Regional differences in winter sea-level variations in the Baltic Sea for the past 200 years

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Introduction

We present a statistical analysis of the relationship between winter Baltic sea-level and large-scale atmospheric forcing in the past 200 years, using long gauge records and climate reconstructions of SLP, precipitation and air-temperature covering the European land area (*Luterbacher et al., 2002, 2004; Pauling et al., 2006*). We aim at confirming the heterogeneous regional response of sea-level to large-scale forcing at multi-decadal timescales and at identifying possible factors for this behaviour.

***Fig.1** Sketch of the Baltic Sea, showing the location of sea-level gauges: Kolobrzeg (1815-1999; PSMSL, before 1951 provided by Technische Universität Dresden), Swinoujscie (1815-1996; PSMSL), Stockholm (1801-2000; Ekman, 2003) and Kronstadt (1840-1993; Bogdanov et al., 2000)*

Strategy

The approach is based on simple statistical regression methods to hindcast sea-level variations, examining the skill of different predictors, restricted to those for which long observations or reconstructions are available and which are potentially well simulated by coarse resolution models: SLP (an indicator of geostrophic wind), area averaged precipitation and air-temperature. The timescales of interest are decadal, since future climate change will presumably evolve at these slow timescales. The model reads:

$$SL(t) = \sum_{i=1,N} a_i \, pc_i(t) + SLR(t)$$

where pc_i is the i^{th} PC, a_i is the corresponding regression coefficient, N the number of PCs included in the regression and SLR are the sea-level residuals. The parameters a_i were calibrated in the period 1900-1999.

The sea-level records contain a trend which is caused by a combination of postglacial land uplift and eustatic sea-level changes. On the time scales of our analyses this trend is assumed to be linear and is eliminated.

The analysis is restricted to variations around the long-term linear trend. As we are interested in variability at decadal and longer timescales, all timeseries were smoothed with an 11-year running mean filter.

Relationship between Baltic Sea level and large-scale gridded fields

In the 20th century, sea-level variations in the analysed stations evolve quite coherently, in the 19th century their agreement is less obvious, particularly between the Southern stations and the other two (Fig.2).

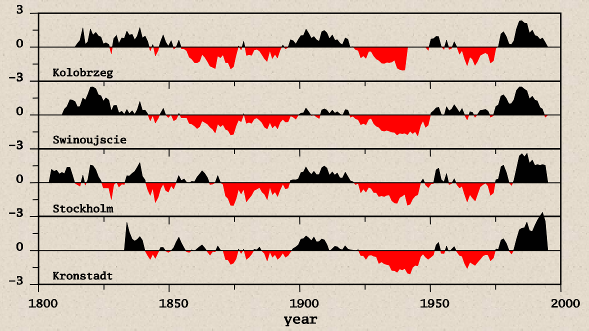

***Fig.2** Relative winter mean (DJF) sea-level height at four stations in the Baltic Sea, deviations from the 1900-1999 mean, linearly detrended, smoothed by a 11-year running-mean and standardized to unit standard deviation.*

When decadally smoothed, the inter-station correlation exceeds 0.85 for all pairs in the 20th century, but in the 19th century the southern stations and the rest falls about 0.5.

The possible external atmospheric forcings (SLP, precipitation, temperature) behave coherently at decadal timescales in the 20th century, while in the 19th century they tend to diverge (not shown). Large negative precipitation anomalies in the last decades of the 19th century, which is not matched by the SLP and temperature, suggests that these factors might force sea-level in a spatially heteorogeneous way.

Thus, as a first predictor in a regression equation SLP is considered. The SLP field is previously decomposed in its Principal Components (PCs) to avoid co-linearity. In a second step we explore whether area-averaged precipitation could be a skilful predictor for the Southern sea-level stations (which show a low calibration and a poor validation skill using SLP as predictor). Fig.3 and Fig.4 show the results (calibration period 20th century).

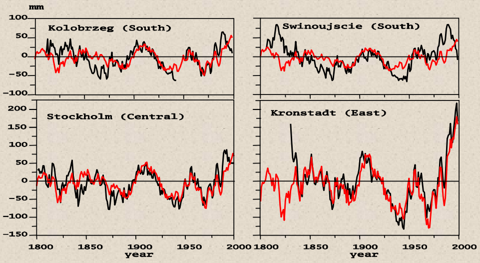

***Fig.3** Decadally smoothed and linearly detrended observed sea-level and reconstructed sea-level (deviations from the 1900-1999 mean) using the SLP field as predictor.*

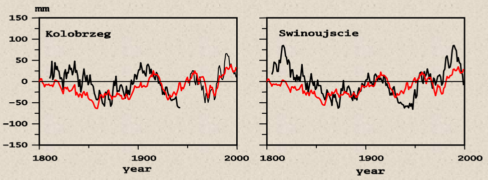

***Fig.4** Decadally smoothed and linearly detrended observed sea-level and reconstructed sea-level (deviations) from the 1900-1999 mean) for the southern stations, using area-averaged precipitation as predictor.*

The skill of the regression was evaluated by the Reduction of Error statistic (RE), which adopts a value of 1 (perfect prediction) and -∞ (negative no skill) and by the correlation coefficient (r) between observations and estimations. Table 1 shows the results for all predictors evaluated for different validation and calibration periods (19th and 20th century).

***Table 1** Reduction of Error (RE) statistic and correlations (r) as an evaluation of the skill of the predictors SLP, precipitation (Prec) and temperature (Temp); using regression methods, indicated for different calibration (CAL) and validation (VAL) periods. The 95% significant values are bold typed.*

RE	***20th CAL***	***19th VAL***	***20th VAL***	***19th CAL***
predictor*	**SLP / Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**
Kolobrzeg	0.65/ 0.39/ 0.05 (0.54)	-0.04/ 0.23/ 0.01 (-0.03)	-0.21/ 0.4/ 0.06 (-0.11)	0.19/ 0.29/ 0.02 (0.01)
Swinoujscie	0.39/ 0.34/ 0.02 (0.72)	0.10/ 0.36/ 0.03 (0.15)	-0.21/0.33/-0.29 (-0.24)	0.08/ 0.34/ -0.01 (-0.10)
Stockholm	0.78/ 0.46/ 0.16 (0.68)	0.34/ 0.01/ -0.25 (0.08)	0.7/ 0.08/ 0.19 (0.63)	0.16/ 0.05/ -0.02 (0.14)
Kronstadt	0.89/ 0.27/ 0.09 (0.50)	0.71/-3.24/-1.2 (-1.35)	0.77/-0.07/ 0.2 (0.43)	0.7/ 0.02/ -0.46 (-0.81)
r	***20th CAL***	***19th VAL***	***20th VAL***	***19th CAL***
predictor*	**SLP / Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**	**SLP/ Prec/ Temp**
Kolobrzeg	**0.81**/ **0.7**/ 0.29 (**0.79**)	0.24/ **0.68**/ 0.19 (0.23)	-0.05/ **0.7**/ 0.29 (-0,01)	**0.46**/ **0.68**/ 0.19 (0.15)
Swinoujscie	**0.63**/ **0.64**/ 0.13 (**0.87**)	0.33/ **0.76**/ 0.22 (0.39)	-0.17/ **0.64**/ 0.13 (0.23)	0.3/ **0.76**/ 0.22 (0.26)
Stockholm	**0.88/ 0.74/ 0.50 (0.89)**	**0.59/ 0.44**/ 0.07 (0.49)	**0.85/ 0.74/ 0.50 (0.88)**	**0.41/ 0.43**/ 0.07 (**0.47**)
Kronstadt	**0.95/ 0.63/ 0.6 (0.88)**	**0.85**/ -0.2/ **0.46 (0.67)**	**0.91**/ -0.63/ **0.6** (**0.82**)	**0.85**/ 0.2/ 0.46 (**0.63**)

*leading SLP PCs/ area-averaged precipitation/ area-averaged temperature (leading temperature PCs)

Summary and Conclusions

Decadal winter sea-level variations in some stations located in the southwestern, central and eastern Baltic Sea tend to be less coherent in the 19th century than in the 20th century. The influence of SLP, precipitation and air-temperature on sea-level varies for the different stations. In the central and eastern Baltic, sea-level variations are well described by SLP alone, whereas in the southern Baltic Sea area-averaged precipitation explains better the decadal variations. The evolution of precipitation in the 19th century could explain the different behaviour of the southern Baltic stations. Temperature (area-averaged and PC representation) is not able to explain the decadal variations in the southern Baltic. If SLP and precipitation trends diverge in future climates, e.g. due to humidity, sea-level trends in different parts of the Baltic Sea may also diverge.

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