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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 (*Illustrierte 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.

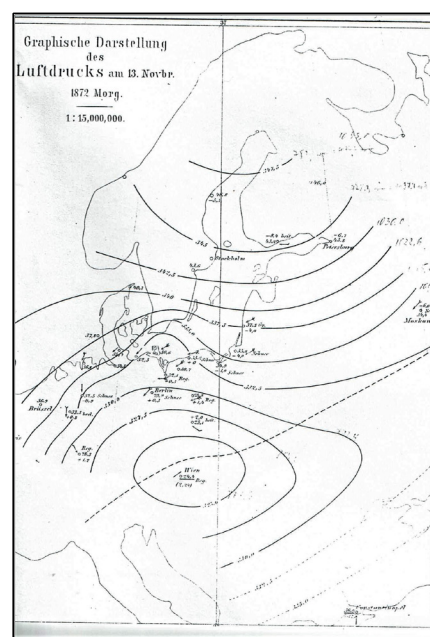
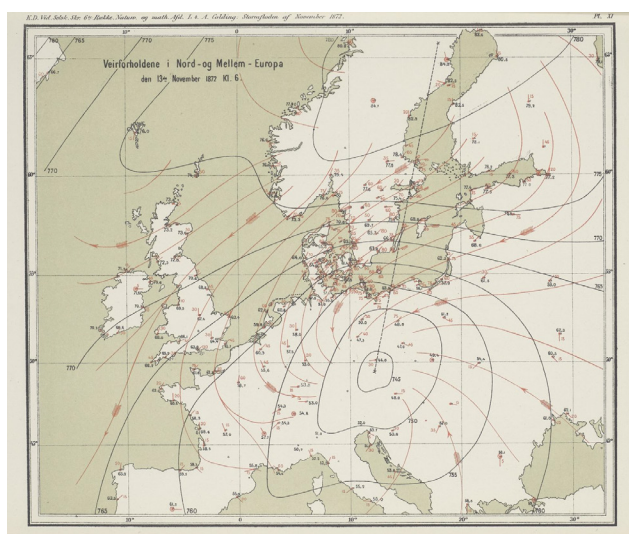


Figure 1: Weather maps, November 13, 1872 in the morning, left: after Colding (1881), right: after Baensch (1875).

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.

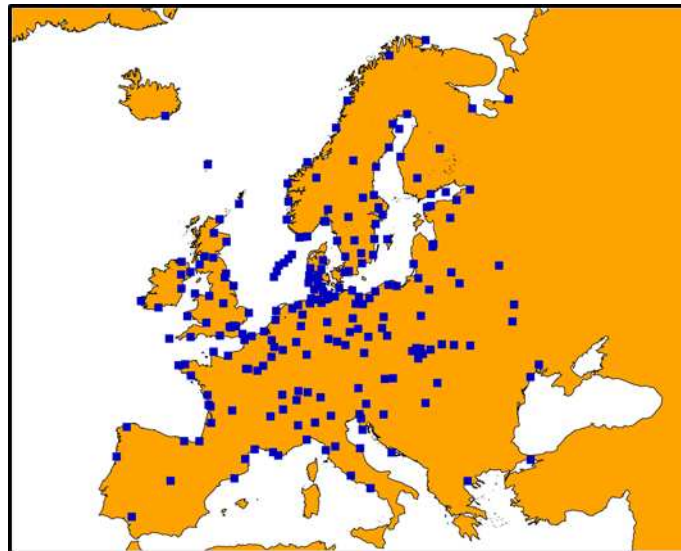


Figure 2: Stations with meteorological data available for the reconstruction.

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

(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 parameterisation 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. Hemmeldorfer 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		W	WSW	1	2	SE	SW	2	1	W	SW	1	3
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		W	WSW	3	3	SW	W	3	3	W	WSW	4	3
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		W	WSW	2	1	SW	SW	2	1	WSW	WSW	3	1
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		W	WSW	1	1	W	W	1	2	W	W	1	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		W	WNW	1	1	S	SE	1	1	SE	SSW	1	2
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		ENE	ENE	1	1	NW	N	1	1	-	N	0	2
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	8	NE		2		ENE	ENE	3	2	N	NE	2	3	SE	ENE	4	2
12	12	NE		4		ENE	ENE	3	2	N	NE	2	3	SE	ENE	4	2
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		ENE	ENE	3	2	N	NE	2	3	SE	ENE	4	2
13	6	N		4		ENE	NE	4	4	NE	E	5	5	ENE	ENE	5	4
13	8	N		4		ENE	NE	4	4	NE	E	5	5	ENE	ENE	5	4
13	12	NE		4		ENE	NE	4	4	NE	E	5	5	ENE	ENE	5	4
13	14	NE		4		ENE	NE	4	3	E	E	3	4	E	E	4	3
13	18	NE		3		ENE	NE	4	3	E	E	3	4	E	E	4	3
13	22	E		3		ESE	ENE	3	3	E	E	2	3	E	ESE	4	4

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 Ha- fen	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.

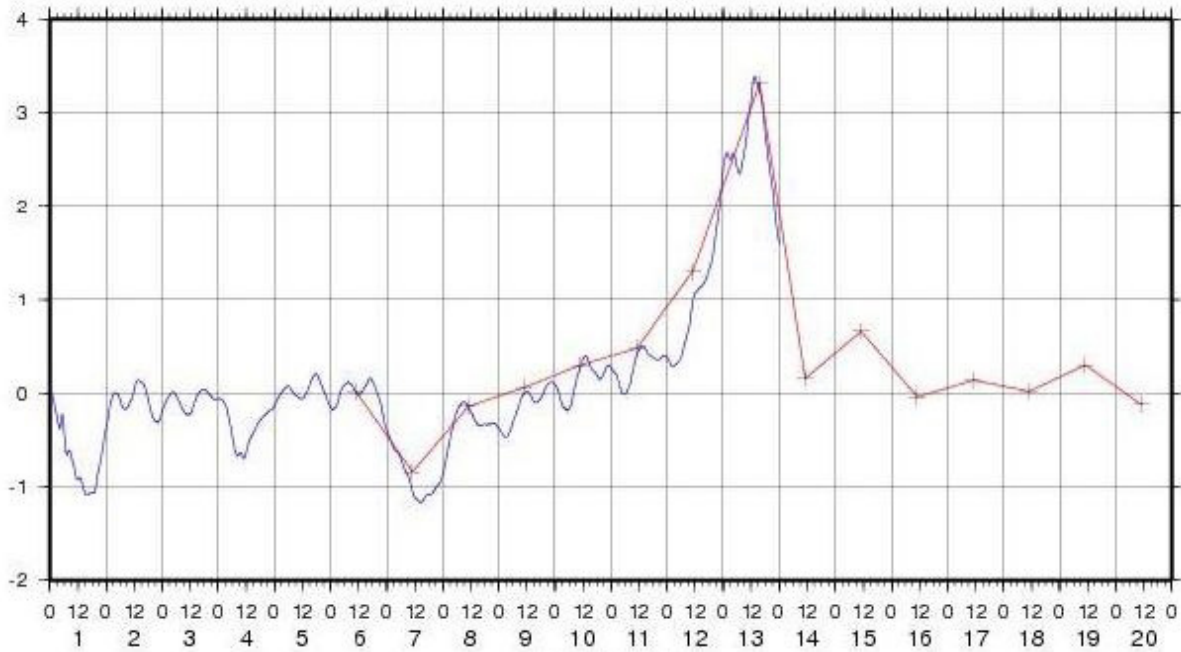


Figure 3a: Water level at Flensburg. Observations (m MW, local time, red) from Baensch (1875), November 6 to 20, 1872 and corrected model data (m NN, blue), November 1 to 13, 1872.

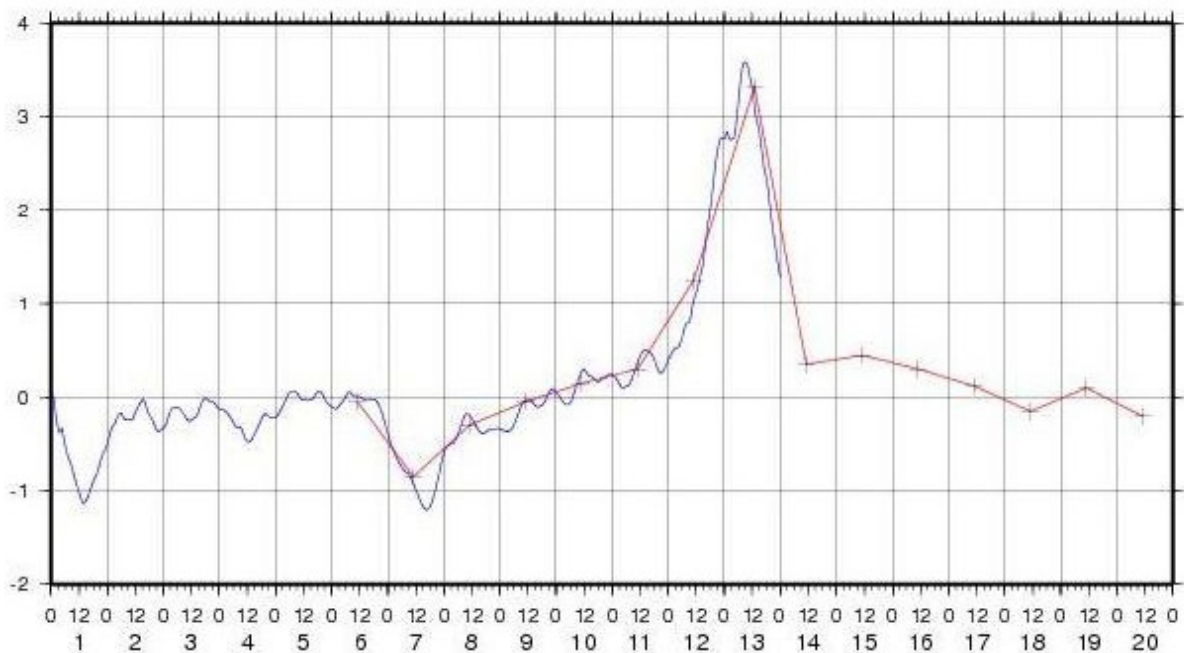


Figure 3b: Water level at Travemünde. Observations (m MW, local time, red) from Baensch (1875), November 6 to 20, 1872 and corrected model data (m NN, blue), November 1 to 13, 1872.

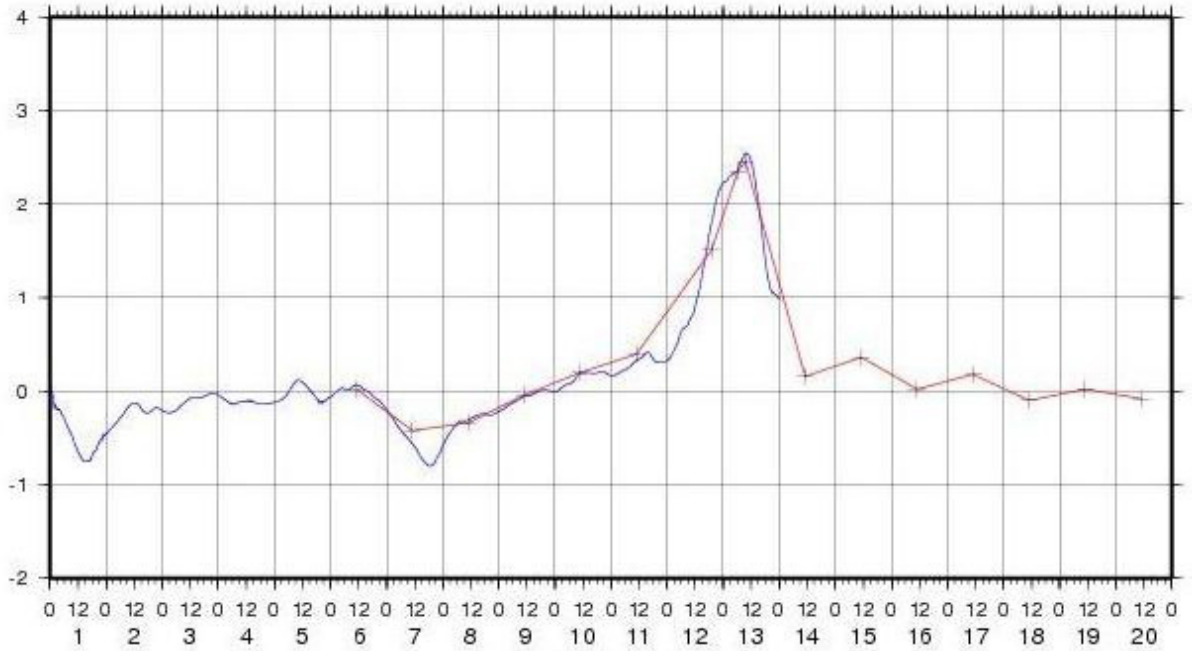


Figure 3c: Water level at Stralsund. Observations (m MW, local time, red) from Baensch (1875), November 6 to 20, 1872 and corrected model data (m NN, blue), November 1 to 13, 1872.

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 Travemuende 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).

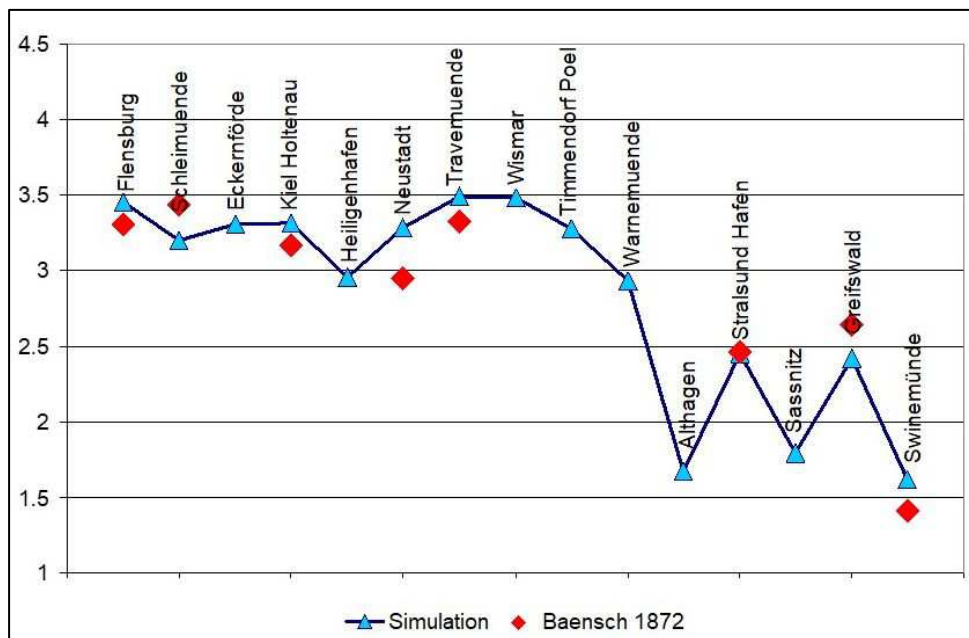


Figure 4: Peak water levels. Corrected model data (m NN, blue), observations (m MW, red) from Baensch (1875) for different places along the German Baltic coast, November 13, 1872.

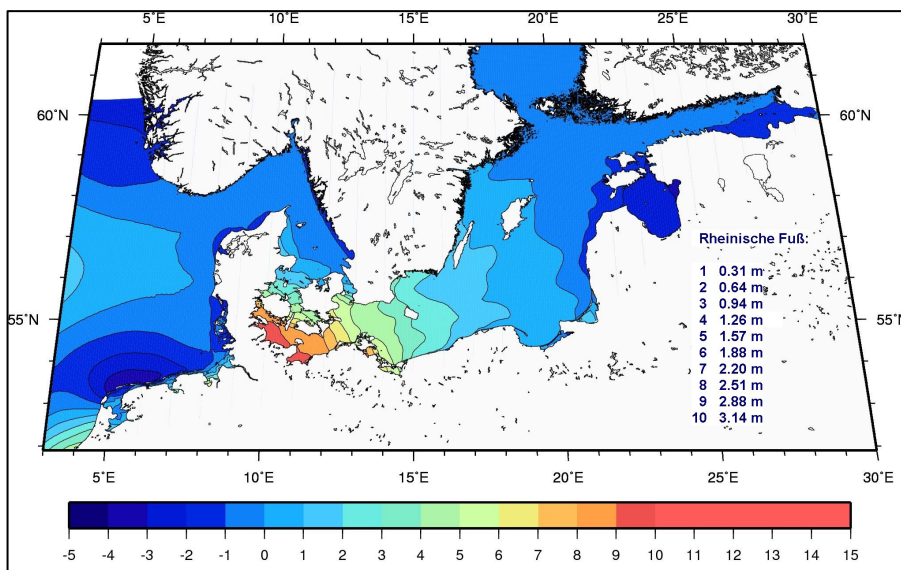


Figure 5a: Corrected water level on November 13, 1872, 2 p.m., converted to Rhenish feet for comparison to Figure 5b.

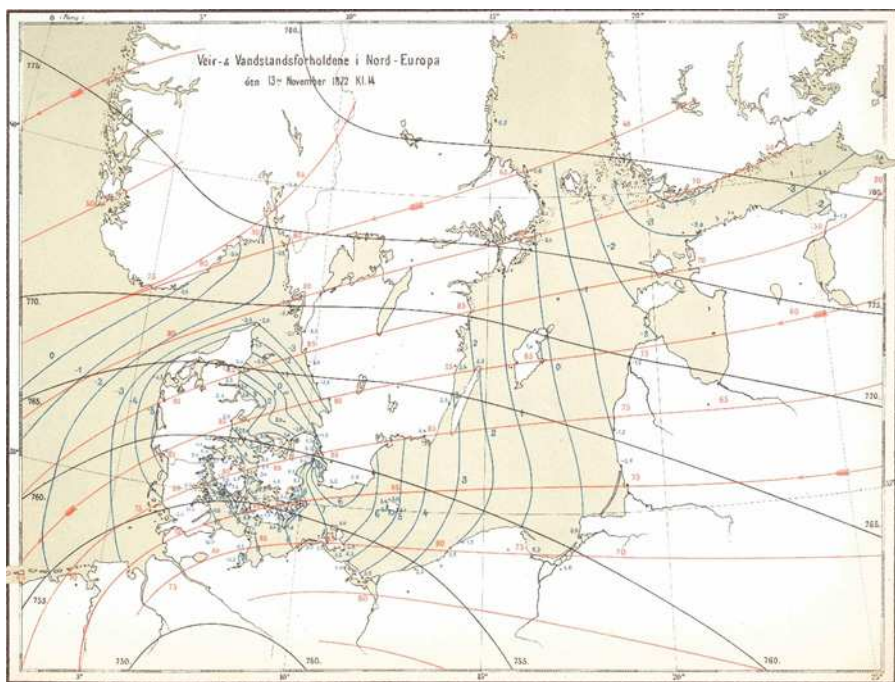


Figure 5b: Contours of water level in Rhenish feet (blue), atmospheric pressure (black) and lines indicating wind direction (red) on November 13, 1872, 2 p.m. (Colding 1881).

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 (Swinoujście), 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 (Kolobrzeg) 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.

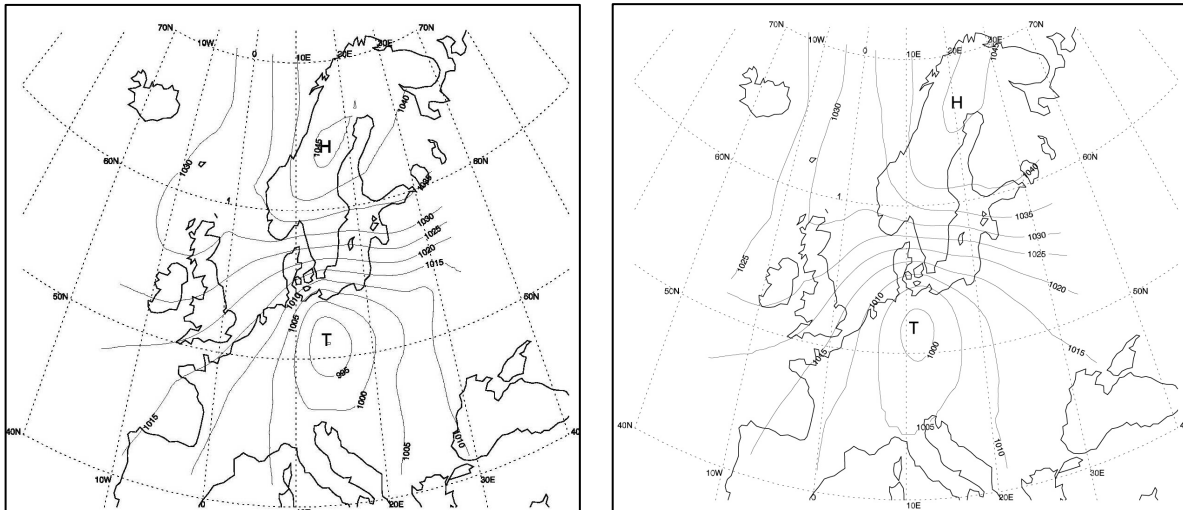


Figure 6a: Reconstructed air pressure fields on November 13, 6 a.m. (left) and 2 p.m. (right).

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.

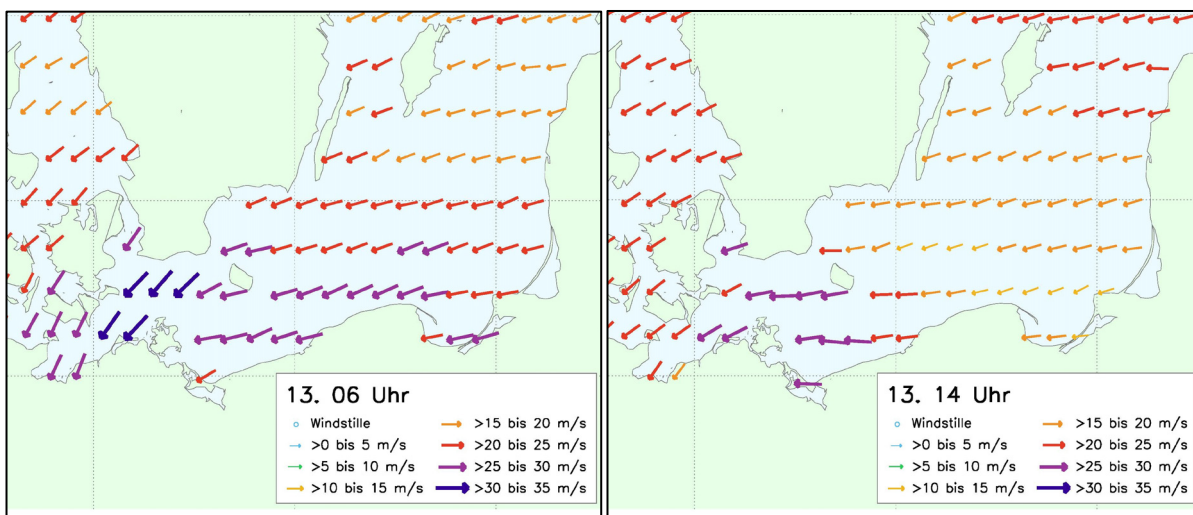


Figure 6b: Reconstructed wind distribution on November 13, 6 a.m. (left) and 2 p.m. (right), Windstille = calm).

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

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 (WNN) 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 Miehle (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 $10^5 \text{ m}^3/\text{s}$ 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 $4.4 \cdot 10^5 \text{ m}^3/\text{s}$ 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/transport/>, section 29).

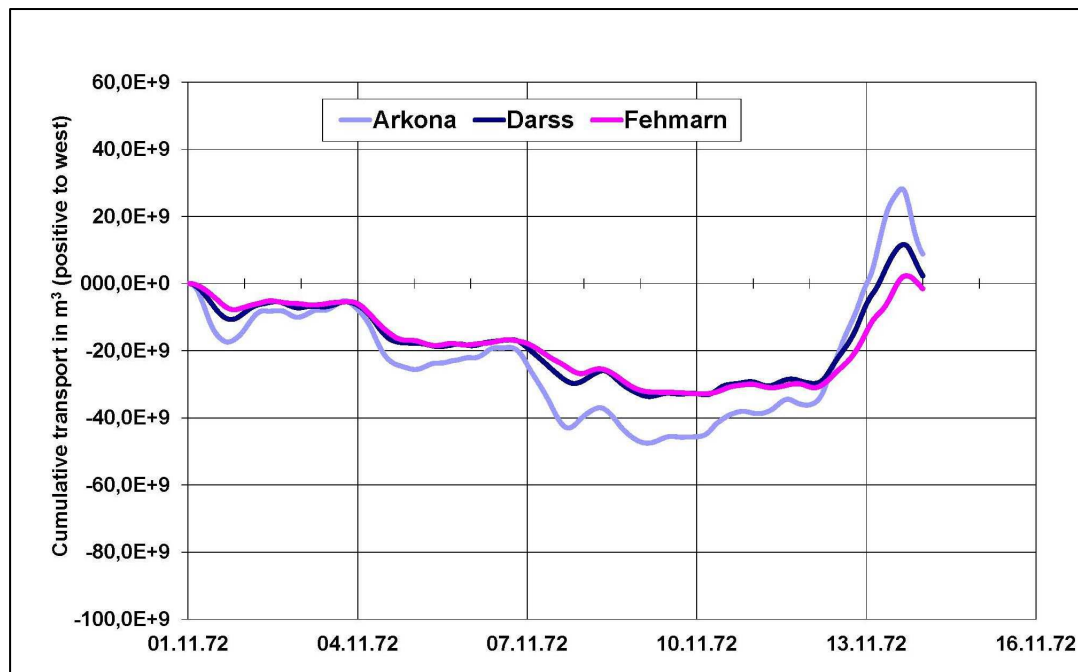


Figure 7: Cumulative transports (positive to the west) across sections at the level of Arkona (light blue), the Darss Sill (dark blue) and of Fehmarn (Belt and Sound, red) between November 1 and 13, 1872. Vertical lines mark the beginning of each day.

The cumulative volume transport from the western to the central Baltic Sea reached its maximum on the morning of November 9, 1872 with $-47.5 \cdot 10^9 \text{ m}^3$. 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 $+28.2 \cdot 10^9 \text{ m}^3$. 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 $+11.6 \cdot 10^9 \text{ m}^3$. Into the Bay of Kiel, a very short and minor cumulative transport, at most $+2.3 \cdot 10^9 \text{ m}^3$, 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.

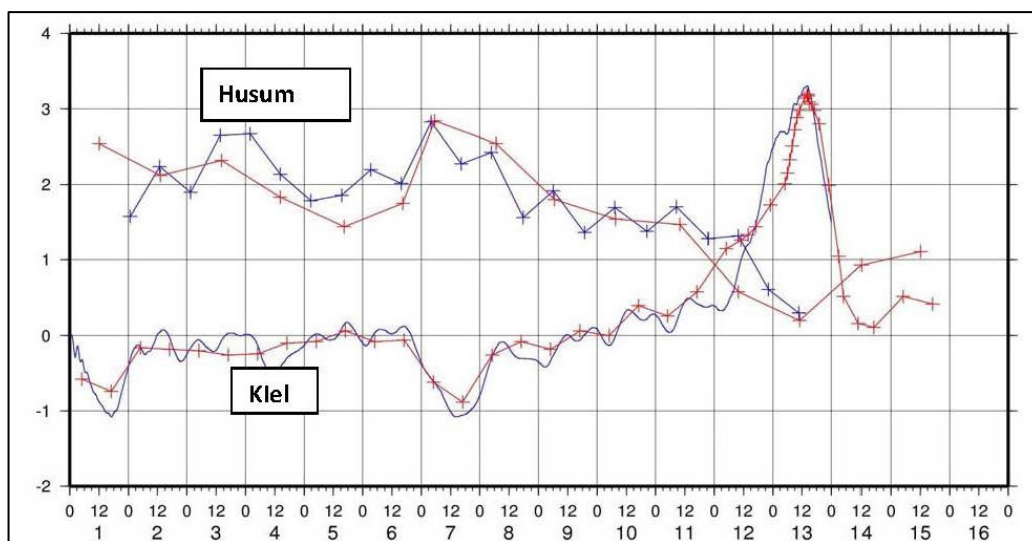


Figure 8: Observed high-tides at Husum (Pralle 1875) and water level at Kiel (Baensch 1875) for November 1 to 15, 1872 compared to corresponding reconstructed values for November 1 to 13, 1872: observations (m MW, local time, red), reconstruction (corrected, m NN, blue). Vertical lines mark the beginning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

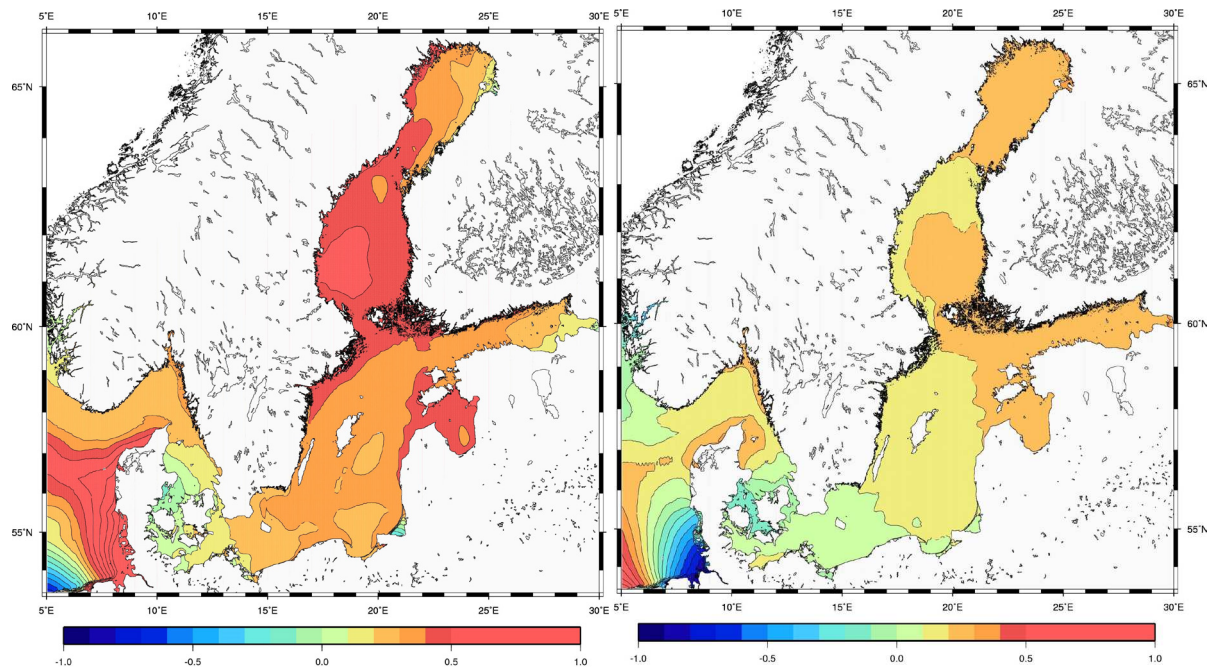


Figure 9: Left: Corrected water level in m NN in the Baltic Sea after 10 days of steady meteorological forcing. Right: Corrected water level of the reconstruction in m NN in the Baltic Sea at November 10, 1872.

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.

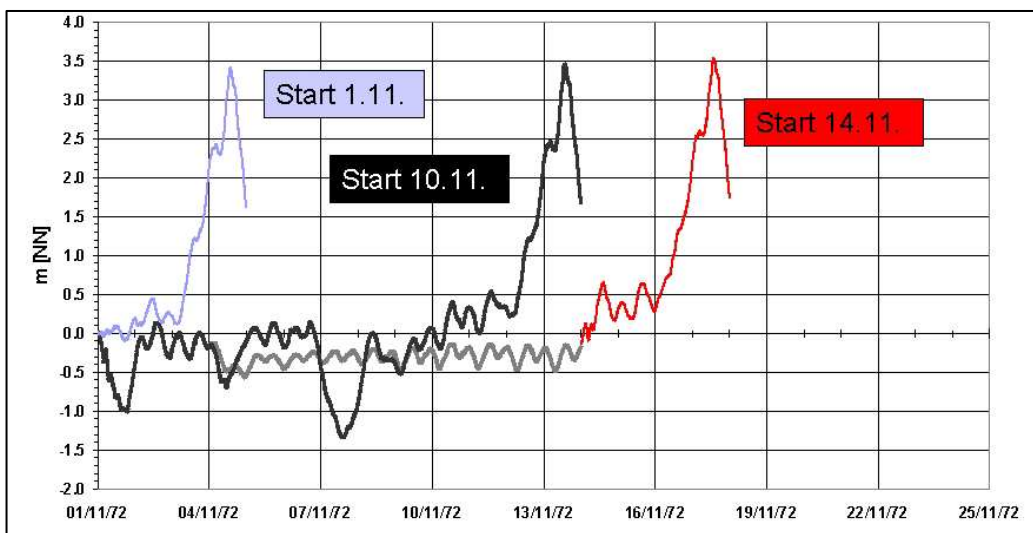


Figure 10a: Water level at Flensburg, for different initial conditions (blue EXP 2, red EXP 3) applying the meteorological forcing of November 10 to 13; compared to the reconstruction (black). Vertical lines mark the beginning of each day.

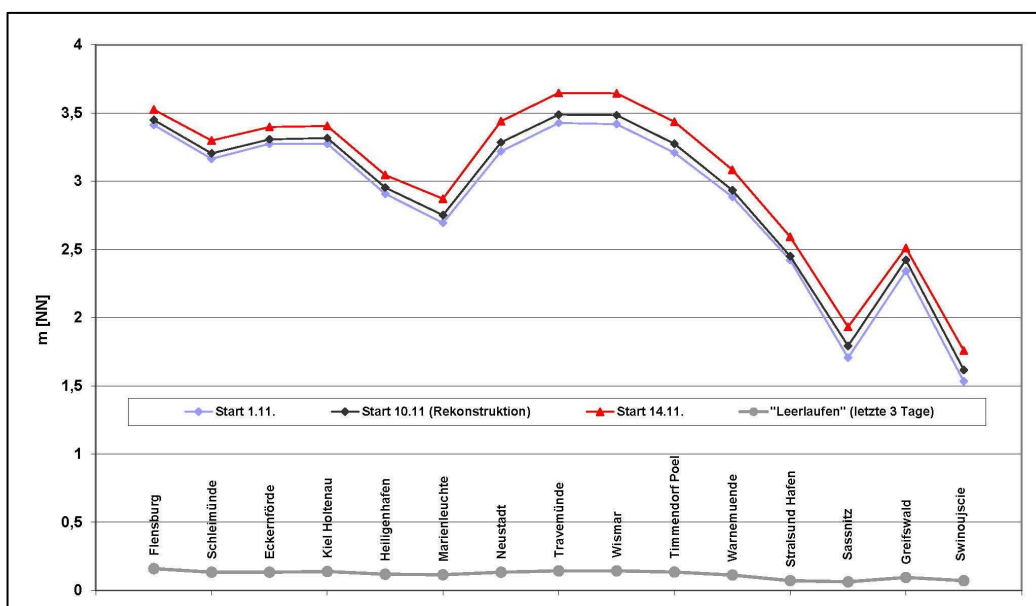


Figure 10b: Peak water levels for different initial conditions (blue EXP 2, red EXP 3) applying the meteorological forcing of November 10 to 13; compared to the reconstruction (black). Below, the peak water levels during the last 3 days of the “emptying phase” from experiment 1 are included.

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, Miehle (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.

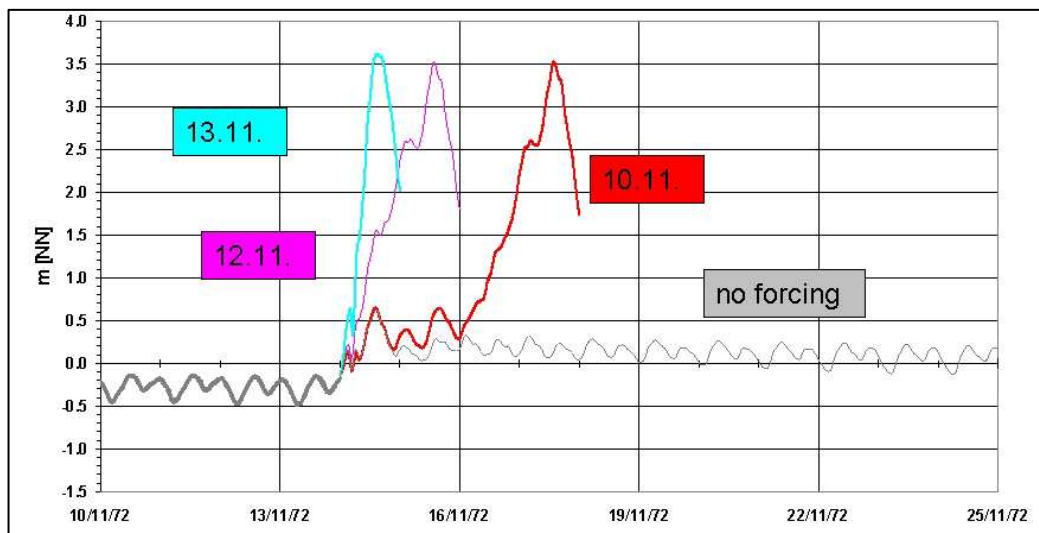


Figure 11: Water level at Flensburg according to EXP 4a (hurricane-force wind only, turquoise, 13.11.), EXP 4b (both storms only, petunia, 12.11.), and to EXP 4c (both storms including the meteorological forcing after change in wind direction, red, 10.11.). Vertical lines mark the beginning of each day.

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 Miehle (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.

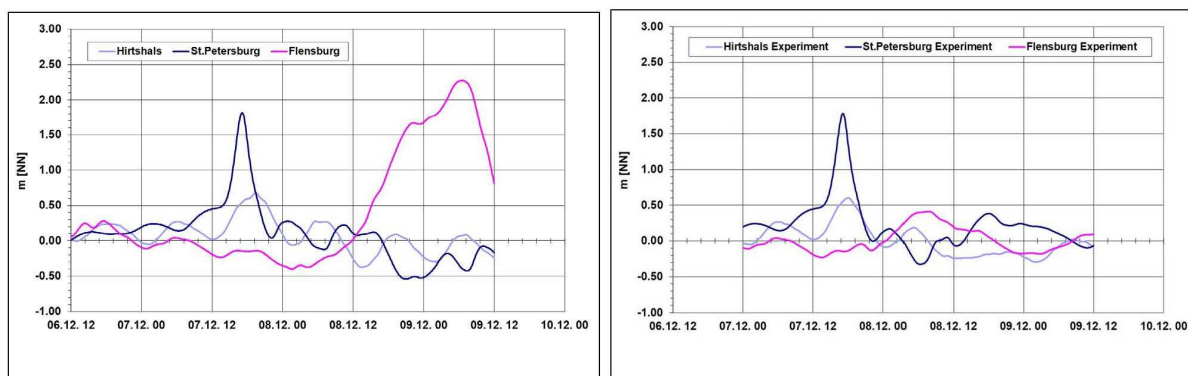


Figure 12: Water levels at St. Petersburg, Flensburg and Hirtshals for a variation of the storm surge in December 1971 (left) and for experiment 5 (right). Vertical lines mark the beginning of each day.

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.

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