Subject: Responses to reviewers' comments and suggestions

Manuscript Number: NHESS-2022-223

Title: Improvements to the detection and analysis of external surges in the North Sea

Dear reviewer,

We want to thank you again and like to express our appreciation for the constructive comments– we believe that the consideration of these comments has greatly enhanced the quality of the revised manuscript.

Please find enclosed in this letter detailed answers to reviewers' comments, as well as the corresponding actions performed to the original manuscript submission.

Sincerely,

Alexander Müller, Dr. Birgit Gerkensmeier, Benedikt Bratz, Clemens Krautwald, Dr.-Ing. Olaf Müller, Dr.-Ing. Nils Goseberg, Dr. Gabriele Gönnert

1 REVIEWER #1

- *"Does the paper address relevant scientific and/or technical questions within the scope of NHESS? Yes*
- *Does the paper present new data and/or novel concepts, ideas, tools, methods or results? Yes*
- *Are these up to international standards? Yes*
- *Are the scientific methods and assumptions valid and outlined clearly? The methodology as a whole should be described in a little more detail, also the distinction Dataset1 and Dataset2*
- *Are the results sufficient to support the interpretations and the conclusions? Yes*
- *Does the author reach substantial conclusions? Yes*
- *Is the description of the data used, the methods used, the experiments and calculations made, and the results obtained sufficiently complete and accurate to allow their reproduction by fellow scientists (traceability of results)? see no 4*
- *Does the title clearly and unambiguously reflect the contents of the paper? Yes*
- *Does the abstract provide a concise, complete and unambiguous summary of the work done and the results obtained? Yes*
- *Are the title and the abstract pertinent, and easy to understand to a wide and diversified audience? Yes*
- *Are mathematical formulae, symbols, abbreviations and units correctly defined and used? If the formulae, symbols or abbreviations are numerous, are there tables or appendixes listing t*
- *hem? Yes*
- *Is the size, quality and readability of each figure adequate to the type and quantity of data presented? Yes*
- *Does the author give proper credit to previous and/or related work, and does he/she indicate clearly his/her own contribution? Yes*
- *Are the number and quality of the references appropriate? Yes*
- *Are the references accessible by fellow scientists? Yes*
- *Is the overall presentation well structured, clear and easy to understand by a wide and general audience? Largely, for elements to be corrected see pdf*
- *Is the length of the paper adequate, too long or too short? Adequate*
- *Is there any part of the paper (title, abstract, main text, formulae, symbols, figures and their captions, tables, list of references, appendixes) that needs to be clarified, reduced, added, combined, or eliminated? see point 4*
- *Is the technical language precise and understandable by fellow scientists? Yes*
- *Is the English language of good quality, fluent, simple and easy to read and understand by a wide and diversified audience? Yes*
- *Is the amount and quality of supplementary material (if any) appropriate? yes*

Answer to General Comment of Reviewer #1:

Thank you very much for your comments on this manuscript and the opportunity to improve it with your helpful comments and further recommendations! Thanks also for providing suggestions for an improved structure of the manuscript. We have adapted the structure to have a more precise division between methodology, results and discussion. The distinction between DataSet1 and DataSet2 has been added to the new Section 3.5, where the two datasets are first mentioned.

Answers to the specific comments on the manuscript are listed below.

Comment 1.1:

"No space before percent in English."

Answer to Comment 1.1:

Thank you for your comment. The formatting has been changed on all occurrences in the paper.

Lines 17-20:

Furthermore, external surges are analysed with regard to their annual and decadal variability, corresponding weather conditions and their interaction with storm surges in the North Sea. 33% of the 101 external surges occur within close succession of each other, leading to the definition of serial external surges, in which one or more external surges follow less than 72 h after the previous external surge. These serial events tend to occur more often during wind–induced storm surges.

Comments 1.1. and 1.3:

"I'm missing a mention here of tidal changes, so in the context here of tidal high water changes in the North Sea."

"Especially here, tidal changes or the trends of tidal high waters should not be ignored."

Answer to Comments 1.1. and 1.3:

Thank you for pointing out another influence on peak water level, that we missed in the introduction. A mention of the effects was added in the introduction.

Lines 34-36:

Additionally, tidal ranges in the North Sea show significant trends, which can superimpose RMSL rise and further increases the long-term variability of peak water levels (Jänicke et al. 2021).

Besides long-term changes […]

Comment 1.4:

"Missing word?"

Answer to Comment 1.4:

Thank you for your correction, the missing word has been added.

Line 132:

The study focuses on the North Sea basin, complementing earlier studies about external surges in this area.

Comment 1.5:

"A source should be cited for this information."

Answer to Comment 1.5:

Thank you for this comment. Two sources have been added.

Line 138:

These marsh coasts also include the unique biotope of the Wadden Sea (Lotze et al. 2005; Reise et al. 2010).

Comment 1.6:

"This should be justified with a source, because for tidal waves, which have been described as similar, this is only valid to a limited extent."

Answer to Comment 1.6:

Thank you for your comment. Further explanation and sources have been added.

Line 144-146:

The height of the external surge at the Aberdeen tide gauge was previously used as a proxy for the height during its entrance into the North Sea (Bruss et al. 2011; Ganske et al. 2018), while Immingham is close to the location where most external surges reach their maximum height.

Comment 1.7:

"The tide gauge Immingham lies far in an estuary, behind piers and other structures. How representative can it be? I do not dispute its general validity, but this should be justified briefly."

Answer to Comment 1.7:

Thank you for this question. Similar to all other tide gauges in this study, the Immingham tide gauge is influenced by local bathymetry and man-made structures. This is less of a problem, because the aim of this study is not to find the height of an idealized surge, but the realistic impacts, which include the effects of these features. Nonetheless, a section has been added to discuss their possible influence.

Line 157-162:

Water levels at these tide gauges are influenced by the local bathymetry, such as their position in an estuary or harbour basins, or man-made structures like breakwaters (Spencer et al., 2015; Serafin et al. 2019). Still, these tide gauges are used in the herein conducted study as they cover the desired timespan, maintain comparability and quantify the effects of external surges on coastal areas, which is the main focus of this study. Inaccuracies in the height of the external surge due to variations of density (Mehra et al. 2009) and runoff in the estuary (Müller-Navarra und Bork 2011) fall within the general uncertainties of the study e.g. due to the calculation of astronomical tides.

Comment 1.8:

"This statement urgently needs a source, especially since Jänicke et al (2020) and Ebener et al (2021) have a different view on that. Is the statement even necessary for the methodology used here? Then Immingham would also cause a problem."

Answer to Comment 1.8:

Thank you for pointing out this inaccuracy. The original point was, that the tide gauge is less affected by man-made impacts than other tide gauges in the Elbe estuary. This would need further discussion of changes in the Elbe estuary and the possible usage of other German tide gauges. As per your suggestion, the statement has been omitted, since it is not essential for the study.

Lines 151-153:

The tide gauge in Cuxhaven has been regularly used as reference tide gauge in German coastal protection considerations as it provides a continuous data series (continuous record is available since 1918, tidal high and low waters since 1843), ~~which is nearly undisturbed (e.g. by man-made impacts),~~ and is influenced neither by barriers like the East Frisian Islands nor by the Elbe estuary fluxes.

Comment 1.9:

"Texel lies on the inner side of a chain of islands and incoming waves are therefore also distorted. For all gauges a general statement would be helpful why the shortcomings of the individual tide gauges are not a problem."

Answer to Comment 1.9:

Thank you for your comment. The study uses data from the tide gauge "Texel Noordzee", which is located on the seaward side of the Texel island. The authors have added the name of the tide gauge to eliminate confusion with the tide gauge "Oudeschild". In the path of the external surges, Texel is the first of the Western Frisian islands, therefore the distortion of the wave due to the barrier islands should be minimal. Further, a general comment on the applicability of the used tide gauges to detect external surges in coastal areas is given in Answer to comment 1.8.

Lines 154-157:

Additionally, the present study uses the tide gauge ~~at~~ "Texel Noordzee" (hereafter called Texel) because it is located in almost even distance to Immingham and Cuxhaven and can thus supplement information about the propagation of external surges after they reached their maximum height near Immingham.

Comment 1.10:

"Maybe I understand it wrong, but below it is explained how directly the non tidal residual is determined... why is hastro referred to here in the formula?"

Answer to Comment 1.10:

The sentence has been rephrased during the restructuring of the methodology section. We hope, this eliminates the doubling in the text and the equation.

Lines 194 & 198:

First, the astronomical tide (h_{astro}) is eliminated from the water level records to retrieve the non-tidal residual (Δh). […]

$$\Delta h_i = h_{obs,i} - h_{astro,i} \quad (1)$$

Comments 1.11 and 1.12:

"Why? The wind can shift from south to north-east and then stay north-east for more than 15 hours?"

"That could be correct, but "not very often" is very non-specific. Does it occur and if so how often is not very often?"

Answer to Comments 1.11 and 1.12:

Thank you for pointing out these critical aspects in our assumptions. The section has been rephrased to highlight that this is merely an assumption, which has so far proven to produce satisfactory results. Your questions highlight the importance of a deeper understanding of the meteorological conditions around external surges, which is also a topic of great interest for the authors. A detailed analysis including wind data from offshore stations or reanalysis data is unfortunately beyond the scope of this paper.

Lines 213-225:

Due to the different main wind direction, the coincidence of either two of the last three factors would require significant and sudden changes in wind conditions.

For the Immingham tide gauge, Rossiter (1959) concluded that the following parameters influence the residuals the most:

- The residual at Aberdeen with a time lag of 5 h
- Northeast winds over the North Sea with a time lag of 6 h

The first accounts for local air pressure as well as external surges propagating southwards along the British coast. As the entrance of external surges is hindered by eastern winds, these two main factors are assumed to not coincide in general. For these two British tide gauges it can therefore be assumed that wind setup does not need to be accounted for during the detection of external surges, which was proven successful in previous studies (Gönnert, 2003). Further research on the meteorological conditions causing external surges is certainly needed, especially focusing on wind and air pressure patterns. This detailed analysis could also enable more detailed statements about the co-occurrence of the weather patterns, that cause non–tidal residuals in Aberdeen and Immingham. This analysis is, however, beyond the scope of this study but will be the focus of further work on external surges in the North Sea.

Comment 1.13:

"I find it very difficult to understand what is happening here. how and why is the RMSE formed and what is the scale of numbers here? Please short additional explanation."

Answer to Comment 1.13:

Thank you for pointing out some aspects in our methods sections that have left the reviewer with confusion. The paragraph has been rewritten and an equation of the RMSE has been added to explain the RMSE error and the contents of Fig. 3.

Lines 271-287:

The accuracy of the hindcast can be assessed by calculating the root mean square error (RMSE) of the verification period (2005-2020):

$$e_{RMS} = \sqrt{\frac{\sum_{i=1}^{I}(\Delta h_{obs,i} - \Delta h_{pre,i})^2}{I}} \quad \textbf{(2)}$$

For the tide gauge in Cuxhaven, the RMSE is used to verify the time lag of 3 h between wind measurements and predicted water levels, that was determined by Müller-Navarra and Giese (1999). The hindcast model generally performs better for high water phases, with a minimum RMSE of 18.5 cm compared to 20.8 cm for low water. Both minima are determined with a time lag of 4 h, but the strong increase for a time lag of 5 h suggests an optimal time lag between 3 and 4h, corresponding generally with the assumption of Müller-Navarra and Giese (1999). The relation between the RMSE and the time lag is shown in Fig. 3.

For the Texel tide gauge, the unknown factors of main wind direction and time lag between wind and water level have to be determined as well. First, the RMSE is calculated for multiple MLRs with varying main wind directions and the separation between onshore and offshore wind at ± 90° of the main direction. The optimal limit between on- and offshore wind is found to be around 20° and 200°, which is close to the general orientation of Texel's coast. The optimization of the time lag is shown in Fig. 3, which determines a time lag of 2 h. The RMSE is lower than in Cuxhaven with 16.3 cm for high water and 16.8 cm for low water phases.

Comment 1.14:

"This should be in the discussion or the relevant analyses should be announced in the introduction or methodology. In any case, this is not a result."

Answer to Comment 1.14:

Thank you for you input on the structure. We moved the paragraph to the discussion and shortened the following paragraph.

Line 604-613:

In the context of coastal protection, serial external surges should also be analysed as interdependent waves, since they can influence peak water level in a couple of different ways depending on the timing between high waters, maximum wind setup and external surge peaks. A single storm surge spanning over multiple tide cycles might well be influenced by two or more external surges in close succession, e.g., resulting in higher peak flood elevations as compared to cases where external surge events are absent. The assumption of interactions between these external surges cannot be verified in this study as it requires more detailed analysis with higher spatial and temporal resolutions, possibly including numerical simulations.

However, this study highlighted the need to assess serial external surges~~, a phenomenon that was found during the analysis of external surges in this study,~~ more thoroughly in the future, particularly as it might alter the design assumptions regarding long-lasting (extreme) water levels stretching a couple of tidal cycles causing increased stress on coastal protection facilities. Further insights on meteorological conditions, causing combined events including a serial external surge event, as well as improved knowledge about propagation velocity of external surges are needed at this point.

Comment 1.15:

"The information is missing for Table 5 and should come earlier"

Answer to Comment 1.15:

Thank you for suggesting improvements to the comparison with the previous dataset. A reference to Gönnert (2003) has been added to Table 5. Due to other restructuring of the paper, the distinction between the datasets is now also mentioned in lines 346-348 (as shown in the answer to comments 1.17 and 1.18).

Comment 1.16:

"The boxplot needs further explanation regarding representation, what do the crosses, the boxes, the intervals mean?"

Answer to Comment 1.16:

Thank you for your comment. Further explanation has been added in the caption of Fig. 3:

Line 470-472 (caption of Fig. 10):

Figure 10: Boxplot of the heights of external surges in Aberdeen, Immingham, Texel, and Cuxhaven from 1995 to 2020. Crosses mark the mean, the boxes represent the upper and lower quartile with the horizontal line for the median. The whiskers show the minimum and maximum height.

Comments 1.17 and 1.18:

"This is methodology."

"These are not results for me, all these things have to be explained earlier for a later comparison which then takes place here.

In general it should be clear from the introduction / methodology what kind of results are to be expected. The actual results are then shown here."

Answer to Comments 1.17 and 1.18:

Thank you for your comment. Section 3.5 has been added to describe the methodology and expected outcome of the analysis for weather situations. The commented lines (408-412 and 434-445) have been moved to this section and altered to give a coherent section:

Line 345-373:

2.5 Meteorology

External surges found in this study are mainly compared to the dataset of Gönnert (2003), that spans the years 1971 to 1995. To distinguish between the datasets, the dataset of Gönnert is hereafter called DataSet1 and the dataset derived from the automated approach is called DataSet1.

The occurrence of external surges in the North Sea basin is strongly coupled to storm systems in the North Atlantic. Although the process of the physical meteo–oceanic coupling is not within the scope of this work, it will be important to correlate the observations from the tide gauge data to general weather pattern. To briefly repeat meteorological conditions in a context of surge generation, the European weather situations during the beginning of the observed external surges are assembled first. The European weather situations were originally defined by Hess and Brezowski (1977) and determined by Werner and Gerstengarbe (2010) for the duration from 1881 to 2009. From 2010 onwards, the records from German Meteorological Service (2021) are used. The Agency for Roads, Bridges and Waters Hamburg (2012) found 61 of the 73 external surges of Dataset1 to occur during four weather situations (WZ: western situation cyclonic, WA: western situation anticyclonic, SWA: south western situation anticyclonic, BM: high pressure bridge Central Europe).

The characterisation of external surges with respect to low pressure cells can be summarized from Werner and Gerstengarbe (2010) as follows:

- WZ: Single disturbances with high–pressure cells in between travel from Ireland over the British Isles, North and Baltic Sea towards Eastern Europe. The driving low–pressure cells is located north of 60° N.
- WA: The central low–pressure cell is often located north of 65° N with single disturbances travelling from west of Scotland over Scandinavia towards the Baltic.
- SWA: A low–pressure system is mostly located over the middle of the North Atlantic and the western Norwegian Sea. Single disturbances travel to the northeast.
- BM: A high–pressure bridge between the Azores and Eastern Europe with an eastward directed frontal zone north of it and single disturbances travelling eastwards.

In the analysis of DataSet2, an additional weather situation is identified, that correlates with an increased number of external surges (NWZ, north western situation cyclonic) and has the following characteristics:

- NWZ: Extensive low–pressure area over Scotland, the Norwegian Sea and Scandinavia with single disturbances travelling over the British Isles towards eastern Central Europe.

The detailed analysis of weather situations is presented in Sect. 3.2, while Sect. 3.3 analyses the influence of external surges on storm surges in the German Bight.

Comment 1.19:

"This is also more of a discussion."

Answer to Comment 1.19:

Thank you for your further input on the structure of the paper. The paragraph has now been omitted in large parts, as it doubles with the more detailed contents of the respective discussion. Only lines 477-479 have been moved to line 609-610.

Line 540:

~~Findings presented above already underline the need to further investigate the phenomenon of serial external surge events, as they might play an important role to determine the maximum range of combined extreme events, applied for example for determination of design level heights. It can be assumed that higher quantities of extreme events during a serial external surge event increase the potential for an unfavourable superposition of storm surge and external peaks. Hence, this requires consideration of the increased time span of serial external surges (compared to the time span of combined events with one external surge) in the determination of design standards.~~

Lines 612-613:

Further insights on meteorological conditions, causing combined events including a serial external surge event, as well as improved knowledge about propagation velocity of external surges are needed at this point.

3 Added references

The following references were added during the revisions of the manuscript:

Amin, M. (1982): On analysis and prediction of tides on the west coast of Great Britain. In: *Geophysical Journal International* 68 (1), S. 57–78. DOI: 10.1111/j.1365-246X.1982.tb06962.x.

Boesch, Andreas; Müller-Navarra, Sylvin (2019): Reassessment of long-period constituents for tidal predictions along the German North Sea coast and its tidally influenced rivers. In: *Ocean Sci.* 15 (5), S. 1363–1379. DOI: 10.5194/os-15-1363-2019.

Bruss, Gerd; Gönnert, Babriele; Mayerle, Roberto (2011): Extreme scenarios at the Germen north sea coast - a numerical model study. In: *Int. Conf. Coastal. Eng.* 1 (32), S. 26. DOI: 10.9753/icce.v32.currents.26.

Dronkers, Job; Stojanovic, Tim (2016): Socio-economic Impacts—Coastal Management and Governance. In: Markus Quante und Franciscus Colijn (Hg.): North Sea Region Climate Change Assessment. Cham: Springer International Publishing (Regional Climate Studies), S. 475–488.

Jänicke, Leon; Ebener, Andra; Dangendorf, Sönke; Arns, Arne; Schindelegger, Michael; Niehüser, Sebastian et al. (2021): Assessment of Tidal Range Changes in the North Sea From 1958 to 2014. In: *Journal of geophysical research. Oceans* 126 (1), e2020JC016456. DOI: 10.1029/2020JC016456.

Jensen, Jürgen; Mudersbach, Christoph; Dangendorf, Sönke (2013): Untersuchungen zum Einfluss der Astronomie und des lokalen Windes auf sich verändernde Extremwasserstände in der Deutschen Bucht.

Lotze, Heike K.; Reise, Karsten; Worm, Boris; van Beusekom, Justus; Busch, Mette; Ehlers, Anneli et al. (2005): Human transformations of the Wadden Sea ecosystem through time: a synthesis. In: *Helgol Mar Res* 59 (1), S. 84–95. DOI: 10.1007/s10152-004-0209-z.

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Mikhailova, M. V. (2011): Interaction of tides and storm surges at the Elbe River mouth. In: *Water Resour* 38 (3), S. 284–297. DOI: 10.1134/S0097807811030079.

Müller-Navarra, Sylvin (2013): On Tidal Predictions by Mean of Harmonic Representation of Inequalities. Hamburg (Reports of the Federal Maritime and Hydrographic Agency (BSH), 50).

Müller-Navarra, Sylvin; Bork, Ingrid (2011): DEVELOPMENT OF AN OPERATIONAL ELBE TIDAL ESTUARY MODEL. In: *Int. Conf. Coastal. Eng.* 1 (32), S. 48. DOI: 10.9753/icce.v32.management.48.

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Reise, Karsten; Baptist, Martin; Burbridge, Peter; Dankers, Norbert; Fischer, Ludwig; Flemming, Burghard et al. (2010): The Wadden Sea - A universally outstanding tidal wetland. Wadden Sea Ecosystem No. 29. Commen Wadden Sea Secretariat. Wilhelmshaven.

Serafin, Katherine A.; Ruggiero, Peter; Barnard, Patrick L.; Stockdon, Hilary F. (2019): 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. In: *Coastal Engineering* 150, S. 1–17. DOI: 10.1016/j.coastaleng.2019.03.012.

Siefert, Winfried (1991): Ober Eintrittswahrscheinlichkeiten von Windstau, Oberwasser und örtlichem Wind in einem Tidefluß am Beispiel der Elbe. In: *Die Küste* (52), S. 171–190.