

Comments on Hoogakker et al. Reviews and syntheses: Review of proxies for low-oxygen paleoceanographic reconstructions.

This is a comprehensive review that covers all aspects of proxies for oxygen deficiency as well as a broader suite of related biogeochemical processes. Given current interest in marine deoxygenation, it is certainly timely and will be widely read by the extensive research community working on oxygen proxies. The structure of the review is quite complex, with a lot of sections and subsections, and would benefit from some reorganisation. I have made specific suggestions below, as well as some editorial suggestions and comments directly on the pdf.

Response: thank you for the thorough and constructive comments, including on the pdf. We especially appreciate the suggestions for improving structure and clarity throughout and will make sure these are implemented in a revision.

Suggestions for improving structure

1) The Introduction mainly deals with the state of oxygen in modern oceans, drivers of deoxygenation and the difficulties of modelling current and future oxygen concentrations. The final paragraph of the Introduction (lines 119-143) stands out because it discusses in some detail, and at some length, the difficulties of representing oxygen in models of ocean physics. This may be important background information, but it gives the impression that it is what the review is about. The actual topic of the review is referred to only in the final sentence, where it appears almost as an afterthought ('We also need proxy-based oxygen reconstructions....').

Response: based on this and the comments of Reviewer 2, we will remove lines 119-142.

The rationale for the review, and its structure, are only outlined later in sections 4 and 5. I would suggest some editing of lines 119-143 to make this paragraph a bit shorter and less detailed and then following it with the justification for the review and its format, currently given in sections 4 and 5 (on p. 8). The section on proxies (currently section 2) would then follow on logically from this introduction.

Response: we will reorganize sections 2, 4 & 5 as suggested.

2) Section 3, Figure 1. You introduce the term 'Oxygen Deficient Zone' (with capitals) for the first time in Fig. 1, whereas oxygen minimum zones (without capitals) are first mentioned in the Introduction; subsequently, the terms are referred in the text as ODZs (54 times) and OMZs (25 times), so together they figure quite prominently in the text. Fig. 1 shows the ranges of oxygen concentrations that each of these two kinds of zone is associated with, which would imply they are different. However, it's never explained what the terms mean and what, if any, are the differences between them. You often seem to use

ODZ as a synonym of OMZ (e.g., p.46-54). Section 3 would be the obvious place to clarify whether these terms refer to different things, or whether OMZs are a particular kind of ODZ.

Response: we will make sure both terms are capitalized at first use. In answer to the question, the two terms really come from different literatures, with ODZs being used primarily in the nitrogen literature with the implication that an ODZ is an OMZ with low enough oxygen levels that denitrification may occur. Hence the frequent usage in the nitrogen isotope section. We will include a short explanation of this in Section 3.

Perhaps you could also mention in Section 3 the different units used to measure oxygen levels and maybe also the conversion factors for switching between them. In this case, the section heading could be simplified to 'Terminology and units'. You seem to use $\mu\text{mol kg}^{-1}$ consistently, except in a few places where other units creep in. These include nM in line 1527; $\mu\text{mol/L}$ on Fig. 10 axis (p. 62); μmol on axis of Fig. 13 (p. 70).

Response: we will simplify the section heading. We will add a short discussion of units, and correct the axis on Fig 13 to $\mu\text{mol/L}$ and alter the units on nM to nmol/L for consistency.. Unfortunately, the conversion factors between O₂ units are not straightforward as the temperature, salinity, and/or density of seawater usually needs to be accounted for. Also see comment by Ellen Thomas.

3) p. 21 and 22 - Section 6.2.4 (Organic carbon and trace element burial) and Section 6.2.5 (Other factors controlling trace element metal preservation/metal isotope fractionation). Perhaps I'm misunderstanding, but given the title of section 6.2.5, I'm unclear why these two sections are given equal status. If you rename 6.2.5 'Factors controlling trace metal preservation and metal isotope fractionation' (i.e., delete 'Other'), then you could renumber this section as 6.2.4 and place the existing Section 6.2.4 as a subsection of it (6.2.4.1), along with those current numbered 6.2.5.1-6.2.5.5.

Response: we will do this.

4) Section 6.6. This whole section seems overly complicated and quite confusing. The short introduction (6.6.1) mentions only benthic taxa, whereas section 6.6 covers planktic taxa as well. The following subsections 6.6.2 to 6.6.6.2 switch twice from benthic to planktic with two sections on methods in between. I would suggest putting everything relating to benthic forams together under one heading (split into two subsections), followed by a section on planktic forams. So the arrangement would be something like this -

6.6. Foraminiferal assemblages

Under this main heading you could add one or two sentences (not a separate section) to introduce the topic.

6.6.1. Benthic foraminifera

6.6.1.1. Relationship to bottom-water oxygen and proxies (your 'Historical perspectives....' Section).

6.6.1.2. Factors influencing proxies and their interpretation. This would include your current section 6.6.6.1, which includes two biological topics: the interplay between oxygen and the organic matter supply, and nitrate respiration.

6.6.2. Planktic foraminifera

6.6.2.1. Relationship to water-column oxygen. Perhaps this could combine your sections 6.6.3 and 6.6.6.2 since there only seems to be a tenuous distinction between them.

I'm not sure what to suggest for your sections 6.6.4 and 6.6.5 (which I think could be combined) and your section 6.6.7 (Marine archives and limitations). Are these just about benthic species or about both benthic and planktic species? If the former, then I would put them after the benthic part. If the latter I would put them after the planktic part.

Response: we will make the section less complicated in our revision, following the various reviewers suggestions where possible. We propose to include a paragraph on planktics at the end of each benthic-focused section.

Section 6.6.8. is also problematic. First, the remarks about the importance of images (lines 2105-2112), which come under this main heading, could be merged with lines 1995-2001 (section 6.6.5), with which they largely overlap. Second, I don't believe that 6.6.8.1 and 6.6.8.2 are sufficiently different to merit separate subsections. If lines 2105-2112 disappear, then you could combine 6.6.8.1 and 6.6.8.2 as section 6.6.8 with the title 'Future directions and open questions.

Sections 6.6.8.1 and 6.6.8.2 will be merged, and we will also merge all non-repeated comments under 6.6.8 into section 6.6.5

Section 6.6.9 Contribution to Morphological Proxies. I'm not convinced that this belongs in the section on foraminiferal assemblages as proxies. It reads more like an introduction to the next main section on foraminiferal morphometrics (6.7). I suggest you combine it with Section 6.7.1. It also overlaps to some extent with section 6.7.2.2.

We will combine this with the existing section 6.7.2.2.

Other points

Are the first three words of the title a statement of the manuscript type? If not, then I suggest shortening it, e.g. – 'Proxies for low-oxygen paleoceanographic reconstructions: reviews and syntheses'.

Response: yes they are a statement of the manuscript type.

9. Section 6.1.1. I'm not sure that the statement - 'The presence of laminations is a key indicator of conditions that are inconsistent with the survival of benthic fauna beyond seasonal timescales' (line 255-256) is necessarily correct. Microbioturbation that is not visible to the naked eye has been described from laminated sediments in the Santa Barbara Basin (e.g., Pike et al., 2001 *Geology*, 29, 923– 926). This presumably reflects the presence of meiofaunal organisms such as nematodes and forams, which can survive on very little oxygen (or in the case of forams no oxygen).

This is a good point and this statement will be removed.

10. Please specify here whether you are referring to low resolution CT scanning or high resolution micro-CT (μ CT) scanning.

Response: It is not low-resolution because some CT machines can go down to 30um resolution. It's not a micro-CT per se because it cannot accommodate the whole section. We can refer to it as standard-resolution.

Line 623 etc. The Carter et al. (2020) paper doesn't seem to be included in the reference list.

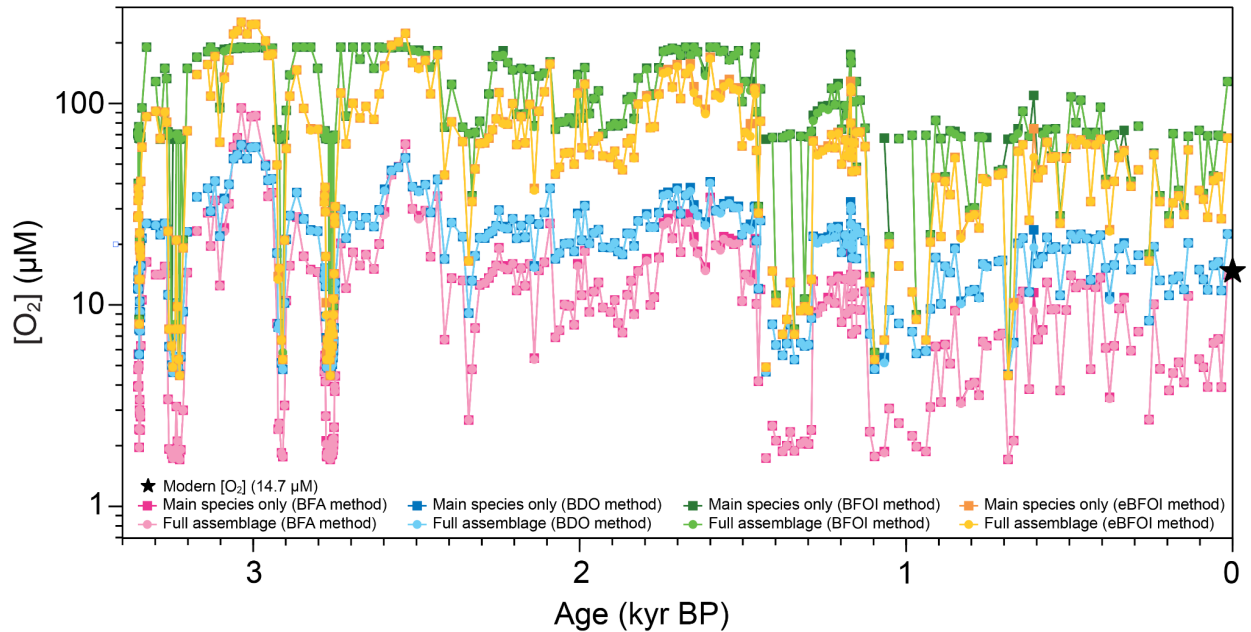
Thank you for catching this. It will be added.

34, Line 1006. You define BHP in line 1002, but you don't explain anywhere what BHT means, as far as I can see.

Thank you for catching this. It will be added in line 1002 ("a bacteriohopanetetrol (BHT) isomer with unknown stereochemistry, BHT-x...").

1. 70, Fig. 13 caption says that the figure compares 4 oxygen indices, in each case based on the main species and the complete assemblages. Data for different indices are shown in different colours and the legend indicates two shades of each colour, one for main species, the other for complete assemblages. However, the figure includes only four lines of data (green, yellow, blue, pink), one for each index, with no differentiation between main species and complete assemblages.

There are actually 8 lines here but substantial overlap makes them hard to see. Thank you for bringing this to our attention. We will play with altering symbols to make the figure clearer or be explicit about the overlap in the figure caption.



71. Section 6.6.4. Analyses and required resources. You refer to ‘wet or dry sieving to separate different size fractions’. It would be useful to say a bit more about the use of different size fractions (usually 63, 125, or 150 μm, sometimes 32 or 250 μm) because these have a strong influence on the composition of foraminiferal assemblages and so are an important issue when analysing them.

Response: we could add some statement, but note that size fraction can vary considerably and can only influence the results? Reviewer 2 suggests shortening this section... We can recommend to use only the size fractions that have been used for the calibration of the transfer functions, because otherwise the results will be biased.

- 72, 6.6.6. Section heading. Here and elsewhere, I’m not sure that ‘Proxy drivers’ is the best expression. It doesn’t sound quite right. Perhaps ‘Environmental influences (or ‘controls’) on proxies’ would be better.

Response: we will rename headings using the term “Environmental influences” rather than drivers.

- 72, Lines 2004-2004. Some metazoans can survive at very low oxygen concentrations. For example, high density, although low diversity, assemblages of nematodes flourish at 0.05 ml.L⁻¹ off Costa Rica (Neira et al., 2018, *Frontiers in Marine Science*). A polychaete species is dominant at oxygen levels of 5-6 μM on in the Pakistan margin OMZ (e.g., Jeffreys et al. 2012, *Marine Ecology Progress Series*).

Response: good point We will remove the clause “compared to other benthic microorganisms such as nematodes or ciliates”

Lines 2044-2045. I’m not an expert in this, but from what I understand, the storage of nitrate allows them to live in the absence of nitrate as well as oxygen. So having stored the nitrate, they can migrate to even deeper sediment levels where there is even less competition and danger of predation. When the nitrate stored in vacuoles is exhausted, they move back up into the nitrate zone and refuel.

Response: yes, we can add this detail. We will follow the suggestion by Ellen Thomas, and add a section foraminifera before the relevant proxy sections. This will be a good place to clarify that detail.

Line 2090. I’m not sure what you mean by complete foraminiferal assemblages. For modern faunas, this term would refer to the live plus dead assemblage. Obviously, that can’t apply to fossil assemblages. Perhaps you could call them ‘mixed assemblages’

Response: we mean to refer to assemblages that take into account all species rather than only one of a few indicator taxa. This will be clarified in the text.

Lines 2116-2118. You could mention that foraminiferal populations can fluctuate over inter-annual, as well as intra-annual time scales, even in the deep sea. Also, it would be worth adding a few words to touch on the wider issue of temporal and spatial heterogeneity and the need to analyse replicate samples in order to provide a realistic assessment of the species-level composition of modern assemblages.

Response: this can be added.

6.6.8.2. Lines 2140-2145. There’s also ancient DNA, which can reveal ecosystem changes over historical and longer time scales across a wide range of taxa. I think this will become an increasingly important tool. For example -

- Barrenechea Angeles et al. (2023). Encapsulated in sediments: eDNA deciphers the ecosystem history of one of the most polluted European marine sites. *Environment International*, 172, 107738. <https://doi.org/10.1016/j.envint.2023.107738>.

- Pawlowska et al. (2022). Ancient foraminiferal DNA: A new paleoceanographic proxy. <https://doi.org/10.5194/egusphere-egu22-9392> EGU General Assembly 2022

Response: thank you for this suggestion. We will add a line mentioning this emerging direction as well.

Table 2, pp. 79-81 occupies a lot of space. You could reduce the size by 1) deleting the left-hand column ('Foraminifera'), and 2) inserting an extra row at the beginning of the benthic entries, merging the cells into one cell stretching across the width of the table, and putting BENTHIC in bold centred in the middle of this cell. The other column headings would remain above this merged cell. The same could be done above the planktic entries. 3) You could then make the three right-hand columns wider, so that the entries in the cells take up less vertical space.

Response: we will work with the formatting as suggested.

Line 2373-2376. 'Nevertheless.....'. Is the intention here to contrast *Bolivina pacifica* with *B. spissa*? In this case, it would be better to start the sentence with 'On the other hand....'

Response: It is not the intention to contrast *B. spissa* with *B. pacifica* but to contrast the pore density (which does not vary with sediment depth) with the size (which varies with sediment depth). This part will be adapted for clarification.

Minor grammatical issues

I've made editorial suggestions directly on the pdf, which I hope will improve the clarity of the text.

In places, paragraph breaks are only indicated by a carriage return. Please indicate them by leaving a blank line, as you do elsewhere in the text.

Please hyphenate 'bottom water' when used as an adjective (bottom-water oxygenation')

'Foraminifera' is a noun. Please write 'foraminiferal' when using the taxon name as an adjective - e.g. 'foraminiferal species', 'foraminiferal assemblages' (not 'foraminifera species' etc). You could also use the phrase 'assemblages of foraminifera'.

Response: thank you for additional editorial comments. We will correct each of these category of grammatical error and take into account the suggestions made in the PDF as well.