Revisions Manuscript:

"A new modelling framework for regional assessment of extreme sea levels and associated coastal flooding along the German Baltic Sea coast"

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Answers to reviewer #3

We would like to thank anonymous referee #3 for the interesting and helpful comments, which have helped us to improve the manuscript. In response to these comments, we have clarified the objectives of our paper and rephrased the research questions. In addition, we have added some detail to the methods section related to the extreme value analysis and better explain the importance for adjusting the elevation data for dikes. Please find our detailed responses to your comments below.

In order to increase readability, we have written our answers in green. All citations of text from the new, revised version of the manuscript are written in italics.

Comments anonymous referee #3

The manuscrit by Kiesel and co authors adresses the difficult problem of coastal flooding at regional scale along Germany Baltic Sea with multiple difficulties, i.e. data resolution, account for dykes, validation, cascade of uncertainties, etc. The authors propose a modelling framework to do do with a key ingredient being the use of mention images for validation of the assessment.

I believe that the results have the potential to be of interest for a wide audience. Yet several aspects remain unclear and I recommend major corrections before publication.

1) Multiple problems are tackled but with different degrees of achievement, and as reader we get lost about the main message. Is the main result the framework ? If so, a figure presenting the different steps would help a lot together with a discussion section dedicated to the limitations of each this step. If the main result is the use of satellite images, this should be reflected in the title as well in the introduction.

We thank R3 for this helpful comment. We agree that the objectives of our paper were not clearly outlined and have therefore, also in response to a comment 2.1 by Reviewer 2 (see our respective response document), rephrased our objectives.

We have adjusted the wording in the text and now state more clearly the objectives of our paper before we elaborate about the methods used. We have also rewritten our conclusions accordingly.

Please find our specific edits below:

First, we have added a sentence at the beginning of the paragraph in the introduction describing the difficulties and limitations of coastal inundation modelling:

State-of-the-art coastal flood maps should consider oceanographic forcings, projected SLR, detailed topographic data on coastal morphology, including anthropogenic coastal protection measures such as dikes, and the effects of land cover on flood propagation.

Second, we point out that studies that have used state-of-the-art hydrodynamic modelling (considering temporal evolution of the surge and the effects of surface roughness) to assess coastal flooding along the entire German Baltic Sea coast still missing.

Along the German Baltic Sea coast, existing studies on coastal flooding have either used state-of-the-art hydrodynamic models, but cover only a small fraction of the study region (Höffken et al. 2020; Vollstedt et al. 2021)*, or assess potential flood extents for the entire region, but rely on global topographic data sources and apply the bathtub approach* (Schuldt et al. 2020)*. In addition, the validation of produced flood extents is not provided.*

There is a need to simulate coastal flooding on a regional scale, considering the limitations of large-scale coastal flood mapping mentioned before. This is particularly true for topographic data sources and the incorporation of coastal protection infrastructure, which constitute the main bottlenecks for the quality of coastal flood risk assessment (Vousdoukas et al. 2018).

Finally, we have rephrased the objective of the paper, now emphasizing that we aim to assess coastal flooding in the study region for an event that is equivalent to existing design heights for state embankments:

Here, we simulate coastal flooding along the German Baltic Sea coast for a storm surge that aligns with the design standard of state embankments in the region, i.e.\ the 200-year return water level. This study aims at: 1) exploring how flood extent may change until the end of the century, if existing dikes are not upgraded, by applying two high-end SLR scenarios (1 m and 1.5 m); 2) identifying hotspots of coastal flooding in the study region, and 3); evaluating the use of SAR-imagery for validating the simulated flood extents. To the knowledge of the authors, this study constitutes the first regional-scale assessment using a high resolution, fully validated, and offline-coupled hydrodynamic modelling framework that incorporates natural and anthropogenic flood barriers to assess extreme sea levels and associated coastal flooding along the German Baltic Sea coast.

2) the pre-treatment of the data for extreme value analysis is unclear to me. The authors use the notation 'esl' which gives the impression that the authors work with total water level. However the authors also mention extreme surges. If this is the second option, how do the authors derive the total water level at the coast to force the flooding model? More speciffically how do the authors handle the convolution with tide? In addition do the authors use skew surge or the instantaneous surge?

Thank you for this important comment (also see response to reviewer 2, comment 1). Since the Baltic Sea is characterised by a microtidal regime, the effects of tide-surge interactions on total water levels can be neglected (Arns et al. 2020). In order to clarify, we have added the tidal amplitudes to section 2, which now reads:

The Baltic Sea is characterised by a microtidal regime (tidal range varying between 0.1 m and 0.2 m (Sterr, 2008), low salinity, strong stratification, and anoxic conditions in many areas (Meier et al., 2022).

In addition, we clarify in section 3.4 that return water levels correspond to surges only (equal to total water level), as tides are negligible in the study region. Please see our suggestion for revision:

Due to the microtidal regime of the Baltic Sea, the derived return periods and water levels correspond only to the surge component, as tidal contributions to ESL (tide-surge interactions) is negligible (Arns et al. 2020).

3) the analysis of fig. 4 shows some similarities of the enveloppe of uncertainties. Could the authors provide more details about its computation. Finally what surprises me is that there is quasi systematic underestimation of the empirical points except for the more extreme points which is overestimated. Not having this last point would change completely the analysis. Could the authors comment on that?

Thank you for this comment, please see our response to a similar comment of reviewer R#2 below. In black, R#2´s comment and in green, our response.

The empirical values in the distribution shown for a TG (Figure 4) show an increasing bias for increasing RPs, but the fit seems insensitive to this. Could you elaborate? This seems also evident from the 2019 event, what is the corresponding RP and how does the error compare to the derived RP error, given that a different meteo forcing is used? The mean (negative) bias for the 2019 event is partly compensated by the positive bias in the stations around some of the unresolved lagoons, you could leave these out to have a better picture of the model performance for this event? (since TGs are used for the flooding at these locations anyways)

Yes, the model generally has a negative bias, especially the for the high ESLs. However, by overestimating the highest event in the model time period, the statistical fits of the model and the observations are very close, see also the return levels in Tab. 4. For some tide gauge locations, the 200-year return levels from the model are higher than return levels obtained from the observation based GEV. This is especially true for the coast of Schleswig-Holstein, where one event is overestimated by the model, thus influencing the tail of the distribution. However, the 95% confidence intervals are large due to the extrapolation and both, the estimated mean return levels of the model and the observation fall into the confidence intervals of each other.

We have compared the observed/measured (TG) return periods for the 2019 event (blue numbers in Fig. 1) with the return periods calculated with our model (black in Fig. 1). We find that the modelled values are within the respective confidence interval for most locations.

However, the estimation of return periods based on the discrete observations (explanation of the term "discrete observation" provided in caption of Fig. 1) are much smaller for many locations compared to the respective RP from the GEV fits (red numbers for GEV based on observations, black numbers for GEV based on model results). We cannot compare the errors here to other meteorological forcings since we only have run this model for the UERRA dataset. But for the whole Baltic Sea, Lorenz und Gräwe (2023) show for a hindcast ensemble of 13 members at ~1.8 km resolution that the ensemble spread of annual mean maximum water levels is in the order of the variability between the meteorological datasets for the 99th percentile wind speeds.

We prefer to not dismiss the lagoons from the comparison, but rather show the limitations of the model resolution.

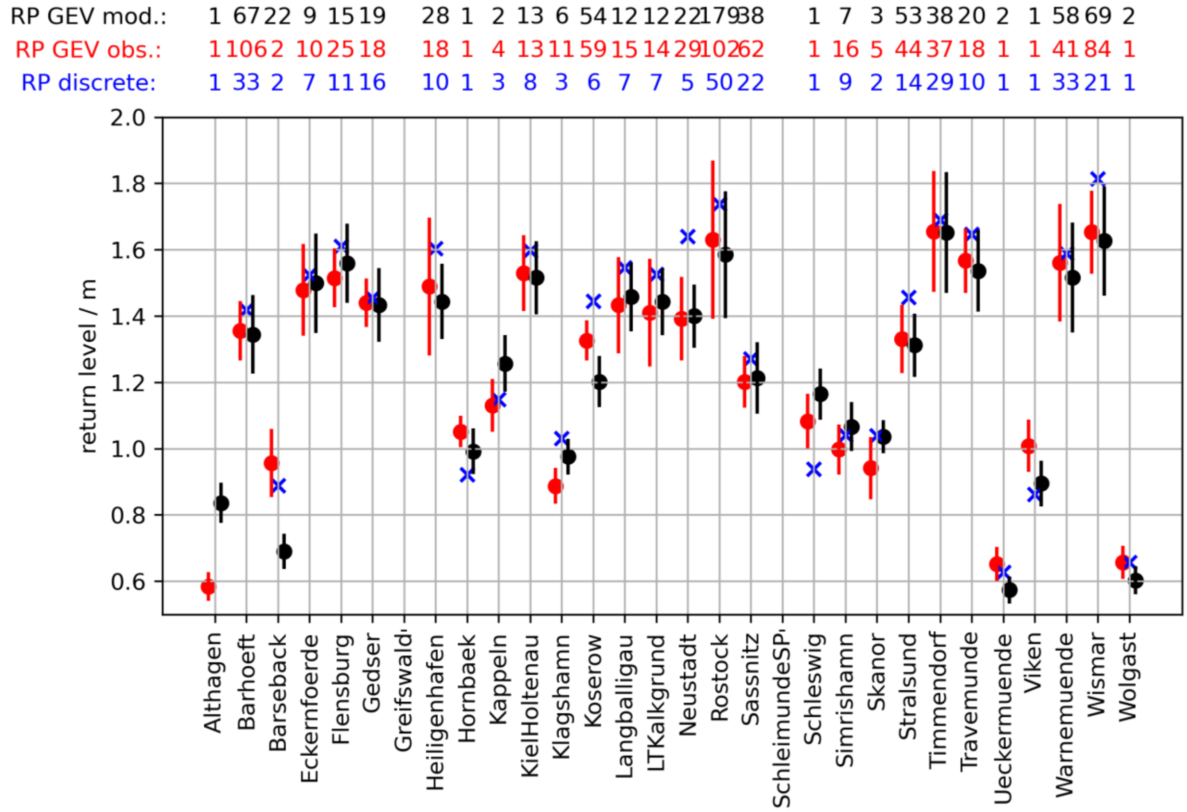

Figure 1: Return levels and 95% confidence intervals based on the observation GEV (red), model GEV (black), and for the discrete return periods of the 2019 event. Discrete means that in case the 2019 event is the highest for a 50-year long data record, the RP is 50 years. If it would be the second highest, the discrete RP would be 25, and so on. The respective return periods from the GEV with a return level as high as the 2019 event are listed in the respective colors above. These RP are usually larger than the discrete ones.

4) The analysis of the differences with the image data (fig. 7 in particular) is of high interest. Could the authors elaborate more on the added value of their updated dem with dykes information. Would it make sense to also compare the results with the ones of a traditional approach without this information? In addition, would it be possible to plot some examples of dem in the vicinity of the dyke to picture how much correction should be done?

We thank Reviewer #3 for this comment. The incorporation of detailed information on the position and elevation of dikes in the study region constitutes one of the major improvements of the developed modeling framework as compared to many other regional or even continental scale assessments (Vousdoukas et al. 2018; Vousdoukas et al. 2016; Hinkel et al. 2021). In order to make this point clearer, we have added a sentence to the respective method section 3.2.3.

The text now reads:

We incorporated detailed information on dikes (location and height) in the modeling framework by using a high-resolution LiDAR derived (1 x 1 m) DEM and comprehensive datasets on the location of both state and regional dikes from local state authorities (Table 1). The incorporation of dikes constitutes one of the major improvements of the applied modeling framework as compared to previous regional or continental scale assessments (Vousdoukas et al. 2016). Elevation data and coastal protection levels are considered as the main bottlenecks for the quality of coastal flood risk assessments (Vousdoukas et al. 2018; Hinkel et al. 2021). Without correcting for dike heights in a 50 m DEM, the simulated flood extent will be overestimated, as the elevation of the dike heights are averaged out due to the resolution (Vousdoukas et al. 2012a; Vousdoukas et al. 2012b). The difference of a DEM with and without dike height correction is shown in Appendix Fig. A1 (here Figure 2).

In order to clarify the importance of the conducted dike height corrections, we further added a figure to the appendix (now Fig. A1), in which we compare the corrected and uncorrected dike height elevations, as suggested by R#3.

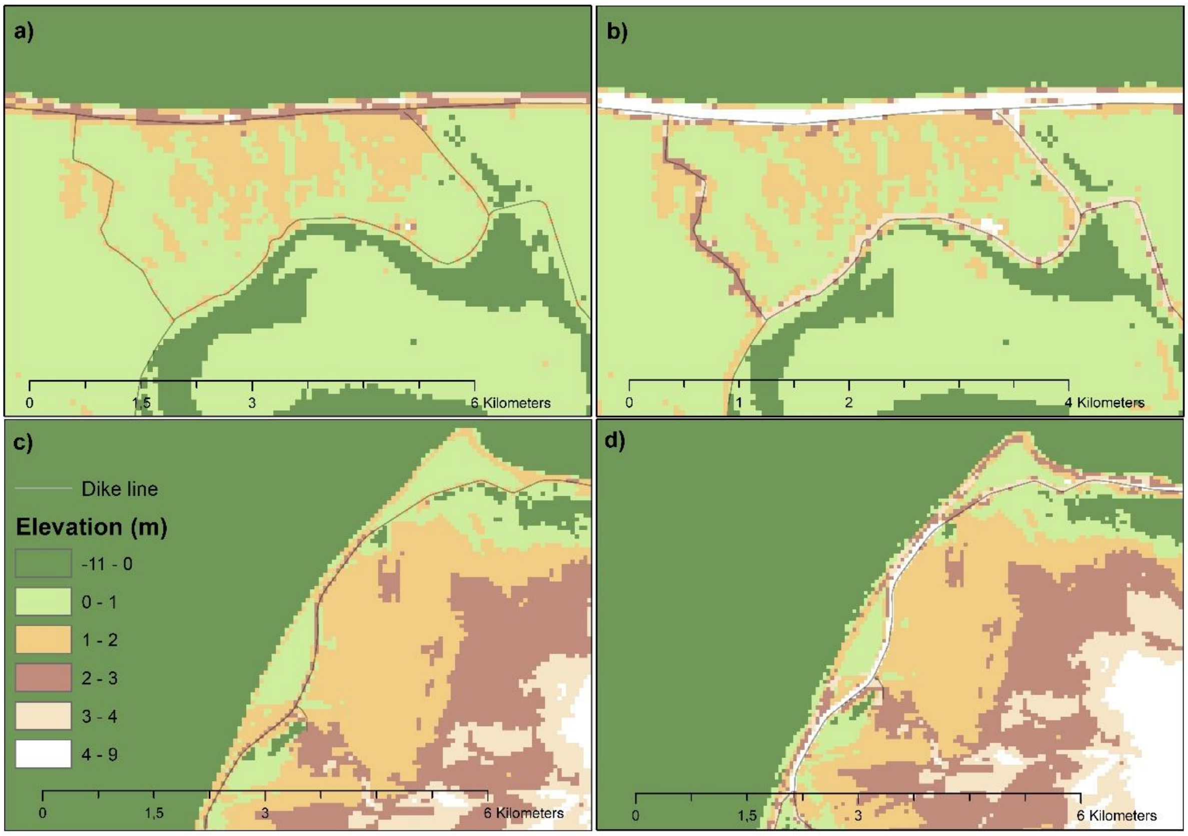

Figure 2: The difference between a DEM that was corrected for dikes (panels b) and d)) and an uncorrected DEM. A) and b) depict the area and dikes around Zingst (MP) and panels c) and d) show the northwestern coastline of the island of Fehmarn (SH).

5) the approach described in appendix A is interesting to account for the time evolution around the surge peak. Given the variability shown in panel a) of fig. A1, could the authors comment on the possible impact of using only the mean time signal instead of a model accounting for this variability?

Thank you for this comment. In response, we have now moved the method from Appendix A1 into the main body of the text. We agree that varying surge duration/intensities can affect coastal flood characteristics. Therefore, we have extended our discussion in section 4.6. The text now reads:

Only a few studies have examined the impact of surge duration and intensity on flood characteristics, but Höffken et al. (2020) *have shown for a case study in the German Baltic Sea that flood extents can vary by 20 % when sea levels rise. The Baltic Sea is characterized by a microtidal regime, which means that high water levels during storm surges can stay for several days and various storm surge intensities are observed* (MacPherson et al. 2019). *Consequently, storm surge hydrographs are spatially and temporarily (between different storm surge events) variable. While we account for the spatial variability by calculating mean storm surge hydrographs for 32 flood boundary stations (Fig. 1) across the study region, the temporal variability is not accounted for as we apply mean surge shapes. Depending on the intensity of surges with a 200-year return water level, we may therefore both over- and underestimate simulated flood extents.*

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