

Summary:

Hoogakker and colleagues provide a very extensive review of various proxy approaches (ranging from trace elements & their isotopes, over biomarkers, nitrogen isotopes, and foraminifera-based proxies) that can be used to reconstruct marine oxygen changes over the Cenozoic. The amount of information included in the paper is immense and has almost textbook dimensions (100 pages of text, including 16 figures, and >53 pages of references). In my opinion, this can be seen as a strength and a weakness of the paper – and I suppose it is an editorial decision if *Biogeosciences* wants to publish such an extended review study or if it would be better to split the review paper into multiple review studies to make it more manageable for readers and also reviewers (a lot of different subsections have a separate introduction already).

Given the paper's extensive nature, I will concentrate my (more detailed) comments on the initial sections, up to and including Section 6.2.6.3. I will provide more general comments, particularly on what I perceive as the manuscript's primary limitation - its structure.

Overall, I am convinced that the information provided by the manuscript will be of great value to the community, but, in my opinion, the text should be shortened significantly. I initially thought the manuscript would be a fantastic way to learn about different proxy approaches used to quantify paleo-oxygenation changes, but I got discouraged by the very long text and vast amount of subsections of the manuscript. This might be fine for general readers who can pick and choose the sections they are interested in (in contrast to a job of a reviewer). However, I still think that a more focused text and a better organization of subsections would improve the usefulness and approachability of the manuscript.

Response: we thank the reviewer for their helpful comments and suggestions. The further suggestions here of which sections could be shortened is an especially helpful perspective. And we definitely appreciate the effort taken to review such a long and broad manuscript.

General comments:

Comment #1.1: Shortening the manuscript and combining duplicate information

Considering the long list of authors and diverse topics covered, I suppose that different groups of authors were responsible for different sections – which is absolutely fine and necessary – however, the manuscript would benefit from a few core authors reviewing the entire manuscript and combining/deleting overlapping information (as also suggested in the review by Ellen Thomas; with nitrogen-dynamics being discussed in multiple sections only being one example).

Response: we agree with the reviewer that a further review of the manuscript will help eliminate repetition and improve flow. We will do so as suggested by this reviewer and Ellen Thomas.

Comment #1.2:

At times, the manuscript is quite wordy and/or provides a lot of detail on topics that are not directly related to the understanding of the specific redox proxies. A few example parts (mainly of the first half of the manuscript that I looked at in more detail) that could (in my opinion) be shortened are: Sections 3; 6.1.1. (especially in 2nd and 3rd paragraph); 6.1.2.

Response: both of these sections will be shortened.

Is the information of the “Materials/Methods” type sections really important for the review paper (e.g., 6.2.2, 6.3.7, 6.5.3, 6.6.4, 6.7.3)? I found these sections rather technical and not very informative/crucial for understanding the specific proxy (but that might, of course, be personal preference).

Response: we feel that including some perspective on the resources needed for each of these approaches is important, however we will shorten and streamline each of these sections.

Some of the future directions sections are rather long (especially 6.2.6 & 6.6.8 & 6.7.8).

Response: these sections will also be shortened.

The introduction to “6.5 Foraminifera trace elements” (6.5.1+6.5.2) consists of more than 7 pages (just text) plus 4 Figures. It should be possible to shorten this text (or combine figures) without losing too much relevant content.

Response: we will condense this section.

Comment #2: Structure

The manuscript includes too many subsections (sometimes up to 5 levels—see, e.g., Subsection in 6.2.3), which is confusing and makes it challenging to pinpoint where the current information ‘lives’ in relation to the overall structure of the manuscript. I think a depth of 3 or 4 subsections should be enough; otherwise, the reader loses orientation.

Response: we will restructure section 6 such that each proxy subsection is on its own, as well as eliminating the 5th level subsections as suggested also by other reviewers.

Section 6 consists of many, many subsections and forms the majority of the text. In contrast, the previous Sections 1 – 5 are very short and do not have any subsections. This should be better balanced. For instance, why are Sections 4 and 5 separate Sections at all – this information could be part of the general introduction. Section 6 could maybe be organized into multiple Sections of similar size (potentially just the current subsections of Sec. 6).

Response: Sections 4 and 5 will be combined and moved upwards as suggested by Reviewer 3.

Comment #3: Introduction

The introduction does not introduce the topic of the review article. The second paragraph explains the causes for ocean deoxygenation and the second half of the introduction exclusively deals with problems in Earth system models to simulate ocean oxygen correctly. This is very surprising as Earth system models are not part of the review paper at all.

More relevant would be a general introduction to oxygenation changes over the Cenozoic and redox-proxies, and how they can help quantify the oxygenation changes. Information given in the different intros throughout the document could here be combined (e.g. such as the information given in 6.1, 6.2.1 and similar sections throughout the manuscript).

Response: we will remove the paragraph on modeling as we agree it is incongruent with the review in its current form and will consolidate repetitive introductory information throughout and move this earlier in the document. This reorganization should make clearer the topic and aims of the review.

Comment #4:

6.2. "Sedimentary redox trace elements and isotopes"

An overview table would be very useful that summarizes/compares the key characteristics, residence times and applications of the different proxies.

Response: this is a great idea - we will include such a table in this section.

Also, for Subsections 6.2.3: Why not combine the elements & their isotopes in one section?

Response: element and isotope sections can be consolidated as suggested.

Comment #5:

The large amount of references for some sentences (sometimes 6-12) makes it difficult to read the text (just a few examples: lines 261, 521, 561, 575, Sections 6.2.3.1.4, 6.2.5.2 in general, 628, ...). It would be helpful to shorten the references given, e.g., only provide the most important references are given or a few examples. Also, it is not necessary to cite the same paper multiple times in consecutive sentences (for instance, see 6.2.3.1.2; 6.2.3.1.4; 6.2.3.3.1)

Response: we will attend to the referencing to avoid repetition as much as possible.

More Technical Comments:

First two sentences of Section 2: Please rephrase. It sounds like seawater temperature, pH, and dissolved oxygen are environmental properties that can generally not be measured directly.

Response: we make sure to rephrase this so it is understood we mean proxies for these direct measures.

Fig 1: the caption says: "Proxy types shown in olive can be used to reconstruct oxygen from benthic settings, those in green can be used for pelagic settings." But I do not see olive and green proxies in the figure.

Response: thank you for catching this. This should read as "grey" and "blue" respectively and will be corrected.

Ln 389: "Fully digested" what does this mean – not clear for a non-data person.

Response: this will be rewritten as "fully or partially dissolved"

Ln. 547: decomposition of organic matter is probably meant here. Organic carbon describes only the C itself contained in organic material. Please check the use of organic carbon throughout the document.

Response: you are correct. We will use "organic matter" here and check throughout the manuscript.

Some of the subsection titles are rather long and should be shortened, see e.g.

Subsections 6.3.3; 6.3.6

Response: these will be shortened to "Biomarkers of microbial processes associated with oxygen deficiency" and "Non-specific/orphan biomarkers from oxygen-deficient depositional settings" respectively

Title 6.6.3 = 6.6.2 -- I suppose, 6.6.3 is Planktic foraminifera

Response: you are correct. Thank you.

Line 398: "This is especially true ..." please rephrase, it is unclear what 2 to 3 cm kyr-1 refers to.

Response: this will be rephrased as "This is especially true in environments with low accumulation rates less than 2 (Jung et al., 1997; Mangini et al., 2001) or 3 cm kyr-1 (Jacobel et al., 2020)."

Fig. 4: It could be made more obvious what boundary condition is changed between a and b.

Response: we will do this.

Line 709: ... the occurrences of (singular)

Response: this will be corrected.

Figure 8: Please include the figure in higher resolution. In particular, the text looks pixelated.

Response: we will make sure this is submitted in higher resolution.

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