92
2022

Journal für Forschung und Praxis
im Küsteningenieurwesen an Nord- und Ostsee

DIE KÜSTE

Journal of Coastal Engineering Research
and Practice at the North and Baltic Sea

1872

An exceptional storm surge in the Baltic

GERMAN COASTAL ENGINEERING RESEARCH COUNCIL
KURATORIUM FÜR FORSCHUNG IM KÜSTENINGENIEURWESEN

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Publisher:
Federal Waterways Engineering Research Institute (BAW)
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P.O. Box 21 02 53, 76152 Karlsruhe
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Printed by: BSH Druckerei Rostock

Legal notice

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ISSN: 0452-7739
ISBN: 978-3-939230-83-0
DOI: https://doi.org/10.18171/1.092100

Hamburg, 2022, volume 92

Table of contents

Editorial

The journal Die Küste in transition

The journal Die Küste has been publishing articles on coastal engineering and coastal research since 1952 and in the predecessor journal Westküste from 1938 to 1943. Through more than eight decades of continuous publication, Die Küste/Westküste has become the knowledge archive for research and technology on the North Sea and Baltic Sea with almost 900 articles. Special issues of Die Küste have dealt with thematic topics such as the storm surges of 1962 and 1976, published regulations such as the recommendations of the Arbeitskreis für Küstenschutzwerke (EAK) or the Overtopping Manual EurOtop, and reprinted selected historical articles. The entire journal series from 1938 onwards is freely accessible as an open access publication. Since 2019 (Die Küste, issue 87), the individual articles are published online in advance and provided with DOI (Digital Object Identifier: identifier for digital publications).

After this long and impressive success story of Die Küste, a modernisation of Die Küste has been initiated in recent years in line with changing boundary conditions for publications and requirements for scientific publications. The contributions in German, which were previously unlimited in length, are now limited to about 30 pages in Die Küste, and preference will be given to contributions in English. The aim is to maintain Die Küste as a relevant specialist publication for German coastal engineering and coastal research, while at the same time developing it into an internationally recognised peer-reviewed journal. Therefore, the Chief Editor is supported by an Editorial Board, which will ensure peer review of the submitted articles. The publication process is now organised via a professional software tool. Die Küste as an "Archive for Research and Technology at the North and Baltic Sea" will become the "Journal of coastal engineering research and practice at the North and Baltic Sea" with a new cover and design.

1872 - An exceptional storm surge in the Baltic

In November 2022 it has been 150 years since the catastrophic storm surge from the 12th to 14th November in 1872 struck the Baltic Sea coasts of Denmark, Germany, and the South of Sweden. An extreme storm surge in combination with high waves resulted in the death of about 300 people and even in Schleswig-Holstein more than 15,000 people lost their homes. Locally, the water level rose to about 3.4 m above Mean Sea Level (MSL), which is extraordinary high for this region with almost no influence of astronomical tides. Since 1872 there has been no storm event of the same magnitude. In fact, the water level record from Travemünde, dating back to the 1820s, states that the maximum water level during the 1872 storm was approximately one meter higher than all observations thereafter.

It is an ongoing discussion in the affected countries whether the 1872 storm should be considered as a design storm event, or whether it was a unique event. Historical records from Germany and Denmark suggest that there have been extreme storm surges during the 14th and 17th centuries. Therefore the question is, what lessons are or perhaps should be learned from the catastrophe in 1872. Another question is, when the need for climate change adaptation is increasing. There is also an increased need to determine relevant design values applicable for the timescale of interest.

This exceptional storm surge in the Baltic was the background for the 150th memorial conference "Baltic storm surge 1872" from 12th - 14th November 2022. The first 2 days of the conference there was a very interesting pre-tour with field trips from Copenhagen to Rostock along the Baltic coast to historical flood sites in Denmark (Copenhagen, Køge Bugt Beach Park, Nykøbing Falster, Kramnitse) and Germany (Burg/Fehmarn, Dahme, Timmendorfer Strand, Lübeck, Rerik and Heiligendamm). On 12th and 13th there were dinner talks on specific topics given by Jacobus Hofstede and Frank Weichbrodt following excursions and finally on November 13th there was a banquet as a memorial dinner.

The conference with about 100 participants was held at the University of Rostock on November 14th, 2022.

Welcome addresses were given by Frank Thorenz (KFKI) and Minister Dr. Till Backhaus (Ministerium für Klimaschutz, Landwirtschaft, ländliche Räume und Umwelt des Landes Mecklenburg-Vorpommern). Thereafter the conference was opened by Carolin Hallin and me.

In the first session, chaired by Carolin Hallin, regional talks were presented:

- 1872 in Schleswig-Holstein: the beginning of public coastal flood defense (Jacobus Hofstede)
- 1872 in Mecklenburg-Vorpommern, The storm surge 1872 - a landmark event for coastal protection in M-V (Frank Weichbrodt)
- 1872 in Denmark: 1872, what if a number becomes reality again? (Per Sørensen)
- 1872 in Sweden - the forgotten storm (Caroline Hallin)

In the second session, chaired by Arne Arns, the following thematic talks are given:

- Best estimates for historical storms surges over the last 1000 years (Jürgen Jensen)
- Improved estimates of coastal extreme water levels along the German Baltic Sea coast using historical information (Leigh McPherson)
- Geomorphological proof of 1872 (Aart Kroon)
- The risk of forgetting. Flood protection at the Baltic Sea coast through remembrance and commemoration (Laura Tack)
- How does memories of the 1872 influences todays risk perceptions and flood protection? (Nina Baron)

A concluding panel discussion, moderated by Ingrid Holzwarth, rounded off the event. In the closing ceremony, I took the opportunity to thank all participants and sponsors with very personal words.

Special Edition Die Küste, issue 92

On the occasion of the 150th memorial of the 1872 storm surge, this special edition of Die Küste is released with the title "1872 - An exceptional storm surge in the Baltic". It compiles articles on the storm surge from November 12th to 14th November, historical storm surges (e. g. 1320, 1625) as well as on coastal zone management today and in the future. This edition of Die Küste also includes an English translations of what are probably the most important historical works on the 1872 Baltic storm surge: a complete translation of an article from, 1875 by Baensch and a comprehensive summary of an article by Colding. While the work of Baensch (1875 is valued today primarily for its collection of a huge number of meteorological and hydrological reliable data, Colding's paper (1881) derives its importance from the physical theories presented therein. Therefore, Colding used all available data on the storm surge of 1872, especially those collected by Baensch, to modify his ideas on sea level response to wind and confirmation of his theories.

I hope you enjoy reading the special edition of Die Küste!

Jürgen Jensen
(Chief Editor Die Küste)

November 2022

Die Küste, 92, 2022 https://doi.org/10.18171/1.092102

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).

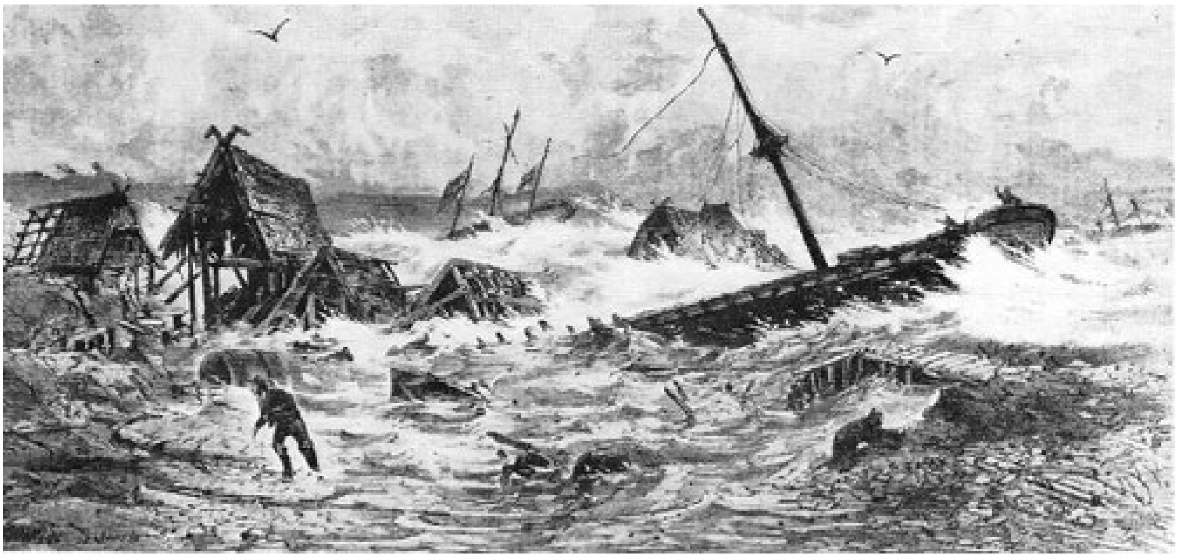

Figure 1: The damage caused in Haffkrug located at Lübeck Bay/German Baltic Sea Coast during the storm surge of November 1872 (Illustration: C. Rettich und C. Heyn).

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.

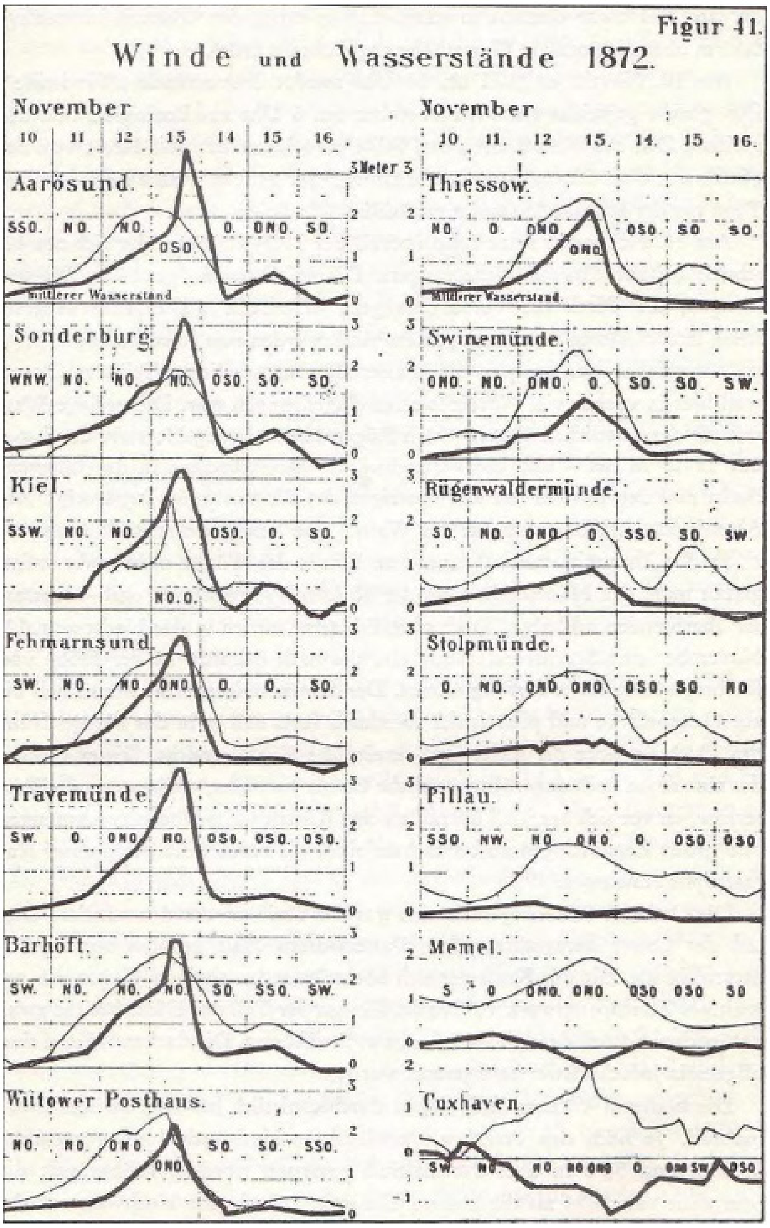

Figure 2: Sea level/hydrograph (above MSL) at different gauge stations along the Baltic Sea during the storm surge of November 1872 (after Lentz (1879) as in Kiecksee (1972) but the original reference is referred to Baensch (1875)).

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).

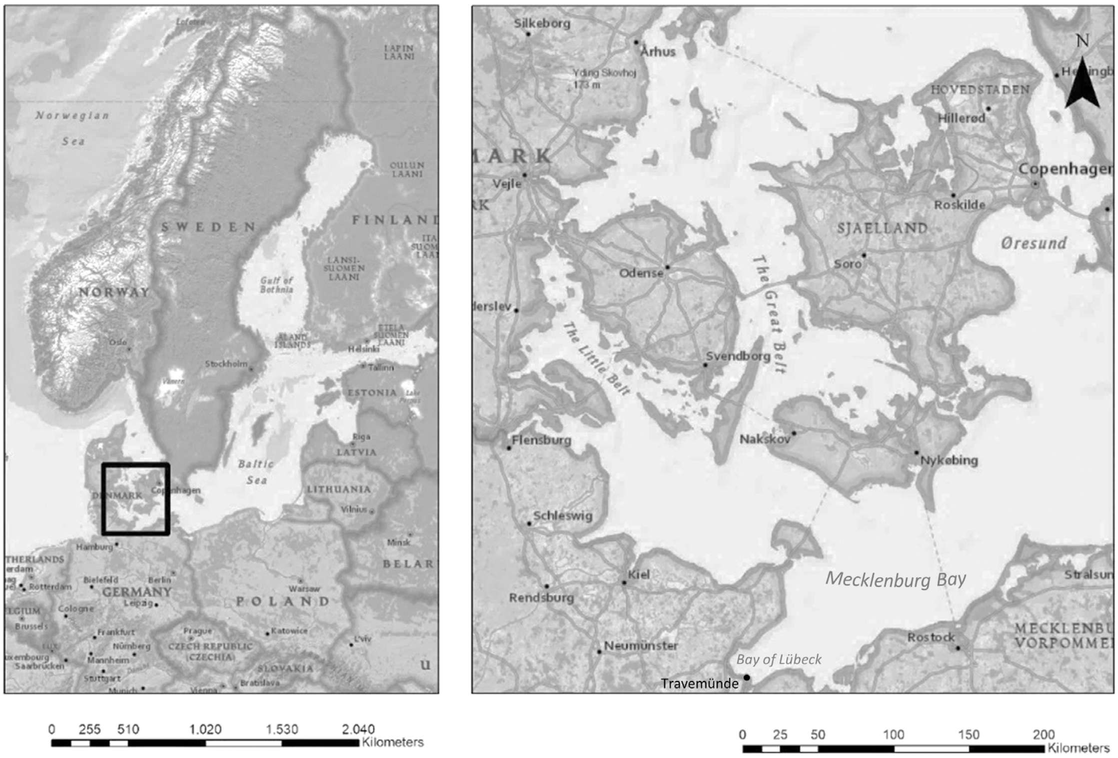

Figure 3: Map of the Baltic Sea. The figure on the left presents the Baltic Sea and its connections with the North Sea. The figure on the right shows a closer map of the southwestern Baltic Sea.

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.

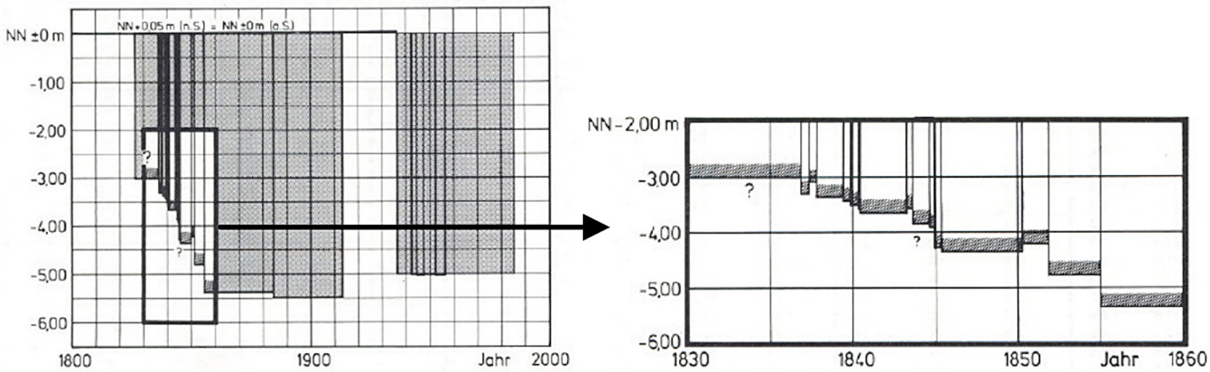

Figure 4: Diagram of gauge datum heights for the Travemünde gauge (?- uncertain datum heights; no changes have been noted in the original files) (Jensen and Töppe 1986).

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 $\triangleq$ 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).

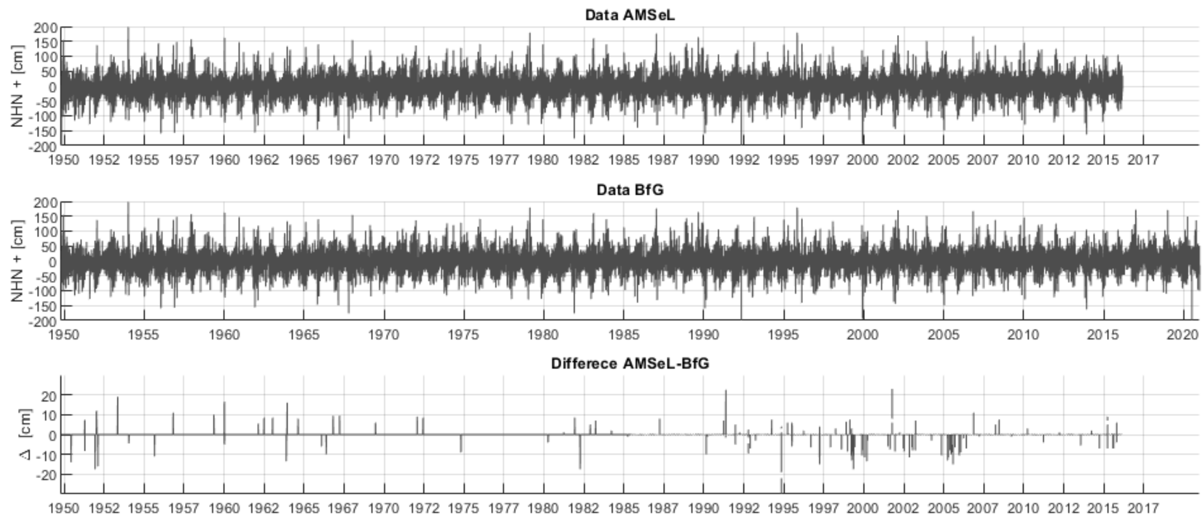

Figure 5: Water level differences between AMSeL-Ostsee and BfG hourly datasets since 1950.

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.

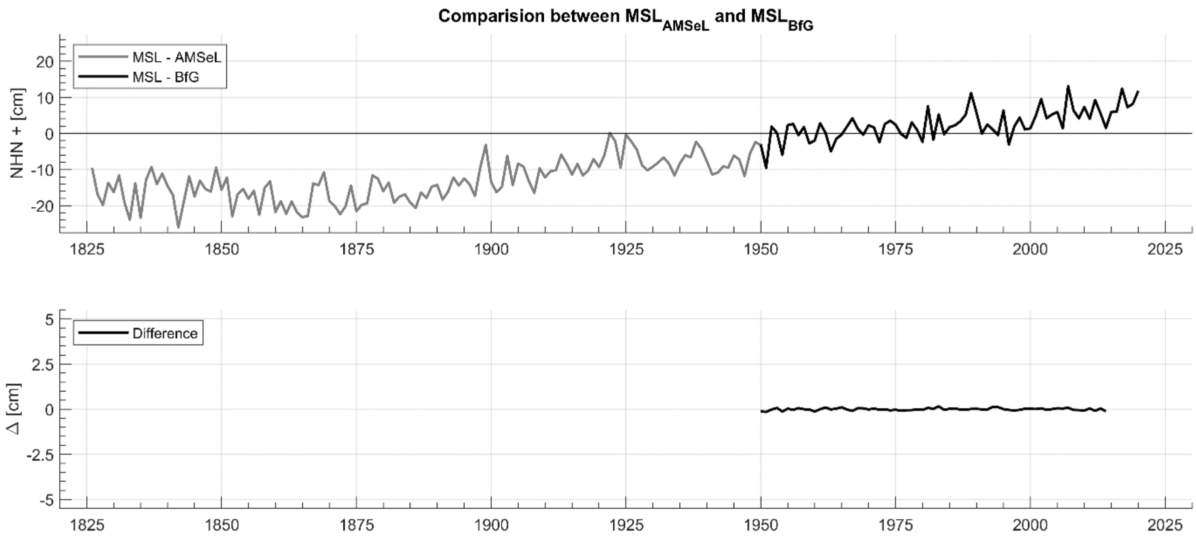

Figure 6: MSL development since 1826 at Travemünde gauge, where the figure above shows a comparison between MSL calculated from AMSeL_Ostsee and BfG datasets and the figure below illustrates the differences between the calculated MSL.

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.

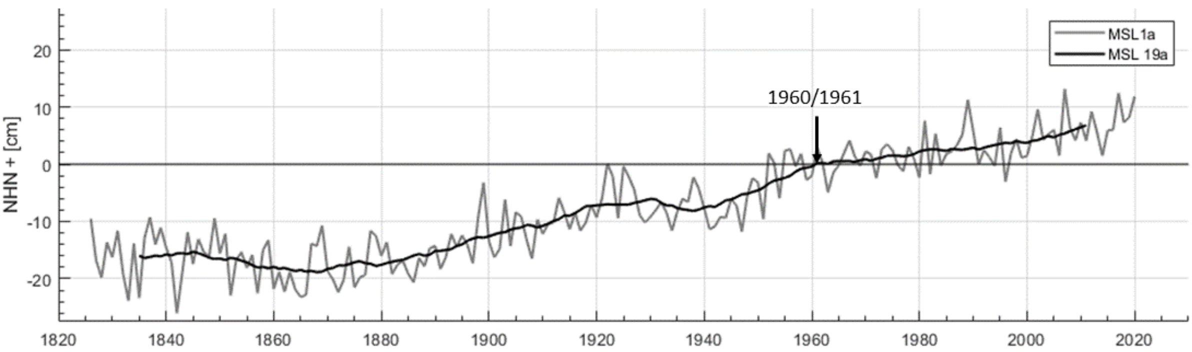

Figure 7: 1-year average and 19-year moving average of MSL data from year 1826 to 2020 at Travemünde gauge, which was equal to NHN in 1960/1961.

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.

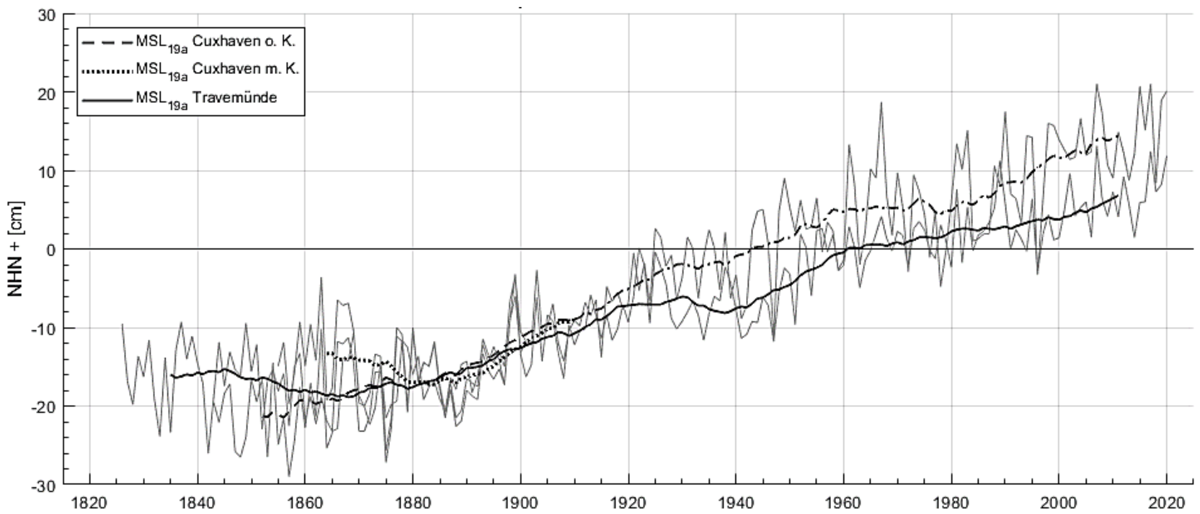

Figure 8: Comparison between the development of 19-year averaged MSL (MSL_{19a}) at Travemünde and Cuxhaven gauges.

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).

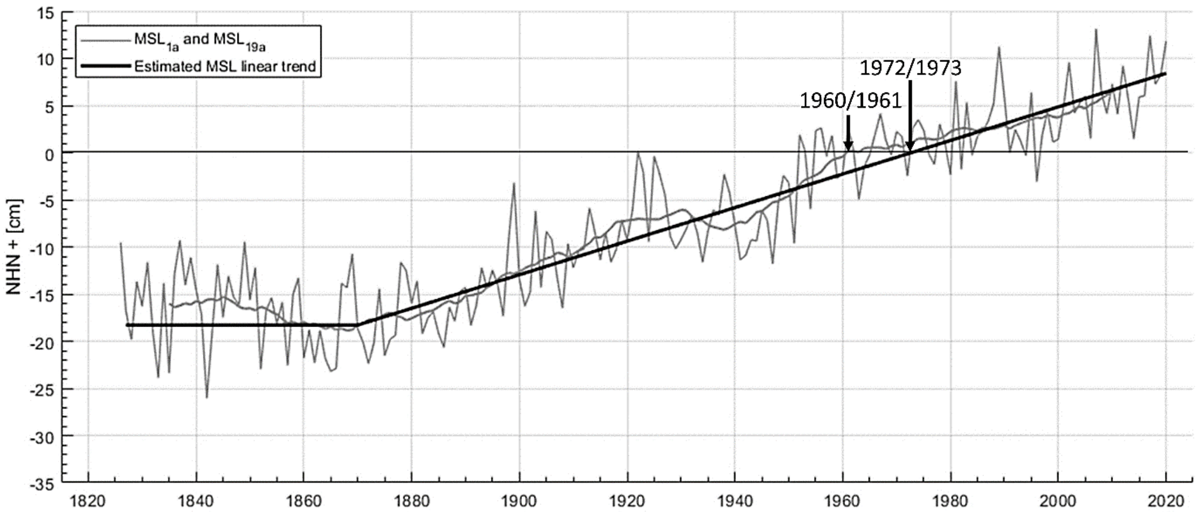

Figure 9: Estimated MSL linear trend (black bold line) and calculated 19 years MSL at Travemünde gauge from 1826 to 2020.

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.

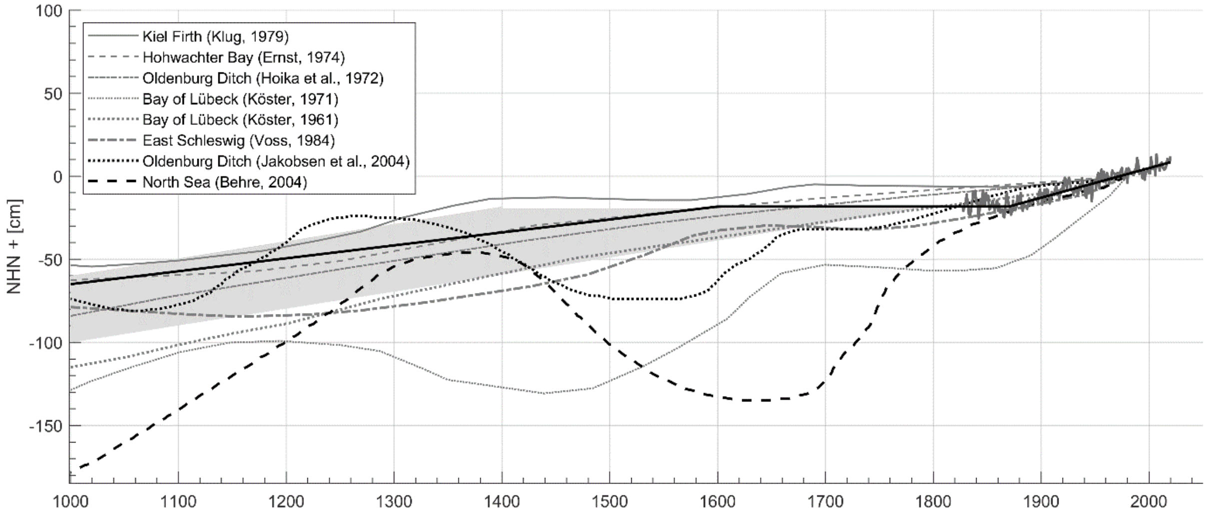

Figure 10: MSL estimation and uncertainties for possible variations of MSL development according to different references at the southwestern Baltic Sea since year 1000 and gauge records since 1826 in Travemünde gauge.

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)

 https://doi.org/10.18171/1.092102

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)

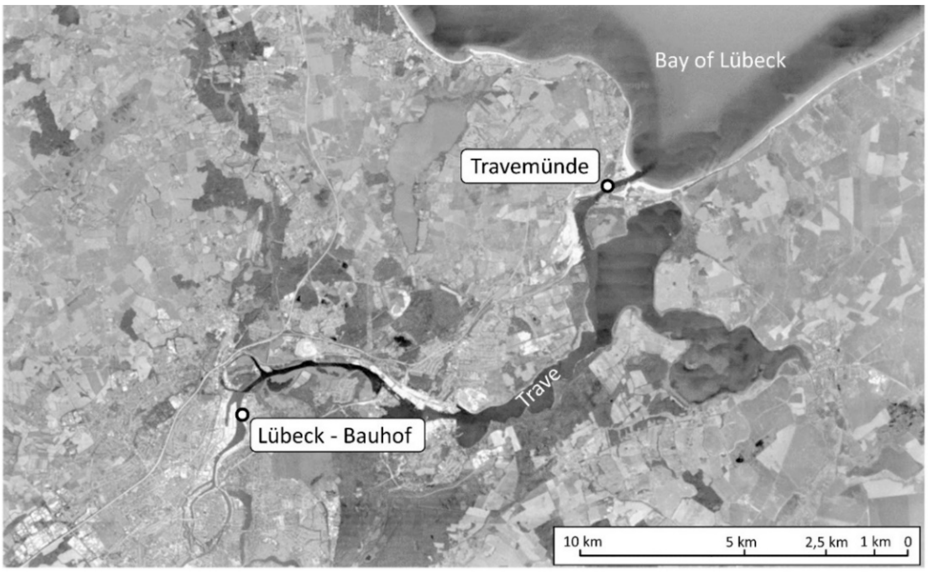

Figure 12: Geographical location of Travemünde- and Lübeck gauge stations (Google Earth).

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).

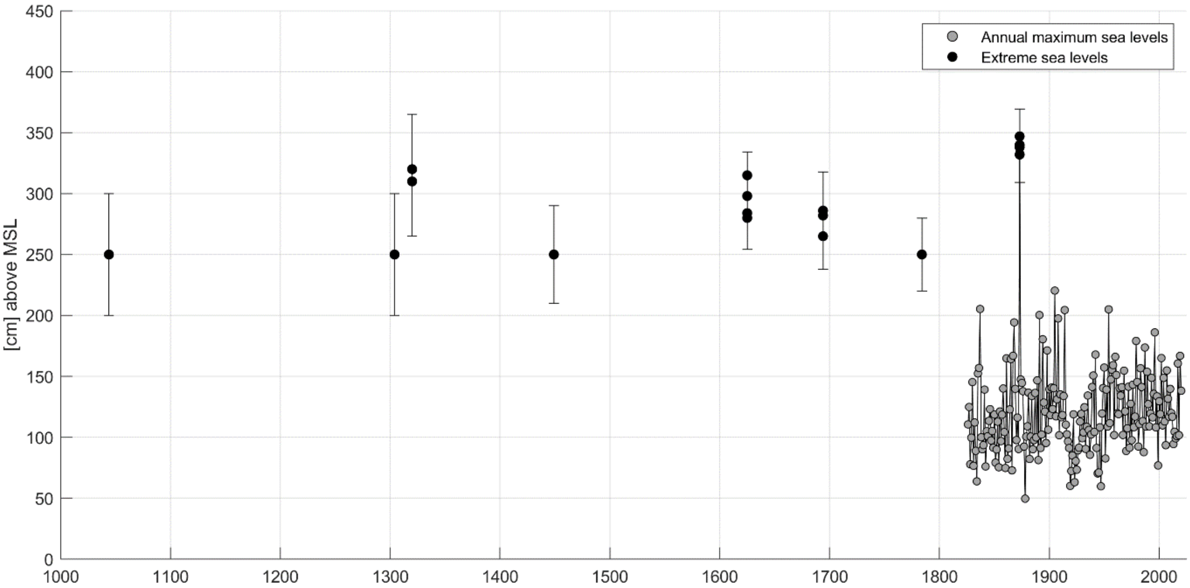

Figure 13: Historical storm surge levels since year 1044 and estimated uncertainties in peak water level at Travemünde gauge station.

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).

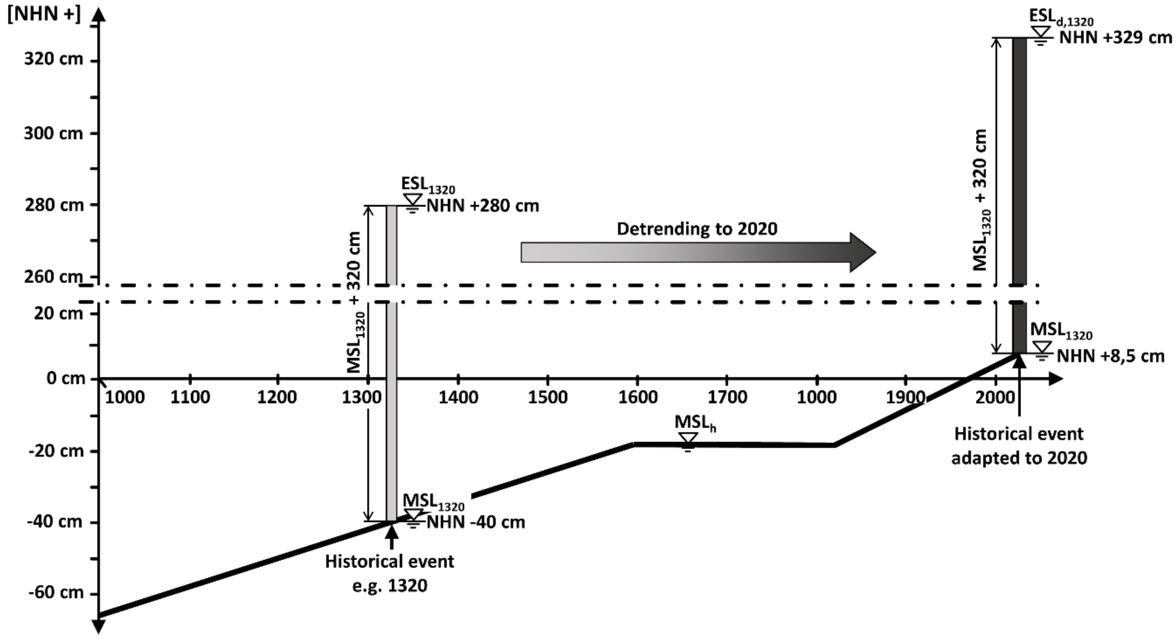

Figure 14: Illustration of detrending historical extreme sea level ($ESL_{d,h}$) by considering MSL changes.

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.

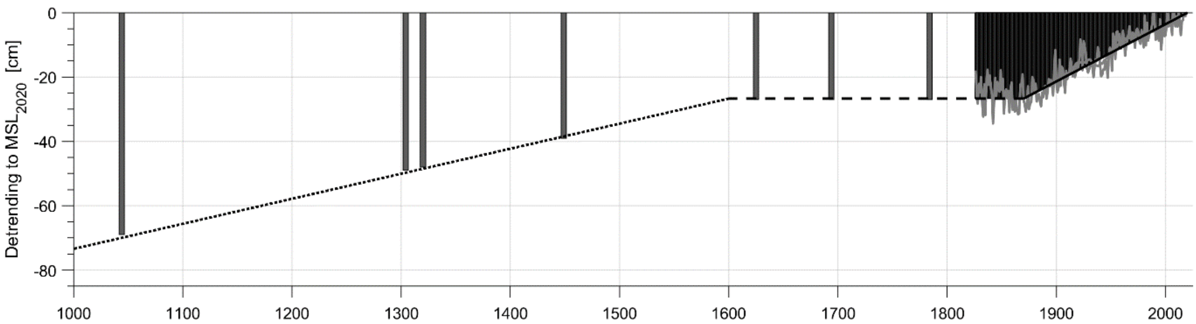

Figure 15: Values of detrending due to a vertical shifting of the estimated MSL-curve by the value of MSL_{2020}.

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.

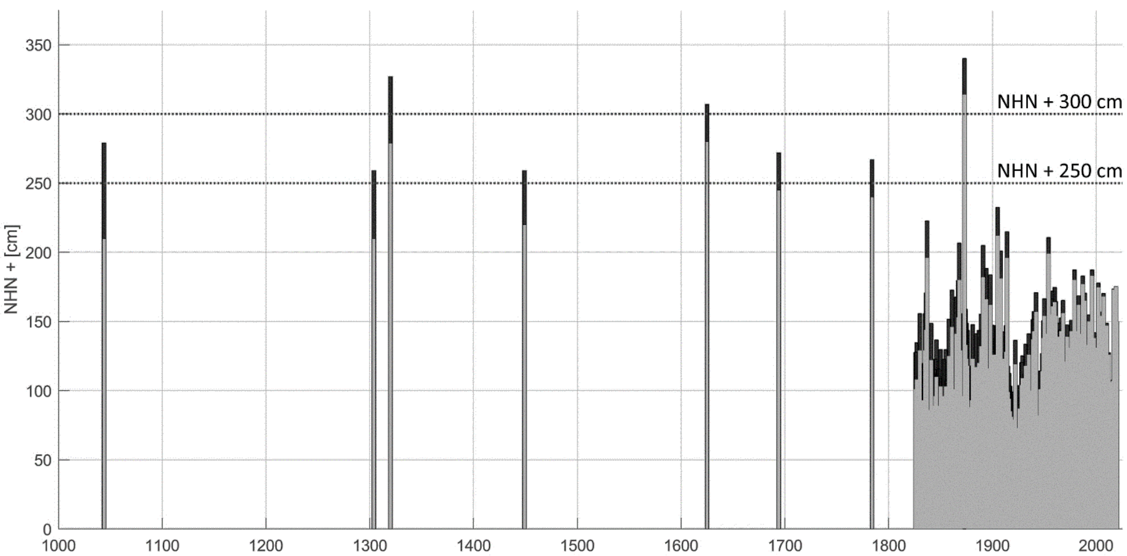

Figure 16: Detrending the MSLR of historical storm surges ESL_h and annual ESL at Travemünde gauge.

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.

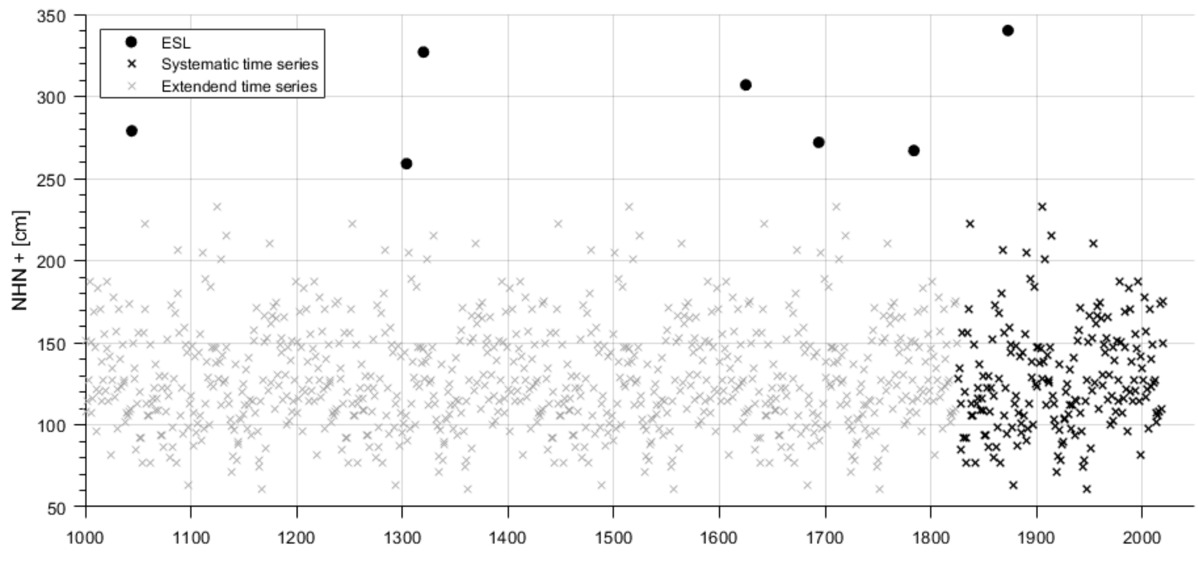

Figure 17: Generated database by the extension of the systematic data to the historical period.

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).

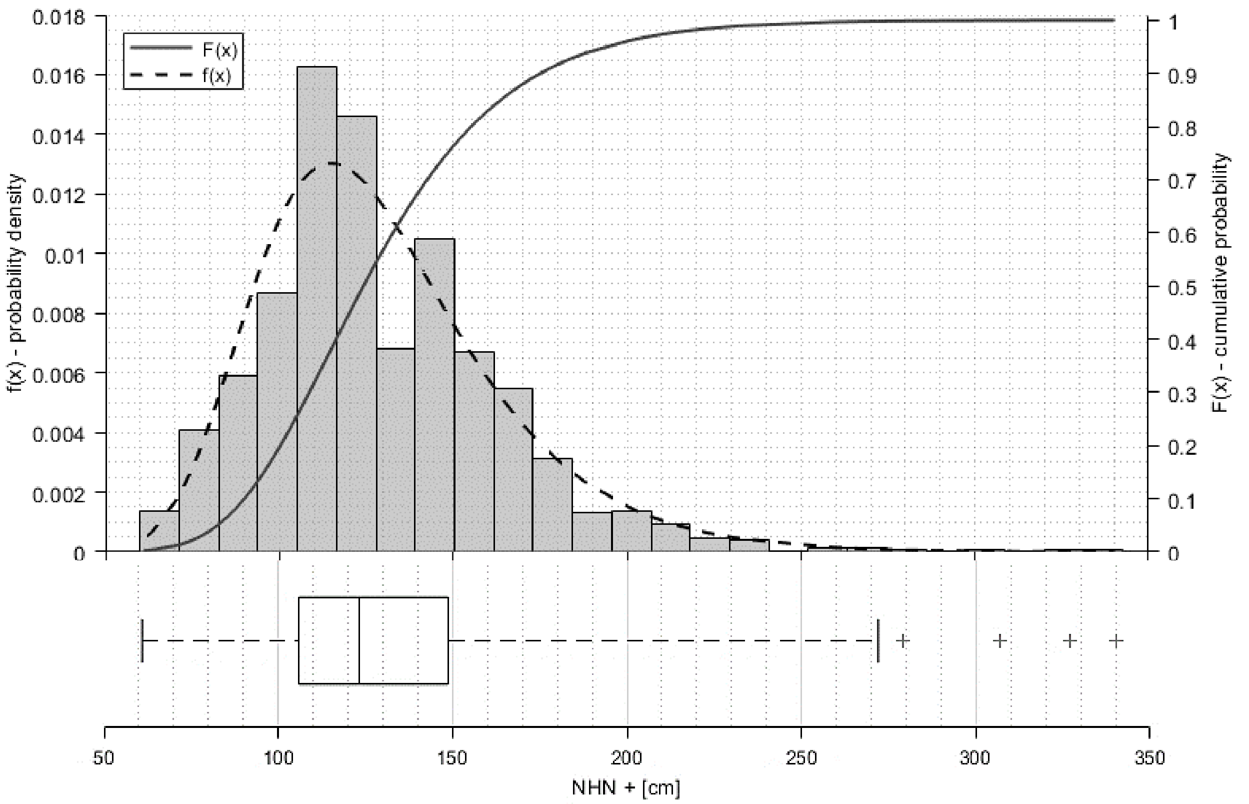

Figure 18: Histogram and probability density function of the extended dataset. The probabilities are classified in the boxplot. Values that exceed 2.5 times the interquartile distance are so-called outliers.

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

Cal. Year	ESL NHN + [cm]	ESL_{d2020} NHN + [cm]	MSL_{19a} NHN + [cm]
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

Cal. Year	ESL NHN + [cm]	ESL_{d2020} NHN + [cm]	MSL_{19a} NHN + [cm]
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

Cal. Year	ESL NHN + [cm]	ESL_{d2020} NHN + [cm]	MSL_{19a} NHN + [cm]
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	-

 https://doi.org/10.18171/1.092107

Preface to the translation of "Die Sturmflut vom 12./13. November 1872 an den Ostseeküsten des Preußischen Staates" (Mit Zeichnungen auf Blatt F bis P im Text) by Otto Baensch (* June 6th, 1825 in Zeitz; † April 7th, 1898 in Berlin)

The original article „Die Sturmflut 12./13. November 1872 an den Ostseeküsten des Preußischen Staates (Mit Zeichnungen auf Blatt F bis P im Text)" was published in German by Otto Baensch (actually Otto von Baensch) in the "Zeitschrift für Bauwesen" 1875 by Ernst & Kern in Berlin. This article is one of the most valuable and comprehensive publications on the catastrophic storm surge of November 1872, and the English translation is intended to make this authentic historical document of the time available to an international audience.

The extensive meteorological and hydrological data on the 1872 storm surge collected by Baensch with great quality have been incorporated in numerous publications that were published afterwards. E. g. the impressive work of Colding (1881), also presented in its English translation in this issue of "Die Küste", is based on the collection of Baensch reliable data. Colding's paper derives its importance from the physical theories. Therefore, he used all available data on the storm surge of 1872, especially those collected by Baensch, to modify his ideas on sea level response to wind. Based on his analysis of air pressure and the derived wind field data from Baensch, Colding was able to make an important contribution to the still lasting controversy about the cause of the extreme water levels during the storm surge of 1872. Recent publications on historical storm surges in the Baltic Sea, such as Jensen et al. (2022), also printed in this issue of Die Küste, also refer to Baensch's high-quality and very well-researched data.

The translation into English was prepared by Mrs. Michaela Stiller and produced by me with the support of Simon Beckmann, Christoph Blasi, Dr. Jacobus Hofstede, Rena Jensen and Dr. Gudrun Rosenhagen. The authentic character of this contemporary document should be preserved as much as possible, therefore the original drawings were not translated. I would like to sincerely thank all those involved for their support during the translation.

The following is to be noted regarding the remarkable career as an engineer and natural scientist of Otto Baensch (see Wikipedia, https://de.wikipedia.org/wiki/Otto_Baensch_(Ingenieur): Otto Baensch studied surveying and mathematics at the University of Halle from 1842 to 1847 and entered the Prussian civil service after attending the Berlin Bauakademie. In the early days, he was mainly engaged in the construction of churches in the province of Pomerania. After overseeing reconstruction work on Cammin Cathedral, he took charge of the new construction of Heringsdorf Church on Usedom in 1848. In 1855 he became a land architect in the administrative district of Legnica (Liegnitz). From 1858 he was construction manager of the Ruhr-Sieg Railway. Between 1852 and 1871, Otto Baensch was a hydraulic engineering inspector in Stralsund and Coeslin (Cöslin). During this time, he wrote, among other things, about harbour construction, lighthouses and dike construction.

After his transfer to the Prussian Ministry of Trade, Commerce and Public Works in Berlin, his tasks included the regulation of the Elbe and Rhine rivers, the canalization of the lower reaches of the Main River from Frankfurt to Mainz (1882 to 1885) and dike

 https://doi.org/10.18171/1.092107

construction in the province of Schleswig-Holstein. From 1886, he led the construction of the Kaiser Wilhelm Canal (1887 to 1895), today's Kiel Canal.

Otto Baensch was an honorary citizen of the city of Zeitz and was awarded the honorary title of “Geheimer Oberbaurat”. In 1895, Otto Baensch was awarded the personal title of nobility “Otto von Baensch” by the Kingdom of Bavaria, but he did not make use of it.

November 2022
Jürgen Jensen

The storm surge of November 12th–13th, 1872, on the Baltic coasts of Prussia

Baensch, Otto translated by Jürgen Jensen

Keywords

Baltic Sea, storm surges, damages, historical storm surges 1320, 1625 und 1872, water level, hydrotechnical and meteorological phenomena, historic units of measurement, Prussia

Schlagwörter

Ostsee, Sturmfluten, Schäden, historische Sturmfluten 1320, 1625 und 1872, Wasserstand, hydrotechnische und meteorologische Phänomene, historische Maßeinheiten, Preußen

Zusammenfassung

Der Originalartikel „Die Sturmflut vom 12./13. November 1872 an den Ostseeküsten des Preußischen Staates - Mit Zeichnungen auf Blatt F bis P im Text" wurde von Otto Baensch (eigentlich Otto von Baensch) in der Zeitschrift für Bauwesen 1875 von Ernst & Kern in Berlin veröffentlicht (Baensch 1875). Diese Publikation ist einer der wertvollsten und umfassendsten Beiträge zur katastrophalen Sturmflut im November 1872. Die Sturmflut vom 12. und 13. November 1872 hat sich auf die damaligen preußischen Küsten der Ostsee verheerend ausgewirkt und war im Vergleich zu allen aus früherer Zeit bekannten Sturmflutereignissen hinsichtlich der Folgen so katastrophal, dass Baensch sehr weitsichtig eine detaillierte Untersuchung des Phänomens „Sturmflut" in seinen Ursachen und Verlauf sowie eine Dokumentation der Folgen und Schäden für zwingend erforderlich hielt. Dazu wurden die damaligen Regierungen von Danzig, Cöslin, Stettin, Stralsund und Schleswig, sowie die Provinzen von Stade und Aurich aufgefordert, alle verfügbaren Daten und Beobachtungen sowie weitere Hinweise zu recherchieren und zu dokumentieren, um die meteorologischen und hydrologischen Prozesse der Sturmflut 1872 zu einem Gesamtbild zusammenzuführen. Die Daten wurden von Baensch in erstaunlicher Quantität und Qualität recherchiert und mit bis heute hervorragenden Grafiken aufbereitet. Diese Daten stellen bis heute die wertvollste Datengrundlage zur Sturmflut vom 12. und 13. November 1872 dar. Die Publikation von Baensch (1875) wird bis heute vor allem wegen der Sammlung einer großen Zahl zuverlässiger meteorologischer und hydrologischer Daten der Sturmflut 1872 geschätzt. So nutzte z. B. Colding (1881) die Daten von Baensch zur Sturmflut von 1872, um seine ozeanographischen und physikalischen Theorien über die Reaktion des Meeresspiegels auf Windeinwirkungen zu bestätigen und zu modifizieren.

Darüber hinaus hat Baensch auch die Wasserstände und Schäden der historischen Ostseesturmfluten von 1304, 1309, 1320, 1625, 1694 und 1784 aus Archiven und Chroniken mit erstaunlicher Qualität zusammengetragen. Diese historischen Daten werden bis heute verwendet.

Zu der bemerkenswerten Karriere als Ingenieur und Naturwissenschaftler von Otto Baensch (6. Juni 1825 in Zeitz; † 7. April 1898 in Berlin; vollständiger Name: Otto Friedrich Bernhard Baensch) ist Folgendes festzuhalten: Otto Baensch studierte von 1842 bis 1847 Vermessungstechnik und Mathematik an der Universität Halle und trat nach dem Besuch der Berliner Bauakademie in den preußischen Staatsdienst ein. Anfänglich war er vor allem mit dem Bau von Kirchen in der Provinz Pommern beschäftigt. Nachdem er Umbauarbeiten am Camminer Dom geleitet hatte, übernahm er die Leitung des Neubaus der*

Heringsdorfer Kirche (1848) auf Usedom. 1855 wurde er Landbaumeister im Regierungsbezirk Liegnitz. Ab 1858 war er Bauleiter der Ruhr-Sieg-Bahn. Zwischen 1852 und 1871 war Otto Baensch Wasserbauinspektor in Stralsund und Köslin. In dieser Zeit verfasste er u. a. Schriften über Hafenbau, Leuchtfeuer und Deichbau.
Nach seiner Versetzung in das preußische Ministerium für Handel, Gewerbe und öffentliche Arbeiten in Berlin gehörten die Regulierung von Elbe und Rhein, die Kanalisierung des Mainunterlaufes von Frankfurt bis Mainz (1882 bis 1885) und der Deichbau in der Provinz Schleswig-Holstein zu seinen Aufgaben. Ab 1886 leitete er den Bau des Kaiser-Wilhelm-Kanals (1887 bis 1895), des heutigen Nord-Ostsee-Kanals. Otto Baensch war Ehrenbürger der Stadt Zeitz und wurde mit dem Ehrentitel Geheimer Oberbaurat ausgezeichnet. Vom Königreich Bayern wurde Otto Baensch 1895 der persönliche Adelstitel „Otto von Baensch" verliehen, von dessen Verwendung er aber keinen Gebrauch machte.

1 The Storm Surge of November 12th–13th, 1872 on the Baltic Sea Coasts of the Prussian State

The storm of November 12th–13th, 1872, had such a devastating effect on the Prussian coastal districts of the Baltic Sea, and its occurrence was so serious in comparison with all those known from earlier times, that it certainly called for a detailed study of the entire phenomenon in its causes and course, as well as a clear demonstration of its consequences for the beach districts and the buildings located within them.

For this purpose, the governments of Gdansk (Danzig), Coeslin (Cöslin), Szczecin (Stettin), Stralsund and Schleswig, as well as the provincial authorities of Stade and Aurich were asked to collect the material available for this purpose, and the following discussion of the meteorological and hydro-technical phenomena combines this collected material into an overall picture of the whole phenomenon, using other auxiliary sources, which could be obtained from isolated brochures, from scattered notes or local observations.

From the observation material in meteorological relation, the details have been excluded as far as they would have complicated the discussion. Only that has been used which allows the phenomenon to be overlooked in the simplest possible reproduction. In order to make the tables of figures easier to understand, they have been presented graphically throughout.

2 Historical Storm Surges

Phenomena such as the storm surge of November 12th–13th, 1872 have been reported as far back as historical records go; but it is always the historian, not the technician, who passes on the bare facts in a few words to posterity.

The oldest storm tide, of which the chroniclers report, also only according to oral tradition, was at the beginning of the 14th century; according to Berckmann and Kantzow at Stralsund in the year 1304, according to another Stralsund chronicle in 1307, according to Micraelius in 1309 and according to the Lübeck chronicle in 1320.

Berckmann reports about this storm tide in the Stralsund chronicle:

„Im J. 1304 umme alles Gades hilligen (am 1. November) weyede so ein groth stormwind, nicht gehört bi minschen thiden, Böme uth de erden, Dörpe, möhlen umme un mackede so groth water umme dit land, datt dat nye - Deep uthbrack; um da de von Cickeren plegen eren weiten tho seyen up den Ruden und tho gande von einem lande up dat andere, dat wafs water,"

Or: In the year 1304 around All Saints' Day, a great storm wind, not heard in human times before, knocked down trees from the earth, villages and mills and drowned the land with so much water that the "Neue Tief" (New Deep, erosion channel and later fairway south of Mönchgut) broke out and that the people of Zicker (place on Mönchgut) who used to sow their wheat on Ruden (seems to be missing the conclusion: "could no longer get there") and the whole area between one land (Mönchgut) and the other (Ruden) was flooded with water.

About the same event, Thomas von Kautzow says: In the same year, there was an enormous storm. It tore off the land of Ruden from Rugen (Rügen), between which previously ran only a small river one could jump over.

The distance from Ruden to Rugen (Rügen) is today one German mile.

If we consider that the storm surge at that time tore Ruden away from the island of Rugen, forming the "Neue Tief", while the most recent storm surge submerged the whole of Ruden, except a few dune sections, and tore away large parts of the beach everywhere, we can conclude that the storm surge of November 12th–13th, 1872 is the most devastating in terms of its impact.

The next storm tide mentioned by chronicles after the one at the beginning of the 14th century was that of February 10th, 1625. Water level marks of it on the blue tower in Lübeck and on the old official building in Travemuende (Travemünde) have preserved a consistent reference for the assessment of the height of the tide. According to these marks, the water level reached an absolute height of 23' 9" = 7.454 meters (prussian foot ≙ 31.3854 cm, prussian inch ≙ 2,615 cm, 23' und 9" ≙ 7,454 meters), a height of 2.804 meters above mean sea level.

If we compare this level with that of the flood of November 12th–13th, 1872, which reached 3.380 metres above mean sea level, we find that the level of February 10th, 1625 is 0.576 metres lower; and nevertheless also the damage caused by this storm surge was very considerable, as the chronicler Becker at Lübeck and M. Johannem Stein, preacher at Rostock, tell.

It is worth mentioning at this point that according to Stein "on February 10th at noon, the water not only rose suddenly and unusually high, but also that soon afterwards a terrifying and unheard of impetuosity arose from a violent and strong northeasterly gale. It blew in such a way with incessant hissing and roaring, mixed with heavy snow and rain, that thereby not only at sea and at Warnemünde, but also here in Rostock great damage was done," etc.

The last storm tide to be mentioned here is the one of January 10th–11th, 1694, from which a water level mark has also been preserved at the blue tower in Lübeck, according to which this tide exceeds the one of 1625 by a small amount, namely by 0.019 metres. Accordingly, the flood of 1694 would be in line with that of 1872 in terms of height – as far as the water level marks show.

The later storm surges do not reach the two specifically mentioned ones of 1625 and 1694 (of the storm surge that took place in September of the year 1784 nothing exact can be stated, since no water level marks of the same have survived to our time), as the graphic representation of the highest and lowest water level of the Trave estuary, as a point strongly exposed for storm surges at the Baltic Sea coast in the later years, can be seen in Figure 1 of the drawings.

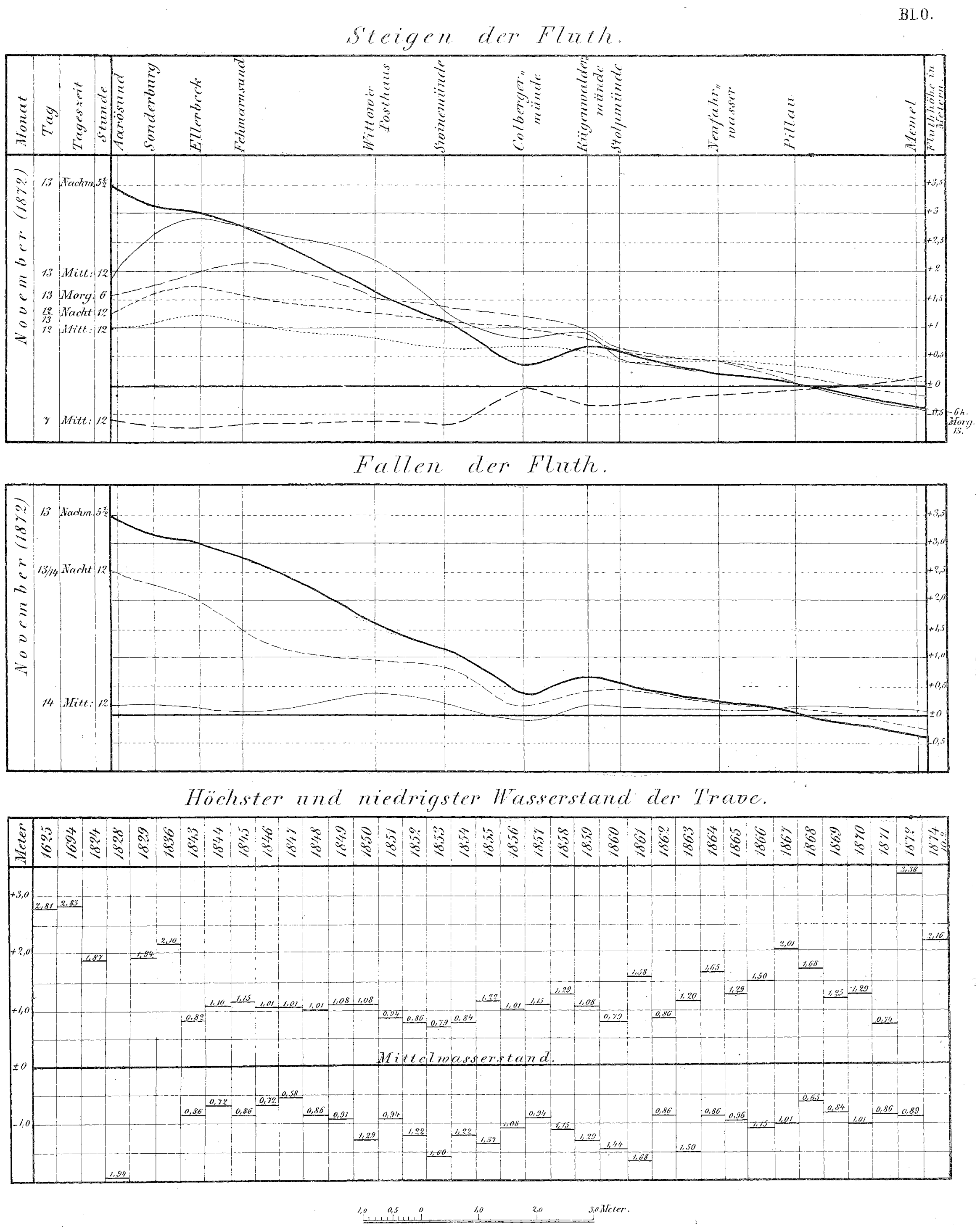

Figure 1: Rising Tide, Falling Tide, Highest and Lowest Water Level of the Trave.

It should not go unmentioned here that in more recent times similar phenomena have occurred more frequently, even if not as devastating in their effects.

3 The Meteorological Phenomena before and during the Storm Surge

3.1 The Absolute Values of the Atmospheric Pressure and the Temperature together with the Wind Movement

In order to determine the origin of the storm from NE or ENE which caused the storm surge, as well as the reasons for the increased strength of the storm, which reached hurricane strength only on one part of the Baltic Sea coasts, it is necessary to get a picture of the atmospheric conditions over the area in question before and during the storm surge.

The area of observation including the Prussian coasts is far too limited for the evaluation of such movements of the atmosphere. Furthermore, from the stations outside Prussia, the data for the evaluation of the deviation of the condition from the mean values of the air with respect to pressure and temperature are lacking. Before examining the meteorological conditions on the Baltic coast in particular, an attempt has been made to draw a general picture of the conditions and changes in the atmosphere just before and during the storm surge over Northern and Central Europe, from Haparanda to Vienna and from Paris to Moscow. It is based on the observation results published daily in the “Staats-Anzeiger”.

The observation material of the atmospheric pressure in the mornings of November 10th, 11th, 12th and 13th is compiled to graphical representations. They comprise four tables of the mentioned area of Europe and show in lines the position of the same barometer reading at intervals of 2.5 to 2.5 Paris lines in the morning of each observation day. Those lines will be called “equal pressure lines”.

From the change of the phenomena represented by 24-hours observations, one is able to judge the variations of the atmosphere also for the intervening time.

These maps, Figure 2 and Figure 3, are drawn at a scale of 1:15,000,000 and show only the natural demarcation between land and water of Northern and Central Europe. Furthermore, the meteorological stations are indicated by small circles. Because of the small scale and space, the names of the individual stations are described in the map, Figure 3.

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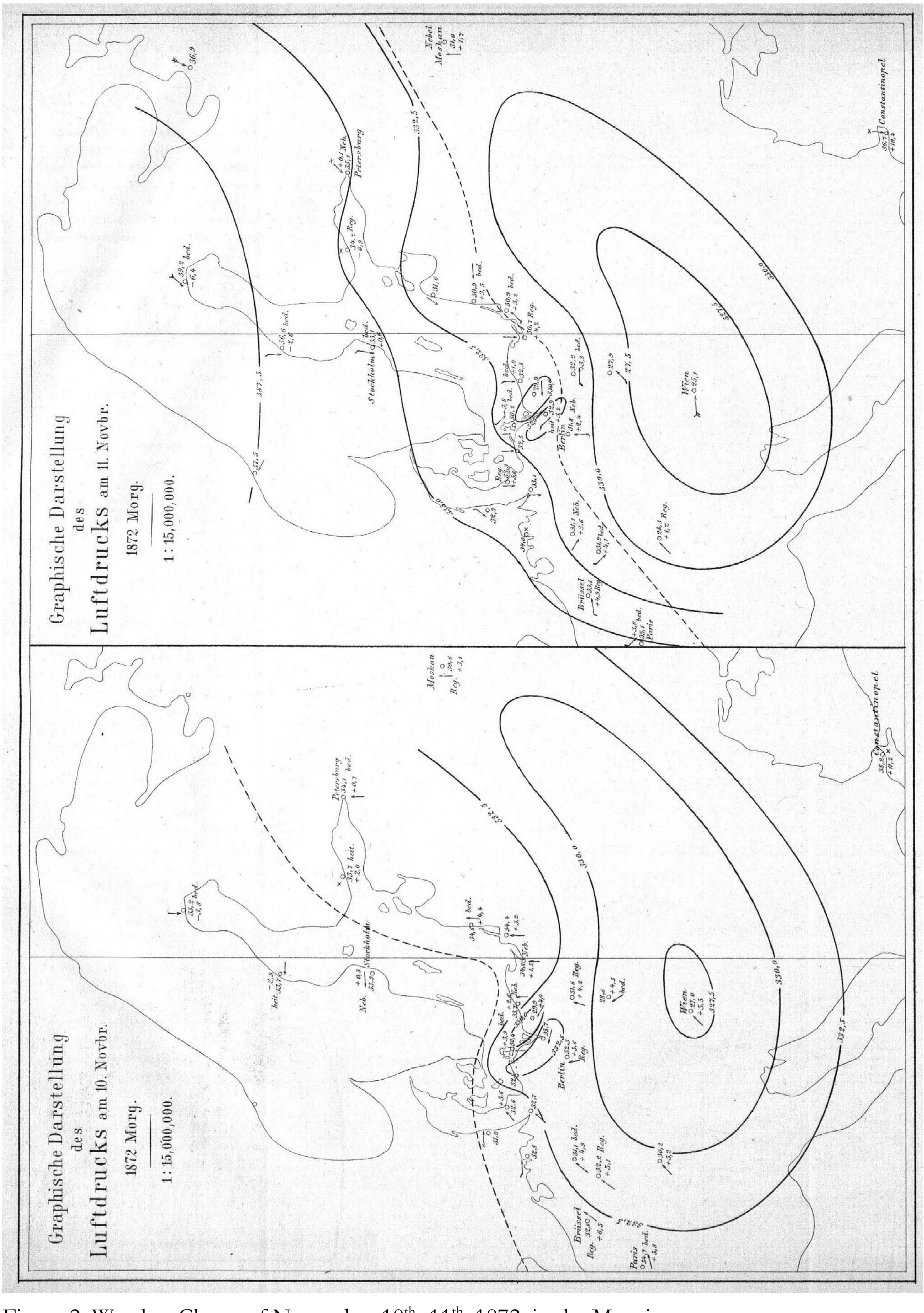

Figure 2: Weather Charts of November 10th–11th, 1872, in the Morning.

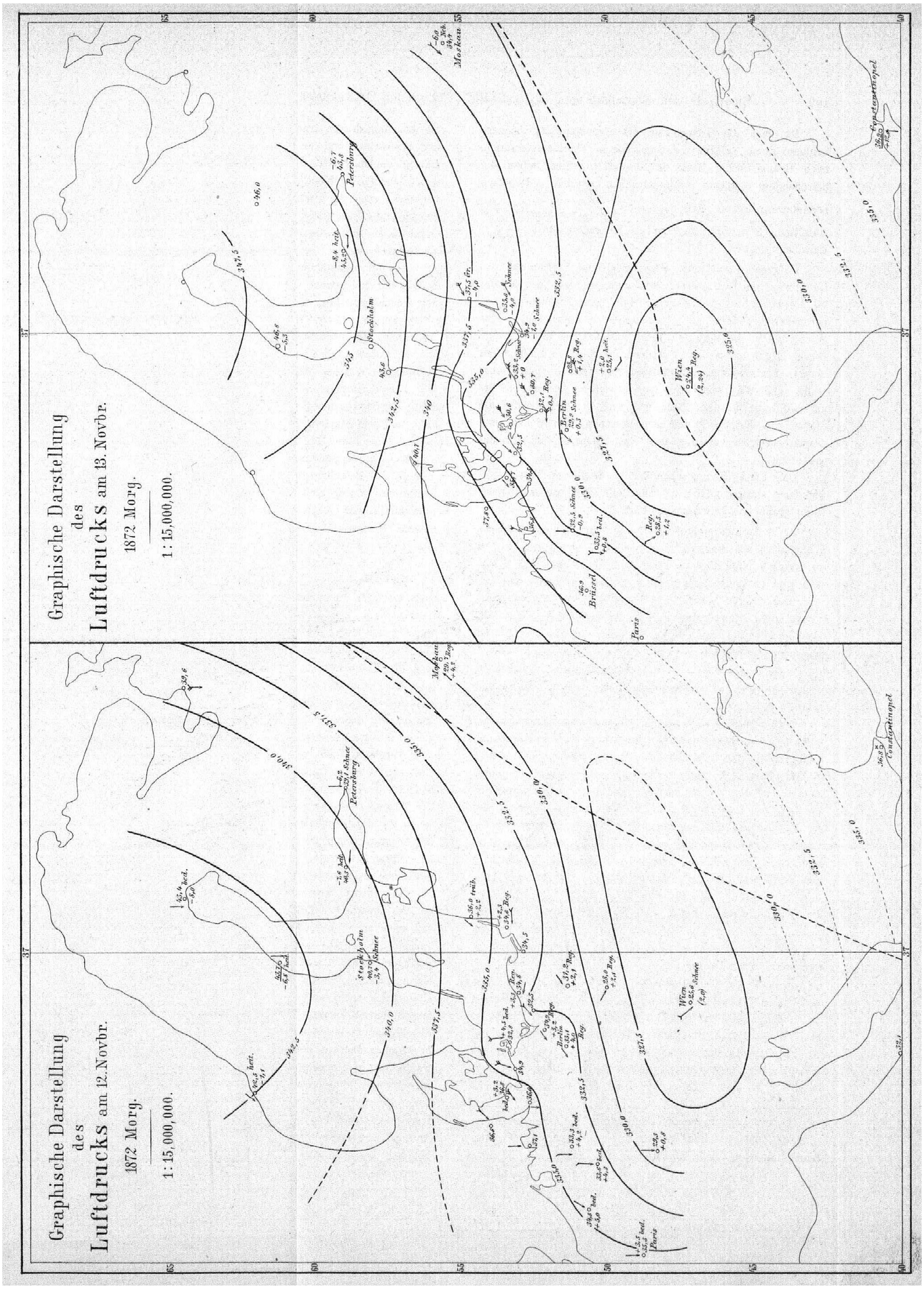

Figure 3: Weather Charts of November 12th–13th, 1872, in the Morning.

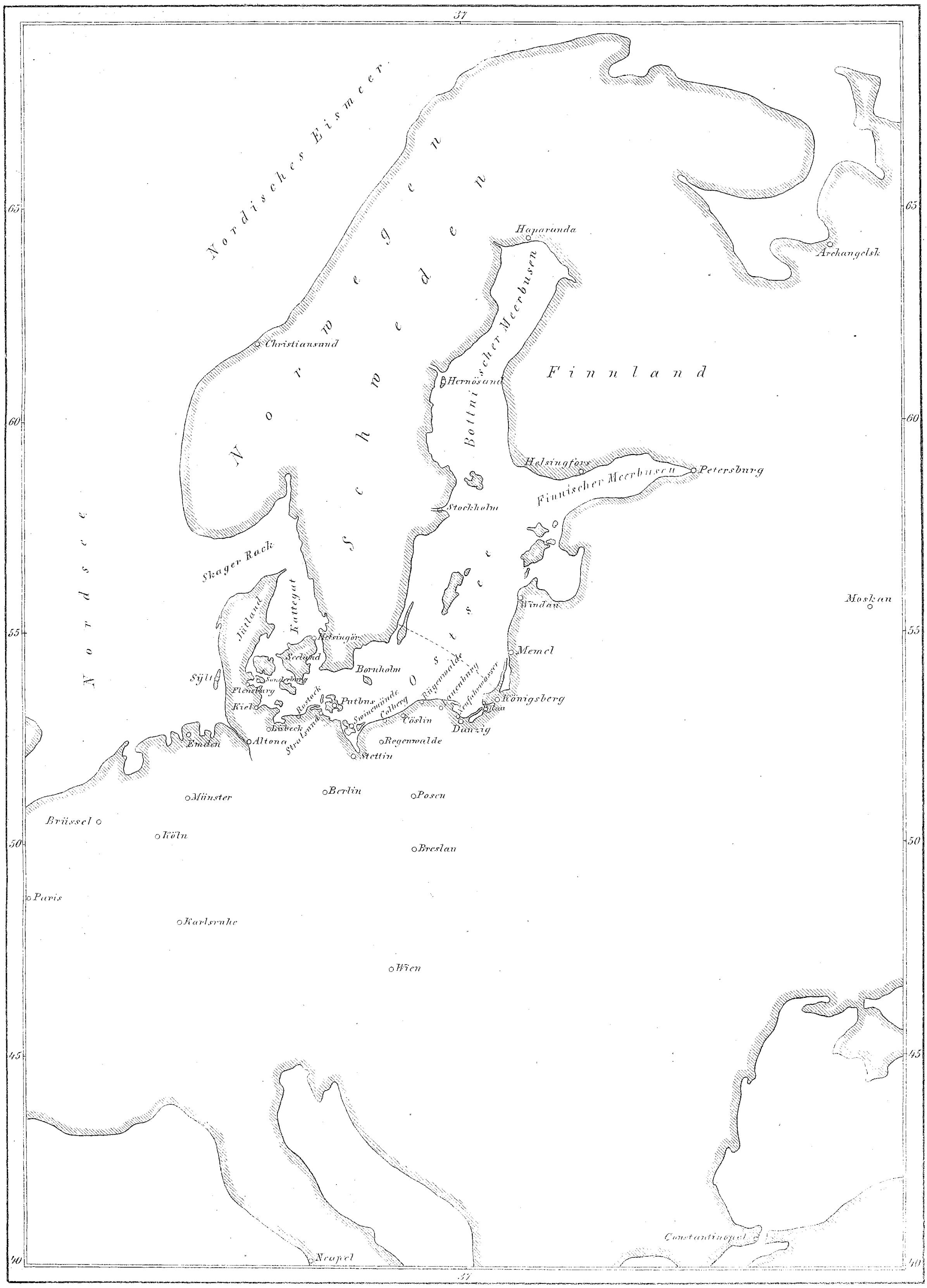

Figure 4: Map of the Meteorological Stations plotted in the Air Pressure Analysis of Figure 2 and Figure 3.

The barometer readings published in the above-mentioned daily weather bulletins and the readings reduced to 0 °R are shown numerically in Paris lines, precisely only the numbers above 300 lines.

As the stations themselves are at different heights above sea level, the air pressure would also have had to be reduced to sea level. This was not done, because at a difference of 100 feet the deviation of the barometer reading is on the average only 1.033 Paris lines, i.e. less than the distances of the equal pressure lines from each other, which are wide in 2½ Paris lines, and therefore the characteristics of the lines can suffer a loss of accuracy which is not too significant. Another reason for this was that the altitude is only known for a small proportion of the weather stations. Only in one report, namely in the one by G. v. Boguslawski – as a supplement to the report of the government in Szczecin (Stettin) – were the altitude differences of individual observation sites mentioned in the table.

For the sake of completeness, it would be desirable that at least once a year the relevant information were given in connection with the daily weather report.

In order to be able to see the connection of the wind with the distribution of the atmospheric pressure on the graphic representations, the direction as well as the intensity of the wind are given, the former is indicated by small arrows, which adapt themselves to the orientation of the maps, the latter by small flags. In terms of intensity, the following degrees are established as the norm:

windstill (calm),
windig (breezy),
starker Wind (strong wind),
Stürmisch (stormy),
Sturm (storm)
Orkan (hurricane)

Since the temperature also serves as a basis for safe conclusions, the observed thermometer readings have been inscribed in absolute numbers next to the respective stations according to Réaumur's scale. Accordingly, for any station this means: stormy, barometer reading 32.1 Paris lines, −0.3 °R cold with snow.

32,1,
— 0,3 Schnee:

Overlooking this graphical representation of the air pressure and the other phenomena of the morning of November 10th, we find that over Central Europe a barometric minimum, with its major axis over Vienna (Wien), extends in the direction from WSW to ENE. This minimum was the flood channel for the Equatorial Current that had prevailed since the beginning of the month, as evidenced by the reported wind and temperature observations. This is the normal situation for the Equatorial Current, and one of the reasons for the strength of the struggle between the Polar and Equatorial Currents, which, as is well known, is always repeated.

That this struggle already took place on November 10th in the beginning of its development is shown by a glance at the relevant graphical representation, see Figure 2 and Figure 3.

In Haparanda, on the morning of November 10th, a moderate wind blew directly from the north; in Memel, Petersburg and Moscow (Moskau) a moderate wind blew directly from the south. At Helsingfors (Helsinki) there was no wind, and at Stockholm and Härnösand there was a straight easterly wind.

This shows that between Haparanda and Härnösand the two currents were directly opposite each other and kept the balance, and that in Härnösand and Stockholm there was a flow of the accumulated air to the west. Finally, in Petersburg and further to the east, no trace of the influence of the Polar Current was recognized.

If one adds the temperature observations, according to which the thermometer showed −3.8 °R in Haparanda, -2.9 °R in Härnösand, on the other hand +0.3 °R in Stockholm, +2.0 °R in Helsingfors (Helsinki), +0.7 °R in Petersburg and +3.1 °R in Moscow (Moskau), so one finds – apart from the relatively small effects of the local position of the stations – not only the confirmation of the situation previously explained. Furthermore, if one now additionally considers the "General View of the Sky", which is reported from Haparanda as "overcast", from Härnösand as "clear", from Stockholm as "fog", from Helsingfors (Helsinki) as "clear", from Petersburg as "cloudy", the border between Polar and Equatorial Current, i.e. the zone in which the air masses of the two currents mix and are usually characterized by fog, can be approximately determined.

Therefore, one can conclude that in Härnösand only the air of the Polar Current, but in Stockholm the same air mixed with warm, light air of the Equatorial Current, had to flow westward into the oceanic basin.

The temperature in Helsingfors (Helsinki), which is +1.3 °R higher than in Petersburg, which is almost at the same latitude, can probably be explained by the stationary air of the Equatorial Current.

If one now goes further south to determine the boundary line between Equatorial and Polar Current, then one finds from Coeslin (Cöslin) to Memel the direction of the wind marked as Equatorial Current. As to the difference in temperature and the "General View of the Sky", Gdansk (Danzig) reports only +l.5 °R and "fog", Coeslin (Cöslin) +2.0 °R as well "fog", however, Koenigsberg (Königsberg) and Memel +3.8 °R or 4.4 °R; respectively i.e., in Gdansk (Danzig) and Coeslin (Cöslin) the warm moist air of the Equatorial Current was already mixed with the cold dry air of the Polar Current.

From the above follows that near Gdansk (Danzig) the Polar Current had already entered the Equatorial Current in a wedge shape on November 10th in the morning. Accordingly, the extrapolation of the discussed boundary has been drawn in the graphic representation as a broken line; the extrapolation of this line from Coeslin (Cöslin) to the west has been likewise determined according to this principle.

Comparing in both areas of the air currents the air pressure at Stockholm represented by the equal pressure lines with the maximum of 333.9", at Coeslin (Cöslin), immediately near or on the boundary of the two air current areas discussed above, with 333.7", it results in the area of the Polar Current a difference of 0.2" at a distance of 80 miles or 0.25" at 100 miles, whereas for the area of the Equatorial Current with the minimum in Vienna (Wien) of 327.0" - between Vienna (Wien) and Coeslin (Cöslin) there is a difference of 6.7" at a distance of 90 miles or 7.4" at 100 miles.

It can be seen from this that the pressure of the cold air accumulated in the north was almost in equilibrium, in contrast to the warm air of the Equatorial Current, which was moving along in rapidly decreasing pressure. If we consider this fact, particularly unfavourable at extremely low atmospheric pressure, in connection with the partial intrusion of the Polar Current into the Equatorial Current evident from the boundary line of the two air currents, the outcome of the struggle already in progress can generally be foreseen.

If we now compare the graph of the air pressure on November 10th with that in the morning of November 11th, a significant change becomes apparent, especially in the area of the Polar Current. The Polar Current itself had gained significant terrain in the previous 24 hours, as shown by the borderline between the Polar and Equatorial Currents, marked in the graph for November 11th and drawn according to the same principle as before.

During this advance of the Polar Current, especially where the partial intrusion had occurred and where also on this day a further advance in the torn marked boundary line is evident, the air pressure has become lower, because the equal pressure line of 332.5" has advanced significantly from the minimum air pressure to the north beyond Riga. Both this fact and an absolute decrease of the minimum at Vienna by 1.9" are probably proofs that the Polar Current on the line mentioned above lifted the Equatorial Current so that the latter passed over the former while the cold air in the lower layers advanced. If the arithmetic sum of the air pressure from the lower cold current and the warm current flowing above has suffered a reduction, although cold heavy air has penetrated into these areas, then it can only be concluded that the upper warmer current has moved with greater force and that the resulting reduction of the air pressure has not yet been compensated by the heavier layers of the lower cold air. This phenomenon is all the more characteristic, however, because, contrary to the normal simultaneous movements of the thermometer and barometer, it also marks a simultaneous fall of the barometer with the falling thermometer and thus permits a conclusion as to the eminent force of the Equatorial Current in the upper layers.

On the other hand, we find that the air pressure in the southwestern direction from the island of Rugen (Rügen) has changed only insignificantly, e.g. for the equatorial pressure line 332.5 not causing any displacement, while between Moscow (Moskau) and Petersburg the same line has advanced south eastward from the maximum at Haparanda; a proof that the Equatorial Current at Moscow (Moskau) resisted - albeit relatively, and thus the air pressure has increased.

Comparing the differences in atmospheric pressure in the two areas against each other, between Haparanda and Gdansk (Danzig) – at a distance of about 185 miles – there is a difference of 8.5" or 4.6" at 100 miles; between Gdansk (Danzig) and Vienna (Wien) at a distance of 95 miles, there is a difference of 5.6" or 5.9" at 100 miles.

If one compares the differences in atmospheric pressure of the previous day of 0.25" and 7.4" with those of this day of 4.6" and 5.9", and takes into account that the air pressure on November 10th in the morning decreasing from Stockholm to the north still increased in Stockholm itself by l.2" with a difference of 4.1" to 125 miles to the north, we find confirmed that the air of the Polar Current region, which was still almost in equilibrium 24 hours before, advanced from the north to the south with rapidly increasing pressure. In doing so, it pushed back the Equatorial Current in its entire front, even lifted up the Equatorial Current in the extension discussed above, and thus penetrates wedge-shaped into the latter below.

With these phenomena of November 11th, an attentive observer would have foreseen the onset of a stronger current, since the struggle was already present in such pronounced symptom.

If the progress of the effects of the Polar Current from the morning of November 10th to the morning of November 11th was already a significant one, the graphic representation of the atmospheric pressure of the morning of November 12th shows the complete collapse of the Polar Current for the area in question. One station in the north, Moscow (Moskau), still gives us information about the presence of the descending Equatorial Current, by the direction of the wind and by the temperature.

While in Petersburg the temperature was −6.8 °R with northerly wind, in Moscow (Moskau) it was +4.2 °R with wind from SW; there is a colossal difference of 10.4 °R between the two places. Together with the rain reported from Moscow (Moskau), the convergence of the Equatorial Current and the Polar Current may be plotted into the graphic slightly to the northwest of Moscow (Moskau).

To determine approximately the whole convergence line, the observations of Vienna (Wien) remain. As the effects of the Polar Current - northwesterly wind with snow and a daily mean temperature of 2 °R only - are to be regarded as fixed, the boundary between the two air currents going east of Vienna (Wien) and west of Moscow (Moskau) has been drawn by approximation in a broken line into the map of November 12th.

Considering the change of the air pressure in the last 24 hours, or in other words, the shift of the equal pressure lines, more closely, it turns out that all stations which were in the area of the Polar Current on the morning of the November 12th show increased air pressure ore the equal pressure lines have shifted down from north to south, respectively; namely, since the morning of November 11th the increase in pressure in Haparanda amounts to 4.2''' and in Vienna (Wien) to 0.5'''. This general increase in air pressure in the whole Polar Current region is not only the product of the still increasing pressure in the north, but also of the resistance, even if only relative, of the Equatorial Current. If we note the difference in air pressure on the morning of November 12th in the entire Polar Current region, we find that between Haparanda and Vienna (Wien), between maximum and minimum, at a distance of 275 miles, there is a difference of 17.8''', or of 6.5''' at 100 miles.

The change in atmospheric pressure in the equatorial region, on the other hand, results in a diminution of the same, namely at Moscow (Moskau) by 1.3'''. This decrease in air pressure, together with the wind direction - SW in Moscow (Moskau) - confirms not only the Equatorial Current in Moscow (Moskau), but also shows that the Polar Current - between Petersburg and Moscow (Moskau) - moves besides the Equatorial Current approximately in parallel with the latter. This causes a decrease of normal attack and the increase of the air pressure resulting from it ceases.

The reports from several stations made on the morning of November 12th, namely in the Baltic Sea, of the increasing intensity of the Polar Current appearing as a strong and stormy wind from NNE and E, leave no doubt about the resulting consequences. The direction of the Polar Current was more and more directed from NE to SW and its course thus pointed to the western basin of the Baltic Sea.

On the morning of November 13th, when the raging storm had reached its climax at the Prussian coasts, the conditions of the atmospheric pressure had become quite different in the meantime. Unfortunately, due to the lack of observations from the meteorological stations, no graphic representation can be given of the atmospheric processes for the intervening period from the morning of November 12th to the morning of November 13th.

What is especially noticeable on the map of November 13th as to air pressure is the change in the boundary between the Polar and Equatorial Currents, in favour of the latter. This boundary line has made a turn from the direction SSW/NNE to SW/NE in such a way that Vienna (Wien) has again entered the area of the Equatorial Current, while Moscow (Moskau) has now entered the area of the Polar Current.

In Vienna (Wien), there is rain and the daily mean temperature increased by 0.24 °R with wind from SW, in Moscow (Moskau), however, there is fog at a temperature of −6.0 °R and strong wind from NE. Both tracks took their natural direction, namely the Polar Current, by deflecting the Equatorial Current on November 12th at the level of Moscow (Moskau), prepared its parallelism with the latter, lost its normal position of the attack front and took its direction all in all more to the west. As a result, the southern Equatorial Current blowing at the height of Vienna (Wien) was more and more relieved from the attack of the Polar Current. With the intensity of the Equatorial Current, its return to its natural direction from SW to NE was facilitated by the deflection of the Polar Current. Only while at the beginning of November the Equatorial Current dominated the Baltic Sea area, it is pushed back on its whole path to the south and the Baltic Sea with the northern part of Germany taken as a flood bed by the Polar Current. The days from November 10th to 13th form the transition period from the first situation to the second.

If we now compare the conditions of the air pressure on the morning of November 13th with those on the morning of November 12th, we find that there was an increase in the pressure maximum near Härnösand of 3.1". From there in a southeastern direction, corresponding to the change of the area of the Polar Current, there is a steady increase in air pressure up to beyond Moscow (Moskau) – in Moscow (Moskau) itself by 4.7". In the southwestern direction from Härnösand to Rugen (Rügen), the pressure increase occurred only up to the equal pressure line 335.0", but from there to the minimum near Vienna (Wien) there is a significant decrease in air pressure, especially in the equal pressure line 332.5". The differences are 16.3" at 130 miles or 12.5" at 100 miles in the Härnösand-Putbus profile line on the morning of November 13th, and 8.4" at 100 miles on the morning of November 12th.

The readings on the Putbus-Vienna (Wien) profile line on the morning of November 13th were 6.2" at 95 miles or 6.5" at 100 miles against 7.6" at 100 miles on the morning of November 12th. These colossal differences had to be followed by phenomena of such eminent and disastrous force as from November 12th to 13th at night, because, while afterwards on the morning of November 12th the pressure between Härnösand and Vienna (Wien) decreased rather evenly; by the morning of November 13th the pressure in the northern region had increased enormously. This might be caused in part by the cold air advancing from the north, while at the same time the Equatorial Current resumed its old direction, and thus north of Vienna (Wien) again restricted the profile of the Polar Current.

Just this latter swing of the Equatorial Current in its natural direction shows that the initially normal attack of the Polar Current was defeated, which could have led to a complete breaking of the free flow and then would have resulted in a strong northwesterly and northerly storm at the coasts.

This breakthrough failed because of the strong resistance of the Equatorial Current. A lateral air movement was initiated in the north, directed more to the NE, which gave the Equatorial Current the strength to return to its natural direction from the SW, but with simultaneous restriction of the tidal profile of the Polar Current at the height of Rugen (Rügen), as a result of which the air was forced more to the NE, had to assume a high speed, and turned into the dangerous hurricane.

In the four graphs (Figure 2 and Figure 3), the position of the air movements on the four days of struggle will give an approximate overview of how the changes proceeded:

As the change in the direction of the Equatorial Current from November 12th to 13th already caused the high velocity of the air over the western basin of the Baltic Sea, a special, one might say local, phenomenon seems to have contributed to this.

In the cartographic representations of the air pressure, Figure 2, November 10th and 11th, there is a relatively small minimum over Putbus, Regenwalde, Rostock and Szczecin (Stettin) with an adjacent maximum. The minimum extending over Putbus - Regenwalde, the maximum over Rostock – Szczecin (Stettin), or from NW to SE.

On the two graphs for November 10th and 11th, the maximum exceeds the equal pressure line to the north and the minimum does not reach the next equal pressure line to the south.

That this minimum was able to influence the direction of the air masses moving above is shown by the four graphs of the air pressure. On the morning of November 10th, the wind directions west and south of this minimum were southwesterly, while in Regenwalde and Szczecin (Stettin) they were SE and ESE, respectively. That means the Equatorial Current moving southeast of the minimum was forced to make a 90° turn and follow the direction of the minimum, as a result of the air's effort to return to equilibrium. However, since the air flowed incessantly from the south-west towards the minimum, the minimum had caused its own air flow from the SE to the NW, and, considered separately, indirectly resisted the air flow blowing from the SW, or rather accumulated it, meeting at 90°, the relative maximum located directly southwest of the minimum can be explained.

The same conditions at the same place are noticeable on the other three days, although less pronounced on November 12th and 13th.

The causes of these peculiar air pressure conditions are not discernible.

On the morning of November 10th, when the area under discussion - with the relative minimum - lay inside the Equatorial Current, the Polar Current penetrating the lower layers lifted the Equatorial Current with its light air and an upward flow of air therefore occurred at the place in question. But since, as commented before, still on the morning of November 13th, the characteristics of the minimum and the maximum - in relative importance – after the cold heavy air of the Polar Current had flown over it already for two days and such an insignificant space of the air would have been balanced very soon, or this relative minimum would have changed in its position, we have to be satisfied with the fact of the existence of this relatively low air pressure in the direction of Putbus – Regenwalde.

Nevertheless, it must be emphasized that this local minimum must have given reason to increase the speed of the heavy cold polar air approaching from the NE. Furthermore, the development of the hurricane, which is reported by the pilot stations, started at Colberg and extended towards Kiel, must certainly be regarded as a related phenomenon.

3.2 The Relative Values of Air Pressure and Temperature together with the Wind Movement

If the preceding discussion covered the area of Central and Northern Europe, the meteorological observation material submitted by the governments from stations near the Prussian coasts of the Baltic and North Seas is, for the sake of completeness, combined into an overall picture to show the situation and changes of the atmosphere, especially on the coasts where the storm surge occurred.

 https://doi.org/10.18171/1.092107

In that discussion, the absolute observation material of the four stormy days was discussed, while in the following, the relative observation material, related to the mean barometer and thermometer readings of 20 days, namely from November 1st to November 20th, 1872, is treated.

The material used here consists of the observations of the barometer, thermometer, wind direction and wind intensity made at the individual stations at 6 a.m., 2 p.m. and 10 p.m.

Analogous to the principle of deviations from the normal state, the deviations of the air pressure as well as of the temperature of the respective stations and the corresponding period, are compiled in figures in the following Table 1,Table 2 and Table 3. The calculations were made for the respective locations and the corresponding time according to Dove, in the case of the barometer for the month of November, and in the case of the thermometer for each of the 5 days of the month of November. The used mean values are added in a clear manner, so that the absolute value can be reconstructed from the mean and the deviation. In addition, the wind directions in a wind rose divided into 16 parts and finally the wind intensities by numbers in gradations from 0 to 5 are calculated and compiled in the following tables (see Table 1 to Table 3). In these tables, the meteorological stations follow their geographical position from west to east; the times continuously from top to bottom.

In order to obtain the observations of a place contained in a main column also pictorially, graphical profile representations were made for each station. They were put together in Figure 5, Figure 6, Figure 7 and Figure 8.

Table 1: Observations and Mean Values of Air Pressure and Temperature as well as Wind Direction and Force at Emden, Sylt, Altona, Kiel and Lübeck between November 1st and 20th, 1872, at 6 a.m.; 2 p.m. and 10 p.m.

Tabelle I.

Jahr und Monat	Datum	Tageszeit	Stunde	Emden.						Sylt.						Altona.						Kiel.						Lübeck.					
				Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.	Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.	Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.	Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.	Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.
	1	Morg.	6		−2,0		−0,4	SW	1		−5,0		—	WSW	2		−2,2		+0,9	SW	1		−3,3		−0,3	SW			−2,2		+0,2	W	3
		Mitt.	2		−1,8	+5,76	+2,8	SW	1		−4,1	fehlt	—	WSW	2		−1,7	+5,78	+4,1	SW	1		−2,8	+5,79	2,9	SW			−2,0	+5,27	+4,0	W	2
		Abd.	10		−4,2		+1,9	WSW	2		−4,3		—	WSW	2		−3,2		+2,4	SW	0		−3,3		+0,0	S			−2,6		−0,2	W	2
	2	Morg.	6		−5,2		+1,8	WSW	2		−7,6		+3,4	WSW	2		−4,1		+3,6	S	1		−5,2		+3,1	SW			−4,4		+4,1	WSW	3
		Mitt.	2		−5,1		+3,9	S	1		−6,2		+3,5	WSW	2		−3,9		+5,1	S	1		−4,6		+4,6	SW			−4,0		+6,0	W	3
		Abd.	10		−6,3		+2,7	SW	1		−7,6		+2,7	WSW	—		−5,7		+3,5	S	0		−6,2		+3,1	SSW			−5,2		+3,8	W	3
	3	Morg.	6		−6,5		+0,2	SW	2		−8,8		+0,9	WSW	1		−6,2		+2,1	S	2		−7,2		+1,6	SW			−6,2		+1,8	W	3
		Mitt.	2		−4,2		+2,7	W	1		−7,5		+2,5	WNW	1		−5,0		+3,1	S	2		−6,2		+1,6	—	0		−5,0		+2,8	WSW	3
		Abd.	10		−1,2		+0,5	NW	2		−4,8		+1,7	WNW	2		−2,5		+1,9	—	0		−3,7		+1,3	W			−4,1		+1,9	WSW	3
	4	Morg.	6		+1,1		+0,3	WSW	1		−2,0		+1,1	WNW	2		+0,1		+0,3	SW	2		−1,1		−0,1	W			−0,4		−0,2	W	1
		Mitt.	2		+2,0	+5,15	+2,8	W	1		−0,4	+5,87°	+1,7	WNW	2		+1,0	+5,13	+2,3	W	2		+0,1	+4,95	+2,3	W			+0,3	+4,24	+2,7	NW	2
		Abd.	10		+1,3		−0,9	—	0		−0,3		+1,2	WNW	1		+1,8		±0	—	0		+1,0		−0,5	SW			+1,7		−1,2	NW	1
	5	Morg.	6		−1,7		+1,0	S	2		−2,6		+0,9	SW	2		±0		−0,1	SSO	1		−1,4		±0	SSW			+0,2		−0,7	W	2
		Mitt.	2		−2,3		+3,5	SW	1		−4,4		+3,0	S	1		−1,9		+2,7	SSO	1		−2,7		+1,5	SSW			−1,7		+1,5	SW	2
		Abd.	10		−1,0		+4,1	SW	1		−3,9		+3,3	WSW	1		−1,5		+4,8	—	0		−2,7		+3,7	WSW			−1,9		+4,9	SSW	1
	6	Morg.	6		−0,1		+2,8	SW	1		−2,7		+2,5	WSW	1		−0,3		+4,5	SW	1		−1,4		+3,1	SW			−0,9		+4,4	WSW	1
		Mitt.	2		−0,1		+4,2	SW	2		−2,7		+3,8	SSW	2		−0,3		+5,3	SW	1		−1,3		+4,8	SW			−0,7		+5,8	W	1
		Abd.	10		−1,3		+5,6	SW	1		−4,1		+4,1	SW	2		−1,1		+5,2	—	0		−2,4		+5,0	SW			−1,2		+5,6	WSW	3
	7	Morg.	6		+1,2		+3,1	SW	2		−3,1		+4,0	WSW	3		−0,1		+5,1	SW	1		−1,4		+4,1	WSW			−1,2		+5,9	W	3
		Mitt.	2		+2,2		+4,7	W	2		−0,8		+4,0	W	3		+1,8		+5,5	W	1		+0,5		+4,9	SW			+0,9		+5,7	W	3
		Abd.	10		+3,6		+2,9	WSW	2		+0,4		+3,6	NW	3		+3,1		+2,9	—	0		+1,7		+2,9	SW			+2,7		+2,5	W	3
	8	Morg.	6		+3,8		+0,9	SW	1		+0,6		+3,6	W	2		+3,7		+1,3	SW	1		+2,3		+2,1	WSW			+3,2		+1,4	W	1
		Mitt.	2		+2,8		+3,4	SW	1		+0,4		+4,2	W	2		+3,0		+3,6	SW	1		+1,6		+4,3	SW			+2,7		+5,0	W	2
		Abd.	10		+2,1		+2,7	SW	1		−0,2		+3,8	W	1		+1,7		+3,7	—	0		+0,9		+3,4	SW			+1,4		+3,9	W	2
	9	Morg.	6		+1,9		+0,3	WSW	1		−0,6		+2,2	W	2		+1,4		+1,7	SW	1		+0,6		+1,3	SW			+1,4		+0,5	W	1
		Mitt.	2		+1,9	+4,38	+3,3	WSW	1		−1,1	+5,03°	+2,6	W	1		+1,0	+4,05	+3,9	SW	1		−0,6	+4,07	+3,0	SW			+0,3	+3,30	+3,9	WNW	2
		Abd.	10		−1,6		+2,0	WSW	1		−1,6		+2,4	W	1		−1,3		+1,2	—	0		−1,8		+1,4	SW			−0,8		+0,8	WNW	1
1872 November	10	Morg.	6		−3,9		+1,1	W	1		−5,4		±0	—	0		−3,7		+1,0	SW	1		−4,3		+0,1	S			−3,8		±0	W	1
		Mitt.	2		−4,0		+3,7	W	1		−5,4		+1,1	SW	1		−4,5		+2,4	SW	1		−4,9		+1,7	SSW			−4,6		+2,4	W	1
		Abd	10		−3,8		−0,6	—	0		−4,3		−0,2	ONO	1		−3,8		+1,0	—	0		−4,2		+0,	SSW			−3,8		+1,0	—	0
	11	Morg.	6	336,71 Pariser Linien	−2,7		−2,3	—	0	336,43 Pariser Linien	−3,9		−1,0	NO	1	336,35 Pariser Linien	−3,3		+0,9	N	1	336,52 Pariser Linien	−3,6		+0,9	N		335,84 Pariser Linien	−3,3		+0,2	ONO	1
		Mitt.	2		−2,2		+1,1	NO	1		−2,9		+1,1	NO	1		−2,7		+2,5	NO	1		−2,5		+1,6	NO			−2,6		+1,8	ONO	2
		Abd.	10		−1,0		−0,9	NO	1		−1,6		−1,0	NO	2		−1,4		+0,4	—	0		−1,5		+1,1	NO			−1,4		+0,7	ONO	2
	12	Morg.	6		+0,4		+1,1	NO	2		+0,2		−1,2	NO	2		−0,4		+1,2	N	1		±0		+0,7	NO			−0,7		+1,8	ONO	3
		Mitt.	2		+0,8		+1,0	NO	2		+0,9		−0,2	NO	2		−0,2		+1,7	NNO	1		+0,5		+1,0	ONO			−0,1		+1,6	ONO	4
		Abd.	10		+1,6		−1,0	NO	3		+2,0		−2,6	NO	2		+0,8		−0,7	—	0		+1,6		−0,8	NO			+0,8		−0,4	ONO	4
	13	Morg.	6		+0,1		−3,0	NNO	2		+1,4		−3,6	NO	2		−2,0		−2,0	N	2		−0,9		−2,4	NO			−1,7		−1,4	ONO	4
		Mitt.	2		−2,5		−2,7	NNO	3		−1,2		−3,6	NO	3		−4,1		+0,4	NO	3		−2,8		−1,5	NO			−3,6		+0,6	ONO	4
		Abd.	10		−2,3		−2,0	O	2		−1,8		−2,6	NO	3		−1,3		+0,2	—	0		−1,5		+2,0	OSO			−1,0		+1,4	OSO	3
	14	Morg.	6		−0,1		−3,4	O	1		−0,5		−0,1	ONO	2		+0,4		−0,6	ONO	2		+0,5		+0,7	OSO			+0,7		−0,7	OSO	1
		Mitt.	2		+0,6	+2,67	±0	O	1		+0,7	+3,58°	+0,4	O	1		+0,9	+2,52	+2,9	O	2		+1,1	+2,62	+2,4	OSO			+1,0	+1,85	+3,1	OSO	1
		Abd.	10		+1,4		−3,0	O	1		+1,1		−1,0	O	2		+0,5		+0,9	—	0		+1,4		+1,6	ONO			+1,2		+1,1	OSO	1
	15	Morg.	6		−1,1		+2,0	NNO	1		−0,7		+0,6	ONO	2		−1,6		+3,3	NO	1		−1,3		+3,2	O			−1,1		+2,9	OSO	1
		Mitt.	2		−1,7		+1,2	SSO	1		−1,9		+1,4	ONO	2		−1,8		+4,0	ONO	1		−1,8		+4,2	OSO			−1,9		+4,2	SO	1
		Abd.	10		−0,8		−1,4	SO	1		−2,5		+1,2	ONO	1		−0,2		−1,0	—	0		−2,0		+3,7	SO			−1,0		+1,1	SO	1
	16	Morg.	6		+0,9		−3,1	OSO	1		−0,1		−1,2	SSO	1		+1,8		−1,9	OSO	1		+1,8		+1,4	SO			+2,6		−2,0	SSW	1
		Mitt.	2		+1,1		0,1	O	1		+1,4		±0	SO	1		+2,3		+1,3	O	1		+2,4		+1,0	O			+2,5		+1,0	SSO	1
		Abd.	10		+0,9		−2,7	OSO	1		+1,5		−1,5	O	1		+2,1		±0	—	0		+2,3		+0,4	O			+2,6		−0,2	OSO	1
	17	Morg.	6		+0,4		−1,9	SO	1		−0,1		+1,3	O	1		+0,3		+2,3	ONO	0		+0,1		+3,4	O			±0		+3,0	—	0
		Mitt.	2		−0,4		−0,6	O	1		−2,4		+2,3	O	1		−0,4		+2,8	ONO	1		−0,9		+2,9	W			−0,6		+3,3	W	1
		Abd.	10		−1,3		−1,6	O	1		−1,7		+0,8	S	1		−0,3		+1,3	—	0		−0,5		+1,2	SSW			±0		−0,8	W	1
	18	Morg.	6		−2,4		−0,9	O	1		−2,8		−0,6	SO	1		−1,1		−1,2	OSO	1		−1,3		−0,6	SO			−0,5		−0,8	SW	1
		Mitt.	2		−2,7		+1,1	S	1		−3,4		±0	OSO	1		−2,3		+1,2	OSO	1		−2,6		+1,5	OSO			−2,3		+1,7	SSO	2
		Abd.	10		−4,3	+1,90	+0,9	SO	1		−4,4	+2,21°	+0,3	OSO	1		−3,0	+1,62	+0,6	—	0		−3,3	+1,82	+1,0	SO			−2,6	+0,99	+0,7	SSO	2
	19	Morg.	6		−7,1		−0,8	O	1		−5,5		−0,1	O	1		−5,1		+0,7	OSO	1		−4,8		+0,5	SO			−4,1		−0,2	OSO	2
		Mitt.	2		−5,5		+1,1	—	0		−6,1		+0,6	O	1		−3,7		+2,1	SO	1		−5,8		+1,8	SO			−5,5		+3,0	S	2
		Abd.	10		−4,3		−0,2	—	0		−6,2		+1,0	O	1		−4,0		+1,9	—	0		−4,8		+2,0	OSO			−3,8		+2,2	S	2
	20	Morg.	6		−5,2		+3,6	SW	1		−6,1		+1,0	OSO	1		−5,1		+1,7	SO	1		−4,6		+1,6	SSO			−4,0		+1,8	S	2
		Mitt.	2		−3,4		+4,2	SW	1		−5,8		+4,2	SSW	1		−3,5		+6,0	SW	1		−4,5		+4,3	WSW			−3,8		+5,2	WSW	2
		Abd.	10		−2,3		+3,7	SW	1		−4,1		+4,2	SW	1		−1,9		+4,4	—	0		−2,6		+3,4	S			−1,9		+3,3	WSW	1

Table 2: Observations and Mean Values of Air Pressure and Temperature as well as Wind Direction and Force at Putbus, Swinoujscie (Swinemünde), Szczecin (Stettin), Regenwalde and Coeslin (Cöslin) between November 1[st] and 20[th], 1872, at 6 a.m., 2 p.m. and 10 p.m.

Tabelle II.

Jahr und Monat	Datum	Tageszeit	Stunde	Putbus. Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.
1872 November	1	Morg.	6	335,2 Pariser Linien	−4,4	+5,41	−0,6	SW	3
		Mitt.	2		−4,0		+3,1	—	3
		Abd.	10		−3,3		−0,7	SW	2
	2	Morg.	6		−5,3		+3,4	S	2
		Mitt.	2		−5,0		+6,3	SW	2
		Abd.	10		−6,7		+2,8	SO	2
	3	Morg.	6		−7,6		+2,8	S	2
		Mitt.	2		−7,4		+3,6	S	3
		Abd.	10		−6,1	+4,31	+1,6	W	3
	4	Morg.	6		−4,8		+2,0	W	3
		Mitt.	2		−2,2		+2,9	W	3
		Abd.	10		−1,2		−0,7	SW	2
	5	Morg.	6		−0,7		−1,0	S	1
		Mitt.	2		−2,7		+3,2	SO	2
		Abd.	10		−3,2		+1,7	SO	2
	6	Morg.	6		−2,1		+4,4	W	2
		Mitt.	2		−1,8		+5,0	SO	2
		Abd.	10		−2,3		+4,6	S	2
	7	Morg.	6		−2,5		+5,0	SW	3
		Mitt.	2		−1,1		+5,6	SW	3
		Abd.	10		+0,6		+1,8	SW	3
	8	Morg.	6		+0,8		+1,8	W	2
		Mitt.	2		+0,9		+4,8	SW	2
		Abd.	10		−0,5	+3,54	+2,5	SW	2
	9	Morg.	6		−1,0		+1,7	W	1
		Mitt.	2		−1,2		+3,7	SW	2
		Abd.	10		−3,7		±0	S	1
	10	Morg.	6		−4,7		+0,4	S	1
		Mitt.	2		−6,2		+1,0	SO	1
		Abd.	10		−6,0		−0,2	W	1
	11	Morg.	6		−5,0		+0,3	NW	1
		Mitt.	2		−4,3		+1,8	N	1
		Abd.	10		−2,9		+1,5	NO	2
	12	Morg.	6		−2,3		+2,1	N	2
		Mitt.	2		−1,8		+1,9	NO	3
		Abd.	10		−1,5		−0,3	NO	4
	13	Morg.	6		−4,6		−1,2	NO	5
		Mitt.	2		−3,9		+0,6	O	3
		Abd.	10		−1,0		+1,7	O	2
	14	Morg.	6		−0,3	+2,43	+0,4	O	1
		Mitt.	2		+0,5		+1,9	O	1
		Abd.	10		+0,3		+2,6	O	1
	15	Morg.	6		−1,7		+3,4	SO	2
		Mitt.	2		−1,9		+3,9	SO	2
		Abd.	10		−1,8		+4,5	SO	1
	16	Morg.	6		+0,9		−1,4	SO	1
		Mitt.	2		+1,8		+0,9	O	1
		Abd.	10		+0,5		+3,1	O	1
	17	Morg.	6		−1,3		+3,9	O	1
		Mitt.	2		−1,6		+1,9	O	1
		Abd.	10		−1,3		+2,7	O	1
	18	Morg.	6		−1,9		+0,3	O	1
		Mitt.	2		−2,7		+0,9	SO	1
		Abd.	10		−3,6	+1,26	+1,3	SO	2
	19	Morg.	6		−4,8		+0,7	SO	2
		Mitt.	2		−5,2		+2,5	SO	1
		Abd.	10		−5,1		+1,2	SO	1
	20	Morg.	6		−4,6		+1,4	SW	1
		Mitt.	2		−4,9		+2,4	S	1
		Abd.	10		−4,8		+3,5	W	1

Datum	Tageszeit	Swinemünde (Leuchtthurm). Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.
1	Morg.	332,80 Pariser Linien	−1,3		+1,3	WSW	2
	Mitt.		−1,0		+4,2	WSW	2
	Abd.		−0,9		+3,2	WSW	2
			−0,8		+1,2		
2	Morg.		−2,4		+2,2	SSW	2
	Mitt.		−2,1		+5,2	WSW	2
	Abd.		−2,0		+4,2	SW	2
			−2,9		+3,2		
3	Morg.		−3,4		+3,2	SW	1
	Mitt.		−3,4	+4,75	+3,2	WSW	3
	Abd.		−3,4		+2,2	SSW	2
			−2,4		+2,2		
4	Morg.		−1,2		+0,2	W	2
	Mitt.		+0,6		+2,7	NW	2
	Abd.		+1,2		+1,2	WNW	1
			+1,8		+0,2		
5	Morg.		+0,8		−0,8	SW	1
	Mitt.		+1,6		+2,2	SW	2
	Abd.		−0,3		+1,2	SW	1
			−0,3		+1,2		
6	Morg.		−0,5		+5,5	NW	1
	Mitt.		+0,5		+5,5	W	1
	Abd.		+0,4		+6,5	WSW	1
			+0,4		+6,5		
7	Morg.		−0,5		+5,5	WSW	3
	Mitt.		+1,4		+7,5	W	4
	Abd.		+1,5		+5,5	W	3
			+2,7		+2,6		
8	Morg.		+2,7		+2,5	W	1
	Mitt.		+2,6	+3,52	+4,5	WSW	3
	Abd.		+2,6		+3,5	WSW	2
			+1,6		+3,5		
9	Morg.		+1,7		+2,5	W	1
	Mitt.		+0,7		+2,5	W	1
	Abd.		+0,8		+1,5	W	1
			−0,2		+0,5		
10	Morg.		−1,2		+0,5	SO	1
	Mitt.		−2,2		+1,5	O	1
	Abd.		−3,2		+1,0	NO	1
			−3,2		+1,0		
11	Morg.		−2,2		+1,7	—	0
	Mitt.		−1,7		+2,2	NO	1
	Abd.		−1,2		+2,2	SO	1
			−1,2		+1,2		
12	Morg.		−1,2		+2,2	ONO	4
	Mitt.		−1,2		+2,2	ONO	4
	Abd.		−0,2		+1,2	ONO	4
			−2,1		+0,2		
13	Morg.		−2,1		+0,2	ONO	5
	Mitt.		−1,1	+2,75	+0,2	O	4
	Abd.		−1,0		+0,8	O	4
			+1,0		−0,8		
14	Morg.		+1,9		−0,2	OSO	1
	Mitt.		+2,3		+2,2	SO	1
	Abd.		+2,3		+2,2	OSO	1
			+1,8		+2,2		
15	Morg.		+0,7		+3,2	SO	1
	Mitt.		−0,4		+4,2	SO	1
	Abd.		−0,4		+5,2	OSO	1
			+0,6		+4,2		
16	Morg.		+2,8		+2,1	SSW	1
	Mitt.		+2,7		+4,1	SW	1
	Abd.		+2,8		+3,1	OSO	1
			+2,8		+3,1		
17	Morg.		+1,8		+2,1	SO	1
	Mitt.		+0,8		+2,1	SSO	1
	Abd.		+0,9		+1,1	SSO	1
			+0,8		+2,1		
18	Morg.		+1,0		−0,9	SSW	1
	Mitt.		+1,0	+1,91	+0,1	SSW	1
	Abd.		−0,1		+1,1	SSW	1
			−1,0		+0,1		
19	Morg.		−2,0		−0,9	SSO	1
	Mitt.		−2,2		+2,1	SSO	1
	Abd.		−3,1		+1,6	SSO	1
			−2,6		+1,1		
20	Morg.		−2,0		+0,1	SW	1
	Mitt.		−2,2		+2,1	SSO	1
	Abd.		−1,2		+3,1	SSW	1
			−0,2		+3,1		

Datum	Tageszeit	Stunde	Stettin. Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.	Regenwalde. Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.	Cöslin. Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Wind-richtung.	Stärke.
1	Morg.	6	337,0 Pariser Linien	−1,7	+5,51	+0,5	W	1	336,0 Pariser Linien	−4,5	+4,97	+0	SW	0	336,1 Pariser Linien	−1,9	+4,88	−0,9	SW	1
	Mitt.	2		−1,9		+4,2	W	1		−4,5		+4,0	SW	2		−1,5		+3,5	SW	1
	Abd.	10		−1,4		−0,1	WSW	1		−3,0		−1,2	SW	0		−0,6		−1,4	SW	1
2	Morg.	6		−3,1		+1,7	SW	1		−5,0		+1,9	S	2		−2,6		+3,3	S	1
	Mitt.	2		−3,6		+6,1	SW	1		−6,2		+6,5	SW	1		−2,7		+6,3	SW	1
	Abd.	10		−3,3		+2,5	SW	1		−6,8		+3,3	SW	0		−2,8		+3,4	SW	1
3	Morg.	6		−5,1		+2,5	SW	2		−8,1		+2,9	SW	1		−4,3		+3,0	SW	1
	Mitt.	2		−4,8		+4,2	WSW	2		−8,0		+4,7	SW	2		−4,2		+4,4	SW	1
	Abd.	10		−4,1	+4,50	+1,9	WSW	1		−6,4		+2,5	SW	2		−3,6		+2,2	SW	1
4	Morg.	6		−1,8		+0,9	W	1		−4,6	+4,12	+1,3	W	2		−2,1	+3,97	+1,0	W	1
	Mitt.	2		−0,2		+3,5	WNW	2		−3,2		+3,9	W	2		−0,7		+1,9	W	1
	Abd.	10		+1 4		−1,1	W	2		−0,9		−0,7	W	2		+0,7		+0,8	NW	1
5	Morg.	6		+1,4		−1,5	SW	1		−0,9		−1,5	W	0		+1,4		−3,0	SW	1
	Mitt.	2		−0,6		+1,9	SSW	2		−3,6		+2,3	S	1		+0,6		+1,7	SW	1
	Abd.	10		−1,0		+1,1	SW	1		−6,0		+1,6	SW	1		−0,1		+0,5	SW	1
6	Morg.	6		−0,6		+2,6	W	1		−3,0		+1,9	SW	0		−0,3		+1,5	SW	1
	Mitt.	2		+0,2		+5,9	W	1		−2,5		+6,1	SW	1		+0,4		+5,2	NW	1
	Abd.	10		+0,3		+3,7	W	2		−2,2		+4,1	SW	0		+0,5		+3,5	SW	1
7	Morg.	6		−0,2		+5,8	W	2		−3,1		+5,8	W	3		−0,6		+6,3	SW	3
	Mitt.	2		+1,0		+6,8	WNW	2		−2,2		+6,0	W	3		+0,8		+6,2	NW	1
	Abd.	10		+2,7		+2,6	W	2		+0,4		+1,6	W	1		+2,1		+3,0	NW	1
8	Morg.	6		+3,1		+1,0	W	2		+1,1		±0	SW	2		+2,8		+1,6	W	1
	Mitt.	2		+3,0		+4,7	W	2		+0,4		+4,4	SW	2		+2,8		+5,0	W	1
	Abd.	10		+2,0		+2,7	SSW	2		−0,5		+2,1	SW	2		+2,1	+3,00	+2,6	W	1
9	Morg.	6		+1,0	+3,40	+2,0	WSW	1		−1,5	+3,97	+1,8	WSW	2		+0,8		+1,8	W	1
	Mitt.	2		+0,5		+4,8	W	2		−2,5		+3,6	W	1		+0,6		+4,5	W	1
	Abd.	10		−0,5		+0,2	NW	1		−3,7		−1,0	W	0		±0		−0,4	W	1
10	Morg.	6		−3,3		+1,2	O	1		−6,1		±0	SO	0		−2,4		−1,0	S	1
	Mitt.	2		−5,3		+1,2	O	2		−7,6		−0,6	O	2		−4,5		+1,0	O	1
	Abd.	10		−4,8		±0	N	1		−8,1		−0,8	O	2		−5,2		−0,6	O	1
11	Morg.	6		−4,1		−0,2	NO	1		−6,0		−1,6	O	0		−3,8		−2,0	N	1
	Mitt.	2		−3,3		+2,4	NO	2		−5,1		+1,0	O	2		−2,8		+3,0	NO	1
	Abd.	10		−2,5		+0,4	NO	1		−4,5		±0	NO	3		−2,1		+0,9	NO	1
12	Morg.	6		−2,1		+0,9	NO	1		−3,4		+1,2	NO	2		−1,3		+2,0	NO	1
	Mitt.	2		−1,6		+1,6	ONO	2		−3,0		+1,4	NO	3		−0,6		+1,4	NO	2
	Abd.	10		−2,3		+0,7	NNO	4		−3,4		+0,4	NO	4		−1,7		+0,5	NO	4
13	Morg.	6		−4,9		−2,0	O	4		−5,2		−1,6	NO	4		−2,9		−1,3	ONO	3
	Mitt.	2		−3,3		+1,7	O	3		−4,0		−0,6	NO	3		−1,2		−1,3	O	3
	Abd.	10		−0,3		+0,5	O	2		−0,8		−0,2	NO	2		+0,9		−0,4	O	3
14	Morg.	6		+0,7	+2,39	+0,9	O	1		−0,3	+2,00	+0,6	O	1		+1,9	+1,32	+0,5	SO	1
	Mitt.	2		+1,2		+2,5	OSO	2		+0,8		+2,0	SO	1		+2,0		+1,9	SO	1
	Abd.	10		+1,3		+2,5	NO	1		+0,1		+3,8	SO	2		+2,6		+4,1	SO	3
15	Morg.	6		−0,6		+2,9	OSO	3		−1,4		+3,6	SO	2		+1,1		+4,7	SO	3
	Mitt.	2		−0,8		+5,1	OSO	2		−2,5		+6,8	SO	1		+0,5		+7,7	SO	3
	Abd.	10		0,5		+4,9	SO	2		−2,6		+6,4	O	2		+0,6		+6,9	SO	3
16	Morg.	6		+2,3		+1,1	SSW	2		+0,5		+1,4	SO	0		+2,9		+2,6	SW	1
	Mitt.	2		+3,0		+1,8	OSO	2		+0,6		+1,6	S	0		+3,8		+3,1	SW	1
	Abd.	10		+1,8		+2,2	O	1		−1,2		+3,2	O	1		+3,1		+3,7	SW	1
17	Morg.	6		+0,2		+2,8	O	1		−1,9		±0	SO	0		+1,7		−0,6	SO	1
	Mitt.	2		−0,1		+1,9	OSO	2		−2,4		+2,2	SO	1		+0,9		+1,1	S	3
	Abd.	10		+0,5		+3,0	OSO	1		−1,5		+3,0	SO	0		+1,1		+2,0	S	1
18	Morg.	6		±0		−0,2	SO	1		−1,9		±0	SO	0		+0,5		+2,2	S	1
	Mitt.	2		−1,0		+2,4	SSO	2		−3,0		+3,6	SSO	0		−0,4		+3,8	S	1
	Abd.	10		−1,8		+0,4	S	1		−2,9	+0,41	−0,2	SO	0		−0,8	+0,55	+1,4	S	1
19	Morg.	6		−3,3	+0,97	−1,3	SO	2		−4,4		−0,8	SO	0		−2,2		+0,3	S	1
	Mitt.	2		−3,6		+2,2	O	2		−4,9		+2,4	SO	0		−2,8		+2,8	S	1
	Abd.	10		−3,8		+2,0	OSO	1		−5,4		+0,6	SO	0		−3,0		+1,5	S	1
20	Morg.	6		−3,1		+1,4	SO	1		−4,4		+1,8	SW	0		−2,5		+1,4	SO	1
	Mitt.	2		−3,0		+3,6	SW	2		−4,4		+3,8	S	0		−2,0		+3,4	S	1
	Abd.	10		−1,2		+3,7	S	1		−3,5		+4,6	S	0		−1,1		+4,2	S	1

Zeitschrift f. Bauwesen. Jahrg. XXV. 12

Table 3: Observations and Mean Values of Air Pressure and Temperature as well as Wind Direction and Force at Lauenburg, Gdansk (Danzig), Koenigsberg (Königsberg) and Memel between November 1st and 20th, 1872, at 6 a.m., 2 p.m. and 10 p.m.

Tabelle III.

Jahr und Monat	Datum	Tageszeit	Stunde	Lauenburg.						Danzig.						Königsberg.						Memel.					
				Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Windrichtung.	Stärke.	Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Windrichtung.	Stärke.	Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Windrichtung.	Stärke.	Bar.-Mitt.	Reduc. Bar.-Stand	Temp.-Mitt.	Reduc. Temperat.	Windrichtung.	Stärke.
1872 November	1	Morg.	6		— 3,0			W	3		— 3,5		+ 0,6	W	1		— 2,9	+ 4,47	— 1,2	SO	3		— 4,9	+ 4,58	+ 3,6	W	3
		Mitt.	2		— 2,6			W	2		— 3,1	+ 5,23	+ 3,1	W	2												
		Abd.	10		— 1,5			W	1		— 1,8		+ 0,5	WSW	1												
	2	Morg.	6		— 2,6		+ 2,5	S	2		— 2,7		— 1,3	SSW	1		— 1,8		+ 0,4	SO	1		— 1,8		+ 3,5	SW	1
		Mitt.	2		— 2,8		+ 5,9	W	2		— 3,2		+ 5,8	SW	1												
		Abd.	10		— 3,0		+ 2,1	W	1		— 3,2		+ 1,7	SW	1												
	3	Morg.	6		— 4,9		+ 2,9	S	2		— 5,9		+ 0,9	S	1		— 4,0		+ 2,1	SO	1		— 4,0		+ 1,7	SO	1
		Mitt.	2		— 4,9		+ 3,9	W	2		— 6,4	+ 4,53	+ 3,7	SW	1												
		Abd.	10		— 4,5		+ 2,5	W	2		— 4,7		+ 0,5	SW	1												
	4	Morg.	6		— 3,6	+ 4,26	+ 1,6	W	2		— 4,2		+ 1,7	WSW	1		— 3,6	+ 3,67	+ 1,7	SW	3		— 4,7	+ 4,03	+ 3,2	SW	1
		Mitt.	2		— 2,1		+ 1,7	W	2		— 2,7		+ 1,9	WNW	1												
		Abd.	10		— 0,5		+ 0,1	W	1		— 1,1		— 0,1	WNW	2												
	5	Morg.	6		+ 0,2		— 1,1	WSW	2		— 0,4		— 1,4	NW	1		— 0,4		+ 1,3	W	3		— 1,2		+ 2,2	W	1
		Mitt.	2		+ 0,3		+ 1,1	SW	2		— 0,2		+ 0,6	W	1												
		Abd.	10		— 0,4		+ 0,5	SW	1		— 0,7		— 2,2	SW	1												
	6	Morg.	6		— 1,0		+ 0,8	S	0		— 1,3		— 1,0	S	1		— 0,3		— 0,5	SO	1		± 0		— 1,4	SO	1
		Mitt.	2		— 0,5		+ 3,6	SSW	2		— 0,8		+ 1,8	S	1												
		Abd.	10		— 0,4		+ 3,5	SSW	2		— 0,6		+ 2,5	SSW	1												
	7	Morg.	6		— 1,9		+ 6,7	SW	3		— 2,1		+ 5,3	SW	2		— 1,8		+ 6,3	SW	4		— 2,0		+ 5,8	S	1
		Mitt.	2		— 0,2		+ 6,4	W	3		— 0,9		+ 6,4	WNW	2												
		Abd.	10		+ 0,9		+ 3,5	W	2		+ 0,4		+ 3,3	WNW	2												
	8	Morg.	6		+ 1,3		+ 2,8	W	3		+ 0,8		+ 2,9	WNW	2		+ 0,7		+ 3,6	SW	3		— 0,4		+ 5,3	W	3
		Mitt.	2		+ 1,8		+ 4,5	W	2		+ 1,3		+ 4,3	W	2												
		Abd.	10		+ 1,0		+ 3,2	W	2		+ 0,5		+ 2,5	W	2												
	9	Morg.	6		— 0,5	+ 2,87	+ 3,0	W	2		— 0,9	+ 3,26	+ 2,3	WSW	2		— 0,7	+ 2,20	+ 3,0	SW	3		— 1,4	+ 2,53	+ 4,3	W	1
		Mitt.	2		— 0,2		+ 3,7	W	1		— 0,8		+ 3,9	W	1												
		Abd.	10		— 1,0		+ 0,9	W	1		— 1,4		— 0,6	WSW	1												
	10	Morg.	6		— 2,5		— 0,8	SSO	1		— 2,8		— 1,8	S	1		— 2,4		+ 1,0	S	1		— 2,4		+ 1,9	S	1
		Mitt.	2		— 4,8		+ 1,2	OSO	2		— 5,1		+ 1,0	SO	1												
		Abd.	10		— 6,2		+ 0,4	OSO	1		— 6,8		+ 0,5	SO	2												
	11	Morg.	6	336,36 Pariser Linien	— 5,4		+ 0,1	NO	0	337,2 Pariser Linien	— 6,5		+ 0,9	NNO	2	336,8 Pariser Linien	— 5,9		+ 1,0	SW	1	337,0 Pariser Linien	— 6,1		+ 1,0	O	0
		Mitt.	2		— 3,8		+ 2,2	NO	2		— 4,7		+ 2,1	NNO	2												
		Abd.	10		— 2,6		+ 1,6	NO	3		— 3,2		+ 1,1	NO	1												
	12	Morg.	6		— 2,0		+ 1,2	NO	3		— 2,7		+ 2,2	NO	3		— 2,2		+ 1,2	O	3		— 1,0		+ 0,5	NO	1
		Mitt.	2		— 1,0		+ 0,5	NO	3		— 2,0		+ 1,0	ONO	3												
		Abd.	10		— 0,9		— 1,6	NO	3		— 1,5		— 1,2	ONO	3												
	13	Morg.	6		— 2,3		— 2,5	O	4		— 2,3		— 2,8	ONO	3		— 1,3		— 5,5	NO	4		+ 0,5		— 5,7	NO	3
		Mitt.	2		— 0,8		— 1,9	O	2		— 0,8		— 2,0	O	3												
		Abd.	10		+ 1,2		— 1,4	O	2		+ 0,8		— 1,5	OSO	3												
	14	Morg.	6		+ 1,6	+ 2,46	— 1,4	O	2		+ 1,4		— 1,1	SO	1		+ 2,7	+ 1,08	— 1,2	SO	1		+ 3,3	+ 1,68	— 4,7	O	2
		Mitt.	2		+ 2,9		+ 2,1	SO	1		+ 2,5	+ 1,82	+ 1,7	SSO	1												
		Abd.	10		+ 2,8		+ 1,2	SO	1		+ 2,9		+ 0,5	SSO	1												
	15	Morg.	6		+ 1,6		+ 2,3	SO	3		+ 1,8		+ 1,6	SO	1		+ 3,1		+ 1,3	SO	1		+ 1,2		— 0,7	O	1
		Mitt.	2		+ 1,0		+ 4,8	SO	2		+ 1,0		+ 4,4	SO	1												
		Abd.	10		+ 0,8		+ 4,5	SO	2		+ 0,8		+ 4,9	SO	1												
	16	Morg.	6		+ 1,9		+ 4,7	SW	1		+ 1,6		+ 4,4	S	1		+ 2,7		+ 4,1	SO	1		+ 3,3		+ 1,9	SO	1
		Mitt.	2		+ 3,3		+ 3,6	SW	1		+ 2,8		+ 5,1	S	1												
		Abd.	10		+ 2,6		+ 3,5	SW	1		+ 2,4		+ 2,4	SO	1												
	17	Morg.	6		+ 1,3		— 0,8	OSO	2		+ 1,2		— 1,2	OSO	1		+ 2,3		— 0,6	SO	3		+ 3,3		— 0,9	O	1
		Mitt.	2		+ 0,8		+ 2,0	OSO	1		+ 0,6		+ 1,6	SO	2												
		Abd.	10		+ 0,9		+ 1,3	OSO	1		+ 0,6		+ 0,8	SSO	1												
	18	Morg.	6		+ 0,1		+ 1,4	SO	1		± 0		+ 0,8	SSO	1		+ 1,1		— 1,2	SO	1		+ 2,0		— 1,3	SO	1
		Mitt.	2		— 0,4		+ 1,5	SO	2		— 0,8		+ 1,3	S	1												
		Abd.	10		— 1,0		+ 0,5	SO	1		— 1,2		+ 0,1	S	1												
	19	Morg.	6		— 2,4	+ 1,24	— 0,2	SO	1		— 2,8	+ 1,00	— 0,8	S	1		— 2,1	— 0,01	+ 0,3	SO	1		— 1,1	+ 0,65	± 0	O	1
		Mitt.	2		— 2,9		+ 0,9	SO	1		— 2,9		+ 0,2	S	1												
		Abd.	10		— 3,3		+ 2,0	SO	1		— 3,4		+ 0,7	SSW	1												
	20	Morg.	6		— 3,2		+ 1,6	SW	1		— 3,7		+ 1,6	SSW	1		— 2,6		+ 1,6	SO	1		— 2,4		+ 1,9	SO	1
		Mitt.	2		— 2,3		+ 2,7	SW	1		— 2,6		+ 2,9	SW	1												
		Abd.	10		— 1,6		+ 3,9	SW	1		— 1,9		+ 2,8	S	1												

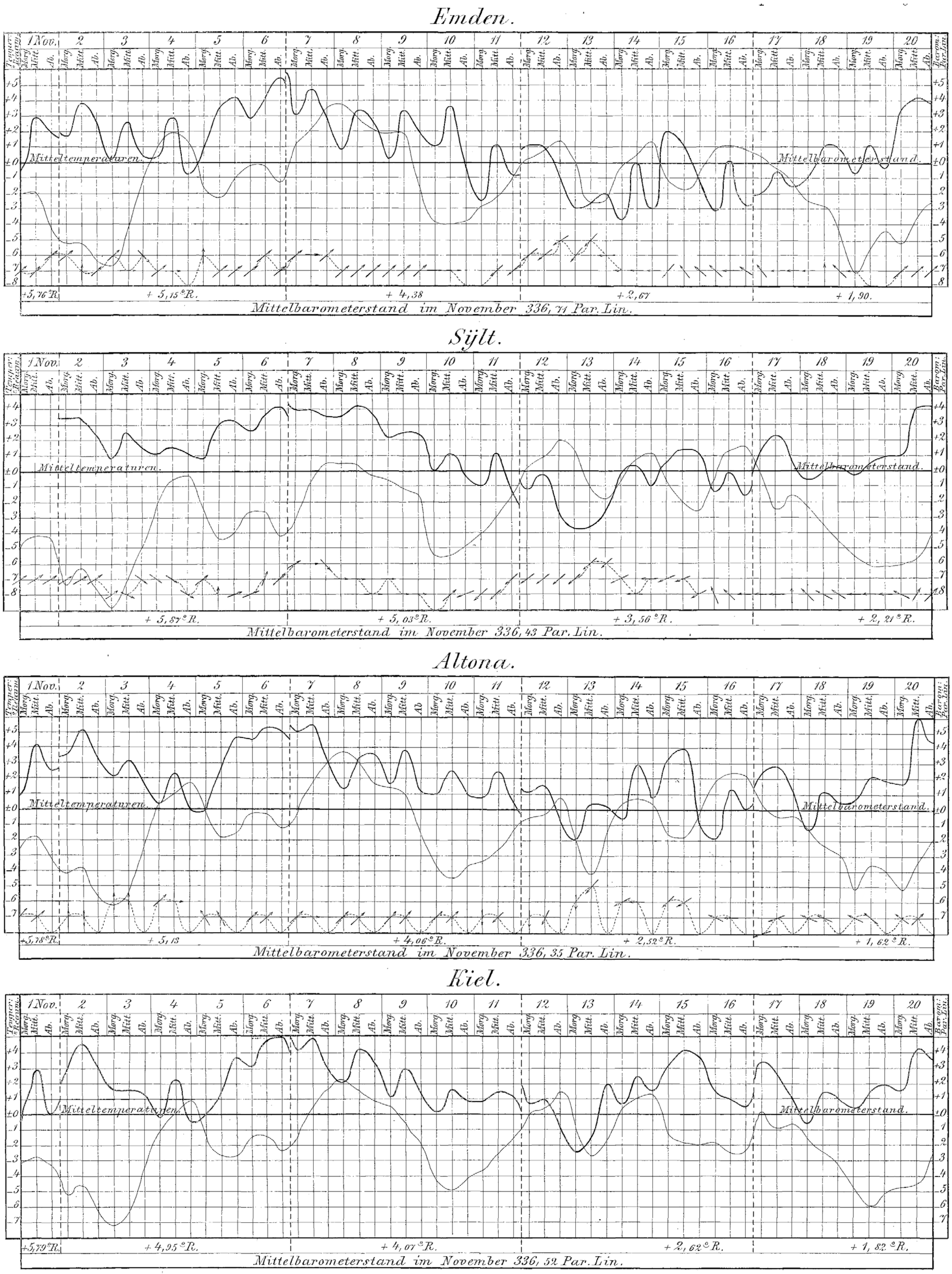

Figure 5: Storm surge of November 12th–13th, 1872, at the Baltic Sea, Graphical Representation of the Meteorological Tables, Table 1, Table 2, Table 3.

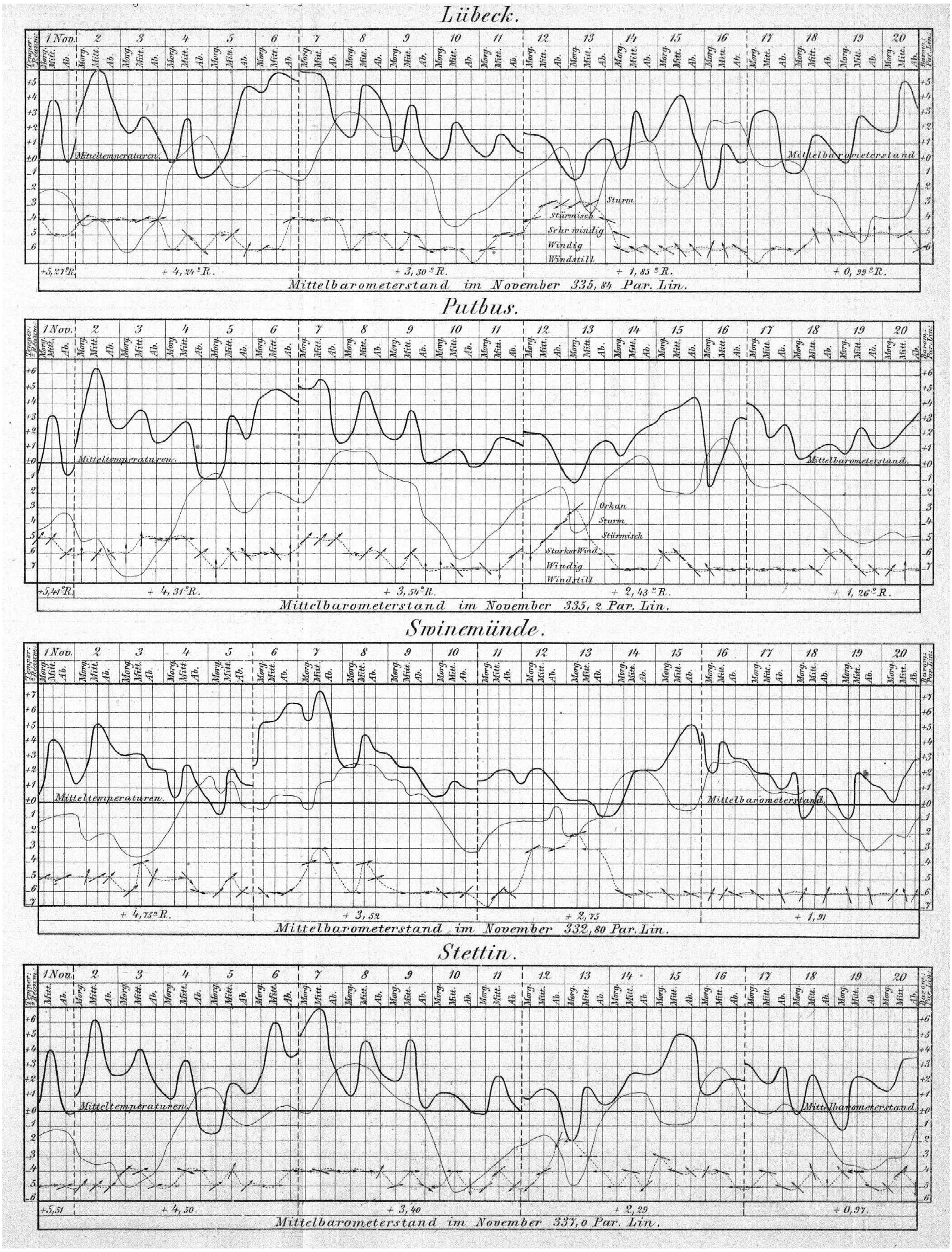

Figure 6: Storm surge of November 12th–13th, 1872, at the Baltic Sea, Graphical Representation of the Meteorological Tables, Table 1, Table 2, Table 3.

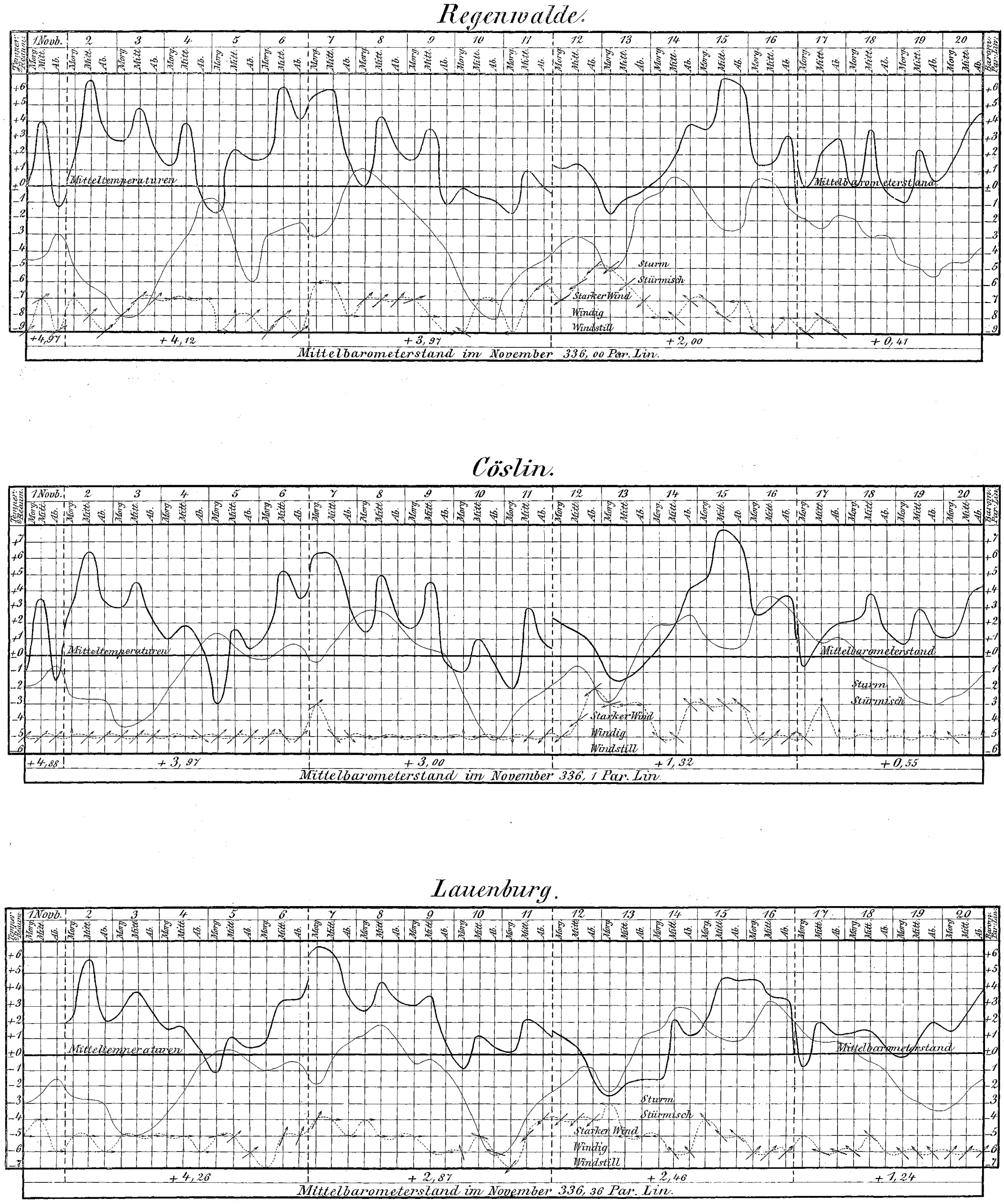

Figure 7: Storm surge of November 12th–13th, 1872, at the Baltic Sea, Graphical Representation of the Meteorological Tables, Table 1, Table 2, Table 3.

These individual profile representations show on the ordinates the deviations from the mean temperature (left) and barometer readings (right) in the observation intervals. The numbers of the deviations from the mean reduced in the tables are plotted with + or − upwards or downwards and these fixed points of the observations are connected with each other by a coherent curve.

The curves drawn in fine line are those of the deviations of the air pressure; those marked in strong line are the deviations of the temperature. For the sake of simplicity, exactly the same zero point is shown for both, i.e. the mean barometer reading and mean temperatures refer to only one abscissa axis; furthermore, for the ordinates for the barometer, 1 Paris line is assumed to be equal to 1 degree Réaumur for the thermometer. Since five-day mean temperatures were used, the curves of the deviation of the temperature at the respective days had to be set off according to the stepwise decrease of the mean temperature from 5 to 5 days. This is easily evident in the graphic representations at the transition points. In this way only, the relation between the temperature and the air pressure could be visualized.

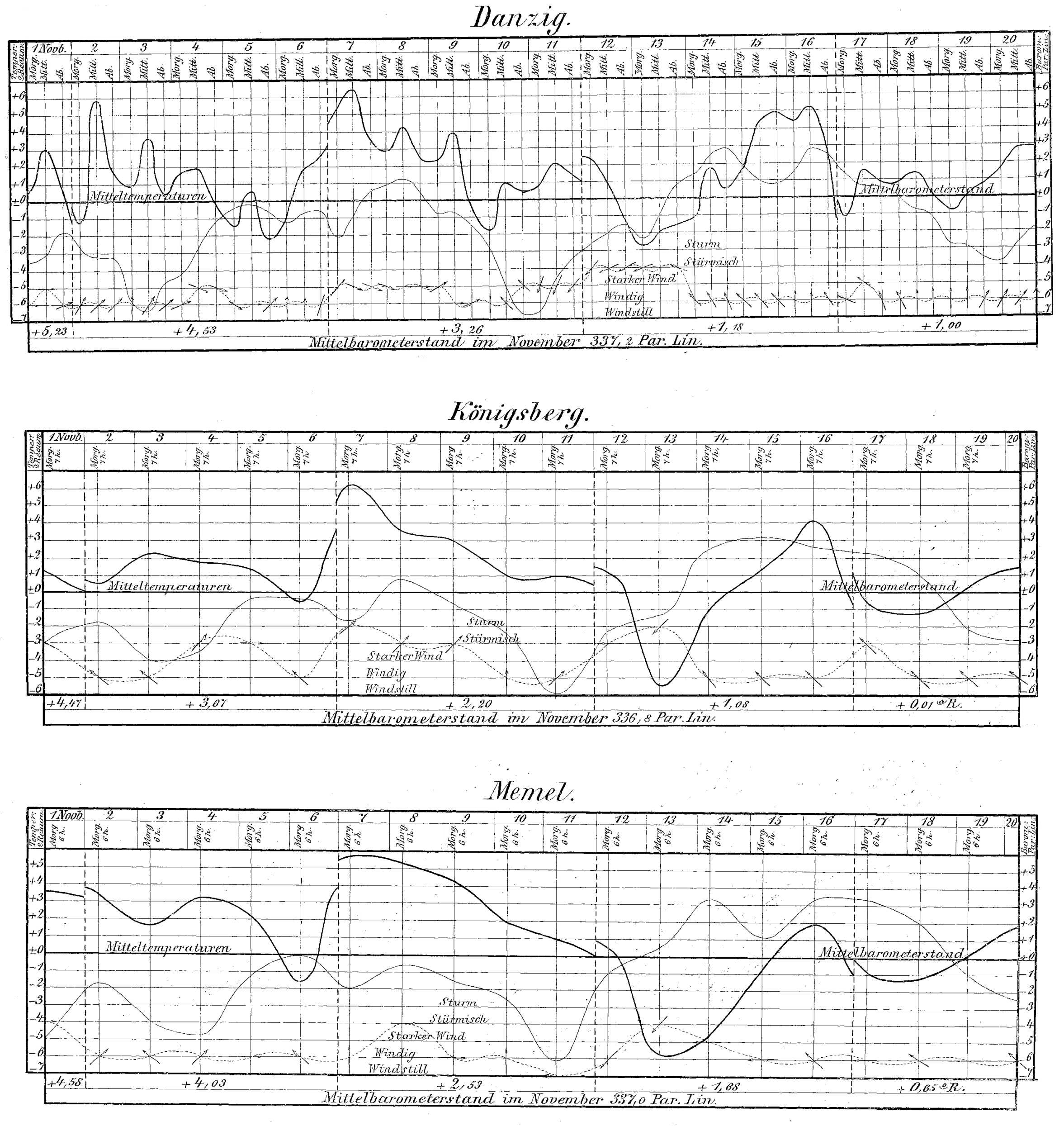

Figure 8: Storm surge of November 12th–13th, 1872, at the Baltic Sea, Graphical Representation of the Meteorological Tables, Table 1, Table 2, Table 3.

The wind directions are printed by small arrows at the ordinates, which adapt to the normal orientation of the graph, i.e. north-up orientation (Figure 5 to Figure 8). The wind intensity in the five gradations is represented again by a curve in a broken line, where the five lowest horizontals of the profiles are used for the intensity level, so that in calm conditions the abscissa axis coincides with the curve.

Furthermore, these profiles have been put together in Figure 9 and Figure 10 as an aerial picture: namely the wind movement for itself and next to it the deviations from the mean air pressure as well as from the mean temperatures have been compiled.

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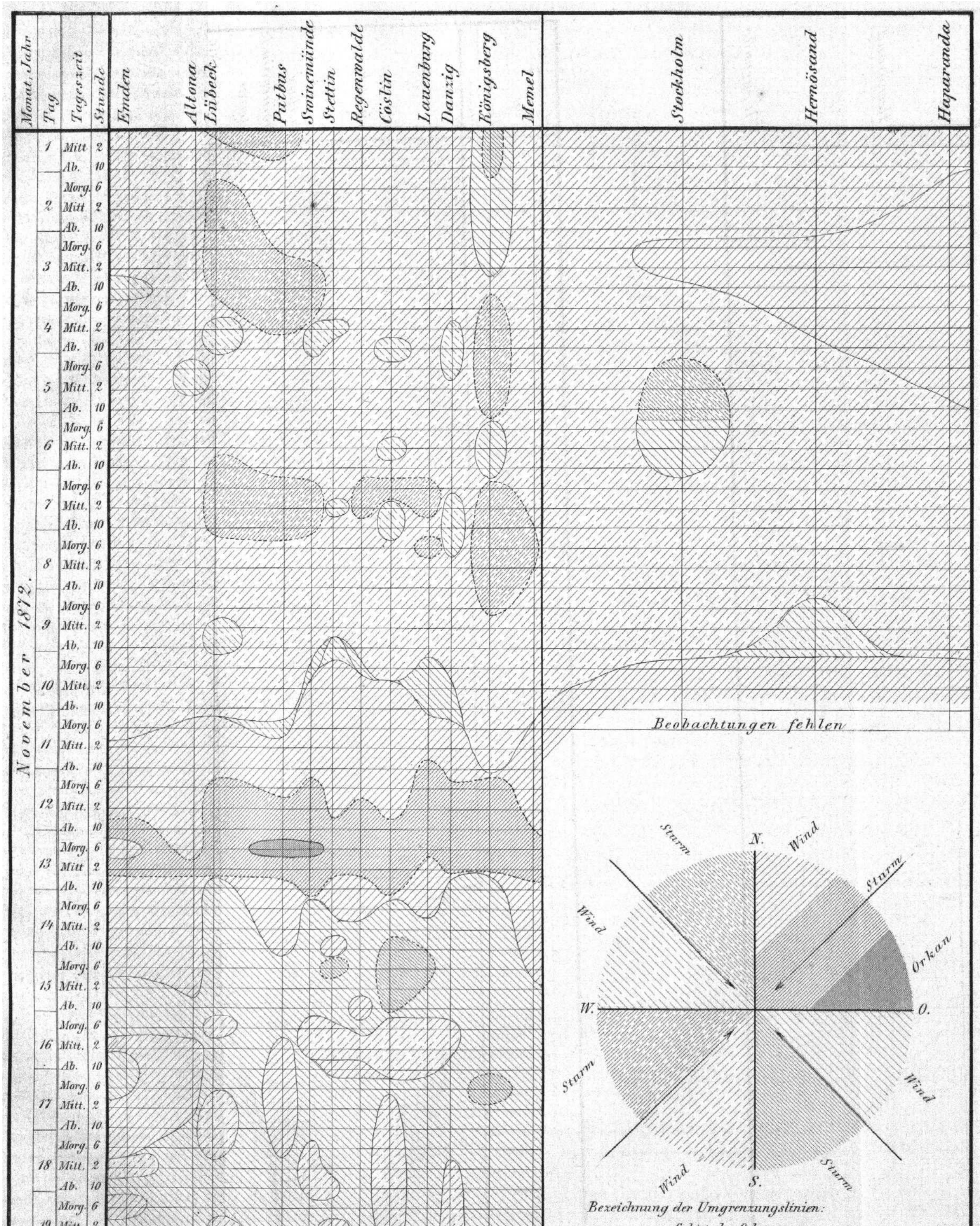

Figure 9: Graphical Representation of the Wind Movement at the Meteorological Stations near the Coasts of the Baltic Sea.

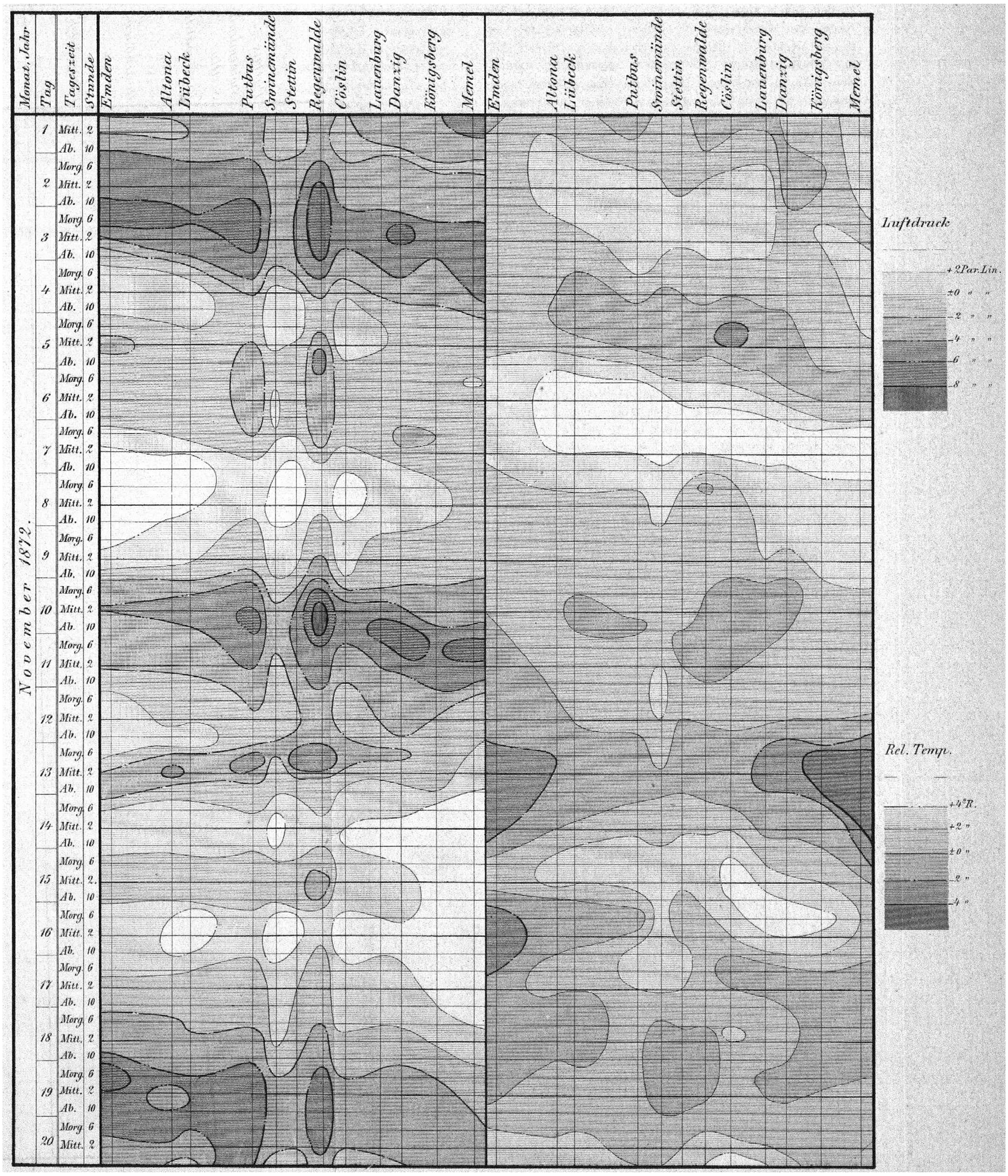

Figure 10: Graphical Representation of the Relative Air Pressure and the Relative Temperature at the Meteorological Stations near the Prussian Baltic Sea Coasts.

The stations are indicated from left to right, the times from top to bottom, whereby the geographical position of the stations in relation to their distance from each other is taken into account.

In the overall representation of the wind movement, the four quadrants have been treated separately for the wind direction, as shown by the different hatching of the areas, whereby all westerly winds have been hatched in broken lines, all easterly winds in continuous lines. All winds of the southwest quadrant have been designated SW, all winds of the northwest quadrant NW etc., so that the intermediate variations within the quadrant have not been transferred to the surface image, in order not to make this unclear.

In each wind direction the higher or lower intensities are kept apart by keeping the hatching only darker or lighter while maintaining the characteristics. Since the wind directions as well as the wind forces often extend at several places over the same and longer time, the similar winds are delimited by lines which mark the existence of this wind direction according to time and place.

The overall representation of the barometer and temperature reading is given in such a way that those areas which show the same barometer or thermometer readings according to time and location are delimited by lines and are made darker where these readings were low and lighter where they were higher. These lines, taken from the profiles, are delimited for the barometer reading by 2 to 2 Parisian lines, for the thermometer by 2 to 2 degrees Réaumur. Also in these bounded areas the degree of extent is characterized by broken lines.

In order to obtain as correct a picture as possible in the graphic representation of the temperature, i.e. uninfluenced by the effects of the sun, only those ordinates of the individual representations have been used which correspond to the morning observations. Imagine the extreme points of this ordinate connected by a curve and this curve projected onto the plane.

Compared to the earlier atmospheric presentation covering Northern and Central Europe, this surface image now shows only the zone where the actual battle between Polar and Equatorial Current took place, and it characterizes even more sharply that constant barometric minimum between Putbus and Regenwalde, which runs uniformly through the entire observation period and also appears in the thermometer readings, however less pronounced.

The strong Equatorial Current from November 1st in the evening to November 3rd in the evening, progressing in time from West to East, is expressed in the low barometer readings and simultaneous higher temperatures. The light attacks of the Polar Current on November 4th are still rejected by the Equatorial Current on November 5th and 6th, as indicated by the falling of the barometer and rising of the thermometer, but then it begins with greater force. From November 6th to November 10th, the northwesterly winds appear now and then at the height of Gdansk (Danzig), Coeslin (Cöslin), Szczecin (Stettin) and Lübeck, the barometer rises as a result of the advancing cold air, which, however, cannot take on speed since its path is blocked by the Equatorial Current; however, the thermometer begins to fall constantly due to the cold air. Thus, November 10th approaches and with it a northeasterly wind with decreasing temperature, but also, quite abnormally, with falling barometer. The latter abnormality clearly indicates that the cold air came to dominate only in a thin layer over the Baltic Sea area while the Equatorial Current continued to dominate in full strength in the upper air layers. On November 12th, in the lower layers, as a result of the ever-increasing rejection of the Equatorial Current, the northeasterly. wind became more and more active. The lateral flow of cold air on the northwestern side of the Equatorial Current made the latter come to the fore again, and as a result of this it jumped back in the night of November 12th-13th, did not allow itself to be broken by the Polar Current, but diverted the latter's path to the east. The restriction of the profile of the Polar Current at its border with the Equatorial Current between Regenwalde and Kiel, the unchanged position of the local barometric minimum at the height of Putbus, increased the former to a hurricane. It took possession of the Baltic Sea area, was pushed through the east to the southeast with increasing temperature, and finally had to give up the field completely to the

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Equatorial Current on November 19th and 20th. The Equatorial Current had thus claimed the battlefield and the intense attack of the Polar Current was beaten off under the outbreak of an eminent hurricane.

Figure 9 and Figure 10 thus give an overview of the local battle over the Baltic Sea area, without making known the acting forces at their sources, while in the earlier the whole appearance is shown on the whole European terrain. It is clear from this that tracing the symptoms on the instruments at the Baltic stations along the line of the incipient battle by no means gives a sufficient overview since comparing the deviations from the mean barometer and thermometer readings is of little help in foreseeing the coming events. Rather an examination of the absolute values of the air pressure and the temperature in wide areas is necessary in order to get a full picture of the battlefield and of the opponents, and thus to have a correct basis for a forecast.

4 Tidal Movements in the Baltic Sea during the Storm Surge of November 12th–13th, 1872

4.1 The Actual Conditions of Water Levels, Currents and Salinity of the Baltic Sea

4.1.1 Water levels

The hitherto discussed phenomena in the area of the atmosphere, which the storm surge showed in its wake, will now be assessed in their effects on the water surface, and in doing so, it will be necessary to first give some information about the available material and its use. The material used here is taken throughout from the observations made at the tide gauging stations by pilot or harbour officials. The latter refer to the absolute water levels read at the gauges, the direction of the current, the direction of the wind, the strength of the same, and some weather notes. Furthermore, notes on salinity and specific gravity of the Baltic Sea water are taken from the detailed memorandum of the Schleswig government, edited by the former building inspector Bargum, for this part.

The observation area in the Baltic Sea extends from Aarösund to Memel, the time of the observations used from November 6th to November 20th, 1872, since the phenomena from November 6th to November 9th are of such importance and also of decisive weight in the occurrence of the storm surge.

The zero points of the tide gauges are located at quite different heights and since the height of the tide gauges in relation to each other has not yet been officially determined by all of them, all absolute water levels read at the tide gauges had to be reduced to the level of the mean water of the Baltic Sea in order to bring them into relation to each other. The average water levels of the stations were taken as the level, whereby the gauge stations in the province of Schleswig-Holstein, which have only been established in recent years, have the shortest time period for determining the same. As far as possible, a comparison of these mean water levels with the levellings made by the Office of Land Triangulation on the Baltic Sea coast in connection with some sea gauges has shown that the mean water levels observed at the gauges can be regarded without substantial error as coinciding with the level of the Baltic Sea, for illumination of the storm surge, in that errors of up to about 1 decimetre at the most may have occurred, an error limit which, in the case of such a significant water change as occurred here, does not in any case significantly cloud the picture to be created.

It is more questionable whether the water levels on the coast are in harmony with those in the open sea, since all the observations are only on the coast. However, also in this respect, great differences are not assumed; rather it may be assumed that the water changes in the open sea will move in similar lines with those on the beach. Comparisons made in this respect between two tide gauges, one at Thiessow on Mönchgut, the other on the east side of the island of Greifswalder Oie, 2 miles out to sea, have not revealed any differences of particular value, and it only requires a comparison of the profiles of the water levels between Thiessow and Greifswalder Oie given in Figure 14 to confirm this. Unfortunately, the gauge on Greifswalder Oie was knocked away from the sea in the evening of November 13th, making further observation impossible.

The reduced water levels or the fluctuation of the absolute water levels observed at the gauges by the height of the mean water level, as well as the wind directions observed at the same times and places - according to the 16-part wind rose and the intensity of the wind in 5 gradations - as in the I. section - are compiled from the stations evident from the head of the diagram in Table 4 to Table 8.

On the basis of these tables, graphical profile representations of the water level and the wind intensity of the individual stations have been drawn on Figure 11, Figure 12, Figure 13, Figure 14 and Figure 15, the representation of which will be clear to every technician even without further explanation. The distance of the horizontal lines from each other is 0.5 metres for the water level and means at the same time a unit for the wind intensity. The wind direction is again expressed by arrows with north-up orientation. These profiles, which will have their special interest for the individual stations, are not particularly considered here, but only served as a basis for an overall picture of the wind movement and the water change over the whole area from Aaroe to Memel, on which the connection between the different stations is easier to see at a glance. By connecting the profile points found from the observations, which the above-mentioned tables prove, by means of uniform curves, the possibility arose to interpolate all times not observed and thus to gain the material for the overall overviews of the graphical representations in Figure 16.

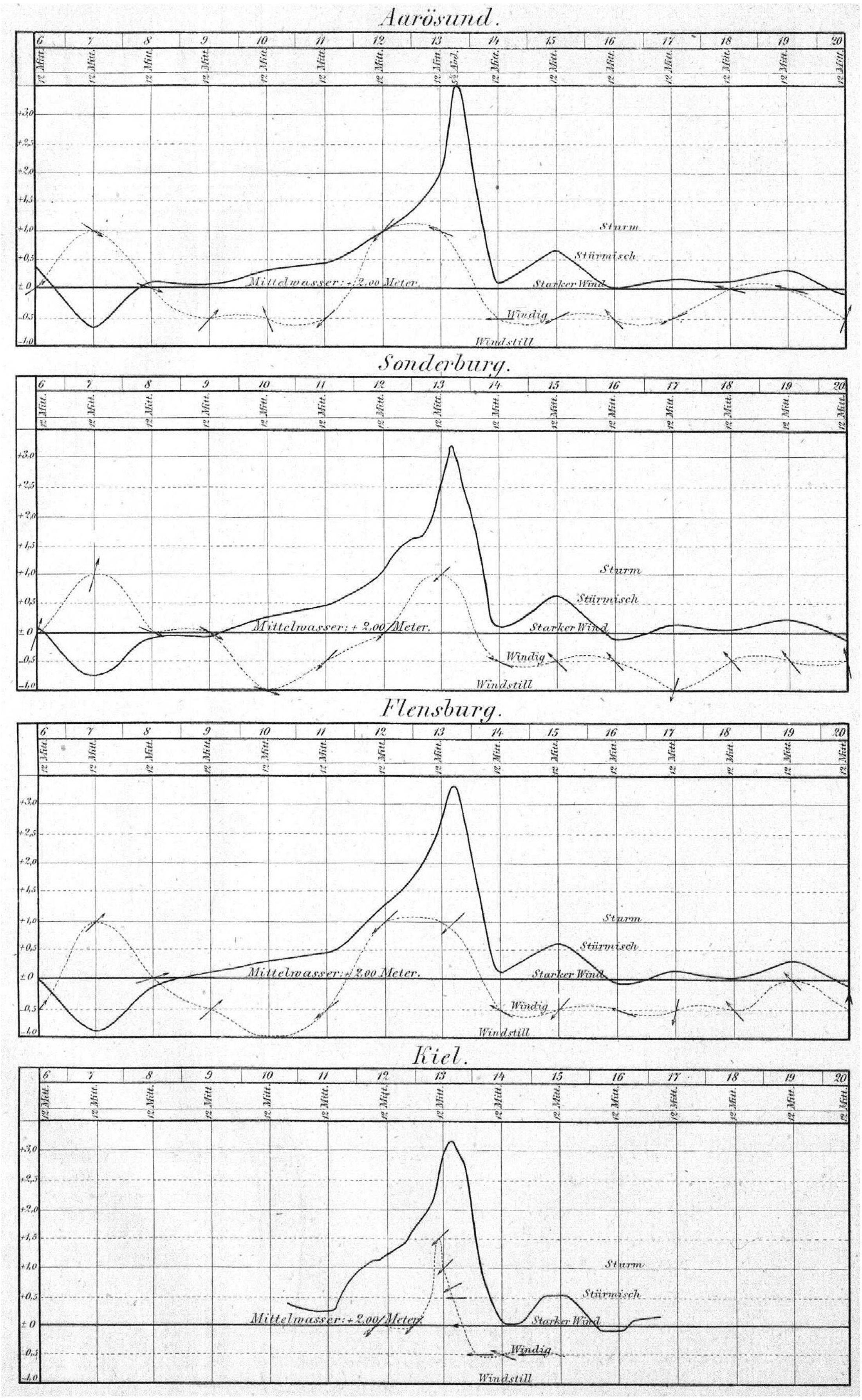

Figure 11: Graphical Representation of the Water Level and Wind Intensity in the Individual Stations (Aarösund to Kiel).

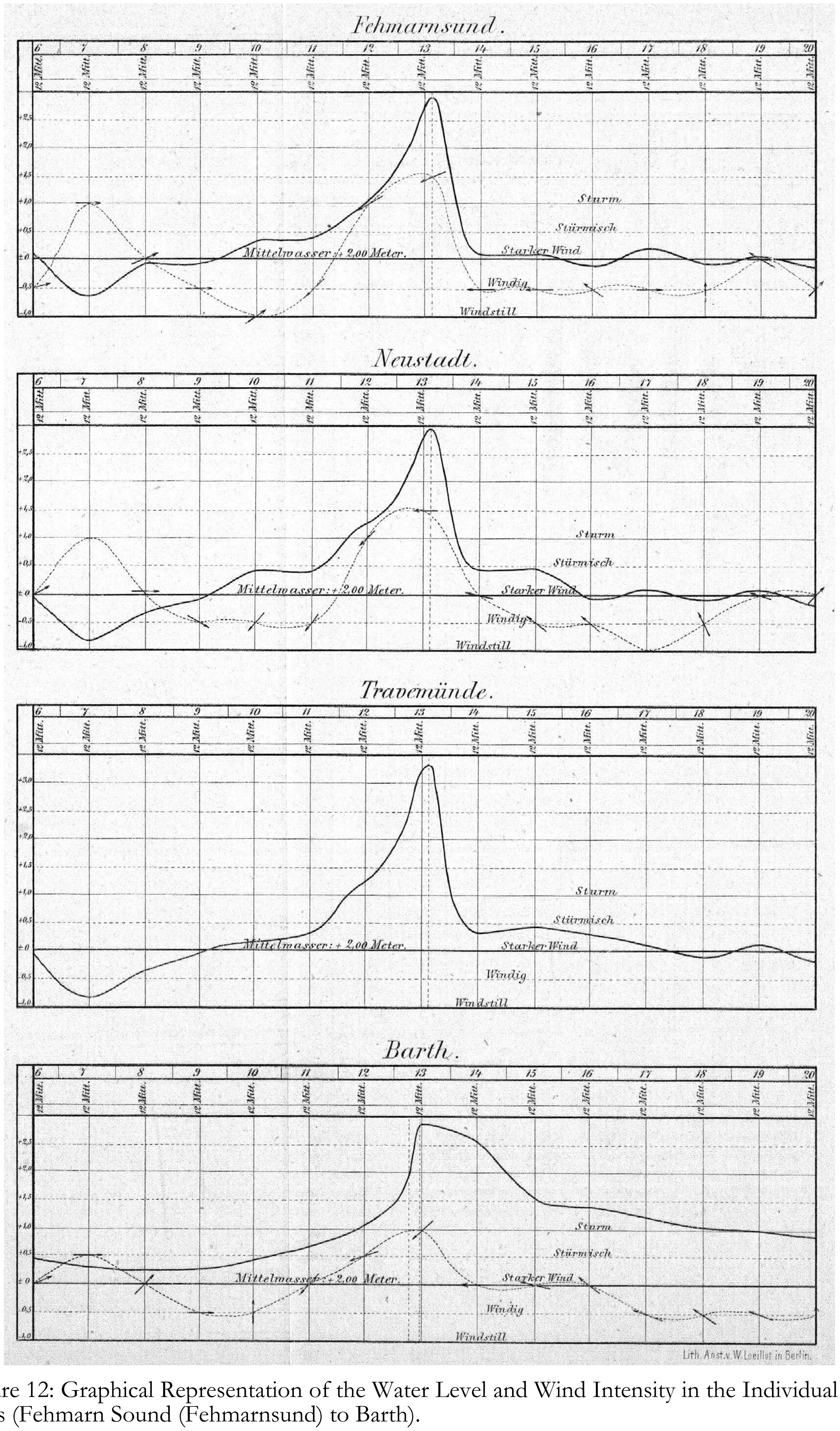

Figure 12: Graphical Representation of the Water Level and Wind Intensity in the Individual Stations (Fehmarn Sound (Fehmarnsund) to Barth).

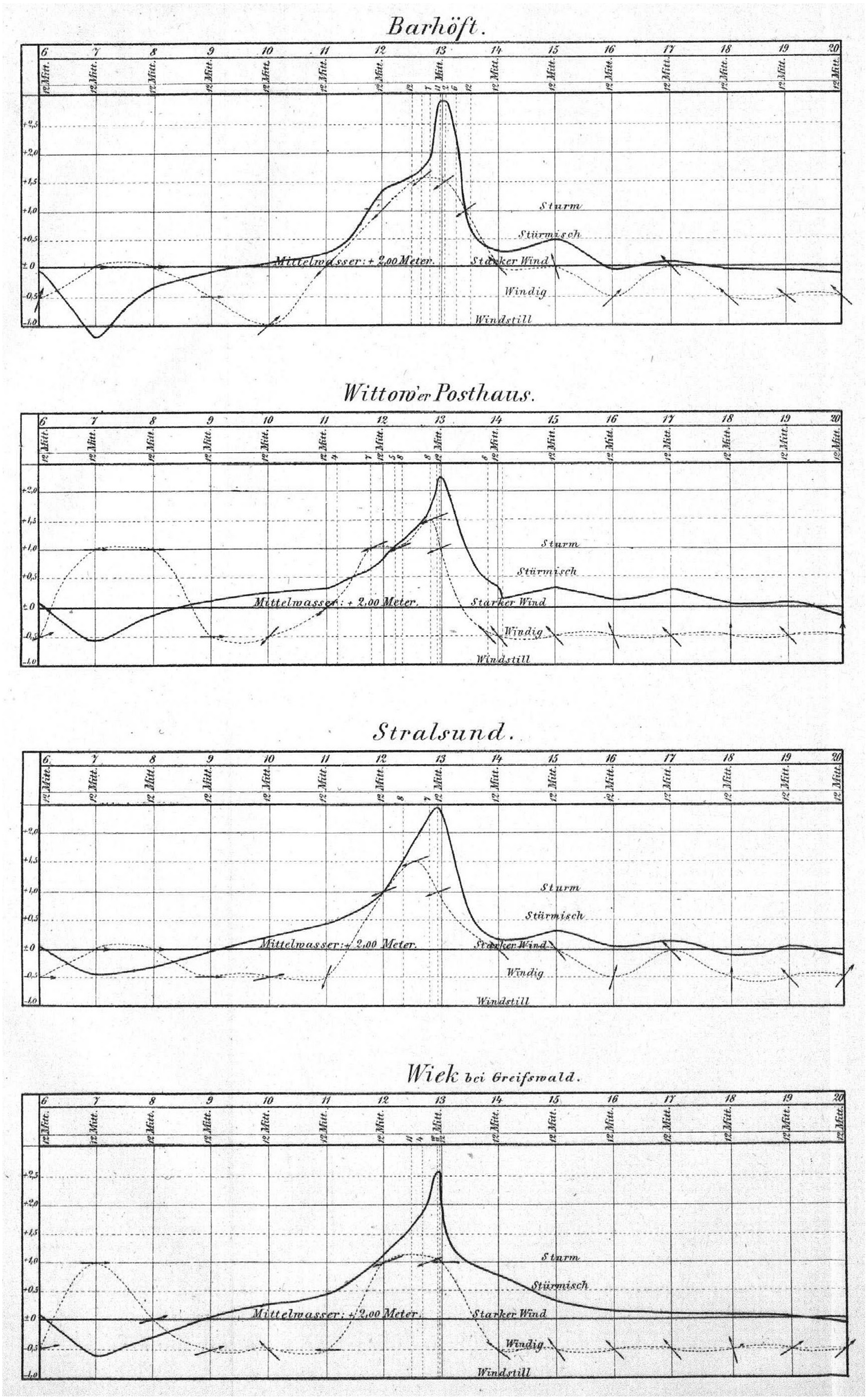

Figure 13: Graphical Representation of the Water Level and Wind Intensity in the Individual Stations Barhöft to Wiek).

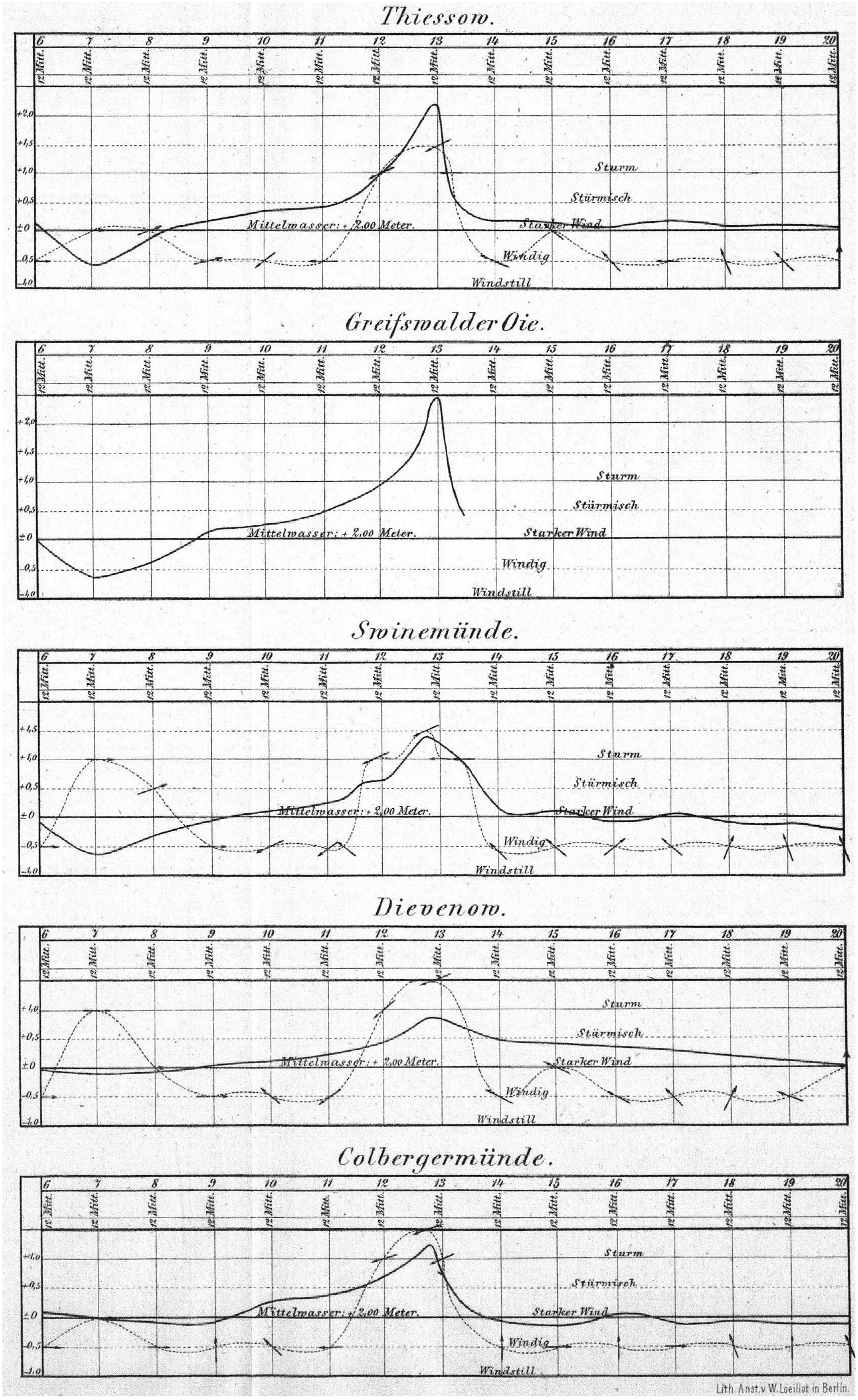

Figure 14: Graphical Representation of the Water Level and Wind Intensity in the Individual Stations (Thiessow to Colbergermuende (Colbergermünde)).

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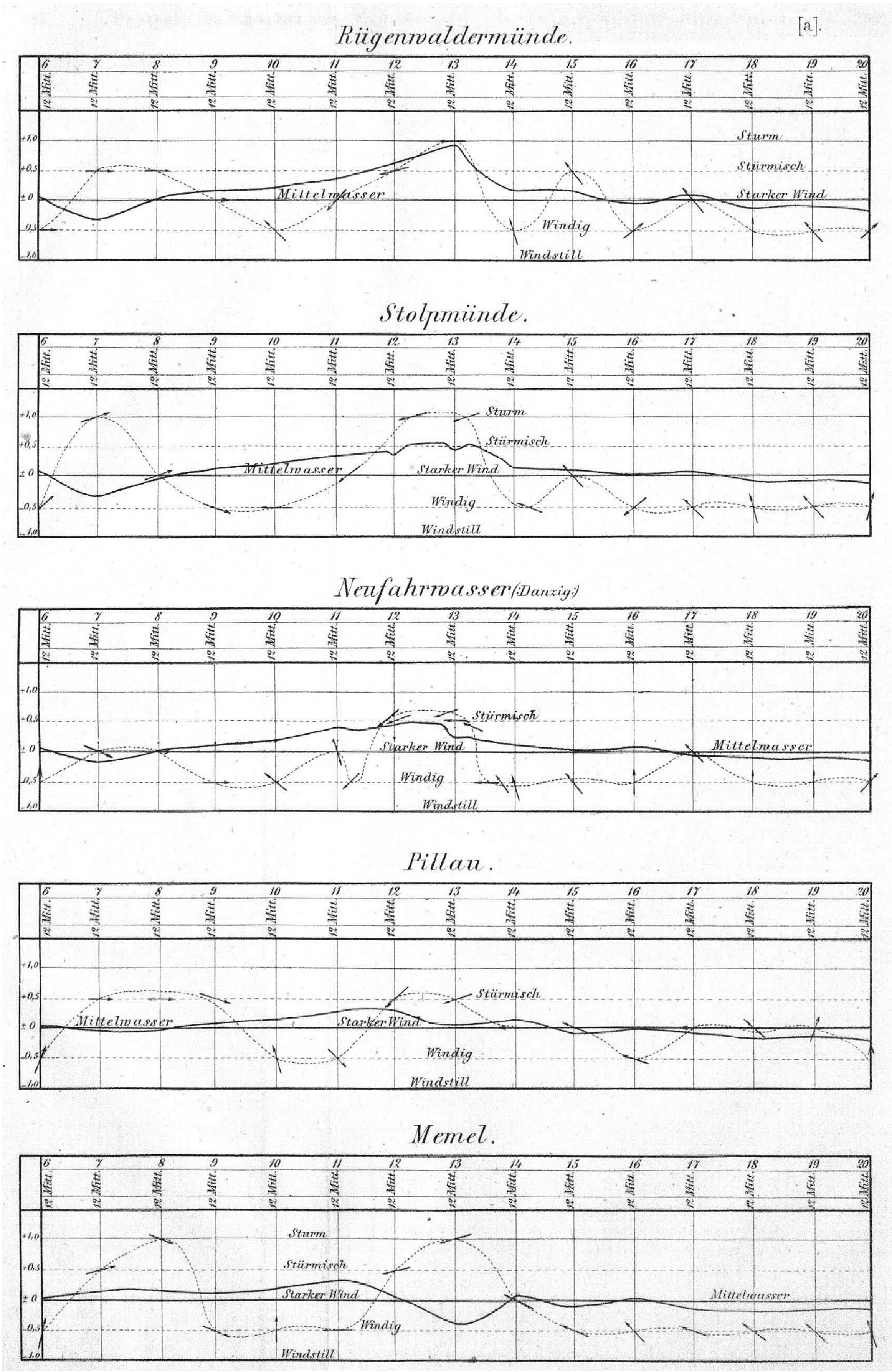

Figure 15: Graphical Representation of Water and Wind movement on the Meteorological Stations near the Baltic Sea.

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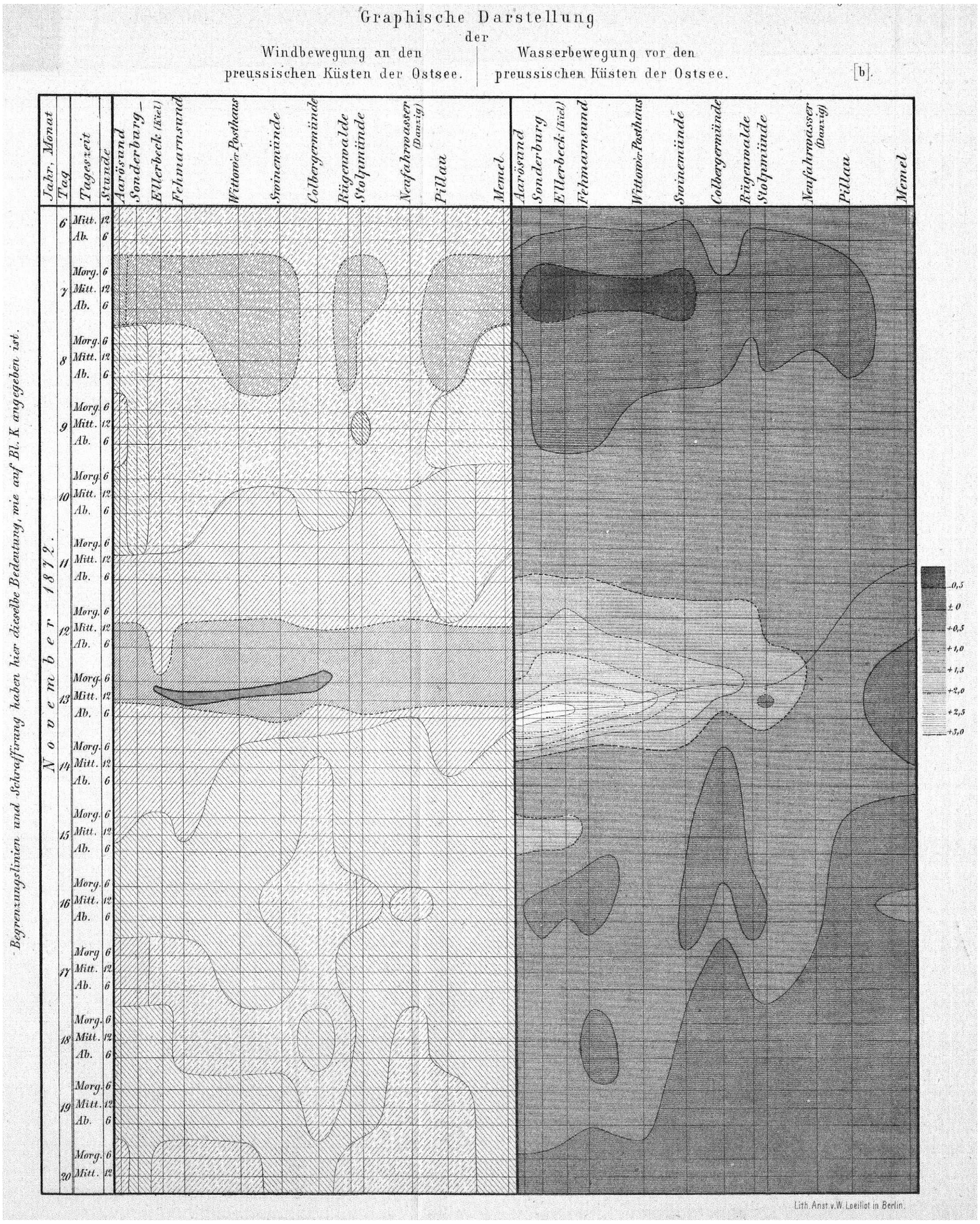

Figure 16: Graphical Representation of Wind and Water Level Movement along the Prussian Baltic Sea Coasts.

From these individual profiles, the two surface images in Figure 16 on the wind and water movement in the period from November 6th to November 20th inclusive have been obtained by marking the height of the water level above or below mean water at the relevant times of the various stations and drawing their horizontal curves, which belong to the same water level height in increments of 0.6 metre each. In this way, the fluctuation of the level of the Baltic Sea at the beach stretches of the observation stations over the whole area from the Prussian-Danish to the Prussian-Russian border can be surveyed at a glance. To

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facilitate this overview, the lowest water levels are shaded dark, while the highest water levels are kept light.

	Höchster Wasserstand Meter	am 13. November Nachmittag
Schleimünde . . .	3,44	3 h 30′
Rabelsund	3,44	4 h
Kappeln	3,30	4 h 45′
Arnis	3,12	5 h 15′

In the same way, in Figure 16, the direction and the intensity of the wind have been marked for the relevant times of the selected stations, although, for the sake of clarity, the winds have been marked only according to their 4 quadrants. In order to emphasize the intensity, the same is delimited according to the observation areas and now the difference of the two main movements is characterized by a hatching, namely for the west side of the wind rose in torn, for the east side of the wind rose in sharply drawn hatching, which still emphasizes the greater or lesser intensity by a denser, respectively further hatching.

Subsequent to Figure 16, if one follows the time, above all the storm from the west side of the wind rose, lasting 24 or 48 hours, respectively, between November 6th–7th at noon and until the morning of November 9th, is shown. Since this storm became of great importance for the development of the storm surge, it may be noted right here in relation to the size of its area that this westerly storm, according to the reports of v. Boguslawski, extended from the Scottish coasts over the North Sea, over Schleswig-Holstein and over the large basin of the Baltic Sea. As for the processes of this storm, according to the graphic representation in Figure 10, it already occurred once at Lübeck on the morning of November 2nd, moved along the Baltic Sea, and marked Koenigsberg (Königsberg) on the morning of November 4th. The general wind direction from November 1st to 10th or even 11th respectively was from the southwestern quadrant.

The fateful northeast was first signalled on November 10th at noon from the Wittow post house to Stolp, then on November 11th at noon to Nowy Port (Neufahrwasser) and Memel, and finally on the morning of November 12th also in Pillau, i.e. in the whole extension of the observation area. At noon on November 12th, the NE wind, which in the meantime had become stronger and stronger, appeared as a gale on the whole line, except at Ellerbeck; the increase in strength was thus simultaneous up to the Holstein coast. The hurricane, on the other hand, which began shortly after midnight between November 12th and 13th in Colberg, rose like an island out of the storm sea, gradually spreading across the area, and disappeared again between Ellerbeck and Sønderborg (Sonderburg) on the morning of November 13th, continuing in Fehmarn Sound (Fehmarnsund) until the afternoon.

The decrease of the storm to strong or moderate winds, respectively occurs again almost at the same time on November 13th in the afternoon on the whole line, in Swinoujscie (Swinemünde) continuing in strength until about 8 p.m.. The boundary between the normally occurring wind shifts from the NE quadrant into the SE quadrant forms a very irregular line with respect to time. First one meets the SE in Nowy Port (new fairway), namely in the evening of November 13th, then evenly progressing along the coast until the morning of November 14th in the Wittower post house, then also in the afternoon of November 15th gaining terrain to the east and finally in the evening of November 15th on the whole observation line as the sole dominator of the area.

During the period from November 14th to 20th, southwestern quadrant winds reappeared intermittently to give way alternately to SE until the SE wind had regained possession almost all along the line in the Baltic area from November 18th to 20th.

The graphical representation of the water movement in the Baltic Sea before, during and after the storm surge, compared with the wind movement, provides an easy overview of the correlation, although it should not be forgotten that the observation material on the water levels was collected more often during the day only in the period from November 11th to 14th, while before and after this period it was recorded only at noon according to the existing regulations, so that for these latter periods the intermediate elements in the observation are missing.

The comparison shows in the first row the effect of the westerly storm prevailing from November 7th to 8th inclusively. It can be seen that the water level, which had reached the mean water level on the evening of November 6th, dropped rapidly and significantly on the whole line from Aarösund to behind Pillau under the influence of the southwesterly storm. In particular, the large basin of the western and southernmost part of the Baltic Sea was affected, which must have been the most vulnerable to the attack as well as to its situation. From Aarösund to Swinoujscie (Swinemünde), the water fell by more than 0.5 metres below the mean water level. At noon on November 8th, however, the water began to rise again, namely in Aarösund due to the close connection with the Kattegat, and on the eastern wing of the observation line from Rögenwalde to the mean water level. In the evening of November 9th, this level was also reached in Sønderborg (Sonderburg), Ellerbeck and Fehmarn Sound (Fehmarnsund). The water continued to rise steadily, and especially in the western part of the Baltic Sea from November 9th onwards faster than in the remaining part, which can be seen in the approach of the horizontal, i.e. in the shortening of the times, in Figure 16.

In order to be able to follow the movement of the storm surge even more specifically, two longitudinal profiles of the Baltic Sea from Aarösund to Memel are attached in Figure 1, in which the rise and fall of the water is shown according to the various more important time periods, whereby the mean water level lying in the gradient is assumed to be horizontal at 0. The boundary between the low water level of the Baltic Sea in the western basin and the higher water level in the northern basin is shown at the level of Pillau, i.e. at the location where the water level swings to the NE. Also, the water levels of the whole following tide show that the neutral line, around which the level of the lake fluctuates, is maintained without significant deviations at the level of Pillau, and in the orientation plan Figure 4 this neutral boundary is entered in a broken line.

From the evening of November 9th until 6 p.m. in the afternoon of November 11th, the water at Aarösund, which had been rising since November 7th, was raised to a height of 0.5 metres above mean water; the same height was not reached until midnight at Rügenwalde, while at Stolpmünde it was not until the afternoon of November 12th, while at Nowy Port (Neufahrwasser) this height was not reached at all.

The rise of the tide up to the height of 0.5 metres above mean water thus occurred from west to east, and the water level in this first period, under the influence of the steady northeasterly wind, forms a fairly evenly inclined surface rising toward Holstein.

Following the further rise of the tide, then according to Figure 16 the equal water level line +1.0 metres shows that this level was first reached at Ellerbeck, namely in the night from November 11th to 12th within about 12 hours, while the same water level at Aaroe occurred 6 hours later at noon on November 12th. The progress of the tidal wave was thus significantly delayed between Alsen and the Danish islands.

Table 4: Meanwater Level at Aerosund, Sønderborg (Sonderburg), Flensburg, Ellerbeck, Fehmarn Sound (Fehmarnsund) and Neustadt

Tabelle IV.

Gebiet			Ostsee																				
Pegel-Stationen			**Aaroesund.**			**Sonderburg.**			**Flensburg.**			**Ellerbeck.**			**Fehmarnsund.**			**Neustadt.**					
Mittelwasser			+ 2,00 m			+ 1,88 m			+ 2,00 m			+ 0,006 m			+ 1,97 m			+ 2,05 m					
Tage im Novbr.	Stunde	Tageszeit	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke			
6	12	Mitt.	+ 0,36	SW	2	+ 0,10	WSW	2	± 0,00	SW	1	....	SW	....	+ 0,03	WSW	1	— 0,03	WSW	2			
7	12	Mitt.	— 0,64	WNW	4	— 0,74	WSW	4	— 0,84	SW	4	....	SW	....	— 0,67	W	4	— 0,85	W	4			
8	12	Mitt.	+ 0,10	WNW	2	— 0,06	WNW	2	— 0,14	WSW	2	....	SW	....	— 0,07	WSW	2	— 0,29	W	2			
9	12	Mitt.	+ 0,08	SW	1	— 0,04	WNW	2	+ 0,06	SW	1	....	SW	....	— 0,05	W	1	— 0,01	NW	1			
10	12	Mitt.	+ 0,32	SSO	1	+ 0,26	WNW	0	+ 0,30	SW	0	....	SSW	....	+ 0,33	SW	0	+ 0,41	NO	1			
11	12	Mitt.	+ 0,46	NO	1	+ 0,44	NO	1	+ 0,48	NO	1	....	NO	....	+ 0,41	NO	1	+ 0,39	NO	1			
	4	Nachmitt.																					
	8	Abd.																					
12	6	Morg.	....	....	....	....	....	....	....	....	....	+ 1,15	NO	2									
	7	Morg.																					
	12	Mitt.	+ 1,00	NO	4	+ 1,08	NO	2	+ 1,30	NO	4	+ 1,26	NO	2	+ 1,05	NO	4	+ 1,25	NO	4			
	3	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 1,33	NO	2									
	4	Nachmitt.	....	....	....	+ 1,32																	
	5	Nachmitt.																					
	6	Abd.	....	....	....	+ 1,52	....	....	....	....	....	+ 1,44	NO	2									
	8	Abd.	....	....	....	+ 1,62																	
	12	Nachts	....	....	....	....	....	....	....	....	....	+ 1,73	—	2									
13	4	Morg.	....	....	....	+ 1,62																	
	6	Morg.	....	....	....	....	....	....	....	....	....	+ 2,01	NO	3									
	7	Morg.	....	....	....	....	....	....	....	....	....	+ 2,15	NO	3									
	8	Morg.	....	....	....	+ 1,90	....	....	....	....	....	+ 2,33	NO	3									
	9	Morg.	....	....	....	....	....	....	....	....	....	+ 2,51	NO	3—5									
	10	Morg.	....	....	....	....	....	....	....	....	....	+ 2,72	NO	4									
	11	Mitt.	....	....	....	....	....	....	....	....	....	+ 2,88	NO	4									
	12	Mitt.	+ 2,00	OSO	4	+ 2,59	NO	4	....	....	....	+ 2,98	NO	3									
	2	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 3,14	ONO	3									
	2½	Nachmitt.	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	+ 2,95	O	5			
	3	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 3,17	O	3	+ 2,89	ONO	5						
	3½	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 3,17	O	2									
	4	Nachmitt.	....	....	....	+ 3,10	....	....	....	....	....	+ 3,09	O	2									
	4½	Nachmitt.	....	....	....	+ 3,20	....	....	+ 3,31	NO	4												
	5	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 3,06	O	2									
	5½	Nachmitt.	+ 3,50																				
	6	Abd.	....	....	....	....	....	....	....	....	....	+ 2,98	O	2									
	8	Abd.	....	....	....	+ 2,72	....	....	....	....	....	+ 2,80	O	2									
	12	Nachts	....	....	....	+ 2,20	....	....	....	....	....	+ 1,99	O	1									
14	4	Morg.	....	....	....	....	....	....	....	....	....	+ 1,05	O	1									
	8	Morg.																					
	12	Mitt.	+ 0,12	O	1	+ 0,13	OSO	1	+ 0,16	OSO	1	+ 0,16	OSO	1	+ 0,05	O	1	+ 0,41	OSO	5			
	2	Nachmitt.																					
	4	Nachmitt.																					
	6	Abd.	....	....	....	....	....	....	....	....	....	+ 0,11	O	1									
15	12	Mitt.	+ 0,68	ONO	1	+ 0,58	SO	1	+ 0,66	NO	1	....	O	....	+ 0,07	O	1	+ 0,45	SO	1			
16	12	Mitt.	± 0,00	SO	1	— 0,10	SO	1	— 0,04	OSO	1	....	SO	....	— 0,17	SO	1	— 0,07	SO	1			
17	12	Mitt.	+ 0,10	ONO	1	+ 0,16	NNO	0	+ 0,14	NNO	1	....	W	....	+ 0,19	W	1	+ 0,11	—	0			
18	12	Mitt.	+ 0,08	OSO	2	+ 0,03	SO	1	+ 0,02	SO	1	....	OSO	....	— 0,03	S	1	— 0,07	SSO	1			
19	12	Mitt.	+ 0,30	OSO	2	+ 0,21	SO	1	+ 0,30	SO	2	....	SO	....	+ 0,01	SO	2	+ 0,11	OSO	2			
20	12	Mitt.	— 0,06	SSW	1	— 0,16	SSO	1	— 0,12	S	1	....	WSW	....	— 0,19	SW	1	— 0,19	SW	2			

Table 5: Meanwater Level at Travemuende (Travemünde), Barth, Barhöft, Wittower Post House, Stralsund and Wiek next to Greifswald

Tabelle V.

Gebiet			Ostsee																	
Pegel-Stationen			**Travemünde.**			**Barth.**			**Barhöft.**			**Wittower Posthaus.**			**Stralsund.**			**Wiek** bei Greifswald.		
Mittelwasser			+ 5,20 m			+ 1,25 m			+ 1,18 m			+ 1,18 m			+ 1,18 m			+ 1,26 m		
Tage im Novbr.	Stunde	Tages-zeit	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke
6	12	Mitt.	− 0,05	WSW	....	+ 0,40	WSW	2	− 0,06	SSW	1	+ 0,04	WSW	1	+ 0,02	W	1	+ 0,05	WSW	1
7	12	Mitt.	− 0,85	W	....	+ 0,29	W	3	− 1,18	W	2	− 0,53	W	4	− 0,42	W	2	− 0,63	W	4
8	12	Mitt.	− 0,30	WSW	....	+ 0,24	SW	2	− 0,32	W	2	− 0,14	W	4	− 0,34	W	2	− 0,27	WSW	2
9	12	Mitt.	− 0,05	WSW	....	+ 0,24	W	1	− 0,04	W	1	+ 0,07	W	1	− 0,04	W	1	+ 0,04	WSW	1
10	12	Mitt.	+ 0,15	SW	....	+ 0,40	S	1	+ 0,12	SW	0	+ 0,25	NO	1	+ 0,20	WSW	1	+ 0,31	SO	1
11	12	Mitt.	+ 0,30	O	....	+ 0,63	NO	2	+ 0,28	NO	2	+ 0,31	NO	2	+ 0,40	NNO	1	+ 0,44	O	1
	4	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 0,39								
	8	Abd.																		
12	6	Morg.																		
	7	Morg.	....	....	....	....	....	....	....	....	....	+ 0,63	ONO	4						
	12	Mitt.	+ 1,25	ONO	....	+ 1,05	ONO	3	+ 1,32	NO	4	+ 0,78	ONO	4	....	ONO	4	+ 0,18	ONO	4
	3	Nachmitt.																		
	4	Nachmitt.																		
	5	Nachmitt.	....	....	Windstärke nicht angegeben	....	....	....	....	....	....	+ 1,02	ONO	4						
	6	Abd.																		
	8	Abd.	....	....		....	....	....	....	....	....	....	....		+ 1,51	ONO	5			
	12	Nachts	....	....		....	....	....	+ 1,62	NO	5	....	....		....			11h + 1,62	ONO	4
13	4	Morg.	....	....		....	....	....	....	....	....	....	....		....	....	....	+ 1,88	ONO	4
	6	Morg.																		
	7	Morg.	....	....		+ 1,89	....	....	+ 1,94	NO	5	....	....	....	7h 20m + 2,35					
	8	Morg.	....	....		....	....	....	....	....	....	+ 1,65	ONO	5						
	9	Morg.																+ 2,64	ONO	4
	10	Morg.	....	....		....	....	....	....	....	....	+ 2,12	ONO	5	10h 30m + 2,46	....	....	+ 2,64	ONO	4
	11	Mitt.	....	....		+ 2,83	NO	4	+ 2,92	NO	5	+ 2,27	ONO	4		ONO	4			
	12	Mitt.	....	....		....	....	....	....	....	....	....	....	....	....	....	....	+ 1,88	O	4
	2	Nachmitt.	+ 3,32	NO		....	....	....	+ 2,92	NO	5									
	2½	Nachmitt.																		
	3	Nachmitt.																		
	3½	Nachmitt.																		
	4	Nachmitt.																		
	4½	Nachmitt.																		
	5	Nachmitt.																		
	5½	Nachmitt.																		
	6	Abd.	....	....	....	....	....	....	+ 1,32	NO	5									
	8	Abd.																		
	12	Nachts	....	....	....	....	....	....	+ 0,72	NO	5									
14	4	Morg.																		
	8	Morg.	....	....	....	....	....	....	....	....	....	+ 0,47	SO	1						
	12	Mitt.	+ 0,35	OSO	....	+ 2,55	O	2	+ 0,31	SO	2	+ 0,33	SO	1	+ 0,16	SO	2	+ 0,78	SO	1
	2	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 0,18	SO	1						
	4	Nachmitt.																		
	6	Abd.																		
15	12	Mitt.	+ 0,45	OSO	....	+ 1,55	OSO	2	+ 0,54	SSO	2	+ 0,33	SO	1	+ 0,36	SO	2	+ 0,31	SO	1
16	12	Mitt.	+ 0,30	OSO	....	+ 1,39	SO	2	+ 0,02	SW	1	+ 0,07	SSO	1	+ 0,02	SSW	1	+ 0,16	SO	1
17	12	Mitt.	+ 0,12	NW	....	+ 1,25	OSO	1	+ 0,10	SO	2	+ 0,31	SO	1	+ 0,18	SO	2	+ 0,15	SO	1
18	12	Mitt.	− 0,15	SSO	....	+ 1,10	80	1	+ 0,02	SO	1	+ 0,02	S	1	− 0,10	S	1	+ 0,13	SSO	1
19	12	Mitt.	+ 0,10	SO	....	+ 1,03	OSO	1	− 0,06	SO	1	+ 0,07	SO	1	+ 0,02	SO	1	+ 0,05	SW	1
20	12	Mitt.	− 0,20	WSW	....	+ 0,95	S	1	− 0,11	SO	1	− 0,14	S	1	− 0,08	SW	1	− 0,16	SW	1

Table 6: Meanwater Level at Thiessow, Swinoujscie (Swinemünde), Dievenow, Colbergermuende (Colbergermünde) and Ruegenwaldermuende (Rügenwaldermünde)

Tabelle VI.

Gebiet			Ostsee														
Pegel-Stationen			**Thiessow.**			**Swinemünde.**			**Dievenow.**			**Colbergermünde.**			**Rügenwaldermünde.**		
Mittelwasser			+ 1,26 m			+ 7,06 m			+ 2,04 m			+ 1,52 m			+ 1,09 m		
Tag im Novbr.	Stunde	Tages-zeit	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke
6	12	Mitt.	+ 0,15	W	1	− 0,05	W	1	− 0,02	W	1	+ 0,10	W	1	+ 0,06	W	1
7	12	Mitt.	− 0,55	W	2	− 0,63	W	4	− 0,16	W	4	± 0,00	W	2	− 0,30	W	3
8	12	Mitt.	− 0,11	WSW	2	− 0,26	WSW	3	− 0,06	W	2	− 0,08	W	1	+ 0,06	W	3
9	12	Mitt.	+ 0,21	WSW	1	− 0,03	W	1	+ 0,02	W	1	− 0,06	S	1	+ 0,17	W	2
10	12	Mitt.	+ 0,36	NO	1	+ 0,10	ONO	1	+ 0,06	SO	1	+ 0,28	SO	1	+ 0,24	SO	1
11	12	Mitt.	+ 0,47	O	1	+ 0,26	NO	1	+ 0,24	NO	1	+ 0,36	O	1	+ 0,37	NO	2
	4	Nachmitt.															
	8	Abd.	....	....	....	+ 0,31	SO	1									
12	6	Morg.															
	7	Morg.	....	....	....	+ 0,63	ONO	4									
	12	Mitt.	+ 0,99	ONO	4	+ 0,65	ONO	4	+ 0,44	NO	4	+ 0,68	ONO	4	+ 0,61	ONO	3
	3	Nachmitt.															
	4	Nachmitt.															
	5	Nachmitt.	....	....	....	....	....	....	....	....	....	+ 0,83					
	6	Abd.															
	8	Abd.	....	....	....	+ 0,94	ONO	4									
	12	Nachts	....	....	....	....	....	....	....	....	....	....	ONO	5			
13	4	Morg.															
	6	Morg.															
	7	Morg.	....	....	....	+ 1,41	ONO	5	....	....	....	+ 1,23					
	8	Morg.															
	9	Morg.	+ 2,19	ONO	5	....	....	....	....	....	....	....	ONO	5			
	10	Morg.															
	11	Mitt.															
	12	Mitt.	+ 2,19	ONO	5	+ 1,26	O	4	+ 0,84	ONO	5	+ 0,83	ONO	4	+ 0,95	O	4
	2	Nachmitt.															
	2½	Nachmitt.															
	3	Nachmitt.															
	3½	Nachmitt.															
	4	Nachmitt.															
	4½	Nachmitt.															
	5	Nachmitt.															
	5½	Nachmitt.															
	6	Abd.	+ 0,62	O	4												
	8	Abd.	....	....	....	+ 1,04	O	4									
	12	Nachts															
		Morg.															
	8	Morg.	....	....	....	+ 0,42	OSO	1									
	12	Mitt.	+ 0,21	OSO	1	+ 0,21	SO	1	+ 0,48	OSO	1	− 0,03	S	1	+ 0,17	SSO	1
	2	Nachmitt.															
	4	Nachmitt.															
	6	Abd.	....	....		+ 0,02	OSO	1									
15	12	Mitt.	+ 0,21	SO	2	+ 0,10	SO	1	+ 0,40	OSO	2	− 0,19	W	1	+ 0,17	SO	3
16	12	Mitt.	+ 0,07	SO	1	− 0,05	SW	1	+ 0,34	OSO	1	+ 0,05	S	1	− 0,02	SW	1
17	12	Mitt.	+ 0,23	O	1	+ 0,02	SO	1	+ 0,26	SO	1	− 0,11	W	1	+ 0,06	SO	2
18	12	Mitt.	+ 0,07	SSO	1	− 0,13	SSW	1	+ 0,20	SSW	1	− 0,03	SSO	1	− 0,10	S	1
19	12	Mitt.	+ 0,07	SO	1	− 0,13	SSO	1	+ 0,08	OSO	1	− 0,13	S	1	− 0,07	SO	1
20	12	Mitt.	± 0,00	S	1	− 0,24	SSO	1	± 0,00	S	2	− 0,16	SSO	1	− 0,15	SW	1

Table 7: Meanwater Level at Stolpmünde, Nowy Port (Neufahrwasser), Pillau, Memel, Wolgast and Auelam.

Tabelle VII.

Gebiet			Ostsee												Peene					
Pegel-Stationen			**Stolpmünde.**			**Neufahrwasser** bei Danzig.			**Pillau.**			**Memel.**			**Wolgast.**			**Anclam.**		
Mittelwasser			+ 0,71 m			+ 3,53 m			+ 2,41 m			+ 0,47 m			+ 1,26 m			+ 2,04 m		
Tage im Novbr.	Stunde	Tageszeit	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke	Abweich. vom Mittelwasser	Windrichtung	Windstärke
6	12	Mitt.	+ 0,05	SW	1	+ 0,05	S	1	+ 0,03	SSW	1	+ 0,05	SSO	1	— 0,02	WSW	1	— 0,05	SW	1
7	12	Mitt.	— 0,30	WSW	4	— 0,13	WNW	2	— 0,03	W	3	+ 0,16	WSW	3	— 0,31	W	2	$\pm$ 0,00	W	1
8	12	Mitt.	— 0,03	WSW	2	+ 0,03	W	2	— 0,01	W	3	+ 0,16	WNW	4	— 0,18	SW	1	— 0,34	W	1
9	12	Mitt.	+ 0,15	WNW	1	+ 0,13	W	1	+ 0,07	WNW	3	+ 0,10	WNW	1	— 0,05	W	1	— 0,31	W	1
10	12	Mitt.	+ 0,23	O	1	+ 0,19	SO	1	+ 0,15	SSO	1	+ 0,19	S	1	+ 0,04	W	1	+ 0,03	NW	1
11	12	Mitt.	+ 0,36	....	....	+ 0,39	NNW	2	+ 0,31	NW	1	+ 0,32	O	1	+ 0,33	NO	1	+ 0,24	NO	1
	4	Nachmitt.	....	NO	2		NO	1												
	8	Abn.	....	....	....	+ 0,37														
12	6	Morg.	....	....	....	+ 0,41														
	7	Morg.	+ 0,41	....	....	....	NO	3												
	12	Mitt.	+ 0,36	....	....	+ 0,45	ONO	3	+ 0,29	NO	3	+ 0,03	ONO	3	....	NO	4	+ 0,52	O	4
	3	Nachmitt.																		
	4	Nachmitt.																		
	5	Nachmitt.	+ 0,52	ONO	4	....	ONO	3	....	....	....	....	....	....	+ 0,55					
	6	Abd.	....	....	....	+ 0,49														
	8	Abd.																		
	12	Nachts	....	....	....	....	ONO	3												
13	4	Morg.																		
	6	Morg.	....	....	....	+ 0,47	....	....	....	....	....	....	....	....	+ 1,56					
	7	Morg.	+ 0,55	....	....	....	ONO	3												
	8	Morg.																		
	9	Morg.	....	....	....	....	....	....	....	....	....	....	....	....	+ 1,67					
	10	Morg.	....	....	....	....	....	....	....	....	....	....	....	....	+ 1,77					
	11	Mitt.																		
	12	Mitt.	+ 0,47	....	....	+ 0,23	O	3	+ 0,03	ONO	3	— 0,42	ONO	4	+ 1,69	NO	4	+ 1,13	O	4
	2	Nachmitt.	....	....	....	....	....	....	....	....	....	....	....	....	+ 1,56					
	2½	Nachmitt.																		
	3	Nachmitt.																		
	3½	Nachmitt.																		
	4	Nachmitt.	....	....	....	....	....	....	....	....	....	....	....	....	+ 1,25					
	4½	Nachmitt.	....	ONO	4															
	5	Nachmitt.	+ 0,55	....	....	....	OSO	3												
	5½	Nachmitt.																		
	6	Abd.	....	....	....	+ 0,23	....	....	....	....	....	....	....	....	+ 0,75					
	8	Abd.																		
	12	Nachts	....	....	....	....	O	1												
14	4	Morg.	....	....	....	+ 0,15														
	8	Morg.	+ 0,31				SO	1												
	12	Mitt.	+ 0,15	....	....	+ 0,13	SSO	1	+ 0,17	O	2	+ 0,03	OSO	2	+ 0,66	ONO	1	+ 0,84	OSO	1
	2	Nachmitt.																		
	4	Nachmitt.	....	OSO	1	....	SSO	1												
	6	Abd.	+ 0,15	....	....	+ 0,07														
15	12	Mitt.	+ 0,10	SO	2	+ 0,03	SO	1	— 0,03	OSO	2	— 0,10	OSO	1	+ 0,52	OSO	1	+ 0,71	OSO	1
16	12	Mitt.	$\pm$ 0,00	NO	1	+ 0,05	S	1	— 0,01	OSO	1	+ 0,03	SO	1	+ 0,35	SO	1	+ 0,58	SO	1
17	12	Mitt.	+ 0,02	SO	1	— 0,07	SO	2	— 0,09	O	2	— 0,13	OSO	1	+ 0,27	S	1	+ 0,47	SO	1
18	12	Mitt.	— 0,08	SSO	1	— 0,15	S	1	— 0,17	SO	2	— 0,15	SO	1	+ 0,21	SO	1	+ 0,37	S	1
19	12	Mitt.	— 0,08	SO	1	— 0,13	S	1	— 0,15	SSW	2	— 0,15	SO	1	+ 0,17	SO	1	+ 0,29	OSO	1
20	12	Mitt.	— 0,13	SSW	1	— 0,19	SW	1	— 0,19	S	1	— 0,13	SSO	1	+ 0,08	S	1	+ 0,18	S	1

Table 8: Meanwater Level at Lebbin, Wollin, Stepenitz and Szczecin (Stettin).

Tabelle VIII.

Gebiet			Swine			Dievenow			Haff			Oder		
Pegel-Stationen			Lebbin.			Wollin.			Stepenitz.			Stettin.		
Mittelwasser			+ 0,99 m			+ 1,96 m			+ 0,78 m			+ 0,47 m		
Tage im Novbr.	Stunde	Tages-zeit	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke	Abweich. vom Mittelwasser	Wind-richtung	Wind-stärke
6	12	Mitt.	— 0,11	W	1	— 0,12	W	0	— 0,07	NW	1	+ 0,03	W	1
7	12	Mitt.	— 0,13	W	2	— 0,08	W	2	— 0,04	W	1	+ 0,05	WNW	2
8	12	Mitt.	— 0,21	W	2	— 0,16	W	2	— 0,08	W	1	— 0,08	SW	1
9	12	Mitt.	— 0,17	W	2	— 0,18	W	1	— 0,05	SO	1	— 0,06	W	1
10	12	Mitt.	— 0,05	O	0	— 0,12	O	1	+ 0,13	O	1	+ 0,03	O	1
11	12 4 8	Mitt. Nachmitt. Abd.	+ 0,11	N	1	+ 0,06	N	1	+ 0,29	NO	1	+ 0,22	SO	1
12	6 7 12 3 4 5 6 8 12	Morg. Morg. Mitt. Nachmitt. Nachmitt. Nachmitt. Abd. Abd. Nachts	+ 0,27	NO	1	+ 0,14	NO	4	+ 0,50	NO	2	+ 0,42	NO	2
13	4 6 7 8 9 10 11 12 2 2½ 3 3½ 4 4½ 5 5½ 6 8 12	Morg. Morg. Morg. Morg. Morg. Morg. Mitt. Mitt. Nachmitt. Nachmitt. Nachmitt. Nachmitt. Nachmitt. Nachmitt. Nachmitt. Nachmitt. Abd. Abd. Nachts	+ 0,43	NNO	4	+ 0,26	O	4	+ 0,50	NO	4	+ 0,60	O	4
14	4 8 12 2 4 6	Morg. Morg. Mitt. Nachmitt. Nachmitt. Abd.	+ 0,65	O	1	+ 0,58	O	1	+ 0,66	NW	1	+ 0,76	O	1
15	12	Mitt.	+ 0,53	O	1	+ 0,42	SO	4	+ 0,53	O	1	+ 0,60	OSO	1
16	12	Mitt.	+ 0,43	O	1	+ 0,40	S	0	+ 0,45	O	1	+ 0,55	O	1
17	12	Mitt.	+ 0,35	O	1	+ 0,26	SO	1	+ 0,31	SO	1	+ 0,39	SO	1
18	12	Mitt.	+ 0,23	O	1	+ 0,22	SSW	1	+ 0,25	SO	1	+ 0,33	SSO	1
19	12	Mitt.	+ 0,13	O	1	+ 0,06	OSO	1	+ 0,13	S	1	+ 0,31	SO	1
20	12	Mitt.	+ 0,05	S	1	+ 0,02	S	1	+ 0,05	SO	1	+ 0,16	SW	1

The same level, however, was only reached to the east on November 13th at 6 a.m. between Colbergermuende (Colbergermünde) and Rügenwalde, at a time when the rise of the north-east tower at the height of Colberg was already becoming a hurricane. At midnight on November 12th–13th the level of the sea was shaped in a fairly uniform slope according to Figure 1 from Memel to Ellerbeck and the delay of the progress of the tide only remained noticeable up to Aaroe.

From this point, which shows a water level height corresponding to the ordinary high tides, the conditions change in a striking way, but according to the hurricane-like occurrence of the storm marked by the pilot stations. This hurricane, first signalled in Colbergermuende (Colbergermünde), progressed from Colbergermuende (Colbergermünde) to Ellerbeck from about 2 a.m. until 7 a.m., driving the Baltic Sea level, which had already risen to high tide, in front of it in a mighty wave. At 6 a.m. in the morning of November 13th, this wave grows with its crest, Figure 1, lying near Fehmarn Sound (Fehmarnsund). The narrowness of Fehmarn Sound (Fehmarnsund) is a hindrance to its progress, but the pressure is so enormous that the level of the water surface at noon on November 13th (Figure 1) sinks between Rügenwalde and Swinoujscie (Swinemünde), whereas the upwelling water mass rises almost 1 metre in 6 hours from Swinoujscie (Swinemünde) to Ellerbeck, and although the gale subsides at noon along the entire coastline, this wave still rises to a height of 1.5" from Ellerbeck to Aaroesund in 5½ hours.

Here it is to be emphasized in particular, how the rise of the tide, namely west of Swinoujscie (Swinemünde), was clearly proportionate to the wind intensity and how even after cessation of the hurricane the enormous tidal wave continues to propagate at a constant rate and only peters out when hitting the surrounding mainland after the Little Belt. In Figure 16 the crests of the highest local water level line are connected by a sharply drawn line, the course of which characterizes the contemporary local maximum water level on the whole coastline. In Figure 1, on the other hand, the profile lines of the observation times from 12 noon to 5:30 p.m. of November 13th indicate to what extent the lake level was driven under the pressure of the hurricane. The maximum of the crest was 3.17 metres above sea level (a.s.l.) at Ellerbeck at 3:20 p.m. On the way of this wave up the Little Belt into that wedge-shaped narrowing strait and finding its termination against solid land, its crest is still lifted by 0.5 metres.

During the entire course of the storm surge in the western part of the Baltic Sea, the neutral boundary line at the high point of Pillau, which station shows only a slight change of water, is conspicuously prominent, and when the stations further to the NNE located stations are missing in the observation circle, already the single station Memel suggests that during this whole phenomenon low water levels existed in the northern basin of the Baltic Sea, especially since the further station at Windau in Curland with a water level of 4 feet on November 11th at 1 p.m., also on November 13th at 5 p.m. marks the minimum water level with 1 foot 4 inches. No relationship to the mean water level could be given there.

From the building inspector Bargum a compilation of the wind speeds with the water levels is given, which was formed from the observations at Ellerbeck. According to this, those relations took place which can be taken from the table on p. 189/190 above.

If in these periods the highest wind speed occurred in the morning at 10 a.m. and the highest water level at 3:40 p.m., while the wind speed decreased from 30.7 metres to 16.8 metres, it follows that the elevation of the water level in this period was no longer the result of a strong wind pressure, but the consequence of a progressing crest of a tidal wave moving from east to west, as can be seen in Figure 1, which found its origin in the area of the Baltic Sea between Colberg and Wittower Post House.

A similar progress of the wave results in the Schlei, which cuts into the land like a river up to 5.5 miles. The movement of the flood crest gives the following record for November 13th:

	Höchster Wasserstand Meter	am 13. November Nachmittag
Schleimünde	$3,_{44}$	$3^{h}\ 30'$
Rabelsund	$3,_{44}$	4^{h}
Kappeln	$3,_{30}$	$4^{h}\ 45'$
Arnis	$3,_{12}$	$5^{h}\ 15'$

	Höchster Wasserstand Meter	am 13. November Nachmittag
Nifs	$3,_{03}$	$6^{h}\ 30'$
Missunde	$3,_{05}$	$7^{h}\ 45'$
Haddeby	$3,_{24}$	$9^{h}\ 15'$
Gottorf	$3,_{34}$	$9^{h}\ 30'$

Datum	Stunden von	Stunden bis	Windgeschwindigkeit pro Secunde Meter	Richtung des Windes	Ansteigung des Wassers pro Stunde Centimeter	
12. November	Morgens 6 Uhr	Mittags 12 Uhr	von $6,_{9}$ bis $13,_{7}$	NO.	$1,_{83}$	
	Mittags 12 Uhr	Abends 6 Uhr	$13,_{7}$	NO. zu O.	3	
12. zum 13. November	Abends 6 Uhr	Morgens 6 Uhr	$13,_{7}$ bis $19,_{4}$	NO. bis NO. zu O.	$4,_{75}$	
13. November	Morgens 6 Uhr	Morgens 9 Uhr	$19,_{4}$	NO. zu O. bis NO.	$16,_{6}$	
	Morgens 9 Uhr	Morgens 10 Uhr	$30,_{7}$	NO.	21	
	Morgens 10 Uhr	Morgens 11 Uhr	$25,_{7}$	NO.	16	Windgeschwindigkeit in Cuxhafen Morgens $11^{h}\ 45'$ im Max. $14,_{29}{}^{m}$
	Morgens 11 Uhr	Mittags 2 Uhr	$19,_{4}$	NO. bis ONO.	$8,_{66}$	
	Mittags 2 Uhr	Mittags 3 Uhr	$19,_{4}$	O. zu N.	3	
		Mittags 3 Uhr 20 Min.	$19,_{4}$ bis $16,_{8}$	O. zu N. zu O.	Höchste Fluth mit $3,_{17}{}^{m}$ am Pegel	
		Mittags 4 Uhr	$16,_{8}$	O.	Starkes Fallen	

The termination of the Schlei at its western terminus raises the water level by a small amount; the speed of the crest of the tidal waves averages about 0.9 miles per hour.

The characteristic phenomenon at most coastal points, especially at Travemuende (Travemünde), Sønderborg (Sonderburg) and Aabenraa (Apenrade), whereby the water stopped rising for a short time in the evening of November 12th, is the moment when the storm had actually reached its maximum after a normal course, but due to the sudden swinging of the equatorial current towards a narrow river bed, it increased its speed to the height of the hurricane and thus raised the water to the abnormal height.

The falling of the tide is characterized in comparison with the rising by the short time intervals in which the former occurred, and here the wind is unmistakably involved too. While the increase in wind intensity from NE begins already in the evening of November 10th and lasts until noon of November 13th, i.e. about 66 hours, the decrease comprises only about 18 to 20 hours, whereby it must be taken into account that in the meantime already the turn of the wind to SE prepared itself, which promoted the falling of the water.

For this reason, the falling part of all profile curves of the storm area west of Ruegenwaldermuende (Rügenwaldermünde) is unequally steeper, the area of the falling tide, Figure 16, is unequally narrower than the rising part, and only Barth, not lying directly on the open sea, shows the opposite, which will be discussed in more detail later when listing the destruction that occurred.

It is obvious that such a significant change of the water level after the completion of the force causing it cannot take place in a uniform return of the water level to the normal height, but in oscillations that result in an alternating rise and fall of the water, a uniform wave movement along the entire coast, and both the water level scales of the profiles, Figure 11 to Figure 16, show this, as well as the longitude profile of the Baltic Sea shown in

Figure 1. These oscillations last longest where the level difference was greatest, i.e. at Aarösund, and appear weakest at the neutral position of the whole level movement, i.e. at the level of Pillau. On average, the even level had already returned at Pillau on November 15th, but not at Aarösund until November 20th.

The tide, to the extent that it had to fill the inland waters, also raised the latter and generated a maximum water level above mean sea level of:

2.19 metres at Thiessow,
1.41 metres at Swinoujscie (Swinemünde)
0.84 metres at Dievenow
within the Oder estuaries:
0.65 metres at Lebbiner Bergen
0.58 metres at Wollin
0.88 metres near Stepenitz
0.76 metres near Szczecin (Stettin)
1.77 metres near Wolgast
1.13 metres at Anclam
above mean water level.

4.1.2 Currents

The Sound (Oeresund), which is one of the three straits connecting the Baltic Sea with the North Sea, will be considered as the most important of the three mouths of the Baltic Sea when evaluating the incoming and the outgoing current, since observations of these are available.

In the month of October 1872, according to the notices in the Baltic Sea newspaper, a current from the north, i.e. incoming (thus outgoing on 29 days), was only observed for the Baltic Sea on 2 days, namely on October 24th and 31st near Elsinore.

From November 1st to 10th, incoming current from the North Sea only occurred in the Sound:

throughout the whole of November 1st
for half a day on November 4th,
throughout the whole day on November 6th and 7th
and throughout the whole day on November 8th,
adding up to four and a half days of incoming current from the North Sea between October 31st and November 10th.

Observations of the current are also found at Aarösund and Sønderborg (Sonderburg), and indeed the current was:

		outgoing	incoming
at Aarösund in October	days	12	19
from November 1st to 10th	-	5	5
at Sønderborg (Sonderburg) in October	days	12	19
from November 1st to 10th	-	4	6

Between these two observations in the Sound and the area of the Little Belt, the former deserve preference, because with the low profile of the Little Belt, the influence of moderate winds and the locality can give rise to special phenomena, which make the occurrence of a continuous current clearer only with stronger wind movements. In the Sound, the outgoing or incoming movement of water depends only on the prevailing winds over the area of the North Sea and the Baltic Sea, insofar as the same is not conditioned by the slight influence of the tide and ebb in the Kattegat. Thus, during the period from October 31st to November 10th, within 4½ days, not only did the receiving water for the Baltic Sea basin stop, but at the same time large quantities of North Sea water were supplied to the Baltic Sea, and thus the mean water level of the latter had to rise considerably above the usual level. Taking into account that the prevailing westerly winds accelerated the rather constant incoming undercurrent of salty water into the Baltic Sea, the rise of the mean water level was a certain consequence of this air movement, since usually the difference in quantities between the outgoing upper current and the incoming undercurrent must be equal to the water supplied to the Baltic Sea of its precipitation area, reduced by the amount of the evaporation quanta.

Within the Baltic Sea basin, unfortunately only 3 of the gauging stations on the Baltic Sea record the movement of the coastal current. These are Colbergermuende (Colbergermünde), Ruegenwaldermuende (Rügenwaldermünde) and Stolmünde. In recent times, these observations have been supplemented by the stations established in the Baltic Sea by the Commission for the Investigation of the German Seas.

At Colbergermuende (Colbergermünde), the coastal current was:
from November 1st to 9th inclusive from west,
from November 10th to 14th inclusive from east
and then from west again.

At Rügenwalde the coastal current was:
from November 1st to 9th inclusive from the west,
from November 10th to 16th from east
and then from west again.

At Stolpmünde, at last, the coastal current was:
from November 1st to 4th inclusive from west,
on November 5th there was standstill,
from November 6th to incl. 9th from west,
on November 10th there was standstill,
from November 11th to 15th included from east
and then from west again.

According to the above, there is no need for further proof that, with respect to the direction of the current, abnormal conditions in favour of a supply of North Sea water to the Baltic Sea prevailed in the period from October 31st to November 10th.

During the northeast current, the current had to take the direction of the Belts or the Sounds, respectively, on the coasts it had to take the direction of the storm. In the Lübschen fairway the coastal current running north from the Trave to Neustadt met the oncoming sea state at Pelzer Haken where it created a great choppy sea with complete eddies. Outside Pelzer Haken to Fehmarn, meanwhile, the coastal current resumed its northerly direction. In the Fehmarn Belt and Sound, strong currents from the east occurred throughout the tide. At Bülk, off Schleimünde, at Alsen, and at all points of the Little Belt, a strong northward current was observed.

4.1.3 Salinity and Specific Weight of the Baltic Sea Water

Since the salinity of the Baltic Sea water is on the average different from and lower than that of North Sea water, and these two waters communicate, consideration of the observations of the specific gravity (which increases with the increase of the salinity) of the water in different parts of the Baltic Sea will serve to elucidate the causes of the height of the storm surge.

Since salinity and specific gravity are inseparable concepts, it should be mentioned here that an increase of 1% in salinity causes an increase of 0.007639 in specific gravity, and that accordingly each increase of 0.01 in specific gravity causes an increase of 1.309% in salinity.

At Sønderborg (Sonderburg), where the annual average of the specific gravity of the water is 1.01308 t/m³, the same was found to be l.01518 t/m³ on November 1st, l.01648 t/m³ on November 5th, and 1.01859 t/m³ on November 9th with maximum salinity in the period from November 1st to 20th.

If the salinity of the water at Sønderborg (Sonderburg) is calculated, the average salinity is l.7l2%, the content on November 1st is 1.987%, on November 5th 2.157% and on November 9th 2.434% and the increase of salinity on November 1st is 0.875%, on November 5th 0.444% and on November 9th 0.722% against the annual average.

If no further annual means of other stations are available, it will be useful if results of some stations are brought together and compared among themselves because of their absolute differences.

At Fehmarn Sound (Fehmarnsund), the specific gravity of the water was l.00925 t/m³ on November 1st, 1.00947 t/m³ on November 4th, 1.00959 t/m³ on November 7th (maximum from November 1st to 20th), and l.00914 t/m³ on November 9th. Calculating the salinity, we find that at Fehmarn Sound (Fehmarnsund) it was l.211% on November 1st, 1.240% on November 4th, l.255% on November 7th, and 1.196% on November 9th.

At Nowy Port (Neufahrwasser), finally, the specific gravity of the water on November 1st was 1.00638 t/m³, on November 5th only 1.00553 t/m³, but on November 11th it reached the maximum with 1.00751 t/m³.

If we also calculate the salt content of the water, we get 0.835% on November 1st, 0.724% on November 5th and 0.983% on November 11th.

For a better parallelization of the observations, it may be noted here that, taking as a basis the fact that the salinity of the water of the Baltic Sea is significantly lower than that of the North Sea, and that this decrease occurs first more rapidly and then more slowly from west to east, Dr. Oscar Jacobsen, on the Pommerania, has found that the salinity of the water of the Baltic Sea is lower than that of the North Sea. On the Pommerania during the expedition to investigate the German armies in July 1871 from Kiel Bay to off Darserort, Oscar Jacobsen found salinity to be from 1.330% to 0.932% from the northern tip of the island of Rügen to east of Bornolm from 0.771% to 0.789%.

The supply of salinity from the North Sea usually occurs, as long as the Baltic Sea is draining, through an undercurrent, which up to now has been observed at Sønderborg (Sonderburg) incoming as often as outgoing.

Since it is obvious that any wind direction that retards the general upper current of the Baltic Sea, respectively capsizes in the incoming current, an acceleration of the undercurrent may also be assumed, which will therefore have taken place in the period from October 31st to early November and must increase the salinity in the western basin of the Baltic Sea.

 https://doi.org/10.18171/1.092107

A further confirmation of this supply of stronger salt water from the North Sea is based in the glow of the Baltic Sea in the autumn of the year 1872, as had never previously been seen in living memory. However, stronger chemical stimulants for the glowing animals belong to the glow of the sea, as earlier experiments of Ehrenberg taught, who poured some diluted hydrochloric acid into the water of the Baltic Sea and brought the little animals contained in it to the momentary glow.

4.2 The Causal Connection of the Phenomena for the Occurrence of the Tide

Summarizing the previously listed facts on wind and water movement, as well as the current and the salinity of the Baltic Sea water, a picture emerges which depicts the storm surge of November 12th–13th, 1872, as an exceptional revolution of the elements air and water as far as history goes.

The fact alone that the current in the Sound was outgoing for the Baltic Sea during the entire month of October, with the exception of two days – on October 24th and 31st – proves, if one assumes that during effective westerly storms the Sound, the Great Belt and the Little Belt are subject to a similar current – that the influx of North Sea water causing the abnormal height of the storm surge and the accumulation of inflows from the precipitation area took place immediately before the storm surge itself.

This grant of North Sea water will have occurred, albeit intermittently, from October 31st. On November 1st, after the flow had already been incoming for the Baltic Sea under the same influences from the morning of October 31st, a storm from the southwest raged over the North Sea and the Holstein coasts, which, decreasing to strong and moderate winds, also moved over the basin of the Baltic Sea as far as off Koenigsberg (Königsberg), where a storm from the southeast was weaving at the same time. This southwest storm kept the current in the Sound as incoming for the Baltic Sea also on November 1st during the whole day.

The water levels of the Schleswig-Holstein stations, which were 0.5 to 0.8 metres above mean sea level at noon on November 1st, prove that large water masses from the North Sea entered the Baltic Sea during the two days of October 31st and November 1st.

This southwest storm could not and cannot at all quickly compensate for the subsidence caused by it in the southern basin of the Baltic Sea by the incoming current from the North Sea; for on November 1st, the water at Ruegenwaldermuende (Rügenwaldermünde) and Stolpmünde had fallen about 0.25 metres below the mean water level, i.e. the water masses had been diverted to the northeast by the southwesterly storm. (Coastal flow was from west to east).

On November 4th, however, the inflow of North Sea water and the buildup of the receiving water became visible in front of the two latter stations, where the water had risen by 0.5 metres, i.e. to about 0.25 metres above mean water since November 1st, although the wind had not changed its direction, but remained at a fairly constant strength on the west side of the Baltic Sea.

Even if on November 2nd and 3rd the current in the Sound was outgoing for the Baltic Sea, the persistent air flow from the southwest justifies the conclusion that only a weak surface current took place in the Sound, which by no means satisfied a full pre-flood. This assumption is also in agreement with the annual observations of the Danish Lootsen (Pilotes') Administration, which shows that the current in the mouths of the Baltic Sea is already fluctuating with ordinary southwest winds, unless strong wind speeds lead to a subsidence in the western basin of the Baltic Sea and thus cause a stronger current from the north.

The same game is repeated in the following days.

On November 4th, with the general wind direction still prevailing from the southwesterly quadrant, the current was incoming in the Sound as a result of moderate northwest winds in the Kattegat for the Baltic Sea. In the afternoon, the wind jumped up to west northwest and dropped back to southwest on November 5th; and therefore, on November 4th in the afternoon as well as on November 5th there is outgoing current again. This continued until the afternoon of November 6th. Then, on November 6th rose the significant westerly storm, which passed the English and Scottish coasts, fluctuating between west northwest and southwest - blowing from west in the eastern stations of the Prussian coast, completely encompassing the North Sea.

In the so-called Lübische Fahrwasser, Travemuende-(Travemünde)-Darserort, the water level sank almost 1 metre below mean water at noon on November 7th, while at noon on November 6th it was still 0.25 metres above mean water on average. The lowering of the level extends steadily upward to the neutral axe at Pillau. The gradient towards the Baltic Sea increases and the incoming current carries the North Sea water towards the Baltic Sea at a corresponding speed. This persistent westerly wind, lasting until November 9th, gave the incoming current sufficient time for the water to flow in.

At noon on November 9th, the water in all stations was already up to 0.25 metres above mean water.

In Koenigsberg (Königsberg), the storm continued until 9 a.m., and accordingly, a significant inflow of water into the Baltic Sea must have occurred in the meantime.

Quite in harmony with these movements is the increase in the salinity of the Baltic Sea water for:

Sønderborg (Sonderburg) from November 1st to 9th by 0.447,

Fehmarn Sound (Fehmarnsund) from November 1st to 7th by 0.044,

Nowy Port (Neufahrwasser) from November 1st to 11th by 0.148.

It should not be forgotten how the incoming North Sea water mixes with the Baltic Sea water, depending on the size of the part of the Baltic Sea basin passed through and the swell there.

The outgoing current observed in the afternoon of November 7th in the hour is, like the outgoing currents discussed above since October 31st, only of short duration and is of no importance.

The earlier discussed storm from west northwest to southwest on the evening of November 6th had reached its end on November 8th, between Rugen (Rügen) and Pillau only in the evening of November 9th, and changed very quickly into a strong wind and then decreased to moderate speed, so that on November 10th even calm winds are reported by several stations, and very calm winds from southeast, south to southwest at the remaining stations. During this weak wind or calm, respectively in the westernmost and easternmost stations, the northeasterly has already sent its first forerunners between Rugen (Rügen) and Stolp. Therefore, the uninterrupted further rise of the sea can no longer be explained by the inflow from the west, but by the water masses dammed up in the east and north, which partly followed their own gravity, partly were pushed back by the beginning northeast wind. These water masses, now evading to the west, were followed by the north-east, which gained in terrain as well as in intensity, so that now, progressing from west to east, a continuously faster increasing rise of the tide occurred, which seemed to have reached its climax in the evening of November 12th, since at several stations, especially the western ones, a standstill of the rise of the tide, an equilibrium between wind strength and level change of the sea level, was observed at that time.

If one takes into account that on November 9th, as a result of the westerly storm, the level on the western side of the Baltic Sea had risen by almost 1 metre, decreasing accordingly towards Pillau, the water level line at noon of November 12th was by no means an abnormal one under the average northeasterly wind, which was not yet stormy. Rather, it was one corresponding to the previous course of natural phenomena, which on the whole seems only moderately influenced by the northeastern wind.

The pause that occurred in the evening of November 12th can only be explained by the fact that the pressure of the water accumulated to the west was in balance with the intensity of the NE wind blowing at that time.

Only the hurricane occurring shortly after midnight near Colberg was able to reshape the level line of the Baltic Sea existing at 12 p.m. (see Figure 1), which corresponds in its entire inclination to the level differences occurring during similar events, now favourably prepared, in a way as it appears in the three further level lines of November 13th.

The overcome force of the water can be recognized quite clearly by the now changed direction of the level lines on Figure 16. Up to November 12th these show an inclination from west to east at night or a leading of the tide rise on the west side against the east side. This advance is weakened at midnight, the lines become less inclined from west to east, and at noon on November 13th they already reach a parallel position to the time horizontals lying as abscissas.

It is precisely in these successive stages of the flood period that caused the intense development of the enormous swelling of the water on the western side of the Baltic Sea basin, which, according to the above description, is thus characterized in three stages, namely:

In the period from October 31st to November 9th filling of the Baltic Sea with North Sea water and end of the inflow closure of the foreshore.

In the period from November 9th to the evening of November 12th, oscillation of the Baltic Sea water to the west with the basin overfilled.

On November 13th, impact of the northeast hurricane on the western part of the Baltic Sea, the level of which had already reached a significant height due to the preceding events.

Notes on the wave height were obtained from the Neustadt construction district by the district master builder Heydom. These are for some main points above the highest water level

at Sierksdorf	1.50 metres
at Neustadt	0.25 metres
at Pelzerhaken	l.75 metres
at Kellenhusen	1.75 metres
at Dahme	2.00 metres
inland at Grabe	1.00 metres
at Fehmarsund on the Holsteiner side	2.00 metres
also on Fehmarn side	l.50 metres
at Heiligenhafen	1.50 metres
at Flügge	1.00 metre
at Albersdorf	0.50 metres

at Lemkenhagen	0.30 metres
at Westermarkelsdorf	1.00 metre
at the Weissenhäuser bridge	1.75 metres

The size of the swell on the more northern coasts of Schleswig is given, according to fairly consistent data, as 4 metres wave height, i.e. to 2 metres above high water, while in the bays it has decreased to 2 metres, i.e. to 1 metre above high water.

The height of the waves moving against the high shore was, of course, greater. At Schleimünde, the waves have risen to the top of the 50-feet high lighthouse standing on the head of the northern breakwater and have at times enveloped it to such an extent that it could not be seen from Maasholm, 0.5 mile away, and was considered lost.

5 Remarks on the Above

At the end of these results concerning the phenomena of the storm surge, it must be added that there are difficulties involved in collecting sufficient observations for such natural events because in many cases such observations are incomplete and incompletely carried out.

The meteorological material is least complete and is then least sufficient when its procurement is most necessary, namely at the time of extraordinary deviations from normal conditions. The intention was also to include a short note on the storm tide of February 9th–10th, 1874, which was also of great interest, but this was impossible due to the lack of sufficient observational material. One of the first requirements for a future central office for oceanography will therefore be to obtain the observations in a completely uninterrupted sequence if it wants to reliably fulfil its task. With phenomena in the atmosphere developing so quickly at times, punctuality and speed of submission of these observations to the collection point will become an unquestionable necessity.

With this material, the observations obtained at the pilot stations, which are characterized by a greater certainty with respect to the wind directions, since the observations of these stations are rarely clouded by local conditions, should not be underestimated, and in addition, the observations of the sea conditions with respect to water level, current and direction, as well as the strength of the swell, constitute valuable observations that support the conclusions to be drawn. Breaking winds are sometimes preceded by rolling with a corresponding swell, which may well mark the upcoming events. Self-registering tide gauges in the Baltic Sea at the pilot stations have only been installed in Swinoujscie (Swinemünde). It would be advisable to install them at several suitable stations and thus to obtain tide curves in a more reliable form than allowed by temporary observations, which suffer from uncertainty at night in particular. The representation of the tide curves in profiles, which are obtained from the registration of temporary observations, as was done in the present case to supplement the intermediate elements, constitutes an interpolation rather than an observation, forming only a poor substitute for the lack of material.

More far-reaching than up to now, the observations from the south would have to be obtained for the meteorological stations, insofar as they cover the area on which the equatorial current moves, before the incursions of the polar current into the Baltic Sea give rise to the storm surges in this area. This seems all the more necessary, since the phenomena occurring here generally precede the catastrophes in the Baltic Sea by days, and the same therefore substantiate the forecast more securely.

6 The Hydrotechnical Phenomena of the Storm Surge

In the following, the effects of the storm surge on the natural as well as on the artificial boundaries of the Baltic Sea, as well as the resistance of the existing structures are described as they have resulted from the official reports or from own observation of individual localities.

For orientation in the localities, however, one will have to use special maps, especially the Prussian Sea Atlas of 1841 and the map of the Duchies of Schleswig, Holstein and Lauenburg, by Geerz.

6.1 Natural Boundaries and Waterways

6.1.1 Sandy Beach

District of Szczecin (Stettin)
The beach has increased in width almost throughout and in stretches very significantly. Between the piles in front of the Streckelberg, the beach has formed advantageously. In general, the foot of the high shore or the foredunes has receded everywhere, so that the piles at Streckelberg have lost their connection to the shore. The widening of the foreshore is a consequence of the break-off of the high bank or the dune, which had covered the foreshore with material.

District of Schleswig
Since the destruction on the coasts is mainly due to the effect of the swell at a more than usual height, the shallow, low lying, and therefore immediately flooded sandy beach has suffered almost no changes at all because it was exposed to lesser attacks. There are very few larger dunes at this beach. Instead, the beach consists mainly of a gravelly material, which is tossed up higher with the waves and is often called Haffstock. The high tide has changed this stock in that the material has been hurled with the waves over the top of the gravel wall so that the entire sand and bedload wall lying parallel to the coast has made an inland movement. The size of the movement itself cannot be determined; in general, the beach here is a beach divided many times by inlets, which does not continue in coherent lines and therefore a material migration is carried out to an even lesser extent, as the coastal currents also occur in a less intensive form than on the Pomeranian coastlines.

6.1.2 Clay Bank

District of Szczecin (Stettin)
The clay bank in front of Groß-Horst has been washed away because of the too low position of the stone revetment in front of it.

Also in the vicinity of the church at Hoff, several break-offs of the high bank have taken place.

District of Schleswig
The clay bank has broken off almost everywhere to a considerable extent.

Depending on the location of the bay the banks of the Lübschen Fahrwasser were affected most by a northeasterly storm.

In the southernmost corner of this bay, the Trave flows into the sea in a northeasterly direction. Half a mile west of the mouth of the Trave is Lake Hemmelsdorf, 500 ha in size. Between the two bodies of water there is a plateau rich in hills, 30 to 45 metres high, which borders the Baltic Sea with a convexly broken off shore, the "Brothener Ufer", up to 20 metres high. From the width of the Brothen shore as a base, a 3/8 mile, 1¼ mile high isosceles triangle extends into the sea, whose clayey bottom, gradually dropping to 17 meters water depth, is covered with many large stones (erratics), and is therefore called "stone reef".

The beach in front of the Brothen shore is very narrow, rises to the foot of the shore about ½ to 1 metre above mean water, and – like the reef - is covered everywhere with large stones as residuals of the broken clay shore.

Each sustained high tide washes away the foot of the high bank, which is followed by a post-fall of the upper clay masses, which often cover the beach in large blocks, like mountain debris. These are washed away by the next high tide and only the stones they contain remain on the beach. Since time immemorial, entire plots of the best wheat soil have disappeared from the heights of the Brothen shore. In this storm tide again considerable areas have fallen from the height into the sea.

These processes of the present have been repeated since time immemorial, and as far as lore goes, the waves have not only made an elevation over 1 mile long disappear completely, but its debris has already sunk as a stone reef to a depth of 17 metres under water. Every sustained easterly wind, which drives the waves over the stone reef, gives the water in the southwestern part of the bay a clay-yellow colour, even when little or no clay is washed away at the level of the foot of the Brothen shore; this is a sign that the waves are still attacking the reef at sea.

The precipitation from this murky water makes itself unpleasantly noticeable eastward by closing the Travemuende (Travemünde) fairway. West of the stone reef, this clay silt is found deposited in the northern part of Hemmelsdorfer See, the so-called shallow lake, which has a depth of only 4½ metres in the extension of about 400 ha, while from the bend on, in the eastward bent southern tip, which is protected against NE, the bottom of the so-called deep lake drops abruptly to 43 metres.

The northern part of the shallow lake becomes shallower and shallower towards the Baltic Sea. Up to 1½ metres water depth it has extensive cane and reed stands, which also still form small groups at shallow places with elm and willow bushes, until a grass felt has built the first dam over the lake bottom; this is so weak that one always finds oneself in a wave valley when crossing; it is so broken through that one has to use caution not to step through; but towards the sea it becomes more and more solid.

To protect this lowland, that is the lake and a strip of meadow about ¼ mile wide, the sea itself has thrown up the material and the wind has built up a sand dune out of this material about 3 metres high.

The assertion, based on this account, that the lowlands of the Hemmelsdorfer Sea were once a part of the Baltic Sea and were separated from it by the silt of the Brothen shore, and later by a dune, should be all the more evident from the foregoing if it is added here that sea shells, sea grasses, and rounded beach stones have been found in the bottom of the meadows bordering the lake.

The clay share has also broken off at other points along the coast, although the phenomena that have occurred here have occurred on a less grand scale than on the Brothen shore with the exception of the stretch of coast from Heiligenhafen to the Bröck in the Hohwachter Bucht, this is true on almost all high shores as well as between Haffkrug, south of Neustadt, and Grömitz, north of Neustadt, from Dameshoeved to Dahme, from Siggen through the Fehmarn Sound (Fehmarnsund) to Heiligenhafen, from Staberhuck to Gahlendorf on Fehmarn, at Weissenhaus west of the Bröck, off Hohenfelde and Schmel, on the ½ mile long clay wall, from Stein to Laboe in the Bay of Kiel, at the lighthouse establishment at Bülkerhuck, on the Schwansen coast between Langholz and Boknis, off Schönhagen, as well as on the high shores of the Angeln countryside, on the east and north coasts of Alsen, and between Apenrade and Gjenner Bay.

Apart from the coastal location, the geological conditions of the clay shore have been of essential importance for the extent of the erosion.

The solid subsoil is almost everywhere formed by a blue-grey, very resistant clay marl, the surface of which rises several metres above the daily water level, but in places also sinks below it. On this subsoil lie in various directions, interspersed with larger and smaller boulders, other clay and loam masses that are easier to dissolve in the water, sometimes alternating with sand layers, but also containing only individual larger sand masses or sand bubbles. According to the occurrence of the sand, the type of erosion has been very different. The sand bubbles were washed out by the water and as a result caves were formed, which were still present up to 10 metres depth after the storm surge. However, the caves were mostly buried during the storm surge by the unsupported softened clay mass hanging over them, and this was soon licked away by the oncoming wave.

However, these break-offs did not take on the dimensions of those that took place on such stretches of shore where a layer of sand was continuously embedded. The latter was soon washed out and as a result the soil above this layer was washed away. The nature of the erosion can still be clearly seen in the contours of the shore; while these follow more the straight or evenly curved line of the beach on the stretches of coast with continuous sand stratification, the clay shore with injected sand bubbles shows the most peculiar irregular formations, to the extent that firmer material was encased by the more easily soluble material.

A short time after the storm surge, the clay walls were dull and reflective, and in some places the most resistant material, the clay marl, had taken on almost the pointed forms of basalt in individual blocks that had remained standing. Later, the soil debris collapsed and an embankment with the usual slope for this type of soil was formed.

The extent of the erosion on the clay bank as a result of the storm tide of November 12th–13th, 1872, could only be determined by the fiscal lighthouse establishment at Bülkerhuck, since exact terrain surveys from the time shortly before the destruction in other cases were not available.

The attached situation drawing in Figure 17 of the named establishment, however, gives insight into the size of the demolition there in the years 1868 to 1872, whereby it is to be noted that up to the time of the last storm tide a substantial change in the borders against the sea had not occurred since 1868.

The area used for farming at Bülkerhuck was:

in	1806	20 acres,
-	1868	16 acres-
after the last storm tide		13 acres-

It was not evident in all of the cases where the eroded clay was taken by the sea. Almost everywhere, the sea had taken on a clay-yellowish-grey colour, which in the bays partly disappeared only after 4 weeks.

The material deposited at Bülkerhuck consists only of sand and rubble; the clay content of the washed-up shore dissolved in the water has continued and was probably deposited on the seabed near the coast only after the calm of the sea had set in. This at least is supported by the observation that on the formerly white seabed in Strander Bay, between Friedrichsort and Bülck, there is now a thin yellow layer, apparently clay, which can only come from the quarries near Bülckerhuck.

6.1.3 Dunes

District of Gdansk (Danzig)

The dune structures suffered only on a short stretch on the Hela peninsula near the new lighthouse at Heisternest. Here, waves rose up to 3.20 metres above the mean water level, destroying part of the newly established pre-plantings and attacking the base of the dunes. No other pre-plantings suffered significant damage. On the contrary, it should be emphasized that calamities, such as the overturning and silting up of river mouths, e.g. of the Piasnitz River on the western border of the administrative district, which always occur during higher storm surges, were not noticed after the storm surge in question.

District of Coeslin (Cöslin)

The foredunes on the coast of the Coeslin (Cöslin) governorate (Regierungsbezirk) have been considerably damaged.

Since the wind direction at the time of the strongest current hit the rear Pomeranian coast at a very acute angle, the water level (cf. the profile on Figure 1) did not reach such a considerable height here as it usually does during strong storms, and especially during the storm that raged in November 1867, the water rose much higher.

The wave action, however, was very violent, and it is to this that the beautifully cultivated foredunes have been attacked to such an extent that almost the third part of them has been completely destroyed and must be laid out anew.

The advantage of the foredunes, however, has been unmistakable, since they have protected the main dunes from heavy demolition.

Severe damage to the main dunes has only occurred in places where there were no foredunes.

District of Szczecin (Stettin)

Along the beach, from Swinoujscie (Swinemünde) westward to below Hammelstall, the foredunes, the grass plantations and the old fences have been washed away by the sea; mostly the older dunes have also been attacked very severely, up to a width of 10 metres, and the front row of them has even been partially broken through, especially at Cölpiner See, near Damerow and Zinnowitz.

The break near Damerow is the largest and also the deepest. It extends about 150 metres inland with an average width of 50 metres and a depth of 1 metre below the average water level of the Baltic Sea. On the beach, the depth was only 0.3 meters and the inland meadows have a height of 0.5 metres above the mean water level of the Baltic Sea, so that after the fall of the tide the water no longer flows through and, consequently, there is no seepage causing the ground to break.

In order to get a full understanding of this collapse, it must be noted that where the tide cannot enter inward because the dune or the high bank rises above the tide, the beach only forms in evenly curved lines in the situation and that sudden deep cracks can only be the result of an outgoing current. This has also taken place at Damerow, where the tide overflowed the low terrain and poured into the backwater, raising this inland basin in water level. With the rapid fall of the lake level, the high inland water poured over the low terrain towards the lake and cut a stream channel, which became deepest where the overthrow took place, while towards the lake a smaller depth was maintained, since here the water receded only slowly. That part of the inland water that is deeper than the low foreland had to pass through the Peene near Wolgast and created a longer lasting outgoing current in the outflow of the Peene, which could only have a favourable effect on the deepening of the Peene outlet, especially on the barrel bank. This phenomenon was repeated after the flood of February 9th, 1874.

The dunes between Ahlbeck and the western pier, as well as in front of Dievenow, have also broken off in significant width.

In the Fritzow dunes a breakthrough with flooding has occurred, but to a lesser extent than at Lake Cölpin. The width of the beach has increased significantly both landward and seaward, as everywhere.

District of Stralsund

Darsser Ort and Dars Peninsula:

The dunes along the west side of the Dars in the Ahrenshoop field on the border with Mecklenburg are completely destroyed, from there to the tar kiln south of the Dars lighthouse they are badly broken off; from here north and then west to halfway to Prerow the foredunes are almost completely destroyed, while from there to the Prerow stream they are badly damaged and in part completely destroyed.

Zingst Island and Sundische Wiesen (eastern part of Zingst Island):

The dunes are completely destroyed except for a short stretch east of Lake Papen at the Prerow Stream and small remnants near Prahmort. The destruction of this peninsula will be discussed in more detail in the section on dikes.

Hiddensee Island:

The insignificant dunes have suffered greatly on the whole island and are completely destroyed in front of the village of Vitte and its field, as well as in front of the villages of Plogshagen and Neuendorf, also on both sides of the breakthrough south of Plogshagen, while they have suffered greatly on the rest of the island and also on the Gellen.

Opposite the village of Vitte about 6 and near the breakthrough 1 bank collapses had formed. The latter find their cause in the same conditions as at Damerow, in that smaller lowlands had absorbed so much water during the storm surge that after the sea had fallen an outflow was formed by the drainage, which produced these incisions.

Wittower Post House on Rugen (Rügen):

The small dunes on the Bug are very badly affected, partly completely destroyed, especially in the northern part of the Bug. The part initially located south of the land belonging to the municipality of Dranske, the so-called neck, that thin outlet of the Bug to the Wittow peninsula, has been washed away so considerably in a length of about 136 metres that, with an average width of 3.6 metres, it is still only 50 to 60 centimetres above mean water at the lowest point, while on both sides it rises to 1.7 metres above the same. The subsoil of this low-lying land connection consisted of clay covered with a layer of gravel. Since an inland water, the Wyker Bodden, is situated behind it, a strong overcurrent is generated here, which made an attack of this place all the more violent and caused its subsidence. During the storm tide of February 9th–10th, 1874, the surface of the terrain strip sank to slightly below mean water and this caused a fortified ridge to be built here to prevent a decisive ground failure.

Thiessow at the Southern Tip of Rugen (Rügen):

The entire dune range from Thiessow to Lobbe and from Lobbe to Göhren and at the southern tip of Thiessow has been destroyed. The part of the dune range from Thiessow to Lobbe was washed away at about 5 a.m. on November 13th and from then on the Baltic Sea poured through this dune breach through the Hagensche Wieck and the Zicker lake into the Greifswalder Bodden and the Rügen Bodden, so that the water here is said to have risen by about 1.25 metres in about 2 hours, while at the same time the tide around the southern tip of Rugen (Rügen) took its way to the same basin. The eastern outlet of the Thiessower Höft, a front head, was very strongly attacked by current and swell and the debris of fallen clay masses lay in large parts at the foot of the Höft.

Ruden Island:

On the island of Ruden, the dunes on the eastern beach have been almost completely washed away, and only at the northwestern tip are weak dune ridges still visible. High tides of the same type completely submerge the island, with the exception of a few higher dune crests.

District of Schleswig

True dune formation on a larger scale is not found on the east coast of Schleswig-Holstein. On those stretches of shore where a shallow beach forms the boundary of the sea, the waves have raised an embankment by washing out and accumulating coarse debris, which they rarely cross. In some places, namely on the Schwansen shore and on the north coast of Fehmarn, these dune formations have risen to a height of more than 3 metres.

During this storm surge, these dune-like embankments did not flood and also remained intact in their well scarred outer slope, partly covered with heather instead of beach grasses. The discussed formation of dunes on Fehmarn has even been intensified by the flood in that the masses of sand and debris churned up by the surf have been thrown out of the sea onto the lagoon and have created an elevation of the same, as well as the formation of an approximately 5-fold seaward slope, whereby, without the foot of the dune having receded, the top of the same has moved about 10 meters further inland, the dune thus having become that much thicker.

The beach wall located at the Schmöler and Stackendorfer beaches, as well as in front of the Probsteier salt marshes proved less resistant. It had an average height of barely 3 metres and was at its lowest point not less than 2½ metres high, consisted of sea sand planted with beach grass and had an irregular shape and slope, sometimes formed a rounded ridge, sometimes a more dike-like shape and in such strong dimensions that the thickness of the wall, measured 1½ metres below the upper edge, was at least 20 to 30 metres and in many cases considerably more. The direction of the beach wall went from eastsoutheast to westnorthwest so that the same in the outer slope against eastnortheast during the storm surge was hit by strong sea state.

At 7 a.m. the eastern part was destroyed first, the western about between 7:30 and 8 a.m., so that the destruction of the whole 1.5 miles stretch was completed in an hour, and, according to information given on the spot, down to about 1½ metres below the former top.

According to the Kiel observations, a water level of 2.15 to 3 metres above zero occurred from 7 to 8 a.m. Now, even if the same water level may not be assumed to have prevailed in front of the beach stretch in question, so much seems certain that an overflow of the 2½ to 3 metres high embankment could not have occurred during this time. Therefore, the effect of the swell and the overturning of the waves on the irregular, albeit very wide, sand body is to be stated as the cause of the destruction.

In the very shallow and evenly sloped solid beach ridge that remained after the upper part was washed away situated about 1.5 metres above mean water, some hydraulic heave has occurred. Here the lower material is uneven and less firm, or the embankment at such a place was particularly low and therefore here water passed over the same.

The even weaker, only 2 to 2.5 metres high beach dune with about 12 times the outer area, covered with individual beach grasses, as they occur among others at Waterneversdorf in the Hochwachterbucht, apart from on the described stronger dune also at the Schwansener Strande, in front of the Schlei, on the peninsula Kekenis located south of Alsen, etc., has - apart from a few dunes and some breaks as a result of overflowing at low places – essentially preserved its form, but has moved inland by about 10 metres in its entirety, whereby the drainage channels on the seaward side have been exposed and buried on the landward side. The sea has carried out this work with great regularity, and from the observation of this careful natural dam formation, often extending for miles, it becomes understandable that the popular belief, which could not explain such an effect, has attributed the formation of the sacred dam at Dobberan to a saint who built it at the command of the monks in one night for the protection of the monastery.

The breaches that occurred in the dunes described above took place off the coast of Schwansen without exception at those places where, in order to get to the beach, one had to drive over the dune. Here there will have been low, rugged places, over which the water first passed and fell with a strong gradient into the lowland behind the dune. Considerable scouring in the affected terrain confirms this course. Therefore, special care must be taken in the construction of such crossings to avoid such destruction.

The dune formation, weakest in its dimensions, which occurred especially in the inland part of the district of Oldenburg, consisted of loose drifting sand, mixed with sea grass and small debris, and almost everywhere reached only an equal height of 1.5 metres above mean water. The crest and landward slope were usually sparsely covered with beach grass and other beach vegetation, which was insufficient to prevent the sand from blowing away and

 https://doi.org/10.18171/1.092107

the resulting constant variability of the dune. Nevertheless, even these weak beach dunes provided substantial protection against the lower tides of the Baltic Sea by keeping the ordinary high tide from the lands behind them, most of which rise only a few feet above the mean water level.

As a result of this storm tide, these low beach dams, as far as they were exposed to wave action, almost completely disappeared and collapsed into the lowlands behind them, so that now a tide only 0.75 metres high would already flood them.

There has been a lack of deliberate dune cultivation on the Baltic Sea in this administrative district. Only on the Lootsen Island at Schleimünde were plantings of sand grasses and fences made, but only on a very small scale. These have completely silted up as a result of the shifting of the dune described above.

6.1.4 Transverse overflows of Fairways, Reduced Water Depth, Deepenings etc.

District of Gdansk (Danzig)

There has been no change in the depth of the harbour's entrance line to Nowy Port (Neufahrwasser).

District of Coeslin (Cöslin)

The storm has had no noticeable effect on the depth in the mouth of Colberg harbour. The mouth of Rügenwalde harbour, on the other hand, was so silted up that here, where there is usually a depth of 3 metres, only a water depth of about 2 metres remained.

The storm had a very favourable effect on Stolpmünde harbour. Here, a bank moving from west to east had pushed itself so far in front of the harbour mouth that only in the northeast direction a 3.75 metre deep entrance channel was open, making it difficult for ships to enter in SW winds. After the storm, this sand had completely disappeared, and a depth of 3.7 to 4.4 metres had formed in the whole sea gate.

District of Szczecin (Stettin)

The fairway of the Dievenow has shifted a lot. The sand masses on the shore breaks have been deposited here and in the fairway at Falkenberg. The water depth in the harbour entrance to Swinoujscie (Swinemünde) has not changed, whereas the smaller outlets on the coast, Camper Lake, Rega, Liebelose, Dievenow, Schlohn – with a significant shift to the west, have shown strong but only short-lasting drops in water depth.

District of Stralsund

Stralsund Harbour. The water depth had decreased by about 30 centimetres right at the exit from the harbour to the fairway channel, across which the stream cuts.

No further decreases of water depths in the harbour were noticeable. Likewise, it is noted that the depth of the outer parts of the dredged channel leading to the stream has remained unchanged.

City of Barth. In the channels and gullies leading to the shipyards, drops in water depth of up to 1.25 metres have appeared.

Wittow Post House. In the Libben and the channel near Alt-Bessin the water became moderately shallower by about 0.31 metres.

District of Schleswig
Transverse overflows of fairways have only occurred in a few places and, as a natural consequence, no significant reductions in depths of the fairway have been observed.

The piers at Burg auf Fehmarn, made of fascines and stone packings, extended only a few feet above mean water. They were therefore soon submerged and no longer capable of holding back a significant amount of seaweed, which had been lying in the corner between the northern harbour pier and the Kirchberg near Burgtiefe and had been picked up by the water.

As a result, the seaweed was deposited in the dredged harbour channel, reducing its depth by an abundant 0.5 metres.

At Schleimünde, the 2.8 metres high and the 1.8 metres high end wall built at the root of the northern breakwater, which lie side by side at the NW end of the structure behind the dune, had not yet been backfilled on November 12th. The storm tide did an excellent job on the 9 feet wall, but oversanded the 1.8 metres high wall by 3 feet and carried significant masses of sand over it into the Schlei. Effective measures prevented the siltation from reaching the fairway on this occasion.

If, moreover, no soil deposits have taken place to such an extent that depth reductions or constrictions in the fairway could be noticed, the reason for this is to be found in the fact that in all narrows and in the harbour mouths a very strong outgoing current prevailed with falling water.

However, special deepenings caused by this storm were only noticed in Eckemförder Harbour. Here, the dam closing Windebyer Noor was torn away by the storm surge, whereupon the tide entered the approximately l/8 mile large inland basin, Windebyer Noor, and deposited the material of the dam in large banks in the Noor. The water that has penetrated here has caused washouts up to 3 metres deep as it drains into the narrow part of the inner harbour, and even on the barre in front of the harbour there is still a depression of 0.7 metres.

6.2 Artificial Bank Protection Structures

6.2.1 Groynes

District of Coeslin (Cöslin)
The pile groynes in front of the high clayey shore at Jershöft have proven themselves well and have contributed considerably to the protection of the shore. The construction consists of 2 rows of piles about 0.18 metres thick, which are driven close together so that the joints of the inner row are covered by the piles of the second row. This double pile wall is cut horizontally at mid-water level or 0.15 metres above it and runs under the beach embankment without any particular fixed connection to the high bank. Its purpose is to keep the depth away from the beach, to widen the foreshore by accumulating sand, and thus to be conducive to the culture of the foreshore dune without altering the natural beach slope, which would not be achieved with a higher crown of works. Partially, the construction of only one row of piles has already served the purpose.

These pile groynes have held up well. Only three groynes at the eastern end of the system have been washed out and become rootless.

Even if deep holes have not been torn out, the connection to the foreshore will have to be restored.

District of Stralsund

Zingst Island:

The pile groynes, which were built along the beach to facilitate the landings, have been damaged in many places and, in particular, many of the piles consisting of a row of piles, both at the heads and in the middle, have been torn out; the pile works adjacent to the beach have also been largely bypassed by the tide. Since the flood, most of the piles have been re-siltated. On the whole these destructions are beyond the measure of the usual destructions. The similar works locally inspected after the storm of February 9th–10th, 1874, before the breach in the beach at Damerow, administrative district of Szczecin (Stettin), showed the same characteristics. Both points are consistent in that the tide overflowed the lowland and that both the incoming tide took the agitated sand of the foreshore inland, and the outgoing tide threw any remaining material further out to sea, causing the waterline to recede considerably. In addition, the works, especially by the incoming and outgoing current, entered into a substantially different attack than for which they were intended, namely for a coastal current parallel to the beach line. Precisely in this, however, the abnormal destructions and evasions will have to be sought, which did not appear at any other point of the coast.

Hiddensee Island:

The island of Hiddensee has a breakthrough south of the village of Plogshagen, and the passage is structured by 2 coupirs of submerged fascines installed at about 2.5 metres below mean water.

One of the winged structures made of piles near the coupirung is destroyed. The coupirung itself has not suffered and even after this flood considerable siltations are perceptible, while within the coupirung the water level decreases rather than deepens.

District of Schleswig

The stone groynes at Bülkerhuck, Figure 17, are to be considered as shore protection structures first. These were built in 1870/71 to protect the very exposed lighthouse. There are seven of them, of which the end groynes VI and VII rise in the line of their crest from the mean water level to the former terrain height of the high bank, i.e. up to 2.15 metres, while groynes I to V lie at the height of the daily water with their roots in the foreshore and extend only to the foot of the former high bank.

https://doi.org/10.18171/1.092107

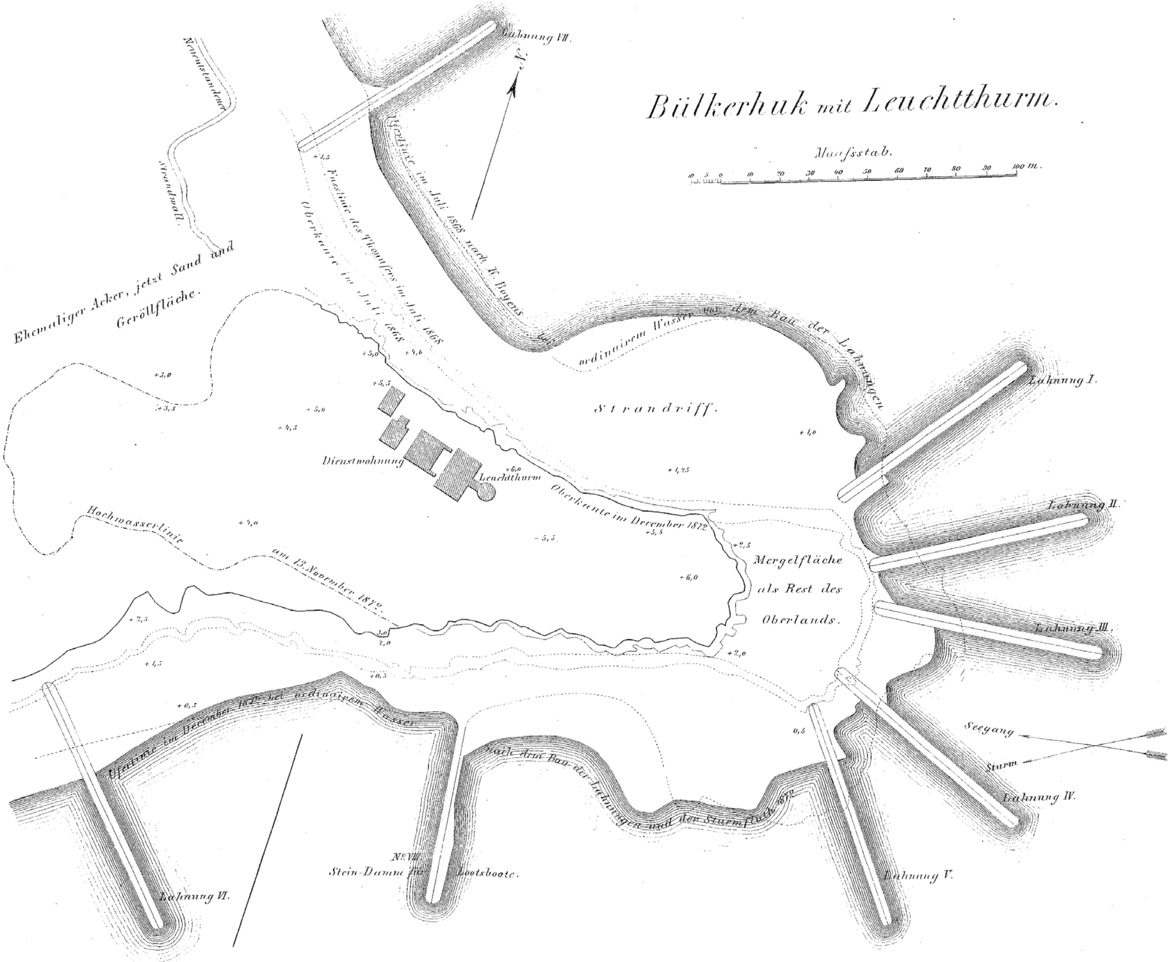

Figure 17: Bülkerhuck with Lighthouse.

The resistance of the groynes has shown that the 6 small ones have not given protection against the break-off. Groynes No. VI and VII have not had a particularly recognizable favourable effect either; the latter, however, does not seem to have been without any influence on the deposition of the broken-off material. On the other hand, a stone embankment No. VIII, which has been in place for some time, has contributed to the collection of the washed away soil.

The groynes are constructed as stone embankments, which are piled against a double pile wall and paved with 1½ -fold side slopes. The large groynes have held up very well during this storm surge, only in the upper part of them some stones have been displaced, others have fallen out. The smaller groynes, which lie horizontally from the shoreline to the head, have, with regard to the shallow beach next to the pile wall, only small stones throughout, which are more or less thrown apart by the swell and have not been spared even on the most recent occasion. The fact that these light structures have not suffered more is probably due to their low position, as a result of which they have been 3 metres deep under water.

6.2.2 Stone Works and Stone Revetments

District of Szczecin (Stettin)
The stone revetment at the foot of the clay bank of Groß-Horst held up well, but because of its low position it could not prevent the clay bank from being washed away.

District of Stralsund
Island of Hiddensee:
The stone groynes at Dornbusch have held up quite well on the whole, and considerable siltation has even occurred in some places. On the other hand, the shore between two stone structures has collapsed and one stone structure has been almost completely smashed and sanded in, so the high shore has been attacked.

Wittow Post House:
The shore structures, stone groynes and catch fences have on the whole performed well.

Arcona and Vitte on Wittow:
The seawall on the high shore at Arcona, which consisted of a stone revetment resting on the bare chalk shore and supported against a row of piles at the foot, was swept from both ends on the evening of November 12th and overtaken by the surf from 3 to 10 a.m. on November 13th. As a result, the stone revetment was washed away, especially in the upper part, and the stones were thrown down and driven away by the swell. As a result, about half of the stone cover was completely destroyed, a further quarter of it was badly damaged, and the remaining parts were more or less loosened. The stone structures placed in front of the shore suffered less, probably because in their deeper position the attack on them by the swell was of lesser intensity. Only three of the revetments were severely damaged and almost completely destroyed while the others held up quite well.

The lining walls built in front of the clayey shore near the village of Vitte were churned up from the north side by a northerly current on the evening of November 12th and later completely destroyed by the surf passing over their upper edge, the stones being swept away by the sea. The walls were built almost plumb and dry without mortar.

Ruden Island:
The revetments on the northeastern beach have been preserved fairly well, while those on the eastern beach have been more or less damaged by the tearing out of stones. In general, these structures are separated from the sandy beach at the roots, and since they usually consist only of smaller stones resting between strongly constructed wattle fences, these stones have been thrown out and some of them deposited close by.

Thiessow:
At the southern tip of Rugen (Rügen) on Mönchgut, a section of stone works has been constructed, consisting of larger stones, which also rest between strong wattle fences, as on Rugen (Rügen), but have been more carefully paved in the crown. The same had so far offered good resistance. They lie with the top at mid-water level, with the root at l.6 metres above mid-water and the crown has a slope of 1:20. The same had caused the large sand beach to widen and provided good shore protection.

At high tide, however, the clay shore has been reached, washed away and the groynes have all been detached at the root. The stone structures most exposed to the wave action were destroyed by throwing out the stones, which were deposited on the seaward side of the structures by the storm. On the Holstein coasts, where a tightly closed pile wall forms the enclosure in place of the wattle fences, against which the packing is inserted with great strength, the stones have rarely been thrown out.

Greifswalder Oie:

Of the revetments built here, all have suffered to a greater or lesser extent and are in need of repair. The one located to the east has suffered the most, breaking open at about 45" or 14.1 metres, and its stones have been swept away by the sea.

District of Schleswig

The stone coverings made for the protection of shore stretches or at road embankments etc. have – apart from the protective covering at Haddebyer Damm, vis-à-vis Schleswig, which was made of irregular stones without gravel bedding - not suffered at all by the direct wave impact, but have remained intact, no matter whether with flat or with steep construction, if the terrain behind the same or the crest is not washed out. Where the crest was washed out, the stones were thrown backwards.

The most magnificent picture of such destruction is provided by the stone cover in front of the Grand Ducal Oldenburg village of Niendorf, northwest of Travemuende (Travemünde), in the Neustadt Bay, and therefore a description of this devastation may follow: "The now destroyed 460-metre stone deck was constructed at Niendorfer Strande in 1869. Since the floods of the previous years had repeatedly destroyed the shore protection there, this construction was carried out only after careful consideration. The slab formed a circular arc of 6.3 metres radius in the transverse profile, which belonged to a circular section of 0.43 meters height, which rested with the hollow side upwards on a 1½ fold sloped embankment and was extended downwards to such an extent that the total arch height was 6.9 metres. The slope was 3.72 metres long.

The crest was 3.72 metres, the foot 0.29 metres above mean water and the footpath paved along the crest of l.72 metres width had a 0.07 metres drop inland. The stone cover was bedded in gravel, which was separated from the underlying sand by a 0.14 metres thick layer of clay. The gravel contained aggregate stones up to 10 lbs. in weight. The minimum dimensions of the revetment stones were 0.43 metres in height and a minimum weight of 200 lbs. The stones were well fitted together and carefully interlocked from below with wedge-shaped pieces of stone so that the returning wave could not throw a grand out of the joints. In the course of time the slope had been covered with sand up to half its height and was in an intact condition when this storm tide came in.

At 6 p.m. on November 12th, when the water was 1.5 metres above mean water, the first splash waves passed over the stone revetment, and it was not discernibly damaged until 4 in the morning of November 13th. Later the stone cover lost the upper half. It broke only when the water, rising higher in the meantime, washed away the sand on the back of the ridge. Of course, it must have been easy to tear off the stones from the top layer by layer. Stones weighing more than 1000 lbs. have been flung away by the water, and all broken off stones lie inland".

In contrast, the stone embankment at the "Großer Gottorfer Damm" near Schleswig, made of rough stones on a gravelbed, has held up, although this embankment was submerged to a height of 1.3 metres and was broken from the inside in 4 places, but fortunately always in such a way that the outer, well-fortified bank against which the embankment leaned was preserved.

Similar conditions in one direction or another have also been seen elsewhere, e.g. at Eckernförde, Apenrade, etc.

It can therefore be regarded as established that slabs made of rough stones over clay banks with a twofold or one-and-a-half fold slope and bedded on gravel resist wave action excellently as long as their crest is not flooded, and that they still prove their worth in the event of complete flooding if the crest of the embankment is not washed out, but that they are lost if the crest is washed away or breaks, since the upper edge of the slope thus loses its hold.

In the construction of such slabs, therefore, the aim must be to keep the crest free of water or, if this cannot be done, to make it as resistant as possible to the attacks of the sea.

6.2.3 Dikes and Dams

District of Szczecin (Stettin)

The fascines embankment in Swinoujscie (Swinemünde) in the fortress moat between the lighthouse and the eastern pier has been completely destroyed and this passage has been restored by an emergency bridge.

The embankment on the left bank of the river Swine, from the construction yard to the pilot station, has been severely damaged by overflowing along its entire length.

The road embankment between Bannemin and Hammelstall was severely damaged by the flood. The residents of Hammelstall had punctured the dam to give the water a faster outflow into the backwater.

District of Stralsund

Zingst Island:

The sea dikes on Zingst have suffered considerably from the flooding as well as from the receding water, and the dike has been destroyed over an average of 1/8 of its length; deep scouring has also occurred in many cases.

The inland dikes near Zingst have suffered less, showing only insignificant damage, at least as far as their bodies are concerned. In contrast, the inland dike at Müggenburg, especially in front of the old Straminke, has suffered considerable damage. The nature of the destruction will be discussed in more detail here. The sea dike was located about 95 metres from the water line, was 2 metres high above mean water, had 2-fold inner and 3-fold outer slope. The only material present was dune sand, which was covered with 0.13 metres thick turf and showed dense scarring.

As long as the flood did not exceed the dike crest, the dikes, despite their light construction with a crest width of 1.25 metres, held their own. With the flood, however, the crown and inland embankment were destroyed and the fall of the dike began. Since the dike had provided a convenient footpath for passers-by on its crown, the turf on it had died in many cases, and it was mainly these points where the flooding caused the first destruction, while whole stretches of the dike remained well preserved, as the rapidly growing inland water level in the floodplain moderated the attacks of the overflow on these stretches.

Since the breaching of the sea dike occurred mainly in front of the village of Zingst, the main current passed through the village itself, accompanied by strong seas, and caused the most considerable destruction to the dwellings here. The incoming current, which mainly had to fill the large inland basins, emerged with great force in the resulting strong inland gradient, and the water level curve in Figure 12 for Barth shows the rapid growth of the inland water when the height of 2 metres above mean water was exceeded by the tide. As a result, the inland basins reached a water level of 2.83 metres. The water level curve in Figure 13 for Barhöft also shows the rapid fall of the tide, while the same curve for Barth shows the opposite phenomenon. According to the situation, the curve of falling tide at Barth remained dependent on 2 discharges. Once the water at Barhöft had to go into the sea, at the same time it could find its outflow over the low peninsula of Zingst to the sea. However, the latter flow could not act sufficiently and so the falling curve at Barth is seen to decrease only slowly. This lowering decreases even more when the tide in the inland hedges had receded to l.5 metres above mean water and it found only the outflow at Barhöft open, the peninsula lying at about 1.5 metres above mean water. The strong current running back across the peninsula to the sea, however, brought new very disadvantageous destruction in its wake, because not only was the whole foreshore denuded of sand, which was thrown to the sea, so that the whole foreshore showed almost only the bare turf of the subsoil, but also the edge of the green land broke off and those edges, which lay particularly low, finally had to take up alone the current, which the deeper subsidences concentrated on these places. As a result, deep watercourses were formed, into which large lawns hung, and these watercourses were cut deep into the inland. With this outgoing stream, therefore, a complete destruction of the foreshore and the adjoining meadow areas had occurred, while on the latter, still further inland, lay large sandy areas which the incoming stream had carried inward from the dunes as the tide grew.

Exactly the same phenomenon in all details had also occurred on the Fischland south of Wusterow. These destructions were a reason to restore the embankment not only for the protection of the villages and lands, but also to extend the whole length of this peninsula in order to obtain a good foreshore, so that the incoming and outgoing currents would be blocked and the effect of the beach constructions would be secured.

Wolgast. These weak dikes along the Peene River for the protection of the properties behind them have suffered greatly from the overtopping water and have sunk very much.

Wiek near Greifswald. The dikes enclosing the Rykflufs are flooded and have suffered multiple breaches as a result of this and the backflow of the water.

District of Schleswig

The dikes built on the Baltic Sea coasts in front of the lowlands were closely connected with the dune, and the district of Oldenburg in particular had such larger structures, which were almost without exception destroyed by the storm surge.

In front of Lake Gruber, a dike was located on the dune-like beach ridge, which was filled with sand, was 3.8 metres above the daily water level of the Baltic Sea determined there, had a crown width of 3.9 metres and a twice sealed inland dike, as well as a four times sealed outer dike, up to 2.2 metres above mean water, from where the embankment joined the existing beach profile.

 https://doi.org/10.18171/1.092107

The crown and the upper part of the outer embankment were covered with beach grasses, the lower part of the outer embankment and the beach, up to about 3 meters from the base of the dike, were protected by a layer of boulders, which had a thickness of 0.3 metres in the angle of connection, and levelled out both downwards towards the beach and upwards to the middle of the outer embankment. The outer beach was planted with marram up to a height of about 1" above mean water.

The dike in front of the Klostersee lake, also a sand dike on the beach ridge, had somewhat weaker dimensions, 3.44 metres crown width, 3.44 metres height above zero and a four times sealed outer dike and a twice sealed inner dike.

The dike in front of the Klostersee was completely destroyed by the storm tide at 6 a.m. on November 13th, the one in front of the Gruber See at 7 a.m., to such an extent that the place where the latter had stood can hardly be found anymore.

The highest level of the Baltic Sea was marked by the engineer Bong-Schmidt at 2:30 p.m. with 3.2 metres above mean water.

The height measurement agrees very closely with the Kiel observation. One will therefore come close enough to the truth if one also assumes agreement for the morning times of November 13th, but takes into account that–- because the highest water level in Neustadt Bay occurred one level earlier than in Kiel Bay–- the earlier, coinciding water levels off Gruber and Klostersee Lowlands may also have occurred about one hour earlier than in Kiel.

According to the observations of the Imperial Shipyard in Kiel, taking into account that the water level observed there at 7 or 8 a.m. already occurred at 6 or 7 a.m. in the Neustädter Bucht, the water here was:

	6 a.m.		2.15 metres	above	zero,
-	7 a.m.	-	2.88 metres	-	-

Therefore, these dikes of the Klostersee and of the Gruber See were already destroyed, when the crowns of them were still respectively 3.44–- 2.15 = 1.29 metres and 3.80–- 2.89 = 1.47 metres high above the early level of the Baltic Sea.

Therefore it is to be stated for these dikes that the rapid destruction of the same, even at a water level which at the Grubersee dike was still completely within the vault covering of the sluices, is to be regarded only as an effect of the swell on the loose sand and sod material of the four fold sloped outer dike embankment.

This fact is confirmed by the observations made on the spot, namely by the perception of inhabitants of the village of Dahme, who were still able to walk on the dike crest on the morning of November 13tth and noticed how the outer dike embankment was completely washed away and the dike therefore only formed a perpendicular wall against the attacks of the sea.

Some of the dikes on the island of Fehmarn were still under construction. They, as far as they were built of sand and rubble, have also without exception been almost completely torn away, while the dikes built of cohesive material and clay, despite inadequate embankment, are partially preserved.

A description of their construction and the nature of their destruction may be omitted here, since these dikes have almost all been attacked by the water entering in open places from the inside, i.e. from a side which was not equipped to resist the sea state.

The Barsbeck dike, in front of a part of the Probsteier salt marshes, does not consist of sand, but of binding dike soil. It is directed approximately from south to north, its outer slope does not face easterly winds, and thus did not have to withstand such a strong swell during the storm surge as the dikes in the Oldenburg district. The dike has a length of 2.2 km, an average height of 2.39 metres, and a lowest height of 2.02 metres above Kiel zero. It is therefore lower than the Gruber and Klostersee dikes.

Furthermore, the dike has an average crown width of about 2 metres and a sealed slope, with outwardly 3 to 4 fold, inwardly 2 fold the height of the dike.

Between 9 and 10 a.m., when the water passed over the low dike, foundations failed in some places due to insufficient stocking. A significant difference between this damage and the complete destruction of the Oldenburg dikes can be found in the fact that the Barsbeck dike, although having fractures, remained repairable as a dike, while the other dikes disappeared completely up to a certain height.

This circumstance can only be attributed to the more resistant material and it has been confirmed here that the clay dikes are able to resist the attacks of the sea with success, while the sand dikes are incomparably less resistant, an experience which is already known, but whose value becomes illusory where no materials other than sand are available and where therefore only flat embankments can form a supplement for the resistance.

This experience has also been made on dams exposed to storm surge.

The Eckernförde Bay offers the richest resource in this respect, and in view of the interest aroused by the particularly hard-hit town of Eckernförde, it is permissible to dwell here and start by providing a description of the terrain before shedding light on the extent of the destruction.

The western end of the Eckernförde Bay is formed by the town of Eckernförde and the causeway from here to Kiel.

The town of Eckernförde is located on a peninsula, which rises 3.2 metres above the mean water level of the Baltic Sea at its highest point. This peninsula separates the Windebyer Noor (Lagoon) from the Eckernförder Bay. North of the town there is a harbour about 80 metres wide, which used to connect the lagoon with the bay. This connection was cut off in 1856 by the construction of a dam through the harbour, so that the high water levels of the bay could no longer affect the lagoon and drainage of the lagoon into the harbour only took place through a lock that closes when the outer water level rises.

Both the dams just described and the causeway to Kiel were destroyed.

The dam, about 7 meters wide, was made of sand and its crown was about 2 metres above mean water level; the roadway was paved and the shoulder had been reinforced by tar-concrete. On the harbour side, a retaining wall of granite on sill grate had been built at mean water level above fascine packing, originally so high that the top of the wall fell into the edge of the subgrade.

A lowering of the fascines had necessitated the later construction of an earth embankment above the wall, which was well scarred at the time of the storm surge. The front embankment had a 2-fold slope and was secured at the foot with a stone fill.

On the evening of November 12th, water seepage was noticed on one side of the embankment. At 8 a.m. of November 13th the first break-offs occurred on the dam, and after 1.5 hours it disappeared completely. On November 18th, at the place where the dam had stood, the water level was 2.8 metres below zero.

At 8 a.m. in the morning of November 13th, the water in the harbour of Kiel reached a depth of 2.8 metres, and since similar conditions prevailed in the harbour of Eckernförde, it may be assumed that the dam was flooded around this time and broke as a result. This is confirmed by the statements of eyewitnesses.

The causeway leading through the meadows in front of the Goossee etc. along the beach at the Eckemförder Bay to Kiel was filled with sand and provided with clay embankments, which were placed on the flat sandy foreshore.

The height of the dam was 3.3 metres above mean water level. The dam was not flooded, but the 3 breakthroughs were caused by the swell. On long stretches, the clay embankment on the seaward side is still standing, while the rest of the road has disappeared.

The breakthroughs have occurred at those places where descents led to the beach, and as a result the protective clay cover and the grass surface were interrupted. This is clear evidence of the value of clay over sand and the caution required when providing descents from dikes and dams. It should also be mentioned here that in the case of overflowing, a macadam surface is preferable to a pavement, since it also offers a better guarantee against destruction due to its impermeability.

An enumeration of all further destructions observed at dams and dikes would only tire and it is already clear after the phenomena mentioned here that care must be exercised in the choice of the material to be used for dam constructions, which are to resist either the swell or the overflowing water, and–- if clay is too difficult to procure for filling–- the sand body should be provided with clay embankments in any case, if stone revetments cannot be envisaged either.

6.3 Port and Shipping Structures

6.3.1 Port Entrances

District of Gdansk (Danzig)
There were no adverse effects of the storm tide on the harbour structures at Nowy Port (Neufahrwasser).

District of Szczecin (Stettin)
The pile works (advanced works or the head of the eastern pier) in Swinoujscie (Swinemünde) held up very well on the whole. Some concrete blocks in the same, which load the stone pack, have shifted; one block is shattered; one strut is broken, and 2 piles on the seaward side have broken off under the breast bar. Some of the filler stones between the concrete blocks have been thrown out.

The blocks, which were kept in stock on the breastwall and the top of the pier, have been thrown down by the breaking waves and were deposited on the harbour-side slope of the pier. Immediately adjacent to the small lighthouse, the pavement of the breakwater has been ripped open. The top layer of the breast wall is damaged in several places by the large stones thrown up from the seaward side; the paving over the breakwater has been lifted off in a few places; the two short outer banks made this year have been destroyed; on the seaward stone throw, from the beacon to the old pier head, many shifts and changes against the former condition are apparent. However, these damages have not grown to a dangerous extent.

A very large quantity of stones has been thrown from the sea over the wall into the harbour. When clearing up the gap created in the stone body of the eastern breakwater next to the light beacon, large cavities were revealed under the uppermost thick layer of

 https://doi.org/10.18171/1.092107

pavement, which is supported in an arch shape against the foundations of the breast wall on the one hand and the light beacon on the other.

District of Schleswig

Here only the harbour buildings of Schleimünde are to be remembered.

That the attack of the sea here has been a very powerful one is already evident from the foregoing, but nevertheless only the unfinished work on the newly built northern breakwater has suffered damage, while on the other hand the head of the old southern breakwater, which is still awaiting reconstruction, has been completely shaved with the beacon, and all the provisional structures, as well as the old pilot establishment, have been completely destroyed. The new breakwater is enclosed in the upper masonry by 2 retaining walls, of which the seaward one, which supports the 1.15 metre high parapet with its upper edge 3.44 metre above mean water level, is constructed according to Emy's profile.

The inner wall is 2.58 metres high above mean water and stands at such a distance from the first that the pier without the parapet is 3.44 metres wide. The space in between, as far as the structure is touched by water on both sides, is filled with scree, landward with pure sea sand and paved in the upper course.

At the head, the pier widens circularly to a diameter of 7.8 metres between the parapets and the profile here shows Emy's curve all around. On the centre of the pier head stands the lighthouse.

The base of the concave wall is protected by a masonry embankment sloping from 0.8 metre above mean water in a triple arrangement to 0.8 metre below mean water, which is supported along the pier by foot piles, but should be secured in front of the head by large masonry concrete blocks.

On these constructions, for which only granite was used as stone material, damage occurred only in so far as they were unfinished or had been executed so recently that the cement had not been able to harden sufficiently. These have affected only the masonry embankment and the concrete blocks. The latter, which were ready to be toppled and were placed on tipping frames at a height of 0.8 metres, were completely destroyed. The sea had overturned them on November 12th, but they had not visibly suffered any significant damage. On November 14th, only small chunks of the blocks were left. Since the breakage occurred only in the mortar joint, the insufficient quality of the mortar, or in any case the too early exposure of the blocks to the waves, is responsible for this. The blocks were no more than 4 weeks old, some only a few days, and the mortar was not very strong.

On the stretch where the paving of the breakwater is over sand, it has caved in, proving that under the upwelling of the water between the walls, part of the sand has been washed out.

On the section filled with rubble, no such subsidence has occurred, but here the cement painted into the joints of the paving stones has been thrown out in many cases. This phenomenon can only be explained by the fact that here, too, water has entered between the walls from below, forcing the air in the interstices of the rubble under the cover and compressing it to a tension sufficient to break the cement and allow the air to escape through the resulting opening.

6.3.2 Wooden and Stone Quay Walls

District of Coeslin (Cöslin)
At the port of Colbergemünde, the backfill behind the wooden walls sank in some places.

In the port of Stolpmünde, the backfill soil of the piles has been washed out in some places. This has occurred in particular at the final piling of the outer harbour, where the waves have even penetrated some of the three-inch planking.

District of Stralsund
A new pier has partially lost its revetments due to the impact of vessels.

The older piles and quay walls have been washed out and the cladding destroyed. The iron balm quay wall has suffered major damage from the impact of large seagoing vessels.

The deck plates protruding about 0.16 metre in front have been detached almost everywhere, and a part of them together with the upper part of the masonry has fallen into the harbour.

The protrusions of such deck plates should be avoided everywhere where waves attack.

District of Schleswig
The devastations observed on piles and quay walls are limited almost everywhere to a few easily removable backwashes and insignificant damage. More important are only the destructions in Eckernförde, which provide interesting comparisons.

The deepening of the harbour in Eckernförde, already mentioned above, led to the collapse of the part of the quay wall built a few years ago, which was founded on concrete but only at a depth of about 1 metre below mean water level. Another part of the wall, which is still under construction and whose foundations consist of a sill grate placed 3 metre below mid-water, has been preserved. The old wooden piling has also been washed free, the waves have partly torn off the back covering, but the piles and anchors are still standing.

6.3.3 Landing Stages, etc.

District of Coeslin (Cöslin)
In the harbour at Golbergermünde, forty to fifty planks of the gangways and unloading bridges have been loosened and drifted away.

District of Stralsund
The wrought-iron swing bridge has suffered some damage to the fore-legs and has had to be readjusted.

The major part, which can be considered as the total damage of the destroyed port buildings, requires the restoration of the steamship landing bridge for the ferry traffic to Rugen (Rügen). This bridge was constructed of wood, without infill, with its forward end 0.92 metre above mean sea level. It lost its planking due to the uplift of the water and wave action.

The total destruction happened suddenly when the steamship “Hertha”, pushed by another ship, ran into the bridge and cut the planking. The “Hertha” was carried further with the decking attached to the ship on both sides to the filled ramp (ferry hatch) about 30 metres away, on which it remained lying with the decking.

Barth. Of the harbour structures, this storm surge almost completely destroyed the large loading bridge 60 feet long and 30 feet wide; a smaller bridge 30 feet long and 16 feet wide was completely destroyed.

6.3.4 Lighthouses

District of Szczecin (Stettin)
The oscillations of the lighthouse at Gr. Horst were so significant during the hurricane that the rotating device momentarily stood still, but then resumed a faster movement.

District of Schleswig
No further damage was done to the lighthouse at Schleimünde, except that the shutters of the window on the lowest floor broke and, as a result, this window also broke, putting the basement and first floor under water.

The lighthouse built on the very exposed Friedrichsort sand reef in Kiel Bay in 1866 also suffered little. However, as in the past, a settling of the cement-lined stone cone by about 3 centimetres, as well as a deviation of the cone from the tower wall by about 2 centimetres on the north side, became noticeable, as well as some cracks in the joints of the stone cone. The reason for this can be found in the construction of the building.

The tower itself is built of bricks on a pile grid, 5.5 metres in diameter. In order to create an outer foot slope, a 2-meter-wide fascine ring was first laid around the tower in a diameter of about 17 metres, up to a height of 0.4 metres above mean water level, and the inner space, gradually rising towards the tower, was filled with gravel. The base outside the fascine ring is a twofold slope made of coarse stones, and the upper layer of the fascines is covered with stones in the form of slabs. On the cone, which is filled with gravel, a layer of bricks is placed with stones, and these are covered with large boulders. The latter, as well as the stones of the lower slab first placed at the base of the cone, are grouted with cement.

The fact that the slab situated at mean water level, made of rather light stones, suffered little is due to the rapid rise of the water. Nevertheless, the settling of the stone cone is partly explained by the fact that the base of the grouted cone only has the above-mentioned slab for support, and partly by the fact that the inner gravel core will have been somewhat washed out under the buoyancy of the water through the fascines and thus caused to sink.

6.3.5 Navigation Marks

District of Szczecin (Stettin)
The bell buoys and two buoys from the harbour entrance to Swinoujscie (Swinemünde) drifted onto the beach at Ahlbeck; the remaining harbour buoys were recovered at Möwenhaken.

District of Schleswig
Of the large buoy beacons only one, the one on the middle ground of the Eckernförde Bay, was driven away and stranded to the southwest of it.

It lay at 4 fathoms water depth in front of a stone of about 1000 pounds weight and in front of 12 fathoms of 1.125 inch chain, of which about 3 fathoms were shackled for better balancing of the buoy. The blame for this buoy being displaced is probably borne by the following circumstances: the stone lay on a firm clay foundation, in which it could not sink; the buoy had its place at the extreme western edge of the plate, from where the terrain drops off abruptly to greater depths; also, the beacon offers a strong wind trap and there will have been violent shocks during the heavy seas. Instead of shackling, this buoy has now received increased load weight and is now ahead of 12 fathoms of chain.

All the pointed buoys have maintained their places, even the most awkwardly situated one on Klaverberg, 0.375 miles from Bülkerhuck. These buoys lie continuously off 6 fathoms of chain, half 1 inch, half 0.625 inch thick, on a stone weighing about 500 pounds on 3 fathoms of water.

The small buoys in the Schlei, on the other hand, have not been able to withstand the tearing current coming in and going out, since they were anchored with considerably less weight.

The accidents in the villages on the coast were not the subject of this publication, which only had the technical part of the whole flood phenomenon as its purpose.

However, it should not remain unmentioned that a small brochure, titled: "Die Sturmfluth vom 13. November 1872, Glückstadt 1873", gives a very detailed account of this subject for the province of Schleswig-Holstein.

7 Annex: Historic (non-metric) units of measurement

Fundamental to the idea of weights and measures are the concepts of uniformity, units, and standards. The historical development of units was generally through trade and conquest. Even though the idea of units caught on quickly over wide areas, they differed regionally, which implies some uncertainty into recalculation into modern systems.

Historically, two types of measurement systems can be distinguished into evolutionary systems, which developed more or less out of habits, and planned systems, such as the International System of Units (SI; Système Internationale d'Unités), used by the worldwide scientific community and most nations. In the following uncommon, ancient units are explained.

Length and surface dimensions

Measurements of length in many parts of the world were once commonly made in miles, yards, feet and inches. Depending on the region, however, these units varied in definition, e.g. a foot usually equaled 28 to 32 cm, in extreme cases also 25 and 34 cm. The Law of December 10th, 1799 stated that one metre is equal to exactly 443.296 French lines, the units being the Paris line: 1 line = 1/12 inch = 1/144 feet. It was not until 1875 that the metric system was established as the international base unit for length. However, even today, old units of measurement are still in use in some areas of Anglo-America.

For conversion purposes, these are currently defined as follows:

1 mile ≙ 1760 yards ≙ 5280 feet ≙ 63.360 inches
inch ["]/[in]: 1"≙ 2,54 cm
English foot [']/[ft]: 1' ≙ 12" ≙ 30,48 cm
Prussian inch ≙ 2,615 cm (used by Baensch)
Prussian foot ≙ 31,3854 cm (used by Baensch)
yard [yd]: 1 yd ≙ 3' ≙ 0,9144 m

 https://doi.org/10.18171/1.092107

mile [mile]: 1 mile ≙ 1609,344 m

Surface dimensions were made in square feet or acres. One acre was once defined out of habit as area, that can be ploughed in one day with one ox. Acres are still used to describe large areas in the US. Today one acre is equal to 4047 m^3.

Air temperature

As a unit of measurement for temperature, the Réaumur (R) scale, introduced in 1730 by R.A. Ferchault de Réaumur, used to be common until the beginning of the 20^{th} century. It is defined as the interval between the boiling point of water at normal atmospheric pressure (80 °R) and the melting point of ice (0 °R) divided into 80 equidistant parts (Réaumur degrees; symbol: °R/°Ré). Accordingly, a temperature difference of 1 °C corresponds to a temperature difference of 4/5 °R.

Atmospheric pressure

Atmospheric pressure used to be measured by mercury barometers. The height of the mercury column was mostly given in feet, inch or Paris lines. According to the above-described dimensions of length, the sizes varied regionally. Since the height of the mercury column depends on the temperature and the gravitational acceleration at the measurement location, it has to bes reduced to 0 °C and normal gravity in sea level at 45 ° latitude for comparison purposes. Later the height of the mercury column was given in mm Hg and Torr where 1 mm Hg corresponds to 1.332 mbar. On June 1^{st}, 1975 the atmospheric pressure started being expressed in hectopascals (hPa) with 1 hPa equals 1 mbar. (The air pressure data used by Baensch for the analysis of the isobars were not reduced to sea level.)

 https://doi.org/10.18171/1.092106

Results of some investigations by A. Colding on the storm surge in the Baltic Sea from November 12 to 14, 1872 and on the relationships of the winds to the currents and water levels

Translated from German by Ingrid Bork

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Summary

Regarding the cause of the extraordinary high water levels in the Baltic Sea during the storm on November 13, 1872, there are mainly two conceptions. While Baensch (1875) founded the idea of an already overfilled western Baltic met by the storm, Colding (1881) postulated the high water levels as purely wind induced. Because of the still ongoing debate of this issue a translation of an excerpt of Colding's work is given.

Keywords

Baltic Sea, storm surge, 1872 Baltic Sea flood

Zusammenfassung

Zur Ursache der außergewöhnlich hohen Wasserstände in der Ostsee während des Sturms am 13. November 1872 gibt es hauptsächlich zwei Vorstellungen. Während Baensch (1875) die Idee begründete, dass der Sturm auf eine bereits überfüllte westliche Ostsee traf, postulierte Colding (1881) die hohen Wasserstände als rein windbedingt. Wegen der noch heute andauernden Debatte zu diesem Thema wird die Übersetzung eines Auszugs von Coldings Originalarbeit gegeben.

Schlagwörter

Ostsee, Sturmhochwasser, Hochwasserkatastrophe 1872

1 Preface

„Ergebnisse einiger Untersuchungen von A. Colding über die Sturmfluth vom 12. bis 14. November 1872 in der Ostsee und über die Beziehungen der Winde zu den Strömungen und Wasserständen." is an anonymous German summary which appeared in „Annalen der Hydrographie und Maritimen Meteorologie" (10, 1–5, 1882). The original work "Nogle Undersøgelser over Stormen over Nord- og Mellem Europa af 12te–14de November 1872 og over den derved fremkaldte Vandflod i Østersøen. Avec un résumé en Français." was published in Copenhagen in 1881 and is readily available in academic libraries.

 https://doi.org/10.18171/1.087106

While the work of Baensch (1875), presented in its English translation in this issue of "Die Küste", is valued today primarily for its collection of reliable, official data in "digital" form, Codling's paper derives its importance from the physical theories presented therein. Colding laid special emphasis on the experimental confirmation of his physical theories. Therefore, he used all available data on the storm surge of 1872, especially those collected by Baensch, to modify his ideas on sea level response to wind, which Colding had developed in the context of an engineering project. Based on his analyses of air pressure and the derived wind fields, he was able to make an important contribution to the still lasting controversy about the cause of the extreme water levels during the storm surge of 1872.

Ludvig August Colding (1815–1888) was a Danish physicist and engineer.

After an apprenticeship as a carpenter, he enrolled at the Polytechnic Institute in Copenhagen and graduated in mechanics in 1841.

He worked as a teacher before being appointed inspector of roads and bridges in Copenhagen in 1845. Codling's importance and influence grew until he was appointed state engineer for Copenhagen in 1857. He oversaw a vast range of public housing, transport, lighting and sanitation projects and gained a high reputation throughout Denmark and internationally. He retired from professional engineering in 1886.

Besides these projects Colding found time for private scientific work in fluid mechanics, hydrology, oceanography and meteorology as well as electromagnetism and thermodynamics. He was largely responsible for founding the Danish Meteorological Institute in 1872.

In his first scientific paper in 1839 he summarised work on compression and friction of various materials. He is better known as a pioneer of the mechanical theory of heat. In particular, he postulated the law of conservation of energy independent of Joule. His contribution was initially little appreciated, although in 1843 he published his theses in the Notices of the Danish Academy of Sciences.

From 1856 he was a member of the Royal Danish Academy of Sciences and from 1875 also a member of the Royal Swedish Academy of Sciences. In 1871 he became a full professor and Honorary Doctor of the University of Edinburgh, the contemporary centre for natural sciences.

2 Results of some investigations by A. Colding on the storm surge in the Baltic Sea from November 12 to14, 1872 and on the relationships of the winds to the currents and water levels[1].

The Danish engineer Prof. Dr. A. Colding is one of the co-founder of the mechanical theory of heat and the author of several papers promoting the theory of the flow of water and air in the writings of the "Royal Danish Academy of Sciences at Copenhagen", 1870–1876[2]. In the paper cited in note 1, he discussed in detail the results of his own earlier investigations (1858) on the relations of the winds to the current and water level conditions at Copenhagen. In the same direction, he also discussed in detail the numerous reports that he had received about the great storm surge of November 12 to 14, 1872.

We are communicating the following excerpts from the resume attached by Prof. Colding to his paper as an appendix.

In 1858 Prof. Colding, in his capacity as City Engineer of *Copenhagen*, had been commissioned to examine the project of the extension of the harbour of *Copenhagen*[3] southwards by means of a shipping canal to be built along the quays, through the *Kallebo-Strand*[4] and to

 https://doi.org/10.18171/1.087106

open out in the deeper parts of the *Kjöge* Bay[5], preferably with regard to the resulting changes in the masses of pure water flowing into the harbour from *Kjöge* Bay from south to north on the one hand and from the Sound from north to south on the other. For this purpose, Prof. Colding carried out a series of observations on the movements of the water in the harbour of *Copenhagen* and its surroundings at different wind directions from October 18 to November 1, 1858 three times a day, 7 am·, noon and 5 pm, which revealed a decisive influence of the wind on the direction of the current. The wind conditions at that time were very favourable for the above mentioned purpose, as the wind direction as well as the strength were very different and caused characteristic currents and water levels on the coasts concerned.

The places of observation were as follows: In the *Sound* and along the east coast of *Amager* at Fort *Treskroner* and at *Dragör*; on the west coast from *Amager* to *Kongelund*; along the coast of *Zealand*: Customs House at *Copenhagen*, *Gammelholm*, *Langebro*, *Gasanstalt*, *Strandegaard* and *Hudinge-Strand*.

A discussion of these observations, which are originally set out in a table, shows that the easterly winds accumulate the water in *Kjöge* Bay in such a way that the level of the water rises with the direction of the wind from the east coast of *Amager* towards the coast of *Zealand*, and that these winds produce a northward setting current[6] both in the *Sound* and in the harbour of *Copenhagen*. If the wind now turns from east to north, the speed of the current will decrease, while in *Kjöge* Bay the water level follows the turn of the wind and sinks the more the more northerly the wind gets. The westerly winds, on the other hand, drive the water out of *Kjöge* Bay eastwards towards the Swedish coast, so that there is a lower water level on the Zeeland coast and a high water level on the east coast of *Amager;* at the same time these winds cause a southward setting current in the *Sound* and in the harbour of *Copenhagen*.

On the basis of these observations, Prof. Colding sets up the following two sentences for the relationships between the winds, the currents and the water level in the Baltic Sea (see loc. cit. page. 295; Résumé page. 53):

1. "The west winds drive the water of the Baltic Sea towards the coasts of Russia and raise the water level there, while it is lower on the Swedish coasts, south of them, and on the southern coasts of the Baltic Sea and along the Danish islands. This low water level south of Falsterbo in turn causes a current to flow from the Sound to the Baltic Sea. These same westerly winds also drive the water of the North Sea into the Kattegat, at the same time as the water of the Kattegat is forced from the Jutland coast to the Swedish coasts, so that there is a high water level at Elsinore. Taken together, these various effects of the westerly winds provide the conditions for a strong southward current through the Sound."
2. "The east winds exert an opposite effect; they drive the waters of the Kattegat into the North Sea and far away from the Swedish coast; this produces a low water level at Elsinore, and satisfies the condition for a current from south to north through the Sound. On the other hand, the easterly wind accumulates the water of the Baltic Sea on the Danish coasts south of Sweden, and this high water level south of Falsterbo, combined with the low one at Elsinore, consequently produces a comparatively strong north-setting current in the Sound."

The great storm surge of November 13, 1872 gave Prof. Colding reason to check his above-mentioned observations and opinions about the effects of the wind on the currents and the water level with regard to their correctness also for other places on the coasts of the *Baltic Sea*. The terrible and immensely fast propagating inundations on the Danish and German coasts were out of all proportion to the strength of the storm, which was no greater than on other occasions, and this led Prof. Colding to the opinion that the storm surge of November, 1872 was an effect – albeit much greater and far more widespread – of the same cause which he had proved in the vicinity of *Copenhagen* in October 1858.

When Prof. Colding asked various newspapers and authorities in *Denmark* and *Germany* to send him observations and investigations concerning this storm surge, he received 400 communications, the most important of which was the treatise by Mr. Geh. Baurath Baensch: „Die Sturmfluth an den Ostseeküsten des Preußischen Staates vom 12/13. November 1872. 33 pp. folio with 10 copperplates, on behalf of the Ministry of Trade, Commerce and Public Work, Berlin 1875."[7]

From the information obtained from this and from synoptic maps made available to him by the Danish Meteorological Institute in *Copenhagen* on the distribution of air pressure, the direction and strength of the wind in the area from *southern Europe* to *Spitsbergen* and from *America* to the interior of *Russia* in the days from November 12 to 14, 1872, Prof. Colding graphically depicted the water levels, air pressure, wind speed and direction for 274 locations within the above-mentioned areas on 6 plates for the days from November 12 to 14, 1872. Prof. Colding also constructed synoptic charts for *Northern* and *Central Europe* on 8 plates for these three days from 6 to 6 hours, and a chart for November 13, 2 pm., at which time the floods on the Danish coasts reached their maximum.

Prof. Colding summarizes the conclusions drawn from these maps as follows (see ibid, pp. 298–304 resp. 56–62):

"When examining the isobars drawn on these maps, it will be seen from their position that during the storm there was an extraordinary disturbance of equilibrium throughout the atmosphere, which had as a necessary consequence an corresponding tendency of the air masses, to restore the same through large, long-lasting atmospheric currents according to the location of the isobars."

"The motion of these air currents follows, of course, the general laws for currents of fluid bodies, according to which 1) the trajectories of motion are determined by the magnitude and direction of the driving forces; 2) the currents are the more powerful, the greater these forces and the air masses in a state of motion are; 3) the resistance experienced by the movements of these currents close to the surface increases with the unevenness of the latter. This resistance is therefore larger on the continents and islands than on the seas; the atmospheric currents therefore tend to travel preferentially over the seas, where this resistance is a minimum[8]. But even here there is a noticeable friction between the water of the sea and the mass of air sweeping over it; owing to the active force thereby produced, the latter lags behind the water on the surface of the sea, and thereby the surface water is urged forward in the direction of the wind. By the friction of the water molecules against each other, this surface movement of the sea gradually spreads to the lower layers, and if the wind blows steadily from the same direction, the movement of the water particles caused by it will be propagated from the surface to the entire depth of the sea, with a maximum at the surface and a minimum at the bottom[9]. Furthermore, because the surface on which the wind exerts its action is either horizontal or inclined, and because in calm

 https://doi.org/10.18171/1.087106

weather the water is thereafter either at rest or in motion in the direction of the slope, a large number of special currents arise in the seas due to the action of the wind on the surface, as I have proved in "Vidensk. Selbskabs Skrift", 5e series, Vol. 11, No. III, 1876.[10]

"If namely, the wind blows over an immovable sea, which is so limited that the current produced by the wind is hindered in its movement or finds no outlet on the coasts, the force of the wind will damming up the water against the obstacles of its movement in such a way that the surface of the sea then forms an inclined surface, the slope of which is directed opposite to the direction of the wind. Owing to this inclination of the surface, the water is affected in its movement not only by the force of the wind which urges it forward, but also by the gravity which tends to draw it backward; the simultaneous effect of these two forces is expressed in a double current, namely, an upper one in the direction of the prevailing wind, and a lower one in the opposite direction at the bottom of the sea. This latter current, however, is of very low strength. But if the wind persists for a long time, the level rises to a certain height, which for the place in question depends only on the strength of the wind; once that height is reached, the lower stream carries with it at every instant a quantity of water equal to that carried by the upper stream."

"When examining the distribution of air pressure over the whole large area hit by the storm in the period from November 12 to 14, it turns out that at midnight on November 12 the air pressure rose to 780 mm in northern *Sweden* and *Norway*, while in the southern part of the *Baltic Sea* it remained at the mean level of 760 mm, and was below the mean throughout *Central Europe*, with a minimum of 745 mm in the vicinity of *Vienna*. If one connects the centre of the highest with that of the lowest pressure by a straight line, one finds that at this time (midnight of November 12 to 13) this line is directed almost exactly from north to south. In the following 12 hours, up to noon on November 13, the air pressure in northern *Sweden* and in *Norway* was still increasing, and the air masses were moved more and more to the SE; in the southern part of the *Baltic Sea* the air pressure remained approximately at the same mean level of 760 mm, while the minimum of the same propagated without great change in the barometer reading from *Vienna* to the Bohemian border near *Eger* and the line connecting the centres of high and low air pressure was directed from NNE to SSW. Still 12 hours later, at midnight of November 13 to14, the air pressure in northern *Sweden* and in *Norway* was still 780 mm, but the air masses had been pushed even more to the SE; the centre of the lowest pressure had moved from *Eger* to *Amsterdam*, with the air pressure increasing to 750 mm. The line connecting the centres of the highest and lowest air pressure had taken on the direction NE – SW."

"From this it follows in evidence that during the storm the whole atmosphere moved 'with the sun', whereby the high pressure air masses steadily advanced to the SE, while those of low pressure continued to the NW. This rotational movement of the air still continued on November 14 and 15. With this rotation of the air masses of the entire atmosphere during the duration of the storm, the isobars and the wind directions at the same time performed this same rotating movement 'with the sun'.

"Because as a result of this movement the wind direction during the storm turned from NE through east to SE, the wind gradually pushed the water from the *Gulf of Finland* and from the northern parts of the *Baltic Sea* southwards and later more and more towards the German and Danish coasts, where it rose to the extraordinary height just before the wind had turned sufficiently to the SE to give the water a free outlet through the *Sound*, the *Great* and the *Little Belt* and thereby to bring about an end to the flooding."

In order to be able to compare closely the observed actual changes in the water level with those which the storm itself might have produced, Prof. Colding drew on eight larger-scale maps (larger in scale than the eight maps for *Northern and Central Europe* mentioned above) those countries and their coasts, from which he had records of changes in the height of the water level, i.e. along the coasts of the *Baltic Sea* and *Denmark*, and in different colours, the isobars (black), the wind paths (red) with indication of the direction of the moving air masses by arrows with the wind and strength by numbers, finally the heights of the water level (above mean) observed at the respective time in Danish feet at the places indicated by these numbers (blue). From these latter data he further deduced the heights of the water levels for a large number of intermediate points and, by connecting these with the locations of the water levels actually observed on the surface of the seas, he drew the lines of equal water level (blue).

From these three systems of curves Prof. Colding (loc. cit. pp. 301–304 and Résumé. pp. 59–62) derives the following conclusions.

"While the direction of the wind at all places is related to the lines of equal pressure in such a way that the wind paths intersect all isobars at an angle of about 30°, the curves of the water level clearly show a tendency to intersect the wind direction at right angles wherever local conditions permit the sea to be raised by the force of the wind without causing a pressure capable of producing a lateral pressure. But if the local conditions are not such as to force the wind-induced rise of the sea to follow the direction of the wind, while the sea level forms an inclined plane and the water has a lateral outflow, the horizontal curves of the level can no longer intersect the wind direction at right angles because this deviates from the direction in which the ocean current is moving."

"But since, during the storm of November 13, 1872, the horizontal level curves on the surface of the sea tended to perpendicularly intersect the wind direction, where the original, driving forces which had disturbed the balance of the sea water were the only dominant ones, as follows from the eight maps drawn, it turns out at every point of the sea that the resultant of the effective forces which caused the inundation of November 13 had exactly the same direction as the wind. Thereafter, there can be no doubt that the effect of the storm on the surface of the sea alone caused the inundation. But this conclusion can only be regarded as correct if it can be proved that the force which produced the whole series of raises of the sea not only had the same direction as the wind, but also had the same strength.

In the above (note 2c) mentioned treatise "On the effect of the wind on ocean currents" Prof. Colding gave formulae which can also be applied to those currents that are not only caused by gravity, but by gravity in connection with the wind.

If one now with the help of these formulae, which are valid for all points of the coast under consideration, where the level curves of the sea are perpendicular to the direction of the wind, and where, consequently, the water cannot flow off sideways, calculates the height to which the wind, according to its strength and the depth of the water, can raise the surface of the sea, it is found that everywhere this height coincides so closely with that actually observed, that the difference is certainly only due to errors of observation. This remarkable agreement between the elevation of the sea, calculated from the strength of the wind, and that observed during the storm of November 13, 1872, is clear proof that the storm and the path it took must be regarded as the sole cause of the flood of November 13.[11]"

 https://doi.org/10.18171/1.087106

Finally, Prof. Colding, using the formulae developed in the above-mentioned treatise, drew up a series of profiles of the water levels from one coast to the other, showing the rise and fall of the water which took place during the storm in the time between one observation and the other.

"By means of these formulae one can on the one hand calculate the amount of water which, at a given point in time, flows into the *Kattegat* through the *Sound* , the *Great* and the *Little Belt*, and on the other hand, by determining at the same time how much the sea level rises from one moment in time to the next over an area of known size, one can derive that amount of water that accumulates from second to second below the rising level in the *Sound* and the *Belts* during the period considered."

In carrying out these investigations for the time of the storm and floods of November 12 to 14, 1872, Colding finally found that for all places from which he had received records of the water level, the calculation of the water movement was in complete agreement with the observation.

3 Acknowledgement

The translation was made, taking into account suggestions from translators Google and DeepL. Colding's CV is based on information given by the Dänish and English Wikipedia.

I especially thank Jürgen Jensen and Gudrun Rosenhagen for their support and for checking the translation.

4 Notes

1 Report and excerpt from the treatise by Prof. Dr. A. Colding, City Engineer in Copenhagen: "*Nogle Undersögelser over Stormen over Nord- og Mellem-Europa af 12 te –14de November 1872 og over derved fremkaldte Vanflod i Östersöen. Med 23 Planen and Kort. (Avec un résumé en français). Kjöbenhav.1881. Copy from "Vidensk. Selsk. SKr. 6. R., naturvidensk, og mathem.. Afd* .", Vol. I, 4, pp. 247–304.

2 These treatises are:
a. Strömungsforholdene i almindelige Ledninger og i Havet, med 3 Tavler (1870);
b. Lovene for Vandet's Bevägelse i Jorden, med 2 Tavler (1872);
c. Fremstilling af Resultarterne af nogle Undersöglerser over de ved Vindenskraft fremkaldte Ströminger i Havet (1876).

3 See „Segelhandb. f. d. Ostsee", I, pp. 211–215.

4 Ibid. page 227.

5 Ibid. page 228.

6 About the currents in the Baltic Sea see „Segelhandb. f. d. Ostsee", part I, chap. II, pp. 50–61.

7 This treatise, based on a wealth of official material, gives a very detailed presentation (in text, tables and plates) of the overall course of this phenomenon and its consequences for the beach districts of the German coast of the Baltic Sea and the buildings located within them.

8 Cf. on this the remarkable treatise by S. M. Guldberg and H. Mohn in Christiania: „Ueber die gleichförmige Bewegung der horizontalen Luftströme" in the Austrian journal f. Meteor., 1877, pp. 49–60. Note of referee.

9 Cf. the essays by Prof. K. Zöppritz: „Zur Theorie der Meeresströmungen" in these Annals, 1878, pp. 239–243 and 1879, pp. 155–159. Note of referee.

10 See note 2 – sub c.

11 The abnormal height of the storm surge may also have been caused by the inflow of water from the *North Sea* through the *Sound* etc. into the *Baltic Sea* under strong SW storms (from November 1 to 9) shortly before it, which dammed up the water in the latter towards the east and raised its level. The return current generated by the east storm thus had to bring back all the more powerful water masses to the southern and western coasts of the *Baltic Sea* and produce higher water levels on these.
Geh. Baurath Baensch divides in the above mentioned treatise (page 21) the development of the enormous swell of water on the west side of the Baltic Sea basin into three periods: 1) from October 31 to November 9, 1872: Filling of the Baltic Sea with North Sea water and closure of the "Vorfluth"; 2) from November 9 to 12 in the evening: swinging out of the Baltic Sea water to the west with the basin overfilled; 3) on November 13: impact of the northeast hurricane-force wind on the western part of the Baltic Sea, the level of which had already reached a significant height due to the earlier supply of North Sea water. Note of referee.

5 References

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The 1872 super-storm surge in the Baltic – the Danish perspective

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Summary

The super-storm surge (water levels above 3m) that hit the Danish and German coastlines in the western Baltic Sea on November 13, 1872, is the worst natural disaster in modern Danish history.
The meteorological and oceanographic causes for this extreme event have been analysed using the relatively few observations from November 1872 combined with re-analysis outputs from modern operational forecasting models. Key findings for the days November 11-14, 1872, are:

- The Baltic Sea was exposed to north-easterly storm to hurricane force winds
- The extreme water levels were solely wind generated.
- Theories of backwash of water from eastern Baltic or higher than normal water level in the Baltic Sea is refuted. The extraordinary water levels on 13 November 1872 can most likely be attributed to the length of the storm/hurricane.
- The western Baltic Sea, in particular the Arkona Basin area, was exposed to 8-10 m waves.

The combination of a super-storm surge and extreme waves caused severe damage along the Danish Baltic Sea coastlines. Around 90 people drowned in the Danish coastal areas, especially in the flat southern parts of the two islands of Lolland and Falster. Houses and local infrastructure were destroyed leaving thousands homeless the following winter. Additionally, an unknown number of sailors drowned when several hundred sailing ships shipwrecked during the storm. A nationwide collection of money to help the many victims was initiated and successfully implemented.
Super-storm surges will inevitably hit the Baltic Sea again. A detailed high-water statistics, including historical surge registrations, reveal a return period of around 300 years for a 1872 size super-storm surge.
In preparing for the next super-storm surge, it is, however, important to consider the sea level rise due to climate change. According to national authorities, the sea level in the Danish waters will rise around 0.5 m before 2100.

Keywords

Baltic Sea, Super-storm surge, L.A. Colding, hurricane, ocean models, waves, destruction, economic help, return period, sea level rise

Zusammenfassung

Die Supersturmflut mit Wasserständen von über 3 m über Mittelwasserstand, die am 13. November 1872 die dänischen und deutschen Küsten in der westlichen Ostsee traf, ist die verhängnisvollste Naturkatastrophe in der modernen dänischen Geschichte.
Die meteorologischen und ozeanographischen Ursachen für dieses Extremereignis wurden anhand der relativ wenigen Beobachtungen vom November 1872 in Kombination mit Re-Analysen moderner operationeller Vorhersagemodelle analysiert. Die wichtigsten Ergebnisse für die Tage vom 11. bis 14. November 1872 sind:

- *Die Ostsee war nordöstlichen Stürmen mit Orkanstärke ausgesetzt.*
- *Die extremen Wasserstände wurden ausschließlich durch Wind verursacht.*
- *Theorien über einen Rückschwapp-Effekt von angestauten bzw. hohen Wasserständen aus der östlichen Ostsee sind widerlegt.*
- *Die außergewöhnlichen Wasserstände am 13. November 1872 sind höchstwahrscheinlich auf die Dauer des Sturms zurückzuführen.*
- *Die westliche Ostsee, insbesondere das Gebiet des Arkonabeckens, war 8-10 m hohen Windwellen ausgesetzt.*

Die Kombination aus einer Supersturmflut und extremen Windwellen verursachte schwere Schäden an den dänischen Ostseeküsten. Rund 90 Menschen ertranken in den dänischen Küstengebieten, insbesondere in den flachen südlichen Teilen der beiden Inseln Lolland und Falster. Häuser und die örtliche Infrastruktur wurden zerstört, so dass Tausende im folgenden Winter obdachlos wurden. Außerdem ertrank eine unbekannte Zahl von Seeleuten, als mehrere hundert Segelschiffe während des Sturms Schiffbruch erlitten. Ein landesweiter Spendenaufruf zur Unterstützung der vielen Opfer wurde danach initiiert und sehr erfolgreich durchgeführt.
Extreme Sturmfluten werden die Ostsee unweigerlich wieder heimsuchen. Eine detaillierte Hochwasserstatistik, einschließlich historischer Sturmflutregistrierungen, zeigt eine Wiederkehrperiode von etwa 300 Jahren für eine Sturmflut der Größenordnung von 1872.
Bei der Vorbereitung auf die nächste extreme Sturmflut muss jedoch auch der Anstieg des Meeresspiegels infolge des Klimawandels berücksichtigt werden. Nach Angaben der nationalen Behörden wird der Meeresspiegel in den dänischen Gewässern bis zum Jahr 2100 um etwa 0,5 m ansteigen.

Schlagwörter

Supersturmflut, Ostsee, L.A. Colding, Hurrikan, Ozeanmodelle, Wellen, Zerstörung, wirtschaftliche Hilfe, Wiederkehrperiode, Meeresspiegelanstieg

1 Introduction

The storm surge on November 13, 1872, was the worst natural disaster in Denmark during the past 2–300 years. Approximately 90 people drowned, and thousands were without a home the following winter. More than 250 ships grounded or wrecked along the Danish coasts, and nearly 200 sailors drowned. Especially the very flat southern parts of the two islands, Lolland and Falster, were severely damaged.

The present article summarizes information on the 1872 storm surge that was recently published in a book (in Danish) by the two authors (Aakjær and Buch 2022 – in the

 https://doi.org/10.18171/1.092104

following called AaB22). Here we discuss the newly-made reconstructions of the weather, water levels and waves, as well as evidence from contemporary eyewitness accounts. It will appear that the two sources of information, although 150 years apart, support each other well.

Storm surges in the Baltic were not unknown to the local population in 1872. The low-lying areas were protected by dikes that were large enough to protect against a normal storm surge. However, the unprecedented hurricane wind force, water levels around 3 m and up to 10 m waves took everybody by surprise. The existing dikes were inadequate and were quickly broken down by the storm surge, and large areas were flooded.

In AaB22, the term super-storm surge is introduced based on the following arguments:

- The official Danish definition of a storm surge is a water level with a return period of 20 years or more.
- For most Danish water level stations in the Baltic Sea, this criterion corresponds to a water level of about 1.5 m.
- A super-storm surge is defined as a storm surge with a maximum water level twice the operational storm surge criterion, i.e., 3 m or higher.

The definition makes the 1872 storm surge a super-storm surge, and historic records display only very few super-storm surges in the Baltic Sea in the past.

2 Ludvig August Colding – a Danish scientist and water engineer

An operational network of weather or water level stations did not exist in Denmark in 1872. The Danish Meteorological Institute (DMI) was founded in April 1872 with only four employees. So by November 1872, the institute had not been able to implement an operational observation network nor to issue weather forecasts or warnings of storms and storm surges.

Still, due to the initiative and hard work of Ludvig August Colding (1815–1888), there is an extensive database of basic meteorological parameters and water level observations in the Danish region from the days around November 13, 1872. Colding was a Danish scientist and hydraulic engineer. He worked most of his life as a chief engineer in Copenhagen, where he introduced running water and gas as well as an efficient sewer system in the 1850s and 1860s. Until then, Copenhagen was a crowded, dirty, and unhealthy city with several cholera epidemics.

Figure 1: Ludvig August Colding (1815–1888). From Wikipedia.

 https://doi.org/10.18171/1.092104

Besides his practical skills, Colding also performed several more theoretical studies on energy conservation, tropical cyclones, and water flow. Colding saw the storm surge as a great opportunity to test the theories he had developed in the 1850s from flow measurements in the harbour of Copenhagen for a larger basin. He announced an invitation in all Danish newspapers to send him observations of air pressure, wind, temperature, and water level. Luckily, he received hundreds of replies, which made it possible for him to write a thesis on his observations and other findings from the 1872 storm surge (Colding 1881).

In addition to the collection of observational data, he did pioneering theoretical work. In his thesis from 1881, he showed that the water level above the mean sea level, H, was related to the square of the wind velocity, V, the wind fetch, d, and the inverse of the water depth, D,

$$H = const \times V^2 \times \frac{d}{D} \tag{1}$$

This means high winds and shallow water give rise to high water levels. He also found that the entire Baltic Sea was influenced by the 1872 storm surge, with water levels above 3 m in the western part of the Baltic and 1 m below normal in the eastern part. Finally, he showed that a line from Stockholm in Sweden to Pillau in Kaliningrad was not affected by the storm surge. Thus, he discovered the nodal line for the Baltic Sea seiche.

3 A hurricane from the northeast

Based on Colding's work and data from many other sources, Rosenhagen and Bork (2009) produced a comprehensive analysis of the sea surface pressure and surface winds for the period November 1 to 14, 1872.

The wind analysis shows hurricane winds 32–33 m/s just east of the island of Falster, when the wind culminated at 06 UTC on November 13 (Figure 2). It is remarkable how persistent the storm/hurricane was both in time and space. East of Falster, the hurricane winds lasted for 9 hours, and the area was subject to storm conditions for almost 24 hours.

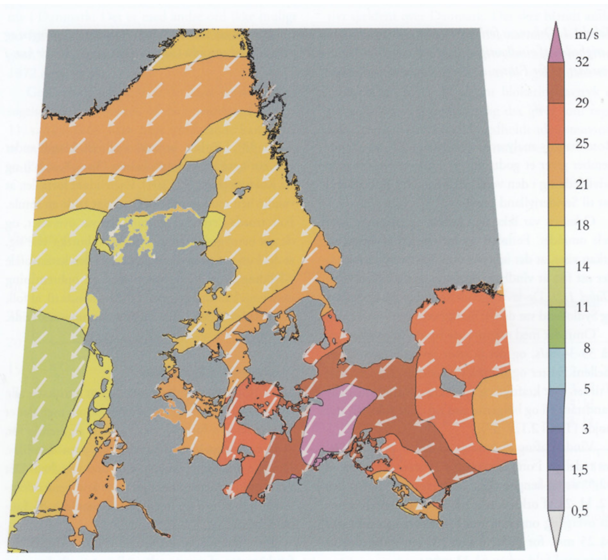

Figure 2: Wind speeds at 06 UTC in the morning of November 13. Hurricane winds are seen east of the island of Falster. From AaB22.

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The time evolution of the wind speeds in a cross-section along the 55°N is displayed in Figure 3. It is seen that the centre of the storm/hurricane was stationary for almost 24 hours, which is very unusual for a strong low-pressure system. This made it possible for the water levels and waves to develop over a long time and reach the very high levels shown in the next chapter.

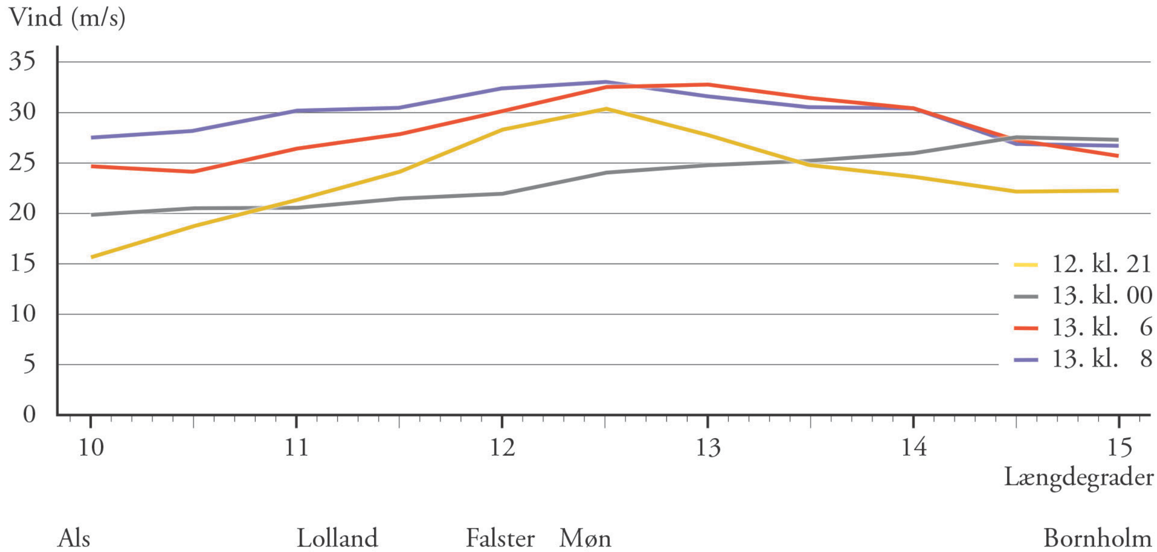

Figure 3: Development of the wind speed along 55°N. From AaB22. Yellow: 21 UTC November 12. Green: 00 UTC November 13. Orange: 06 UTC November 13. Red: 08 UTC November 13.

Additionally, Figure 3 shows that the storm/hurricane had two phases. The north-easterly winds increased during November 12, and at 21 UTC, it reached almost a hurricane force of 31 m/s east of Falster (yellow curve). From 21 UTC until midnight, the winds decreased to a storm force of 25 m/s (green curve), but just 6 hours later, the winds reached their maximum force of full hurricane 32–33 m/s (orange curve).

4 Storm surge and waves

In Denmark, an operational network of water level stations was not initiated until 1884. In November 1872, the water level observations were taken by local harbour authorities using a simple staff gauge. The quality of these observations can naturally be questioned since no national reference level existed, and the water level board was extremely difficult to read under the severe weather conditions around November 13, 1872. Nevertheless, they represent the best available water level information from that time. Colding (1881) collected water level observations from around 140 locations in Denmark for the period November 12–14, 1872. The maximum water level for selected localities is displayed in Figure 4.

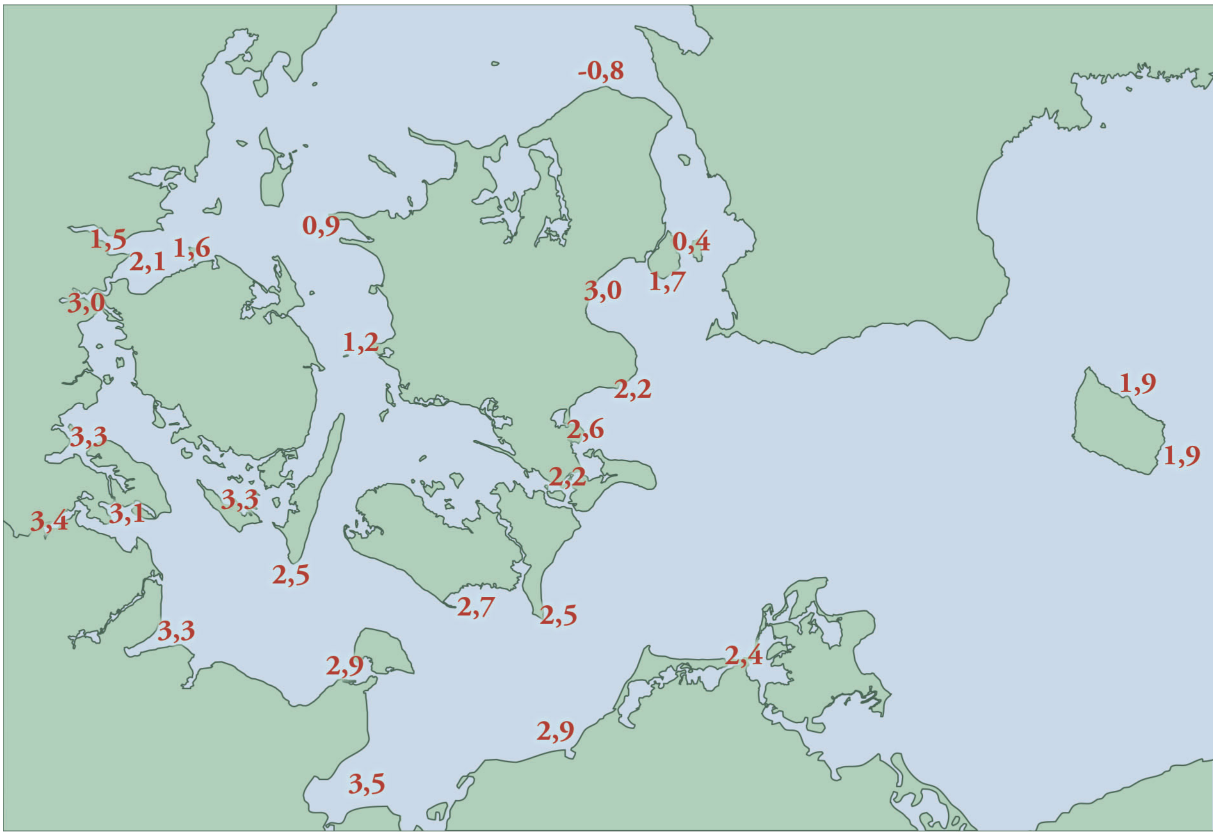

Figure 4: Maximum water levels (m) in the western Baltic on November 13, 1872. From AaB22.

The maximum water levels range from 1.9 m on the island of Bornholm to 3.3 m along the southeast coast of Jutland. This makes the November 1872 storm surge one of the worst storm surges ever to hit the Danish Baltic coastline.

The Danish Meteorological Institute (DMI) has analyzed the extraordinarily high water levels by running their operational storm surge model forced with meteorological fields based on the surface pressure analysis by Rosenhagen and Bork (2009) (DMI 2022a). A couple of examples of the model simulation results are shown in Figure 5.

The highlights of the model simulations are:

- The water level in the western Baltic started to rise already around midnight between November 11 and 12, 1872. On the evening of November 12, the water levels reached the storm surge criterion of 1.5 m, and it lasted until the morning of November 14.
- The time of maximum water level moved from east to west. The high water peaked November 13 in the morning at Bornholm, around noon at eastern Zealand and Falster, and in the early evening at South Jutland.
- The good agreement between the model output and the observed water levels confirms that the storm surge was entirely wind-generated. The main reason for extreme water levels can be attributed to the fact that the atmospheric pressure systems generating the north-easterly storm and hurricane were relatively stationary for an unusually long period ranging from November 11 to 14, 1872.

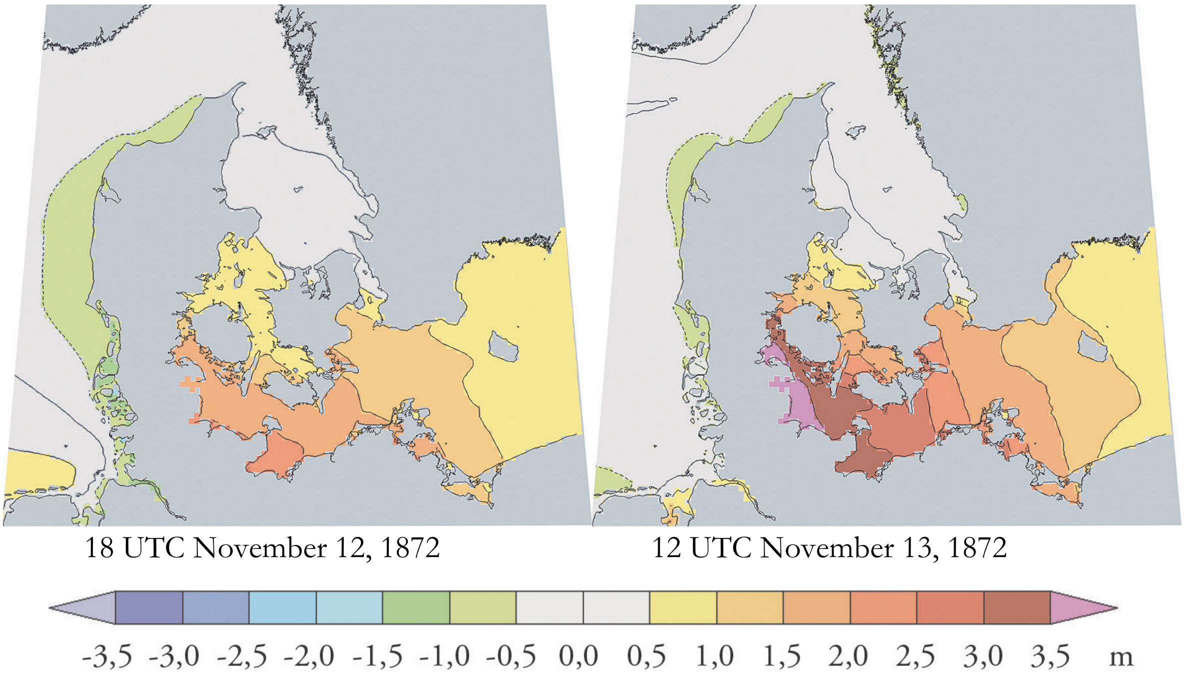

Figure 5: Model simulated water level distribution in the western Baltic Sea on 18 UTC November 12, 1872, and 12 UTC November 13, 1872. From AaB22.

A small but vital detail in the development of the storm surge is reflected in evidence from contemporary eyewitness accounts following the storm surge. According to these reports, local people noted that around 21 UTC on November 12, 1872, the wind and the water level started to weaken. They took this as a sign that the worst part of the storm and the surge was over. They went reassured to bed just to wake up a few hours later to discover that the wind and water levels were increasing fast. This temporary weakening of the storm surge is well reflected in the model simulations, see Figure 3 and 6.

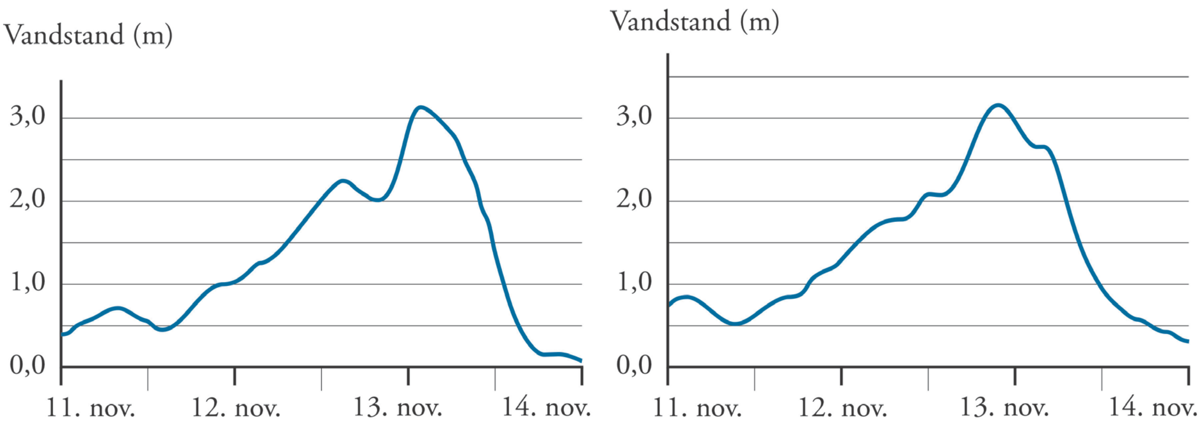

Figure 6: Model simulation of the water level development between 12 UTC November 11 to 12 UTC November 14 at two localities A: Gedser, B: Kolding. From AaB22.

The wave field in the western Baltic during the November 1872 hurricane has been calculated using DMI's operational wave model (DMI 2022a). Ocean waves of 8–10 m dominated the Arkona Basin area, see Figure 7. These extreme waves, on top of a 2–3 m water level, caused severe damage along all the coastlines in the region. In northern Bornholm, the harbours of Allinge and Svaneke were destroyed, and along the southeast coast of Falster, the dikes and houses were completely wiped out.

Additionally, the hurricane winds and high waves were disastrous to the ship traffic in the western Baltic, which in 1872 was primarily composed of sailing ships. A study by Ejdorf (2002) revealed that more than 250 ships grounded or wrecked along the Danish Baltic coastline on November 13, 1872, and nearly 200 sailors lost their lives.

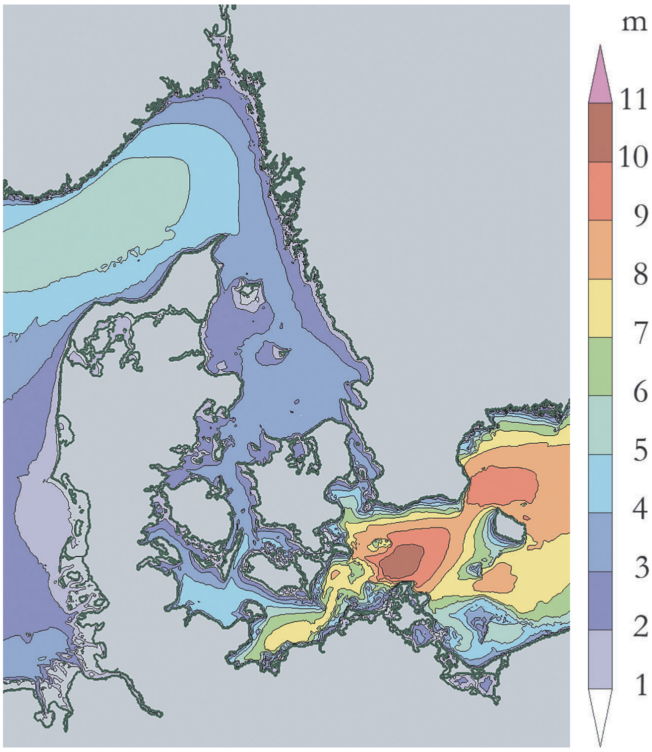

Figure 7: Wave heights in the western Baltic Sea 09 UTC November 13, 1872. From AaB22.

5 Damages and help

The damages along the Danish coasts have been described in detail in AaB22. This chapter will give some examples of the most serious damage to the coasts, buildings, and people. It will also describe the incredible help to the victims both from the local population and from people all over Denmark.

5.1 The Island of Falster

The storm surge made a very large impact on the two lowland islands, Lolland and Falster. 80 people drowned here and many hundreds or thousands were homeless in the following winter.

In 1872 the two islands looked very different from today. The southern part of Falster at that time is displayed in Figure 8A. The area was dominated by an open sea area, Bøtø Nor, with the low-level barrier, Bøtø, to the east, mainly composed of sand, and only inhabited by 120 people. The people in Falster were used to storm surges. High water levels happened almost yearly but were normally not much higher than 1.5 m. The dikes toward the Baltic Sea were built to protect them against this type of frequent flooding, but against a super-storm surge, they didn't stand a chance. In this area, the storm, water levels and waves were at a maximum. In combination with the low-lying landscape and the insufficient

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dikes, Bøtø was completely flooded (Figure 8B), and 26 out of the 120 inhabitants drowned under circumstances that are described in the many heart-breaking eyewitness reports.

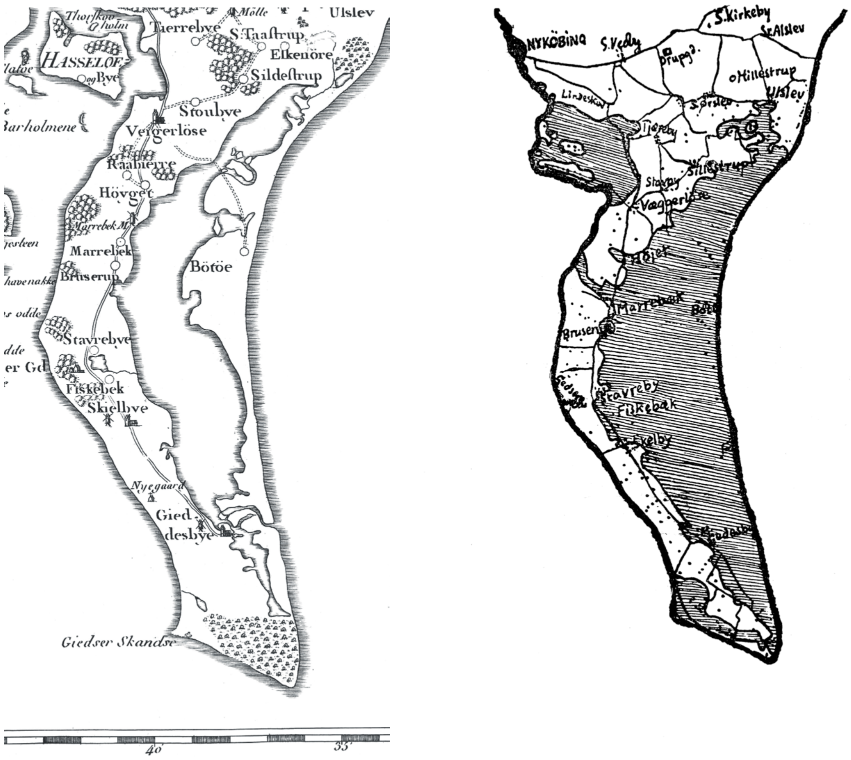

Figure 8: A, left: Map of southern Falster from 1776. In 1872 the landscape looked about the same with open water, Bøtø Nor, in the middle. B, right: Map of the large, flooded areas in November 1872. From AaB22.

Most of the houses in the flooded areas were of poor quality, half-timbered with clay walls. These types of houses have been used in Denmark since the stone age. They can easily persist heavy rains, but the clay walls will disintegrate quickly during a flood and render no real protection against the fierce weather. Many houses were broken down by the water, and people tried to survive by climbing the thatched roofs and hoping for the best. Figure 9 shows such a house that survived the flooding.

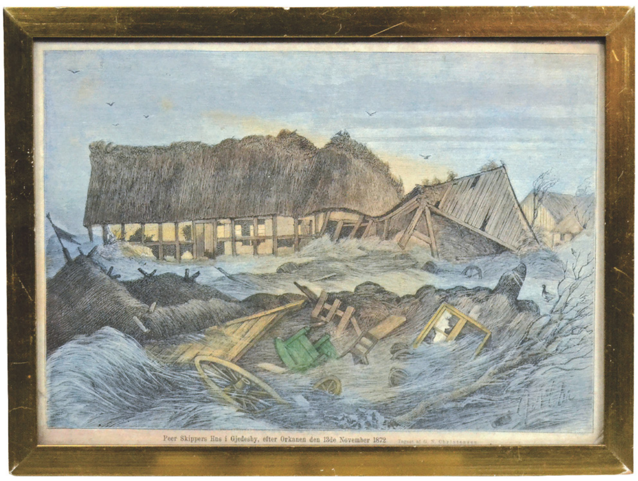

Figure 9: Coloured drawing of Per Skippers house in Gedesby close to the southern tip of Falster. From Museum Lolland-Falster.

5.2 The island of Bornholm

Bornholm is situated isolated from the rest of Denmark in the Baltic Sea. Unlike the rest of Denmark, Bornholm rises steeply from the seashore, and as such, Bornholm is not the most potentially flood-prone part of Denmark. There exist, however, some unique photographs from Allinge and Sandvig on the northern tip of Bornholm showing the devastating powers of the 1872 super-storm surge (Figure 10).


Figure 10: Two outstanding photographs from Bornholm the day after the storm surge by the local photographer Gottlieb Støckel. A, left: The schooner Robert was thrown up on the quay in Allinge. The bow thruster went through one of the windows of a house along the quay and broke off. B, right: The British brig Caledonia stranded near Sandvig. Caledonia was thrown far up on the rocks and broke into two parts. From Museum Bornholm.

The maximum water levels on Bornholm were around 1.9 m above normal. From Figure 10, it is obvious that a flood of 1.9 m is not able on its own to lift the heavy ships as it is seen in the photographs. However, as seen in Figure 7, the waves were up to 10 m just off the northern tip of Bornholm near Allinge and Sandvig. It is therefore likely that the combined effect of 1.9 m water levels and up to 10 m waves was the reason for the devastating destruction of the harbours of Allinge and Svaneke on the north coast of Bornholm.

5.3 The storm surge heroes

Several rescue actions did successfully save people from drowning during the super-storm surge. Many of them were described in detail in the newspapers, and the stories went around Denmark. In April 1873, the stories also reached the Danish king's ear, and he gave 41 of these hero's honours, mostly in terms of medals of honourable rescue at sea. Two examples of the most spectacular actions are illustrated in Figure 11.

On the east coast of Zealand, the three-masted Norwegian bark, Atlas, was stranded at the foot of the 40 m high cliffs of Stevns (Figure 11A). The local people, who gathered on top of the cliff, saw the crew fight for its life in the 6–8 m waves. After a while, the 40-year-old farmer, Niels Andersen cried out: *"This is no time for talking, we need to act!"* He and a few others got a robe around the waist, and they miraculously succeeded in saving 12 sailors up the ladders of the 40 m high cliffs in the extremely fierce weather.

The iconic drawing from Falster displaying the rescue action made by the two brothers Olsen is seen in Figure 11B. They rowed in a small boat against the storm and high waves to get to a farm, Nørrevang on Bøtø, where 22 people were stranded in the attic. After the super-storm surge broke the insufficient dikes, Nørrevang was flooded, and only the roof could be seen in the waves. Nørrevang was at the time in a better state than the surrounding farms and houses, so people had gathered in the attic of Nørrevang to save their lives. The two brothers succeeded in reaching the farm, but due the fierce weather conditions they had to wait until the storm had ceased a little before they could row the 22 stranded people in security. The brothers and three other persons, who did a similar rescue action got medals for their heroic actions from the Danish king in April 1873.

Figure 11: A, left: Postcard from the 1920'es showing the 40 m high cliffs of Stevns with the ladders the locals used to get access to the sea. Archive for Local History, Stevns. B, right: An artist's impression of the terrifying situation in southern Falster during the storm surge. It shows the action of the two brothers Olsen, who rescued 22 stranded people in a rowboat from the attic of a flooded farmhouse. From Museum Lolland-Falster.

5.4 The economic help

The many stories on the injuries and tragic fates of the storm surge victims in Danish newspapers made a great impression in Denmark. A nationwide collection of money to help the victims started. The big job of collecting the money and distributing them to the neediest was placed into the hands of a private organization in Copenhagen called the Central Committee. They asked the local authorities to list every loss, person by person, together with their economic situation. The Central Committee would only give help to the poor people and not to the richer.

On the other hand, the Danish government refused to give any financial help, so the victims of the storm surge were left to get help from family, neighbours, or the Central Committee in Copenhagen. During November and December 1872, the Committee collected more than 1 million rigsdaler, which compares to more than 250 million Euros in today's money. Almost one third of this money was given to the heavily damaged areas in Lolland and Falster.

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5.5 Building 80 km of new dikes

After the flood, the lowlands of Lolland and Falster were completely open to the sea, and a new even minor storm surge. The Danish government quickly sent several hundred soldiers to build temporary protection. It was, however, soon realized that the task of building new dikes that could protect the low areas from a super-storm surge like the one in 1872, was not possible to undertake locally. In May 1873, a law for building new and much higher dikes, therefore, was passed in the Danish Parliament.

Many discussions went into deciding on the new dikes. In Falster, it was straightforward to place the new 17 km dike along the eastern coastal line to a height of 4 m. In Lolland, however, it was after long discussions finally decided to place the new dikes as far out in the Baltic Sea as possible, making it possible to dam large shallow fjords and lakes. This led over the years to much new farmland. The large dike in Lolland was built to a height of 4 m along a 63 km coastline. The construction was all done by hand and took several years to build.

6 A new super-storm surge in a changing climate

Storm surges and flooding in the western Baltic Sea happen occasionally. However, the long timeseries of water level observations from Travemünde (Rosenhagen and Bork 2009) shows that the November 1872 storm surge is the most severe event and the only super-storm surge that has occurred in the area since the observations started in 1826. It was nearly 1 meter higher than the second most severe storm surge in 1904.

It seems inevitable that a super-storm surge will hit the western Baltic Sea again in the future. From a planning and disaster prevention perspective, it is of interest to know when this will happen. This question is impossible to answer, but it is possible to calculate the frequency of such an event through high water statistics.

The official Danish high water statistics are prepared by the Danish Coastal Authority at regular intervals and are based on water level observations of well-documented quality. The statistics are unfortunately biased by the fact that the first ten Danish water level stations were established between 1884–1893. The 1872 super-storm surge and other previous extreme surges are therefore not included in the statistic. This makes it impossible to calculate a proper value for the return period of an 1872-size storm surge.

The Danish consulting company COWI has, on behalf of the local authorities in Køge, proposed to overcome this by establishing a water level time series as far back in time as possible. The modern measurements were supplemented with water level information subtracted from historic accounts, knowing that the quality of these data is undocumented and, therefore, to some degree questionable.

The data for Køge (see Figure 12) was divided into four categories:

1. 1955 to 2017, observed data
2. 1825 to 1955, eyewitness accounts quality assured up against measured water levels from Travemünde and after 1891 also data from Gedser
3. 1500-1824, eyewitness accounts from Køge, southern Danish Baltic Sea and Germany. The period was characterized by the availability of print media
4. 1044 to 1499, eyewitness accounts – all in handwritten reports

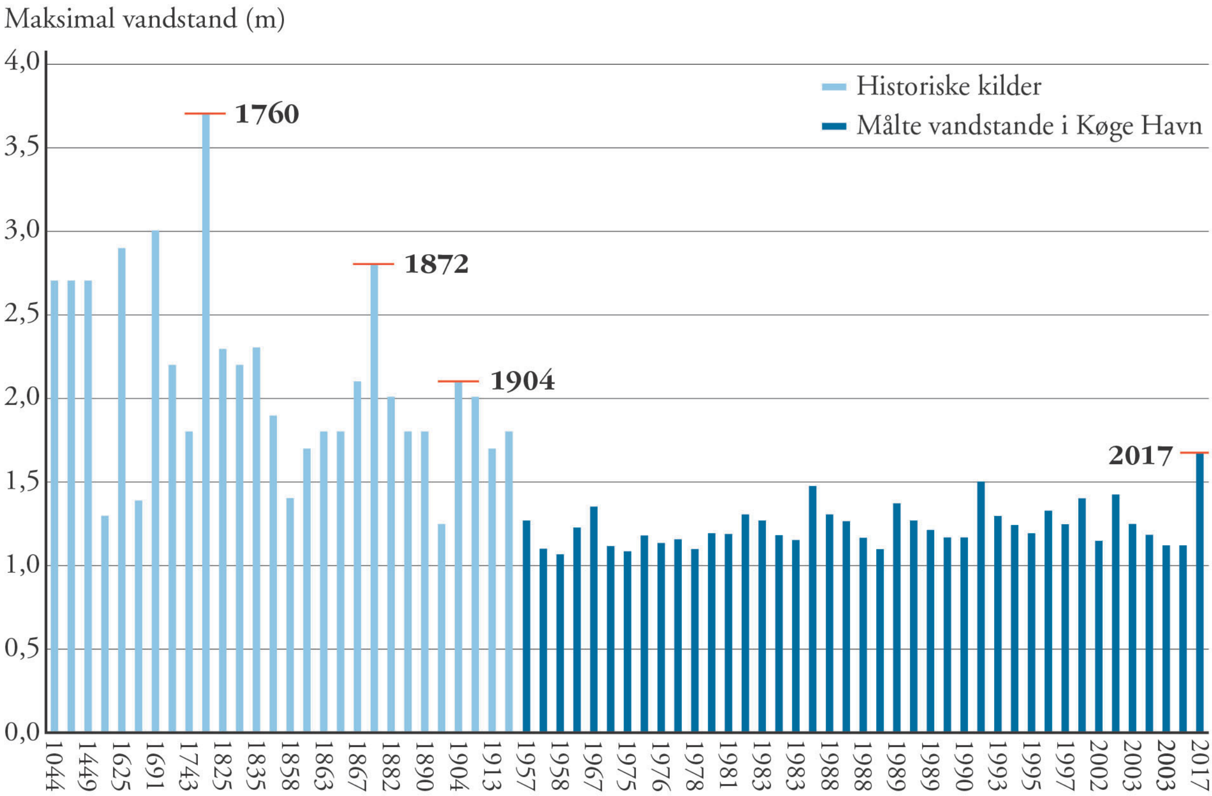

Figure 12: Maximum water levels in Køge the last approximately 1000 years, Dark blue columns = observed data, light blue columns = historical eyewitness accounts. From COWI (2016) and Køge Kommune (2018).

It is seen that historically there has been other super-storm surges than the one in 1872, especially the ones in 1625 and 1760 are relatively well-documented by eyewitness accounts.

Based on these data, COWI (2016) has prepared high water statistics for Køge as an alternative to the official one (see Figure 13). These statistics can be regarded as representative of most localities along the Danish Baltic Sea coastline. According to the alternative statistics, the return period for an 1872 size super-storm surge is around 300 years.

This value for the return period in Køge is smaller than the return period of 500–1000 years calculated for Travemünde in Jensen et al. (2022). The main difference in the two historical time series of water levels in the two statistical analyses is the inclusion of the storm surge in 1760, which hit the Danish east coasts. The 1760 storm surge is not reported in German files (Jensen et al. 2022), which might be because it was reported as an easterly storm which primarily affected the Danish coasts.

A future super-storm surge in the western Baltic Sea will undoubtedly cause damage on the vulnerable coastlines but not in the same order as in 1872 since:

- Parts of the coastline are well protected by dikes built after the 1872 storm surge.
- Houses and coastal infrastructures are built more solidly.
- Today there are weather and storm surge forecasts that well in advance can be communicated to authorities and the public allowing for preparedness actions to be initiated and implemented.

Severe damage must however be expected since many coastlines are still not well protected and many new houses, hotels etc. have been build close to the coastline in recent years.

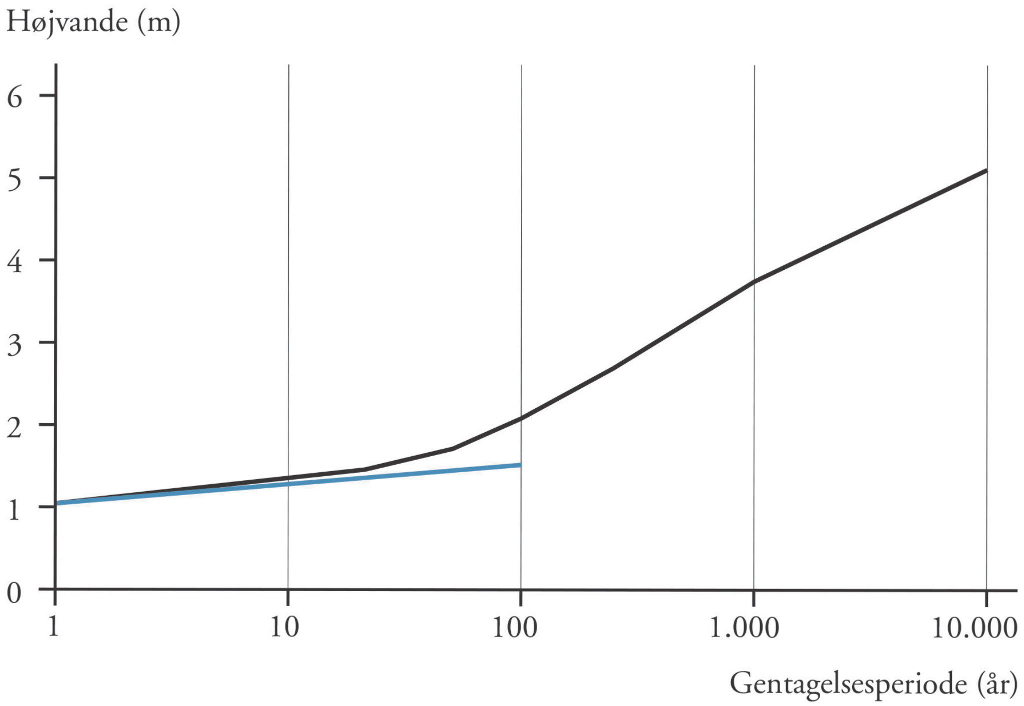

Figure 13: High water statistic for the city of Køge. Light blue curve = official statistic. Dark curve = alternative statistic including historical data. From COWI (2016).

In preparing for the next Baltic super-storm surge, an additional dimension must be added to the planning, i.e., sea level rises due to climate change. The Intergovernmental Panel on Climate Change (IPCC) settled in the first part of its sixth assessment (IPCC 2021) that the earth has warmed with approx. 1.1 °C compared to the mean temperature for the period 1850–1900. The IPCC further predicts that the temperature is likely to increase by 2.5–4.0 °C before the year 2100. This is significantly above the goal articulated in the Paris Agreement in 2015: *"Limit the global heating to well below 2 °C, preferably to 1.5 °C compared to pre-industrial levels"*.

Global heating means sea level rise in the world ocean due to the expansion sea water due to heating and melting of glaciers and the Greenland and Antarctic icecaps. IPCC (2021) predicts the global sea level to rise between 0.3–1.0 m before 2100. The actual rise will strongly depend on how effectively the international society manages to reduce carbon dioxide emissions.

Atmospheric and ocean circulation will be altered due to climate change and land masses will sink or rise, which effects regional differences in the sea level rise. DMI (2022b) has estimated that the sea level in Danish waters will rise around 0.5 m before the end of the present century. In practise, this means that a super-storm surge in 2100 will be 3.5 m above the present mean sea level, or 0.5 m higher than in 1872. This is important to consider when planning storm surge prevention initiatives.

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The 1872 catastrophic storm surge at the Baltic Sea coast of Schleswig-Holstein; lessons learned?

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Summary

November 13, 2022 marks the 150th anniversary of the most severe storm surge to date along the Baltic Sea coast of the German Federal State of Schleswig-Holstein. Thirty-one people died in the floods and about 15,000 became homeless. It was the last storm surge in Schleswig-Holstein, in which human lives were lost. Given this and in the face of strongly increasing mean and extreme sea levels in future, the 1872 storm surge constitutes an admonition or rather a plea for sustainable coastal flood risk management.
Along the Baltic Sea coast of Schleswig-Holstein, peak water levels of the 1872 storm surge probably varied among about NHN +2.4 and +3.4 meter. The highest local wind speeds and waves occurred four to 10 hours earlier than peak water levels in Schleswig-Holstein. The unprecedented height of the 1872 storm surge in Schleswig-Holstein resulted from an external surge that propagated into the area from the central Baltic Sea region and piled up here on top of already prevailing very high storm surge water levels. The 1872 storm surge represents a singular event in Schleswig-Holstein, which makes it scientifically challenging to assess its probability of occurrence. Present-day coastal flood defense, spatial planning and disaster management, as cornerstones of public coastal flood risk management in Schleswig-Holstein, generally and in combination consider the lessons learned after the 1872 flood calamity. In the light of intensifying utilizations, the need to improve the status of the environment and with regard to stronger rising sea levels in future, implementing sustainable coastal flood risk management remains a challenge.

Keywords

Schleswig-Holstein, Baltic Sea, storm surge, flood catastrophe 1872, coastal flood defense

Zusammenfassung

Am 13. November 2022 jährt sich zum 150sten Mal die bisher schwerste Katastrophenflut in der westlichen Ostsee, bei der allein in Schleswig-Holstein 31 Menschen umkamen und etwa 15.000 obdachlos wurden. Es war das letzte Sturmflutereignis in Schleswig-Holstein, bei dem Menschenleben zu beklagen waren. Aus diesem Grund und vor dem Hintergrund stark steigender mittlerer und Extremwasserstände in der Zukunft, stellt diese Flutkatastrophe eine Mahnung und einen Appell für ein nachhaltiges Management von Hochwasserrisiken an den Küsten dar.

Diese Abhandlung beginnt mit einer Beschreibung der Sturmflut des Jahres 1872 und ihrer Folgen in Schleswig-Holstein. Der Fokus liegt dabei auf den besonders betroffenen Orten Dahme und Eckernförde. Anschließend wird dargestellt, wie die während der Sturmflut gewonnenen Erkenntnisse in den Jahrzehnten nach der Sturmflut und heute in der Planung und Umsetzung von Küstenschutzmaßnahmen und des Hochwasserrisikomanagements generell umgesetzt wurden und werden. Nach einer Ausarbeitung der Komponenten des integrierten Hochwasserrisikomanagements wird die Abhandlung mit einer Diskussion über die Lehren aus der Sturmflut fortgesetzt. Sie endet mit den nachfolgenden Schlussfolgerungen.
Die Sturmflut von 1872 erreichte an der Ostseeküste von Schleswig-Holstein wahrscheinlich maximale Wasserstände zwischen NHN +2,4 und 3,4 m. Die höchsten lokalen Windgeschwindigkeiten und Wellen traten in Schleswig-Holstein vier bis 10 Stunden früher auf als die Höchstwasserstände. Die einzigartige Höhe der Sturmflut vom 13. November 1872 in Schleswig-Holstein wurde durch eine externe Flutwelle aus dem zentralen Ostseeraum verursacht, die sich auf bereits vorherrschende sehr hohe Sturmflutwasserstände auftürmte. Entsprechend stellt die Sturmflut in Schleswig-Holstein ein singuläres Ereignis dar, weshalb seine statistische Einordnung eine wissenschaftliche Herausforderung darstellt. Als Hauptbestandteile eines integrierten Hochwasserrisikomanagements an den Küsten berücksichtigen Küstenschutz, Raumordnung und Katastrophenschutz in Schleswig-Holstein generell und in Kombination die nach der Flutkatastrophe gesammelten Erfahrungen. Vor dem Hintergrund intensiver Nutzungen und die Notwendigkeit einer ökologischen Zustandsverbesserung sowie im Hinblick auf den beschleunigten Meeresspiegelanstieg bleibt die Umsetzung eines nachhaltigen Küstenhochwasserrisikomanagements eine Herausforderung.

Schlagwörter

Schleswig-Holstein, Ostsee, Sturmflut, Flutkatastrophe 1872, Küstenschutz

1 Introduction

November 13, 2022 marks the 150th anniversary of a catastrophic storm surge that hit the coastlines of the western Baltic Sea region. In Germany, Denmark and Sweden, about 300 people died, 127 of them at sea (Fredriksson et al. 2017, Kiecksee 1972). In the German Federal State of Schleswig-Holstein (Figure 1), 31 people died in the floods, about 2,850 houses were destroyed or uninhabitable and more than 15,000 persons became homeless and needy (Kiecksee 1972). It was the last storm surge in Schleswig-Holstein, in which human lives were lost. Since 1872, the number of inhabitants and physical assets or, rather, tangible damage potentials have multiplied.

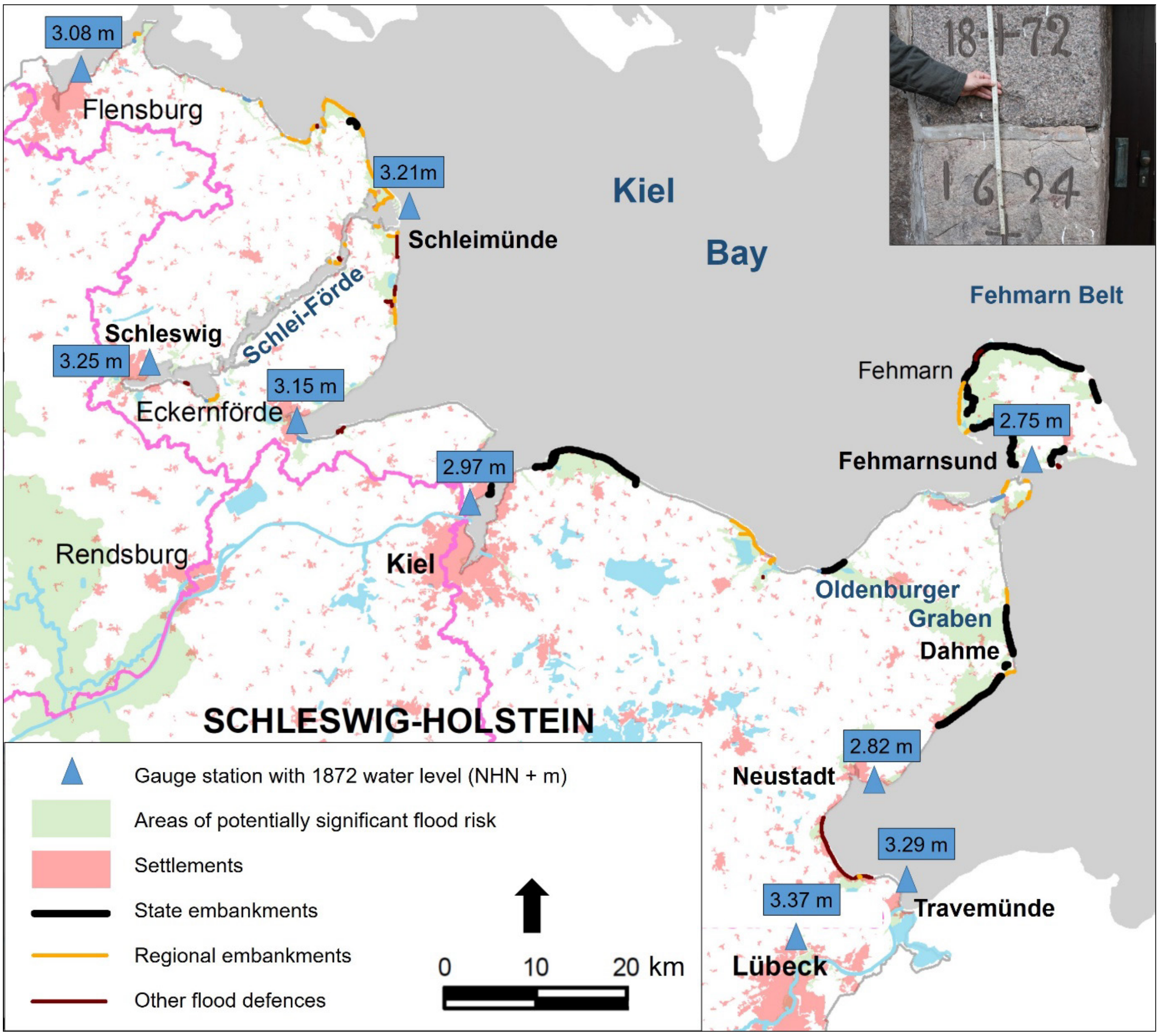

Figure 1: overview of the Baltic Sea coast of Schleswig-Holstein with coastal lowlands (in green), coastal flood defenses and 1872 storm surge water levels (gauge data: NHN = "Normalhöhennull" = German ordnance datum). The inset at the top right of the figure shows high water marks from the storm surges 1694 and 1872 at the former Gottorf water mill in Schleswig (photo: J. L. A. Hofstede).

Today, more than 30,000 people live and damage potentials of almost seven billion Euros are present in the about 315 km² large coastal lowlands along the Baltic Sea of Schleswig-Holstein. MELUND (in press) defines these lowlands as the areas situated less than 2.5 m above German Ordnance Datum NHN (≈ mean sea level). This is the area that could potentially, i.e., without coastal flood defenses, flood during a storm surge with a yearly probability of 0.005. Although the flood defense standards have strongly improved since 1872, a comparable storm surge could still have disastrous impacts due to the multiplied population density and damage potentials. Given this and in the face of strongly rising mean and extreme sea levels in future (IPCC in Press), the 1872 storm surge in Schleswig-Holstein constitutes an admonition or rather a plea for sustainable coastal flood risk management.

This paper starts with descriptions of the storm surge and of its impacts with a focus on two severely affected municipalities in Schleswig-Holstein: Eckernförde and Dahme. The next section describes the implementation of the findings, gained during and directly after the 1872 surge, in the planning and execution of coastal flood defense measures and coastal flood risk management in the following decades and today. After an elaboration of the components of integrated flood risk management, the paper continues with a discussion about the lessons learned from the storm surge and ends with some conclusions.

2 The 1872 storm surge in Schleswig-Holstein

2.1 Meteorology and hydrology

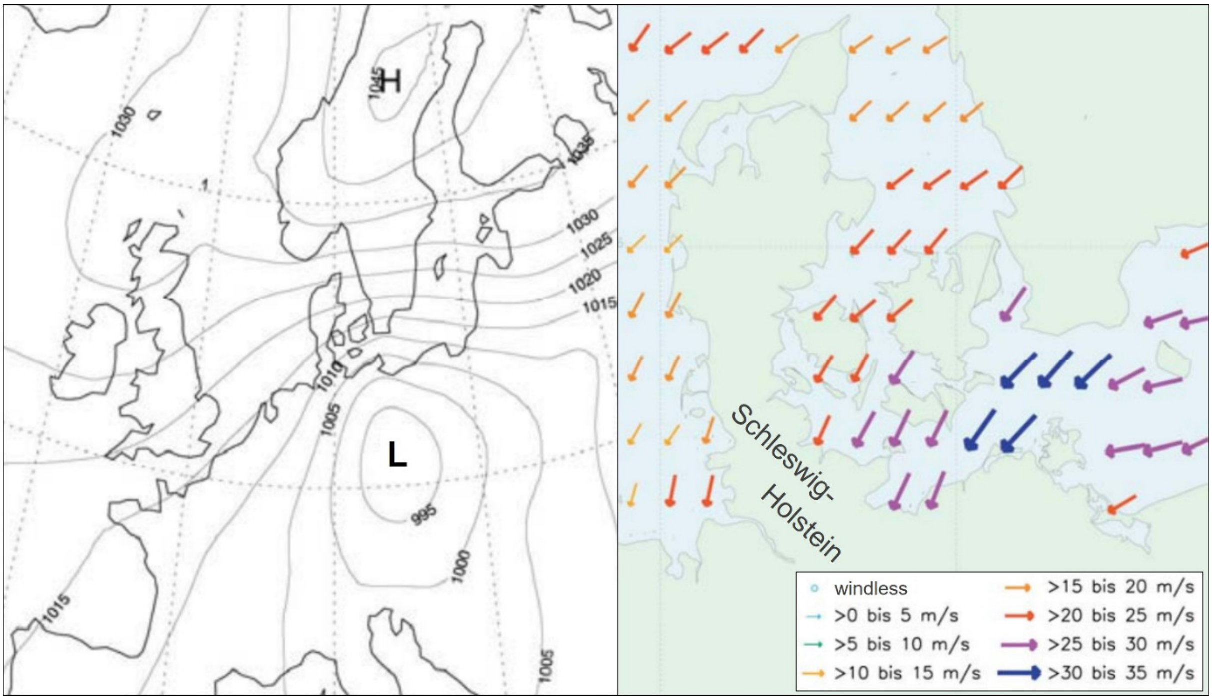

Figure 2: reconstructed air pressure fields and wind velocities in the western Baltic Sea region on November 13, 6 a.m. (source: Rosenhagen und Bork 2009).

Although the 1872 storm surge reached its maximum water levels on November 13, the causative weather situation started already two weeks before (Rodloff 1972, Rosenhagen und Bork 2009). From November 1 to 10, a strong and stable low-pressure system over Scandinavia induced strong westerly winds that "pushed" seawater away from the German Baltic Sea coasts towards the east. This resulted in falling water levels in the western Baltic Sea and, in compensation, water inflow from the North Sea via the Kattegat. In effect, the Baltic Sea filled up with water. Around November 10, the weather situation changed, the westerly winds waned and water started to flow back from the east. A high-pressure system evolved over Scandinavia, accompanied by a low-pressure system in central Europe. Both weather systems continually intensified until November 13, when extreme air pressure gradients induced a northeasterly hurricane (Figure 2). Peak wind velocities in Schleswig-Holstein occurred in the late morning. In Kiel, the hurricane reached a maximum of about 31 m/s around 10 a.m. (Baensch 1875).

Baensch (1875) comprehensively described the hydrology of the 1872 event, including the establishment of 23 storm surge curves recorded at Prussian gauges in the Baltic Sea. Figure 3 depicts coastal flood hydrographs from the gauges Travemünde, Fehmarnsund (positions in Figure 1) and Stralsund (situated about 135 km to the east of Travemünde) from November 11 to 14. The curves show that water levels continuously rose for more than two days. Such a long and strong rise of sea levels as well as the resulting maximum storm water levels were and are unprecedented in the region. Further, the gauge stations Fehmarnsund and Travemünde visualize the well-known effect of increasing surge levels from the outer towards the inner parts of bights.

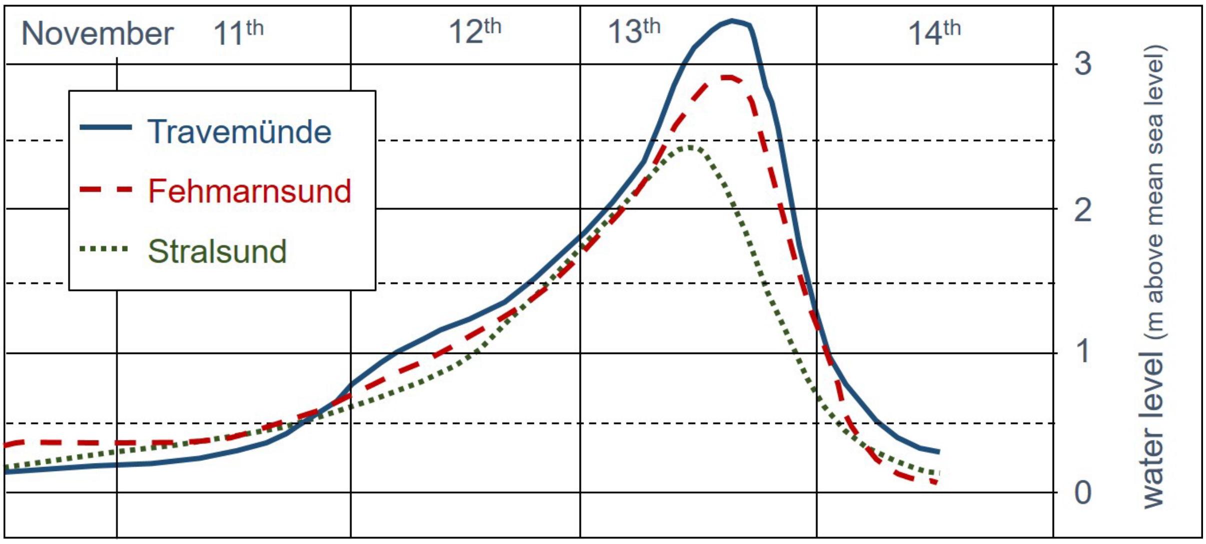

Figure 3: Storm surge curves at Travemünde, Fehmarnsund and Stralsund gauge stations from November 11 to 14 (adapted from Baensch 1875).

Figure 1 depicts known maximum water levels of the 1872 storm surge at gauge stations in Schleswig-Holstein. Lübeck gauge station recorded the highest water level in Schleswig-Holstein with 3.38 m above mean water level (NHN +3.37 m). At the former "Blue Tower" in Lübeck, high water marks existed of two earlier extreme floods that occurred in the years 1625 and 1694. A regional railway company dismantled the Blue Tower in the late 19th century to make room for a new railway line. Based on these marks, Baensch (1875) established maximum water levels of 2.80 m (1625) and 2.82 m (1694) above mean water level, i.e., 0.58 resp. 0.56 m lower than the flood from 1872. Baensch applied the mean water level of his time, thus assuming that no secular mean sea level changes occurred among 1625 and 1872. According to Baensch (1875), no reliable height information exists of older storm surges, whereas the storm surges that occurred among 1694 and 1872 were significantly lower. Based on historical data, Jensen et al. (2022) reassessed the heights of storm surge water levels in Travemünde over the last 1,000 years and concluded that a comparable surge height as in 1872 may have occurred in 1320. At the former Gottorf water mill in Schleswig, high water marks exist from the storm surges in 1694, 1836 and 1872 (inset in Figure 1). According to these marks, the peak water level in Schleswig in 1694 was about 0.6 m lower than in 1872, as the water level reached NHN +3.25 m at the local gauge station (Figure 1).

Figure 4 depicts the yearly highest water levels (HW) at gauge station Travemünde from 1826 to 2020, one of the world's longest continuous HW time series. Here, the 1872 water level reached NHN +3.29 m. The second highest storm surge water level was recorded in 1904 with NHN +2.15 m, i.e., 1.15 m lower than the 1872 peak water level.

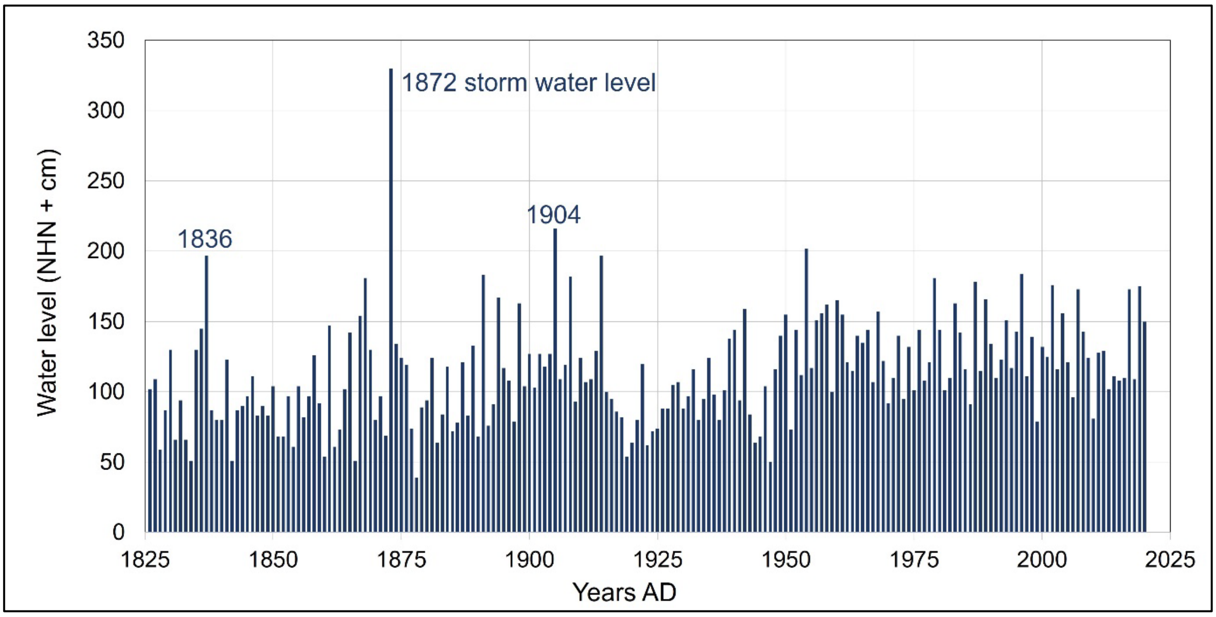

Figure 4: the yearly highest water levels at gauge station Travemünde from 1826 to 2020 (data from LKN.SH; data not corrected for mean sea level rise).

An internal report from the State Water Management Authority Lübeck (WWA Lübeck 1946) lists, for each of the Dike and Drainage Boards on the island of Fehmarn (location in Figure 1), maximum water levels for the 1872 storm surge. The values vary among 2.37 and 2.68 m above mean sea level. The data stem from local inquiries after the storm surge and do not have the same accuracy as gauge data. The lowest water levels appeared expectedly along the downwind-side western shorelines, the highest to the northeast and in the Fehmarnsund. The listed water levels are lower than along the mainland coast, which seems physically plausible. In synthesis, maximum water levels along the Baltic Sea coast of Schleswig-Holstein probably varied among about NHN +2.4 and +3.4 m.

Based on reported peak water levels and their occurrence times in the Schlei firth (location in Figure 1), Baensch (1875) established a mean progression velocity of the surge wave in this firth with about seven km per hour. The lowest speeds occurred at the mouth and in the broader inner part of the firth, the highest velocities in the narrow central part. At the mouth, in Schleimünde, maximum water level (NHN +3.21 m) occurred around 3:30 p.m. At the inner end, in Schleswig, water level reached its maximum (NHN +3.25 m) around 9:30 p.m., i.e., almost 10 hours later than the maximum wind velocities in the region (see above). Baensch (1875) reported that peak water levels within the Schlei decreased from the mouth towards the inner parts. At the broader inner end of the firth, however, local surge levels increased again and even exceeded the values observed at the mouth (Figure 1). This kind of surge progression is typical for the Schlei and probably relates to its particular shape.

2.2 Impacts

In 1872, large parts of the coastal lowlands along the Baltic Sea coast of Schleswig-Holstein were still unprotected. Only some lowlands like the Oldenburger Graben (Figure 5) already featured coastal flood defenses. As these under dimensioned defenses all collapsed during the storm surge, the impacts in Schleswig-Holstein were disastrous. More than 300 km² of coastal lowlands with numerous settlements as well as harbor areas of larger towns like Flensburg and Lübeck flooded. According to Kiecksee (1872), the floods damaged or ruined about 2,850 houses, 31 people died and more than 15,000 persons became homeless and needy. Kiecksee (1972) gives a comprehensive and regionalized overview of the flood impacts and of the recovery measures after the flood in the western Baltic Sea region. With numerous data and facts, he documents that not only the surge and its impacts, but also the public and private readiness to help after the catastrophe were unprecedented. This subchapter contains a description of the catastrophic impacts in two particularly affected villages in Schleswig-Holstein: Dahme and Eckernförde.

Dahme is a small coastal municipality with about 1,250 inhabitants (Figure 1 and 5). With almost one million overnight stays per year, seaside tourism dominates local economy. Parts of Dahme lie in the about 43 km² large coastal lowland Oldenburger Graben. In this lowland, about 1,900 people live and 366 million Euros of capital assets exist (Fachplan Küstenschutz Ostseeküste 2022).

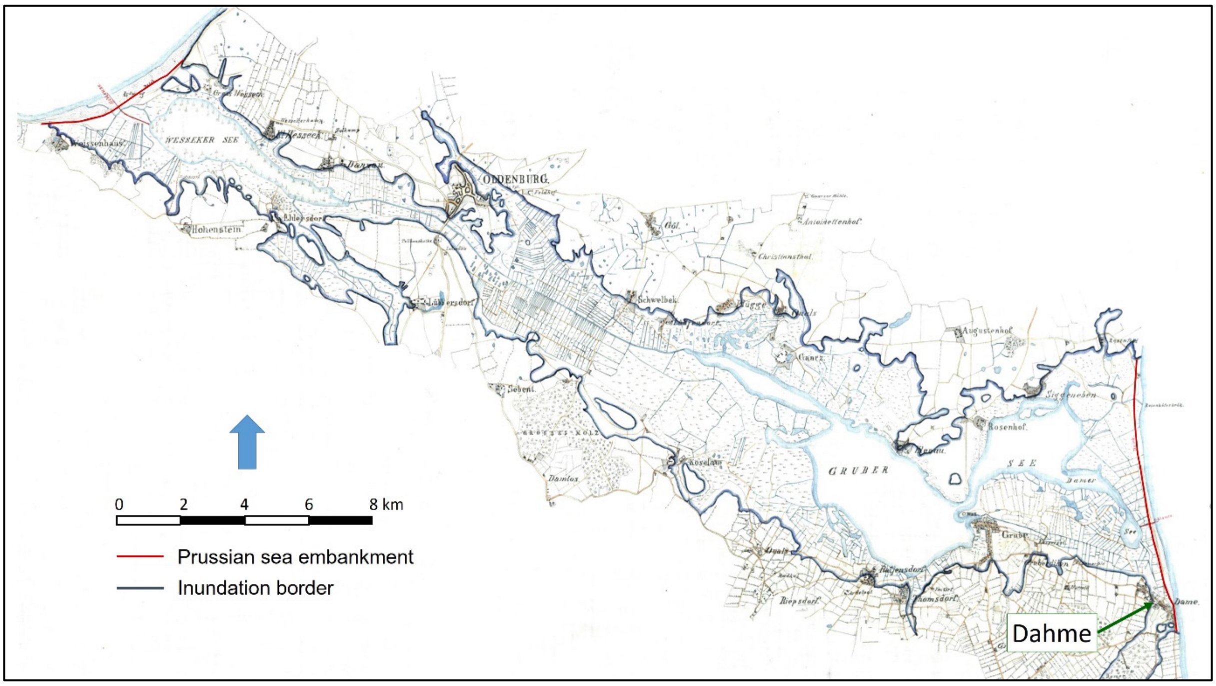

Figure 5: historical map from 1878 showing embankments and inundated area in the coastal lowland "Oldenburger Graben" (location in Figure 1) during the 1872 storm surge (source: LASH Abt. 402 A 24 Nr. 36).

In the late 1860ies, as part of a socio-cultural aid for the newly established province of Schleswig-Holstein, the Prussian Government initiated a comprehensive coastal flood defense program (Kannenberg 1958). One of the first larger measures was, in 1868 and 1869, the erection of an about 5.5 km long sea embankment in front of Dahme and the Oldenburger Graben (Figure 5). It was probably designed based on observations from the last severe storm surge that had occurred in the region in 1836 (Figure 4). This storm surge resulted in maximum water levels of about 2.0 m. In all, the embankment was about 3.0 m high, considering a local wave run up of about 1.0 m. The embankment, that consisted of sandy material and had relatively steep slopes, lay on top of dunes and beach ridges. November 1872, three years after finalization of the flood defense, storm surge water levels in the area rose to about 2.8 m above normal. Unsurprisingly, the embankment collapsed, amongst others directly in front of Dahme (Kiecksee 1972). After breaching of the defenses, the floodwaters swiftly inundated not only large parts of the village, but also the Oldenburger Graben (Figure 5). Ten persons died in the floods in Dahme, more than in any other municipality in Schleswig-Holstein. According to Reher (1931), only 20 from 80 to 90 houses that originally existed in the village were still inhabitable after the flood. The strong flood currents ruined 40 to 50 houses and washed 20 other houses away. In all, 51 families with about 300 persons (i.e., more than half of the total population) became homeless. Most of the livestock drowned.

Eckernförde is a coastal city with about 21,700 inhabitants (Figure 1). It is situated in the inner part of Eckernförde Bight that faces towards the northeast, i.e., that is directly exposed to northeasterly storms and waves. Major parts of the inner city are flood prone coastal lowland (Figure 6). Here, about 1,250 people live and 130 million Euros of capital assets exist (Fachplan Küstenschutz Ostseeküste 2020). In contrast to Dahme, there are no technical flood defenses in Eckernförde. An elevated promenade on former beach ridges, partly protected by revetments, and an elevated harbor area protect the low-lying inner city from flooding. Responsible city authorities are planning a comprehensive flood defense scheme (PROKOM 2017).

Figure 6: Maps of the city of Eckernförde. The left image displays a historical map from 1864 (source: PROKOM 2017). The right image shows the present situation; including hypsometric layers; note that the green and yellow areas are flood prone (source: KIS-SH).

As no flood defenses existed in 1872, the rising waters more or less steadily inundated the city. Most of the damages to buildings occurred along the "Jungfernstieg" road (Figure 6) and resulted from wave impacts. Flood marks on both sides of this road, however, show that some of them withstood the flood (Figure 7).

Figure 7: Flood marks in the historical town center of Eckernförde (photos: M. Hamann).

The devastation in Jungfernstieg actually furthered the upcoming fish industry. In the "cleared" space, it was easy to raise e.g. new smokehouses, which contributed to following decades of economic prosperity (Schinkel 2001). Despite of the 1872 calamity, new buildings arose even at the seaward (eastern) side of the road. As shown in Figure 6 (left image), first developments on existing beach ridges had only started here after 1864. Until the mid-1970s, commercial uses prevailed along the seaward side of the Jungfernstieg. Afterwards, the area converted into a residential area. In all, waves and currents destroyed 78 houses and damaged 138 in the 1872 storm flood (Kiecksee 1972). After the catastrophe, 112 families were homeless and 150 to 160 families with about 400 persons needy. Although the numbers of damaged houses and needy persons after the flood were significantly higher in Eckernförde than in Dahme, nobody died here in the floods.

2.3 Statistical appraisal of the 1872 storm surge

From Figure 4, it becomes clear that the 1872 water level clearly stands out. In relation to NHN, the peak water level in 1872 is more than 50% higher than the second highest recorded water level. From a statistical point of view, this is an indication that, in Schleswig-Holstein, the event is an outlier that does not belong to the population. This makes it scientifically challenging to assess its probability of occurrence. The German joint research project MUSTOK (Jensen 2009) investigated meteorology and hydrology of the 1872 event. Mudersbach and Jensen (2009) corrected the 1872 value at gauge station Travemünde (Figure 4) for mean sea level rise until 2006. With a newly established distribution function, they calculated a recurrence interval of 10,000 years for the 1872 storm surge water level if it would reoccur in 2006. They concluded that the statistical population used could not describe the storm surge. Extending the population with historical data (inter alia, the 1625 and 1694 peak water levels) and modelling results on hydro-meteorologically possible extreme water levels in the region (Bork and Müller-Navarra 2009) reduced the recurrence interval of the event to about 3,400 years. Based on numerical modelling of the 1872 event, Bruss et al. (2009) stated that the extreme peak water levels in Schleswig-Holstein resulted mainly from a combined water transport into the area from the central Baltic Sea and the Kattegat, driven by an extraordinary supra-regional meteorological situation rather than by local weather.

The fact that peak water levels in Schleswig-Holstein occurred four to 10 hours later than the observed maximum local wind velocities (Baensch 1875), supports this hypothesis. In Kiel, for example, after a maximum of 31 m/s around 10:00 a.m., local wind velocity was in the order of 17 m/s during peak water level around 3:30 p.m. (Figure 8). Although the local wind already decreased, the water level in Kiel still rose by more than 0.5 m. In Schleswig, local wind velocity was probably less than 10 m/s during peak water level. Hence, highest wind velocities and peak water levels did not coincide in Schleswig-Holstein. This indicates that an external surge wave, caused by a northeasterly hurricane in the central Baltic Sea region, entered Kiel Bay via the Fehmarn Belt and approached the coastline of Schleswig-Holstein. Here, it piled up on top of already raised storm water levels. Without the external surge wave, peak water levels may have resembled those of the 1625 and 1694 storm water levels in Schleswig-Holstein (see Ch. 2.1). This extraordinary multi-causal emergence of local peak water levels supports the hypothesis that the 1872 storm surge represents a singular event in Schleswig-Holstein. Further, the time lag among highest wind velocities and peak water levels indicates that, fortunately, maximum wind waves probably occurred several hours before peak water levels in Schleswig-Holstein.

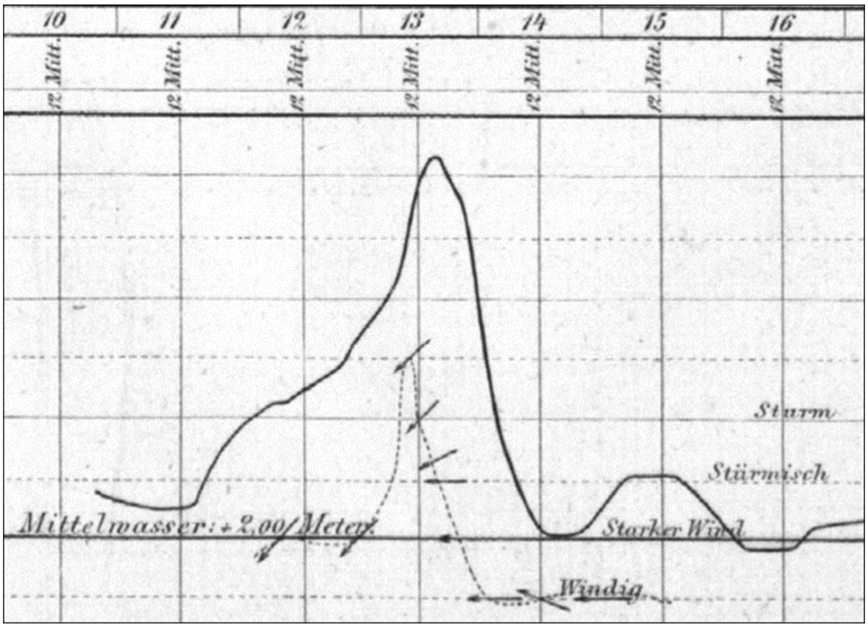

Figure 8: wind curve (dotted line) and flood hydrograph of the 1872 storm surge at Kiel gauge station (taken from Baensch 1875).

3 Coastal flood defense after the 1872 storm surge

Less than one month after the catastrophic flood, Prussian Government passed a decree for a comprehensive coastal flood defense program, including design criteria (Kannenberg 1958). One forward-looking criteria was that new sea embankments should be erected sufficiently landward of dunes and beach ridges, instead of on top of them. Based on observations made during the storm surge (Baensch 1875), this measure envisaged a reduction in hydraulic loads on the outer slope of the embankments as well as the creation of a buffer zone for coastal erosion during storm surges. After evaluation of the 1872 hydraulic loads, it was further stipulated that:

- the height of the new embankments should be about 5.0 m above mean sea level,
- the crest width should be about 3 to 4 m,
- the outer slope should have a gradient of 1:6, the inner slope 1:2,
- the embankment should have a cover of at least 0.6 m of erosion resistant material like clay.

Figure 9a visualizes the Prussian standard design for sea embankments (Eiben 1992). In the building campaigns after 1872, one-to-one implementation of this design did not occur (Kannenberg 1958). Although the erection of new embankments normally took place behind natural dunes and beach ridges, mean height of the embankments was normally up to about four meter above mean sea level. The outer slopes had gradients among 1:3 and 1:6; the inner slopes were normally steeper than 1:2. For most embankments, no information exists about their composition. Figure 9b displays the profile of the sea embankment in the Probstei near Kiel from 1882. With a maximum height of NHN +4.0 m, it lies directly behind the beach and partly on top of a pre-existing consolidated beach ridge.

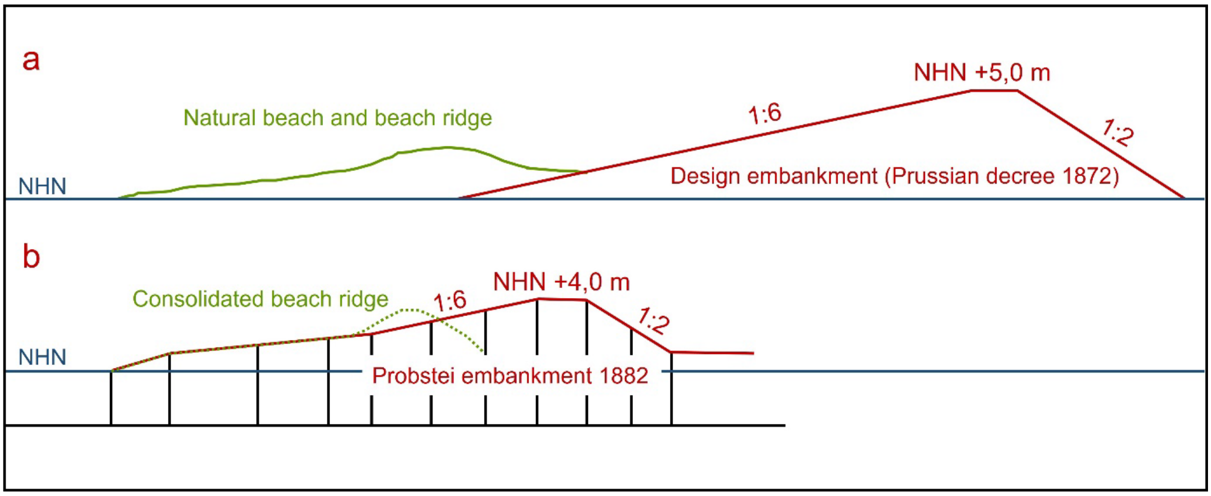

Figure 9: design profile of a sea embankment according to the Prussian design criteria (Figure 9a) and of the 1882 sea embankment in the Probstei near Kiel (Figure 9b) (adapted from Eiben 1992).

Until 1882, with technical and financial support from the Prussian Government, about 70 km of sea embankments arose along the Baltic Sea coast of Schleswig-Holstein (Kannenberg 1958). These defenses protect about 145 km² of coastal lowlands. Newly founded Dike and Water Boards became the task to maintain the embankments and secure the drainage of the lowlands. In these boards, all potentially affected landowners were member (with the power of co-decision according to landholding). In the year 1972, upon request of the boards, Schleswig-Holstein State Government took over technical and financial responsibility for the sea embankments. Conform the Schleswig-Holstein State Water Act, these coastal flood defenses passed as rededicated state embankments into state ownership.

One of the first measures after 1872 was the erection of a 5.5 km long new embankment in front of Oldenburger Graben near Dahme (Kannenberg 1958). The new crest height was about 4.2 m above mean sea level. Outside of Dahme, the new embankment ran behind the dunes and beach ridges, as stipulated in the Prussian decree. In front of Dahme, due to limited space, the new embankment lay again in an exposed situation directly behind the beach and featured relatively steep paved slopes. The expectation was that a paved outer dike slope should be able to withstand the higher hydraulic loads. The embankment and its foreland came into the possession of the newly founded local Dike and Water Board. It was governmental intention that the foreland should remain free from utilizations (Runde 1883). However, the upcoming of seaside tourism thwarted this specification. In 1920, local community erected a swimming pool in front of the embankment (Reher 1931). A concrete walking trail (promenade) on the foreland of the embankment followed, protected by a low flood defense wall situated directly on the beach. Based upon a public beach building plan from 1921, the area behind the wall but in front of the sea embankment increasingly filled up with touristic infrastructures (Kannenberg 1958). Today, dense touristic utilizations prevail in front of the embankment (Figure 10).

Figure 10: Aerial photo of Dahme seaside (Photo: LKN.SH / VPS).

After taking over the responsibility in 1972 (see above), state administration checked and listed the state embankment in front of Dahme as unsafe (i.e., not able to withstand the 1872 storm surge). Planning of a strengthening campaign started around the year 2,000. Achieving formal approval for public coastal flood defense measures may take 10 years or more in Germany, due to comprehensive state, national and EU legislation as well as the challenge of achieving local acceptance. The strengthening campaign went from 2010 to 2013 (Hofstede 2011). The design height based on the 1872 storm water level and included an additional margin of 0.5 m to account for sea level rise. Considering local wave run up, the existing about 5.5 km long embankment became a new crest height of NHN +4.8 m. A layer of clay covers a sandy core. Outside of Dahme, about 3.7 km was constructed with a seaward gradient of 1:8 and an inside gradient of 1:3. In Dahme, the challenge was to consider the existing touristic infrastructure on the foreland as well as dense housing and public infrastructure behind the embankment (Figure 10). Existing buildings and uses have a legal right of continuance and local community would not have accepted their removal. In consequence, the seaward gradient remains steeper and, over a stretch of about 0.7 km, a flood defense wall on top of the sea embankment secures the prescribed flood safety standard. Three passages through the embankment that are lockable in case of flood emergency enable easy access to the seaside facilities. In order to secure coherence for overbuilt NATURA 2000 sites, a specialized company removed moist dune habitats from the construction site and relocated them on prepared new dunes (Hofstede 2011). In synthesis, the new sea embankment fulfills the Prussian design criteria from 1872.

4 Integrated flood risk management

In order to minimize the risks of coastal flooding, building flood defenses is only one brick in the wall. Hofstede (2007, 2011b) describes a holistic and integrated approach that combines technical and non-technical measures in a coastal flood risk management cycle (Figure 11).

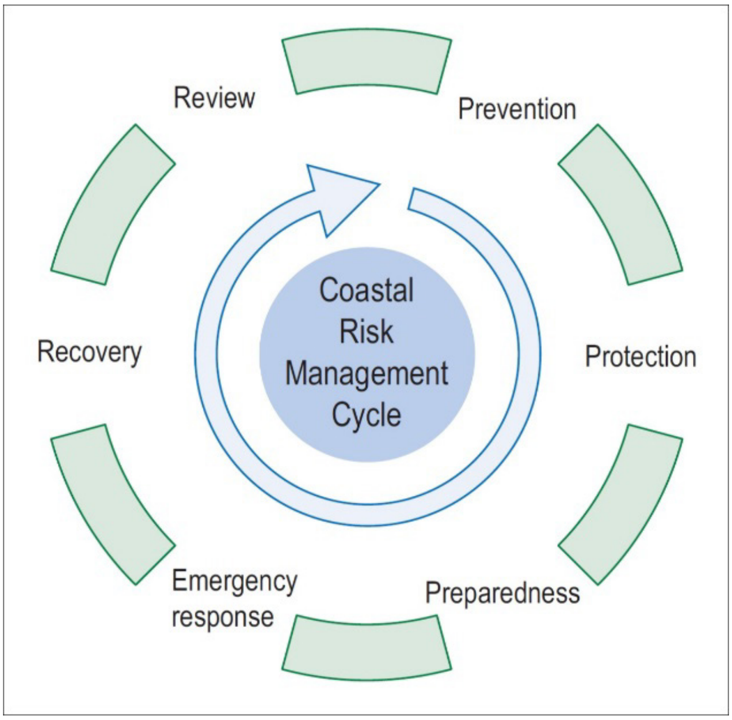

Figure 11: The cycle of integrated coastal flood risk management (source: Hofstede 2007).

Starting point in the cycle is prevention that aims at avoided or minimized flood risks, e.g., by stipulating building ban zones in flood hazard areas. The objective of protection is a minimized probability of a harmful flood event to occur, e.g., by building sea embankments. Preparedness has much to do with flood risk awareness of the affected population and the responsible decision makers (i.e., politicians). An important instrument to achieve this is appropriate risk communication. Informed people are more willing to take resp. order preparatory actions (including evacuation). Further, they accept the high costs and other possible constraints associated with coastal flood risk management (Hallin et al.

2021). Emergency response manages the "worst case" scenario, i.e., the possibility of flooding. Flood warning and evacuation are two well-known measures. Recovery comprises aftercare measures, such as provisional reparation of collapsed defenses and medical attendance for the injured. Finally, review stands for learning from new information and research outcomes as well as from disasters. It aims at an optimized next control loop (cycle) and monitoring and research programs are an important aspect of this element.

Main actors in the field of coastal flood risk management are spatial planning, coastal flood defense and disaster management. Whereas spatial planning focusses on prevention, flood defense aims mainly at protection but also deals with prevention and preparedness. Finally but evenly important, disaster management has a focus on emergency response but also deals with preparedness and recovery. All sectors consider review and should have a holistic view. The Dutch multi-layer safety approach from 2009 (van Herk et al. 2014), which defines three so called safety layers to reduce flood risk: protection, spatial planning and disaster management, closely resembles the cycle. The Floods Directive of the European Union (2007) sets a focus on prevention, protection and preparedness (including flood forecasts and early warning systems), i.e., on measures before the flood occurs.

4.1 Prevention

With respect to prevention, Schleswig-Holstein State Government updated in 2018 the State water Act and included building ban zones of 150 m behind the seaward edges of dunes, beach ridges and cliffs as well as in coastal lowlands that are not adequately protected by state embankments or other flood defenses with comparable safety standards. This in order to avoid and reduce damage expectations as well as to create a buffer zone for intensifying coastal retreat due to stronger sea level rise. The new state development plan for Schleswig-Holstein (MILIG 2021) considers these land use requirements by the definition of congruent areas of preference for coastal flood defense and for climate change adaptation along coasts. If implemented appropriately, these restrictions prevent rising damage expectations in future due to coastal floods in Schleswig-Holstein.

4.2 Protection

With respect to protection, state administration regularly performs safety checks of the State embankments. According to the last check in 2020, four State embankments along the Baltic Sea coast (i.e., 20 out of 70 km) need strengthening in order to meet the safety standards (MELUND in press). The design of these schemes base upon a statistically derived storm surge water level with a yearly probability of 0.005 and contains several extra safety factors:

- broadened crest width of 5.0 m (previously 2.5 m),
- low outer slope gradient of 1:10 (previously upward steepening profile),
- reduced allowable wave overtopping of 0.5 l/(s*m) (previously 2.0 l/(s*m)), and
- safety margin to account for future sea level rise of 0.5 m.

The low gradient significantly reduces wave run up and allows for a further heightening of the embankment if stronger sea level rise should make this necessary. With this staggered procedure or climate change adaptation pathway, a total sea level rise of approximately

2.0 m can be balanced (Hofstede 2019). In synthesis, after strengthening, the State embankments should be able to withstand the 1872 storm surge if it would reappear in this century. State embankments and other coastal flood defenses with a similar safety standard protect about half of the coastal lowlands and the affected population along the Baltic Sea coast of Schleswig-Holstein. This highlights the significance of prevention, preparedness and emergency response in an integrated and holistic flood risk management.

4.3 Preparedness

With respect to preparedness, nowadays the conditions for early warning are much better as in 1872. Operational models of the German Federal maritime and Hydrographic Agency (BSH) allow first indications of storm water levels up to six days before the event. Eight to 15 hours before a storm surge occurs, BSH starts with issuing regionalized flood warnings with expected maximum water levels. This gives disaster management authorities enough time to prepare appropriate measures and to inform the local population. BSH directs flood warnings to all regional disaster management authorities and to the public. While authorities use official communication structures, the public is warned e.g. by the smartphone app NINA, which is part of the Modular Warning System MoWaS (BBK 2021). The Federal Office of Civil Protection and Disaster Assistance (BBK) established MoWaS, since the civil protection siren network was dismantled after the end of the cold war in the 1990s. End devices triggered by MoWaS include all warning media e.g. radio, television, Internet, mobile apps.

However, warning of the affected population can only be effective when accompanied by an appropriate risk communication. People have to know what to do in case of warning. Risk communication comprises clear and honest information about possible hazards in the peoples own residential and working environments, how to prepare individually and, related to that, clear advice how to react if a warning is issued. The BBK provides information for emergency preparedness and emergency actions for a number of hazards e.g. severe weather, fire, floods and industrial disasters. Nonetheless, the need to prepare is not evident for many inhabitants of coastal lowlands. This could be a side effect of the high coastal defense standard and very few real events in the past decades.

4.4 Emergency response

With respect to emergency response, the present situation differs completely from 1872. As laid down in the German Constitution (Grundgesetz) from 1949, emergency response in Germany is in the responsibility of the Federal States (Länder). The states maintain disaster management authorities on state and county level as well as procedures for this purpose. These are laid down in state specific disaster management acts, e.g. in the Schleswig-Holstein State Disaster Management Act (Landeskatastrophenschutzgesetz Schleswig-Holstein) and in specific disaster management plans on different levels. On the state level, the responsibility is broken down to regional administrative levels. In Schleswig-Holstein, the Chief Administrative Officer of the County is in charge of disaster management and takes over the command in case of a disaster in his county. If the emergency event occurs in more than one county, the Schleswig-Holstein State Ministry of the Interior becomes responsible and takes over the entire command of operations. On the local level, the fire brigades play a major role in hazard control and therefore as well in disaster management. In the majority of Schleswig-Holstein's municipalities, firefighters work as volunteers, only the four major cities maintain a professional fire brigade. However, all local fire brigades have the legal status of a municipal authority, and so they are the main instrument of the mayor, who is in charge of local hazard control. So today the capacities for hazard control are much better than 1872, when the first volunteer fire brigades just had been founded (e.g., in Eckernförde in 1871).

In view of the lack of real events, responsible authorities together with local fire brigades and voluntary associations like the Red Cross conduct storm surge exercises to test their preparedness (availability of personnel, equipment, material and infrastructures) as well as to optimize disaster management plans and procedures. These plans provide for the successive actions taken with increasing predicted and observed storm water levels, from the establishment of a flood-monitoring center and an operational headquarters to emergency measures like placing sandbags or evacuation of endangered areas.

5 Discussion

5.1 Lessons learned

The 1872 storm surge with its catastrophic consequences was a turning point in coastal flood defense along the German Baltic Sea coast. Responsible administration reacted promptly with the establishment and issuing of design criteria for stronger sea embankments. At this time, when anthropogenic climate change and stronger sea level rise were not relevant, these criteria were certainly forward-looking and sustainable. The implementation of a buffer zone with natural dunes and/or beach ridges in front of the new embankments considered coastal erosion during storm surges. The flatter outer slope guaranteed optimal dissipation of incoming waves. Crest height and width considered both still water level and wave run up. A thick cover of clay prevented erosion of the outer and inner slopes by wave breaking resp. wave overtopping. Finally, as a non-technical flood risk measure to avoid damage expectations, Prussian policy already aimed at avoiding utilization of the forelands of the new embankments.

Already with the first measures, financial constraints resulted in deviations from the original design criteria. The local decision to erect the Probsteier embankment partly on top of an existing fortified beach ridge directly behind the beach (Figure 8b) mainly aimed at cost reduction (Runde 1883). In this respect, it is worthwhile to note that only 10 years after the catastrophe, the responsible local public construction officer stated that, due to the extenuated design, the newly erected embankment would probably not withstand the 1872 event (Runde 1883). The allocation of public financial means has, at least in part, to do with setting of political priorities and their changes through time. One month after the 1872 event, Prussian Government issued design criteria that would avoid a replication of the calamity. It was certainly realized that the application of these criteria imply huge efforts and costs, but the catastrophe was still visible and in the minds. The necessity (priority) of using private and public means for recovery was widely accepted. For example, Schleswig-Holstein civilians donated about 700,000 Taler in the months after the event as aid for needy people, 150 years ago an enormous amount of money (Kiecksee 1972). In 1874, only two years after the storm surge, concrete flood defense measures in Dahme started with already extenuated design criteria. Less than three generations after the calamity, the foreland of the sea embankment was increasingly overbuild with touristic facilities (Reher 1931). In Eckernförde, directly after the calamity, new commercial buildings arose along the "Jungfernstieg", even at the seaward (eastern) side of the road. In the mid-1970s, the area converted into a residential area. Accordingly, damage expectations due to flooding and, thus, the flood risk increased. It may be discussed whether these examples are indicative for a general human aptitude to forget bad experiences and to ignore or suppress hazards, especially when an apparent possibility of creating income or other short-term benefits exists. According to Hallin et al. (2021), collective forgetting of disasters constitutes a threat with respect to robust flood risk assessment and sustainable urban planning. This pinpoints the relevance of raising awareness for coastal flood risks by the responsible authorities, especially in the light of men-induced strongly rising sea levels in future (IPCC in Press). It further emphasizes the need for restrictive spatial planning that avoids further increasing damage potentials in coastal lowlands.

From a coastal flood risk management perspective, it is of high relevance to realize that the under dimensioned embankment from 1869 may be one reason why people died in Dahme. Based on eyewitness accounts, Reher (1931) reports: "*people in Dahme relied on the new sea embankment, which brought the people no safety but harm. Without the embankment, the water would have come in steadily, giving the people time to react and bring themselves and their belongings into safety. Instead, after breaching of the embankment, the impounded waters swiftly expanded into the village and forced the people to flee on the lofts. Many of the frame houses collapsed under the massive hydraulic loads.*" In the unprotected city of Eckernförde, more damages to houses occurred than in Dahme but nobody died. Here, the rising waters more or less gradually inundated the city; giving the inhabitants the time to react that was missing in Dahme. Further, the inhabitants of Dahme seemingly over trusted their new embankment and were, thus, not adequately aware of the remaining flood hazard. This underlines the importance of appropriate risk awareness in the potentially affected population (see above) as well as the need for effective disaster management in protected areas; including flood warning and evacuation in time before breaching of the embankments occurs.

5.2 Integrated flood risk management in Dahme and Eckernförde

As described above, the flood protection status differs greatly between Dahme and Eckernförde. Hence, also the elements of the risk management cycle (Figure 11) each need a different emphasis.

5.2.1 Dahme

A state embankment protects Dahme from flooding through storm surges. According to the Schleswig-Holstein State Water Act, state embankments provide adequate protection against coastal flood. In consequence, the Schleswig-Holstein State Development Plan (MILIG 2021) does not provide for flood-related land use restrictions in coastal lowlands protected by state embankments. The plan only states that in these lowlands, local building plans should consider the interests of coastal flood defense. Building planning is in the responsibility of the municipalities. Hence, it seems realistic that in Dahme, where tourism constitutes the dominant economic factor, further development behind the embankment will occur. The fact that it was not possible to relocate existing touristic infrastructure seaward of the embankment in the course of the last strengthening campaign, underpins this expectation.

According to the State Master Plan Coastal Flood and Erosion Management (MELUND in press), a coastal flood defense structure provides adequate protection if it can withstand a storm surge with a yearly probability of 0.005. This automatically implies that a residual hazard for breaching and flooding remains. As in the disaster of 1872, the people in Dahme feel safe behind the state embankment (which provides "adequate" protection). This may lead to an underestimation of the remaining hazard and underlines the need for constant risk communication in order to raise awareness of the flood risk. Implementing an effective risk communication strategy still poses a challenge for the state, county and municipal disaster management authorities, although well elaborated disaster management plans and appropriate local emergency provisions are available.

5.2.2 Eckernförde

Because Eckernförde has, in contrast to Dahme, no adequate protection against coastal flooding, the focus is more on prevention and preparedness. In not adequately protected lowlands, the Schleswig-Holstein State Water Act stipulates a general building ban. New developments in these areas are allowable only after implementation of appropriate measures to secure adequate protection. The State Master Plan Flood and Erosion Management (MELUND in press) defines respective measures like coastal raising the area. Accordingly, a local building plan in Eckernförde from 2017 specifies the minimum height for the ground floor in living rooms with 2.95 m and in commercial rooms with 2.45 m above NHN (Stadt Eckernförde 2017). Most buildings in the flood prone historical town center lie between 1.8 m and 2.5 m above NHN. As stated above, these buildings have a legal right of continuance. However, this right ends with the implementation of changes in use or structural alterations of the building. Strict implementation of the new regulations could impede the preservation of historic buildings and have a massive impact on local merchants, restaurants and other touristic infrastructures. For these reasons, the local building plan stipulates that exceptions are acceptable if individual measures like waterproof doors and windows, backflow flaps and/or protection of heating, ventilation and other relevant utilities provide adequate flood protection.

In order to enhance flood safety in the historical town center, the local parliament has adopted a coastal masterplan (PROKOM 2017), which comprises technical flood defense measures. Although economic efficiency, technical feasibility and ecological impacts needs consideration (Roggesack 2006), the aim is to achieve adequate flood safety for the city center. Finally, as in Dahme, there is the need to raise the awareness and preparedness of the inhabitants. The last critical flood event is probably too long ago to remain in the personal and common memories. However, some almost-critical floods in the last decade brought back this topic into the local public discussion, as newspaper articles show. To be prepared for the worst case, the town administration is preparing evacuation plans for the historical town center including information leaflets for the local residents. Further, the local public services have prepared an emergency power supply system (Stadt Eckernförde 2017).

6 Conclusions

Based on the descriptions and the discussion, the following conclusions are drawn:

- Along the Baltic Sea coast of Schleswig-Holstein, peak water levels of the 1872 storm surge probably varied among about NHN +2.4 and +3.4 m.
- The highest local wind speeds and waves occurred four to 10 hours earlier than peak water levels in Schleswig-Holstein.
- The unprecedented height of the 1872 storm surge in Schleswig-Holstein resulted from an external surge that propagated into the area from the central Baltic Sea region and piled up here on top of already prevailing very high storm surge water levels.
- The 1872 event was a singular event in Schleswig-Holstein, which makes it scientifically challenging to assess its probability of occurrence.
- Present-day coastal flood defense, spatial panning and disaster management, as cornerstones of public coastal flood risk management in Schleswig-Holstein, generally and in combination consider the lessons learned after the 1872 flood calamity.

In the light of intensifying utilizations, the need for ecological recovery and with regard to stronger rising sea levels in future, implementing sustainable coastal flood risk management remains a challenge.

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Modelling the extreme storm surge in the western Baltic Sea on November 13, 1872, revisited

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Summary

Works from 2009 were revisited to mark the 150th anniversary of the catastrophic flood of 1872 in the western Baltic Sea. At that time, the weather situation for November 1 to 13, 1872 was reconstructed from historical data and adjusted to historical water level data in an iterative process. Multiple uses of the resulting wind fields by other authors make an English representation worthwhile. A detailed presentation and evaluation of historical information as well as the description and evaluation of the reconstruction process and derived potential causes for the particular severity of the flood is given. The latter are discussed on the basis of numerical experiments that have received little attention so far. Deviating from common ideas, a "Vorflut" in particular is contradicted as an essential preconditioning process.

Keywords

Baltic Sea, storm surge, 1872 Baltic Sea flood, reconstruction

Zusammenfassung

Anlässlich der 150-jährigen Wiederkehr der katastrophalen Flut von 1872 in der westlichen Ostsee wurden Arbeiten aus dem Jahr 2009 wieder aufgegriffen. Damals wurde die Wettersituation für den 1. bis 13. November 1872 aus historischen Daten rekonstruiert und in einem iterativen Prozess an historische Wasserstandsdaten angepasst. Die vielfache Nutzung der resultierenden Windfelder durch andere Autoren macht eine englische Wiederbetrachtung sinnvoll. Die Abhandlung enthält eine detaillierte Darstellung und Bewertung der historischen Informationen sowie die Beschreibung und Beurteilung des Rekonstruktionsverfahrens und daraus abgeleiteter potentieller Ursachen für die besondere Schwere der Flut. Letztere werden anhand von bisher wenig beachteten numerischen Experimenten diskutiert. Abweichend von gängigen Vorstellungen wird besonders einer „Vorflut" als wesentliche vorbereitende Ursache widersprochen.

Schlagwörter

Ostsee, Sturmhochwasser, Hochwasserkatastrophe 1872, Rekonstruktion

1 Introduction

In the sub-project MUSE-Baltic Sea of the KFKI MUSTOK project, from 2005 to 2008, extreme floods were searched for along the German Baltic Sea coast, which could occur under current climate conditions (Schmitz 2009, Bork and Müller-Navarra 2009b). Whereas in the previous comparable project MUSE-North Sea (Jensen et al. 2006) water levels within the German Bight of about 1 m above maximum observed were simulated, the respective water levels in the Bays of Kiel and Mecklenburg remained below the highest observed values which occurred during the storm surge of 1872.

In co-operation between the German Meteorological Service, DWD, in Hamburg and the Federal Maritime and Hydrographic Agency, BSH, an attempt was made to determine the specific meteorological situation that led to such very high water levels in the western Baltic Sea. The first aim was to reconstruct the surface wind field in its spatiotemporal development during the period November 1 to 13, 1872. The few available wind observations from that time are insufficient to transfer them to a uniform spatial grid. The wind field was therefore derived from manual air pressure analyses. That leaves relatively large room for subjective interpretation due to partly very incomplete pressure data. This tolerance was used to carry out model simulations with iterative changes in the wind field until the historical water levels were approached by the model as best as possible. Using the meteorological data base gained in this way, various processes could be separated and examined with respect to their influence on extreme water levels of the Baltic Sea.

2 Data base

The flood of November 1872 with its devastating consequences has been described directly after the catastrophe in journals (Illustrirte Zeitung 1872) and official reports (Quade 1872, Anonymous 1872) including first attempts to explain potential causes. As the storm surge coincided with the beginning of systematic meteorological observations and oceanographic studies of the Baltic Sea (Meyer 1871), scientific papers on the storm surge were presented in the following years (Baensch 1875, Colding 1881). Lentz (1879) also discusses his theory on the effect of the wind on the water level using the example of the storm surge of 1872. Krüger (1910) critically evaluated various additional sources (Mayer 1873, Ackermann 1883). Later Kiecksee (1972) discussed the causes of the storm surge and in particular its damage. Recently, a comparative study on the effects of the storm surge of 1872 with reference to coastal flood risk management in Germany, Denmark and Sweden was published by Hallin et al. (2021). In the following, the historical literature on water level, air pressure and wind are commented. Unfortunately, there is little or no information on other potentially important parameters such as water temperature or salinity.

2.1 Previous work on water level

An important part of the papers of Baensch (1875) and Colding (1881) comprises the compilation of meteorological and oceanographic observational data. Colding made use of any kind of information he received in response to a general call, as well as on Baensch's data. The latter exclusively used official gauge records of the water level. The gauge in Warnemünde, for example, has existed since 1855 (Stigge 2003). Although self-recording gauges worked in Swinemünde since 1870 and in Arkona since 1872 (Birr 2005), stick gauges were commonly used. Their readings were not always unambiguous. For example, the pilot ladder for Travemünde quotes 3.41 m above mean sea level as maximum water level on November 13, 1872, while the district administrator notes 3.26 m above mean sea level (Anonymous 1872). Baensch (1875) reports 3.32 m above mean sea level for November 13, 1872, 2 p.m.

Uncertainties of the same order result from the reduction of gauge data to mean sea level, for example from the more general problem of defining mean sea level. Seibt (1881) based his calculation of the mean water levels for coastal gauges on observation periods of different lengths. More recent studies on the reference level were used by Mudersbach and Jensen (2009). An updated study on the subject is given by Dangendorf et al. (2022). Baensch (1875) relates a maximum error of 0.1 m to this kind of problem. An additional error in using stick gauges resulted from their partly primitive attachment, so that they became unusable after severe ice formation (Meyer 1871).

Colding (1881) constructed a first set of contour maps of water level for the entire Baltic Sea and the eastern North Sea from gauge measurements and other data at seven different times during the period from November 12 to 13 (e.g. Figure 5b). In doing so, he interpolated between available data. With regard to Colding's continuation of the lines of equal water level into the open North Sea, it must be noted that the contemporary representation of the tides followed a misconception by Airy (1845), although a more correct approach had already been published by Whewell (1836) (after Cartwright 1999).

Baensch (1875) and Colding (1881) have drawn the temporal development of the water level at many places. While Baensch (1875) also gives the underlying data in tabular form, Colding (1881) only notes the numerical values in his maps. Lentz (1879) graphically evaluates the same water level records as Baensch (1875), probably independently of the latter. Lentz (1879) presents graphically surge data for Cuxhaven and, in tabular form, water level data for Copenhagen. In addition to these main papers, Pralle (1875) compares water levels in Kiel and Husum. The Swedish Meteorological and Hydrological Institute, SMHI, has related water level records in Öland Norra Udde to NN (cf. Figure 9 in Rosenhagen and Bork 2009). There is also information on the water level at Grönskär, an island in the Stockholm archipelago. The longest time series are those for Stockholm (since 1774) with daily measurements for 1872 (Ekman 1988, Rosenhagen and Bork 2009) and for Kronstadt (since 1804). In today's data sets for Kronstadt, the gauge records for 1872 are missing (Klevanny 2008, personal communication). However, Bogdanov et al. (2000) give monthly mean values for 1872. Numerical values are also given in the maps of Colding (1881). For Cuxhaven, water level records exist since 1841 (Müller-Navarra et al. 2013). For November 1872, however, only high tide (HW) and low tide (NW) readings were taken, but not during the night. These historical data were corrected to NN at BSH. The surge values given by Lentz (1879) obviously make use of the same data. For Den Helder, the tides were related to NAP (NN-NAP=+0.02 m) by Rijkswaterstaat.

Based on this information, the maximum water levels on the German Baltic Sea coast during the storm surge of 1872 have been repeatedly compiled and evaluated (Krüger 1910, Jensen and Töppe 1986, Baerens 1998, Baerens et al. 2003, Mudersbach and Jensen 2009). The values of the water level measurements vary considerably in some cases e.g. due to registration time. Even when the highest water level was determined according to tide marks and witness statements, the values differ.

2.2 Previous work on air pressure and wind

The storm surge of 1872 coincided historically with the establishment of national meteorological services. Their measurements are taken into account in the historical considerations.

The most detailed contemporary elaboration of the storm surge is from Colding (1881). He constructed a second set of maps for the entire Baltic Sea area. These show isopleths of atmospheric pressure and wind direction as well as punctual information on wind direction and wind speed for the period from November 12 to 13, 1872 (e.g. Figure 1, left). Another extensive early source is that of Baensch (1875), which describes the development of the weather situation by means of maps of the morning air pressure fields for November 10 to 13, 1872 (e.g. Figure 1, right). The publication also contains extensive station-related data on wind and air temperature, which are, however, limited to the Baltic Sea coasts of the Prussian state. Later authors follow in their presentations either Colding (Hennig 1911 and 1919, Seifert 1952) or Baensch (Kruhl 1973, Thran and Kruhl 1972). Thran and Kruhl (1972) in particular reconstructed weather maps in comparison to all four maps by Baensch.

The representations in Baensch (1875) and Colding (1881) for the morning of November 13, 1872 differ mainly in the presence of a low over the southern Baltic Sea. In Baensch (1875) it is the remnant of a small-scale marginal depression that had been found north of Berlin on November 10 and 11, 1872. It is important to note that the air pressure data used by Baensch for the analysis of the isobars were not reduced to sea level, as necessary for the exact comparability of the values. Although the Baltic Sea coastal region is predominantly rather flat, more or less small inaccuracies will exist.

Since van Bebber's (1891) publication on frequent tracks of low-pressure systems over Europe, the weather situation that led to the flood of 1872 has been described with great agreement in subsequent literature as a Vb situation (Hennig 1911 and 1919, Krüger 1910, Kohlmetz 1967, Kruhl 1973). They describe a low-pressure system moving on the van Bebber Vb track from the Adriatic Sea around the eastern side of the Alps to Central Europe.

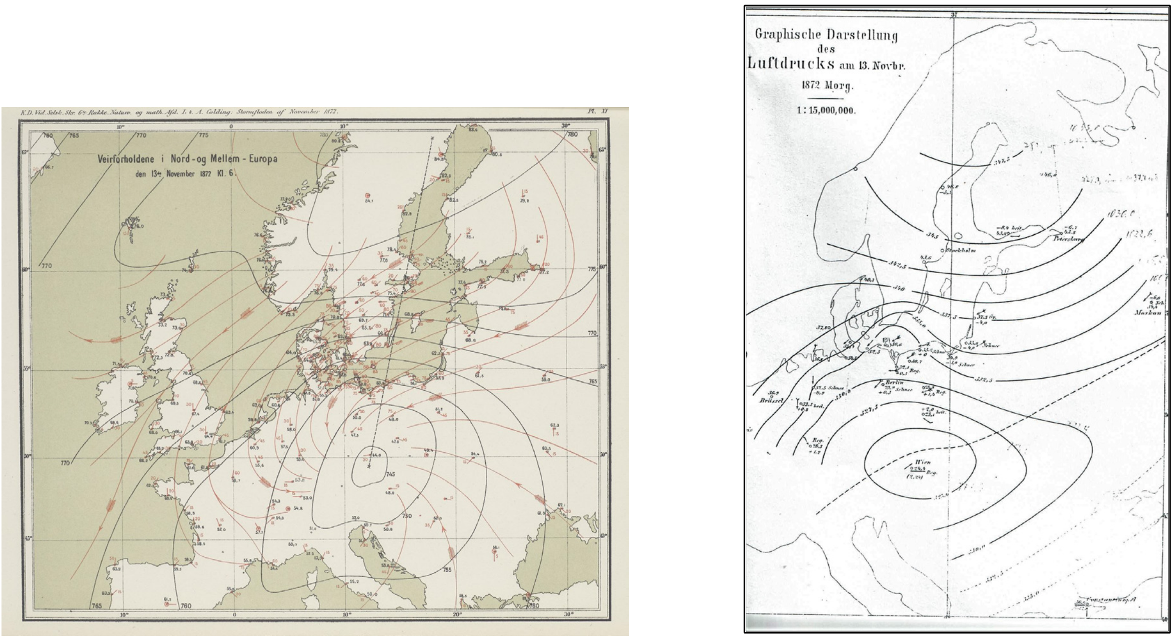

Figure 1: Weather maps, November 13, 1872 in the morning, left: after Colding (1881), right: after Baensch (1975).

3 Reconstruction

3.1 Procedures

The goal of this investigation, to clarify the causes of the extraordinary storm surge of 1872 on the basis of current meteorological and oceanographic knowledge with numerical models, required in particular a digital reconstruction of the meteorological fields. However, the available 1872's observed data are not sufficient for a reanalysis with a three-dimensional numerical atmospheric model. Also the air pressure analysis available until 2009 from the EU project EMULATE (Ansell et al. 2006) with mean daily values of the air pressure in a 5 degree grid obviously cannot explain the severe storm at November 13, 1872 in the area of the western Baltic Sea. Therefore, the classical meteorological method was used: drawing of weather maps, determining the geostrophic wind from the pressure fields and estimating the wind at a height of 10 m. The more comprehensive "Twentieth Century Reanalysis" (Compo et al. 2011), which was published later, recorded the meteorological situation before and during the Baltic Sea storm surge much better in terms of quality, but was still inadequately in terms of quantity (Feuchter et al. 2013). This is due to the unchanged low data base.

3.2 Analysis of air pressure fields

For the meteorological analyses, all available air pressure and temperature observation data, independent of the evaluation status, of the period November 1 to 13, 1872 were requested from the national meteorological services of Europe. The request resulted in collecting the values from more than 230 observation stations (Figure 2), of which more than 175 had at least two reports per day.

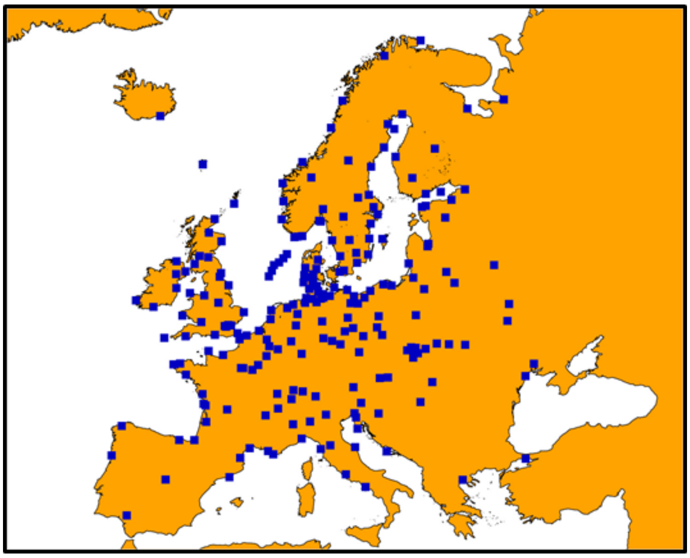

Figure 2: Stations with meteorological data available for the reconstruction.

In 1872, the metric system had not yet been introduced. Measurements of air pressure were often in inch and feet, which had non-uniform regional length. The application of the data therefore required after the digitization an extensive checking and standardisation of the differently evaluated data. The details of place and time were also not entirely comprehensible. All air pressure data were put into a uniform status, reduced to sea level and converted to hectopascal (hPa) and, regarding time, to UTC.

The geographic distribution of the checked data collective was inconsistently dense. Almost all air pressure values came from land or island stations (see Figure 2), with the highest density over northern Germany. However, as with Colding (1881) and Baensch (1875), there were hardly any ship's observations from the North and Baltic Sea. This uneven distribution of data with wide parts of areas without any information provides poor prerequisites for a numerical interpolation. By tracking the weather situation over time with meteorological experience, more accurate results can be achieved and readjustments in particular are made easier. In addition, the manual analysis offers the opportunity for a further examination of the data and obvious wrong data could be eliminated.

Since the oceanographic model system used later to calculate water levels requires wind data as one driving force up to the northeast Atlantic, the daily mean values of air pressure available from the EMULATE project (Ansell et al. 2006) were used as support. The number and distribution of the available data allowed three manual analyses per day for the European land areas as well as for the North Sea and Baltic Sea for the period from November 1 to 11, 1872 and six each for November 12 and 13.

The hand drawn isobars were then digitised with the help of the geo information system ArcGIS (ESRI 2004) and interpolated to a geographical grid of 0.5 degrees grid width. For control purposes, the generated grid point data were then evaluated again as isobaric fields.

The results showed partly unrealistic structures, especially at the outer edges. By changing to natural neighbour (in space) interpolation, this kink could later be largely eliminated (Kählke 2011, ESRI 2009).

3.3 Derivation of wind fields

For each grid point of the 0.5-degree grid, the geostrophic wind was calculated from the pressure values of the four surrounding grid points. The method bases on the balance of the Coriolis force and the pressure gradient force (Alexandersson et al. 1998). Above 100 m height, this approximation determines the real wind to 90 % to 95 % (Möller 1973). Since the pressure gradient force is inversely proportional to the distance between the isobars, the geostrophic wind can be calculated solely from the air pressure distribution.

However, this does not take into account the influence of friction on the rough surface (land or sea), which causes a rotation of the wind and a reduction of the wind speed. For the ageostrophic change in wind direction at sea, an angle of 30 degree was chosen after test simulations regarding the water level. When the wind blows from land onto the sea, the slowing effect of the rough land surface is noticeable near the coast. In addition, greater roughness also causes an increase in the ageostrophic angle of the wind direction. As the storm on November 13 came from the north-east, it blew mainly over water in the central Baltic Sea, but also over southern Sweden and the Danish islands. Taking into account the distance of the grid points to the coast could incorporate such effects. But they were neither considered in the estimation of the wind speed at 10 m height nor later in the forcing in the oceanographic model. An error estimate cannot be given.

For the wind speed at a height of 10 m, empirical approaches exist whereby the reducing influence of friction can be estimated. A comparison of the approaches of Duun-Christensen

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(1975), Hasse (1974) and Luthard and Hasse (1981 and 1983) showed a great sensitivity to thermal stratification, represented here by the difference between air and water temperature.

Since the storm surge of 1872 was accompanied by a massive cold spell (seen in the air temperature data), the bottom winds calculated according to the approach of Hasse (1974), which takes into account the temperature difference of water and air, gave the best agreement with the observed values and provided the decisive water level increase in the oceanographic model. For the estimation of the temperature stratification, the air temperature data of the collected archival data of the national meteorological services were used. For the water temperature, climatological monthly mean surface temperature values for November (Janssen et al. 1999) were applied.

3.4 Derivation of water level

The simulation of the storm surge of 1872 was carried out with the operational model system of the BSH (Kleine 2004, Dick et al. 2008), which takes into account the influence of the Northeast Atlantic and the North Sea on the water level of the Baltic Sea. Numerically, the model system at that time was based on finite differences with grid spacing of 0.9 km in the western Baltic Sea and the German Bight, 5 km in the rest of the North Sea and the Baltic Sea, and 10 km in the Northeast Atlantic. Vertically, generalised coordinates were used with up to 25 layers in the western Baltic Sea and the German Bight, 30 in the rest of the Baltic and North Sea and one in the Northeast Atlantic.

The Northeast Atlantic was described by a two-dimensional barotropic model. In the area of the North and Baltic Sea, a baroclinic three-dimensional model calculated the prognostic variables of layer thickness, horizontal current, temperature, salinity, ice thickness and ice compactness. Vertical current velocity and water level are then diagnostic variables. All prognostic variables require initial and boundary conditions.

The most important boundary condition here is the momentum input at the surface. In the area of the North Sea and Baltic Sea it is determined from the reconstructed 10 m winds. The parameterisation of the wind shear uses the linear approach for the wind shear coefficient of Smith and Banke (1975) for wind speeds up to 30 m/s. For higher wind speeds, the wind shear coefficient is kept constant. The above-mentioned change in interpolation method for the air pressure fields resulted in slightly higher maximum wind speeds and thus higher peak water levels for the western Baltic Sea. We compensated for this in the oceanographic model by reducing the wind speed threshold in the wind shear coefficient parametrisation from 30 m/s to 25 m/s.

The approach of Smith and Banke (1975) for the wind shear coefficient applies to neutral temperature stratification. The existing instability during the flood period is thus only taken into account in the estimation of the 10 m wind from the geostrophic wind. Since only the water level was to be simulated, the complex construction of air temperature fields from the data was dispensed with. Instead, the heat flux from air to water was calculated by setting the air temperature explicitly equal to the temperature of the water surface.

To drive the northeast Atlantic barotropic model, only wind values, derived from EMULATE data were used. Although very inaccurate, this simulates an inflow from the northeast Atlantic into the North Sea, especially during the first 10 days of the investigated period. The resulting boundary values for the North Sea were accordingly not included in the iteration process to adjust pressure to water level.

Tides are accounted for in the model equations via the potential of the tide-generating forces as direct tides (Müller-Navarra 2002). Co-oscillation tides are prescribed at the open north respectively west edge of the North Sea in the form of 14 partial tides. The corresponding constituents were added for 1872. The model results usually are in UTC. However, this is only important regarding tides. That they were correctly adjusted to 1872's data is seen for example in results for Flensburg and Husum (Figure 3a and Figure 8). The meteorological forcing is given in UTC.

The initial state of temperature and salinity was described by climatological November values (Janssen et al. 1999). Accordingly, only relative changes in salinity during the first 10 days of the simulation are accounted for. Such information could be understood as an indication of water transport but were not evaluated. No attempt is made to interpret the relative temperature fields either.

More importantly, only climatological values can be used for river inputs. However, we are not aware of any extreme inflows in the period under consideration (Krüger 1910). It is further assumed that the Baltic Sea was ice-free at the beginning of the simulation on November 1, 1872. During the simulation period, no ice formed in the model due to the inaccurate estimate of the heat flux, despite the cold spell mentioned.

A particular problem arises with regard to the water level. On the one hand, the water level in the model is related to an equipotential surface of the gravity, while, the measured data, on the other hand, is related to the mean sea level. This results in a necessary correction of modelled water level up to −0.422 m (St. Petersburg) for the Baltic Sea. In detail, the mean model sea level shows different horizontal deviations from the "mean water level". Accordingly, the initial distribution for the water level, which determines initial layer thickness, was constructed from annual mean values of the operational model for 2002 and the daily mean value of November 1, 1872 at Landsort. There are no gauge values for Landsort for 1872, but there are for Grönskär. According to Colding (1881), the water level there was 0.0 m on November 1. This value is also assumed for Landsort. For details and references compare Bork and Müller-Navarra (2009a, chapter 3.1.1).

4 Verification

4.1 Wind

The data of wind direction and wind speed at 10 m were calculated directly from the geostrophic wind independently of the known observed values. Their verification was thus possible with the available observations of wind force and direction from the coastal stations of the Baltic Sea. For this purpose, a comparison was made between the values of the coastal stations and the nearest sea point of the reconstructed wind grid data set. The wind observation values of the coastal stations (three observation times per day) were taken from the publication by Baensch (1875, Tables I to IV). The wind directions there were indicated in different angular spacing. There are stations with 8 and with 16 direction classes. For Flensburg, this less detailed data from table IV was also used for verification. The wind speed is given in a 6-level scale. An assignment to wind speed classes could only be roughly estimated. The values given in Table 1 were used to convert the wind forces to speeds in metres per second.

Table 1: Wind scale used by Baensch (1875) and its conversion to wind speed in m/s.

Wind scale (Baensch)	Converted wind speed classes
0	0–2 m/s
1	3–9 m/s
2	10–14 m/s
3	15–20 m/s
4	21–28 m/s
5	> 29 m/s

In any way, deviations are to be expected between wind observations at coastal stations and values calculated for nearby sea points. In addition, there are the mentioned uncertainties due to the standardisation of the collected air pressure values as well as finally the freedom of interpretation in manual air pressure analysis. In addition, especially the conversion method between geostrophic and 10-meter wind via the empirical approaches and the estimation of the thermal stratification necessary for this involves multiple simplifications.

A very effective check of the wind grid data was finally carried out indirectly by comparing the water level simulated by the oceanographic model system with the existing gauge data. While the reconstructed wind fields for the period from November 1 to 11, 1872 showed satisfactory agreement with the gauge data at the first attempt, the water level from November 12 onwards reacted sensitively and with large changes in the peak water level to relatively small changes in the pressure field. Although the overall shape of the water level curves matched during the first test run, the maximum heights did not. Eight modifications of the pressure field resulted in only minor changes. At last, a significant improvement was achieved by taking into account the thermal stratification when calculating the 10-m wind from the geostrophic wind. The change in the course of the iterations is shown for Flensburg in Rosenhagen and Bork (2009).

There remains, however, another problem. Numerous dam breaches and water ingress into the hinterland (e.g. Hemmelsdorfer See) on the Baltic Sea coast caused the water level to fall despite a persistent storm (Quade 1872, Griesel 1921). Where this is registered by gauges, the effect would enter the iteration and reproduce data on water level that modify the local wind in an ambiguous way. Therefore, no such locations were taken into account.

A comparison of the observed and the reconstructed winds for four Baltic Sea stations is shown in Table 2. Despite the simplified calculation methods, there is very good overall agreement both in terms of direction and speed of the wind during the time considered.

Table 2: Wind direction and force from observed data (left columns B) according to Baensch (1875), and from the reconstruction at the nearest grid point at sea (right columns R) for Flensburg, Lübeck, Putbus and Swinemünde between November 1 and 13, 1872.

Nov.1872		Flensburg				Lübeck				Putbus				Swinemünde			
day	hour	direction		force		direction		force		direction		force		direction		force	
		B	R	B	R	B	R	B	R	B	R	B	R	B	R	B	R
1	6		SW		3	W	W	3	2	SW	W	3	3	WSW	WSW	2	2
1	14		WSW		2	W	WSW	2	3	-	SW	3	2	WSW	WSW	2	2
1	22		SSW		1	W	SSW	2	1	SW	SW	2	2	WSW	SW	2	1
2	6		SSW		3	WSW	SW	3	2	S	SW	2	2	SSW	SSW	2	2
2	14		SSW		2	W	SW	3	1	S	SW	2	1	WSW	SSW	2	3
2	22		S		2	W	S	3	2	SE	SW	2	1	SW	SSW	2	3
3	6		SSW		1	W	SSW	3	2	S	SW	2	1	SW	SSW	1	3
3	14		WSW		1	WSW	WSW	3	2	S	W	3	1	WSW	WSW	3	2
3	22		WSW		2	WSW	W	3	2	W	W	3	2	SSW	WSW	2	2
4	6		WSW		3	W	W	1	2	W	W	3	3	W	WSW	2	3
4	14		W		2	NW	W	2	1	W	W	3	2	NW	W	2	2
4	22		SW		1	NW	WSW	1	1	SW	W	2	1	WNW	WSW	1	1
5	6		S		2	W	SSW	2	2	S	SW	1	1	SW	WSW	1	1
5	14		S		2	SW	SSW	2	3	SE	S	2	1	SW	S	2	3
5	22		WNW		1	SSW	W	1	1	SE	S	2	1	SW	SSW	1	3
6	6		SW		1	WSW	WSW	1	1	W		2	0	NW	WSW	1	1
6	12	SW		1													
6	14		W		1	W	WSW	1	2	SE	SW	2	1	W	SW	1	3
6	22		SW		3	WSW	WSW	3	2	S	SW	2	2	WSW	SW	1	2
7	6		SW		3	W	WSW	3	3	SW	W	3	3	WSW	WSW	3	3
7	12	SW		4													
7	14		W		2	W	WSW	3	2	SW	W	3	3	W	WSW	4	3
7	22		SW		2	W	WSW	3	1	SW	W	3	3	W	W	3	2
8	6		SW		2	W	WSW	1	2	W	SW	2	2	W	WSW	1	3
8	12	WSW		2													
8	14		W		2	W	WSW	2	1	SW	SW	2	1	WSW	WSW	3	1
8	22		W		1	W	WSW	2	1	SW	W	2	1	WSW	WSW	2	2
9	6		W		2	W	WSW	1	1	W	W	1	2	W	W	1	1
9	12	SW		1													
9	14		W		2	WNW	WSW	2	1	SW	W	2	2	W	WSW	1	1
9	22		SW		1	WNW	SW	1	1	S		1	0	W	SW	1	1
10	6		SW		1	W	WNW	1	1	S	SE	1	1	SE	SSW	1	2
10	12	SW		0													
10	14		SE		0	W	SSE	1	1	SE	N	1	1	E	ENE	1	1
10	22		SE		0	-	NNE	0	1	W	NW	1	1	NE	NNW	1	1
11	6		E		1	ENE	ENE	1	1	NW	N	1	1	-	N	0	2
11	12	NE		1													
11	14		N		1	ENE	NNE	2	1	N	NE	1	1	NE	NNE	1	1
11	22		NE		1	ENE	NE	2	2	NE	NE	2	1	NE	ENE	1	2
12	6		NE		2	ENE	ENE	3	2	N	NE	2	3	SE	ENE	4	2
12	ß8		NE		2												
12	12	NE		4													
12	14		NE		3	ENE	NNE	4	3	NE	NE	3	3	ENE	NE	4	3
12	22		NE		2	ENE	NNE	4	5	NE	NE	4	4	ENE	ENE	4	3
13	0		NE		3												
13	6		N		4	ENE	NE	4	4	NE	E	5	5	ENE	ENE	5	4
13	8		N		4												
13	12		NE		4												
13	14		NE		4	ENE	NE	4	3	E	E	3	4	E	E	4	3
13	18		NE		3												
13	22		E		3	ESE	ENE	3	3	E	E	2	3	E	ESE	4	4

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4.2 Water level

The water level observations cannot be used for the verification of the model simulations, as some of the observations were used to modify the constructed air pressure field towards a better modelling of the gauge measurements. That this was achieved satisfactorily is shown by the time series in Figure 3a-c and the peak water levels (Figure 4). This is less true for water levels in the remaining Baltic Sea. A comparison for Ölands Norra Udde is given in Rosenhagen und Bork (2009).

In the North Sea, the data for Den Helder and Cuxhaven are not reproduced despite error correction (for potential causes compare Janssen 2002). In contrast, the agreement for Husum is very good (Figure 8). Finally, in Figure 5a, a spatiotemporal distribution of the water level is given in comparison to one of the first set of maps by Colding (1881) in Figure 5b, which presents contours of water level together with lines indicating wind direction.

In figures and tables historical data are with respect to mean local water level (MW) in 1872 and local time, while model data are corrected in height to account for differences of model zero to NN (Mudersbach and Jensen 2009, Bork and Müller-Navarra 2009a, 3.1.2). Furthermore, model values are always extracted at a grid point near the station where measurements were taken, compare Bruss and Bork (2009, Figure 2).

Table 3 demonstrates the variation of data and includes corrections to model results for some stations. In Figure 5a model water levels are corrected in similar way as initial values.

Table 3: Extreme water levels evaluated by different authors (Baensch 1875, Baerens 1998, Mudersbach and Jensen 2009 Table 1) and corrections applied.

Gauge	Baensch 1875	Baerens 1998	Mudersbach 2009	Correction
	[m MW]	[m MW]	[m NN 2006]	[m]
Flensburg	3.31	3.08	3.27	−0.164
Schleimünde	3.44	3.21		−0.169
Eckernförde		3.15	3.40	−0.167
Kiel Holtenau	3.17	2.97	3.30	−0.169
Neustadt	2.95	2.82		−0.195
Travemünde	3.32	3.30	3.15	−0.195
Wismar		2.84	2.97	−0.195
Warnemünde		2.45	2.70	−0.216
Stralsund Hafen	2.46	2.41	2.56	−0.245
Greifswald	2.64	2.66	2.79	−0.246

Furthermore, the time of model data is corrected to local time, assuming one hour difference to UTC.

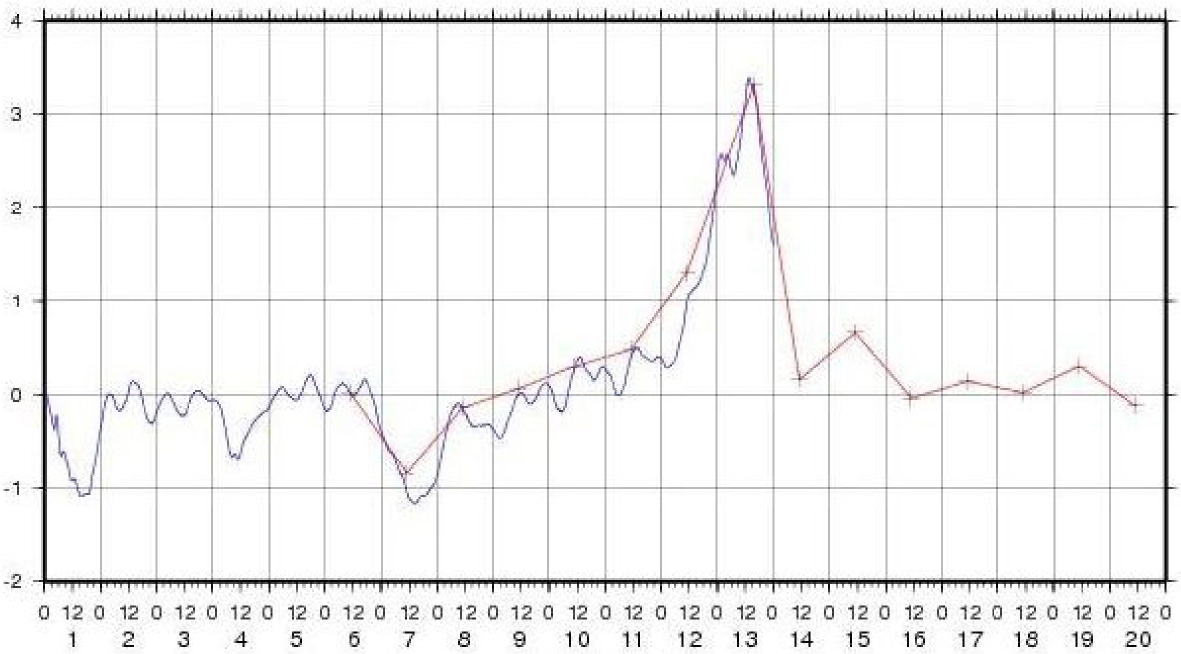

Figure 3a: Water level at Flensburg. Observations (m MW, local time, red) from Baensch (1875), November 6 to 20, 1872 and corrected model data (m NN, blue), November 1 to 13, 1872.

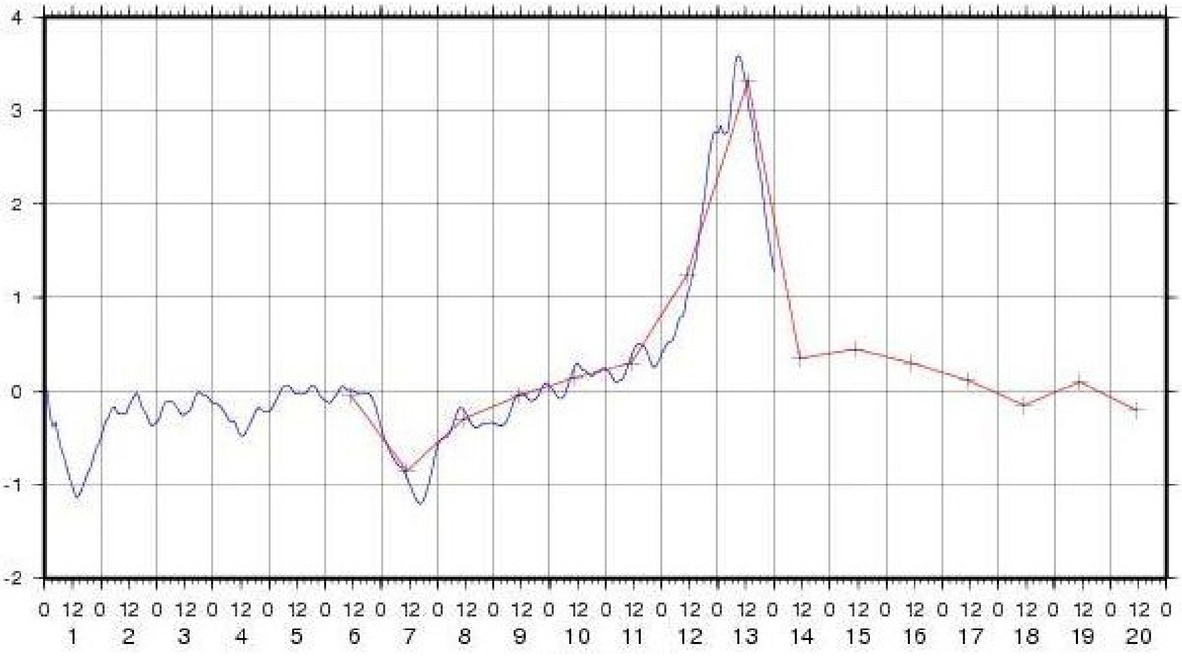

Figure 3b: Water level at Travemünde. Observations (m MW, local time, red) from Baensch (1875), November 6 to 20, 1872 and corrected model data (m NN, blue), November 1 to 13, 1872.

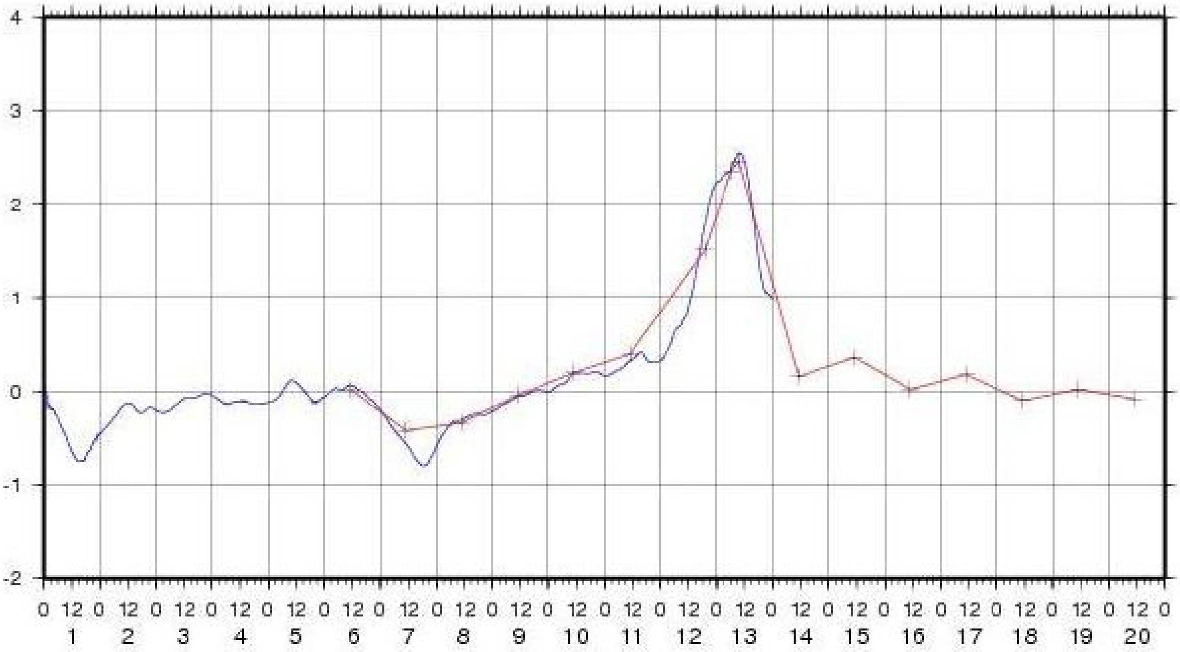

Figure 3c: Water level at Stralsund. Observations (m MW, local time, red) from Baensch (1875), November 6 to 20, 1872 and corrected model data (m NN, blue), November 1 to 13, 1872.

From Figure 3a-c it also is obvious that level readings not always coincide with time of maximum water level. E.g. for Flensburg and Travemünde there are only three readings during the time of the storms: November 12, midday, November 13, 4:30 p.m. and November 14, midday. For Stralsund and other places in the Bay of Mecklenburg there is additional information around the time of peak value of the flood. The most detailed observations exist for Kiel Holtenau (Figure 8).

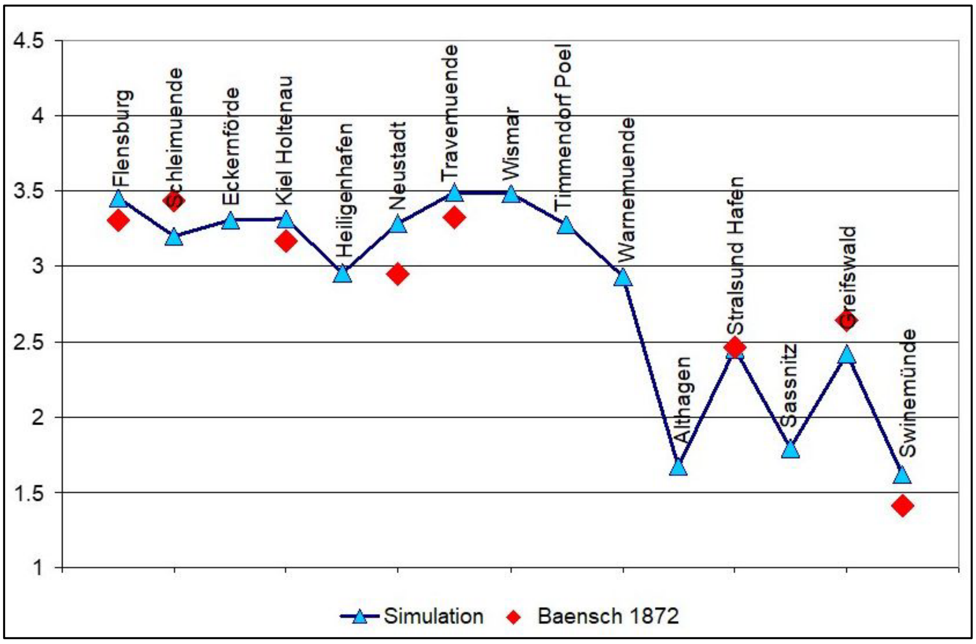

Figure 4: Peak water levels. Corrected model data (m NN, blue), observations (m MW, red) from Baensch (1875) for different places along the German Baltic coast, November 13, 1872.

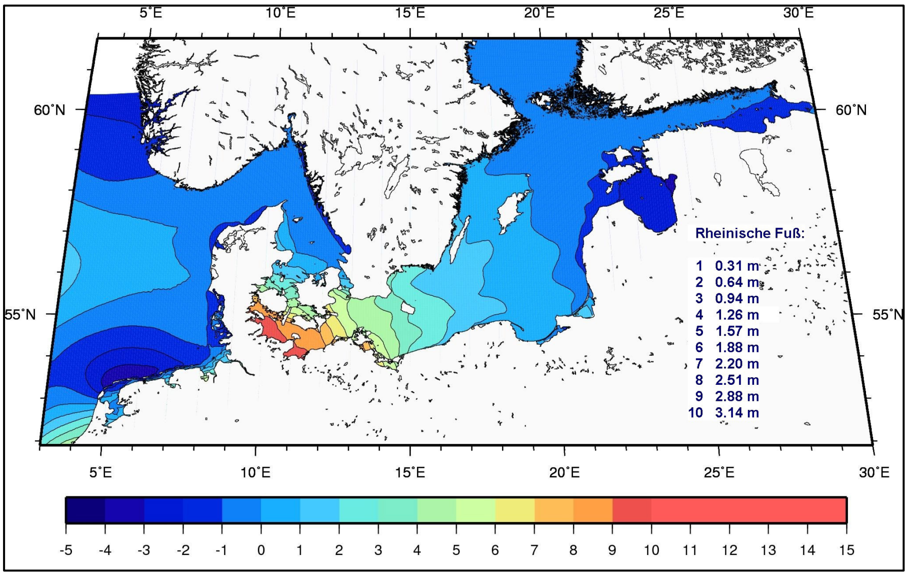

Figure 5a: Corrected water level on November 13, 1872, 2 p.m., converted to Rhenish feet for comparison to Figure 5b.

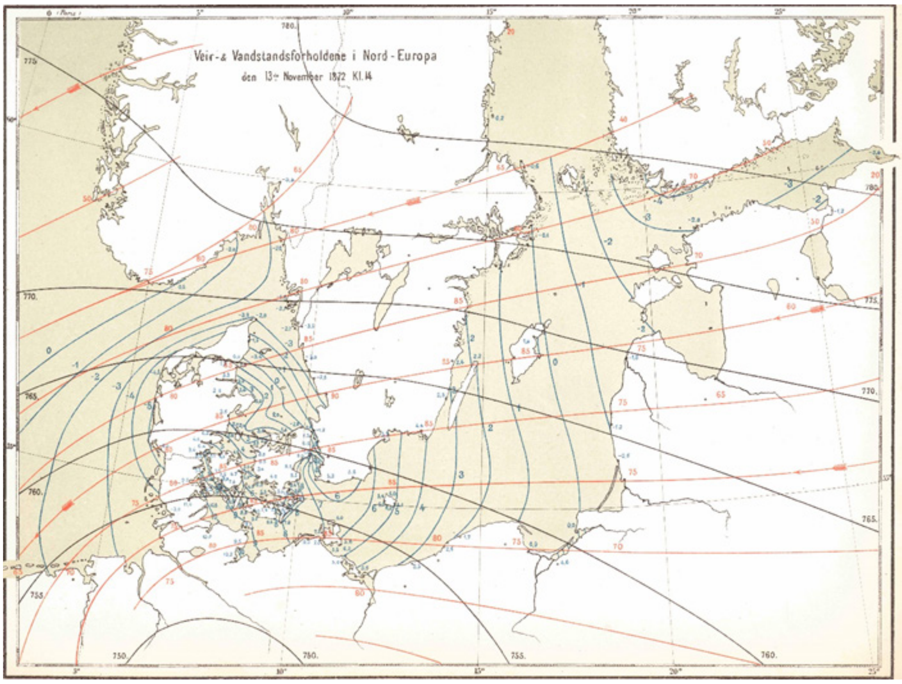

Figure 5b: Contours of water level in Rhenish feet (blue), atmospheric pressure (black) and lines indicating wind direction (red) on November 13, 1872, 2 p.m. (Colding 1881).

5 Weather pattern before and during the storm surge

5.1 Historical descriptions

In addition to measured and observed values, there are various contemporary descriptions of the weather before and during the storm surge.

The information on the course of the weather in November 1872 is incomplete, but in part quite differentiated. According to Quade (1872), there was severe gale from NE observed in Warnemünde as early as November 12. Hurricane-force wind from NE started there at midnight and turned to SE on November 13 around 2 pm. In Stralsund and Swinemünde (Swinoujscie), both storm and hurricane-force wind blew from NE (Baensch 1875). Krüger (1910) emphasises the change in wind direction of the extreme wind on November 13 from ENE east of Rügen to NE west of Rügen. In the attempt to explain the unusually high-water levels of 1872, later authors greatly simplify the course of the weather. Kiecksee (1972) writes about southwestern winds over the entire Baltic Sea from November 1 to 10, which intensified into a storm in the period from November 6 to 9. From November 10 in the evening to November 11 in the morning, he constructs a phase of calm over the entire Baltic Sea, followed by a wind from northeast, which increased to a storm in the course of November 12. Afterwards, he follows the description of Baensch (1875) for November 13, according to which gale-force winds first appeared around 2 a.m. at Colbergmünde (Kolobrzg) and reached Kiel (Ellerbeck) at 7 a.m. on November 13.

Contemporary explanations of the meteorological event are partly pictorially descriptive and are hardly sufficient to clarify the causes of the three-dimensional event. Baensch (1875) describes in detail a battle of polar and equatorial air masses. Kohlmetz (1967) and other authors explain the strong winds over the Baltic Sea from the Vb-weather situation. Baensch (1875) additionally outlines a secondary low over the river Oder.

5.2 Results of the reconstruction

The reconstruction of the weather situation of the period considered results in a rough division into three phases for the southern Baltic Sea, similar to the description in the historical sources:

November 1 to 9: prevailing westerly and south-westerly winds,
November 10: weather change,
November 11 to 13: increasing easterly winds with storm up to hurricane-force from northeast over the western Baltic Sea on November 13.

More details on the weather situation before and during the storm surge for the period from November 1 to 13, 1872 are presented in Rosenhagen and Bork (2009).

Contrary to what was predominantly described, the reconstruction does not explain the storm situation as the result of a typical Vb weather situation. Rather, on November 10, an extensive low-pressure system with two centres moved from the North Sea towards Central Europe. While the eastern centre shifted eastward, the western part migrated south-eastward towards Central Europe. There it remained until after November 13. Between November 10 and 12 the Central European low hardly intensified. Only with the inclusion of an Adriatic low-pressure area in the night of November 13 a rapid deepening to pressure values below 995 hPa occurred. Compare Figure 6b. Since November 11, the low over Central Europe was confronted with increasing high air pressure over Northern Europe, with the centre of the high slowly moving towards Central Scandinavia. In the second half of the day on November 12, the Scandinavian high intensified to more than 1045 hPa.

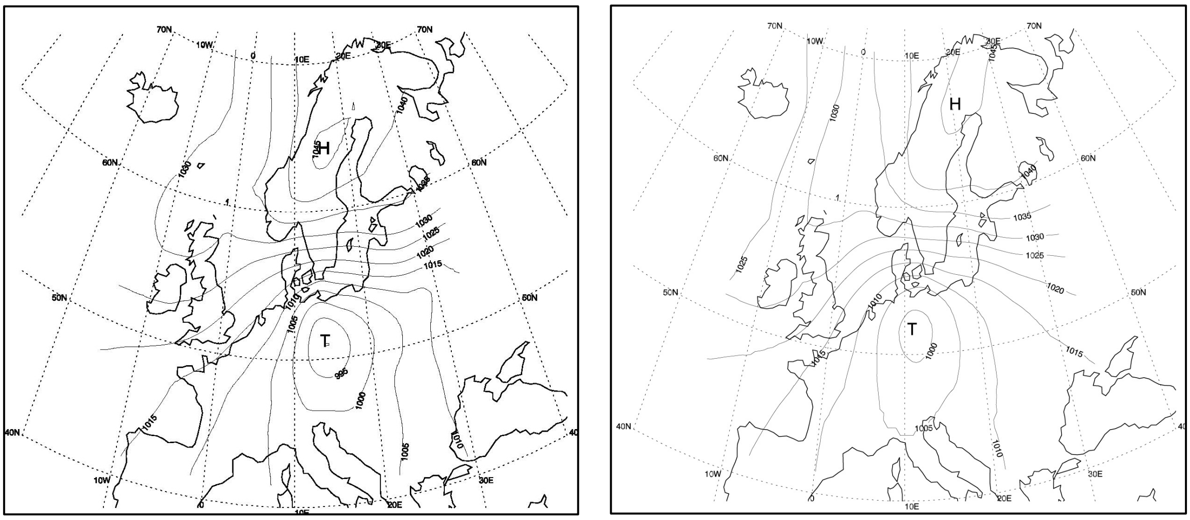

Figure 6a: Reconstructed air pressure fields on November 13, 6 a.m. (left) and 2 p.m. (right).

This resulted in an extreme air pressure gradient over the entire southern Baltic Sea leading to wind speeds of gale-force and more. Compare Figure 6b. While a north-eastern storm raged in the western part, easterly wind directions prevailed over the central and eastern areas of the southern Baltic Sea.

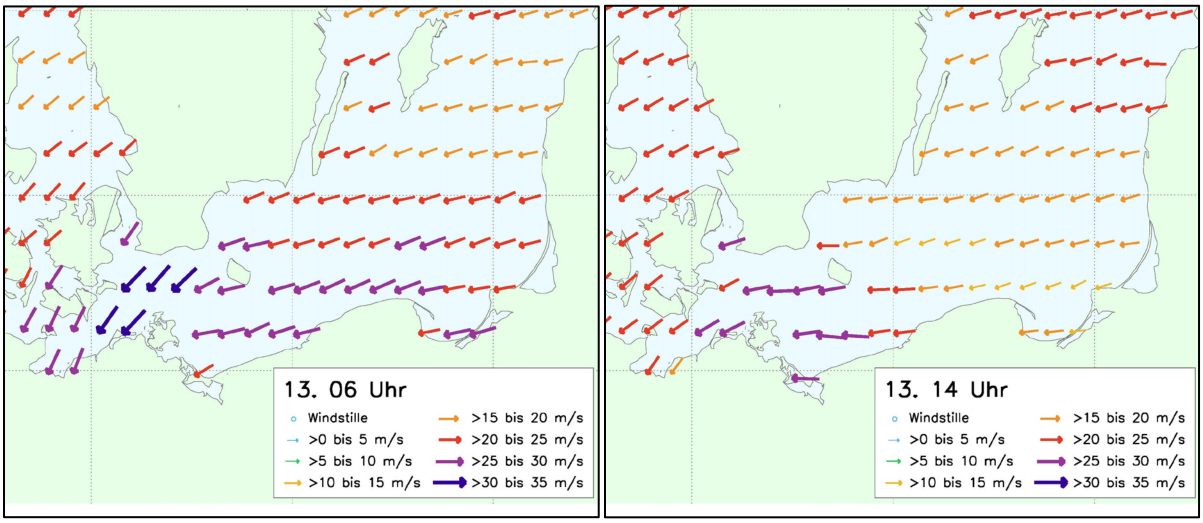

Figure 6b: Reconstructed wind distribution on November 13, 6 a.m. (left) and 2 p.m. (right), Windstille = calm).

Further wind distributions around 6 h, 3 h before and at the time of the peak water level for Flensburg, Travemünde and Greifswald can be found in Bork and Müller-Navarra (2009b) in comparison with the wind fields causing extreme surges calculated in project MUSE-Baltic-Sea.

6 Numerical Experiments

In the project MUSE-Baltic Sea, a total of 31,800 realizations of potentially extreme weather conditions were calculated using an ensemble prediction system (EPS) at 37 target dates (Schmitz 2009). Following a preliminary investigation (Bruss et al. 2009), 15 of these

 https://doi.org/10.18171/1.092103

were finally used to drive the model system of the BSH (Northeast Atlantic, North Sea and Baltic Sea).

In Bork and Müller-Navarra (2009b), the focus of the investigation was on a comparison of these extreme storm floods with that of 1872. Here the statements on the storm flood of 1872 are detailed.

In all figures, model values are always extracted at a grid point near the station where measurements were taken, compare Bruss and Bork (2009, Figure 2).

6.1 Motivation

The popular scientific image of the storm surge of 1872 is shaped by early ideas and roughly corresponds to the picture that Krüger (1910) draws of the typical course of a storm surge in the western Baltic Sea.

"Just as the high tide is preceded by a low tide, so too are the wind-generated tides in the western Baltic Sea. It is stormy SW to W (WNW) wind that creates these low tides on the coasts of the western Baltic Sea. They drive the water away from our coasts into the northern part of the Baltic Sea, filling it up and often creating storm surges on the Russian coasts.

These westerly winds, which cause low tide on our coasts, as soon as they prevail at the entrance to the Baltic and North Sea – here best as westerly to north-westerly – cause a current moving from N to S through the Sound and the Belts and thus an inflow of water from the Kattegat, further from the North Sea and the Atlantic Ocean into the Baltic Sea, then – preferably south-westerly winds – a further filling of the northern Baltic Sea.

These strong W to SW winds filling the northern Baltic are caused by deep (pressure) minima taking their migration north of us across Scandinavia or across the Baltic in a roughly west-easterly direction (the stormy weather on the right-hand side of the depression track!).

If, after a long period of strong westerly blowing winds, a strong N to NE wind suddenly develops, the water masses are driven back from the northern Baltic Sea and thrown particularly against the southern coasts of the western Baltic Sea, causing severe flooding here.

A hydrological sign of these storm surges is a rise in the water level on the southern coasts of the western Baltic Sea even with westerly winds, a sign that the northern Baltic Sea is already completely filled, so that a reverse flow had to occur despite the adverse winds.

If this sign is accompanied by a rapid rise in the barometer as a second (meteorological) sign with westerly winds after it had previously shown a very low level, the residents of the western Baltic Sea can count on a storm surge. The rise in the barometer indicates an air pressure maximum approaching from NE, which in connection with a low minimum approaching from the Atlantic (very low barometer reading!) caused the strong N to NE storms and thus the storm surges in the western Baltic Sea are."

The controversy in contemporary and more recent literature about the causes of the very high-water levels during the storm flood of 1872 also reflects aspects of this idea.

Since the hurricane-force wind on November 13, 1872 was devastating in its consequences, but according to contemporary information not completely exceptional in its strength, some authors suspect additional causes for the very high-water levels of 1872: in an increased mean water level of the entire Baltic Sea (Baensch 1875, Kiecksee 1972, Baerens 1998), in an increased return transport caused by wind (Grünberg 1873, Kiecksee 1972, Weiss and Biermann 2005). According to Grünberg (1873), this then leads to an extreme increase in the water level in the western Baltic Sea due to winds that prevent outflow into the North Sea. Other authors also discuss an unfavourable interaction with the Kattegat (Pralle 1875, Eiben 1992). It was also occasionally postulated that the storm on November 12, 1872 contributed to the high-water levels (Kiecksee 1972).

Colding (1881), on the other hand, emphasizes the sole effect of the storm for the flood on November 13, 1872. Krüger (1910) blames the turning of the hurricane-force wind as it progresses west for the particularly high water levels on the coast of Schleswig-Holstein. Lentz (1879) points out the particular expansion of the wind field. Recent investigations also suggest that the spatial extent of the strong wind band could have had a maximizing effect (Irish et al. 2008).

In addition to an increased filling level of the Baltic Sea, compensating processes such as seiches of the entire Baltic Sea are discussed as increasing causes for extreme storm floods (Meinke 2003, Fennel and Seifert 2008). Contemporary literature on the storm flood of 1872 also speaks of swinging back, supported by the effects of the wind (Grünberg 1873, Baensch 1875). Sager and Miehlke (1956), on the other hand, find no evidence of large-scale seiches in connection with extreme events.

6.2 Influence of the water level of the central and northern Baltic Sea

The calculations by Colding (1881) were later given little credit and in a German summary (Anonymous 1882) the translator noted the additional influence of a "Vorfluth" (previous filling of the Baltic Sea) in a footnote. The emphasis on the mean water level of the central and northern Baltic Sea is probably related to the beginning understanding of the circulation of the Baltic Sea (Meyer 1871). Today's ideas about the circulation of the Baltic Sea are more differentiated.

An overview of the physical conditions in the Baltic Sea including tides, storm surges and swell can be found in Feistel et al. (2008). The discussion presented here focuses on a storm flood in the western Baltic Sea consisting of the Bay of Kiel and the Bay of Mecklenburg. These parts of the Baltic Sea are flat and, together with the Kattegat, Belts and Sound, are part of the multi-connected transition area between the North Sea and the Baltic Sea. Of significant importance for the physical exchange processes are the Great Belt, the Fehmarn Belt, the Sound and the shallow sills (Darss and Drogden Sill) as boundary to the Arkona Sea and the central Baltic Sea (Jacobsen 1980).

Particularly important for the dynamics of storm floods in the western Baltic Sea is the short-term barotropic exchange across the sills and through the Belts and the Sound. In large-scale storm conditions, it reaches the order of magnitude of 10^5 m^3/s or 0.1 Sverdrup within a few hours (Müller-Navarra 1983, Lass and Matthäus 2008).

The inflow from the North Sea and the Atlantic is also emphasized in the quotation above (Krüger 1910). Weidemann (1950) outlines the position of the high- and low-pressure areas for optimal inflow and outflow conditions. In fact, the reconstruction shows air pressure distributions that favour an inflow, especially on November 4, 1872 (Rosenhagen and Bork 2009). However, the exchange rates between the western and central Baltic Sea change direction several times in the reconstruction at the level of Arkona. The maximum transport (15-minute average) from the western Baltic Sea is reached on November 4, 1872 with $4.4 \cdot 10^5$ m^3/s or 0.44 Sverdrup. A similarly high outflow was also modelled for November 7, 1872. These values already show that a preconditioning "Vorflut" of the Baltic

Sea through 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 together with swell.

For the argumentation in relation to the storm surge of 1872, the period over which an inflow situation can last must be considered. Literature and reconstruction assume SW to WNW winds up to November 10, 1872 in the Bays of Kiel and Mecklenburg. However, wind speeds vary greatly during this phase (compare Table 2).

More clearly than transport rates, a cumulative transport [m^3] describes the net flow from and into the western Baltic Sea. For the reconstruction, Figure 7 shows cumulative volume transports from the beginning of the simulation on November 1, 1872 for Fehmarn Sound and Fehmarn Belt, across the Darss Sill and into the central Baltic Sea (Arkona). The border to the central Baltic Sea was drawn from the east side of Rügen to Ystad in Sweden (compare Bruss and Bork (2009) Figure 15 and Baltic Operational Oceanographic System, BOOS, http://www.boos.org/transports/, section 29).

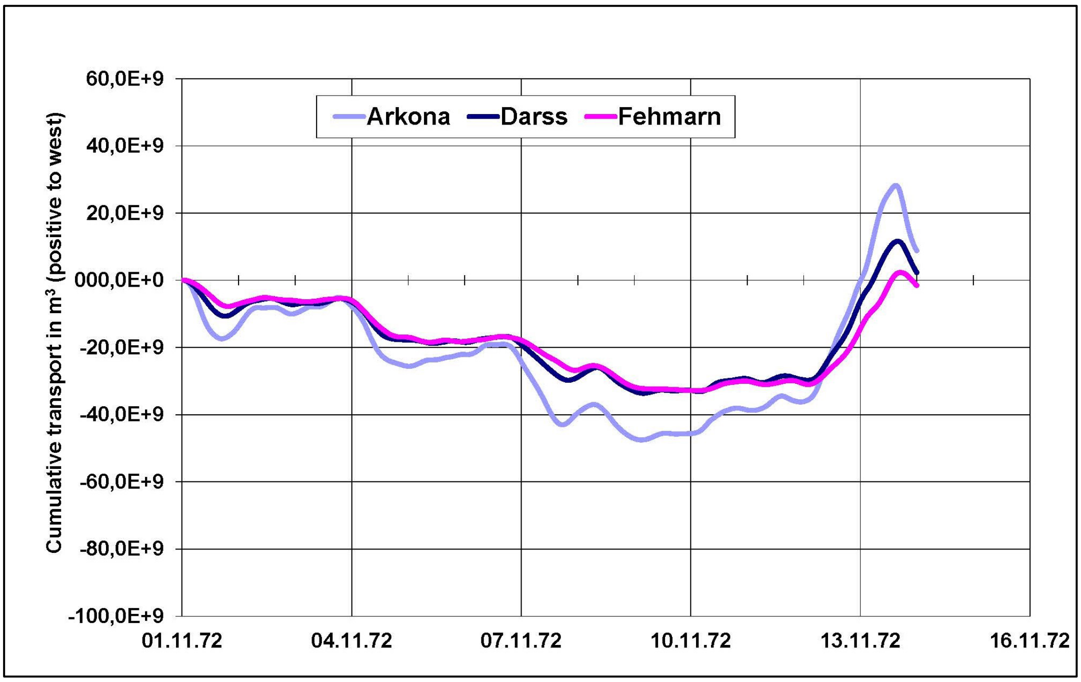

Figure 7: Cumulative transports (positive to the west) across sections at the level of Arkona (light blue), the Darss Sill (dark blue) and of Fehmarn (Belt and Sound, red) between November 1 and 13, 1872. Vertical lines mark the beginning of each day.

The cumulative volume transport from the western to the central Baltic Sea reached its maximum on the morning of November 9, 1872 with $-47.5 \cdot 10^9$ m^3. A significant decrease in the net outflow into the central Baltic Sea begins with the storm on November 12, 1872. At the beginning of the hurricane-force wind, the transport from the western Baltic Sea is then compensated and during November 13, 1872 a net inflow from the central Baltic Sea to the western Baltic Sea begins. It is at its maximum on the afternoon of November 13, 1872 with $+28.2 \cdot 10^9$ m^3. At the end of the reconstruction period it has already fallen to a third of this value.

The cumulative transport across the Darss Sill ran parallel to that at Fehmarn for a long time. Compared with Arkona, a significant decrease begins at about the same time, full compensation, however, is achieved a little later. In contrast, the maximum cumulative transport over the Darss Sill into the western Baltic Sea is reached at the same time, but is significantly lower at $+11.6 \cdot 10^9$ m³. Into the Bay of Kiel, a very short and minor cumulative transport, at most $+2.3 \cdot 10^9$ m³, occurs through the Fehmarn Belt and Fehmarn Sound.

In summary, the reconstruction shows that the cumulative transport into the central Baltic Sea was determined by the air pressure distribution on November 4, 1872. and November 7, 1872. In the remaining time until the weather change on November 10 it kept relatively constant. I. e. during such periods no substantial transport of water to or from the western Baltic Sea took place. A positive cumulative transport from the central Baltic Sea is only achieved with the hurricane-force wind on November 13, 1872. An increase in the water level in the western Baltic Sea and especially in the Bay of Kiel "even with westerly winds" (Krüger 1910, Grünberg 1873) cannot be explained by water transport from the northern Baltic Sea.

Pralle (1875) and Eiben (1992) also found a rise in the water level before November 12, 1872, but suspect only an unfavourable interaction with the Kattegat as the cause. As evidence of this, they cite the development of the water level in Husum and Kiel over time, in which, from November 8, 1872, a steady decrease in the mean water level in Husum corresponds to a steady increase in Kiel. Figure 8 shows the particularly well-documented development of the water level in Husum and Kiel in comparison with the reconstruction. According to the data, only the modelled high tides are given for Husum.

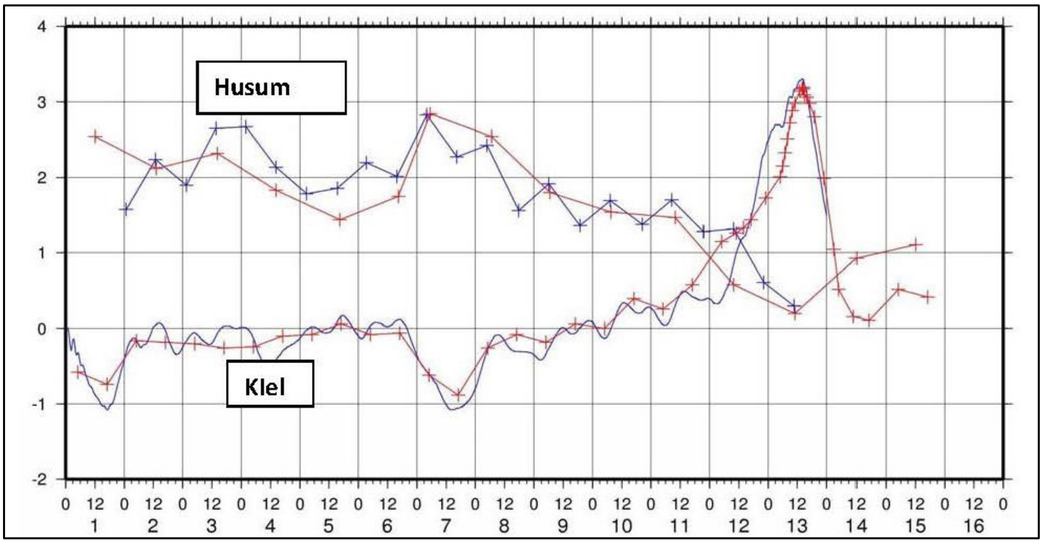

Figure 8: Observed high-tides at Husum (Pralle 1875) and water level at Kiel (Baensch 1875) for November 1 to 15, 1872 compared to corresponding reconstructed values for November 1 to 13, 1872: observations (m MW, local time, red), reconstruction (corrected, m NN, blue).Vertical lines mark the beginning of each day.

6.2.1 Experiment 1

Despite the above results of the reconstruction, the idea persists that long-lasting favourable winds could have led to the central and northern Baltic Sea being filled in at the beginning of November 1872 (Vorflut) and later contributed to an increase in the water level in the western Baltic Sea.

Therefore, in a numerical experiment, the wind distribution of November 4, 1872 was assumed to be stationary for the period from November 4 to 14, 1872. The associated air pressure field (see Rosenhagen and Bork 2009) led to the maximum inflow rate into the central Baltic Sea during the reconstruction period, but only lasted there for a short time.

After the water level in Landsort no longer increased, and even decreased slightly, the meteorological forcing was switched off in the entire model area on November 14, 1872 and calculations continued until the water level curve in Landsort flattened out significantly on December 2, 1872.

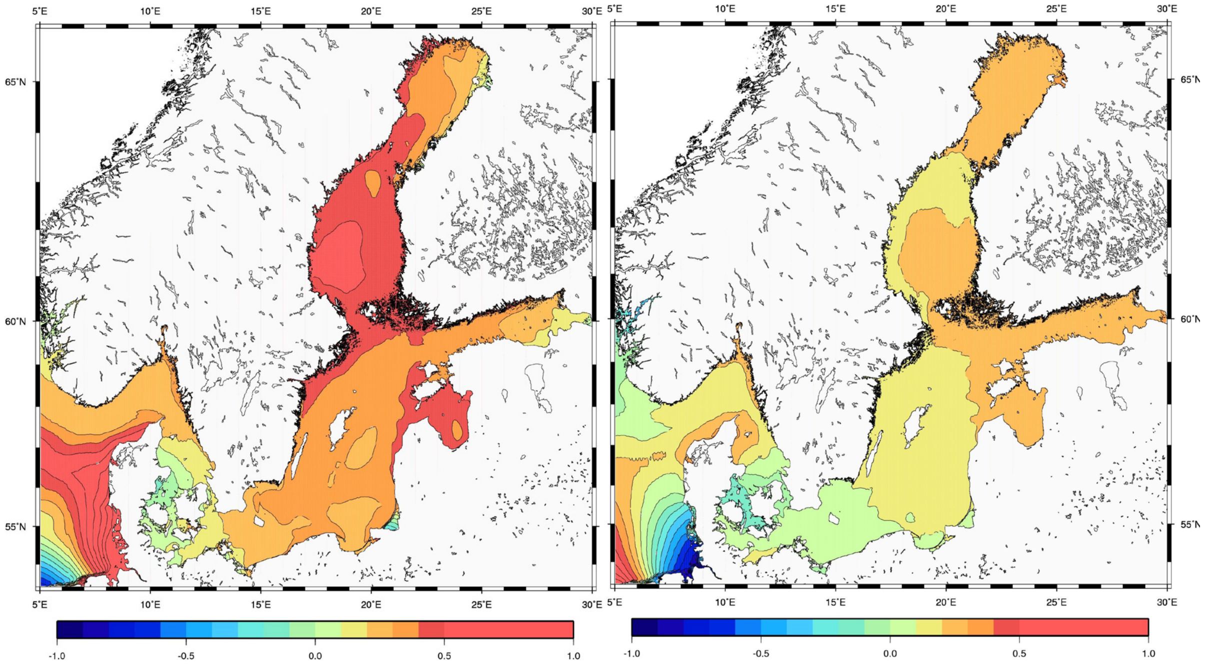

Figure 9: Left: Corrected water level in m NN in the Baltic Sea after 10 days of steady meteorological forcing. Right: Corrected water level of the reconstruction in m NN in the Baltic Sea at November 10, 1872.

Figure 9 shows the water level across the Baltic Sea at the end of the steady meteorological forcing compared to that during the reconstruction at the start of the weather change. The latter is significantly lower, in the central Baltic by about 0.2 m. In the Gulf of Bothnia, the difference is most pronounced. There, the water levels in the experiment on the Swedish coast reach values of over 0.5 m. These are clearly caused by the local, stationary wind on the north side of the low-pressure area and are independent of the water transport from the western Baltic Sea.

The reconstruction (Figure 9 right) also shows slightly increased water level (between 0.2 and 0.3 m) in the Gulf of Finland and Riga. The determination of its cause is difficult, since at the time of the second increased transport rate into the central Baltic Sea (on November 7, 1872) there was a depression over northern Scandinavia which also favoured an influx into these regions.

6.2.2 Experiment 2 and 3

As a contribution to the discussion about the influence of the degree of filling of the entire Baltic Sea on the water levels after the reversal of the weather situation on November 10, 1872, two further numerical experiments are presented. The reconstruction from November 10 to 13, 1872 was used as the meteorological forcing. Only the initial conditions for the water level were varied. This was realized by shifting the chronological assignment of the meteorological data to the beginning of the reconstruction (November 1, 1872, EXP 2) and the end of the filling experiment (November 14, 1872, EXP 3).

Figure 10a shows the development of the water level at Flensburg over time for the reconstruction and the two experiments. Figure 10b shows the corresponding distribution of the peak water levels. Experiment 2 starts with the initial state of the reconstruction on November 1, 1872. The resulting peak levels hardly differ from the reconstruction itself throughout. The greatest differences to the reconstruction are achieved in the third experiment, which started with an artificially generated high filling of the Baltic Sea (start on November 14, 1872), e.g. 0.16 m in Timmendorf on Poel and 0.08 m in Flensburg.

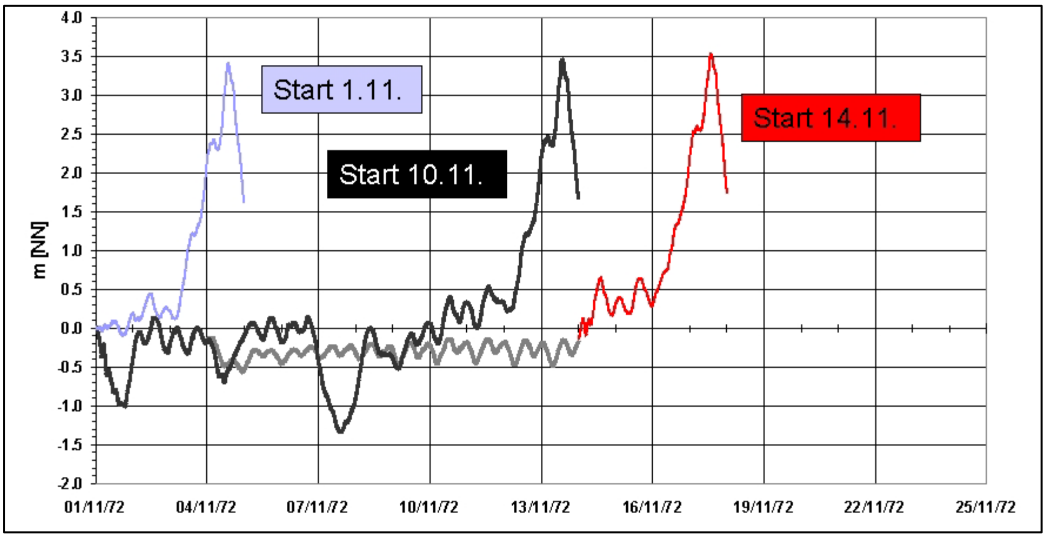

Figure 10a: Water level at Flensburg, for different initial conditions (blue EXP 2, red EXP 3) applying the meteorological forcing of November 10 to 13; compared to the reconstruction (black). Vertical lines mark the beginning of each day.

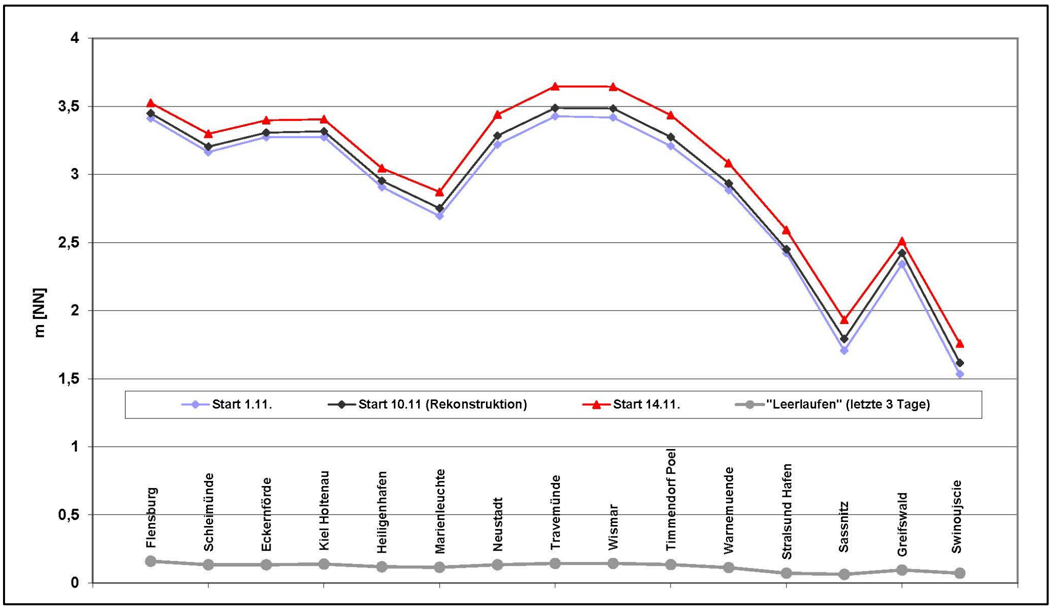

Figure 10b: Peak water levels for different initial conditions (blue EXP 2, red EXP 3) applying the meteorological forcing of November 10 to 13; compared to the reconstruction (black). Below, the peak water levels during the last 3 days of the “emptying phase” from experiment 1 are included.

In summary, it can be said that steady winds in the central Baltic Sea, which favour the inflow into the Baltic Sea, simulate higher water levels than in the reconstruction, but such winds are not observed for a long time. Rather, BOOS (http://www.boos.org/transports/) shows transport rates that have been documented for many years (daily average, inflow into the central Baltic Sea positive) for November, for example 2021, also briefly changing transport directions.

Finally, a clarification of terms is useful. "Vorflut" in the older literature describes a wind-related event with a spatially inhomogeneous rise in the water level, which completely filled the northern Baltic Sea in 1872 (Grünberg 1873; Baensch 1875). "Vorfüllung", on the other hand, is understood as an increase in the water level throughout the Baltic Sea.

The degree of "Vorfüllung" is well captured by the water level at Landsort. In MUSE-Baltic Sea, periods during which the mean water level in Landsort exceeds 0.15 m above sea level over 20 days were defined as periods with increased fill levels (Mudersbach and Jensen 2009). It should be noted that the water level in Landsort shows a clear annual variation with a range of 0.216 m, a maximum in December, which on the average was 0.084 m and a relative minimum of 0.048 m in November when considering data from the years 1899 to 1992 (Hupfer et al. 2003, local values corrected for eustatic changes). In 1872, during the reconstruction, starting on November 1, the value of 0.15 m was exceeded several times, but only for a short time in each case. Data are not available for Landsort. In the data from Norra Udde and Nedre Stockholm (see Rosenhagen and Bork 2009), the reference value of 0.15 m was exceeded only once up to November 10, 1872.

A climate-related rise in the sea level of the Baltic Sea is not discussed in connection with the storm flood of 1872. Krüger (1910) assigns the major storm floods up to 1904 to wet or dry periods (according to Brückner 1890) and finds that the majority of these storm floods, and especially that of 1872, occurred during a dry period.

6.3 Impact of the storm on November 12 on the peak water level 1872

Colding (1881) explains the water level in the Baltic Sea during the storm on November 13, 1872 as a direct result of the wind alone. To do this, he draws lines of equal water level based on collected data and compares them with values from wind data according to a relationship he had derived earlier. His formula corresponds to today's ideas, but neglects the Ekman transport (Ekman 1905). However, his maps also contain lines of wind direction. Noticing that the water level increases perpendicular to the wind direction and not parallel, he corrects his calculations accordingly and finds his theory confirmed.

The assumption is occasionally made in the literature (Kiecksee 1972) that the surge caused by the storm on November 12, 1872 contributed significantly to the increased water level during the hurricane-force storm on November 13, 1872. Enderle (1989) studied the time that elapsed between the onset of a storm and the peak water level in Flensburg. For storms from the north and from the east over the central Baltic Sea it is about 7 hours including the time that elapses between the wind picking up and the first water level change at a specific location. For storms over the western Baltic Sea, such delay disappears. For locations in the Bay of Mecklenburg, Miehlke (1990) calculated the time it takes a long wave on the optimal path (greatest depth) after a storm over the central Baltic Sea to contribute to the local surge. The times are between three and eight hours, depending on the starting point. These estimates confirm a statement by Baensch (1875), according to which the water level at the end of the storm on November 12 has reached a steady state in the western Baltic Sea.

6.3.1 Experiment 4

In experiment 4, the question is investigated whether a surge caused by the storm of November 12, 1872 increases the surge caused by the hurricane-force wind. Contradicting, there is the assumption that an existing stationary surge and the associated circulation make it more difficult to increase the corresponding water level further (Jeffreys 1923 and Heaps 1965).

Based on the water level at the end of the filling experiment (EXP 1, cf. Figure 9 left), simulations were carried out with the meteorological conditions of November 10 to 13 (EXP 4c) and of November 12 to 13 (EXP 4b). Finally, the conditions of November 13, 1872 alone were used (EXP 4a).

The difference in water level resulting from EXP 4c, which only neglected the phase before the weather change and the experiment driven by the complete meteorological forcing of the reconstruction, shows only slight differences in the peak water levels for all locations.

At Flensburg, the surge exclusively caused by the hurricane-force wind on November 13 exceeds the surge caused by a combination of the preceding storm and the one on November 13 and thus confirms theoretical considerations. The result for Flensburg is representative for the Bay of Kiel. In other places, the corresponding peak values are well below those caused by both storms.

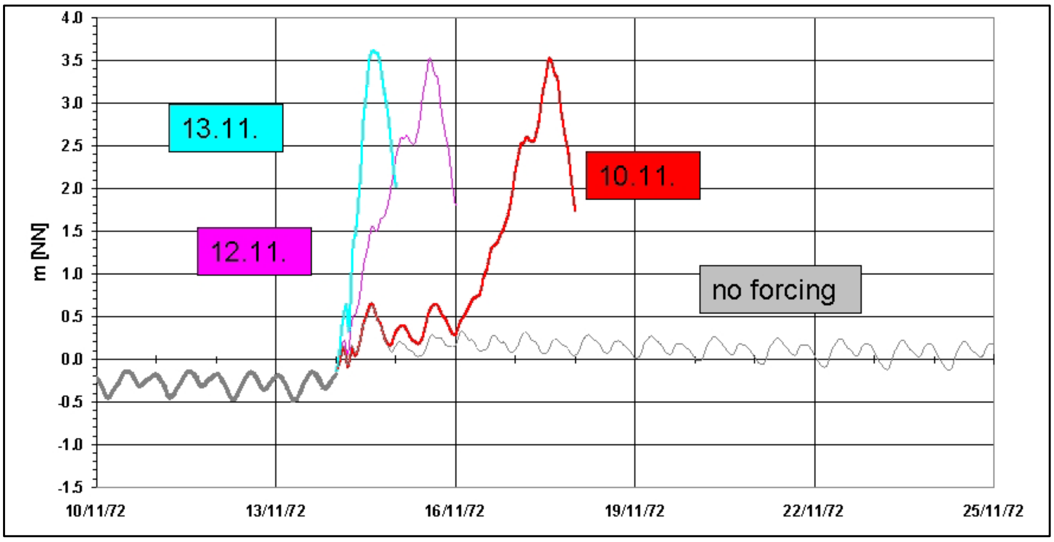

Figure 11: Water level at Flensburg according to EXP 4a (hurricane-force wind only, turquoise, 13.11.), EXP 4b (both storms only, petunia, 12.11.), and to EXP 4c (both storms including the meteorological forcing after change in wind direction, red, 10.11.). Vertical lines mark the beginning of each day.

Experiment 4 confirmed the thesis that the storm the day before rather had a hindering influence on the surge caused by the hurricane-force wind on November 13, only concerning results in the Bay of Kiel. The reasons for the different dynamic behaviour in the Bay of Mecklenburg (Travemünde to Warnemünde) were not examined in detail. A possible explanation is that the direction of the hurricane-forced wind on November 13, 1872 was not optimal for the Bay of Mecklenburg with ENE (Baensch 1875).

6.4 Influence of seiches on extreme storm floods

Another cause assumed to be significant in the literature for storm floods are oscillations of the entire Baltic Sea (Leppäranta and Myrberg 2009, Lass and Matthäus 2008) or also local oscillations (Enderle 1981). These latter are also cited regarding the storm flood of 1872. According to Meinke (2003), seiches covering the whole Baltic are predominantly assigned to storm surges where the causing storm comes from the north-west or follows a relatively rare path from the north-east.

For the storm flood of 1872, after the "Vorflut", a "swinging of the Baltic Sea water to the west with overfilled basins" is postulated as maximizing (Baensch 1875). For other storm floods, local oscillations and, in particular, oscillations in the western Baltic Sea/central Baltic Sea/Finnish Gulf system were assumed to be relevant (Meinke 2003, Fennel and Seifert 2008). Sager and Miehlke (1956), on the other hand, "hardly ever found any indication of their [seiches] occurring" in extreme situations.

Detailed theoretical statements on seiches of the Baltic Sea can be found elsewhere (Bork and Müller-Navarra 2009b). Only a few aspects should be emphasized here.

In model investigations, seiches are often generated by artificial surface deflection. In addition to such balancing processes, oscillations that are excited by low-pressure areas passing through have also been investigated in the literature (Gill 1982).

In models like the one used in MUSE-Baltic Sea, there are no "free" waves determined only by gravity, even without meteorologically forced movements. Rather, after an initial deflection, oscillations are always under the influence of earth rotation, tides, internal and bottom friction, and tidal interaction with the North Sea.

Furthermore, the response of models to deflections from equilibrium is significantly determined by the quality of the representation of the bathymetry (Jönsson et al. 2008). With sufficiently fine resolution of the Baltic Sea, the oscillations of individual bays and gulfs turned out to be decoupled and the oscillations of the central Baltic Sea occur only as a superimposition of radiation from the individual systems. Therefore, conclusions from level recordings on seiches of the entire Baltic Sea are fundamentally questioned. The model used in MUSE-Baltic Sea (as of 2009) resolves the western Baltic Sea better and the rest of the Baltic Sea worse than would be necessary for complete decoupling. The joint simulation of the North Sea and the Baltic Sea is particularly good at recording the oscillating behaviour of the Bay of Kiel.

6.4.1 Experiment 5

To simulate a return to equilibrium from maximum deflection in St. Petersburg, the wind was reduced linearly to 0 m/s and the air pressure to a constant value during the hour after the maximum water level there.

During the reconstruction of 1872, neither St. Petersburg (at the end of the Gulf of Finland) nor Ratan (in the middle of the Gulf of Bothnia) reached particularly high-water levels. Therefore, experiment 5 resulted in Flensburg only in disturbances similar to those at the time of the weather change on November 10, 1872 (cf. Bork and Müller-Navarra 2009b, Figure 21).

In order to get a clear picture, the experiment was also carried out for an extreme variation of the 1971 storm flood generated in MUSE-Baltic Sea.

In this realization, the storm came from the north-east on a path favourable for flooding in St. Petersburg (Averkiew and Klevanny 2007). Only later, when the storm had subsided over the Gulf of Finland, the low-pressure area led to a storm surge in the western Baltic Sea. Although at the time of the maximum water level in St. Petersburg, water levels in the western Baltic Sea were below sea level e.g. in Flensburg, the causes of both were clearly decoupled.

Figure 12 shows the development of the water level in the experiment 5 (right) compared to the original realization (left) for Flensburg and St. Petersburg. The water level in Hirtshals, which has about the same tidal phase (principal semidiurnal lunar constituent, M_2-tide) as Flensburg (Müller-Navarra 1983), is also included.

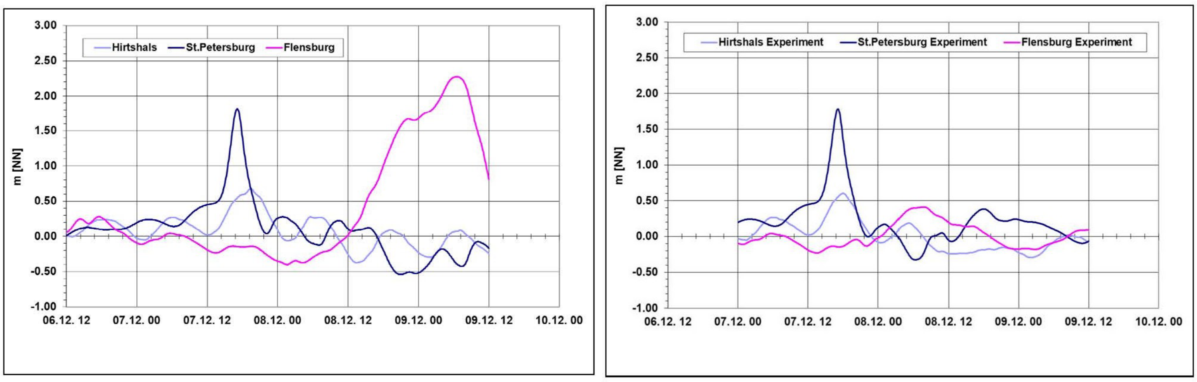

Figure 12: Water levels at St. Petersburg, Flensburg and Hirtshals for a variation of the storm surge in December 1971 (left) and for experiment 5 (right). Vertical lines mark the beginning of each day.

The disturbance, which spreads at the speed of long waves, reached the western Baltic Sea much earlier than the low-pressure area that caused the storm over the western Baltic Sea. The signal in Flensburg (and other places in the western Baltic Sea) was less than a third of the original deflection of water level in St. Petersburg.

For 1872, too, the disturbance reached Flensburg long before the first storm on November 12, but in contrast to experiment 5 it appears to not be attenuated. In this case, local (!) seiches were probably excited by the disturbance. For example, such oscillations in bays were documented for the Bays of Eckernförde and Kiel with regard to a storm in 1961 by Geyer (1965).

6.5 Discussion

Returning to the statements by Krüger (1910), it is unquestionable that westerly winds are offshore for parts of the western Baltic. It is also true that they may cause an influx to the central and northern Baltic from the Atlantic and the North Sea. However, such fluxes are short-term only. Additionally, they changed direction several times between November 1 and 10, 1872.

In particular, the reconstruction shows no positive cumulative transport into the western Baltic Sea prior to the onset of the hurricane-force wind on November 13, 1872. Increased water levels in the Bay of Kiel before November 12 were explained by the interaction with the North Sea (Pralle 1875).

Furthermore, the reconstruction did not show any extremely high water levels in the northern Baltic Sea and even these cannot be clearly attributed to the influence of the wind over the western Baltic Sea. Oscillations in Flensburg in Experiment 5 (1872) should be interpreted as local seiches.

Of course, it also remains undisputed that storm from the N and NE causes flooding on parts of the coast of the western Baltic Sea. In the controversy over additional causes for the extreme flood of 1872, Colding's (1881) thesis was supported by Experiment 4.

The graphical representations of the results from Section 6.2 to 6.4 are summarized in Table 4a-b below.

Table 4a: Peak water levels in m NN concerning the effect of water level, experiment 1 (EXP 1), experiment 2 (EXP 2, Start 10.11.), experiment 3 (EXP 3, Start 14.11.) compared to the reconstruction (R), compare Figure 10.

	EXP 1	EXP 3	EXP 2	R	Difference EXP 3 – EXP 2
Flensburg	0.13	3.53	3.41	3.45	0.08
Travemünde	0.03	3.65	3.43	3.49	0.16
Stralsund	0.04	2.59	2.42	2.45	0.14
Landsort	0.39	0.41	0.09	0.21	0.18
St. Petersburg	0.91	0.57	0.09	0.91	-0.34

Table 4b: Peak water levels in m NN concerning the effect of wind, hurricane-force wind only (EXP 4a, 13.11), both storms (EXP 4b, 12.11.) and meteorological forcing since weather change (EXP 4c, 10.11.), compare Figure 11.

	EXP 4a	EXP 4b	EXP 4c	Difference EXP 4a – EXP 4 b
Flensburg	3.61	3.53	3.53	0.08
Travemünde	3.51	3.61	3.65	-0.11
Stralsund	2.76	2.60	2.59	0.15
Landsort	0.50	0.41	0.41	0.09
St. Petersburg	0.43	0.45	0.57	-0.14

7 Conclusions

The weather from November 1, 1872 to November 13, 1872 has successfully been reconstructed as well as the resulting storm surge on November 13, 1872. However, the iterative adaptation of the air pressure to the water level data concentrated on the German coast and still offers potential for other coastal regions.

The reconstruction and the numerical experiments presented support the thesis that the extreme water levels in the western Baltic Sea during the storm flood of 1872 were caused solely by the stormy winds, especially by the hurricane-force wind on November 13, 1872. Winds above 20 m/s for November 13, 1872 in comparison to maps of extreme variations of observed storms realized in the project MUSE-Baltic Sea are shown in Bork and Müller-Navarra (2009b). These indicate that the hurricane-force wind on November 13, 1872 differed from other extreme storms only by small, random deviations in direction, spatial extent and temporal development.

In contrast, the assumption of preconditioning events such as a "Vorflut" is rejected and consequently also a contribution of "back flowing water or a swinging back" of water piled up in the central or northern Baltic Sea. So there have been no amplifying effects on the flood caused by the hurricane-force wind.

8 Acknowledgements

We especially thank the National Meteorological Services of the European countries who provided their historical meteorological records. These were the National Meteorological Services of Austria, Begium, Belarus, Croatia, Denmark, Estonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Norway, Poland, Portugal, Russia, Slovakia, Spain, Sweden, Switzerland, The Netherlands, Ukraine and United Kingdom. Only this made the reconstruction of the devastating storm surge possible at all.

Furthermore, we would like to thank all colleagues of the German Meteorological Service, DWD, in Hamburg, the Federal Maritime and Hydrographic Agency, BSH, and of other German and foreign departments for the extensive support of the investigation.

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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.

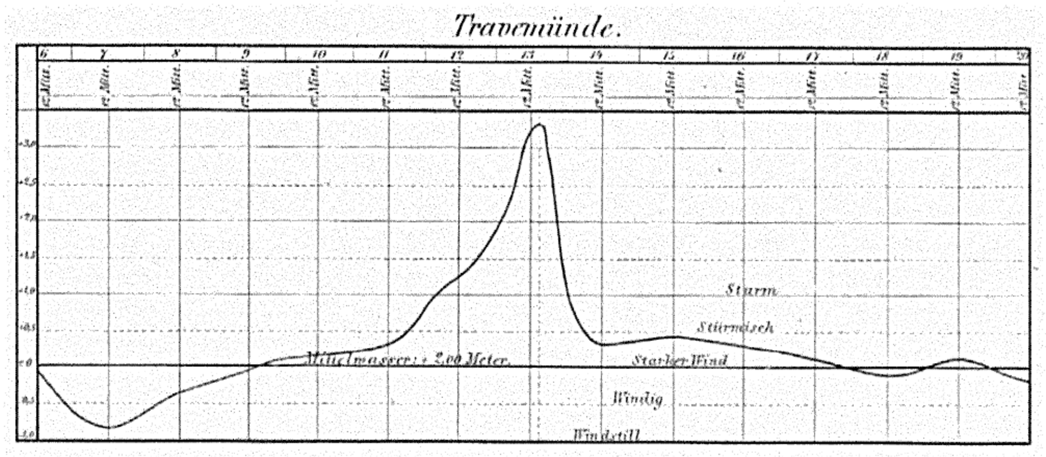

Figure 3: Hydrograph for the storm surge of 1872 according to Baensch (1875), exemplary for the gauge station of Travemünde.

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.

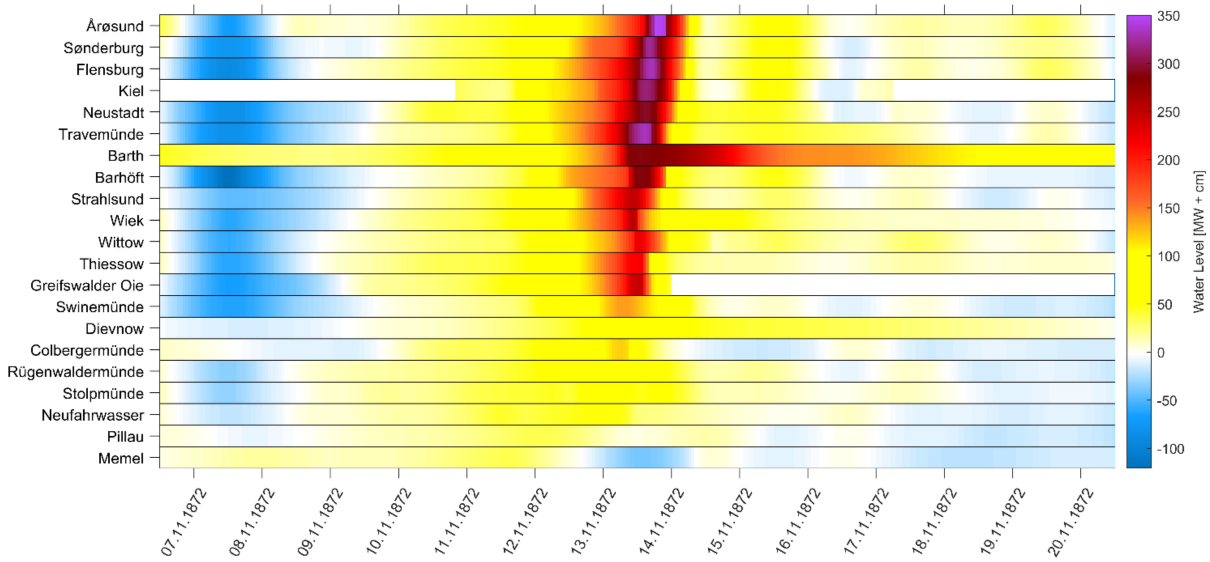

Figure 4: Summary of the hydrographs from 06.11.1872 to 20.11.1872 at the gauge stations according to Baensch (1875).

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.

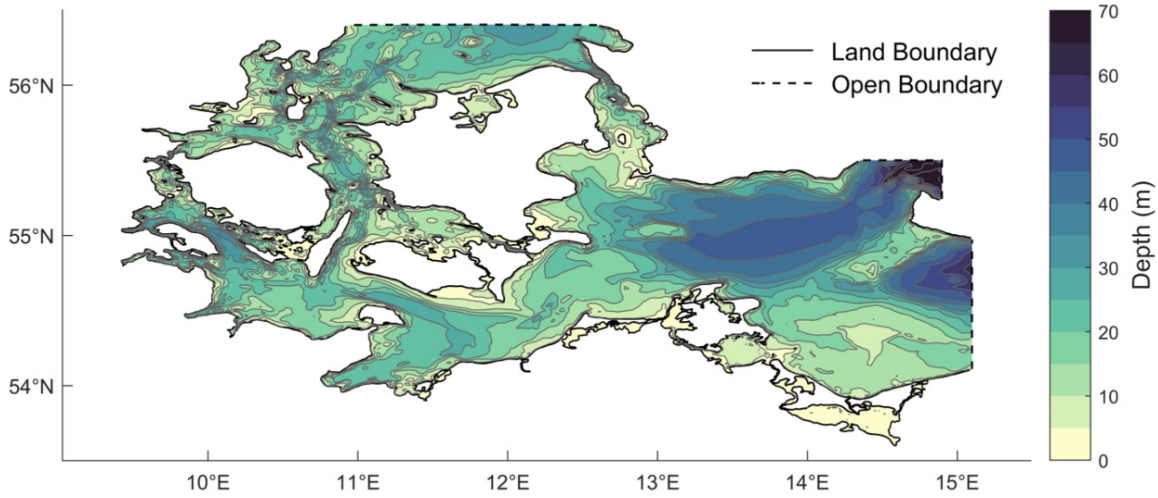

Figure 5: Bathymetry (model domain) of the used hydrodynamic Model based on SCHISM with boundary information.

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:

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

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

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

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).

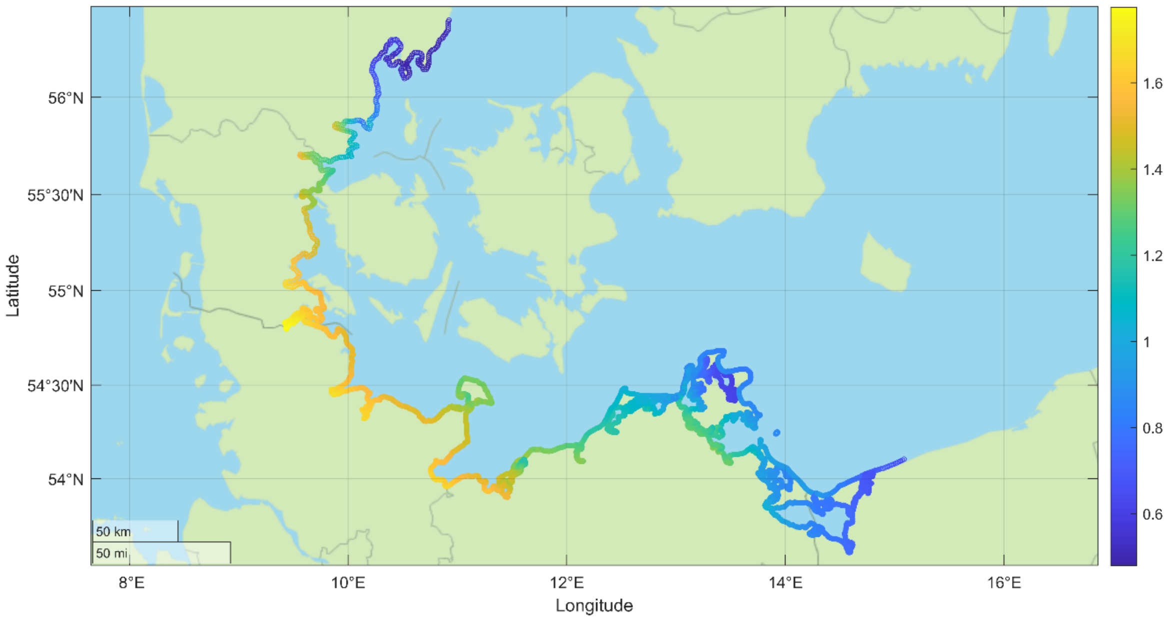

Figure 6: Peak water levels of the model-generated data of the storm surge 1872.

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.

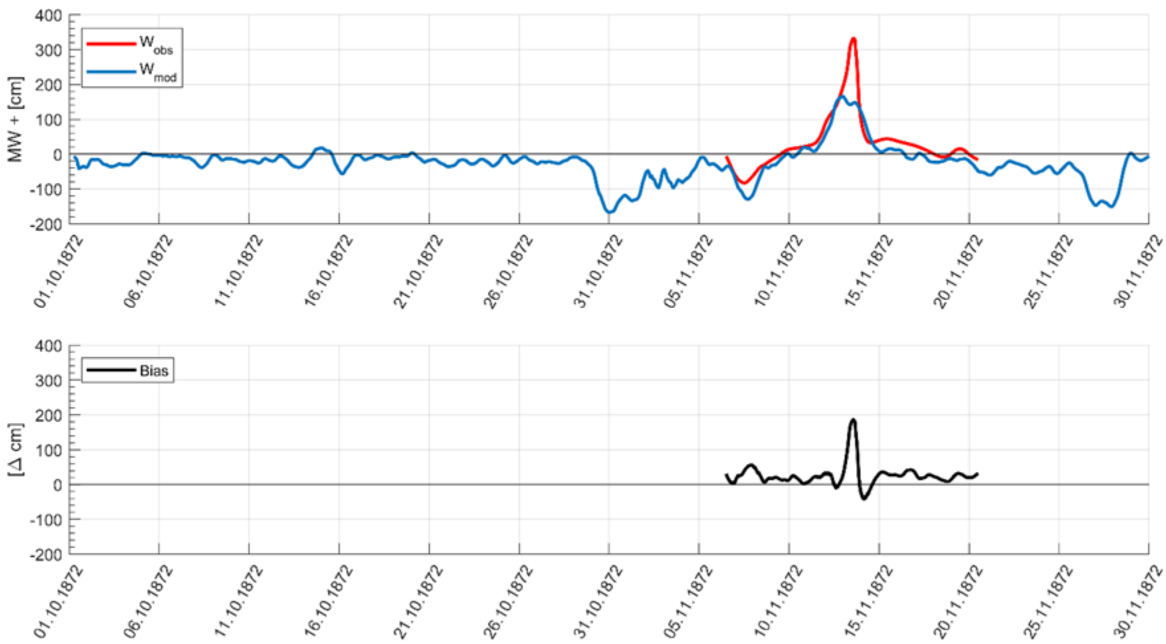

Figure 7: Comparison of the model-generated hydrograph with the water level hydrograph according to Baensch (1875) for Travemünde gauge. In addition, the bias between the hydrographs is shown below.

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.

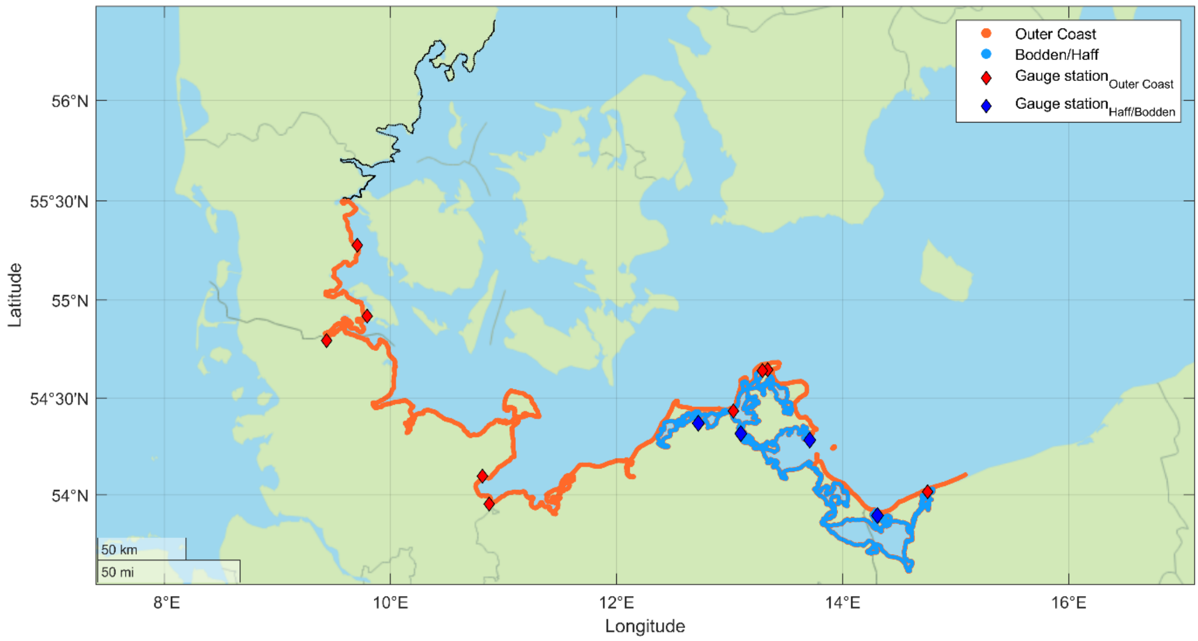

Figure 8: Visualization of the division of the coastline into two parts to respect the local conditions for statistical correction of the model data, including the distribution of the associated reference gauge stations used for Bias Correction.

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.

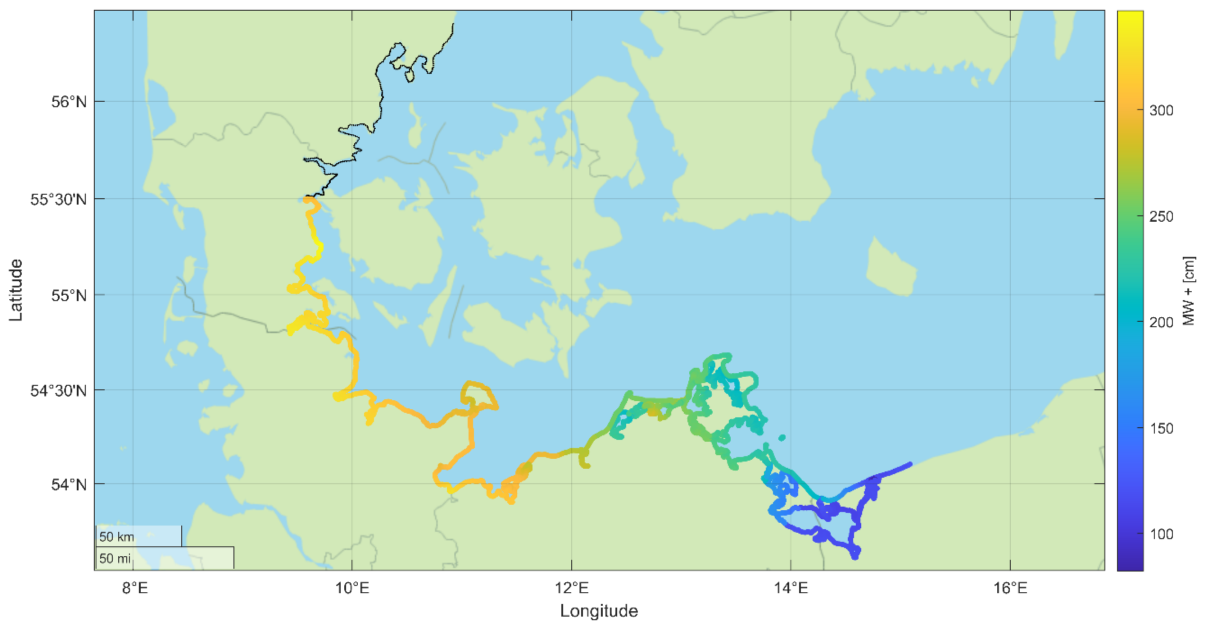

Figure 9: Peak water levels of the corrected, model-generated water levels along the Baltic Sea.

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.

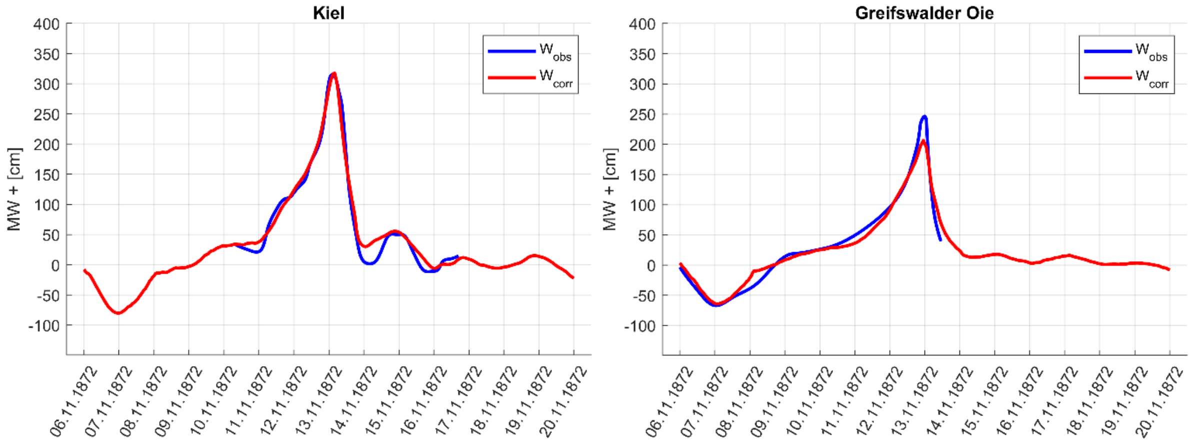

Figure 10: Comparison between corrected and measured hydrograph at the two gauges Greifswalder Oie and Kiel, to validate the assumptions made with the invers-distance weighted Bias Correction.

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.

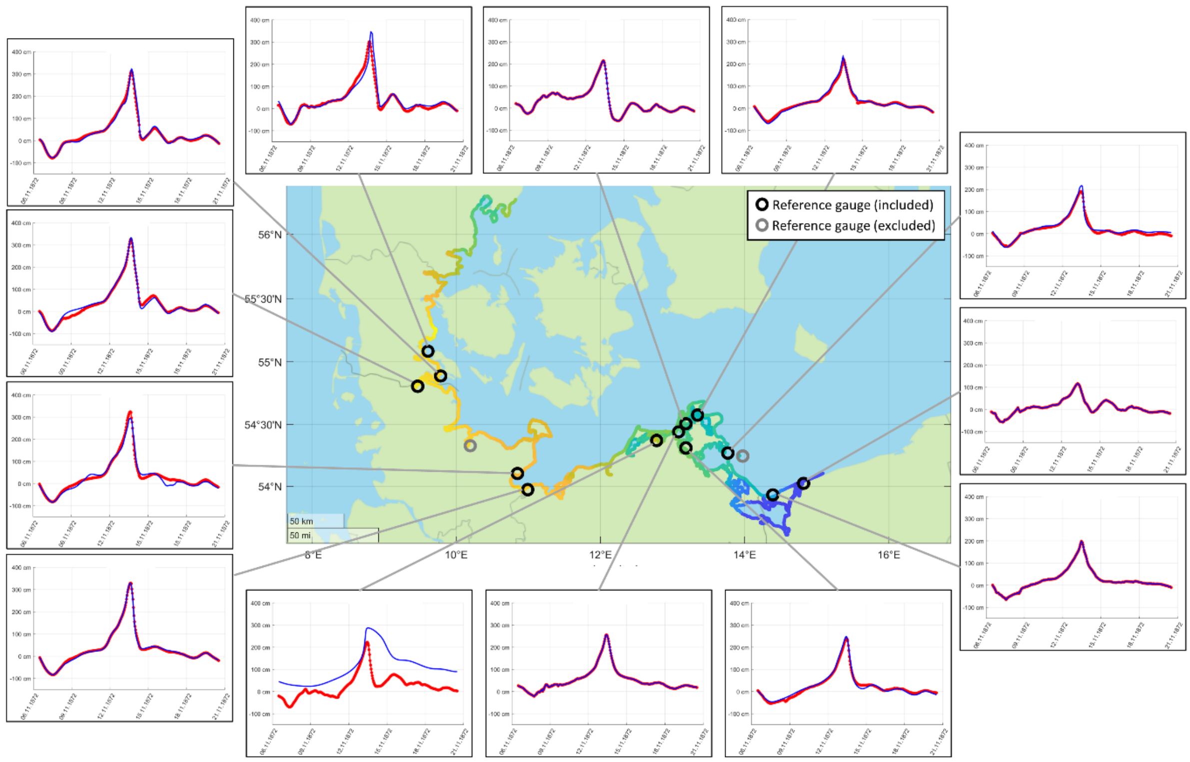

Figure 11: New generated hydrographs at the reference gauge stations as a result of validating the assumptions made with the Bias Correction by removing reference values from the collective.

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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ISBN 978-3-939230-83-0

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