



The potential of *Arctica islandica* growth records to reconstruct coastal climate in north west Scotland, UK

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ARTICLE INFO

Article history:

Received 19 September 2008

Received in revised form

23 June 2009

Accepted 23 June 2009

ABSTRACT

This paper describes potential methods for reconstructing past marine environmental and climatic variability in Scottish coastal waters through the investigation of annual growth increments measured from shells of the long-lived marine bivalve *Arctica islandica* (L.). This is accomplished by using a combination of sclerochronological and dendrochronological techniques which were employed to determine the age of specimens and to create growth chronologies. Using negative exponential detrending methods, a preliminary *A. islandica* master chronology for the Lynn of Lorn, Scotland has been produced. This chronology indicates highly suppressed growth between the mid 1940s and late 1980s. The growth response of this species to the sea surface temperatures in Scottish coastal waters appears to be complex, most notably during recent decades when land-use changes and marine aquaculture may influence shell growth at this site.

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1. Introduction

Annually resolved information of past changes in the marine environment and oceanic climate from the mid- and high-latitude shelf seas is limited to a few instrumental records which are restricted both in terms of their length and of their spatial coverage (Inall et al., 2008). Currently, the two primary alternative sources for gaining annually resolved records for marine environments are corals (e.g. Buddemier et al., 1974; Hudson et al., 1976; Wilson et al., 2006) and bivalves (e.g. Weidman et al., 1994; Witbaard, 1997; Schöne et al., 2003). With the exception of some deep-water corals, from which annually resolved palaeoclimate records are rare (e.g. Roberts et al., 2006), the mid- and high-latitude shelf seas lack the reef-forming corals of the tropics. Bivalves, on the other hand, are commonly found in the cooler northern latitudes and therefore hold more potential than corals for palaeoclimate work in these regions.

Sclerochronology is “the study of physical and chemical variations on the accretionary hard tissue of organisms, and the temporal context in which they formed” (Jones et al., 2007), and has much in common with dendrochronology, which can be considered the forbear of this field of research. Initial work in

sclerochronology focused on corals (e.g. Hudson et al., 1976). Later, the field diversified and other records including bivalves (e.g. Jones, 1980; Witbaard et al., 1994) and otoliths (Hedger et al., 2008) were investigated. There is also the potential to use coralline red algae (Halfar et al., 2008) and coralline sponges (Böhm et al., 2002) to provide high-resolution marine proxy records. Recently, research has focused on using the marine bivalve *Arctica islandica* (Linnaeus, 1767) as a proxy for changes in both the marine environment and the climate (e.g. Witbaard, 1996; Marchitto et al., 2000; Schöne et al., 2003, 2005; Wanamaker et al., 2007, 2008a; Schöne and Fiebig, 2009; Butler et al., 2009). *A. islandica* is a sub-littoral, infaunal bivalve (Witbaard, 1997) found in muddy and silty sediments (Thompson et al., 1980) in water depths between 4 m (Rowell et al., 1990) and 280 m (Thompson et al., 1980). Within a sectioned shell (see Scourse et al., 2006; Fig. 2), growth increment lines and growth increments are apparent, the latter reflecting inter-annual differences in growth rate. Several studies have identified the annual nature of these increments in this species. Such studies have included, (1) oxygen isotope profiling of individual increments (Weidman et al., 1994; Witbaard et al., 1994) to indicate seasonality, (2) marking and recapture of ‘live’ samples to determine how many increments were ‘laid down’ during a known period of time (Jones, 1980), (3) variations of ¹⁴C concentration within increment chronologies to locate the ¹⁴C bomb-pulse of the 1950s and 1960s (Weidman and Jones, 1993; Kilada et al., 2006), and (4) utilising time-dependant, natural or

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anthropogenic radionuclide signals, taken up from the surrounding water, in order to test annual chronologies (Witbaard et al., 1994). Annual growth increments allow the age of a specimen to be determined by counting the number of complete growth increment lines present within the hinge plate of the shell (see Scourse et al., 2006; Fig. 2). In some studies it has even been possible to identify daily growth increments (Schöne et al., 2005).

Support for using the species as a proxy for environmental changes are: (1) its well-documented longevity – the oldest known specimen is 405 years old (Wanamaker et al., 2008a,b), (2) in addition to growth increment width changes, other parameters such as $\delta^{18}\text{O}$ variations (Weidman et al., 1994) and ^{14}C changes (Witbaard et al., 1994) can be measured on annual to sub-annual time-scales, (3) cross-matching of shells from a site can be carried out, indicating a common response to local environmental/climate factors (Wanamaker et al., 2008a), (4) fossil shells can be cross-matched to generate a floating chronology for a site (Scourse et al., 2006), although radiocarbon dating is currently required for grouping samples in roughly similar time frames, (5) master chronologies can be extended beyond the range of the living shells by cross-matching dead-collected specimens into the chronology (Marchitto et al., 2000), and (6) the distribution of *A. islandica* in the mid- and high-latitudes during the Holocene is widespread (see Scourse et al., 2006).

In sclerochronology, as in dendrochronology, there is the need to detrend raw growth data because of the presence of a non-linear ontogenetic growth effect; typically a period of higher growth rates are observed during the juvenile stages (Witbaard, 1997). To date, within the majority of *A. islandica* sclerochronological literature, detrending methods involve using some form of smoothing filter, e.g. flexible splines (Scourse et al., 2006), or moving averages (Epplé, 2004). The application of such flexible detrending methods removes the low frequency ontogenetic growth trend to maximise the year-to-year signal, thereby facilitating crossdating, but fail to fully capture potential multi-decadal or longer time-scale trends present within the data. Alternative detrending methods are therefore advisable for the purpose of studying long-term environmental change. In this study, we experiment with using negative exponential functions, which potentially retain more information at multi-decadal and longer time-scales.

Individual detrended time-series are known as standardised growth index (SGI) series and the temporal synchronicity of such series is assessed by matching the sequence of wide and thin incremental indices between samples. In dendrochronology, this procedure, known as crossdating (Douglas, 1941; Stokes and Smiley, 1968), is vital to ensure dating control and verifies that the data are annually resolved. The concept of applying crossdating within sclerochronology is relatively new (Marchitto et al., 2000; Helama et al., 2006; Scourse et al., 2006; Butler et al., 2009). Recently, the potential to cross-match SGI series data has been demonstrated for fossilised *A. islandica* specimens from the North Sea, where a floating chronology has been created for the period AD 1000–1400 (Scourse et al., 2006), whilst Butler et al. (2009) have successfully constructed a 489-year chronology by cross-matching together dead and live samples for the Irish Sea.

The primary aim of this paper is to review the sclerochronological methods currently being applied to *A. islandica* and to highlight the potential of applying more refined data processing methods that are commonly used in modern dendrochronology. Although sclerochronology has existed since the 1970s (e.g. Hudson et al., 1976), its application still has much to learn from dendrochronology, which has a long and established record. Using methods prevalent in dendrochronology, a revised methodology for constructing growth increment chronologies in *A. islandica* is proposed. This methodology should facilitate the study of past

climatic and environmental change. These methods are outlined here, together with a preliminary investigation of the statistical relationships between SGI series and regional climate variables from north west Scotland.

2. Regional setting

Samples were collected from two sites off the west coast of Scotland (Fig. 1), a region, which is influenced by the relatively warm, saline waters of the North Atlantic and is thus indirectly affected by the North Atlantic's meridional overturning circulation (Inall et al., 2008).

The main sampling location is the Lynn of Lorn (C1), a well-mixed coastal site with a water depth of 11–17 m where the mixing processes are different from those at the Loch Creran (C2) fjord site which is described in more detail in Gage, 1972a and Gage, 1972b.

The primary field site (C1) was characterised as having sediments consisting of silty mud with variable amounts of silt and gravel (Collier and Brown, 2005). Samples were collected close to sampling station V18 of Brown and Collier (2008) which was classified as habitat type SS.SMu.CSaMu.VirOphPmax based on the classification scheme of Connor et al. (2004). Annual seawater temperature in the area ranged from 5.6 °C (Jan–Mar), to 15.1 °C (Aug–Sep) (daily average of 240 measurements, August 1995 to March 2009; M.D.J. Sayer, unpublished data). Salinity averages range from 33.3 to 34.1 (estimated from Firth of Lorne from Heath, 1995). Mean, maximum and residual current speeds ranged from 3.4 to 7.3, 20.1 to 38.4 and 1.7 to 3.6 cm s^{-1} respectively. The residual direction varied between south and west (T.A. Wilding, unpublished data).

This research, which uses *A. islandica* as a proxy to reconstruct past shelf sea environmental change, has focused on north west Scotland because the number of instrumental records of marine environmental change available for the region are limited, both in their spatial coverage and in terms of the longevity of the series (see Fig. 1a). Thus, the mollusc data shown here could potentially provide an invaluable extension to the sparse instrumental data available.

3. Materials and methods

3.1. Field sampling

All 'live' shells discussed herein (except C2-MS1) were collected by SCUBA divers from the UK NERC National Facility for Scientific Diving (NFSD), near Oban, Scotland.

Diving was chosen over routine dredging as the preferred collection method because it is less harmful to the surrounding benthos and furthermore, the diver can accurately log the location from which the samples were collected. This approach makes it possible to revisit the site either for collection of additional samples or to gain more information regarding the location from which samples were collected, such as *A. islandica* density, sediment and associated flora and fauna.

3.2. Biometric data

Biometric data including shell dry weight and height (measured along the line of maximum growth from the umbo to the ventral margin) were recorded for all shell specimens from the field area as well as for those from the National Museum of Scotland (NMS) archive. To gain an insight into national biometric trends, shells stored in the NMS archives were divided into two categories: (1) single shells and (2) paired shells (i.e. those still articulated). For



Fig. 1. a) Location of instrumental datasets for the west coast of Scotland. The longest instrumental datasets are 1) Tiree Passage (T) (Dr. Mark Inall, SAMS); 1980–2008 (with some gaps in the record), 2) the Ellett Line (thick line) (Dr. Estelle Dumont, SAMS); 1975–2008 (except 1986 and 2002), and 3) Millport (M) (Millport Marine Laboratory); 1953 to present. The square on map 2a illustrates the location of the field sites shown in 2b. b) Field site locations. C1 Lynn of Lorn, C2 Loch Creran (corresponding to sample site C5, Gage, 1972b) and location of Saulmore dataset collection site (S) (Dr. Martin Sayer, UK NERC Facility of Scientific Diving).

reasons of comparability, only the results for the single shells are presented here. The NMS shells come from over 20 sites around the United Kingdom, ranging from Shetland in the north to Guernsey in the south, and were collected at various, unfortunately sometimes unknown, times using various sampling methods. Data from dead- and live-collected specimens from site C1 (named “study site shells”) were also analysed to provide the local sample set which could be compared to the national database. Such data are important not only to understand the dynamics of the sample population, but also to build up an understanding of how its biometrics compare to biometric data from around the UK as a whole. If age data are compared to height and weight datasets then there is the potential to pre-select shell material of an approximate age for further, detailed analysis. Biometric data may also provide useful information on the growth rates of shells from different locations and environments. Population age structure can be inferred from biometric data and such data would make, for example, responsible diver collection easier, if shells of a known age were required to enhance or extend the replication of a master chronology. Such information can also allow divers to carry out on-site population structure surveys so that we can gain a better understanding of age structures for a particular site. Such studies have been carried out already for the North Sea, using a variety of trawl collections (Witbaard and Bergman, 2003).

3.3. Sectioning

Specimens were sectioned along the line of maximum growth (see Scourse et al., 2006) to examine the internal growth increments. In order to prevent the shell from breaking while this procedure is undertaken, the wings of the shell are cut off using a circular diamond saw and the line of maximum growth is marked

on the shell. The marked shell is mounted in Aeropia epoxy resin in Metprep silicon moulds using a mix of 40% hardener to 60% epoxy which is heated at a low temperature for 90 s in a microwave to remove any bubbles present. Once the resin has set, sectioning along the marked line of maximum growth is undertaken using a circular diamond saw. In specimens where the hinge plate (see Scourse et al., 2006) is not sectioned correctly, it is possible to grind the section at a coarse level (74 μm) to reach the line of preferred sectioning (see Jones, 1980). Once correctly sectioned, the working surface is prepared by following a grinding and polishing procedure, working with increasingly finer grinding levels on a rotating lapping machine with water dripping onto the grinding plate surface for lubrication purposes. Initial polishing is performed using silicon carbide powder, which is mixed with water to create a paste; this paste is applied to a glass plate which is then used to polish the surface of the shell. The final polishing stage is performed on a rotating polishing machine using 3 μm and 1 diamond paste. All these stages require the operator to hold the resin block onto the surface of the grinding/polishing plates and continuously move the block to ensure even removal of any scratches present.

The polished sections are etched in hydrochloric acid (HCl) (Thompson et al., 1980) by being submerged in a 1.5% (HCl) solution for between 1.5 and 2 min, rinsed in deionised water and left to dry, under a fume hood. Cellulose acetate, 35 μm thick, is applied to the surface of the section, and acetone is used to adhere it. The specimens are left under the fume hood for one hour to allow the acetate to ‘mould’ itself to the relief of the etched surface. After this, the acetate sheets can be slowly removed from the resin block and trimmed down to allow the peel to be mounted between a standard microscope slide (75 mm \times 25 mm \times 1.2 mm) and a cover-glass (64 mm \times 22 mm). Where a peel is too large to fit onto a single slide, it is cut into two pieces and mounted on two different

slides. Mounting peels between slide and a coverglass reduces the amount of distortion and improves the final image obtained when the peel is photographed.

3.4. Growth increment counting and width determination

Acetate peels were examined under polarising microscope at a magnification of $\times 40$ and $\times 100$, then photographed using a digital camera attached to the microscope. These images are stitched together in Adobe Illustrator™ and Adobe Photoshop™ to create a composite from which growth increment widths are measured in the hinge plate. Prior to this, all growth increment decades are marked, following the dendrochronological procedures outlined in Stokes and Smiley (1968). As mentioned previously, the correct dating of the samples is crucial. To ensure that dating is correct, multiple samples are compared and crossdated. This entails a careful comparison of common point years between samples which allows the identification of missing or misidentified increments that could disrupt the accuracy of dating. Once dating control has been established, growth increment widths are measured using the programme CooRecorder (version 7.1 – Larsson, 2008a). The programme CDendro (version 7.1 – Larsson, 2008b) is used to graphically compare different growth time-series as well as to quantify the crossdating quality between series by using Pearson's correlation coefficient after the series have been high-pass filtered. If the crossdating is incorrect then correlations will be weak and non-significant.

3.5. Chronology construction

Once crossdating of measurements has been confirmed, a chronology can be constructed. This procedure is performed by following dendrochronological methods (Cook and Briffa, 1990) and has multiple steps. Firstly, the growth increment measurements are detrended to remove the ontogenetic growth trend present within the series (Fig. 2). For this study, the raw data have been detrended using a negative exponential function using ARSTAN (Cook, 1985) (Fig. 2). The use of a negative exponential function to detrend data is not new within the sclerochronological literature. Strom et al. (2004, 2005) and Nielsen et al. (2008) used this method, but with different mollusc species. With the exception

of Butler et al. (2009), negative exponential detrending has not been commonly applied to *A. islandica*. Witbaard et al. (2003) used a negative exponential function to detrend *A. islandica* growth records, but in conjunction with a 66-year spline as a second processing step. Such a practice is carried out by some dendrochronologists, as it is believed that such processing first removes the juvenile growth and then secondly reduces the residual noise still present within the record (Borgaonkar et al., 1999); however, it also removes potential long-term variability in the series. As the negative exponential function both removes the ontogenetic growth trend and preserves the longer-term variability in the shell, at frequencies up to the mean length of the samples (Cook et al., 1995), it is not necessary to carry out such double detrending.

Once the raw data have been detrended, the SGIs are averaged together to derive an index master chronology. The robustness of this mean chronology is related to the number of series used and the between series correlation (a measurement of common signal). The weaker the common signal, the more series needed to derive a robust mean site chronology.

It is common practice to use signal strength statistics in dendrochronology to assess the 'quality' of the resultant chronology. The seminal paper describing relevant signal strength statistics is that by Wigley et al. (1984) where the Expressed Population Signal (EPS) statistic is derived. Essentially, the EPS can be thought of as an empirical assessment of how the average of a sample of time-series correlates with the theoretical population time-series. The derivation of the EPS can be described as dividing the signal by the total variance (signal + noise). The EPS is calculated using the following equation:

$$\text{EPS}(t) = \frac{n(t)\bar{r}}{n(t)\bar{r} + (1 - \bar{r})} \approx \frac{\text{signal}}{\text{total variance}}, \quad (1)$$

where $\text{EPS}(t)$ is the Expressed Population Statistic at time t , $n(t)$ is the number of series at time t and \bar{r} is the inter-series correlation between all possible pairs of time-series in the sample (often referred to as RBAR). Wigley et al. (1984) showed that an EPS value greater than 0.85 was desirable to ensure a robust mean chronology.

The EPS equation above can be rearranged (see Wilson and Elling, 2004, for an applied example) to determine how many shells would be needed to derive a robust chronology:

$$n = \frac{(\bar{r} - 1) \text{EPS}(x)}{\bar{r}(\text{EPS}(x) - 1)}, \quad (2)$$

where $\text{EPS}(x)$ is the 0.85 value suggested by Wigley et al. (1984) and the mean between series correlation is defined by \bar{r} (RBAR).

3.6. Master chronology and instrumental data series analyses

To assess which marine environmental variables have a significant impact upon *A. islandica* growth rates, correlations between the Lynn of Lorn SGI master chronology and monthly instrumental time-series were undertaken. The instrumental data used for this comparison are the Met Office Hadley Centre's gridded sea surface temperature (SST) data (Rayner et al., 2003).

As the mollusc data show such a pronounced suppressed period between 1940 and 1980, the analyses were undertaken using both unfiltered and first differenced transforms. The latter transform allows a stringent assessment of the inter-annual signal in the mean chronology, which is especially important in this study as the EPS signal strength (see Section 4.3) identified a relatively weak common signal in the proxy data at these high frequency time-scales. The correlation analysis was carried out over the period from 1946 to 2005, as this is the period for which all

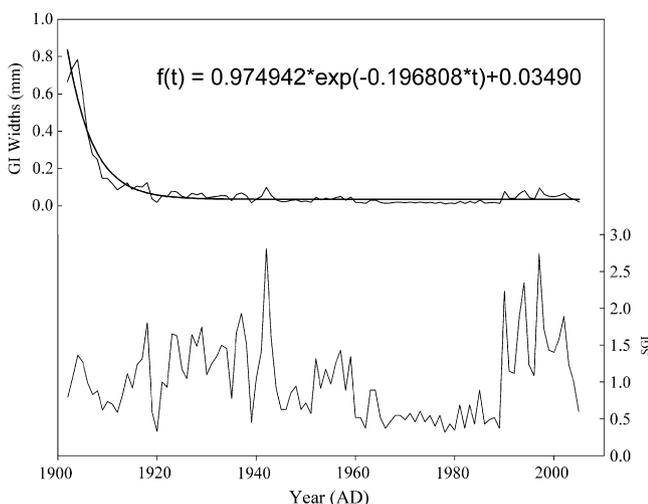


Fig. 2. *A. islandica* growth increment data for shell C1-L10 with the negative exponential detrending curve fitted to the data, together with the equation for the curve shown (top panel), where $f(t)$ is the function fitted to the data at year t . The standardised growth index (SGI) for the same shell is illustrated below.

crossdated shells are present within the first differenced master chronology. To allow an assessment of the temporal stability of any relationship found, the analysis was undertaken over two sub-periods of equal length (1946–1975 and 1976–2005).

3.7. Sclerochemistry: radiocarbon sampling

Radiocarbon dating has been employed in other studies (Turekian et al., 1982; Witbaard et al., 1994) to demonstrate that growth increments are annual. As *A. islandica* incorporates ^{14}C into its shell from the surrounding seawater, the past ^{14}C activity of that seawater should be recorded in the shell as it grows. In this study, we have undertaken radiocarbon analyses in order to establish whether or not the growth increments observed in shells from north west Scotland are annual in nature; we do this by comparing with radiocarbon data obtained from *A. islandica* from the North Sea.

All shells for the North Sea, German Bight (54°N 6°E, water depth approximately 37 m) study were obtained from live-captured specimens collected from dredge hauls in 1990. Shells were prepared by slicing each shell radially from the umbo through the ventral edge along the axis of maximum growth using a slow-speed petrographic saw with twin diamond-edged blades. A shell slice ~2 mm thick was obtained and the outer shell layer was then sub-sectioned into samples comprising one or more annual bands. Growth band chronology was precisely determined from photographed thin-sections of the shells. Samples were prepared for AMS analysis by first etching them in 10% HCl for 30 s to remove surface contaminants, followed by conversion to CO_2 in anhydrous phosphoric acid at 60 °C (overnight), and finally conversion to graphite using a hydrogen reduction and iron catalytic process (Gagnon and Jones, 1993). Preparation and analysis were carried out at the National Ocean Sciences AMS Facility at the Woods Hole Oceanographic Institution. All $\Delta^{14}\text{C}$ data were age-corrected to 1950 and normalized to $\delta^{13}\text{C}$ (PDB) value of -25‰ , according to methods outlined by Stuiver and Polach (1977). A $\delta^{13}\text{C}$ of $+2.0$ was assumed

for the shell aragonite based on the mean $\delta^{13}\text{C}$ value of other *A. islandica* shells from the eastern North Atlantic.

Nine samples were drilled along the outer prismatic layer of NMS specimen (C2-MS1) as part of an investigation into the marine radiocarbon reservoir effect in Scottish coastal waters (following Cage et al., 2006). The specimen that was live-collected at site C2 (Fig. 1) in 1968 was part of a benthic survey of Loch Creran (Gage, 1972a,b). Out of the nine samples prepared, seven yielded radiocarbon dates, sample numbers 7 (sclerochronological years 1941–1947) and 8 (sclerochronological years 1954–1957) were less than 4 mg and unfortunately yielded no radiocarbon results during laboratory analysis. Our sampling method grants us the opportunity to sample within a single growth increment during the early, rapid growth phase and to determine the exact sclerochronological age of that sample and to determine sclerochronological age within one to two years during the later, slow growth phase. These sampling ranges are illustrated within Fig. 5 as horizontal error bars with the weighting of the plotted data point being at the middle of the bands sampled.

4. Results

4.1. Biometric data

Biometric data (height and weight) for samples from the NMS archives and site C1 are presented in Fig. 3. The data for the live- and dead-collected shells from C1 have been combined into 'C1 shells'.

From these data it is possible to conclude that a positive relationship exists between height and weight in *A. islandica* specimens. By including the NMS samples, which were collected around the whole of the British Isles, it is apparent that the height–weight relationship of the C1 site is consistent with the larger UK dataset. Closer inspection of the live-collected data from the study site gives an interesting insight into the population structure. The range in weights between the largest (90.08 g) and smallest (38.895 g) samples collected live is 51.19 g and the height range for the

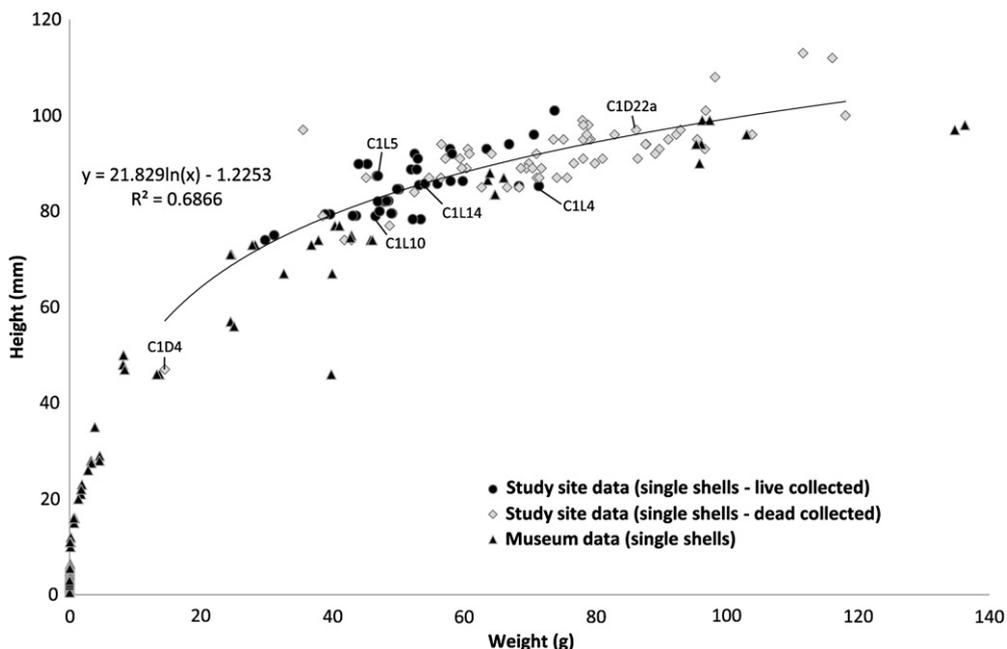


Fig. 3. Biometric data for a) the study site for this research – single shells live-collected (circles), b) the study site –single shells dead-collected (diamonds), and c) Museum (NMS) data – single shells (triangles). The NMS shells come from a range of sites across the United Kingdom and were collected at various dates. The trend line illustrates the growth curve for all shells from the field site. The oldest and youngest shells aged thus far and some shells on which crossdating has been undertaken are also indicated.

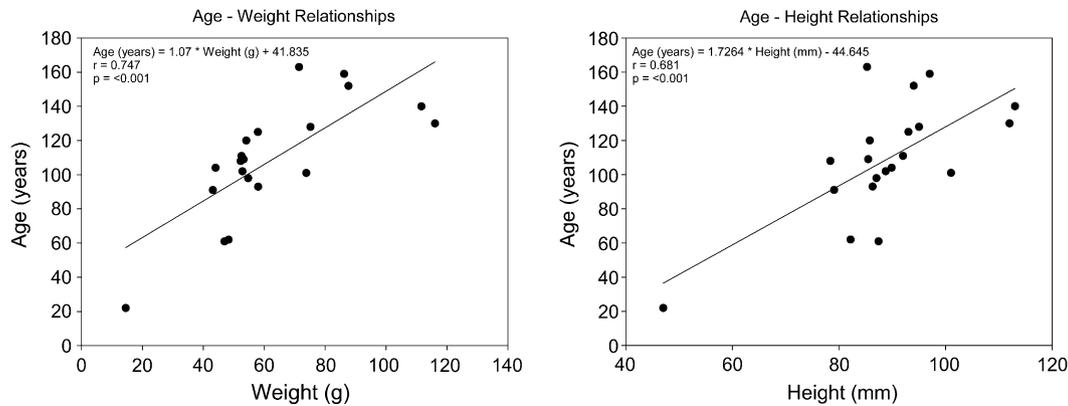


Fig. 4. Age – weight and age – height graphs for both dead- and live-collected *A. islandica* samples at site C1. Included in the graphs are the linear regression lines and their respective equations.

samples (smallest, 78.35 mm; largest, 103 mm) is 24.65 mm. The youngest live-collected sample processed from the dataset was 61 years old when it died (C1-L5; height 87.39 mm, weight 46.93 g) while the oldest live-collected shell was 163 years old upon death (C1-L4; height 85.25 mm, weight 71.429 g).

Currently, there are age, height and weight data for twenty shells, amongst which there are both dead- and live-collected specimens. Analysis of these data indicates that there is a statistically significant linear relationship present between weight and age (correlation coefficient = 0.747, p -value < 0.001) and height and age (correlation coefficient = 0.681, p -value < 0.001) (Fig. 4). The line of best fit for each of these two correlations could potentially be used to predict the age of unknown samples.

4.2. Radiocarbon measurements

Radiocarbon results, reported as ^{14}C concentration (percent modern carbon (pMC) equivalent) were obtained from seven samples along the growth axis of the outer prismatic layer of specimen C2-MS1 (Table 1). One sample (SUERC-2290), drilled close to the ventral margin of the shell and estimated to span the interval 1960–1966, yielded a pMC value of 113.5 ± 0.55 , clearly placing this portion of the shell in the “post-bomb” era i.e. post-1950. As a further test of the annual chronology established from specimen C2-MS1, which is based on the counting of growth increments, the sample mean age of SUERC-2290 (estimated from the sampling density within annual bands to be weighted towards a shell mean age of 1965) has been plotted together with unpublished radiocarbon data from *A. islandica* shells collected from the North Sea (Table 2; Fig. 5). Despite the differences in regional oceanography between these two sample sites, both are from well-mixed shelf sea locations and the data are in close agreement and constrain sample SUERC-2290 to a short window of time in the mid to late 1960s. We therefore conclude, within the limitations of the

available data, that the growth increments in specimen C2-MS1 are annual in nature.

4.3. Chronology construction

A total of twenty-two shells from site C1 were live-collected (twenty of these were collected over the summer of 2006, while the other two were collected in summer 2008). Of these, nine specimens have so far been successfully prepared, measured and dated with a tenth shell proving problematic because of highly suppressed growth in the late 20th century. Therefore, for this paper we developed a preliminary site master chronology using the nine successfully dated series (Fig. 6). Using the mean inter-series correlation between the SGI time-series, we apply equation (2) of methods Section 3.4 to estimate how many shells would theoretically be required to create a robust chronology. For this study, the mean inter-series correlation value was calculated over the common period of overlap between all SGI time-series. The mean inter-series intercorrelation, using Pearson’s correlation (r) coefficient statistics, between the nine SGI series for 1945–2005 is 0.37, giving a predicted n value of 10. Therefore, we will need approximately 10 shells to develop a robust chronology that is representative of the theoretical population. However, because of a strong common decadal trend in the data series which could inflate the r value, we also performed the analysis after the data had been transformed by first differencing. This tests the signal strength of the chronology at inter-annual time-scales only. After transformation, the mean inter-series intercorrelation value is reduced to 0.09 increasing the number of shells required to create a robust chronology to 57.

Fig. 6 shows the preliminary C1 site master chronology with associated 2-sigma error bars. A notable feature of this record is the pronounced suppressed growth interval in all shells from the 1940s to the late 1980s, after which shell growth increases. There are periods where the error is noticeably larger – for example during

Table 1

Radiocarbon data from Loch Creran: sample C2-MS1 was live-collected in 1968.

Sample	Shell ID	Accession number	^{14}C enrichment (% modern $\pm 1\sigma$)	Conventional radiocarbon age (years BP $\pm 1\sigma$)	Calendar age (years AD)
1	C2-MS1	SUERC-2280	96.06 ± 0.48	323 ± 41	1882
2	C2-MS1	SUERC-2281	94.70 ± 1.56	438 ± 133	1890–1891
3	C2-MS1	SUERC-2282	95.62 ± 1.21	360 ± 101	1893–1895
4	C2-MS1	SUERC-2283	95.73 ± 0.38	351 ± 32	1901–1908
5	C2-MS1	SUERC-2284	94.27 ± 1.46	475 ± 125	1911–1918
6	C2-MS1	SUERC-2288	96.17 ± 0.36	314 ± 30	1923–1927
9	C2-MS1	SUERC-2290	113.50 ± 0.55	Post AD 1950	1962–1967

The two samples which did not yield results (numbers 7 and 8) are not included within this table. The $\delta^{13}\text{C}_{\text{PDB}}$ content of all samples analysed is assumed to be $0.0 \pm 0.1\text{‰} \pm 0.1$ for all values is 0.0, these values were estimated due to insufficient material being sampled for an independent measurement to be generated.

Table 2

Radiocarbon data from the North Sea (German Bight; samples were live-collected in 1990).

Sample	Shell ID	Accession number	$\Delta^{14}\text{C}$ (‰)	Error \pm	Calendar year assigned
1	N-8A	OS-0093	-50.0	3.9	1948 ^a
2	N-8A	OS-0094	-64.1	12.2	1950 ^a
3	N-8A	rec#1018	-83.3	13.2	1954 ^a
4	N-8A	OS-0090	-24.2	3.9	1959 ^a
5	N-8A II	OS-1351	+9.5	7.8	1960
6	N-8A	OS-0089	+26.2	4.3	1961–63 ^a
7	N-8A II	OS-1349	+119.6	9.1	1963–64
8	N1-B	OS-0130	+234.2	8.5	1966
9	N-8A II	OS-1350	+239.3	13.3	1967–68
10	N1-B	OS-0128	+222.8	7.6	1969
11	N-8A	OS-0091	+210.7	4.1	1969–71 ^a
12	N1-B	OS-0642	+228.4	5.0	1970
13	N-8A II	OS-1424	+216.7	3.8	1971–72
14	N1-B	OS-0099	+220.4	6.2	1974
15	N-8A	OS-0088	+216.0	10.5	1974–75 ^a
16	N-8A II	OS-1400	+186.7	3.7	1976
17	N1-B	OS-0097	+173.0	5.4	1980–81
18	N-8A	OS-0087	+133.7	13.5	1979–83 ^a
19	N1-B	OS-0096	+137.2	6.1	1982–87
20	N1-B	OS-0131	+126.4	7.0	1989–90

^a These dates have been lagged by 7 years from those originally logged because of a logging error in the original. Samples from shell N-8A II (an adjacent slice from the same shell as N-8A) were later run to corroborate the chronology. The shell $\delta^{13}\text{C}$ value for all samples is 2.0‰.

the 1890s–1900s. Ultimately, more data are needed to overcome individual series' noise in the final master chronology. As stated above, using first difference transformed SGIs, the EPS analysis suggested that 57 mollusc time-series would be needed to derive a robust chronology at high frequency time-scales. In this paper, we use only nine. The first portion of the chronology (from 1843 to the 1890s) is derived using measurements from only one shell. The index values for this period also appear to be somewhat inflated with regards to the rest of the chronology, likely caused by an imperfect fit of the negative exponential function applied to this shell (C1-L4). Due to the lack of data replication within the master chronology prior to 1946, this section of the chronology is not used for analysis purposes.

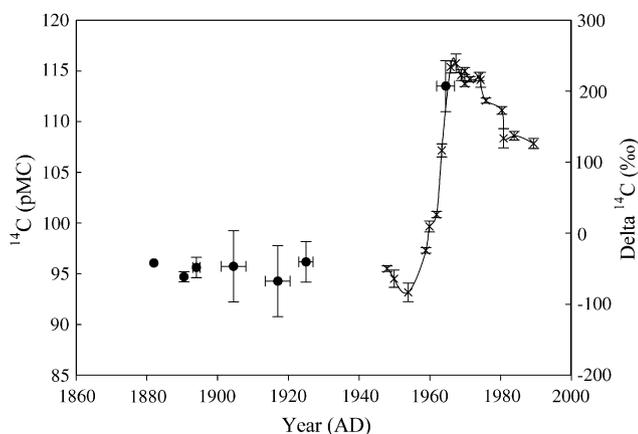


Fig. 5. Radiocarbon data from the seven samples taken from shell C2-MS1 (circles) with their associated 1 σ error bars (shell C2-MS1 was live-collected in 1968). The vertical error bars represent the laboratory-reported measurement errors whilst the horizontal errors are those related to the sampling method (not all samples were from a single growth increment). Radiocarbon measurements from *A. islandica* are also presented from the German Bight, North Sea (crosses) suggesting that the final sample from C2-MS1 which was dated between 1962 and 1967 by band width counting (and predates 1968), fits into the upwards portion of the bomb-pulse signal recorded in the North Sea data, thus supporting our chronology.

4.4. Master chronology and instrumental data series comparisons

The correlation analyses between the master chronology and monthly, seasonal and annual gridded SST dataset (HadISST (Rayner et al., 2003)) are illustrated in Fig. 7 for both the unfiltered and first differenced transforms. For the unfiltered data, there is a significant (95% C.L.) positive correlation with September SSTs over the 1946–2005 period. Using the first differenced transforms, however, a significant negative relationship for October and the September to November seasonal average is noted (Fig. 7)

These full period results do not, however, appear to be time-stable. Using the unfiltered time-series, there appears to be no response to SSTs over the early 1946–1975 period, whereas significant positive correlations are noted after 1976 for September and October. When the first differenced transforms are used, the opposite situation is observed. In this instance, there are statistically significant (95% C.L.) negative correlations for the earliest period (1946–1975) for the months September, October, November, December, and the September to November and July to December seasonal averages. For the later period (1976–2005), no significant correlations are observed.

5. Discussion

5.1. Biometrics

Knowledge about population biometrics is important for understanding the relationship between the height (mm), weight (g) and age (years) of *A. islandica* populations. Our analyses show that these three indices are related to one another, providing population age-structure information and allowing the estimation of shell ages without needing to section the shells. Current work on biometrics from the 'live' collected specimens from site C1 indicates that there is the potential to use either the shell's height or weight measurements as a reliable predictor for age. Of the two variables, height is potentially more valuable, enabling divers to carry out preliminary, non-destructive site assessment surveys. Comparisons of weight-height data from dead and 'live' specimens from site C1 (Fig. 3) with those measured from NMS shells indicate that the local field-collected individuals agree with the larger British Isles dataset.

There would be an advantage in developing a national database of *A. islandica* specimen height, weight and age values for the purposes of accurately assessing national growth trends and also to facilitate improved estimates of shell ages without sectioning. Such data would also allow targeted sampling at site C1. By building up a database related to *A. islandica* population structure dynamics along the west coast of Scotland, there would be the potential to begin to derive information concerning population recruitment. Cargnelli et al. (1999) highlights the importance of understanding *A. islandica* population recruitment for understanding periods of unfavourable conditions in the field area, such as adverse environmental changes and an increase in predation. Such an understanding would, for example, provide useful insight into the possibility of building long, cross-matched records for a given region.

5.2. Chronology construction

Sclerochronology, as a discipline, relies on the accurate construction of growth chronologies that have verified dating control, to inform us about marine environmental changes in the past. In order to employ mollusc growth increment data as a potential palaeoclimate resource, the data must be detrended to remove ontogenetic growth trends. Although flexible splines facilitate crossdating of the high frequency signal (e.g. Epplé, 2004; Helama et al., 2006; Scourse et al., 2006), such detrending approaches remove potential secular

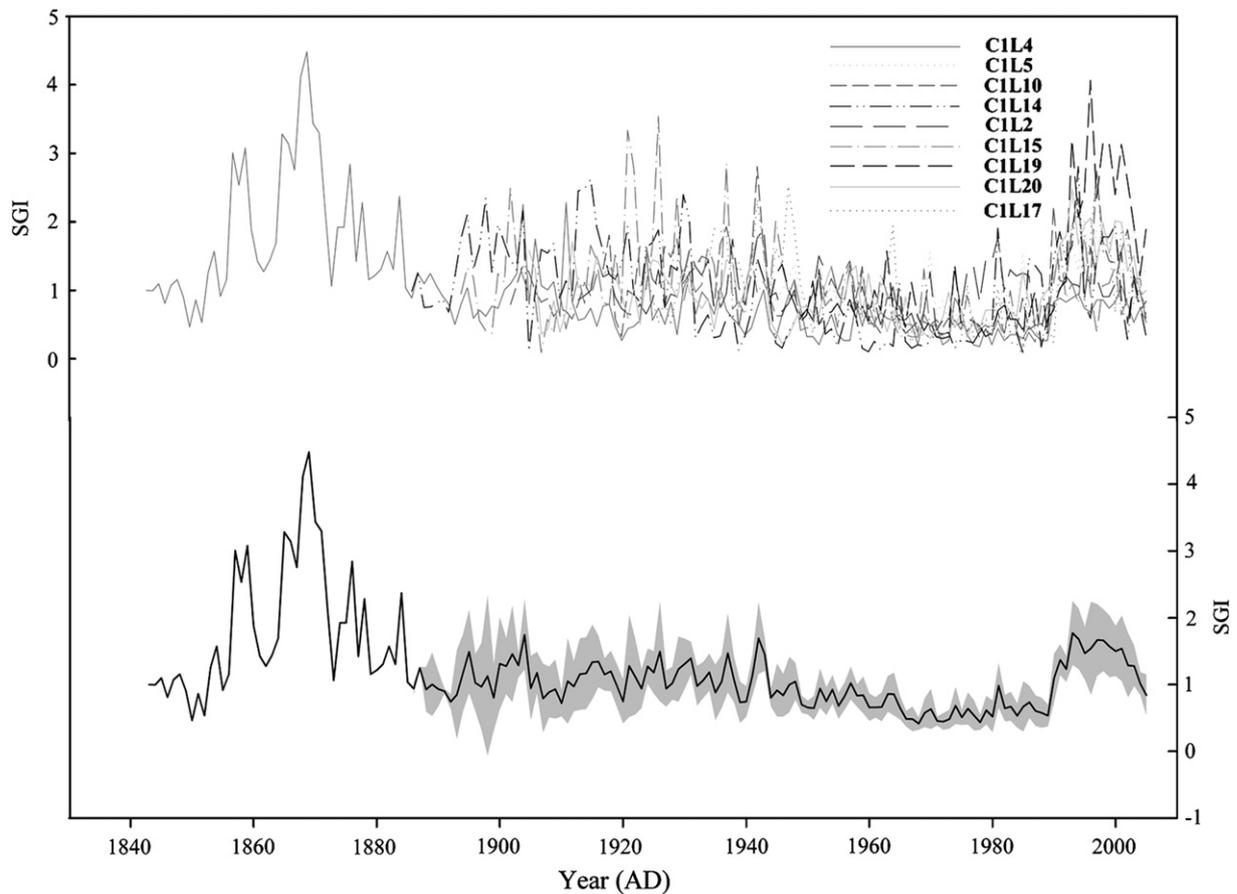


Fig. 6. SGI data for nine *A. islandica* specimens from site C1 (upper panel) have been crossdated and standardised according to the methods described in the text. These standardised series have been combined to create a master chronology for site C1 (lower panel) extending back to 1843 (black line) with the associated errors (in grey). The errors are expressed as a two sigma deviation from the master chronology.

scale growth trends that may be related to some aspect of environmental forcing – a problem which Helama et al. (2006) acknowledged. In this paper, we employed a more rigid detrending method (the negative exponential function). The application of flexible splines for crossdating in CDendro (Larsson, 2008b) and COFECHA (Grissino-Mayer, 2001) ensures accurate dating, while later detrending using a negative exponential function preserves the longer-term environmental signal in the growth record and ultimately in the master chronology. However, even using this more conservative approach, the amount of longer-term information contained in the master chronology is still determined by the mean length of the samples. This is commonly referred to in dendrochronology as the “Segment Length Curse” and many more samples will be needed before information at time-scales longer than the mean length of the samples can be obtained (Cook et al., 1995).

We should also note that ongoing experimentation (not presented here), suggests that an adaptive power transform (Cook and Peters, 1997) may need to be applied to some of the raw data series prior to detrending so as to minimise end effect index inflation, which may result in an artificial upward trend at the end of the detrended time-series. Such an effect would cause an artificial growth pattern to be observed in the final SGI master chronology, thereby biasing any comparative analyses with instrumental data.

When determining the number of shells that should be included within the chronology to reach an EPS value of 0.85, caution must be advised in the interpretation of the results. For the C1 master chronology, the proposed value of 10 shells must be considered to be an optimistic estimate. Firstly, this is because the RBAR value is

derived from a very small dataset and so the resultant measure of coherence could change markedly as more data are added. Also, and perhaps more importantly, the between series correlations are partly inflated because of common decadal trends between the series (Fig. 6), with all the series showing a marked decrease in index values between the mid 1940s and late 1980s. If the SGI series are transformed to first differences (essentially removing all time-scale trend above annual resolution), the mean inter-series correlation drops to 0.09 which leads to 57 shells being required. This highlights the fact that the common signal at inter-annual time-scales between the shells at this location is weak.

The EPS analysis and generally weak common signal indicate that many more samples are required to derive a robust chronology for this location; this is the focus of ongoing work. It will also be valuable to return to the records to see if there is any phenomenon present which could explain the lack of synchronicity within the data. Within many of the specimens from this site, there is a period of highly suppressed growth from the mid 1940s to the late 1980s (growth increments during this period can be as thin as 0.009 mm). While this may be caused by some environmental factor, it makes crossdating through this period very difficult. As more series are added into the chronology, potential dating errors should be minimised and the chronology will become more robust. In order to improve the robustness of the master chronology within the suppressed growth period of the mid 1940s to the late 1980s, the addition of more juveniles would be of great benefit, because of the faster growth rates which would very likely be recorded within these shells for that period.

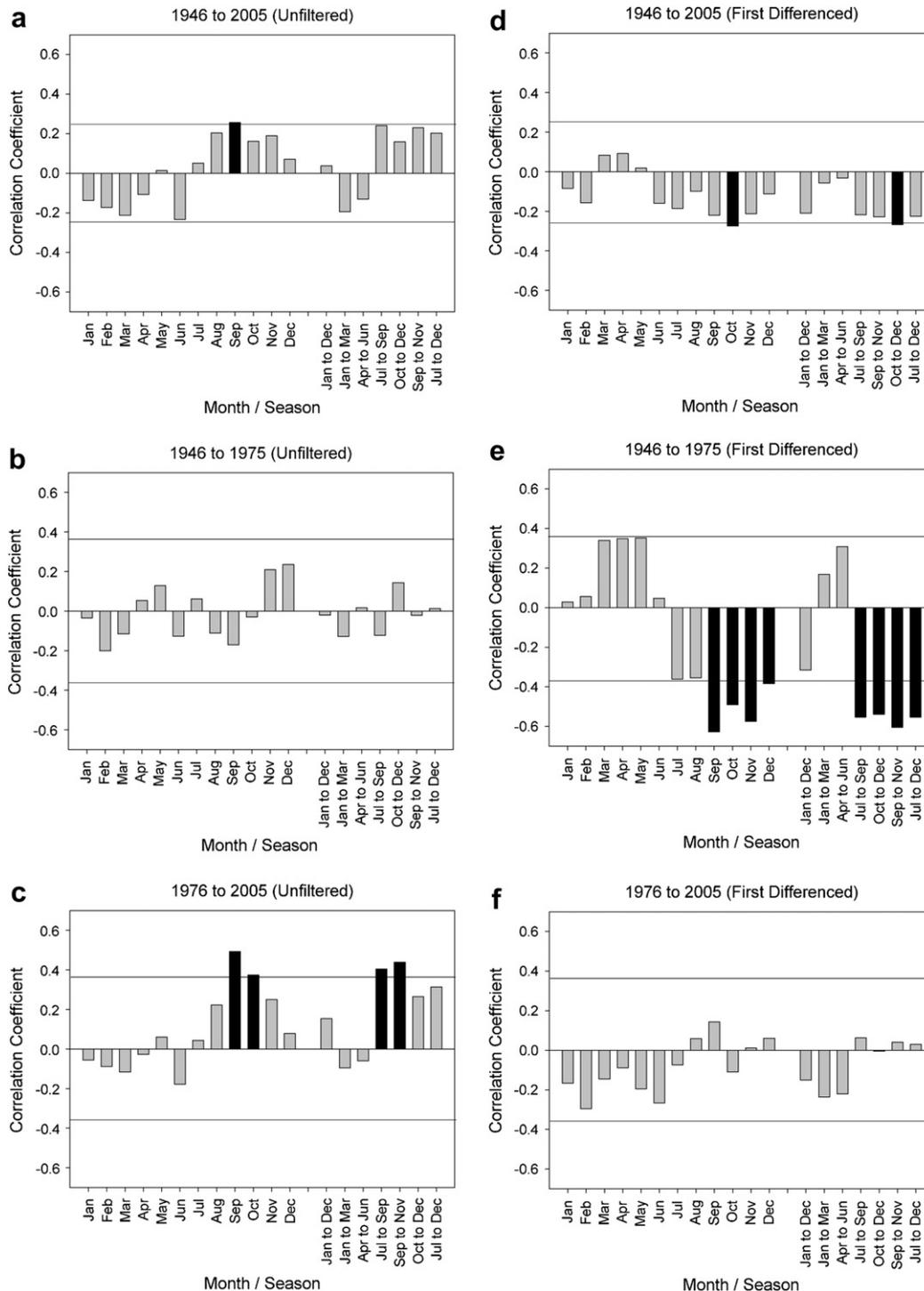


Fig. 7. Correlations between the unfiltered Lynn of Lorn (site C1) master chronology and the unfiltered HadISST sea surface temperature dataset (Rayner et al., 2003) and the first differenced Lynn of Lorn (site C1) master chronology and the first differenced HadISST sea temperature dataset (Rayner et al., 2003). The horizontal lines of the graphs denote the significance levels (two-tailed at 95% confidence). Those data which are statistically significant are depicted in black. a) Correlations from 1946 to 2005 – unfiltered; b) Correlations from 1946 to 1975 – unfiltered; c) Correlations from 1976 to 2005 – unfiltered; d) Correlations from 1946 to 2005 – first differenced; e) Correlations from 1946 to 1975 – first differenced; and f) Correlations from 1976 to 2005 – first differenced.

5.3. Proxy – climate comparison

The results from the correlation analyses between the master chronology and monthly SST values are highly ambiguous and appear to be not only unstable through time, but are also varied in the frequency domain (Fig. 7). For both unfiltered and first

differenced versions of the correlations carried out, there are no statistically significant correlations between the master chronology and the January to June temperatures.

Over the summer – autumn period, however, a significant relationship with SSTs is noted. Correlations using the unfiltered time-series indicate a positive relationship with SSTs, but only in

the period after the mid-1970s, and this is possibly related to the jump from the suppressed growth pattern to the enhanced pattern. When climate correlation analyses are undertaken using first differenced series, however, the relationship with SSTs is negative and is only significant for the pre mid-1970s period. Although these results should be interpreted cautiously because of the short length of the analysis window, they imply that the growth response of the molluscs in this environment is frequency dependent – that is, there are different environmental controls at inter-annual and decadal scales. To exacerbate this situation, the relationship does not appear to be time-stable, which suggests that further environmental factors also influence growth before and after the mid-1970s. At this time, while working with growth increment data from a single site, it is not possible to identify either the causes of or the reasons for these ambiguous results and the results can only be further assessed by contextualising them through examination of independent mollusc chronologies from other sites: to address this a further four sites are being investigated.

In an attempt to explain the change in the relationship between the master chronology and SSTs, it is hypothesised here that food availability may act as a causal linking mechanism. Testing this potential relationship may be achieved through an investigation of the relationship between the master chronology and Continuous Plankton Record (CPR) datasets. Visual assessment between the Lynn of Lorn master chronology and CPR data for the west coast of Scotland (Beaugrand et al., 2002) indicates that there is potentially a relationship between phase changes in CPR abundance and changes in growth rates. A relationship between *A. islandica* growth rates and plankton abundances has previously been found for the North Sea (Witbaard, 1996), lending plausibility to the hypothesis that food availability may influence shell growth.

Another possible influence on *A. islandica* growth rates, which may explain the lack of a time-stable relationship between growth rates and SSTs, are changes in land use and management over the years. The widespread introduction of aquaculture into the sea lochs of north west Scotland may have affected eutrophication, plankton dynamics and ultimately *A. islandica* growth rates. Salmon fish farming was introduced in Loch Creran (Fig. 1) in 1983 and there are now also several mussel farms and an oyster farm present within Loch Creran (Wilson et al., 2007). The effect of this aquaculture on the field area requires further investigation: to fully evaluate the potential impacts of land use and changes in sea loch water quality through aquaculture on growth in *A. islandica* is beyond the scope of the current study.

A third possibility that may explain the lack of time-stability and coherence between the growth record and SST dataset, together with the conflicting correlations seen at the high and low frequencies, is related to the depth of the water from which the molluscs were collected. Epplé et al. (2006) noted low inter-series correlation between mollusc shells sampled at a shallow marine setting (15–20 m deep) in the inner German Bight (North Sea). This apparent lack of synchrony was attributed by the authors to the conditions in which the shells had grown. Factors such as tidal movements, salinity fluctuations, temperature fluctuations and turbidity, which are more prominent in a shallow, coastal water environment, were some of the suggested reasons for a lack of common signal between the shells. It is possible that shallow water environments provide problems for obtaining a synchronous growth signal within the shell of *A. islandica* and this could account for not only the poor signal strength, but also the non time-stable relationship present between the SST dataset and the master chronology from our field site (11–17 m deep). However, this anecdotal observation requires further exploration before any conclusions can be drawn as to the potential effects of shallow water on *A. islandica* sclerochronology. In order to investigate this

possible link, more sites around the Scottish coast, including several sites from within fjords, need to be sampled.

6. Conclusions

Although it is well established that the growth increments of *A. islandica* are indeed annual in nature (Turekian et al., 1982; Witbaard et al., 1994), this study has validated this observation for a new location on the Scottish west coast where ^{14}C data from shell material of known age from the mid-1960s are in close agreement with ^{14}C data obtained independently from the North Sea basin. Analysis of biometric data for samples collected from the study region have indicated that there is the potential for divers to use the height of molluscs at the seabed in order to obtain estimates of sample ages. The primary benefits of this biometric relationship are the ability to target specimens of certain ages, and the facility to carry out *in situ* assessments of population age structure. *A. islandica* shells from the continental shelf seas of north west Scotland have the potential to extend local marine instrumental records provided that careful crossdating and suitable detrending methods are used and that data calibration and verification are carried out. Currently, no calibration or verification has been undertaken on the master chronology from the Lynn of Lorn because of an apparent conflicting response in the frequency domain and a temporal instability with SST data. This is not to say that *A. islandica* cannot be used to reconstruct SSTs for the region, but, as the master chronology currently stands for site C1 (Fig. 1), this is not possible.

The research presented herein has focused on detrending approaches for *A. islandica* increment measurements and the environmental controls on growth of this species in the Lynn of Lorn. In order to verify the three hypotheses proposed above – namely: (1) the possible link between growth rates and CPR abundance, (2) the influences of land use and coastal zone changes, such as the introduction of marine aquaculture, on *A. islandica* growth, and (3) the possibility that in shallow water environments *A. islandica* do not show synchronous growth rates; comparisons between chronologies created using shells drawn from a variety of sites need to be undertaken. Currently, four new sites within Scottish fjords are being investigated, with the eventual aim of developing a series of growth chronologies from sites with different ecological and environmental conditions around the north west coast of Scotland. Comparisons of these datasets would not only confirm the dating between sites, but might also provide a useful insight into what is controlling *A. islandica* growth rates in the region, particularly during the suppressed growth period of the 1940s–1980s.

Future research should also focus on the application of appropriate detrending methods for the creation of growth index chronologies. Doing so will ensure the preservation of high and low frequency signals within the record, thus providing a better understanding of past environmental change. Finally, isotopic measurements (e.g. $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$) are also likely to provide meaningful climate signals (e.g. temperature) (Schöne et al., 2004). An additional advantage of these is that, unlike growth increment measurements, such geochemical data do not call for detrending and so the potential to preserve the low frequency environmental and climate signals is significantly improved.

Acknowledgements

This research would not have been possible without the financial support of the University of St. Andrews and SAGES, as well as the technical support given by Andy Mackie and Stuart Allison at the School of Geography and Geosciences (University of St. Andrews).

Thanks also go to the NMS for allowing access to their *A. islandica* collections, including sample NM921–415 (allocated sample number C2-MS1 for the purposes of this study). Estelle Dumont and Mark Inall (SAMS) generously provided some of the instrumental marine climate records. SCUBA divers at the NFSD (SAMS) collected all the samples from C1 used as part of this research (NERC grant No: NE/NFS02008/02). We thank the NERC radiocarbon laboratory (allocation No: 981.0402) for dating support, Helen Beddow-Twigg and Jodi Old for their help in ageing some of the samples and Jotham Gaudoin for proof reading this manuscript. Help and advice was also received from Professor James Scourse, and Dr. Paul Butler at the School of Ocean Sciences, Bangor University. We thank Dr. Alan Wanamaker Jr. and an anonymous reviewer for their helpful comments.

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