Reply to RC2 for the paper titled: Sea level reconstruction reveals improved separations of regional climate and trend patterns over the last seven decades.
Author(s): Shengdao Wang et al.
MS No.: essd-2025-251
MS type: Data description paper

RC2 general comments:

This manuscript introduces a modified spatial-temporal sea-level reconstruction method/product that combines two complementary decomposition techniques with reduced-space optimal interpolation, extending geocentric (absolute) sea-level anomalies back to 1950. The manuscript provides two main improvements. First, the reconstruction products support more cleanly separating climate-related sea level variability (e.g., ENSO, PDO) from the long-term trend within a spatiotemporal framework. Second, after quantifying climate-related variabilities, the authors assess their influence on regional short-term trend estimates as well as on regional long-term trends and accelerations. Other minor contributions include testing different gap-filling methods for tide gauge records to increase record availability. Comparison between different ways to correct vertical land motion at tide gauges to better match tide-gauge and satellite altimetry sea level. Overall, the datasets and their derived results are likely to benefit the sea-level and climate communities. The authors have provided both the products and core plotting/analysis codes at the data availability link, which facilitates a user-friendly experience. However, I still have several comments/concerns that, once addressed, should make the manuscript suitable for publication.

Dear Reviewer and Editor

Thank you for your insightful comments and suggestions. We have addressed each point and revised the manuscript accordingly. In particular, we (1) added a schematic of the modified CSEOF–OI reconstruction workflow in the supplementary information; (2) expanded the validation from 5°×5° to the native 1°×1° grid and revised the comparisons in Figure 6e–g; and (3) provided an additional figure (RC2_Fig1) and one table (RC2_Table1) to help answer your questions better. Below, we respond point by point. For readability, our responses appear in **blue**, and the corresponding manuscript changes are marked in **red**. We believe these revisions, in response to your constructive comments, substantially strengthen the paper.

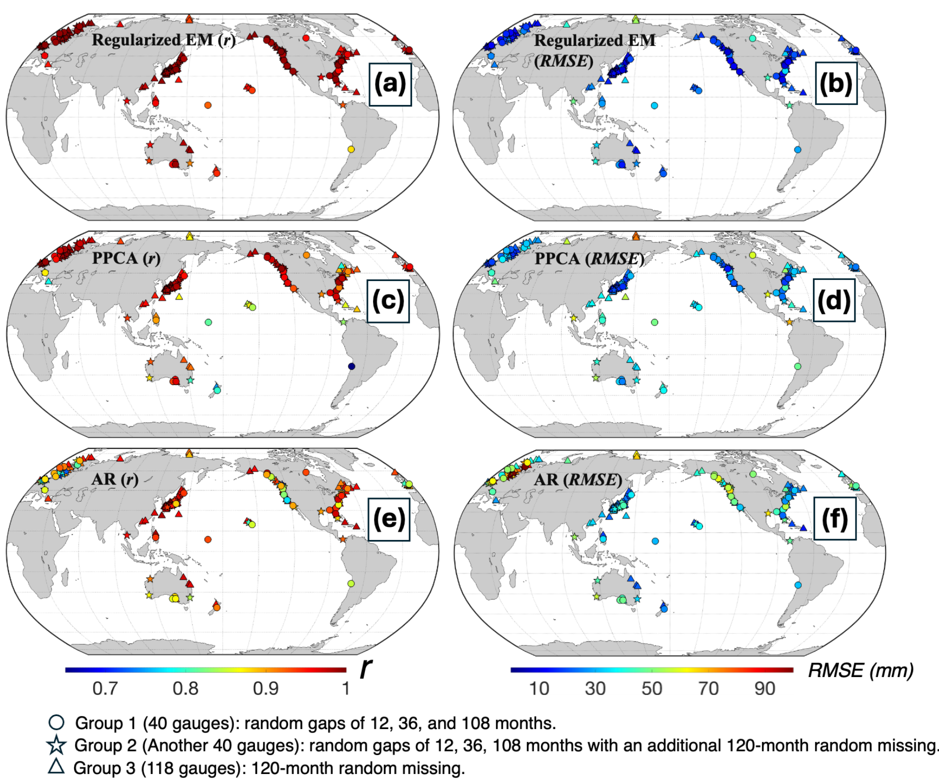
On behalf of all authors

Best regards,

Shengdao Wang

RC2-Q1: The manuscript tests three gap-filling approaches (regularized EM, PPCA, AR) for tide gauges by using 48 nearly complete 70-year records and concludes that regularized EM performs best, as illustrated in Figure 2. Since the reconstruction process uses many more gap-filled tide gauges, please include a robustness test on a broader sample, e.g., considering setting the gauge record length shorter to include a larger set of near-complete gauge records, and report whether the ranking of methods is stable.

Reply: Thanks for the suggestion. To test robustness on a broader sample, we extended the evaluation to 198 tide gauges with continuous records from January 1980 to December 2021. We formed three simulation groups (marker shapes in RC2_Fig1): Group 1 (40 gauges) with random gaps of 12, 36, and 108 months; Group 2 (another 40 gauges) with random gaps of 12, 36, 108, and 120 months; and Group 3 (118 gauges) with 120 months randomly missing. Each gauge was randomly assigned the specified gaps to mimic realistic missing-data scenarios. The results (RC2_Fig1 and Table RC2_Table 1) show that Regularized Expectation–Maximization (EM) retains the best performance across all groups—higher correlation coefficients and lower errors—indicating that the ranking of methods is stable under a larger, more diverse test set. We will include these results in the Supplementary Information.



RC2_Fig1: Spatial maps of the correlation coefficient (r) and root-mean-square error (RMSE, mm) between gap-filled tide-gauge records via three gap-filling methods and their corresponding complete ("true") records: Regularized EM (panels a, b), Probabilistic Principal Component Analysis (PPCA; panels c, d), and autoregressive (AR) modeling (panels e, f). The assessment uses 198 tide gauges with near-complete monthly records spanning January 1980–December 2021. Circles, stars, and triangles denote Group 1, Group 2, and Group 3, respectively. Group 1 (40 gauges) is assigned random gaps of 12, 36, and 108 months; Group 2 (another 40 gauges) is assigned the same random gaps plus an additional 120 random missing months; Group 3 (118 gauges) is assigned 120 random missing months.

RC2_Table 2: Performance of the three gap-filling methods based on the average Pearson correlation coefficient (*r*) and root-mean-square error (RMSE, mm) between the 198 gap-filled records (January 1980–December 2021) and their complete counterparts, evaluated separately for Group 1, Group 2, and Group 3, and for the overall mean.

	Pearson correlation coefficient (r)				*RMSE (mm)*			
	Group 1	*Group 2*	*Group 3*	*Mean*	*Group 1*	*Group 2*	*Group 3*	*Mean*
PPCA	*94.14%*	*95.48%*	*95.97%*	*95.49%*	*29.13*	*29.33*	*25.88*	*27.25*
Regularized EM	*97.94%*	*97.98%*	*98.91%*	*98.50%*	*17.76*	*20.87*	*13.11*	*15.64*
AR modeling	*89.50%*	*83.38%*	*95.70%*	*91.92%*	*46.50*	*61.42*	*31.89*	*40.88*

Detailed changes in the manuscript:

- We added the RC2_Fig1 as Fig. S 1 and RC2_Table 3 as Table S1 in the supplementary information.

- And add a few sentences after Line 151 to indicate the additional tests: To test generalizability, we used 198 tide-gauge records that are nearly missing-free over January 1980–December 2021, cropped all series to this common window, and repeated the gap-filling experiments. Using the three gap-filling methods, we imposed the three missing-data scenarios: (i) 40 gauges with a single contiguous gap of 12, 36, or 108 months; (ii) another 40 gauges with the same single-gap setting plus one random 120-month gap; and (iii) an additional 118 gauges with 120 months of random missing across the record. Performance was assessed against the complete ("true") series. Full results are in Fig. S4 and Table S1. And results indicate Regularized EM again performs best across other methods—i.e., higher correlation coefficient and lower RMSE—and showing that the method ranking remains the same under a larger, more diverse test set.

RC2-Q2. In the section GNSS-derived vertical land motion at tide-gauge locations compared with the results from the altimetry minus tide-gauge (SA-TG) approach, this comparison should provide the GNSS data selection criterion used in Figure 3, e.g., collocation criteria, time spans, etc. More generally, in this section, please refocus SA-TG approach, which was used in the reconstruction, and present the other two correction approaches briefly. This will avoid letting side methods overshadow the main workflow and will make the procedure easier to follow.

Reply: Thank you for the suggestion. The GNSS-based VLM rates used for validation are from Hammond et al. (2021). Their solution applies standard screening (record length ≥ 3.5 years) and models annual/semiannual terms and offsets/jumps to mitigate non-linear behavior (e.g., steps). Record lengths at tide-gauge sites are heterogeneous (~3.5–26.5 years). Checking Nevada Geodetic Laboratory logs for the GNSS stations shows in Figure 3 calendar coverage from October 1994 to December 2020, with a median record length of 9.93 years (mean 10.42 years). Using the collocation information for the stations in Figure 3, the median GNSS and tide-gauge distance is 2.21 km, and 220 out of 253 stations hold a distance between GNSS station and tide gauge stations within 20 km.

Detailed changes in the manuscript:

- For better re-focus on the SA-TG approach, we will revise for Lines 209–226 (concise for better focus):
  Global Navigation Satellite System (GNSS) can provide VLM estimates at collocated gauges, but in practice, its utility is limited by the scarcity of long, stable records (Wöppelmann et al., 2019) and influenced by long-period geophysical signals (Santamaría-Gómez & Mémin, 2015; Santamaría-Gómez et al., 2017). Additionally, in some regions, even minor geographic misalignments (a few kilometers) between the GNSS receiver and tide gauge can cause GNSS-estimated vertical land motion to inadequately represent gauge location motions due to the high spatial variability (Bevis et al., 2002; Oelsmann et al., 2021). Precise leveling provides an accurate tie, but it is labor-intensive and rarely maintained.

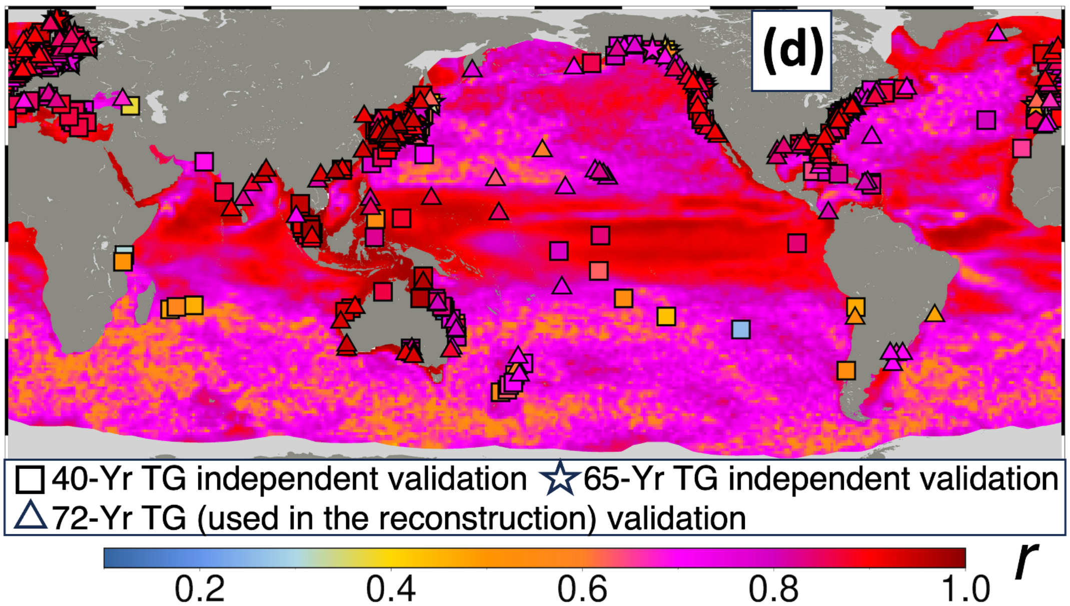
  Other methods to estimate VLM have used the satellite altimetry minus tide gauge (SA–TG) approach (Nerem and Mitchum, 2002; Kuo et al., 2004, 2008; Ray et al., 2010; Wan, 2015; Wöppelmann and Marcos, 2016; Oelsmann et al., 2021). In particular, Kuo et al. (2004) and Kuo et al. (2008) applied a network adjustment to reduce VLM error estimates to <0.5 mm yr^{-1} in semi-enclosed seas and lakes. Wan (2015) jointly solved for geocentric sea-level trend and VLM at global tide gauges. Wöppelmann and Marcos (2016) further showed that accurate VLM estimation via SA–TG requires a common data span of ≥20 years between altimetry and tide gauge data—a criterion that has been met.

RC2-Q3. For the validation on the modified sea level reconstruction product in Figure 6d, the manuscript emphasizes applying long-term tide gauge records excluded from the reconstruction as independent validations, which is good. However, it should also report the comparison between the gauges used in the reconstruction process and their collocated reconstruction series to assess whether potential overfitting exists. For Figure 6g, since produced from this study in 1° × 1° resolution, please also compare the full-resolution 70-year trends with other gridded reconstruction over their common period if comparable-resolution product exists.

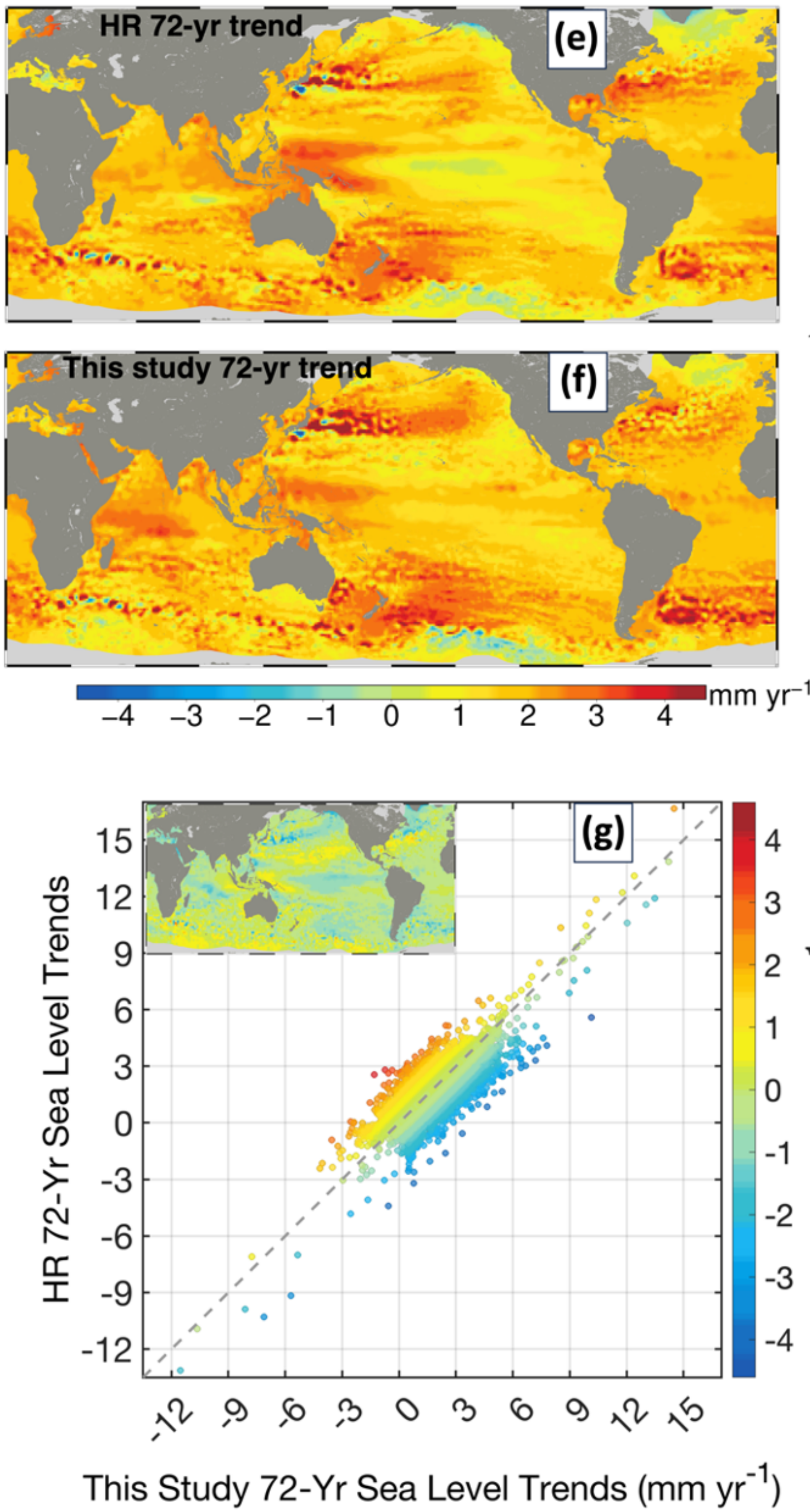
Reply: Thank you for the suggestion. We have added a comparison between the tide gauges used in the reconstruction and the co-located reconstruction and visualized this in the revised Figure-6d. We also adopted the related minor suggestion in the later part "Line 464 to Line 466 "This validation was performed over 40 years (January 1982 to December 2021; 224 gauges) and 65 years (January 1967 to December 2021; 34 gauges), yielding a consistent median r=0.85 (85.19% for 40 years and 84.76% for 65 years)." to update the validation period so that it includes January 2022, consistent with the reconstruction span (January 1950–January 2022). Accordingly, Figure 6d has been updated in two ways: (1) Added comparison between gauges which used in the reconstruction and collocated reconstruction. (2) Extension of the two validation windows to include January 2022.

We also agree that users benefit from validation at the native 1°×1° grid and from a clearer assessment of reliability in the pre-altimetry era, especially over the open ocean. To achieve this, we will: Revise Figure 6 panels e, f, and g to present 1°×1° comparisons to evaluate the regional sea level trend cover 1950 to 2021.

Detailed changes in the manuscript:



- Figure 6 d (revised, caption shows for panel d): Panel (d) compares the detrended monthly modified reconstruction to two types of linear detrended tide gauge records not used in the reconstruction as long-term independent validations: 40-year series (January 1982– January 2022) from 224 stations (squares) and 65-year series (January 1957– January 2022) from 34 stations (pentagrams), and 225 stations (triangle) used in the reconstruction process spanning from January 1952 to January 2022.
- And Revise in the Lines 462 to 466 into: This validation was performed over 40 years (January 1982 to January 2022; 224 gauges) and 65 years (January 1957 to January 2022; 34 gauges), yielding a consistent median r=0.85 (85.24% for 40 years and 84.70% for 65 years). For gauges that were used in the reconstruction process (January 1950 to January 2022, 225 gauges), the results show a median r =0.85 (84.76%). The similar performance between gauges used in the reconstruction and those not used indicates a low risk of overfitting.
- Revise the context from Lines 470 to 475 into: Due to the spatial resolution difference between the two reconstruction products, we examine sea level trends from 1950 to 2021 across each 1°×1° grid in various ocean basins by first resampling the products from Dangendorf et al. (2024) with the exact spatial resolution with our product, then hold the comparison across each grid (Within our 1° ocean grid, >99.9% of cells have a corresponding value in the re-gridded Dangendorf field), as detailed in Figure 6e- f. Further analysis based on Figure 6g reveals that ~40% of the 1°×1° grids exhibit discrepancies (absolute) below 0.30 mm yr^{-1}, while ~80% of the grids show discrepancies under 0.74 mm yr^{-1}, and ~92% maintain discrepancies less than 1 mm yr^{-1}

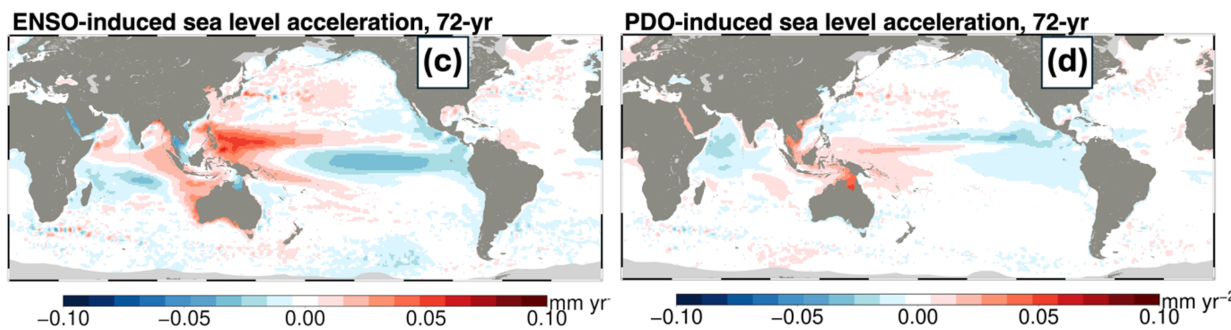


- Figure 6 (**e,f,g, revised**): Panels (e)–(f) depict regional geocentric sea-level trend over 1950–2021 from HR (Dangendorf et al. 2024, re-gridded at 1° × 1°) and from the modified reconstruction, (g) highlights the regional differences.

RC2-Q4. In Figure 9, the 70-year combined ENSO–PDO induced sea-level acceleration is spatially prominent. To better serve users who are interested in multi-decadal sea level acceleration studies, the authors should also include separate spatial maps showing the ENSO-induced and PDO-induced acceleration coefficients, respectively.

Reply: Thank you for the suggestion. We have computed and now provide separate spatial maps of ENSO-induced and PDO-induced sea-level acceleration (new Figure. 9c–d). For clarity, the long-term accelerations in Fig. 9 are evaluated over 1950–2021 (72 years), and we have made the wording consistent throughout the manuscript.

Detailed changes in the manuscript:



- Figure 1 c,d (Newly added, caption only shows for panel c and d, other panel order shown in revised manuscript changed accordingly). Panels (c) and (d) illustrate the respective sea level acceleration coefficient contributed from the 72-year ENSO-induced sea level and the PDO-induced sea level, respectively.

RC2-Q5. Add a flowchart of the modified reconstruction procedure to highlight the steps implemented in the reconstruction section more clearly.

Reply: Thank you for the suggestion. We made a schematic flowchart of the data-processing workflow in the Supplementary Information to give readers a quick overview of the full pipeline.

Detailed changes in the manuscript:

- The flowchart is as follows, and added into the supplementary figure as Fig. S 6:

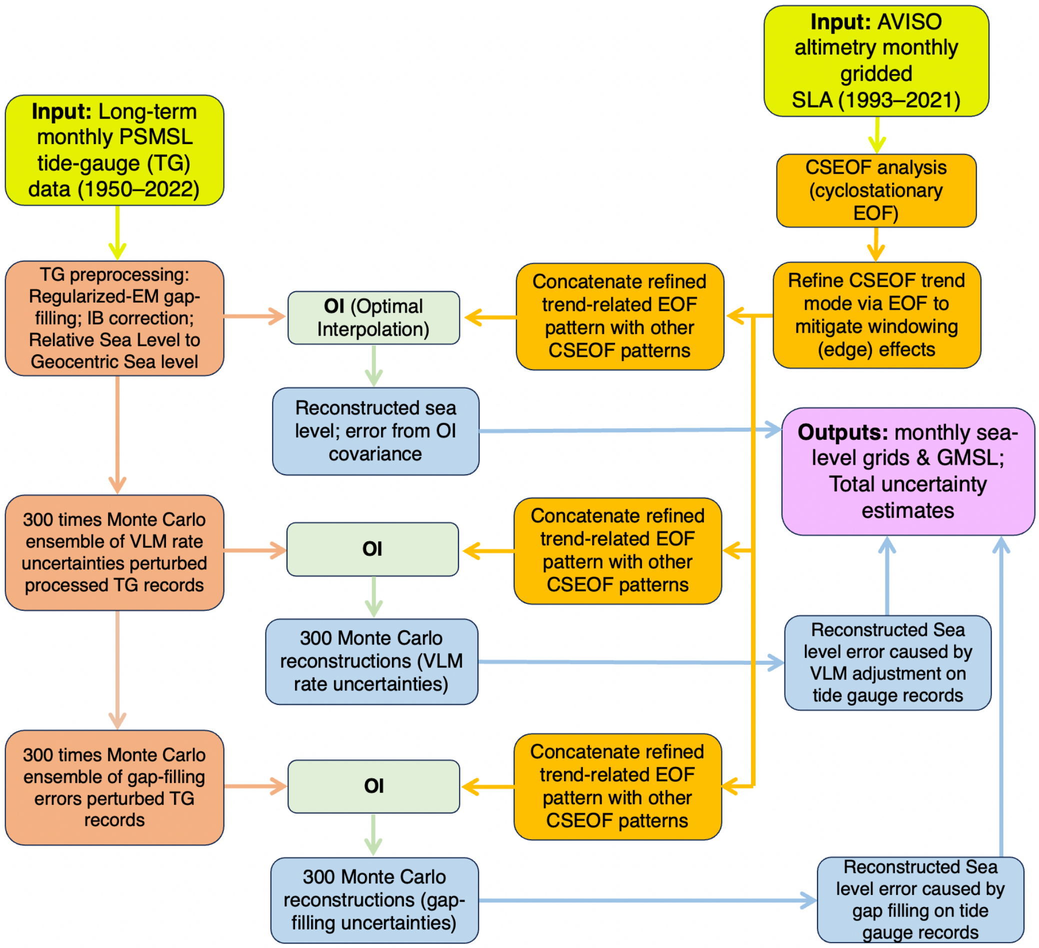


Fig.S 6 (Newly added figure in manuscript). Schematic flowchart of the modified sea-level reconstruction procedure. Inputs are monthly PSMSL tide-gauge records (January 1950–January 2022) and AVISO gridded sea-level anomalies (SLA, January 1993–December 2021). Outputs are 72 years (January 1950–January 2022) of monthly sea-level grids and a global mean sea-level (GMSL) time series, each with corresponding error estimates.

- At line 433, we added a sentence directing readers to the schematic flowchart for a clearer overview of the sea-level reconstruction workflow: For an overview of the modified reconstruction, see the schematic flowchart in Supplementary Information Fig. S6.

Minor suggestions:

Line 25, exhibit -> exhibits

Done, thanks.

Line 68, spatiotemporal sea level changes -> spatiotemporal changes in sea level

Done, thanks.

Line 103, the estimate of -> estimating, difficult -> challenging

Corrected, thanks.

Line 112, mirrors -> was similar to

Got it and corrected, thanks.

Line 134, PSMSL, first time showing in the main text, should provide the full name.

Got it and corrected, thanks.

Line 162, mitigate -> address

Got it and corrected, thanks.

Line 189, needed-> necessary

Got it and corrected, thanks.

Line 218, long-> largely

The entire sentence has been rewritten and detailed in the previous Q2. Thanks.

Line 225, to be estimated -> estimation

Got it and corrected, thanks.

Line 227 to Line 229, “An issue that might be regarded as a mere matter of language is examined here … entails circular logic or tautological reasoning.” Should simplify/reorganize these two sentences.

We appreciate the suggestion. After careful review, we agree that the sentence at Lines 227–229 (“An issue that might be regarded as a mere matter of language is examined here … entails circular logic or tautological reasoning.”) is hard to understand. As the purpose of the sentence is to help emphasize the upcoming several lines, removing it does not affect the logic, results, or conclusions. We have deleted this sentence.

Line 234, not -> rather than

Got it, thanks.

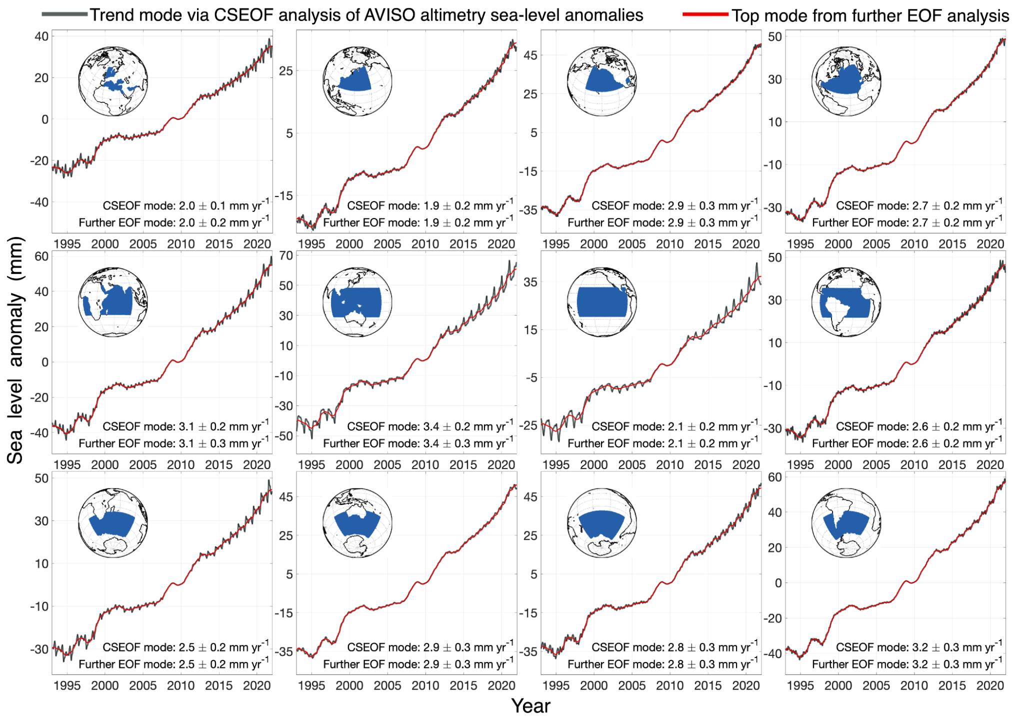
Line 324, corresponding the -> the corresponding

Got it, thanks.

Line 335, In Figure 4, the author should add the trend values of the CSEOF trend mode estimated regional trends, and trend values from the further refined trend mode. Also, anomlies -> anomalies

Will add this information in the revised figure, thanks.

Detailed changes in the manuscript:



- Figure 4 (revised): Identification of regional average trend mode in monthly AVISO altimetry sea level anomalies using CSEOF analysis. Subsequent EOF decomposition of these trend components has further delineated the primary component. The insets highlight the respective geographic study regions in blue. The values at the bottom of each panel report the fitted regional mean trends from the CSEOF trend mode and from the subsequent EOF mode, demonstrating their consistency.

Added this information in the revised manuscript, thanks.

Line 393, initial and terminal -> near beginning and end

Got it, thanks.

Line 450, and respective reconstruction -> and their respective reconstructions

Got it, thanks.

Line 464 to Line 466 “This validation was performed over 40 years (January 1982 to December 2021; 224 gauges) and 65 years (January 1967 to December 2021; 34 gauges), yielding a consistent median r=0.85 (85.19% for 40 years and 84.76% for 65 years).” Since the reconstructed sea level is from January 1950 to January 2022, consider updating this comparison to also include January 2022.

Solved together in RC2-Q3, thanks.

Line 541, in line -> consistent

Got it, thanks.

Line 560, before -> prior to the

Got it, thanks.

Line 577, suggesting -> suggest, meet -> meeting

Got it, thanks.

Line 578, partly -> have been partly

Got it, thanks.

Line 586, ENSO, PDO-induced sea level -> ENSO and PDO-induced sea level

Got it, thanks.

Line 621, increased -> increasing

Got it, thanks.

Line 627, evident by most of the strong rising areas concentrating on the low-latitude Pacific -> as evident by the concentration of the strongest rising areas in the low-latitude Pacific.

Got it, thanks.

Line 641, contrasted by -> in contrast to

Got it, thanks.

Line 642, western -> West

Got it, thanks.

Line 652, the critical need to account for both ENSO and PDO influences for understanding short-term sea level changes. -> the importance of considering both ENSO and PDO influences in understanding short-term sea level changes.

Got it, thanks.

Line 658, during -> over

Got it, thanks.

Line 705, generally between 1 and 2 mm yr^{-1} -> typically ranging from 1 to 2 mm yr^{-1}

Got it, thanks.

Line 730, estimate -> estimating

Got it, thanks.

Line 750, scales -> timescales

Got it, thanks.

Line 762, multi-decades -> multiple decades

Got it, thanks.

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