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TELLUS

Influence of large-scale atmospheric circulation on European sea level: results based on the wavelet transform method

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ABSTRACT

We examine relationships between the variability in the long-term time series of European sea level and the large-scale atmospheric circulation represented by the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) indices using the wavelet transform (WT). Results demonstrate that between 10% and 35% of the variance in winter mean sea level may be explained by the atmospheric circulation influence. However, the relationship between atmospheric circulation and sea level shows remarkable changes over time, especially between the earlier part of the twentieth century and the 1990s. Four dominant signals with periods 2.2, 3.5, 5.2 and 7.8 yr are detected and analysed by the WT using time series of sea level typically 150 yr long together with the NAO/AO indices. Cross-wavelet power and wavelet coherence confirm the linkages between the two parameters for selective time periods.

1. Introduction

In this paper we focus on the long-term variability of the winter sea level along the European coast and in the Baltic Sea during the past one and half centuries and its relationship to the large-scale atmospheric circulation represented by the North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) winter indices. The questions we address are the following. How strong are the relationships between the NAO/AO and sea level? How much of the variability in sea level can be explained by the atmospheric indices? How stable are the relationships over time?

The AO, the Northern Hemisphere (NH) annular mode, is a key aspect of climate variability in the NH. The AO is defined as the leading empirical orthogonal function (EOF) of NH sea level pressure (SLP) anomalies poleward of 20°N (Thompson and Wallace, 1998), and characterized by an exchange of atmospheric mass between the Arctic and middle latitudes. The NAO is the best-known mode of atmospheric variability in the North Atlantic sector, and has long been recognized as a major circulation pattern influencing climate over the North Atlantic, Europe and North America (Dickson et al., 1996; Hurrell, 1996). The NAO is characterized by a north–south SLP pattern, with centres located over Iceland and the Azores Islands. Wallace (2000) argues that the NAO and AO represent a single phenomenon, and the NAO may be viewed as a regional manifestation of the AO for the North Atlantic sector. Although the AO winter index is highly correlated with the NAO winter index (Deser, 2000; Jevrejeva et al., 2003; Kodera and Kuroda, 2003), there is a considerable controversy as to whether or not the AO and NAO are similar entities, and it is not clear whether the mechanism governing the AO variability is similar to that of the NAO (Deser, 2000; Ambaum et al., 2001; Monahan et al., 2001). The forcing for the NAO and AO, and the impacts of the NAO and AO on the North Atlantic sector, remain open questions.

In our previous studies (Jevrejeva and Moore, 2001; Jevrejeva et al., 2003) we found that the time series of the NAO and AO winter indices consist of the same leading signals with identical quasi-periodicity 2.2–2.4, 7.8 and 12.8 yr. On the other hand, there were remarkable differences in development of these signals over time, dissimilar time–frequency patterns and different contributions from these signals to the total variance. Additionally, striking differences in behaviour revealed by low wavelet coherence between the leading signals of the NAO and AO during 1920–1950, and a shift in the period of maximum coherence from 2–7.8 to 7.8–20 yr around 1950, motivated us to utilize both the NAO and AO winter indices in the present study.

In the last decade, there has been a growth in observational and model studies that suggest that there is a link between the NAO and North Atlantic Ocean variability (e.g. Deser and Blackmon

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1993; Marshall et al. 2001). As shown by Wanatabe and Kimoto (2000) and Frankignoul et al. (1998), a leading pattern of sea surface temperature (SST) variability in the North Atlantic is a direct response of the ocean to the anomalous air–sea fluxes driven by the NAO. Variability in the temperature of the upper subtropical ocean (Molinari et al., 1997) and interdecadal variations in the intensity of ocean gyres (Curry and McCartney, 2001) are related to NAO forcing. It was also found that changes in the mean circulation pattern over the North Atlantic are accompanied by pronounced shifts in the storm tracks (Merkel and Latif, 2002). With regard to these considerations, we expect sea level to vary with changes in the NAO/AO, since sea level is an integrated indicator of climate variability, which reflects changes in the dynamics and thermodynamics of the atmosphere, ocean and cryosphere. Changes in the NAO/AO would generate a sea level response through a number of processes: the direct influence of changed atmospheric pressure; changes in wind stresses; and changes in atmosphere–ocean fluxes leading to ocean density changes. Additionally, there are impacts from wind-driven oceanic circulation and storm surges, linked to the state of the NAO/AO (Bacon and Carter, 1991). Fluctuations in any of these components could affect the sea level variability.

Recently published results show that the NAO modulates sea level in the Baltic Sea (Andersson, 2002) and in the Mediterranean Sea (Tsimplis and Josey, 2001). The connection between changes in the NAO and sea level over the north-west European continental shelf was investigated for the period 1955–2000 using a two-dimensional model of tides and storm surges together with tide gauge data (Wakelin et al., 2003). The results show an increase in correlation between the periods 1959–1979 and 1980–2000 (Wakelin et al., 2003); a similar tendency was also detected by Andersson (2002).

Here we focus on the long-term variability of winter sea level along the European coast and in the Baltic Sea over the past one and half centuries. We do not modify our time series by eliminating long-term trends, which may be caused by long-term ocean or meteorological forcing or by vertical land movements; we preserve all statistical properties of the time series. It is assumed that the time series can be considered as a combination of long-term trends, quasi-periodic oscillations and noise. We focus on quasi-periodic oscillations with periodicities less than 30 yr only. We discuss the influence of the NAO and AO on sea level variability in the time–frequency domain, investigating the significant components of each of the long-term time series, their inter-relationships and how the relationships have developed over time. This is achieved by using the advanced spectral methods: wavelet and wavelet coherency. Wavelet analysis is used to isolate the time-scales of sea level variability, while the method of wavelet coherency is used to examine the link between sea level and NAO/AO variance. We present new results from analysis of the longest time series from the Baltic Sea: Swinoujscie (since 1811), Tallinn (1835) and Kronstadt (since 1835).

2. Data

We examined the longest time series of sea level from the coastal observation stations situated along the European coast and along the Baltic Sea collected by the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player, 2003). Data, detailed information and plots of time series can be found at http://www.pol.ac.uk/psmsl. Additionally, sea level data sets from Kronstadt (Bogdanov et al., 2000) and Tallinn (Jevrejeva et al., 2000) from the Baltic Sea were analysed. The locations of the tide gauges are given in Fig. 1. Most of the time series span a 150-yr period (Table 1). Missing data in the time series of mean sea level were reconstructed by linear interpolation from nearby gauges, where correlation coefficients were not less than 0.8.

Atmospheric circulation is represented by the NAO winter index (1825–1999; Jones et al., 1997) and the AO

Table 1. Description of the data sets

Location	Observation period	Missing years	Number of missing years
Aberdeen	1862–2001	1975–1980	6
Brest	1807–2000	1835–1846 1856–1861 1943–1952	28
Cuxhaven	1843–2001		
Delfzijl	1865–2001		
Esbjerg	1889–1997		
Kronstadt	1835–1993		
Maasluis	1848–2001		
Marseille	1885–2000	1997, 1998	2
Newlyn	1916–2001		
Swinoujscie	1811–1999	1945–1950	6
Tallinn	1842–1995		
Travemunde	1856–1984	1985–1992	7
Wismar	1848–1999		

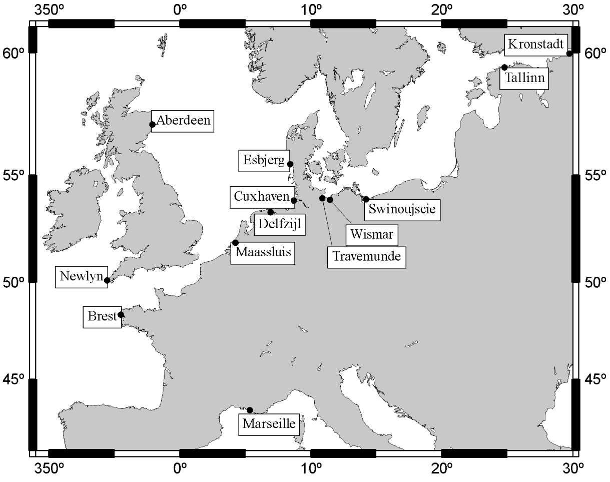

Fig 1. Location of the stations used in this study.

winter data (1851–1997) produced by Thompson and Wallace (1998).

The NAO influence on climate persists throughout the year, although it is stronger in winter than in other seasons, when the NAO presents the strongest pressure gradients (Hurrell, 1996). Additionally, we focus on the winter seasons when, through strong heat fluxes at the surface and deeper mixed layer in the ocean, the atmosphere is likely to be most strongly linked to the ocean (Lamb, 1984). In this paper we show only the results from analysis of the relationship between the calculated winter mean sea level (December–March) and the corresponding NAO/AO winter index time series. A detailed analysis of the relationship between monthly mean sea level and monthly NAO/AO throughout the year was performed. Our results reveal that the strongest influence of large-scale atmospheric circulation on the mean sea level is during the winter season only.

For the running correlation analysis the linear trends were extracted from time series in order to compare them with previously published results. For the wavelet analysis, the original data sets were used.

The variability in time series of winter sea level was analysed on time-scales of two years and longer. Oscillations with 2–12 yr periodicities are called ‘high-frequency signals’, 13–30 yr are called ‘low-frequency signals’, and longer than 30 yr are called ‘low-frequency non-linear trends’.

3. Statistical methods

Wavelet transform (WT) is a tool for analysing localized variations of power within a time series (Foufoula-Georgiou and Kumar, 1995). The WT of a time series is its convolution with the local basis functions, or wavelets, which can be stretched and translated with flexible resolution in both frequency and time. By application of WT, we decompose the time series into time–frequency space, in order to determine both the dominant modes of variability and how those modes vary in time (Torrence and Compo, 1998). Wavelet analysis provides a natural way of following gradual changes in the natural frequency of a climatic oscillator.

The ability of the wavelet techniques to capture variability in two time series was discussed by Torrence and Compo (1998) and Torrence and Webster (1999). They introduced the cross-wavelet spectrum, which is complex valued, and the cross-wavelet power, as the magnitude of the cross-wavelet power spectrum. In our study, the cross-wavelet power is calculated in order to estimate the covariance between two time series, and the wavelet coherence is calculated to measure the cross-correlation between two time series as a function of frequency.

We used the continuous wavelet transform (Morlet wavelet), as it is quite well localized in both time and frequency space. Statistical significance was estimated against a red noise model (Torrence and Compo, 1998). The phase relationship between two time series in time–frequency space is described by the phase angle, and the statistical significance of the phase angle was estimated against a red noise model (Jevrejeva et al., 2003).

To quantify the phase relationship between two time series, the circular mean of the phase for those areas with higher than 5% statistical significance was estimated (Jevrejeva et al., 2003). We calculated the 95% confidence value of the mean phase assuming a Von Mises distribution (e.g. Zar 1999). The spread of the Von Mises distribution is characterized by a parameter κ, which reveals the local phase field with respect to its information quality. For small κ, the phases tend to a uniform distribution and for large κ they tend to a normal distribution with variance $1/\kappa$.

We calculated wavelet coherence as a measure of the intensity of the covariance of the two series in time–frequency space (Torrence and Webster, 1999). We used Monte Carlo methods with red noise to determine the 5% statistical significance level of the coherence (Jevrejeva et al., 2003) and to provide the mean phase and its standard error at 95% confidence level.

Additionally we have used regression and running correlation methods.

4. Results

4.1. Results from regression and running correlation methods

There is a clear spatial pattern in the correlation between mean sea level and the NAO/AO in winter. The results from regression analysis show that the linear correlation coefficients between the time series of winter mean sea level and the NAO/AO winter index range across the region (see Fig. 2) from −0.51 in the south-west (Marseille) to 0.76 in the north-east (Kronstadt), which is consistent with a positive NAO winter index corresponding to the anomalously low atmospheric pressure in the north (high latitude) and high atmospheric pressure in the south (Central North

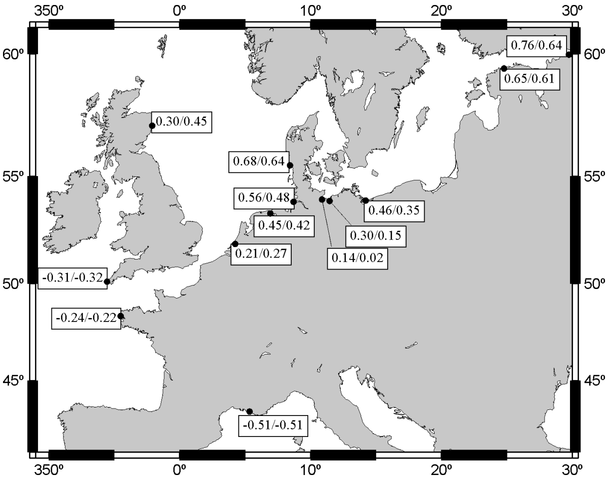

Fig 2. Correlation coefficient between the winter AO/NAO indices and the winter mean sea level time series.

Atlantic). This results in a hydrostatic increase and decrease in the northern and southern sea levels, respectively, which also leads to anomalies in atmosphere–ocean heat fluxes (e.g. Hurrell 1996; Pozo-Vázquez et al. 2001).

The highest correlation coefficients were found for the time series in Kronstadt, Tallinn (Baltic Sea) and Esbjerg (Danish coast of the North Sea). The distribution of coefficients in Fig. 2 suggests that strong westerly winds, the large potential for storm surges and the geographical setting of the observation place (such as on the eastern side of basins) are essential factors in the relationship between the NAO/AO winter index and sea level. The NAO/AO plays the role of a master switch for shifting storm tracks (Merkel and Latif, 2002) and the geographical distribution of correlation coefficients is in good agreement with the modelling results by Wakelin et al. (2003), emphasizing the major role of increasing westerly winds and increasing surge levels during the strong positive NAO winter index, when the surge component of sea level is greatest.

The correlations between the AO and sea level time series are higher than the correlation coefficients between the NAO and sea level, which is consistent with the results of Thompson and Wallace (1998), showing that the AO accounted for 42% of European wintertime temperature variation, while the NAO explained only 32%.

To investigate the evolution of the relationship over time, a running correlation analysis was performed. Figure 3 displays the running correlation coefficients between the NAO winter index and winter mean sea level, showing the considerable fluctuation of the correlation coefficients. The fact that the relationship is not stable indicates that other processes, not encompassed by the indices, are important and may have changed over time. Most time series demonstrate decreasing of correlation coefficients around 1900–1920, which is in good agreement with results for Stockholm published by Andersson (2002). Our results are also consistent with an increase in correlation between the periods 1959–1979 and 1980–2000 presented by Wakelin et al. (2003). No correlations significantly different from zero were found for Wismar (Fig. 3f) and Travemunde (not shown) for the time period prior to 1960.

Running correlation coefficients between the AO winter index and winter mean sea level (not shown here) display the same pattern, suggesting that the relationships between the

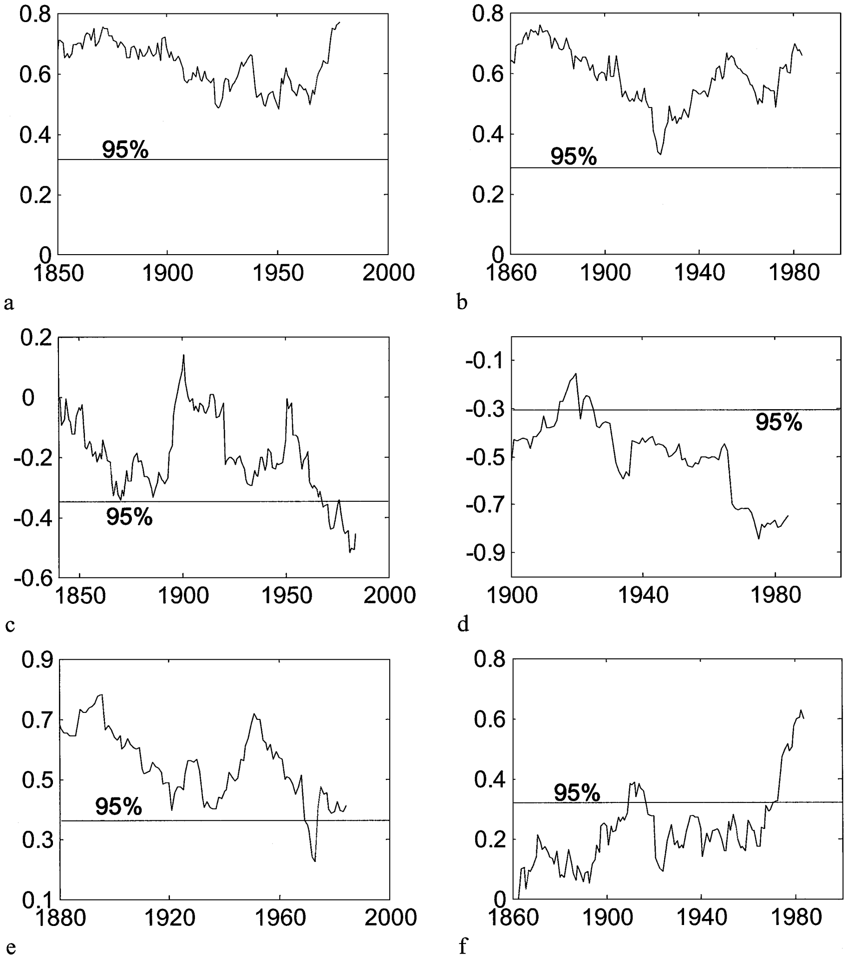

Fig 3. Running correlation coefficients between the NAO winter index and the winter mean sea level (30-yr window): (a) Kronstadt; (b) Cuxhaven; (c) Brest; (d) Marseille; (e) Aberdeen; (f) Wismar.

NAO/AO winter index and winter mean sea level is highly non-stationary.

4.2. Results from the wavelet transform

4.2.1. High-frequency variability associated with the NAO/AO. To isolate the different time-scales of variability, and to analyse the changes of variance in the time series of sea level, the Morlet wavelet was applied. Figures 4 and 5 show the wavelet power spectrum of the winter NAO/AO index and sea level, displayed as a function of the period and time. The left axis is the Fourier period; the bottom axis shows the time in yr. The strong non-stationary behaviour of the spectra is clearly seen. There is no evidence for a single persistent temporal mode of variability in the time series of NAO/AO indices and sea level during the observation periods and the amplitude and

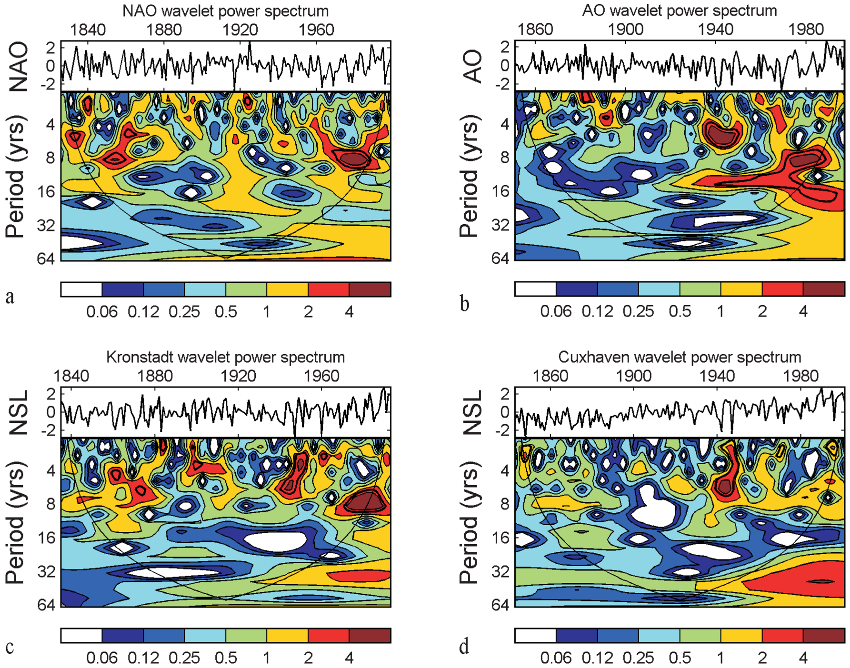

Fig 4. Normalized time series (top plot) and wavelet power spectrum (Morlet) of (a) the NAO winter index and (b) the AO winter index. Normalized sea level time series (NSL) and wavelet power spectrum (Morlet) at Kronstadt (c) and at Cuxhaven (d). Contours are in variance units. In all panels, the black thick line is the 5% significance level using the red noise model; the solid line indicates the cone of influence. The colour bar represents normalized variances.

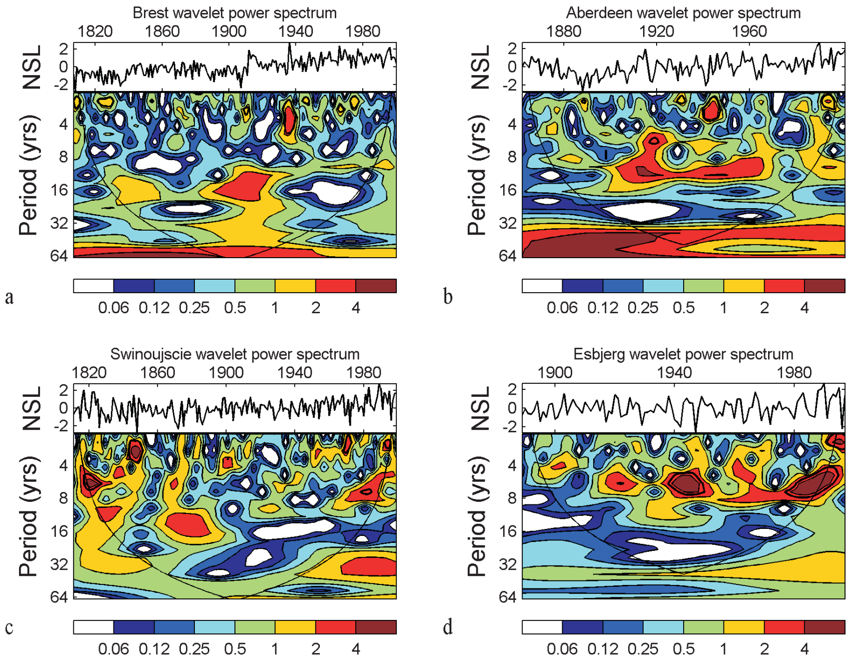

Fig 5. Normalized sea level time series (NSL) and wavelet power spectrum (Morlet) at Brest (a), Aberdeen (b), Swinoujscie (c) and Esbjerg (d). Contours are in variance units. In all panels the black thick line is the 5% significance level using the red noise model; the solid line indicates the cone of influence. The colour bar represents normalized variances.

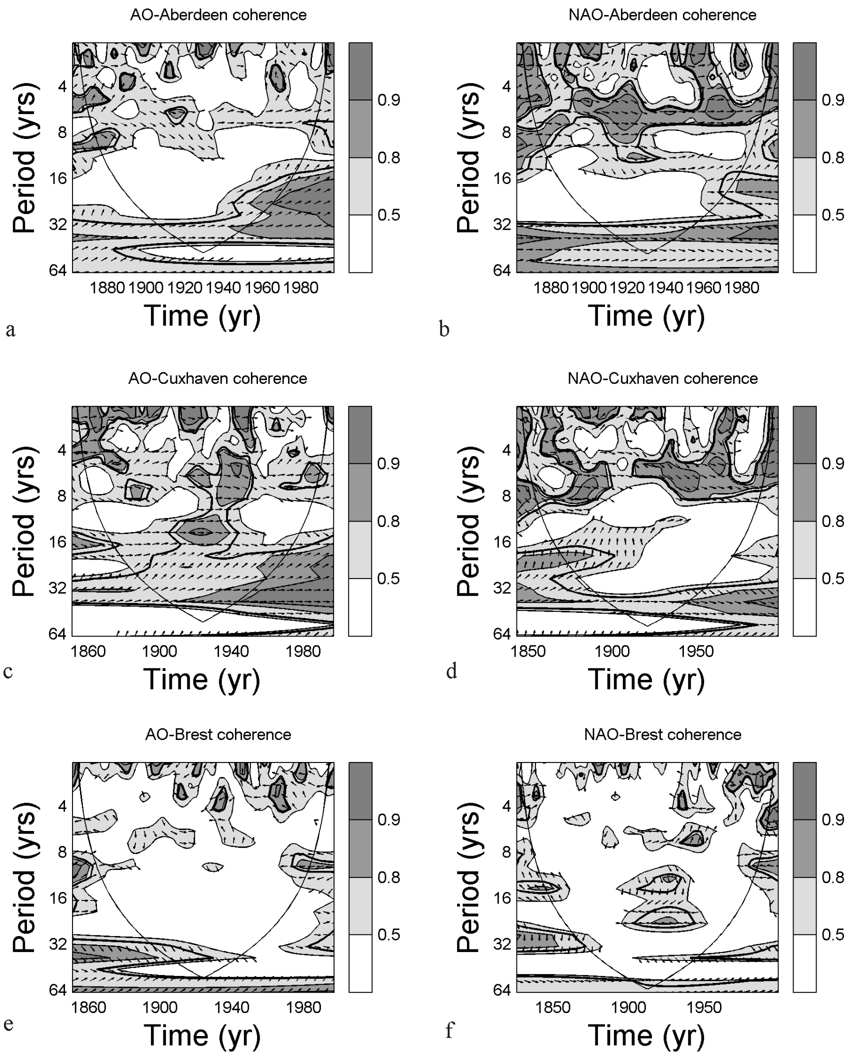

Fig 6. The wavelet coherency and phase between AO/NAO and sea level at Aberdeen (a, b), Cuxhaven (c, d) and Brest (e, f). Contours are wavelet squared coherences of 0.5, 0.8 and 0.9. The vectors indicate the phase difference between the AO/NAO and the mean sea level. In all panels, the solid line indicates the cone of influence.

strength of the modes of variability change dramatically with time.

Most of the time series show high power in the wavelet power spectrum at 2.2–3.5 and 5.2–7.8 yr periods (Figs. 4c , d and 5), which are associated with similar signals in the NAO/AO time series (Figs. 4a and b; Jevrejeva and Moore, 2001; Pozo-Vázquez et al., 2001; Andersson, 2002). All plots show increasing strength in 5.2–7.8 yr frequency bands since 1940.

To identify frequency bands within which time series of sea level and the NAO/AO index are covarying, the wavelet coherency method was used. Results demonstrate substantial influence from the NAO winter index on the variability of sea level in Aberdeen (Fig. 6b). The main contribution to variance is associated with the 5.2–7.8 yr band. High power is also seen in the 2.2–4 yr band for the time periods 1880–1900, 1940–1960 and around 1970. The phase difference is stable (0 ± 2°) in the area of significant coherence, with a rather chaotic pattern outside the region of significance (Fig. 6, Table 2).

Table 2. Statistics of phase difference between oscillations from time series of the AO/NAO and sea level

Location	AO Mean angle of phase difference	Kappa (κ)	NAO Mean angle of phase difference	Kappa (κ)
Aberdeen	349 ± 6	2.2	1.7 ± 2	7.1
Brest	190 ± 10	2.3	185 ± 13	1.1
Cuxhaven	354 ± 2	7.4	11 ± 3	3.9
Delfzijl	353 ± 4	6.5	12 ± 5	6.3
Esbjerg	16 ± 2	13.1	3 ± 1	11.1
Kronstadt	0 ± 2	11.9	8 ± 3	6.1
Maasluis	348 ± 9	1.8	10 ± 4	3.5
Marseille	163 ± 2	7.9	183 ± 5	3.6
Newlyn	180 ± 5	10.6	178 ± 8	2.2
Swinoujscie	6 ± 5	7.3	17 ± 8	4.0
Tallinn	4 ± 1	12	6 ± 3	5.1
Travemunde	359 ± 18	1.1	18 ± 24	1.6
Wismar	350 ± 6	3.1	5 ± 3	5.0

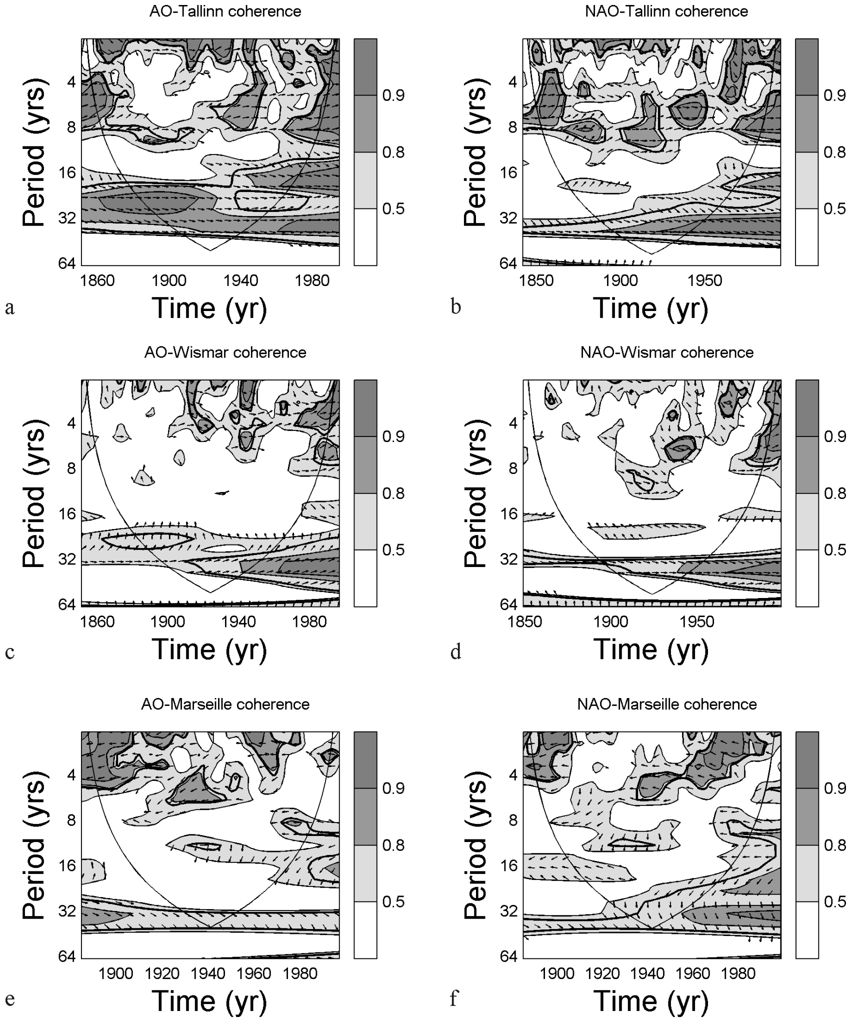

Fig 7. The wavelet coherency and phase between AO/NAO and sea level at Tallinn (a, b), Wismar (c, d) and Marseille (e, f). Contours are wavelet squared coherences of 0.5, 0.8 and 0.9. The vectors indicate the phase difference between the AO/NAO and mean sea level. In all panels, the solid line indicates the cone of influence.

A similar pattern is observed for the coherency between the NAO and Esbjerg (not shown here). There is less influence from the NAO on the sea level in Cuxhaven (Fig. 6d), although there is qualitative similarity. The NAO signature is mostly associated with the 5.2–7.8 yr signals between 1860–1900 and 1920–1980. The high-frequency signals (2.2–3.5 yr) contribute to the variance during 1860–1870, 1880–1900 and around 1960.

Figure 6a demonstrates that there is weak influence from the AO on the sea level in Aberdeen, and the phase difference is randomly distributed (Table 2). By contrast, there is a substantial influence from the AO on the sea level in Esbjerg (not shown here) and Cuxhaven (Fig. 6c). The AO signature associated with 2.2–2.5 yr oscillations is detected for the period 1860–1945. Signals with 5.2–7.8 yr periods show high coherence during 1880–1900, 1920–1950 and 1960–1980. The phase difference is stable inside the coherency areas (Table 2).

Results for Aberdeen are difficult to explain. It appears to be that 7.8-yr signals in sea level are associated with similar signals from the NAO as well as with identical signals in the SST of the North Atlantic Ocean (Moron et al., 1998; Jevrejeva and Moore, 2001). Recently published results by Rodwell et al. (1999), Latif et al. (2000) argue that the NAO variability is partly forced by global SST and sea-ice anomalies. Rajagopalan et al. (1998) and Tourre et al. (1999) show strong broad-band coherence between the NAO and the tropical Atlantic SST in the 8–20 yr period band, suggesting a significant mid-latitude–tropical interaction.

The relationships between the NAO/AO and mean sea level variability in Brest (Figs. 6e and f), Newlyn, Maassluis and Delfzijl (not shown here) are also rather weak. Most of the results for the phase difference are not statistically significant (Table 2). The influence from AO on the sea level in Brest is seen for the time periods 1880–1910, 1945–1950 and 1976–1982 via the 2.2–2.8 yr signals; for the period 1910–1915, 1930–1935 and 1960–1972 by the signals with 3.5–5.2 yr periodicities; over the last 30 yr there is a signature from 12–14 yr signals.

The wavelet coherency between the NAO/AO and sea level in Tallinn (Figs. 7a and b) and Kronstadt is greater than 0.8 for most of the record in the 2–8 yr band. There is a large influence from the 5.2–7.8 yr band during 1850–1870, 1930–1950 and since 1960. The influence from the NAO/AO on mean sea level in Swinoustje is weak. For the Wismar time series (Figs. 5c and d), the signature from the NAO is only seen around 1940 via the signals with 5.2–7.8 yr periodicity, around 1960 with 2.2–3.5 yr oscillations and since 1970 in the 2.2–7.8 yr band. According to the results from Kauker and Meier (2003), the NAO describes up to 50% of the SLP variance over northern Scandinavia, but only 10–30% of the variance over the Baltic Sea. The SLP pattern shows a strong meridional gradient over the Baltic Sea, causing strong zonal geostrophic winds, which influence sea level along the eastern coast of the Baltic Sea.

The influence from the NAO/AO on sea level time series of Marseille (Figs. 7e and f) is mostly shown in the 2.2–4.0 yr band until 1900, in the 5.2–7.8 yr band between 1930 and 1950, and 2.2–5.7 yr between 1950 and 1980. For the period 1900–1930 there is no signature of the NAO signals in the Marseille sea level. The considerable influence from the NAO/AO observed over the last 30 yr can be explained by the combined effect of atmospheric pressure anomalies and changes in evaporation and precipitation (Tsimplis and Josey, 2001).

In general, the NAO/AO winter index and European sea level time series show high coherency in the 2.2–3.5 and 5.2–7.8 yr bands during the observation period. Relatively low coherency of 2.2–7.8 yr signals during the time period from 1900 to 1930 suggests that sea level variability is driven by other processes at that time. Since 1940, there is a shift in the period of maximum coherence from 2.2–3.5 to 5.2–7.8 yr.

4.2.2. Low-frequency variability in time series of sea level. There are remarkable contributions from the low-frequency signals (12–18 yr periods) during 1880–1960 for Brest, Aberdeen (Figs. 5a and b) and Newlyn (not shown here), possibly related to the 13–15 yr period of variability in the SST (Moron et al., 1998), and variability in the heat transported by the thermohaline circulation, driven by the temperature and salinity differences in the Atlantic Ocean (Deser and Blackmon, 1993; Rajagopalan et al. 1998; Rodwell et al. 1999). Such changes in the thermal structure of the ocean can result in steric (density) sea level changes (Knutti and Stocker, 2000).

There is low-frequency (12–30 yr periodicities) variability in the Marseille time series (not shown here), perhaps linked to the deep water mass formation or water exchange between the Mediterranean Sea and Atlantic Ocean (Bethoux et al., 1998; Samuel et al., 1999). Time series from Cuxhaven, Esbjerg (Figs. 4d and 5d), Delfzijl and Maassluis (not shown here) do not show similar patterns.

Oscillations with 12–30 yr periods in wavelet power for the Baltic Sea time series are probably linked to the propagation of the Atlantic water masses through the Danish Straits and decadal variability in freshwater budget (Meier and Kauker, 2003).

There is no low-frequency variability in time series of the NAO and AO until 1940 (Figs. 4a and b), which is in agreement with results from Pozo-Vázquez et al. (2001). They found highly non-stationary behaviour in the NAO index and discovered that maximum power is concentrated in periods of less than 15 yr.

4.3. *Differences between the influence of the NAO and AO*

Decomposition of the time series of the winter NAO and AO indices shows that, in general, these time series are characterized by the same leading signals with near-identical quasi-periodicity (Jevrejeva and Moore, 2001; Jevrejeva et al. 2003), namely 2.2–2.4, 7.8 and 12.8 yr. However, Jevrejeva and Moore (2001) demonstrated that there are differences in how those signals change over time, and also different contributions from those signals to the total variance. The time–frequency patterns (Figs. 4a and b) are different for the NAO/AO time series.

For each analysed station, except Aberdeen, the influence of the AO is stronger than that of the NAO (Figs. 6 and 7). There is a dominant influence from the AO via signals with periodicities 2.2–3.5 and 5.2–7.8 yr prior to 1930. A shift from variability in 2.2–5.2 to 5.2–12.8 yr bands is detected since 1940. In general, the results show that the variability until 1930 was mostly determined by the signals in the 2.2–3.5 yr band, the variability during 1935–1950 is associated with signals 5.2–7.8 yr periodicities, and since 1960 there is a link to 7.8–12.8 yr oscillations. For the last 30 yr, the similarity in the NAO and AO wavelet power spectrum is primarily associated with 7.8–12 yr oscillations.

We believe that the AO winter index has a more direct physical link to sea level than does the NAO (and therefore has generally greater statistical significance), as the AO represents coupled stratospheric and tropospheric circulation variability that accounts for vertical planetary wave propagation. In our study we interpret the AO as a physical phenomenon associated with the split up of the polar vortex and related changes in the stratospheric and tropospheric fields. The AO index represents variance due to stratospheric vortex regime changes, which are picked up as the leading coherent pattern of variability (Ambaum and Hoskins, 2002). Additionally, the AO pattern, which is defined as a mean state of troposphere, not only of surface pressure field (Monahan et al., 2001), has a more zonal character than that shown by the NAO pattern (e.g. Deser 2000; Baldwin and Dunkerton 2001; Castanheira and Craf 2003). These considerations explain the higher correlation between the AO winter index and sea level time series compared with the NAO/sea level variability. The AO winter index and sea level are linked by the leading signals of AO to the sources of high-frequency variability (2.2–5.7 yr) via the stratosphere. The mechanism responsible for the linkage between the AO and tropical forces is not yet clear. However, for 2.2–3.5 yr quasi-biennial oscillations (QBOs) a mechanism has been described by Baldwin et al. (2001): the QBO modulates extratropical wave propagation, affecting the breakdown of the wintertime stratospheric polar vortices. The polar vortex in the stratosphere affects surface weather patterns providing a mechanism for the QBO to have an effect on high-latitude weather patterns, and hence on sea level variability.

5. Summary and conclusions

European tide gauge records back to 1800s have been used to examine the variability in time series of sea level and their link to the large-scale atmospheric circulation, represented by the NAO and AO winter indices. Our results demonstrate that there is a considerable co-variability between the winter NAO/AO index and winter sea level along the European coast during the last 150 yr via signals with 2.2–3.5 and 5.2–7.8 yr periodicities.

The NAO/AO seems to play a role in managing the westerly wind intensity and direction of storm tracks as well as pressure distribution. This explains why the influence from the atmospheric circulation is more clearly seen along eastern coastal areas in the path of strong westerly winds. Our results are consistent with modeling results from Wakelin et al. (2003), suggesting that during the winter seasons the wind stress is playing an important role, generating the storm surges, which contribute to the sea level variability.

For the Baltic Sea time series, the contribution from the atmospheric circulation is 10–35% of the variance. However, our results show that for the southern part of the Baltic Sea (Wismar, Travemunde, Swinoujscie) the influence from the NAO/AO is rather weak. This can be explained by the influence of a strong meridional gradient in SLP pattern over Baltic Sea, causing a strong zonal geostrophic wind, which affects sea level rise only along the eastern coast of the Baltic Sea (Kauker and Meier, 2003). Moreover, the study by Omstedt et al. (2004) shows a northward shift in the low-pressure tracks, linked to the observed upward trend in NAO during the last 30 yr (Merkel and Latif, 2002). In addition, there are some local effects such as regional steric effects (Stigebrandt, 1985); and the water exchange between the Baltic Sea and the North Sea (Heyen et al., 1996; Samuelsson and Stigebrandt, 1996).

In general, the relationship between the AO winter index and sea level is stronger than the NAO winter index/sea level relationship due to vertical planetary wave motion which connects the stratosphere and troposphere. This linkage is demonstrated by the ability of coupled stratospheric–tropospheric circulation models to reproduce the variability in the AO, where vertical planetary wave propagation is included (Ambaum and Hoskins, 2002; Castanheira and Craf, 2003).

Results also show that the relationship between the atmospheric circulation and sea level is not stable and varies considerably in time. The correlation is weaker during the nineteenth century when compared with the twentieth century. The highest correlation coefficients are during the last 30 yr, demonstrating an increasing influence from large-scale atmospheric circulation compared to the period prior to 1920. Similar results for the Stockholm time series were presented by Andersson (2002). A highly variable correlation with the NAO has also been demonstrated for the temperature time series in Europe (Moberg et al., 2000) and for the ice conditions in the Baltic Sea (Jevrejeva, 2002; Omstedt and Chen, 2001).

We have introduced new results from cross-wavelet and coherence analysis between the time series of long-term European mean sea level and the atmospheric circulation patterns represented by the NAO and AO winter indices. Decomposition of time series locally in both frequency and time provides us with a new view of the rather complicated variability in time series of mean sea level and its link to large-scale atmospheric circulation. We have found the signature of the 2.2–2.8, 3.5, 5.2–5.7 and 7.8-yr oscillations associated with the NAO and AO in time series of mean sea level, and a shift from variability in 2.2–5.2 to 5.2–12.8 yr bands is detected since 1940. Cross-wavelet power and wavelet coherence confirm the linkages between the atmospheric circulation and variability in sea level for a selective time period. Our results from long-term sea level records show that the amplitudes and relative strength of the detected signals change dramatically over time, illustrating that relationships detected for relatively short time periods should be carefully used in climate reconstruction or prediction.

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