Estimation of the influence of regional climate on recent past and future sea-level changes in the Baltic Sea with statistical methods and simulations of climate models

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Introduction

Long-term variations of mean sea level in the Baltic Sea have been caused in the past by different sources, mainly geological (glacio-hydro-isostatic effect) and climatological. The dominant long-term trend in sea level observations from most locations in the Baltic Sea is effectuated by the combination of isostatic change due to postglacial rebound and eustatic change due to global or at least North Atlantic sea-level change. Although the mean sea level of the ocean is presently increasing, this effect is partially balanced by the uplift of the Scandinavian land plate, and reinforced by the simultaneous sinking of the southern Baltic coast (the Earth's response to past changes in ice and water loads)[1]. This isostatic trend varies between -1 and 9 mm / year relative to the geodit. The smallest values are in the south and the largest in the Bothnian Bay near the coast of northern Sweden (see *Fig. 1*)[2].

In a region with a complex coastline structure such as the Baltic Sea, variations in sea level may be caused by more processes than in the open ocean. A primary factor modulating Baltic Sea level at inter-annual timescales is the near-surface wind forcing, which may pile water masses from the North Sea into the Baltic and hinder the outflow of Baltic Sea water into the North Sea. However, as we will explain below, the influence of the wind forcing seems to be spatially heterogeneous and the wind forcing signal is not present in all gauge stations with the same strength. Sea-ice formation in wintertime, runoff, evaporation, salinity variations and current

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[1] BACC / Baltic Assessment of climate change for the Baltic Sea Basin, author team 2008.

[2] Rosentau et al. 2007.

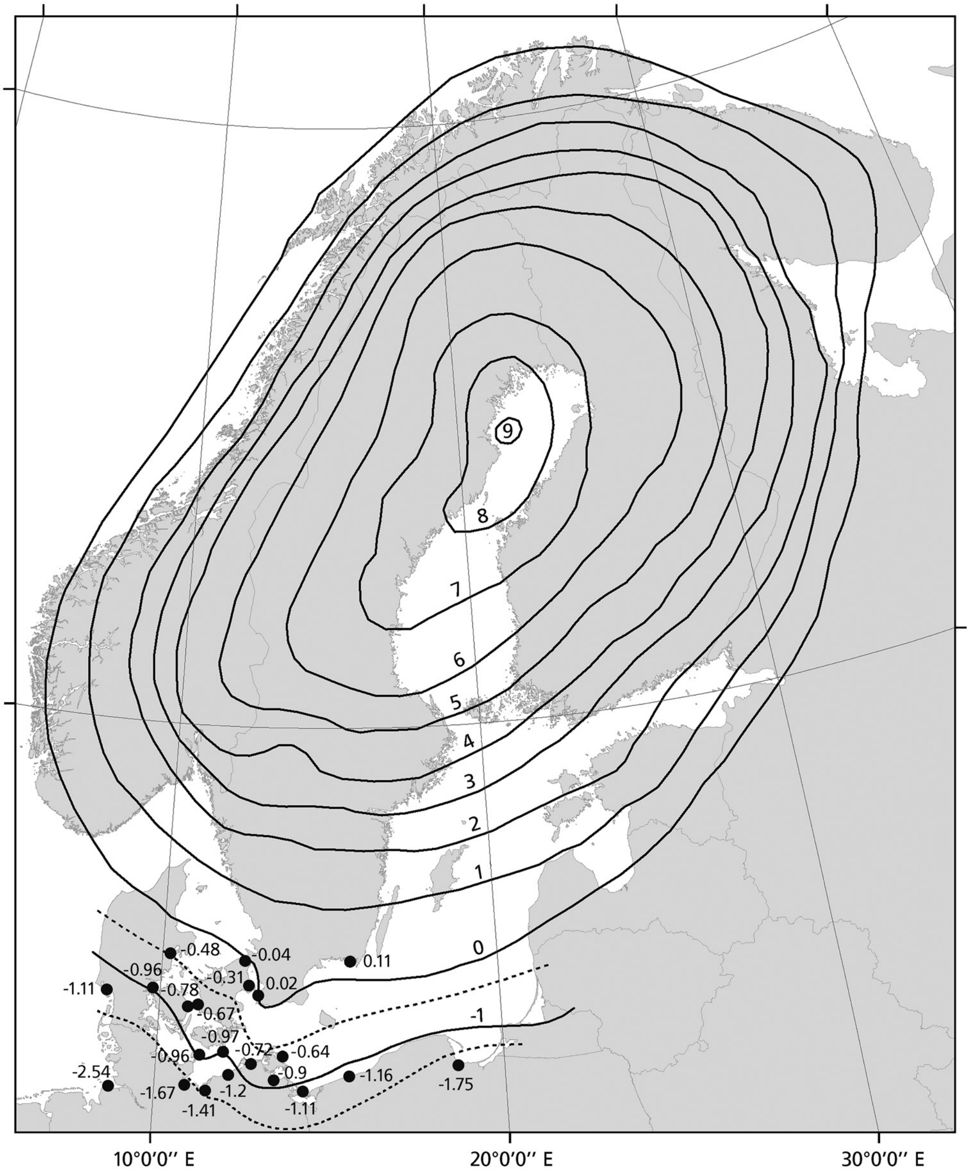

Fig. 1. Map of vertical crustal movement relative to the sea level (mm/year). Synthesis of Ekman's (1996) data from Fennoscandian glacio-isostatic uplift region and new data gauge measurements from the southern Baltic Sea (from Rosentau et al. 2007).

variations, may also contribute to the inter-annual variability of sea level in the Baltic. These regional factors may act at inter-annual and decadal timescales. The question, however, arises as to whether these regional climate factors can be quantitatively relevant to the explanation of past and future long-term sea-level trends.

To estimate the climate influence on past and future sea-level variability in the Baltic Sea, it is therefore necessary to study the behaviour of long-term trends in sea-level variations, and also to gain a deeper understanding of the long-term variations around the trend. Baltic Sea-level variations at inter-annual to decadal timescales are generally believed to be caused essentially by variations in wind forcing, in particular (although not exclusively) by the North Atlantic Oscillation

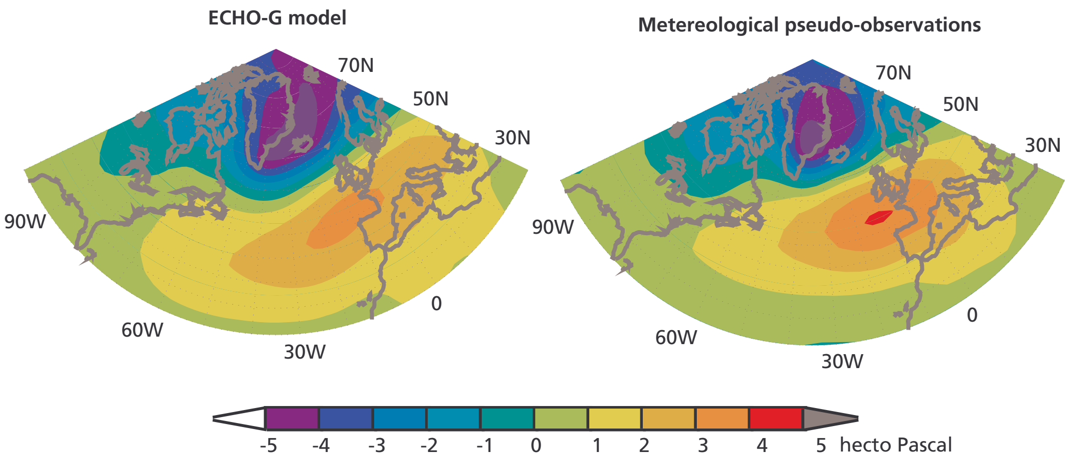

Fig. 2. Pattern of the North Atlantic Oscillation (NAO), calculated as the eigenvector of a principal component analysis of the winter (December–February) mean North Atlantic-European sea level-pressure field. Right, derived from the meteorological reanalysis of the National Centre for Environmental Prediction (NCEP) in the period 1948–1990; Left, from a climate simulation with the model ECHO-G driven by historical external forcing in the same period. The NAO pattern is closely linked to the strength of the wind over the Baltic Sea trough the geostrophic relation.

(NAO), the sea-level pressure (SLP) sea-saw that pervades the inter-annual climate variability in the North Atlantic–European sector. At monthly timescales and longer, the near-surface wind is closely related to the gradient of the SLP field through the geostrophic relation: The wind direction follows the isobars and its strength is proportional to the pressure gradient. *Figure 2* shows the patterns of the NAO, derived from the meteorological reanalysis of the National Centre for Environmental Prediction (NCEP) in the period 1948 to 1990 and from a climate simulation with the model ECHO-G.

Although the NAO is the dominant large-scale SLP pattern over the Baltic Sea, the variability of the NAO explains only 32 % on average of the total variability[3]. At the location Landsort the total variability is found to be explained almost completely through three SLP patterns (including the NAO), but due to the regional heterogeneity this result cannot account for the whole Baltic Sea region. Numerous previous studies have investigated this link, either through the analysis of observational data[4] or output of model simulations[5]. Most of these studies have focused on limited regions of the Baltic Sea (e. g. Stockholm, Finish Coast), pointing out that the correlation between long-term mean sea level and the NAO index is strongest during the wintertime.

However, this correlation also varies in time and has undergone considerable decadal variations in the past two centuries[6]. Additionally, there exist regional differences in the spatial correlation between the NAO-index and the Baltic Sea level[7]. This varying strength is also found for other SLP patterns, indicating that other climate factors, superimposed on the SLP, may be also modulating sea-level variations.

The interest in identifying the role of these other factors lies in their possible influence in future (and probably also past) climate change. Although their influence within the present climate maybe smaller than that of the NAO, large temperature or precipitation changes in the

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[3] Meier / Kauker 2003; Kauker / Meier 2003.

[4] E. g. Heyen et al. 1996; Johansson et al. 2001; Andersson 2002; Omstedt et al. 2004; Yan et al. 2004; Jevrejeva et al. 2005.

[5] E. g. Samuelsson / Stigebrandt 1996; Meier et al. 2004.

[6] Andersson 2002; Jevrejeva 2005.

[7] Hünicke / Zorita 2006.

future, as envisaged in climate simulations driven by diverse scenarios of greenhouse trace gases, may impinge a stronger fingerprint on Baltic Sea-level changes.

Global climate models try to represent as realistically as possible all the external and internal processes that are relevant in the climate system and are today perhaps the best available tool to estimate climate changes. However, due to the limitation of computer power, the spatial resolution of these models is of the order of 300 km at mid-latitudes. Therefore important details for the simulation of regional climate, such as important topographic details of finer scales, e. g. the Baltic coast line, cannot be represented in an adequate manner. Consequently, small processes, such as precipitation, are not well simulated. Also, the Baltic Sea itself is only roughly represented in these models and the connection to the North Sea is excessively overestimated. Several regionalisation methods have been proposed to solve this scale gap. One important family of methods is the so called statistical downscaling methods. The statistical regionalisation methods aim at bridging this scale gap by setting up statistical relationships between large-scale variables, i. e. climate variables that have long spatial scales of variations and the local variables that vary rapidly in space. The assumption is that the large-scale variables, such as the sea-level-pressure or the air temperature in the troposphere can be well represented in the model. Simulated changes in these large-scale variables can be used to estimate changes in the local scale variables through adequate statistical models, which have been previously designed and calibrated with observational data sets. This step allows for the estimation of future or past local changes under climate scenarios, in a manner consistent with the changes of the atmospheric circulation simulated by global climate models. This method incorporates in an empirical way the small-scale factors that are missing in climate models.

In summary this paper represents (1) the development of a statistical transfer function between Baltic Sea level and meteorological forcing by statistical downscaling techniques in the instrumental period (using also proxy-based climate reconstructions) and (2) the interpretation of the output of global climate model simulations with coupled atmosphere ocean models. Section 2 presents the data (observational records, reconstructions and model data) used in this study. Section 3 describes the method by presenting the applied statistical models and their application and skill. The results are discussed and interpreted in Section 4 and in Section 5 the conclusions and an outlook is presented[8].

Datasets

Baltic Sea level observations

For analyses in the 20th century we used data from 30 Baltic Sea tide gauge stations from the Revised Local Reverence (RLR) dataset of the Permanent Service for Mean Sea Level (PSMSL[9]). For the analysis back to 1800 the four longest sea-level records from stations situated along the Baltic coast, Kolobrzeg (PSMSL, and updated by Technische Universität Dresden), Swinoujscie (PSMSL), Stockholm[10] and Kronstadt[11] were selected. *Figure 3* shows the location of the sea-level gauges.

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[8] Detailed results of this study can be also found in Hünicke/Zorita 2006 and Hünicke et al. 2008. Several results have also been published and discussed during national and international conferences (e.g. Hünicke/Zorita 2003; Id. 2004; Hünicke et al. 2006).

[9] Woodworth/Player 2003.

[10] Ekman 2003.

[11] Bogdanov et al. 2000.

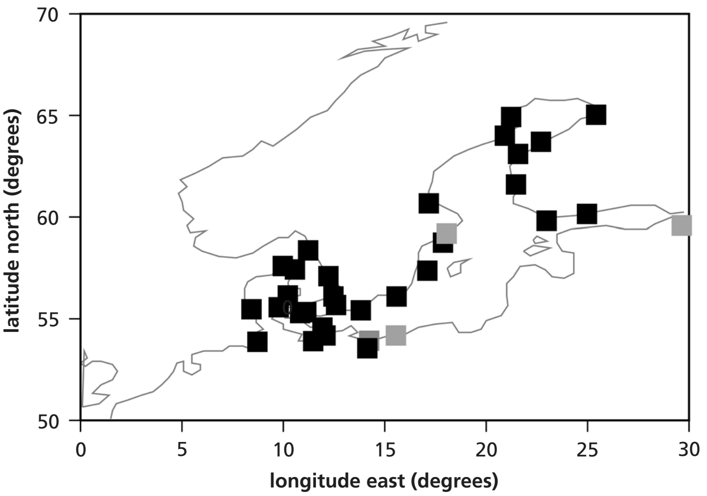

Fig. 3. Sketch of the Baltic Sea, showing the location of the sea-level gauges. The grey squares indicating the four longest available sea-level records (from Hünicke / Zorita 2008).

The observation records contain a trend which is caused by a combination of postglacial land uplift and eustatic sea-level change. On the time scales 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. As we are interested in the regional climate factors that may drive sea-level variations, we therefore focus on the inter-annual and decadal variations around this long-term trend.

Climatic Data sets

Observational and reanalysed[12] climate data

The following gridded climatic data sets were used:

- 5° × 5° monthly mean sea-level-pressure (SLP) from the National Centre for Atmospheric Research (NCAR[13]) for the region 70 W to 40 E and 15 N to 85 N,
- 2.5° × 3.75° monthly precipitation totals from the Climate Research Unit (CRU)[14] for the region 11.25 E to 26.25 E and 52.5 N to 62.5 N,
- 5° × 5° monthly means of near-surface air temperature[15] for the region10 E to 30 E and 50 N to 65 N.

Furthermore, as for the calculation of the NAO-index, monthly values of sea-level air pressure data from south-west Iceland and Gibraltar[16], obtained from the website of the Climatic Research Unit of the University of East Anglia, UK, were used.

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[12] Result of homogenous data assimilations with a weather prediction model in hindcast modus.

[13] Trenberth / Paolino 1980.

[14] Hulme et al. 1998.

[15] Jones / Moberg 1999.

[16] Jones et al. 1997.

Climate Reconstructions

The last 200 years of long gridded winter climate reconstructions, based on early instrumental station series (pressure, temperature and precipitation) and documentary data (not including sea-level data) from Eurasian sites have been extracted for our region of interest:

- 5° × 5° sea-level pressure fields[17] for the region 30 W–40 E; 30–70 N
- 0.5° × 0.5° precipitation reconstructions[18] for the region 11–26 E and 52–62 N
- 0.5° × 0.5° temperature reconstructions[19] for the region 10–30 E and 50–65 N.
  These reconstructions are coincident with corresponding observational records in their calibration period 1901–1990 (for precipitation 1901–1983).

Model Data

We used the output of three climate simulations for the period 1756 to 2100 with the global climate model ECHO-G, comprising the spectral atmospheric model ECHAM4 (horizontal resolution T30, c. 3.75° × 3.75°) and the ocean model HOPE-G (horizontal resolution: c. 2.8° × 2.8° [20]. All three simulations were driven by the same estimation of past solar variability, atmospheric greenhouse gas concentrations and radiative effects of stratospheric volcanic aerosols until AD 1990[21], and from 1990 onwards by IPCC scenario B2 of future greenhouse gas concentrations of carbon dioxide and methane (anthropogenic aerosols were not considered)[22]. One ensemble member was started in year 1000, the other two were branched out in the year 1756 by slightly changing the atmospheric state. Additionally, the output of two simulations with the General Circulation Models (GCMs) HadCM3[23] and ECHAM / OPYC3[24] driven by the SRES scenarios A2 and B2 for the period 1950–2100 were obtained via the internet from the Intergovernmental Panel on Climate Change (IPCC) Data Distribution Centre.

The SRES scenarios of concentrations of anthropogenic greenhouse gas and other anthropogenic forcings, such as aerosols, are based on projections of future economic activity and abatement policy measures. The A2-scenario specified slightly more than an doubling of atmospheric greenhouse gas concentrations by the end of the 21st century and the SRES B2-scenario less than doubling of concentrations, all relative to their pre-industrial levels (c. 1750).

As we are interested in variability at decadal and longer timescales, for the analysis of the times series behind 1900 until 2100 all time-series were smoothed with an 11-year running mean filter.

Methods

To estimate the amount of variability in sea level which can be explained by the atmospheric circulation (and not only the NAO) a linear regression model between sea level as predictand and the time series of the leading principal components (PCs) of the SLP field, as predictors, has been set up for each station and season. The number of PCs included in the regression was the one yielding the best model skill in the validation period.

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[17] Luterbacher et al. 2002.

[18] Pauling et al. 2006.

[19] Luterbacher et al. 2004.

[20] Legutke / Voss 1999.

[21] von Storch et al. 2004.

[22] IPCC 2001.

[23] Gordon et al. 2000.

[24] Roeckner et al. 1999.

$$SL\ (t) = \sum_{k=1}^{N_{eof}^{S}} a_k^S pc_k^S(t) + SLR^S(t) \quad \textit{Equation 1}$$

where $pc_k^{S\ t}$ are the time series of the k^{th} PC and a_k^S are the regression coefficients of the leading N_{eof}^{S}, whereby the super index S stands for SLP. The first sum in the r. h. s. in *Equation 1* represents the part of sea-level variations that can be linearly described by the evolution of the SLP field. The second term in the r. h. s. of *Equation 1* SLR^S is, i. e. the Baltic Sea-level residuals that cannot be linearly described by the SLP field. For the calculation of the PCs of SLP and the estimation of the regression coefficients, only data from the period 1960–1998 have been used. Once these coefficients had been estimated by Least Mean Square-Error, the time series associated with the leading PCs which were determined for the whole period 1900–1998 and *Equation 1* (without the term SLR) was used to reconstruct the sea-level time series in the whole period 1900–1998. Thus, the comparison between sea-level reconstruction and observations outside the calibration period 1960–1998 is an independent test of the skill of the statistical model.

In a next step the statistical model *Equation 1* was augmented to include winter precipitation as a predictor. This is technically done in the same way as for SLP, namely through the PCs of the precipitation field in the Baltic Sea area. The idea behind including precipitation is that although much of the information about precipitation variations is, surely, already contained in the SLP field, since the NAO index is positively correlated with average rainfall in wintertime, perhaps other processes may cause precipitation variations that are not directly linked to the dynamics implied by the large-scale SLP field. The model in *Equation 1* is thus rewritten:

$$SL\,(t) = \sum_{k=1}^{N_{eof}^{S}} a_k^S pc_k^S(t) + \sum_{m=1}^{N_{eof}^{S}} b_m^P\, pc_m^P(t) + SLR^{SP}(t) \quad \textit{Equation 2}$$

where the new term, with additional regression coefficients, corresponds to the PCs of precipitation. Both predictors, SLP and precipitation stand on equal footing, i. e. no hierarchical regression has been performed, and therefore the regression coefficients in *Equation 2* corresponding to the SLP part may now be different from those in *Equation 1.*

In a third step, the reconstruction model has been further augmented by the inclusion of air-temperature as a predictor.

The rationale here is that air-temperature plays the role of an imperfect surrogate of water temperature and this may influence sea level by the expansion of the water column. Thereby, it can be assumed, that the air-temperature can be used in a statistical sense as a representative of the temperature of the water column, at least up to intermediate depths[25]. Also, the use of air-temperature allows its application to the output of three-dimensional climate models (which do not realistically represent water temperature, due to their coarse resolution).The third statistical regressions model reads:

$$SL\,(t) = \sum_{k=1}^{N_{eof}^{S}} a_k^S pc_k^S(t) + \sum_{m=1}^{N_{eof}^{P}} b_m^P\, pc_m^P(t) + \sum_{i=1}^{N_{eof}^{T}} c_i^T pc_i^T(t) + SLR^{SPT}(t) \quad \textit{Equation 3}$$

where again the new regression coefficients correspond to the PCs of the air-temperature field in the Baltic Sea region. As in the case of precipitation, the SLP field already contains much of the information conveyed by the temperature field, as, for instance, in wintertime the NAO is

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[25] Hünicke / Zorita 2006.

responsible for much of the inter-annual temperature variability in the Scandinavian region[26]. However, at longer timescales, other factors such as variations in external forcing, solar variability and volcanic effects[27] or variations in the sea-surface temperature in the North Atlantic linked to the meridional overturning circulation may also be potentially relevant.

The parallel analysis of the relationships between sea-level, SLP, temperature and precipitation in the 20th century was carried out separately for the seasonal means in winter (December–February) and summer (June–August).

For the extension of the analysis back to AD 1800 the same strategy of regression models was used as shown for the 20th century, but SLP, precipitation and air-temperature were used as sole predictors and the analysis was focused on the winter season. The SLP field in the European region is again previously decomposed in its principal components (PCs) to avoid co-linearity of the predictors and the resulting instability of the regression which, simplified, reads

$$SL(t) = \sum_{\mathrm{i=1,N}} a_i pc_i(t) + SLR(t) \quad \textit{Equation 4}$$

where pc_i is the i^{th} PC, is the corresponding regression coefficient, N the number of PCs included in the regression and SLR are the sea-level residuals.

The calibration of this statistical model was set up for the period 1900–1990. For validation the period before 1900 was reserved. For the calculation of the PCs of SLP and the estimation of the regression coefficients, only observational data from the period 1900–1999 was used (see data section). Once the coefficients had been estimated by Least Mean Square-Error, the respective climate reconstruction time series associated with the leading PCs was determined for the last 200 years by projecting each- the SLP, precipitation and air-temperature anomalies (deviations from the 1900–1998 mean) – onto the corresponding eigenvectors. The analysis was set up for the four longest sea-level records available along the Baltic coast (see *Fig. 3*). This allowed a comparison between sea-level reconstructions and observations outside the calibration period (1900–1999) as an independent test of the skill of the model.

Measure of the Skill

The skill of the regressions was evaluated by the Reduction of Error (RE) statistic[28] and by the correlation coefficient between observations and estimations, both evaluated in the validation period. The RE is defined as

$$RE = 1 - \frac{\sum_t (o_t - p_t)^2}{\sum_t o_t^2} \quad \textit{Equation 5}$$

where o_t are the observed anomalies and p_t the predicted anomalies at time ^{t}, relative to the mean of the calibration period. The sum extends over the validation period.

The RE may take values between 1 (perfect prediction) and $-\infty$. A value of zero indicates a skill equal to climatology (simply taking the value of the mean in the calibration period as the

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[26] Hurrell 1995.

[27] Stott et al. 2000.

[28] by Storch/Zwiers 1999.

prediction). Negative values indicate a skill worse than climatology. One advantage of using the RE as a measure of explained variance is that it takes into account changes in the mean between the calibration and the validation period, whereas the correlation between reconstructions and observations in the validation period does not. Also, the correlation coefficient is insensitive to differences in the amplitudes between real and estimated variations.

It has to be noted that the other factors, perhaps not directly related to temperature, precipitation and wind, may also be relevant for sea-level variations for particular stations. For instance, sea ice in winter play a prominent role, and the water balance in the Baltic Sea may be also influenced by evaporation and run-off. However, our final goal is to be able to use the output of climate simulations as predictors in the statistical transfer methods. Due to their coarse resolution, neither sea ice nor run-off is properly simulated in the climate models and they could not be used as predictors with confidence. The rationale here is, therefore, that the three predictors may be considered as, perhaps indirectly, a large part of the variations of the local driving factors. For instance, precipitation should be connected to run-off.

Results

Statistical Analysis of the relationship between Baltic Sea level and meteorological forcing in the observational record

This section analyses and identifies the patterns of variability of the meteorological forcing, which are most important for the variations of sea level in the Baltic. The physical mechanism that gives rise to the statistical relationships is also investigated. The relative importance of the NAO, of the integrated rainfall in the Baltic Sea drainage basin and of air-temperature is investigated in the instrumental period and the result form the basis for further statistical analysis beyond the time period in which observational climate records are available.

Relationship between Baltic Sea level and sea-level pressure

The following remarks, demonstrated in *Figures 4 and 5*, and adapted from Hünicke / Zorita have to be considered[29].

- The correlation between the NAO-index and the sea-level variations in the period 1900–1998 range between 0.1–0.8, but they are predominately weaker in the summer season (0.2–0.5) than in winter (0.1–0.8) *(Fig. 4)*.
- The correlations between NAO and sea level are weaker in the southern Baltic Sea.
- The relationship between NAO and Baltic Sea level has undergone strong variations in time. *Figure 5* shows the moving correlation between the winter NAO index and winter sea level in a 21-year moving window for four sea-level stations in the Baltic Sea.
- There are decadal periods with inter-annual correlations as low as 0.25, although in recent decades the correlation has been as high as 0.8. In Warnemünde, the correlation with the NAO has even been negative for some periods.
- All correlations tend to increase around 1965 up to a correlation coefficient of 0.9.

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[29] Hünicke / Zorita 2006.

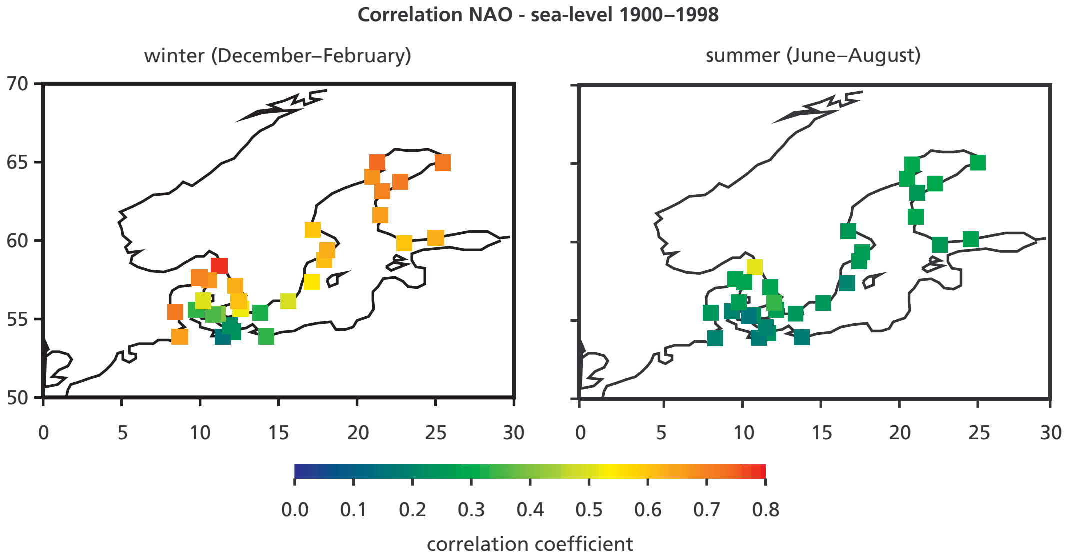

Fig. 4. Correlation between the seasonal means of the North Atlantic Oscillation index and seasonal mean (linearly detrended) Baltic Sea level, 1900–1998 (adapted from Hünicke / Zorita 2006).

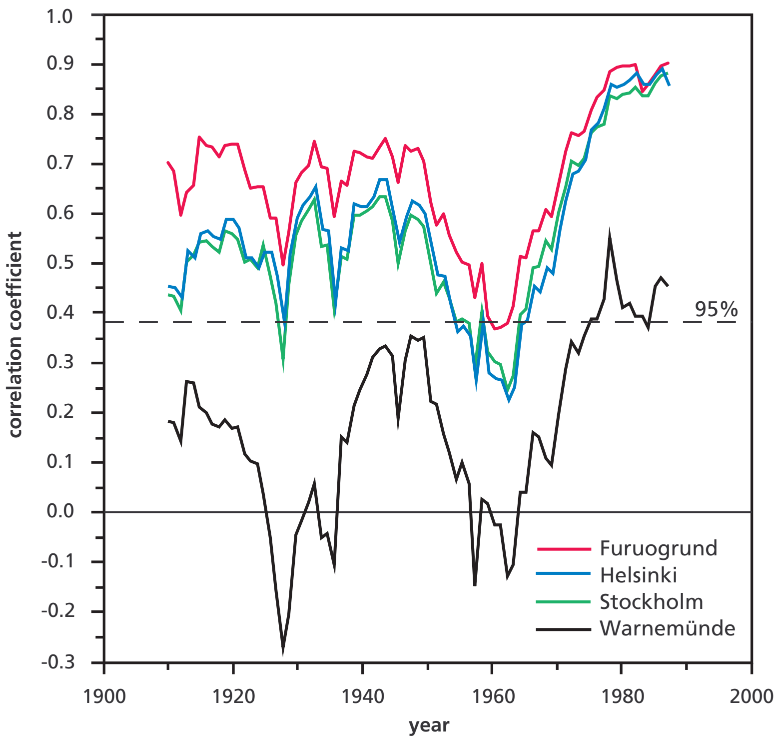

Fig. 5. Moving correlation (21-year window) between winter (December–February) mean Baltic Sea level and the winter NAO index for the four selected stations that should be representative of the behaviour of Baltic Sea level: Furuogrund (North), Stockholm (West), Helsinki (East) and Warnemünde (South), shown in the right panel. 1900–1998 (adapted from Hünicke / Zorita 2006). The two-sided 95 % significance level is indicated.

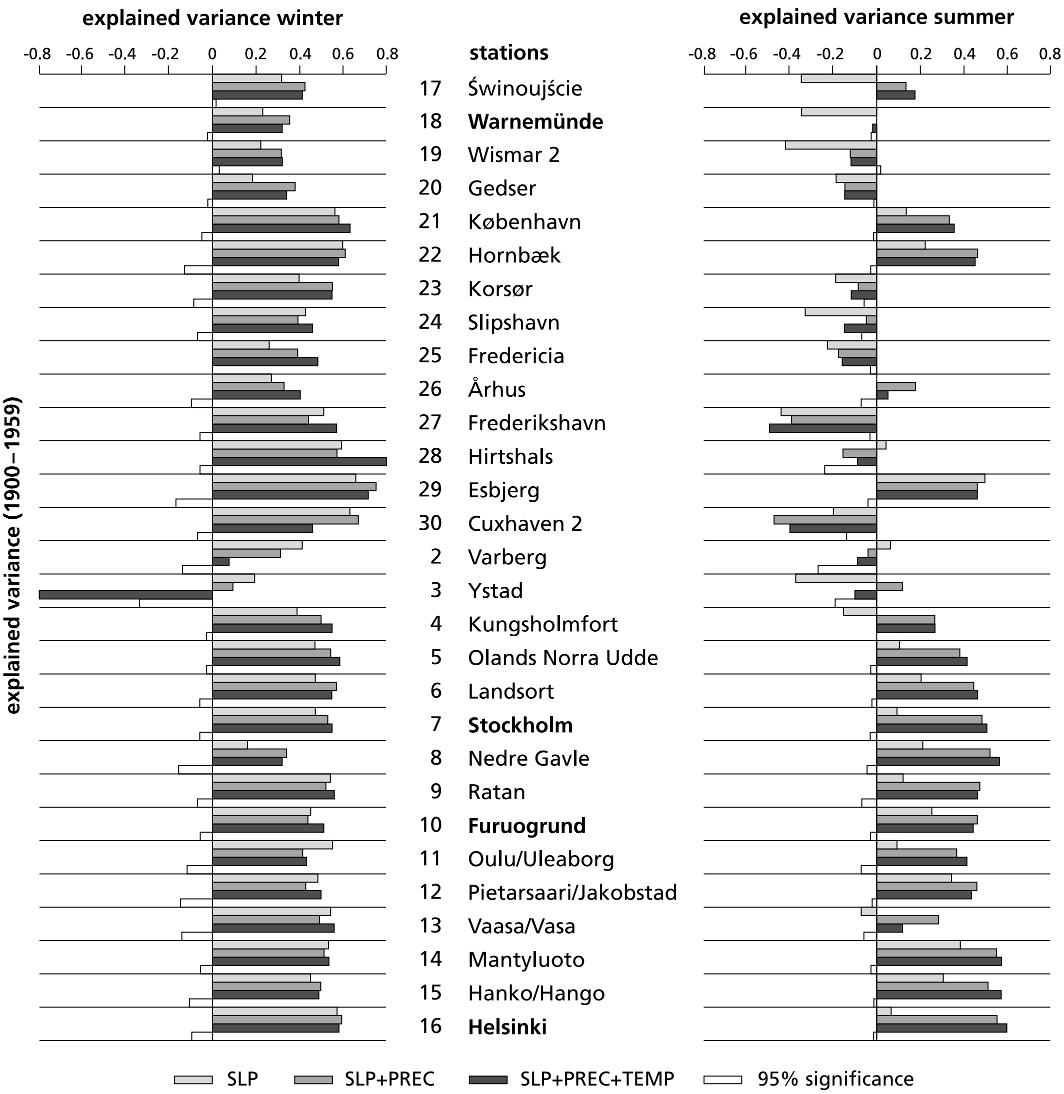

Fig. 6. Fraction of inter-annual variance (Reduction of Error or Brier Skill Score) in the validation period (1900–1959) in winter and summer that can be explained by SLP, by SLP and the additional predictor precipitation (SLP+PREC) and by SLP, precipitation and temperature (SLP+PREC+TEMP) for 29 stations. The 95 % significance level was estimated by using synthetic Monte Carlo predictors (Gaussian white noise) instead of the real temperature and precipitation predictors. The stations are ordered geographically clockwise, starting in the Southwest (from Hünicke / Zorita 2006).

Climate influence on decadal Baltic Sea level variations in the 20th century

A series of simple statistical models as described in the previous section linking sea level in the Baltic Sea and SLP, precipitation and air-temperature, introduced step-wise as predictors, show that in winter- and summertime precipitation and air-temperature contribute to determine the part of sea-level variability that cannot be linearly explained by SLP (thus by the forcing of the geostrophic wind). These results can be interpreted as a detection of the influence of precipitation and temperature on Baltic Sea level. *Figure 6* illustrates the relative importance of SLP, precipitation and temperature in determining sea-level variations in the 30 Baltic stations analysed here.

In wintertime, their additional contribution is small compared to that of sea-level pressure (of the order of additional 15 % of variance), but it is statistically significant and their inclusion as predictors helps to explain past deviations in the evolution of sea-level, with higher than normal precipitation and temperature values linked to a positive contribution of sea-level anomalies.

In summer, precipitation and temperature explain a substantial part of the sea-level variability, except in the Kattegat region. Positive summer sea-level anomalies are linked to higher than normal rainfall but to lower than normal temperatures, suggesting that the statistical link between sea level and temperature may artificially arise by the observed negative correlation between rainfall and temperature. For some stations, precipitation and temperature can, in addition to the variance explained by sea-level pressure alone, explain, 35 % of the total variance.

The geographical distribution of this variance tends to be larger in the southern stations, both in winter and in summer; although in summer the additional variance is spatially distributed in a slightly more homogenous way. This is consistent with the higher correlations with the NAO found in the northern stations and also with the fact that in summer the correlation with the NAO is geographically more homogeneous than in winter.

Statistical Downscaling of climate drivers of decadal Baltic Sea level variability with climate reconstructions

We use long gridded winter climate reconstructions developed by Luterbacher et al. and Pauling et al., derived from a combined data set of early instrumental station series (pressure, temperature and precipitation) and documentary proxy data (but not sea-level data) from Eurasian sites[30]. The goal is to analyse the feasibility of statistically determining Baltic Sea-level variations from large-scale, coarse resolution, climate fields. The analysis was first set up for the period 1800–2000, in which long-term sea-level observation records are available for validation. In a further step, after calibration and validation of the model, the full length of the climate reconstructions (500 years) was included in the developed transfer function to study the low-frequency-variability of sea level back to 1500.

For the sea level stations located in the central (Stockholm) and especially for the eastern Baltic Sea the model skill is high taking SLP as predictor (see *Fig. 7*). The best model skill was found by using the three leading SLP fields as predictor. For Stockholm, the validation RE (as a measure of the skill, see data section) reaches a value of 0.35 and a significant correlation r of 0.59. For Kronstadt the RE reaches a value up to 0.60 and a significant correlation of even 0.85, using the two leading SLP patterns as predictor.

This also confirms the relevance of the SLP for sea-level variations in this area at longer timescales and in the 19th century. In the validation period no sub-periods can be identified where the estimated and observed sea-level deviate. This indicates that the information contained in the SLP field is enough to determine decadal sea-level variations very accurately. This agreement also supports the quality of the SLP reconstructions in the 19th century.

In contrast to Stockholm and Kronstadt, the calibration skill using SLP as predictor for the stations in the southern Baltic Sea is considerably lower and the validation skill is very poor. Observations and estimations are clearly uncorrelated at decadal timescales in the first half of the 19th century[31].

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[30] Luterbacher et al. 2002; Id. 2004; Pauling et al. 2006.

[31] See Hünicke/Zorita 2006 for details.

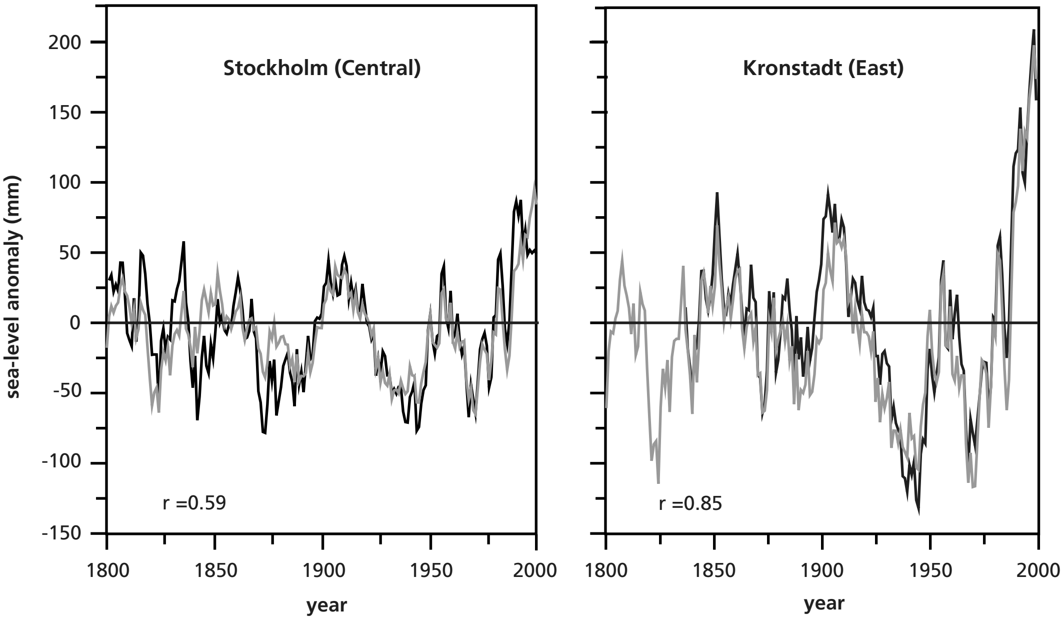

Fig. 7. Decadally smoothed and linearly detrended observed (black line) sea level and reconstructed (grey line) sea-level deviations from the 1900–1999 mean, using the SLP field as predictor (adapted from Hünicke et al. 2008). The decadal correlation r between observations and reconstructions in the 19th century is indicated in each panel.

In a further step we explore whether precipitation may be a skilful predictor for sea-level variations in the southern Baltic, where SLP performed poorly. The reasoning behind this is that variations in the total water volume are influenced by the freshwater balance. Obviously, run-off would be a more convenient predictor than rainfall, but global climate models are normally equipped with simple run-off schemes to represent only the largest river basins in the world and therefore it is not feasible to use this predictor in a statistical downscaling application. Spatially averaged rainfall should, however, indirectly contain information about the run-off flowing in to the Baltic from its drainage basin.

Figure 8 shows the time series of the NAO index (the leading PC from the SLP reconstructions) and area-averaged winter precipitation together with the standardised winter sea-level anomaly at Swinoujscie. In the 20th century the time-series of the NAO index and the time-series of winter precipitation evolve in parallel, but they deviate in the 19th century. Interestingly, precipitation behaviour is more similar to the southern Baltic Sea-level record.

The result of using winter mean precipitation as sole predictor for the southern Baltic Sea stations is depicted in *Figure 9*. The skill of the predictor, though not perfect, has increased relatively to the SLP for both observed sea-level stations, with significant correlations of 0.68 and 0.76, respectively. The RE values, however, are of negative sign. The combination of a high verification correlation but a negative verification RE likely indicates a change in the long-term mean value of the 19th and the 20th century which is not captured by the precipitation as predictor. This is further discussed in Hünicke et al.[32].

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[32] Hünicke et al. 2008.

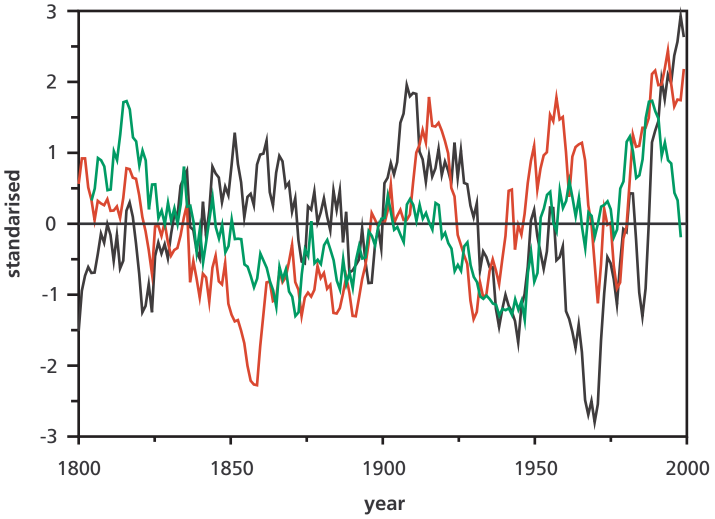

Fig. 8. Time series of the leading PC of the gridded SLP field (black) and area-averaged precipitation in the Baltic Sea Region (red), together with the standardised winter sea-level anomalies at Swinoujscie (southern Baltic Sea), smoothed by an 11-year low-pass filter.

Observed and estimated sea-level variations in the 19th century (validation period) evolve more in agreement than with SLP as predictor, although low frequency deviations between both times series at the beginning of the 19th century still remain. A possible reason for that deviations might be deficiencies in the very low-frequency variability in the precipitation reconstructions. The inclusion of SLP as additional predictor does not increase the skill of the model.

In a next step, winter air-temperature was also used as a sole predictor (not shown), with both representations of the temperature (Baltic Sea area-averaged and PCs), but the model did not show any 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 for the 19th century, probably no new information is introduced by using temperature as predictor.

After calibration and validation of the model, the full length of the climate reconstructions (500 years) was applied to the transfer function to estimate the low-frequency-variability of sea level back to 1500. As illustration, the result for Kronstadt (not shown), as the station where the best model skill was reached, are briefly discussed. One important message contained in is that the sea-level trend which can be attached to the trend in the sea-level-pressure (and therefore to the wind) is in the last 300 years of the order of 0.3 mm / year for Kronstadt. This number is less than the isostatic trend estimated for this station, but it is not much smaller. If future trends in SLP are expected to be larger than those observed in the past 300 years, then this contribution could achieve the same order of magnitude as the isostatic or eustatic contribution. This possibility is investigated in the next Section. Also noteworthy is the fact that periods of higher inter-annual variability are not necessarily connected to periods of lower or higher sea-level. For instance, the decades around 1900 show a maximum of mean sea level but a minimum in the inter-annual variations, whereas in the last decades of the 20th century both magnitudes are in phase. Therefore, we can not simply conclude, from these results alone, that an increase of future sea level will be accompanied by increased variability and stronger or more frequent extremes. This question deserves a more detailed analysis.

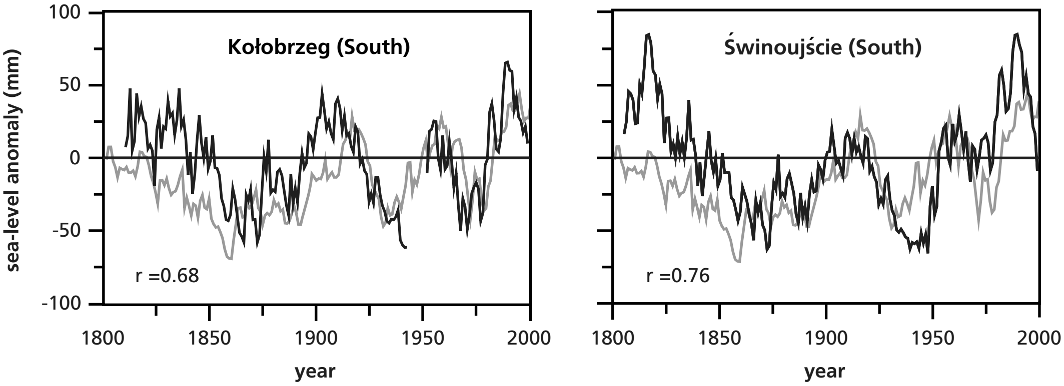

Fig. 9. Decadally smoothed and linearly detrended observed (black line) sea level and reconstructed (grey line) sea-level deviations from the 1900–1999 mean, using area-averaged precipitation as predictor (adapted from Hünicke et al. 2008). The decadal correlation r between observations and reconstructions in the 19th century is indicated in each panel.

Contribution of regional climate drivers on past, recent and future sea-level variability estimated by climate model simulations

Once the statistical models had been validated and physically interpreted, the past sea-level variations related to climatic variations could be reconstructed by feeding these transfer functions with the large–scale climate changes simulated by the global model ECHO-G. Although the global climate models do not realistically represent the Baltic Sea due to the coarse spatial resolution (350 km), the output of the statistical model when driven by simulated fields of climate predictors provides an estimation of the consequences of past and future climate variations for Baltic Sea level.

Based on the results of the previous section, winter SLP was used as a predictor for the stations Kronstadt and Stockholm and mean Baltic average winter precipitation for the stations Swinoujscie and Kolobrzeg. *Figure 10* shows the results, taken the predictor from (ensemble) climate simulations with the global climate models ECHO-G, HadCM3 and ECHAM4 / OPYC3 driven by IPCC SRES future scenarios anthropogenic radiation forcing A2 and B2.

The results for the ECHO-G indicate that simulated changes in the 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.

These results specifically depend on the climate model ECHO-G and on the driving Scenario. However, most state-of-the art climate models used to simulate future climate changes[33] tend to agree qualitatively with the results of ECHO-G shown here, namely increased westerly winds and increased precipitation in boreal winter at mid and high latitudes, although the magnitude of these changes are model dependent. To illustrate of the uncertainties due to the global climate

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[33] Giorgi et al. 2002.

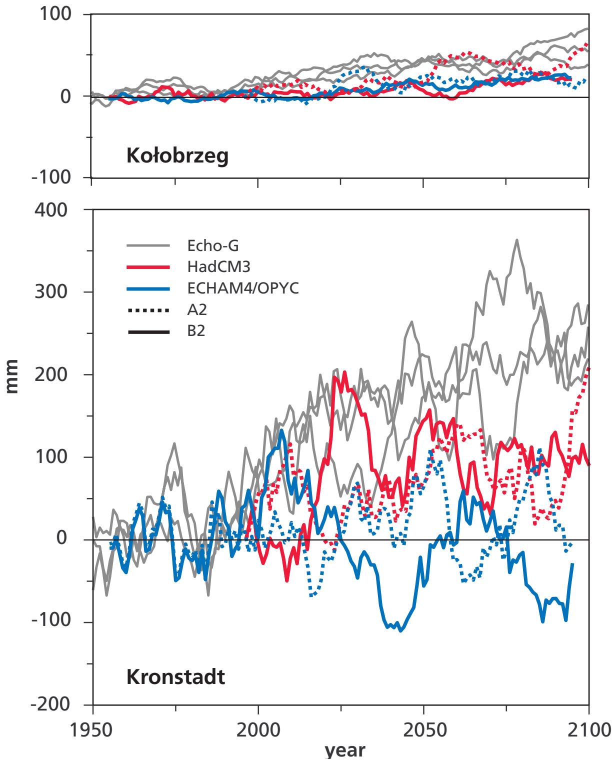

Fig. 10. Estimations of the contribution of SLP (lower panel) and precipitation (upper panel) changes to future winter sea-level change for two stations in the Baltic Sea, based on regression between observed sea level and the predictors. For the estimations, the predictors were taken from (ensemble) climate simulations with the global climate models ECHO-G, HadCM3 and ECHAM4/ OPYC3 driven by IPCC SRES future scenarios of anthropogenic radiation forcing A2 and B2. Time series are smoothed by an 11-year low-pass filter. Upper panel: for the southern sea-level station Kolobrzeg, based on regression models with observed Baltic winter rainfall as predictor. Lower panel: for the sea-level station Kronstadt, based on regression models with observed Baltic winter SLP as predictor.

model, sea-level changes were also estimated using the simulations with the climate models HadCM3 from the Hadley Centre for Climate Prediction in Exeter (UK) and ECHAM / OPYC (as with ECHO-G also from the German Climate Computing Centre), driven by the scenarios A2 and B2 (see also *Figure 10*). The SLP signal on sea-level changes is noisier, but tends to be upwards. The rainfall contribution is more similar and points toward upward sea-level trend in all cases.

Apart from this, the simulation in the past 250 years indicates some interesting variations (not shown). For instance, sea level in the last stages of the Little Ice Age (about 1500–1800) tends to be lower than present, with superimposed decadal variations. This is consistent with the results obtained from the SLP reconstructions for Kronstadt back to 1500, which were briefly discussed above. Whether the variations are driven by external forcing or by internal (chaotic) processes has to clarified. To investigate this aspect a twin simulation of the last millennium with different initial conditions can be compared with the present simulation. This twin simulation has already been performed. If, for instance, the variations of estimated sea level in the Dalton Minimum (around 1800) appear consistently in both simulations, they can be linked to external climate forcing (solar variability or volcanic activity). This linkage would allow an estimation of sea-level sensitivity to external climate factors based on observational records alone, namely those of sea level and past external forcing. The value of the sensitivity thus ascertained could be used for estimations of future sea-level changes under prescribed scenarios of anthropogenic greenhouse gas forcing.

Conclusions and Outlook

This study has focused on the estimation of the influence of regional climate factors on the sea-level variations in the Baltic Sea. For this purpose, statistical transfer functions linking sea-level records with regional climate variables have been developed and tested in the past two centuries, using climate reconstructions and a few long sea-level records. Climate simulations with global climate models of the Late Holocene and of the 21st century were then regionalised using these transfer functions.

The results presented here indicate that regional climate factors cannot be neglected and need to be, at least in principle, taken into account in the estimation of future, and past, sea-level variations. The influence of these regional factors is spatially heterogeneous and an individual analysis of each gauge station seems to be necessary. Sea level-pressure is not an adequate large-scale predictor for all stations in the Baltic Sea. For the central and eastern part of the Baltic, sea-level variations can be largely accounted for by the wind forcing (SLP). For the stations investigated in the southern Baltic Sea, area-averaged precipitation seems to be a more reasonable predictor for sea-level variations than SLP. This result agrees with the low correlation between the winter NAO-index (first SLP pattern) and winter sea level in the southern Baltic.

Based on these findings, a different behaviour of future sea level in different parts (central and eastern, southern) of the Baltic Sea might be possible, depending on the future trends of station-depended relevant regional factors (e. g. area-averaged precipitation in the southern Baltic).

The analysis, together with climate simulations with a time horizon until AD 2100 indicate 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. However, although most models agree on the direction of change of these regional factors, the magnitude of this contribution may be dependent on the model used in the climate simulations.

Our plan is to extent this type of analysis to longer timescales and to cover the last 8000 years. For this purpose a very long simulation with a state-of-the-art climate model is required. At these timescales, other process giving rise to regional climate variations will have to be considered. Variations in the orbital parameters of the Earth, which influence the annual cycle of insolation, play a major role in slow variations of regional climate. Also, abrupt climate changes in the North Atlantic region triggered by fresh water intrusions from postglacial lakes into the North Atlantic Ocean may modulate ocean currents and convection processes, with potential influences on sea-level changes around the whole North Atlantic coasts. To estimate how large these influences could have been for Baltic Sea level is the final objective of ongoing work.

Abstract

The analysis of the contribution of regional climate forcings to decadal sea-level variations in the Baltic Sea in the instrumental period is essential to understand past and future sea-level changes. The statistical relationships between Baltic Sea-level observations as regional variable (predictand) and large-scale climatic data sets (predictor) at decadal timescales back to 1800 show considerable variations among gauge stations: in the central and eastern Baltic SLP is a good predictor, in the southern Baltic Sea area-averaged precipitation shows a higher predictive skill. Once these statistical models have been validated and the physic interpreted, past and future sea-level variations related to climatic variations are reconstructed by feeding these models with large-scale climate changes simulated by different global climate simulations driven by IPCC SRES future scenarios of greenhouse gas concentrations. It is found that the future trend in sea-level rise caused by changes in these regional forcings may be of the same order of magnitude as the global thermal expansion, although this contribution may strongly depend on the climate model.

Zusammenfassung

Um den Einfluss und Beitrag klimatischer Faktoren auf dekadische Meeresspiegeländerungen der Ostsee in der Vergangenheit und Zukunft abschätzen zu können, ist eine Analyse der Zusammenhänge in der Beobachtungsperiode unabdingbar. Die statistische Beziehung im Zeitraum 1800–2000 zwischen gemessenen Pegelzeitreihen und großräumigen klimatischen Datensätzen weißt deutliche gebietsabhängige Unterschiede auf. Während in den Bereichen der zentralen und östlichen Ostsee der Bodenluftdruck (Wind) als ein guter Prädiktor für die dekadischen Wasserstandsvariationen fungiert, stellt in der südlichen Ostsee Niederschlag (gemittelt über das Einzugsgebiet) den besseren „Vorhersager" dar. Diese statistischen Beziehungen können, nach Validierung und physikalischer Interpretation, in Form von Transferfunktionen verwendet werden, um den Einfluss der klimatischen Faktoren auf vergangene und zukünftige Wasserstandsschwankungen zu rekonstruieren. Die hierzu notwendigen klimatischen Datensätze werden aus Klimasimulationen mit globalen Klimamodellen und den entsprechenden IPCC Zukunftsszenarien genommen. Das Ergebnis zeigt, dass zukünftige Trends im Meeresspiegel der Ostsee, verursacht durch Änderungen der untersuchten Klimafaktoren, etwa in der gleichen Größenordnung liegen wie die globale Wärmeausdehnung. Die Ergebnisse variieren jedoch abhängig vom verwendeten Klimamodell.

Résumé

L'analyse de l'influence des facteurs climatiques régionaux sur les fluctuations décennales du niveau de la mer dans la Baltique pour la période observée est essentielle à la compréhension des changements futurs du niveau de la mer. Les liens statistiques entre les observations du niveau de la Baltique (prédictand) et les enregistrements climatiques à grande échelle (prédicteur) sur des échelles décennales remontant à 1800 affichent des variations considérables parmi les stations de mesure: Dans le centre et l'est de la Baltique, SLP (Sea Level Pressure) est un bon prédicteur; dans le sud de la Baltique, la précipitation moyenne régionale se révèle plus performante. Après validation de ces modèles statistiques et interprétation des phénomènes physiques, on simule les fluctuations passées et futures du niveau de la mer, liées aux variations climatiques, en introduisant dans les modèles des changements climatiques à grande échelle. Ceux-ci sont déclenchés par des simulations du climat global, générées elles-mêmes par des scénarios futurs de concentrations de gaz à effet de serre de l'IPCC SRES. On constate que la tendance future de l'élévation du niveau de la mer causée par des modifications des facteurs régionaux peut être du même ordre de grandeur que l'expansion globale du réchauffement, quoique cette influence dépendra fortement du modèle climatique utilisé.

Y.G.

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