

Statistical Downscaling of climate drivers of decadal winter Baltic Sea level variability in 1800-2100

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1 Introduction

Present estimations of future global sea-level change are based on simulations with coarse-resolution global climate models. In coastal regions and semi-enclosed seas, as the Baltic Sea, atmospheric circulation patterns and others may cause large deviations from the global sea-level trends. In wintertime inter-annual Baltic sea-level variability at its northern and eastern boundaries are strongly influenced by the strength of westerly winds, closely linked, via the geostrophic relationship, to the North Atlantic Oscillation (NAO). Stronger westerlies in positive phases of the NAO, cause sea-level to rise in some areas of the Baltic Sea. This process cannot be represented in a global climate model. It is therefore reasonable to assume that the estimation of future Baltic Sea level rise requires the application of downscaling methods, to translate trends in large-scale forcing fields to regional sea-level trends. In this study we analyse the feasibility of statistically determining Baltic Sea level variations from large-scale, coarse resolution climate fields. To address these questions the instrumental climate records are too short and thus we analyze long winter sea-level records (around 200 years long) and gridded reconstructions of sea-level pressure (SLP), air-temperature and precipitation covering the European land area (Luterbacher et al., 2002, 2004, Pauling et al., 2006). These reconstructions coincide with corresponding observational records in their calibration period 1901-1990 (for precipitation 1901-1983) and did not include any sea-level information as predictors.

An ensemble of General Circulation Model (GCM) climate simulations for the period 1756-2100 is used to quantify the contribution of SLP, and precipitation to possible future Baltic Sea level changes. Although these estimations may be obviously model and scenario dependent, they may be indicative of the order of magnitude of their possible contributions and of the uncertainty originating in the choice of climate model.

2. Methods

Our approach is based on simple statistical regression methods to hindcast sea-level variations, calibrated in the 20th century and validated in the 19th century, examining the skill of different predictors. The processes actually responsible for winter sea-level variations in the Baltic Sea at decadal timescales are complex, as sea-ice, precipitation, run-off, all may affect sea-level and in some regions more strongly than in others. In this study, however, the predictors have to be restricted to those that are potentially well simulated by coarse resolution models. In practise, this limits the choice to SLP (an indicator of geostrophic wind), area averaged precipitation and air-temperature.

Our timescales of interest are decadal, since future climate change will presumably evolve at these slow timescales. Therefore, all time series were smoothed with an 11-year running mean filter.



Fig.1 Sketch of the Baltic Sea, showing the location of the sea-level gauges.

We focus on winter means (December to February) of the four longest sea level records from stations situated along the Baltic coast (Fig.1), obtained via internet from the Permanent Service for Mean Sea Level (PSMSL).

The records contain a trend which is caused by a combination of post-glacial land uplift and eustatic sea level change. On the timescales of our analysis this trend is assumed to be linear and is eliminated by statistically estimating the linear trend and subtracting it from each sea-level record. Therefore, the analysis is restricted to variations around the long-term linear trend.

At decadal timescales and at mid-latitudes, surface wind is closely related to SLP through the geostrophic relation. Furthermore, SLP gradients may also influence sea-level through the inverse barometric effect. SLP is therefore considered as the first predictor in a simple regression equation with sea-level at one station SL_i as the predictand. The SLP field in the European region is previously decomposed in its principal components (PCs) to avoid co-linearity of the predictors and the resulting instability of the regression which simplified 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 by least-square error minimization. To estimate sea-level variations outside the calibration, the SLP anomalies relative to the calibration period are projected onto the Empirical Orthogonal Function (EOF) previously calculated in the calibration period. The number N of PCs included in the regression was the one yielding the best model skill in the validation period.

The skill of the regression was evaluated by the Reduction of Error (RE) statistics. The RE attains a value of unity for a perfect estimation and a value of zero for a skill equal to that of climatology. In further steps the statistical model has been augmented to include winter precipitation and winter air-temperature as a sole predictor, with both representations (Baltic Sea area averaged and PCs) and also the predictor skill of temperature in combination with SLP has been tested.

After calibration and validation, the statistical model could be applied to the corresponding output of climate simulations with the global climate models ECHO-G, HadCM3 and ECHAM/OPYC3, driven by the IPCC SRES scenarios A2 and B2.

3. Results

For the stations Kronstadt and Stockholm, the model skill is high (see Fig.2, upper panel). This agreement also supports the quality of the SLP reconstructions in the 19th century. In contrast, the calibration skill for the stations in the Southern Baltic, Kolobrzeg and Swinoujscie, is considerably lower, and the validation skill is very poor (not shown).

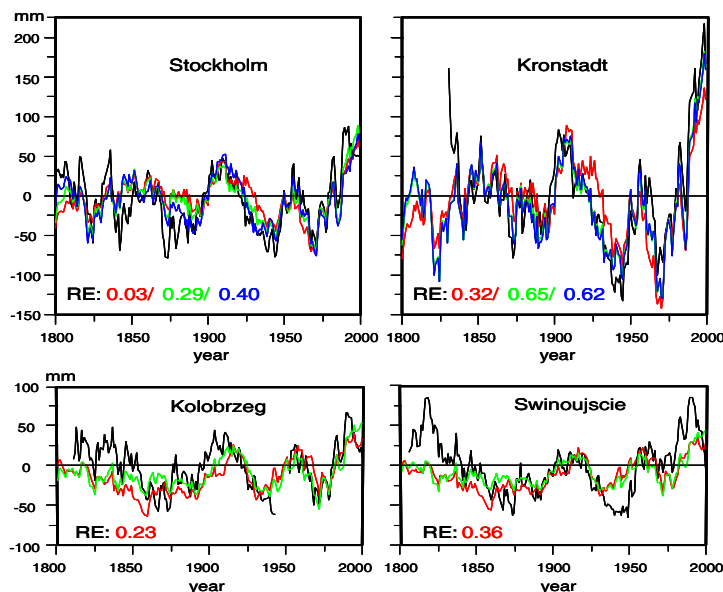


Fig.2 Winter sea-level records (black), linearly detrended and smoothed by a 11-year low-pass filter, and corresponding estimations. Upper panel: using stepwise the three leading SLP PCs as predictors (red 1/green 1-2/blue 1-3). Lower panel: using mean precipitation as predictor (red) and mean precipitation and the two leading PCs of the large SLP field (green). The validations (1800-1899) Reduction of Errors (RE) are indicated in each panel.

These results indicate that SLP is not an adequate large-scale predictor for all stations in the Baltic Sea and that an individual analysis for each gauge station is necessary. It is noteworthy that although sea-level variations seem relatively coherent among the four stations at decadal timescales in the 20th century, they are less so in the 19th century. We now explore if precipitation could be a skillful predictor for sea-level variations in Kolobrzeg and Swinoujscie, where SLP showed a poor performance in the 19th century. Since precipitation could influence sea-level after a lag of a few months, both winter and autumn precipitation, seasonally averaged, were considered as predictors. The skill of winter precipitation, though not perfect, has increased relative to the SLP for the Southern stations (Fig.2, upper panel).

Observed and estimated sea-level variations in the 19th century evolve more in agreement, although low-frequency deviations between estimation and observed records at the beginning of the century still remain. These deviations might be tentatively explained by deficiencies in the very low-frequency variability in the precipitation reconstructions. In contrast, autumn precipitation has a very poor skill in the calibration and validation periods (not shown). Therefore, although part of the winter precipitation surely lies in form of snow and contributes to sea-level variations with a lag, the time-series indicate that this lag within a season. As in the case of SLP, the reasonable skill of rainfall for the Southern

Baltic station supports the validity of the winter precipitation reconstructions in the 19th century (Pauling et al., 2006) in this region.

The use of winter air-temperature as a sole predictor did not result in any model improvement relative to the SLP-only model. Also temperature in combination with SLP is not able to replicate sea-level in the Southern Baltic in the 19th century. Winter temperature in this region is strongly connected to the NAO, so that probably no new information is being introduced by using temperature as predictor.

Based on the previous results, SLP was used as a predictor for the stations Kronstadt and Stockholm, and mean Baltic average precipitation for stations Swinoujscie and Kolobrzeg to study their contribution to future winter sea-level changes. The results from the ECHO-G simulations (driven by the IPCC SRES scenarios B2) indicate that simulated changes in SLP, and therefore the changes in the geostrophic wind, can contribute to changes in sea-level in Kronstadt and Stockholm with a trend of the order of 2 mm/year and 1 mm/year, respectively, provided that the linear statistical model remains valid under this rather strong intensification of the meridional atmospheric pressure gradient. For the stations in the Southern Baltic Sea, the simulated changes brought about by simulated changes in precipitation are of the order of 0.5 mm/year and therefore smaller. Both factors, SLP and precipitation, contribute to an increase of sea-level. This result tends to agree qualitatively with most state-of-the-art climate models used to simulate future climate changes (Giorgi et al, 2001). As an illustration of uncertainty: the results from the HadCM3 and ECHAM/OPYC simulations (driven by the IPCC SRES scenarios A2 and B2) show a noisier, but tentatively positive SLP signal on sea-level changes. In contrast, the rainfall contribution is more similar and positive in all cases.

4. Summary

The skill of large-scale predictors to determine decadal sea-level variations in the Baltic sea in the 19th and 20th centuries has been tested by statistical analysis of long sea-level records, observational gridded data sets and gridded climate reconstructions. It is found that the predictor skill may vary considerably among gauge-stations. The SLP reconstructions in the 19th century show large skill for the station Kronstadt, and therefore, they likely represent good approximation to the real SLP fields in this century. For Stockholm, and especially for the Southern Baltic stations, the skill of SLP is much lower. In the latter stations area-averaged winter precipitation shows a larger skill than SLP. The result agrees with the low correlation between the winter NAO-index (first SLP-pattern) and winter Sea-level in the Southern Baltic.

This could indicate that past and future sea-level variations around the eustatic trend may be caused by different physical mechanism. If the future trends of these predictors diverge, they may imping spatially diverging trends on future sea-level. To test this possibility climate simulations for the period 1750-2100 were used to quantify the contribution of SLP and precipitation to past and future Baltic sea-level changes. The analyses indicated that the trend in sea-level rise caused by changes in the regional climate forcing might be of the same order of magnitude as the global sea-level rise due to thermal expansion of the surface water layers, although it may strongly depend on the model used in the climate simulations.

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