainty that is useful essentially comes from surface disequilibrium effects due to biology, and that this part generally dominates the uncertainty due to physical processes, which can hence be safely ignored. In summary, the authors argue that AOU can be safely used in more contexts than currently recognised, with broad implications for studying past and future ocean climates.

Overall Recommendation

This is a very nice and interesting study, that I hope will be promptly published in Biogeosciences, but I don't think it is ready yet. My overall recommendation is to send the manuscript back for revisions with the intent to publish once all issues are addressed. I must note that I hesitated marking these as "major" as they affect most of the manuscript, but it is quite short, so that in practice I think these revisions will not take that much work, so I ended up marking them as "minor".

Principal criteria	Excellent (1)	Good (2)	Fair (3)	Poor (4)
Scientific significance	✓			
Scientific quality		✓		
Presentation quality			✓	

While I understood (I think) the details of the paper, the process of understanding was greatly hindered by some choices made by the authors, and some missing pieces in the explanations. I list my Referee General Comments (GC) first and then my more detailed Referee Comments (C) below.

General Comments

GC1. **"debt"**: I see a terminology issue here. Maybe there is precedent in the literature that I don't know about, but I find "O_2 debt" a little confusing here, and I feel like it does not fit. To me, "debt" means something that is owed or that must be repaid/rectified somehow. As far as I understand, there is an existing concept of "O_2 debt" used in biology to describe the oxygen deficiency in an organism (e.g., Taylor, 1982), but that does not fit here either. I strongly suggest avoiding this terminology of "debt" and to instead rely on the well-established, existing terminology that the authors already use anyway.

GC2. **Biological contribution**: I have carefully thought about decomposing drivers of oxygen changes before (Pasquier et al., 2024) and yet, on my first attempt, I became more and more confused about what the authors were trying to do with their comparisons between AOU and TOU as I read through the manuscript. The fact that some statements are simply incorrect about what AOU and TOU are did not help (see, e.g., **C27**, **C28**, **C29**). My main issue is that the authors did not clearly define what the oxygen's biological contribution is. It would be much clearer in my opinion to define it as the tracer O_2^{bio}:

$$O_2^{bio} \equiv O_2 - O_2^{abiot}.$$

This definition (the "≡" symbol means this is a definition, not a mere statement of equality, although some prefer ":=") is clear and intuitive: The biological contribution is the residual between the base state and the abiotic state. This can be written as the natural decomposition, $O_2 = O_2^{bio} + O_2^{abiot}$.

Then one can very simply show that

$$O_2^{bio} = \left(O_2^{pre} + TOU\right) - \left(O_2^{pre} - O_2^{dis,bio}\right) = O_2^{dis,bio} + TOU,$$

and proceed to compare AOU and TOU to O_2^{bio}. Or proceed to show that

$$AOU = O_2^{bio} + O_2^{dis,phy}$$

and proceed to show that $O_2^{dis,phy}$ is small, so $AOU \approx O_2^{bio}$ (Plotting $O_2^{dis,phy}$ would be helpful for this argument.)

GC3. **AOU/TOU sign convention**: Going against the well-established sign convention is not only confusing but also technically incorrect. The term "oxygen utilisation" clearly means that it accounts for the amount of oxygen consumed, which can only be positive (there is no "negative consumption"). The author's choice to switch the convention reads as absurdly as, e.g., "spending minus 10 euros for a meal" or "using −10 L of petrol to go there". I **strongly** suggest the authors should reconsider this convention choice.

GC4. **Figures**: Some figures require quite some energy to parse and understand. In the days of AI-assisted coding, LLMs can be used very efficiently to make publication quality plots, with colors, legends, text labels, and so on, in minutes. I have laid out many detailed comments below about them, and while some may be a matter of taste, they are grounded in fairly consensual principles in the science of making scientific figures. I think this manuscript would greatly benefit from better figures.

Comments

C1. N cycle effect: What about denitrification? Is that cause for concern too as it could de-correlate ∂O2/∂t and ∂DIC/∂t?

C2. "confronting the model" is used throughout instead of just "running the model". This is a matter of style I guess, but it appears a little awkward for me.

C3. No space between unit and element, e.g., "mmolC / m³", not "mmol C / m³" otherwise it parses as "mmol times C per m³" instead of "mmol of carbon per m³". This applies to the entire manuscript, including figures and tables. Please check carefully.

C4. Use "×" symbol for multiplication instead of "*". This applies to the entire manuscript, including figures and tables. Please check carefully.

C5. The use of "variant" is a little confusing when the authors real;y mean "model configuration". Please clarify and be consistent.

C6. Throughout, the authors use "A (B, C)" or "A and B (C)" to refer to "A, B, and C" or simply "A, B, C". These inconsistencies are a little distracting and confusing sometimes.

C7. The authors use the word "idealized tracers" for preformed and regenerated tracers, but this is incorrect : These tracers are not idealised, they are just tracers that cannot be observed and must be modelled. This is because models allow us to "tag" the preformed/regenerated property onto the tracer as it enters/leaves the surface. I suggest to just call them "preformed" and "regenerated" throughout.

C8. L14: "with the atmosphere" → "with the surface"

C9. L24: quantity → metric

C10. L25: given → calculated from

C11. L25: concept → assumption

C12. L44: Why is it pragmatic?

C13. L65: integrated? over the entire ocean? Please clarify.

C14. L85: "We implemented": Does that mean the authors added the functionality (for simulating preformed tracers) to the model? Or simply that they used an existing functionality in the model? Please clarify.

C15. L85–90: The presentation of preformed tracers can be simplified. For example, what about:

> The preformed tracers DIC^{pre}, O_2^{pre}, and PO_4^{pre} represent the DIC, O_2, and PO_4 that would be transported and mixed conservatively from the surface into the interior without any interior sources or sinks.

C16. L90: A common name for these "remineralized" tracers is "regenerated". I understand this might not be the preferred term for the authors, but it is widely used in the literature when decomposing tracers into preformed and regenerated components.

C17. L108: This is incorrect :

> Within the interior ocean DIC^{sat} is a passive tracer, i.e. has no sources or sinks.

Passive tracers are tracers that don't participate in the dynamics, as opposed to active tracers, like temperature and salinity, which affect density. I think the authors mean "conservative" here.

C18. L153: As for L108, I think the authors mean "conservative" here .

> That is, computing O_2^{sat} can give a smaller value compared to O_2^{sat} from an explicit O_2^{sat} tracer which is computed at the surface given surface temperature and salinity and mixed passively in the interior ocean.

I think the key word that is missing here is "non-linearity": O_2^{sat} is a nonlinear function of *T* and *S*, so that even if *T* and *S* were transported conservatively, O_2^{sat} itself may not be conservative. This is a common issue with "derived" tracers, such as potential temperature, which is not exactly the same as conservative temperature (e.g., Jackett et al., 2006).

C19. L169–178: This paragraph is confusing to me. It is about how difficult it is to compute $DIC^{dis,bio}$ compared to $O_2^{dis,bio}$.

- **a.** The explanation of the difference is confusing. Is it the reason for the difficulty the size of the atmospheric and ocean reservoirs? Or is it the fact that DIC affects atmospheric CO2 and the climate? Or both? This is unclear in the current phrasing. Please clarify.
- **b.** What is different between the "normal" model and the "AllPumps" model? Aren't all the marine carbon pumps turned on in the default setup? Is that an "additional" experiment? Please clarify.
- **c.** In the "NoBioPumps" model, the atmospheric CO2 is still allowed to evolve but the total (ocean + atmosphere) carbon is conserved, presumably at the preindustrial level. But then that means that the surface DIC and atmospheric CO_2 are higher, so the climate is warmer, and so the ocean is also warmer, and the circulation is different, and so on. Please clarify exactly how the steady-state "NoBioPumps" model looks like. In particular its climate and its ocean circulation. This seems important to interpret the results.
- **d.** The authors state (here and later in the results) that "there is no meaningful definition of an abiotic DIC tracer". What "meaningful" means here is unclear and appears to be in direct contradiction with what the authors actually do, which I consider to be meaningful. So I disagree with this statement, even if it is open to interpretation. I would suggest avoiding general statements like this one and simply explaining the factual reasons behind the authors' methods. I don't understand why the "NoBioPumps" model's DIC is not a meaningful definition of an abiotic DIC tracer, since it is exactly that: a model configuration where the biological pumps are turned off, so that the ocean carbon cycle is purely abiotic. Please clarify.

C20. L195: A 17-character-long superscript is, to say the least, a little unwieldy. Surely it's possible to come up with better notation here. I also must admit I dislike the COU* and BGC* notation. I am actually having a hard time tracking these convoluted model configurations. I also don't see the point of the "COU" (and "AllPumps") notations at all, since these are the default configuration. A table/matrix or a diagram showing what is turned on/off in each model configuration would be very helpful.

C21. L222–224: Sentence is hard to parse and confusing. Why mention cooling in this context? Shouldn't we assume this means this is a steady state, such that there is no cooling? Please clarify and simplify.

C22. L229: "estimate of estimates of" → "estimates of"

C23. L239: Why is "biological" in quotes?

C24. L239–242: $O_2^{dis,bio}$ and co were already defined in the methods section, so just use them. E.g., replace

> We refer to this 'biological' contribution to the total O_2 disequilibrium as $O_2^{dis,bio}$ (...)

with

> This 'biological' contribution is quantified by $O_2^{dis,bio}$ (...)

C25. L241: Why is abiotic in quotes?

C26. L244: If the authors agree to avoid the term "O_2 debt", they could simplify

> where waters with a large O_2 debt from organic matter degradation return to the surface

to something like

> where waters biologically stripped from their original O_2 return to the surface

C27. L245–147: This is an incorrect (or at least ambiguous) definition for TOU:

> TOU is an appropriate measure of the accumulated O_2 utilization of interior ocean waters since last contact with the atmosphere

No, TOU is the accumulated O_2 utilisation of interior ocean waters since last contact **with the surface layer** (rather than with the atmosphere). That surface layer is exactly the volume in the model where the O_2^{pre} tracer is reset to total O_2 (and TOU reset to zero).

C28. L245–248: This is also incorrect :

> The fact that AOU is larger than TOU (Fig. 1a, c, e) in magnitude indicates that (...) TOU is (...) in fact not a good measure of the total accumulated O2 debt associated with the degradation of organic matter in the interior ocean

The point of TOU is precisely to account for the **true** oxygen utilisation in the ocean interior. The fact that AOU is not equal to TOU is by no means an indication that TOU underestimates or overestimates oxygen utilisation; it only indicates that AOU is an inexact approximation of TOU.

C29. L248–249: This is incorrect :

> AOU, in turn, adds the information of the effect of biologically induced undersaturation of waters at the beginning of their next journey through the interior ocean. AOU equals TOU+$O_2^{dis,bio}$ (...). It hence provides a very reliable global state estimate of the total biological effect on O_2, and we will discuss in the following to which extent AOU agrees with TOU+$O_2^{dis,bio}$ in a changing climate and for other variants of our model.

AOU does not “add” any information. I understand the authors mean that AOU is affected by the state of oxygen saturation when waters leave the surface layer, which would be correct, but that is not what the sentence says.

This goes back to my general comment **GC2**: Without a clear definition of what the “total effect on O_2” means, the statement is just an empty assertion on undefined terms. I think using my recommended definition for O_2^{bio} would make this much clearer and more precise.

C30. L259: What about “of the former difference” → “of ΔAOU” for clarity?

C31. L268: “from” → “with”

C32. L314–317: This is convoluted and **very** unclear:

> We refer to the fraction in DIC which can be attributed to the soft tissue pump as ‘soft tissue pump carbon’, C^{soft}. In analogy to our findings above, we consider C^{soft} to be a composite of (a) C^{soft} accumulated since last contact with the atmosphere and (b) a recirculated biotic component of the carbon disequilibrium.

What is C^{soft}? It is not really defined here. Saying it is “a composite of (a) and (b)” is open to interpretation: What is a “composite”? Worse, (a) includes C^{soft} itself. Thus even if “composite” was clearly defined, this would still be a circular definition. Furthermore, “a recirculated biotic component of the carbon disequilibrium” is quite convoluted, for no reason. Much clearer would be **an equation**! I assume that it is

$$C^{soft} = DIC^{remin} + DIC^{dis,bio,COU*\text{-}BGC*},$$

given the parenthetical in the abstract. This equation (or the correct equation if mine is incorrect) should be in the main text. And $DIC^{dis,bio,COU*\text{-}BGC*}$ should be removed from the abstract because it’s too obscure without a proper definition, which the abstract is not for. I also reiterate the comment I made in **C19.d**.

Figure comments

C33. Remove author signature overlaid on the side of almost every panel in every figure (main and supplement).

C34. Colormap choices: Use diverging colormaps for diverging data (disequilibriums) and sequential colormaps for sequential data (AOU, TOU, etc.) Applies to

- Figure 1c–j.
- Figure S1a (and possibly c and d but cannot tell from hidden titles/units).
- Figure S2a–c (all panels).

C35. Figure 1:

- **a.** Remove nonsensical x-axis ticks in panels a and b.
- **b.** Remove author signature overlaid on the side of every colorbar
- **c.** panel j title is cropped
- **d.** The “transect” is a little confusing: Atlantic goes from 70°N to 80°S, but then there is a 60°S indicated over the Antarctic, and then back to 80°S for the Pacific. Maybe a map can be added in the supplement to clarify the “transect” line?

C36. Figure 2:

- **a.** panel a:

   i. "ΔO_2^{util}" in the y-axis label has not been defined. Just use "ΔO_2" since it's an axis for changes in oxygen, and not all of them are about utilisation anyway.
   ii. Title isa also incorrect
   iii. "Temporal development" → "Time series"
   iv. compliment: labels next to the data is great!
  b. panels b and c: Place labels next to the data like in panel a.
  c. all panels: second y-axlis ticks can be removed.

C37. Figure 3:
  a. Add some color and a legend or some text labels to help the reader.
  b. Format tick labels the same (currently a ".0" appears only on the y-axis)
  c. Use better titles: they are all technically "state estimates", so panel (a) title is unhelpful, and the last 2 are identical, which is also unhelpful.

C38. Supplementary figures: It would be convenient and helpful to place the captions with the figures instead of on separate pages.

C39. Figure S1:
  a. White band covering panel c) title means we don't know what is plotted.
  b. White band covering panel d title means we are unsure if it is just O_2^{pre} that is plotted.
  c. Remove author signature overlaid on the side of panel c
  d. Remove author signature overlaid on the side of panel d

C40. Figure S3: x-axis ticks labels are too small and formatted with unnecessary leading zeros.

C41. Figure S6: Add a legend or some text labels to interpret the different time series at a glance.

C42. Figure S7: place labels next to data.

C43. Figure S8: x-axis ticks labels are too small and formatted with unnecessary leading zeros.

Final Remarks

I think this is a very nice and interesting study that will benefit a wide audience once it has been polished and published in Biogeosciences. Congratulations to the authors for thinking about AOU and TOU in this novel way.

Checklist

Does the paper address relevant scientific questions within the scope of BG?	Yes
Does the paper present novel concepts, ideas, tools, or data?	Yes
Are substantial conclusions reached?	Yes
Are the scientific methods and assumptions valid and clearly outlined?	Almost
Are the results sufficient to support the interpretations and conclusions?	Yes
Is the description of experiments and calculations sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)?	Yes
Do the authors give proper credit to related work and clearly indicate their own new/original contribution?	Yes
Does the title clearly reflect the contents of the paper?	Yes
Does the abstract provide a concise and complete summary?	Yes but improvable
Is the overall presentation well structured and clear?	Mostly yes
Is the language fluent and precise?	Fluent yes, could be more precise
Are mathematical formulae, symbols, abbreviations, and units correctly defined and used?	Mostly yes
Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated?	Yes, see comments
Are the number and quality of references appropriate?	Yes
Is the amount and quality of supplementary material appropriate?	Yes

Bibliography

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