11.09.2024

Answer to Referee 2:

The authors wish to thank the anonymous reviewer for his/her comments which helped us to improve the quality of the paper. We are pleased to address the point-by-point answers to your review in blue in the supplement to this comment.

Additionally, during the review process, we decided to revise the extreme value analysis (EVA) calculation method by removing the constant seasonal component. Recent studies have highlighted changes in the seasonal cycle of sea level within the same domain (Hermans et al., 2022; Roustan et al., 2022), suggesting that the assumption of a constant seasonal cycle may no longer be valid. Therefore, the seasonal term from equation (4) has been removed. The analyses have been re-performed and figures have been updated accordingly, which slightly affects the results. However, this modification does not affect the main text and conclusions of the paper.

Best regards,

The authors.

Specific comments

- It is unclear to me how the uncertainties in the return level estimates were estimated. The authors should further elaborate on this point as it is also important for assessing the differences between the static and the dynamic approach.

Thank you for the comment. A sentence has been added to the Methods section (Sect. 2.4) to explain how the confidence intervals are computed: “The calculation of confidence intervals in the package used for this study (Mentaschi et al., 2016) relies on the Delta Method (asymptotic intervals) which tends to produce narrower and symmetric confidence intervals compared to other methods like the bootstrap method (Caires, 2011). This method has been used to propagate error components related to the uncertainty in estimating the long-term trend and long-term variability (99th percentile) to the error associated with fitting the stationary extreme value distribution, thereby combining both sources of uncertainty.”

- The authors state that they validated the 1 in 10 year return water level instead of the 1 in 100 year. From an impact/risk assessment perspective however the latter is potentially more important. I therefore believe that the authors should further report on the validation of the 1 in 100 year water level.

As mentioned by the reviewer, the 1-in-100-year level could be potentially more important for impact studies. However, as stated L94-97, we only have 35 years of tide gauge records to validate the model. Therefore, we focused on the 1-in-10-year level in the main text instead of the 1-in-100-year level, as the uncertainties associated with observed estimates of the 1-in-10-year return level are lower (see Tab. S4.1). For example, the differences between the 1-in-100-year ESWLs and ETWLs are significantly smaller than the margin of error computed from the tide gauge estimates, which is not the case for the 1-in-10-year levels. The table S4.1 has been included in the Supplementary Materials to provide the mean validation for different return levels.

Return level	1-in-5-year level	1-in-10-year level	1-in-20-year level	1-in-50-year level	1-in-100-year level
RMSE ESWLs (m)	0.40	0.43	0.46	0.50	0.53
RMSE ETWLs (m)	0.32	0.33	0.35	0.38	0.40
Mean uncertainty of return levels for tide gauge data (m)	0.08	0.10	0.13	0.18	0.22

Table S4.1: Comparison of ESL return periods computed from model outputs and tide gauges over 1970-2014: RMSE (in meters), calculated as the root mean squared deviations between modeled return levels and tide gauges return levels (see locations of tide gauges in Fig 3b), for different return periods. Mean uncertainty calculated for the tide gauge data in meters calculated as the amplitude of the 95% confidence intervals for each return period.

- The authors have employed the empirical Stockdon et al. model for estimating wave contribution. Besides several assumptions associated with the use of this model, the authors have assumed a constant beach slope of 4% (note that Hinkel et al., 2013, used a global value of 2% for estimating erosion). Considering that there are several other datasets (which the authors actually cite) and the fact that one could even use land slope as a proxy, I find the use of a constant slope value a little oversimplistic. The authors have commendably performed a sensitivity analysis to explore the effects of their assumption; nevertheless, if I am not mistaken, the figure in the supplementary material suggests substantial differences (both in absolute values but also in patterns) depending on the chosen value (unless I am misunderstanding something). I think the authors should further elaborate on this point.

The limitations related to the Stockdon et al. (2006) parameterization and particularly the use of a constant beach slope have been expanded and moved from Section 2.3 to a dedicated section in the Discussion:

“Estimation of the wave contribution

In this study, the wave contribution is evaluated based on a generic parameterization (Stockdon et al., 2006), as seen in other climate studies (Melet et al., 2018, 2020; Lambert et al., 2020). This approach appears pragmatic given the wave model resolution of 10 km and the coastal processes that are poorly resolved in the wave model. However, this parameterization comes with notable limitations. It assumes sandy beach conditions, which may not accurately reflect the diverse sediment types found along many European coastlines, such as rocky shores or mixed sediments. Additionally, the parameterization is designed for deep water conditions, which may not be representative of all coastal points of the domain, as they are not all purely deep water. The model also relies on a prescribed beach slope β, which varies across different coastal areas. Regional estimates of β are being developed (Vos et al., 2020) but public estimates of this environmental parameter applicable in empirical formulations are not yet available for the European region. While other studies offer global-scale beach slope information, they typically provide either the nearshore slope (Athanasiou et al., 2019) or the sub-aerial coastal slope (Almar et al., 2021), rather than the foreshore beach slope required in equation (2). Incorporating these values would introduce a regional spatial information that may not be accurate, leading to other type of uncertainties—resulting in either underestimations or overestimations of the wave contribution. Therefore, we opted to maintain a constant representative value of 4% from Melet et al. (2020). Sensitivity analyses were conducted using slopes of 2% and 10% in the Supplementary Materials (Sect. S3). Amplification factors and allowances of ESLs are found to be strongly sensitive to the value of the beach slope. For these reasons, we used here the wave contribution only to derive future changes in the large-scale wave contribution (in %) or to investigate the timing between different contributions, both being independent of the choice of the beach slope. To obtain precise and reliable estimates of coastal wave processes such as wave setup, runup, and total water level for adaptation measures, localized studies are needed (e.g., Serafin et al., 2019). However, our study does not aim to provide such localized estimates.”

- Line 258 – I find the argument that the replication of the north-south gradient is enough to indicate that the single forcing GCM is “to some extent” representative of the projected changes rather weak. Also, “to some extent” is very vague.

Thank you. We agree with you. This part of the sentence has been deleted.

- The authors conclude that changes in ESL depend on changes in MSL, with coastal contributions having a lesser effect. Considering that some important parts of the coast have not been considered, can the authors really generalise this conclusion based on their results?

A new paragraph has been added at the end of the Discussion to address the challenges in capturing dynamic changes in extremes. Additionally, as explained in the conclusion (L432-440), we cannot conclude that changes in ESLs are only dependent on changes in MSL, as the results are expected to vary by region depending on the dominant processes and their timing, with the magnitude of projected changes in GCM forcing, and with the regional configurations implemented.

“Challenge on dynamic changes in extremes

Our findings align with previous modeling studies using barotropic dynamic approaches (Jevrejeva et al., 2023; Muis et al., 2020; Vousdoukas et al., 2018), indicating that changes in ESLs primarily depend on mean SLR. This challenges recent research showing that historical trends in storm surges (Reinert et al., 2021; Calafat et al., 2022; Tadesse et al., 2022; Roustan et al., 2022) and tides (Pineau-Guillou et al., 2021) have been comparable in magnitude to historical mean sea level rise trends. However, the conclusions these authors draw from historical trends do not necessarily apply to future trends, which is the main focus of this article. Further research is needed to better understand and quantify dynamic projected changes in all the extreme components, their interactions, and timing (e.g., Melet et al., 2024). Currently, dynamic approaches typically do not account for projected changes in all coastal sea level components (mean sea level, tides, storm surges, waves, freshwater discharge) or their nonlinear interactions. These approaches often lack resolution to accurately capture the various contributions and their nonlinear interactions, as previously discussed. This can result in a misrepresentation of ESLs and their changes, potentially underestimating the significance of dynamic changes in extremes. Additionally, most studies projecting dynamic changes in extremes rely on small ensembles of model simulations or emission scenarios, similar to our study, due to the high computational cost of simulating all the different components and the limited availability of forcing data (Vousdoukas et al., 2017, 2018; Muis et al., 2020, 2022; Jevrejeva et al., 2023). For instance, global climate models used for driving projections often have relatively low atmospheric resolution, typically around 1° (0.5º in this study), with only a few models being part of the HighResMIP project (0.25º) that better simulate extreme winds responsible for storm surges. Even with a 0.25° resolution, it may still be insufficient to accurately resolve historical and future atmospherically driven contributions, including for instance extra-tropical cyclones in our region. The use of dedicated products such as downscaled atmospheric forcing (e.g., Euro-CORDEX, Outten and Sobolowski, 2021) may offer a promising alternative. Finally, as suggested by Calafat et al. (2022), differences between driving climate models and internal climate variability may also lead to robustness challenges in projecting ESLs. For example, Muis et al. (2022) found little agreement between projected changes in storm surges using different HighResMIP models."

References

Almar, R., Ranasinghe, R., Bergsma, E. W. J., Diaz, H., Melet, A., Papa, F., Vousdoukas, M., Athanasiou, P., Dada, O., Almeida, L. P., and Kestenare, E.: A global analysis of extreme coastal water levels with implications for potential coastal overtopping, Nat Commun, 12, 3775, https://doi.org/10.1038/s41467-021-24008-9, 2021.

Athanasiou, P., van Dongeren, A., Giardino, A., Vousdoukas, M., Gaytan-Aguilar, S., and Ranasinghe, R.: Global distribution of nearshore slopes with implications for coastal retreat, Earth System Science Data, 11, 1515–1529, https://doi.org/10.5194/essd-11-1515-2019, 2019.

Caires, S.: EXTREME VALUE ANALYSIS: WAVE DATA, JCOMM Technical Report No. 57, 2011.

Calafat, F. M., Wahl, T., Tadesse, M. G., and Sparrow, S. N.: Trends in Europe storm surge extremes match the rate of sea-level rise, Nature, 603, 841–845, https://doi.org/10.1038/s41586-022-04426-5, 2022.

Hermans, T. H. J., Katsman, C. A., Camargo, C. M. L., Garner, G. G., Kopp, R. E., and Slangen, A. B. A.: The Effect of Wind Stress on Seasonal Sea-Level Change on the Northwestern European Shelf, https://doi.org/10.1175/JCLI-D-21-0636.1, 2022.

Jevrejeva, S., Williams, J., Vousdoukas, M. I., and Jackson, L. P.: Future sea level rise dominates changes in worst case extreme sea levels along the global coastline by 2100, Environ. Res. Lett., 18, 024037, https://doi.org/10.1088/1748-9326/acb504, 2023.

Lambert, E., Rohmer, J., Le Cozannet, G., and Van De Wal, R. S. W.: Adaptation time to magnified flood hazards underestimated when derived from tide gauge records, Environ. Res. Lett., 15, 074015, https://doi.org/10.1088/1748-9326/ab8336, 2020.

Melet, A., Meyssignac, B., Almar, R., and Le Cozannet, G.: Under-estimated wave contribution to coastal sea-level rise, Nature Clim Change, 8, 234–239, https://doi.org/10.1038/s41558-018-0088-y, 2018.

Melet, A., Almar, R., Hemer, M., Le Cozannet, G., Meyssignac, B., and Ruggiero, P.: Contribution of Wave Setup to Projected Coastal Sea Level Changes, Journal of Geophysical Research: Oceans, 125, e2020JC016078, https://doi.org/10.1029/2020JC016078, 2020.

Melet, A., van de Wal, R., Amores, A., Arns, A., Chaigneau, A. A., Dinu, I., Haigh, I. D., Hermans, T. H. J., Lionello, P., Marcos, M., Meier, H. E. M., Meyssignac, B., Palmer, M. D., Reese, R., Simpson, M. J. R., and Slangen, A.B.A.: Sea Level Rise in Europe: Observations and projections, State Planet., 1–106, in press, https://doi.org/10.5194/sp-2023-36, 2024.

Mentaschi, L., Vousdoukas, M., Voukouvalas, E., Sartini, L., Feyen, L., Besio, G., and Alfieri, L.: The transformed-stationary approach: a generic and simplified methodology for non-stationary extreme value analysis, Hydrol. Earth Syst. Sci., 20, 3527–3547, https://doi.org/10.5194/hess-20-3527-2016, 2016.

Muis, S., Apecechea, M. I., Dullaart, J., de Lima Rego, J., Madsen, K. S., Su, J., Yan, K., and Verlaan, M.: A High-Resolution Global Dataset of Extreme Sea Levels, Tides, and Storm Surges, Including Future Projections, Frontiers in Marine Science, 7, 2020.

Muis, S., Aerts, J., Álvarez Antolínez, J. A., Dullaart, J., Duong, T. M., Erikson, L., Haarmsa, R., Irazoqui Apecechea, M., Mengel, M., Le Bars, D., O'Neill, A., Ranasinghe, R., Roberts, M., Verlaan, M., Ward, P. J., and Yan, K.: Global projections of storm surges using high-resolution CMIP6 climate models: validation, projected changes, and methodological challenges, Climatology (Global Change), https://doi.org/10.1002/essoar.10511919.1, 2022.

Outten, S. and Sobolowski, S.: Extreme wind projections over Europe from the Euro-CORDEX regional climate models, Weather and Climate Extremes, 33, 100363, https://doi.org/10.1016/j.wace.2021.100363, 2021.

Pineau-Guillou, L., Lazure, P., and Wöppelmann, G.: Large-scale changes of the semidiurnal tide along North Atlantic coasts from 1846 to 2018, Ocean Science, 17, 17–34, https://doi.org/10.5194/os-17-17-2021, 2021.

Reinert, M., Pineau-Guillou, L., Raillard, N., and Chapron, B.: Seasonal Shift in Storm Surges at Brest Revealed by Extreme Value Analysis, JGR Oceans, 126, e2021JC017794, https://doi.org/10.1029/2021JC017794, 2021.

Roustan, J.-B., Pineau-Guillou, L., Chapron, B., Raillard, N., and Reinert, M.: Shift of the storm surge season in Europe due to climate variability, Sci Rep, 12, 8210, https://doi.org/10.1038/s41598-022-12356-5, 2022.

Serafin, K. A., Ruggiero, P., Barnard, P. L., and Stockdon, H. F.: The influence of shelf bathymetry and beach topography on extreme total water levels: Linking large-scale changes of the wave climate to local coastal hazards, Coastal Engineering, 150, 1–17, https://doi.org/10.1016/j.coastaleng.2019.03.012, 2019.

Stockdon, H. F., Holman, R. A., Howd, P. A., and Sallenger, A. H.: Empirical parameterization of setup, swash, and runup, Coastal Engineering, 53, 573–588, https://doi.org/10.1016/j.coastaleng.2005.12.005, 2006.

Tadesse, M. G., Wahl, T., Rashid, M. M., Dangendorf, S., Rodríguez-Enríquez, A., and Talke, S. A.: Long-term trends in storm surge climate derived from an ensemble of global surge reconstructions, Sci Rep, 12, 13307, https://doi.org/10.1038/s41598-022-17099-x, 2022.

Vos, K., Harley, M. D., Splinter, K. D., Walker, A., and Turner, I. L.: Beach Slopes From Satellite-Derived Shorelines, Geophysical Research Letters, 47, e2020GL088365, https://doi.org/10.1029/2020GL088365, 2020.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., and Feyen, L.: Extreme sea levels on the rise along Europe's coasts, Earth's Future, 5, 304–323, https://doi.org/10.1002/2016EF000505, 2017.

Vousdoukas, M. I., Mentaschi, L., Voukouvalas, E., Verlaan, M., Jevrejeva, S., Jackson, L. P., and Feyen, L.: Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard, Nat Commun, 9, 2360, https://doi.org/10.1038/s41467-018-04692-w, 2018.