

Storm surges in the western Baltic Sea

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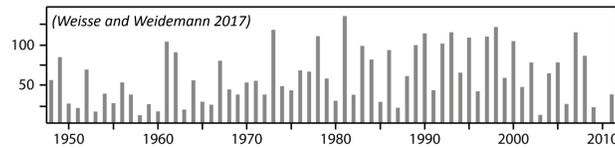
Introduction

Extreme sea levels are a regularly occurring phenomenon in the western Baltic Sea, in particular during the storm season from late fall to early spring. As in other shelf seas, wind set-up causing storm surges certainly is the most relevant effect. However, in the semi-enclosed Baltic Sea there are a number of additional atmospherically driven processes that may influence extreme sea levels and their distribution:

- Fluctuations in water exchange through the Danish Straits and to a smaller amount in river runoff and precipitation may lead to variations in the Baltic Sea volume with corresponding sea level variations of up to 50 cm on time scales of weeks to months.
- Oscillations in the seiche frequency band are observed which may, when favorably coupled with wind driven sea level variations, substantially contribute to extreme sea levels.

Variations in Baltic Sea volume

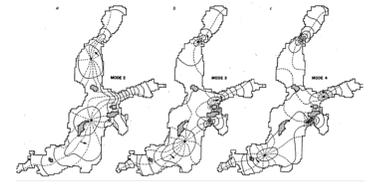
Due to limited transport capacity across the Danish Straits, the response of Baltic Sea level to external fluctuations is strongly damped at higher frequencies. For longer frequencies transport through the Straits will lead to corresponding changes in Baltic Sea volume which may have an impact on the height and frequencies of extremes. Baltic Sea volume is usually measured at tide-gauge Landsort in the Baltic proper. The Figure shows the number of days per year, in which mean sea level in Landsort exceeds the long-term average by 15 cm or more.



Theory of Baltic Sea seiches

Oscillations in the seiche frequency band are observed in Baltic Sea level data. The table shows theoretical oscillation modes in hours for the entire Baltic Sea with and without presence of Coriolis forcing based on calculations with a two-dimensional numerical model.

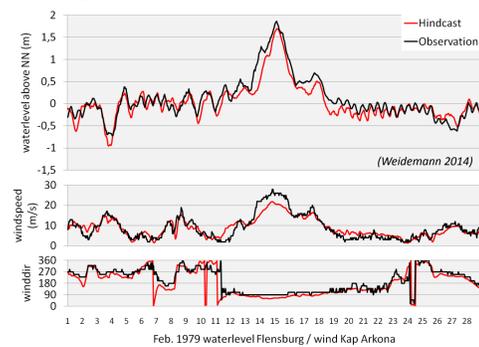
Mode	1	2	3
Period (f=0)	40.5	27.7	23.7
Period (f≠0)	31.0	26.4	22.4



The modelling approach

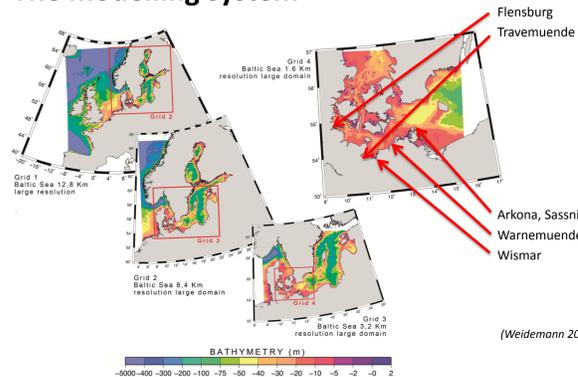
- a model based data base for both, the assessment of long-term variability and change and the analysis of contributions from Baltic Sea volume changes and oscillations in the seiche frequency band on extreme Baltic Sea sea levels
- atmospheric conditions from the coastDat-2 data base (Geyer 2014)
- a reconstruction of past (1948-2011) Baltic Sea levels at high spatial and temporal detail

How good can we model?

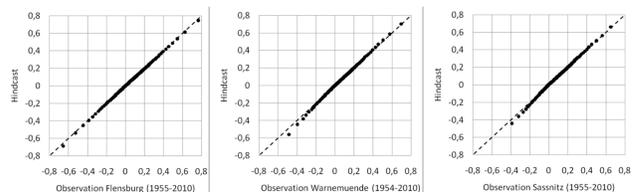


The Figure shows a comparison between observed (black) and hindcast (red) water levels in Flensburg (top) and wind speed (middle) and direction (bottom) in Kap Arkona for February 1979.

The modelling system

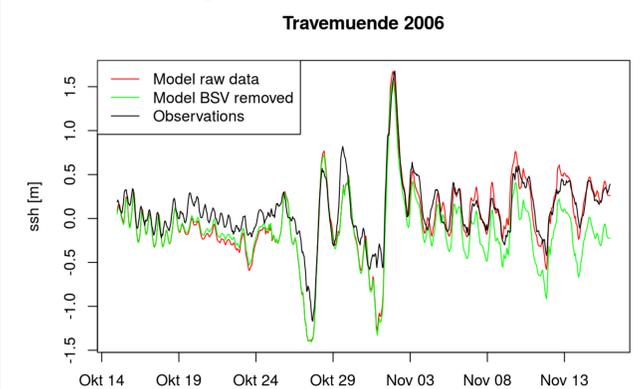


The Figure illustrates the ocean model system used for the multi-decadal reconstruction. Shown are the four nested model grids with spatial resolution ranging from 12.8 to 1.6 km from grid 1 to grid 4 respectively. Tides from FES2004 were used as boundary conditions in grid 1 while atmospheric forcing was taken from downscaled global reanalysis (Geyer 2014).

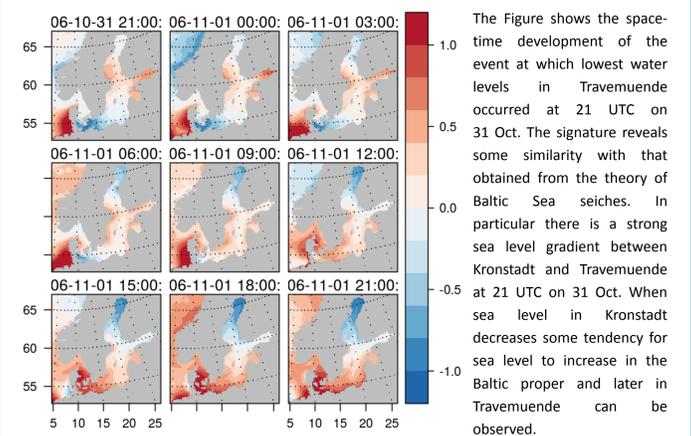


The Figure shows a comparison between observed and modelled frequency distributions of Baltic Sea levels at three stations along the German Baltic Sea coastline. Quantiles from 1% to 99% are shown. In general good agreement is inferred.

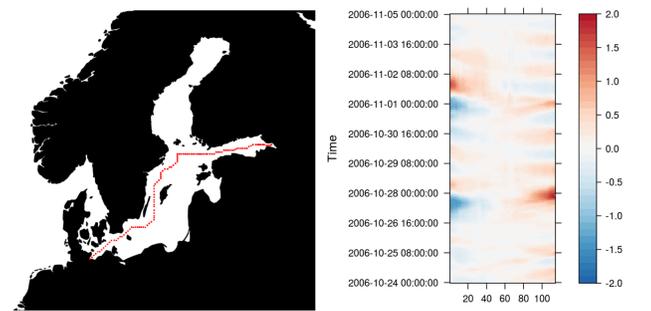
Oscillations in the seiche frequency band



The Figure shows an example for the presence of oscillations in the seiche frequency band in the observations and the model hindcast. In the observations these oscillations reached amplitudes of about 2m that are also clearly visible in the model run. Volume changes did not substantially contribute to these oscillations but are responsible for changes on longer time scales.



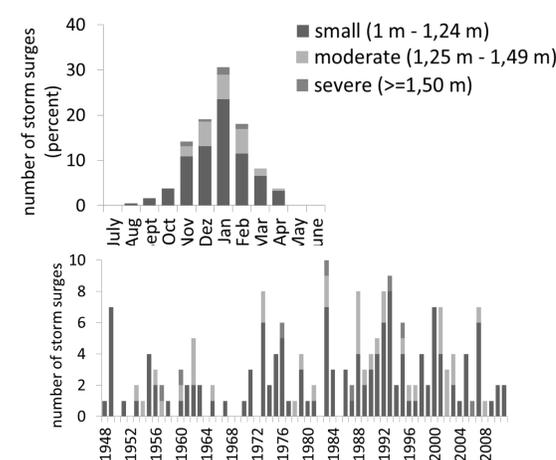
However, there is also a positive sea level anomaly building up in the Kattegat and some inflow is probably superimposed on the seiche like pattern.



The Figure on the right shows a Hovmoeller diagram of hourly sea level anomalies along a cross section from Travemuende, Germany to St. Petersburg, Russia. There are indications of out-of-phase oscillations at both ends of the cross section while sea level in the middle of the section (Baltic proper) varies around zero.

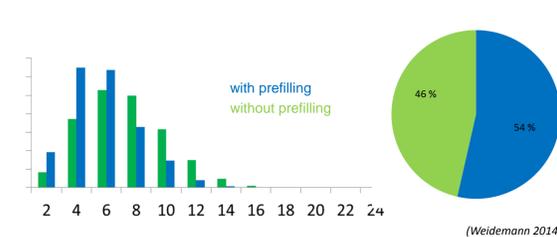
Long-term statistics for Wismar

Distribution of storm surges



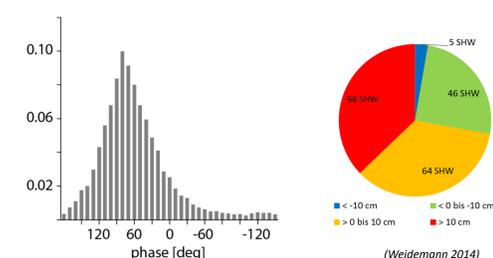
The Figure shows the seasonal and long-term distribution of storm surges in Wismar, Germany obtained from the multi-decadal hindcast conditioned upon intensity. Generally most surges occur during the winter storm season. While there is pronounced inter-annual and decadal variability no substantial long-term change in storm surge frequency could be inferred.

Surges and Baltic Sea volume changes



The height of storm surges and Baltic Sea volume changes was not found to be independent. This is exemplarily demonstrated for Wismar. Here extreme sea levels with and without contributions from high filling levels (FL-H, prefilling) occurred at about equal shares (right Figure). However, during FL-H phases, generally lower wind speeds were needed to sustain comparable peak water levels. This is demonstrated in the left Figure which shows relative frequencies of wind speeds in m/s in Wismar in-between 20 days before and two days after extreme sea level events with (blue) and without (green) FL-H conditions.

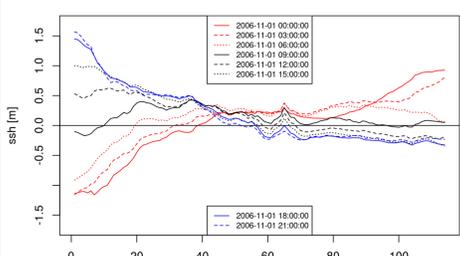
Are there systematic contributions from oscillations in the seiche frequency band?



Oscillations in the seiche frequency band also contributed to some of the observed extremes usually with a site-specific preferred phase shift. The figure on the left shows the frequency of hours in Wismar with extreme sea levels conditioned upon the phase of the longest oscillation in the seiche frequency band (31 hours) where zero-phase refers to the maximum of the "seiche-induced" sea level.

For the case of Wismar, contribution from oscillations in the seiche frequency band to extremes was found to be small (< 10 cm) in about 60% of the cases. In 37% of the cases the contribution exceeded 10 cm and in some cases (3%) the contribution actually lowered the extremes by more than 10 cm (right).

Travemuende - St. Petersburg



The Figure shows a sequence of cross sections every three hours starting with the maximum sea level in St. Petersburg at 00UT on 01 Nov. A drop of sea level in St. Petersburg is associated with a corresponding increase in Travemuende while changes in the Baltic proper are small and around zero. The time between the maxima in St. Petersburg and Travemuende is 18-21 hours. If we would assume that these variations are associated with seiches, this would correspond to a full cycle between 36 and 42 hours close to the theoretical values of 31 and 39 hours. Clarification is still needed on whether or not such sea level variations represent free or forced oscillations.