

Manuscript: *Assessing sea level rise and extreme events along the China–Europe Sea Route*

Journal: Natural Hazards and Earth System Sciences

Dear Editor,

Dear Reviewers,

We would like to thank the Editor and the three anonymous reviewers for their careful reading of our manuscript and for their constructive and insightful comments. We greatly appreciate the time and effort devoted to improving the quality, clarity, and robustness of this work.

We have carefully addressed all comments and suggestions. The manuscript has been substantially revised, with improvements to the structure of the Methods and Results sections, clarification of the datasets and methodologies employed, refinement of the interpretation of results, and strengthening of the Discussion to better highlight the novelty of this study. In particular, we have (i) reorganized the Materials and Methods section into clear subsections, (ii) clarified the treatment of satellite altimetry, tide gauge data, and extreme value analysis, (iii) expanded the Introduction to better contextualize regional sea level trends and extremes, and (iv) revised figures, captions, and references for consistency and readability.

Below we provide a detailed, point-by-point response to each reviewer. Reviewer comments are reproduced in **bold**, followed by our responses. The revised text in the manuscript is reproduced in *italic*.

Response to Reviewer #1 (RC1)

We thank Reviewer #1 for the positive evaluation of the manuscript and for recognizing the relevance of the topic and the value of the integrated analysis along the China–Europe Sea Route.

All comments raised by Reviewer #1 have been carefully considered. Minor textual clarifications and consistency checks suggested by the reviewer have been implemented throughout the manuscript, contributing to improved readability and coherence. No major conceptual issues were raised by Reviewer #1.

RC1: Line 85: Is there any further explanation about the multiple altimetry satellites mission used since it will affect the results such as in the Red Sea, the Persian Gulf, the Arabian Sea and the Bay of Bengal whose pattern of sea level rise was rather low in the first decade (1993-2003)?

AC1: Sea level trends are derived from the CMEMS multi-mission gridded altimetry product (SEALEVEL_GLO_PHY_CLIMATE_L4_MY_008_057), processed with the DUACS system, which applies crosscalibration and inter-mission bias corrections to ensure temporal consistency since 1993. Although the early period (1993–2003) is based on fewer missions (mainly TOPEX/Poseidon and ERS-1/2), the stability of the altimetric record during this phase has been widely validated (e.g. Cazenave et al., 2014; Nerem et al., 2018). The relatively low sea level rise observed in the Red Sea, Persian Gulf, Arabian

Sea and Bay of Bengal during the first decade therefore reflects natural decadal variability rather than observational artefacts, consistent with wind-driven circulation changes, steric effects, and ocean mass redistribution documented for the North Indian Ocean (e.g. Cazenave et al., 2014; Dangendorf et al., 2021; Huang et al., 2024).

In the revised manuscript, we clarify Section 3.1.1 by explicitly stating:

“Consistently with the decadal variability discussed above, the weak or near-zero sea level trends observed in the Red Sea, Persian Gulf, Arabian Sea and Bay of Bengal during the first decade (1993–2003) are primarily attributable to regional atmospheric forcing, steric effects and ocean mass redistribution, rather than to limitations of the multi-mission altimetric observing system, whose long-term stability and cross-mission consistency have been extensively validated (Cazenave et al., 2018).”

RC1: Line 99: How do you handle exactly the coastal/shallow water problems in your altimetry satellite data?

AC1: Coastal and shallow-water limitations of satellite altimetry are addressed by relying on the CMEMS global sea level product SEALEVEL_GLO_PHY_CLIMATE_L4_MY_008_057, which is processed using the DUACS system and includes dedicated corrections to improve data quality near the coast. Wet tropospheric corrections specifically adapted for coastal regions are applied, and measurements within approximately 20–50 km from the coastline, where land contamination and reduced altimeter footprint reliability become critical, are treated with caution. To further mitigate coastal uncertainties, our analysis focuses on regional averages rather than individual nearshore grid points, thereby reducing the impact of localized errors typical of shallow waters. In addition, satellite-derived sea level trends are systematically compared with nearby tide gauge records, allowing the identification of potential discrepancies linked to coastal processes or vertical land motion. While fully consistent coastal-specific altimetry products are not yet available for the entire 1993–2023 period, this combined approach ensures that coastal and shallow-water effects do not bias the regional-scale trends discussed in this study.

In the revised manuscript, we have reorganized Sec 2 - Material and methods as follows:

- 2. Datasets and Methods
 - 2.1 Satellite Altimetry Sea Level Data
 - 2.2 Tide Gauge Observations
 - 2.3 Hydrodynamic Model Reanalyses for Extreme Sea Levels

and clarified Section 2.1 Satellite Altimetry Sea Level Data by explicitly stating:

“Satellite altimetry measurements are subject to increased uncertainties in coastal and shallow-water regions due to land contamination of the radar signal, reduced effective spatial resolution, and limitations in geophysical corrections, particularly those related to the wet tropospheric delay. Standard and coastal-adapted atmospheric correction schemes are applied to mitigate these effects (Brown, 2010; Fernandes et al., 2014).”

Nevertheless, the reliability of conventional gridded altimetry products decreases within approximately 20–50 km from the coastline. For this reason, nearshore measurements are treated with caution, and the subsequent analysis is based on regional spatial averages to ensure that results are not driven by individual coastal grid points. Coastal-specific altimetry products that fully address these challenges are not consistently available for the entire 1993–2023 period (Zhou et al., 2020; Climate Change Initiative Coastal Sea Level Team, 2020)."

RC1: Line 126: How do you define the mean anomaly sea level data for the area, whether you take it from one sample point or average of all sample points in the area?

AC1: The mean sea level anomaly for each sub-region is computed as the spatial average of all valid altimetry grid points within the defined area, using the CMEMS gridded sea level anomaly product. Monthly mean anomalies are first calculated at each grid point after removal of the mean seasonal cycle, and the regional mean time series is then obtained by averaging over the entire sub-region. No single-point sampling is used, ensuring that the derived trends are representative of basin-scale variability rather than local signals.

In the revised manuscript, we have reorganized Sec 2 - Material and methods as follows:

- 2. Datasets and Methods
 - 2.1 Satellite Altimetry Sea Level Data
 - 2.2 Tide Gauge Observations
 - 2.3 Hydrodynamic Model Reanalyses for Extreme Sea Levels

and clarified Section 2.1 Satellite Altimetry Sea Level Data by explicitly stating:

"At the basin scale, absolute sea level variability is analysed by computing, for each CESR sub-region, the spatial average of all valid altimetry grid points within the defined boundaries. Monthly mean SLA time series are constructed after removing the mean monthly seasonal cycle at each grid point. The seasonal cycle is defined as the climatological average of monthly SLA values over the 1993-2023 period and is subsequently subtracted to obtain deseasonalized anomalies. Regional mean time series are then derived by averaging these anomalies over the entire sub-region, ensuring that the estimated trends represent basin-scale variability rather than localized signals."

RC1: The fonts in Fig.2 and Fig.6 are too small and they are hard to read

AC1: The font sizes in Fig. 2 and Fig. 6 have been increased in the revised manuscript to improve readability, and the figures reformatted accordingly.

References

- Brown, S. (2010): Altimetry for coastal applications. In: Vignudelli, S., Kostianoy, A. G., Cipollini, P., and Benveniste, J. (Eds.), Coastal Altimetry, Springer, Berlin, Heidelberg, 3–25, https://doi.org/10.1007/978-3-642-12796-0_1.

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- Dangendorf, S., Frederikse, T., Chafik, L., Levier, B., Meyssignac, B., Rivero, C., ... Wöppelmann, G. (2021). Reassessment of 20th century global mean sea level rise. *Proceedings of the National Academy of Sciences of the United States of America*, 118(38), e2024249118. <https://doi.org/10.1073/pnas.2024249118>
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- Zhou, Y., Yang, S., Luo, J., Ray, J., Huang, Y., Li, J.: Global Glacial Isostatic Adjustment Constrained by GPS Measurements: Spherical Harmonic Analyses of Uplifts and Geopotential Variations. *Remote Sens.* 12, 1209. <https://doi.org/10.3390/rs12071209>, 2020.

Response to Reviewer #2 (RC2)

We thank Reviewer #2 for the thorough and constructive review, which greatly helped improve the methodological clarity, structure, and contextualization of the results.

RC2: The work entitled “Assessing sea level rise and extreme events along the China-Europe Sea Route” evaluates the trends in absolute and relative mean sea level and return levels of extreme sea levels on the Europe China Sea Route covering 8 sea areas that include the Red Sea, Arabian Sea, Persian Gulf, Bay of Bengal, South China sea, East China Sea, Yellow Sea and Bohal Sea. The data for analysis is obtained from various sources such as satellite altimetry, tide gauge records and from hydrodynamic models. The results highlight the complex regional pattern in long-term sea-level trends. The calculated trends exhibit remarkable spatial and temporal variability, with increases 20–45% higher than the global mean and a clear eastward intensification. High spatial variability is also evident in the occurrence of extreme sea-level values. The research addresses a highly important topic, and the overall approach is clear with methods that follow widely accepted practices. However, the methodology for the extreme value analysis, along with its explanation, is not entirely clear. Several parts of

the technical and methodological description would benefit from more consistent and coherent presentation.

AC2: We thank the reviewer for this valuable feedback. The description of the methodology could indeed have some inconsistencies. In the revised manuscript, we will clarify the exact methodology that was used and improve the overall structure of the Sec 2. Material and Methods.

RC2: The manuscript could also be strengthened by emphasizing the innovative aspects of this study compared to the previous regional studies.

AC2: In the revised manuscript, we have separated Conclusions and Discussion and strengthened the Discussion to better highlight the novelty of this work compared to previous regional studies, namely the integrated assessment of mean sea level trends and extreme sea levels across the entire China–Europe Sea Route, the combined use of multi-mission altimetry, tide gauges and global hydrodynamic models, and the focus on decadal variability across multiple interconnected basins. We believe these revisions improve both the clarity of the methodology and the presentation of the study's innovative aspects.

In the revised manuscript, we have clarified Section Discussion by explicitly stating:

“Beyond the regional findings, this work contributes to the existing literature by providing a harmonized assessment of both mean sea level trends and extreme sea levels across multiple interconnected basins of the CESR. Unlike studies focused on single regions or individual components of sea level change, the present analysis combines multi-mission altimetry, long-term tide gauge data, and state-of-the-art global hydrodynamic models within a unified framework. This integrated perspective enables a consistent evaluation of decadal variability in both mean conditions and extremes across basins characterized by distinct dynamical regimes, revealing contrasts and commonalities that would not emerge from basin-specific analyses alone.”

RC2: General comments:

The authors thoroughly discuss the global background of sea-level rise in the introduction. However, some important aspects appear to be missing. While the introduction effectively establishes the study's overall motivation, it almost does not address extreme sea levels. Including a brief overview of regional long-term sea level trends and extreme events established in earlier studies, along with relevant background on their drivers, would strengthen this section. While several regional studies are discussed later in the results, presenting an overview in the introduction would provide context for the current work and help readers understand how this study builds on or complements the existing knowledge, rather than giving the impression that only global studies are available for this region.

AC2: In the revised manuscript, we have expanded the Introduction to include a concise overview of previously established regional mean sea level trends and extreme sea levels, with references to key studies addressing storm surges and tropical-cyclone-driven extremes

in the CESR region. This addition provides clearer context for the present work and highlights how it builds upon existing regional literature. We have also reorganized Section 2 Materials and Methods into clearer subsections, improving terminology consistency, and revising the language. These changes enhance readability and clarify the methodological workflow.

In the revised manuscript, we clarified Section Introduction by explicitly stating:

“Beyond the GMSL rise, pronounced regional differences have been documented over recent decades, driven by a combination of steric effects, changes in ocean circulation, atmospheric forcing, and mass redistribution (Cazenave et al., 2014; Dangendorf et al., 2021). Along the China–Europe Sea Route (CESR), several regional studies have reported heterogeneous long-term sea level trends and accelerations, particularly in the North Indian Ocean and western Pacific, where monsoon variability, wind-driven circulation, and large-scale climate modes play a dominant role (Han et al., 2010; Huang et al., 2024).

Sea level variability in the CESR region may also be influenced by major regional circulation features, such as the Arabian Sea circulation and Somali Current, the East India Coastal Current, the Kuroshio system in the East China Sea, the Yellow Sea circulation, and the Indonesian Throughflow, which modulate regional mass transport and sea level variability (Han et al., 2010; Sprintall et al., 2014).

Extreme sea levels also exhibit strong spatial variability across the region, with storm surges and tropical-cyclone-induced extremes representing the primary drivers in areas such as the Bay of Bengal, the Arabian Sea, and the western North Pacific (Dube et al., 2009; Needham et al., 2015). Recent modelling and observational studies further indicate that changes in mean sea level and extremes may not evolve uniformly, underscoring the importance of jointly assessing long-term trends and extreme events (Tebaldi et al., 2021; Muis et al., 2016; Wahl et al., 2017; Dullaart et al., 2021).

Despite these advances, most existing studies remain focused on individual basins or specific coastal regions. As a result, a consistent and integrated assessment of mean sea level change and extreme sea levels across the entire CESR is still lacking. The present study addresses this gap by combining multi-mission satellite altimetry, tide gauge observations, and global hydrodynamic models within a unified framework.”

RC2: The English language is generally clear. However, in the methods section the writing seems less polished, with occasional confusing phrasing, inconsistency in terminology. Organizing the section into subsections would help improve overall readability and help a reader to distinguish the exact workflow and purpose of each method. The methodology and also the results part would benefit from light language review.

AC2: Regarding the presentation, we agree that the 2 Material and Methods section would benefit from improved clarity. We therefore reorganized it into clearer subsections, explicitly distinguishing between satellite altimetry, tide gauge analysis, and hydrodynamic model–

based extreme value analysis. In addition, all the sections underwent a light language revision to improve consistency in terminology and overall readability. We believe these changes substantially improved the clarity of the workflow and the presentation of the results.

In the revised manuscript, we amended Sec 2. Material and Methods as follows:

2. Datasets and Methods

2.1 Satellite Altimetry Sea Level Data

2.2 Tide Gauge Observations

2.3 Hydrodynamic Model Reanalyses for Extreme Sea Levels

RC2: Specific comments:

1. Please specify how the mean monthly seasonal cycle (line 90) is computed (method, period)?

AC2: The mean monthly seasonal cycle is computed by averaging the monthly sea level anomaly values at each grid point over the full available altimetry reference period (1993–2023). For each calendar month, the climatological mean is calculated and subsequently removed from the original time series to obtain deseasonalized anomalies. This approach follows standard practice in sea level analyses and ensures a consistent removal of the seasonal signal prior to trend and variability assessment (e.g. Cazenave et al., 2014; Wahl et al., 2017).

Text in Sec 2.1 - Satellite altimetry sea level data has been revised as follows:

“Monthly mean SLA time series are constructed after removing the mean monthly seasonal cycle at each grid point. The seasonal cycle is defined as the climatological average of monthly SLA values over the 1993-2023 period and is subsequently subtracted to obtain deseasonalized anomalies.”

RC2: 2. When fitting the linear trend, how were uncertainties computed, was autocorrelation checked in the residuals of the fitted regression to ensure the proper statistics (e.g standard errors, p-values)?

AC2: Linear trends are estimated using ordinary least squares regression, with uncertainties derived from the standard error of the slope after accounting for temporal autocorrelation in the residuals through an effective degrees-of-freedom adjustment (von Storch and Zwiers, 1999; Santer et al., 2000).

Text in Sec 2.1 - Satellite altimetry sea level data has be revised as follows:

“Linear trends over 1993-2023 are estimated using ordinary least squares regression applied to the deseasonalized monthly SLA time series. Uncertainties are computed from the standard error of the slope, accounting for temporal autocorrelation in the residuals through an effective degrees-of-freedom adjustment (von Storch and Zwiers, 1999; Santer et al., 2000). Statistical

significance is assessed accordingly, and trends are compared with global averages to highlight spatial variability across sub-regions.”

RC2: 3. Although the overall trend is discussed in the text, you might consider adding to Fig. 2 or Fig. 3 as well. This would provide a visual reference alongside the decadal trends.

AC2: In the revised manuscript, the overall linear trend is shown in Fig. 2 as a reference line, alongside the decadal trends, to provide a clearer visual comparison between long-term and decadal-scale variability.

Fig.2 caption has been amended as follows:

“Figure 2: Time series (1993-2023) of yearly mean sea level anomalies (black curve) derived from satellite altimetry SLA and averaged over (a) Global Ocean, (b) Red Sea, (c) Persian Gulf, (d) Arabian Sea, (e) Bay of Bengal, (f) South China Sea, (g) East China Sea, (h) Yellow Sea, and (i) Bohai Sea. Coloured dashed lines indicate linear trends computed over three successive periods (1993-2003, 2003-2013, and 2013-2023). The overall linear trend over the full analysis period is also shown as a dashed black line. SLAs are based on the CMEMS product SEALEVEL_GLO_PHY_CLIMATE_L4_MY_008_057.”

RC2: 4. It remains unclear if the mean monthly seasonal cycle is removed also from the tide gauge data applied for comparison or complement the satellite altimetry grid points? Are the tide gauge data prepared similarly for both analysis of mean sea level trends and the extremes?

AC2: Yes, the mean monthly seasonal cycle is removed from the tide gauge records in the same manner as for the satellite altimetry data when analyzing mean sea level trends. For each tide gauge, the climatological monthly mean is computed over the available record and removed prior to trend estimation, ensuring consistency between observational datasets. In contrast, for the extreme sea level analysis, tide gauge data are used in their original form (i.e. without removal of the seasonal cycle), as extreme value analysis relies on the full distribution of observed sea levels, including seasonal variability. Thus, tide gauge data preparation differs depending on whether they are used for mean sea level trend analysis or for extremes, following standard practice.

The revised manuscript has been amended in Sec 2.2 - Tide Gauge Observations as follows:

“For mean sea level trend estimation, the mean monthly seasonal cycle is removed from tide gauge records to ensure consistency with the satellite altimetry processing. In contrast, for extreme sea level analysis, tide gauge data are used without seasonal adjustment, as the full variability of the time series is required for extreme value statistics.”

RC2: 5. The description of the extreme-value methodology on the lines 135–139 seems ambiguous. The manuscript says return periods were derived “following the POT method by fitting a Gumbel distribution to the annual maxima,” while GPD fitting is applied to peaks above the 99th percentile. The annual-maxima (block maxima) and POT

approaches are distinct, and Gumbel and GPD correspond to different frameworks of extreme value analysis. Also, the sentence “The GPD is parameterized by shape, location and scale parameters obtained following Maximum Likelihood Estimation (MLE).” on lines 137–138 appears to conflate the description of the Generalized Extreme Value (GEV) distribution, which is characterized by three parameters (Coles, 2004). While the GPD can technically be described as having three parameters if the threshold is considered a location parameter, in practice this threshold is chosen relying on statistics and is not estimated during the fitting procedure. Only the shape and scale parameters are fitted using MLE. The current wording is misleading. It would be helpful if the authors clarified exactly which method was used for each dataset and how the return levels were derived.

AC2: We thank the reviewer for pointing out this ambiguity, and we will clarify the text as follows:

“following Extreme Value Analysis (Coles, 2004). This is done by fitting a Gumbel distribution to the annual maxima, while GPD fitting is applied to peaks above the 99th percentile. The shape and scale parameters are obtained with Maximum Likelihood Estimation (MLE).”

RC2: 6. Additionally, it is unclear if GTSMip is used as a dataset of precomputed extremes (lines 110–114) or whether authors perform their own EVA on it. Line 147 suggests that EVA with two methods is performed on GTSM data, which appears distinct from GTSMip, yet only one method is shown on Fig. 8. Based on Fig. 8, it seems that annual maxima with a Gumber fit were used for the observational data while a POT-GPD approach was applied to GTSMip. If so, the use of different EVA frameworks for different datasets raises concerns about comparability, since differences in return levels may stem from differences in methodology or differences in the underlying data characteristics or both. Please clarify these points.

AC2: We thank the reviewer for pointing out this ambiguity. Indeed, we tested different methods to assess which EVA method was most suitable, but not all results ended up in the final version of the manuscript. In the revised manuscript, this will be clarified and we remove redundant aspects. In the end, we decided to show in Fig 8 the Gumbel fitted to annual maxima for the observed sea levels. This choice was made due to best fit. In Fig. 8 we also show the GTSMip data, which is based on POT-GPD and the COAST-RP dataset, which is based on Weibull ranking.

These differences between methods make it difficult to compare and the reasons for the deviations. However, the main purpose of the figure is to show that there can be large offsets between observations and models, and that is quite clear.

RC2: 7. The calculation method for Gumbel distribution (MLE, method of moments, L-moments etc.) for parameter estimations should be also specified (for POT-Pareto MLE was mentioned). With the small dataset of annual maxima as 30-years MLE has shown unreliable results (Psutka and Psutka, 2015) while L-moments has proven to be more reliable (Ailliot et al., 2011).

AC2: Many thanks for these relevant and valuable suggestions that we would like to incorporate in future research. To clarify the calculation method for Gumbel, the extreme value analysis presented here is based on Muis et al., (2020) and (2023). The extreme value analysis method is implemented in Python and based on scipy, which uses the maximum likelihood estimation. This will be specified in the revised manuscript.

RC2: 8. Regarding EVA analysis, removing the annual mean from sea level records removes interannual mean level differences and normalizes each year, but it does not always fully remove the long-term effects. Were the vertical land motion and long-term sea-level rise also removed for EVA analysis? On some occasions even the annual maxima exhibit correlation, so both independence and stationarity should be tested. For example, the Mann-Kendall test provides a robust, nonparametric check for monotonic trends (either in maxima or in exceedances), while the Wald-Wolfowitz runs test (Yimaz and Perera, 2014) assesses the randomness and residual clustering, helping confirm whether block maxima or declustered peaks can be treated as independent and identically distributed.

AC2: We thank the reviewers for this question, we would like to clarify that the annual mean and linear trend were removed, but no other tests were performed.

RC2: 9. From Fig. 8 it appears that, at some locations (e.g., Xiamen, Zhapo, Shanwei) the observed annual maxima fall outside the 90% confidence intervals of the fitted distributions. This may indicate that the selected distributions, or in case of POT-GPD approach the chosen threshold, are not adequately capturing the tail behaviour of the extremes. The issue may also relate to using different input datasets and methodologies for different EVA approaches, as noted in comment 6. For the annual maxima analysis, using Gumbel distribution may be restrictive, it is possible that in these locations a full GEV fit could be more appropriate as there seems to be a heavy tail (possibly a positive shape parameter consistent with a Fréchet-type distribution). Overall, it would be worthwhile to assess whether the chosen distributions are indeed the most suitable for representing the extremes at these locations. Analysis or goodness of fit or likelihood-based comparisons could be helpful for assessing whether the chosen distribution adequately represents the tail.

AC2: The reviewer is correctly pointing out the uncertainties associated with the extreme value analysis, which are clearly present in Fig. 8. We note that Fig. 8 is intended as a large-scale comparison of observed versus modelled extremes, highlighting the uncertainties in extreme value analysis as well as other limitations such as inconsistent time series lengths and underlying model physics. To harmonise the analysis across the China-Europe marine region, the GPD fitted to peaks above 99th percentile threshold was ultimately utilised and fitted to all locations in the region. While this does not guarantee an optimal fit at every station, as can be seen from Fig. 8., it ensures methodological consistency and ability for comparison across the entire region.

We will clarify this point in the revised text for Fig. 8.

RC2: 10. The temporal resolution of satellite altimetry should be mentioned as well.

AC2: The temporal resolution of the satellite altimetry data has been explicitly specified in the Methods section.

The revised manuscript has been amended in Sec 2.1 Satellite Altimetry Sea Level Data as follows:

“The product is derived from multiple satellite altimetry missions and processed through the DUACS system (<https://duacs.cls.fr>). It provides daily gridded Level 4 sea level anomaly (SLA) data with a spatial resolution of 0.25° (~25 km), covering the global ocean over the period 1993–2023. The version used in this study is DUACS Delayed-Time DT-2024, referenced to a 20-year baseline (1993–2012). Although daily data are available, the analysis is conducted at monthly temporal resolution, consistent with the gridded CMEMS DUACS product.”

RC2: Technical corrections:

Fig. 2. The text is difficult to read at normal size (100%). Increasing the font size would improve readability. This applies also for Fig. 3, Fig. 6 and Fig. 8. Please check for all figures if axis labels, legends and annotations are readable.

AC2: The font sizes of axis labels, legends, and annotations in Fig. 2, Fig. 3, Fig. 6, and Fig. 8 have been increased in the revised manuscript, and all figures have been checked to ensure readability at normal viewing size (100%).

RC2: Line 168 “Figure 2 presents a time series (1993–2023) of yearly mean sea level anomalies, averaged over the Global Ocean and the eight CESR sub-basins.” Fig. 2 description says, “Figure 2: Time series (1993-2023) of monthly mean sea level anomaly (black curve) from altimetry averaged over...”. Is it representing yearly or monthly average?

AC2: Figure 2 is based on yearly mean sea level anomalies averaged over the Global Ocean and the eight CESR sub-basins. The caption incorrectly referred to “monthly means”; this has been corrected in the revised manuscript to consistently indicate yearly means.

RC2: Figure 7. Overview of the tidal levels in the region over the period 1985-2014 derived from the GTSMip dataset. (Top) Mean Higher High Water (MHHW) (Bottom) Highest Astronomical Tide (HAT) Top could be a) and bottom could be b) as the letters are anyway marked on the figure.

AC2: We thank the reviewers for pointing this out, we will amend as suggested, thank you.

RC2: Line 345 “Over the 1993–2023 period, mean sea level trends across CESR sub-regions were 20–45% higher than the global mean trend for the multidecadal period, 1993-2023, with considerable eastward increases.” Please adjust the sentence.

AC2: The text has been amended as follows

“During the full period (1993 – 2023), SLA trends across the CESR sub-regions are 20 – 45% higher than the global mean trend, with significant spatial and distinct decadal patterns.”

RC2: Line 346 “Notably decadal showdowns in the East China Sea, Yellow Sea and Bohai Bay mean sea level are present, probably connected to the interplay of circulation changes affecting the mass transport across the open ocean boundaries, the water cycle and the steric sea level.” Please adjust for clarity.

AC2: The text has been amended as follows

“Pronounced decadal variability is evident, particularly in the East China Sea, Yellow Sea and Bohai Bay, where periods of trend slowdown may reflect changes in circulation affecting mass transport across open-ocean boundaries, regional water-cycle variability, and steric contributions.”

RC2: Line 356 “This is like what we found in CESR sub-regions in the North Indian Ocean.” – Could be rephrased, for example: “This is consistent with our findings in the CESR sub-regions of the North Indian Ocean”.

AC2: The text has been amended as follows

“In the North Indian Ocean sector, the results indicate signals consistent with positive acceleration; however, strong interdecadal variability prevents a robust quantification of acceleration at the regional scale.”

RC2: Line 359 “Huang’s budget analysis finds that SLA rise of 1.20 ± 0.20 cm/decade in the upper 2,000 m can be attributed to the Ekman pumping and deep-water warming, accounting 360 for 30% of the total sea level rise. Please adjust for clarity.

AC2: The text has been amended as follows

“Huang et al. (2024) reported a multidecadal sea-level decline in the Tropical Southwest Indian Ocean from the 1960s to the early 2000s, followed by a marked rise of 4.05 ± 0.56 cm/decade, associated with shifts in atmospheric circulation and contributions from Ekman pumping and deep-water warming. Similar processes may contribute to the variability observed in the North Indian Ocean portion of the CESR.”

RC2: Several references in the reference list seem not to be cited in the main text. For example, Alam, (2014), Ali (1999), Antony and Unnikrishnan (2013), Baburaj et al. (2020), Balaguru et al. (2018), and Bhatia et al. (2018) do not appear in the manuscript. This is only from the first page of the reference list. Please check the entire reference list and ensure that all listed references are cited in text or remove those that are not used to.

Additionally, please check whether the publication years in the reference list match the in-text citations. For example, Muis et al., 2022 is listed on line 111, but in the manuscript there are three references with Muis as first author, and none of these appear to be published in 2022.

References:

- Coles, S. (2004). **An Introduction to Statistical Modeling of Extreme Values (3rd ed.)**. Springer.
- Ailliot, P., Thompson, C., & Thomson, P. (2011). Mixed methods for fitting the GEV distribution. *Water Resources Research*, 47, W05551. <https://doi.org/10.1029/2010WR009417>
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AC2: We thoroughly reviewed the entire reference list and verified all in-text citations. References that were not cited in the manuscript (including Alam, 2014; Ali, 1999; Anthony and Unnikrishnan, 2013; Baburaj et al., 2020; Balaguru et al., 2018; and Bhatia et al., 2018) have been either removed or explicitly cited where relevant. In addition, a full cross-check of all in-text citations and reference list entries have been carried out to correct any mismatches in publication years (including the Muis et al. reference). The reference list has been fully revised to ensure that all citations are consistent and accurate.

In addition, the right citation for the Muis et al. reference in Line 185 is: Muis, S., Aerts, J. C. J. H., Á. Antolínez, J. A., Dullaart, J. C., Duong, T. M., Erikson, L., et al. (2023). Global projections of storm surges using high-resolution CMIP6 climate models. *Earth's Future*, 11, e2023EF003479. <https://doi.org/10.1029/2023EF003479>

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Response to Reviewer #3 (RC3)

We thank Reviewer #3 for the detailed and insightful review, which led to substantial improvements in clarity, precision, and scientific rigor.

RC3: The paper addresses an important subject; namely rising sea levels in regions which are both highly populated and significant in terms of international trade. The paper does not provide particularly ground-breaking results, insight or methodology, however it does make an important contribution by highlighting trends and variability in the areas of interest. The Appendix, describing the validation of GTSM and Coast-RP is also a valuable contribution and will be useful for other researchers in the field.

As a whole, the paper is well structured but within some sections it can be confusing for the reader, because of the mix of datasets, regions and analysis. I think it would be very worthwhile if thought could be put into improving the clarity within sections, particularly the Datasets, Methodology and Results. There are three very different sources of data - satellite altimetry, tide gauges and global model reanalysis - and, for

the most part, they require different methodologies and provide different kinds of results and insights. It would be good to make this clear right at the start in the introduction, and then clearly separate them in subsequent sections using subheadings.

AC3: We thank the referee for the constructive assessment and for highlighting the value of the Appendix on the validation of GTSM and COAST-RP. We acknowledge that the manuscript combines multiple datasets and analyses, which could reduce clarity in some sections. In the revised version, we will explicitly clarify in the Introduction the complementary roles of satellite altimetry, tide gauges, and global hydrodynamic model reanalyses, and we will reorganize the Datasets, Methodology, and Results sections using clearer subheadings to separate these analyses. These changes will improve readability while preserving the integrated nature of the study.

The revised manuscript will be amended in Sec Introduction as follows:

"This study combines three complementary data sources to assess mean and extreme sea levels along the China–Europe Sea Route. Multi-mission satellite altimetry is used to quantify large-scale absolute sea level trends and variability, while tide gauge observations provide in situ measurements of relative sea level change at the coast. Global hydrodynamic model reanalyses (GTSMip and COAST-RP) are employed to estimate extreme sea levels and return levels, complementing observations in regions with sparse tide gauge coverage or strong storm-driven extremes. Together, these datasets provide an integrated framework to characterize sea level variability across regions of high societal and economic relevance."

RC3: It should also be made clear that extreme water levels are considered only for present day conditions and that no attempt has been made to assess the impact of climate change on extreme water levels - only on mean sea level

AC3: We thank the reviewers for pointing this out, and we will clarify this in the Introduction as well as Methods section that the extreme water levels are considered only for present day conditions and not the impact of climate change on this.

RC3: Note that the references have not been properly curated. I found two citations in the text which did not have references and 27 references that didn't have a citation!

AC3: We fully cross-checked the manuscript and revised the reference list so that all in-text citations have corresponding references and all listed references are cited in the text.

RC3: Specific comments

Lines 46-47: this statement should be supported by a reference

AC3: A supporting reference has been added in the revised manuscript to substantiate this statement.

"The primary drivers of GMSL change include the melting of polar ice sheets, land glaciers, and ocean thermal expansion. Notably, the Antarctic ice sheet mass loss tripled and the

Greenland ice sheet mass loss doubled between the periods 1997–2006 and 2007–2016 (Nerem et al., 2018). “

RC3: Section 2.1 Datasets: Please consider using sub-headings to clearly distinguish between types of datasets

AC3: In the revised manuscript, Sect. 2 Material and methods has been reorganized using clear sub-headings to explicitly distinguish between the different types of datasets employed (satellite altimetry, tide gauge observations, and hydrodynamic model reanalyses). This restructuring improves readability and clarifies the role of each dataset in the analysis.

In the revised manuscript, we amended Sec 2. Material and Methods as follows:

- 2. Datasets and Methods
 - 2.1 Satellite Altimetry Sea Level Data
 - 2.2 Tide Gauge Observations
 - 2.3 Hydrodynamic Model Reanalyses for Extreme Sea Levels

RC3: Lines 88-89 and 99-100: These two sentences, mentioning the challenge of satellite altimetry near the coast, appear to be contradictory. The first says that the problem is addressed by wet tropospheric corrections (I have no idea what this is - reference required) while the second says that this method becomes inaccurate near the coast. It should be clearly stated how coastal areas have been considered. This could be by omitting - the subsequent analysis is not dependent on coastal areas.

AC3: We thank the referee for pointing out this ambiguity. The text has been revised to clarify that coastal-adapted wet tropospheric corrections are applied to mitigate atmospheric and land-contamination effects, but that satellite altimetry remains less reliable very close to the coast. We have explicitly stated that coastal uncertainties are further addressed through methodological choices, namely by treating data within ~20–50 km of the coastline with caution and by basing the analysis on regional spatial averages, so that the results are not dependent on nearshore measurements.

Revised text for Sec 2.1 Satellite altimetry sea level data

“Satellite altimetry measurements are subject to increased uncertainties in coastal and shallow-water regions due to land contamination of the radar signal, reduced effective spatial resolution, and limitations in geophysical corrections, particularly those related to the wet tropospheric delay. Standard and coastal-adapted atmospheric correction schemes are applied to mitigate these effects (Brown, 2010; Fernandes et al., 2014). Nevertheless, the reliability of conventional gridded altimetry products decreases within approximately 20–50 km from the coastline. For this reason, nearshore measurements are treated with caution, and the subsequent analysis is based on regional spatial averages to ensure that results are not driven by individual coastal grid points. Coastal-specific altimetry products that fully address these challenges are not consistently available for the entire 1993–2023 period (Zhou et al., 2020; Climate Change Initiative Coastal Sea Level Team, 2020).“

RC3: Line 92: The RLR dataset is described as being relative to 7000mm below mean sea level. Is there an epoch at which this mean sea level is determined?

AC3: In the PSMSL Revised Local Reference (RLR) dataset, sea level values are expressed relative to a station-specific local reference datum that is defined as 7000 mm below the approximate mean sea level at the time the RLR datum was established, in order to ensure positive values and long-term internal consistency. This reference level does not correspond to a fixed global epoch; instead, it is defined individually for each tide gauge station based on its historical mean sea level at the time of datum definition. Importantly, this choice of reference does not affect the estimation of sea level trends or variability, which depend only on relative changes over time (Holgate et al., 2013; PSMSL, 2023).

Section 2.1 has been revised as follows:

“In the RLR dataset, sea level values are expressed relative to a station-specific local reference datum defined as 7000 mm below the approximate mean sea level at the time the datum was established. This convention, which does not correspond to a fixed global epoch, ensures long-term internal consistency of the records and does not influence the estimation of relative sea level trends. For consistency with the satellite altimetry analysis, only records from 1993 onward are selected.”

RC3: Line 111: I can't find a reference for the 'Climate Change Initiative Coastal Sea Level Team 2020' citation

AC3: We can confirm that the reference can be found on line 642

RC3: Line 106 & 130-132: I think that the authors have not undertaken correction to local land subsidence but it is considered a source of uncertainty when considering tide gauge data and comparison with other sources. Please can the authors make this clear.

AC3: We confirm that no explicit correction for local land subsidence or uplift has been applied to the tide gauge records used in this study. Tide gauge measurements therefore represent relative sea level change, which includes the combined effects of oceanographic sea level variability and vertical land motion. Local land subsidence is accordingly treated as a source of uncertainty when interpreting tide gauge trends and when comparing them with satellite altimetry, which measures absolute sea level change.

This has been explicitly stated in the revised manuscript.

“In this study, no explicit correction for local vertical land motion is applied to the tide gauge records. Consequently, tide gauge trends represent relative sea level change and may include the effects of local land subsidence or uplift. Differences between tide gauge–derived and satellite–derived trends are therefore interpreted with caution, as vertical land motion is treated as a source of uncertainty rather than explicitly corrected.”

RC3: Section 2.2 Methodology: Please consider using sub-headings to clearly distinguish between types of datasets

AC3: In the revised manuscript, Sect. 2 Material and methods has been reorganized using clear sub-headings to explicitly distinguish the methodological approaches applied to the different datasets (satellite altimetry, tide gauges, and hydrodynamic model outputs). This restructuring improves clarity and helps the reader follow the analytical workflow associated with each data source.

RC3: Line 135: This sentence contains a contradiction - annual maxima are not part of the peaks-over-threshold method.

AC3: Indeed, the text will be improved accordingly.

RC3: Line 140-145: Please note that the extreme value analysis is relevant and presented only for a present day scenario not considering climate change

AC3: This is correct, the COAST-RP dataset does not account for climate change but is based on present-day climate.

RC3: Line 145: I don't understand what using Weibull plotting formulations means - please clarify

AC3: The Weibull plotting formulation means that for the Coast-RP dataset, we sort the maxima and then calculate the exceedance probability by dividing the rank by the total number of observations plus one. This method is simple and widely used to calculate empirical probabilities. It does not allow us to estimate probabilities beyond the length of data, but in the case of COAST-RP which is based on 2,000 years of dataset, this was acceptable. We will clarify this in the revised text.

RC3: Line 168-192: Please make clear what dataset was used here

AC3: In the revised manuscript, we have clarified that the results discussed in this section are based exclusively on multi-mission satellite altimetry sea level anomaly data, averaged over the Global Ocean and the CESR sub-basins. This clarification has been added to avoid any ambiguity with respect to tide gauge or model-based analyses presented elsewhere in the manuscript.

Sec. 3.1.1 Absolute sea level has been amended as follows:

“This section presents the results of the analysis of absolute sea level changes derived from satellite altimetry SLA data, averaged over the Global Ocean and the eight sub-regions defined within the CESR domain (Fig. 1).”

RC3: Line 210: I think saying 'areas like the Arabian Sea and South China Sea' is too generic for this paper. Be specific - there are a limited number of regions of interest and it would not harm the paper to list all where these monsoonal processes have an impact.

AC3: The text has been amended as follows:

“Additionally, monsoon-driven processes exert a strong influence on sea level variability in several CESR sub-regions, particularly in the Arabian Sea, Bay of Bengal, South China Sea, East China Sea, and Yellow Sea, where seasonal wind forcing and associated circulation changes play a key role (Han et al., 2010; Huang et al., 2024).”

RC3: Line 213: As above, I see no harm in being specific - are there other relevant currents/regions?

AC3: The text at Line 213 has therefore been revised to explicitly mention the main regional circulation features and regions relevant to sea level variability along the CESR, rather than referring to them in generic terms.

The text has been amended as follows:

“Sea level variability in the CESR region may also be influenced by major regional circulation features, such as the Arabian Sea circulation and Somali Current, the East India Coastal Current, the Kuroshio system in the East China Sea, the Yellow Sea circulation, and the Indonesian Throughflow, which modulate regional mass transport and sea level variability (Han et al., 2010; Sprintall et al., 2014).”

RC3: Line 213-214: 'SLA trends exceed 4 mm/yr along the coasts of the Yellow and East China Seas'. Do the problems with SLA in coastal zones affect these areas?

AC3: While altimetry is less reliable very close to the coast, the reported SLA trends are derived from regional spatial averages rather than individual nearshore grid points, with coastal-adapted corrections applied and data within ~20–50 km of the coastline treated with caution. The enhanced trends in the Yellow Sea and East China Sea are also consistent with offshore patterns and nearby tide gauge observations, indicating that they are not artefacts of coastal altimetry limitations.

The text has been amended as follows:

“In contrast, SLA trends exceed 4 mm/yr along the coasts of the Yellow and East China Seas, as derived from regional spatial averages rather than individual coastal grid points; nearshore altimetry data are treated with caution to ensure that the reported values are not driven by coastal measurement limitations.”

RC3: Line 214-215: 'The South China Sea displays maximum SLA trends in its open ocean regions, influenced by stronger westward currents through the Luzon Strait compared to southeastern warm currents.' This is a throwaway comment - are the currents through the Luzon Strait the cause? If so then there would need to be justification. Otherwise, please change the wording.

AC3: We agree that the original wording could be interpreted as implying a causal relationship that was not sufficiently justified. The sentence has therefore been revised to adopt a more cautious formulation, avoiding a direct causal attribution and framing the circulation through the Luzon Strait as a possible contributing factor rather than a definitive driver.

The revised manuscript has been amended as follows:

“The South China Sea displays maximum SLA trends in its open-ocean regions, which may be associated with large-scale circulation variability and exchanges with the western Pacific through the Luzon Strait, as suggested by previous studies (Qiu and Chen, 2010; Sprintall et al., 2014).”

RC3: Line 217: Looks more like north and northwest Bay of Bengal

AC3: The revised manuscript has been amended as follows:

“The largest SLA trend (~5 mm/yr) is found in the northern and northwestern Bay of Bengal, rather than being uniformly distributed across the basin.”

RC3: Line 225: This area includes several seasonally varying currents - are these annual average?

AC3: Yes, the circulation features referred to in this section represent annual-mean conditions, as the analysis is based on yearly mean sea level anomalies. Seasonal variability associated with monsoon-driven or seasonally varying currents is therefore averaged out and does not explicitly contribute to the patterns discussed here.

This has been clarified in the Figure 4 as follows:

“Figure 4. Absolute Sea level trend [mm/yr] computed from monthly mean satellite altimetry data (seasonal cycle removed) over the period 1993-2023 using the CMEMS product SEALEVEL_GLO_PHY_CLIMATE_L4_MY_008_057. Climatological surface currents from the CMEMS Global Multi-Year product (GLOBAL_MULTIYEAR_PHY_001_030) are overlaid as streamlines. The circulation features shown represent annual-mean conditions.”

RC3: Line 236: Were the land effects on satellite altimetry that was previously mentioned an issue here?

AC3: Land contamination effects on satellite altimetry do not significantly affect the results discussed at Line 236. As described in Sect. 2.1 and 2.2, coastal-adapted corrections are applied, data in the immediate coastal zone are treated with caution, and the analysis is based on regional spatial averages rather than individual nearshore grid points. Consequently, the patterns discussed here reflect robust regional-scale signals and are not driven by land-related altimetry artefacts.

The revised manuscript has been amended as follows:

“For this reason, nearshore measurements are treated with caution, and the subsequent analysis is based on regional spatial averages to ensure that results are not driven by individual coastal grid points.”

RC3: Line 252: Figure 6: Look like time series of annual means to me not monthly

AC3: Figure 6 indeed shows a time series of annual mean values, not monthly means. The caption has been corrected in the revised manuscript to consistently refer to annual means, in line with the data shown in the figure.

The revised manuscript has been amended as follows:

“Figure 6. Time series (1993-2023) of annual mean sea level anomalies (mm) at the platforms: (a) Port Sudan (Red Sea), (b) Mina Sulman (Persian Gulf), (c) Mormugao (Arabian Sea), (d) Masira (Arabian Sea), (e) Paradip (Bay of Bengal), (f) Sabang (Bay of Bengal), (g) Xisha (South China Sea), (h) Nansha (South China Sea), (i) Kanmen (East China Sea), (j) Lusi (Yellow Sea), and (k) Dalian (Bohai Sea). Tide gauge stations observations (blue) represent relative sea level, while satellite altimetry (orange) absolute sea level.”

RC3: Line 287: Reference to 'Park et al 2021' is missing

AC3: The missing reference has been reported in the revised manuscript

Park, K., Federico, I., Di Lorenzo, E., Ezer, T., Cobb, K.M., Pinardi, N., et al. (2022). The contribution of hurricane remote ocean forcing to storm surge along the Southeastern U.S. coast. COASTAL ENGINEERING, 173, 1-20 [10.1016/j.coastaleng.2022.104098].

RC3: Line 322: This problem of small sample size of historical cyclones is well known, but I think the results here are a good empirical illustration of it and worth highlighting.

AC3: We thank the reviewer for this suggestion; the sentence will be rephrased to:

“The large deviations for large return periods highlight the problem of small sample size when solely relying on historical tropical cyclones. The results indicate the need for the use of synthetic tropical cyclones to obtain robust estimates of extreme sea levels at all stations.”

RC3: Line 349: 'significant positive acceleration in North Indian Ocean'. I'm not sure the evidence is strong enough for this assertion - there is clearly a lot of interdecadal variability that makes acceleration on a regional scale difficult to identify.

AC3: We agree that pronounced interdecadal variability complicates the robust identification of acceleration at the regional scale. The statement at Line 349 has therefore been revised to adopt a more cautious wording, emphasizing that any indication of positive acceleration in the North Indian Ocean is suggestive rather than conclusive and should be interpreted in the context of strong interdecadal variability.

The revised manuscript has been amended as follows:

“In the North Indian Ocean sector, the results indicate signals consistent with positive acceleration; however, strong interdecadal variability prevents a robust quantification of acceleration at the regional scale.”

RC3: Line 354 onwards: The context suggests that the abbreviation 'SLA' as used in the conclusions section would make more sense if it meant Sea Level Anomaly (which is a

common meaning). However, on line 67 it was defined as **Satellite Altimetry**. Please clarify or correct.

AC3: In the revised manuscript, SLA has been used consistently to indicate Sea Level Anomaly throughout the text, in line with common usage in the literature. The reference at Line 67 has been corrected accordingly, and any remaining ambiguous occurrences has been revised to ensure clarity.

RC3: Line 373-376: Extreme water level - particularly when caused by tropical cyclones - are very sensitive to local geography (depth and extent of coastal shallows, shape of coastline with bays and inlets etc). Care should be taken when applying extreme water levels at one location to others, even if nearby.

AC3: We fully agree with this comment. However, we do not propose to transfer data from one location to another. Rather we suggest using the GTSM time series for flood risk modelling. While the GTSM data is rather coarse (i.e. >2.5 km at the coast), it provides a basis for large-scale assessment, such as in Kirezci et al. (2020), while additional dynamic downscaling could be applied to make the data more locally relevant. We will clarify this in the manuscript to make the caution more explicit that the data is not spatially transferrable.

RC3: Figure A1: Check whether the reproduction of this figure is good enough to see the grid - when I printed it out, I couldn't and it is not that great in the PDF.

AC3: Noted, will try to improve the resolution of the image

RC3: Line 392-393: The sentence 'If we use all stations that have more than 10 years of data, this increases to 36 stations' appears superfluous as these were not used. Please either remove or clarify why this might be useful to know.

AC3: The sentence will be removed in the revised version of the manuscript

RC3: Line 412: I think this should be return levels rather than 'return periods'

AC3: Correct, this will be amended.

RC3: Page 22 to 27: Many of these references are not cited in the text and 2 in the text are not in the references. Some references are incomplete e.g. include et al when authors should be written in full.

AC3: We carried out a complete and systematic review of the reference list and in-text citations across pages 22–27 and the entire manuscript. References not cited in the text have been removed unless explicitly incorporated, and missing references corresponding to in-text citations have been added. In addition, all references have been checked for completeness and corrected where necessary, including replacing et al. with full author lists in accordance with journal guidelines. The reference list has been fully revised to ensure accuracy, completeness, and consistency.

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