An Improvement to short term variability in Global Mean Sea level reconstruction

Reviewer 1

General Comments:

This manuscript proposes a correction to the Empirical Orthogonal Function (EOF) model used for estimating historical global mean sea level prior to the satellite altimeter period. This correction relies on local winds, the SOI and the signal of tide gauges to "correct" for these local effects impacting coastal sea level that are not captured by the large scale altimeter signal, particularly as expressed through EOFs.

I think this is a useful approach and it is well described in the manuscript. Congratulations to the authors.

I was a little surprised that there was not a larger difference between the corrected and uncorrected GMSL estimates (Figure 12). Perhaps further improvements would result from correcting for the effect of Gravity, Rotational and Deformational (GRD) impacts from changes in the distribution of mass of water stored on land on sea levels, during ENSO events for example. Note Wang et al. (2024) has attempted to include these GRD impacts on reconstructions. There are alternate (possibly better) ways of including these effects the authors might wish to investigate in subsequent studies.

Reply : We thank the reviewer for pointing this out and have added a sentence in the introduction referencing Wang et al. 2024. (Lines 64 to 67)

In addition, following the reviewer's suggestion, we recalculated the GMSL reconstruction after removing VLM induced by contemporary GRD from the tide gauge records. The GRD data was obtained from Frederikse et al. (2020). Here we applied the GRD correction to the individual tide gauge observations before any averaging into 1°x1° bins took place and prior to reconstructing the GMSL as outlined in the methodology in the manuscript. Please note, that the GRD dataset stopped in 2018 so it is two years shorter than the manuscript results. We find that applying the GRD correction does not change the reconstructed GMSL trends significantly (see Fig. R1 and compare with Fig. 12), and unfortunately it also does not improve the GMSL variability of the corrected reconstruction (Fig. R2),

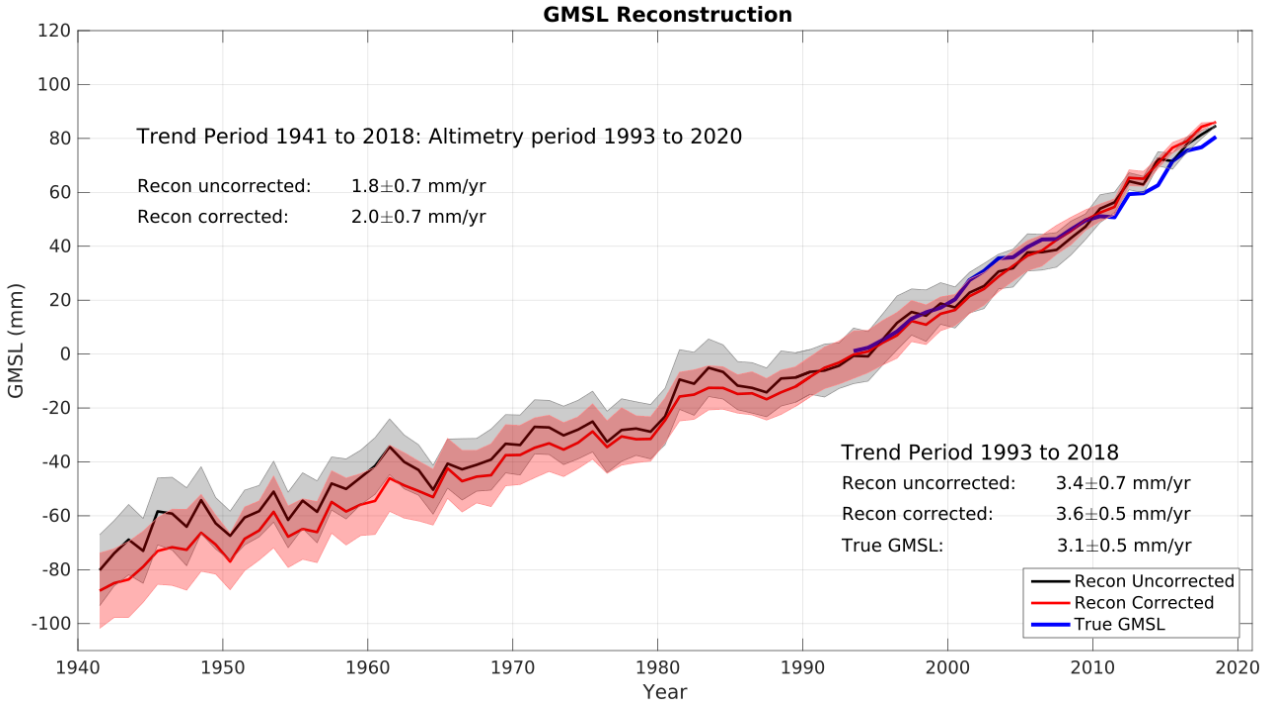
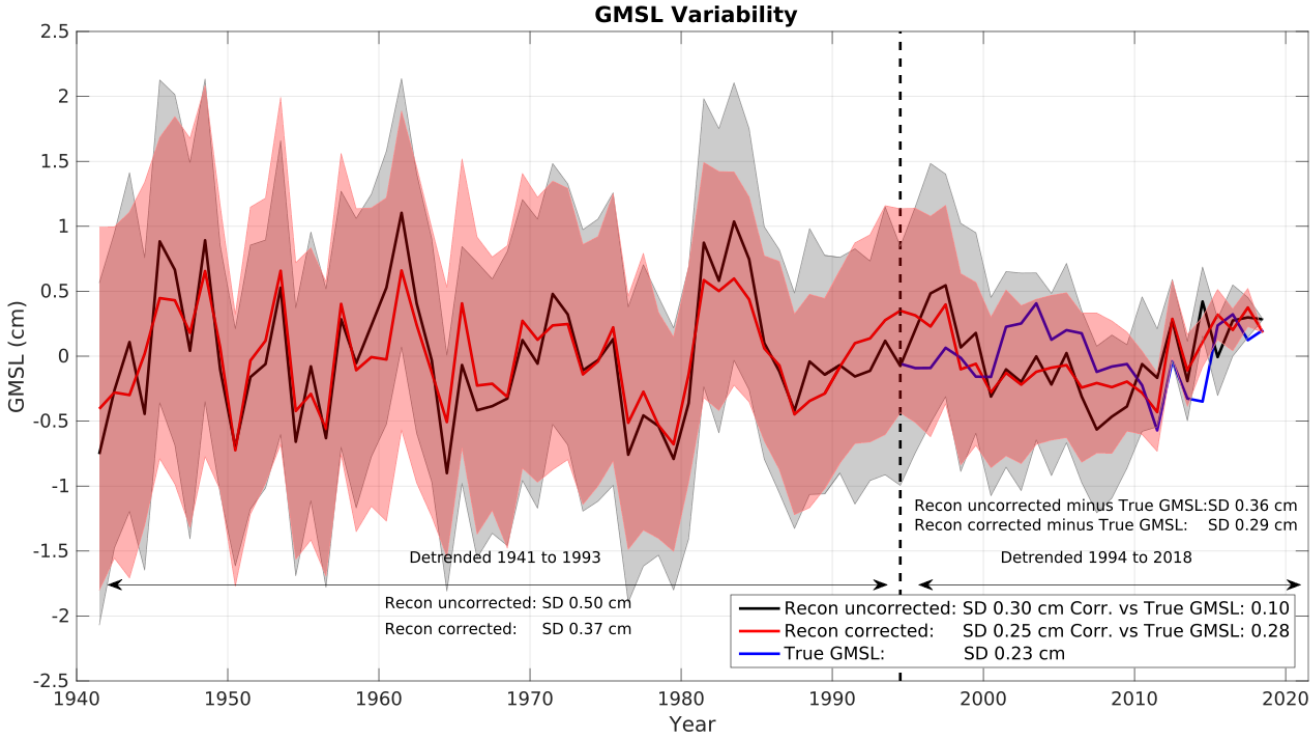


Fig R1 The uncorrected (black line) and corrected (red line) EOF reconstructions derived from Eq. (1) see manuscript, had the GRD applied to the tide gauge observations prior to reconstruction. The 1-sigma uncertainty intervals, shaded grey and light red respectively, reflect the sensitivity of the reconstruction to the number of tide gauges as evaluated SD using a bootstrap method. The 'true' GMSL derived from altimetry is



shown as a blue line (1994 to 2018).

Fig R2 The variability of the GMSL that has been detrended for two time periods 1941 to 1993 and 1994 to 2018 showing the uncorrected (black line) and the corrected (red line) EOF reconstruction with the GRD correction applied prior to reconstruction, derived from Eq. (1), see manuscript The 1-sigma uncertainty intervals shaded grey (uncorrected) and light red (corrected) reflect the sensitivity of the reconstruction to the number of tide gauges as evaluated standard deviation (SD) using a bootstrap method. The detrended 'true' GMSL derived from altimetry is shown as a blue line (1994 to 2018).

Here we have added the following paragraph to the Discussion (lines 663-669):

To test this and following Wang et al. (2024), we recalculated the GMSL reconstruction after correcting the tide gauge records for contemporary GRD-induced VLM, using GRD data from Frederikse et al. (2020). Unfortunately, we found that applying the GRD correction did not improve the GMSL variability of the corrected reconstruction. An alternative would be to use GPS observations of VLM, however, long, continuous GPS records are available at only a very limited number of tide gauge sites.

I was surprised that there was no discussion of coastal trapped waves known to be important on the American and Australian coasts. These waves are consistent with the idea behind these corrections of winds affected coastal sea levels with a much reduced impact on sea levels off shore at altimeter grid points. These waves also allow the impacts of remote winds affecting local sea levels, again as studied on the American and Australian coasts. Similarly, ENSO impacts can travel very large distances on the American and Australian coasts. I think the authors should discuss the implication of coastal trapped waves and propagation of remote signal such as those associated with ENSO and distant coastal winds.

Reply :We thank the reviewer for this comment. Coastal trapped waves are indeed relevant to the differences between altimetry and tide gauge observations that are described in the paper. We have added a paragraph in the discussion to discuss coastal trapped waves in some detail (line 620 to 633).

There remains some trend differences in Figure 12. Although they are not significant, it would be useful to understand the reasons for the differences. I suspect that GIA differences may be at the heart of these differences. Could the authors comment please rather than just state they are not significantly different.

Reply :We have added text in the discussion. Thank you (line 634 to 638)

I recommend that the paper is published after consideration of these comments.

Detailed Comments for the authors to consider:

Lines 60-64: It may be useful to note that Wang et al. (2024) has extended the EOF technique by dispensing with mode zero and instead including spatially variable fingerprints.

Thank you for brining Wang et al. (2024) to our attention. We have added this reference to the revised manuscript and a comment to the Introduction. (lines 64 to 67)

Lines 269-282: Would using winds parallel and perpendicular to the coast be useful?

Reply :Yes, determining the wind angle of approach to the coastline may be a useful enhancement to the regression model. This will be investigated in future work. A comment has been added to the text. Thank you.(lines 652 to 653)

Line 559-560: Can you make the quantitative (and statistical) reasons for preferring on model 3 clearer. I did not pick up this clear preference given the additional parameters used in this more complex model.

Reply :We added text to justify why we chose Model 3 and made it clear. (see lines 518-519) Thank you

References

Wang, Jinping, et al. 2024. Improved sea-level reconstruction from 1900 to 2019. *Journal of Climate*, 37 **(24), 6453-6474. DOI 10.1175/JCLI-D-23-0410.1**

Reviewer 2

The study addresses a limitation of EOF-based GMSL reconstructions in capturing interannual variability. The proposed approach of examining and modelling the Signal Differences between tide gauges and nearby altimetry is well motivated, and the reported improvement in the reconstructed GMSL variability is promising. The manuscript is generally clearly structured, and the topic is meaningful to the sea-level reconstruction community.

Two methodological details require clarification before publishing. In particular, the treatment of GIA corrections and reference frames, and the possible contribution of non-linear and periodical vertical land motion signal to the estimated Signal Differences.

1. Please clarify the treatment of GIA corrections and reference frames. The manuscript states that the tide-gauge records are corrected for GIA, while the altimetry data are also corrected using the ***drad250*** GIA correction. Since tide gauges measure relative sea level whereas satellite altimetry measures absolute sea level, it is unclear whether these two GIA corrections place the two datasets into the same reference frame. The manuscript seems to apply two different GIA-related corrections: a relative sea-level GIA correction to tide gauges and a ***drad250*** radial-deformation correction to

altimetry. Please explain how their application ensures that the corrected tide-gauge and corrected altimetry records are comparable in a common reference frame before calculating the Signal Differences.

Reply : We thank the reviewer for raising this very important point. We did find that GIA Altimetry correction was applied incorrectly in the original manuscript. We confirm that the Altimetry GIA was applied correctly in this revised manuscript and the subsequent analysis redone. To clarify the GIA corrections, in this study, tide gauge data were corrected using the relative sea level prediction (drsl250.PSMSL.ICE5Gv1.3_VM2_L90_2012b), which includes both the geoid change and vertical land motion contributions (https://psmsl.org/train_and_info/geo_signals/gia/peltier/index.php). For the altimetry data, we applied the geoid-only GIA correction, obtained as the sum of the relative sea level and vertical land motion components (dsea250.1grid.ICE5Gv1.3_VM2_L90_2012 + drad250.1grid.ICE5Gv1.3_VM2_L90_2012). We have revised the manuscript text to make this distinction clear. (Please see lines 191 to 194)

2. Recent studies have shown that vertical land motion (VLM) at tide-gauge sites cannot always be represented as a purely linear process, and that nonlinear VLM can affect tide-gauge relative sea-level records and their interpretation (Oelsmann et al., 2024). In addition, GNSS studies have identified quasi-periodic surface displacement signals near a 6-year period, including vertical components (e.g., Ding and Chao, 2018). Similar signals have also been reported in satellite-altimetry-minus-tide-gauge residuals and have been considered when aligning tide-gauge and altimetry records for sea-level reconstruction (Wang et al., 2025). Because the Signal Differences in this study are defined as the difference between tide gauge and altimetry, it would be useful for the authors to clarify whether such vertical land-motion-related signals could contribute to the estimated differences. If these land-motion-related signals can be incorporated into the framework, they may further improve the resulting GMSL reconstruction. It will be better if the authors test this possibility. If such an analysis is beyond the scope of the present study, the authors should acknowledge this issue as a potential limitation and discuss how it may affect the interpretation of the regression-based correction.

Reply :We have added a paragraph in the discussion that addresses the VLM. Thank you (see lines 655 to 665).

Other comments

Line 117:

"though linear regression" should be "th**r**ough linear regression."

Reply : Corrected, thank you (line 121).

Line 158:

The sentence “A total of seven yearly observations were removed from the entire data set during this procedure” is somewhat unclear. Please specify whether these seven removed observations correspond to seven station-years across different tide gauges, seven years from a single tide gauge, or another configuration. It would also be helpful to list the affected tide-gauge stations and years, or provide this information in a table or supplement.

Reply : We have added text in the manuscript that references a table (Table1) showing the tide gauges that have been affected. Thank you (see lines 161 to 171)

Line 160:

The manuscript states that the quality-controlled tide-gauge stations were spatially averaged into 1° × 1° tide-gauge bins. Please clarify the exact binning procedure. For example, were all stations falling within the same 1° × 1° grid cell averaged directly, or was an additional distance criterion used? Please also specify how stations with overlapping or different temporal coverage were combined within each bin.

Reply : We have added text to the manuscript to make it clearer, thank you (lines 174 to 177)

Lines 221-223: The notation may be visually confusing because the summation operator $\sum$ and the covariance matrix $\sum$ appear very similar. I suggest better to distinguish it clearly from the summation symbol.

Reply : We changed the summation operator $\sum$ to a bold font and placed the upper limit (i=N) and the lower limit (i = 1) above and below $\sum$ making it more obvious this the symbol represents the summation operator compared with the covariance matrix $\sum$ that is not bold and does not have upper and lower limits. Thank you (lines 240 to 243)

Line 296:

There is an extra period after “reconstruction.” Please change “reconstruction..” to “reconstruction.”

Reply : Corrected, thank you.

Line 315:

“using 229 tide gauge” should be “using 229 tide gauges”

Corrected, thank you. (line 340)

Line 425:

Reply : “less of factor” should be “less of a factor.”

Corrected, Thank you (line 450)

Line 582:

Reply : "large scale" should be hyphenated as "large-scale" when used adjectivally.

Corrected, thank you. (line 609)

References:

Oelsmann, J., Marcos, M., Passaro, M., Sanchez, L., Dettmering, D., Dangendorf, S., & Seitz, F. (2024). Regional variations in relative sea-level changes influenced by nonlinear vertical land motion. *Nature Geoscience*, *17*(2), 137–144. https://doi.org/10.1038/s41561-023-01357-2

Ding, H., & Chao, B. F. (2018). A 6-year westward rotary motion in the Earth: Detection and possible MICG coupling mechanism. *Earth and Planetary Science Letters*, *495*, 50–55. https://doi.org/10.1016/j.epsl.2018.05.009

Wang, S., Shum, C. K., Bevis, M., He, X., Zhang, Y., Ding, Y., Zhang, C., & Montillet, J.-P. (2025). Sea level reconstruction reveals improved separation of regional climate and trend patterns over the last seven decades. *Earth System Science Data*, *17*(12), 7055–7077. https://doi.org/10.5194/essd-17-7055-2025

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