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Best estimates for historical storm surge water level and MSL development at the Travemünde/Baltic Sea gauge over the last 1,000 years

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Summary

The protection of human life against flood events is an important task of public interest, especially in times of climate change. For this purpose, the robust design of flood protection structures (e. g. dikes and dams), as well as flood and disaster management are of great importance. Therefore, high-quality hydrological time series (e. g. water levels, discharges) as well as information about water levels of historical storm surges are needed, e. g. to derive design values and assigned probabilities of occurrence using extreme value statistical approaches. Existing methods for dimensioning coastal protection structures are based on the evaluation of systematic recordings (e. g. water levels, discharges), which are usually only available on the German Baltic Sea coast for the last decades.

Floods and storm surges are natural events that have always posed a threat to life on the coast and may also cause great damage in the future due to the more intensive use of coastal space and the consequences of climate change. In the past centuries, these extreme events have repeatedly caused catastrophic floods in inland as well as coastal areas and, as a consequence, many fatalities and enormous damage in Germany. The devastating Baltic Sea storm surge of November 12/13, 1872, in which 277 people lost their lives, led to the highest water levels ever recorded on the German Baltic Sea. In this context, the question arises whether the Baltic Sea storm surge of 1872 is representative for coastal protection or has a singular and consequently not design-relevant character.

Therefore, the aim of this study is the compilation and evaluation of historical storm surge water levels over the past 1,000 years at the German Baltic Sea coast with special regard to the gauge Travemünde. Taking into account the mean sea level rise (MSLR) and the different gauge datums or different height reference systems, a homogeneous and comparable time series of storm surge water levels is provided for the Travemünde gauge, related to the current mean sea level (MSL) in 2020, as a basis for the design of coastal protection structures.

For the last 1,000 years, the development over time of the MSL („Best Estimate") was reconstructed; over this period, the MSL has risen by about 70 cm by the year 2020. At Travemünde gauge, based on 19-year averages, MSL reached NHN ±0 cm at 1960/61; based on a linear MSLR, the intercept with NHN ±0 cm is about 1972/73. In 2020, MSL reaches a height of about NHN+8.5 cm. In the course of climate change, a significantly higher MSLR can be assumed in the future.

The storm surge of 1872 also reached the highest water levels in the context of the historical storm surges of the last 1,000 years at Travemünde gauge and almost at the entire German

Baltic Sea coast (at Travemünde gauge at NHN+3.14 m in the fairway and +3.29 m at the nearby Vogtei). However, by detrending the MSL changes, the often-presented singularity of this storm surge cannot be confirmed. The maximum water levels of the storm surges of 1320 and 1625 may have been only 1 to 5 decimeters lower in relation to MSL_{2020} than the corresponding water levels of the storm surge of 1872. Until today, the water levels of all storm surges after 1872 have been more than 1 m lower than those of the storm surge of 1872. The devastating storm surge of 1872 should continue to be used as a reference for coastal protection on the Baltic Sea coast, regardless of the „appropriate" safety (return period) for which coastal protection on the Baltic Sea is designed. A clear recommendation which maximum peak water level (NHN+3.14 m or +3.29 m) at the storm surge of 1872 should be used for statistical analyses of the time series for the Travemünde gauge cannot be given. To avoid a possible underestimation, the higher value should be used in statistical analysis. Flood and disaster management should definitely assume water levels similar to the storm surge of 1872, plus MSLR.

Keywords

Baltic Sea, Travemünde, storm surge, detrending, MSL, ESL, DSL, 1872

Zusammenfassung

Der Schutz der Menschen vor Hochwasserereignissen ist eine wichtige Aufgabe der Daseinsvorsorge, insbesondere in Zeiten des Klimawandels. Dazu ist die robuste Bemessung von Hochwasserschutzbauwerken (z. B. Deiche und Dämme), sowie das Hochwasser- und Katastrophenmanagement von großer Bedeutung. Für diese Aufgabe werden nicht nur qualitativ hochwertige hydrologische Zeitreihen (z. B. Wasserstände, Abflüsse) benötigt, sondern auch Wasserstände von historischen Sturmfluten, um z. B. mit extremwertstatistischen Ansätzen Bemessungswerte und zugeordnete Eintrittswahrscheinlichkeiten abzuleiten. Aktuelle Methoden zur Bemessung von Küstenschutzbauwerken basieren auf der Auswertung von systematischen, qualitativ hochwertigen Pegelaufzeichnungen, die in der Regel für die deutsche Ostseeküste nur für die letzten Jahrzehnte vorliegen.

Hochwasser und Sturmfluten sind Naturereignisse, die schon immer eine Bedrohung für das Leben an der Küste darstellten und auch zukünftig aufgrund der intensiveren Nutzung des Küstenraumes und den Folgen des Klimawandels große Schäden verursachen können. Diese Extremereignisse haben in den vergangenen Jahrhunderten sowohl im Binnen- als auch im Küstenbereich immer wieder zu katastrophalen Überschwemmungen und in der Folge zu vielen Todesopfern und enormen Schäden in Deutschland geführt. Die verheerende Ostseesturmflut vom 12./13. November 1872, bei der 277 Menschen ums Leben kamen, hat zu den höchsten Wasserständen an der deutschen Ostseeküste geführt, die jemals beobachtet wurden. Insofern stellt sich die Frage, ob die Ostseesturmflut von 1872 für die Bemessung von Küstenschutzbauwerken maßgebend ist oder einen singulären und damit nicht bemessungsrelevanten Charakter hat.

Ziel dieser Bearbeitung ist deshalb die Zusammenstellung und Aufbereitung von historischen Sturmflutwasserständen über die vergangenen 1000 Jahre an der deutschen Ostseeküste mit Fokus auf den Pegel Travemünde. Unter Berücksichtigung des Meeresspiegelanstiegs und der verschiedenen Pegelnullpunkte bzw. unterschiedlicher Höhenreferenzsysteme wird für den Pegel Travemünde eine homogene und vergleichbare Zeitreihe von Sturmflutwasserständen, bezogen auf den aktuellen Meeresspiegel im Jahr 2020, bereitgestellt. Für die letzten 1000 Jahre wurde dazu der zeitliche Verlauf des MSL-Anstiegs („Best Estimate") rekonstruiert; über diesen Zeitraum ist der mittlere Meeresspiegel (MSL) bis zum Jahr 2020 um etwa

70 cm angestiegen. Am Pegel Travemünde erreichte der MSL auf Basis von 19-jährigen Mittelwerten zum Zeitpunkt 1960/61 die Höhe NHN ±0 cm; auf Basis eines linearen MSL Anstiegs ist der Schnittpunkt mit NHN ±0 cm etwa im Jahr 1972/73. Im Jahr 2020 erreicht der MSL eine Höhe von etwa NHN +8,5 cm. Im Zuge des Klimawandels ist zukünftig von einem deutlich beschleunigten MSLR auszugehen.

Die Sturmflut von 1872 hat auch im Kontext der historischen Sturmfluten der letzten 1000 Jahre am Pegel Travemünde und fast an der gesamten deutschen Ostseeküste zu den höchsten Wasserständen geführt (am Pegel Travemünde zu NHN +3,14 m im Fahrwasser bzw. +3,29 m an der nahen Vogtei). Durch eine MSL-Trendbereinigung kann die oft dargestellte Singularität dieser Sturmflut im Vergleich zu historischen Sturmfluten aber nicht bestätigt werden. Die maximalen Wasserstände der Sturmfluten von 1320 und 1625 dürften bezogen auf den MSL_{2020} *nur 1 bis 5 Dezimeter geringer als die entsprechenden Wasserstände der Sturmflut von 1872 aufgelaufen sein. Bis zum heutigen Datum sind die Wasserstände bei allen Sturmfluten nach 1872 über 1 m geringer aufgelaufen als bei der Sturmflut 1872. Die verheerende Sturmflut von 1872 sollte weiterhin als Referenz für den Küstenschutz an der Ostseeküste herangezogen werden, unabhängig davon, auf welche „angemessene" Sicherheit (Wiederkehrzeit) man den Küstenschutz an der Ostsee auslegt. Eine eindeutige Empfehlung welcher maximaler Scheitelwasserstand (NHN +3,14 m oder +3,29 m) bei der Sturmflut von 1872 für statistische Analysen der Zeitreihe für den Pegel Travemünde genutzt werden sollte, wird nicht gegeben. Um aber eine mögliche Unterschätzung zu vermeiden, sollte der höhere Wert genutzt werden. Das Hochwasser- und Katastrophenmanagement (bzw. Gefahrenabwehr) an der Ostseeküste sollte von möglichen Wasserständen ähnlich der Sturmflut 1872, zuzüglich des Meeresspiegelanstiegs, ausgehen.*

Schlagwörter

Ostsee, Travemünde, Sturmflut, homogenisieren, MSL, ESL, DSL, Sturmflut 1872

1 Introduction

With more than 85 million people living around the Baltic Sea region, where 15 million people live within only 10 kilometers of the shores (Elmgren et al. 2015), the monetary value of the Baltic Sea rose over the years with increased agricultural, industrial and tourist use. The Baltic Sea region is also considered one of the most important seas in Europe as it surrounded by eight of 28 European countries. Unfortunately, the Baltic Sea has been always exposed to the risk of storm surges (Baensch 1875, Jensen and Töppe 1990, Jensen and Müller-Navarra 2008, Hupfer 2010).

Floods and storm surges are natural events that have always posed a threat to life and property on the coast (Ellis and Sherman 2014) and may also cause great damage in the future due to the more intensive use of coastal areas and the consequences of climate change. In the past centuries, these extreme events have repeatedly led to catastrophic floods in both inland and coastal areas and, as a result, to many fatalities and enormous damage in Germany. Devastating storm surges, e. g. in 1362, 1634 and 1717 on the North Sea coast and in 1320, 1625 and 1872 on the Baltic Sea coast, led to the greatest catastrophes in northern Germany in the past 1,000 years, along with wars and epidemics, and changed the coastline and the islands many times. The earliest reliable record of an extreme storm surge at the Baltic Sea dates from 1044 AD (Jensen and Töppe 1990). The three flood disasters with the highest number of fatalities in the past 150 years include the flood disaster in July 2021 in western Germany with about 190 fatalities, the storm surge on the North Sea coast of 16 February 1962 (the so-called Hamburg flood) with over 300 fatalities, and the devastating Baltic storm surge of 12/13 November 1872.

The most severe flood event on the Baltic Sea since records began occurred in November of 1872 as sea levels reached heights never seen before. By reviewing old studies and archives, we found inconsistencies among several authors, as they did not agree on a uniform height value for this storm surge. For example, the extreme sea level (ESL) reached at Travemünde gauge ranges from 332 cm above MSL (Baensch 1875) to 340 cm above MSL (Petersen and Rohde 1990, MELUR 2013).

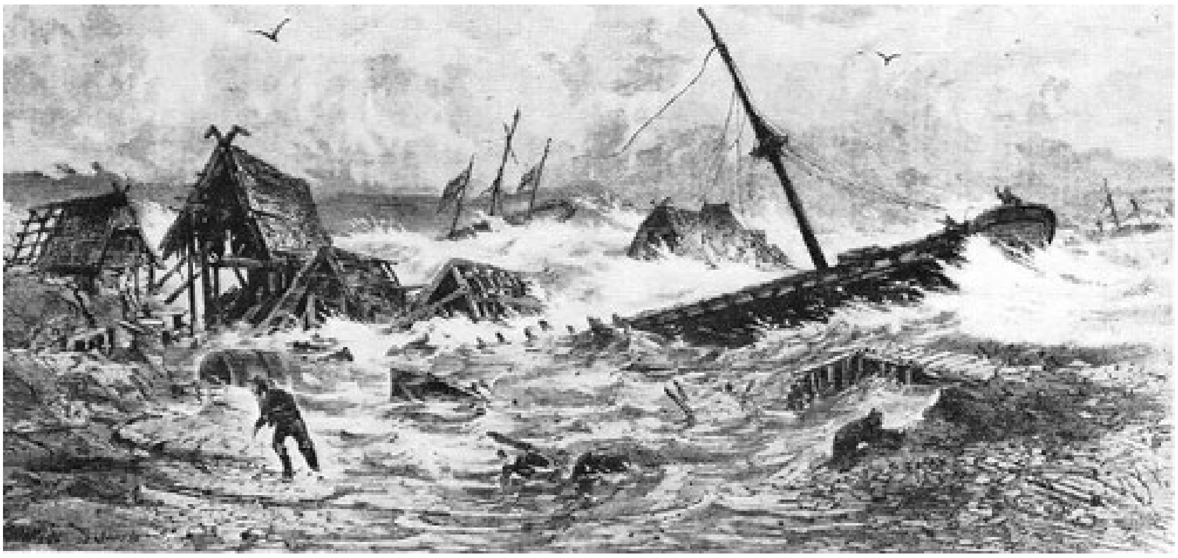


Figure 1: The damage caused in Haffkrug located at Lübeck Bay/German Baltic Sea Coast during the storm surge of November 1872 (Illustration: C. Rettich und C. Heyn).

This catastrophic flood was caused by a severe storm surge induced by strong northeasterly and easterly winds that blew across the southern part of the Baltic Sea and resulted in massive damage on the Danish, German, and Swedish Baltic Sea coast (see Figure 1). Total number of deaths was estimated to be about 279 (e. g. Kiecksee 1972), including one hundred in Denmark, 63 in Germany, five in Sweden and 109 drowned at sea. In Schleswig-Holstein alone, 15,160 people were in need of help, 2,850 buildings were destroyed or severely damaged, 31,500 hectares of land were flooded so that supplies and crops were rotted and wells were full of salt water. The death and damage toll made this event one of the major international natural disasters in the southern Baltic Sea (Hallin et al. 2021). Sea levels and winds from 10.11.1872 to 16.11.1872 at various Baltic Sea gauge stations are shown in Figure 2.

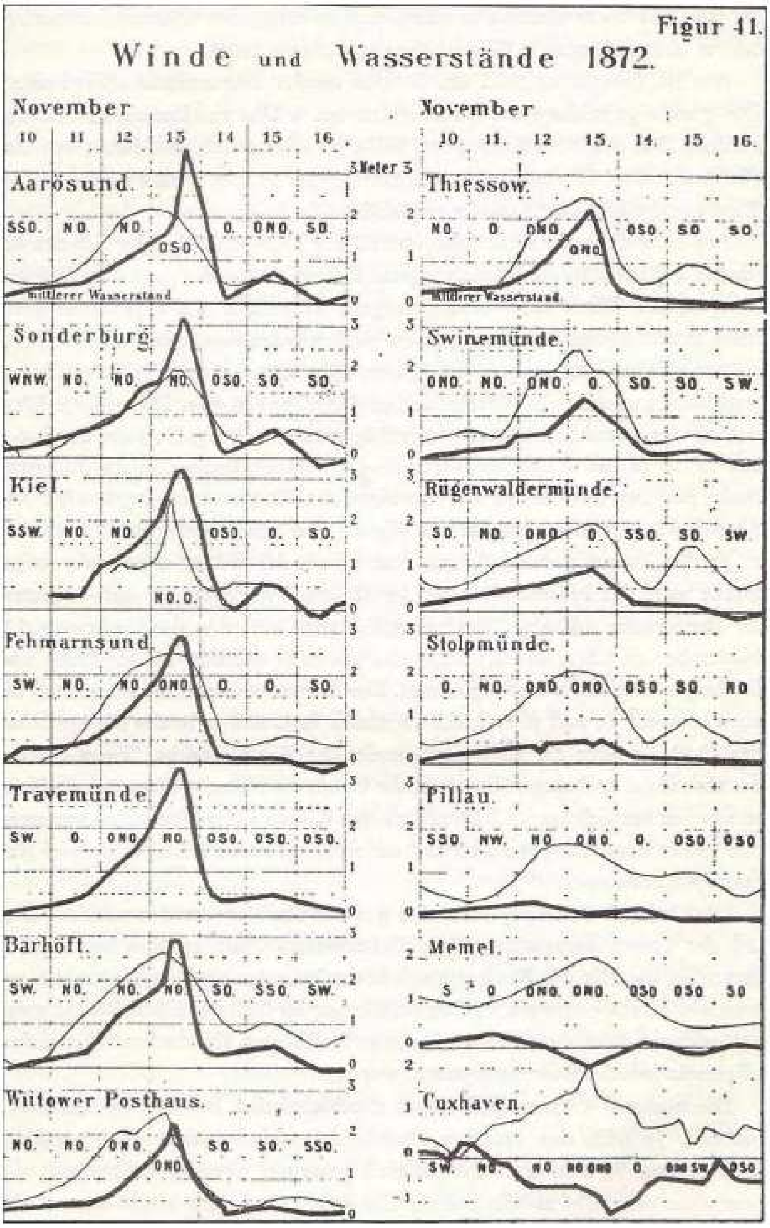


Figure 2: Sea level/hydrograph (above MSL) at different gauge stations along the Baltic Sea during the storm surge of November 1872 (after Lentz (1879) as in Kiecksee (1972) but the original reference is referred to Baensch (1875)).

Due to climate change amplified mean sea level rise (MSLR) researchers have indicated ESL in Europe could rise by one meter or even above by the end of the century (Vousdoukas et al. 2020), which makes the storm surges effects more dangerous in the near future. The vulnerability of coastal communities to flood risks makes coastal flood protection a necessity, and reliable methods are required to protect the coast from expected severe storm surges. For the efficient planning and design of coastal defense structures, it is important to understand the stochastic behavior of storm surges (Jensen 1985). Design sea levels (DSL) for coastal protection design tasks are usually defined using extreme value analysis that estimates probabilities for rare events. In principle, all known extreme value statistical methods are based on the analysis of observed data. The main disadvantage of this method is that the extrapolation period is limited by the recorded observation period. According to Pugh (2005), the extrapolation time should not exceed four times the length of the observation data. In addition, direct methods are sensitive to outliers (Tawn et al. 1989). Since these particularly extreme values are significantly higher than other observations, the results become even more uncertain. The storm surge of 1872 represents until now a one-time measured event (see also Hofstede and Hamann 2022), which may be classified as an "outlier" and therefor excluded from the extreme value analyses. The return period of this storm surge has been investigated in many studies and it shows large differences as it ranges from 180–200 years (Niemeyer et al. 1996), 200 to more than 2,500 years (Jensen and Töppe 1990) up to 3,400–10,000 years (Mudersbach 2009; Hünicke et al. 2015).

Despite the importance of the direct approach of extreme value analysis, but it presents rather a challenging task when available data records are short compared to design return periods. This applies specially to the Baltic Sea, where the number of ESLs are substantially lower compared to other regions (Jensen and Müller-Navarra 2008). The literature increasingly recommends improving the statistical evaluation and reducing the uncertainties, which leads to more reliable determination of DSL. An obvious approach to improve the statistical robustness of risk assessments is to increase the number and time span of available sea level data sets. The research work of the last years clearly shows that the consideration of historical events in extreme value statistics is increasing in importance (DWA-M 552 2012; Schumann 2007; Frau et al. 2018; Prosdocimi 2018; MacPherson et al. 2019; Reis and Stedinger 2005).

2 Study Area

Surrounded by Denmark, Estonia, Finland, Latvia, Lithuania, Sweden, Germany, Poland, and Russia the Baltic Sea stretches throughout north east Europe with an area of approx. 415,000 km^2. It is considered a relatively shallow semi-enclosed sea with mean depth of 52 m and a maximum of up to 459 m in Landsort Deep (Dietrich and Köster 1974). Its only connection with the North Atlantic Ocean is through the North Sea via the Danish straits (the Øresund, the Great Belt (Storebælt) and Little Belt (Lillebælt)), therefore the Baltic Sea consider a small, intra-continental tributary of the Atlantic Ocean (see Figure 3). Through these connections, processes that are generated on the North European Shelf and in the Northeast Atlantic partially enter into the Baltic Sea.

Due to its topography and location, the Baltic Sea is considered the largest brackish water system in the world (Hupfer 2010). Its salinity is generally lower than the salinity of ocean water, and it is subject to strong fluctuations depending on the inflow conditions. Since approx. 75% of the inflow comes through the Kattegat as salt water and 25% as fresh water from the surrounding rivers and rainwater, the salinity increases accordingly from the North Sea side wests (2.5% in Kattegat and Skagerrak) to the north-east (0.3% to 0.5%) (Jensen and Mudersbach 2009). Moreover, estuarine flow supplied by discharge of the surrounding rivers dominate its mean circulation (Lehmann et al. 2002, Nausch et al. 2008).

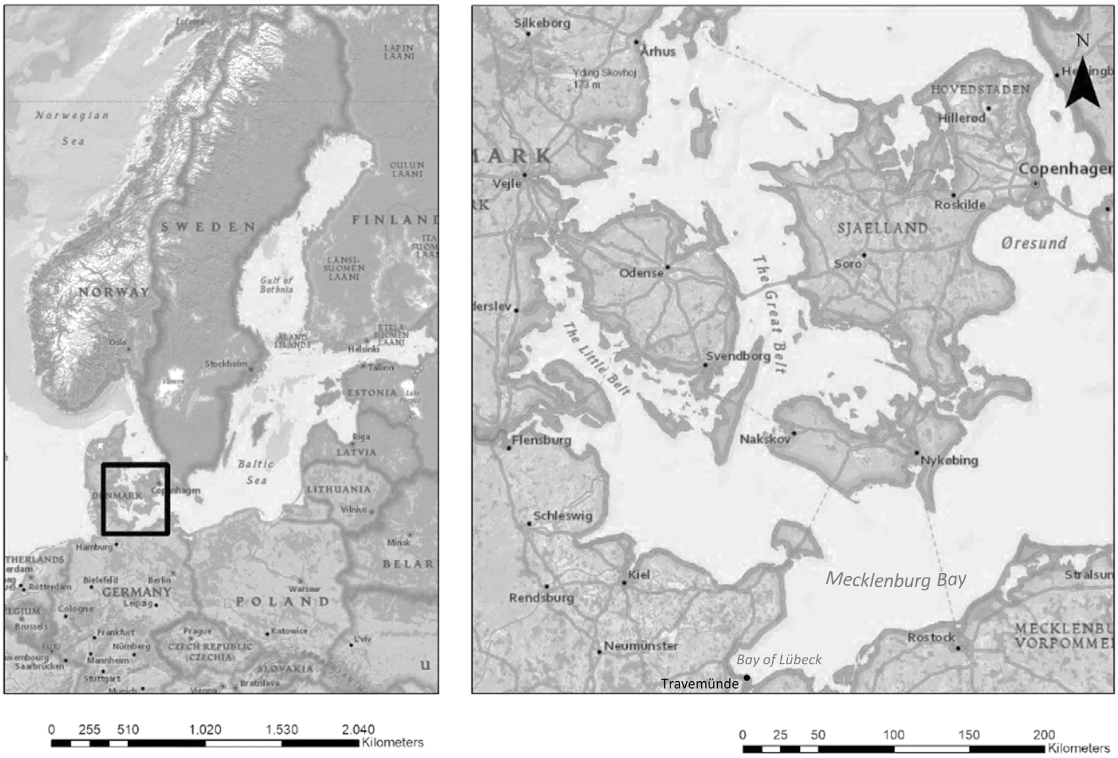


Figure 3: Map of the Baltic Sea. The figure on the left presents the Baltic Sea and its connections with the North Sea. The figure on the right shows a closer map of the southwestern Baltic Sea.

The German Baltic Sea coast has a length of 2,247 km, of which 1,712 km falls in the state of Mecklenburg-Western Pomerania and 535 km in the state of Schleswig-Holstein (Koppe 2002). Our study area spans the southwestern Baltic Sea with a focus on the Bay of Lübeck. The western Baltic Sea is a shallow transition zone characterized by the exchange of water between the North Sea and the Baltic Sea. The Bay of Lübeck is located southwest of Mecklenburg Bay and distinguished as the largest bay in the southwestern Baltic Sea as seen on the right side of Figure 3.

After the Vistula ice age 16,000 years ago, Scandinavian glacier ice masses began to melt, which changed the mass load on the continent and in nearby oceans, including the Baltic Sea. This phenomenon is called glacial isostasis where its movement processes called glacial isostatic adaptation (GIA), which depending on the region, raises or lowers the land masses vertically. Land uplift processes along with water level changes in the North Sea are of great importance regarding relative sea level in the Baltic Sea. The annual changes in the isostatic processes can be well estimated, as shown in many publications, e. g. Ekman (1988), Johansson (2004), Hünicke et al. (2015), Johansson et al. (2014). While large parts of Scandinavia are still rising, the German Baltic coast is sinking. Trends and mean sea level changes will be discussed further in the paper.

Tides in the Baltic Sea are small, around 10 cm, except in the eastern Gulf of Finland where higher amplitudes have been observed (Lilover 2012). Therefore, they contribute less to ESL. The interaction of various meteorological and hydrological factors causes storm surges in the Baltic Sea. The decisive factor is the storm-related wind set-up. With regard to the southwestern Baltic Sea, low-pressure areas with westerly winds that cross the Baltic Sea are usually the main trigger for storm surges. Seiches, water bay accumulation, and the level of pre-filling of the Baltic Sea via the Danish Straits contributes in the intensity of storm surges.

Seiches are longitudinal oscillations within the Baltic Sea with periods of 26.75 to 28.55 hours (Weisse and Weidemann 2017). They are resulting by the position and shape of the basin and are therefore also called "bathtub effect". The mainly driving force is the changing force and/or direction of wind. Hence, back-swiping water mater masses can lead to strongly increased water levels.

The wind conditions in the Baltic Sea region are determined by the westerly wind belt or the North Atlantic Oscillation (NAO) of the northern hemisphere. When there is a long lasting of north to northeast storms over large parts of the Baltic Sea, considerable amounts of water are transported southward by the frictional force of the wind acting on the sea surface, due to the long wind strike length over the sea. When the water body meets coastal areas, they accumulate leading to temporal sea level rise. In bays the narrowing borders and decreasing water depths can amplify the sea level rise strongly (MELUR 2013).

Due to the one-sided southwesterly opening of the Baltic Sea to the North Sea, the inflow and outflow of Baltic Sea water are linked to the inflow and outflow conditions of this area. Constant wind conditions in a dominant wind direction can significantly influence the water masses of the Baltic Sea (Patzke and Fröhle 2019). While winds from the east carry the water towards the North Sea, which results a reduced water level, persistent westerly and southwesterly winds, pushes the salt water mass into the Baltic Sea. The rising water level over a period of days to weeks is called prefilling. An increased pre-filling can contribute to increased water levels (Hupfer et al. 2003), but has no significant influence on the occurrence of an extreme event (Mudersbach and Jensen 2009).

3 Overview of systematic water level records since 1826

Looking back at the history of water level recordings at the German Baltic Sea, the oldest gauge records began locally around 1810, where daily maximum water levels were measured. Along the German Baltic Sea coast, for example, the Travemünde gauge was set up in the course of construction work at the harbour. It thus primarily served shipping and port operations. This continued until the Geodetic Institute Potsdam (GIP) took over the responsibility of measuring water levels and installed mareographs at various gauge stations. Thus, one to four equidistant recordings were made daily (Kelln 2019). At the end of the 19th century, it was begun to measure the water level systematically (Kaiser et al. 2012). Systematic water level recordings provide uninterrupted and temporally equidistant measurements, while historical floods are defined as events that occurred before the systematic water level recordings began. Flood marks on buildings or reports in archives and chronicles considered, for example, as important sources for collecting historical flood events (Deutsch and Pörtge 2013).

Recorded water levels are mostly related to the zero point (PNP) of a gauge station. Over time, these zero points experienced many shifts and changes, which were not always archived. Therefore, in some cases the conversion of historical events above MSL to known height systems is complicated and may leads to great uncertainties. In general, historical floods are defined as events that occurred before the systematic water level recordings began. Flood marks on buildings or reports in archives and chronicles consider as important sources for collecting historical water levels (Deutsch and Pörtge 2013). However, the accuracy of these Data, e. g. of storm surges, is significantly lower than the accuracy of the systematic recordings. Consequently, historical storm surges have uncertainties with regard to the exact time of occurrence, the spatial exposure, the height of the relative peak water levels, the height referencing of the water levels and the conversion of different units of length (feet, meters). Moreover, at the beginning of the observations, the reference datums (PNP) were determined locally and arbitrarily (Liebsch et al. 2000). Depending on the geographical location, measurements were made in "*Lübeck foot*", "*Hamburg foot*", "*Rostock foot*" or old scales like "*cubit*". The metric system was first introduced on January 1st, 1872. Since about 1975, water levels have been recorded digitally, and sent directly to responsible water and shipping authorities (Hupfer et al. 2003), whereas the first continuously recorded levels existed since the 1980s (Ikse 2005).

The available time series vary in length at the German Baltic Sea coast, with the majority of gauge stations beginning between 1901 and 1921. Travemünde gauge is having the longest time series at the German Baltic Sea coast, with continuous records since 1826 (Jensen and Töppe 1986). Jensen and Töppe (1986) evaluated the original water level recordings at Travemünde gauge and managed to compile changes of PNP to the reference datum as Figure 4 shows.

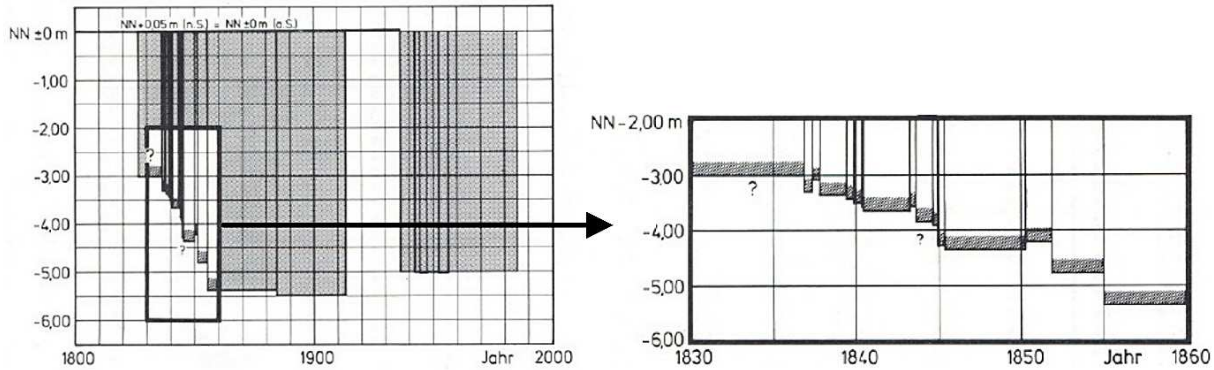


Figure 4: Diagram of gauge datum heights for the Travemünde gauge (?- uncertain datum heights; no changes have been noted in the original files) (Jensen and Töppe 1986).

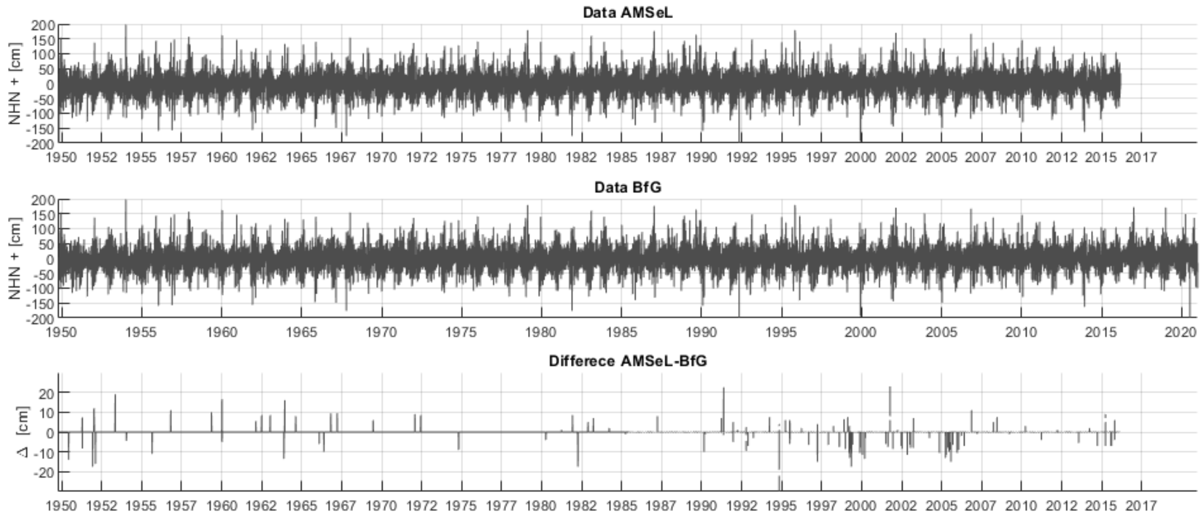
The investigation in Jensen and Töppe (1986) was referred to the reference datum NN (Normal Zero). This was the reference system for heights above sea level in Germany from 1879 to 1991. In 1992, NHN (Normal Height Zero) was introduced as its successor in Germany. The two reference systems differ by a few cm at most and the conversion between the reference datum systems is locally variable. In Travemünde, the difference between the datum systems is very small (NHN ≙ NN −1 cm). Thus, due to the similarity, the following heights related to NN are approximated and replaced by NHN.

We aim to take advantage of the fact that Travemünde gauge has the longest time series of continuously systematic tide gauge records at the Baltic Sea. In the context of the BMBF (Federal Ministry of Education and Research) research project AMSeL-Ostsee (Kelln et al. 2019a, Patzke and Fröhle 2019), high quality monthly datasets were compiled and generated for gauge stations at the Baltic Sea coast (Kelln et al. 2019b).

4 Mean Sea Level Development in the Baltic Sea

4.1 MSL development since 1826

To have an idea of the MSL changes since 1826 at the bay of Lübeck, we used the dataset of the BMBF research project AMSeL-Ostsee to calculate the annual mean values from 1826 to 2015. These data were supplemented with a high-resolution sea level dataset from 1950 to 2020 provided by Federal Waterways and Shipping Administration and prepared by the Federal Institute for Hydrology (BfG). Because the BfG dataset was provided in relation to the reference datum or zero point (PNP in Germany), a conversion into a uniform height reference system (German ordinance datum) was first carried out. As part of AMSeL_Ostsee project and after collaboration with the authorities in Stralsund and Lübeck, it was decided that the reference datum equals to NHN −501 cm at Travemünde gauge (Patzke and Fröhle 2019). This value was used in the conversion of both BfG and AMSeL_Ostsee datasets into NHN. To verify the time series, the data sets are plotted against each other with uniform temporal resolution from 1950 to 2015 (see Figure 5).


Data AMSeL

Data BfG

Differece AMSeL-BfG

Figure 5: Water level differences between AMSeL-Ostsee and BfG hourly datasets since 1950.

The two time-series demonstrate differences at some points in time, but show a high degree of conformity. Therefore, both datasets can be used.

Since high-resolution datasets are available, the MSL is computed as the arithmetic mean of all registered values over a certain period of time. In the case of gaps in the data sets, recommendations of the Permanent Service of Mean Sea Level (PSMSL, http://www.psmsl.org) are followed. MSL monthly values were only calculated if water level values were available for at least 15 days of the same month. An MSL annual value is then only calculated if 11 or 12 monthly values are available for the relevant year. All MSL time series were calculated based on calendar year.

Before combining the MSL annual values from different datasets into a long-term time series, it was first checked whether the time series are suitable for this. Annual MSL values computed from the BfG hourly dataset was compared with those calculated on the basis of monthly values (AMSeL_Ostsee dataset) for Travemünde gauge for the period of 1950 to 2020. Figure 6 shows relatively small differences between both MSL time series. Small variations in the calculated MSL curves can be explained due to the differences between the two datasets. However, both time series are almost congruent, and no systematic differences can be determined from the residuals shown (see Figure 5). Thus, it was decided that MSL time series generated from the BfG-hourly values and AMSeL_Ostsee-monthly values can be linked and analyzed without further correction.

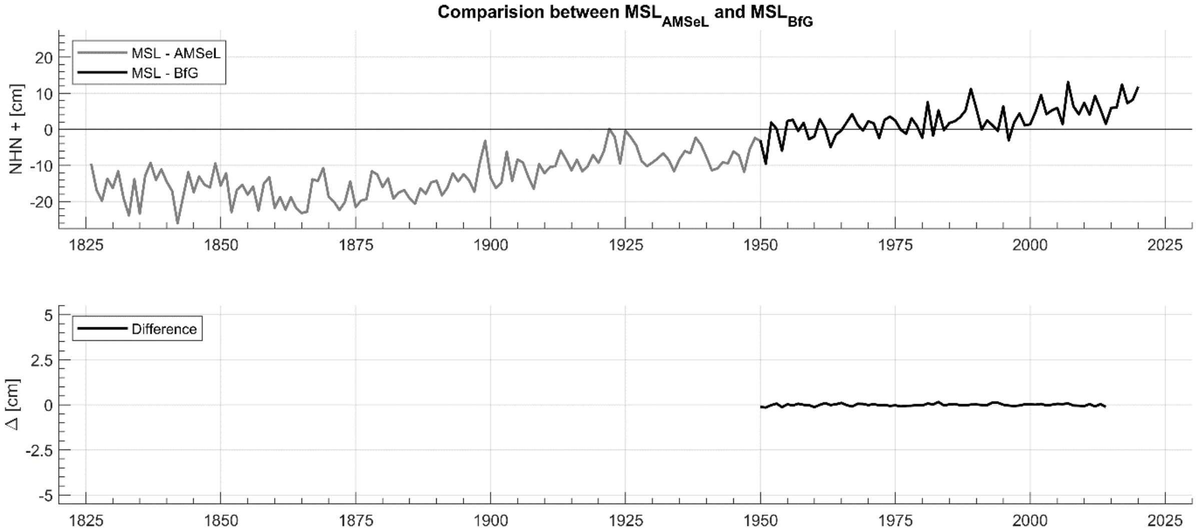


Figure 6: MSL development since 1826 at Travemünde gauge, where the figure above shows a comparison between MSL calculated from AMSeL_Ostsee and BfG datasets and the figure below illustrates the differences between the calculated MSL.

To quantify the long-term development of the MSL time series, the 19-year average of MSL (MSL_{19a}) (Period of the nodal tide, even the Nodal tide is very small) is also computed (see Figure 7). The analysis of the MSLR reveals that an acceleration took place at the second half of the 19th century around the 1870s and continued up until the 1930s at which point a slight deceleration is detected. An overall tendency of acceleration over the last few decades is observed with noticeable acceleration phases around 1940 and 1975 until today.

One more important fact can be concluded from the 19-year average MSL curve is that between 1960 and 1961 the MSL is equal to NHN at Travemünde gauge. There has been a debate in scientific research for a long time about the exact time where MSL equals to zero NHN and year 2000 was adopted in many studies. Here we provide a more accurate time estimate, which will give a great deal of help in classifying historical events and quantifying the changes in the development of MSL curve.

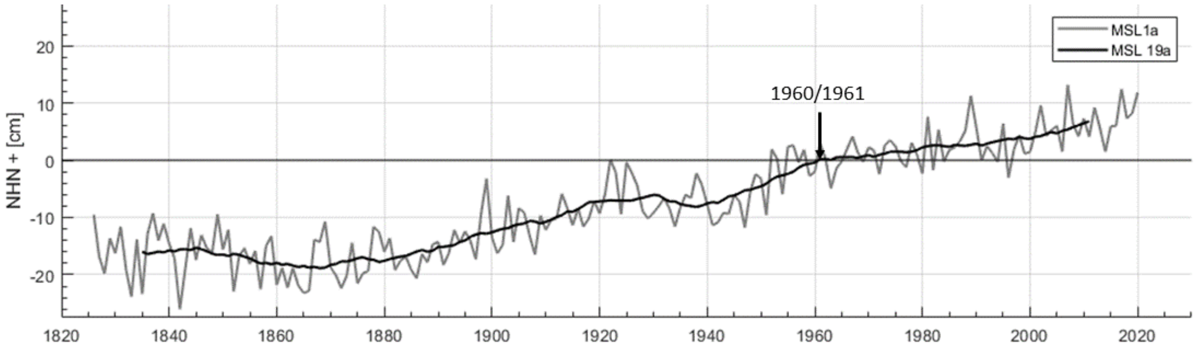


Figure 7: 1-year average and 19-year moving average of MSL data from year 1826 to 2020 at Travemünde gauge, which was equal to NHN in 1960/1961.

The southwestern Baltic Sea is characterized as typical shallow water with water mass exchange with the North Sea (Hupfer et al. 2003). Hence, studies have shown that the mean sea level development in the Baltic Sea is influenced by the mean sea level variability in the North Sea. As a simple analogy in terms of communicating tubes, the North Sea can be seen as the damped gauge of the Atlantic and the Baltic Sea correspondingly as the damped gauge of the North Sea. To validate our results, we compare the MSL development in Cuxhaven (MSL_{19a} Cuxhaven o.K.) (Niehüser et al. 2016), located at the North Sea, with the MSL development in Travemünde. To respect the influence of possible land movements of the Cuxhaven lighthouse (compare to Siefert and Lassen (1985)), the water levels at the tide gauge Cuxhaven were corrected in Niehüser et al. (2016) (MSL_{19a} Cuxhaven m.K), as shown in Figure 8.

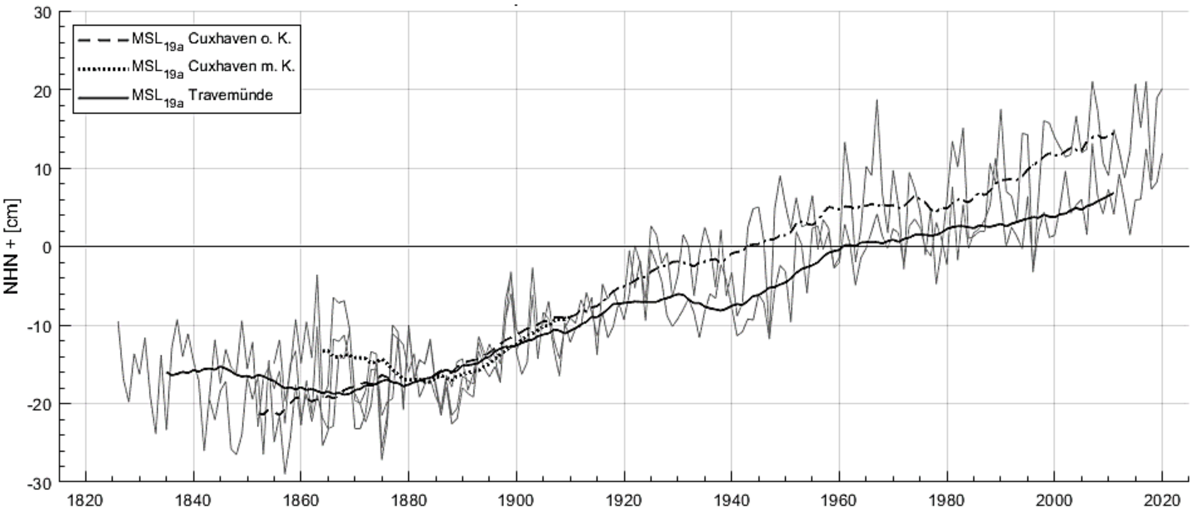


Figure 8: Comparison between the development of 19-year averaged MSL (MSL_{19a}) at Travemünde and Cuxhaven gauges.

The comparison of the two time-series shows very high similarities, which indicates regional coherence. The results show that a large part of MSLR signal in the southwestern Baltic Sea is implied from the North Sea. This was also investigated by Kelln et al. (2020), which suspected a connection between the sea level variability in the Baltic Sea, the North Sea and the Northeast Atlantic. However, a little bit higher MSL trends are observed for the Cuxhaven gauge in comparison to Travemünde gauge. However, the temporal function of the two trends shows a great similarity or agreement.

Based on the high quality relative MSL (RMSL) time series, Kelln et al. (2019a) and Kelln (2019) analysed changes in MSL at each tide gauge and spatially for the entire southwestern Baltic coastline for different time periods. For the period 1900 to 2015 a linear trend of 1.2 ± 0.1 mm/yr was estimated for the southwestern Baltic coastline. In terms of mean rise in sea level in the southwestern Baltic Sea, Kelln et al. (2019a) derived a rise of 1.67 ± 0.07 mm/yr for the period of 1900 to 2015 at Travemünde gauge. The Bay of Lübeck is sinking with rates of approximate 0.1 mm/yr due to vertical land movements caused by glacial isostatic adjustment (GIA). Hence, a correction of GIA was necessary. After correcting the RMSL time series, the MSL trend decreases for Travemünde to 1.55 ± 0.07 mm/ yr (Kelln et al. 2019a, Kelln 2019).

To estimate a MSL change for the period of 1835−2020 we present two approaches as shown in Figure 9. These are the 19-years mean average (MSL_{19a}) and, in order to make it more practicable, a linear trend. We estimate a linear trend of 1.77 mm/yr for the period of 1870−2020 and a linear trend of 0 mm/yr for the period of 1835−1870. The linear MSL trend function leads to an intersection with NHN around 1972/1973 at the Travemünde gauge (see also Figure 7).

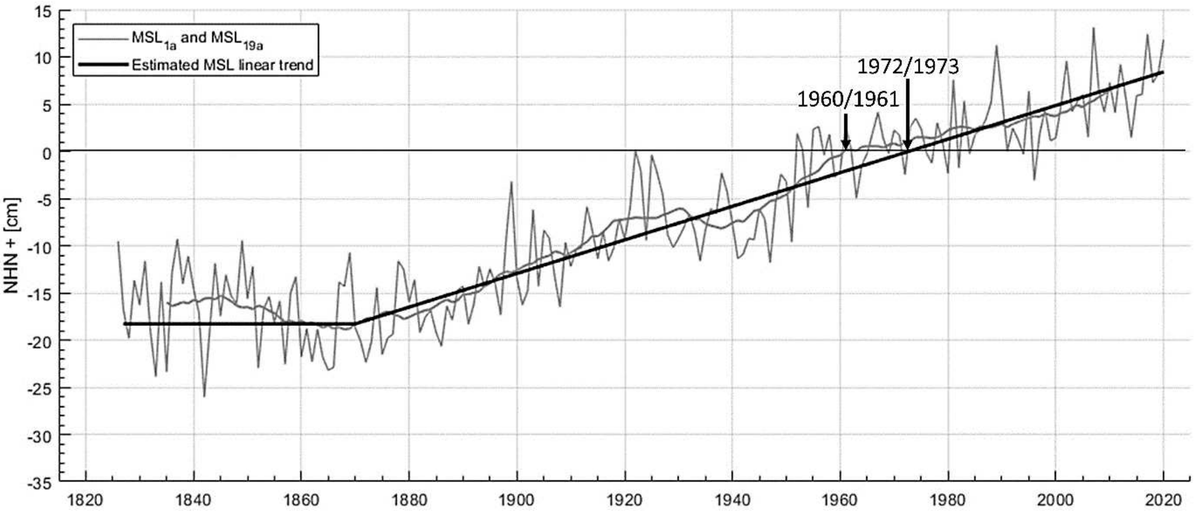


Figure 9: Estimated MSL linear trend (black bold line) and calculated 19 years MSL at Travemünde gauge from 1826 to 2020.

4.2 MSL development over the last 1,000 years

In the attempt to classify heights of historical storm surge events to an actual reference datum (for example NHN in Germany), this paper investigates historic changes in MSL at the southwestern Baltic Sea. Information about the development of MSL goes back to the Holocene Epoch and the beginning of the genesis of the Baltic Sea (Köster 1961, Klug 1980, Kolp 1979, Kliewe and Janke 1982). Many studies have also tried to reconstruct the postglacial MSLR in the southwestern Baltic Sea (Klug 1980, Lampe 2003, Schumacher 2003, Jakobsen et al. 2004, Baerens et al. 2003). For our study, MSL curves in the Bay of Lübeck, especially since the year 1000, are of high interest. It has been agreed between old and modern studies that the MSLR in the Baltic Sea is characterized as fluctuating (Klug 1980, Kolp 1979, Schumacher 2003, Baerens et al. 2003, Jakobsen et al. 2004). By comparing some of these studies, we found clear differences between them, so we will try to present and analyze these differences to estimate a MSL curve representing the Bay of Lübeck.

Klug (1980) examined the sea level development in the southwestern Baltic Sea and distinguished the MSL development in three transgression phases over the past 2,000 years. The first phase ended around the 9th century, the second lasted until the first half of the 17th century and the third continued until the middle of the 19th century.

Klug (1980) determines a mean sea level of NHN −60 cm at year 900 for the coastline of Schleswig-Holstein. According to Baerens et al. (2003), in the following transgression water level rose up slightly to NHN −50 cm, followed by a slowdown or even standstill in transgression. During and shortly after the Medieval Climatic Optimum, which also known as the Medieval Warm Period, a conspicuous MSLR up to NHN −25 cm until the year 1400 was caused. This is followed by a regression phase, which can be verified by peat decomposition horizons in the coastal floodplain bogs (Jancke and Lampe 2002, Jeschke and Lange 1992). This regression phase is related to the Little Ice Age between about 1500 and 1750. Information about sea level at this phase are not well known. Around 1850 the modern transgression, also called Modern Warm Period, was causing a MSLR by 20 cm up to the present. After 1580 sea level began to rise to its present level.

On the other hand, Jakobsen et al. (2004) detected also a transgression phase around year 1100, but they estimated the sea level by around NHN −80 cm, followed by a sharp rise, which possibly leads to a MSL of NHN −20 cm around year 1100−1300. Then a regression phase took place where sea level fell again to a level around NHN −80 cm. After 1580 sea level began to rise to its present level.

After evaluating the values mentioned above, we tried to find a compromise between various MSL reconstructions as Figure 10 shows. A conservative approach is chosen, which mostly lies in the upper range of the curves. Estimations of sea level around the Medieval Warm Period and the Little Ice Age period presented a challenge. It was therefore decided as an engineering decision, to assign an uncertainty band, which should take uncertainties into account, to get a simple handling.

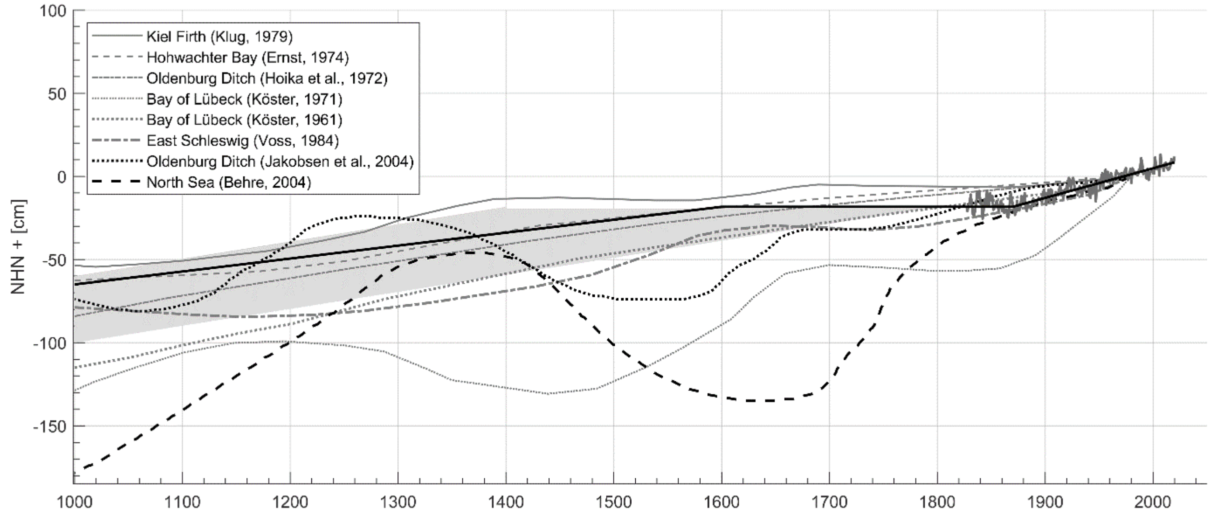


Figure 10: MSL estimation and uncertainties for possible variations of MSL development according to different references at the southwestern Baltic Sea since year 1000 and gauge records since 1826 in Travemünde gauge.

For Travemünde area, we estimate the MSLR between the MSL curves of East Schleswig and the Kieler Firth − fitting to the linearized MSL estimation of the systematic records since 1835 in Figure 9. The solid black line represents our estimation of MSL development in Travemünde. Although it is a compromise, but it reflects MSL development of the North Sea as well as the MSL of the gauge data records. The estimated MSL changes at Lübeck Bay are presented in Table 1.

Table 1: Estimated MSL changes at Lübeck Bay for three transgression periods in the past 2,000 years.

Time Period [year]	**MSL change [mm/yr]**	**MSL_h [NHN + cm]**
1000 – 1600	0,78	−65 to −18,3
1600 – 1870	0	-18,3
1870 – 2020	1,77	−18,3 to + 8,5
1826 – 2020	19 years mean average	(see Appendix)

Using Table 1, historical information [cm above MSL] can be converted in the reference system [NHN +cm]. The reference system provides a reliable height system used in Germany and easy to be converted to other height system of interests.

5 Compilation and reconstruction of extreme historical sea levels

Despite their importance, incorporating historical events into the statistical analyses goes along with many challenges, therefore they shouldn't be used for a (statistical) analysis without further investigation (Deutsch and Pörtge 2013). Hence, we investigate in this section the available database about historical (ESL_h).

The oldest mention of a storm surge goes back to Florus' *Epitome of the Histories of Titus Livy*, in which the emigration of the Cimbri from Jutland and Schleswig-Holstein is said to have been caused by heavy land losses due to storm surges around the year 120 BC − even if there is much room for subjective interpretation here. The first reliable information is known for the year 1044 in Rügen that is described in contemporary literature as "*Enormous storm surge at the Baltic Sea*". Since the beginning of the 14th century, the occurrence of storm surges has been documented in the chronicles of coastal cities, e. g. Lübeck, Stralsund and Wismar, even though these the transcriptions are often incomplete and do not contain quantitative information, e. g. water levels. Thus, often there is only a mention of "*huge water*" as result of heavy storms. Furthermore, the exposure of the storm surges can often only be estimated, as reports often been transmitted only locally. In hydrological literature, they speak of "detection limits". In other words, only storms/floods that were with a certain impact are recorded. The detection limits provide an important piece of information, namely that (probably) no mentioned storm surge was below that limit (see for example Bulletin 17c (England et al. 2018)).

Information about historical floods is collected from old archives and flood marks. A large collective of ESL_h was already elaborated in (Schröder (1742), Boll (1865), Hennig (1904) and Krüger (1910)). In Table 2, we give an overview of the known storm surges since 1044. Bold printed events represent storm surges of special significance. Information in brackets is associated with a high degree of uncertainty.

Table 2: Information about historical extreme sea level (ESL_h) at the German Baltic Sea coast before systematical recording began in 1826, oriented by Krüger (1910).

Date	Wind Direction	Exposure	Remarks
1044	-	-	"*Enormous storm surge at the Baltic Sea*"
1134	-	-	"*Severe storm surge*", *Waterland*!"
01.11.1304 (1303, 1307, 1309)	NE	Pomerania to Schleswig	"*great stormwind, never heard in living memory*" (Chronicle of Strahlsund); A new gully was formed between Rügen and Rude
30.11.1320 (06.12.1321)	NE	Pomerania to Schleswig	Water level rose up to *7 cubitorium* in the harbor of Travemünde (Chronicle of Lübeck)
1360 (?)	-	Bay of Danzig	-
1365	-	Bay of Pomerania	-
04.12.1374	NE	Pomerania to Schleswig	-

17.01.1396	N-NE	Pomerania, Mecklenburg	-
21.11.1412	N	West of Rügen	-
15./16.10.1449	NE	Prussia to Schleswig	“*grot storm [...] grot water*”, intense damage in Lübeck (Chronicle of Stralsund)
28.01.1467	N	Pomerania to Schleswig	-
April 1488 (?)	NNE	Bay of Danzig	-
15.09.1497	NW	Prussia, Pomerania, Mecklenburg	Formation of the gully near Pillau; Lebamünde was destroyed probably
02.02.1515 (?)		Bay of Danzig	-
January 1519	ENE	west of Rügen	-
11.01.1552	N W.	Prussia, Pomerania, Mecklenburg	-
06.12.1554*	N-NE	Pomerania, Mecklenburg	-
08.02.1558	NW-N	Pomerania, Mecklenburg	-
Summer in 1570	NW-N	Prussia, Pomerania	Lebamünde was destroyed
14.02.1573	NE-E	west of Darss	-
04.03.1577	NE-E	Darss-Zingster Bodden	-
14./15.02.1589	-	Mecklenburg, Schleswig	-
21./22.01.1596	N	Pomerania, Mecklenburg	-
1604	NW-N	Upper Pomerania	-
29.03/ 04.04.1607	-	Mecklenburg, Schleswig u. Holstein	-
09.02.1609	NE	Pomerania to Schleswig	-
28.11.1615	NW	Mecklenburg	-
13.07 1619	NE	Darss-Zingster Bodden	-
15.09.1623	N-NE	Mecklenburg	-
10.02.1625	NE	West-Pomerania to Schleswig	Is said to have cost the lives of 9,100 people in the Baltic Sea region;
1644	-	Mecklenburg	-
08.04 1645	-	Mecklenburg	-
13.10.1649	NE-E	Pomerania, Mecklenburg	-
16.11.1660	(N-NE)	Mecklenburg	-
07.09.1663	NE	Pomerania to Schleswig	-
09.01.1668	(N-NE)	Mecklenburg, Holstein	-
05.03 1689	(E)	Darss-Zingster Bodden	-
24.11. (02.12.)1690	NE	Pomerania to Schleswig	-
07.12.1693*	N	Bay of Danzig, Upper Pomerania	-
10./11.01.1694	(NE)	West-Pomerania to Schleswig	-
31.10. to 01.11.1702	NW	Prussia	-
Nov. 1708	(NW)	West-Prussia, Pomerania	-
1709	(N-NE)	Upper Pomerania to Mecklenburg	The spit between the Baltic Sea and Lake Camper breached.
06.03.1718	-	Mecklenburg	-
1736*	(N-NE)	Bay of Pomerania	Gullys through Usedom
1741*	(N-NE)	Bay of Pomerania	-
Spring 1742	(NE-E)	Darss-Zingster Bodden	-

Nov. 1742	(NE-E)	Darss-Zingster Bodden	-
27.02. to 02.03.1747	(N-NE)	West of Rügen	-
12./13.12.1747	(N-NE)	W.-Prussia, Pomerania (to Schleswig?)	-
1750	(E)	Darss-Zingster Bodden	-
19.10.(?) 1767	(NE)	W.- Pomerania to Schleswig	-
28.09.1784	(NE)	Pomerania to Schleswig	"*a little lower than 1694 in Lübeck*"
30.10.1785	(NW-N)	Pomerania to Schleswig	-
Jan. 1791*	NE	Bay of Pomerania	Breakthroughs through Usedom
Nov. 1792*	NE	Bay of Pomerania	
1793	NW-N	Upper Pomerania	-
Spring 1795		Mecklenburg	-
03.11.1801	NE	Mecklenburg	-
03.09.1814 (?)	NE	Upper Pomerania	-
11.11.1820	N	Mecklenburg	-
Jan. 1822	NW	Upper Pomerania	-
11.03.1822*	NW	Upper Pomerania, danish Islands	-
30./31.03.1822*	NE	area around Stralsund	-
4./5.12.1823	(NW-N)	Upper Pomerania	-
05.01.1825	N	Pomerania, Mecklenburg	-

Referring to Table 2, the storm surges from 1044, 1304, 1320, 1449, 1625, 1694, 1784 and 1872 seems to be the most remarkable events at the German Baltic coast. Even if detection limits can change over time, we expect in conformity to Krüger (1910) at least 2.50 m above MSL as level of significance for mentioning storm surges, e. g. in chronicles. With focus on Travemünde and Lübeck we try to investigate all available water levels of intense storm surges since 1044. For this purpose, excerpts from the original references of the very first surges are cited i. e. in Mayer (1873). In addition to, excerpts of the Lübeck Chronicle and Strahlsunder Chronicle were available and investigated.

The first reliable information about a historic storm surge is from 1044, even there is no water level recorded. Contemporary references describe the storm surge as "*Enormous storm surge at the Baltic Sea*" (see Table 2). Because this storm surge apparently represented an outstanding event, that was worth been documented and transmitted for the first time, a water level of >2.5 m above MSL is assumed.

For the storm surge of 1304, Berckmann (1833) descibed in the Chronicle of Strahlsund a "*huge water*" at All Saint´s Day that leads to a new gully (*Nye-dep: new deep*) between Ruden and Rügen, but no water level has been recorded either. Consequently, a water level of at least 2.50 m above MSL is assumed as well. An event of this magnitude would probably have affected the entire German coastal area, but it is not mentioned further in other chronicles.

In the chronicle of Lübeck, a storm surge in 1320 is described as "*In nocte beati Nicholai (6. Dec.) aqua in portu Travene a solito suo statu crevisse dicebatur in altitudinem 7 cubitorium*". Meaning, the water level rose up from its usual level to a height of *7 cubitorium* in the harbour of *Travene*. One cubitus (also cubiti) corresponds to 44.36 cm or, as in old English scale (*cubit*) 45.72 cm, so that the water is supposed to have reached 3.1 to 3.2 m above MSL in *Travene*.

In addition to, the destruction of the *Holsten*-bridge in Lübeck by a *great waterflood* is described. Thus, for the first time there is an information about the water level in addition to the descriptions of the damage.

This extraordinary storm surge is not mentioned in Pomeranian chronicles, so one can conclude that 1304 and 1320 could be the same event. Since there are repeatedly gaps in the records of individual chronicles, it cannot be excluded that independent events may have taken place.

In the chronicle of Stralsund, we read about extensive damage in Lübeck caused by a storm surge of 1449. Again, the occurrence of the storm surge is not mentioned in the Lübeck chronicle. This demonstrates that indications of the oldest storm surges are unreliable in some cases, since chronicles from different cities rarely coincide. It was decided to tabulate the number of possible events to let the user of the data decide on the probability of occurrence.

With the beginning of the 17th century the records of water level increased, so that there are also coincident notes. In addition, there are a number of storm surge marks that can be used to derive water levels. Therefore, many descriptions describe the extent of the storm surge of 1625, e. g. in *Theatrum Europaeum*. Furthermore, there are storm surge marks in Lübeck and Travemünde that records the occurred water levels until today. According to Baensch (1875), the height of the storm surge mark is located at 2.80 m above MSL in Lübeck that agrees (allegedly) with the storm surge mark in Travemünde. Because Baensch did not have knowledge of a change in MSL (for a detailed retrospective of sea level research at the German Baltic Sea Coast compare to Kelln and Jensen (2020)), the associated mean water level is assumed to be the level of 1875, which is fortunately comparable to 1625 (see Figure 10), so there is no need for correction. In agreement, Krüger (1910) mentions a water level of 2.86 m above MSL for the 1625 surge in Lübeck. In contrast to Baensch (1875), Krüger (1910) reports a height slightly over 3.0 m above MSL for the storm surge mark of 1625 in Travemünde. The accepted value for 1625 published by the authorities in MELUR (2013) is NHN +280 cm for Travemünde, that is equal to 298 cm above MSL referring to Figure 10/Table 1. This value seems be derived of Baensch (1875), but simply replaced [m] above MSL by NHN +[m], and therefore might be wrong.

For the storm surge of 1694 there is also a storm surge mark in Lübeck that Baensch (1875) used to derive a height of 2.82 m above MSL that almost corresponds to Krüger (1910) with a height of 2.86 m above MSL. Again, it can be assumed that the contemporary MSL was referred in each case. So, Baensch was fortunate again, that the MSL was almost constant between 1694 and 1875 and his information is therefore valid. For the first time, there is also a scientific indication as a file note of the water level records in Travemünde gauge station. Jensen and Töppe (1990) were able to recapitulate a water level of 2.65 m above MSL using the file note. The authoritative value for 1694 published in MELUR (2013) is NHN +290 cm for Lübeck, that is equal to 272 cm above MSL referring to Figure 1/Table 1.

For the storm surge of 1784 there is less information available. In Krüger (1910) it is described as "*a little lower than 1694 in Lübeck*", so we expect a water level of at least 250 cm above MSL.

The storm surge of 1872 is probably the best documented historical storm surge. Due to increasing water level measurements and the advancing understanding of storm surges, luckily "*for the first time, it was the technician, not the historian, who handed down the bare fact to* *posterity in a few words*" (Baensch 1875). The reports by Baensch (1875), Lentz (1879) and Quadde (1872) as well as the more recent works by Kiecksee (1972) and Petersen and Rhode (1979) have been evaluated as outstanding literature on the flood event. In Baensch (1875), a water level of 3.38 m above MSL is reported for 1872 in the *Trave* (Lübeck) and 3.32 m above MSL for Travemünde gauge. Krüger (1910) agrees with 3.38 m above MSL in Lübeck. In addition, a storm surge mark is located in Travemünde at the former administrative building *Alte Vogtei*, that is located at a height of 3.40 m above MSL referring to Petersen and Rhode (1979). The storm surge mark is shown in Figure 11. Thus, different heights are not necessarily to be in competition with each other. In fact, they could take local conditions into account and show the uncertainty of historical measurements. The most known value of the 1872 storm surge is NN +330 cm (NHN +329 cm), which is also used in the general plan Schleswig-Holstein reference (MELUR 2013 and 2022), and considered the currently official value for this storm surge. Jensen and Töppe (1990) considered a value of NHN +315 cm to be authoritative. This value is the closest to the value mentioned in Baensch (1875) which equates to NHN +314 cm, referring to Figure 10.

A flood mark of 1625 is located next to the surge mark of 1872 at the *Alte Vogtei* (Figure 11), which is only about 25 cm lower than the water level of 1872. In contrast, Baensch reports a less of 0.56 m between the storm surges in Lübeck. For a difference of 25 cm between the marks, with reference to the value for the storm surge mark of 1872 in Petersen and Rhode (1979), a water level of 3.15 m above MSL can be derived for 1625, since the mean water levels of 1625 and 1872 are comparable (compare to Figure 10). This derived water level corresponds to the statement in Krüger (1910) which is "slightly higher than three meters"

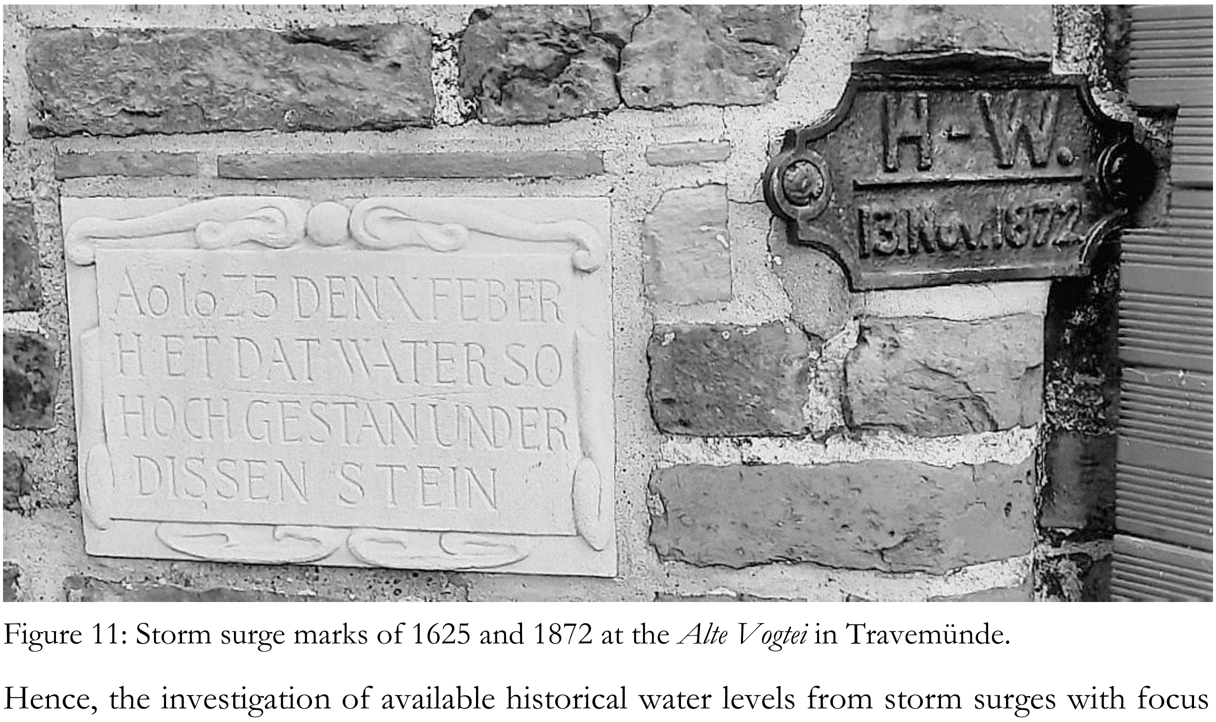


Figure 11: Storm surge marks of 1625 and 1872 at the *Alte Vogtei* in Travemünde.

Hence, the investigation of available historical water levels from storm surges with focus on Travemünde and Lübeck shows large differences in different references, some of them can't be explained. For some of them it is assumed that the different water levels originate from different measurements. In Table 3 the ESL and all results are summarized, each with the related reference and value.

Table 3: Most remarkable historical extreme sea levels (ESL_h) above MSL recorded at Travemünde and/or Lübeck gauge since 1044.

Date	**ESL_h** [cm above MSL]	**Gauge/ Location**	**References**
?.?.1044	>250	Travemünde	Krüger (1910)
01.11.1304	>250	Travemünde	*Chronicle of Strahlsund*
30.11.1320	310 – 320	*Travene (?)*	*Chronicle of Lübeck*
15.-16.10.1449	>250	Travemünde	*Chronicle of Stralsund*
10.02.1625	280	*Trave (?)*	Baensch (1875)
	~300	Travemünde	Krüger (1910)
	315	Travemünde	Storm surge mark, ref. to Petersen und Rhode (1979)
	298*	Travemünde	MELUR (2013)
10./11.01.1694	265	Travemünde	Jensen and Töppe (1990)
	272	Lübeck	MELUR (2013
	282	Lübeck	Baensch (1875)
	286	Lübeck	Krüger (1910)
28.09.1784	~250	Lübeck	Krüger (1910)
13.11.1872	332	Travemünde	Baensch (1875)
	340	Travemünde	Petersen and Rohde (1979)
	347*	Travemünde	Kelln et al. (2019b)
	338	Lübeck	Baensch (1875); Krüger (1910)

*converted [MSL + m] to [NHN + m] by using MSL-development in Figure 10/Table 1

In order to complete the list of historical extreme sea levels, we respect that for a couple of storm surges, only water peak levels at Lübeck are available, e. g. for the storm surge of 1320. To investigate the spatial height transmission between Travemünde and Lübeck, we tried to make a comparison between ESLs at Travemünde and Lübeck gauges (see Table 4).

It became apparent that different datasets consist large differences, although some of them were measured systematically. For example, there is a huge difference of more than 1 m for the storm surge of 1883, that can't be explained. So, a simple comparison was difficult to made. Anyways, by comparing values of similar references, we were able to determine the differences between −3 to +16 cm, where in most cases Lübeck gauge shows slightly higher values (+5 to +9 cm) than the Travemünde gauge. This could be explained by the geographical location of both stations (see Figure 12). When offshore winds from the northeast push the water masses of the Baltic Sea to the coasts, the water is caused to accumulate in the bay, which leads to higher water levels in Lübeck. With regard to the uncertainties, it was decided to apply ESL from Lübeck to the Travemünde.

Table 4: Comparison of different datasets of systematic ESL between Travemünde and Lübeck; bold values are used in this paper.

Date	Travemünde [NHN +m]	Lübeck [NHN +m]	Difference [Δ m]
30.12.1867	1.70 m [1]* **1.80 m** [2]	1.77 m [1]*	+0.07 **-0.03**
13.11.1872	3.22 m [1]* **3.14 m** [5]* 3.29 m [2][3]	3.20 m [1]*[5]* 3.36 m [4]	-0.02 **+0.06** +0.07
05.12.1883	**1.17 m** [2] 2.34 m [3]	- -	- -
25.11.1890	1.95m [1]* **1.82 m** [2] 2.46 m [3]	- - 2.53 m [4]	- - +0.07
20.11.1893	**1.66 m** [2]	1.64m [1]*	-0.02
31.12.1904	**2.12 m** [2] 2.62 m [3]	- 2.67 m [4]	- +0.05
09.01.1908	**1.81 m** [1]* 1.84 m [2] 2.26 m [3]	- - 2.35 m [4]	- - -0.09
30.12.1913	1.89 m [1]* **1.96 m** [2]	2.05 m [4]	+0.16 +0.09
04.01.1954	2.04 m [1]* **1.99 m** [2]	- -	- -
27./28.1989	**1.65 m** [2]	1.75 m [1]*	+0.10

*converted [MSL + m] to [NHN +m] by using MSL-development in Figure 10/Table 1

[1] Petersen und Rhode (1979)

[2] WSA Lübeck (2017)/ Kelln et al. (2019b)

[3] DGJ, Travemünde (2017)

[4] DGJ, Lübeck (2017)

[5] Baensch (1875)

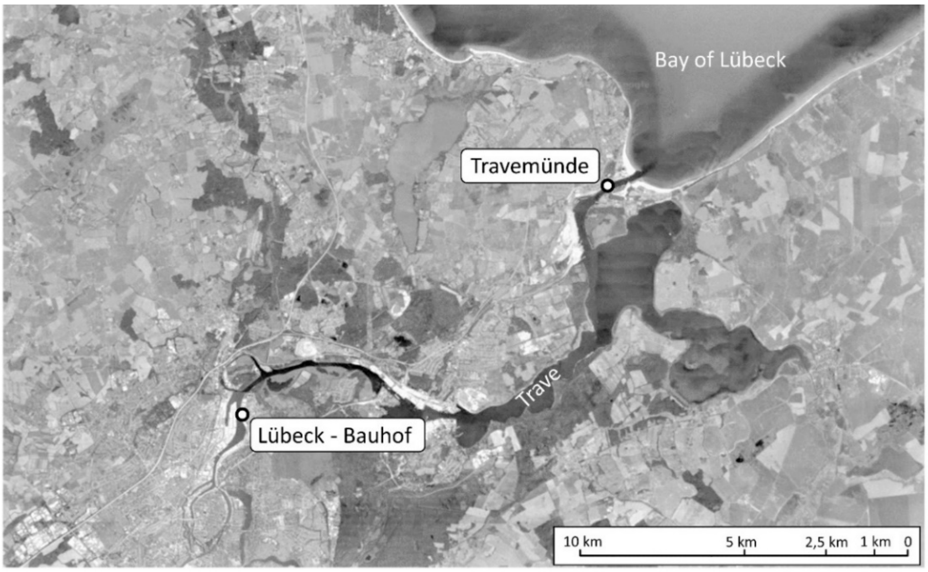


Figure 12: Geographical location of Travemünde- and Lübeck gauge stations (Google Earth).

We conclude from the investigation that uncertainties are an essential component to be taken into account when dealing with ESL_h. Hence, an uncertainty up to ±5 dm is assumed for the storm surge in 1044, which is reduced to ±2.5 dm for storm surges until the 19th century. Uncertainties of well-documented storm surge events since the 20th century could be reduced to ±1 dm and can be reduced even more actual time series of high-resolution data (see Figure 13).

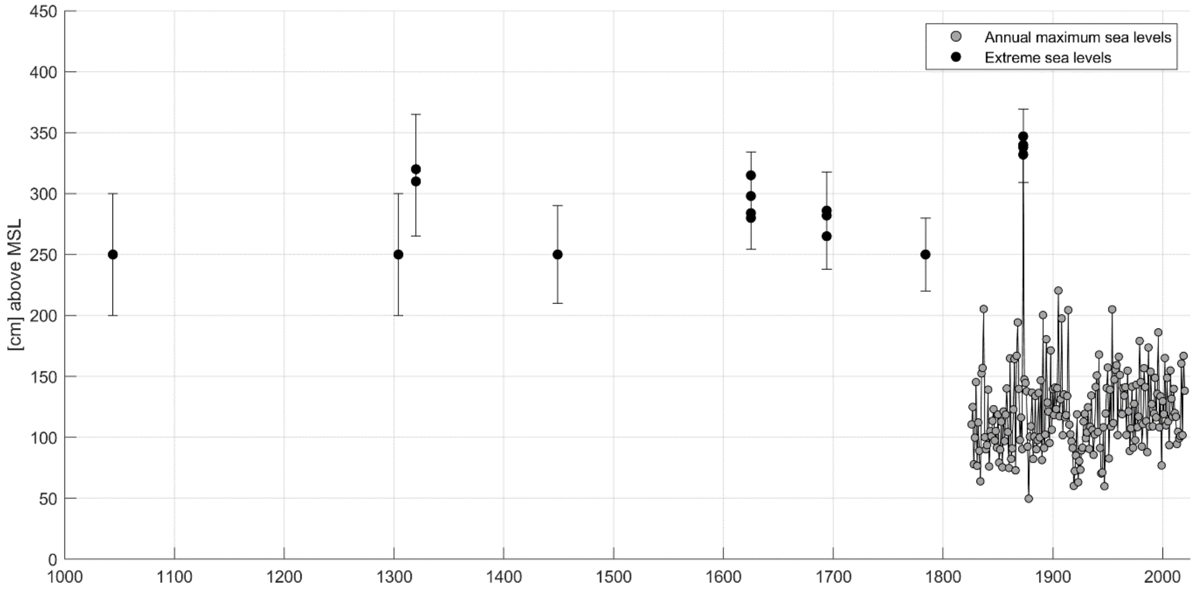


Figure 13: Historical storm surge levels since year 1044 and estimated uncertainties in peak water level at Travemünde gauge station.

6 Detrending ESL at Travemünde gauge station by the trend of historic MSL changes

The next important point that needs to be discussed is the detrending of the nonstationary dataset. Storm surge peak water levels recorded at a gauge station are influenced by MSLR, the status of coast (coastal protection measures, e. g. dikes), the bathymetry of the basin and changes in meteorology/climate. In this respect, all storm surge water levels would have to be homogenized to a reference year of MSL, a certain state of the coast and the bathymetry. A correction of ESL due to changes in the bathymetry is not possible; the effect on sea level will be rather small. So, homogenizing (adjusting) the recorded water level to a certain status, results in detrending the ESL by the change of MSL. For example, the storm surge of 1320, would have to be adapted to the current status of MSL in order to be incorporated in the statistical analyses (see Figure 14). For the detrending, we chose the year 2020 as reference. The values of detrended time series will change according to the chosen reference year (i. e. could be even higher in ten years, where the reference year is for example 2030).

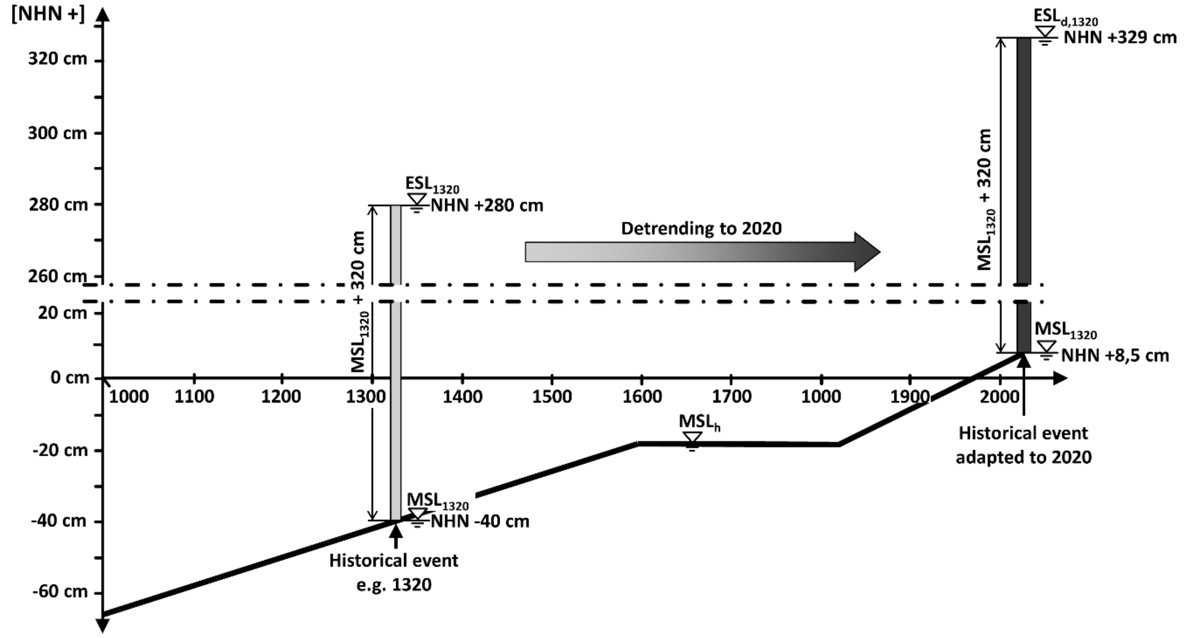


Figure 14: Illustration of detrending historical extreme sea level ($ESL_{d,h}$) by considering MSL changes.

Therefore, the values of detrending to 2020 result in MSL_{2020} − that is approximated by +8,5 cm − added to the corresponding MSL_h. This leads to a vertical shifting of the MSL curve for the estimation of detrending to MSL_{2020} , as shown in Figure 15.

Table 5 represents the values of MSL_h according to our best estimate MSL curve, where with the estimated trends MSL_h results rounded in NHN −62 cm at 1044, NHN −41 cm at 1304, NHN −40 cm at 1320 and NHN −18 cm at 1625, 1694, 1784 and 1872. The table also shows the values of extreme sea level after being detrended to MSL_{2020} namely $ESL_{d,h}$. That leads to a rounded value for the detrending of 70 cm for the storm surge 1044, 50 cm for 1304, 49 cm for 1320, 27 cm for 1625, 1694, 1784 and 26 cm for 1872.

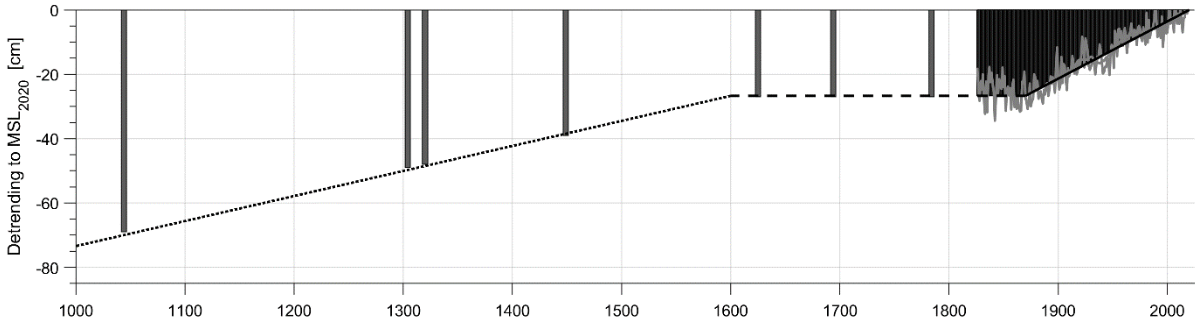


Figure 15: Values of detrending due to a vertical shifting of the estimated MSL-curve by the value of MSL_{2020}.

Table 5: Detrending of ESL$_{h}$ to MSL$_{2020}$ by the change of MSL; including MSL$_{h}$.

Date	**ESL$_{h}$ MSL + [cm]**	**MSL$_{h}$ NHN+[cm]**	**ESL$_{h}$ NHN+[cm]**	**Detrending to MSL$_{2020}$ [cm]**	**ESL$_{d,h}$ NHN+[cm]**
?.?. 1044	>250	−62	>188	70	>258
01.11.1304	>250	−41	>209	50	>259
30.11.1320	310-320	−40	270-280	49	319-329
15.-16.10.1449	>250	30	220	39	259
10.02.1625	280 – 315	−18	262 – 297	27	289 – 324
10./11.01.1694	265 – 286	−18	247 – 290	27	274 – 317
28.02 – 01.03.1784	250	−18	232	27	259
11./13.11.1872	**332** – 347	−18	**314** – 329	26	**340** – 355

in bold we present our recommendation

In the Annex, all ESLs since 1826 along with the detrended values (ESL$_{d2020}$) and the MSL$_{19a}$ are provided. Due to the 19-year moving averages, there´s no information for the first and last 9 years. The ESL$_{h}$ and ESL at Travemünde gauge before and after detrending are shown in Figure 16. As historical data, we decided to display the mean value from the range of possible values of each event, so one can easily convert values to one's preferences. As can be seen, three storm surges have values over three meters NHN. The highest surge is still the storm surge of 1872 with at least NHN +340 cm, followed by the storm surge of 1320 with respectively NHN +319 to 329 cm and 1625 with NHN +289 to 324 cm. Consequently, after detrending the data to reference year 2020, the flood of 1872 does not represent a singular event. The historical flood events in the Table 5 rather represent the collective of extreme events, which, however, have not been reached since 1872 (see also Figure 16). This statement is independent of the uncertainties of measuring historical water levels and the reconstruction of the historic MSLR (see also Figure 10).

It is important to note that most likely at least a total of 8 events with maximum water levels of NHN +250 cm and 3 with maximum water levels of NHN +300 cm (related to MSL$_{2020}$) have occurred in Travemünde in the last 1000 years.

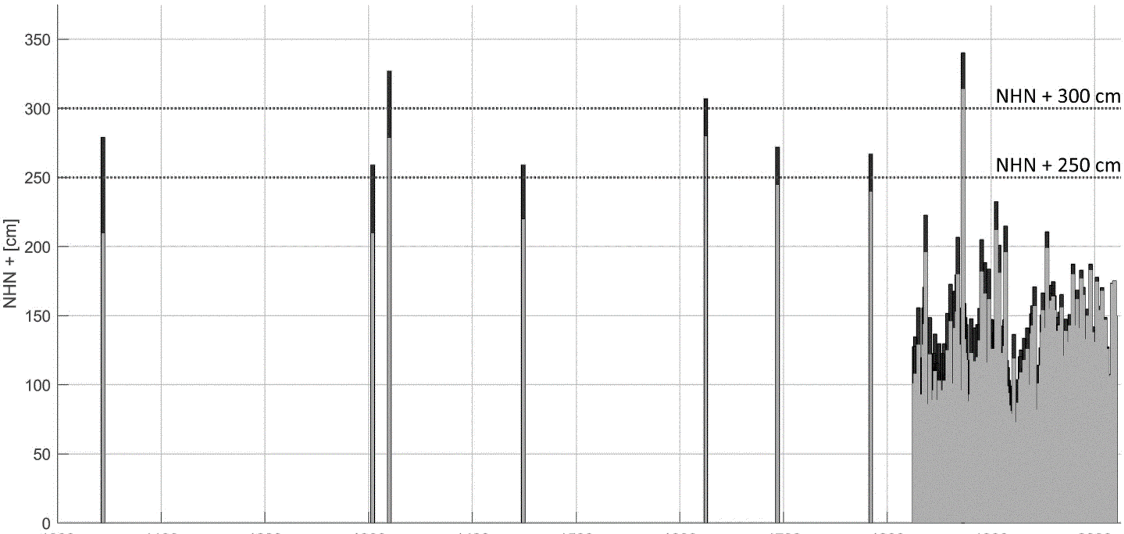


Figure 16: Detrending the MSLR of historical storm surges ESL$_{h}$ and annual ESL at Travemünde gauge.

7 Outlier Test

Finally, an outlier test is performed to evaluate the singularity of the storm surge of 1872. Outliers are data points that depart significantly from the trend of the remaining data, e. g. water levels caused by different processes than the rest of the data sample. Inclusion of outliers can significantly affect the statistical parameters computed from the data, especially for small samples. Therefore, any procedure of treating outliers requires judgment involving both mathematical and hydrologic considerations (England et al. 2018).

The discussion of whether the 1872 storm surge was an outlier is more of a theoretical or statistical question than a physical based. Factually, the storm surge of 1872 is the highest storm surge over the period of about 1000 years. But within these thousand years some storm surges occurred (e. g. in 1044, 1304, 1320, 1449, 1625 and 1694), which were most likely only a few decimeters lower than the storm surge of 1872 (see Table 5). Regardless of the quality or uncertainty of the height of historical storm surges, it would then be necessary to examine which of the historical storm surges should be considered outliers and which should not (e. g., only the 1872 storm surge?).

For this purpose, it is necessary to create an extended time-series for the time span until at least 1044. DVWK (1999) proposes an approach that transfers the detrended systematic data-series to the historical period in respect to historical ESL, that is adapted for this analysis. Thus, basing on the annual maxima time-series of ESL, a fictional time-series dating back until year 1000 was created, as seen in Figure 17. A similar approach using a Monte-Carlo simulation is used in MacPherson (in prep.). The extension of the systematic data to the historical period is accompanied by the assumption that basic boundary conditions in the hydrological system have not changed fundamentally within the last 1,000 years. This hypothesis is not unrestrictedly valid due to climate changes and changes in bathymetry, but in mean, it seems to be an acceptable assumption.

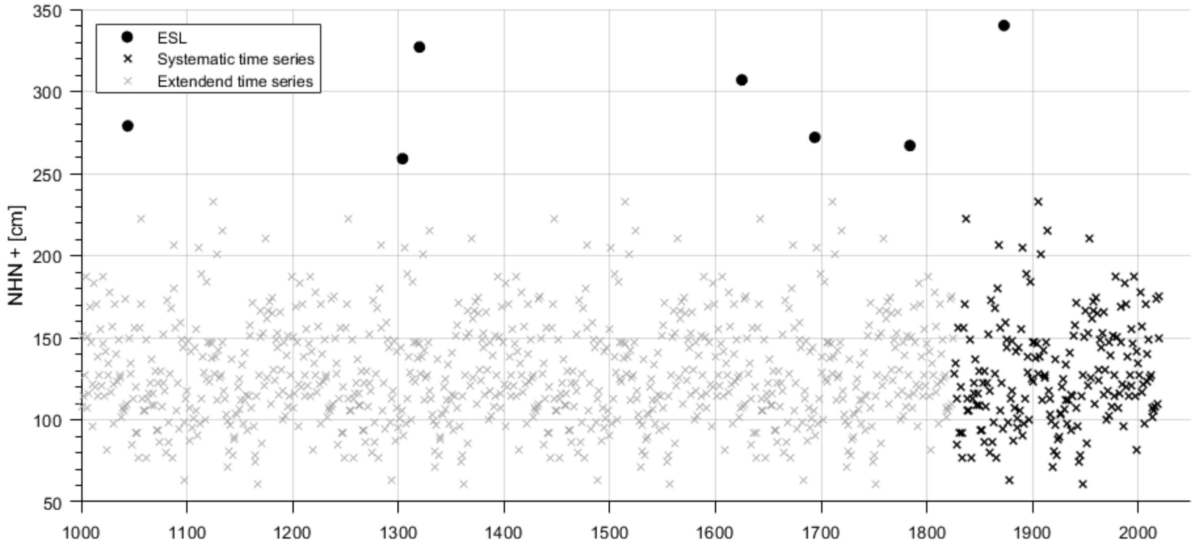


Figure 17: Generated database by the extension of the systematic data to the historical period.

To check for an outlier, the generalized extreme value density function (GEV), that is valid for Block Maxima, is derived from the sample of the database. The statistical parameters can be calculated as usual from the created database. Therefore, the maximum likelihood estimation is used to estimate the parameters. An outlier can thus be determined by exceeding a defined probability. Furthermore, no clear definition in extreme value statistics for the identification of an outlier is clearly recommended. In this context, statistical outliers are defined by the subjectively determined deviation from the mean or median. Furthermore, and for the description of the characteristic values of the distribution function, a boxplot is also presented. Here, an outlier is a value that is more than 2.5 times the interquartile range away from the bottom (25th- percentile) or top (75th percentile) of the box (see Figure 18).

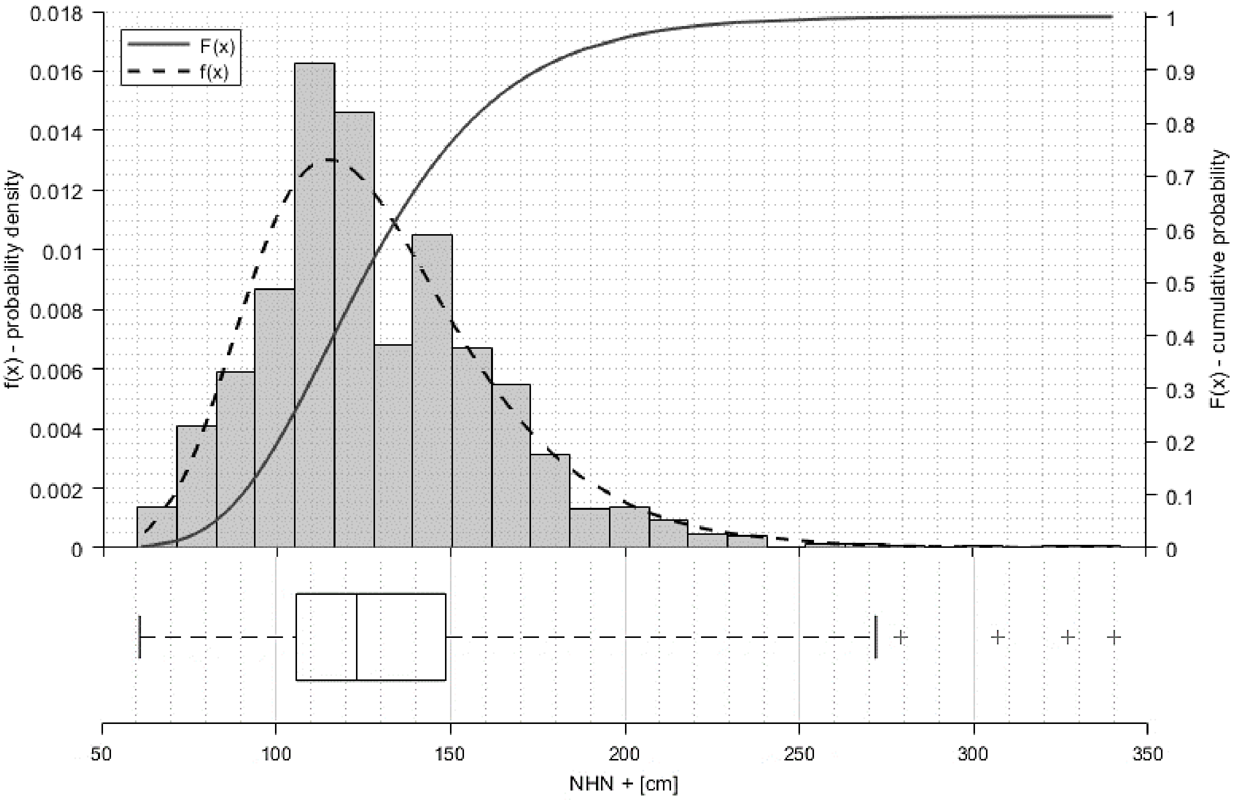


Figure 18: Histogram and probability density function of the extended dataset. The probabilities are classified in the boxplot. Values that exceed 2.5 times the interquartile distance are so-called outliers.

By our statistical definition of outliers, the four highest storm surges are defined as statistical outliers: 1044, 1320, 1625 and 1872. From the scientific (hydrologic) point of view, there's no indication for calling these events outlier, since these originate from similar genesis. Hence, these historical storm surges should be taken into account in the assessment to describe the population of ESL, especially at the Baltic Sea, where of information of intense ESL is rare. Historical events are the most valuable information to improve the statistical assessment (Mudersbach and Jensen, 2009). Hence, excluding historical ESL is a waste of high valuable information. All available relevant information should be used to derive the design values.

Black and grey swans is a popular concept within risk management. The term black swan was stated by economist Nassim Nicholas Taleb to symbolize an extremely unlikely, unpredictable event with major impact. A grey swan is an event with major impact, but which possibly could be predicted. As shown, the 1872 storm is a grey swan. If it has happened before it can happen again, and we need to remind ourselves about that once in a while, even though we do not necessarily have to design for it (Fredriksson et al. 2016). Finally, the question arises, lessons learned?

8 Conclusions and recommendations

In this paper, historical storm surges of the last 1,000 years were re-evaluated in terms of water levels (MSL & ESL) and related to the German reference datum NHN and to MSL. In addition, the annual maxima of the storm surges were updated since the beginning of the regular tide gauge recordings from 1826 until 2020 for the Travemünde gauge.

MSLR and extreme storm surges are considered to be one of the major risks for coastal areas. In order for coastal protection measures to be effective and to cope with the impact of climate change and within MSLR, the knowledge of the development of MSL is of great importance. Therefore, MSL changes since year 1000 were analyzed and then a best estimate was suggested to help with the classifying of historical storm surges. As one important fact was concluded, that MSL is equal to NHN between 1961 and 1973. This fact makes referencing of historical water levels more precise and helps with detecting and quantifying changes in the development of MSL.

The specifications for flood protection or safety against flooding, the required design values and the precautionary measure due to climate change remain an important basis for life on the coast. The frequency of ESLs in the Baltic Sea is considered to be low compared to the North Sea, which can be explained by the complexity of the meteorological effects that causes storm surges in this region, which is why long-time sea level series are necessary for a representative statistical analysis. So far, the most devastating storm surge that ever hit the Baltic Sea in 1872 has been excluded from statistical analysis. The design heights on the German Baltic Sea coast are based in both Schleswig-Holstein and Mecklenburg-Vorpommern on a statistical approach with a return period of T = 200 years (e. g. (MELUR 2013 and 2022, EU Flood Directive 2007). After classifying and detrending all historical storm surges, we determined that 1872 might not be an outlier as usually assumed and other historical storm surges maybe almost as high as 1872. According to initial estimates, a return period of between almost T = 500 and 1000 years for the Travemünde gauge can be assumed empirically for the storm surge event of 1872 if historical storm surge events are taken into account (see also Jensen and Töppe 1990).

The crucial question for coastal protection measures is how the design sea level (DSL) is determined and which methodological approaches or data are used for this purpose. This determination can also be risk-based and adhere to economic considerations. The design water levels for coastal protection do not necessarily have to be based on the highest storm surge water levels that have ever occurred. However, all available relevant information should be used to derive the design values. Especially for disaster management or possible evacuations, including historical events are important to avoid fatalities due to flooding. In this respect, we recommend using all available information on historical storm surges in terms of height and duration. Also for extreme value analyses for the estimation of design water levels, it is recommended to consider all saved data and historical water levels and the consequences of climate change, e. g. sea level rise.

According to the IPCC Special Report on the Ocean and Cryosphere (SROCC) in 2019, global MSLR will further accelerate in future (Oppenheimer et al. 2019). The German coastal states have agreed to use the IPCC-scenario with the highest adaptation needs for long-term precautionary planning along the coasts. For this SSP5-8.5 scenario, projections for MSLR until 2100 relative to a baseline of 1995-2014 at the gauge Travemünde range from 0.59 to 1,16 m (0.84 m likely range) (https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool). The average rate of sea level rise by the end of this century may reach about 12 (7.8 to 18.0) mm/a at the gauge Travemünde for the SSP5-8.5 scenario. This is more than six times as high as observed over the last century and four times as high as today (e. g. Dangendorf et al. 2022).

Especially after the catastrophic flood events in the Eifel and in the Ahr valley in July 2021 with 189 dead, the relevance of considering historical extreme events has been tragically proven. According to the relevant recommendations (e. g. DWA 552), both the spatial and the temporal context or the corresponding information extension, i. e. also the consideration of historical events, must be taken into account when determining design events.

Thus, a time series of ESL was elaborated, which covers most of the historical floods in the southwestern Baltic Sea. This time series could be used e. g. by the so-called integrated extreme value statistics (e. g. Schumann 2007) in further studies to improve the statistical extreme value analyzes (e. g. MacPherson et al. 2019, MacPherson et al. in prep.) in order to derive a more reliable design height. In addition, a climate surcharge (currently 1.0 m in Germany along the Baltic Sea) and its interaction with storm surges, must be considered for future risk management and coastal protection measures.

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10 Annex

Cal. Year	ESL NHN + [cm]	ESL_{d2020} NHN + [cm]	MSL_{19a} NHN + [cm]
1826	101	127.7	-
1827	108	134.7	-
1828	58	84.7	-
1829	86	112.7	-
1830	129	155.7	-
1831	65	91.7	-
1832	93	119.7	-
1833	65	91.7	-
1834	50	76.7	-
1835	129	155.7	−16.0
1836	144	170.7	−16.4
1837	196	222.7	−16.2
1838	86	112.7	−16.0
1839	79	105.7	−16.1
1840	79	105.7	−15.8
1841	122	148.7	−16.0
1842	50	76.7	−15.6
1843	86	112.7	−15.5
1844	89	115.7	−15.7
1845	96	122.7	−15.3
1846	110	136.7	-15.6
1847	82	108.7	-15.9
1848	89	115.7	-16.4
1849	82	108.7	-16.6
1850	103	129.7	-16.5
1851	67	93.7	-16.7
1852	67	93.7	-16.4
1853	96	122.7	-16.5

Cal. Year	ESL NHN + [cm]	ESL$_{d2020}$ NHN + [cm]	MSL$_{19a}$ NHN + [cm]
1854	60	86.7	-16.9
1855	103	129.7	−17.1
1856	81	107.7	−17.7
1857	96	122.7	−18.1
1858	125	151.7	−17.9
1859	91	117.7	−18.2
1860	53	79.7	−17.9
1861	146	172.7	−18.3
1862	60	86.7	−18.1
1863	72	98.7	−18.4
1864	101	127.7	−18.7
1865	141	167.7	−18.5
1866	50	76.7	−18.8
1867	153	179.7	−18.6
1868	180	206.7	−18.9
1869	129	155.7	−18.8
1870	79	105.7	−18.3
1871	96	122.5	−18.1
1872	68	94.3	−17.7
1873	314	339.2	−17.7
1874	133	159	−17.5
1875	123	148.8	−17.1
1876	118	143.6	−17
1877	73	98.5	−17.3
1878	38	63.3	−17.4
1879	88	113.1	−17.8
1880	93	117.9	−17.6
1881	123	147.7	−17.3
1882	63	87.6	−17.1
1883	83	107.4	−16.9
1884	117	141.2	−16.7
1885	71	95	−16.4
1886	77	100.9	−16
1887	120	143.7	−15.7
1888	82	105.5	−16
1889	132	155.3	−15.8
1890	67	90.1	−15.2
1891	182	205	−15.1
1892	75	97.8	−15
1893	90	112.6	−14.8
1894	166	188.4	−14.3
1895	116	138.3	−14
1896	107	129.1	−13.4
1897	78	99.9	−13
1898	162	183.7	−12.8
1899	103	124.5	−12.9
1900	126	147.4	−12.6
1901	102	123.2	−12.3
1902	126	147	−12
1903	117	137.8	−11.9
1904	126	146.6	−11.4
1905	212	232.5	−11.2
1906	108	128.3	−11.1
1907	118	138.1	−10.6
1908	181	200.9	−10.7
1909	92	111.8	−11.1
1910	123	142.6	−10.8
1911	106	125.4	−10.4
1912	108	127.2	−9.9
1913	128	147	−9.6
1914	196	214.9	−9
1915	99	117.7	−9
1916	94	112.5	−8.6
1917	85	103.3	−8
1918	81	99.2	−7.3
1919	53	71	−7.3
1920	63	80.8	−7.2
1921	79	96.6	−7.1
1922	119	136.4	−7
1923	61	78.3	−7.1
1924	71	88.1	−7.1
1925	73	89.9	−7.1
1926	87	103.7	−7.1
1927	87	103.6	−6.8
1928	104	120.4	−6.6
1929	109	125.2	−6.3
1930	90	106	−6.1
1931	96	111.8	−6.2
1932	118	133.7	−6.8
1933	82	97.5	−7.2
1934	97	112.3	−7.2
1935	126	141.1	−7.7
1936	100	115	−7.9
1937	79	93.8	−8
1938	100	114.6	−8.2
1939	137	151.4	−7.9
1940	143	157.2	−7.6
1941	93	107.1	−7.3
1942	157	170.9	−7.5
1943	82	95.7	−6.9
1944	61	74.5	−6.3
1945	65	78.4	−6.2
1946	101	114.2	−5.8
1947	48	61	−5.3
1948	114	126.8	−5.2
1949	138	150.6	−4.8
1950	154	166.5	−4.6
1951	73	85.3	−4.1
1952	141	153.1	−3.4
1953	109	120.9	−2.9

Cal. Year	ESL NHN + [cm]	ESL_{d2020} NHN + [cm]	MSL_{19a} NHN + [cm]
1954	199	210.7	−2.6
1955	114	125.6	−2.4
1956	150	161.4	−2
1957	155	166.2	−1.3
1958	161	172	−0.8
1959	99	109.9	−0.6
1960	164	174.7	−0.4
1961	154	164.5	0.2
1962	120	130.3	0.2
1963	114	124.1	0
1964	139	149	0.5
1965	134	143.8	0.5
1966	143	152.6	0.5
1967	106	115.4	0.5
1968	156	165.3	0.4
1969	121	130.1	0.7
1970	91	99.9	0.8
1971	109	117.7	0.6
1972	139	147.5	1
1973	94	102.4	1.1
1974	131	139.2	1.5
1975	100	108	1.5
1976	143	150.8	1.5
1977	107	114.7	1.4
1978	120	127.5	1.5
1979	180	187.3	1.8
1980	143	150.1	2.2
1981	100	106.9	2.5
1982	109	115.8	2.6
1983	162	168.6	2.6
1984	141	147.4	2.5
1985	115	121.2	2.3
1986	90	96.1	2.7
1987	177	182.9	2.6
1988	114	119.7	2.5
1989	165	170.5	2.7
1990	133	138.3	2.9
1991	109	114.2	2.5
1992	122	127	2.9
1993	150	154.8	3.1
1994	116	120.6	3.4
1995	142	146.5	3.5
1996	183	187.3	3.7
1997	110	114.1	3.6
1998	138	141.9	4.1
1999	78	81.7	3.8
2000	131	134.6	3.7
2001	124	127.4	4.1
2002	174.6	177.8	4.2
2003	114	117	4.6
2004	154	156.8	4.9
2005	119	121.7	4.7
2006	95	97.5	5.1
2007	168	170.3	5.3
2008	138	140.1	5.8
2009	121	123	6.1
2010	147	148.8	6.4
2011	124	125.6	6.8
2012	126	127.4	-
2013	100	101.2	-
2014	106	107.1	-
2015	105	105.9	-
2016	107	107.7	-
2017	173	173.5	
2018	109	109.4	
2019	175	175.2	-
2020	150	150	-