BIRGIT HÜNICKE & EDUARDO ZORITA

Institute of Coastal Research, Helmholtz-Zentrum Geesthacht, Germany

birgit.huenicke@hzg.de, http://coast.gkss.de/staff/huenicke/Poster_ICS_0511.pdf

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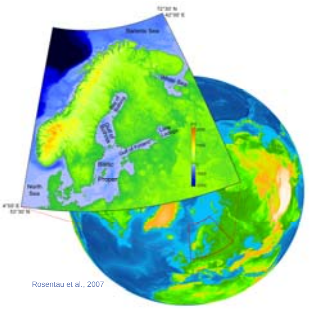
Recent sea-level change in the Baltic Sea

Introduction:

As a consequence of increasing concentrations of greenhouse gases in the atmosphere, the global rate of sea-level rise is expected to accelerate in the future. Some studies indicate that this acceleration has already been detected in the 20th century record of global sea-level rise *(Merrifield et al., 2009)* while others do not detect a significant change *(Holgate, 2007; Houston and Dean, 2011)*. For regional planning agencies more important than the global number is, however, the regional acceleration.



The Baltic Sea *(Fig.1)* is a region strongly influenced by isostatic rebound from the last deglaciation, with the Earth crust in the Northern Baltic rising at roughly 10 mm/year and in parts of the Southern Baltic sinking at about 1 mm/year. Time series of sea-level measured by coastal gauges thus display strong linear trends due to isostasy. The values of these trends form the basis for sea-level rise projections related to coastal protection, with a rough estimate of possible sea-level rise caused by climate change added to the isostatic trends.

Fig.1 Location of the Baltic Sea Region and the Baltic Sea Area.

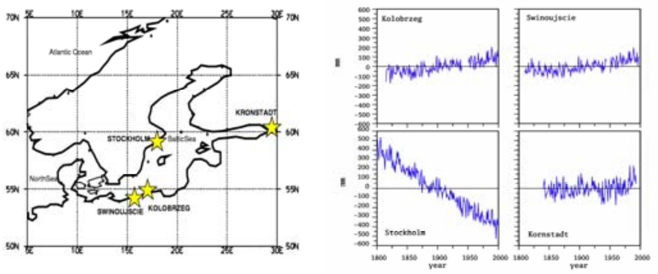


Fig.2 Annual mean sea-level in four gauge station in the Baltic Sea that report particularly long records: Swinoujscie (PSMSL), Kolobrzeg (PSMSL; before 1951 TU Dresden), Stockholm (Ekman, 2003) and Kronstadt (Bogdanov et al., 2000).

Deviations from a constant long-term trend, e.g. as an accelerating component, should be considered in future projections. The identification of a change in the long-term trend is hampered by other regional factors that cause variations in sea-level at multiple timescales, such as the North Atlantic Oscillation and other temperature and precipitation variations *(e.g. Hünicke et al., 2008).*

Methods:

Four local series of annual mean sea-level *(Fig.2)* are assumed to follow the statistical model:

$$sl(t) = sl_o + bt + at^2 + e(t)$$

sl : annual mean sea-level t : time (years) e : residuals

The parameters b and a are estimated by fitting the observed annual sea-level records to the statistical model by Ordinary Least Squares (OLS). This method is known to be not optimal when the residuals e are not distributed as Gaussian white noise. However, even when these conditions are not fulfilled , the OLS estimation is unbiased. For the statistical significance of the present of trends or acceleration, the structure of the residuals has to be taken into account. Here, a method based on bootstrapping of the residuals that conserves their serial correlation structure has been applied *(Christiansen et al., 2010).*

Results:

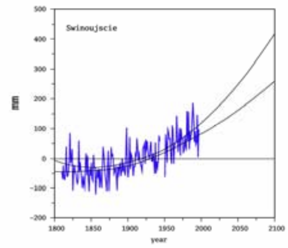
The estimated accelerations of annual sea-level in the Baltic Sea are all positive, and statistically significantly different from zero *(Table 1).* Also, the estimated magnitudes are all similar and they can be considered equal within the uncertainty ranges.

Table 1 Estimations of the acceleration in annual mean sea-level in four gauges in the Baltic Sea in the period 1800-2000. The last two columns indicate the 5% -95% uncertainty range.

unit: 10^{-2} mm/year^2	best estimate	5th	95th
Kolobrzeg	0.55	0.31	0.87
Swinoujscie	0.55	0.35	0.78
Stockholm	0.32	0.15	0.50
Kronstadt	0.46	0.24	0.69

This is consistent with a climate influence in the last 200 years. An alternative interpretation, namely that the isostatic trend is slowing down, would not be consistent with the same sign of the acceleration for all four gauges, some located in sinking others in rising areas.

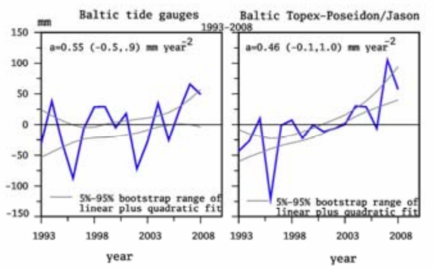
Baltic Sea level has slightly accelerated through the last 200 years.



To illustrate the magnitude of the acceleration, the linear and quadratic trend can be extrapolated into the future unchanged. The additional contribution of the quadratic term to the simple linear extrapolation is, however, small. For example the historical acceleration implies a sea-level rise in the Southern Baltic of ~30cm by year 2100 *(Fig.3)*. However, this number does not take into account future changes in the acceleration, and cannot be interpreted as a prediction.

Fig.3 Extrapolation of the linear trend and acceleration for Swinoujscie. The confidence interval stem from the bootstrap distribution of the corresponding parameters.

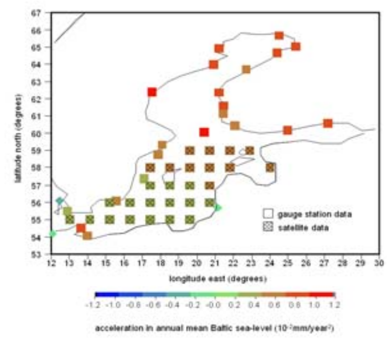
The question arises as to how these findings compare with satellite data for the last few decades. For that purpose, all available tide gauge data which report between 1993 to 2008 were selected for the Baltic Sea Region (53N to 67N,12E to 30E) from the PSMSL* RLR datasets. In addition, a combined satellite data set on a 1°*1° grid was downloaded from the CSIRO website: *http://www.cmar.csiro.au/sealevel/sl_data_cmar.html* for the same time period. For both datasets, each of the time-series (annual means) was fit to a linear and quadratic trend over the observed period. For the tide gauges as well for the satellite data, a positive acceleration of the annual mean sea-level averages could be detected *(Fig.4).*



***PSMSL** =Permanent Service for Mean Sea Level (http://www.psmsl.org/)
RLR -> Revised Local Reference

Fig.4 Time-series of annual mean Baltic sea-level averages (1993-2008) derived from 24 tide gauges (left panel) and 77 grid points of combined satellite data (corrected for inverse barometer and GIA) of TOPEX/ Poseidon, Jason-1 and Jason-2/OSTM sea level fields (right panel).

Within the satellite era (1993-today), available tide gauge readings cover most of the North and South-East Baltic coasts, whereas the satellite data cover the South and South-East Baltic open ocean. The spatially averaged acceleration is comparable in both data sets.



Spatially resolved, the acceleration values ranges between 0.39 to 0.54 10^{-2} mm/year² for the satellite data. For the tide gauge data, the range lies between -0.38 and 1.12 10^{-2} mm/year² within the different stations, with a tendency to more positive values in the north and less positive values in the south. The same spatial gradient tendency is depicted in the satellite data *(Fig.5).* It has to keep in mind, that the satellite data do not provide measurements near the coast and thus are not directly comparable with the tide gauge data.

Fig.5 Acceleration values of annual mean Baltic sea-level averages derived from tide gauges and from satellite altimetry (1993-2008). (preliminary results)

Outlook:

Future sea-level rise in the Baltic will be determined by several factors, some of them still poorly known, such as the dynamics of polar ice sheets. Many planning agencies broadly assume a continuation of the present linear trends, allowing for an additional 'climate contribution'. The estimation of an acceleration rate can contribute to improve these pragmatic estimations. A closer analysis of these first findings will be the focus of future research. The analysis is planned to be expanded to the North Sea. As the North Sea is the only connection of the Baltic Sea to the worlds ocean, this analysis is expected to give information about how strongly global sea-level effects Baltic sea-level.

References: *Bogdanov et al. 2000.* Mean monthly series of sea level observations (1777-1993) at Kronstadt gauge. Reports of the Finnish Geodetic Institute 2000: 1, 34pp. *Christiansen et al., 2010.* A Surrogate Ensemble Study of Sea Level Reconstructions. J Climate 23, 4306-4326. *Ekman, M. 2003.* The world's longest sea level series and a winter oscillation index for Northern Europe 1774-2000. Small Publ Hist Geophys 12, 30pp. *Holgate, SJ. 2007.* On the decadal rates of sea-level change during the 20th century. Geophys Res Lett 34, L01602. *Houston and Dean, 2011.* Sea-Level acceleration Based on US Tide Gauges and Extensions of Previous Global-Gauge Analyses. J Coast Res, doi: 10.2112/JCOASTRES-D-10-00157.1 *Hünicke et al. 2009.* Regional differences in winter sea-level variations in the Baltic Sea for the past 200 years. Tellus 60A, 384-393. *Merrifield et al. 2009.* An anomalous recent acceleration of global sea level rise. J. Climate 22, 5772-5781. *Rosentau et al. 2007.* Relative Sea level change in the Baltic Sea since the Littorina Transgression, Z geol Wiss 35, 3-16.