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Contribution of regional climate drivers to future winter sea-level changes in the Baltic Sea estimated by statistical methods and simulations of climate models

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ABSTRACT

A statistical downscaling approach is applied to the output of five different global climate model simulations driven by 21st century future scenarios of greenhouse gas concentrations. The contribution of sea-level pressure and precipitation changes to regional future winter sea-level changes is estimated for four Baltic sea-level stations by establishing statistical relationships between sea level as predictand and large-scale climate fields as predictors. Using sea-level pressure as predictor for the central and eastern Baltic Sea level stations, three climate models lead to statistically significant 21st century future trends in the range of the order of 1 to 2 mm/year. Using precipitation as predictor for the stations in the southern Baltic coast all five models lead to statistically significant trends with a range of the order of 0.4 mm/year. These numbers are smaller, but of the order of magnitude as the predicted global sea-level rise.

Keywords: Baltic Sea, regional sea-level, climate modelling, statistical downscaling, future trends, IPCC AR4 simulations

Introduction

Present estimations of future global sea-level change are based on simulations with coarse-resolution global climate models (GCMs). The simulated sea-level changes mostly depend on the heat-flux into the ocean, on changes in the ocean circulation and on estimations of the rate of Greenland ice-sheet melting (Meehl et al. 2007). A global average of sea-level rise, however, ensconces considerable regional variations that may be caused by other processes that operate at regional and local scales and which are not properly represented in GCMs. The understanding of the local and regional processes that affect mean sea-level variations, which may themselves be affected by present and future climate change, is important for a better estimation of the global sea-level change. However, the regional effect is also relevant because anthropogenic climate change may affect these local processes directly and local sea-level variations might be, for the region of interest, more important than the global warming signal.

The Baltic Sea with its complex coastline and bathymetry is a clear example of a complex coupled ocean-atmosphere land system in which sea-level variations at inter-annual and longer timescales are still not fully understood. It is a semi-enclosed sea, located in the transition zone between continental and maritime climates and connected to the North Atlantic Ocean through the narrow and shallow Danish straits (up to 16 km wide and about 18m deep). With a total area of 415000 km² and a drainage area of 1.74 million km² it is one of the largest brackish seas in the world (BACC author team 2008). Generally, the main factors affecting the long-term Baltic sea-level are land uplift, global eustatic sea-level rise (1-2mm/year during the 20th century) and the water balance of the Baltic Sea (Meier et al. 2004). The glacio-hydro-isostatic effect (the Earth response to past changes in ice and water loads) is still reflected in a land uplift, relative to the mean sea level, of a maximum of 9 mm/year in the northern Baltic, about 5mm/year in the central Baltic and a downward movement of 1mm/year in parts of the southern Baltic Sea (Ekman 1996; Rosentau et al. 2007).

Due to the coarse spatial scale resolution of global climate models (in the range of 2 to 4 geographical degrees), the Baltic Sea is only very schematically represented in current GCMs by a few grid cells. Important topography-dependent processes, like the exchange of water masses between the North Sea and the Baltic Sea (Gustafsson and Andersson 2001), the large heterogeneity in precipitation (due to the presence of mountain ranges in the Scandinavian Peninsula) or the different basins of the Baltic Sea (and the exchange of water masses between them) cannot be properly accounted for. Therefore it is reasonable to assume that the estimation of future Baltic sea-level requires the application of dynamical (Meier 2006) or statistical (Wilby et al. 1998) downscaling methods to translate trends in large-scale forcing fields to the regional scale. In general, downscaling techniques are used to infer local information from coarse scale information. As a consequence of the strong interaction between the atmosphere, land and ocean, a dynamical downscaling of the Baltic Sea requires a regional ocean model driven by the output of a regional atmospheric model. However, long simulations with such a model are time and cost-intensive and do not exist yet for the period spanning the whole of the 20th century. In statistical downscaling, large-scale forcing fields are connected to local sea-level variations by means of statistical transfer functions, which are then applied to the output of scenario simulations with global, coarse resolution, climate models. The establishing of the statistical relationship between Baltic sea-level and climatic data sets in the observational record allows for an estimation of regional climate change by statistical means through the application of the regression models to the corresponding output of global climate model simulations.

In recent studies of Hünicke and Zorita (2006; 2008) and Hünicke et al. (2008) different approaches of statistical downscaling were used to investigate the influence of atmospheric forcings on past and present Baltic sea-level variability on decadal scales in the instrumental period. Atmospheric forcing factors were restricted to those for which long term observations or reconstructions are available, and which are potentially well simulated by coarse resolution models. The results indicate that the influence of the analysed atmospheric forcings on sea level vary geographically. On the one hand they could confirm, by using sea-level pressure (SLP) as a predictor in a simple regression analysis, that decadal sea-level variations in sea-level stations in the northern and eastern Baltic Sea are strongly influenced by the atmospheric circulation patterns. On the other hand they found that decadal variations in sea-level stations in the southern Baltic Sea can be better explained by using area-averaged precipitation as predictor. The physical links between these large-scale predictors and sea level are discussed in Hünicke and Zorita (2006; 2008) and Hünicke et al. (2008).

The water balance of the Baltic Sea is strongly exposed to the influence of North Atlantic atmospheric circulation patterns, which drive wind, rainfall and temperature, all factors that directly or indirectly may influence the long-term behaviour of Baltic sea-level (The BACC author team 2008). It is well established that in wintertime, inter-annual sea-level variations and its northern and eastern boundaries are influenced by the westerly winds, related to the SLP pattern of the North Atlantic Oscillation (NAO) (Andersson 2002). The NAO, which expresses the intensity of the pressure gradient between the Azores High and the Icelandic low, has the strongest influence on the Northern European climate during the winter months (Hurrell 1995). Thereby, a high NAO index is characterised by higher than normal pressure in the subtropics and lower than normal pressure in the Icelandic region. Thus, a positive NAO phase is connected to stronger westerlies, which cause comparatively higher sea level in some areas of the Baltic Sea. However, this relation is not uniform for the whole Baltic Sea region and several studies indicate that the connection between individual Baltic sea-level stations and the NAO may be heterogeneous in time and in space (Jevrejeva et al. 2005; Hünicke and Zorita 2006). Whereas in the central and northern gauge stations the NAO exerts a strong influence on winter sea-level variability at inter-annual timescales, this influence is much weaker in the southern Baltic Sea.

Although the NAO is the dominant SLP large-scale pattern of the North Atlantic, it explains, on average, only 32% of the total variability of sea-level at inter-annual timescales (Kauker and Meier 2003). To estimate the full amount of variability in sea level which can be explained by the atmospheric circulation (and not only by the NAO) it is therefore reasonable to consider the whole SLP field of the North Atlantic -West European sector. This includes the impact of the west wind component (NAO), but also other relevant SLP patterns. The relation between the whole SLP field and sea level in wintertime seems to be also more stable in time and space, as tested on multi-decadal timescales by Hünicke et al. (2008) for the past 200 years.

Precipitation is closely related to the freshwater balance of the Baltic Sea (including in- and outflows, river run-off and net precipitation). Also, variations in salinity cause changes in water density, which in turn is related to sea level. However, the mechanism by which precipitation may be affecting sea level more strongly in the southern Baltic Sea is still poorly understood and a statistical analysis is not powerful enough to answer this question as it cannot be completely conclusive. Potential climate drivers are all statistically correlated to some degree and climatically and relevant processes are deeply entangled. Nevertheless, the result can represent an interesting working hypothesis that can be addressed by long simulations with a regional coupled ice-ocean model (dynamical downscaling) which incorporate a more comprehensive range of physical processes than a statistical approach.

However, the following analysis is based on two assumptions: (a) the statistical relationship represents real physical links between the predictors and the sea level, (b) the applied empirical statistical functions that describe the detected influence of the large-scale factors (SLP and precipitation) on Baltic sea-level will remain unchanged in a future climate.

Although GCMs cannot realistically represent the Baltic due to the coarse spatial resolution (about 350 km), all predictors are represented in the climate model by several grid points and have a large-scale character. Within the usual framework of climate predictions for future decades it can also be assumed that these predictors are potentially well simulated by the climate models. Therefore, the output of the statistical model, when driven by the fields simulated by the climate model, gives an estimation of their consequences of past and future climate variations for Baltic sea-level and may allow an interpretation of possible changes in Baltic sea-level.

Recently, numerous climate modelling groups produced an unprecedented number of climate change simulations, beginning in the late 19th century and ending at the end of the 21st century, in the frame of the Fourth Assessment Report (AR4) by the Intergovernmental Panel on Climate Change (IPCC). As some of these models are related, the output of only five of these GCM simulations driven by future scenario A2 of greenhouse gas concentrations (4th IPCC Special Report on Emissions Scenarios (SRES)) is applied. The A2 scenario is a high emission scenario and its analyses can therefore yield information about potentially highest impact. For these simulations the contribution of SLP and precipitation changes to future winter sea-level change are estimated by applying simple linear regression models with sea level as predictand and SLP (for the sea-level stations in the central and eastern part of the Baltic Sea) and area-averaged precipitation (for the sea-level stations in the southern Baltic coast) as predictor. Thereby, the analysis is restricted to four long sea-level time-series in the Baltic Sea. Section 2 represents the data sets (observational records and model output) used for this study. Section 3 describes the application of the statistical regression models to the output of GCM simulations. In Section 4 the results of the statistical downscaling approach are analysed. Section 5 presents a discussion of the findings of this study and of their possible future consequences as well as a comparison to dynamical downscaling results.

Data sets

The following focuses on winter season, defined here as the mean of the months December, January, February (DJF). As the interest lies in the variability at decadal and longer timescales, all time-series are smoothed with an 11-year running mean filter.

Baltic sea-level observations

Following Hünicke et al. (2008) winter means of four of the longest time-series of sea-level records (up to 200 years long) from stations situated in the central, eastern and southern Baltic coast are examined: Swinoujscie (Permanent Service for Mean Sea level [PSMSL]; Woodworth and Player 2003), Kolobrzeg (PSMSL; before 1951 provided by Technische Universität Dresden), Stockholm (Ekman, 2003) and Kronstadt (Bogdanov et al. 2000). The length of the sea-level time-series used in the following analysis is adjusted to the length of the climate model runs (approximately 1860 to 1990, with minor changes depending on the climate model, see Section *Climate model data*).

The sea-level records contain a trend which is caused by post-glacial land uplift. On timescales of this analysis, the trend can be assumed to be linear (Peltier 1998) and is eliminated by statistically estimating the individual linear trend by a linear least-mean-square fit and subtracting it from each sea-level record. Nevertheless, the values of land uplift (and the downward movement in parts of the Baltic Sea) are difficult to estimate exactly, as the observed gauge records are also contaminated by climatic-induced trends. Therefore, the procedure possibly eliminates also the linear trends that may be caused (partly) by eustatic sea-level change, but also by the long-term trends of the regional climate forcing. These trends, which have different physical origins, can unfortunately not be separated by statistical methods alone. Thus, the calibration of the statistical model is restricted to variations around the overall long-term linear trend.

Figure 1 shows the location of the four sea-level gauges used in this study. The two southern sites are not located far from each other. The rationale behind it is that the analysis is supposed to include as much as possible available gauge station data, as it provides the possibility to detect/ minimize errors in gauge measurements. For instance, the specific location of the tide gauge can lead to inhomogenities in the measurements. The position where the tide gauge is located (e.g. in bay harbour, protected entrance) induces local effects (e.g. specific wind pattern, currents, etc), which might influence sea-level variability, especially in a Sea with a complex coastal morphology as the Baltic Sea.

Climatic data sets

Climate observations

The following gridded climatic data sets were used for the calibration of the regression models applied in this study: 5°x5° monthly mean SLP from the National Centre of Atmospheric Research (NCAR, Trenberth and Paolino 1980) for the geographical region 30°W to 40°E; 30°-70°N and 0.5°x0.5° monthly precipitation means from Mitchell and Jones (2005) for the geographical region 11°-26°E; 52-62°N. The geographical distributions of the climate data sets considered for this study were selected based on the climate data sets used by Hünicke and Zorita (2006).

Climate model data

The output of monthly SLP and total precipitation of five IPCC AR4 coupled GCM simulations driven by the 4th IPCC SRES future scenario A2 of greenhouse gas concentrations is used. The model simulations are downloaded from the Multi-Model Dataset Archive of the Programme of Climate Model Diagnosis and Intercomparison (PCMDI) (http://www-pcmdi.llnl.gov/). This dataset, officially known as the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project (CMIP3) multi-model dataset, is the dataset used by IPCC working group 1. The five GCMs selected for this study are listed in Table 1 along with a reference for more complete documentation. In case that a multi simulation ensemble with one model is available, the first simulation, as defined in the dataset archive, is chosen. All models contain forcing by greenhouse gases and tropospheric sulphate aerosols. For more details see Meehl et al. (2007).

The GCM data grid output was interpolated to the grid resolution of the observational data sets and the geographical window corresponds to the observational climate data sets (see Section *Climate observations*).

Method

Before applying a simple regression equation with sea level at one station sl_i as the predictand, all time-series are smoothed by an 11-year low-pass filter. For the central (Stockholm) and eastern (Kronstadt) Baltic sea-level stations the SLP field in the European region is used as predictor. Consequently, the SLP field (observation record 1900 to 1999, see Section *Climate observations*) is decomposed into its principal components (PCs) to avoid co-linearity of the predictors and the resulting instability of the regression. The regression model reads:

$$sl(t) = \sum_{i=3} a_i \, pc_i(t) + SLR(t) \qquad (1)$$

where pc_i is the i^{th} PC, a_i is the corresponding regression coefficient, i the number of PCs included in the regression and SLR are the sea-level residuals. The parameters a_i are calibrated in the time-period 1900 to 1999 by ordinary least-square error minimization. The cut-off number i =3 of PCs included in the regression is the one yielding the best model skill in the validation period (Hünicke and Zorita 2008). Once the coefficients have been estimated by Least Mean Square-Error, the respective climate model time-series associated with the leading SLP PCs are determined for the whole time-period (around 1860 to 2100, with minor changes depending on the climate model run, see Section *Climate model data* for details) by projecting the simulated SLP anomalies (deviations from the model 1900-1998 mean), onto the observational spatial eigenvectors of loadings from the PC analysis.

The applied regression models were validated in a former study by Hünicke et al. (2008) in the time period 1800-1899, based on gridded climate reconstructions of SLP (Luterbacher et al. 2002) and precipitation (Pauling et al. 2006).

For the southern Baltic sea-level stations (Swinoujscie and Kolobrzeg) area-averaged precipitation is applied as the predictor. The procedure using area-averaged precipitation is in principle the same as using SLP as the predictor. Thereby, the precipitation time-series is handled in the same way as a single PC of the SLP field. The regression model is:

$$sl(t) = a \; prec \; (t) + SLR(t) \tag{2}$$

where $prec$ is the time-series of area-averaged precipitation, a is the corresponding regression coefficient and SLR are the sea-level residuals.

The trends of the estimated future sea-level changes and their 95% confidence intervals are calculated by a linear fit by least-square-error minimization.

Results

The estimation of future winter sea-level change for four Baltic sea-level stations by applying simulations of different GCMs driven by 4th IPCC SRES future scenario A2 indicate that the future trend in sea-level rise caused by the applied regional factors is larger than the past variability.

Figure 2 shows the results for the two Baltic sea-level stations, Stockholm (central Baltic Sea) and Kronstadt (eastern Baltic Sea), for which SLP was used as the predictor. The reason for choosing SLP as the predictor is that SLP gradients are closely related to the surface wind (through the geostrophic relation), which is one of the immediate forcings for sea-level variations in the Baltic Sea (e.g. Andersson 2002). Also, SLP influences sea level through the inverse barometric effect (Ponte 1994).

Hünicke et al. (2008) supported by statistical analysis the dominant role of SLP for the sea-level stations in Stockholm and Kronstadt for decadal and longer timescales. The estimated linear trends of the contribution of SLP changes to future winter sea-level change, together with their 95% confidence interval are given in Table 2. The results clearly differ when the simulated SLP from different climate models are used. For both sea-level stations, Stockholm and Kronstadt, the simulations with the UKMO HadCM3, MPI ECHAM5 and NOAA GFDL CM 2.1 climate models show a clear statistically significant positive signal on sea-level changes. The strongest signal is obtained by applying the SLP output of the NOAA GFDL CM 2.1 simulation to the regression models with trend values for the 21st century of 1.24 ±0.18 mm/year for Stockholm and even of 2.53 ±0.34 mm/year (95% confidence interval) for Kronstadt. The ECHAM5 model also produces much higher values for Kronstadt than for Stockholm, but the values reach 0.88 ±0.13 mm/year for Stockholm and 1.25 ±0.26 mm/year for Kronstadt. The HadCM3 model also produces positive trends, but much weaker and more similar between the two sea-level stations with values of 0.32 ±0.13 mm/year for Stockholm and 0.29 ±0.26 mm/year for Kronstadt. Whereas the NCAR CCSM 3.0 model shows no statistically significant trend for both sea-level stations, the NASA GISS model produces a minor upward trend of 0.14 ±0.09 mm/year for Stockholm.

Several studies pointed out so far that the NAO (represented through the first SLP PC) has a strong influence on sea-level stations in the northern, eastern and central Baltic Sea, but a much weaker influence in the southern Baltic stations (e.g. Jevrejeva 2005). Hünicke et al. (2008) confirmed that SLP is not an adequate large-scale predictor for the sea-level stations Kolobrzeg and Swinoujscie, which are situated in the southern Baltic and found that area-averaged precipitation is a better predictor to explain the decadal sea-level variations in this region. The causes of this behaviour in the southern Baltic Sea are still poorly understood and the mechanisms by which long-term trends and precipitation, and in general fresh water balance, can effect long term trends in sea level might be entangled. As the Danish Straits are open for transport variations on timescales larger than one month (Samuelsson and Stigebrandt 1996), the explanation of an unlagged correlation between winter precipitation and Baltic winter sea level due to the direct volume effect does not hold. Thus, on the timescale of the present analysis, additional in- and outflows, river run-off or net precipitation over sea does not affect the sea level in the Baltic in a barotropic sense significantly. However, precipitation affects salinity and variations in salinity cause changes in water density, which in turn is related to sea level. According to Ekman and Mäkinen (1996), the mean climatological spatial distribution of salinity is partly responsible for the mean sea-level gradient in the Baltic Sea.

Following the findings of Hünicke et al. (2008), area-averaged precipitation was used as predictor for the two southern Baltic sea-level stations Kolobrzeg and Swinoujscie. Again, the estimated linear trends for the 21st century, together with their statistical significance (95% confidence interval), are given in Table 2.

The estimation of the contribution of precipitation changes to future winter sea-level changes shows a much more uniform result across simulations than in the case of SLP. All simulated precipitation changes contribute to a clear and statistically significant upward trend in the 21st century in both sea-level stations in the southern Baltic Sea. Also the changes are of the order of 0.4 mm/year and therefore much smaller than in the case of SLP, the spread using precipitation as predictor is smaller (compared to the results for Stockholm and Kronstadt using SLP as predictor), which leads to a more robust result.

Similar to the findings using SLP, the strongest signal is reached by applying the precipitation output of the GFDL CM 2.1 simulation to the regression models. Thereby the 21st century trends reach values of 0.63 ±0.05 mm/year for Kolobrzeg and 0.54 ±0.04 mm/year (95% confidence interval) for Swinoujscie. Again, the ECHAM5 model delivers quite similar results with trend values of 0.60 ±0.04 mm/year and 0.52 ±0.04 mm/year, respectively. The lowest trends are estimated by using the precipitation output of the GISS model with values of 0.17 ±0.04 mm/year for Kolobrzeg and 0.14 ±0.03 mm/year. The results for the CCSM 3.0 and HadCM3 climate models are quite similar with estimated changes of the order of 0.24 ±0.05 mm/year and 0.30 ±0.05 mm/year for Kolobrzeg and of 0.21 ±0.05 mm/year and 0.26 ±0.04 mm/year for Swinoujscie, respectively.

Discussion and conclusions

The estimation of the contribution of regional climate drivers to future winter sea-level changes by applying five different GCM simulations driven by the 4th IPCC SRES future scenario A2 to a statistical downscaling approach leads to several conclusions:

The contribution to changes in sea level in the central and eastern Baltic stations by using simulated changes in the SLP field as the predictor in a simple linear regression model depends on the GCM. Three out of five GCMs lead to statistically significant future trends for the 21st century with a range of the order of 1mm/year for Stockholm in the central Baltic and even more than 2mm/year for Kronstadt in the eastern part of the Baltic Sea. The trends are in general, of the same sign; only the NCAR model shows a negative, but non-statistically significant trend.

This reflects a high spread, but nevertheless, the conclusion can be drawn that the contribution of SLP to sea-level changes in the investigated stations points to an upward trend in sea-level rise which is larger than the past variability of sea level. The change of sea level between the late 21st and the early 20th century represented by the mean-squared difference for this periods leads to higher values in all analysed sea-level stations compared to the variations within the 20th century (not shown). These results tend to match those obtained by Miller et al. (2006) in their analysis of the annular mode within the Northern Hemisphere (NH), also known as Artic Oscillation (AO), by using the same IPCC model simulations, among others, as present here. The annular mode of the NH is defined as the PC of northern hemispheric SLP and has a hemispheric scale character, of which the NAO is its regional manifestation in the North Atlantic. Both are indicators of the strength of the zonal westerlies over the North Atlantic. Similar to the results of our analysis, the GFDL CM 2.1 model shows the highest changes of SLP between the late 21st century and early 20th century for the winter month (DJF), followed by the HadCM3 model which interestingly represents higher SLP changes than the ECHAM5 model does. This stands in contradiction to the present findings. The SLP changes in the CCSM 3.0 model for the AO are still of positive sign, but the values are low. This does not agree with the results as the CCSM 3.0 model lead to a negative, but non significant, trend. As would be expected, this suggests that regional patterns (e.g. NAO or others) are of more importance for regional sea-level changes than the large-scale annular mode (AO).

The differences between the ECHAM4 and HadCM3 model scenarios during winter, regarding wind speed, were also discussed in a study by Räisänen et al. (2004), who found in the ECHAM4 scenarios a stronger simulated SLP gradient between northern and central Europe compared to the HadAM3H scenarios, leading to stronger westerlies in northern Europe. These results confirm the findings of the present study. Also, the differences are found in a dynamical downscaling approach of simulated sea level in past and future climates of the Baltic Sea by Meier et al. (2004), which will be discussed below in more detail.

Interestingly, using simulated changes in precipitation as the predictor in the regression model, the different GCMs show a smaller spread. All five GCMs lead to a statistically significant upward trend in 21st century Baltic sea-level in the southern Baltic stations with a range of the order of 0.4 mm/year.

These results agree with the findings summarised in the BALTEX Assessment of Climate Change for the Baltic Sea Basin (BACC author team 2008). According to that report, precipitation increases in the 2nd half of the 20th century and a general increase in precipitation is projected for the Baltic Sea basin, except for the southernmost areas in summer. Also, the changes in the atmospheric circulation imply a slight increase in westerly winds over the northern North Atlantic and northern Europe.

As already pointed out, a large part of this variation is associated with the NAO, particularly in winter. However, different models simulate NAO variability with different skill and also the amplitude varies between the models (Osborn 2004). For instance, the ECHAM5 is quite sensitive to anthropogenic greenhouse gas forcing. Simulated NAO changes in other models tend to be more moderate or even of negative sign (Stephenson et al. 2006). Gillett et al. (2003) and others have suggested that current climate models may underestimate the sensitivity of the atmospheric circulation to greenhouse gas forcing. Future regional precipitation changes may also be model-dependent, although the climate models included in the 4th IPCC Assessment Report tends to produce an increase in winter precipitation in the Baltic Sea Region (Giorgi and Bi 2005).

The skill of each individual climate model is not easy to assess by comparing their performance in the 20th century. When the statistical transfer functions are applied to the SLP and precipitation simulated by the suite of IPCC models in the 20th century, the resulting sea-level time-series display in general less variability than when the transfer functions are applied to the observational gridded data sets, although some models perform better than others. This is reflected in Table 3, which shows the standard deviations of the estimated sea-level time series. As expected, the results differ between the climate models. In case of SLP as predictor (Stockholm and Kronstadt), the amplitudes agree pretty well. The results of the CCSM 3.0 and the GFDL CM 2.1 model, in particular, show a good agreement with observations, which indicates that the variance of the climate model output conforms statistically to observations. The GISS, HadCM3 and ECHAM5 underestimate the amplitude, but the numbers are still of the same order of magnitude as the variance out of observations. Interestingly, the models that display a higher variability, closer to observations, simulate a lower trend. For instance, the trend simulated by the CCSM 3.0 model is statistically non-significant. The model producing the largest future trend (ECHAM5) clearly underestimates the 20th century variance.

In case of precipitation (Kolobrzeg and Swinoujscie) the standard deviation derived from the gridded observations shows much higher (approximately double) values than those derived from all models. The models producing higher precipitation-driven variations are different from those with highest SLP-driven variability. A consistent pattern among models does not seem to emerge, so that it is difficult to ascertain the causes for the underestimation of precipitation variability. However, observed precipitation probably contains a non-negligible error component that may inflate the measured variability, and which is not present in the models.

At this stage, therefore, the envelope of the results obtained from this model suite may be just interpreted as a rough range of uncertainty.

However, the findings qualitatively agree with the results of a dynamical downscaling approach with a regional atmospheric ocean model by Meier et al. (2004). They used the Rossby Centre Atmosphere Ocean Model (RCAO), driven by the global models HadAM3H and ECHAM4/OPYC3 under the future scenarios A2 and B2 and combined a range of simulated global eustatic sea-level rises with the impact of simulated regional wind changes for the Baltic Sea. By using two future scenarios, the uncertainties stemming from the large scale forcing and from the future external forcing could be characterised. Taking only the wind factor into account, the results of the present statistical downscaling approach and of the dynamical downscaling approach of Meier et al. (2004) are rather close.

In both approaches, the statistical and the dynamical downscaling, the projected sea-level change is underestimated due to the partly missing remote factor. As stated before, the main factors affecting the long-term Baltic sea-level are land uplift, eustatic sea-level rise and the water balance of the Baltic Sea. Thereby, the eustatic sea-level rise contains two contributions: (1) the remote sea-level rise in the North Sea, North East Atlantic or even on larger (global) scale due to changing heat content and due to changing circulation, and (2) the local change in the Baltic Sea due to changing salinity. Meier et al. (2004) used the global mean sea-level rise from the GCMs at the lateral boundary in the northern Kattegat. As sea-level change in the North Sea could be quite different from the global mean sea-level change, this approach may misrepresent the remote factor. In the present statistical approach, the SLP data set used for the calibration of the regression models cover the North Atlantic region. This includes the impact of the west wind component, but also other relevant SLP patterns. Nevertheless, the sea-level rise on larger (global) scales is missing in the statistical downscaling.

The contribution of the regional climate drivers to future Baltic sea-level changes may be of the same order of magnitude as the global sea-level rise: Climate projections for the end of the 21st century under different scenarios of atmospheric greenhouse gases foresee increases in the global sea-level in the range of 18 to 59 cm, with respect to the 1980 to 1999 mean (Meehl et al. 2007), whereby about three-fourths of this increase will be mainly caused by the thermal expansion of the water column. In case of the southern Baltic Sea the application of precipitation as predictor leads to a quite good agreement of all five global climate models used for the presented regression analysis. It has to be kept in mind, however, that these estimations comprise only the partial contribution of some selected large-scale regional predictors to the local potential change, and that there are other regional factors such as the isostatic contribution to relative sea-level changes or substantial changes in the sea-ice cover, and global sea-level rise, which have to be considered for an estimation of the total regional sea-level rise.

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Table 1 List of Global Climate Models. Additional information on the models and assumed forcings is available at http://www-pcmdi.llnl.gov/ipcc/model_documentation/ipcc_model_documentation.htm.

Model	***Institution/ Country***	***Time period***	***Reference***
NCAR CCSM 3.0 (POP OGCM)	National Center for Atmospheric Research/ USA	1870-2099	Meehl et al. 2006
NASA GISS Model E-R (Russell OGCM)	Goddard Institute for Space Studies/ USA	1880-2100	Hansen et al. 2002
UKMO HadCM3	United Kingdom Meteorological Office, Hadley Centre/ UK	1860-2099	Pope et al. 2000
MPI ECHAM5	Max Planck Institute for Meteorology, Germany	1860-2099	Jungclaus et al. 2006
NOAA GFDL CM 2.1	Geophysical Fluid Dynamics Laboratory/ USA	1861-2100	Delworth et al. 2006

Table 2 Estimated linear trends of the contribution of SLP and precipitation changes to future winter sea-level change (2000 to 2100), together with their 95% confidence interval.

Trends mm/year (95% confidence interval)	***Kolobrzeg***	***Swinoujscie***	***Stockholm***	***Kronstadt***
Global climate models	predictor precipitation		predictor sea-level pressure	
NCAR CCSM 3.0 (POP OGCM)	0.24 (±0.05)	0.21 (±0.05)	-0.19 (±0.21)	0.01 (±0.38)
NASA GISS Model E-R (Russell OGCM)	0.17 (±0.04)	0.14 (±0.03)	0.14 (±0.09)	0.13 (±0.17)
UKMO HadCM3	0.30 (±0.05)	0.26 (±0.04)	0.32 (±0.13)	0.29 (±0.26)
MPI ECHAM5	0.60 (±0.04)	0.52 (±0.04)	0.88 (±0.13)	1.25 (±0.26)
NOAA GFDL CM 2.1	0.62 (±0.05)	0.54 (±0.04)	1.24 (±0.18)	2.53 (±0.34)

Table 3 Standard deviation of the estimated sea-level time-series in the 20th century. For the estimations, the predictors were taken from a) climate observations and b) climate simulations with five different global climate models.

Standard deviation of estimated sea-level time-series in the 20th century	***Kolobrzeg***	***Swinoujscie***	***Stockholm***	***Kronstadt***
	predictor precipitation		predictor sea-level pressure	
a) climate observations	22.72	23.33	36.64	70.16
b) climate model data				
NCAR CCSM 3.0 (POP OGCM)	8.60	8.84	36.64	66.36
NASA GISS Model E-R (Russell OGCM)	5.45	5.60	22.85	44.29
UKMO HadCM3	8.99	9.23	21.18	44.46
MPI ECHAM5	10.11	10.39	24.25	48.68
NOAA GFDL CM 2.1	9.73	10.00	34.86	63.82

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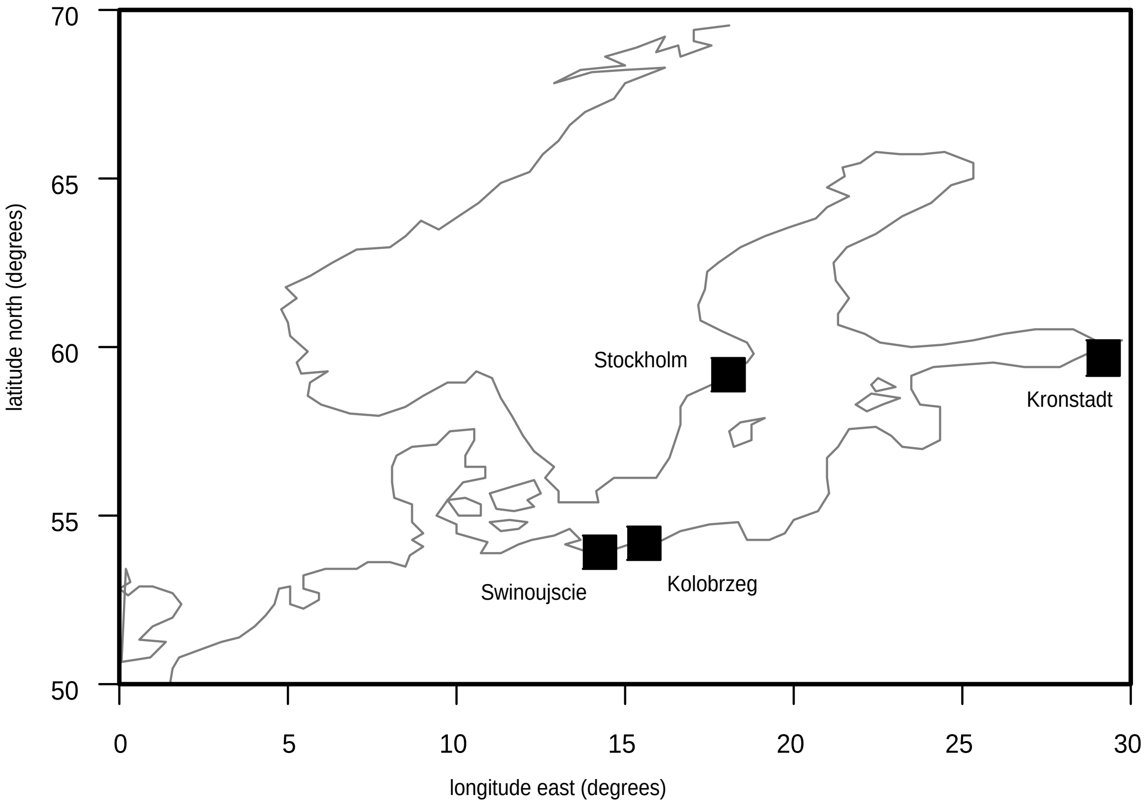

Fig. 1 Sketch of the Baltic Sea, showing the location of the sea-level gauges (Hünicke et al., 2008).

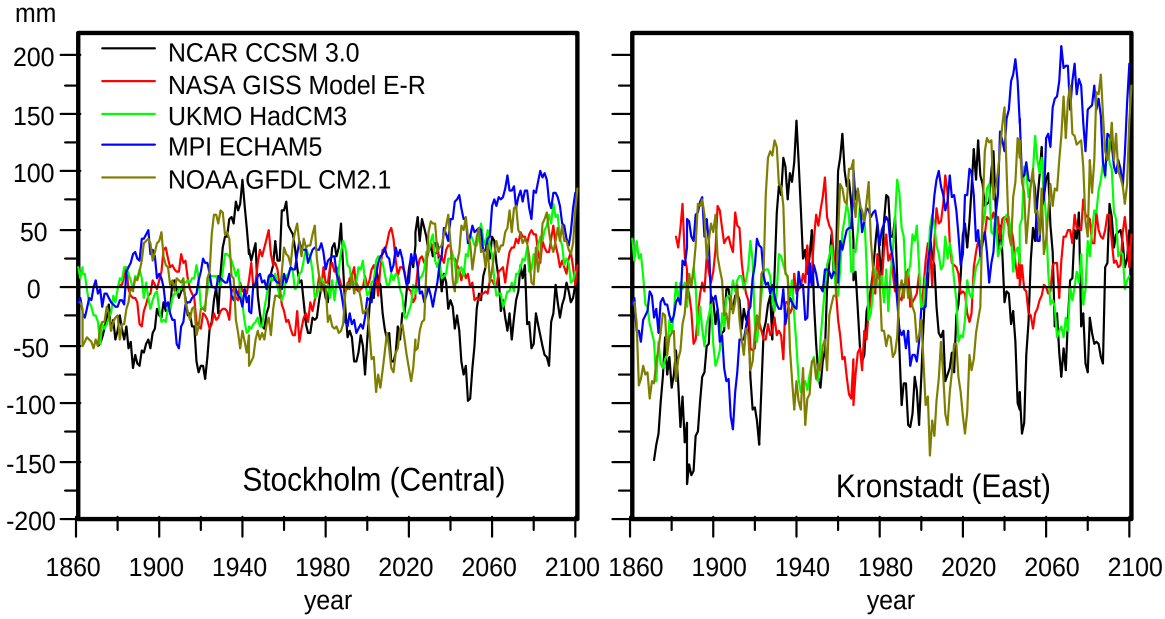

Fig. 2 Estimations of the contribution of SLP changes to future winter sea-level change for two stations in the Baltic Sea based on regression between observed sea-level as predictand and SLP as predictor. For the estimations, the predictors were taken from climate simulations with the global climate models CCSM 3.0, GISS E-R, HadCM3, ECHAM5, GFDL CM 2.1, driven by IPCC SRES future scenarios of anthropogenic radiation forcing A2. The regression model was calibrated with observations in the period 1900 to 1999. Time-series were smoothed by an 11-year low-pass filter.

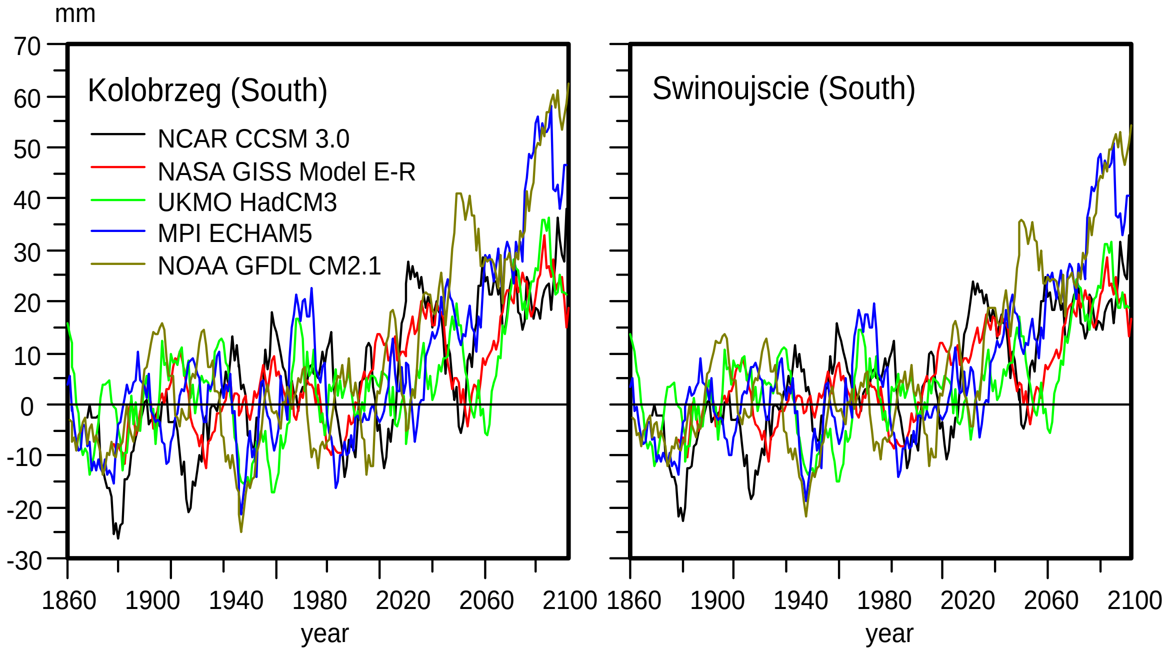

Fig. 3 Estimations of the contribution of precipitation changes to future winter sea-level change for two stations in the southern Baltic Sea based on regression between observed sea-level as predictand and area-averaged precipitation as predictor. For the estimations, the predictors were taken from climate simulations with the global climate models CCSM 3.0, GISS E-R, HadCM3, ECHAM5, GFDL CM 2.1, driven by IPCC SRES future scenarios of anthropogenic radiation forcing A2. The regression model was calibrated with observations in the period 1900 to 1999. Time-series were smoothed by an 11-year low-pass filter.