

## Peer Review Report

# Review Report on Global mean and relative sea-level changes over the past 66 Myr: Implications for Early Eocene ice sheets

Original Research, Earth Sci. Syst. Soc.

Reviewer: Jacqueline Austermann

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### EVALUATION

#### **Q 1** Please summarize the main findings of the study.

The goal of this study is to quantify global mean sea level variations over the past 66 Million years with a particular focus on estimating ice sheet variations during the warm Eocene that has generally been considered to be ice free. The authors find that while ice free conditions existed for parts of the the Eocene, this epoch also experienced significant ice sheet growth and decay, which likely occurred on Antarctica. This result is based on two independent records: (1) deep sea sediment cores that record the combined signal of ice sheet and temperature variations and (2) direct sea level observations from the New Jersey margin. Both records require a significant amount of processing and correcting to extract the baristatic or ice-equivalent sea level. This work also provides global mean sea level estimates for other time intervals since the Eocene and compares sea level trends to CO2 trends. This study builds on the author's prior work (Miller et al, 2020), which it extends in several ways.

#### **Q 2** Please highlight the limitations and strengths.

The study is very comprehensive, spanning a range of earth science topics and disciplines (mostly observations and statistical methods). I particularly appreciated the detailed discussion about how their results differed from previous work by Rohling et al. and why. As this discussion reflects, there are multiple assumptions that go into different parts of the analysis but the authors appropriately acknowledge these. They also perform several sensitivity tests that explore how results are sensitive to some of these assumptions. Overall the authors make a compelling case for Eocene ice sheet variability, which raises interesting and important questions about ice sheet variability during warm periods.

#### **Q 3** Please comment on the methods, results and data interpretation. If there are any objective errors, or if the conclusions are not supported, you should detail your concerns.

All my comments are included in the detailed review below (Q 5). Overall the methods are extensive and sound to my knowledge. The results hinge quite critically on the conversion of oxygen isotope data to sea level, which is not really my expertise. I provide some feedback but input from other might be useful. The statistical methods are thorough and appropriate. The overall approach, interpretation of results, and discussion are appropriate. I think there are some editorial choices of ordering paragraphs, figures, and such that can be improved and I comment on that in the PDF. I will highlight three aspects that I think are most critical in their revisions:

\* In their statistical treatment the authors look for the coherent signal between BSL and RSL in NJ. However, the better quantity to compare to RSL is GMGSL. They account for ocean volume and thermosteric effects in their comparison but they do so in a statistical way rather than an observationally driven way. They do quantify the other contributions so it seems more consistent to me to model GMGSL and RSL.

\* I don't understand the last component of their ice-free budget. I agree up to 71m, but beyond that seems to be ice that could have been on Antarctica during earlier glacials, but not ice that is here today and would raise BSL back then. If this value is revised it has implications for the interpretation of their BSL inference.

\* They compare CO2 trends to GMGSL trends, however, the more appropriate curve to compare to is BSL. If that is done, quite a bit of their interpretations don't seem to hold for me. There isn't a secular trend in the BSL timeseries for example.

Lastly, I note below that data underlying the study are not available. It would be useful to provide the GMGSL, BSL, etc. time series as supplemental material.

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**Q 4** **Check List**

Is the English language of sufficient quality?

Yes.

Is the quality of the figures and tables satisfactory?

Yes.

Does the reference list cover the relevant literature adequately and in an unbiased manner?

Yes.

Are the statistical methods valid and correctly applied? (e.g. sample size, choice of test)

Yes.

If relevant, are the methods sufficiently documented to allow replication studies?

Yes.

Are the data underlying the study available in either the article, supplement, or deposited in a repository? (Sequence/expression data, protein/molecule characterizations, annotations, and taxonomy data are required to be deposited in public repositories prior to publication)

No.

Does the study adhere to ethical standards including ethics committee approval and consent procedure?

Not Applicable.

If relevant, have standard biosecurity and institutional safety procedures been adhered to?

Not Applicable.

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**Q 5** **Please provide your detailed review report to the editor and authors (including any comments on the Q4 Check List):**

I've left my detailed review as comments in the attached PDF. For the ease of responding to the different points I exported the comments and am pasting them here:

LIST OF COMMENTS FOR DOCUMENT:10091\_Manuscript\_reviewed.pdf

Paige 4  
remove?

Paige 5  
this paragraph is a repetition

Paige 5  
referring to all results figures in the introduction seems strange to me. As is this last paragraph summarizes a lot of the results, which I don't think is the purpose of the introduction. This paragraph may summarize what is done in the paper but in my opinion should not include results or figure references.

Paige 5  
unclear what this means

Paige 6  
I understand that this is how Gregory defines it but want to note that in the GIA community this term is used differently. SL is the difference in height between the sea surface and the solid Earth while RSL is SL relative to the present. (e.g. Kendall et al., 2005).

Paige 6  
This becomes a bit ambiguous – if RSL is the difference between the sea surface and the solid Earth, are sediments included in the solid Earth? If so, it's not sediment supply and RSL that produce transgressions and regressions but instead sediment supply causes a change in RSL, which then leads to a transgression or regression.

Paige 6  
paragraph repeated

Paige 6  
this paragraph seems like it would fit better in the introduction section

Paige 7  
can you cite the 'previously published compilation' here?

Paige 7  
this is not my area of expertise but seems very important for this work so hopefully another reviewer can comment on the validity of this approach.

Paige 8  
how representative is this of the entire pacific and southern ocean?

Paige 8  
This factor can be highly variable depending on what ice sheet melts and when (as for example Winnick and Caves point out). It would be good to acknowledge and explain that here. I see this is done in the results section but I think it's worth noting this here (as well).

Paige 8  
repetition of paragraph

Paige 9  
repetition continued

Paige 9  
described?

Paige 9  
reformat

Paige 9  
would this be better placed in the results section?

Paige 9  
seems like result / discussion

Paige 9  
result / discussion

Paige 10

This calculation seems to treat ice above and below floatation the same, however the former affects GMSL while both terms together affect  $\delta l_{O\_SW}$ . How is that dealt with? You talk about this in the results section but it might be worth already flagging it in this section.

Paige 10

this is a bit hard for me to follow. Could you clarify / justify this to a non-expert? Where does the 20% come from?

Paige 10

why / reference?

Paige 10

can you provide a justification for these values? Without more background these seem a bit arbitrary.

Paige 11

I would suggest removing this section. This is already clear from the background section and after reading it it left me wondering what was used for the thermosteric correction so I think just going straight to that makes more sense.

Paige 12

In the first paragraph of your background section I think you actually distinguish between GMSL and GMGSL where  $GMSL = \theta + BSL$  and  $GMGSL = \theta + BSL + OBVSL$ . If this is correct then I think this should be GMGLS. If this isn't correct then I would suggest rewording the first paragraph of the background section.

Paige 12

The SOM text that provides more information on the statistical modeling for CO2 and RSL is not referenced in the main text. Please refer to it where appropriate otherwise the reader won't know that you elaborate on different parts of this method.

Paige 12

move out of subscript

Paige 12

I would suggest moving this explanation up to where you first explain the revision in approach from your 2020 paper.

Paige 13

remove

Paige 13

This assumes that proxies only record longterm variations and not ice age variability. Can you justify this assumption?

Paige 13

the equation reads  $I_k(t)$ , which is different to it being a linear term  $I_k * t$ . Can you clarify which one it is?

Paige 13

This should be stated earlier and then doesn't need to be repeated here.

Paige 13

It seems to me that this is a result of the work so should be moved to the results section.

Paige 13

It seems like this should be  $I_0 * t$  and  $I_k * t$ , right?

Paige 13

I'm a little confused by the parameter name choices: why is the constant  $I_0$  estimated with prior  $\sigma_I$  while the constant  $c_0$  is estimated with a prior that has the same name ( $c_0$ )? Same question for the next sentence.

Paige 14

could the offsets not also be negative numbers?

Paige 14

This should probably be Table SOM 2

Paige 14

add space

Paige 14

similar question to above – if these are linear, are they  $I * t$ ?

Paige 14

Why are you not looking for the coherent signal between GMGSL (instead of BSL) and RSL in NJ? You are accounting for ocean volume and thermosteric effects here but in a stastical sense rather than the more observationally driven approach described above (where you construct GMGSL). By doing that it seems like you're neglecting some information that you already compiled. Can you expand on this choice?

Paige 14

How is this enforced?

Paige 15

I believe these results figures should be described and referred to in the results section.

Paige 15

This should probably be Results and Discussion.

Paige 15

the wording here is a bit odd – satellite images aren't of BedMachine but rather satellite images did (in part – I assume) inform BedMachine. The images are also not of the ice volume.

Paige 15

sorry I can't highlight the words I want to here, which are 'once compensated for'. I see that you elaborate on this a bit more in the next sentence but this wording as is is quite ambiguous and without reading on it doesn't make sense. What is compensated for what? Maybe rephrase this and the next sentence to clearly explain what is meant here the first time this is mentioned.

Paige 15

Can you expand on how this is calculated? Did you do a rebound calculation for Antarctica to see how much rebound what have happened under deglaciation in the marine based sectors? Paxman et al. (2022) provide those grids in case this is useful.

Additionally, how do you deal with the remainder of ice that is 'truly' below floatation and would therefore affect  $\delta l_{O\_SW}$  but not BSL?

Paige 15

also this reference: <https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014PA002769>

Paige 15

I don't understand this logic here. I see how you get to 71m, but anything in addition to that is ice that could have been there during a glacial, not ice that is here today and would raise BSL back then. Therefor an ice-free

world should have a maximum BSL of 71m (and uncertainties mentioned earlier in this paragraph should be propagated).

Paige 15

In figures that show a specific component of SL (e.g. BSL) can you change the y axis label to reflect that? That might just affect Figs. 2 & 3.

Paige 15

I believe the upper ice-free limit is around 71m (see above), which would mean that your BSL curve exceeds this limit around 4 times (the time intervals mentioned here). Can you explain this?

Paige 16

higher compared to what time?

Paige 16

Could you maybe draw horizontal lines across the geologic boundaries so that it's easier to see in the SL panel what time range the early eocene spans? Maybe the figures get too busy if that's done for all boundaries but doing it for the Eocene ones might be useful (given that that's the main focus of this paper).

Paige 16

what are the uncertainties on these quantities? Can you show uncertainties in BSL on the figures? I see that you explore uncertainties at the end of the manuscript, but I think here [after describing the BSL result] would be a better place to expand on that.

Paige 16

I think this is a bit more nuanced here: thermosteric contributions could be this rapid, but they can't explain this magnitude. On the other hand, ocean geometry changes could have this magnitude but can't be this rapid.

Paige 16

rates of at least?

Paige 16

It seems like these sentences might be better suited in the methods than results section.

Paige 16

Also this may be better placed in the methods along with a description of how the sensitivity of your result to associated assumptions will be explored (which you explain in this section)

Paige 16

I'm not sure I understand this sentence

Paige 17

Before moving here it seems like it would be good to describe the results from adding thermal expansion and ocean geometry change, which takes you from BSL (described above) to GMGSL (used here).

Paige 17

these figures show GMGSL and RSL not, BSL.

Paige 18

repeated section

Paige 18

The figures seem to be a bit out of order, it would be great to have them ordered as they are discussed in the results section.

Paige 18

This text seems to almost be identical to the caption. Please rephrase either to avoid repetition. I would rephrase the text here to state what the graphs show rather than saying what they are.

Paige 18  
during what time period?

Paige 18  
overlay

Paige 18  
This seems to be written from a perspective of revising Miller et al (2020) rather than describing the results here first and then drawing the comparison. I would change this, i.e. first describe where RSL and GMGSL fit or not and then attribute it to the relevant sources with reference to earlier work as appropriate.

Paige 19  
It's not clear to me why Fig. 5 includes the CO<sub>2</sub> result. It seems like this would be more appropriate on a BSL time series figure (e.g. 3 or 4).

Paige 19  
Rather than focusing on the uncertainties here it might be interesting to describe the OBVSL component and it's main drivers and uncertainties. It seems like this section doesn't need to summarize the BSL or thermosteric result.

Paige 19  
These time periods are not really the ones that this paper focuses on though.

Paige 19  
the uncertainty band in Fig. 4 suggests much larger values than this.

Paige 19  
I appreciate that the authors have looked in detail at the results by Rohling and compare and contrast their findings. However, the section has some repetition in it and I think could be streamlined

Paige 20  
and there's a systematic offset.

Paige 20  
This seems to contradict what is written in line 740 and visible in Fig. 7, which is that amplitudes in Rohling appear smaller than those in your BSL estimates.

Paige 20  
Above you say that Rohling scales use a "quadratic equation that relates  $\delta^{18}O_b$  to sea-level change". What do they even need  $\delta^{18}O_{SW}$  for / why does this then even affect their BSL?

Paige 20  
Fig. 7 and 8 show that sea level fluctuations are smaller in the Rohling approach than yours though, which seems contrary to what you describe here.

Paige 21  
[This refers to the highlighted section starting line 821]

Paige 21  
I'm not sure this restatement of the methods is needed here.

Paige 21

This reads like they impose variations to be small. Is that correct? The text above does not mention such a direct constraint.

Paige 22

I already comment on this elsewhere but am noting again here that it seems like it would make more sense to show BSL next to CO2 or BSL+thermal expansion next to CO2 instead of GMGSL

Paige 22

There doesn't seem to be a BSL lowering trend over this time period though - why not? This seems to be contradict to the point you're making here.

Paige 22

this isn't marked in Fig. 5 so I'm not sure why this refers to the Figure here.

Paige 22

I don't see longterm secular changes in the BSL curve (Fig. 4), which is the relevant one here. I see it in Fig. 5 because it includes the ocean geometry component, which causes a secular trend. Therefore I don't see the connection between CO2 and SL they're trying to make here. CO2 is secular and BSL changes more stepwise - maybe since thresholds are an important part of the cryosphere?

Paige 22

I suggest moving this section after the BSL result is first discussed.

Paige 22

I'm not sure why there's a reference to Fig. 10 here.

Paige 22

I understand that the Lear et al. correction yields unrealistic results but I don't see how those by Cramer et al. do. What is the basis for stating that your approach is more reasonable than the one by Cramer et al?

Paige 22

How did you test compatibility? It's not clear to me that the black line isn't equally compatible with the RSL data.

Paige 31

why not just add a colorbar?

Paige 31

what do these correspond to? 1 sigma?

Paige 32

Left panel and Right panel is bolded in other captions.

Paige 32

This kind of text should be in the main text, not the caption.

Paige 33

Paige 33

which two records?

Paige 33

You actually quantify these contributions so could you compare this? Or just use GMGSL to start with (see my earlier comment in the methods)?



QUALITY ASSESSMENT

<b>Q 6</b> → Originality	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
<b>Q 7</b> → Rigor	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
<b>Q 8</b> → Significance to the field	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
<b>Q 9</b> → Interest to a general audience	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
<b>Q 10</b> → Quality of the writing	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>
<b>Q 11</b> → Overall quality of the study	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>