The Baltic storm surges of 1872 and 2023 – what do they have in common?

Elke M.I. Meyer[1], *Lidia Gaslikova*[2], *Nikolaus Groll*[2] *and Ralf Weisse*[2]

[1] *Institute of Coastal Systems - Analysis and Modeling, Helmholtz-Zentrum Hereon, 21502 Geesthacht, Germany, elke.meyer@hereon.de*
[2] *Institute of Coastal Systems - Analysis and Modeling, Helmholtz-Zentrum Hereon, 21502 Geesthacht, Germany*

Summary

The Baltic Sea storm surge of 20 October 2023 was one of the highest observed on the east coast of Schleswig-Holstein. The storm of 13 November 1872 is still the highest recorded one in the western Baltic Sea in the last two centuries. In Flensburg, a water level of 3.31 m during the November 1872 event and 2.27 m in October 2023 were observed. Both storm events occurred in autumn and are characterised by a similar atmospheric weather situation with a stationary high pressure area over Scandinavia and a low pressure area over Central Europe. This led to a strong pressure gradient over the western Baltic Sea and resulted in strong easterly winds with up to 30 m/s at Lighthouse Kiel and particularly high wind surges, which in both cases challenged the coastal protection at the east coast of Schleswig-Holstein.

Keywords

severe storm surge Baltic Sea, similar weather situation, strong pressure gradient over the western Baltic Sea, DWD reconstruction 1872

Zusammenfassung

Die Ostseesturmflut vom 20. Oktober 2023 war eine der höchsten, die an der Ostküste Schleswig-Holsteins beobachtet wurde. Der Sturm vom 13. November 1872 ist nach wie vor die höchste beobachtete Sturmflut in der westlichen Ostsee in den letzten zwei Jahrhunderten. In Flensburg wurde im November 1872 ein Wasserstand von 3.31 m gemessen und im Oktober 2023 wurden 2.27 m maximaler Wasserstand gemessen. Beide Sturmereignisse ereigneten sich im Herbst und sind durch eine ähnliche atmosphärische Wetterlage mit einem stationären Hochdruckgebiet über Skandinavien und einem Tiefdruckgebiet über Mitteleuropa gekennzeichnet. Diese Situationen erzeugten einen starken Luftdruckgradienten, welcher zu starkem Ostwind mit bis zu 30 m/s am Leuchtturm Kiel sowie über der westlichen Ostsee mit hohem Windstau führten, die den Küstenschutz im Osten Schleswig-Holsteins herausforderten.

Schlagwörter

Schwere Sturmflut Ostsee, Ähnliche Wetterlagen, Starker Luftdruckgradient über der westlichen Ostsee, DWD-Rekonstruktion 1872

Received 30.09.2024, reviewed 10.10.2024, revised 17.01.2025, accepted 28.01.2025, available online 14.02.2025.

1 Introduction

In this paper, we analyse and compare the most recent prominent storm surge event in the western Baltic Sea, which occurred on 20 October 2023, with one of the most extreme storm surge events since the beginning of the records in the region, the storm of 13 November 1872. Both events were considered as at least severe storm surges (BSH 2023) with disastrous damage at the east coast of Schleswig-Holstein and in Denmark as well as in Sweden (Kiesel et al. 2024). The main focus is on the comparison of atmospheric conditions as the key driver for these events in search for commonalities and differences in the underlying processes but also the resulting water levels are discussed.

The storm of 1872 remains in the collective memory in the region as a disastrous event, and even 150 years later, the knowledge of flooded regions and the resulted damage, e.g. labelled by flood marks in Denmark and Germany (Hallin et al. 2021) is present. The severe storm surge 1872 has already been intensively investigated (Rosenhagen and Bork 2009, KFKI 2022). In particular, the works of Baensch (1875) and Colding (1881) were seminal, because they collected, sorted and categorised the data on a holistic way for the first time and shortly after the event. In contrast to the recent event of 2023, where numerous observational data of water levels as well as atmospheric parameters like wind vectors or sea-level pressure are available, the data for the event 1872 were scarce. Very few records of observed water levels from the gauges were accessible and additionally their consistency suffered from the changing gauge reference system over the time (Baerens et al. 2003). Thus, several estimates of maxima water levels for the 1872 event exist in the literature as summarized by Mudersbach and Jensen (2009), showing the peak water level, for example in Flensburg (Table 1 and Figure 1), reaching between 3.08 m and 3.31 m. Despite some uncertainties it can be stated that the peak water levels reached during the 1872 event remain unrivalled for the entire south-western Baltic coast and represent an important benchmark for the coastal safety management (MELUR 2022).

During the storm surge on 20 October 2023, the second highest water level in the observation since 1872 was registered with 2.27 m above mean water level (MW) in Flensburg and 2.15 m in Eckernförde (Table 1 and Figure 1). In the southern parts of the German Baltic Sea the water levels in October 2023 were not as high compared to water levels from previous storm surge events, placing the 2023 surge events within the highest 11 observed events for Travemünde and Warnemünde. Before October 2023, the storm surge event of 31 December 1904 was the second highest in the records, especially in the western Baltic Sea, with peak water levels of 2.23 m in Flensburg and 2.12 m in Eckernförde above mean water level (DGJ 2005, DGJ 2022, WSV 2023). This event is often not included in the long-term analysis of water level extremes in the Baltic Sea and in the return value estimates (e.g. Kiesel et al. 2023, Groll et al. 2024) because the year 1904 is beyond the established atmospheric and consequently hydrodynamic reanalysis period and currently available atmospheric data are too scarce to enable the realistic reconstruction of the event. Therefore, we consider it is important to include this event in the discussion of storm surge extremes. It also had more prominent impact in the south-western Baltic Sea, with peak water levels reaching 2.63 m in Travemünde and 1.90 m above mean water level (MW) in Warnemünde (Table 1).

Table 1: Observed peak water levels for the storm surge events 13 November 1872, 20 October 2023 and selected highest surge events at the German Baltic Sea coast. Modelled peak water levels for the 2023 event. The data are presented in their original and were not corrected to the change of the gauge reference level from MW to the base height level (Normalhöhennull (NHN), Deutsche Haupthöhennetz (DHHN2016) or Normaal Amsterdams Peil (NAP), for more details on the reference differences see Mudersbach and Jensen (2009) and Bork et al. (2022).

Event	13.11.1872	13.11.1872	13.11.1872	31.12.1904	20.10.2023	20.10.2023
Data source	Baensch 1875	Baerens 1998	Mudersbach and Jensen 2009	DGJ, 2005 & Stigge (1994)	WSV, 2023	Model
	[m MW]	[m MW]	[m NN 2006]		[m DHNN2016]	[m NAP]
Flensburg	3.31	3.08	3.27	2.23	2.27	2.1
Schleimünde	3.44	3.21	-	2.11	2.07	1.9
Eckernförde	-	3.15	3.40	2.12	2.15	1.9
Kiel-Holtenau	3.17	2.97	3.30	2.25	1.95	1.83
Travemünde	3.32	3.30	3.15	2.63	1.79	1.62
Wismar	-	2.84	2.97	2.28	1.57	1.61
Warnemünde	-	2.45	2.70	1.90	1.50	1.53
Greifswald	2.64	2.66	2.79	2.39	1.51	1.38

Event	04.01.1954	15.02.1979	13.01.1987	03.11.1995	01.11.2006	04.01.2017	02.01.2019
	DHNN2016 = m NAP						
Flensburg	1.81	1.81	-	1.81	1.72	1.79	1.68
Schleimünde	1.6	1.81	-	1.82	1.65	1.64	1.6
Eckernförde	1.75	1.84	-	1.98	1.67	1.7	1.64
Kiel-Holtenau	1.8	1.93	1.72	1.97	1.75	1.69	1.67
Travemünde	1.99	1.78	1.75	1.81	1.7	1.71	1.73
Wismar	2.07	1.62	1.72	2.01	1.81	1.82	1.90
Warnemünde	1.74	1.31	1.44	1.62	1.64	1.62	1.69
Greifswald	1.87	-	1.46	1.82	1.45	1.68	1.70

The storm surge event of 20 October 2023 has been described and investigated in recent reports and publications (BSH 2023, Kiesel et al. 2024 and Groll et al. 2024). Kiesel et al. (2024) offered a description of the storm surge event and a comprehensive discussion on the storm impact at the coast, looking at different aspects of the related flood risks based on the observational data. In particular, the variability and the shape of hydrographs was mentioned as an important factor influencing the duration of the flood wave and the extent of the flooding. They emphasized the localized effect of this particular storm, with strong easterly winds leading to much higher water levels in the western part of the Baltic Sea and moderate increases in the south-western part. The authors debated the simultaneous exposure and questioned the necessity to consider spatial dependency for large-scale risk assessments.

Figure 1: Map of the investigated locations in the Baltic Sea.

Groll et al. (2024) put the event of 20 October 2023 in the context of other recent storm surge extreme events in the region, namely the storms from 04–05 January 2017 and 02 January 2019, as well as more generally in a climate perspective of the past 65 years. They used reanalysis data and calculated water levels for the period from 1958 until 2023 looking at the different components contributing to the total extreme water level. In particular, they estimated the impact of prefilling on the water levels during the events. Prefilling is an increased amount of water in the Baltic Sea happening on the timescales of days to weeks due to an additional inflow from the North Sea associated with the persistent westerly winds (Lehmann and Post 2015). A strong prefilling could alter the total water level by several decimetres, if it occurred before the storm surge event. For the 2023 event both studies concluded that the prefilling prior to the storm was present, and this condition contributed about 25 cm (20–50 cm) to the peak water levels. Contrarily, for the storm 1872 Bork et al. (2022) concluded that there was no impact of prefiling of the Baltic Sea on the water level at the German Baltic Sea coast.

In the following, we compare and discuss the atmospheric situations during the 1872 and 2023 events in chapter 2. In chapter 3, we compare water level observations for the selected storm events for the south-western Baltic Sea and discuss differences in spatial pattern of the surge distribution based on the water level simulations. We conclude with a discussion of atmospheric patterns associated with the storm surge extremes and how the considered two events fit into the multi-decadal statistics.

2 Atmospheric situations in 1872 and 2023

The atmospheric situation for the 1872 storm event was already reconstructed and described in detail by several authors e.g. Baensch (1875), Colding (1881), Rosenhagen and Bork (2009), Bork et al. (2022). Rosenhagen and Bork (2009) used the pressure and temperature data from 230 weather stations to reconstruct the weather situation within two weeks prior to the storm surge event. Thus, their weather charts are based on a higher density of weather station data than older ones or any current reanalysis products. For the sake of completeness, we summarize the development of the storm here. During 12 and 13 November 1872, a stationary/blocking high pressure system (with maximum sea level pressure of 1047 hPa) was located over middle Scandinavia and a low pressure system over the Lusatia (with minimum sea level pressure of 990 hPa). A strong pressure gradient over the western Baltic Sea caused extreme wind speed over the Baltic Sea (Rosenhagen and Bork 2009, Figure 2a). The relative position of the high- and low pressure (high-over-low) systems resulted in strong winds from easterly and north-easterly directions, with wind speeds near Lübeck (close to Travemünde) estimated between 21 m/s and 28 m/s for at least 24 hours on the 12 and 13 November 1872 (originally Baensch 1875). The peak wind speeds reached 30–35 m/s on 13 November (Rosenhagen and Bork 2009). In the reconstruction by Colding (1881) the low pressure system was located more to the south-east over Vienna, Austria, this resulted in a somewhat smaller pressure gradient than estimated by Rosenhagen and Bork (2009). Still, Colding (1881) suggested in agreement with the paper by Baensch (1875), that the strong pressure gradient and the resulting high wind speed generated high wind surge in the Baltic Sea, leading to extremely high water level in the western Baltic Sea. This is supported by the recent study of Bork et al (2022), where the strong winds were named as the main reason for the observed water levels, while other effects like the Baltic Sea prefilling, seiches, etc. were minimal.

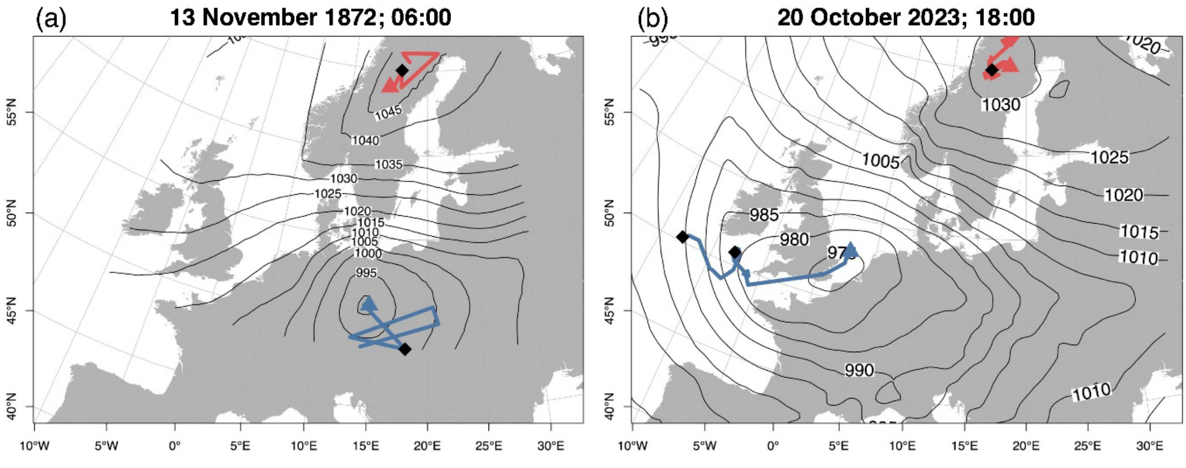

Figure 2: (a) Pressure chart for 13 November 1872 06:00 and tracks of high (red) and low (blue) for 12 November, 06:00 till 13 November 1872, 08:00 period based on the data from Rosenhagen and Bork, 2009. Black diamonds mark midnight. (b) for 19 – 20 October 2023 based on coastDat3 reanalysis.

During the event of October 2023, a high pressure area moved from Svalbard to Scandinavia, became stationary and intensified (~1030 hPa). A low pressure area (~975 hPa) moved from south-western Ireland to southern England and became stationary as well (Figure 2b). Thus, it developed a high-over-low weather pattern, similar to the 1872 event.

A strong pressure gradient built up over northern Germany and resulted in high wind speed (> 20 m/s), reaching the speed of 28 m/s (BSH 2023 and Kiesel et al. 2024) with an easterly wind direction (DWD 2023, Figure 3) at least two days before the water level peak at the east coast of Schleswig-Holstein. Although the wind speed was high during the storm, it was not unprecedented during the past seven decades of historical data (Groll et al. 2024) and it is rather a combination of high wind speed and prolonged easterly direction that was extraordinary.

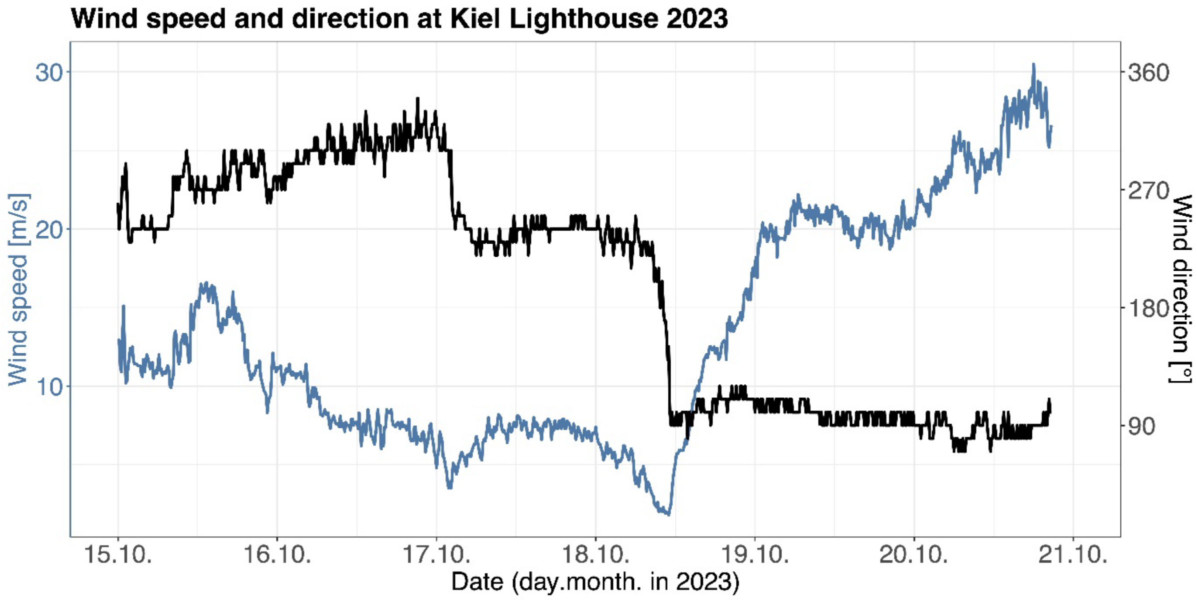

Figure 3: Observed wind speed and direction (10 min) from Kiel Lighthouse for 15-20 October 2023. In the evening of 20 October 2023, the anemometer was broken.

Summarizing, in both situations, 1872 and 2023, very strong pressure gradients developed over the western Baltic Sea. In comparison, the maximum wind speeds were higher during the storm in 1872 storm (up to 35 m/s in 1872 vs. 29 m/s in 2023), although the categorical nature of observations in 1872 as a source of uncertainty must be kept in mind. The duration of strong winds is comparable, with wind speeds rising from over 10 m/s to the maximum within 2 days. The wind directions remain stable in both cases, with easterly-northeasterly winds in 1872 and easterly winds in 2023.

3 Water level records and simulations

Different studies provided slightly varying results for the observed water levels during the 1872 event. Figure 4 and Table 1 summarize the observations estimated by Baensch (1875), Baerens (1998), Mudersbach and Jensen (2009) for different locations along the German Baltic Sea coast. The dataset is complemented with the recent peak water level observations of the 2023 event (WSV 2023). The water levels observed during the storm event of December 1904 (DGJ 2005, Stigge 1994), as an event resulted in second highest recorded water levels after 1872 in parts of the region but usually omitted from the assessments due to the lack of consistent data, are included. To put the records of 1872 and 2023 events in a historical context, peak water level observations for several storm events, which are within the top five recorded events since 1950 for the considered locations, are also included.

Comparing to 1872, the 2023 storm resulted in lower peak surge by 1 m in Flensburg, by 1.36 m in Travemünde and by 1.28 m in Greifswald, using Mudersbach and Jensen (2009) estimations. Comparing to the 1904 event, the surge magnitudes were similar at the north-western part of the German coast (Flensburg and Eckernförde) during 2023, farther to the south the water levels decreased, building up the discrepancy up to 0.88 m (Greifswald). This underlines the localised nature of the 2023 event, whose impact focussed on the western German Baltic Sea coastline, because of the prevailing eastern wind direction during the storm (Figure 3) in contrast to the other two major events. When compared to other high surge events, for the western area (Flensburg, Eckernförde) the events 2023 and 1904 remain unprecedented since 1950, with the next surge events of 1995 and 1979 showing about 0.45 m lower peak water levels. For the south-western part (Bay of Mecklenburg) the event of 2023 was unremarkable, as was mentioned before, but the 1904 remained the second highest surge event since 1872. Some later rivalling storms (e.g. 1954, 1995, 2019) resulted in more than 0.6 m (Travemünde) and more than 0.2 m (Wismar) lower peak water levels. It has to be mentioned, that most of the shown highest events affected the entire south-western Baltic Sea coast except for the events on 13 January 1987 and 15 February 1979 as well as 2023 and 1872 events. The later had a considerable impact in the Bay of Mecklenburg though, still the drop in the surge heights from west to east of the region was about 0.5 m. When the atmospheric situation is considered, both 1979 and 1987 events showed a hint to the high-over-low sea level pressure pattern and north-easterly to easterly winds (not shown) somewhat similar to the 2023 and 1872, whereas during other events (e.g. 1995 or 2019) the prevailing northerly winds were observed (e.g. Groll et al 2024).

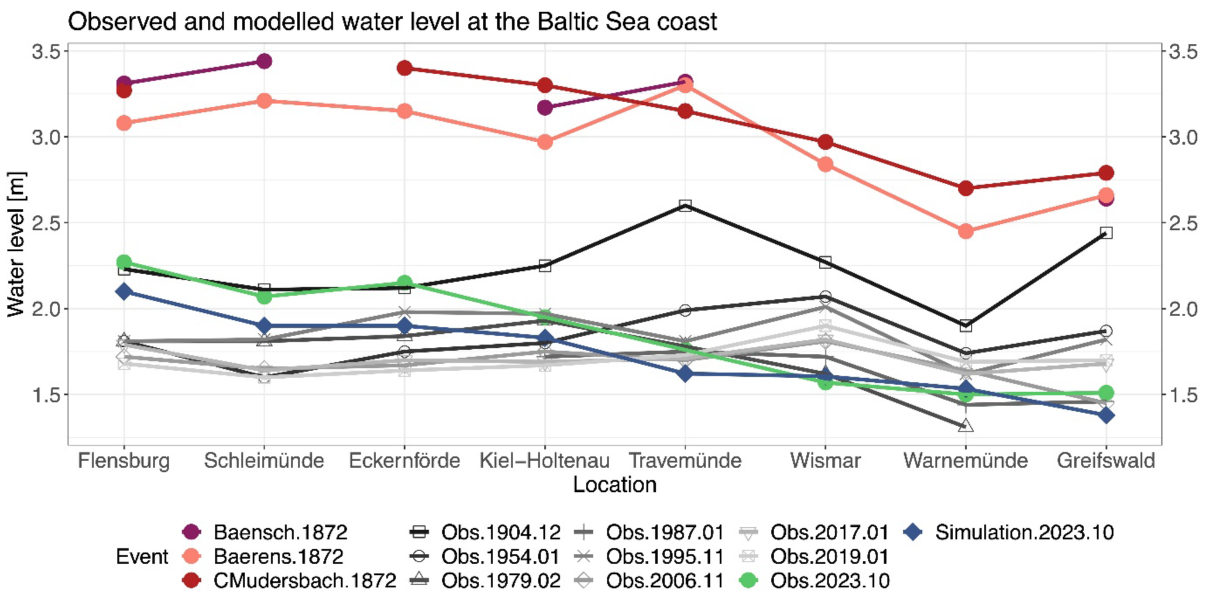

Figure 4: Peak water levels observed during selected major surge events and modelled for 2023 at the German Baltic Sea coast, from north to south and west to east. See also Figure 1 for the location.

To look more consistently at the spatial extent and distribution of the surge related to the 2023 storm, a hydrodynamic water level simulation with the model TRIM-NP (Casulli and Cattani 1994, Kapitza 2008) was used. The hydrodynamic model has already been used to investigate e.g. storm surge events and prefilling processes in the Baltic Sea (Groll et al.

2024, Weisse and Weidemann 2017). The simulation starts on 1 October 2023 to include possible pre-conditions before the storm and ends on 30 October 2023. The atmospheric forcing was used from the Cosmo-CLM simulation (Geyer 2014, Petrik et al. 2021). It is available in hourly temporal resolution and with a spatial resolution of 0.165°. Cosmo-CLM has been used for various atmospheric investigations and is well tested for hydrodynamic applications(e.g. Groll et al. 2024).

In Figure 5b the maximum simulated water level at each grid points during the event 2023 is shown. Consistent with the observations (Figure 4), highest water levels are simulated at the east coast of Schleswig-Holstein and southern Denmark with more than 1.75 m and locally over 2 m at the coast. The predominantly easterly winds provided perfect conditions for building up surge in the Bay of Kiel (Figure 1) with the water being pushed to the northern east coast of Schleswig-Holstein. In line with that, the Bay of Mecklenburg shows lower water levels than the Bay of Kiel with observed peak water levels of 1.79 m for Travemünde and 1.95 m for Kiel (Table 1). Additionally, to the local wind effect, a prefilling prior to the event contributed about 0.25 m (0.2 m–0.5 m) to the total water level (BSH 2023, Groll et al. 2024).

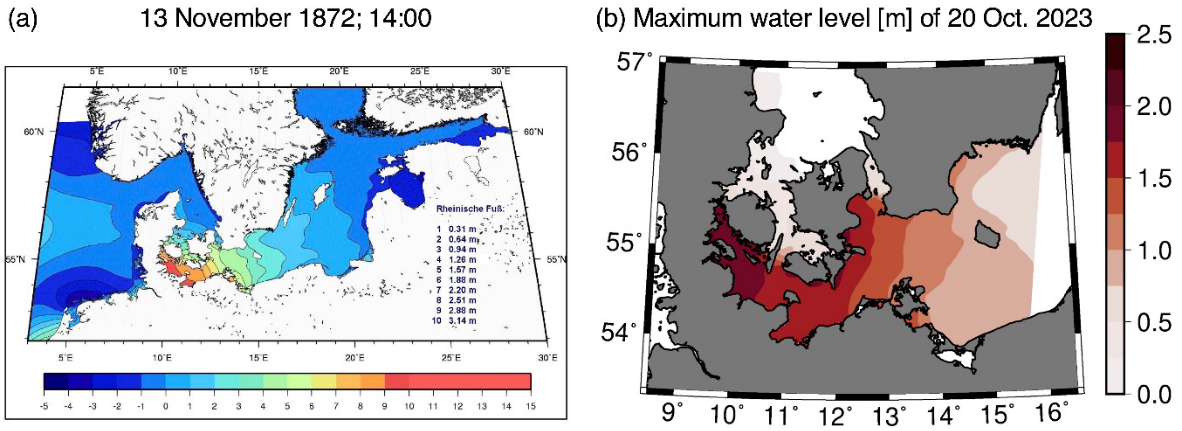

Figure 5: a) Simulation of water level for 13 November 1872, 2pm, converted to Rheinish feet from Bork et al. 2022, Figure (5a); (b) maximum water level during 20–21 October 2023 calculated by TRIM-NP and COSMO-CLM.

For the 1872 event, the results of the water level simulation by Bork et al. (2022) show similar spatial pattern (Figure 5a), although here the simultaneous water level distribution on 13.11.1872 14:00 instead of the peak water levels during the storm is presented. From the reconstruction by Bork et al. (2022) the maximum water levels were estimated by 3.45 m at Flensburg and 3.49 m at Travemünde. In this case, the highest water levels were simulated for the whole east coast of Schleswig-Holstein including the western part of Mecklenburg-Western Pomerania, which agrees with the available observations (Figure 4). Bork et al. (2022) argued that for this event no considerable prefilling was registered and the surge heights occurred mainly due to the regional wind conditions.

4 Conclusion

In this paper we examine and compare two exceptional storm surge events in the western Baltic Sea, one leading to water levels unprecedented and not exceeded in the last 150 years (13 November 1872), another very recent and resulting in the second highest observed water levels in Flensburg (20 October 2023). Both severe storm surges occurred in autumn and were induced by similar atmospheric situations. Easterly to north-easterly winds persistent during 36 to 48 hours over the Baltic Sea and reaching 30–35 m/s (for 1872) and 29 m/s (for 2023) lead to very extreme increase of water levels in the western part of the Baltic Sea. Both events resulted in the highest surges in the Bay of Kiel with peak water levels about 3.27–3.4 m during 1872 and 1.95–2.27 m during the 2023 event. Both events showed gradually lower water levels further to the east along the German coast, although for the 1872 event the peak water levels in the Bay of Mecklenburg were still remarkably high with 2.7–3.15 m. Although such atmospheric conditions and spatial surge height distributions are not unique, they are still quite rare in the historical data sets and mostly occurred in winter (e.g. 15 February 1979 or 13 January 1987).

We argue that the storm events of 1872 and 2023 had similar large-scale atmospheric situation leading to high-impact surge events in the western Baltic Sea. Both surge events were caused by strong easterly winds. These were induced by a particular atmospheric situation over Europe, known as a high-over-low situation. This refers to a weather situation in which a relatively stable high pressure system is located over Scandinavia and a low pressure system is located to the south (central to western Europe). Variations in the exact location of the high and low pressure systems, as well as the overall pressure gradient, trigger the exact wind field (speed and direction). This causes different water levels at different locations along the Baltic Sea coast. The 1872 event still shows the almost perfect storm conditions for extreme water levels along the western Baltic Sea. The 2023 event, however, shows that even less perfect high-over-low situations can lead to dramatic water levels along the western Baltic Sea. This indicates that high-over-low situations are a potential threat for high water levels along the western Baltic Sea coast, especially for the stretch from Travemünde to Flensburg and the surrounding coasts, in Denmark and Sweden. This could be considered for the coastal warning system in this area. The results also show that for the coasts east of Travemünde, extreme water levels are less influenced by high-over-low situations. They are more likely to be influenced by winds with more northerly components.

The unprecedented nature of historical storm surges occurred prior to the established reanalysis period (i.e. before 1948) suggests the need in the modelling efforts going further back in time, for example in the extension of high-resolution atmospheric and hydrodynamic reanalysis for 100–150 years back. This would allow to obtain the consistent surge statistics which encounter the major historic events. Thus, it would make estimates of e.g. return values, one of the relevant parameters for the coastal protection planning, more realistic than those based on the presently widely used data from the past 60–70 years (e.g. Kiesel et al. 2023).

Further investigations are needed for blocking high pressure situations over Sweden with a simultaneous low pressure area nearby (high-over-low situation) and resulting strong pressure gradients over the western Baltic Sea. This investigation is necessary for future coastal protection assessments, e.g. for design of water level and the duration of stability of the protection.

5 Data

WSV 2023: Wasserstraßen- und Schifffahrtsverwaltung des Bundes, bereitgestellt durch die Bundesanstalt für Gewässerkunde (BfG). Dies gilt für Erst-, Zweit- und jedwede Nachnutzung.
DWD 2023: Deutscher Wetterdienst: "Based on data from Deutscher Wetterdienst, gridded data reproduced graphically"

6 Acknowledgement

The authors would like to thank Gudrun Rosenhagen (Deutscher Wetterdienst) for providing the 1872 data and Wilfried Wiechmann (Bundesantalt für Gewässerkunde) for providing the recorded water levels of the Baltic Sea gauges.

7 References

Baensch, O.: Die Sturmfluth an den Ostsee-Küsten des Preußischen Staates vom 12./13. November 1872. Nr. 25, 1875.

Baerens, C.: Extremwasserstandsereignisse an der deutschen Ostseeküste. Berlin: Freie Universität Berlin, FB Geowissenschaften, 1998.

Baerens, C.; Baudler, H.; Beckmann, B.-R.; Birr, H.-D.; Dick, S.; Hofstede, J. et al.: Die Wasserstände an der Ostseeküste - Entwicklungen - Sturmfluten - Klimawandel 3. Hoch- und Niedrigwasser. In: Die Küste, 66 Sonderheft, 106–216, 2003.

Bork, I.; Rosenhagen, G.; Müller-Navarra, S.: Modelling the extreme storm surge in the western Baltic Sea on November 13, 1872, revisited. In: Die Küste, 92, 163–195. https://doi.org/10.18171/1.092103, 2022.

BSH (Bundesamt für Seeschifffahrt und Hydrographie): Schwere Sturmflut vom 20.Oktober 2023; https://www.bsh.de/DE/THEMEN/Wasserstand_und_Gezeiten/Sturmfluten/_Anlagen/Downloads/Ostsee_Sturmflut_20231020.pdf; last access: 15.12.2024, 2023.

Casulli, V.; Cattani, E.: Stability, accuracy and efficiency of a semi-implicit method for three-dimensional shallow water flow. In: Computers & Mathematics with Applications, 27, 4, 99–112. https://doi.org/10.1016/0898-1221(94)90059-0, 1994.

Colding, A.: 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. In: naturwiderskabelig og mathematisk Afdeling, 1, 4 (6. Raekke), 1881.

DGJ (Deutsches Gewässerkundliches Jahrbuch): Wasserstände und Durchflüsse 2005 für Pegel Mecklenburg-Vorpommerns, 2005.

DGJ (Deutsches Gewässerkundliches Jahrbuch): Wasserstände Schleswig-Holstein, 2022.

Geyer, B.: High-resolution atmospheric reconstruction for Europe 1948–2012: coastDat2. In: Earth System Science Data, 6, 1, 147–164. https://doi.org/10.5194/essd-6-147-2014, 2014.

Groll, N.; Gaslikova, L.; Weisse, R.: Recent Baltic Sea Storm Surge Events From A Climate Perspective. https://doi.org/10.5194/egusphere-2024-2664, (2024, September 9).

Hallin, C.; Hofstede, J. L. A.; Martinez, G.; Jensen, J.; Baron, N.; Heimann, T. et al.: A Comparative Study of the Effects of the 1872 Storm and Coastal Flood Risk Management in Denmark, Germany, and Sweden. In: Water, 13, 12, 1697. https://doi.org/10.3390/w13121697, 2021.

Kapitza, H.: MOPS – A Morphodynamical Prediction System on Cluster Computers (Lecture Notes in Computer Science). In: J.M.L.M. Palma, P.R. Amestoy, M. Daydé, M. Mattoso & J.C. Lopes (Hg.): High Performance Computing for Computational Science - VECPAR 2008, Band 5336, 63–68. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-92859-1_8, 2008.

KFKI – Kuratorium für Forschung im Küsteningenieurwesen (Hg.): Die Küste, 92. 1872 – An exceptional storm surge in the Baltic. https://doi.org/10.18171/1.092100, 2022.

Kiesel, J.; Wolff, C.; Lorenz, M.: Brief Communication: From modeling to reality – Insights from a recent severe storm surge event along the German Baltic Sea coast. https://doi.org/10.5194/nhess-2024-71, 2024.

Kiesel, J.; Lorenz, M.; König, M.; Gräwe, U.; Vafeidis, A. T.: Regional assessment of extreme sea levels and associated coastal flooding along the German Baltic Sea coast. In: Nat. Hazards Earth Syst. Sci., 23, 2961–2985, https://doi.org/10.5194/nhess-23-2961-2023, 2023.

Lehmann, A.; Post, P.: Variability of atmospheric circulation patterns associated with large volume changes of the Baltic Sea. In: Advances in Science and Research, 12, 219–225, https://doi.org/10.5194/asr-12-219-2015, 2015.

MELUR, Küstenschutz des Landes Schleswig-Holstein – Fortschreibung 2022. Ministerium für Energiewende, Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein, Kiel, 2022.

Mudersbach, C.; Jensen, J.: Extremwertstatistische Analyse von historischen, beobachteten und modellierten Wasserständen an der deutschen Ostseeküste. In: Die Küste, 75, 131–161, 2009.

Petrik, R.; Geyer, B.; Rockel, B.: On the diurnal cycle and variability of winds in the lower planetary boundary layer: evaluation of regional reanalyses and hindcasts. In: Tellus A: Dynamic Meteorology and Oceanography, 73, 1, 1804294. https://doi.org/10.1080/16000870.2020.1804294, 2021.

Rosenhagen, G.; Bork, I.: Rekonstruktion der Sturmflutwetterlage vom 13. November 1872. In: Die Küste, 75, 51–70, 2009.

Stigge, H.-J.: Die Wasserstände an der Küste Mecklenburg-Vorpommerns. In: Die Küste, 56, 1–23, 1994.

Weisse, R.; Weidemann, H.: Baltic Sea extreme sea levels 1948-2011: Contributions from atmospheric forcing. In: Procedia IUTAM, 25, 65–69. https://doi.org/10.1016/j.piutam.2017.09.010, 2017.