Sclerochronological records of *Arctica islandica* from the inner German Bight

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Abstract: Sclerochronological records of interannual shell growth variability were established for eight modern shells (26 to 163 years of age) of the bivalve *Arctica islandica*, which were sampled at one site in the inner German Bight. The records indicate generally low synchrony between individuals. Spectral analysis of the whole 163-yr masterchronology indicated a cyclic pattern with a period of 5 and 7 years. The masterchronology correlated poorly to time series of environmental parameters over the last 90 years. High environmental variability in time and space of the dynamic and complex German Bight hydrographic system results in an extraordinarily high 'noise' level in the shell growth pattern of *Arctica islandica*.

Key words: *Arctica islandica*, German Bight, sclerochronology, time series, environmental variability, spectral analysis, masterchronology.

Introduction

Holocene palaeoclimatic reconstructions for the North Atlantic have been predominantly carried out using annually banded terrestrial proxies, such as tree-rings or ice-cores (Cook and Kariukstis, 1990; Luterbacher *et al*., 2002; Davies and Tipping, 2004). The increment of such proxy is controlled by environmental parameters and thus a time series of the proxy reflects historic environmental conditions. Little is known about the influence of the terrestrial climate on the marine realm. So far, palaeoclimatic marine conditions have been reconstructed mainly from oxygen isotope ratios obtained from the calcified annual density bands in tropical corals (Nozaki *et al*., 1978). As these organisms are not present in boreal-cold waters, sclerochronological analysis (measurement of the variable growth increments) of bivalves, has become more attractive for retrospective environmental studies of the North Atlantic (Jones, 1981; Richardson *et al*., 1981; Krantz *et al*., 1984).

The bivalve *Arctica islandica* (Linnaeus, 1767) is a particularly useful marine 'recorder', owing to its longevity of >200 years (Thompson *et al*., 1980) and its occurrence in the entire North Atlantic (Nicol, 1951). First studies on *A. islandica* were carried out on the continental shelves along the US coast (Jones, 1983; Weidmann *et al*., 1994; Marchitto *et al*., 2000) and later in the Baltic (Brey *et al*., 1990; Zettler *et al*., 2001) and North Sea (Witbaard *et al*., 1996; Schöne *et al*., 2003). In the North Atlantic, as well as in the North Sea *Arctica* deposits annual growth bands (Jones, 1983), which show similar growth patterns within a population (Witbaard and Duineveld, 1990; Marchitto *et al*., 2000). Shell growth is controlled by at least one environmental parameter, such as water temperature, salinity, food supply and dissolved oxygen. Knowing the functional relation between shell growth and the parameter allows the reconstruction of this parameter as well as of marine palaeo-environmental conditions based on shell growth time series. Depending on the study site and its hydrodynamics, the growth steering factors vary. Water temperature and food supply are commonly found to be the dominant growth factors in *Arctica islandica* from offshore sites (Weidmann *et al*., 1994; Witbaard *et al*., 1997; Schöne *et al*., 2003). In more shallow waters, sea surface salinity (SSS) has been regarded as an essential factor (Zettler *et al*., 2001).

In general, the climate variability in major parts of the Northern Hemisphere is dominated by the North Atlantic Oscillation (NAO), a climate oscillation that strongly influences winter temperature and precipitation in the North Atlantic region (Hurrell, 1995; Portis *et al*., 2001). The states of the NAO are measured by an index, defined as the pressure difference between the Azores and Iceland, reflecting the strength of the westerly winds across the Atlantic basin

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(Hurrell, 1995, 1996). The westerly winds also have an impact on the salinity content in the German Bight (Becker and Kohnke, 1978; Heyen and Dippner, 1998).

Compared with offshore environments, less is known about the ecology of *Arctica* inhabiting dynamic estuary-like habitats such as the German Bight. This study analyses whether *Arctica islandica* living in the dynamic nearshore habitat of the German Bight is a suitable proxy for environmental parameters that allows reconstruction of past environmental conditions from sclerochronological time series (shell growth chronologies).

Study area

The German Bight is a shallow marginal sea (22 m average water depth) located in the southeastern part of the North Sea. Here, tides, wind, fluvial freshwater inflows and density differences cause a complex flow regime characterized by dynamic gradients and by large annual oscillations in salinity and water temperature (Mittelstaedt *et al.*, 1983). In the southern German Bight, SSS ranges between <25 psu in spring to 35 psu in late summer (Schott, 1966; Sündermann *et al.*, 1999), predominantly owing to the annual cycle in freshwater discharge of the rivers Elbe and Weser (Taylor and Stephens, 1980; Grabemann *et al.*, 1983; Heyen and Dippner, 1998), which attain their maximum values in March–April (Elbe: 718 m^3/s, Weser: 327 m^3/s; Lenhart *et al.*, 1996). Mean sea surface temperature (SST) varies between 2°C in February and >18°C in August (Radach *et al.*, 1995). Phytoplankton blooms occur in March/April and August (Reid *et al.*, 1990; Edwards *et al.*, 2001).

Material and methods

Shell samples

The eight shells of *Arctica islandica* used in this study were collected in May 2002 by a commercial fisherman with a beam trawl north of the East Friesian Island Spiekeroog in 15 to 20 m water depth along a transect of about 500 m length (Figure 1).

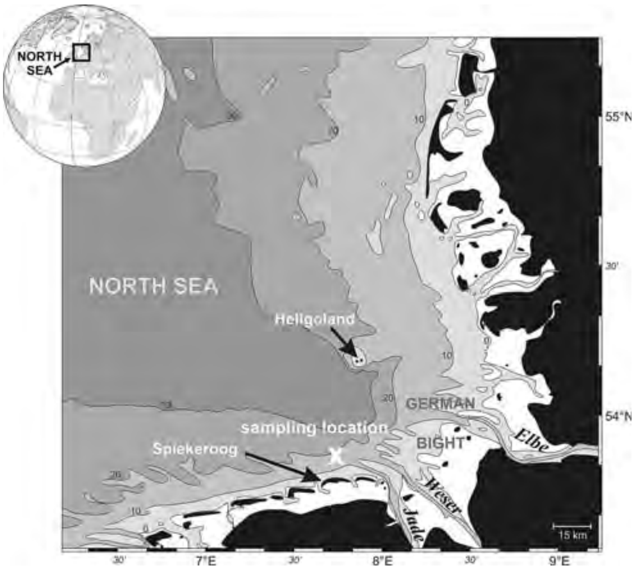

Figure 1 Bathymetric map of the German Bight showing the sample location of the bivalves

Shell growth

In *A. islandica*, a shell growth band increment represents the annual growth period (the amount of calcium carbonate deposited during the year). Each growth band increment is delimited by a growth line deposited in the colder winter months when shell deposition slows down or ceases (Merrill *et al.*, 1961; Thompson *et al.*, 1980) (Figure 2). Cross-sections and acetate peels were prepared of all left-hand valves following the method of Ropes (Ropes, 1985), additionally these cross-sections were etched with glutaraldehyde acetic acid (Mutvei *et al.*, 1994) after peel preparation to improve readability of the growth bands increments. In each shell section subsequent growth bands increments were identified and measured under a microscope. As all specimens were caught alive, it was possible to assign a particular calendar year to every growth band increment. Two different statistical methods were used to remove the ontogenetic trend (decreasing band increment width with age) of decreasing width of

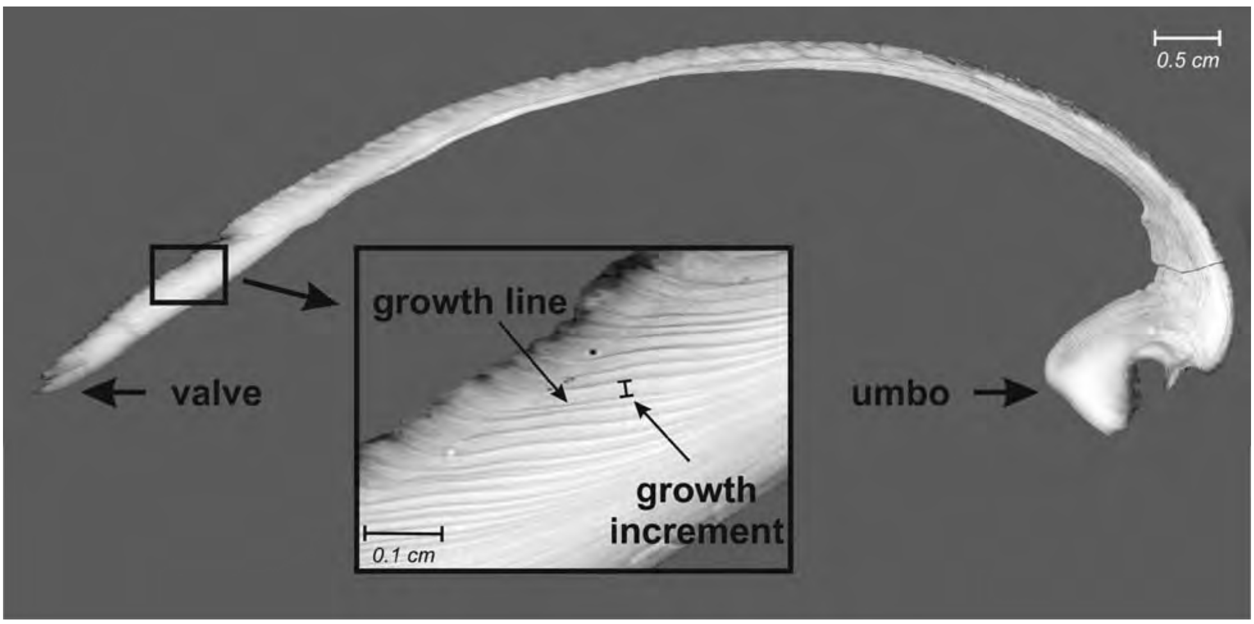

Figure 2 Cross-section of *Arctica islandica* from the German Bight with a shell length of 9.22 cm (from the outer shell to the umbo)

growth increment GI_i width with age i from the data. Standardized growth increments SGI were computed by (i) a 7-yr moving average filter (MAV)

$$SGI_{MAV,i} = \frac{GI_i}{\sum_{i-3}^{i+3} \overline{GI_i}} \tag{1}$$

and (ii) a simple exponent smoothing (SES) procedure:

$$SGI_{SES,i} = \frac{GI_i}{GI_{i,Predicted}} \tag{2}$$

where $GI_{i,Predicted}$ is the estimate of a simple exponential function fitted to the growth increment series. Detrending of growth increments GI resulted in a standardized time index series for each specimen which indicate whether or not the annual standardized growth increment SGI_{MAV} or SGI_{SES},

Table 1 List of environmental data sets used in the present study, including time span, measurement location and source

Environmental parameter	Time span	Data resolution	Recording location	Data source
SST	1880–2001	Monthly	Data field: 188 and 37	GISST, Version 2.3b (http://www.metoffice.com/research/hadleycentre/obsdata/GISSI.html)
SST	1873–1881	Monthly	Heligoland Reed (Isle of Heligoland)	Data provided by Federal Maritime and Hydrographical Agency, Hamburg, FRG (BSH)
	1883–1892			
	1908–1944			
	1960–1995			
SST+SSS	1924–1988	Annual	LV Weser 53°52′N 07°50′E	Light vessels (LV) positioned in the southern German Bight data provided by Federal Maritime and Hydrographical Agency, Hamburg, FRG (BSH)
			LV Amrumbank 54°33′N 07°53′E	
			LV Außeneider 54°13′N 07°18′E	
			LV Borkumriff 53°44′N 06°24′E	
			LV Bremen 53°47′N 07°08′E	
			LV Elbe 1 54°00′N 08°07′E	
			LV Elbe 4 53°56′N 08°40′E	
			LV P11 / P8 54°10′N 06°21′E	
			LV P15 / P12 LV 54°00′N 07°51′E	
SSS	1873–1881	Monthly	Heligoland Reed (Isle of Heligoland)	Data provided by Federal Maritime and Hydrographical Agency, Hamburg, FRG (BSH)
	1883–1886			
	1888–1893			
	1907–1919			
	1927–1944			
	1960–1995			
Elbe river discharge	1908–2000	Monthly	Gauge in Neu Darchau	Data provided by Local Waterways and Shipping Office, Lauenburg
Weser river discharge	1977–2000	Monthly	Gauge in Intschede	Data provided by Local Waterways and Shipping Office, Verden
Precipitation	1851–1997	Annually	City of Emden	Data available at Levitus and Boyer (1994) (retrieved 2 May 2006 from http://www.cdc.noaa.gov/cdc/data.nodc.woa94.html)
Chlorophyll *a*	1975–1976	Daily	East Friesian Isle of Norderney	Data provided by J.E.E. van Beusekom from the Alfred-Wegener-Institut für Polar- und Meeresforschung, Bremerhaven, Germany
	1978–1982			
	1984–1992			
	1994–2000			
Chlorophyll *a*	1966–2000		Heligoland Reed (Isle of Heligoland)	Data published by Radach and Bohle-Carbonell (1990)
Chlorophyll *a*	1997–2002	Daily	54.097°N, 7.86°E (in front of the Isle of Spiekeroog)	SeaWiFS (retrieved 2 May 2006 from http://daac.gsfc.nasa.gov/data/dataset/SeaWiFS)
Chlorophyll *a*	1966–1970	Hourly		Data provided by Federal Maritime and Hydrographical Agency, Hamburg, FRG (BSH)
	1974–1980			
	1985–2000			
Winter NAO index SL (Station Lisboa)	1864–2002	Annually		Data provided by Hurrell, (retrieved 2 May 2006 from http://www.cgd.ucar.edu/cas/jhurrell/indices.html)
Winter NAO index PC (principal component)	1899–2002	Annually		Data provided by Hurrell, (retrieved 2 May 2006 from http://www.cgd.ucar.edu/cas/jhurrell/indices.html)

respectively, during a particular year was above or below lifetime average (mean = 0, SD = 1).

From the eight standardized index series, a 163-yr masterchronology was constructed by computing the average SGI_{MAV} and SGI_{SES} per calendar year. Synchrony among the eight standardized time index series was analysed by the running similarity statistics using a white noise order of 1 (retrieved 2 May 2006 from http://www.unifrankfurt.de/~grieser/dfg/node40.html). Running similarity was assessed by the index G

$$G(a,b,...,m) = \frac{1}{n-1}\sum_{i=1}^{n-1}\left|\sum_{k=1}^{m} Gak,i\right| \quad (3a)$$

and

$$Ga,i = \begin{cases} \frac{1}{m} & \text{if} \quad \Delta_{a,i} > 0 \\ 0 & \text{if} \quad \Delta_{a,i} = 0 \\ -\frac{1}{m} & \text{if} \quad \Delta_{a,i} < 0 \end{cases} \quad (3b)$$

where $\Delta_{a,i}$ is the difference in SGI of two successive years ($\Delta_{a,i} = SGI_{i+1} - SGI_i$), n is the number of growth bands increments and m the number of shells compared. The running similarity index G ranges between 0 (perfect negative synchrony) and 1 (perfect positive synchrony).

A spectral density analysis (SAS-Institute, 2002) was applied to explore the 163-yr masterchronology for cyclic patterns.

Environmental data

Time series of available environmental data, such as SST, SSS, river discharge, precipitation, phytoplankton and atmospheric data, the NAO indices assumed to be relevant for the investigation area (the NAO indices assumed to be relevant for the investigation) were taken from published sources (Table 1). Unfortunately most data sets have gaps or cover a few years or decades at best.

Relations between environmental data and shell growth chronologies

Statistical relations between the *A. islandica* masterchronology and environmental data time series were analysed by correlation and partial correlation and subsequent construction of a multiple linear model (Deutsch, 2003). Owing to the large gaps in the SSS time series we decided to work with two data sets, one including SSS (55 years between 1908 and 1995) and one excluding SSS (83 years between 1908 and 2002).

Results

Shell growth chronologies

The age of the eight *A. islandica* specimens and hence the length of the shell chronologies ranged from 26 to 163 years covering the time span 2002–1840 (Figure 3). Synchrony between the growth patterns of the eight shells was very poor, as indicated by running similarity values between 0.30 and 0.64 (maximum overlap) and between 0.42 and 0.69 (26 year overlap), respectively (Table 2). Spectral density analyses indicates significant periodic components ($P < 0.05$) in the 163-yr masterchronology with distinct peaks between 5 and 7 years (Figure 4).

Relations between environmental data and shell growth chronologies

Correlations between the masterchronology and environmental parameter time series are poor, as no significant relation could be detected (Tables 3 and 4). Owing to the poor correlation, we abstained from the construction of a multiple linear model.

Discussion

The eight specimens analysed here show a low growth synchrony, as indicated by the running similarity values (Table 2, Figure 3). This is in contrast to the findings of Witbaard *et al.* (1996) and Schöne *et al.* (2003), who studied shells from offshore sites. We conclude that the poor synchrony results from the environmental conditions in the coastal sampling area. Situated just north of the Wadden Sea and within the Elbe-Weser estuary, this subtidal area is part of a highly dynamic region with extreme fluctuations in salinity, turbidity, temperature and other parameters. Tides in this area range between 3.5 and 6.2 m (Lassen and Siefert, 1991). North of the East Friesian Island Norderney tidal currents up to >1 m/s have been recorded (Umweltbundesamt, 1999). Tidal dynamics combine with wind-driven currents and river runoff dynamics. The Wadden Sea topography adds further spatial variability.

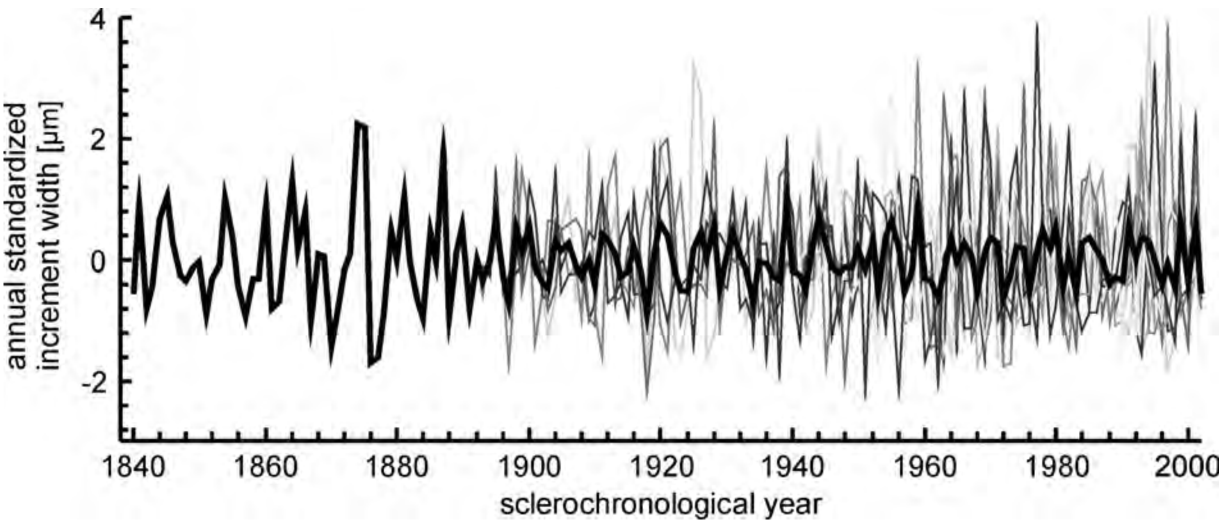

Figure 3 163-yr masterchronology (black line) of *A. islandica*. Grey lines indicate the eight standardized time index series the masterchronology is based on. Note that between 1840 and 1896 only one shell was available for the masterchronology, therefore amplitudes are higher than between 1896 and 2001

Table 2 Pair-wise calculation of running similarity between the eight specimens for 26 years (1976–2002) below the diagonal and for the period of maximum overlap, that is, lifetime of the younger specimen, above the diagonal (moving average standardization technique). Overall running similarity of all eight shells over 26 years is 0.50

Spec	SL (cm) Age (yr)	NSP 4	NSP 5	NSP 6	NSP 7	NSP 13	NSP 17	NSP 20	NSP 24
NSP 4	8.54 60		0.52	0.53	0.61	0.46	0.47	0.51	0.64
NSP 5	9.22 163	0.67		0.43	0.39	0.58	0.52	0.53	0.47
NSP 6	9.46 106	0.69	0.48		0.59	0.44	0.52	0.48	0.57
NSP 7	9.15 106	0.67	0.54	0.60		0.67	0.61	0.49	0.54
NSP 13	6.41 26	0.46	0.58	0.44	0.67		0.46	0.58	0.58
NSP 17	8.63 63	0.54	0.67	0.49	0.58	0.46		0.45	0.44
NSP 20	8.44 110	0.58	0.46	0.44	0.46	0.58	0.50		0.51
NSP 24	9.24 108	0.67	0.46	0.65	0.54	0.58	0.52	0.54	

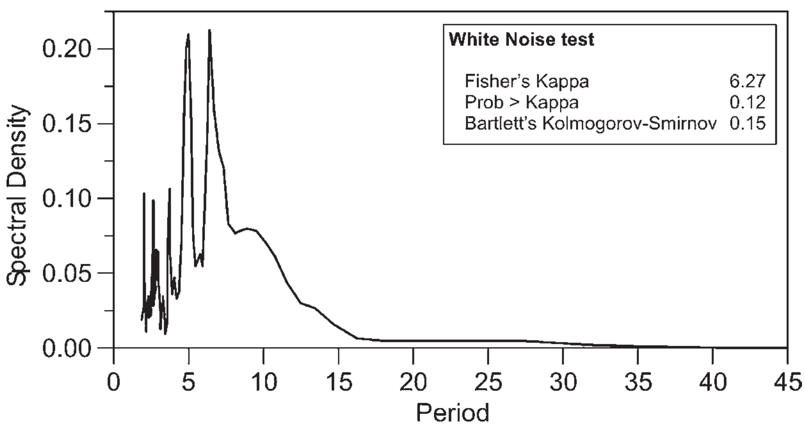

Figure 4 Spectral density analyses of the 163-yr masterchronology. The time series shows significant periodic components ($P < 0.05$). Note peaks between 5 and 7 years

Table 3 Correlations and partial correlations between environmental data (NAO, SST, Elbe river discharge and precipitation) and masterchronology of standardized growth increments SGI between 1908 and 2002 ($n = 83$). Coefficients in the first column refer to SGI_{SES} and coefficients in the first row refer to SGI_{MAV}. No SSS data are available for this time span

	Mean SGI_{MAV}	NAO (PC)	SST	Elbe discharge (Spring)	Elbe discharge (Summer)	Precipitation
Correlation matrix						
Mean SGI_{SES}		0.0084	– 0.0060	– 0.1113	0.0880	0.0140
NAO (PC)	– 0.0322		0.6498*	– 0.0119	– 0.4009*	– 0.1613
SST	0.0575	0.6498*		– 0.0138	– 0.4073*	– 0.0238
Elbe discharge (Spring)	– 0.0357	– 0.0119	– 0.0138		0.3899*	0.3939*
Elbe discharge (Summer)	0.0232	– 0.4009*	– 0.4073*	0.3899*		0.2351*
Precipitation	0.0520	– 0.1613	– 0.0238	0.3939*	0.2351*	
Partial correlation matrix						
Mean SGI_{SES}		0.0065	0.0081	– 0.1820	0.1600	0.0632
NAO (PC)	– 0.0669		0.5810*	0.1427	– 0.1954	– 0.1873
SST	0.1052	0.5810*		0.0461	– 0.2374*	0.1240
Elbe discharge (Spring)	– 0.0703	0.1427	0.0461		0.3838*	0.3507*
Elbe discharge (Summer)	0.0515	– 0.1954	– 0.2374*	0.3838*		0.0525
Precipitation	0.0528	– 0.1873	0.1240	0.3507*	0.0525	

*Significant at $\alpha = 0.05$.

Table 4 Correlations and partial correlations between environmental data (NAO, SST, SSS, Elbe river discharge and precipitation) and masterchronology of standardized growth increments SGI between 1908–1919, 1927–1944 and 1960–1995 ($n = 63$). Coefficients in the first column refer to SGI_{SES} and coefficients in the first row refer to SGI_{MAV}

	Mean SGI_{MAV}	NAO (PC)	SST	SSS (Win–Spr)	SSS (Spr–Sum)	Elbe discharge (Spring)	Elbe discharge (Summer)	Precipitation
Correlation matrix								
Mean SGI_{SES}		0.0212	−0.0118	0.0349*	0.0864	0.0870	−0.0530	0.0095
NAO (PC)	−0.0900		0.6953*	−0.2404	0.0809	−0.0440	−0.3906*	−0.0986
SST	−0.0328	0.6953*		−0.2153	−0.0410	−0.0449	−0.3843*	−0.0396
SSS (Win–Spr)	0.1624	−0.2404	−0.2153		0.5301*	−0.6127*	−0.3036*	−0.4107*
SSS (Spr–Sum)	−0.0034	0.0809	−0.0410	0.5301*		−0.5667*	−0.6421*	−0.3727*
Elbe discharge (Spring)	−0.0231	−0.0440	−0.0449	−0.6127*	−0.5667*		0.4872*	0.4746*
Elbe discharge (Summer)	0.0715	−0.3906*	−0.3843*	−0.3036*	−0.6421*	0.4872*		0.2044
Precipitation	−0.0231	−0.0986	−0.0396	−0.4107*	−0.3727*	0.4746*	0.2044	
Partial correlation matrix								
Mean SGI_{SES}		−0.0045	0.0213	0.1026	0.0866	−0.0712	0.1995	0.1035
NAO (PC)	−0.0116		0.5658*	−0.2554	0.0920	0.0196	−0.1538	−0.1453
SST	0.0840	0.5658*		−0.0814	−0.3112*	−0.0541	−0.3456*	−0.0542
SSS (Win–Spr)	0.2118	−0.2554	−0.0814		0.1960	−0.3844*	−0.0833	−0.2137
SSS (Spr–Sum)	0.0203	0.0920	−0.3112*	0.1960		−0.1311	−0.5715*	−0.1658
Elbe discharge (Spring)	0.0114	0.0196	−0.0541	−0.3844*			0.1962	0.2606
Elbe discharge (Summer)	0.1160	−0.1538	−0.3456*	−0.0833	−0.1311	0.1962		−0.2037
Precipitation	0.1455	−0.1453	−0.0542	−0.2137	−0.1658	0.2606	−0.2037	

*Significant at $\alpha = 0.05$.

The interaction of these factors may result in such small-scale variability in environmental conditions (eg, turbidity or food supply) that a strong random component is added to the growth pattern of each individual clam. The water temperature regime at shallow sites in the German Bight may be of particular significance. *A. islandica* is a temperate, cold water species (Cargnelli *et al.*, 1999). The presumed temperature optimum for adults is about 6–16°C, whereas temperatures >20°C cause mortality (Merrill and Ropes, 1969). Water temperature in the German Bight can rise up to 18°C in summer, taking *A. islandica* close to its thermal limits. This may enhance the clam's sensitivity to other environmental stress or even induce growth reduction or cessation.

We could not detect a correlation between our masterchronology and time series of environmental parameters relevant for the North Sea and German Bight (Tables 3 and 4). This is in contrast to studies by Schöne *et al.* (2003), where a highly significant linear correlation occurred between annual growth rates of *A. islandica* from the central North Sea and the instrumental winter NAO index. They report that positive winter NAO conditions result in higher shell growth rates, because shell growth is largely controlled by food supply (Witbaard *et al.*, 1997), which in turn is steered by winter NAO-induced forcing of atmospheric circulation.

Again, the dynamics of the nearshore German Bight may explain our results, although the spectral analysis of the 163-yr masterchronology indicated a cyclic pattern with distinct 5- and 7-yr periodicities, which are within the range of frequencies reported for instrumental winter NAO indices (Hurrell, 1995). Local variability in time and space obscure the large-scale superior parameters, thus preventing them from imprinting a clear signal on the clam growth history, and keeping synchrony of growth between specimens low, as discussed above.

Conclusions

High spatial and temporal environmental variability at our nearshore investigation site is assumed to be the major reason for the poor synchrony between specimens as well as between the masterchronology and time series of superior environmental parameters. The only way to check whether *A. islandica* from the German Bight does record large-scale superior parameters at all would be the analysis of many more individuals and of longer time series in order to cancel out the locally induced statistical noise. The spectral density analysis of the 163-yr masterchronology (Figure 4) indicates that it may be a worthwhile approach, because the distinct 5- to 7-yr periodicity detected is within the range of frequencies reported for instrumental and proxy NAO indices.

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