A SEASONALLY RESOLVED BOTTOM-WATER TEMPERATURE RECORD FOR THE PERIOD AD 1866–2002 BASED ON SHELLS OF *ARCTICA ISLANDICA* (MOLLUSCA, NORTH SEA)

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ABSTRACT

Existing studies on recent global warming are almost exclusively based on environmental data from the Earth's surface. Seasonal information on the effects of climate change on subsurface settings of mid to high latitudes is extremely scarce. Here, we present the first temperature proxy record from bottom (c. 50 m) water settings of the North Sea employing the oxygen isotope composition of ocean quahog shells. Results indicate that $\delta^{18}O_{aragonite}$ measured across shells of *Arctica islandica* can provide reliable estimates (± 0.25 to $\pm 0.4\,°C$) of the ambient bottom water temperatures. Over the period AD 1880–2001, warming trends in bottom waters are of the order of 0.042 to 0.138 °C/decade. Apparently, the annual maximum-temperature trend shows a twofold increase over the past four decades (0.236 °C/decade) while the minimum-temperature trend has remained relatively stable (0.042 °C/decade). During the same time interval, however, annual maximum temperatures at the sea surface quadrupled. Shell oxygen-isotope-derived winter temperatures also provide a proxy for the winter North Atlantic oscillation index (WNAO). Some 28 to 50% of the variability in minimum temperatures below the thermocline can be explained by changes of the WNAO. Our new tool enables testing and verification of climate models prior to the 20th century greenhouse forcing. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: ocean quahog; thermocline; temperature; oxygen isotope; sclerochronology; model

1. INTRODUCTION

Marine archives of seasonal environmental variability in mid to high latitudes are extremely scarce. Meteorological records, such as the extended reconstructed sea-surface temperature (ERSST) data set (National Oceanic and Atmospheric Administration; www.cdc.noaa.gov) cover surface conditions during the past 100 to 150 years. Much less is known about conditions in the bottom water, where measurements were only taken occasionally (e.g. Levitus *et al.*, 2000). High-resolution, decadal to centennial reconstructions of such settings require extensive modelling. For example, the Hamburg Shelf Ocean Model (HAMSOM; Pohlmann, 1996 a–c) provides monthly reconstructed bottom-water temperatures (BWTs) for the period 1969–82 (note: all years are AD). Such models are based upon atmospheric heat flux and wind stress data and cannot easily be extended beyond times of instrumental measurements.

For times and places without direct measurements, climate system modellers rely on proxy records. High-resolution environmental reconstructions in mid to high latitudes have predominantly been derived from trees.

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Tree rings, however, lack temporal resolution sufficient to determine seasonal environmental fluctuations. More importantly, these data cannot be used reliably to interpret marine temperatures of the same latitudes. This is partly achieved by using marine sedimentary archives, i.e. microfossils contained in oceanic sediments (Williams *et al.*, 1979; Jiang *et al.*, 2001; Andrews and Giraudeau, 2003). However, the temporal resolution of laminated sediments is limited, and ranges from decades to millennia depending on the dating technique (^{14}C, ^{210}Pb, etc.) and sedimentation rate. Marine microfossils are too short-lived and cannot provide a precise long-term (centennial to millennial) record of environmental changes. Furthermore, the possibility of reconstructing seasonality from microfossils is generally limited. They can only illustrate variations in seasonal extremes over centuries or millennia.

Seasonal data from mid- to high-latitude bottom-water can be vital for obtaining more reliable records of ocean–atmosphere feedback mechanisms (CLIVAR, 1995; Barnett *et al.*, 2001; Houghton *et al.*, 2001). These records are also necessary to distinguish natural variability from anthropogenic forcing and to quantify human-induced climate change. Moreover, centennial to millennial high-resolution records of mid- to high-latitude marine winter temperatures could provide an extremely useful tool for reconstructing changes of the North Atlantic oscillation (NAO) prior to human forcing. The NAO governs the climate of the Northern Hemisphere and is most pronounced during winter. Existing reconstructions of the winter NAO (WNAO) are almost exclusively based on terrestrial proxies, e.g. ice cores (Appenzeller *et al.*, 1998), stalagmites (Proctor *et al.*, 2000), tree rings (Cook *et al.*, 2002) and snow accumulation rates (Glueck and Stockton, 2001), on documentary data (Rodrigo *et al.*, 2001), or on a combination of historical and other proxy records (Luterbacher *et al.*, 2002). A major drawback of some of these proxies is that environmental conditions during winter are recorded indirectly (e.g. tree data are summer biased, because they do not grow during winter), and clear seasonal time constraints do not exist. Recently, Schöne *et al.* (2003a) presented the first marine proxy for the WNAO based on shell growth rates of the bivalve mollusc *Arctica islandica* L. collected alive from bottom waters of the North Sea and the Norwegian Sea.

Shells of bivalve molluscs provide an excellent century-scale archive of natural climate variability outside the tropics with seasonal resolution. Bivalves are sensitive environmental biomonitors. They are abundantly available, easy to obtain and to measure, and can be extremely long lived (more than 375 years, confirmed radiometrically). In addition, bivalve molluscs offer several advantages over other environmental reconstructions based on accretionary biological hard parts, especially trees and corals. First, shells of *A. islandica* provide multi-proxy records of environmental variables. Changes of environmental parameters are recorded in variations of growth rates (Marchitto *et al.*, 2000; Schöne *et al.*, 2003a,b) and stable isotopes (Weidman *et al.*, 1994; Marsh *et al.*, 1999; Schöne *et al.*, 2004c, 2005). Unlike corals, shells of *A. islandica* incorporate the stable oxygen isotopes in equilibrium with ambient seawater, which allows one to calculate absolute palaeotemperatures from fossil specimens (Weidman *et al.*, 1994). Second, shells of *A. islandica* provide high-resolution proxy data because they grow by daily accretion of carbonate (Schöne *et al.*, 2005). Third, *A. islandica* is apparently less severely affected by stand effects than are trees. For example, it is not necessary to sample only the 'dominant' specimens of a population, i.e. the highest trees, or specimens from a specific ecotone, i.e. trees from near the timber line (Schöne *et al.*, 2003a,b). So far, only one previous study has employed *A. islandica* as a long-term (one century) bottom-water palaeothermometer (Marsh *et al.*, 1999). The reconstructed annual BWTs from the period of 1875 to 1983 from the oxygen isotope record of *A. islandica* shells from the mid-Atlantic Bight and found a good agreement between reconstructed and measured water temperatures. Fourth, *A. islandica* exhibits a broad biogeographic distribution. Its occurrence is not restricted to the North and Baltic Seas. *A. islandica* is common in the entire North Atlantic Ocean (Nicol, 1951) and lives in water depths between 14 and 256 m (Merrill and Ropes, 1969; Ropes, 1978; Serchuk *et al.*, 1982). This makes *A. islandica* a unique archive of past ocean temperatures.

We present here the first seasonally resolved proxy record of North Sea BWT (∼50 m water depth) inferred from shell oxygen isotope ratios from the period 1866 to 2002. Results are compared with instrumental and modelled sea-surface temperature (SST) and BWT data of the North Sea. The main objectives of the present study are to analyse (1) how precisely BWTs can be reconstructed from shell oxygen isotopes, (2) how the bottom shelf waters respond to global warming, and (3) whether shell oxygen isotope-derived temperature (aside from shell growth rates) estimates can provide an additional proxy for the WNAO.

2. REGIONAL SETTING

The North Sea is a semi-enclosed sea on the continental shelf of northwest Europe. In mid- to high-latitude summer, thermal stratification leads to the development of a shallow mixed layer.

Only the upper 25 m of the North Sea are well mixed and almost isothermal (Nielsen *et al*., 1993; Kröncke and Knust, 1995). The thermocline prevents mixing of surface and bottom-waters and inhibits warming of bottom waters due to solar radiation. Consequently, cold temperatures from the previous winter (HAMSOM: average over 1958–97 is 6.5 °C) prevail in deeper waters during summer. Thus, summer bottom waters 'memorize' the temperatures of the previous winter. In the autumn, strong winds and weakening stratification lead to a disruption of the thermocline. Downward mixing of warmer surface water results in an abrupt rise in BWTs. In 50 m water depth, maximum temperatures are attained in November (HAMSOM: average over 1958–97 is 8.7 °C). Subsequently, BWTs cool rapidly in the following months due to convective overturning. Some 90% of the temperature variation in deeper water settings of the central North Sea results from downward mixing of surface ocean water, and advection of North Atlantic water into the North Sea accounts for the remaining 10% of the variation (Pohlmann, 1991). Hence, the North Sea bottom waters are closely tied to atmospheric circulation patterns. Bottom waters of the stratified central and northern North Sea reliably record the effect of the WNAO on the surface water during the previous winter, because the winter temperatures are conserved below the thermocline.

3. MATERIAL AND METHODS

A total of 12 specimens of *A. islandica* collected alive from c. 50 m water depth of the central North Sea (56 °N, 4 °E) during the early 20th century (collections of the Zoological Museum, University of Kiel) and between 1998 and 2002 were used in the present study (Figure 1, Table I). Annual increment counts ensured the precise determination of the ontogenetic ages and an exact calendar alignment of each shell portion. Specimens grew between 9 and 46 years (Table I). During early ontogenetic stages, *A. islandica* shells grow at very high rates (Cargnelli *et al*., 1999), i.e. up to 20 mm per year (own observation). This makes high-resolution analyses of the shell record possible. The overwhelming majority of the samples used here came from youth portions of the shells (around years 1 to 20; see Table I).
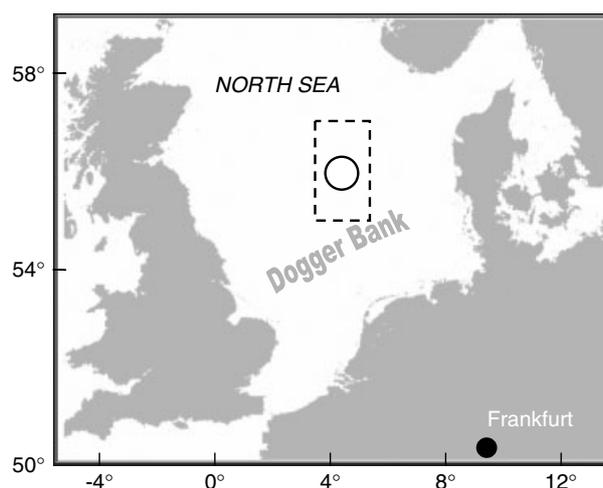
Figure 1. Map showing sample locality (open circle) at Tail End, Dogger Bank, in the central North Sea. The rectangle indicates the ERSST data grid used for comparison with shell oxygen-isotope-derived temperature. HAMSOM-BWT$_{50}$ data were calculated for the position where the molluses lived

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Table I. List of *A. islandica* specimens sampled for oxygen isotope analysis

Shell ID	Age/years sampled	Date of death	No. of isotope samples
WH241_St579-A1R	4−12 (1993−2002)	July 2002	115
DBG13.2-A2R	6−7 (1961−62)	May 1998	8
DBG13.3-A2L	4−15 (1954−65)	May 1998	57
DBG13.1-A2L	6−13 (1965−72)	May 1998	42
DBG13.3-A1R	6−44 (1959−97)[a]	May 1998	110
DBG13.2-A1L	4−8 (1969−72)	May 1998	19
DBG13.1-A3L	6−20 (1966−80)	May 1998	60
	47−52 (1992−97)		55
DBG13.1-A1L	5−16 (1947−58)	May 1998	115
08V_N16-A1R	2−8 (1901−07)	May 1908	28
05III_St13-A1L	3−21 (1866−84)	Mar 1905	113
03V_N4a-A2L	4−13 (1883−92)	May 1903	60
03V_N4a-A1L	3−10 (1893−1900)	May 1903	59
Sum			841

[a] Ontogenetic ages 30−44 (1983−97) sampled with *c*. 1000 μm resolution. All other samples: 50−500 μm spatial sampling resolution.

3.1. Sample preparation

Soft tissues from recently collected samples were removed and one valve chosen from each specimen. The chosen valve was mounted on a plexiglass cube and coated with JB KWIK-WELD, a quick-drying metal epoxy resin. Two 3 mm thickness sections were cut from the valves along the axes of maximum growth with a Buehler Isomet low-speed saw. The sections were subsequently mounted on a glass slide, ground and polished on glass plates with 800 and 1200 grit SiC and 1 μm Al_2O_3 powder.

3.2. Growth pattern analyses

In order to resolve annual growth structures (Figure 2) in the outer layers of the shells, one polished section from each specimen was immersed in a solution of 0.5% acetic acid, 12.5% glutardialdehyde, and 5 g (per litre solution) Alcian Blue powder for 25 min at 37−40 °C (slightly modified after Mutvei *et al.* (1996)). Immediately afterward, the etched sections were rinsed with demineralized water and air-dried. This process is adequate for resolving shell internal growth patterns. It not only etches (acetic acid) the carbonate portions of the shell, but also dries the organic matrix with glutardialdehyde. Simultaneously, Alcian Blue stains mucopolysaccharides and glucosamides, which are apparently enriched near the growth lines.

We determined the ontogenetic ages of the specimens by counting the number of annual increments from the umbo to the ventral margin under a reflective-light binocular microscope. In addition, daily microincrements were studied between the annual growth breaks.

3.3. Stable isotope analyses

The remaining unetched, polished sections from each shell were ultrasonically rinsed with demineralized water prior to the extraction of carbonate samples for oxygen isotope analyses. Because annual growth rates decrease rapidly as the shell matures, the youth portions of the shells were sampled in preference to maintain a consistent sampling resolution. Hence, the isotope data obtained from different years and different shells can be compared with each other. Following the shape of the microgrowth increments (equivalent to daily increments; Schöne *et al.*, 2005), aragonite powder was milled from years four to nine of the outer shell layer under a binocular microscope. We employed a cylindrical diamond drill bit (1 mm diameter, Komet/Gebr. Brasseler GmBH & Co. KG model no. 835 104 010) mounted on a Rexim Minimo drill. Spatial milling resolution parallel to the microincrements was about 50−500 μm. Each of the 841 powder samples covers
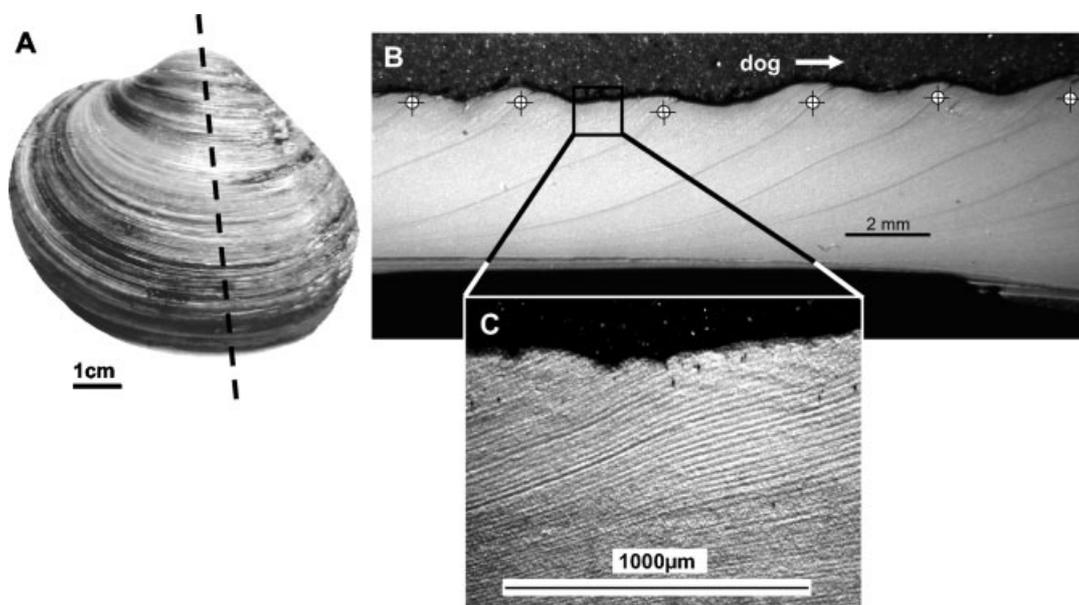
Figure 2. Growth structures in shells of *A. islandica*. Shells are cut along the axis of maximum growth (dashed line, A). Etched and stained polished cross-sections reveal distinct annual (B) and daily (C) growth lines (dark lines) and growth increments (brighter portions between two successive growth lines); dog: direction of growth. Growth-increment counts enable precise calendar dating of each shell portion

8 days to 1.5 months of growth (Schöne *et al.*, 2005) and yielded 40–60 µg of carbonate powder for isotope analysis. Twenty-one isotope samples were taken from over 30 1-year-old shell portions with a spatial sample resolution of about 1000 µm, which represents a temporal resolution of approximately 1 year. Samples were processed in a Finnigan MAT 253 mass spectrometer equipped with a gas bench (University of Frankfurt). Oxygen isotope ratios of the shell aragonite ($\delta^{18}O_{aragonite}$) are reported relative to Venna Peedee belemnite (VPDB) based on an NBS-19 value of $-2.20‰$. The average analytical error of individual oxygen isotope measurements is $\pm0.07‰$.

Stable oxygen isotope ratios of bivalve shells allow the reconstruction of the environmental conditions that prevailed during shell formation. $\delta^{18}O_{aragonite}$ of *A. islandica* is deposited in isotopic equilibrium with ambient seawater (Weidman *et al.*, 1994; Marsh *et al.*, 1999; Marchitto *et al.*, 2000), and is controlled by both the temperature and the $\delta^{18}O$ of the ambient seawater ($\delta^{18}O_{seawater}$) in which the shells formed. Measurements of the $\delta^{18}O_{seawater}$ of the central and northern North Sea indicate average values close to 0‰ standard mean ocean water (SMOW; Mook, 1971; Hickson, 1997). Assuming constant $\delta^{18}O_{seawater}$ (which is feasible for the setting in which the shells lived and for the past centuries), water temperatures $T_{\delta^{18}O}$ can be calculated from $\delta^{18}O_{aragonite}$ using the empirically determined temperature relationship by Grossman and Ku (1986). More important than reconstructing absolute temperatures is that $\delta^{18}O_{aragonite}$ allows estimation of the variability of temperatures on seasonal to interannual time scales. We have rewritten Grossman and Ku's (1986) equation so that all water values are corrected to the SMOW scale, whereas the $\delta^{18}O_{aragonite}$ is measured relative to PDB:

$$T_{\delta^{18}O}(°C) = 20.60 - 4.34[\delta^{18}O_{aragonite} - (\delta^{18}O_{seawater} - 0.20)] \tag{1}$$

Thus, assuming no change in $\delta^{18}O_{seawater}$, a 1‰ shift in shell $\delta^{18}O_{aragonite}$ equals a temperature change of 4.34 °C in ambient seawater. The isotope precision error of 0.07‰ hence translates into an uncertainty of ±0.15 °C.

Annual minimum and maximum $T_{\delta^{18}O}$ of contemporaneous shells were arithmetically averaged. The conformance of $T_{\delta^{18}O}$ in overlapping sections is quite good. On average, deviation between minimum oxygen isotope-derived temperatures of different contemporaneous shells is 0.38 °C and 0.55 °C for maximum $T_{\delta^{18}O}$.

The relatively small difference in $T_{\delta^{18}O}$ is not surprising, because all specimens were collected from the same region (see above). Differences most probably reflect variable sampling resolution.

3.4. Water temperature data sets

The ERSST is based on the Comprehensive Ocean–Atmosphere Data Set (COADS) and employs statistical methods that avoid problems with non-stationarities in the climate system and make a stable reconstruction of SST for periods of sparse data possible (Smith and Reynolds, 2003; details therein). Reliable ERSST data start in 1880. For the current study we use the ERSST data from grid box 55–57 °N, 4–6 °E.

Temperatures in 50 m water depth (55–56 °N, 5–6 °E) were reconstructed using HAMSOM (Backhaus, 1985; Pohlmann, 1996a; Schrum and Backhaus; 1999); in what follows these are referred to as HAMSOM-BWT$_{50}$. HAMSOM refers to a three-dimensional (3D) baroclinic shelf sea model, which predicts the 3D-flow field, the sea-surface elevation and the distribution of temperature and salinity. The model version used here covers the entire North and Baltic Seas system with a horizontal resolution of about 10 km (Siegismund, 2001). The water column is vertically subdivided into 20 layers. In order to resolve the stratification adequately, the upper eight layers have a thickness of only 8 m. It was possible to run the predictive model for all of the above-mentioned parameters for the period 1958 to 1997 with a time step of 20 min. The model was forced by realistic data for the same period by employing data on atmospheric heat flux and wind stress fields provided by the National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis. Data on river runoff came from historical data. Statistical methods were required to fill missing data for some rivers. For the open lateral boundaries of the Atlantic, realistic time-dependent temperature and salinity data were developed (Janssen *et al.*, 1999) ensuring that the proper advective temperature and salinity signals were included in the model. HAMSOM has been extensively validated over many years, in particular by Pohlmann (1997). He tested the capability of the model to reproduce the onset of the stratification through a comparison of model results with observational data.

4. SHELL GROWTH OF *A. ISLANDICA* SHELLS BELOW THE THERMOCLINE

Oxygen isotope-derived temperatures and microgrowth increment counts were previously used to assign calendar dates to shell sections (Goodwin *et al.*, 2001; Schöne *et al.*, 2003a,b, 2004a). Knowing the time contained in a certain shell section provides the prerequisite for using geochemical data of bivalve shells, such as *A. islandica*, for palaeoclimate reconstructions.

4.1. Daily growth rates

The seasonal temperature cycle inferred from $\delta^{18}O_{aragonite}$ ratios is strongly asymmetric (left-skewed) and has a characteristic saw-tooth-shaped pattern (see also Schöne *et al.* (2005)). An example is depicted in Figure 3. The $T_{\delta^{18}O}$ minimum occurs at the beginning of the growth period, i.e. after the annual growth line. A small, gradual increase in $T_{\delta^{18}O}$ is followed by an abrupt temperature rise. A distinct peak occurs immediately before the following annual growth break (Figure 3). Reconstructed minimum and maximum temperatures, closely match the HAMSOM-BWT$_{50}$ for the area in which the shells lived. The number of microincrements, $(213–228)\pm7$, between the minimum and maximum reconstructed temperatures closely matches the expected number of days to occur between the intra-annual minimum and maximum temperatures ($\sim$220, Figure 4). These findings support Schöne *et al.* (2005) in their hypothesis that microincrements form on a daily basis. Daily increment counts make the precise determination of the time contained in each isotope sample possible. Each isotope sample of the specimen used in the present study represents a temperature average over 7 to 50 days (see Figure 3).

4.2. Growth period

According to Schöne *et al.* (2005), the main growth period of *A. islandica* living in shallow surface waters (above the thermocline) starts in February, i.e. 1 month before the coldest temperatures are reached, and ends
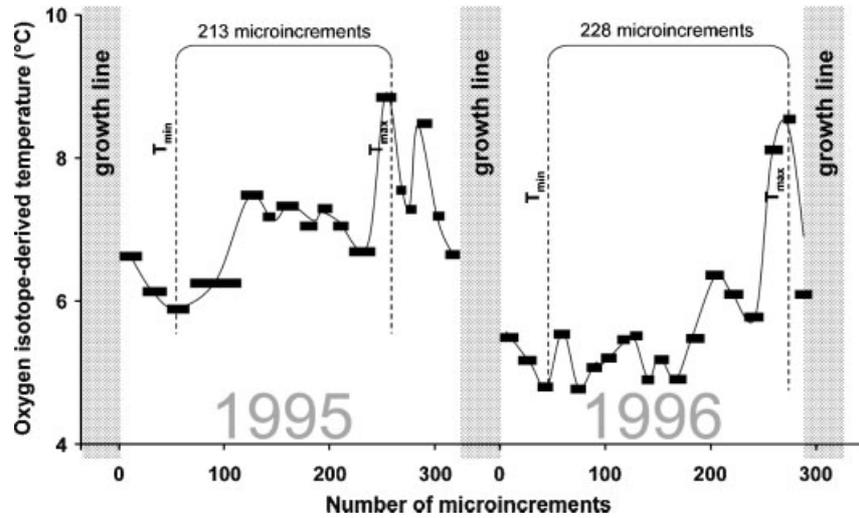
Figure 3. Temperatures inferred from shell oxygen isotope ratios show a strongly asymmetric (left-skewed) and saw-tooth-shaped pattern (specimen WH241_St579-A1R). Shells record the annual minimum and maximum temperatures. The number of microgrowth increments between the minimum and maximum reconstructed temperatures closely coincides with the expected number of days to occur between the intra-annual temperature minimum and maximum (~220). Hence, microincrements were interpreted to form on a daily basis. Daily increments enable the precise determination of the length contained in each isotope sample. Widths of black bars represent temporal coverage of samples (7 to 50 days)
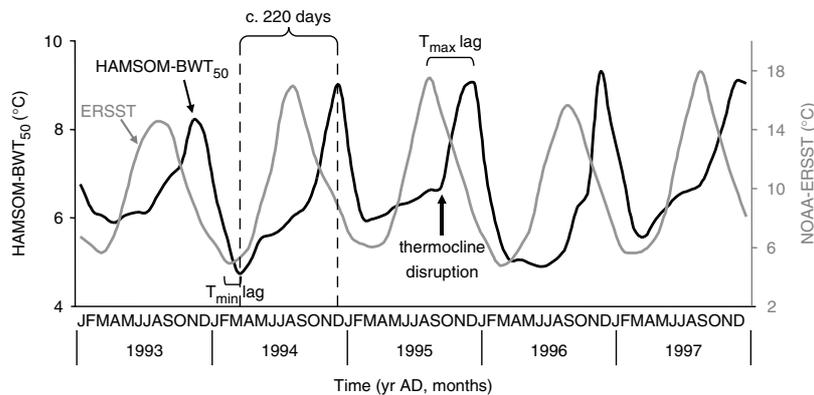
Figure 4. North Sea BWTs (HAMSOM-BWT$_{50}$, black) show a distinct, non-sinusoidal seasonal temperature cycle, and lag the surface water temperatures (ERSST, grey) by about 3 months. The BWT maximum during November results from the disruption of the thermocline and the downward mixing of warm surface waters

in September, i.e. some weeks after the warmest temperatures have occurred. However, the present study exclusively employed shells from below the thermocline. Thus, a revised calendar arrangement of the growth record is required (see below).

North Sea BWTs show a distinct, non-sinusoidal seasonal temperature cycle, and lag behind the surface water temperatures by about 3 months (Figure 4). Below the thermocline, minimum temperatures usually occur about 1 month later than at the surface, i.e. during award March, whereas maximum temperatures are attained during November, i.e. 3 months later than at the sea surface. The temperature maximum during November results from the disruption of the thermocline and the downward mixing of warm surface waters (Figure 4; Pohlmann, 1996b).

We anchored the $T_{\delta^{18}O}$ of *A. islandica* to the minimum HAMSOM-BWT$_{50}$ (Figure 5). Shell growth starts about 20 to 45 microincrements before the minimum temperatures are reached, i.e. during February, and
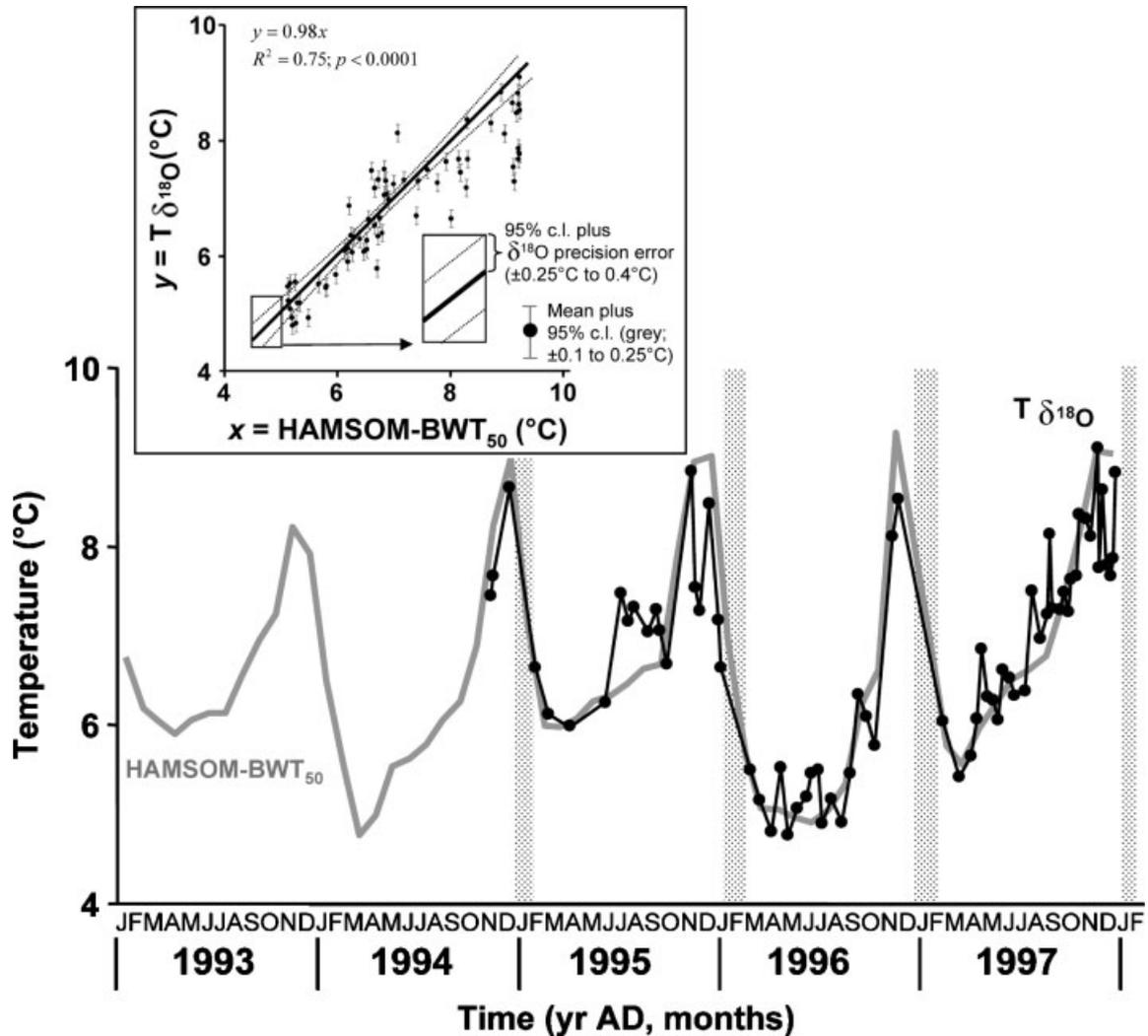
Figure 5. The calendrically aligned oxygen-isotope-derived temperature record closely (black) matches the HAMSOM-BWT$_{50}$ (grey). We forced the regression line ($T_{\delta^{18}O}$ versus HAMSOM-BWT$_{50}$, scatter plot) through the origin and calculated a slope of $0.98 \pm 0.04\,°C$. This result matches the expected slope of $1\,°C$ almost exactly and suggests that shell oxygen-isotope-derived temperature can precisely reconstruct temperatures of the ambient water. Precision error is 0.25 to $0.4\,°C$

stops as soon as the temperatures decrease during December. Possibly, the cessation of shell growth in December–February is related to spawning (Jones, 1980, 1981). Our findings suggest that specimens of *A. islandica* below the thermocline precipitate aragonite mainly from February through to December and record both the minimum and maximum temperatures (Figure 5).

5. RESULTS

The results indicate that shell oxygen isotopes can reliably be used to reconstruct ambient BWTs and, more importantly, temperature trends of bottom water during the last century. In the following we compare the $T_{\delta^{18}O}$ record with observational and modelled water temperatures and demonstrate that minimum $T_{\delta^{18}O}$ are closely related to the WNAO.

5.1. Shell oxygen-isotope-derived temperature record

Figure 5 shows that calendrically aligned oxygen-isotope-derived temperatures match HAMSOM-BWT$_{50}$ temperatures almost perfectly ($r = 0.86$, $R^2 = 0.75$, $p < 0.0001$). We obtained a slope of $0.98 \pm 0.04\,°C$. Hence, a change in $T_{\delta^{18}O}$ by $1\,°C$ roughly equals a $1\,°C$ shift in HAMSOM-BWT$_{50}$. Oxygen isotopes underestimate the maximum temperatures, however, by up to $0.7\,°C$, whereas minimum temperatures are reliably recorded. From July to September, $T_{\delta^{18}O}$ is more variable and individual measurements may deviate by up to $1\,°C$ from HAMSOM-BWT$_{50}$ (Figure 5). Within the 95% confidence limits, HAMSOM-BWT$_{50}$ can be estimated from $T_{\delta^{18}O}$ with an accuracy of ±0.1 to $\pm0.25\,°C$. Owing to the analytical uncertainty of individual oxygen isotope measurements ($\pm0.15\,°C$), the maximum possible error in the temperature estimates is 0.25 to $0.4\,°C$ (Figure 5). The largest prediction errors ($0.4\,°C$) are likely for reconstructions of warm temperature, whereas the error for minimum temperatures is smaller ($0.25\,°C$).

Most other shells used in the present study were sampled with slightly lower temporal resolution (on average, 1.5 months per isotope sample). Hence, oxygen isotopes underestimate the most positive HAMSOM-BWT$_{50}$ values by up to $1\,°C$ (Figure 6: see period of 1958–97). However, oxygen-isotope-derived temperature curves very much resemble the general temperature trends (Figure 6). For example, the general decrease in winter temperatures during the mid 1860s to the mid 1880s is well established in the $T_{\delta^{18}O}$ record. Seasonal extremes, e.g. the hot summer of 1947 — a well-known 'pointer year' in dendrochronological studies (e.g. Kroupovà, 2002; Schweingruber and Nogler, 2003) — are clearly recorded by the shells (Figure 6). Note that the preceding winter (1947) was one of the coldest during the past 120 years in central Europe (also compare http://www.metoffice.gov.uk/education/historic/winter). Shells growing during the same time period record similar absolute $T_{\delta^{18}O}$ values (e.g. 1969, Figure 6).

The correlation between calculated ($T_{\delta^{18}O}$), reconstructed (ERSST), and modelled (HAMSOM-BWT$_{50}$) seasonal temperature extremes was evaluated using standard ordinary least-squares regression (Figure 7). Older shell portions with low sample resolution, i.e. less than three $T_{\delta^{18}O}$ values per year, were omitted. Minimum $T_{\delta^{18}O}$ values explain 59% (1958–97) of the HAMSOM-BWT$_{50}$ and 43% (1880–2001) to 52% (1958–97) of the ERSST minimum temperature variability. The correlation between minimum temperatures T_{min} of the ERSST and HAMSOM-BWT$_{50}$ data set is higher (shared variance 73%, 1958–97) than the correlation between $T_{\delta^{18}O}$ and ERSST or HAMSOM-BWT$_{50}$. Maximum SSTs (ERSST) share less variance with maximum BWTs (T_{max}). Only 6% (1958–97) to 16% (1880–2001) of the variability in maximum $T_{\delta^{18}O}$ is explained by the maximum ERSST. The correlation between maximum ERSST and maximum HAMSOM-BWT$_{50}$ temperatures is also small (shared variance 7%, 1958–97; Figure 5). Maximum $T_{\delta^{18}O}$ exhibit an astoundingly good correlation to T_{max} of the HAMSOM-BWT$_{50}$ record (shared variance 48%; Figure 7). This result is in agreement with the $T_{\delta^{18}O}$-HAMSOM-BWT$_{50}$ plot shown in Figure 5. Despite lower sampling resolution, the values are almost as high as for minimum temperatures.

5.2. Historical temperature trends

ERSST shows clear warming trends over the past 120 years (Figure 8). From 1880 to 2001, minimum winter SSTs (ERSST) increased by about $0.041\,°C$/decade, while maximum summer temperatures increased by about $0.058\,°C$/decade. As expected, the annual average surface temperatures T_{av}, calculated as $(T_{max} + T_{min})/2$, also exhibit a positive trend ($+0.050\,°C$/decade). Over the same period, BWTs $T_{\delta^{18}O}$ calculated from shell oxygen isotopes suggest a similar warming trend for T_{min} ($0.042\,°C$/decade), but a greater warming for T_{max} ($0.138\,°C$/decade) and, consequently, T_{av} ($0.094\,°C$/decade).

For comparison with the HAMSOM-BWT$_{50}$, we calculated the T_{min}, T_{max} and T_{av} trends for the period from 1958 to 1997 (Figure 8). In surface waters, annual warming trends were significantly higher during the past four decades than during the preceding century. Whereas the warming trend of average T_{min} doubled ($+0.094\,°C$/decade), T_{max} trends quadrupled ($+0.248\,°C$/decade) during the past four decades. Below the thermocline, T_{max} warmed at similar rates to surface waters ($+0.229\,°C$/decade). However, winter BWTs increased at significantly lower rates than surface-water temperatures (Figure 8). The HAMSOM-BWT$_{50}$ data set suggests a rise of annual winter minimum of $+0.018\,°C$/decade. The $\delta^{18}O_{aragonite}$-derived temperature
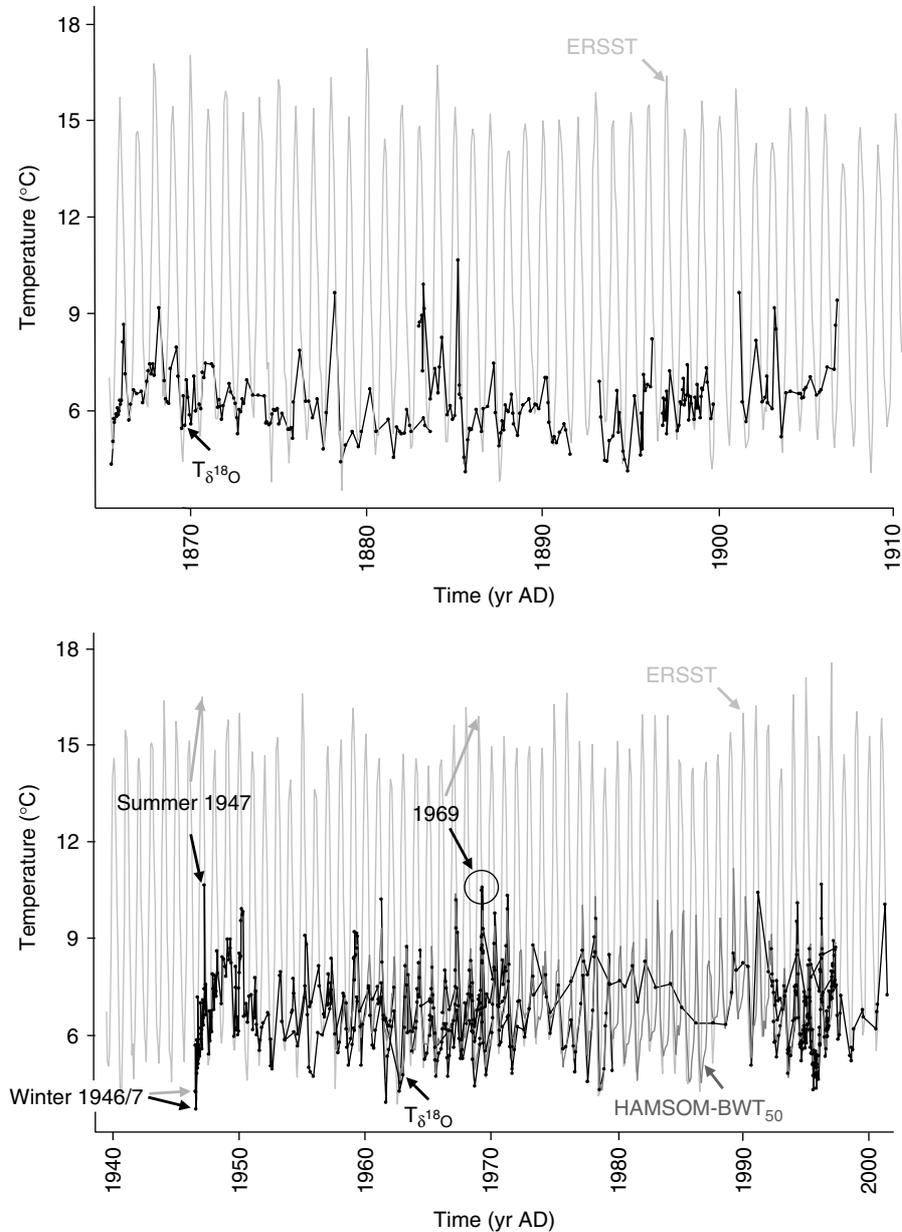
Figure 6. Oxygen-isotope-derived temperature curves (black) resemble the general temperature trends (HAMSOM-BWT$_{50}$, dark grey; ERSST, light grey) very well. Seasonal temperature extreme, such as the hot summer of 1947 (a well-known 'pointer year' in dendrochronological studies), or the preceding winter are clearly recorded by the shells. Note that HAMSOM-BWT$_{50}$ and shell oxygen-isotope-derived winter temperatures (e.g. 1947) are in good agreement. $T_{\delta^{18}O}$ values inferred from different shells for the same time (e.g. circle at 1969) are almost exactly similar. The new record covers the period of 1866 to 2002; temporal resolution varies with sample size

trends reflect the HAMSOM-BWT$_{50}$ changes: $+0.033\,°C/decade$, $+0.236\,°C/decade$ and $+0.144\,°C/decade$ for T_{min}, T_{max} and T_{av} respectively.
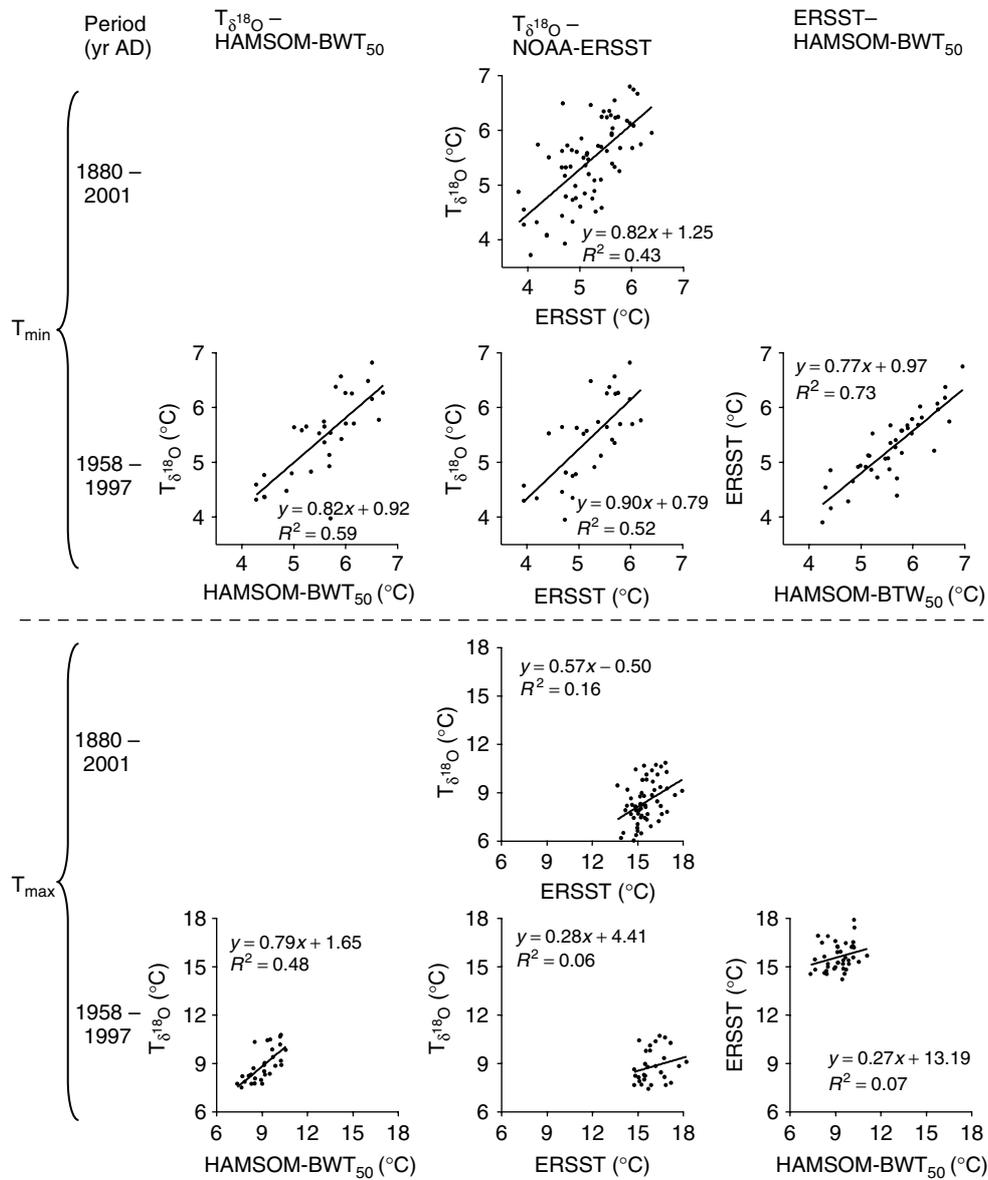
Figure 7. Standard ordinary least-squares regression between calculated ($T_{\delta^{18}O}$), reconstructed (ERSST), and modelled (HAMSOM-BWT$_{50}$) seasonal temperature extremes (T_{min} and T_{max}). Minimum $T_{\delta^{18}O}$ values explain 59% of the HAMSOM-BWT$_{50}$ and 43 to 52% of the ERSST minimum temperature variability. Shared variance between ERSST and HAMSOM-BWT$_{50}$ is 73%. Whereas only 6 to 16% of the variability in maximum $T_{\delta^{18}O}$ is explained by the maximum ERSST, the maximum $T_{\delta^{18}O}$ values exhibit a good correlation to T_{max} of the HAMSOM-BWT$_{50}$ record (shared variance 48%). Shared variance between ERSST and HAMSOM-BWT$_{50}$ is 73%; $p < 0.0001$

5.3. Relation between winter temperature and NAO index

North Sea minimum temperatures exhibit a positive correlation with Hurrell's (1995) WNAO index (Figure 9). Minimum (December–March) ERSST data share 44% (1880–2001) to 46% (1958–97) of the variance with the WNAO. The correlation is equally good below the thermocline: 41% of the variability of the HAMSOM-BWT$_{50}$$T_{min}$ over 1957–97 is explained by the WNAO, and 31% (1880–2001) to 50% (1958–97) by T_{min} inferred from shell oxygen isotopes (Figure 9).
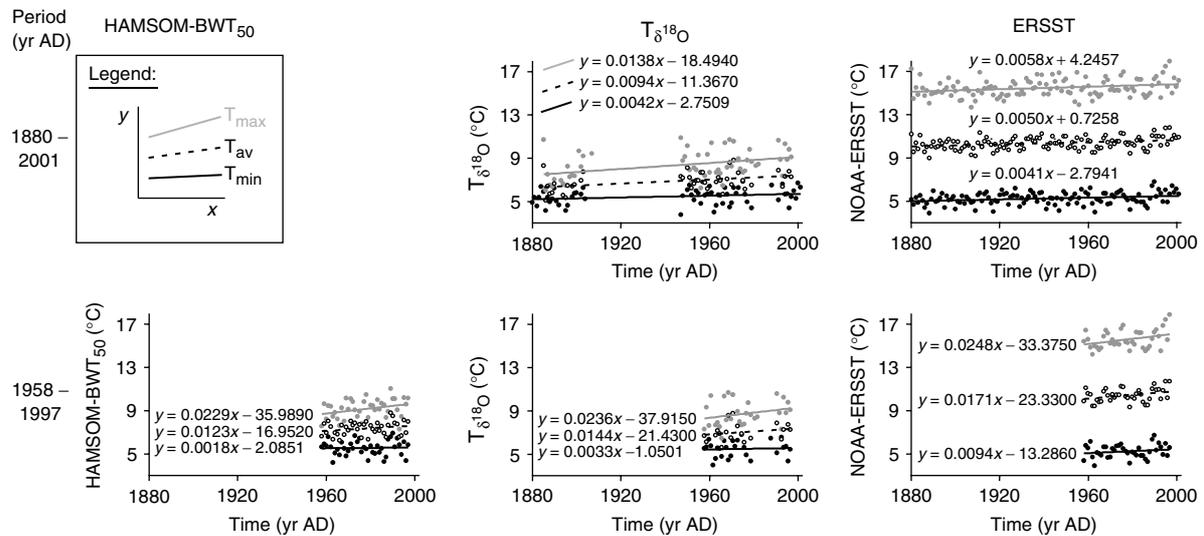
Figure 8. Historical temperature trends below (HAMSOM-BWT$_{50}$, $T_{\delta^{18}O}$) and above (ERSST) the thermocline. Clear warming trends occur in all data sets. During the past four decades, warming trends have intensified. Maximum temperatures have increased more strongly than minimum water temperatures

6. DISCUSSION

A. islandica provides an excellent archive of BWTs. The present study demonstrates that oxygen isotope ratios from shells of the extremely long-lived bivalve mollusc *A. islandica* can provide quantitative estimates of past BWTs. A sampling resolution of approximately 20 isotope samples per annual growth increment yields a temporal resolution of about 1 to 6 weeks. Daily growth rates are not constant, but vary with temperature, so that the number of daily increments contained in each isotope sample varies throughout the year. Thus, BWTs can be reconstructed from shell oxygen isotopes with a precision better than ±0.25 to $\pm0.40\,°C$ (Figure 5).

Owing to their long life spans, ocean quahogs register the magnitude and frequency of seasonal BWT extremes over long time periods, i.e. several centuries. The time span of these reconstructions is not limited to the life span of a single *A. islandica* specimen, since recent advances in absolute dating techniques, such as the amino acid racemization dating technique (Goodfriend 1992; Goodfriend *et al.*, 1996, 1997), enable dating of (sub)fossil shell portions with an accuracy of 1 to 15 years. In addition, shells with unknown calendar ages can be dated to the nearest year or month with cross-dating techniques developed by dendrochronologists (Fritts, 1976). Based on similar growth patterns, growth-increment time series of synchronous trees with overlapping life spans can be strung together to form mean and master chronologies spanning centuries and millennia. Similar techniques were recently applied to a variety of different bivalve mollusc species (Jones *et al.*, 1989; Marchitto *et al.*, 2000; Schöne, 2003; Schöne *et al.*, 2003a,b, 2004b; Strom *et al.*, 2004).

6.1. Comparison between measured/modelled and $\delta^{18}O_{\text{aragonite}}$-derived temperatures

Below the thermocline, $T_{\max}$ prevails only for a few weeks in November (Figure 4). Absolute $T_{\max}$ values are, therefore, difficult to obtain from shell oxygen isotope ratios, because the sampling resolution in most of the shells studied was about 1.5 months per isotope sample. As a result, $T_{\max}$ may be underestimated by up to $1\,°C$ (note that error in temperature estimates in Figure 5 is smaller, because spatial resolution was better than in most other specimens).

Relative changes in both $T_{\min}$ and $T_{\max}$ can be reconstructed from shell oxygen isotopes with almost the same reliability. The R^2 values between the shell oxygen-isotope-derived and HAMSOM-BWT$_{50}$ seasonal temperature extremes are almost the same: 0.48 and 0.59 respectively (Figure 7). We attribute these findings to the consistent spatial sampling resolution of the youth portions of different specimens.
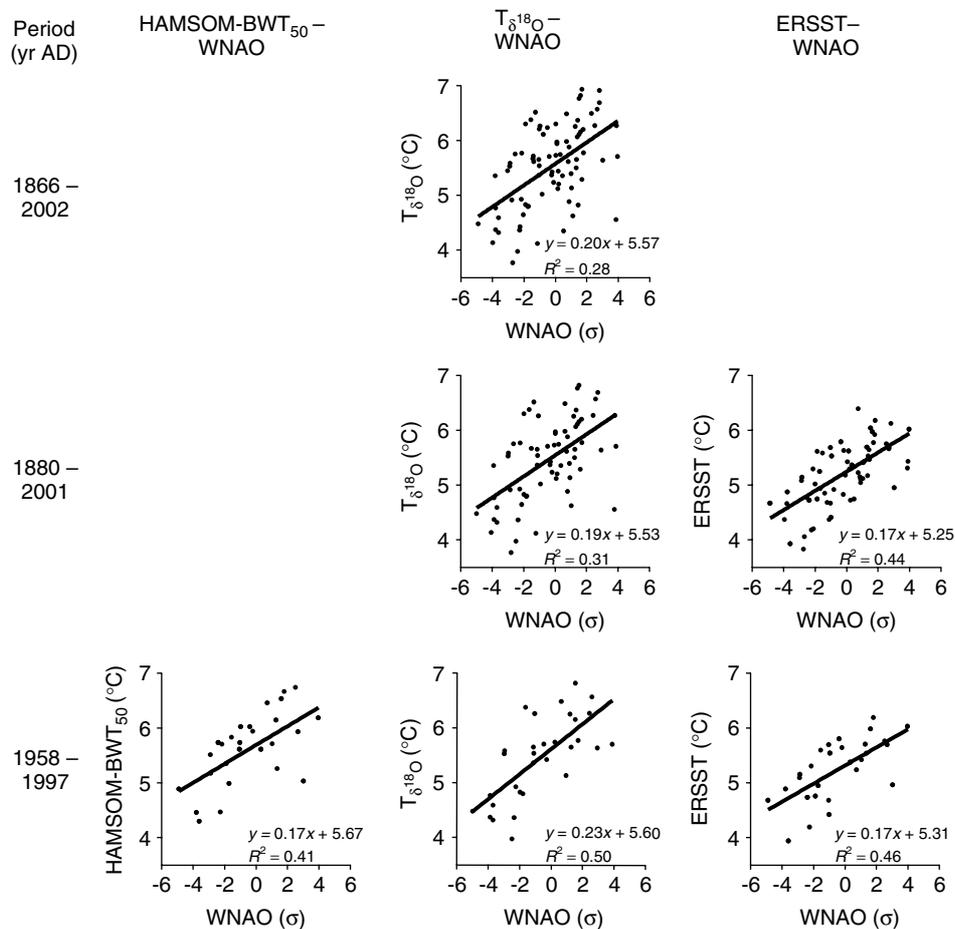
Figure 9. Intra-annual minimum temperatures closely correlated to the WNAO. Shell oxygen-isotope-derived water temperatures provide a reliable proxy for the WNAO ($p < 0.0001$)

Shell oxygen-isotope-derived temperatures, in particular T_{max}, are less well correlated to surface water temperatures (Figure 7). Whereas 43 to 52% of the variability in winter minimum $T_{\delta^{18}O}$ is explained by coldest surface water temperatures, summer temperatures are only explained by 6 to 16% (Figure 7). BWTs do not just mirror the existing SST. In the central North Sea the summer thermocline acts like an isolator that prevents the heat from being dispersed from the surface into the deeper layers. On the contrary, the bottom water conserves the temperature of the preceding winter. The good correlation ($R^2 = 0.73$) between T_{min} (observational records) of bottom and surface waters (preceding winter) is explained by convective overturning and enhanced mixing of the water column during winter.

6.2. Temperature trends in surface and bottom waters

Despite the potential error of up to 0.25 to 0.4 °C in individual temperature estimates, the *A. islandica*-based temperature reconstruction confirms the magnitude of the warming trends over the past four decades predicted by HAMSOM-BWT$_{50}$ for the North Sea (Figure 8). Analytical errors in temperature estimates are randomly distributed over the entire time series. We would not find centennial- and decadal-scale trends in the proxy data if BWTs had remained unchanged. Hence, the observed trends reflect true systematic temperature trends.

Owing to the scarcity of data, the effects of global change on the world's oceans over longer (decadal to centennial) time scales are not known (Levitus *et al.*, 2000) and very difficult to model (Banks and Wood,

2002). The mean conditions prior to anthropogenic forcing and the natural variability that also exists are, at present, poorly known. Quantitative estimates of the mean temperature increase for the $0-300$ m layer are limited to the 1948 to 1998 period (Levitus *et al.*, 2000). Thus, the present paper provides a step toward a better understanding of the unknown. Our data not only demonstrate that the general warming trends occurred in deeper water settings, but that the warming trends have intensified during the past decades. Seasonally, maximum BWTs show stronger warming than minimum temperatures, resulting in an increase in the mean seasonal temperature range.

When compared with SST trends over the period from 1880 to 2001, the minimum increase of minimum $T_{\delta^{18}O}$ in the bottom water is of nearly the same magnitude ($0.042\,°C/\text{decade}$ versus $0.041\,°C/\text{decade}$; Figure 8). $T_{\min}$ trends in bottom waters are remarkably stable. The trend is roughly the same for the past 120 years and the last 40 years. However, deeper water $T_{\max}$ has increased at a much faster rate during the past 40 years (approx. $0.23\,°C/\text{decade}$) than during the past 120 years ($0.138\,°C/\text{decade}$). An accelerated increase in water temperature since the mid 1960s has been reported from many different localities on land and sea (Hurrell, 1995; Houghton *et al.*, 2001). It is now generally accepted that increased anthropogenic emissions of greenhouse gases such as carbon dioxide, water vapour, ozone and trace gases account for the observed unusual global warming trends (Karl and Trenberth, 2003). The present study confirms that warming is not restricted to the surface mixed layer.

According to shell oxygen isotope data, $T_{\max}$ below the thermocline increased by more than twice as much as surface waters from 1880 to 2001 (Figure 8). The absolute $T_{\max}$ trend should be interpreted with care. As mentioned earlier, $T_{\delta^{18}O}$ may provide slightly less reliable absolute summer temperature estimates because of the low sampling resolution employed here. Thus, the summer warming trend predicted by shell oxygen isotopes for bottom water may be too large. On the contrary, comparison with the modelled BWTs during summer indicates that $T_{\max}$ values reconstructed from shell isotopes are in good agreement with the HAMSOM-BWT$_{50}$ record, so that the oxygen-isotope-derived temperature trend may reflect a true warming trend of the bottom water.

During the past four decades, $T_{\max}$ of bottom water has increased significantly faster than winter temperatures ($T_{\delta^{18}O}$: $0.033\,°C/\text{decade}$ versus $0.236\,°C/\text{decade}$ and HAMSOM-BWT$_{50}$: $0.018\,°C/\text{decade}$ versus $0.229\,°C/\text{decade}$). Consequently, the spread between $T_{\min}$ and $T_{\max}$, the seasonality, has increased. Similar trends can be observed at the sea surface (Figure 8). The summer temperature warming trend exceeds that of the winter temperatures by more than a factor of two ($0.094\,°C/\text{decade}$ versus $0.248\,°C/\text{decade}$).

6.3. Tool for tracking changes of the NAO

In a previous study, Schöne *et al.* (2003a) demonstrated that variable growth rates of shells of *A. islandica* record changes of the WNAO. Here, we show that the shells contain another proxy archive of the changes of the WNAO, i.e. oxygen isotopes. Minimum $T_{\delta^{18}O}$ shares 28 to 50% of variability with the WNAO (Figure 9). These findings are not astounding, because winter temperatures of the North Sea are governed by the WNAO. Positive WNAO (strong sea-level pressure difference between the Azores and Iceland) years result in mild winters, whereas negative WNAO years result in cold winters. Seasonal temperature minima of the North Sea are thus in good agreement with the winter WNAO index (Figure 9). Shells of the ocean quahog that lived below the thermocline provide an extremely useful tool for reconstructions of the WNAO, because they reliably (winter temperatures are conserved below the thermocline) record the seasonal temperature minima in their oxygen isotope ratios (Figure 9).

7. IMPLICATIONS AND CONCLUSIONS

The present study provides a proxy-based temperature reconstruction of mid- to high-latitude marine temperatures with seasonal resolution. The results indicate that (1) shells of *A. islandica* provide reliable estimates of water temperatures below the thermocline, (2) warming trends occur in bottom waters and have intensified during the past four decades and (3) temperatures inferred from oxygen isotope ratios of *A. islandica* shells provide an excellent proxy for the WNAO.

Our new tool enables testing and verification of climate models prior to the 20th century greenhouse forcing. Seasonal temperature proxies reconstructed from shells of *A. islandica* can significantly contribute to our understanding of the effects of global change on BWTs in mid to high latitudes. Future studies will focus on the temporal extension of the oxygen isotope record before industrialization.

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