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Determining Storm Surge Return Periods: The Use of Evidence of Historic Events

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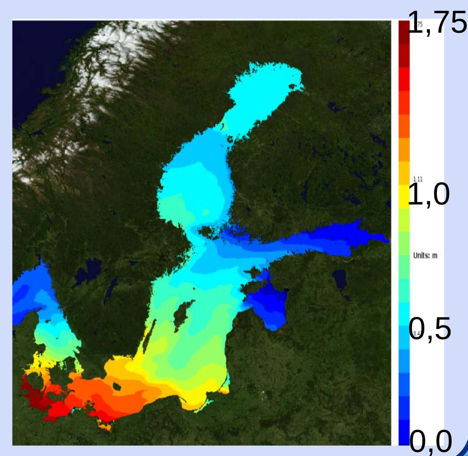
Storm Surge January 4, 2017

After a long period of westerly winds, the mean sea level of the Baltic Sea was about 0,5 meters above normal, with a tilt towards north and east. A heavy low pressure system caused winds from north east over the entire area, releasing and enforcing a seiche of the tilted water and at the same time blocking outflow to the North Sea. This caused a "quiet storm surge" – a surge without a storm – on the south western Baltic shores, with sea levels of 1,57 meters just south of Copenhagen in Køge and 1,77 meters further towards west in Aabenraa.

With present days statistics, this was considered a 100 year event. The surge was well forecasted, minimizing damages and avoiding casualties.

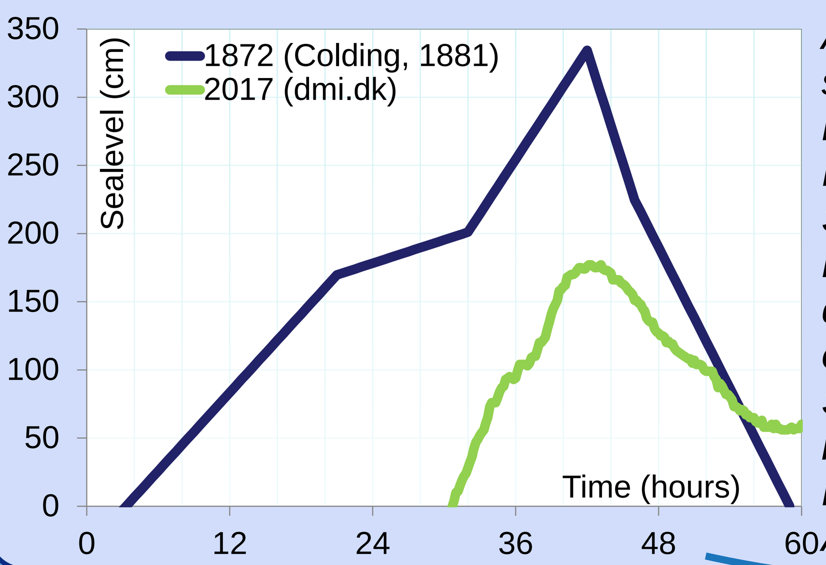
In many places, including Copenhagen, serious flooding would have occurred if the water had been a few 10s of centimeters higher.



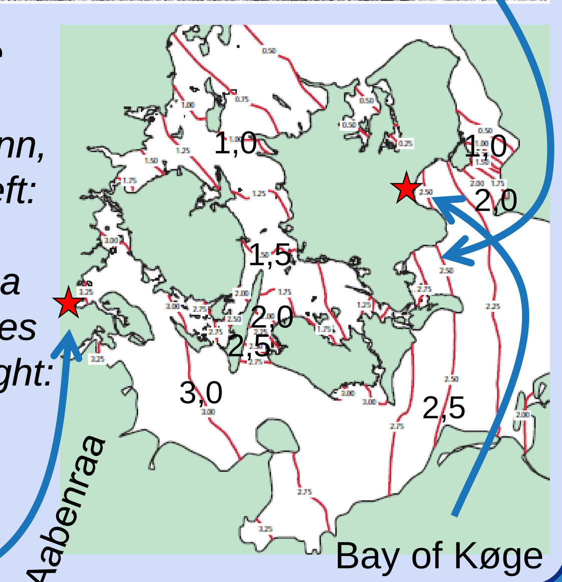
Left: Map of areas hit by storm surge. Ref: Danish Storm Council. Right: Sea level from the DMI ocean model. Ref: Copernicus (CMEMS BalMFC).

Storm Surge November 12, 1872

The preconditioning of the 1872 storm surge was similar to that of 2017, with a mean sea level of 0,3 meters above normal, but it was followed by a broad, long lasting storm system, causing winds of 20-30 m/s over the entire Baltic area. Massive floodings occurred, including areas that are now urban.



Above: Damages the storm surge in 1872. Ref: Holger Drachmann, Illustreret Tidende. Left: Sea level (cm) in the Danish town Aabenraa during the storm surges of 1872 and 2017. Right: Sea level (meters) reconstructed by the Danish Coastal Authorities (2011).



Abstract

Storm surges are a major concern for many coastal communities, and rising levels of surges is a key concern in relation to climate change. The sea level of a statistical 100-year or 1000-year storm surge event and similar statistical measures are used for spatial planning and emergency preparedness. These statistics are very sensitive to the assessments of past events, and to future sea level change.

The probability of a major storm surge from the Baltic Sea hitting the Copenhagen metropolitan area is officially determined by the Danish Coastal Authority based on tide gauge records. We have a long history for tide gauge measurements, with 120 years of data available for the calculations. However, the oldest of these tide gauge stations was set up after a major storm surge in 1872, and no events of similar severity have occurred since.

Including the evidence of the historic events from the 18th century changes the return period statistics, with a best estimate of a 100 year event changing from 1.5 meters (Sørensen et al. 2013) to 2.6 [2.2 – 2.8] meters (present study) in Køge just south of Copenhagen. Thus, with the tide gauge-based statistics, the storm surge on January 4 2017 was a 100 year event, but with the revised statistics using historic evidence, much larger events can be expected.

Further, we assess the very large impact of sea level rise on the storm surge statistics. As an example, according to the official statistics of southern Copenhagen, the flooding of a present day 100 year event will statistically occur every 10 years with just 27 cm of mean sea level rise.

Materials

The present study focuses on the bay of Køge, just south of Copenhagen, where the sea level of historic events, corrected to present day conditions have been estimated, taking land rise and observed mean sea level change into account (COWI, 2016, table below). For this study, only events with strong historic evidence such as measurements from other places in the regions or high water markings on houses have been taken into account, with the first event in 1825.

We are presently investigating indications of a storm surge in 1941, and therefore, to be on the safe side, our data record is assumed to end in 1933.

We estimate the uncertainty (1 standard deviation) to be 0.15 meters, based on variations in the historic evidence and uncertainty on the land rise and mean sea level change.

The storms causing the surges can be split in 2 types. Type 1 is most common and has a low pressure system passing from the Atlantic towards east. Type 2 has a high pressure over northern Scandinavia and a low pressure moving from south to north over central Europe. The storms in 1872 and 1913 were of this type.

Date	Sea level*, meters
3 Jan 1825	2.30
18 Oct 1828	2.35
19 Dec 1835	2.16
12 Nov 1872	2.86
31 Dec 1904	2.20
30 Dec 1913	1.93

Dates of historic events and estimated sea level for a similar surge today in Køge, meters (COWI, 2016).

Method

We use a peak-over-threshold (POT) method, with fitting of the number of events in a time period considered with a Poisson distribution and a generalized Pareto distribution (GDP) being used for the exceedances. The GDP has a shape parameter which describes if and how the distribution is saturated at high return periods, and a scale parameter, which for low shape parameter values roughly defines the increase in return height when the return period is increased by a factor of ten.

Since the material contains uncertainty, the uncertainty of the GDP distribution is also estimated by bootstrapping, using Monte Carlo simulations with observations perturbed within the uncertainty estimates.

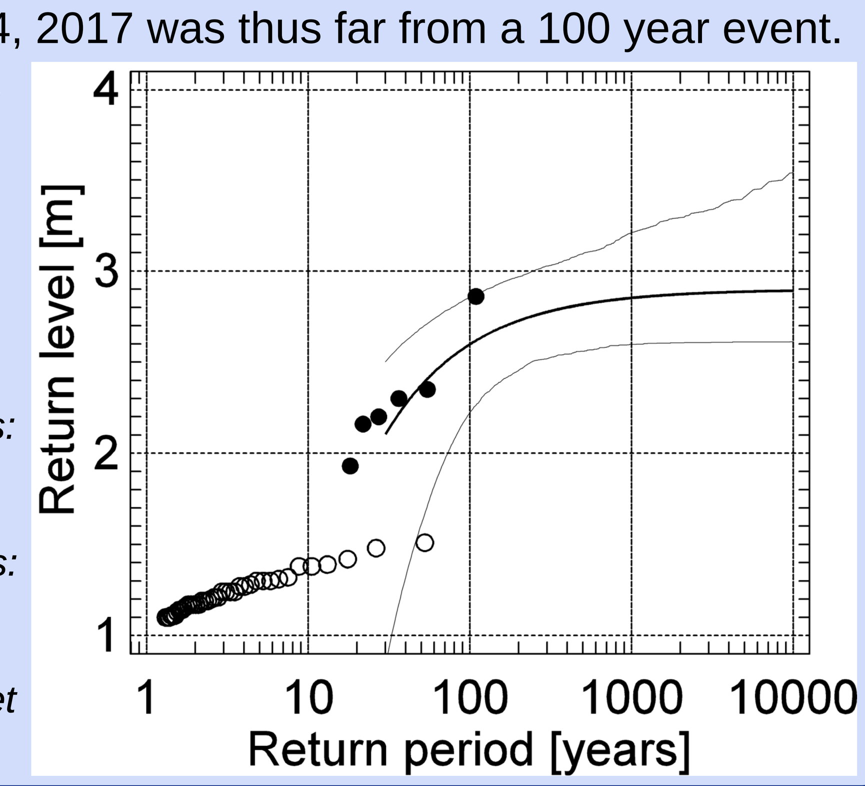
The hypothesis of a GDP distribution is tested with a Kolmogorov-Smirnov test (K-S test), where a value close to 1 indicates that the GDP distribution fits the data well.

Results

The best fit of the historic events are obtained with a frequency of exceedance of 0.06 events per year, scale parameter of 0.96 [0.64 – 1.53] meters, shape parameter of 0.8 [0.3 – 1.3], and a K-S test value of 0.9. This results in a 100 year event of 2.6 [2.2 – 2.8] meters and a 1000 year event of 2.9 [2.6 – 3.1] meters.

With the revised statistics, the storm surge on January 4, 2017 was thus far from a 100 year event.

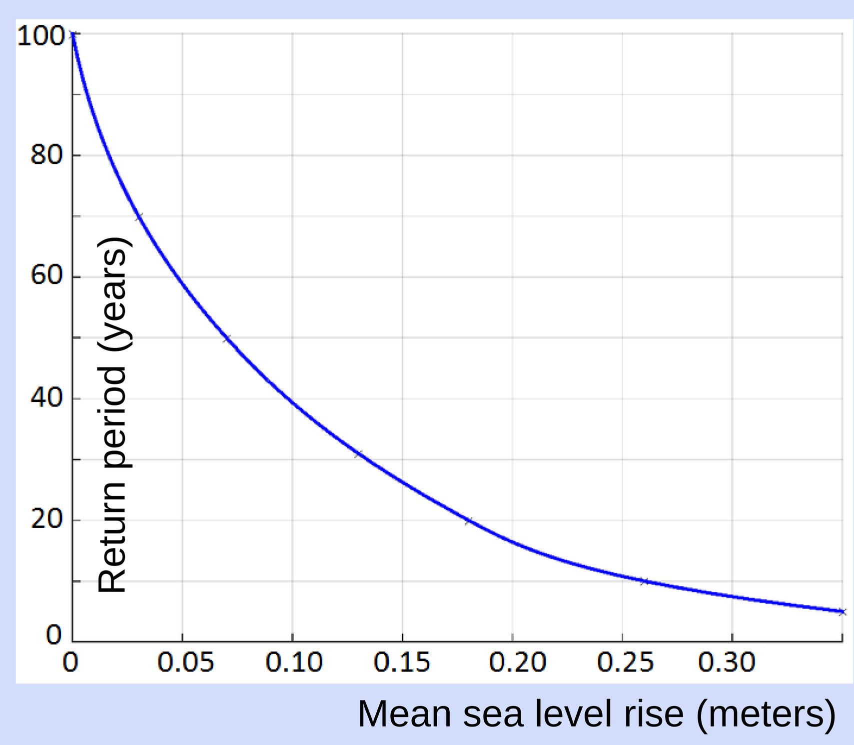
Return level as function of return period (best fit and 90% confidence interval). Filled circles: historic events. Open circles: observed events (Sørensen et al. 2013).



Future Storm Surges

There are two key parameters for the effect of climate change on storm surges: mean sea level changes (relative to land) and changes in the wind.

Mean sea level changes are expected to have the highest impact, massively changing return periods for a given level of flooding. The figure illustrates the change in return period of a present day 100 year event as a function of mean sea level rise for Aabenraa (based on Sørensen et al. 2013). For instance, a present day 100 year event will occur every 10 years with 0.26 meters of mean sea level rise. Figures are very similar for Danish stations within the southwestern Baltic region, including Copenhagen.



Change of storm surge return period (years) as function of mean sea level rise (meters) for the town of Aabenraa, Denmark.

The effect of changing wind patterns is less certain. Ensemble studies of regional climate models show a decrease in the mean wind speed over the North East Atlantic, but a small increase in the highest wind speeds over the south western Baltic Sea.

Since the Arctic region is heated more than the global average, we speculate that Type 2 storm systems will become less likely in the future, and the largest storm surges will be from Type 1 storms. However this needs further investigation.

Literature

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