

# The long-term variability of extreme sea levels in the German Bight

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## Authors' response

### RC3 Review by Anonymous Referee #3

We thank Anonymous Referee #3 for the helpful comments. Responses to the individual comments are listed below. Page and line numbers in the responses refer to the updated version of the manuscript; changes therein are marked in red.

1. Comment by Referee:

*The abstract is good and might be even easier to grasp for someone not working in the field if not all abbreviations are introduced there. The NAO or SLP could be introduced later, since they are mentioned only once in the abstract.*

Response:

In order to sharpen the main message, the abstract has been rewritten. Abbreviations not needed have been left out.

2. Comment by Referee:

*Could you mention briefly how those processes that are not included in the model, like ice sheet melt or land uplift might alter your ESL analysis.*

Response:

These processes affect global and regional sea level gradually, and can both add upon another or cancel each other out. Such processes act on long time scales, and thus have a transient and different effect rather than sea level variations on interannual to multidecadal timescales, which are addressed in this study. Impacts of such long-term processes are expected for the entire sea level distribution, as the mean state gradually shifts and, potentially, the distribution's shape also changes. The ESL analysis might hence be affected by gradual changes in the background sea level. Exclusion of these long-term processes, however, makes it possible to isolate for changes in ESL variability due to both dynamic and thermodynamic effects without the influence of a gradual change in BSL.

A paragraph addressing these issues is already part of the discussion. However, a couple of explanatory lines have been added (p. 21, line 4f.):

*'Furthermore, a transient sea level rise due to melting of ice sheets, post-glacial isostatic rebound or the thermosteric effect is not accounted for in the model and a potential increase in ESL with a gradual rise in the BSL could not be investigated. Such transient sea level changes can further impact ESL on longer time scales, since the sea level distribution shifts with changes in BSL and may potentially also change in shape.'*

3. Comment by Referee:

*At the end of the first paragraph in Section 3.1 you mention that the long-term trend from the observations was removed. Was it a linear trend and was the residual of the fit tested for being mostly white noise?*

Response:

Yes, a linear trend. The residual is not entirely white noise though, as it includes cyclicity, e.g. the annual cycle. The corresponding ESL in terms of annual maxima however have been tested positively for being white noise. An explanation has been added in the text (p. 8, line 2).'

4. Comment by Referee:

*In the caption of Figure A2 you mention that "The respective long-term mean has been removed for both time series." and you show the MHW as a dashed line in the figure. The information from the figure and the caption might become clearer if either both the long-term mean and the MHW would be indicated in the figure or was it anyway the MHW which was removed as implied in the text in Section 3.1?*

Response:

In this Figure (now Fig. A1) only the long-term mean has been removed, it is thus the  $y=0$  line. It has now been added to the Figure. In Section 3.1, we compare values respective to the MHW (i.e. the dashed line in Figure A.1.). Additionally, we also changed the solid line to dots in the observation-based figure.

5. Comment by Referee:

*I am not against a conservative approach to show only the 50-year return values from a 50 year long record. Others calculate up to three-fold return periods given the length of a time series. Are there reasons to not calculate the 100-year return level at Husum & Norderney?*

Response:

Yes, we want to only show the non-parametric estimates based on observations, otherwise assumption have to be made, e.g. about the choice of the fitted extreme value distribution. At this stage of the model-data comparison we prefer to stick to non-parametric statistics.

6. Comment by Referee:

*In the last paragraph of Section 3.1 you argue that the model is spatially coherent along the German Bight coast and in Figure A7 you show the average along the coast. I think you need to show the median with interquartile range or something similar to support that claim. It would allow the reader to assure herself that local effects and such are not playing an important role.*

Response:

The figure has been adjusted to show the range among German Bight points rather than the mean only. Note that due to a rearrangement of the Supplementary Material, the Figure is now Fig. A6.

7. Comment by Referee:

*On Page 12 you argue that the pattern of the composites are robust against minor changes in the threshold of what constitutes "high ESL". It might help the reader to integrate "minor changes" into the story a little better if those changes could be related to a number. For example mean plus 1.5 standard deviations plus/minus 0.25 standard deviations, or 80 to 120 periods of "high ESL".*

Response:

Due to the high fluctuations in ESL, the corresponding SLP pattern also shows quite a large variance, which manifests in changes in spatial extent and strength of individual years of the composite. However, the wider spatial characteristics of the associated SLP anomaly averaged over periods of enhanced ESL remains similar if the threshold value changes. We adjusted the text accordingly, toning down some statements, and now explain the term ‘minor changes’ in more detail (p. 13, line 27f.):

*“... minor changes in its value, specifically the range of plus/minus 0.25 standard deviations around the chosen threshold. Yet, in the case of the ESL composites, the spatial variability of associated SLP patterns is large and single years can differ in shape and magnitude. The broader spatial character of the mean anomaly pattern, however, remains robust.”*

8. Comment by Referee:

*In the discussion on page 17 the non-parametric estimates of return levels are compared to various estimates from fitting distributions with certain parameters to the sampled distributions. I think this discussion would become clearer if the non-parametric estimates had been introduced in a sentence or two. How did you exactly determine the non-parametric estimates? This could also be added to the method part.*

Response:

The non-parametric estimates were inferred via an empirical cumulative distribution. A paragraph has been added in the methods section (p. 7, lines 10f.):

*“These non-parametric estimates have been inferred by first ranking the data points of the sea level time series and associating a cumulative probability to each value. The probability of exceedance is  $P = m/(N+1)$ , where  $m$  is the rank of  $N$  observations ordered in decreasing order. Following Eq. 2, return periods are again defined as the reciprocal of the respective probability of exceedance.”*

9. Comment by Referee:

*On page 19, line 29 you mention that the GCM does not account for melting ice sheets. Is the global mean thermosteric effect included in the analyzed sea level?*

Response:

No, as a Boussinesq model, the thermosteric effect is not accounted for and not included in the analysis. However, even though the thermosteric effect is also prognostically calculated by the model and could in theory be added linearly, this is problematic as the parent GCM exhibits considerable drift in the global thermosteric sea level; with the effect from the deep ocean, the 100-year spin-up used in our setup would be too short to account for this. We therefore rather focus on changes in dynamics.

We now briefly address this issue in the discussion (p. 21, line 4f.):

*“Furthermore, a transient sea level rise due to the melting of ice sheets, post-glacial isostatic rebound or the thermosteric effect is not accounted for in the model and a potential increase in ESL with a gradual rise in the BSL base could not be investigated. Such transient sea level changes can further impact ESL on longer time scales, since the sea level distribution shifts with changes in BSL and may potentially also change in shape.”*

All technical corrections have been incorporated.