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The 1872 Baltic Sea Storm Surge

Dennis Feuchter[1], Christof Jörg[1], Gudrun Rosenhagen[2], Renate Auchmann[1], Olivia Martius[1], Stefan Brönnimann[1*]

[1]*Oeschger Centre for Climate Change Research and Institute of Geography, University of Bern, Switzerland*

[2] *Deutscher Wetterdienst, Bernhard-Nocht-Str. 76, D-20359 Hamburg, Germany*

Abstract

On 13 November 1872, the Baltic Sea coast from Denmark to Pomerania was devastated by an extreme storm surge caused by high winds. This is still the strongest surge on record, and understanding its development can contribute to improved risk assessment and protection. In this paper we trace this event in sea-level pressure and wind data from the "Twentieth Century Reanalysis" (20CR) and compare the results with other observation-based data sources. The analysis shows that, in the ensemble mean of 20CR, the general development is qualitatively well depicted, but with much reduced strength compared to other data sets. The same is true when selecting the ensemble member with maximum wind speeds

1. Introduction

An extreme storm surge devastated the western Baltic Sea coast in November 1872. Today, this event is considered as the strongest storm surge on record in this area, with peak sea level anomalies of 3.2 m (Koerth, 2009; Rosenhagen and Bork, 2008). The event caused large damages and loss of life. In total, the storm surge cost the lives of 271 people, left 15000 homeless and destroyed 2800 buildings. Figure 1 shows a destroyed building in Niendorf near Lübeck. The island of Usedom was parted in two during this event (Koerth, 2009; Sävert, 2013). Rosenhagen and Bork (2008) reconstructed sea-level pressure and, using a geostrophic approximation, wind fields for this event based on historical instrumental pressure and temperature observations. The wind fields were then used to simulate peak sea levels. Such case studies are invaluable and provide detailed, case-specific information, but they cannot be performed for all possible extreme events, globally. In contrast, the "Twentieth

* Corresponding author: Stefan Brönnimann, University of Bern, Institute of Geography, Hallerstr. 12, CH-3012 Bern, Switzerland. E-mail: stefan.broennimann@giub.unibe.ch

Figure 1. Destroyed building in Niendorf at the Baltic Sea coast after the storm surge of 1872 (Source: Gemeindearchiv Timmendorfer Strand).

Century Reanalysis" (20CR, Compo et al., 2011) provides six-hourly, global, three-dimensional weather data back to 1871 and could potentially be used for analysing many extreme events. However, 20CR was not produced specifically for extreme events and its suitability needs to be assessed on a case-by-case basis.

In this paper we analyse the Baltic Sea flood of 1872 in 20CR. We analyse sea-level pressure and wind fields and compare the results with those provided by Rosenhagen and Bork (2008). The paper is organised as follows. Section 2 introduces the data sets used; results of the comparison are shown in Section 3. A brief discussion follows in Section 4. Finally conclusions are drawn in Section 5.

2. Data and Methods

The analyses in this paper are based on version 2 of the Twentieth Century Reanalysis (20CR, Compo et al., 2011), which provides six-hourly, three-dimensional, global atmospheric data back to 1871. 20CR is a reanalysis data set that is based on the assimilation of only surface pressure and sea-level pressure data. The land-based observations are from the International Surface Pressure Database (ISPD), marine data are from the International Comprehensive Ocean-Atmosphere Dataset (ICOADS) (see Compo et al., 2011). The assimilation is performed with a variant of the Ensemble Kalman Filter. Background fields are provided by the NCEP/CFS model (Saha et al., 2010), using monthly sea surface temperature and sea ice (Rayner et al., 2003) as boundary conditions. 20CR is an ensemble product that consists of 56 equally likely members. Here we use both the ensemble mean and the individual members. We focus in our paper on the variables wind and sea-level pressure (SLP).

In 1872, not many pressure observations were assimilated into 20CR. Their locations for the case of 13 November 1872, 6 and 12 UTC, *i.e.* during the peak of the storm surge, are

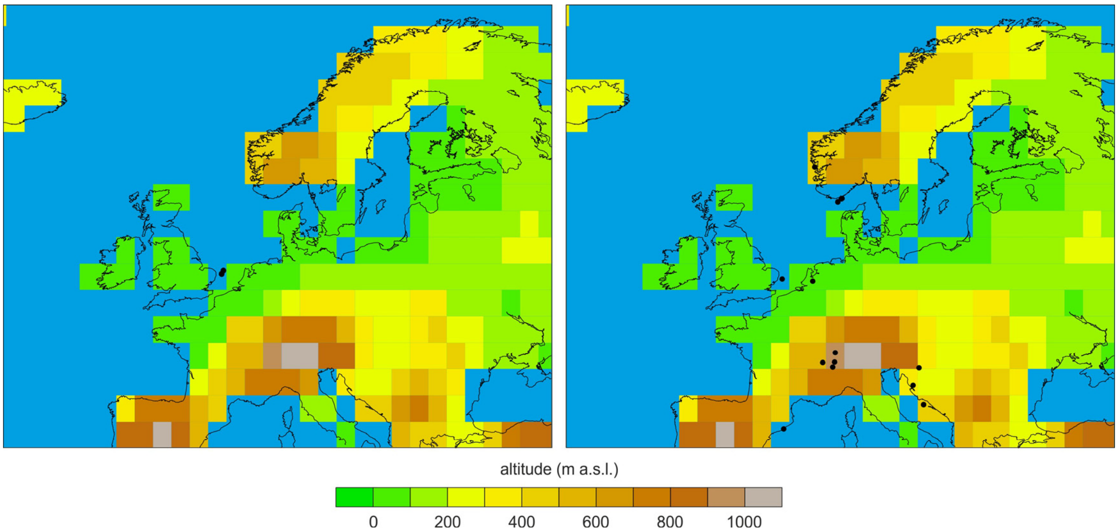

Figure 2. Map showing the surface and sea-level pressure measurements assimilated into 20CR on 13 November 1872, 6 UTC (left) and 12 UTC (right). Colours indicate the orography in 20CR and the land-sea mask as depicted in the Gaussian grid (192x94 cells).

shown in Figure 2, together with the orography and land sea mask of 20CR. For the assimilation window contributing to the 6 UTC field, only two observations from one ship were available in the southwestern North Sea. For the 12 UTC time step, more observations were available, but none in the vicinity of the Baltic Sea. Note that the resolution of 20CR is 2° x 2° and hence we do not expect local details to be well represented.

As a reference we use gridded reconstructions of wind and sea-level pressure from Rosenhagen and Bork (2008). These reconstructions are based on a much larger set of observations, encompassing pressure and temperature readings from 175 stations in the region. From these data, SLP charts were produced by manual synoptic analysis. These sea-level pressure charts were digitised and were then used, in a second step, to derive 10 m wind. A geostrophic approximation was used, which provides sufficiently accurate results over the ocean (given the short roughness length of the ocean). The gridded fields are given on a 0.5° x 0.5° grid several times per day. Daily SLP fields from 20CR were further compared with those from the gridded EMULATE data set (Ansell et al., 2006), which is also based on observations.

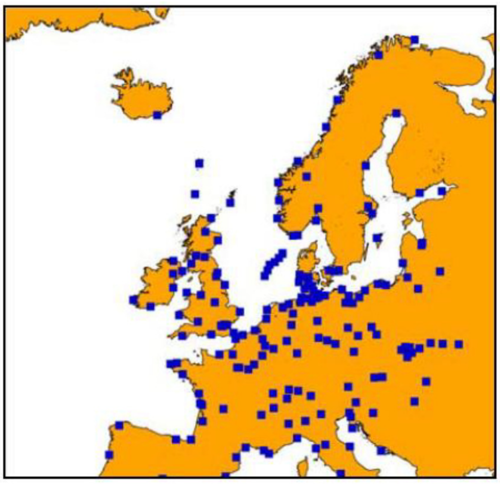

Figure 3. Map showing the pressure measurements used in Rosenhagen and Bork (2008).

3. Results

3.1. Evolution of the event in Rosenhagen and Bork (2008)

Rosenhagen and Bork (2008) reconstructed the weather situation leading to the devastating storm surge. Analysing the evolution of the event from 1 to 13 November 1872 they distinguished three phases, which are represented in the form of SLP fields in Figure 4:

(1) Prior to 10 November 1872, a low-pressure system (985 hPa on 8 November, see Fig. 4, top left) over the North Sea and Scandinavia caused westerly to southwesterly winds over the Baltic Sea. Water entered the Baltic Sea from the North Sea. Due to the sustained, strong westerly winds sea level rose in the northeastern part of the Baltic Sea, but dropped in the southwestern part. This mechanism was also described by Ekman (2007).

(2) On 10 November 1872, the situation changed. On 12 November 1872, an Atlantic low (pressure 1000 ha) moved over Central Europe, while in Scandinavia sea-level pressure rose to 1035 hPa in the centre of a high pressure system (Fig. 4, middle left). The southwesterly wind calmed down and a period of weak winds established temporarily. On 13 November, the high pressure system over Scandinavia and the low over Central Europe both intensified to 1045 hPa and 995 hPa, respectively. As a consequence, strong easterly to northeasterly wind set in over the Baltic Sea. Waters previously pushed to the north now surged towards the southwestern part of the Baltic Sea (see also Ekman, 2007). On the morning of 13 November 1872, the storm surge peaked. According to Rosenhagen and Bork (2008), the low pressure system over central Europe (now over Lusatia) had a core pressure of 990 hPa, the high over middle Scandinavia reached 1047 hPa, producing an extreme pressure gradient. Winds reached hurricane strength.

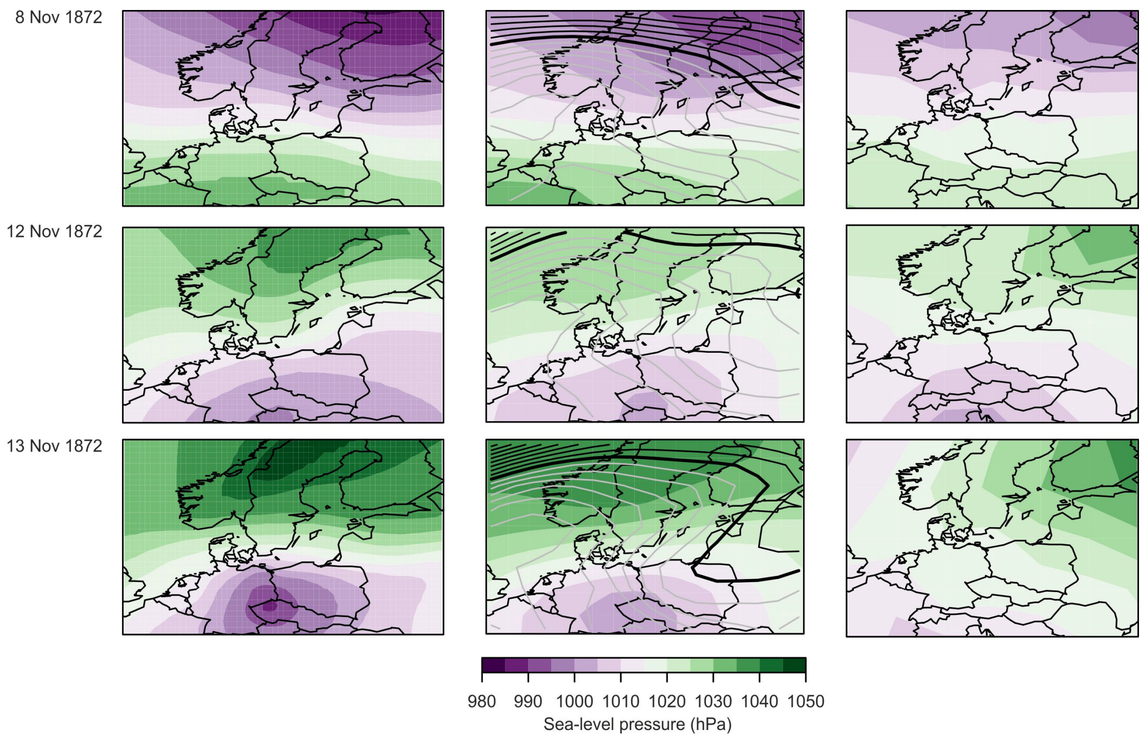

Figure 4. Sea-level pressure on 8 (top), 12 (middle) and 13 (bottom) November 1872, 6 UTC from (left) the data of Rosenhagen and Bork (2008) and (middle) 20CR reanalysis (contours indicate the ensemble standard deviation, thick black is 4 hPa, thin grey is < 4 hPa, step is 0.5 hPa) and (right) EMULATE daily means.

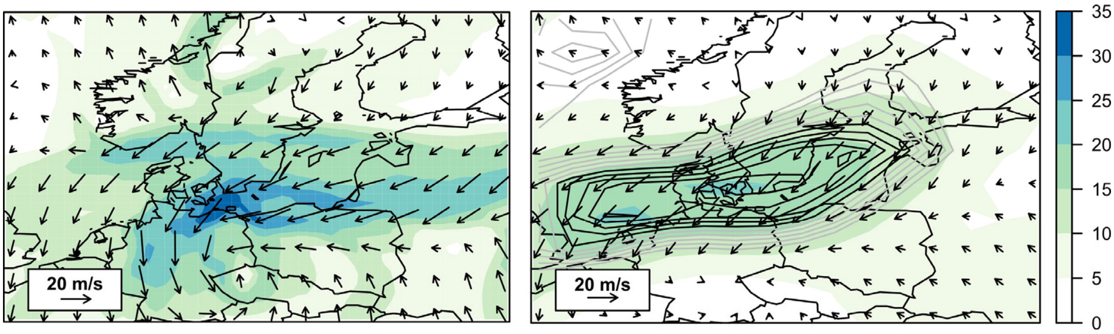

Figure 5. Wind at 10 m over the Baltic Sea on 13 November 1872, 6 UTC, from (left) the data set of Rosenhagen and Bork (2008) and (right) 20CR reanalysis. Colours indicate wind speed. Contours (right) indicate the ensemble maximum of wind speed in 20CR, with a spacing of 1 m/s starting at 15 m/s (grey). Contours 20 to 24 m/s are shown in black.

(3) In the afternoon of 13 November 1872, winds then calmed down again with a decreasing pressure gradient (Fig. 4, bottom left). The wind turned again to easterly, and sea level on the western Baltic coasts finally dropped again.

Figure 5 (left) shows 10 m winds from Rosenhagen and Bork (2008) for 13 November 1872, 6 UTC, during the peak of the event. Maximum wind speeds of 30 to 35 m/s are found at the location of the strongest pressure gradient. Winds are from the northeast, blowing towards the German and Danish coasts.

3.2. The event in the Twentieth Century Reanalysis and EMULATE

In 20CR ensemble mean, pressure extrema of 1000 and 1030 hPa, respectively, were located over Scandinavia and France on 8 November 1872 (Fig. 4, top middle). EMULATE shows a similar pattern, but less pronounced absolute values. On 12 November 1872, the high pressure system over Scandinavia is much weaker in 20CR (max. 1029 hPa) compared to Rosenhagen and Bork (2008) and shifted to the east in EMULATE. The low over Austria is relatively well captured. On 13 November 1872 the high over Scandinavia strengthened with values up to 1041 hPa in the ensemble mean of 20CR. The strength of the low remained unchanged (min. 1005 hPa), but the size decreased. The pronounced local amplification of both, the high and the low, found in Rosenhagen and Bork (2008) is not seen in 20CR, while EMULATE shows a rather different pattern.

Winds at 10 m in the ensemble mean of 20CR on 13 November, 6 UTC (Fig. 5) show northeasterly flow peaking at 20 m/s over Denmark and southern Sweden. While the spatial pattern of the wind maxima fits well with Rosenhagen and Bork (2008), the magnitude is much weaker. Even when considering the ensemble maximum wind speed at each grid point, maxima remain below 25 m/s

4. Discussion

Winds are much weaker in the ensemble mean of 20CR compared to the reconstructions of Rosenhagen and Bork (2008), which is due to the weaker pressure gradient. A comparison of pressure maxima and minima for the three data sets and three days shown in Figure 4 (8, 12,

Table 1: Maxima, minima, and maximum difference of sea-level pressure in Rosenhagen and Bork (2008) (here denoted RB2008), EMULATE, 20CR ensemble mean for three selected dates (in hPa). 20CR Extreme indicates the lowest minimum, highest maximum, and highest difference found in any of the ensemble members.

	RB2008			EMULATE			20CR Ensemble mean			20CR Extrema		
	Min	Max	Diff.	Min	Max	Diff.	Min	Max	Diff.	Min.	Max.	Diff.
8 Nov 1872	985	1030	45	993	1025	32	991	1029	39	980	1033	53
12 Nov 1872	1000	1035	25	1003	1035	32	1004	1028	24	1004	1035	31
13 Nov 1872	995	1045	50	1008	1038	30	1002	1040	37	1001	1050	49

and 13 November 1872) is listed in Table 1, along with corresponding differences between maxima and minima. On 8 November, the agreement between the data sets is generally good, also in the ensemble mean of 20CR, while in the extreme ensemble members even lower minima, higher maxima, and stronger gradients are found.

On 12 November, gradients have the opposite direction and are weaker in all data sets. The comparison of the pressure distribution over Europe for 13 November shows large differences. Compared to Rosenhagen and Bork (2008), both the ensemble mean and 20CR EMULATE fail to reproduce the strong, rather local pressure systems. As a consequence, minima and maxima as well as differences are far too weak in the ensemble mean. To some extent this is due to the ensemble smoothing effect (see Brönnimann et al., 2013). However, the ensemble standard deviation is low. While some of the ensemble members do show stronger extremes, even in the most extreme ensemble member, the pressure minimum is still 6 hPa higher than in Rosenhagen and Bork (2008) and the strongest gradient found in any member is still slightly below that found in Rosenhagen and Bork (2008). Also, a slight temporal shift appears in that in 20CR, the high pressure system continues to strengthen during 13 November whereas the opposite is the case in the data from Rosenhagen and Bork (2008).

The general picture emerging from analysing the surface wind on 13 November 1872 is a good agreement between Rosenhagen and Bork (2008) and 20CR in terms of the flow direction, which is northeasterly in both cases. However, there are large discrepancies with respect to the wind speed, While Rosenhagen and Bork (2008) find wind peaks of hurricane strength (>32.7 m/s), 20CR ensemble mean wind speed remain at 20 m/s, while the ensemble maximum approaches 25 m/s. There are various possible causes for this. First, this is a direct consequence of the underestimation of pressure differences. Second, the geostrophic approximation of Rosenhagen and Bork (2008) might lead to a slight overestimation of actual wind speed. Note also, that the vertical resolution of 20CR is not very high near the surface (the lowest model level is at ca. 40 m), meaning that deriving 10 m wind speeds is uncertain.

In order to assess the effect of the winds on the sea level, Rosenhagen and Bork (2008) used gauge readings from Baensch (1875) for the period 1-20 November 1872. The lowest level during this period was reached on 7 November 1872 between 12 and 18 UTC. As a consequence of strong westerly winds, waters in the Baltic Sea were pushed eastward, leading to a sea level decrease in Travemünde. The wind field from 20CR for this day shows also westerly winds, with highest speeds West of Denmark. Hence, there is a good agreement between 20CR and observations in this case.

It should be noted that the reference used for this study, Rosenhagen and Bork (2008) itself is a reconstruction. Comparison with actual observations, apart from the qualitative comparison with tide gauge measurements, was not performed and could produce slightly different results.

5. Conclusions

In this paper we have analysed to what extent an extreme event, the Baltic Sea flood of 1872, is reproduced in the "Twentieth Century Reanalysis". We have used the synoptic reconstruction of Rosenhagen and Bork (2008) as a reference. 20CR well depicts the evolution of the event, consisting of (1) water transport into the Baltic Sea due to westerly winds, (2) the sudden change of the wind direction to north and northeasterly winds and (3) the return flow of the waters to the western coast, accompanied by strong winds. All three phases are well represented in 20CR. Also, the pattern of maximum wind speed on 13 November 1872 is well reproduced. However, the strength of the extrema is strongly underestimated in the ensemble mean and it is also underestimated in the ensemble members. In particular, the low pressure system is less deep and wind speeds are much lower in 20CR, even in the most extreme ensemble members. The EMULATE daily SLP data set also does not capture the small scale extrema in the pressure distribution on 13 November 1872.

Overall 20CR captures this extreme event only qualitatively, while it underestimates the magnitude. Arguably, this is due to the paucity of assimilated information, which is much less than in Rosenhagen and Bork (2008). Only very few stations contributed to the atmospheric states produced in 20CR, and none was in the region of the observed wind maximum. The work by Rosenhagen and Bork (2008) shows that much more pressure measurements would be available. Future versions of surface-based reanalyses could make use of more extensive data sources.

Acknowledgments

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