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Possibility of statistical correction of hydrodynamic-numerical model results using the example of the storm surge of 1872

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Summary

Life along the coasts of the Baltic Sea has been, is, and will continue to be characterized by storm surge events. In November1872, there was an extraordinary storm surge in the area of the German and Danish Baltic Sea coast of dimensions never reached since (e.g. Jensen and Töppe 1986, 1990). The peak water levels were above all previously known values – even though similar storm surge catastrophes have been reported from time to time in the last 1000 years. The storm surge, which is nevertheless often referred to as "singular" (or outlier), represents the beginning as well as the greatest challenge of modern coastal protection in the Baltic Sea region. Besides the exceptionally peak water levels, the first measurement of the water levels, as well as the detailed description of the genesis, the course and the consequences are the unique aspects of this storm surge (e.g. in Baensch 1875). However, the available hydrographs are only locally available and may be associated with uncertainties.
In order to improve the data basis and thus the decision basis for coastal protection, the integration of information from historical events is recommended (e.g. in DWA M-552). Information on water levels, especially from historical events, is often available only locally. Therefore, to obtain a valid basis for the safety assessment of sections without observed information about water levels, a hydrodynamic simulation for spatial and temporal information extension is indispensable.
To obtain a complete picture of the water levels of the storm surge of 1872 the event was simulated using an existing hydrodynamic-numerical model of the Baltic Sea. Simulations, especially of extreme events, are often accompanied only by compromises in the accuracy of the results. To achieve results that satisfy high qualitative demands, model-generated data can be corrected using a statistical correction function (called Bias Correction). Using the example of the storm surge of 1872 in the south-western Baltic Sea, the statistical correction of model results was demonstrated to be a suitable post-processing for an optimization of model results. The semi-statistical and semi-hydrodynamic data set for the coastline of the Baltic Sea in the observation area validly reflects the available locally water level observations during the storm surge and satisfies high quality standards. The conclusions can be adapted to other historical storm surges, e.g. 1837, 1891, 1905 (cf. Jensen et al. 2022), if necessary, and thus integrated into the database. This can be used as a basis for an adaption of the coastal protection level and disaster management for the German Baltic Sea coast.

Keywords

Baltic Coast/Sea, storm surge 1872, hydrodynamic modelling, Bias Correction

Zusammenfassung

Das Leben an den Küsten der Ostsee war, ist und wird auch in Zukunft durch Sturmflutereignisse geprägt sein. Im November 1872 kam es im Bereich der deutschen und dänischen Ostseeküste zu einer außergewöhnlichen Sturmflut von seitdem nie wieder erreichten Ausmaßen (z. B. Jensen und Töppe 1986, 1990). Die Scheitelwasserstände lagen über allen bisher bekannten Werten – obwohl in den letzten 1000 Jahren immer wieder von ähnlichen Sturmflutkatastrophen berichtet wurde. Die Sturmflut, die dennoch oft als „singulär" (oder als Ausreißer) bezeichnet wird, stellt sowohl den Beginn als auch die größte Herausforderung des modernen Küstenschutzes dar. Neben den außergewöhnlich hohen Scheitelwasserständen, ist die erstmalige Messung und Überlieferung der Wasserstände, sowie die detailtreue Beschreibung der Genese, des Verlaufs und der Folgen die Besonderheit dieser Sturmflut (z. B. in Baensch 1875). Die verfügbaren Ganglinien sind jedoch nur lokal verfügbar und können mit einer unbekannten Unsicherheit behaftet sein. Um die Datenbasis und damit die Entscheidungsgrundlage für den Küstenschutz zu verbessern, wird die Integration von Informationen aus historischen Ereignissen empfohlen (z. B. in DWA M-552). Informationen über Wasserstände, insbesondere aus historischen Ereignissen, sind oft nur lokal verfügbar. Um eine valide Grundlage für die Beurteilung der Sicherheit von Abschnitten ohne beobachtete Wasserstandsinformationen zu erhalten, sind daher hydrodynamische Simulationen zur räumlichen und zeitlichen Informationserweiterung unerlässlich.

Um ein vollständiges Bild der Wasserstände der Sturmflut von 1872 zu erhalten, wurde das Ereignis mit einem vorhandenen hydrodynamisch-numerischen Modell der Ostsee simuliert. Simulationen, insbesondere von Extremereignissen, sind oft mit Kompromissen hinsichtlich der Genauigkeit der Ergebnisse verbunden. Um Ergebnisse zu erhalten, die hohen qualitativen Ansprüchen genügen, können modellgenerierte Daten mit einer statistischen Korrekturfunktion (Bias-Korrektur genannt) korrigiert werden. Am Beispiel der Sturmflut von 1872 an der südwestlichen Ostsee wird gezeigt, dass die statistische Korrektur der Modellergebnisse ein geeignetes Mittel zur nachträglichen Optimierung der Modellergebnisse ist. Damit wurde ein semi-statistischer und semi-hydrodynamischer Datensatz für die Ostseeküste im Beobachtungsgebiet generiert, der die lokal verfügbaren Wasserstandsbeobachtungen während der Sturmflut valide widerspiegelt und qualitativ hohen Ansprüchen genügt. Die Erkenntnisse lassen sich ggf. auf andere historische Sturmfluten, z. B, 1837, 1891, 1905 (cf. Jensen et al. 2022), übertragen und so in die Datenbasis integrieren.

Dieser Datensatz kann dann als Grundlage für eine Anpassung des Küstenschutzniveaus und des Katastrophenmanagements für die deutsche Ostseeküste genutzt werden.

Schlagwörter

Ostsee, Sturmflut 1872, hydrodynamische Simulation, Biaskorrektur

1 Introduction

The local water level in coastal regions is of fundamental importance for stakeholders dealing with e.g. nature or coastal protection. Even small changes can have considerable impacts on the life of residents as well as on flora and fauna. In extreme cases, water level rises by several meters, as a result of persistent, onshore storms, can cause severe destruction in addition to the typical storm damages. Direct damages from storm surges can include the destruction of buildings, coastal protection structures, collapsed steep banks, stranded ships, and even injuries and fatalities. In addition to material damages, immaterial damages, such as the interruption of shipping traffic and port operations, but also psychological damages, such as the loss of trust in coastal protection, can occur, which is difficult to quantify.

The development and intensity of storm surges are subject to various influences. Of particular importance of a storm surge in the Baltic Sea, is the degree of filling of the basin in the initial phase. During the event, mainly the wind surge and oscillations influence the water levels. Baltic Sea water level variability due to tides is in the range of centimeters to a few decimeters. Depending on the meteorological conditions, the storm surge-relevant factors interact and determine each storm surge differently (Weisse and Meinke 2017).

In history, the consequences of storm surges with extreme water levels often represented a significant impact in the lives of coastal residents. The experience of the floods was therefore often reported in folk songs, myths, or chronicles of towns. In addition to the destruction of buildings, fatalities and the loss of livestock, diseases and epidemics often occurred in the years following a storm surge, causing the population to suffer for many years after the storm surge (Petersen and Rohde 1979). It is important to keep in mind that the main focus of the reports was the impact of the storm surge on the population and not the documentation of hydrological or meteorological data, which is of use for coastal engineering.

Known as one of the most devastating natural disasters in living memory, the highest storm surge ever recorded on the German Baltic Sea coast occurred in the night of November 12th to 13th in 1872, when water levels of up to 3.5 meters above mean water level (MW) were recorded. From November 1th to 10th, mainly westerly to southwesterly winds, at times stormy, acted over the Nordic Seas and Scandinavia. At the Baltic Sea, water masses were pushed eastward to the Baltic and Finnish coasts, forming a slope with high water levels in the eastern Baltic Sea and lower water levels in the west. This further increased inflow through the Skagerrak and Kattegat from the North Sea, and filled up the Baltic Sea. On November 10th, a temporary phase of weak winds set in over the Baltic Sea, initiating the return of water westward. By the 13th, easterly to northeasterly winds intensified this westward transport of water. As a result, water levels at the German and southern Danish Baltic coasts rose throughout. On the morning of November 13th, an extreme air pressure gradient was present over the western Baltic Sea and the northeasterly storm reached hurricane strength. The flood disaster reached its peak with a strong wind surge and high waves, after which the wind weakened rapidly and shifted to an easterly direction. Thus, water levels started to subside (Rosenhagen and Bork 2009). In contrast to common ideas, the revised work of Bork et al. (2022) rejected the assumption of a significant contribution of preconditioning events such as an increased previous filling of the Baltic Sea (“prefilling state”) and also of back flowing of the water piled up in the central or northern Baltic Sea. It was shown by numerical experiments, that wind induced water transport and its later effect on the peak water levels during extreme storm floods is less important than the local wind accumulation on the flat coasts. Because there have been no amplifying effects on the flood, the storm surge was thus solely caused by the hurricane-force wind (Bork et al. 2022).

However, as consequences, at least 271 people died, 15,160 people were left homeless, and 2,860 houses were destroyed or severely damaged. The surge affected the outer Baltic coastline as well as the Bodden and Haffs (e.g. Baensch 1875, Kiecksee 1972, Petersen and Rohde 1979). A comparative, recent work on the consequences of the storm surge in Denmark, Germany and Sweden is presented in Hallin et al. (2021).

In Figure 1, exemplary for the German Baltic Sea coast, the collapse of a farmhouse in Niendorf by the huge water masses of the storm surge of November 12th/13th, 1872 is shown.

Figure 1: Collapse of a farmhouse in Niendorf while people on the roof trying to escape the waters of the storm surge in 1872; drawing by C. Oesterley (AI colorized to highlight details).

This storm surge, often referred to as "singular", represents the beginning as well as the most challenging task of modern coastal protection in the region. Although severe storm surges occur less frequently at the Baltic Sea than at the North Sea, their impacts can be just as destructive. The time between (very) severe storm surges, which is usually quite long, should not obscure the fact that there is a risk of a (very) severe storm surge, such as the November 12th/13th 1872 storm surge, along the Baltic Sea coasts at almost any time (Petersen and Rohde 1979).

2 Data basis of the storm surge of November 12th/13th in 1872

2.1 Observed water levels

In the former Prussian coastal districts of the Baltic Sea, the storm surge was such an extensive phenomenon, that the importance of documenting its genesis, course and consequences in detail, and thus preserve them for posterity, quickly became apparent. For this purpose, the authorities of Danzig, Cöslin, Stettin, Stralsund and Schleswig, as well as the provincial authorities of Stade and Aurich were ordered to collect and compile existing records. Using these records, Otto von Baensch compiled his report *The storm surge of November 12th-13th in 1872 on the Baltic coasts of the Prussian state* in 1875, giving an impression of the entire storm surge that is still remarkable in its attention to detail (a translation of the original source was made in Jensen (2023)). As far as historical records date, similar catastrophes like the storm surge of November 12th/13th in 1872 are mentioned (1044, 1304, 1320, 1449, 1625, 1694, 1784; e.g. Jensen et al. 2022), but *"it was always only the historian, not the technician, who handed down the bare fact in a few words to posterity"* (Baensch 1875). Thus, in addition to the extraordinary water levels, the detailed and for the first time in history quantitative documentation of the genesis, the development and the damages of the storm surge is the special value of the 1872 event.

Figure 2: Spatial distribution of the gauge stations provided in Baensch (1875) along the coast of the Baltic Sea. Map adapted from Baensch (1875) with reference to Table 1.

Table 1: Gauge station names referring to the ID´s in Figure 2.

[ID] Station	[ID] Station	[ID] Station
[1] Årøsund	[8] Barhöft	[15] Dievenow (Dziwnów)
[2] Sønderborg	[9] Stralsund	[16] Colbergermünde (Kolberg)
[3] Flensburg	[10] Wiek	[17] Rügenwaldermünde (Darłówko)
[4] Kiel	[11] Wittow	[18] Stolpmünde (Ustka)
[5] Neustadt	[12] Thiessow	[19] Neufahrwasser (Danzig)
[6] Travemünde	[13] Greifswalder Oie	[20] Pillau (Baltijsk)
[7] Barth	[14] Swinemünde	[21] Memel (Klaipėda)

Besides detailed descriptions and explanations of the meteorological conditions, water level hydrographs from the storm surge between November 6th and 20th, 1872, are provided for a total of 21 different gauge stations along the southwestern Baltic Sea coast from Årøsund to Memel. All gauge stations were part of Prussia in 1872 so information was collected on stations that are localised in areas that belong today to Denmark, Poland, Lithuania and Russia. In Figure 2, the gauge stations of the hydrographs provided in Baensch (1875) along the south western coast of the Baltic Sea are shown.

Self-registering gauge stations had been installed on the Prussian Baltic Sea coast only in Swinemünde so far. Hence, the continuous drawn hydrographs are reconstructed by temporal observations at water gauge staffs.

Before the establishment of the metric system in Germany, measurement e.g. of water levels, used to have different, local units (e.g. feet, inch). Thus, depending on the respective location, water levels were measured in *Lübeck feet*, *Hamburg feet* or *Rostock feet*. With introduction of the metric system on 01.01.1872, the gauge staffs along the entire Prussian Baltic Sea coast were standardized. However, a uniform height reference system was not introduced until 1879 (Liebsch et al. 2000). In order to be able to compare the hydrographs to each other, the water levels were related to the mean water level (MW). For this purpose, the MW of each gauge station was averaged by Baensch (1875), who estimated a maximum error of about 1 decimeter – *"an error which, in the context of such a significant water change as occurred here, only slightly blurs the happened"*. Therefore, the hydrographs were given in meter above mean water level [MW + m] and no further conversion between units was needed. In Figure 3, as an example, the hydrograph of the gauge station Travemünde with a peak water level of 332 cm above MW is presented.

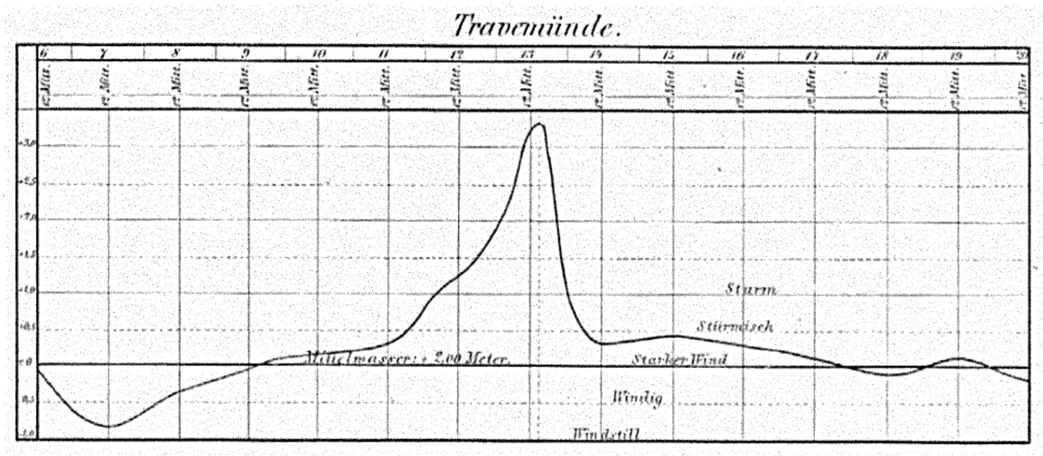

Figure 3: Hydrograph for the storm surge of 1872 according to Baensch (1875), exemplary for the gauge station of Travemünde.

The provided hydrographs are available as analog charts. So, for further analysis, the hydrographs were vectorized by using the digitizing program Didger, which is a geoprocessing toolbox for e.g. digitizing, geographic referencing, reprojection, tiling, and mosaicking. This enabled the further processing with an analysis software. For this purpose, the software Matlab® (R2020b) with the Statistics and Machine Learning Toolbox was used. The software is a high-level programming language designed for numerical calculations of matrix operations.

In Figure 4 the digitized hydrographs, color-coded and sorted by the spatial distribution along the coastline from Årøsund in Denmark to Memel in Lithuania are summarized.

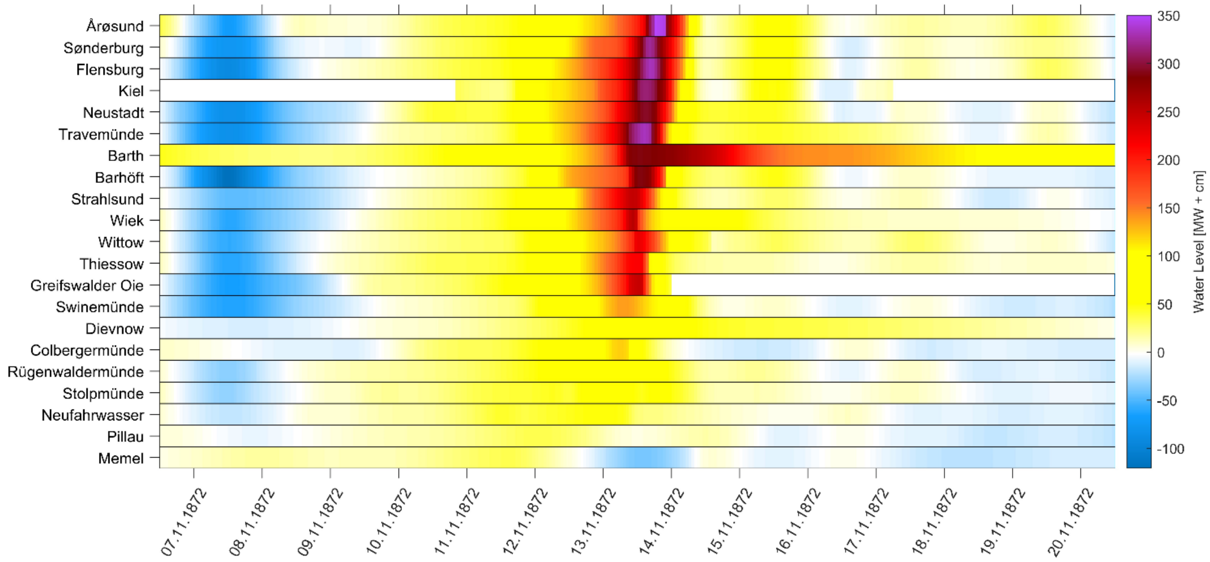

Figure 4: Summary of the hydrographs from 06.11.1872 to 20.11.1872 at the gauge stations according to Baensch (1875).

During the first phase of the event, the comparison of the hydrographs shows the influence of the westerly storm that occurred from November 7th to 8th. This caused the water to drop more than 0.5 meters below MW from Aarösund to Swinemünde. On the 8th, the water began to rise again. From November 9th to 12th water levels in the eastern part of the Baltic Sea rose considerably. On the morning of the 13th, when the storm reached its maximum intensity, the water levels west of Swinemünde exceeded 1.5 meters above mean sea level. Although the storm weakened, water levels from Kiel to Årøsund still rose, reaching their maximum of up to 3.5 meters above mean sea level. Hence, the focus of the storm surge on the southwestern coast of the Baltic Sea is clearly visible. At most gauge stations, water levels following the peak event are characterized by a rapid decrease – compared to the slower rising prior. In many areas, water levels remained higher than 2.00 meters above MW for several hours. During the whole process of the storm surge in the western part of the Baltic Sea, a neutral boundary line can be seen around Pillau, at which level there is only a slight change of water.

Compared with the nearby gauge stations, the course of the gauge station in Barth differs remarkably. An explanation can be seen in its special geographic location in the Zingst stream in the Bodden area. The Bodden area is only connected to the Baltic Sea via small channels, act as an effective low pass filter and characterizes its hydrodynamics. That means that the levelling of the water masses with the Baltic Sea can only take place slowly. Therefore, higher water levels in advance and a damping and delay of the flood peaks can be explained. Additionally, a false assumption of the MW by Baensch (1875) is possible.

Next, the hydrographs of the locations Kiel and Greifswalder Oie are particularly conspicuous. While it was reported that the Greifswalder Oie gauge was swept away by the storm surge on the evening of November 13th, it can only be guessed that the Kiel gauge staff was not read before or after the storm surge peak or that these data were not transmitted.

Next to the hydrographs in Baensch (1875), peak water level information on the storm surge exists at further locations. Furthermore, there are a large number of storm surge marks and memorial stones, which can be used to reconstruct peak water levels. The hydrographs according to Baensch (1875) partly deviate from official values (e.g. shown for Travemünde in Jensen et al. 2022). However, since the dataset in Baensch (1875) appears to be large and homogeneous it was selected as observation basis.

2.2 Model-generated water levels

Hydrodynamic tide-surge modelling employs numerical techniques to simulate water propagation, driven by tidal forces and atmospheric conditions. As such, it has been widely employed for sea level studies such as storm-surge forecasting (Fernández-Montblanc et al. 2019, Fortunato et al. 2016, Mattocks and Forbes 2008), and hindcasting (Arns et al. 2015, Haigh et al. 2014, Krien et al. 2017, Međugorac et al. 2018). While forecasting is beneficial for early warning systems in regard to extreme sea levels, hindcasts are useful for the creation of sea level data where little or none was available previously. Especially at the Baltic Sea, where extreme sea levels occur less frequently, hydrodynamic models are usefull to complement or extend time series and thus to provide a better basis for estimating the risk of occurrence, which is used to dimension coastal protection. To obtain information on water levels of the storm surge of 1872 at ungauged locations, the event was simulated using an existing hydrodynamic numerical model of the southwestern Baltic Sea (cf. van der Pol et al. 2021). The model was previously set up to simulate recent storm surges. Although the model is not perfectly suited for the calculation of historical storm surges, since necessary forcing information are missing or uncertain and thus some processes are represented incorrectly or not at all, it was decided to post-correct these missing processes by a Bias Correction.

2.2.1 Model Setup and Validation

The model used is based on the modelling Software SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model) (Zhang et al. 2016). Due to its highly flexible framework SCHISM has found a wide range of cross-scale applications worldwide, from creeks to deep oceans: general circulation (Zhang et al. 2015), storm surges (Bertin et al. 2014), tsunami hazards (Zhang et al. 2011), water quality (Wang et al. 2013), oil spill (Azevedo et al. 2014), sediment transport (Pinto et al. 2012), and biogeochemistry (Rodrigues et al. 2009). The model is being distributed as an open-source community-supported model (http://www.schism.wiki).

The applied model is based on a barotropic setup for an unstructured grid and was developed to simulate extreme sea levels along the German Baltic Sea (van der Pol et al. 2021). This is accomplished by using the Reynolds-averaged Navier-Stokes equation (RANS) in hydrostatic form with Boussinesq approximation. The use of an unstructured grid allows for varying resolutions over the model domain. High-resolution grids provide greater accuracy at the expense of computation speed, however unstructured grids allow for high accuracy in areas of interest while maintaining relatively low simulation run-times, without the need for nesting. The model grid consists of 40,951 nodes forming 68,980 triangular elements, where the element size varies from 2 km on the open sea to 300 m on the German Baltic Sea coast. The applied bathymetry was supplied by the European Marine

Observation and Data Network (EMODnet; http://emodnet.eu/bathymetry) with a resolution of 1/8-minute (0.0021°). The applied domain of the hydrodynamic Model as described is shown in Figure 5.

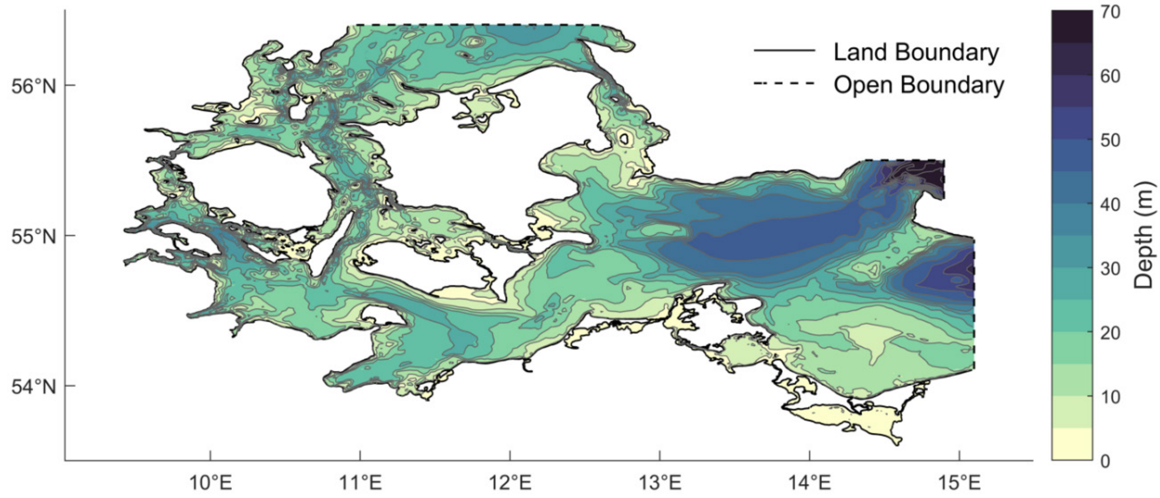

Figure 5: Bathymetry (model domain) of the used hydrodynamic Model based on SCHISM with boundary information.

For model calibration and validation, mean sea level pressures and wind velocities used for model forcing were taken from the EU project "Uncertainties in Ensembles of Regional Re-Analyses" (UERRA), which provides hourly data with an approximate resolution of 11 km (Ridal et al. 2017). The resulting wind stress is computed using the formulation of Pond and Pickard (1983).

Water levels and velocities at open boundaries were extracted from a regional ocean model of the Baltic Sea (Gräwe et al. 2019). Tide-gauge observations supplied by (Schmidt et al. 2017), who compiled a dataset of tide-gauge records of the Baltic Sea, were compared to the simulated water levels for model validation. Individual tide-gauge records are available for scientific purposes on request from local Water and Shipment Authorities and Internes Messnetz Küste (IMK) of the State Agency for Agriculture and Environment in Rostock (StALU).

To test the accuracy of simulations, modelled water levels (W_{mod}) were compared to the corresponding observational high-resolution data (W_{obs}), where available along the German Baltic Sea coast. As suggested by Krause et al. (2005), we use a combination of efficiency criteria and root mean squared error (RMSE) to asses model performance. The first efficiency criteria we measure is the index of agreement (d) as described by Willmott (1981) which gives the ratio of mean square error and potential error (Krause et al., 2005), where $0 \geq d \geq 1$ and d = 1 denotes perfect agreement and d = 0 denotes no agreement:

$$d = \frac{1-\sum_{i=1}^{n}\left|W_{obs,i}-W_{mod,i}\right|^2}{\sum_{i=1}^{n}\left(\left|W_{mod,i}-\overline{W_{obs}}\right|+\left|W_{obs,i}-\overline{W_{obs}}\right|\right)^2} \quad (1)$$

Similarly, we also use the coefficient of determination (r2) which is simply the squared value of the coefficient of correlation (Krause et al. 2005):

$$r^2 = \left\{\frac{\sum_{i=1}^{n}(W_{mod,i}-\overline{W_{mod}})(W_{\mathrm{obs},i}-\overline{W_{obs}})}{\sqrt{\sum_{i=1}^{n}(W_{obs,i}-\overline{W_{obs}})^2}\sqrt{\sum_{i=1}^{n}(W_{mod,i}-\overline{W_{mod}})^2}}\right\}^2 \quad (2)$$

Lastly, we compare absolute error using RMSE, and measure the accuracy of peak water level simulation by measuring the percentage of maximum observed water level (peak %) realized in simulations. These values are calculated as follows:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(W_{obs,i} - W_{mod,i}\right)^2} \tag{3}$$

$$peak\ \% = \left(\frac{\max(W_{mod})}{\max(W_{obs})}\right) \cdot 100 \tag{4}$$

For calibration and validation simulations four storm surge events, occurred in January 1987, November 1995, February 2002 and November 2006, were chosen due to their widespread influence along the German Baltic Sea coast. Bottom friction was controlled using a constant Mannings roughness coefficient, which was determined based on a number of sensitivity simulations. A final Mannings roughness coefficient of 0.19 was found to provide the most accurate results. Validation statistics at the tested tide-gauges are provided in Table 2.

Table 2: Validation statistics of final model setup. For each tide-gauge, statistics are given as the mean value of statistics calculated from each calibration simulation. Also provided is the number of calibration simulations (#) where comparisons between observed and modelled sea levels were possible. Missing comparisons are due to the absence of observational data during calibration simulations. Asterisks (*) denote a Bodden tide-gauge record.

Gauge station	#	d	r2	RMSE (cm)	Peak %	Gauge station	#	d	r2	RMSE (cm)	Peak %
Timmendorf	4	0.97	0.94	8.90	102	Neustadt	3	0.97	0.95	9.49	104
Wismar Baumhaus	4	0.98	0.95	8.01	100	Travemünde	4	0.97	0.95	9.24	106
Dierhagen*	1	0.95	0.93	7.58	114	Greifswald Wieck	4	0.97	0.94	8.74	107
Althagen*	4	0.95	0.93	9.17	113	Lauterbach	4	0.98	0.94	7.36	101
Barth*	4	0.95	0.93	9.43	112	Greifswalder Oie	2	0.97	0.94	7.61	101
Zingst Bodden*	4	0.95	0.93	9.21	108	Greifswald Eldena	4	0.98	0.94	8.67	107
Marienleuchte	3	0.98	0.94	7.92	101	Karnin*	4	0.96	0.95	6.81	105
Göhren	2	0.98	0.95	6.03	99	Karlshagen*	3	0.97	0.95	6.77	107
Sassnitz	4	0.98	0.95	5.94	99	Peenemünde*	3	0.98	0.95	6.25	103
Thiessow	4	0.98	0.95	6.59	101	Wolgast*	4	0.97	0.95	6.90	110
Kamminke*	1	0.95	0.96	6.31	111	Schaprode*	1	0.98	0.92	5.38	103
Ueckermuende*	4	0.97	0.96	6.51	108	Neuendorf Hafen*	4	0.98	0.95	6.25	107
LT Kiel	3	0.97	0.94	9.82	103	Stahlbrode*	3	0.97	0.93	8.96	105
Kiel-Holtenau	4	0.98	0.94	9.43	101	Stralsund*	4	0.98	0.95	7.32	101
Heiligenhafen	3	0.97	0.94	9.09	103	Wittower Fähre*	4	0.98	0.95	5.14	107
Eckernförde	3	0.97	0.94	10.37	104	Ralswiek*	4	0.96	0.94	7.52	110
Schleimünde SP	3	0.97	0.94	10.20	103	Glewitz*	1	0.98	0.95	5.73	95
Flensburg	4	0.97	0.94	10.48	103	Kloster*	4	0.97	0.93	7.60	107
LT Kalkgrund	3	0.97	0.93	10.55	102	Neuendorf Ostsee	2	0.97	0.96	6.61	95
Langballigau	3	0.97	0.93	11.00	101	Rostock	3	0.97	0.94	9.32	103
Koserow	4	0.98	0.94	6.26	99	Warnemünde	4	0.98	0.95	7.56	105
Ruden	3	0.98	0.97	5.62	98	Barhöft*	3	0.97	0.94	5.85	106

Compared to the observed storm surges, the validation simulations showed good results ($d \geq 0.95$; $r^2 \geq 0.92$; RMSE $\leq$ 10 cm; 99 $\leq$ peak % $\leq$ 114) at all gauge stations. This indicates that the model is basically suitable for the simulation of (recent) storm surges. Although the model is not perfectly suited for the calculation of historical storm surges, we decided to use the model for a simulation of the storm surge in 1872.

2.2.2 Hydrodynamic Simulation of 1872

A challenging task of the simulation of events that occurred a long time ago, is the model forcing, since information are missing. The 20th Century Reanalysis Project, which is an effort led by NOAA's Physical Sciences Laboratory (PSL) and CIRES at the University of Colorado, supported by the Department of Energy (DOE), provides a data set for meteorological forcing from the years 1836 to 2015. The 20CR project has generated a four-dimensional global atmospheric dataset of weather to place current atmospheric circulation patterns into a historical perspective (NOAA 2023). The most recent version of this reanalysis (V3), provides 8-times daily estimates of global tropospheric variability across ~75 km grids. These reanalyses assimilate surface observations of synoptic pressure into NOAA's Global Forecast System, and prescribed sea surface temperature and sea ice distribution in order to estimate atmospheric variables, from the surface to the top of the atmosphere. For V3, a set of 80 analyses was calculated for each parameter. As meteorological forcing a *3h ensemble mean* was used, which represents a *very likely state* of the global atmosphere (NOAA 2023). Since it is open source and covers a large time span, it was a good opportunity to test the dataset. An alternative meteorological dataset, specifically of the storm surge of 1872, was elaborated by the work of Rosenhagen and Bork (2009).

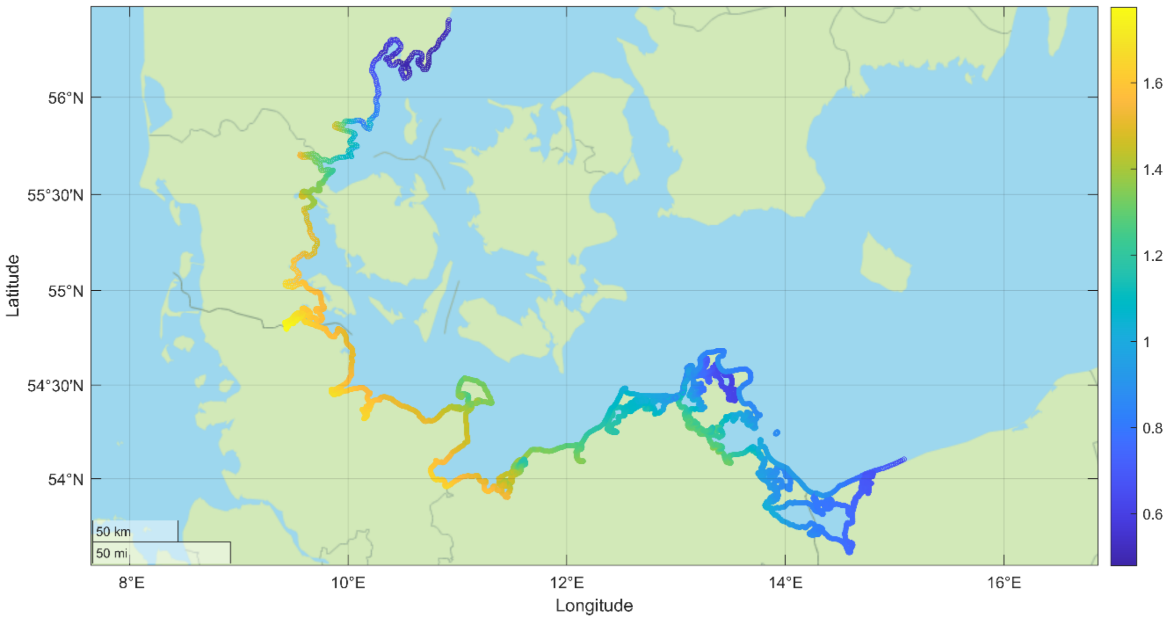

Figure 6: Peak water levels of the model-generated data of the storm surge 1872.

At the open boundaries there is a lack of information, e.g. a back flowing of piled-up water in the eastern Baltic or the prefilling state. But since the storm surge was mostly caused by a hurricane-force wind, the local wind accumulation on the flat coasts is more important than the water flowing and its later effect on the peak water levels. Nevertheless, an error is to be expected.

The model generated data in hourly resolution for a period between 01.11.1872 – 7.00 o'clock and 01.12.1872 – 0.00 o'clock. For the investigation, water levels along the coastline from Denmark to Poland were further investigated. The results were related to mean water level by subtracting the corresponding computed still water level at each point, making them comparable to the hydrographs from Baensch (1875). In Figure 6 the peak water levels at the coastline of the model generated data in the study area are shown.

With peak water levels of a maximum of about 1.70 m above MW, the model-generated water levels are far below the observed water levels. This finding is valid in a similar order for the whole coast. The 15 of the total 21 hydrographs in Baensch (1875) that fit in the model area can be compared with the model-generated hydrographs. Differences between observed water levels W_{obs} and model generated water levels W_{mod} are called model errors or *bias*.

In Figure 7, the model-generated water level hydrograph of the water level reconstructions is compared to the observed one at Travemünde gauge station.

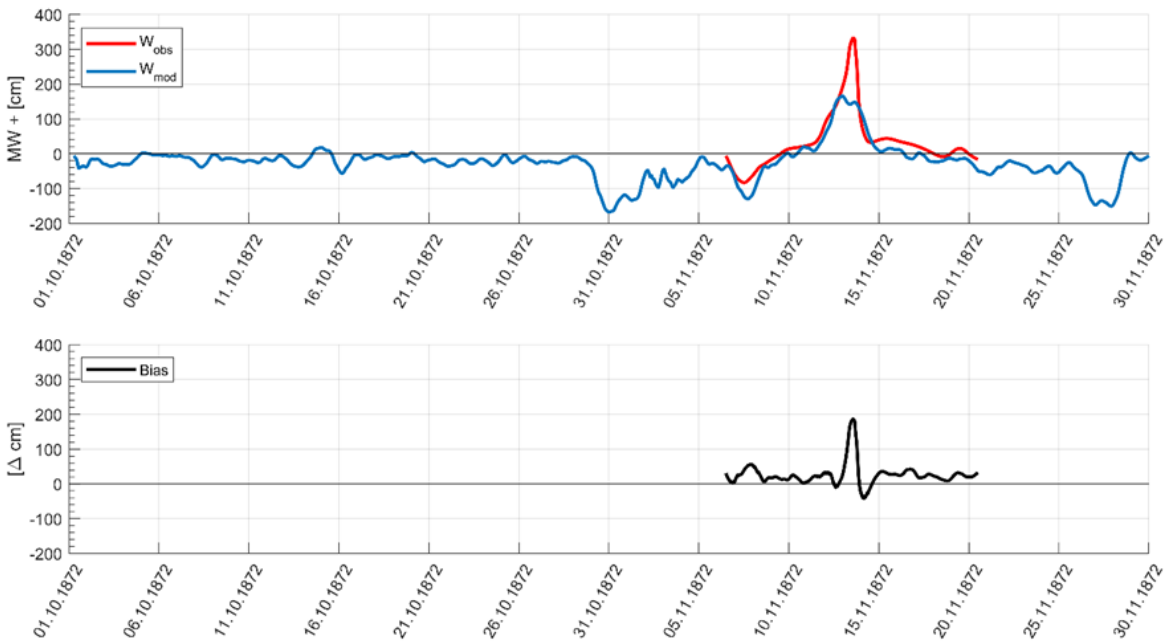

Figure 7: Comparison of the model-generated hydrograph with the water level hydrograph according to Baensch (1875) for Travemünde gauge. In addition, the bias between the hydrographs is shown below.

Even if the simulated hydrograph shows some similarity to the observed water levels, the peak water level shows an especially large difference. Table 3 compares the peak values of the model-generated water level hydrographs ($W_{mod,max}$) with the peak values of the observed hydrographs according to Baensch (1875)($W_{obs,\ max}$) at the evaluated gauge stations.

Table 3: Comparison of the maximum model-generated water levels with the observed peak water levels according to Baensch (1875) during the storm surge of November 12th/13th, 1872.

Gauge station	$W_{obs,\,max}$ [MW + cm]	$W_{mod,\,max}$ [MW + cm]	ΔW_{max} [Δm]
Årøsund	350	150	200
Sønderborg	324	154	170
Flensburg	333	178	155
Kiel	315	164	151
Neustadt	293	159	134
Travemünde	332	166	166
Barth	288	116	172
Barhöft	289	114	175
Stralsund	249	128	121
Wiek	253	69	184
Wittow	226	85	141
Thiessow	217	94	123
Greifswalder Oie	247	87	160
Swinemünde	139	93	46
Dievenow	85	68	17

The large differences between model-generated data and observed data can probably be explained by the following causes/processes:

- Spatial resolution of the input conditions, e.g. wind fields, are not adequate to accurately represent local effects.
- Uncertainties in estimation of input and initial conditions, such as wind conditions and prefilling state.
- Lack of information at the open boundaries.
- Spatial extension is not adequate to calculate the wind surge in total.
- Wind conditions were extrapolated by models and represent a mean of different ensembles; extreme storm surges of this magnitude tend to be underestimated.
- Uncertainties in observed water levels or wrong estimated mean water levels by Baensch (1875).
- Spatial information of the model setup, e.g. bathymetry and coastline, are stationary and does not represent the former state.
- Missing modelling of local processes, like overtopping or bursting of dikes/dunes, especially in the Bodden area.

The accurate simulation of extreme water levels is a challenging task in every simulation, which often can only be solved with compromises. The Bias Correction provides an option to tolerate and correct errors later on. Therefore, the differences between the model data and the water level data are used for further processing without a new calibration or setup of the model.

2.3 Bias Correction

Scientific models are described, e.g. in the Brockhaus Encyclopaedia, as *"a representation of nature, focusing properties that are considered essential and neglecting aspects that are seen as unimportant"*. Hence, compared to models observed water levels are subject to various influences (anthropogenic and natural), which are often only inaccurately described in simulations.

Therefore, in many cases model inaccuracies (errors) must be tolerated and described as uncertainty. Especially in extreme value statistics, even small inaccuracies can lead to large discrepancies in the calculated return intervals (MacPherson et al. 2019). To obtain model results that satisfy high qualitative criteria, a Bias Correction (also known as Climate Model Bias Correction CMBC) can be post-proceeded to the simulation, e.g. as shown in Arns et al. 2013 and 2015.

The *bias,* represents the difference between observed water levels (W_{obs}) (expectation) and model generated water levels (W_{mod})(estimation), which describes an error function of the model-generated data at each gauge station. The bias indicates neglected physical relationships, primarily caused by the internal parameterization of the model and the sensitivity to the external boundary conditions (Arns et al. 2013). Here the reconstructed (observed) water levels by Baensch (1875) serve as expectation. Hence, the Bias Correction function Bc_j of each j^{th} reference gauge station results from the difference of the observed hydrograph ($W_{obs,j}$) and the model-generated hydrograph ($W_{mod,i}$) at the corresponding location i at the coincident time steps. Therefore, the Bias Correction is limited by the available time of observation, which is a severe restriction in this case (compare to Figure 7).

$$Bc_j = W_{obs,j} - W_{mod,i} \tag{5}$$

By adding the bias to the incorrect model-generated data, the error function can be seen as a correction function. Thus, a corrected hydrograph ($W_{corr,j}$) at each reference gauge station j can be determined. The corrected hydrograph corresponds to the observed water levels and thus can be considered error-free.

$$W_{corr,j} = W_{mod,j} + Bc_j = W_{obs,j} \tag{6}$$

However, the transfer function for the intervals between the reference gauge stations cannot be determined by this. Therefore, for each intermediate point the Bias between the reference gauge stations can be interpolated using inverse distance weighting (IDW). Due to IDW, a weight is assigned to each reference location based on its distance d_i from the point i being interpolated. In contrast to linear interpolation, IDW interpolation explicitly assumes that sites that are close together are more similar to each other than sites that are more distant to each other.

A power value p can be used to influence the weighting of the distance. The higher the power value is, the less distant reference locations are included in the calculation and the closer, more similar locations are weighted. A power value of $p=0$ eliminates the influence of the distance and leads to the arithmetic mean. Mathematically, there is no reason for the choice of the power value.

Since the reference stations are located with different distances from each other, the choice of a "*correct"* power value p is challenging and to some point a subjective task. To obtain the weighted influence of IWD, it was decided to assume $p=1$ for the entire model area.

Using this approach, a Bias Correction function (Bc_i) of each i^{th} point on the coastline can be calculated by the sum of inverse distance weighted Bias Correction functions of each reference gauge station.

$$Bc_i = \frac{\sum_{j=0}^{n}\left(\frac{1}{d_j}*Bc_j\right)^p}{\sum_{j=0}^{n}\left(\frac{1}{d_i}\right)^p} \tag{7}$$

Finally, a corrected hydrograph $W_{corr,i}$ at each point i^{th} on the coastline can be calculated.

$$W_{corr,i} = W_{mod,i} + Bc_i \tag{8}$$

Due to the IDW, the power of the correction function is mainly influenced by the proximity and amount of reference gauges. The interpolation between the gauge stations assumes that effects that lead to incorrect calculations also occur at the neighbouring points (Arns et al. 2013). In order to consider local effects in the correction, it is important to create homogeneous conditions between the point to be interpolated and the reference stations to be included in the calculation. In the case of the Baltic Sea, the different shape of the coastline poses a special challenge. In the fjords and bays an accumulating effect can lead to an increase of peak water levels, whereas in the inner area of the Bodden and Haff coast, the dunes and spits in front of the coast can lead to an attenuation and delay of the water levels. Likewise, different water levels and an increased duration of damming can be expected due to the impeded inflow and outflow in the Bodden/Haffs. Interpolation between gauges of different coastal shapes would skew the correction function. Therefore, the coastline of the model was divided into two parts and both parts were processed separately One part is the outer coast including the bays and firths (orange), which is directly exposed to the storm surge, the other part is the Bodden and Haff coast (blue).

In Figure 8 the division of the coastline and corresponding reference gauges is shown.

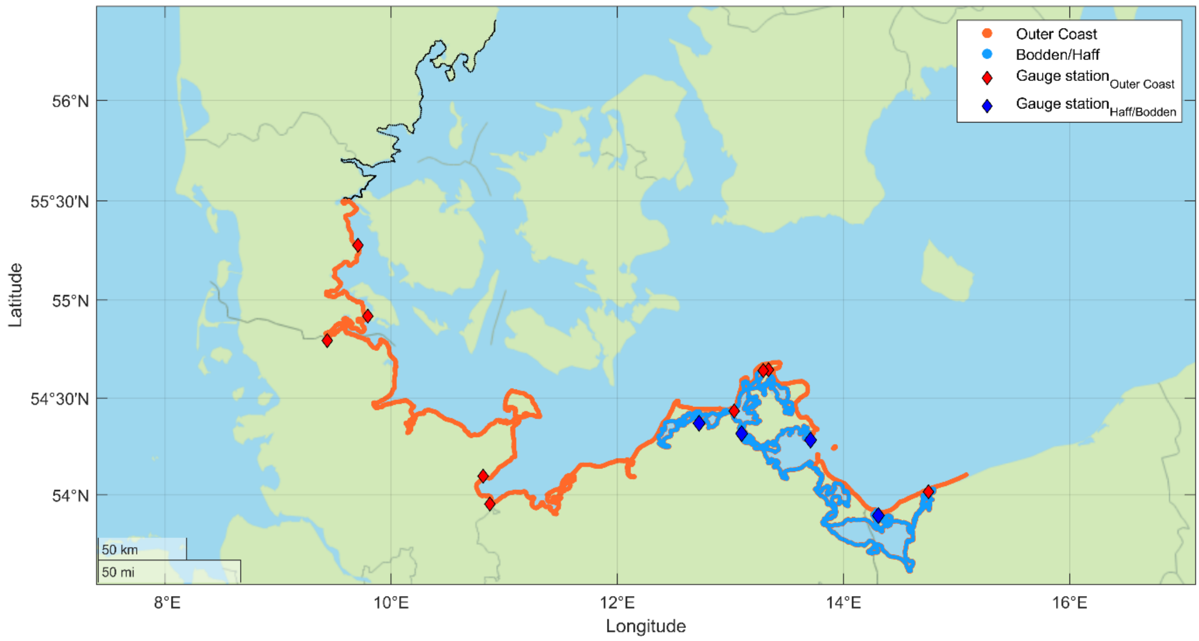

Figure 8: Visualization of the division of the coastline into two parts to respect the local conditions for statistical correction of the model data, including the distribution of the associated reference gauge stations used for Bias Correction.

By interpolation, the study area is limited by the spatial distribution of the reference gauge stations along the coastline. To reduce uncertainties due to extrapolation, the model domain had to be clipped by the spatial extension of the reference gauge stations.

For further calculations, only gauging stations with complete hydrographs are included. Therefore, the records of the gauges Kiel and Greifswalder Oie are omitted as reference gauges. In the further processing, however, these are used for the validation of the results, so that these valuable data can also be used.

With the assumptions described, the model generated water levels at each point on the coastline were corrected by the IDW Bias Correction. This provided a homogeneous data set for the coastline where the bias at the reference gauge stations could be eliminated successfully. The peak values of the corrected, model-generated water levels are shown in Figure 9.

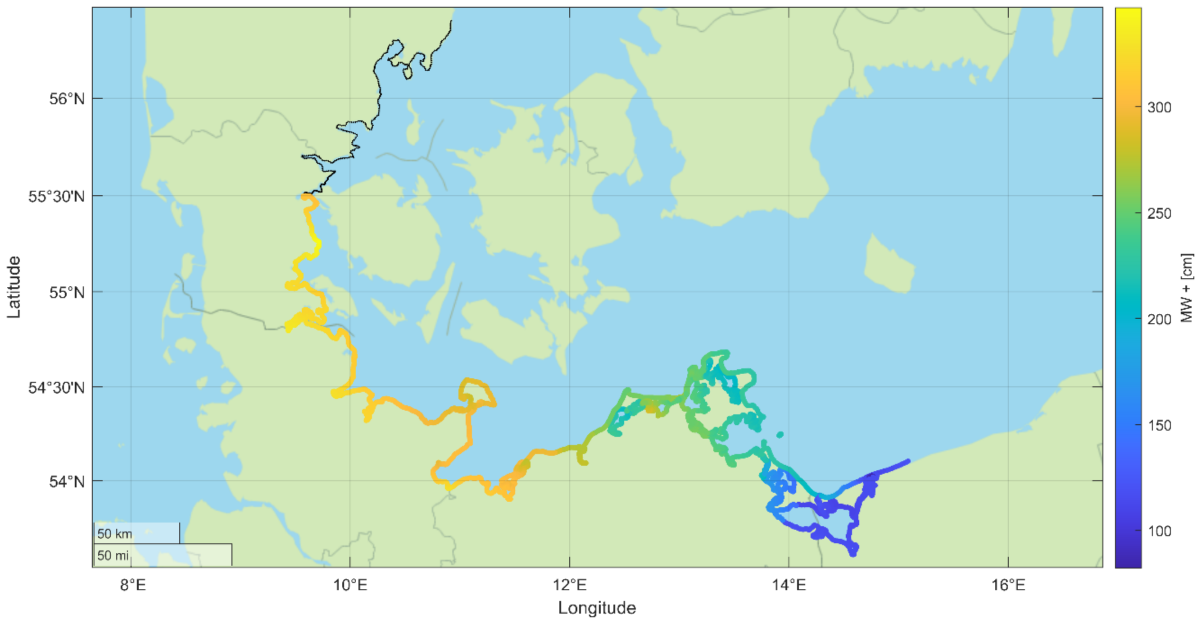

Figure 9: Peak water levels of the corrected, model-generated water levels along the Baltic Sea.

By using both, a process-based, model generated and a statical, data-driven model, a semi-hydrodynamic, semi-statistical data set was generated, that takes both the local effects by the simulation and the water levels of the observation into account. The assumptions made must be validated in a further step.

3 Validation

The plausibility of the assumptions made with Bias Correction, IDW and the dividing of the coastline needs to be checked in a concluding validation. In order to check the validity, corrected hydrographs can be compared with the observed hydrographs at gauge stations with incomplete data series, that were excluded from the set of reference gauge stations. In Figure 10 the incomplete observed hydrographs of Kiel and Greifswalder Oie from Baensch (1875) are compared with the corrected, model-generated hydrographs at the corresponding points on the coastline.

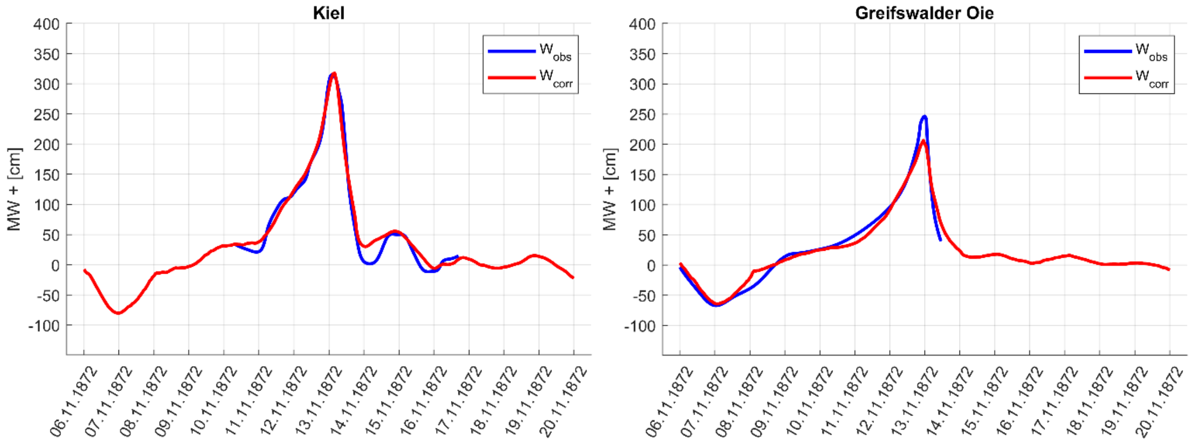

Figure 10: Comparison between corrected and measured hydrograph at the two gauges Greifswalder Oie and Kiel, to validate the assumptions made with the invers-distance weighted Bias Correction.

The corrected model-generated hydrographs show some deviations compared to the observed hydrographs. While the peak value at the Kiel gauge shows good agreement and significant deviations occurred only after the peak value was exceeded, the peak value at the Greifswalder Oie gauge was underestimated by about 40 cm. This is probably explained by the exposed position of the island, which is not represented well by an interpolation from the coast. Nevertheless, the deviations can also be explained by incorrect observations, which are possible with historical information.

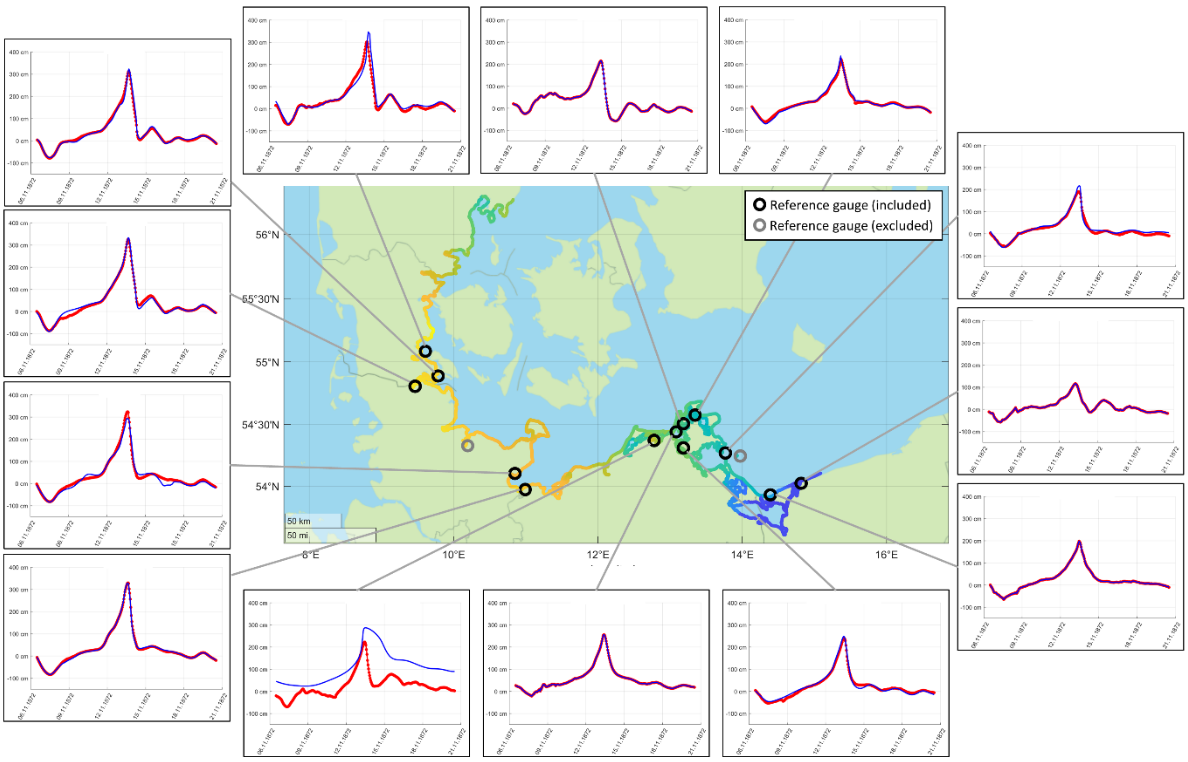

Figure 11: New generated hydrographs at the reference gauge stations as a result of validating the assumptions made with the Bias Correction by removing reference values from the collective.

In a next step of validation, step by step one reference gauge is taken from the collective of reference gauges as the transfer function is generated without the removed gauge station.

At the location of the removed gauge, the simulated hydrograph was then corrected by the corresponding interpolated transfer function and compared with the measured hydrograph of the validation gauge. The resulting difference between the newly interpolated and the measured water levels indicates the transferability of the Bias Correction. If there are large differences between the hydrographs, it can be assumed that there is a general uncertainty in the correction and more reference levels are needed for a reliable correction (Arns et al. 2013).

In Figure 11, the new created hydrographs for validation are compared with the observed hydrographs.

Only small uncertainties appear as differences between the new generated hydrograph for validation and the observed hydrographs appear at most gauge stations. Besides uncertainties in the correction, the differences can also be caused due to measurement errors in the observed hydrographs. The gauge station in Barth once again stands out due to its special spatial location in the Darß-Zingster Bodden area. Since no other reference gauge represents the specific local effects and preconditions, the validation at this gauge station shows a large difference. The large discrepancy at this gauge station can be a result of a missing simulation of local processes, e.g. modelling of dike breaks as documented, or an error in the observed hydrographs by Baensch (1875). This demonstrates the limits of the applied Bias Correction and the importance of having reference gauges that are distributed at representative sites. Therefore, the Barth gauge is of special importance for the correction in the Darß-Zingster Bodden area.

In general, sections with special local effects, such as the exposed location of the island Greifswalder Oie and the mostly isolated location of the gauge station in Barth, the correction showed some uncertainty, which has to be respected in the validation. Nevertheless, the validation proves that the bias can be reduced using the IDW interpolation at most of the gauged stations in a relatively robust way. It can be assumed that also at ungauged sites, where no comparison to measured water levels is possible, the Bias Correction also achieves robust results. Since no major deviations occurred at most of the gauging stations during the validation, the correction performed can be considered suitable for further applications.

4 Summary and conclusion

On the southwestern Baltic Sea coast, the highest storm surge ever measured occurred during the night of November 12th to 13th in 1872, with water levels of up to 3.5 meters above mean water level. Baensch (1875) reconstructed hydrographs from staff gauge readings during the storm surge at various stations along the southwestern Baltic coast and reported them for posterity. It's important to keep in mind that this may be associated with certain uncertainties. Since the available information on water levels is only local, it is often necessary to extend the information spatially, e.g. by simulations. Since (hydrodynamic) models always represent only an image of nature with reduced complexity, compromises in accuracy are often inevitable. Especially in the simulation of extraordinary events, like extreme sea levels, which serve as a basis for the design of coastal protection strategies, high demands in accuracy are made. Therefore, the storm surge of 1872 was simulated with a hydrodynamic model of the Baltic Sea that was validated using recent storm surges. The model-generated peak water levels of the event of 1872 differed considerably from the reconstructed hydrographs. In order to optimize the model results, the *bias* as difference between observation and simulation can be corrected by an inverse distance weighted (IDW) Bias Correction, performed as post-processing to the simulation. This allows for deviations due to inaccurate/unknown boundary conditions or physical relationships neglected in modelling to be compensated for. To perform a successful Bias Correction, it is necessary to consider local effects and create homogeneous conditions between the reference gauge stations, that influence the bias correction. For this reason, the coastline in the study area was divided into areas with similar characteristics according to their geographical location.

As result, a data set of hydrographs of the storm surge was created whose uncertainties were determined in the validation to be within a few centimetres at most gauged stations. Therefore, a robust result can also be expected at ungauged sites. Despite the large Bias of the model generated data, the approach of IDW Bias Correction, post-proceeding to the hydrodynamic simulation, was convincing and was used as a tool to further optimize model results that can satisfy the high criteria in accuracy demanded. To reduce the uncertainties further, model-generated data with smaller bias can be used. Therefore, an improvement, or more suitable hydrodynamic model for historical events is recommended.

Nevertheless, there is the risk of unknown observation errors being included in the correction and leading to an inappropriate correction. Particularly with historical information, a certain inaccuracy must always be assumed, which results on the one hand from imprecise measurement technology, but also from transmission errors. Therefore, a careful verification of the measured values is essential in advance. In addition, a validation including plausibilization of the results, e.g. similar as shown, is recommended. As a next step, the results could be cross-checked against other available water level information, such as storm surge marks, to further assess the accuracy of the results. Since different sources provide different water levels this is often only possible with an uncertainty of several decimetres. Therefore, it is not possible to determine the height of the storm surges with certainty.

A statistical approach to safety-design coastal protection structures, is only justified if the preconditions of statistics are fulfilled. In practice, this is rarely the case, since time series are usually too short, subject to errors, and not stationary. While stationarity can be achieved by removing a significant trend (e.g. Mean Sea Level Rise), the length of time-series is a task hard to handle. Therefore, the use of information that extends the time series is recommended to improve the reliability. The approach seems to be suitable to spatially and temporally extent information at gauge stations with missing high-water levels or ungauged sites, by using the available water information of related stations or storm surge marks in combination with meteorological reanalyses. The used NOAA meteorological dataset, with several ensemble members for the period of 1836 to 2015, can be used by this way for such further simulations of historical events about which there is little water level information, such as 1837, 1891 and 1905 (cf. Jensen et al. 2022). Whether the approach and dataset (ensemble member) are applicable to other storm surges should be considered case-by-case.

Besides the temporal and spatial extension of the information, it can be extended causally as well, e.g. by investigations of meteorological reanalyses (cf. e.g. Ganske et al 2018). Determining an extreme water level with a certain probability of occurrence less from a statistical, but mainly from a hydrological (causal) perspective, is summarized by the term "extreme value hydrology" (in contrast to "extreme value statistics") (Blöschl and Merz 2008). By integrating additional information (temporal, spatial and causal), an improvement of the decision basis can be achieved and appropriate decisions for coastal protection measurements or disaster management can be taken. In contrast, disregarding data is considered a waste of valuable, possibly safety-design relevant information.

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