Response to reviewer's query: MS No.: esd-2022-2: Process-based estimate of global-mean sea-level changes in the common era

We thank the Editor and the three Reviewers for critical comments and suggestions, which helped to revise this manuscript constructively. We provide our answers to each question below.

Reviewer query: black

Answer: Blue

Added/revised text to the main manuscript: Blue, *italics*

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Reviewer 1#

General Comments

This paper quantifies the contribution to Common Era global mean sea level (GMSL) from changes in ocean volume caused by temperature (salinity is not evaluated with justification provided) and from changes in ocean mass (Antarctica, Greenland, and glaciers are separated; land-water storage is not evaluated with justification provided). Each of these contributions is estimated, with uncertainty, through modeling. The sum of the components (GMSL) is reconciled with two, closely-related (and previously published) estimates of GMSL generated through application of a spatio-temporal model to proxy reconstructions. The similarity between modeled and reconstructed GMSL is compelling, except for a notable underestimate for GMSL change since ~1800 CE.

As the authors note, previous efforts to connect Common Era GMSL changes with other parts of the climate system (e.g., ice mass) largely focused on correlations (or lack of) with other proxy data. The application of process-based models in this paper therefore represents a welcome scientific advance and a substantive contribution toward our understanding of how and why GMSL changed during the Common Era. I recommend that it be published in Earth System Dynamics and hope that the open review forum will attract input from others to strengthen the paper further.

I am familiar with the proxy sea-level reconstructions that modeled GMSL is compared to and therefore my review focuses on that aspect of the paper. I am wholly unfamiliar with process-based models and cannot provide an expert evaluation of choices made within and among the models used.

We thank the reviewer for recommending the paper.

Specific Comments

1. Section 2.4 provides a short summary of the proxy-based GMSL reconstructions. I think that this section would benefit from a modest expansion to include some missing (but potentially important) information and some material that appears elsewhere in the paper already.

The Kopp (2016), Kemp (2018), and Walker (2021) GMSL reconstructions are largely iterations of a spatio-temporal statistical model applied to a growing database of Common Era proxy reconstructions. The authors might emphasize a little more that the GMSL reconstructions are less different models and more an evolution in the underlying data. Notably the GSML reconstruction became smoother over these sequential publications. The authors may also want to highlight that the geographic distribution of proxy records is very uneven, but that Kopp (2016) performed sensitivity tests to explore this influence. It is also important to recognize that GMSL is not a quantity that was reconstructed from a proxy, but is rather one component of the relative sea-level signal that is estimated during the record decomposition performed by the spatio-temporal model.

We thank the Reviewer for this suggestion. Iterating the comments from Reviewer 2 on the same, we have expanded the description of proxy-based sea-level reconstruction (section 2.4) as shown below. We also provide reference of Walker et al. (2022) as it is the latest update of the proxy sea-level database:

GMSL derived from proxy-based sea-level reconstruction for the common era from Kopp et al. (2016), Kemp et al. (2018) and Walker et al. (2022) are considered for comparison with our model GMSL. Those GMSL reconstructions are iterations of a spatio-temporal statistical model applied to a growing database of Common Era proxy reconstructions. In this spatio-temporal model framework, GMSL is an estimate of global sea level obtained from the signal "common" to all of the sea-level records in the Common Era proxy database. Since the GMSL is the "globally uniform" term among sites from the spatio-temporal model, the method could give a true estimate of "GMSL" in the presence of spatially complete data. Consequently, the quality of the estimate depends on the geographic distribution of proxy records which is very uneven (however, some sensitivity tests to explore the effect of geographic distribution of proxy records has been done in Kopp et al. 2016). As the Walker et al. (2022) reconstruction is based on the latest update of the proxy sea-level database, and the Kemp et al. (2018) and Kopp et al. (2016) curves do not differ much over the CE, we show GMSL from Walker et al. (2022) and Kemp et al. (2018) in our model comparison. Also note that in Kemp et al. (2018), the GMSL during -100 – 100 CE is made equal to GMSL over 1600 – 1800 CE to avoid a spurious regional sea-level trend component. However, such a constraint is not employed in Walker et al. (2022) reconstruction. As a result, there is an apparent difference between the GMSL curves in these two reconstructions before ~ 600 CE.

Text on lines 363-365 and 374-375 could be moved into section 2.4.

Those texts are moved as suggested.

In this section it might also be appropriate to highlight when notable differences exist between the two GMSL reconstructions (e.g., before ~600 CE).

We agree. As mentioned above, we added this information in section 2.4 itself as:

Also note that in Kemp et al. (2018), the GMSL during -100 – 100 CE is made equal to GMSL over 1600 – 1800 CE to avoid a spurious regional sea-level trend component. However, such a constraint is not employed in Walker et al. (2022) reconstruction. As a result, there is an apparent difference between the GMSL curves in these two reconstructions before ~ 600 CE.

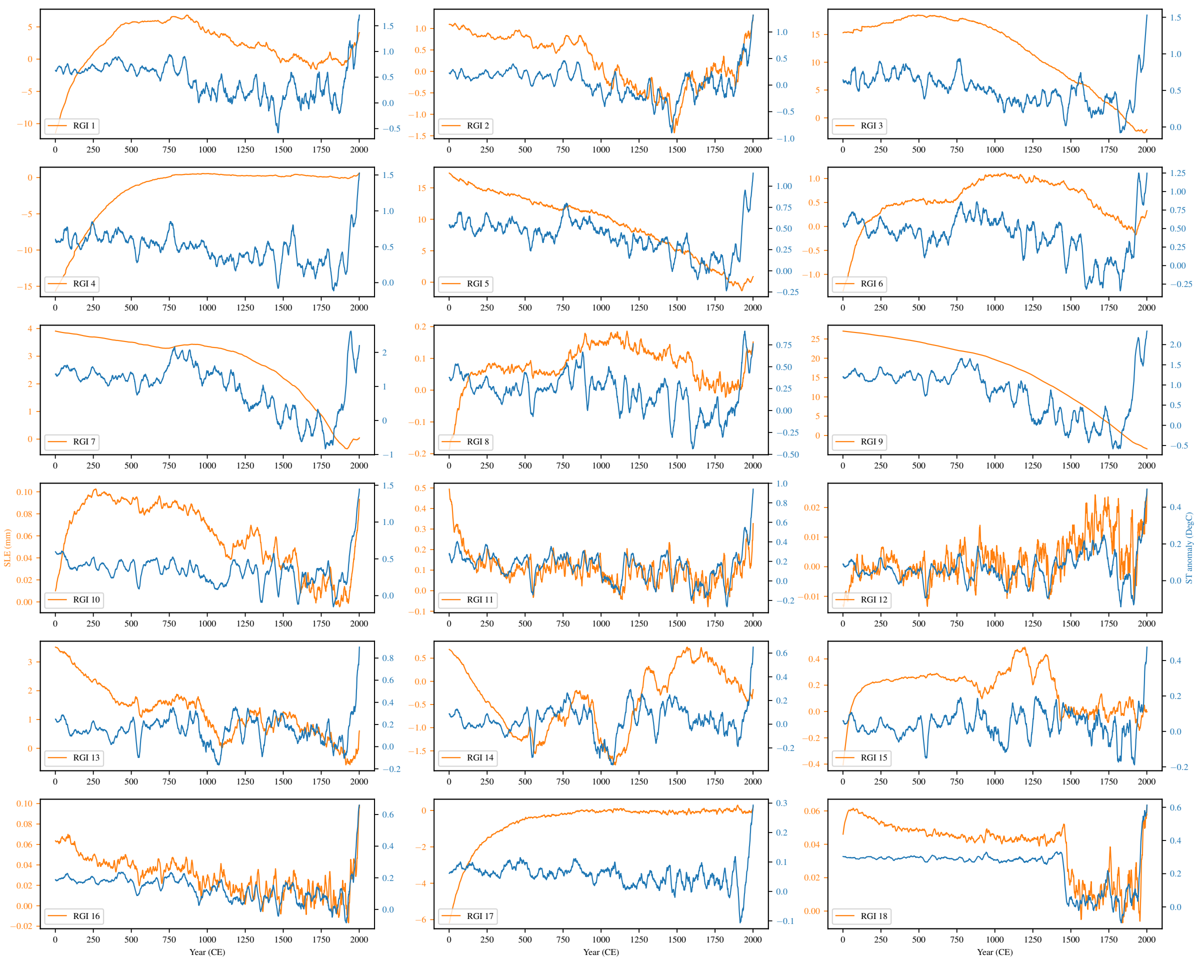
2. Sea-level fingerprints. Changing the mass of water stored on land as ice results a in fingerprint of sea level change. Although it's beyond the paper's focus on GMSL, I think it would be interesting and helpful to show the fingerprints (from individual sources and their sum) that occur as a consequence of the modeled changes in mass from Greenland, Antarctica, and the 18 regions of glaciers. The fingerprints could be compared to the distribution of proxy records, or to estimates of regional sea level trends. It is possible that fingerprinting could help inform model choice if proxy records support/refute particular melt histories. As minimum could the regional contributions from glaciers be provided as a supplemental output for others to convert into sea-level fingerprints.

We thank the Reviewer for this suggestion. However, as mentioned in the comment this is beyond the scope of this first paper and we kept the regional patterns of absolute (thermosteric and barystatic) and relative (GRD and GIA fingerprints) sea-level change during the Common Era as a perspective of this paper. We agree that comparing the available proxy sea-level reconstructions with our model sea level would be a great exercise to understand the role of ocean dynamics in driving the regional sea-level changes over the Common Era as well as the potential biases caused by a spatially non-uniform proxy network. We restrained ourselves showing spatial changes in this paper since those exercises requires additional analyses and discussion and deserve for us a specific paper. We totally understand the importance of characterizing the land vertical movements and corresponding sea-level fingerprints due to last millennium mass redistribution, and we will consider it in a following paper. Nevertheless, all the model simulation we have will be available on a public domain and on personal communication once the paper is published. We have added a few sentences in the conclusion section of the paper to convey this perspective.

3. Glaciers appear to be the single most important driver of Common Era GMSL change, but also the most problematic to model and quantify. Please could the authors show the contributions from the 18

different regions of glaciers. In Figure 3D the glacier contribution is shown against global temperature, which the paper does acknowledge (line 460) is an imperfect comparison since glaciers respond to regional climate. Could the glacier contribution from the 18 regions be compared to regional climate from Neukom et al (2019)?

Sea-level contribution from 18 regions defined in the Randolph Glacier Inventory (RGI; Pfeffer et al., 2014) along with the surface temperature (ST) averaged over each RGI region from Last Millennium Reanalysis (LMR v2; Tardif et al., 2019) data are shown below. We use LMR as it is used to drive the glacier model (section 2.3) and is more consistent; on the other hand, it is hard to obtain regionally downscaled ST from Neukom et al. (2019). We have included this figure (S1; shown below) as a supplementary figure in the paper.



S1: Sea-level contribution (orange) from 18 glacier regions defined in the RGI (excluding Antarctic/sub-Antarctic) and the glacier-area weighted surface temperature (blue) over each region extracted from LMR-v2. All the curves are anomalies with respect to 1841 – 1860 mean. Note that a 31-year running mean is applied on surface temperature and the original annual mean is shown for the glacier sea-level contribution.

The modeled glacier contribution is large (even described as "remarkable" on line 456), which presumably indicates that some proportion of the 18 regions were behaving in a temporally-coherent fashion (growing/melting at the same time as one another), or possibly that a subset of regions dominates the glacier signal. Simultaneous contributions across multiple regions in the pre-anthropogenic Common Era might be surprising since a principal conclusion of Neukom et al. (2019) is that temperature trends were not spatially-coherent during this time. I was therefore surprised to see such a large and sustained glacier contribution, because the Neukom et al (2019) analysis led me to think that as one region warmed, another cooled and therefore that the change in glacier mass (and its contribution to GMSL) would be moderated. This is even more surprising because Neukom et al. (2019) conclude that twentieth-century warming is the only temperature signal which is globally coherent and therefore would affect all the glacier regions simultaneously, yet the contribution to GMSL from glaciers is smaller and slower that it was during times of incoherent temperature variability. I think some regional analysis of glaciers by region would be a useful addition to this paper.

We thank the Reviewer for this comment. As shown in S1 (which is included as a supplementary figure to the paper), there is considerable regional variability in the history of both glaciers and surface temperature throughout the Common Era. The global sum of glacier contribution is indeed the result of very different regional signals. Linking surface temperature with regional glacier changes would be difficult without further diagnoses, nevertheless, we assume that the changes of surface temperature and glaciers might occur over distinct time scales. Neukom et al. (2019) focused on the absence of consistent warm and cold phases at multidecadal to centennial timescales. For instance, the surface temperature shows strong decadal to multi-decadal variability both regionally (S1) and globally. On the other hand, the large-scale glacier changes in the CE are mostly a centennial to multi-centennial response, for which the spatial consistency might appear higher (S1 and Fig. 2d). Bringing discussion on regional changes is probably out of the scope of this present paper which is focused on globally averaged signals (in a similar way, we restrain from describing the regional contribution of thermal expansion in different oceanic basins). However, the salient features of S1 would be added in the discussion part. Also, all the time series shown in S1 will be made available for anyone who wish to explore the regional glacier variability further, once the paper is accepted for publication. We also would like to mention that the global-mean surface temperature is replaced by glacier-area weighted surface temperature averaged over the 18 regions from LMR, in Fig. 2d.

The authors note that modeled GMSL is considerably less than observed and reconstructed twentieth-century rise. The difference is attributed to underestimating the barystatic contribution, especially from glaciers. In particular, the distribution and size of glaciers at the start of the Common Era was set (by necessity) to be the same as that observed in ~2000 CE, despite anthropogenic warming having already impacted them significantly by ~2000 CE (including some glaciers being lost – line 425 – and therefore missing from the modeled contribution throughout the Common Era presumably). The authors discuss how this effect modeled GMSL since ~1800 CE, but offer less insight into how the problem could bias GMSL estimates before 1800 CE (other than suggesting that the very large contribution from glaciers before ~400 CE could be a spin-up effect from using ~2000 CE as the initial state). I would be interested to read an expanded discussion about how modeled GMSL appears to be an underestimate for the past 200 years, but agrees well with reconstructed GMSL at least for ~800-1800 CE despite the difficulties with glaciers. For example, the difference between GMSL as modeled and reconstructed by Walker is large before ~600 CE. Could (and how) might glaciers solve/cause this discrepancy? If some glaciers are missing, does this mean that the modeled contribution from glaciers is a minimum, and would somehow adding them back in to the GMSL calculation fix the discrepancy since ~1800 CE at the expense of creating a new discrepancy before ~1800 CE?

We thank the reviewer for his insightful comments. There are large uncertainties and limitations in simulating the glacier changes for the Common Era and we have noted some of them in the methods and discussion parts (Line 423; as the reviewer pointed out). Given those large uncertainties (especially the initial glacier distribution and right climate forcing at the beginning of the CE), we emphasize that it is virtually impossible to have a quantitative validation, especially during the PCE. We totally agree with the reviewer that the prescribed initial volume may have a huge impact on the rest of the glacier evolution, however, initializing the model with a new state as an alternative can also bring uncertainty (including the spin up to such a new initial state). We have added a few sentences more in the discussion to highlight these uncertainties.

Technical Corrections

Line 49: The Walker et al. paper is cited as a 2020 publication, but it is listed (correctly) as a 2021 publication in the reference list.

This is corrected in the text.

Line 217: Title needs a capital letter.

Corrected

The 20th century is variously referred to as "20thC" (section 4.1), "twentieth century" (e.g., line 30), or "20th century" (e.g., line 204). These could me made consistent throughout the manuscript.

We made it consistent by using *twentieth century*

Line 196: "R" should be changed to "r" for consistency with other titles.

Corrected

I found Figure 1 to be a little confusing. Readers might find it easier if a third panel was added to show the "below 700m" component rather than including it in panel B which is described initially in the caption as the "top 700m". Or alternatively place the below 700 m, above 700m and total in a single panel.

We agree. This figure is redrawn as suggested.

The use of two y-axes in figure 5a to show the same quantity (sea level, cm) at different scales made the figure difficult to use.

We agree. The main objective with figure 5a is to show the consistent changes in global-mean thermosteric sea level with those climate epochs (shown by light shading in the panel) and to quantify the respective contribution of individual processes during each epoch (bar plots). The net barystatic curve shown in figure 5a does not bring anything new so that we discarded it from the panel.