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Compound response of marine and terrestrial ecosystems to varying climate: pre-anthropogenic perspective from bivalve shell growth increments and tree-rings

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Abstract

Annual growth increments from shells of the ocean quahog (*Arctica islandica* L.) from northwest Norway and from tree-ring samples of the Scots pine (*Pinus sylvestris* L.) from nearby coastal areas. The reconstructed annual growth increments were used to compare growth variability in marine and terrestrial ecosystems. Spatiotemporal comparison of the growth records showed statistically significant correlation during the 19th century A.D., indicative of ecosystem-independent response to pre-anthropogenic climate variations. Geographical correlation between marine and terrestrial records was only observed at the local scale. Years with particularly low

winter or high summer North Atlantic Oscillation (NAO) indices showed the best synchronization of marine and terrestrial growth. Despite strong correlation during historical time, our palaeoecological evidence suggests that marine and terrestrial ecosystems may show dissimilar growth reaction to recently observed positive winter-NAO phases.

Keywords: coastal zone; climate change; palaeoecology; clams; atmospheric motion; sclerochronology; dendrochronology; North Atlantic Oscillation

Introduction

Records of change in oceanic, atmospheric and terrestrial systems are needed to enhance our understanding about the anthropogenic impact on different biomes. Such records can be either direct observations of environmental phenomena, or reconstructed series from natural archives that work as proxies for direct observations. In order to be comparable with one another, such proxy records must possess sufficient duration, similar temporal resolution and equivalent seasonal expression. Preferably, absolute dating control should be available. Appropriate records may be produced for aquatic and terrestrial ecosystems by means of sclerochronology (Jones 1983) and dendrochronology (Fritts 1976), using growth increment measurements derived from mollusc shells and tree stems, respectively. Sclerochronological and dendrochronological time series can be cross-dated within a given population (Douglass 1941; Fritts 1976; Marchitto et al. 2000; Helama et al. 2006) and can be directly calibrated against instrumental records (Fritts 1962; Fritts et al. 1971; Jones 1981; Jones and Quitmyer 1996), making them ideal proxy archives for such studies.

Natural variability over large parts of coastal Europe is greatly influenced by the coupled ocean-atmosphere system of the North Atlantic. Oceanic circulation transports heat and moisture towards the north, while extratropical atmospheric patterns typically control the transport of air masses over Western Europe (Hurrell et al. 2001; Wanner et al. 2001; Visbeck 2002). Intensity of heat and moisture transport is not stable, but exhibits notable temporal variability. These changes have great influence on regional ecosystems and society. This is especially the case in Fennoscandia where the climate (Hurrell 1995; Chen and Hellström 1999; Lee et al. 2000; Uvo and Berndtsson 2002) and the flora and fauna (D'Arrigo et al. 1993; Mysterud et al. 2001; Lindholm et al. 2001; Solberg et al. 2002; Post 2003; Macias et al. 2004; Helama et al. 2005) have been shown to vary with the changes attributable to the ocean-atmosphere system of the North Atlantic. Here we examine growth records from marine and terrestrial ecosystems along the coastal areas of northwest Norway by means of sclerochronology and dendrochronology. The focus of the present study is to present and compare the marine growth variability to terrestrial variations during the pre-anthropogenic period, over the first seven decades of the 19th century (A.D.). This 'historical' study period predates the era of anthropogenic climate forcing, and therefore thus provides information about natural climate variability and ecosystem response.

The inter-proxy comparison was accompanied by correlation analysis using environmental data, particularly the record of the North Atlantic Oscillation (Hurrell 1995; Jones et al. 1997), as a predictor. Our goals are (1) to determine if the two proxies show significant common variability, and, if they do, (2) to attempt to link the growth variations with climatic factors. The first issue is

important because the co-variability suggests that the marine and terrestrial systems may respond to the present and future climate fluctuations in a similar manner. The presence of a common growth signal could also allow absolute dating control of late Holocene marine shells using the local tree-ring series as reference material. The latter issue (2) could reconcile the three constituents of the natural perturbations, atmospheric, marine and terrestrial. This is especially important due to the threat of changing climate, where the NAO may play a significant role (Hurrell et al. 2001; Visbeck 2002).

Material and methods

Sclerochronological data

Sclerochronological data were obtained from ocean quahog (*Arctica islandica* L.) shells. One great benefit of this bivalve species for sclerochronological studies is its longevity; it may reach ontogenetic ages of several centuries (Jones 1980, 1983; Ropes et al. 1984, Schöne et al. 2005a). Four specimens for the present study come from Senckenberg Museum (Senckenberganlage 25, Frankfurt am Main, Germany). Four samples were collected alive in July 1861. The precise site of collection is not known, but the old label reads “Tromsø” (see Fig. 1). Previously, Schöne et al. (2003b) have published the growth records of two of these specimen, but there is a mistake in the map by Schöne et al. (2003b: Fig. 1) since the position of the sampling site is marked hundreds of kilometers too far south in that map.

Compared to tree-rings, the structure of shell increment appearance is generally much more complex with increments of different order (periodicities by tidal, daily, lunar and annual cycles) of scale. The annual banding of shell growth was examined for this study. Annual periodicity of *Arctica islandica* shell growth has been studied for independent regions and its character is well known (Thompson et al. 1980; Jones 1980, 1983; Schöne et al. 2005b). In addition, the temporal basis of annual increments coincides with the periodicity of tree-rings and the two types of records thus form potentially suitable counterparts for each other.

Specimens of *Arctica islandica* were mounted on a plexiglass cube and quick-drying metal epoxy resin (JB KWIK-WELD) was applied to the surface of the valves along the axis of maximum growth. Sections of 2-3 mm thick were cut using Buehler Isomet low-speed saw and mounted on a glass slide, ground and polished on glass plates with 6 μm SiC, 4 μm SiC and 1 μm Al₂O₃ powder. Polished sections were immersed in a solution of 500 ml 1% acetic acid, 500 ml 25% glutaraldehyde and 5 g alcian blue powder for 25 minutes at 37-40°C (Schöne et al. 2005a, b). Etched sections were rinsed with demineralized water and allowed to air-dry. Increments were viewed under a reflective light binocular microscope and digitized with a Nikon Coolpix® 995 camera. Shell growth increments were identified and their widths measured in the outer shell layer, from umbo to the ventral edge. Widths of the increments were measured from the outer shell layer to the nearest 1 μm with Scion/NIH version 4.0.2 beta image software (<http://www.scioncorp.com>).

Dendrochronological data

Dendrochronological material, tree-rings of Scots pine (*Pinus sylvestris* L.), was obtained from 8 different sites in northern Norway (Table 1, Fig. 1). Tree-ring sample cores were extracted from living trees using an increment borer. Cores or cross-sections were also sampled from dead trees and tree remains preserved on dry forest ground. The data of three sites (chronologies 1-3 in Table 1) is part of the WSL-Birmensdorf Tree Ring Data 2000 (Schweingruber 1988; Schweingruber et al. 1991) and this data was obtained from the International Tree-Ring Data Bank (part of the NOAA Paleoclimatology Program and World Data Center for Paleoclimatology) (Grissino-Mayer and Fritts 1997). Five of the sites (chronologies 4-8 in Table 1) were collected previously by Kirchhefer (1999, 2000, 2001), who has provided detailed information about the characteristics of the sites and their growth performance as well as dendroclimatic interpretation. The widths of these rings were measured, from pith to bark, under a visible light microscope in a computer aided system.

Climatic data

Local climate records from Tromsø begin in 1867 and did not overlap with shell growth records. Instead, sclerochronological and dendrochronological records were compared with the monthly North Atlantic Oscillation (NAO) indices of Jones et al. (1997). The NAO is characterized by an oscillation of atmospheric mass between the Arctic and the subtropical Atlantic. It produces large changes in the mean wind speed and direction over the North Atlantic, which in turn influence the heat and moisture transport between the Atlantic and the continents around it (Hurrell 1995).

Monthly NAO indices were used here as computed by Jones et al. (1997), that is, from the difference of sea level pressure between Gibraltar and Iceland. The earliest year of this record is 1821. In addition, the monthly temperature mean and precipitation sums from Tromsø were adopted from the dataset of Tuomenvirta et al. (2001) to exemplify the influence of NAO on local climate.

Chronology construction and comparison

Individual series of tree-rings and shell growth increments exhibit a trend as a function of ontogenetic age of the organisms (Huntington 1914; Fritts 1976; Dunca 1999; Marchitto et al. 2000; Schöne et al. 2005). Such a trend, commonly referred to as a growth trend, is largely due to physiological ageing and three-dimensional sizing of the organism and is therefore targeted for removal prior to the analysis of a common growth signal (e.g., Fritts 1976; Helama et al. 2006). In the present study, growth trends were captured using cubic spline function (Cook and Peters 1981) and removed by dividing the observed annual growth value by the expected growth value of the spline curve. 24-year cubic splines with a 50 percent frequency cut-off were fitted individually to each series of shell growth increments and tree-rings (Fig. 2). This rather ‘flexible’ growth trend function thus captures the growth variations at multi-decadal time-scales and removes them from resulting growth indices. This growth trend function was a compromise between those slightly more flexible splines that were previously shown to greatly increase the common growth signal between *Arctica islandica* increment series (Helama et al. 2006) and those more ‘rigid’ spline curves used previously in the region for dendrochronological purposes

(Lindholm et al. 1999; Helama et al. 2004). Moreover, it is noteworthy that the use of described spline function, instead of some ‘deterministic’ growth trend equation, allowed us to use an identical function to model growth trends in both shell growth increment and tree-ring datasets.

Dimensionless ratio-based indices were carefully cross-dated. Variations in tree-rings and shell growth increments were examined separately and synchronized among all available samples from a given site and species. Co-variation between the individual series ensures the dating of each annual growth band, tree-ring or shell increment, to an accuracy of one year, providing absolute dating control of examined characteristics. Cross-dating is a routine procedure of dendrochronological studies (Douglass 1941; Fritts 1976; Wigley et al. 1987); its feasibility and the importance for studies of the periodic shell growth increments were previously demonstrated by Marchitto et al. (2000) and Helama et al. (2006).

Cross-dated index series were averaged into mean time series of species-specific and site-specific chronologies using the arithmetic mean. Statistical estimates of skewness and kurtosis of the mean chronologies implied that the observed annual index values did not violate the assumption of normal distribution. The autocorrelations of the chronologies were in general low and mostly insignificant. The highest level of autocorrelation was observed for the chronology of *A. islandica* (Table 1). The autocorrelation of the series may hamper the assumption of independent observations in estimating the level of statistical significance for Pearson correlations (Yule 1926; Bartlett 1935). Quenouille (1952) provided a formula to estimate the effective number of independent observations (n_{eff}) to be used in testing the correlation between two time series

$$n_{eff} \approx n / (1 + 2r_1r_1' + 2r_2r_2' + \dots)$$

where n is the number of observations and r_1 and r_1' are the autocorrelations of the first and second time series with a lag 1 (Table 1) and r_2 and r_2' are the autocorrelations of the two time series with a lag 2 and so on. With regards to present sample, inclusion of autocorrelations with lag-1 and lag-2 is adequate. In serially correlated time series n_{eff} thus reduces in proportion to the level of autocorrelation. The treatment of Quenouille (1952) was performed prior to comparison of *A. islandica* and *Pinus sylvestris* chronologies and the significance level for the association was estimated according to n_{eff} instead of n .

Results and discussion

Spatiotemporal inter-species comparison

After growth trends were removed and the series cross-dated, the correlation between the *Arctica islandica* index series was 0.330. This result compared well with the similarly detrended and correlated tree-ring chronologies (Table 1). Correlation between the sample series indicated similar growth response to similar external forcings. This suggests that individuals of *A. islandica* probably experienced similar environmental conditions during their life span. Moreover, this would suggest that the shells were collected, if not in a single site, at least from locations nearby to each other. Even more importantly, the obtained common growth signal between the individual shell growth increment index series signified the possibility of averaging

the series into one mean sclerochronology.

Shell increment chronology had the sample size of two or greater between the years 1806 and 1861 and the series could thus be cross-dated over this interval only. Consequently, this was the study period for further growth comparisons.

Correlations between the sclerochronology and different dendrochronologies were evidently highest when computed with the tree-ring data derived from the area near Tromsø (Fig. 3). Since the spatial correlation of climatic phenomena are supposed to decline with longer distances, the similar trend in inter-species correlations could therefore confirm the earlier assumption about the approximate location of sample collection (around Tromsø). Unfortunately, the spatial resolution of tree-ring network did not allow more detailed determination.

The mean correlation between the tree-ring chronologies, over the study period 1806-1861, was 0.421. Correlativity of the tree-ring site chronologies was high enough to support the construction of one regional chronology. As exemplified in Fig. 3, the similarity of growth patterns in shell increments and tree-rings was due to proximity of the sites; inter-species correlations over longer distances were clearly lower than correlations with nearby sites and correlations close to zero were observed when distances exceeded 100 km. A new regional dendrochronology was averaged using the tree-ring series from local site chronology candidates (Fig. 3). This tree-ring chronology was then compared with sclerochronology of *A. islandica*. Accounting for autocorrelation of the sclerochronology (for which the autocorrelation was higher than tree-rings), we detect significant inter-species correlation (Fig. 4) over the available period

indicating that the two ecosystems shared common growth variations significantly more than what could be statistically expected by pure chance. The Durbin-Watson (1951) d -test showed that no statistically significant serial correlation was present (0.01 level) in the residuals from this regression (Fig. 4b).

Climatic interpretation

Significant correlation is observed between growth records derived from the studied marine and terrestrial archives (Fig. 4). Climate has previously shown to synchronize population variability among different species over considerable distances (e.g. Post and Forchhammer 2002) and the described synchrony in inter-species growth dynamics (Fig. 4) is best viewed in the context of climate variability. One particular climatic factor liable to cause growth correlation is summer temperatures. The radial growth of *Pinus sylvestris* is known to benefit especially from warm summer temperatures in the study region (Kirchhefer 1999, 2000, 2001). The growth of *Arctica islandica* has previously shown to depend on growing season temperatures and food availability (Witbaard 1996; Marchitto et al. 2000; Witbaard et al. 2003; Schöne et al. 2003a, 2005). Although the growth response of *Arctica islandica* has not yet been thoroughly studied in the region, these two factors could likewise be assumed to bear significant influence on the growth of the species also here. Fluctuating summer temperatures could thus act as driving force behind the described synchrony of the growth records. It is not however clear how strongly air temperatures are related to the benthic environmental conditions experienced by these bivalves, and there may be some complementary factors explaining the co-variability.

In the North Atlantic, the heat that the ocean gains at low latitudes is carried northward within the Gulf Stream and transferred into the atmosphere by conduction and evaporation. This heat is typically transported over coastal Europe due to atmospheric patterns, ascribed to the North Atlantic Oscillation-index (NAO-index; Hurrell 1995; Jones et al. 1997). According to Hurrell (1995), December through March NAO-index correlates strongly with precipitation of the same season along the Norwegian coast facing towards the North Atlantic Ocean, with coefficients 0.77 and 0.66 in Bergen and Stavanger, respectively. These towns are situated further south than Tromsø, but the NAO bears some influence on the climate of the study region. There is an especially clear NAO-climate connection to temperatures in the study region (Table 2). However, as previously noted by Chen & Hellström (1999) in Sweden, the strength of the NAO-climate association varies regionally and through time. This implies that also the relationships between the NAO and ecosystems are expected to vary as a function of time.

Interestingly, both marine and terrestrial ecosystems have previously been demonstrated to show NAO-dependent behaviour in the study region. According to Schöne et al. (2003b), the long-period shell increment variability ('low-pass' filtered growth records, see details in Schöne et al. 2003b) of *A. islandica* show correlation with winter-NAO-index from the central North Sea up to the coastal Norwegian Sea and in the study region. With regard to forest ecosystems, Macias et al. (2004) studied the dependence of *Pinus sylvestris* tree-ring widths on the NAO in northern Norway and Finland since the year 1880. They showed that while the influence of NAO on tree-rings was evident, it exhibited temporal and seasonal instability. More precisely, it was shown that the correlations between the NAO-indices and tree-rings varied markedly according to the

sign of the NAO-phase (Macias et al. 2004).

Influence of North Atlantic Oscillation (NAO)

In order to test the hypothesis of NAO-related inter-species growth synchrony with our data, we performed a comparison between the sclerochronology, dendrochronology and NAO-indices (Jones et al. 1997). The potential influence of NAO was studied over the temporal overlap between records during the period 1821-1861. Based on the previous studies and localized correlations (Table 2), the influence of NAO on climate was expected to have strongest impact during the winter (December through March). This is the NAO-season frequently discussed in the literature (for review, see Hurrell et al. 2001, 2003; Wanner et al. 2001) due to its significant influence on natural systems. Although the activity of the organisms during the winter is reduced, winter climate may influence subsequent growth, although the proxy archive lags behind. At high latitudes, snow brings inertia for the climate system and the winter climate should not be neglected when studying the climatic sensitivity of organisms (e.g. Vaganov et al. 1999). We therefore chose to compare the sclerochronological and dendrochronological records with winter-NAO (December to March). The mid-summer (July) NAO-season was also tested, as this is the season in which temperatures are liable to be of greatest importance on the growth variability in our marine and terrestrial settings.

As previously mentioned, the influence of NAO on ecosystems may be different during the years of positive to negative NAO-phases in the study region (Macias et al. 2004). Therefore, we estimated the inter-proxy correlations as a function of the NAO-index gradient (Fig. 5). That is,

the annual bivalve and tree growth values were re-aligned according to the NAO-index of each year (in re-aligned series the first and last growth observations were thus associated with the most positive and the most negative NAO-indices, respectively). Re-alignment was performed separately according to winter-NAO-index and mid-summer-NAO-index. The series of correlations using the 20-point window were then calculated in the resulting NAO-domain by sliding the correlation window along the re-aligned time series by one point steps. Correlation coefficient was calculated for each position of the window. The results are shown separately for winter-NAO and mid-summer-NAO (Fig. 5).

Growth synchrony seemed to increase with very positive and decrease with negative mid-summer-NAO-indices (Fig. 5). As the temperatures in the study region were positively correlated with NAO-index (Table 2), the obtained results could indicate that especially the years with warm summers may experience increased growth synchrony between the two records. By contrast, growth synchrony seemed to increase with very negative and decrease with positive winter-NAO-indices (Fig. 5). While Fig. 5 depicts the correlations calculated using 20-point windows, we obtain the correlations 0.937 and -0.545 for the most negative and positive 5-point ends of the winter-NAO-gradient. While these correlations are consistent with the gradient by 20-point correlations (Fig. 5), they also indicate that the influence of the extreme NAO-years is probably even amplified by the most anomalous NAO-phenomena. Since the activity of the organisms is reduced in winter, the interpretation of the growth synchrony due to negative winter-NAO phases probably requires an intra-annually lagged (from winter to spring) physical model, through the local NAO-climate correlations (Table 2).

Climate affects the marine ecosystems indirectly by changing the ecosystem properties that are of importance to the growth of organisms (Ottersen et al. 2001, 2004); significant aquatic properties for the growth of marine organisms include temperature, salinity, food supply, water column stratification and sedimentation (Schöne et al. 2003a; Witbaard et al. 2003). Growth may be influenced contemporaneously or with lagged responses (Witbaard et al. 2003; Ottersen et al. 2001, 2004). The influence of winter-NAO on bivalve growth could be due to intra-annually lagged responses. Snow conditions (depending on both snowfall and winter temperatures, in turn influenced by NAO, see Table 2) in the adjacent land areas may affect spring floods and thus seasonal sedimentation rates with cascading influence on the food supply of marine organisms in coastal waters. Positive growth influence could be derived from increased food supply, but sediment influx may also influence the growth of these organisms negatively, and the potential for non-linear relationship cannot be excluded. With regard to tree growth, the relationship may be more direct, due to thawing and freezing of the soil, as suggested by Kirchhefer (1999). The insulating effect of snow on the root system is known to bear positive influence on the growth and vitality of northern pines (Jalkanen 1993). As parallel evidence, the radial growth of *Pinus sylvestris* has been shown to correlate significantly and positively with mid-winter precipitation and temperature in the study region during the era of local instrumental weather observations (Kirchhefer 2000).

Conclusions

Despite their completely different growing environment as well as distinct physiological and

ecological separation, *Arctica islandica* and *Pinus sylvestris* showed significantly similar growth variability during the studied interval. It would be difficult to explain the correlated growth patterns by means other than climate. We have identified factors that serve as potential predictors linking the two proxy records: summer temperatures and the North Atlantic Oscillation (NAO). Increasing synchronization occurs between inter-species growth records in association with years of negative winter-NAO-index and years of positive mid-summer-NAO-index. This correlation indicates potentially non-linear connection of the ocean-atmosphere system with marine and terrestrial ecosystems. During the recent decades, winter-NAO has experienced a pervasive positive phase (Hurrell et al. 2001) and its influence on the marine and terrestrial ecosystems should be intensively studied. During the years of positive winter-NAO-index, the two ecosystems did not correlate positively. Our palaeoecological evidence thus suggests that the two ecosystems may be showing dissimilar growth reaction to this recent positive NAO phase.

Our spatial analysis confirmed the conceivable geographical origin of the museum shell specimens. This was done with the spatial comparison of sclerochronology with a network of tree-ring chronologies along the coastal areas. Our results implied that a multi-proxy analysis using sclerochronological and dendrochronological series could also be useful to resolve the absolute temporal placement of undated shells by inter-species cross-dating (Fritts 1976). That is to propose that already constructed tree-ring records could potentially be used as master chronologies for nearby collected late Holocene shell material, from archaeological and geological archives (Nielsen et al. 2004) and museum collections.

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Tables

Table 1. Tree-ring (*Pinus sylvestris*) chronologies (No. 1-8) and shell growth (*Arctica islandica*) increment chronologies (No. 9) used in the present study with the name of the locality (Name), abbreviation of the chronology (Abbr), first year of the chronology (Year F), last year of the chronology (Year L), total number of the individual series in the chronology (sample size, SS1) and the number of series overlapping with the cross-dated part of the sclerochronology (between the years 1806 and 1861; SS2). Other statistics include skewness (Skew) and kurtosis (Kurt), the correlation between the individual series within each chronology (r) and the first order autocorrelation (r_1). All these four statistics were calculated over the common period 1806-1861. For the locations of the sample sites, see Fig. 1.

No.	NAME	Abbr	Year F	Year L	SS1	SS2	Skew	Kurt	r	r_1
1	Skibotn	SKI	1775	1978	27	22	-0.144	-0.764	0.576	0.473
2	Lofoten	LOF	1619	1978	6	5	0.400	0.789	0.447	0.226
3	Narvik	NAR	1702	1978	29	13	0.017	0.361	0.212	0.278
4	Vikran	VIK	1599	1992	44	43	-0.033	0.193	0.348	0.259
5	Addjet	ADD	1579	1992	33	27	-0.039	0.114	0.445	0.213
6	Tauskjerring	TAU	1545	1994	32	27	-0.211	-0.465	0.454	0.362
7	Stonglandseidet	STO	1403	1997	66	51	-0.289	-0.207	0.314	0.211
8	Nordreisa	LUV	1515	1995	68	65	-0.601	0.576	0.448	0.241
9	<i>Arctica islandica</i>	AI	1758	1861	4	4	0.099	-0.763	0.330	0.481

Table 2. Pearson correlations ($\times 100$) between monthly North Atlantic Oscillation (NAO) –index and monthly mean temperatures (T) and precipitation sums (P) in Tromsø meteorological station shown separately for the first and second halves of the 20th century. Positive NAO-correlations with temperature and precipitation imply that enhanced NAO-phase brings warm and moisture weather, respectively. Statistically significant ($p < 0.05$) correlations are underlined.

Climate \ Month	J	F	M	A	M	J	J	A	S	O	N	D
T (1900-1949)	<u>40</u>	<u>50</u>	<u>53</u>	<u>29</u>	<u>31</u>	<u>32</u>	15	2	<u>43</u>	17	<u>48</u>	20
T (1950-1999)	<u>33</u>	<u>45</u>	<u>30</u>	25	<u>29</u>	3	<u>33</u>	<u>29</u>	<u>28</u>	<u>43</u>	19	<u>28</u>
P (1900-1949)	-9	1	9	11	-7	20	22	-12	<u>-35</u>	-24	<u>-30</u>	-9
P (1950-1999)	-7	6	12	<u>-39</u>	-14	<u>37</u>	-9	-12	-22	-10	-15	-12

Figure captions

Figure 1. Map showing the tree-ring sampling sites (circles) and the assumed location of the historical shell collection site (triangle). Modified after Kirchhefer (2001). See Table 1 for tree-ring site abbreviations and details.

Figure 2. Determining the growth curve for annual shell growth increments (*Arctica islandica*) (a) and tree-ring (*Pinus sylvestris*) widths (b). Growth curve (thick gray line) was fitted to initial growth measurements (thin black line) using 24-year cubic spline function.

Figure 3. Spatial comparison of inter-species growth synchrony: correlations between the sclerochronology and dendrochronologies are highest for the tree-ring sites in the proximity of the Tromsø. Tree-ring (*Pinus sylvestris*) chronologies chosen to represent the growth comparable to local shell growth (*Arctica islandica*) are shown with filled circles, see Table 1 and Fig. 1 for details about these chronologies.

Figure 4. Correlation (r) between the annual shell growth increments (*Arctica islandica*) and tree-ring widths (*Pinus sylvestris*) (a). The relationship between the shell and tree growth shown with linear regression (b).

Figure 5. Correlation between the shell increments (*Arctica islandica*) and tree-rings (*Pinus sylvestris*) shown as a function of the (a) magnitude and sign of DJFM (December to March, previous winter to growing season) North Atlantic Oscillation (NAO) indices and (b) mid-

summer (July, concurrent to growth) -NAO indices. Vertical axis indicates the correlation coefficient that occurred between the upper (upper horizontal axis) and lower (lower horizontal axis) limit of a particular range of NAO-index.

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Fig 1

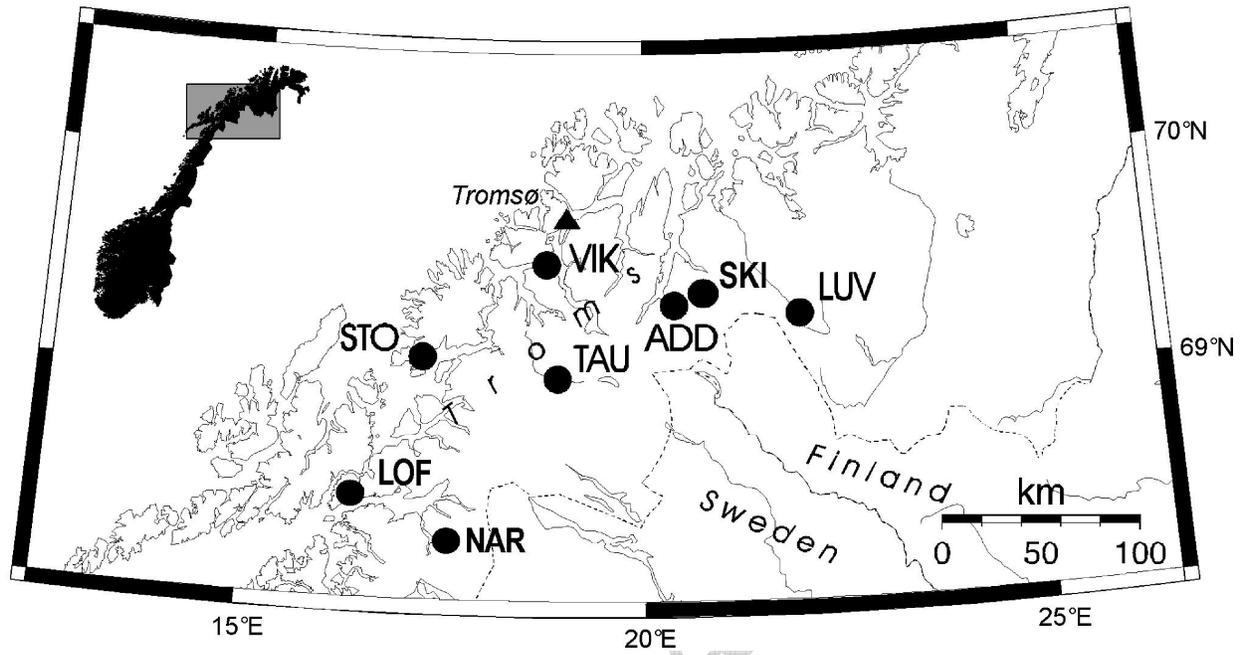


Figure 2

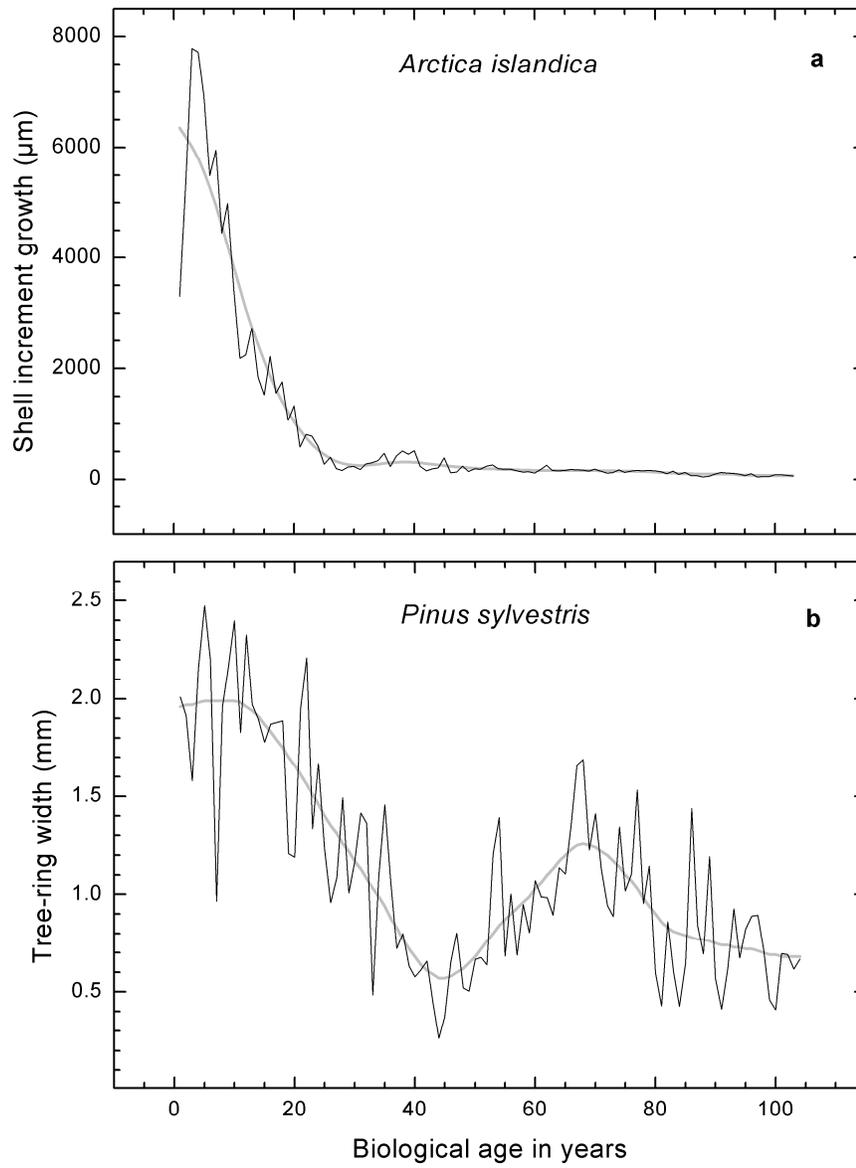


Fig. 3

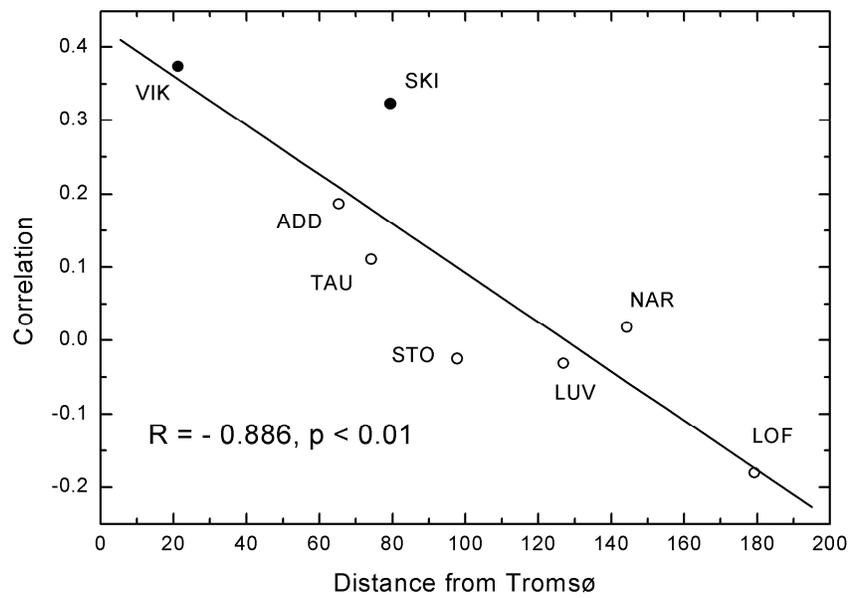


Figure 4

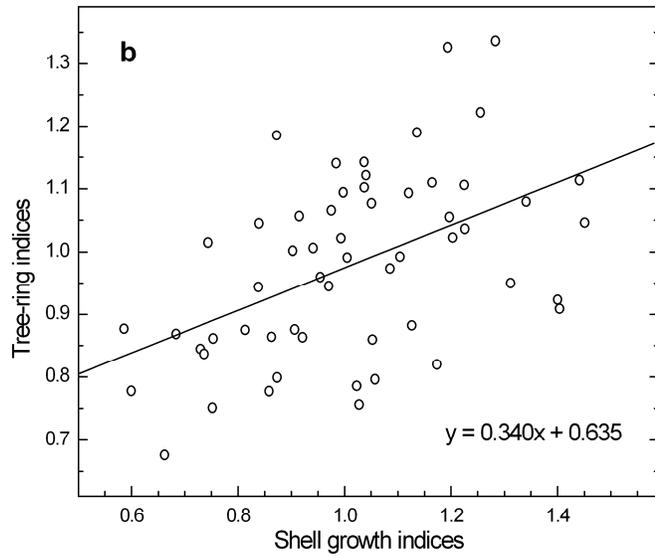
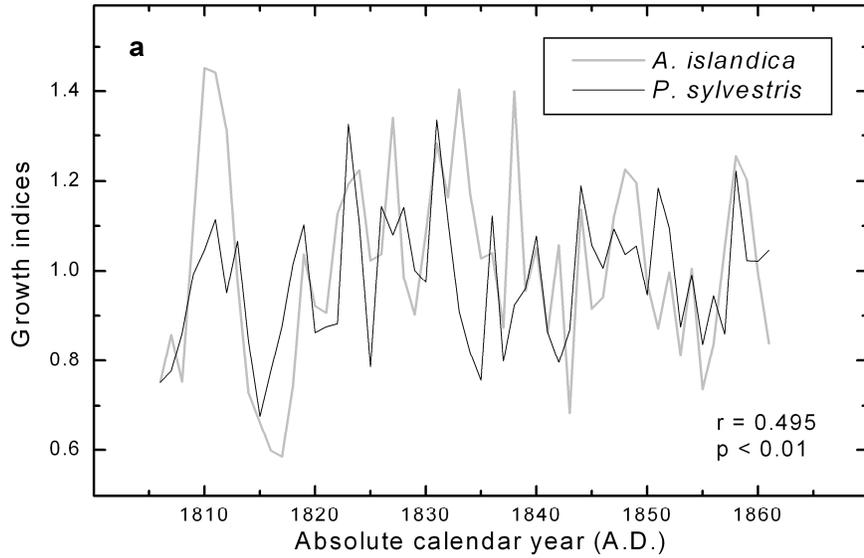


Figure 5

