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Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century

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ABSTRACT

It is known that interannual Baltic Sea level variations in the 20th century can be partially, but not totally, explained by the wind forcing linked to the North Atlantic Oscillation (NAO) and other atmospheric circulation patterns. Using regression analysis linking sea level variations (as predictand) and sea level pressure (SLP), precipitation and air temperature (included stepwise as predictors) it is investigated to what extent precipitation and temperature variations can also contribute to explain Baltic sea level variability, in addition to SLP. In wintertime, their additional contribution is small compared to that of SLP (of the order of additional 15% of variance), but it is statistically significant and their inclusion as predictors help to explain past deviations in the evolution of sea level, with higher than normal temperatures and precipitation values linked to a positive contribution to sea level anomalies. In summer, temperature and precipitation explain a substantial part of the sea level variability except in the Kattegat region. In summer positive 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 temperature and rainfall. For some stations, temperature and precipitation can explain, in addition to the variance explained by SLP alone, 35% of the total variability. Since part of influence of temperature and precipitation might be already contained in SLP, this value represents a lower limit for the influence of these additional factors on sea level variability. However, recent trends of winter sea level in the last 20 yr cannot be described by a linear model with any of the predictors used in this study.

1. Introduction

One of the major concerns associated with expected global climate changes are future sea level variations (IPCC, 2001), since they may have a strong impact on coastal ecosystems and human societies. Future changes of sea level on a global scale are believed to be brought about mainly by warming, and the corresponding expansion of the water column and, on somewhat longer time-scales, by melting of the Greenland ice sheet and land glaciers. The projections for future sea level rise based on thermal expansion of the water column simulated by different coupled ocean–atmosphere models, together with estimations of Greenland ice-sheet melting and land-glacier melting, lie within the range of 11–77 cm (IPCC, 2001). On the other hand, at regional scale the projections derived from these models may differ substantially, as at these scales sea level rise is determined largely by the heat up-take by the ocean, changes in salinity and changes in wind driven ocean circulation. On regional scales, like coastal seas with complex boundary lines such as the Baltic Sea, other additional climatic factors may contribute to a further modulation of the climate signal on regional sea level change in the future. Therefore, a detailed understanding of the physical factors that contribute to the observed variability of sea level is necessary for a complete assessment of possible future sea level changes. Since the relevant time-scales for anthropogenic climate change are decadal and longer, such an analysis should extend beyond the short time-scales of interannual variations.

Baltic Sea level variations at interannual to decadal time-scales are generally believed to be caused essentially by variations in wind forcing, in particular (although not exclusive) by the North Atlantic Oscillation (NAO), the sea level pressure (SLP) sea-saw that pervades the interannual climate variability in the North Atlantic–European sector. Numerous of previous studies investigated this link so far, either through the analysis of observational data (e.g. Heyen et al., 1996; Johansson et al., 2001; Andersson, 2002; Omstedt et al., 2004; Yan et al., 2004; Jevrejeva et al., 2005) or output of model simulations (e.g. Samuelsson and Stigebrandt, 1996; Meier et al., 2004).

Most of these studies focused on limited regions of the Baltic Sea. For instance Ekman (2003 and references therein) and Andersson (2002) based their studies on the 200-year long

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Stockholm sea level record, pointing out that the winter climate, in particular wind, plays the central role for the Baltic Sea level variations. Omstedt et al. (2004) used the Stockholm sea level data set to investigate the climate variations and trends of relevant Baltic Sea time-series on different time-scales. Their result support the hypothesis that the long-term climate change is mostly related to changes in the atmospheric circulation. Johansson et al. (2001) studied the trends in sea level variability in the northern Baltic Sea (Finnish Coast) over the past 100 yr and could confirm a significant link with the NAO air-pressure index in all the observed 13 stations.

On the other hand, Heyen et al. (1996) adopted a larger-scale perspective and used a multivariate statistical technique, canonical correlation analysis, to identify the atmospheric patterns responsible for variations in the modes of sea level variability, finding a strong connection between the anomalies of large-scale sea level air pressure and the sea level variability patterns in winter. Although they investigated the role of precipitation, they found no statistical link between these variable and leading spatial modes of sea level variations.

As pointed out, the role of the NAO is prevalent at interannual time-scales in the winter half year, but the influence of the NAO, as measured by a linear correlation coefficient, is not so strong in other seasons. Also, the correlation between the NAO and Baltic Sea level, even in wintertime, has not been constant over time and has undergone considerable decadal variations in the last two centuries (Andersson, 2002; Jevrejeva et al., 2005). Additionally, there exist regional differences in the spatial correlation between the NAO index and the Baltic Sea level (as illustrated later in this study). This varying strength of the NAO influence indicates that, superimposed on the NAO, other climate factors may be also modulating sea level variations. The interest in identifying the role of these other factors lies in their possible influence within a future climate change. Although their influence within the present climate may be smaller than that of the NAO, large temperature or precipitation changes in the future may impinge a stronger fingerprint on Baltic Sea level changes.

In this paper we set out to investigate the influence of these other possible climate forcing on sea level variations in the Baltic Sea by the analysis of the observational record. We focus on temperature and precipitation as the components with the highest data availability, assuming that they include – due to their relation to other water balance components like river run-off – a high amount of climate information. Due to lack of data, we do not consider in our analysis other factors that may be physically relevant (e.g. evaporation), but we keep in mind the need to include these factors in analysis of regional climate simulations of sea level.

One major problem in this endeavour is that in the present climate record the influence of these factors may be small in comparison with the influence of the NAO and other atmospheric modes. Another serious hurdle is that the NAO is also strongly correlated with these other forcings (e.g. winter temperature or rainfall) (Hurrell, 1995), so that statistically it is difficult to disentangle their influence from that of the wind forcing associated with the NAO. The final goal in this study cannot be, therefore, the exact quantification of their influence (since part of it is already contained in the NAO indices and other atmospheric circulation modes) but to estimate their possible additional contribution, i.e. non-related to the NAO or to the SLP field in general. This additional influence would set a lower limit for their real influence on sea level variations. A quantitative separation of the different contributions to sea level variations, and the estimation of their possible non-linear interaction, can only be reached by numerical experiments with a realistic Baltic Sea ocean model, in which the variations of several forcing factors can be artificially suppressed.

The strategy in this study is the application of statistical regression models, in which Baltic Sea level is the predictand, and SLP (as indicator of the geostrophic wind and therefore primary forcing of sea level variations), precipitation and temperature are the predictors. Time-series of SLP, air temperature and rainfall have a good coverage in the 20th century in the North Atlantic–European sector, allowing for a robust statistical analysis. This cannot be accomplished with wind time-series. The analysis starts with SLP as single predictor, thus yielding an estimation of its total skill in driving sea level variations, and subsequently including step-wise the other two factors, thereby estimating the improvement in predictive skill. By analysing individual gauge stations separately possible regional differences are taken into account.

In this analysis we focus on the summer (June–August) and winter (December–February) seasons.

2. Data sets

Seasonal means of the following data sets were used.

2.1. Baltic Sea level data

We used data from 30 tide gauge stations in the Baltic Sea region (Fig. 1) from the Permanent Service for Mean Sea Level. From this data set, the Revised Local Reverence (RLR) variant was used in the period 1900–1998. The selection of stations was based on the data availability, requiring that at least 75% of the months during the winter season (December–January–February) were covered.

The observation records contain a trend which is caused by postglacial land uplift and eustatic sea level change. At the time-scales of our analysis (100 yr) this trend can be assumed to be linear. To eliminate this influence we subtracted the long-term linear trend from all time-series. Only seasonal means were considered. In case of longer time-scales (e.g. 200 yr and longer) a more sophisticated filtering of postglacial rebound based on evaluation of a geological model would become necessary (Peltier, 1998).

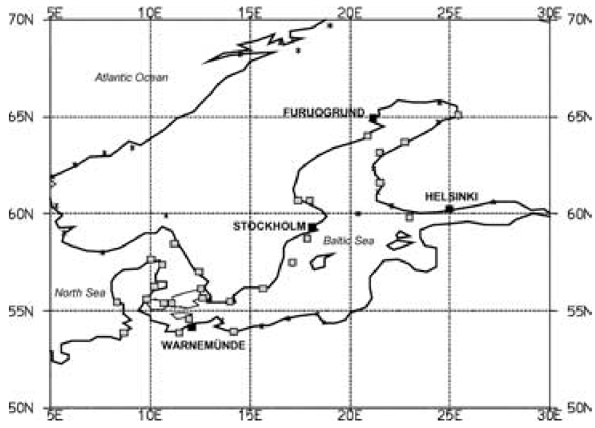

Fig. 1. The location of the sea level gauges.

2.2. *Climatic data sets*

The following climatic data sets were used in this analysis:

- gridded (5° latitude–longitude) North Hemisphere monthly mean SLP from the National Centre for Atmospheric Research (NCAR; Trenberth and Paolino, 1980) in the geographical window 70°W–40°E and 15°N–85°N,
- gridded (2.5° × 3.75° latitude–longitude) monthly precipitation totals from the Climate Research Unit (CRU) (Hulme et al., 1998) in the geographical window 11.25°E–26.25°E and 52.5°N–62.5°N,
- gridded (5° latitude–longitude) monthly means of near-surface air temperature (Jones and Moberg, 2003) in the geographical window 10°E–30°E and 50°N–65°N and
- monthly values of sea level air pressure data from south-west Iceland and Gibraltar (Jones et al., 1997), obtained from the website of the CRU, Norwich.

The period of analysis usually extended from 1900 to 1998, except when precipitation was included in the analyses. In this case, due to the limitation of the precipitation data set, the analysis was limited to 1900–1996.

Furthermore, for some tests, we used monthly water temperature at different depths for 23 Baltic Sea locations, obtained from the Swedish Meteorological and Hydrological Institute and reporting between 1960 and 1996 (Zorita and Laine, 2000).

3. Relationship between Baltic Sea level and SLP

As stated before, a number of studies have established the link between atmospheric circulation and Baltic Sea level variations at interannual time-scales, especially in wintertime. As a recapitulation of the results obtained in these studies, Fig. 2 shows the correlation pattern between the NAO index (from CRU) and sea level variations in the period 1900–1998 for the winter (DJF) and summer (JJA) season. The correlations range between 0.1 and 0.8, but they are predominately weaker in summer (0.2–0.5) than in winter (0.1–0.8) and weaker for the southern Baltic Sea.

The relationship between NAO and Baltic Sea level has also undergone strong variations in time. Figure 3 depicts the correlation coefficient between this winter NAO index and winter sea level in four Baltic Sea stations (Stockholm, Furuogrund, Helsinki and Warnemünde) in 21-year moving windows. It is shown that there exist strong decadal variations in correlations between the NAO and sea level. The correlations may get 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.

As some authors have used other definitions of winter months to calculate these correlations, for the sake of comparison we also carried out a similar analysis using the winter mean sea level for

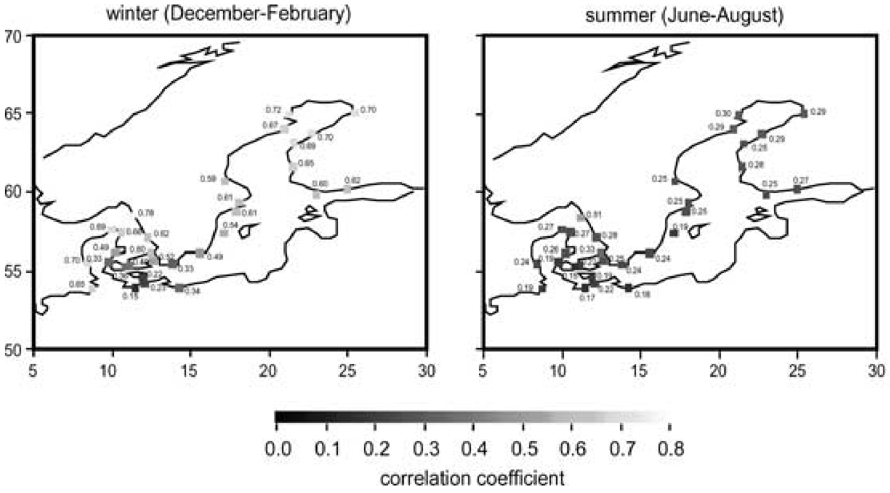

Fig. 2. Correlation between the seasonal means of the NAO index and seasonal mean (linearly detrended) Baltic Sea level, 1900–1998.

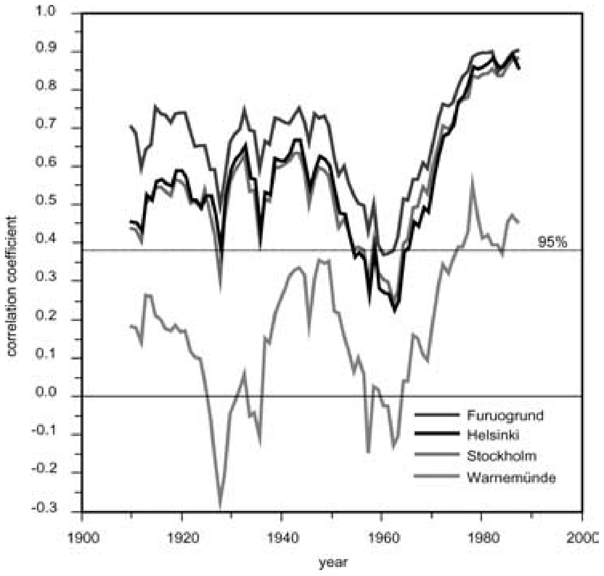

Fig. 3. Moving correlation (21-year window) between winter (DJF) mean Baltic Sea level and the winter NAO index for four selected stations, 1900–1998. The two-sided 95% significance level is indicated.

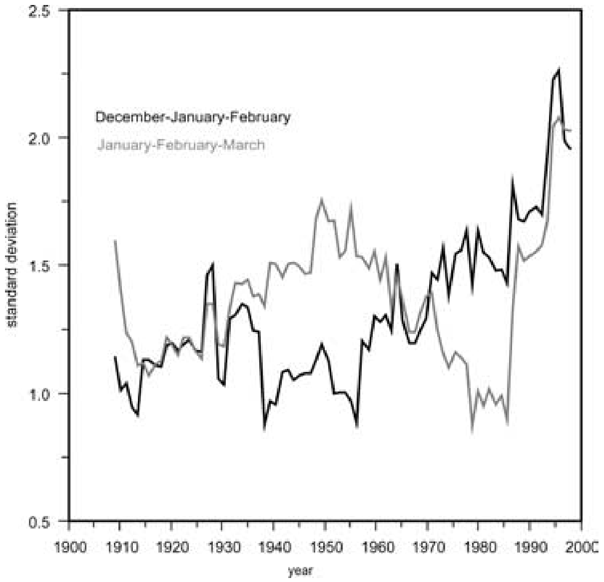

Fig. 4. Comparison between the moving standard deviations (21-year window) of two different winter mean NAO indices, December–February and January–March.

the month January, February and March, which shows, on average, a 0.3–0.4 higher correlation than in December–February (not shown). Noteworthy is the fact that all correlations tend to increase around 1965, up to a correlation coefficient of 0.9 (see also Andersson, 2002). This would be consistent with a stronger variability of the NAO in recent decades, measured by the standard deviation of the NAO index in 21-year moving windows (Fig. 4). As the variations of the NAO index have become larger, the NAO influence, all other factors remaining equal, is probably larger, thereby increasing the correlations between sea level and NAO index.

The physical link between the NAO index and sea level variations in the Baltic Sea is further illustrated in Fig. 5: This figure shows the correlation pattern between sea level, again exemplary for the four stations, and the SLP field in the North Atlantic sector in wintertime. The SLP pattern closely resembles the NAO pattern, albeit with some variations among the sea level stations. The correlation pattern is again weaker for Warnemünde. The generally accepted interpretation of this correlation pattern is that stronger westerly winds are causally linked to higher than normal sea level in all the Baltic Sea.

In the following regression analysis we focus in more detail on these four stations that should be representative of the behaviour of Baltic Sea level: Furuogrund (north), Stockholm (west), Helsinki (east) and Warnemünde (south).

4. Statistical regression analysis

4.1. Winter season

To estimate the amount of variability in sea level which can be explained by the atmospheric circulation (and not only by the NAO) a simple linear regression model between sea level and the time-series of the leading Principal Components (PCs) of the SLP field in the North Atlantic–West European sector has been set up for each station. The period 1960–1998 was used as calibration of these statistical models and the period 1900–1959 was reserved for their validation. The number of leading PCs used in the regression model was set by maximizing the amount of interannual explained variance in the validation. This was done to take into account all possible relevant predictors, but the calculation of the PCs and the estimation of the values of the regression parameters were always strictly performed in the calibration period. The number of PCs varied between 3 and 5.

$$\mathrm{SL}(t) = \sum_{k=1}^{N^{\mathrm{S}}_{\mathrm{eof}}} a_k^{\mathrm{S}} \mathrm{pc}_k^{\mathrm{S}}(t) + \mathrm{SLR}^{\mathrm{S}}(t), \tag{1}$$

where $\mathrm{pc}_k^{\mathrm{S}}(t)$ are the time-series of the kth PC and a_k^{S} are the regression coefficients of the leading $N^{\mathrm{S}}_{\mathrm{eof}}$, whereby the super index S stands for SLP. The first sum in the r.h.s. in eq. (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 eq. (1) is $\mathrm{SLR}^{\mathrm{S}}$, 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 in the period 1960–1998 have been used. Once these coefficients have been estimated by least mean square error, the time-series associated with the leading PCs have been determined for the whole period 1900–1998 by projecting the SLP anomalies (deviations from the 1960–1998 mean) onto the SLP eigenvectors. Equation (1) (without the term SLR) is used to reconstruct the

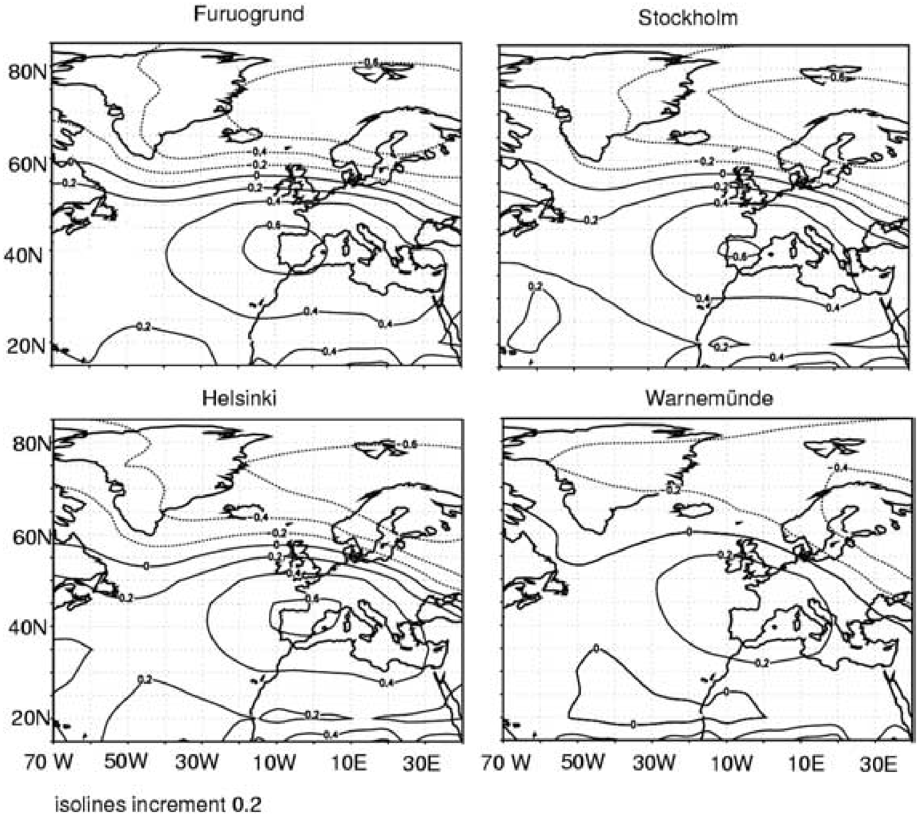

Fig. 5. Correlation patterns between sea level variations in four selected stations in the Baltic Sea and the SLP in winter (December–February), 1900–1998.

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. The results, smoothed with an 11-year running mean, are shown for four stations in Fig. 6 (left column).

For a measure of the variance explained by the model, the reduction of error (RE), sometimes also denoted as the Brier skill score (von Storch and Zwiers, 1999), was used. It is defined as

$$\mathrm{RE} = 1 - \frac{\sum_t (o_t - p_t)^2}{\sum_t o_t^2}, \qquad (2)$$

where o_t is 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 as prediction the value of the mean in the calibration period), and 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. The variances explained by the SLP field in the validation period at decadal time-scales are also indicated in Fig. 6.

The information contained in the SLP is indeed capable of reconstructing much of the past sea level variations, but some clear deficiencies still remain. For instance, in all four stations the SLP field is unable to replicate the sea level broad minimum around 1940 and also underestimates the sea level maximum around 1950. The sea level maxima around 1980 are also missed by the reconstruction, even though they lie within the calibration period. In Furuogrund, the maximum around 1930 cannot be explained by SLP and this is indeed the main reason for the low value of the explained variance compared to Stockholm and Helsinki. Clear limitations in this simple statistical model are especially obvious for Warnemünde, located in the southern Baltic Sea and one of the stations with a weak statistical linkage with the NAO.

Thus, there seems to be a non-negligible amount of sea level variability that cannot be explained linearly from the SLP field, and therefore from geostrophic wind forcing. Can the inclusion of other climate variables in the statistical model lead to an improvement of the explained variance?

To answer this question, the statistical model in eq. (1) was augmented to include winter precipitation as a predictor. This is technically done in the same way as for SLP, namely through

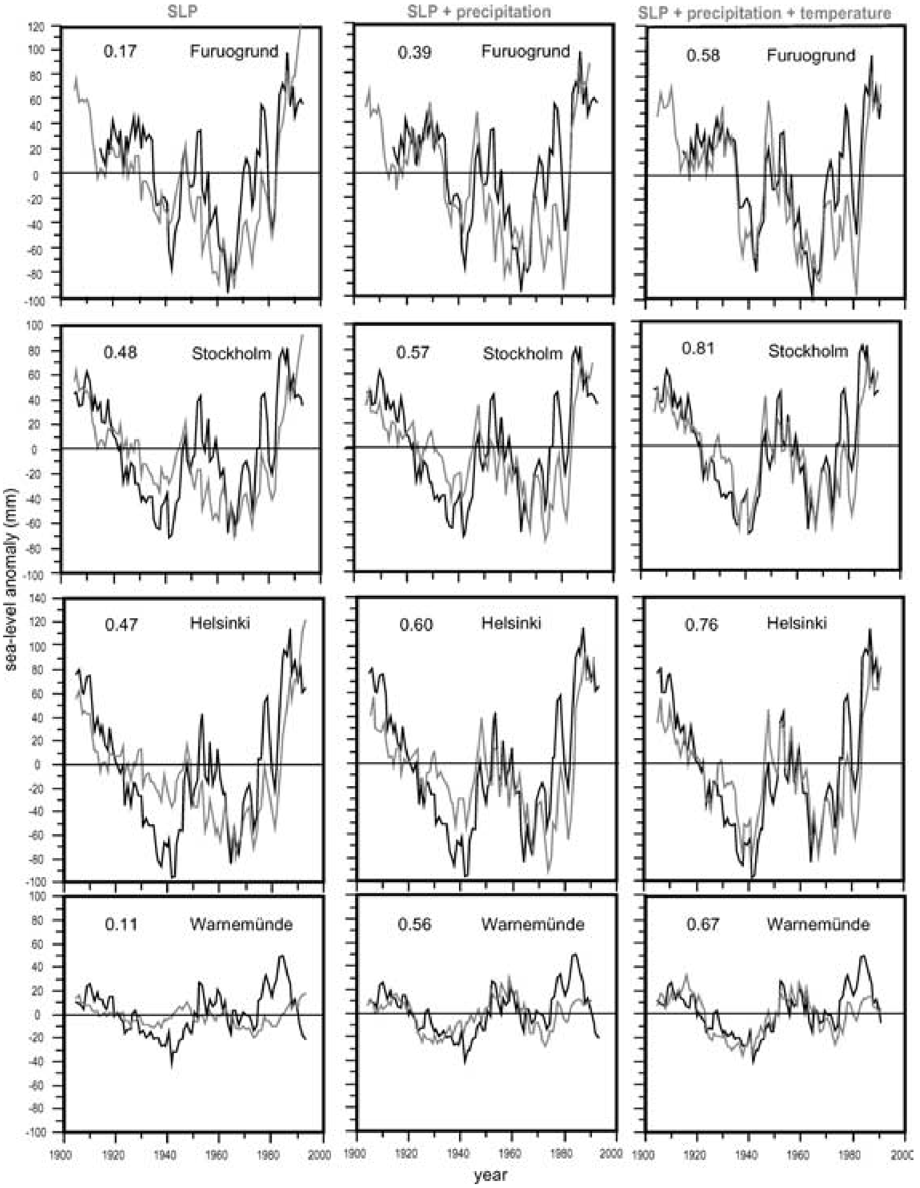

Fig. 6. Winter (December–February) sea level anomalies in four stations in the Baltic Sea (11-year Gaussian mean), observed (black) and reconstructed (grey) from the SLP field (left column), SLP and precipitation (middle column) and SLP, precipitation and temperature (right column). The regression model was calibrated in the period 1960–1990. The number in the left upper corner in each panel indicates the explained variance (Brier Skill Score, see text) in the validation period in the 11-year-mean smoothed time-series. Note the different scales in the *y*-axes.

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, to be sure, already contained in the SLP field since the NAO index is positively correlated with average rainfall in wintertime, perhaps other local processes may cause precipitation variations that are not directly linked to the dynamics implied by the large-scale SLP field. The model in eq. (1) is thus rewritten as

$$\mathrm{SL}(t) = \sum_{k=1}^{N_{\mathrm{eof}}^{\mathrm{S}}} a_k^{\mathrm{S}} \mathrm{pc}_k^{\mathrm{S}}(t) + \sum_{m=1}^{N_{\mathrm{eof}}^{\mathrm{P}}} b_m^{\mathrm{P}} \mathrm{pc}_m^{\mathrm{P}}(t) + \mathrm{SLR}^{\mathrm{SP}}(t), \qquad (3)$$

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 eq. (3) a_k^{S} may now be different as in eq. (1). However, a relevant result of eq. (3) would be if the augmented model could explain additional sea level variability in a validation period, i.e. independent from the calibration. Model 2 is again calibrated for the period 1960–1998 and applied to reconstruct the sea level variations in 1900–1998. Figure 6 (middle column) shows the results of this reconstruction, together with the recalculated explained variances at decadal time-scales in the validation period.

The reconstructions improved, in general, for all four stations. The minimum in 1940 and the maxima around 1950 come closer to the observed values; both lie outside the calibration period and thus the artificial skill is not caused by artificial statistical overfitting. This improvement shows that precipitation, or a variable related to it but not linearly to SLP, is also influencing sea level variations.

As a logical step, the reconstruction model has been further augmented with the inclusion of air temperature as a predictor. The rational here is that air temperature is playing the role of an imperfect surrogate of water temperature and this may influence sea level by the expansion of the water column. Clearly, the statistical reconstructions would have, in principle, more chances to be improved by using water temperatures, not only at the surface but also at various depths.

As a previous step to verify the usability of air-temperature data for our analysis, we calculated lag correlations between winter sea-surface temperature anomalies and mean water temperature anomalies in 20–50-m depth, for 23 Baltic Sea locations, in the period 1960–1996. The correlations tend to be high, with values around 0.9 to 1, which are achieved at lag zero. The 1-month lag correlations were also high and, except for very few exceptions, they were smaller than the simultaneous correlations. On the other hand, the sea surface temperature lags the air temperature by just a few days (Matthäus, 1996), so that it can be assumed that the air temperature can be used in statistical sense as a representative of the temperature of the water column, at least up to intermediate depths. Unfortunately, the water temperature series are not as long as air-temperature time-series, so that they are not as useful in this analysis as air temperature. Furthermore, there is also a tactical reason for using air temperature instead of water temperature as predictor in the statistical model. Such model can be applied to the output of a three-dimensional climate model to estimate future changes in Baltic Sea level. Water temperatures could not be used as predictor, since climate models do not realistically represent the Baltic Sea due to their coarse spatial resolution.

The third statistical regressions model reads

$$\mathrm{SL}(t) = \sum_{k=1}^{N_{\mathrm{eof}}^{\mathrm{S}}} a_k^{\mathrm{S}} \mathrm{pc}_k^{\mathrm{S}}(t) + \sum_{m=1}^{N_{\mathrm{eof}}^{\mathrm{P}}} b_m^{\mathrm{P}} \mathrm{pc}_m^{\mathrm{P}}(t) + \sum_{i=0}^{N_{\mathrm{eof}}^{\mathrm{T}}} c_i^{\mathrm{T}} \mathrm{pc}_i^{\mathrm{T}}(t) + \mathrm{SLR}^{\mathrm{SPT}}(t), \tag{4}$$

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 some of the information conveyed by the temperature field, since in wintertime the NAO is responsible for part of the interannual temperature variability in the Scandinavian region (Hurrell, 1995). However, at longer time-scales, other factors such as variations in external forcing, solar variability and volcanic effects (Stott et al., 2000) or variations in the sea-surface temperature in the North Atlantic linked to the meridional overturning circulation may potentially also relevant.

The sea level reconstructions using SLP, precipitation and air temperature as predictors are shown in Fig. 6 (right column). Again, the reconstructions using air temperature as an additional predictor show some improvements, also in the validation period. The minima around 1940 and maxima around 1950 are almost perfectly replicated in all stations. However, the fit to the observations is still not complete. Ironically, the biggest problem occurs in the calibration period, around 1975, when the match with observations should be theoretically better. Especially disturbing is the mismatch in the last decades of the 20th century in Warnemünde and Furuogrund. Figure 6 (right column) strongly indicates that some other factor remains responsible for much of the upward trend in sea level in the 80s in these stations and the sea level decay thereafter.

Some hints about the physical link between temperature and precipitation and the part of the sea level variations that are not described by SLP, i.e. the residuals in the regression model 1, are given by the correlations between those residuals and both additional predictors. These correlation patterns (Fig. 7) are not the same for all four stations, indicating that indeed the influence of precipitation and/or temperature has some spatial variability.

In the case of precipitation (Fig. 7a), the correlation patterns support the idea that higher rainfall is conductive to higher sea level. This relationship is in general weaker in the northern stations and stronger in Warnemünde. A quantitative estimation of the influence of rainfall is much more difficult due to the role of evaporation and infiltration, which has not been considered here.

Higher temperatures are also linked to higher sea level residuals, suggesting that the mechanism linking both could involve the expansion of the water column (Fig. 7b). Assuming a level of decadal variability of water temperature of 1 K through a layer of about 50 m, the linear sea level increase would be of the order of 10 mm, which agrees with the magnitude of the additional contribution to sea level variations in Fig. 6. However, the relationship may be potentially more complicated, as for instance for Warnemünde, higher sea level residuals are associated with higher temperatures in the southern Baltic and lower temperatures in the northern Baltic.

Figure 8 takes a closer look onto all 30 stations. Figure 8a shows the fraction of interannual variance (not decadal as in Fig. 6) in the validation period (1900–1959) that can be explained by SLP alone and additionally, the stepwise included predictors, temperature and precipitation. To estimate the level of significance of the additional explained variance, the temperature and precipitation PCs were replaced by synthetic Gaussian white noise. The leading seasonal PCs used as predictors were expected to have low autocorrelations from one winter to the following (or from one summer to the following). Therefore, the choice of white, instead of red, noise to estimate the level of

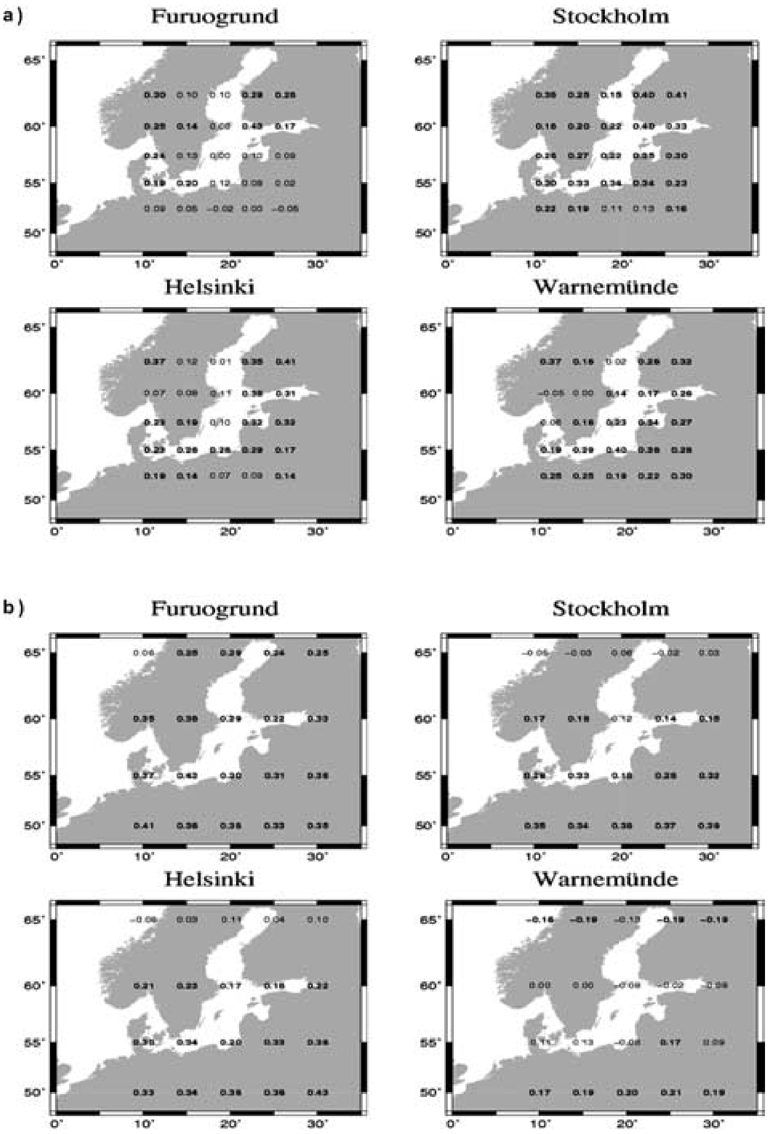

Fig. 7. Correlation patterns between (a) sea level residuals (eq. 1) (part of the sea level not linearly explained by SLP) and precipitation and (b) sea level residuals and temperature in winter, 1900–1996. The 95% significance level is 0.14. Significant values are bold typed.

significance seems justified. To ascertain that this was the case, the 1-year lag autocorrelations of all PCs employed were calculated. The magnitude of all autocorrelations was lower than 0.15 and therefore statistically non-significant at the 95% level, hence justifying the use of red noise in this calculation. In any case, the use of synthetic red-noise with these low autocorrelations changed very slightly the significance levels.

The synthetic explained variances were calculated in 100 realizations with these Monte Carlo predictors and reordered in decreasing values. The 95% significance level for each station was given by the fifth explained variance. Since in reality the distribution characteristics and the spectra of the sea level data change from station to station, the level of significance is also station dependent. Also, the level of significance may be negative, since the mean in the calibration and validation periods in the observations may be different.

Figure 8a shows that the additional influence of temperature and precipitation, albeit small compared to that of SLP, is significant for almost all stations. Geographically, stations located in the Gulf of Bothnia tend to show smaller additional explained variance than those located in the south, as it was already exemplified in Fig. 6, but the case shown there (Warnemünde) is one of the most clear examples. Additionally, temperature seems to be a more important factor in the area close to Stockholm and Hanko in the central part of the Baltic, whereas south of this line precipitation is a more relevant factor. However, the available sea level data set is under-represented in the southeastern Baltic Sea and this description should be completed with a more detailed analysis of this part of the coast.

In summary, both precipitation and temperature contribute to the improvement in the reconstructions of sea level variations, but interestingly their relative contribution is not the same for

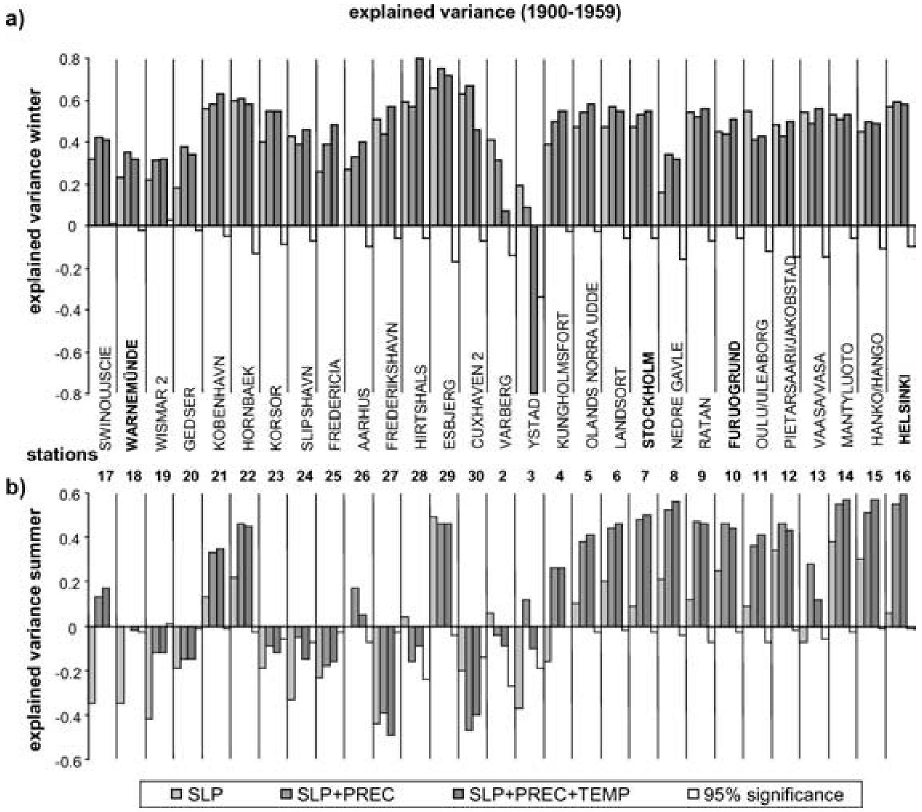

Fig. 8. Fraction of interannual variance (Reduction of Error or Brier Skill Score, see text) in the validation period (1900–1959) in (a) winter and (b) summer that can be explained by SLP, by SLP and the additional predictor precipitation (SLP+PREC) and by SLP, precipitation and air temperature (SLP+PREC+TEMP) 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 ordering of stations is geographically clockwise, starting in the southwest.

all stations. As stated before, the influence of SLP is, in general, less in the southern and high in the northern stations. To test if these conclusions depend on the order in which the predictors (precipitation and temperature) have been included in the model, a similar calculation has been carried out with the ordering of precipitation and temperature interchanged, resulting in very similar results.

4.2. *Summer season*

A parallel analysis of the relationships between sea level, SLP, temperature and precipitation was also carried out for the summer season. The results are briefly described in this section.

The reconstruction of sea level based on the statistical models of eq. (1) (predictor only SLP), eq. (3) (predictor SLP and precipitation) and eq. (4) (SLP, precipitation and temperature) are shown in Fig. 9.

The most important discrepancies between sea level observations and reconstructions from the SLP field alone (Fig. 9, left column) are the minima around 1910 and 1940 and the increasing sea level 1980 onwards, peaking in the early 1990s.

The inclusion of precipitation as predictor considerably improves the reconstruction (Fig. 9, middle column). The minima around 1910, occurring outside the calibration period and therefore again an independent confirmation of the model, are now almost perfectly reproduced in all four stations. Also quite relevant is the match in the last two decades of the 20th century.

The remarkable improvement of the reconstruction model using SLP and precipitation as predictors leaves little room for further improvements when air temperature is included (Fig. 9, right column). Actually, the reconstructions show almost no improvement with respect to the previous case. The explained variances, based on the 11-year Gaussian mean, show even a decrease for Warnemünde, Stockholm and Furuogrund.

The relevance of temperature and precipitation in summer, compared to the winter season, is clearly illustrated in Fig. 8b. The variance additionally explained by these two variables is much more clearly detected for most of the stations in the Baltic Sea. Exceptions are the stations located in the Kattegat region and the southern Baltic, but in general the additional explained variance is larger than the variance explained by the SLP alone. These results justify a further analysis of regression models in which each one of the three predictors is used in isolation (Fig. 10). The

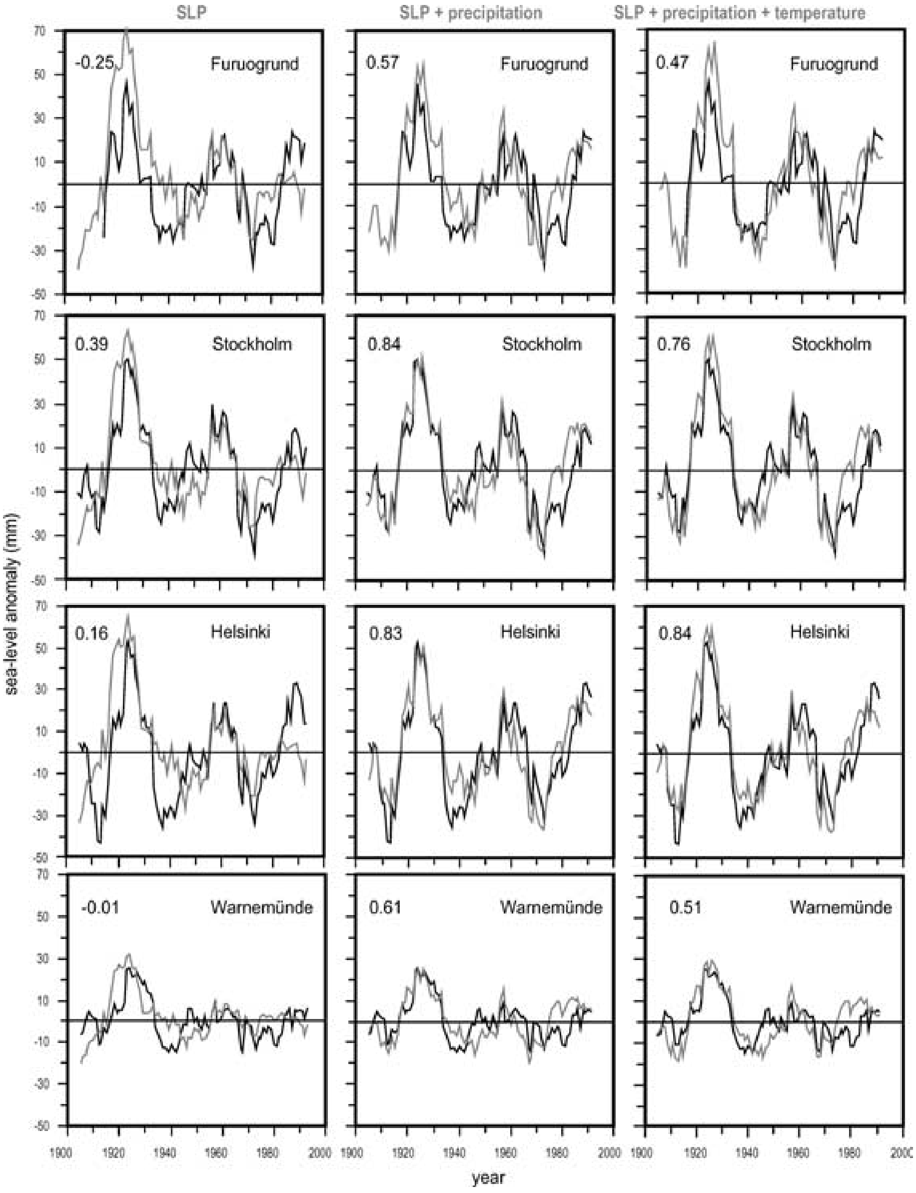

Fig. 9. Summer (June–August) sea level anomalies in four stations in the Baltic Sea (11-year Gaussian mean), observed (black) and reconstructed (grey) from the SLP field (left column), SLP and precipitation (middle column) and SLP, precipitation and temperature (right column). The regression model was calibrated in the period 1960–1990. The number in the left upper corner in each panel indicates the explained variance (Brier Skill Score, see text) in the validation period (11-year Gaussian mean).

variance that can be explained by precipitation or temperature in isolation is often larger than the variance explained by SLP alone, which in some cases, as in the southern Baltic, is even negative. For instance, in these stations the inclusion of SLP as predictor is counter-productive, and precipitation or temperature in isolation produces a model with better skill than with all three predictors.

Figure 10 indicates that precipitation and temperature have similar levels of skill to predict sea level variations, so that the question arise which variable is actually physically connected to sea level variability. Here, statistical analysis can only offer some preliminary clues about the real answer.

The correlation patterns between the sea level and temperature in summer (Fig. 11a) clearly show a sign of the correlation (negative for all four stations) that is not compatible with the hypothetical effect of the water column expansion. Therefore, this link could be, if at all, mediated by other indirect mechanisms. The link to precipitation, on the other hand, is stronger and compatible with the direct influence of rainfall on sea level, as indicated by the correlations between sea level and precipitation

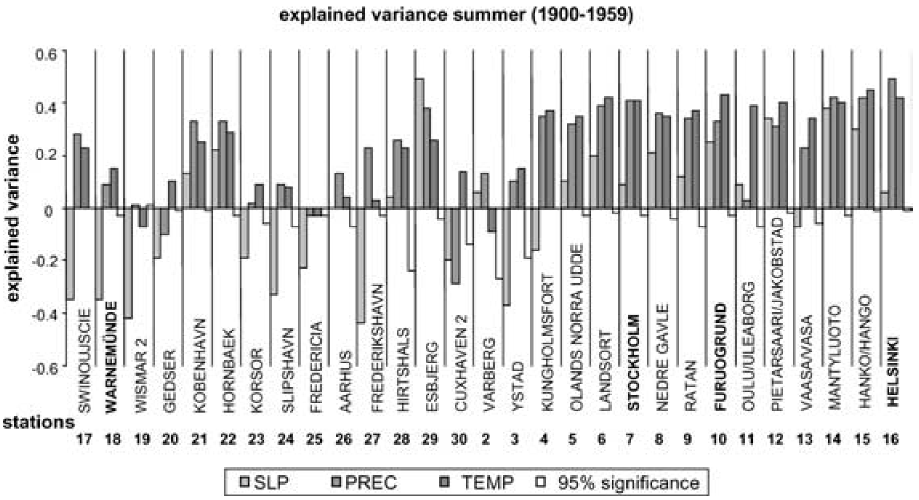

Fig. 10. Fraction of interannual variance of sea level in the validation period (1900–1959) in summer that can be explained by SLP, by precipitation (PREC) and by air temperature (TEMP), each one as isolated predictor. The level of significance has been estimated as in Fig. 8.

(Fig. 11b). This conclusion is also verified if the correlation is calculated between the sea level residuals (of a statistical model with only SLP as predictor) and temperature or precipitation (not shown).

If this interpretation is accepted, the link between temperature and sea level arises artificially, through an indirect correlation to another factor. This factor could be precipitation, as temperature and precipitation in the Baltic Sea region are indeed negatively correlated at interannual and decadal time-scales. The latter relationship is clearly illustrated in Fig. 12.

In summary, although SLP is also able to explain a certain amount of sea level variability in summer, the amount of variance explained by SLP alone is much smaller than in winter. This is consistent with the already known smaller correlation between the NAO and sea level in the summer season.

The influence of precipitation and/or temperature seems to be much more considerable for most stations than in wintertime (except in the Kattegat region). Both variables taken in isolation represent in general a better predictor for sea level than SLP. Which one of these two is the most important factor for sea level variability is difficult to ascertain on statistical grounds alone. However, sea level is positively correlated with precipitation and negatively correlated with temperature, suggesting that the driving role is played by rainfall. Although a statistical analysis alone cannot rule out completely a physical influence of temperature on sea level, a mechanism directly linking negative temperature anomalies with higher sea level in summer is not obvious.

5. Discussion and outlook

A series of simple statistical models linking sea level in the Baltic Sea and SLP, precipitation and air temperature, introduced stepwise as predictors, show that in wintertime precipitation and air temperature contribute to determine an additional part of the part of sea level variability that cannot be linearly explained by SLP (thus by the forcing of the geostrophic wind). In most stations, this additional explaining power of models containing temperature and precipitation as predictors is small (of the order of 15% of the total interannual sea level variance) but it is unlikely to arise by chance, and the inclusion of these predictors helps achieve a better fit to observed sea level variations in a validation period. It should be noted, however, that part of the signal conveyed of the predictor SLP may also contain the possible effect of the other two variables, since in wintertime SLP is strongly positively correlated to temperature and to precipitation anomalies.

The identification of the influence of temperature and precipitation on sea level seems to stand in contradiction to the conclusions obtained by Heyen et al. (1996), who found that precipitation has a little impact on Baltic Sea level variations. They used a statistical method (canonical correlation analysis with previous principal components filtering) that tends to identify the modes of sea level variations that are present in all or a majority of a station network, thereby filtering out the sea level variability that has a more local character. By setting up a linear regression model for each station separately, the statistical model is freed from this constrain and it is reasonable to expect that it can identify weaker signals and signals that are not so coherent spatially.

In the summer season the influence of precipitation and temperature variations on sea level is much stronger than in wintertime and for many stations this influence is stronger than that of the SLP alone. For instance, in Helsinki in summertime, the inclusion of precipitation allows the regression model to explain an additional 35% of the total interannual variance. This may be caused by the smaller variability of the SLP field (and therefore also of the wind) in summer than in winter, thus allowing the

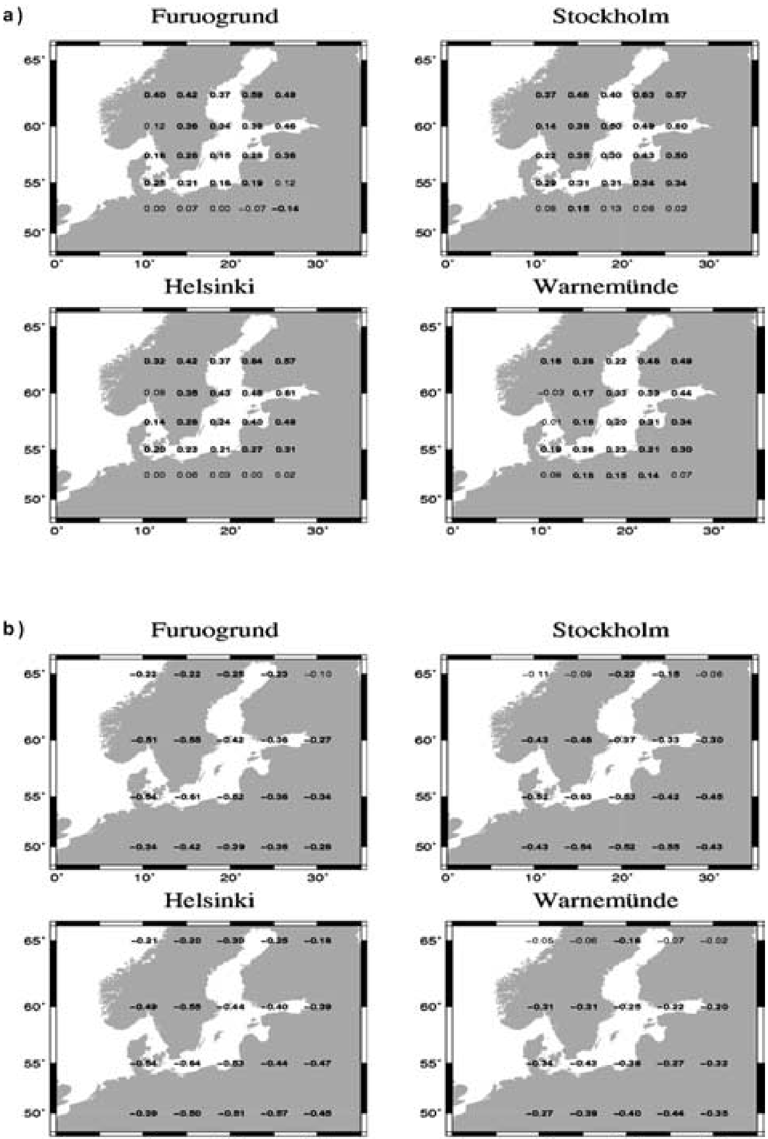

Fig. 11. Correlation patterns between (a) sea level and precipitation and (b) sea level and air temperature in summer, 1900–1996. The 95% significance level is 0.14. Statistically significant correlations are bold typed.

other factors to gain in relative importance. If these results are to be applied for estimations of future sea level changes in the Baltic Sea in a future climate, the observational evidence thus indicates that regional precipitation and temperature changes in summertime have to be taken into account. In this respect it would be important to disentangle the separate effect of temperature and precipitation. In the observational record both variables are negatively correlated. But this relationship may not be extrapolated into the future, since their mean changes will not necessarily be opposite to each other. Therefore, it seems desirable to achieve a quantification of their effect in the past century, possibly by modelling studies.

A simple reasoning indicates that temperature is unlikely to be a driving factor of sea level variations in summer, since in general it is negatively correlated to sea level. This can be speculatively explained by the fact that in summer the stratification of the Baltic Sea hinders the spread of heat-flux into the water column, and therefore the effect of water expansion remains constrained to a relatively shallow layer.

The geographical distribution of the additionally explained variance tends to be larger in the southern stations, both in winter and in summer; although in summer this additional variance is spatially distributed in a slightly more homogeneous 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 (Fig. 2).

The results presented here, therefore, indicate that additional forcing factors cannot be neglected and need to be, at least in principle, taken into account in the estimation of future, and also

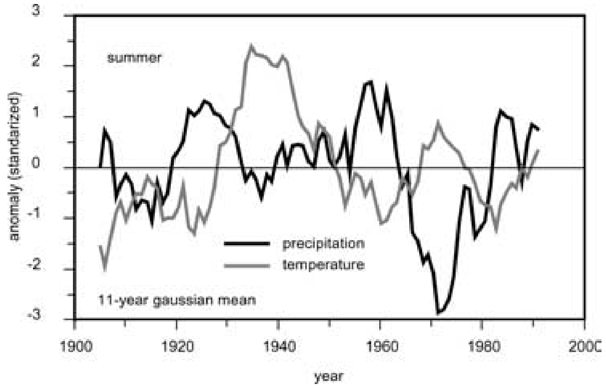

Fig. 12. Summer mean temperature and precipitation anomalies in the Baltic Sea region (see Section 2.2 for details), smoothed with an 11-year Gaussian mean filter, and standardized to unit standard deviation.

of past, sea level variations. The statistical reconstruction model using all three variables constitutes a transfer function between a large-scale climate field and a local climate variable, such as sea level. In this sense, this transfer function can be applied to the output of an atmosphere–ocean climate model, such as those used in the prediction of the effects of anthropogenic greenhouse forcing in the 21st century. Numerical simulations with a Baltic Sea ocean model driven by future climate scenarios also constitute a much more complicated transfer function for the estimation of future changes in the Baltic Sea (Meier et al., 2004). The output of the global climate models could indicate that changes in air temperature in the Baltic Sea area may be as large as to overcome the expected changes in the NAO in a future climate, and thus become a dominant factor in determining future sea level trends in the Baltic Sea. This will be investigated in forthcoming studies.

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References

Andersson, H. C. 2002. Influence of long-term regional and large-scale atmospheric circulation on the Baltic Sea level. *Tellus* **54A**, 76–88.

Ekman, M. 2003. The World´s longest sea level series and a Winter Oscillation Index for Northern Europe 1774–2000. *Small Publ. Hist. Geophys.* **12**, 30 pp.

Heyen, H., Zorita, E. and von Storch, H. 1996. Statistical downscaling of monthly mean North Atlantic air-pressure to sea level anomalies in the Baltic Sea. *Tellus* **48A**, 312–323.

Hulme, M., Osborn, T. J. and Johns, T. C. 1998. Precipitation sensitivity to global warming: Comparison of observations with HadCM2 simulations. *Geophys. Res. Lett.* **25**, 3379–3382.

Hurrell, J. W. 1995. Decadal trends in the North Atlantic Oscillation: Regional temperatures and precipitation. *Science* **269**, 676–679.

IPCC 2001. Summary for policymakers. A report of working group I to the intergovernmental panel on climate change. *IPCC*, 20 pp.

Jevrejeva, S., Moore, J. C., Woodworth, P. L. and Grinsted, A. 2005. Influence of large-scale atmospheric circulation on European sea level: Results based on the wavelet transform method. *Tellus* **57A**, 183–193.

Johansson, M., Boman, H., Kahma, K. K. and Launiainen, J. 2001. Trends in sea level variability in the Baltic Sea. *Boreal Environ. Res.* **6**, 1959–1979.

Jones, P. D. and Moberg, A. 2003. Hemispheric and large-scale surface air temperature variations: An extensive revision and an update to 2001. *J. Climate* **16**, 206–223.

Jones, P. D., Jonsson, T. and Wheeler, D. 1997. Extension of the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *Int. J. Climatol.* **17**, 1433–1450.

Matthäus, W. 1996. Ozeanographische Besonderheiten. In: *Warnsignale aus der Ostsee* (eds.J. L. Lozan, R. Lampe, W. Matthäus, E. Rachor, H. Rumohr and H. von Westernhagen). Parey, Berlin, 17–24.

Meier, H. E. M., Broman, B. and Kjellström, E. 2004. Simulated sea level in past and future climates of the Baltic Sea. *Climate Res.* **27**, 59–75.

Omstedt, A., Pettersen, C., Rohde, J. and Winsor, P. 2004. Baltic Sea climate: 200 yr of data on air temperature, sea level variation, ice cover, and atmospheric circulation. *Climate Res.* **25**, 205–216.

Peltier, W. R. 1998. Postglacial variations in the level of the sea: Implications for climate dynamics and solid-earth geophysics. *Rev. Geophys.* **36**, 603–689.

Samuelsson, M. and Stigebrandt, A. 1996. Main characteristics of the long-term sea level variability in the Baltic Sea. *Tellus* **48A**, 673–683.

Stott, P. A., Tett, S. F. B., Jones, G. S., Allen, M. R., Mitchell, J. F. B. and co-authors. 2000. External control of 20th century temperature by natural and anthropogenic forcings. *Science* **290**, 2133–2137.

von Storch, H. and Zwiers, F. W. 1999. *Statistical Analysis in Climate Research*. Cambridge University Press, Cambridge, UK.

Trenberth, K. E. and Paolino, D. A. Jr 1980. The northern hemisphere SLP-dataset: Trends, errors and discontinuities. *Mon. Weather Rev.* **108**, 855–872.

Yan, Z., Tsimplis, M. and Woolf, D. 2004. Analysis of the relationship between the North Atlantic Oscillation and sea level changes in the northwest Europe. *Int. J. Climatol.* **24**, 743–758.

Zorita, E. and Laine, A. 2000. Dependence of salinity and oxygen concentrations in the Baltic Sea on the large-scale atmospheric circulation. *Climate Res.* **14**, 25–41.