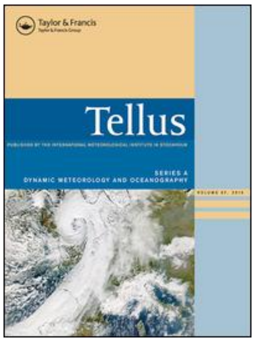

Tellus A: Dynamic Meteorology and Oceanography

ISSN: (Print) 1600-0870 (Online) Journal homepage: https://www.tandfonline.com/loi/zela20

Trends in the amplitude of Baltic Sea level annual cycle

Birgit HÜnicke & Eduardo Zorita

To cite this article: Birgit HÜnicke & Eduardo Zorita (2008) Trends in the amplitude of Baltic Sea level annual cycle, Tellus A: Dynamic Meteorology and Oceanography, 60:1, 154-164, DOI: 10.1111/j.1600-0870.2007.00277.x

To link to this article: https://doi.org/10.1111/j.1600-0870.2007.00277.x

Tellus (2008), 60A, 154–164
Printed in Singapore. All rights reserved

TELLUS

Trends in the amplitude of Baltic Sea level annual cycle

By BIRGIT HÜNICKE[1,2]* and EDUARDO ZORITA, [1]*Institute for Coastal Research, GKSS Research Centre, Max-Planck-Str.1, 21502 Geesthacht, Germany;* [2]*International Max Planck Research School on Earth System Modelling, Hamburg, Germany*

(Manuscript received 9 July 2007; in final form 23 August 2007)

ABSTRACT

Baltic Sea tide gauge data and climatic data sets are statistically analysed to investigate the centennial trends in the amplitude of the annual cycle of Baltic sea level. In almost all gauge stations analysed, an increase of the amplitude (winter–spring sea level) is detected. These trends are not large compared to the decadal variations of the annual cycle, but they are statistically significant. The magnitude of the trends is almost spatially uniform, with exception of the Skagerrak area. Since interannual and decadal variability of sea level displays a clear spatial pattern, the mechanism responsible for the trends in the annual cycle seem to be not regional, but affect the Baltic Sea basin as a whole.

Several hypotheses are proposed to explain these centennial trends on the winter-minus-spring sea level: wind (through the SLP field), the barometric effect, temperature and precipitation. By elimination of three of the working hypothesis, seasonal Baltic precipitation remains a plausible candidate. For the other three, either the sign or magnitude of the trend makes them unlikely the sole explanation.

1. Introduction

According to simulations with global climate models, anthropogenic climate change in the next decades will be likely associated with a general increase of sea level. Most estimations of global sea level rise in the 21st century, due to the thermal expansion, melting of land glaciers and of the Greenland ice-sheet lie within the range of 18–59 cm (IPCC, 2007). The observed long-term global sea level rise in the 20th century has been estimated in the range of 1–2 mm yr^{-1}, but this figure conceals large regional variations due to a number of different processes that may also give rise to long-term trends in regional sea level. In the open ocean the penetration of heat into the deeper layers depends on the mean ocean circulation and on the processes of deep water formation. In coastal regions and semi-enclosed seas atmospheric circulation patterns, rainfall, sea-ice and other causes may result in deviations from the global sea level trends. For instance, sea level in the Mediterranean shows a negative-trend in the last decades, possibly due to trends in the intensity of atmospheric sea level pressure (SLP) patterns, such as the North Atlantic Oscillation (NAO) (Yan et al., 2004). These regional processes may continue to be active in the next decades, so that an understanding of the regional sea level variations at decadal, multidecadal and centennial timescales is relevant for more accurate predictions of regional sea level trends.

The Baltic Sea is one of the regions were multiple factors are likely to contribute to long-term sea level trends. The isostatic adjustment from the melting of the Scandinavian ice-sheet in the early Holocene causes a current negative sea level trend in the northern Baltic coast. Furthermore, 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. Focusing on the Baltic Sea, the influence on sea level by factors external to the Baltic Sea may even be strongly station-dependent. Jevrejeva et al. (2005) found the NAO exerts a strong influence on winter sea level variability at interannual timescales in the central and northern gauge stations, but that this influence is much weaker in the southern Baltic Sea. Therefore, trends in the NAO index, as envisaged in many global climate models (Stephenson et al., 2006) could induce differences in the spatial pattern of sea level rise in the Baltic.

In a recent study, Hünicke and Zorita (2006) put forward an estimation of the relative importance of temperature and precipitation in modulating long-term (decadal) variations of Baltic Sea level in the past century, by analysing time series of sea level-temperature, precipitation and sea level-pressure. The main result of that study suggested that sea level variations in winter and summer are influenced by quite different factors and thus its evolution in a future climate may be also potentially different. In

---

*Corresponding author.
e-mail: birgit.huenicke@gkss.de

DOI: 10.1111/j.1600-0870.2007.00277.x

winter, the widely held view that Baltic sea level variations are indeed mostly modulated by the westerly winds, possibly with additional smaller contributions from temperature (via expansion of the water column) and precipitation (through increased fresh water run-off into the Baltic Sea) was confirmed. However, precipitation seemed to be an important factor for sea level variations in summer.

The question arises as to whether the results of this analysis conducted for interannual timescales, can be extrapolated to longer timescales and therefore become relevant in the context of future anthropogenic climate change. Chen and Omstedt (2005) studied the long-term record of sea level in Stockholm in the period 1873–1995 and found that the long-term trend, once the isostatic adjustment has been removed from the record, depends on the season. They concluded that all months in the calendar year, except June and August, display a positive sea level trend, whereas June and August show a negative trend that they interpret, for the latter month, as due to a negative long-term trend in Baltic precipitation. These authors warn, however, that a detailed analysis of the hydrological budget may be necessary to ascertain this conclusion. They also found that the link between trends in air temperature and the positive trends in sea level for some months of the calendar year may be suggestive, but difficult to prove. For Stockholm, different processes seem, therefore, to be responsible for the different trends through the calendar year. The question arises whether these processes may possibly react differently to regional climate changes brought about by an increase in atmospheric greenhouse trace gases, thus giving rise to different seasonal long trends in Baltic sea level.

Baltic sea level shows a mean annual cycle that usually peaks in the winter months and attains its minimum in early spring. The annual cycle amplitude in sea level has been found to have increased in the 20th century in the North Sea and Baltic Sea (Plag and Tsimplis, 1999), especially in the last decades, a result that coincides with the analysis of Ekman and Stiegebrandt (1990) for Stockholm. This increase is, however, superimposed upon large decadal variations, which these authors interpret in general as a result of decadal variations in the strength of the atmospheric circulation and the resulting changes in wind-stress. As the annual cycle has underdone the strongest variations in the last decades of the 20th century Plag and Tsimplis (1999) raise the question of the influence of anthropogenic climate forcing. However, the response of the atmospheric circulation, and in particular, of the NAO to anthropogenic greenhouse forcing, is still much debated (Stephenson et al., 2006).

The focus of this study lies on the investigation of the centennial trends in the amplitude of the annual cycle of Baltic sea level and their possible physical origins. Section 2 presents the data (observational records) used in this study. Section 3 examines the existing trends in the amplitude (winter–spring sea level) of the annual cycle of Baltic Sea level and their statistical significance by using different trend estimators and significance tests (parametric and non-parametric). In Section 4, possible causes for the trend in the amplitude are investigated by statistically analysing several hypothetical factors: the wind stress forcing (closely associated with the NAO, but also other SLP patterns), the pressure difference between the Baltic Sea and the North Atlantic Region (due to the barometric effect), the temperature (due to thermal expansion through the water column) and precipitation (including a discussion of the role of fresh water balance and salinity). Section 5 presents a discussion of the results and some conclusions.

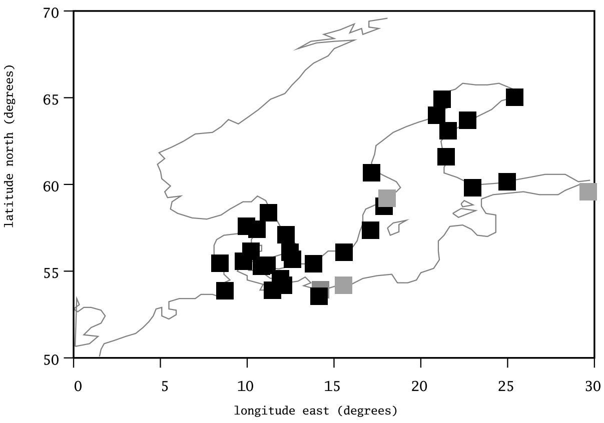

Fig. 1. Sketch of the Baltic Sea, showing the location of the sea level gauges. (The grey squares indicating the four longest available sea level records.)

2. Data sets

2.1. Baltic Sea level observations

For analyses in the 20th century we used data from 30 Baltic Sea tide gauge stations from the Revised Local Reference (RLR) dataset of the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003). For some of the analysis back to 1800, the four longest sea level records from stations situated along the Baltic Coast, Kolobrzeg (from 1815 to 1999; PSMSL, before 1951 provided by Technische Universität Dresden), Swinoujscie (from 1815 to 1997; PSMSL), Stockholm (from 1801 to 2000; Ekman, 2003) and Kronstadt (from 1840 to 1993; Bogdanov et al., 2000) were selected (Fig. 1). Missing values in two of the time series (Kolobrzeg from 1940 to 1950; Swinoujscie from 1945 to 1950) were not filled-in.

2.2. Climatic data sets

The following gridded climatic data sets were used:

1. 5° × 5° monthly mean sea level-pressure (SLP) from the National Centre for Atmospheric Research (NCAR, Trenberth and Paolino, 1980) for the region 70W–40E and 15N–85N,

2. 2.5° × 3.75° monthly precipitation totals from the Climate Research Unit (CRU) (Hulme et al., 1998) for the region 1.25E–26.25E and 52.5N–62.5N,
3. 5° × 5° monthly means of near-surface air temperature (Jones and Moberg, 2003) for the region 10E–30E and 50N–65N.

Furthermore, as for the calculation of the NAO-index, monthly values of sea level air pressure data from southwest Iceland and Gibraltar (Jones et al., 1997), obtained from the website of the Climatic Research Unit of the University of East Anglia, UK, were used.

3. Trends in the amplitude of the annual cycle of Baltic Sea level

For illustration purposes, the seasonal cycle of monthly mean sea level in selected gauge-stations in the Baltic Sea in two different periods, 1900–1930 and 1970–1998, are shown in Fig. 2. Sea level attains a well defined minimum in early spring and a relatively flat maximum in winter. The shape of the annual cycle agrees with the one shown by Chen and Omstedt (2005) for Stockholm. Sea level has decreased from the beginning of the 20th century for all months, except in the station located in the southern Baltic. These long-term trends are mostly due to the isostatic adjustment as a consequence of the last deglaciation. However, no large changes in the shape of the annual cycle can be discerned in Fig. 2. If present, those shifts in the annual cycle have probably been small. In this study it will be assumed that the shape of the annual cycle has remained essentially unchanged.

Similar conclusions can be drawn for the equivalent calculations with four longer sea level records, namely Kolobrzeg, Swinoujscie, Stockholm and Kronstadt. Fig. 3 shows the annual cycles in these four gauge stations in the periods 1850–1880 and 1950–1980.

The influence of the isostatic adjustment in each gauge station in the period 1900–1998 can be roughly subtracted by linearly detrending the sea level records as, at this time scale, the isostatic adjustment can be assumed to be approximately linear. However, linearly detrending will also subtract other possible long-term trends due to other climate processes. Although the influence of isostasy on sea level cannot be statistically separated from long-term trends in climate factors that may also be influencing sea level, it is reasonable to assume that the trend *difference* between any two seasons of the year has to be related to factors different from isostasy. For instance, the trend in the sea level difference between winter and the following early spring, i.e., the trend in the amplitude of the annual cycle, is very probably unrelated to isostasy, as the influence of isostasy at timescales of a few months is negligible. This fact is exploited to identify the influence of long-term climate forcings on Baltic Sea level. In the following, spring will be denoted as the months from March to May and winter as the months from November to January. Seasonal means, as defined within these seasons, of sea level will be considered.

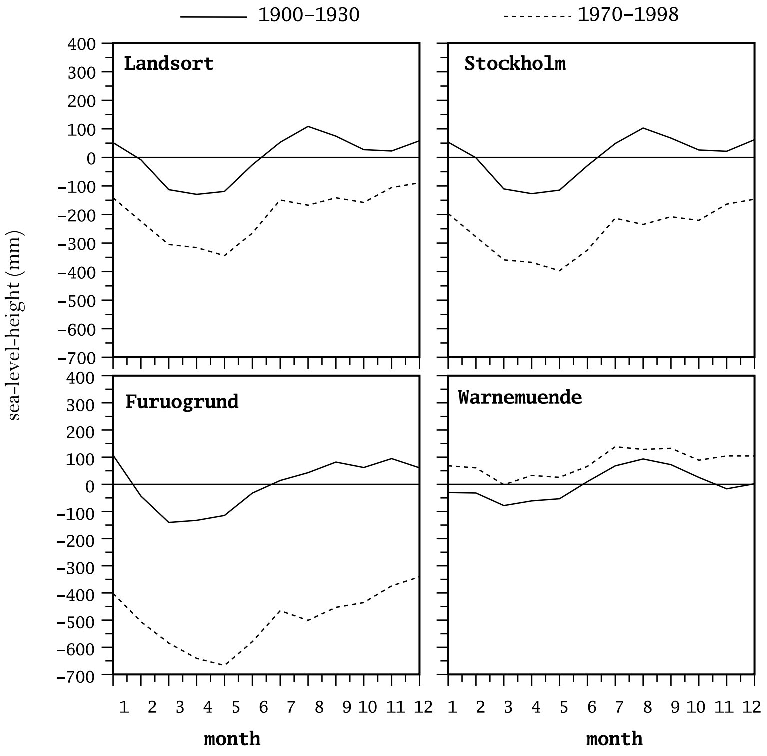

Fig. 2. Sea level annual cycle derived from monthly means averaged in two different periods in the 20th century (1900–1930 solid line, 1970–1998 dashed line) in four selected stations in the Baltic Sea.

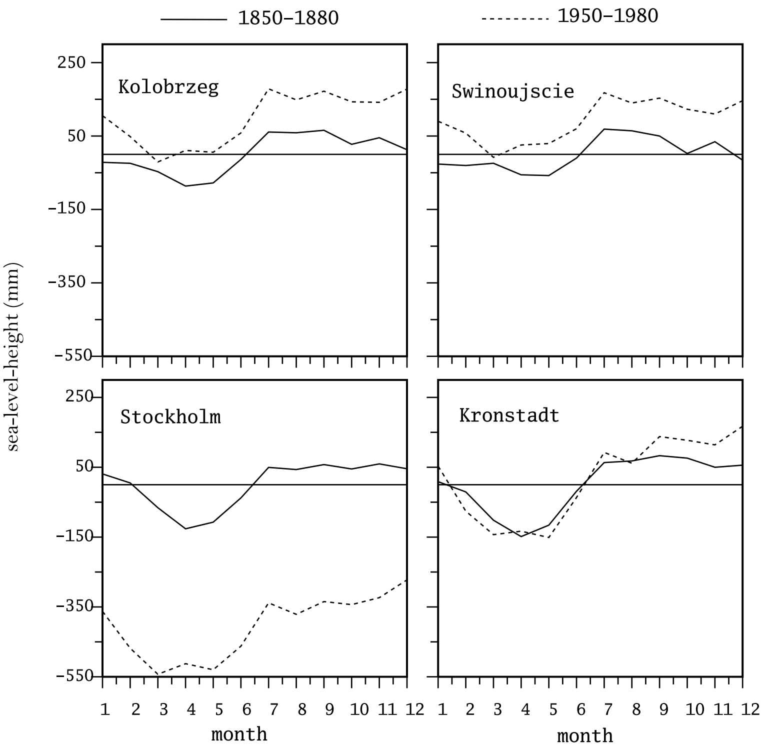

Fig. 3. Sea level annual cycle derived from monthly means in four selected stations in the Baltic Sea, averaged in one period in the 19th century (1850–1880 solid line) and one period in the 20th century (1950–1980 dashed line).

The estimation of linear trends and of their statistical significance by the usual method of a linear fit by least-square-error minimization might be too strongly dependent on the assumptions of independence of the error terms and normality of the data. The independence of the error terms in a linear regression with time series is usually addressed by testing for the presence of lag-1 autocorrelation in the residuals resulting from the linear fit. A usual test for this goal is the *Durbin–Watson test* (Durbin and Watson, 1950). In all following trend estimations, the Durbin–Watson test was applied and only in two cases was the resulting Durbin–Watson statistics outside the range that would indicate the presence of auto correlated residuals. These two cases were for sea level differences in Vaasa and Esbjerg, where the Durbin–Watson statistics indicated a slight positive autocorrelation of the residuals of the linear fit.

The dependence of trend estimation on the normal distribution of the data was addressed by estimating the sea level trends, in addition to the more usual method of linear fit, by a non-parametric method, the *Theil-Sen method* (Sen, 1968). The Theil-Sen trend estimator is defined as

$$\beta = m\left\{\frac{x(t_i) - x(t_j)}{t_i - t_j}, i \neq j\right\}, \tag{1}$$

where m is the median of the ratios $[x(i) - x(j)]/(i - j)$ for $i \neq j$, where x is the variable of interest (e.g. sea level) and i and j comprise all possible time-steps.

Figure 4 shows the linear trends for winter (November–January) minus previous spring (March–May) sea level in the period 1900–1998 for the Baltic sea level gauges, estimated by linear regression and by the Theil-Sen method. The magnitudes

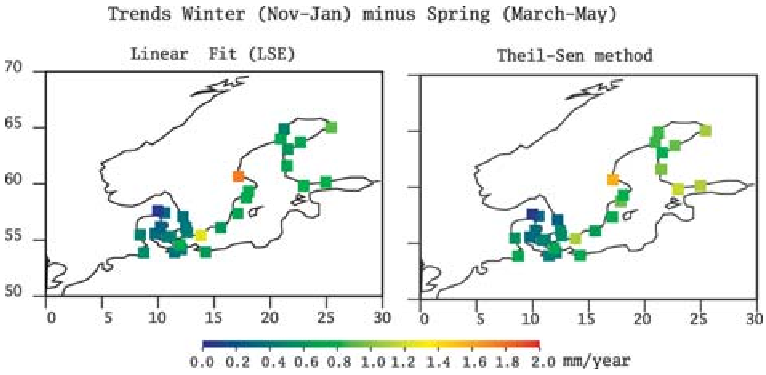

Fig. 4. Trends in the amplitude of the sea level annual cycle winter minus spring in the Baltic Sea estimated in the 20th century by a least-square-error linear fit and by the non-parametric Theil-Sen method.

of the estimated trends are very similar using both methods. All trends are found to be positive, that is, winter sea level has risen relative to spring sea level in all stations in this data set. This result agrees with the trend analysis of Chen and Omstedt (2005) for Stockholm, who found the strongest positive trends in the winter months, whereas in spring and summer these trends were weak or even negative. Similar findings were obtained by Plag and Tsimplis (1999) in a larger set of North Sea and Baltic Sea stations. In the present analysis the largest trend difference are found in the Gulf of Bothnia, in the Gulf of Finland and in the Baltic proper (of the order of 0.8–1 mm yr^{-1}), whereas in the western Baltic the trend differences are smaller (of the order of 0.2–0.4 mm yr^{-1}). It is remarkable that the trends in the southern Baltic, for instance in Warnemünde, are of similar magnitude as in the Gulf of Bothnia and in the Gulf of Finland, although the interannual and decadal variability of sea level in the southern Baltic is much smaller than in the Northern regions.

Although the trend is positive for all stations, its magnitude is not large compared to the decadal variations. Figure 5 shows the smoothed time series of the winter-minus-spring sea level for these four selected stations in the period 1900–1998. The decadal variations are also coherent in these four stations, although the magnitude of these variations is smaller for the station Warnemünde, located in the southern Baltic coast.

To identify the individual stations that present trends in the winter-minus-spring sea level that are individually statistically significant, two tests have been applied to each station separately: the Mann–Kendall test and a permutation test. The *Mann–Kendall test* is a standard non-parametric test for presence of trends in time series, based on the comparison of all possible pairs of data in a time series (Mann, 1945). The number of positive versus the number of negative differences of time-ordered pairs can be compared to the results expected in a truly trendless series and levels of statistical significance in the observed values can be derived. The *permutation test* is based on the reasoning that, under the hypothesis that the series are trendless, a probability distribution of the sample trend can be obtained by random permutation of the elements of the time series (Efron and Tibshirani, 1993). For each station separately, synthetic time series are constructed by reshuffling at random the original time series and the linear trend is calculated by linear regression. This exercise is repeated 1000 times. The 90% significance level is estimated to be the 900th largest trend of these 1000 cases. Figure 6 shows the stations that, according to the Mann–Kendall and the permutation test, have a statistically significant (at the 90% level) long-term trend in their winter-minus-spring difference. In general both tests detect statistically significant trends in all areas sampled by the original station set. The levels of significance are in general slightly above or below the 90% level, perhaps due to the slightly different ratios between long-term trend and interannual variability. But it seems that no spatial clustering of the statistically significant trends occurs, apart from the unavoidable irregular location of the available stations. It seems, therefore, that centennial trends are really present in the

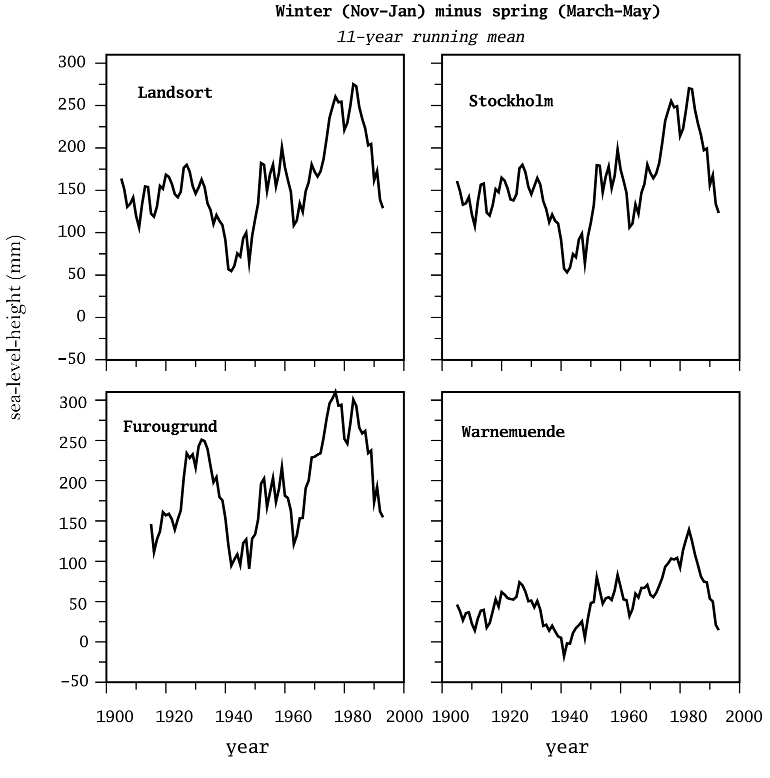

Fig. 5. Decadally smoothed time series of winter-minus-spring sea level in four selected stations in the Baltic Sea in the 20th century.

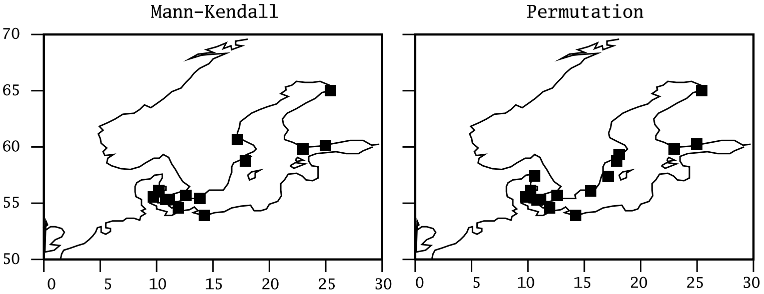

Fig. 6. Stations with statistically significant trends in the 20th century winter-minus-spring sea level. Significance was tested with the Mann–Kendall test and with a permutation test.

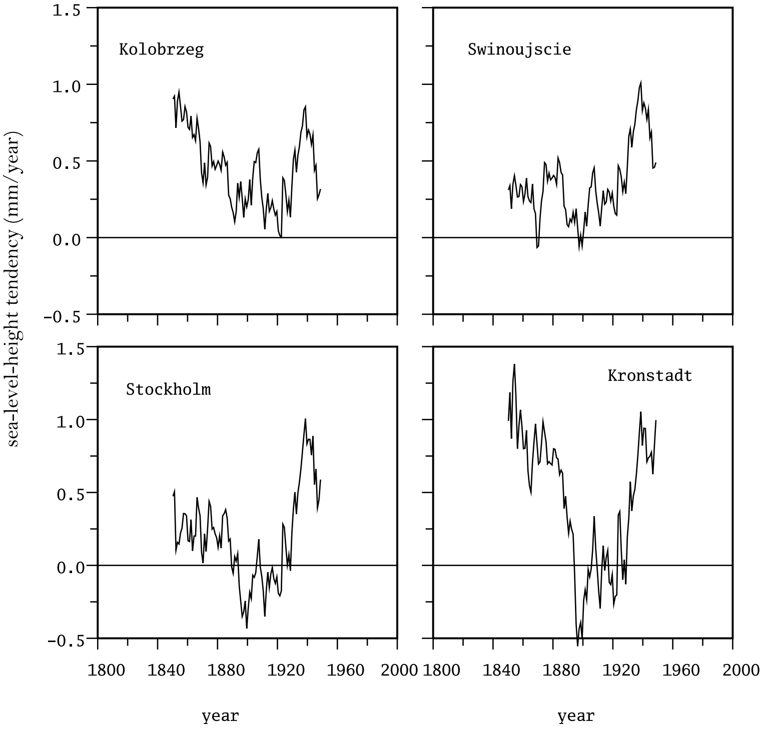

Fig. 7. Linear trends in the winter-minus-spring sea level estimated by linear fit in moving 100-yr windows in four selected stations in the Baltic Sea in the 19th and 20th century. The abscissa of each datapoint indicates the centre of the 100-yr window. Sea level data of Kronstadt before 1840 were not used for this analysis.

amplitude of the annual cycle in the Baltic Sea. The sampling in the southern Baltic is however poor, but as the trend in Warnemünde is of the same order of magnitude as in the northern stations, it is reasonable to assume that this phenomenon has occurred in the whole Baltic Sea.

The widening of the sea level annual cycle can also be observed in longer records of Baltic sea level that cover a large part of the 19th century. Figure 7 depicts the linear trend in the sea level difference winter minus spring for four of these long sea level records, calculated for 100-yr moving windows. The linear trends are almost always positive, with the exception of the 100-yr period centred in 1900 for Stockholm and Kronstadt. In the 19th century, the magnitude of the trends shows larger difference among these four stations. It is also noteworthy that the magnitude of the trend in the 20th century (the last value in the curves in Fig. 7) is the highest for Kronstadt and Stockholm records, but not for Kolobrzeg and Swinoujscie. It is also remarkable that in the 20th century the four linear trends evolve in a coherent way and attain similar absolute values.

4. Possible causes for the increasing amplitude of the annual cycle

The question arises about which factor—or factors—are responsible for the long-term trend in the amplitude of the annual cycle. To answer this question, several hypotheses have been put forward and their plausibility has been statistically analysed.

4.1. Factor 1 – wind stress forcing

It is well known that the winter sea level variations in parts of the Baltic Sea at interannual to decadal timescales are mostly modulated by the westerly winds over the Baltic Sea region. At long timescales the intensity of the westerly winds is closely associated to the NAO, although the influence of the NAO is much stronger in the North and rather weak in the southern Baltic Sea (Jevrejeva et al., 2005; Hünicke and Zorita, 2006). In general, a positive trend in the NAO-index in winter would lead to a positive trend in winter sea level and therefore could explain the more positive trend in wintertime relative to spring. In spring, SLP is known to have a much weaker influence on sea level and consequently will not to be included, at a first step, in this hypothesis. The winter NAO-index shows a negative trend in the period 1900–1998 for the months November–January. The seasonal November–January mean NAO index, standardized to standard deviation unity in the period 1900–1998, shows a trend of -0.006 year^{-1} ± –0.005 (95% confidence interval) in the period 1900–1998. This figure amounts to a mean decrease in 100 yr of roughly one half of the interannual standard deviation. This trend should, in principle, tend to lower sea level in the winter months if the sign of the relationship between the NAO index and sea level can be extended to centennial timescales.

Although the NAO is the dominant SLP large-scale pattern over the North Atlantic, the NAO explains, on average, only 32% of the total variability of sea level at interannual timescales (Kauker and Meier, 2003). Therefore, it could be argued that the remaining SLP variability patterns should also be taken into account to clearly rule out that SLP is responsible for the sea level winter trend. The statistical extraction of the 'non-NAO part' from the SLP field is not straightforward, but we can use regression analysis—linking sea level variations as predictor and sea level pressure as predictand (Chen and Omstedt, 2005; Hünicke and Zorita, 2006) – to test if there is a positive trend detectable in the reconstructed sea level which is caused by the SLP field (including the NAO). Formally, the statistical model reads:

$$SL(t) = \sum_{i=1,N} a_i pc_i(t) + SLR(t), \tag{2}$$

where pc_i are the i th principal component (PCs), resulting from an Empirical Orthogonal Function (EOF) analysis of the SLP field in the North-Atlantic European region (see Section 2), a_i is the corresponding regression coefficient, N the number of PCs included in the regression and SLR are the sea level residuals.

The SLP data have been detrended prior to the calculation of the PCs. Therefore, the statistical model should capture only the interannual relationship between sea level and SLP. Once the regression parameters have been estimated by least-mean-square error minimization, the model is applied with the non-detrended SLP anomalies to estimate the possible contribution of SLP to the sea level winter trend in each of the stations. This contribution is also found to be negative for all stations, with values varying between -0.01 and -0.1 mm yr^{-1}, and therefore, the SLP field as a whole, and not only the NAO, is unlikely to explain a positive trend in winter sea level, again provided that the relationship between wind-stress (here represented by the SLP gradients) and sea level at interannual timescales can be extrapolated to the centennial trends.

Another mechanism that could potentially link wind-stress and Baltic sea level at long timescales can be derived from the relationship between wind speed and salinity, as discussed by Meier (2005) who used a Baltic Sea model to estimate the age of water masses in the Baltic Sea, finding that increased wind-stress is associated, in general, with lower average salinity. The mean horizontal gradient of salinity in the Baltic is one important driver for the mean sea level elevation (Ekman and Mäkinen, 1996) and therefore a plausible reasoning could be that modifications of the salinity field by the wind forcing could also affect long-term sea level changes. At interannual timescales there is also an empirical negative link between the NAO index and Baltic Sea salinity (Zorita and Laine, 2000), which the latter authors tentatively ascribed to higher precipitation in the Baltic Sea area in winters with stronger NAO index. This question is further discussed in Section 4.4 in relation with precipitation changes. This notwithstanding, the sign of the link between wind forcing and sea level within the Meier (2005) mechanism would be the same as with the direct wind-stress forcing on sea level height, and therefore the negative long-term trend in the NAO index could not contribute to the increasing relative sea levels in wintertime.

4.2. *Factor 2 – pressure difference between Baltic Sea and North Atlantic Region*

Another reasonable explanation for trend in the winter-minus-spring sea level is the barometric effect, due to trends in the pressure differences between the Baltic Sea and the North Atlantic Region. To test this hypothesis, sea level pressure differences between the Baltic Sea Region (10E–30E and 50N–65N) and the North Atlantic Area (30W to 10E and 50N to 65N) were calculated. In the spring season a negative trend value of -0.009 mb yr^{-1} was obtained. Assuming a complete equilibrium of sea level to the air-pressure differences, this would result in a positive sea level trend in spring of 0.09 mm yr^{-1}. In the winter season, a positive value in the air-pressure difference between the Baltic and the North Sea of 0.006 mb yr^{-1} was found, which should correspond to a negative Baltic Sea level trend of -0.06 mm yr^{-1}. Thus, the difference of the winter and spring barometric gradients would produce a difference between winter and spring sea level of the order of $+0.15$ mm yr^{-1}. The sign of these barometric trends contribute to the explanation of the observed winter-minus-spring sea level trends, but the barometric effect is too small to explain these trends. Only the stations located in the Skagerrak area display such small trends, but these stations are likely the ones less affected by the pressure seasaw between the Baltic and the North Sea. Plag and Tsimplis (1999) also concluded that the influence of the barometric effect is not strong enough to explain the variations of annual cycle of sea level in the North Sea and Baltic Sea.

4.3. Factor 3 – temperature

Sea level can be affected by temperature directly due to thermal expansion of the water column. For instance, Stigebrandt (2001) estimated an amplitude of 2 cm for the sea level variations in the Baltic Sea associated with seasonal cooling and warming. Hünicke and Zorita (2006) estimated the magnitude of the additional contribution of air-temperature to the amplitude of decadal winter sea level variations of the order of 1 cm. An increasing sea level in winter relative to spring could possibly be traced back to different long-term trends in winter and spring water temperatures in the Baltic Sea. Century-long time series of water temperature are not available, and to test this hypothesis we have to rely on trends in the observed air-temperature in the Baltic Sea region. At these long timescales, air temperature should be closely coupled to water temperature, but the absolute magnitude of the water temperature trends would remain uncertain. As we are analysing seasonal means, the link between air-temperature and water temperature can be considered simultaneous.

Figure 8 shows the evolution of the average air-temperature in the Baltic Sea region smoothed by an 11-yr running mean filter for the winter and spring seasons, for the period 1900–1998. In both seasons a positive trend was obtained, whereby the value for the spring (0.7 ± 0.5 K per century, 95% confidence interval) is higher than for the winter season (0.2 ± 0.6 K per century). If these trends, or at least their relative magnitude, also apply for the water column in the Baltic Sea, temperature is likely not responsible for the difference in the trend in the amplitude of the sea level seasonal cycle. The sign of the difference in trends indicates that this effect cannot theoretically contribute (smaller trend in winter), and also the order of magnitude of the implied sea level trends due to water column expansion is too small to explain a large part of the observed trend in the amplitude of the sea level annual cycle. Assuming that the trend in air-temperature is communicated entirely to the water column, and assuming that in winter the warming penetrates down to 100 m and in spring only down to 20 m, the implied sea level trends would amount to 0.03 mm yr^{-1} and 0.06 mm yr^{-1} for spring and winter, respectively (the effect in winter is larger although the temperature trend is smaller because of the larger assumed heat penetration). Their difference is an order of magnitude smaller than the observed trend in sea level seasonal differences. Only if the spring warmth would reach much deeper levels in the water column could this effect become relevant. As the water temperatures have likely not completely realized the trend in air-temperature, these calculations are probably an upper bound for this effect.

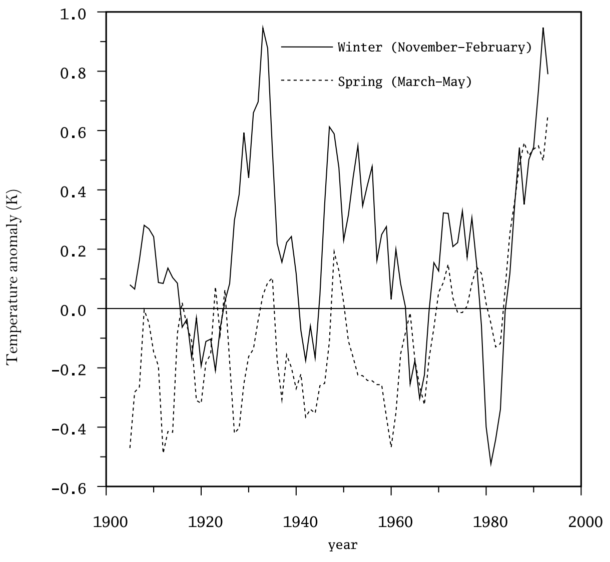

Fig. 8. Decadally smoothed winter (solid line) and spring (dashed line) averaged air-temperature in the Baltic Sea region in the 20th century.

Note that in the statistical analysis of the sea level trends in Stockholm by Chen and Omstedt (2005), these authors also consider it unlikely that temperature trends could be responsible for the different trends in sea level across the calendar year at this station. Note also that the positive trend in winter air-temperature is mainly due to the sharp increase in the last 15 yr of the 20th century. The long-term trend of winter temperature in the period 1900–1980 is actually negative. As shown before, the amplification of sea level annual cycle can be also observed in the mid-20th century relative to the mid 19th century (Fig. 3), when temperature increases were possibly less rapid than in the last 15 yr of the 20th century.

4.4. Factor 4 – precipitation

Hünicke and Zorita (2006) found precipitation to explain a part of the decadal variability of Baltic sea level variations in summertime in the 20th century. According to that analysis, higher than normal precipitation is linked to higher than normal sea level in summertime, but they did not analyse precipitation trends in other seasons, for example, trends in the spring precipitation. However, if this link is also present in spring and maintained at centennial timescales, a negative trend in spring precipitation could explain a more positive sea level trend in winter with respect to spring, thus contributing to the explanation of the widening winter-minus-spring sea level difference. Figure 9 depicts the spatially averaged spring and winter precipitation time series, smoothed with an 11 yr running mean, for the period 1900–1996. It can be seen that spring precipitation in the Baltic Sea shows indeed a slight positive trend in the 20th century (1.4 ± 4 mm month^{-1} per century, 95% confidence interval), whereas in the winter months the trend is also positive but much larger (5 ± 4 mm month^{-1} per century). Therefore, the trend in winter precipitation is statistically significant whereas spring precipitation can be considered as trendless in practical terms. The difference in trends in winter and spring precipitation could in principle explain the increasing difference between winter and spring sea level observed in the last 100 yr.

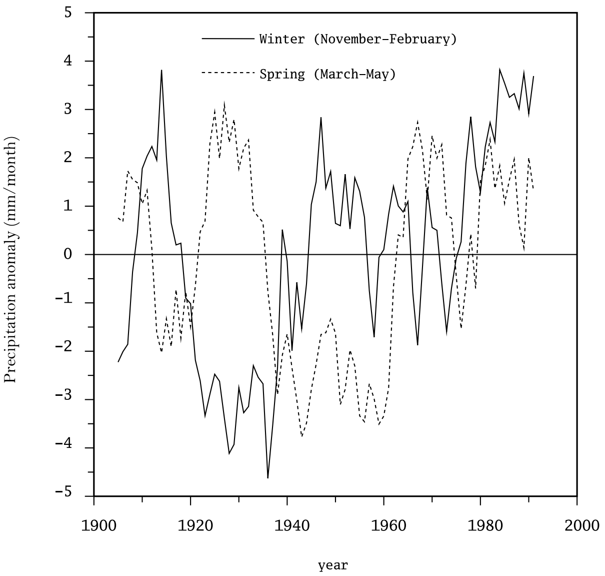

Fig. 9. Decadally smoothed winter (solid line) and spring (dashed line) averaged precipitation in the Baltic Sea region in the 20th century.

However, a number of uncertainties remain before the role of precipitation can be completely ascertained. For instance, trends in evaporation or soil infiltration in the Baltic Sea are difficult to include in the analysis due to the lack of data. Also, precipitation in winter may fall in the form of snow over land and may not be readily available to fully contribute to a rise in sea level. The precipitation trend in the autumn months (September–November) is also relatively large and positive (4 mm month^{-1} per century) so that actually it is precipitation in the whole winter half year that shows a positive trend, which is larger than in the summer half year. Overall, based on the sign of its seasonal trends, precipitation cannot be ruled out as the main contribution to the seasonal sea level trends, but a quantification of its effect is almost impossible by statistical means alone.

Although this analysis has focused on the centennial sea level trends, the decadal variability of the Baltic precipitation in spring and winter shown in Fig. 9 shows one remarkable aspect. Both time series seem to be anticorrelated, although there is no a priori reason to think that winter (November– January) and spring (March–May) precipitation should be linked in any way. The timing of the highest deviations between both, around 1930 and around 1950, coincide also with two maxima in the amplitude of the annual cycle (Fig. 2). Although this timing may be just a coincidence, it could support the role of precipitation in long-term variations of Baltic sea level.

The mechanisms by which long-term trends in precipitation, and in general fresh water balance, can affect long-term trends in sea level may be quite entangled. Sea level will be affected by the net balance between North Sea inflow, from precipitation and run-off on one side and evaporation and outflow on the other side. Precipitation and run-off trends probably have the same sign. However, any imbalance between inflow and outflow longer than a few weeks will tend to cancel, so that it is difficult to substantiate that precipitation can directly affect the whole fresh-water volume in the Baltic Sea. However, precipitation also affect salinity, and therefore water density. Changed salinity gradients could also affect sea level changes, in the same way as the mean sea level gradient is affected by the mean salinity gradient (Ekman and Mäkinen, 1996). The direct magnitude of the influence of long-term salinity trends on sea level is difficult to ascertain, as available salinity time series are not long enough, and the few available salinity time series are not seasonally resolved. To produce a trend in the amplitude of the annual cycle of sea level of 1 mm yr^{-1}, salinity should display a difference of about 0.01 psu yr^{-1} in its seasonal long-term trends, assuming that these trends are communicated to the upper 100 m and that salinity in the North Sea remains constant. In view of the lack of observational data, it would be interesting to see if such trends in seasonal salinity are found in simulations of evolution of the Baltic Sea in the 20th century.

5. Discussion and conclusions

The existence of centennial trends in the amplitude of the annual cycle (winter minus spring) has been detected. These trends are not large compared to the decadal variations of the annual cycle, but they are statistically significant. The magnitude of the trends is almost uniform in the station data set analysed here, with the exception of the Skagerrak area. This is remarkable, as the interannual and decadal variability of sea level displays a clear spatial pattern, with higher values in the Gulf of Bothnia and in the Gulf of Finland (Meier, 2006). This aspect suggests that the mechanisms responsible for the trends in the annual cycle are not regional, but affect the Baltic Sea basin as a whole.

In the present analysis several hypotheses have been proposed as mechanisms to explain the centennial trends in the winter-minus-spring sea level: the effect of wind (through the SLP field), temperature, barometric effect and precipitation. By elimination of three of these hypotheses precipitation appears to be a plausible candidate. For the other three either the sign or the magnitude of the trend make them too problematic to be considered as a sole explanation. However, the barometric effect was found to contribute potentially to the trend in the sea level annual cycle.

Previous studies had already underlined the importance of wind forcing to the changes in the amplitude of the annual cycle sea level variations in the Baltic Sea. Ekman (1999) investigated the connection between variations in the NAO index and the Baltic Sea level, using the sea level time series of Stockholm, since 1825. The main conclusion of this study was that the winter climate, in particular wind, plays the central role for the Baltic Sea level variations. Ekman (1999) also discussed shortly the causes of the long-term variations in the sea level annual cycle, concluding that this is also due to long-term changes in the wind conditions. At first glance, these conclusions might seem to stand in contradiction to the results presented here. But this study was focused on one or a limited region of the Baltic Sea, whereas our results are based on the analysis of 30 Baltic Sea level stations situated around the Baltic Coast, yielding information about the spatial structure of the long-term trends.

As illustrated in Hünicke and Zorita (2006), the correlation between the winter NAO index and winter (DJF) sea level variations in the period 1900–1998 range between 0.1 and 0.8 and shows a spatial heterogeneous pattern with a strong north–south gradient with much weaker values for the Southern Baltic Coast. If changes in the wind climate were to be responsible for the trends in the amplitude of the annual cycle, and the relationship between wind and sea level has the same spatial structure at interannual as at centennial timescales, the spatial pattern of the trends in the amplitude of sea level annual cycle would be also spatially heterogeneous, with higher values in the north and lower values in the south. However, as shown in the present study, the trend differences in the amplitude of sea level annual cycle winter (NDJ) minus spring (MAM) in the Baltic Sea estimated in the 20th century (Fig. 4) show a quite homogeneous pattern with (significant) trends of similar magnitudes in the southern Baltic Sea as in the Gulf of Bothnia and the Gulf of Finland. Therefore, we conclude that the explanation involving wind forcing as main mechanism would not be consistent with similar levels of the trends in the northern and in the southern stations.

It has to be kept in mind, however, that the list of possible mechanism is not closed by the four hypotheses considered here, and that if further mechanisms can be proposed, the role of precipitation may appear less certain. For instance, the Baltic drainage basin has been subject to non-negligible construction of dams and other hydrological public infrastructures, which may possibly have had an influence on the timing of the river discharge into the Baltic Sea. This could also influence the amplitude of the annual cycle of sea level, depending on whether this infrastructure is utilized for the generation of electricity or for artificial irrigation or for water for public consumption, as these needs dictate different timing of the largest release of stored water. Other mechanism that could affect trends in the annual cycle are shifts in the main discharge due to shifts in the melting season, as temperatures in the region also display discernible trends in the 20th century.

An interesting aspect is whether the detected trends in 20th precipitation can continue into the future, potentially modulating also the trends in the sea level annual cycle. Simulations with global climate models (Giorgi and Bi, 2005) driven by different scenarios of anthropogenic greenhouse gas forcing and anthropogenic tropospheric aerosols indicate that dry-season (November–April) precipitation will likely increase in Northern Europe, whereas wet season (May–October) precipitation will likely undergo a slight reduction. Although the definitions of the rainfall seasons in Giorgi and Bi (2005) do not exactly match the definition adopted in this study for the extrema of the sea level annual cycle, the simulated trends in the dry (winter) season are consistent with the trends observed in the 20th century. If a causal link between rainfall trends and greenhouse gas forcing can be established, the difference between winter and spring sea level in the Baltic Sea may continue increasing in the next decades. However, it is noted that the trend in the sea level annual cycle at the end of the 20th century is not unprecedented for all of the stations. Two stations located in the southern Baltic display larger centennial trends in the 19th century. The 20th century trends seem to be more coherent in space and time than in the 19th century.

The analysis presented here should be understood as complementary to modelling studies. Simulations with a regional model of the Baltic Sea (Meier and Kauker, 2003) can help to falsify or confirm these hypotheses.

Acknowledgments

This study is part of the project SINCOS (German Science Foundation) and of the BALTEX program. We thank the Permanent Service for Mean Sea Level based at the Proudman Oceanographic Laboratory (UK), and the Climate Research Unit of the University of East Anglia (UK) for the gridded temperature and rainfall data. The rainfall data were produced by Mike Hulme with support by the UK Department of Environment, Transport and the Regions (Contract EPG 1/1/85). We thank Andreas Richter from the Technische Universität Dresden for providing the sea level data for Kolobrzeg. We thank two anonymous reviewers and D. Bray for fruitful comments.

References

Bogdanov, V. I., Medvedev, M.Yu., Solodov, V. A., Trapeznikov, Yu. A., and co-authors. 2000. Mean monthly series of sea level observations (1777–1993) at the Kronstadt gauge. *Reports of the Finnish Geodetic Institute* **2000:1**, 34 pp.

Chen, D. and Omstedt, A. 2005. Climate-induced variability of sea level in Stockholm: influence of air temperature and atmospheric circulation. *Adv. Atmos. Sci.* **22**, 655–664.

Durbin, J., and Watson, G. S. 1950. Testing for serial correlation in least squares regression, I. *Biometrika* **37**, 409–428.

Effron, B., and Tibshirani, R. J. 1993. *An Introduction to the Bootstrap*, Chapman & Hall, New York, 1993.

Ekman, M. 2003. The world's longest sea level series and a winter oscillation index for Northern Europe 1774–2000. *Small Publ. Historical Geophys.* **12**, 30 pp.

Ekman, M. 1999. Climate changes detected through the worlds longest sea level series. *Global Planet Change* **21**, 215–224.

Ekman, M. and Mäkinen J. 1996. Mean sea-surface topography in the Baltic Sea and its transition area to the North Sea: a geodetic solution and comparison with ocean models. *J. Geophys. Res.* **101**, 11993–11999.

Ekman, M. and Stiegebrandt, A. 1990. Secular changes of the seasonal variations in sea-level and the Pole Tide in the Baltic Sea. *J. Geophys. Res.* **95**(C4), 5379–5383.

Giorgi, P. and Bi, X. 2005. Updated regional precipitation and temperature changes for the 21st century from ensembles of AOGCM simulations. *Geophys. Res. Lett.* **32**, doi:10.1029/2005GL024288.

Hünicke, B. and Zorita, E. 2006. Influence of temperature and precipitation on decadal Baltic Sea level variations in the 20th century. *Tellus* **58A**, 141–153.

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.

IPCC 2007. Climate change 2007: the physical science basis. *Contribution of Working Group 1 to the Fourth Assessment of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK and New York, USA.

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.

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.

Kauker, F. and Meier, M. H. B. 2003. Modeling decadal variability of the Baltic Sea: 1. Reconstructing atmopsheric surface data for the period 1902–1998. *J. geophys. Res.* **108** (C8), 3267.

Mann, H. B. 1945. Nonparametric test against trend. *Econometrica* **13**, 245–259.

Meier, H. E. M. 2005. Modelling the age of Baltic sea water masses: quantification and steady state sensitivity experiments. *J. Geophys. Res.* **110**, C02006, doi:101029/2004JC002607.

Meier, H. E. M. 2006. Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emissions scenarios. *Clim. Dyn.* **27**, 39–68.

Meier, H. E. M. and Kauker, F. 2003. Modelling decadal variability of the Baltic Sea: 2. Role of fresh water inflow and large-scale atmospheric circulation for salinity. *J. Geophys. Res.* **108**(C8), doi:10.1029/2003JC001799.

Plag, H.-P. and Tsimplis M. N. 1999. Temporal variability of the seasonal sea-level cycle in the North Sea and Baltic Sea in relation to climate variability. *Global and Planet. Change* **20**, 173–203.

Sen, P. K. 1968. Estimates of the regression coefficients based on the Kendall's tau. *J. Am. Stat. Assoc.* **63**, 1379–1389.

Stephenson, D., Pavan, V., Collins, M., Junge, M. M., Quadrelli, R., and co-authors. 2006. North Atlantic Oscillation response to transient greenhouse gas forcing and the impact of European winter climate: a CMIP2 multimodel assessement. *Clim. Dyn.* **20**, 381–399.

Stigebrandt, A. 2001. A systems analysis of the Baltic Sea. In: *Physical Oceanography of the Baltic Sea* (eds F. Wulff, L. Rahm and P. Larsson). Springer Verlag, Berlin, Heidelberg, Germany, 19–74.

Trenberth, K. E. and Paolino (jr.), D. A. 1980. The northern hemisphere SLP-dataset: trends, errors and discontinuities. *Mon. Wea. Rev.* **108**, 855–872.

Woodworth, P. L. and Player, R. 2003. The permanent service for mean sea level: an update to the 21st century. *J. Coastal Res.* **19**, 287–295.

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. *Clim. Res.* **14**, 25–41.