

Dear Editor,

we kindly thank reviewer #1 for their constructive feedback on our paper. Below we respond to all their comments and indicate how we intend to adapt our paper based on them.

Sincerely, also on behalf of my co-authors,

Dominique Jenny

Review of “Climate variability, heat distribution and polar amplification in the unipolar ‘doubthouse’ of the Oligocene”

General comments:

The purpose of the paper is confusing. It wasn't clear from the start that it is a literature review and interpretation. The paper also tries to do too much by reviewing the chronostratigraphy, the geography, model-data comparison, fauna and flora, introducing new data using NRL, etc., etc. This could be mitigated by stating earlier (title, abstract, intro) and more clearly the purpose and structure of the paper and by restructuring sections of the paper (see below). The discussion/conclusion sections are a little disappointing. The discussion section doesn't offer any insights into the mysteries or speculation about the remaining Oligocene mysteries (e.g. model-data mismatch, CO₂-climate mismatch). The conclusion section was obviously a last-minute addition and needs to be redone. Critiques aside, I appreciated the thorough overview and learned some new things about the Oligocene. This could be a nice addition with some additional work.

Reply: We agree that the paper needs to be restructured to be more on point, and more in line with what the title and abstract promises. Also in concert with the advice of Reviewer #2, will remove the sections that aren't directly crucial to understand the data review we present (e.g. chronostratigraphy, fauna and flora). In line with this, we will also revisit the discussion and will re-write the conclusion section.

Title:

The title is misleading. This is a review paper and the title should reflect that.

Reply: We will change the title to: “Climate variability, heat distribution and hydrology in the unipolar icehouse of the Oligocene”; a review and data-model comparison” thereby also incorporating a comment by Reviewer #2.

0 Abstract:

Page 2, Line 14-15 – I don't understand this sentence. Wouldn't the Oligocene be a good analogue for a future climate state with unipolar glaciation?

Reply: We will restructure the beginning of the Abstract a bit to make it clearer. Indeed, the Oligocene is a useful analogue, yet we call it imperfect as several boundary conditions, such as continental geography and ice volume aren't exactly the same.

Page 2, Line 28 – Delete “while still maintaining a unipolar icehouse state.”

Reply: This will be removed

1 Introduction:

Most of the paper is well written. The Introduction is the exception and requires careful editing.

Page 3, Line 4 – “equilibrate” is used incorrectly here.

Reply: The wording will be changed here

Page 3, Line 43-44 - Awkward sentence. Please fix.

Reply: Sentence will be fixed

Page 3, Line 51-52 - Awkward phrasing. Please fix.

Reply: Sentence will be fixed

Page 4, Line 80 - I’m not sure why whales are mentioned here.

Reply: The sentence here will be adjusted to reflect the importance of such an evolution in the context of the sentence.

Page 5, Figure 1 caption - Maybe the colors didn’t transfer correctly, but some of the colors and shapes mentioned in the caption don’t match the colors in the legend of the figure (for (b)). Misspelling of “Transition” as well.

Reply: The figure caption will be corrected and the missing methods will be added to the captions.

Page 6, Line 94 – The authors mention variability in continental ice volume paced by eccentricity and obliquity. The authors should follow that with an explanation of why/if that’s significant and how it might be seen in the proxy records (given that they are low resolution).

Reply: An explanation will be added here about the significance of the cyclicity of the record, and where it can be seen.

Page 6, Line 99 – “Here..” Should be start of a new paragraph.

Reply: A new paragraph will be made here.

Page 6, Line 100 – “after a chronostratigraphic section” Awkward phrasing.

Reply: The section between line 99 and 104 will be extended and rephrased to include more detail on the paper's purpose, also considering the above remark entitled 'General Comments' by the reviewer.

Page 6, Lines 99-104 - At the end of the introduction, the authors finally explain that the purpose of this paper is to review the current state of knowledge regarding the Oligocene climate and thus provide constraints on boundary conditions, compile proxy data, and identify points of interest. This point should be made much sooner so that readers understand the purpose of the paper.

Reply: This will be considered in the re-shaping of the introduction.

Page 6, Lines 99-104 - There is no mention of numerical climate simulations as in the abstract. Model-data comparisons are made later in the paper, and should be mentioned here. There is also no mention of constraining ocean circulation or ice dynamics though a large part of the introduction discusses these. The authors need to make clearer how climate simulations are used in this paper with some quick details on them, if anything on the ocean or ice state of the Oligocene is explored further, and potentially more details on the proxy records used and for what reason? There is not much on the purpose of the paper and it's all at the very end of the introduction - they could expand on what the paper will discuss and could mention the main purpose it serves sooner in the introduction.

Reply: We agree with this comment, hence the section between line 99 and 104 will be extended and rephrased to include more detail on the paper's purpose. Especially sections about the modelling will be added and the removed sections will be cut from this section.

2 Oligocene chronostratigraphy and event nomenclature:

This section should be removed completely from the paper or moved to Supplemental Data.

Reply: Most of this section will be removed following the comments by Reviewer #2 and only the sections about relevant nomenclature and isotopic stages will be kept.

Page 7, Line 112 – “GGSP” should be “GSSP”, right?

Reply: Indeed, this typo will be corrected

Page 7, Line 116 - The OMB is stated as 23.04 Ma here and 23.03 Ma in the rest of the sections

Reply: This mistake in the text will be corrected and the sentence will be re-written to be clearer that this date does not mean the OMT.

Page 8, Line 134 – Spell out 'GPTS' as 'geomagnetic polarity time scale (GPTS)'

Reply: This will be added.

Page 9, Line 177 - Why does the last zone end at 23.07 Ma when the Oligocene ends at 23.03 or 23.04 Ma?

Reply: This section will be removed entirely from the paper, as mentioned above.

Page 10, Line 196, 198, 201 - Why is there a question mark after 'Axoprunum'?

Reply: This section will be removed entirely from the paper, as mentioned above.

3 Boundary conditions for Oligocene climate:

Page 11, Line 236 – “boundary conditions” is a modeling term and inappropriate here. Replace with “geography” or “continental position”

Reply: This terminology will be changed

Page 12, Figure 3 caption – Add an elevation scale bar. Also 'NRL' is supposed to be 'NLR'.

Reply: The NLR will be corrected. We will contact the maker of this map for an elevation scale bar. Importantly, however, paleoelevation is very poorly constrained for most of the globe during the Oligocene, which will be included in the caption.

Page 13, Line 266 – “strongly affected regional ocean circulation...” Here the authors are repeating a hypothesis that is by no means certain and should equivocate appropriately “may have strongly affected”. They do this throughout the paper, stating hypotheses, sometimes model results, as fact or certainty. Please clarify appropriately.

Reply: The phrasing here will be adjusted, and the paper will further be checked for more hypotheses that have been worded as statements.

Page 15, Line 348 – The authors mention an increase in ocean methane hydrates, peat, and wetlands as a result of colder temperatures and ice expansion. They could add a sentence that explains how the expansion of those environments are a consequence of colder temperatures and if there is evidence of these expanding during the Oligocene or if it is just a probable guess given the cooling climate.

Reply: This section will be removed entirely from the paper, also following the advice of Reviewer #2.

Page 15, Line 358-380 – How does these CO₂ levels/trends compare with the new CO₂ from Honisch et al., Science?

Reply: The paper of Honisch et al (Cenozoic CO₂ Proxy Integration Project (CenCO₂PIP) Consortium) will be added to the CO₂ section. This paper was published after submission of this paper.

Page 16, Line 377 - “16results” typo

Reply: The typo will be corrected

4 Climate proxy data:

Page 16, Line 385 - Why did the authors choose fossil plant remains to analyze and why only fossil plant remains (not paleosol carbonates, etc)?

Reply: There are of course many more possible archives to include, some of which were described in the Flora and Fauna section but much of this information is fragmented and poorly dated, which limits its usefulness. For this reason, we focused on vegetation data, which we considered useful for data-model comparison.

Page 17, Line 405-407 – The authors mention an absence of high latitude data (no fossil plant remains suitable for their method). How could this absence affect their results, or how much uncertainty does this add when estimating a meridional temperature gradient for the Oligocene?

Reply: This essentially means we cannot independently assess meridional temperature gradients based on vegetation data, which we hence do not do. We include a recommendation to revisit the cited materials from the Antarctic margin for quantitative analyses, to solve this issue.

Page 17, Line 415 - One data point in the NH mid-latitudes is significantly different from the other mid-latitude data points - where is this NH data point? What sort of biome is it from?

Reply: Upon reviewing that specific datapoint, the Makum Coal Field, we re-evaluated its paleolatitude at ~25° N, making its climate reconstruction consistent with the other tropical floras. We have therefore removed the comment about it being anomalously warm amongst mid-latitudinal temperature reconstructions.

Page 18, Figure 4 – Use the same y-axis for each plot. As it lies now, the winter temperatures appear the same as the MATs until you see the slight difference in the y-axes. Also, in the figure caption, it states the (b) plot PI values are in brown but they appear gray just like in plot (a).

Reply: We will adjust the y axis for the plot and change the figure caption to match the color of the figure.

Page 19, Line 460 - Random parenthesis in statement. Also, the authors could add one more sentence on how pH affects the fractionation of oxygen isotopes in this environment (why an overestimation of 1.5°C has to be taken into consideration?).

Reply: The parenthesis will be removed. We will reconsider mentioning the pH influence on the SST reconstructions and minor overestimations.

Page 20, Figure 5 - This is a nice figure, though the shapes are so small I can't really place many of the sites to a line. They could instead do just three different shapes for each type of SST proxy. There are also some SST sites in Figure 3 that aren't in Figure 5 (i.e. Site 913 and others), if they aren't included in Figure 5 then are they still used / needed in Figure 3? Why weren't some used in Figure 5?

Reply: Figure 3 shows all used data sites for all figures presented. Specifically, 913 was only used in Figure 6, and not included in Figure 5 as it did not span the entire Oligocene. To assess long-term trends, we only include Sites that span throughout all of the Oligocene in Figure 5. We do see how this might lead to some confusion and thus will consider including all sites from Figure 6 in Figure 5 as well.

We agree that the figure could be clearer on the symbols and we will try to make the symbols more readable. We will also try to make the Site symbol the same color as the line it is in.

Page 21, Figure 6 - This is a great figure, very concise with a lot of information. It's interesting too that SST seems ~constant from about 40S to 40N for the Oligocene and sort of late Eocene as well, but modern SSTs have a narrower curve peaking from about 20S to 20N. They could mention something on this.

Reply: This is a good point and one that has received attention in recent work. We will add a sentence in the results about the flattened temperature gradient between those latitudes during the Oligocene.

Page 22, Figure 7 - Why reconstruct driest month precipitation and not wettest month precipitation? Along those lines, why reconstruct winter temperatures and not summer temperatures (Figure 4)? Could just include one sentence stating the benefits of understanding winter temperatures and driest month precipitation.

Reply: Thanks for the suggestion. We have included the following sentence in the methods section (L. 392): "These variables were used here as plant distribution is sensitive to average annual conditions, precipitation seasonality, and the temperature of the coldest season, and therefore can be reconstructed with relative confidence."

Page 22, Line 496 – The authors generally state that the Oligocene MAP values are similar to modern day, but the mid-latitude values (for either hemisphere) seem higher than modern values (Figure 7)?

Reply: We agree with this assessment, and will adjust the text and discussion accordingly.

Pages 23 and 24 – The authors don't mention similarities or differences between the models here at all (HadCM3L vs CESM). According to Figure 8, it seems there are a lot of similarities between how the models reconstruct surface temperature compared to the proxy records. It's interesting that you see such similarities between CESM and HadCM3L (though on that - parts C/F/I of Figure 8 could use a darker color for CESM mean temperature difference since the light pink is a bit difficult to see).

Reply: We will add the sentence: "Despite utilizing two very distinct models with different boundary conditions, the temperature discrepancy between the model and data remains similar." at the beginning of this section 4.3.1 Temperature proxy to 515 model comparison, Line 516

We will change the colour of the CESM to a darker colour.

Page 24, Line 533 – The authors say the differences plotted are 'calculated as a pointwise difference between the proxy mean value and the model annual mean'. Two thoughts on this: a) how was the model annual mean calculated (was the annual mean for the corresponding grid cell used or the general region / a group of grid cells) and b) are there any seasonal biases within the proxy records that could be causing greater differences since only annual means are used for the simulations? If not, they could just state somewhere that there are no known seasonal biases for these records.

Reply:

- a) The model annual mean value is derived from the nearest grid point to our study site. We will add a sentence about that in the paper (Line 514)
- b) All proxies come with potential biases. Vegetation does not actually respond to mean annual temperature but to seasonal extremes. Marine proxies from pelagic organisms may suffer from seasonal growth and export. However, all proxies as used here are calibrated to mean annual temperature with an associated error that principally includes such seasonal biases. To accommodate this comment by the reviewer, we will include this information in the paper.

Pages 25 and 26 - Similar to what I said above, similarities and differences between CESM and HadCM3L could be mentioned, I think the light pink color for CESM in Figure 9 parts C/F/I is too difficult to see, and I'm a bit confused on the 'pointwise difference' method regarding which grid cells were used for the model values. I also think red should correspond with drier (according to data) conditions (negative precipitation difference) and blue should correspond with wetter (according to data) conditions (positive precipitation difference). It's a bit confusing that we are looking at precipitation as a 'data minus model' value where the data usually represents wetter conditions than the model simulates and yet the data points on the plot are in red colors which traditionally represent drier conditions but this is really just a preference.

Reply: The color of the CESM in Figure 9 will be adjusted to make it more visible. Also the color for the precipitation will be adjusted so that green colors will be corresponding to wetter conditions and yellow to drier conditions in order to avoid confusion with the temperature modelling results.

Page 27, Line 583 – See inappropriate capitalizations. “Is of great Importance”

Reply: This section will be removed.

Page 27, Section 4.4 – This section on Ice Sheets is out of place. Unlike the rest of Section 4, it has no original data or interpretation. It's simply a literature review and should be included in Section 3.

Reply: This section will be removed from the paper.

5 Flora and faunal changes:

Similar to last comment, why is this section not with the literature review in section 3?

Reply: This section will be removed entirely from the paper.

6 Discussion:

Page 31 – The authors mention there's a discrepancy between SH and NH MAP (in Oligocene and not in modern) in the result section (Figure 7). A discussion of why would be welcome here.

Reply: This is a very good observation and definitely needs to be addressed in the future version of the paper. We thus will add that to the precipitation section of the discussion.

Page 31, line 686-687 – The authors conclude that the Oligocene was anomalously warm relative to CO₂ levels. They should discuss potential explanations for this apparent mismatch.

Reply: We agree that this mismatch needs to be discussed, and we intend to add a 6.3 where we discuss the next challenges for understanding Oligocene climates, which includes climate sensitivity, polar amplification and the response of the hydrological cycle.

7 Conclusions:

It reads as though the authors ran out of energy before the Conclusions. There's no introductory statement and the bulleted list is very sparse. Besides the abstract, the conclusions are the most frequently read section of a paper. The authors don't state that the manuscript is a review or distinguish between their contributions and what's review.

Reply: We will rewrite the conclusions to fit expectations based on the paper.

Page 31, Line 704 - The second conclusion is specific to the proxy records, not so much what the simulations show, so maybe mention that, though I guess they have a conclusion point specific to the simulations below.

Reply: We will make that clearer.

Page 31, Line 706 - I generally agree with the third conclusion, except Oligocene MAP values around the mid-latitudes appear higher than modern MAP mid-latitude values according to Figure 7.

Reply: This will be adjusted.

Page 31, Line 711 - In line with the last conclusion point, the authors could mention that that may be related to the lack/variability/uncertainty in Oligocene CO₂ records. CO₂ is not well constrained so perhaps the Oligocene is, in part, not the "icehouse" it seemed to be before because CO₂ was, in reality, a bit higher than some older records estimated.

Reply: We will add that to the conclusion.