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TELLUS

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

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ABSTRACT

Decadal sea level variations in selected stations located in the southwestern, central and eastern Baltic Sea are found to be less coherent in the 19th century than in the 20th century. The effect of the North Atlantic sea level-pressure (SLP), precipitation and air-temperature in the 19th and 20th centuries from gridded climate reconstructions, and their relationship to Baltic Sea level, are statistically analysed to explain this difference. The influence of these factors on sea level varies geographically. In the central and eastern Baltic, Sea level variations are well described by SLP alone, whereas in the southern Baltic Sea area-averaged precipitation better explains the decadal sea level variations. The evolution of precipitation in the 19th century could explain the different behaviour of the southern Baltic stations; however, the physical mechanism for this relationship remains unclear. The effect of temperature variations is either already contained in the SLP field or is less important for decadal sea level variations than the other two factors.

1. Introduction

Estimations of future global sea level from simulations with coarse-resolution global climate models mostly depend on large-scale processes, such as the heat-flux into the ocean, on changes in the ocean circulation and on the rate of melting of land-ice masses (IPCC, 2007). In regions with complex coastlines, sea level changes may additionally depend on other regional factors which are not properly represented in global models. The Baltic Sea, located between Scandinavia and mainland Northern Europe, and connected to the North Atlantic by the narrow and shallow Danish straits (up to 16 km wide and about 18 m deep) is a suitable example of this. In wintertime, interannual sea level variations at its northern and eastern boundaries are influenced by the westerly winds, related to the sea level-pressure (SLP) pattern of the North Atlantic Oscillation (NAO) (Andersson, 2002). Stronger westerlies in periods with a positive NAO phase cause comparatively higher sea level in some areas of the Baltic Sea. However, some studies indicate that the connection between individual Baltic stations and SLP may be heterogeneous in time and in space. For instance, the correlation between the winter NAO index and winter sea level in the 20th century ranges spatially between 0.1 and 0.8 (Hünicke and Zorita, 2006). Jevrejeva et al. (2005) found that the moving correlation between winter mean sea level and the NAO varied between zero and 0.6 in Wismar (southwestern Baltic Sea) in the period 1860–1980. They concluded that processes other than wind-stress forcing are important for sea level variability. Previous studies have suggested that precipitation and temperature may also contribute to sea level variations (Chen and Omstedt, 2005; Hünicke and Zorita, 2006), thus modulating the correlations between sea level and the NAO. The question arises as to whether these local processes might also significantly influence sea level variability at low-frequencies, that is, multidecadal, so that their contribution should be considered for future sea level projections at local scales.

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

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behaviour. Previous statistical analysis (Heyen et al., 1996), using canonical correlation analysis, considered the relationship between SLP patterns and patterns of sea level anomalies in the Baltic Sea. However, this approach may preclude the identification of a spatially heterogeneous response of sea level to the SLP forcing, as canonical correlation yields in this case coherent patterns of covariations, that is, the variability shared by set of stations that is also connected to the variations in some atmospheric SLP patterns. In this study, we consider each gauge station individually to ascertain whether the effect of large-scale factors may also vary regionally. Our approach is based on statistical regression methods to hindcast sea level variations and on an examination of the skill of the different predictors. The statistical models are calibrated in the 20th century and validated in the 19th century. However, the method is also tested when interchanging validation and calibration periods and also with calibration and validation periods entirely within the 20th century. The gridded climate reconstructions did not make use of any sea level information; therefore this analysis consequently can potentially support the quality of the climate reconstructions.

The analysis is restricted to the winter season. In this season the variability of the atmospheric forcing is largest, making it easier to understand the effect of those individual forcings on sea level variations above other, more local, processes or measurement noise. For instance, as stated before, the role of the NAO on winter sea level in part of the Baltic Sea is well established, and yet the reason for the low and erratic correlation between this leading mode of atmospheric winter variability and sea level in the Southern Baltic is not clear. It is intended, however, to extend this type of analysis for other seasons in future work. The processes responsible for regional winter sea level variations for high-latitude semi-enclosed seas are complex, as sea-ice, precipitation and/or run-off might effect sea level in some regions more strongly than in others. In this study the predictors considered are restricted to those for which long observations or reconstructions are available and which are potentially well simulated by coarse resolution models, so that conclusions may be applied to the output of General Circulation Model (GCM) simulations. In practice, the predictors are SLP (an indicator of geostrophic wind), area-averaged precipitation and air-temperature.

This work is structured as follows. Section 2 presents the data (observational records and reconstructions) used in this study. Section 3 examines the relationship between Baltic Sea level and the large-scale gridded climate fields. The role of the different climate forcings that might effect Baltic Sea level is statistically explored by constructing linear regression models in which these forcings are treated as individual predictors. The statistical models are presented and their application and skill discussed. Section 4 presents a discussion of the results and some conclusions.

2. Data sets

In this study we focus on winter season which is defined here as the mean of the month December, January and February (DJF). As we are interested in variability at decadal and longer timescales, all time-series were smoothed with an 11-yr running mean filter.

2.1. Baltic Sea level observations

We examined winter means of four of the longest time-series of sea level (up to 200 yr long) from coastal observation stations situated along the Baltic Coast (Fig. 1), obtained from different sources: the data collection of the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003) and (documented) sea level records of historical importance, which are not included in the PSMSL data set (Bogdanov et al., 2000; Ekman, 2003). As stated by the PSMSL, this is 'either because the data are not available in the monthly and annual mean format used by the PSMSL, or because they are not true Mean Sea Level (MSL) or even Mean Tide Level (MTL) as such (based perhaps on irregular observations of high and low waters rather than on continuous observations by a "tide gauge" or "tide pole" as now understood)'. Nevertheless, the existence of several previous studies, which used these long historical time-series for their analyses (beside the original publications) should stand for a verification of the data quality (e.g. Andersson, 2002, Omstedt et al., 2004; Chen and Omstedt, 2005; Jevrejeva et al., 2005). Also, we used (undocumented) sea level data provided by the Technische Universität Dresden, which was compiled in the frame of the German Science Foundation Project 'Sinking Coasts' (SINCOS). Detailed information about the sea level data (time period used, data source, missing values) are given in Table 1.

Missing values in two of the time-series (Kolobrzeg 1940–1950; Swinoujscie 1945–1950) were not interpolated or replaced

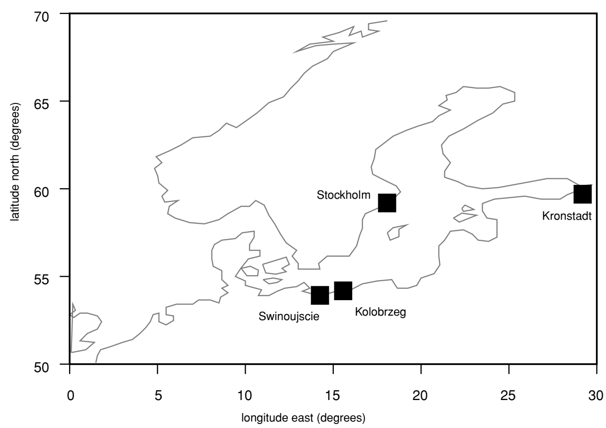

Fig. 1. Sketch of the Baltic Sea, showing the location of the four sea level gauges used in this study.

Table 1. Schematic description of the sea level data sets

Location	Years	Data source
Kolobrzeg	1816–1999	PSMSL, before 1951 TU Dresden
Swinoujscie	1811–1996	PSMSL
Stockholm	1801–2000	Ekman (2003)
Kronstadt	1841–1993	Bogdanov et al. (2000)

by the climatological means. We did not use the entire available Kronstadt time-series (1777–1993) due to frequently missing data in the beginning and because it appears from the original reference that sea level data maybe considered unreliable before 1841. This is also quite clear by a simple visual inspection of the time-series. The values prior to this date appear unreasonably large (higher sea level). Also in the originally Stockholm data set (1774–2000) the beginning missing values are frequent and only from 1825 onwards is the series complete. For the largest gap in 1812–1824, reconstructions of the missing MSL values (by transformation of monthly MSLs from the station Copenhagen) are available from the original reference (Ekman, 2003). We decided to include these reconstructions in our analysis, but for the discussion of our results these caveats should be kept in mind.

The trend in the sea level records, caused by a combination of postglacial land uplift and eustatic sea level change, is assumed to be linear and is eliminated by statistically estimating the individual linear trend by a linear least-mean-square fit and subtracting it from the record. This procedure also eliminates the linear trends that may be caused by eustatic sea level change and by the long-term trends in the regional climate forcing (see Chen and Omstedt, 2005 for discussion). These trends, which have different physical origins, cannot be separated by statistical methods alone and this analysis is, therefore, restricted to variations around the overall long-term linear trend.

2.2. *Climate reconstructions*

We used gridded reconstructions of monthly SLP and temperature and seasonal precipitation as large-scale fields for winter over the 1880–2000 period. Detailed information about references, grid resolution and the geographical area which was considered for each of the climate reconstruction fields are given in Table 2.

The climate reconstructions coincide with corresponding observations in their calibration period (1901–1990 for SLP, 1901–1995 for temperature and 1901–1983 for precipitation): monthly SLP prepared by National Centres for Environmental Prediction (NCEP) (Trenberth and Paolino, 1980), precipitation and temperature fields by Mitchell and Jones (2005) (for more details see original references).

The geographical distributions of the climate reconstruction considered for this study were selected based on the climate data sets used by Hünicke and Zorita (2006).

An important aspect of these climate reconstructions is that they are not simple spatial interpolation of available long-instrumental and indirect (documentary, proxy-based) climate data. The reconstruction method is based on principal component (PC) regression, in which a statistical regression model uses a set of long time-series of local climate data as predictors and the leading PCs of the target field (temperature or precipitation or SLP) as predictands. The regression model is calibrated in a period in which both predictor and predictand overlap (1901–1960 for SLP and temperature, 1901–1956 for precipitation), and verified with the corresponding data in the second part of the 20th century. The PCs of the target field are also calculated in this calibration period. The regression model is then used to reconstruct the PCs of the target field using the long predictor's time-series, under the assumption of being stationary in the statistical relationships. The gridded target field is reconstructed by linearly combining the reconstructed PCs with their corresponding spatial eigenvectors calculated in the calibration period. The final product, although presented as gridded field, is essentially a linear combination of these constant spatial eigenvectors, the linear combination changing through time. Therefore, the effective average spatial resolution is given by the typical spatial scales of these constant eigenvectors. As the PCs of the target fields are calculated in the European land area, the effective resolution of the reconstructed fields will not change over a relatively small area such as the Baltic Sea. Consequently, regional differences in the skill of the predictor to explain sea level variations cannot be ascribed to regional differences in the quality of the climate reconstructions or to regional differences in the spatial resolution

Table 2. Schematic description of the climate reconstructions

Climate field	Grid resolution	Geographical region	Data source
Sea level pressure	$5.0° \times 5.0°$	30°W–40°E; 30°–70°N	Luterbacher et al. (2002)
Precipitation	$0.5° \times 0.5°$	11°–26°E; 52–62°N	Pauling et al. (2006)
Temperature	$0.5° \times 0.5°$	10°–30°E; 50°–65°N	Luterbacher et al. (2004)

of the reconstructions. More details about data and methods can be found in the original references.

3. Relationship between Baltic Sea level and large-scale gridded climate fields

Fig. 2 displays four (linearly detrended and standardized to unit variance) decadally smoothed sea level records from the southwestern, central and eastern Baltic Sea covering the past 200 yr (see Fig. 1 for the location of these stations). Considering these four stations, several subperiods can be identified in which sea level is spatially coherent and other periods in which there are differences among the stations. The most similar behaviour is displayed by the Stockholm and Kronstadt sea level time-series for the entire period. For these stations the subperiods with positive and negative sea level anomalies match almost perfectly. The relative magnitude of the anomalies (the series have been standardized) is also very similar. For the southern stations, some periods of deviation can be found. In the earlier 19th century the southern stations show sustained positive sea level deviations, whereas Stockholm and Kronstadt are more erratic. Around 1850–1875, the southern stations display large negative anomalies, whereas sea level in Kronstadt and Stockholm remained closer to its long-term mean. Around 1900–1925 Swinoujscie remains near the long-term mean sea level, whereas the other three stations show clear positive anomalies. In 1950–1975 the anomalies at Swinoujscie are again near zero, whereas at the other stations they are negative and large. Overall, the agreement between the four stations is larger in the 20th century than in the 19th century. When decadally smoothed, the interstation correlation exceeds 0.85 for all station pairs in the 20th century, but in the 19th century the correlations between the southern stations and the rest falls to about 0.5.

Deficiencies in data quality and changing measurements methods could be invoked to explain part or all of these differences in the 19th century, especially in the earlier decades. However, on the one hand, the similar behaviour of the sea level time-series of the two southern Baltic stations point to a good data quality as both stations are located relatively nearby and therefore a similar behaviour of the sea level variations in these stations might seem logical. This would support the validity of the interstation correlations. On the other hand, it cannot be ruled out that this similar behaviour could also possibly be a result of interpolation processes during the recording or/and post-processing. As we do not have access to original raw data, this question cannot be answered in the present analysis, but it certainly has to be considered as a possibility in the interpretation of the final results.

A view of the possible external atmospheric forcings that may give rise to this behaviour is presented in Fig. 3, showing the time-series of the leading SLP PC in this area, (which is related to the NAO index), the time-series of the averaged precipitation and the time-series of averaged temperature (the latter linearly detrended over the whole period). Again, periods can be identified where the decadal variations of these three potential forcings deviate from each other. In the 19th century precipitation shows a prolonged period of negative sign between 1850 and 1900 that is not matched by the SLP PC or by the averaged air temperature. Temperature and SLP in the 19th show little coherence and even periods of opposite sign of their anomalies—a significant feature taking into account that originally the 20th century positive correlation between the NAO and Scandinavian temperature constituted one of the defining features of the NAO. However, the leading PC of SLP and Baltic air-temperature anomalies, albeit more coherent in the 20th than in the 19th century, also show deviant behaviour around 1930. Overall, for the 20th century, a

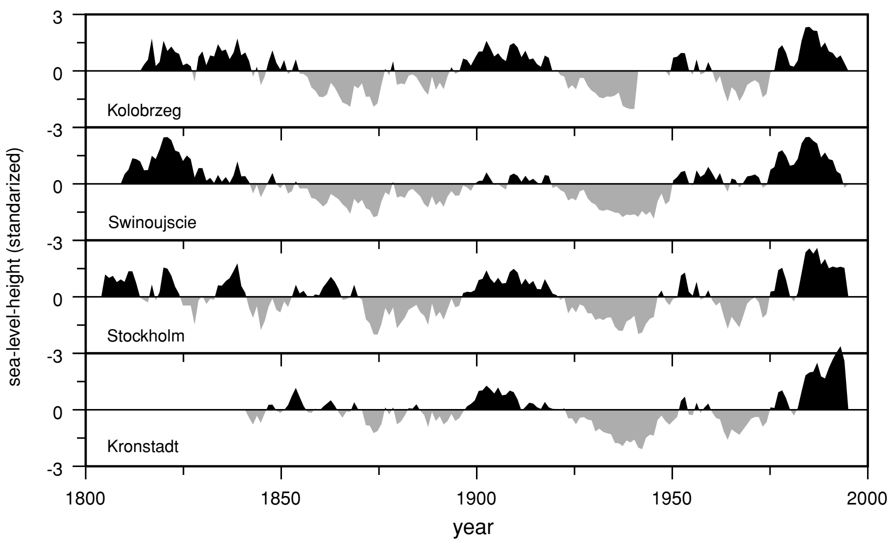

Fig. 2. Relative winter mean (December–February) sea level height at four stations in the Baltic Sea in years 1800–2000: deviations from the 1900 to 1999 mean, linearly detrended, smoothed by a 11-yr running-mean and standardized to unit standard deviation.

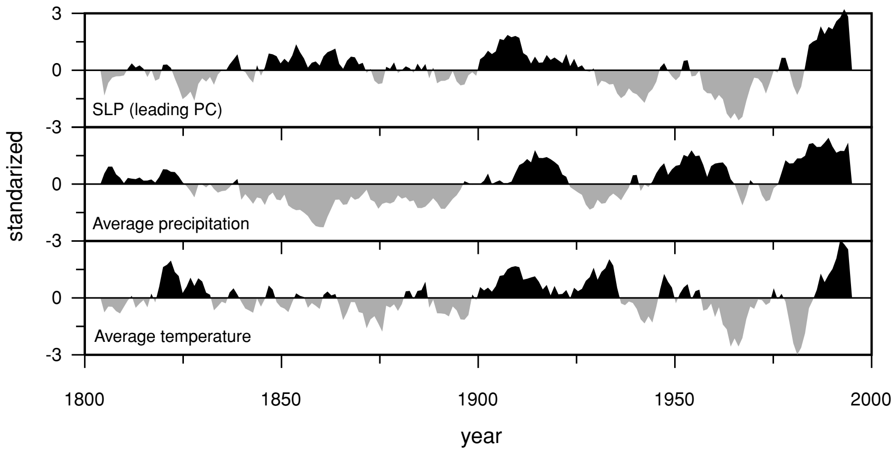

Fig. 3. Time-series of the leading winter SLP principal component in the North Atlantic-European sector, time-series of the area averaged precipitation and time-series of the area averaged temperature in the Baltic Sea region: deviations from the 1900 to 1999 mean, smoothed by a 11-yr running mean and standardized to unit standard deviation (after linearly detrending temperature). The original data stem from European climate reconstructions, see Section 2 for references.

calculation of the mutual correlations between the leading SLP PC, precipitation and temperature was performed with smoothed time-series (11-yr running mean filter) and with unsmoothed (interannual) time-series. Thereby, the statistical significance was estimated by Monte Carlo simulations emulating the same degree of smoothing. The results show that the leading SLP PC is more closely related to temperature than to precipitation. The correlation coefficient between SLP and temperature is 0.77 in the 20th century (smoothed and interannual, both statistically significant at the 95% level), whereas between SLP and precipitation it is 0.46 and 0.36, respectively (only the former being statistically significant at 95% level). Temperature and precipitation indicate weaker relationships, with correlations of 0.24 and 0.26, both not statistically significant.

The role of these different climate forcings that might effect Baltic Sea level is statistically explored in the following by constructing linear regression models in which these forcings are treated as individual predictors, and not in combination. Combinations of predictors have not been considered here, as our goal is to disentangle the effect of the individual predictors. As they may be intercorrelated, it would not be straightforward to interpret the results if a combination of predictors had been used simultaneously.

Although one of the immediate forcings for sea level variations in the Baltic is the surface wind, long observations over the ocean covering the 19th century do not exist. However, at decadal timescales and at mid-latitudes, surface wind is closely related to SLP gradients through the geostrophic relation. SLP gradients also influence sea level through the inverse barometric effect (Ponte, 1994). SLP is therefore considered here as the first predictor in a regression equation to estimate sea level at one station (*sl*). The SLP field is first decomposed in its PCs to avoid colinearity and the resulting instability of the regression. The regression model reads:

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

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 part of 200-yr period by ordinary least-square error minimization and the resulting regression model is validated in the remaining part of this period. To estimate sea level variations outside the calibration period, the SLP anomalies relative to the calibration mean are projected onto the spatial eigenvector of loadings from the PC analysis previously calculated in the calibration period. The cut-off number $N = 3$ 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 (von Storch and Zwiers, 1999) and by the correlation coefficient between observations and estimations, both evaluated in the validation period. The RE is defined as

$$\mathrm{RE} = 1 - \frac{\sum_t [\mathrm{est}(t) - \mathrm{obs}(t)]^2}{\sum_t [\mathrm{obs}(t) - \overline{\mathrm{obs}}]^2}, \qquad (2)$$

where est(t), obs(t) refer to the estimated and observed values at time t, and $\overline{\mathrm{obs}}$ is the mean value of the observations estimated in the calibration period. RE values range between $-\infty$ to unity (perfect ‘prediction’). A value of zero indicates a skill equal to that of climatology (simply taking as prediction the value of the mean in the calibration period), whereas negative values indicate a skill worse than the simple climatological mean. An 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.

Table 3. Reduction of error (RE) statistic and correlations (*r*) as an evaluation of the skill of the predictors SLP, precipitation (Prec) and temperature (Temp) to reconstruct sea level. The analysis period is split in a calibration period (CAL) and a validation period (VAL). Correlations significant at the 95% level (taking into account the degree of smoothing) are bold-typed

RE	CAL 1900–1999	VAL 1801–1900	CAL 1801–1900	VAL 1900–1999
Predictor[a]	SLP/Prec/Temp	SLP/Prec/Temp	SLP/Prec/Temp	SLP/Prec/Temp
Kolobrzeg	0.67/0.48/0.08	0.01/− 0.51/−0.14	0.21/0.43/ 0.03	−0.74/0.05/−0.01
Swinoujscie	0.51/0.41/0.02	0.12/−0.14/ 0.02	0.27/0.55/0.50	−0.98/−0.54/−0.34
Stockholm	0.85/0.53/0.25	0.35/−0.87/−1.12	0.37/0.23/−0.01	0.67/0.27/0.08
Kronstadt	0.90/0.40/0.35	0.60/−9.00/−7.00	0.66/0.02/0.20	0.79/−0.13/−0.15
r	CAL 1900–1999	VAL 1801–1900	CAL 1801–1900	VAL 1900–1999
Predictor[a]	SLP/Prec/Temp	SLP/Prec/Temp	SLP/Prec/Temp	SLP/Prec/Temp
Kolobrzeg	0.82/0.70/0.29	0.26/0.68/0.19	0.56/0.68/0.19	−0.21/0.70/0.29
Swinoujscie	0.72/0.64/0.13	0.37/0.76/0.22	0.57/0.76/0.22	−0.17/0.64/0.13
Stockholm	0.92/0.73/0.50	0.59/0.48/0.00	0.61/0.48/−0.01	0.89/0.73/0.50
Kronstadt	0.96/0.63/0.60	0.85/−0.20/0.46	0.85/0.20/0.46	0.91/−0.63/0.60

[a]Leading SLP PCs/ area-averaged precipitation/ area-averaged temperature.

Note that this analysis represents an evaluation of the skill of the predictors. Therefore, confidence intervals for the sea level estimations are not considered.

A summary of the skill of the regression models using different predictors, and using two different calibration periods, can be found in Table 3. In the following these results are explained in a more detailed way, illustrated with corresponding plots of the resulting time-series for the case with the calibration period 1900–1999. Fig. 4 shows the results for the four Baltic Sea stations when the calibration period is 1900–1999. The sea level

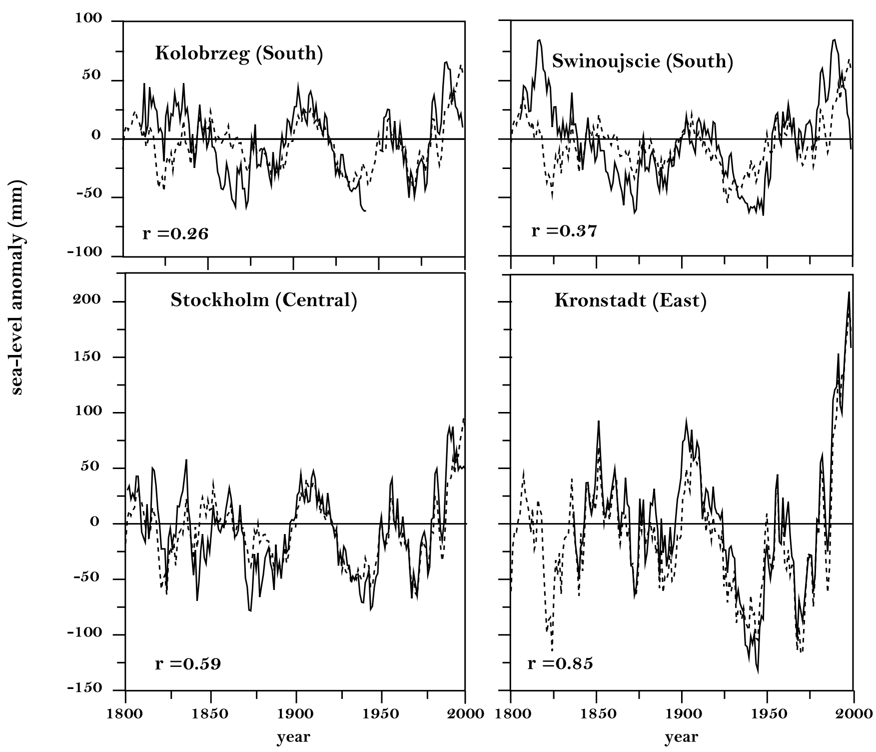

Fig. 4. Decadally smoothed and linearly detrended observed (solid lines) sea level and reconstructed (dashed lines) sea level deviations from the 1900 to 1999 mean, using the SLP field as predictor. Figures within the panel indicate the decadal correlation *r* between observations and reconstructions in the 19th century. The regression model was calibrated in 1900–1999. Note that for Kronstadt the data prior to 1941, although available, have not been used in the analysis.

estimations are compared with observations. For the stations Stockholm and Kronstadt, the model skill is high (validation RE = 0.35 and 0.60) with significant correlations of 0.59 and 0.85, respectively. This confirms the relevance of SLP for sea level variations also at longer timescales and in the 19th century. Only very short periods of disagreement can be found where estimations and observations deviate (for Stockholm around 1850, for Kronstadt around 1960 and 1970), indicating that SLP is sufficient to accurately determine decadal sea level variations in this station. A second important consideration of this agreement is that, as SLP does not contain prior information from sea level and was not focused on the Baltic Sea in particular, the sea level data in Kronstadt and the SLP reconstructions are very likely to be accurate. As stated in Section 2, the accuracy of the SLP reconstructions is very likely to apply to the whole Baltic Sea area, as they are based on the large-scale PCs of the European-wide SLP.

In contrast, the calibration skill for the southern stations, Kolobrzeg and Swinoujscie, is considerably lower, and the validation skill is poor (RE = 0.01 and 0.12) with non-statistically significant correlations of 0.26 and 0.37, respectively. Observations and estimations are clearly not correlated at decadal timescales in the first half of the 19th century. As the estimations for Stockholm and Kronstadt are much better, this mismatch in the southern Baltic is likely not caused by a poor SLP reconstruction in the 19th century. These results confirm that decadal SLP is not an adequate large-scale predictor for all stations in the Baltic Sea, and that other forcings are required to explain the decadal variations in this area. When calibration and validation period are interchanged (Table 3), essentially the same conclusions can be reached. SLP remains a good predictor for Stockholm and Kronstadt, whereas its skill for the southern stations Kolobrzeg and Swinoujscie remains poor.

We now explore if precipitation is a skilful predictor for sea level in stations Kolobrzeg and Swinoujscie. Different mechanisms could give rise to a physical link between precipitation and Baltic Sea level. Precipitation is closely related to the fresh-water balance of the Baltic Sea (in- and outflows, river run-off and net precipitation). Spatially averaged precipitation should also be related to run-off into the Baltic, although not to evaporation. As the southern Baltic Sea does not freeze during normal winters (with the exception of sheltered areas) (Håkansson et al., 1995), an unlagged relation between winter precipitation and winter sea level could be assumed, and spatially averaged winter precipitation can be considered as a sole predictor. On the other hand, precipitation influences salinity, and therefore water density, which in turn is related to sea level. Actually, the mean climatological spatial distribution of salinity is, in part, responsible for the mean sea level gradient in the Baltic Sea (Ekman and Mäkinen, 1996). This is discussed further in Section 4.

Fig. 5 shows that using 1900–1999 as the calibration period, the correlation in the validation period of winter precipitation for Kolobrzeg and Swinoujscie, though not perfect, has increased relative to the SLP, with correlations of 0.68 and 0.76, respectively, which are now statistically significant. The RE values, however, are still of a 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 of the 20th century that is not captured by the precipitation as predictor. In other words, the variations around the changed mean value in the 19th century are relatively well reproduced (high correlation), but the absolute error is still large compared to the typical deviations of the 19th values relative to the 20th mean. Precipitation does not seem able to describe the long-term variations in change in the mean value of sea level. This question is further discussed in Section 4. Nevertheless, as in the case of SLP, the reasonable skill of precipitation for the southern Baltic stations at decadal timescales supports the validity of the winter precipitation reconstructions in the 19th century (Pauling et al., 2006) in this region and at this decadal timescale.

It is noteworthy to mention that precipitation is a much poorer predictor for the sea level variations in Kronstadt and Stockholm than for the southern stations (Table 3). The RE and correlation statistics are lower for these stations than for the southern stations, in particular for Kronstadt, where SLP was an excellent predictor.

This picture of the role of precipitation is essentially the same when the calibration and validation period are exchanged (Table 3). The correlations between observations and estimations in the validation period (now the 20th century) remain high for the southern stations, but it is also high for Stockholm, albeit it is negative for Kronstadt. The RE statistics hover around the value of zero for all four stations. Therefore, it appears that precipitation is indeed a good predictor for the decadal variations of sea level in the southern stations, regardless of the calibration and validation period, but that the very slow variations of sea level which affect the changes in mean value between the 19th century and the 20th century are not well captured by this predictor.

Winter air-temperature was also used as a sole predictor, with both representations of temperature (Baltic Sea area-averaged temperature and PC representation of the temperature field). The rationale for this analysis is that water temperature, which is affected by air-temperature, may modulate the expansion of the water column and thus also sea level. Note that we are analysing seasonal DJF means, as the vertical mixing is greater than in summer, and therefore it is reasonable to assume that variations in air-temperature have had enough time to penetrate into deeper layers. The statistical model with temperature as a sole predictor did not show any improvement relative to the SLP-only model (Table 3). The validation correlations between observations and estimations remain in general non-statistically significant. The exception is for Kronstadt and Stockholm in the 20th century, when the connection between air-temperature and the SLP field, through the NAO, is strong (Hurrell, 1995). Therefore, it seems that these correlations are brought about by the indirect correlation of sea level and temperature with the NAO. To ascertain

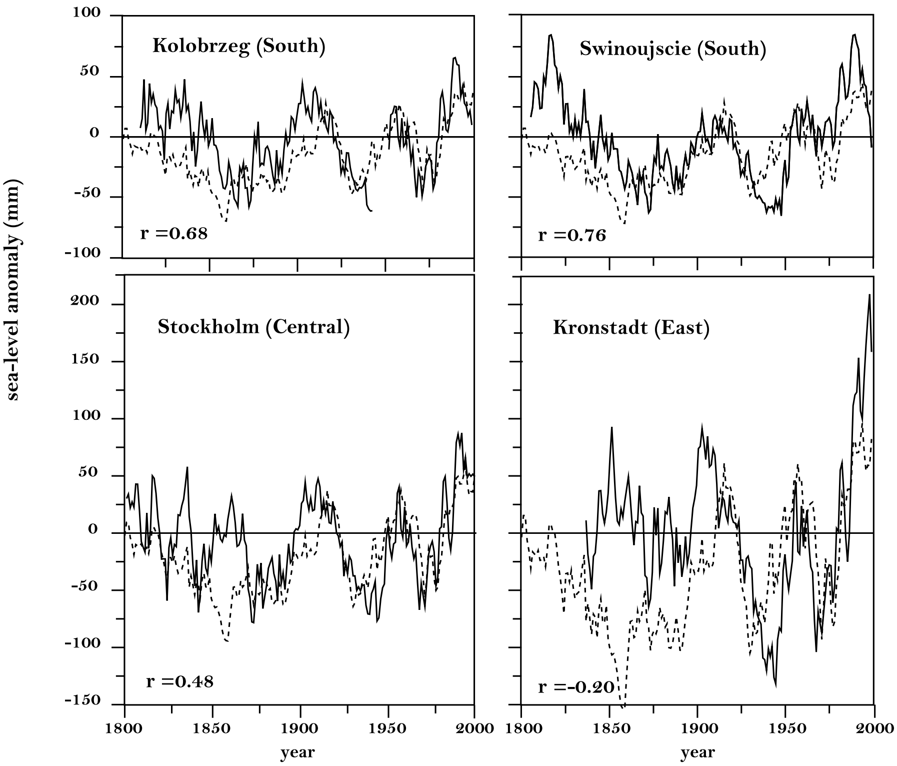

Fig. 5. Decadally smoothed and linearly detrended observed (solid lines) sea level and reconstructed (dashed lines) sea level (deviations from the 1900 to 1999 mean), using area-averaged precipitation as predictor. Figures within the panel indicate the (decadal) correlation between observations and reconstructions in the 19th century.

this result, air-temperature was used in combination with SLP as predictors, to check whether the skill of the regression models increased significantly relative to the models with SLP alone (not shown). This was not the case.

4. Discussion and conclusions

Our study showed that decadal sea level variations in the Baltic Sea may be regionally homogeneous, also at timescales longer than interannual, and it statistically explored the possible role of atmospheric forcings in this spatial heterogeneity. It was found that SLP shows large prediction skill for the station Kronstadt, and somewhat smaller but still high for Stockholm, thereby supporting the dominant role of the atmospheric circulation for these stations, found by previous studies, also at decadal timescales. At these scales the role of other factors, such as for instance sea-ice, which in principle should be an important factor for Kronstadt, seems to be minor or already statistically embedded in the SLP field. The good agreement between observations and reconstructions regardless of the choice of calibration and validation periods, either 1800–1899 (for some stations, a somewhat later start) or 1900–1999, indicates that the quality of the sea level observations in Kronstadt and Stockholm and of the SLP reconstructions is also good, as the SLP reconstructions did not make use of any sea level information and were not even aimed at the Baltic Sea area in particular.

For the southern Baltic stations the skill of SLP at decadal timescales is lower than for Kronstadt and Stockholm, a feature already recognized for interannual timescales by previous studies that indicated a low correlation between the NAO and sea level in the Southern Baltic Sea. For these stations, area-averaged winter precipitation shows a larger skill than SLP in describing decadal sea level variations. However, precipitation is not the sole factor that can explain sea level variations in these stations. On the one hand, its skill measured by the Reduction of Error statistics, which is sensitive to long-term differences of the mean value between the calibration and validation periods, remain unsatisfactory, indicating that another underlying factor is playing a role for slow variations in this region. An alternative explanation, for instance that the linear detrending of the original sea level data to substract the eustatic contribution is a too simplistic approach, seems unlikely as in these stations this eustatic contribution is clearly smaller than in Stockholm.

The mechanism by which precipitation may be affecting sea level more strongly in the southern stations remains unclear. At decadal timescales, changes in the water balance brought about by changes in area average precipitation are affecting all stations in roughly the same manner (provided the mean water circulation is not affected by the additional fresh-water inflow). However, the effect of the wind forcing on sea level is clearly much stronger in Kronstadt and in Stockholm, so that perhaps changes in the overall water balance of the Baltic may be only detected in areas where the effect of the wind is small enough. This explanation, however, remains problematic, as, at decadal timescales, any changes in the water inflow should be equilibrated by corresponding changes in the outflow.

Decadal changes in the spatial distribution of salinity in periods with high or low average precipitation could in principle affect sea level, as, although the total volume on the Baltic may remain constant at these timescales, salinity affects the water density. Unfortunately, long time-series of salinity, even for the surface, spanning the whole 20th century are scarce and their quality for their earlier periods is questionable. From the modelling study of Meier and Kauker (2003), the volume-average salinity in the Baltic Basin is 7.4‰, with decadal variations of the order of 1‰. Thereby, half of the decadal variability of average salinity is caused by the decadal variations in the accumulated freshwater inflow (Meier and Kauker, 2003). Considering as a rough estimate a mean depth of the Baltic Sea of 200 m, and assuming that the salinity in the North Sea remains constant, these decadal salinity variations would be linked to variations of average sea level of 20 cm, which is the right order of magnitude. Therefore, in areas where sea level is not so strongly affected by the wind forcing, as in the Southern Baltic, the effect of salinity could in theory explain a non-negligible part of the decadal variations of sea level. Nevertheless, a reasonable explanation could also be that sea level changes are caused by changes in the currents brought about by local salinity changes. Probably the best way to disentangle this question is by analysing simulations of the Baltic Sea, driven by observed forcings in the 20th century, as all these mechanisms should be well represented, with only minor uncertainties, in the Baltic Sea ocean models (Meier, 2006).

Finally, an alternative explanation for the behaviour in the southern stations may be unresolved problems with data quality. An additional advantage of the modelling approach is that data-quality issues in the southern stations could be better assessed than with the statistical analysis alone. If modelling results and observations clearly disagree in this region, the joint analysis of both data sets may offer some clues (periods, magnitude and timescales of disagreement) about possible observational errors.

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