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Influence of long-term regional and large-scale atmospheric circulation on the Baltic sea level

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ABSTRACT

The connection between variations in the North Atlantic Oscillation (NAO) index and the Baltic sea level has been investigated for the period 1825–1997. The association between the NAO and the strength of the zonal geostrophic wind stress over the Northwest Atlantic suggests an NAO impact on Baltic sea level variations, because the monthly mean sea level mainly is determined by externally driven variations caused by wind conditions over the North Sea. Several period bands were found to have high correlation between oscillations in the winter (JFM) NAO index and the Baltic Sea winter mean sea level. The correlation was, however, higher in the 20th century than in the 19th. During the last two decades, the correlation between the NAO index and the sea level has been exceptionally high. The winter mean of a regional atmospheric circulation index had a correlation with the Kattegat winter mean sea level of 0.93. With the Baltic sea level the correlation was 0.91, compared with the NAO index correlation for the same period of 0.74. The regional index also showed a high correlation with the mean summer and mean autumn sea levels, when the corresponding seasonal NAO indices showed a weak connection. The temporal variation of the connection with the NAO index implies a regional atmospheric circulation occasionally differing from the large-scale circulation associated with the NAO. Seasonal means of the sea level in Stockholm do, however, reflect the regional wind climate to a large extent, and the Baltic sea level is a useful proxy for identifications of climatic dependencies in the region.

1. Introduction

The North Atlantic Oscillation (NAO) is the dominant mode of low-frequency atmospheric variability over the North Atlantic, and it significantly affects the European and Scandinavian climate anomalies. An index of the wintertime NAO (e.g. Hurrell, 1995; Jones et al., 1997) is based on the normalized sea level air pressure difference between the Icelandic low and the Azores high. A high NAO index is characterized by lower than normal pressure in the Icelandic region and higher than normal pressure in the subtopics. The increased pressure difference gives a strengthening of the westerlies onto Europe (Rogers, 1985) and is associated with a change in the Atlantic storm track to a more northerly path (Rogers, 1990). The circulation pattern is also associated with increased air and sea temperatures and increased precipitation in the north-western Europe (Hurrell, 1995; Hurrell, 1996; Hurrell and van Loon, 1997). The last two decades have been dominated by an unusually long period with a positive NAO index. This has led to speculations on climate change, perhaps resulting from anthropogenic causes. The observed trends in sea level air pressure are reproduced by models containing stratospheric dynamics under an increased greenhouse gas scenario (Shindell et al., 1999). The mechanisms governing the NAO are, however, not yet understood, and even decadal trends in the

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NAO could be the result of aggregations of stochastic weather events (Stephenson et al., 2000).

In the Baltic Sea (Fig. 1) several signs of change have been noted. Evidence of secular increases of the amplitudes of the annual and 14-month constituents was found in the sea level recordings at Stockholm by Ekman and Stigebrandt (1990). The changes in the annual constituent's amplitude and phase are confirmed by Plag and Tsimplis (1999), together with evidence in the last decades of a concurring change in the atmospheric circulation pattern over the Baltic and North Seas. Ekman (1998) finds a secular increase in the occurrence of south-westerly winds during winter at Lund (see Fig. 1), commencing in the beginning of the 1900s and the cause of the observed increase in annual mean sea level. As winter conditions play an important part for years with extreme sea level annual means, Ekman (1996a) hypothesizes that the observed sea level increase partly is a cause of the NAO and hence reflects a secular climatic change over the North Atlantic.

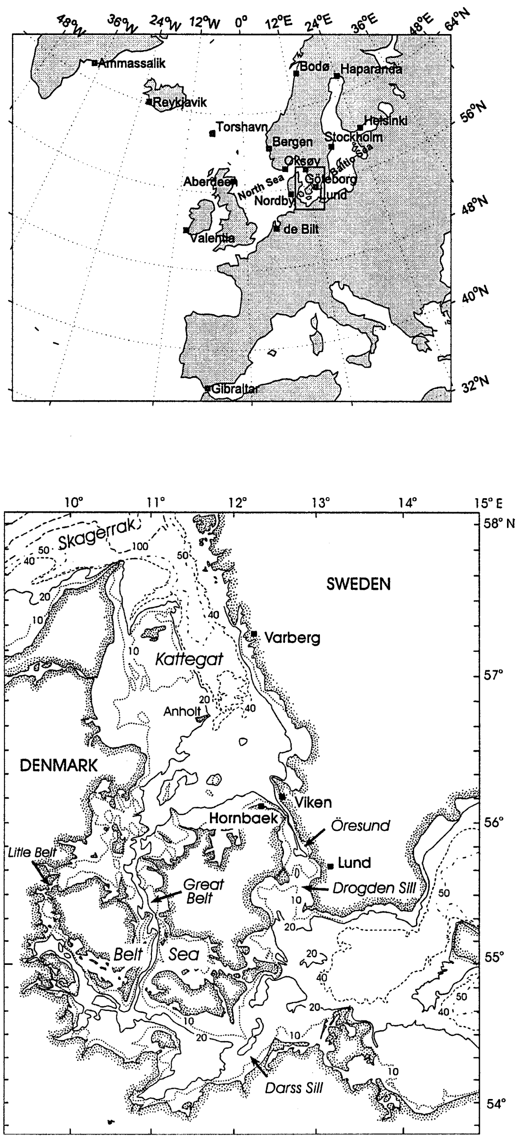

Fig. 1. The upper map is an overview of the Northeast Atlantic, North Sea and Baltic Sea region and the lower map a close-up of the narrow Baltic Sea entrance area.

The water exchange between the Baltic Sea and the North Sea is restricted due to the vast and shallow Baltic Sea entrance area (Fig. 1). The transition area between the two seas consists of the Kattegat, the Öresund and the Belt Sea. The two sills, the Drogden Sill and the Darss Sill, are substantially shallower (8 and 18 m, respectively) than the mean depth (54 m) of the Baltic Sea. The exchange is essentially barotropic and mainly driven by the sea level difference between the southern Kattegat and the Baltic proper (e.g. Jacobsen, 1980; Stigebrandt, 1980). The Baltic Sea response to sea level variations in the Kattegat is a function of amplitude and period of the oscillation. Because of the large basin in combination with topographically induced flow resistance, the connecting sounds acts as a low-pass filter and leads to a reduction of the amplitude. A full response is attained for periods of about one year (Stigebrandt, 1984). Samuelsson and Stigebrandt (1996) found that 50–80% of the total Baltic sea level variability originates from external forcing (Kattegat sea level oscillation and freshwater supply). The external forcing particularly dominates on time-scales of one month or longer. The Baltic Sea behavior is then that of a quarter-wave oscillation with a node at the entrance, and the variance of the oscillations increases from the Baltic Sea mouth towards the north because of the internal forcing (variations in local wind, air pressure and density). Shorter period sea level variations are mainly internally forced where the Baltic Sea acts like a closed basin (half-wavelength oscillation). The nodal line for these variations is situated close to Stockholm. Sea level variability in the Kattegat is the major external forcing component on time-scales of more than a month, while local wind stress dominates on short timescales (<2 weeks) (Carlsson, 1998a). Consequently, the sea level variability in the Baltic Sea is mainly due to variations in the Kattegat sea level and is well represented by the sea level in Stockholm (see also Ekman, 1996b).

Sea level variability in the Kattegat is largely governed by the large-scale zonal wind on timescales of 5 days and longer (Lass et al., 1987; Gustafsson and Andersson, 2001). The tides are small in the Kattegat: the principal lunar tidal component (M_2) has an amplitude of only about 8 cm (e.g. Svansson, 1975), and the restriction of the sounds reduces it to a small fraction of this in the Baltic Sea (Stigebrandt, 1984). Local and regional steric effects can, however, contribute to variations in sea level, particularly to the annual cycle (e.g. Pattullo et al., 1955; Stigebrandt, 1985).

From the dynamics described in the preceding paragraph, we expect the monthly mean Baltic sea level to a high degree be a response to the Kattegat sea level that in turn is governed by the mean zonal wind situation over Skagerrak and the North Sea by setup of sea level against coasts. The fluctuating air pressure will also influence the sea level variations by a direct response due to the inverse barometric effect. As the large-scale meridional pressure difference, as represented by the NAO index, contains information of the magnitude of the mean zonal geostrophic wind field, the Baltic sea level may to a high degree mirror the large-scale atmospheric variability. The relationship between the NAO index and the mean Baltic sea level is investigated here for the period 1825–1997, using the sea level record from Stockholm, Sweden. Sea level air pressure observations around the Nordic Seas are used to identify the regional deviation in the pressure field from the large-scale one. A regional index of meridional air pressure differences is constructed and compared to the seasonal mean sea levels of the Kattegat and the Baltic Sea. The data used are presented in Section 2 and the methods applied in the data analysis are described in Section 3. The results are presented and discussed in Sections 4 and 5, respectively.

2. Data

2.1. Sea level data

The sea level record from Stockholm consists of a complete series of monthly means during the period 1825–1997 (Ekman, 1988). A linear trend is present throughout the series, caused by post-glacial land uplift and eustatic sea level change (e.g. Ekman, 1988, 1999), and this was removed before the analyses. Seasonal means for each year were constructed for winter (January–March), spring (April–June), summer (July–September) and autumn (October–December).

Monthly and seasonal mean sea levels in the Kattegat are based on daily sea level observations for the period 1902–1997. The observations are mainly from Hornbæk in the southern Kattegat, with gaps filled by the observations from nearby Varberg and Viken. The short remaining gaps are covered by linear interpolation.

2.2. Air pressure data

Monthly values of sea level air pressure data from south-west Iceland and Gibraltar (Jones et al., 1997) were obtained from the web site of the Climatic Research Unit (CRU), Norwich (www.cru.uea.ac.uk) and used to calculate monthly means of the pressure difference between Gibraltar and Iceland. Using Gibraltar as the southern station when constructing the NAO index enables an extension back to 1825 compared to the often-used Iceland/Azores or Iceland/Lisbon indices. The respective pressure series are then normalized by subtracting the 30-year period mean (1951–1980) from each monthly mean and dividing it by the long-term standard deviation. The series from Iceland is then subtracted from the Gibraltar one (Jones et al., 1997).

Monthly means of regional air pressure data were constructed from observations consisting of one to three readings a day. Observations are from 13 stations around the Nordic Seas (Alexandersson et al., 1998) and indices of regional pressure differences were created in the same way as the NAO index, by taking the normalized air pressure at the southern station minus the same at the northern location. Due to a lack of data from the 1800s at several stations, the comparisons between different indices had to focus on the 1900s and span from 1902 to 1997. Some gaps in the air pressure series are still present, but with a few exceptions no more than three days of readings are missing in a month. For Lund in 1965, observations are only available for 10 days in February and 23 days in March. Helsinki has no data for

April 1986. The data from Aberdeen lack readings entirely for the year 1900. When data for a month are missing, the long-term mean value for the particular month is used instead to get a complete set of indices.

3. Methods

The co-variability of the pressure difference between Gibraltar and Iceland and the Baltic Sea mean sea level was analyzed on both monthly and seasonal time-scales. The NAO signal in the atmosphere is present throughout the year but is more pronounced in the winter, so it is reasonable to expect its influence on the Baltic sea level to be more notable during the winter months. The relationship was also analyzed in the frequency domain, by variance analysis for the monthly means of the pressure difference and by the cross-coherency between the winter NAO index and winter mean Baltic sea level. A new index of pressure differences representing the regional zonal geostrophic wind field was also constructed and compared to the NAO index and the winter mean sea levels in the Kattegat and the Baltic Sea. A moving correlation was used to investigate the temporal evolution of the atmospheric impact.

3.1. Annual variation and frequency distribution

The annual cycle of the connection between the monthly mean Gibraltar/Iceland pressure difference and the monthly mean Baltic sea level is illustrated by the correlation coefficient for each month of the year. The connection can also be discerned by comparing the variance in the series, both in how the inter-annual energy is distributed over the year and among different frequency bands. The annual distribution of variance for a month is calculated from

$$\mathrm{var}_i = \frac{1}{N}\sum_j (h_{ij}-h_i)^2 \quad i=1,\dots,12;\ j=1,\dots,N \tag{1}$$

where var_i is the mean variance for month i, h_{ij} the mean sea level (or pressure difference) during the ith month of the jth year, h_i is the mean of all monthly means of month i and N is the number of years in the series.

The division of the variance between different period bands can be obtained by variance analysis (Stigebrandt, 1984). The total variance, var, of the series is calculated from the monthly mean sea level (pressure difference) relative to the mean sea level (pressure difference) for the whole period, and contains variance in the record contributed from fluctuations with periods of two months (the Nyquist period) and longer:

$$\mathrm{var} = \frac{1}{N}\sum_j \frac{1}{12}\sum_i (h_{ij}-z_0)^2, \quad i=1,\dots,12;\ j=1,\dots,N \tag{2}$$

where z_0 is the mean sea level of the whole period of N years. With h_j as the annual mean sea level of the jth year, eq. (2) can be rewritten as

$$\begin{aligned}\mathrm{var} &= \frac{1}{N}\sum_j \frac{1}{12}\sum_i [(h_{ij}-h_j)^2 - h_j^2 + 2h_{ij}h_j - 2h_{ij}z_0 + z_0^2] \\ &= \frac{1}{N}\sum_j \frac{1}{12}\sum_i [(h_{ij}-h_j)^2 + (z_0-h_j)^2 + 2(h_j-h_{ij})(z_0-h_j)] \qquad (3)\\ &= \frac{1}{N}\sum_j [\mathrm{var}_j + (z_0-h_j)^2 + \mathrm{Rest}_j] \qquad (4)\end{aligned}$$

where

$$\mathrm{var}_j = \frac{1}{12}\sum_i (h_{ij}-h_j)^2 \tag{5}$$

and the residue

$$\mathrm{Rest}_j = \frac{1}{6}(z_0-h_j)\sum_i (h_j-h_{ij}). \tag{6}$$

The first component in eq. (4) contains variance in the series due to fluctuations with period of 2 months to 2 years, and the second component the contributions due to periods longer than 2 years. The residue (third component) in the present analysis is of the order of 10^{-16} cm^2 (h Pa) and can therefore be neglected.

Using monthly means, yearly means and the whole series mean we have thus divided the total variance into the contribution from 2 months to 2 years and to contributions of longer than two years. By successive averaging over increasingly longer periods the technique [eq. (3)] can be used to determine the variance in arbitrary period bands. For example, from four month means, yearly means and the whole series mean we can divide the total variance into the period bands 8 months to 2 years and periods of longer than 2 years. The method was here used to partition the variance in the Baltic sea level and the Gibraltar/Iceland pressure difference into the period bands 2 to 8 months, 8 months to 2 years, 2 to 6 years, 6 to 12 years and 12 to 36 years for the timeframe 1830–1997.

3.2. *The winter variability*

To investigate the temporal development of the correlation between the winter (JFM) Baltic sea level and the winter NAO index, a moving correlation was used (e.g. Dean and Anderson, 1974). The correlation coefficient is calculated for a window of the series, here with a length of 21 years, and the value is assigned to the middle of the period. The window is then slid along the series with a one-year step at the time to give a successive series of correlation coefficients.

The frequency domains of the mean winter sea level and NAO index were analyzed by discrete Fourier transforms for the period 1826–1997. A Hanning window of length 86 years and a 43-point overlap was used. The same window was used to calculate the squared cross-coherency between the series. The averaging process into winter means gives the dominant peaks for periods from 2 years (Nyquist period) up to the length of the window.

3.3. *Regional air pressure index*

To construct a representative index of the regional atmospheric circulation at sea level, it was assumed that the standardized horizontal component of the air pressure difference is proportional to the tangential wind stress, i.e., the zonal geostrophic wind between two locations. Pressure differences at sea level were calculated between different locations in Europe. To determine the most appropriate geographical locations for Baltic Sea influence, the correlation coefficient between the winter mean of the air pressure differences and the winter mean sea level was calculated for the period 1902–1997. In order to increase the accuracy further, a linear combination of two air pressure differences (APD) was calculated by

$$\mathrm{BAC} = (1 - \alpha)\,\mathrm{APD}_1 + \alpha\,\mathrm{APD}_2 \tag{7}$$

where the weight factor symbol α was determined by optimizing the correlation for the Baltic atmospheric circulation index (BAC index) and the Baltic Sea mean sea level. As well as comparing the BAC index with the Baltic sea level, its adequateness was evaluated by comparison with the winter mean Kattegat sea level. Temporal changes in the connection between the BAC index and the Baltic sea level were also explored by the moving correlation technique.

4. Results

4.1. *Annual cycle of the NAO impact and variance distributions*

The annual cycle of the co-variability between the sea level and the Gibraltar/Iceland pressure difference varied considerably, with a significant correlation during the winter months and a low correlation during spring and summer (Fig. 2). A similar distribution of the correlation with the NAO index was also found for Swedish temperature anomalies (Chen and Hellström, 1999), confirming the large-scale atmospheric circulation influence in the region during winter. In the mean monthly variance, calculated according to eq. (1), the late autumn and winter months dominate, and both series show a maximum in February (Fig. 3), whereas the variance is low during the summer. The partitioning of the total variance into period

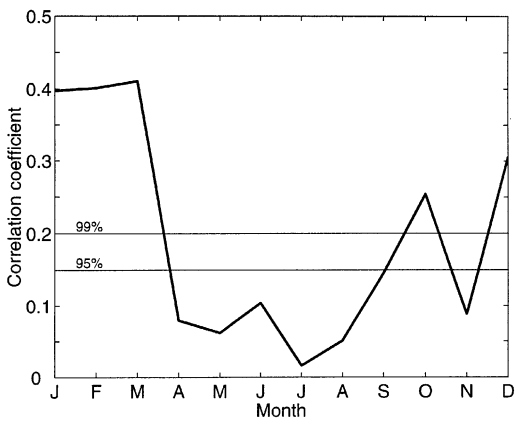

Fig. 2. The correlation between the monthly mean Gibraltar/Iceland pressure difference and the monthly mean Baltic sea level. The calculations are based on 173 year long time-series and are shown with the 95% and 99% significance levels.

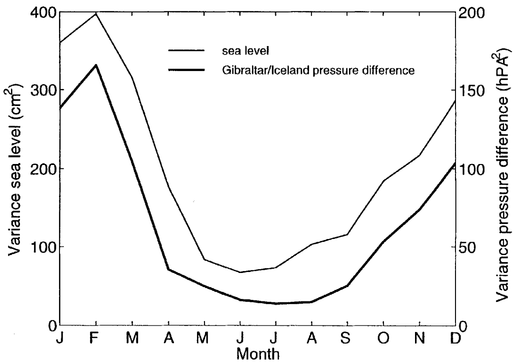

Fig. 3. The seasonal distribution of the mean monthly variance for the monthly mean Baltic sea level and the monthly mean pressure difference between Gibraltar and Iceland.

bands reveals for both series that the main part of the variance occurs in the bands 2–8 months and 8 months to 2 years (Table 1). The relative importance of low-period oscillations is, however, more prominent in the sea level record (cf. Samuelsson and Stigebrandt, 1996)

4.2. Winter variability

The winter means of the Baltic sea level and the NAO index, smoothed with a 3-year running average, for the period 1825–1997 is shown in Fig. 4. The co-variability of the two series is evident but reveals variation in time. The correlation coefficient for the whole period is 0.63. However, the first 86 years, from 1825 to 1911, have a lower correlation coefficient of 0.51 (99% significance level at 0.46). The correlation coefficient increased to 0.73 during the second half of the series (1911–1997). During the last 20 years the similarity of the two series is striking. The temporal evolution of the relationship between the NAO index and the Baltic sea level is illustrated by a 21-year moving correlation (Fig. 5). It can be seen that in the middle of the 19th century the correlation was low. The correlation then increased and, although varying, has fairly high values up until the 1960s. A rapid increase of the correlation can be seen in the last decades, reaching the all-time high for the investigated periods at the end of the series. Thus, the impact of the

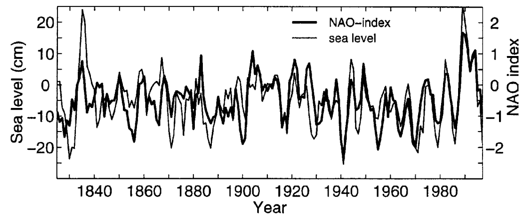

Fig. 4. The winter (JFM) mean of the Baltic sea level and the NAO index for the period 1825–1997, smoothed with a 3-year running mean.

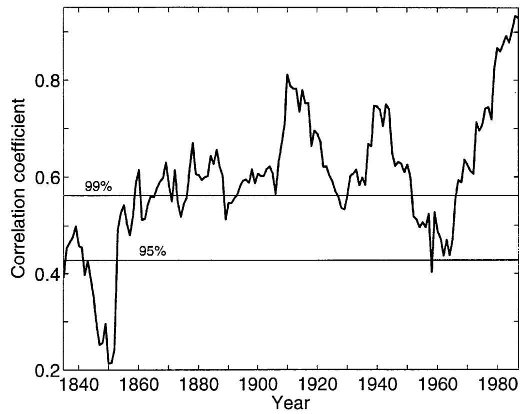

Fig. 5. The moving correlation between the winter (JFM) mean Baltic sea level and the NAO index. The correlation was calculated with a 21-year window and is shown together with the 95% and 99% significance levels.

Table 1. *Contribution to the total variance from different period bands for the monthly mean Baltic sea level and the Gibraltar/Iceland pressure difference calculated for the period 1830–1997*

	Total variance	2–8 months	8 months–2 years	2–6 years	6–12 years	12–48 years
Sea level (cm^2)	246.8	138.1	74.4	22.6	5.9	4.4
(% of total variance)	100	56.0	30.1	9.2	2.4	1.8
Pressure difference (hPa^2)	100.7	63.4	31.5	4.0	1.1	0.5
(% of total variance)	100	63.0	31.3	4.0	1.0	0.5

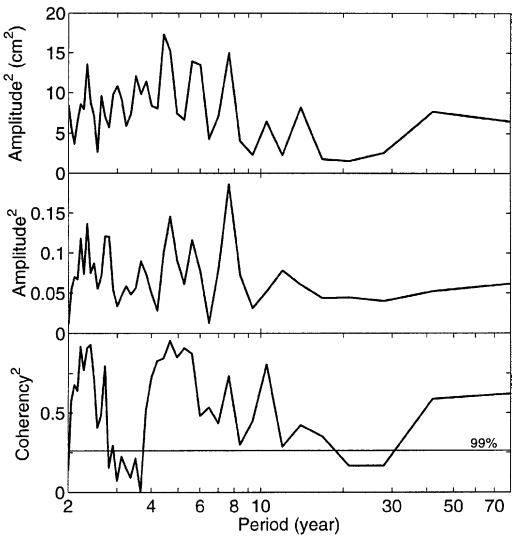

Fig. 6. The amplitude spectra of the winter (JFM) mean of the Baltic sea level (top), the NAO index (middle) and the squared cross- coherency between the two series (bottom).

large-scale atmospheric circulation, as represented by the NAO index, upon the Baltic sea level is not stationary in time.

The amplitude spectra of the winter NAO index and the mean Baltic sea level both show the most dominant peak for oscillations with a period at about 7 years (Fig. 6). This peak is also found in the squared cross-coherency spectra. High values of squared cross-coherency for oscillations with periods of approximately 4–6 years and also at 2.2–2.5 years and 2.7 years imply influence from the NAO on the Baltic sea level on longer time-scales in addition to the inter-annual variability.

4.3. Regional deviations from the wind field represented by the NAO index

The large temporal variability of the correlation between the Baltic sea level and the NAO index implies that the regional circulation over the North Sea at time deviates from that over the North Atlantic. To better reflect regional conditions, horizontal air pressure differences at sea level were determined between geographical locations shown in Fig. 1. Table 2 gives the various correlation coefficients between the winter mean of the normalized pressure differences and the winter mean Baltic sea level using data from the period 1902–1997. There is no obvious way to decide if the pattern seen in Table 2 is significant, but some features are interesting to notice. The calculations show that Gibraltar and de Bilt both give a good correlation when used as the southern location. Iceland is, however, not always appropriate to use as the northern point, as more eastern locations give better results. The highest correlation with the Baltic sea level is obtained when using the air pressure difference between de Bilt and Oksøy. The correlation coefficient is here as high as 0.89, while the correlation with the NAO index is 0.74 for the same period. The de Bilt–Oksøy pressure difference obviously well reflects the zonal geostrophic wind across the North Sea that causes variations in the sea level in Kattegat and which in turns causes variations in the Baltic sea level.

When using the regional BAC index [eq. (7)] the correlation with the winter mean Baltic sea level can be further increased. The best result is obtained by combining the air pressure differences between de Bilt and Bergen and between Gibraltar and Helsinki, with a weight factor $\alpha = 0.35$. The

Table 2. *The correlation coefficients between the Baltic sea level and the normalized air pressure difference between two locations. The calculations are based on winter (JFM) means from the period 1902–1997*

	Iceland	Torshavn	Bodø	Bergen	Oksøy	Göteborg	Lund	Stockholm	Haparanda	Helsinki
Gibraltar	0.74	0.74	0.87	0.77	0.78	0.78	0.70	0.85	0.88	0.87
Valentia	0.72	0.79	0.82	0.79	0.76	0.73	0.57	0.77	0.79	0.77
Aberdeen	0.47	0.64	0.73	0.70	0.57	0.45	0.05	0.58	0.64	0.55
De Bilt	0.64	0.74	0.84	0.88	0.89	0.88	0.81	0.85	0.80	0.81
Nordby	0.41	0.48	0.75	0.77	0.84	0.80	0.37	0.75	0.69	0.66
Lund	0.35	0.37	0.73	0.60	0.72	0.79	—	0.77	0.67	0.66

BAC index is shown together with the NAO index in Fig. 7. In Fig. 8 the BAC index is plotted against the Baltic Sea and Kattegat sea levels. The linear correlation coefficient between the BAC index and the sea level is 0.91 for the Baltic Sea and 0.93 for the Kattegat. The regional winter wind situation as described by the BAC index thus explains more than 80% of sea level winter variance in the respective seas. The linear regression between the BAC index and the sea level time series (Fig. 8) gives the following expressions for the Baltic sea level, h_{Baltic}, and the Kattegat sea level, h_{Kattegat}

$$h_{\mathrm{Baltic}} = 16.72 \times \mathrm{BAC} + 0.18 \tag{8}$$

and

$$h_{\mathrm{Kattegat}} = 11.06 \times \mathrm{BAC} + 0.02. \tag{9}$$

The difference between the proportionality constants is likely caused by the fact that the Stockholm sea level is not representing a true mean Baltic sea level. Amplitudes of oscillations longer than a month are in the Baltic amplified

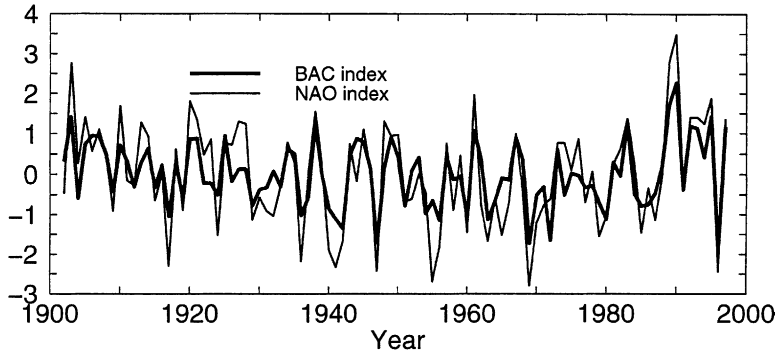

Fig. 7. The BAC index and the NAO index for the period 1902–1997.

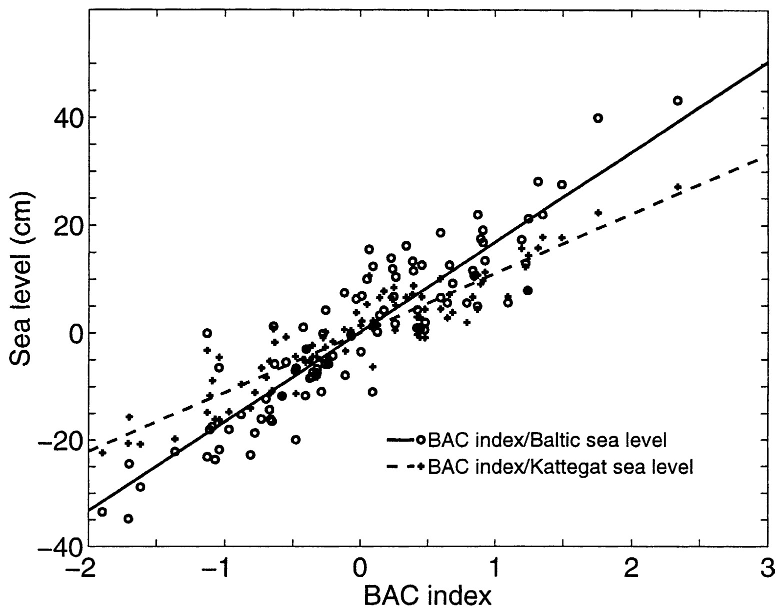

Fig. 8. The winter (JFM) BAC index versus sea levels in the Kattegat and the Baltic Sea. The two linear regressions are given by eqs. (8) and (9).

from the mouth towards the north (Samuelsson and Stigebrandt, 1996), and a linear regression between the monthly mean sea levels at Hornbæck and Stockholm gives a proportionality constant of 1.50. Figure 9 shows the respective model estimates [eqs. (8) and (9)] together with observed monthly mean sea levels. The chosen BAC index also correlates well with the Baltic sea level during autumn ($r = 0.86$) and summer ($r = 0.82$), although processes other than the mean zonal atmospheric circulation apparently increase in importance. During spring the correlation with the BAC index is lower ($r = 0.64$) but still significant. The NAO index gives very weak correlations with the Baltic sea level during these seasons.

The temporal variation of the winter correlation between the BAC index and the Baltic sea level is shown in Fig. 10 together with the correlation between the NAO index and the Baltic sea level. Although varying in time, the correlation with the BAC index is always high compared to the correlation with the NAO index.

During the 20th century the regional zonal wind field has been quite similar to the large-scale one represented by the NAO index. It can be seen in Fig. 11 that the co-variability of the air pressures

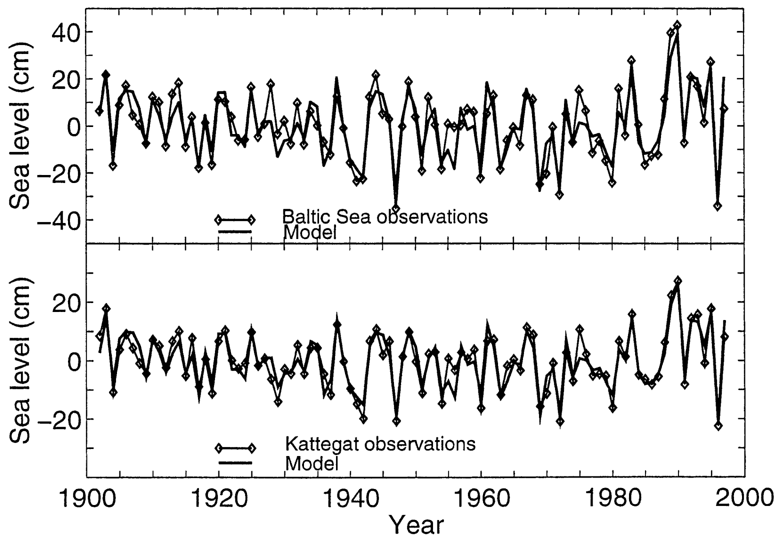

Fig. 9. The Baltic Sea (top) and Kattegat (bottom) winter mean sea level observations and modeled from eqs. (8) and (9), respectively.

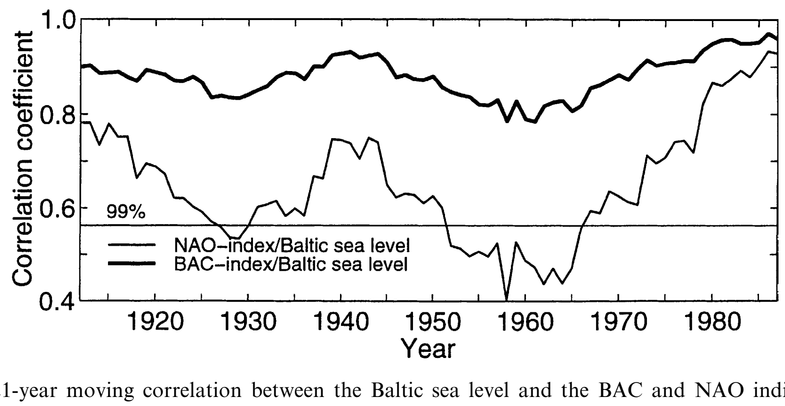

Fig. 10. The 21-year moving correlation between the Baltic sea level and the BAC and NAO indices during the period 1902–1997, together with the 99% significance level.

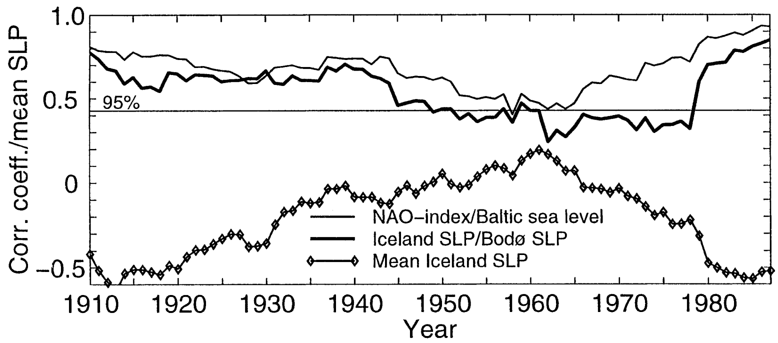

Fig. 11. The moving correlations between the NAO index and the Baltic sea level and between the normalized air pressures at Iceland and Bodø together with the magnitude of the normalized air pressure at Iceland. All calculations were done with a 21-year window for the (JFM) mean and are plotted with the 95% significance level of the correlation calculations.

at Bodø and Iceland is high when the correlation between the Baltic sea level and the NAO index is high. The high correlation between the NAO index and the Baltic sea level increases/decreases when the air pressure in Iceland decreases/increases. This relationship is not equally clear in the 19th century (not shown).

5. Discussion

5.1. *NAO impact on the Baltic sea level*

In this paper it has been shown that there is a significant co-variability between the Baltic Sea winter mean sea level and the winter NAO index. Hurrell and van Loon (1997) identified significant variance in the winter NAO index at biennial periods and for periods of 6–10 years. Those are in agreement with the peaks appearing in the cross-coherency spectra of the NAO index and the Baltic sea level in the present paper. Peaks for oscillations with periods of 2.2–2.3, 5–6 and 7–8 years have also been identified in various other climatological time series (e.g. Alenius and Makkonen, 1981; Hurrell and van Loon, 1997; Chen and Hellström, 1999). It can be concluded that the large-scale zonal wind component over the North Atlantic has a significant effect on sea level oscillations in the Baltic Sea, through its mimicking of the Kattegat sea level, on time-scales of more than a month. This is also the cause for obtained connections between large-scale atmospheric pressure field anomalies and anomalies in the Baltic sea level, using statistical downscaling techniques (Heyen et al., 1996).

The dependence on the atmospheric circulation over the North Atlantic does, however, vary considerably in time. The correlation was weaker during the 19th century than during the 20th. A highly variable correlation with the NAO index in the region has also been demonstrated for temperature anomalies in Sweden (Chen and Hellström, 1999) and at Copenhagen (Hurrell and Van Loon, 1997). During the last decades the correlation between the NAO index and the Baltic sea level has been particularly strong. Plag and Tsimplis (1999) observed a narrowing of the zone between maritimely influenced climate north and continentally influenced climate south of the Baltic Sea entrance during the last 30 years. The concurrence of the intensification and phase shift in the annual cycle of the sea level in their study coincide with the increase in the NAO index connection commencing in the 1960s as seen in the Stockholm mean winter level. Why the connection between the NAO index and the Baltic sea level lately has increased is not readably answered. There is not an obvious connection between a high index value and a strong co-oscillation. High positive NAO index values also occurred in the middle of the 19th century and in the beginning of the 20th century, without showing the same impact on the Baltic sea level as in the last decades. The period 1988–1995 is, however, the longest observed continuous time frame of positive NAO index values, with the highest positive period mean of 2.0 (e.g.

compared with the period 1902–1908 with the period mean of 1.4).

A shift of the center of action of the Icelandic low (Rogers, 1985; Hilmer and Jung, 2000) effects regional winds but will not be seen in the NAO index, which uses two fixed locations. The concurrence of a high correlation between the NAO index and Baltic sea level and a high correlation between sea level air pressure at Iceland and the west coast of Norway (Fig. 11) indicates a more north-eastward location of the Icelandic low pressure center at these times. This gives rise to a steeper, meridional pressure gradient closer to the North Sea than a more westward location of the pressure center would do. Sea level air pressure pattern anomalies for the period 1978–1997 also show more easterly locations of the NAO associated pressure centers, compared to the period 1958–1977 (Hilmer and Jung, 2000). Simulations with a general circulation model by Ulbrich and Christoph (1999) showed a north-eastward shift of the pressure center, under an increased greenhouse gas scenario, compared to the control run. The question arises, wheather we can expect an enhanced NAO impact on the Baltic Sea in future and what affect this will have on the state of the Baltic Sea. Major Baltic Sea inflow events are associated with atmospheric oscillations with a period of about 1–2 months, causing a massive sea level shift in the Kattegat from low to high (Lass and Matthäus, 1996; Gustafsson and Andersson, 2001). More persistent westerly winds during winter might prevent large-amplitude sea level fluctuations needed for major Baltic Sea inflows.

5.2. *Regional climate variability*

It has been found in the present study that an index of pressure differences closer to the Baltic Sea entrance can accurately describe the winter mean Baltic sea level because of the close relation between the regional winds and the Kattegat sea level. The winds are usually strong during the winter and, as wind stress on the sea surface is proportional to the square of the wind speed, the large-scale winds have more impact on the Baltic Sea in the winter. Also mean seasonal values from autumn, summer and spring of the regional index correlate significantly with the Baltic sea level. Apart from the winter season, the NAO index is too crude to be used as a measure of the regional atmospheric circulation. When the geostrophic wind stress over the Baltic Sea entrance area is weak, the major influence on the Baltic Sea mean sea level can, however, come from more local processes as well as from other processes acting on mean sea levels in the North Sea and the North Atlantic. The inverse barometric effect on the Kattegat sea level was considered in the present study using the winter mean of the air pressure at Göteborg, but the effect was very small on the winter mean sea level (not shown). Although the variance in atmospheric pressure is high during the winter months, the main part (more than 80%) of the variance in the Kattegat sea level is caused by fluctuations with periods of less than 2 months (Stigebrandt, 1986). The inverse barometric effect on Baltic Sea monthly mean level is also small, less than one percent of the variance (Wróblewski, 1992). Local and regional steric effects, due to changes in salinity and temperature, also have impacts on the mean sea level. The local steric annual amplitude is about 5 cm in the North Sea (Pattullo et al., 1955) and only about 2 cm in the Baltic Sea (Ekman and Stigebrandt, 1990). However, density variations in the North Atlantic may possibly force some of the annual sea level variations in the Baltic Sea (Stigebrandt, 1985). Carlsson (1998a, 1998b) analyzed the mean sea level topography within the Baltic Sea. She found that at Landsort, close to Stockholm, the effect of air-pressure gradients within the Baltic Sea gave rise to a higher mean sea level during the winter months, underestimated by model runs forced only by water exchange with Kattegat and freshwater supply. The contribution from freshwater supply to the Baltic Sea winter mean sea level is quite small (Carlsson, 1998a), but local river runoff from lake Mälaren can influence the Stockholm sea level record.

The length and quality of the Stockholm sea level record makes the monthly mean sea level record a useful index in itself, and a better index for the regional atmospheric variability than the NAO index. Ekman (1997) showed that years with extremely high (low) annual mean sea levels correspond to considerably warmer (colder) winter temperatures in Stockholm as well as much smaller (larger) ice extents in the Baltic Sea, demonstrating further the coupling between atmospheric circulation and sea level amplitude. The

NAO index has recently been used to study regional responses of ecosystems to climate variability (e.g. Fromentin and Planque, 1996; Belgrano et al., 1998; Post and Stenseth, 1999; Nordberg et al., 2000) and sea ice variability in the Baltic Sea (Koslowski and Loewe, 1994; Loewe and Koslowski, 1998). Since the connection with the NAO index is not a stationary one, a regional index can benefit similar studies in the detection of climatological dependencies.

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