

1 **Reconstructing past seasonal to multi-centennial scale variability in the NE Atlantic**
2 **Ocean using the long-lived marine bivalve mollusc *Glycymeris glycymeris*.**

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25 **Key Points**

26 • The application of $\delta^{18}\text{O}$ data derived from *Glycymeris glycymeris* shells are evaluated
27 as a new robust paleoceanographic proxy

28

29 • Sub-annual and annually resolved $\delta^{18}\text{O}$ data demonstrate significant skill at
30 reconstructing NE Atlantic seawater temperature variability

31

32 • The $\delta^{18}\text{O}_{\text{shell}}$ record is sensitive to North Atlantic variability linked to changes in sub-
33 polar gyre dynamics and the North Atlantic Current

34

Abstract

The lack of long-term, highly resolved (annual to sub-annual) and absolutely dated baseline records of marine variability extending beyond the instrumental period (last ~50-100 years) hinders our ability to develop a comprehensive understanding of the role the ocean plays in the climate system. Specifically, without such records, it remains difficult to fully quantify the range of natural climate variability mediated by the ocean, and to robustly attribute recent changes to anthropogenic or natural drivers. Here we present a 211-year (1799-2010 CE; all dates hereafter are common era) seawater temperature (SWT) reconstruction from the northeast Atlantic Ocean derived from absolutely dated, annually resolved, oxygen isotope ratios recorded in the shell carbonate ($\delta^{18}\text{O}_{\text{shell}}$) of the long-lived marine bivalve mollusc *Glycymeris glycymeris*. The annual record was calibrated using sub-annually resolved $\delta^{18}\text{O}_{\text{shell}}$ values drilled from multiple shells covering the instrumental period. Calibration verification statistics and spatial correlation analyses indicate that the $\delta^{18}\text{O}_{\text{shell}}$ record contains significant skill at reconstructing Northeast Atlantic Ocean mean summer SWT variability associated with changes in sub-polar gyre (SPG) dynamics and the North Atlantic Current. Reconciling differences between the $\delta^{18}\text{O}_{\text{shell}}$ data and corresponding growth increment width chronology demonstrates that 68% of the variability in *G. glycymeris* shell growth can be explained by the combined influence of biological productivity and SWT variability. These data suggest *G. glycymeris* can provide seasonal to multi-centennial absolutely dated baseline records of past marine variability that will lead to the development of a quantitative understanding of the role the marine environment plays in the global climate system.

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Keywords: North Atlantic Ocean (9325), seawater temperatures/SST (4954), climate variability (1616), sclerochronology (9810) Stable isotope geochemistry (1041)

59

1. Introduction

North Atlantic seawater temperature (SWT) variability plays a significant role in the global climate system with the propagation of heat through the northward flowing surface currents (Gulf Stream/North Atlantic Current) acting as a ‘bottom-up’ mechanism for driving atmospheric climate variability (Tandon and Kushner, 2015). Over the last glacial period there is ample evidence that abrupt fluctuations in North Atlantic SWTs, brought about by changes in ocean circulation patterns, were in part responsible for rapid high amplitude fluctuations of ~5-10°C in Northern Hemisphere air temperatures (Heinrich and Dansgaard-Oeschger events;

68 (Broecker, 1998). However, the role that ocean variability plays in the modern climate system,
69 where the magnitude of change is much smaller, is less well understood. Our current
70 understanding is, in part, constrained by the short temporal, and spatially heterogeneous nature
71 of modern observational records (Hurrell and Trenberth, 1999; Smith and Reynolds, 2004), the
72 sparse distribution of sub-polar coralline archives (e.g. Kamenos, 2010; Halfar et al., 2011),
73 and the typically lower resolution (multi-decadal) reconstructions from marine sediment cores
74 that rely on radiocarbon (^{14}C) derived age models. Whilst these latter sediment archives provide
75 invaluable information regarding the amplitude and potential processes of past climate
76 variability (e.g. Lund et al., 2006; Hall et al., 2010; Sicre et al., 2011; Moffa-Sanchez et al.,
77 2014a,b; Mjell et al., 2016) the large uncertainties associated with radiocarbon derived age
78 models typically hinder the application of these data in resolving high frequency (decadal to
79 sub-decadal) spatiotemporal variability and robustly assessing potential leads/lags within the
80 marine system and in the ocean-atmosphere coupling.

81

82 The development of sclerochronological records, incorporating the analyses of the physical and
83 geochemical variations in the accretionary skeletal tissues of aquatic, marine and terrestrial
84 organisms (e.g., Hudson et al., 1976; Oschmann, 2009), provides the opportunity for the
85 generation of absolutely-dated and robustly calibrated reconstructions of past climate
86 variability. Reconstructions derived from the analyses of marine bivalve growth increment
87 width chronologies, constructed using dendrochronological crossdating techniques (e.g. Jones,
88 1980; Jones et al., 1989; Marchitto et al., 2000; Butler et al., 2013), and stable isotope ($\delta^{18}\text{O}$
89 and $\delta^{13}\text{C}$; e.g. Witbaard et al., 1994; Schöne et al., 2005; Wanamaker et al., 2009; Wanamaker
90 et al., 2011; Reynolds et al., 2016) and radioisotope (^{14}C ; Wanamaker et al., 2012) time-series
91 developed from long-lived marine bivalves, such as *Arctica islandica* and *Glycymeris*
92 *glycymeris*, are now realised as robust archives of past marine variability. Hitherto marine
93 bivalve sclerochronological archives have provided robust reconstructions of past SWTs
94 (Schöne et al., 2004; Brocas et al., 2013; Reynolds et al., 2013; Mette et al., 2016; Reynolds et
95 al., 2017), oceanic carbon dynamics (Schöne et al., 2011), marine radiocarbon reservoir ages
96 (Wanamaker et al., 2012), coupled ocean and terrestrial ecosystem dynamics (Helama et al.,
97 2007; Black, 2009; Black et al., 2014) and to investigate the mechanisms and drivers of ocean
98 variability (Lohmann and Schöne, 2013; Reynolds et al., 2016; Reynolds et al., 2017).

99

100 The ability to apply sclerochronological techniques to investigate past climate variability is in
101 part controlled by the geographic distribution of suitable ‘target’ species, which are spatially
102 heterogeneous and dictated by their habitat preferences (for example, SWT, salinity, seafloor
103 sediment type, water depth and the quality and quantity of food supply) amongst other factors.
104 The study areas currently investigated are therefore a compromise between regions that are
105 oceanographically and climatically sensitive and regions where there are abundant populations
106 of the target species. To broaden the spectrum of environments that can be reconstructed it is
107 necessary to extend the range of species that can be utilised as past proxy archives. Previously
108 *A. islandica* has been considered the key archive for sclerochronological applications in the
109 North Atlantic region. This is because of its exceptional longevity (>500 years, Butler et al.,
110 2013) and the fact that shell growth is synchronous between individuals and populations,
111 facilitating the use of crossdating techniques developed by the dendrochronology community
112 to be applied for constructing multi-centennial to millennial length chronologies (Witbaard et
113 al., 1997; Marchitto et al., 2000; Scourse et al., 2006; Butler et al., 2013). *A. islandica* aragonite
114 shell also appears to faithfully record the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ composition of the ambient waters
115 bathing the animal during its lifetime (e.g. Witbaard et al., 1994; Schöne et al., 2005; Reynolds
116 et al., 2016) and its shell is relatively simple to analyse for radioisotope ^{14}C content (Scourse
117 et al., 2012; Wanamaker et al., 2012).

118

119 The marine bivalve *Glycymeris glycymeris* (dog cockle or European bittersweet), has recently
120 been identified as a potential target species and valuable sclerochronological archive in the
121 North Atlantic region (Reynolds, 2011; Brocas et al., 2013; Reynolds et al., 2013; Royer et al.,
122 2013). Similar to *A. islandica*, *G. glycymeris* has a multi-centennial maximum longevity (~200
123 years; Reynolds et al., 2013), shells that consist of internal growth increments with an annual
124 period (Berthou et al., 1986; Brocas et al., 2013; Royer et al., 2013) and the precipitation of
125 aragonite (growth) occurs in synchrony between individuals and populations experiencing
126 common environmental changes (Reynolds et al., 2013; Brocas et al., 2013). These
127 characteristics are all important in facilitating the construction of robust chronologies extending
128 back over many centuries (Reynolds et al., 2013; Brocas et al., 2013). Typically *G. glycymeris*
129 inhabits coarse seabed sediments (sand to gravel), characteristic of high-energy bottom
130 environments, whilst *A. islandica* are more usually found in lower energy muddy to sandy
131 environments (Hayward and Ryland, 1995). Absolutely-dated chronologies constructed from
132 *G. glycymeris* growth increment width series have been shown to be extremely sensitive to

133 SWT variability allowing the direct reconstruction of past SWT variability from the growth
134 increment series alone (Reynolds et al., 2013; Brocas et al., 2013). However, due to the
135 limitations imposed by having to use statistical detrending techniques, necessary to remove the
136 ontogenetic growth signal to enable the generation of the growth increment series these
137 reconstructions are typically insensitive to low frequency variability, a problem recognised by
138 the dendrochronology community as the “segment length curse” (Cook et al., 1995). The use
139 of stable $\delta^{18}\text{O}_{\text{shell}}$ values from within individual growth increments could facilitate the
140 application of *G. glycymeris* series for the reconstruction of past ocean variability across
141 frequency domains. This is because no detrending is required in the construction of a $\delta^{18}\text{O}_{\text{shell}}$
142 series and the physical mechanisms that drive $\delta^{18}\text{O}$ variability in aragonite are relatively well
143 understood (Urey, 1948; Schöne et al., 2013). However, up until now the application of *G.*
144 *glycymeris* $\delta^{18}\text{O}_{\text{shell}}$ analyses as a proxy for seawater temperature (and or density), which has
145 been widely used in *A. islandica* based studies, has yet to be fully investigated.

146

147 The purpose of this study is therefore to: 1) to assess the timing and rate of sub-annual *G.*
148 *glycymeris* shell growth to evaluate the likely seasonal bias in the annually resolved $\delta^{18}\text{O}_{\text{shell}}$
149 series; 2) to evaluate the potential application of $\delta^{18}\text{O}_{\text{shell}}$ series derived from *G. glycymeris* in
150 reconstructing past ocean variability; 3) to evaluate the relative contribution of both salinity
151 and SWTs in driving *G. glycymeris* $\delta^{18}\text{O}_{\text{shell}}$ variability; and 4) to robustly quantify the skill of
152 the annually-resolved $\delta^{18}\text{O}_{\text{shell}}$ data to reconstruct SWTs.

153

154 **2. Oceanographic setting**

155 The *G. glycymeris* shell material examined in this study was collected from the Tiree Passage,
156 located on the western fringes of the Hebridean continental shelf, northwest Scotland
157 ($56^{\circ}37.75\text{N}$, $6^{\circ}24.00\text{W}$; Figure 1). This locality is ideally situated for assessing the potential of
158 *G. glycymeris* records as palaeoceanographic archives due to the proximity of two long-term
159 instrumental oceanographic mooring data sets, in the Tiree Passage (Inall et al., 2009) and at
160 Keppel Pier ($55^{\circ}44' 55 \text{ N}$, $4^{\circ} 54' 20 \text{ W}$; www.bodc.ac.uk/data/), as well as the abundance of
161 both live and fossil specimens.. The regional hydrography is dominated by the relative
162 influence of the European Slope Current (ESC), which is a major branch of the North Atlantic
163 Current (NAC), and the Scottish Coastal Current (SCC; Inall et al., 2009). Both the ESC and
164 SCC are northward flowing currents advecting warm and salty Atlantic waters across the
165 Hebridean shelf. However, the SCC waters, which form in the North Channel between Ireland

166 and Scotland are slightly fresher than the ESC due to the influence of fresh water from riverine
167 and precipitation inputs as Atlantic waters move northwards through the Irish Sea and onto the
168 Hebridean Shelf (Inall et al., 2009). Changes in the strength of the ESC have been investigated
169 using satellite altimetry, tidal gauge, mooring observations and CTD surveys and found to be
170 associated with changes in broader Atlantic meridional overturning circulation (AMOC)
171 strength, SPG dynamics and local wind stress (Inall et al., 2009; Holliday et al., 2015; Xu et
172 al., 2015; Marsh et al., 2016). Given that the ESC dynamics are reflected in the physical and
173 geochemical properties of the Sea of the Hebrides (Huthnance et al., 2009) developing long
174 term baseline records from this region could potentially provide information on the
175 mechanisms and drivers of wider North Atlantic variability.

176

177 **3. Methodology**

178 **3.1 Sample collection**

179 Live and dead (fossil) *G. glycymeris* shells were collected from the Tíree Passage (56°37.75N,
180 6°24.00W; Figure 1) using a mechanical dredge deployed by the *RV Prince Madog* in 2006
181 and via scuba diving by the UK Natural Environment Research Council Facility for Scientific
182 Diving (NFSD) between 2011 and 2014. The shells were collected from water depths of
183 between 25-55 m. Each of the shells sampled in this study had been previously dated as part of
184 the construction of the *G. glycymeris* growth increment width master sclerochronology
185 (Reynolds et al., 2013). In the construction of the growth increment width chronology live and
186 dead-collected *G. glycymeris* shells were crossdated using dendrochronological techniques
187 facilitating the absolute dating of each of the growth increments (Witbaard et al., 1997,
188 Marchitto et al., 2000, Scourse et al., 2006; Butler et al., 2010). The ages of the shells were
189 then independently validated by ‘range finder’ accelerator mass spectrometry (AMS)
190 radiocarbon (^{14}C) dating (Reynolds et al., 2013). The growth increment width chronology
191 subsequently provided an absolutely-dated temporal framework which facilitated the micro-
192 drilling of samples, and the generation of a $\delta^{18}\text{O}_{\text{shell}}$ series, of absolute known ages. Full details
193 of the shell collection, crossdating and ^{14}C analyses are provided in Reynolds et al. (2013).

194

195 **3.2 Stable isotope analysis**

196 Each of the *G. glycymeris* shells examined in this study was prepared using the conventional
197 shell embedding and sectioning methodologies (Richardson, 2001; Brocas et al., 2013;
198 Reynolds et al., 2013). The shells were embedded into epoxy resin and sectioned along the axis

199 of maximum growth from the ventral margin to the umbone (Figure 2). The cut shell sections
200 were then polished using increasingly finer grades of carborundum grit paper (400-4000 grade,
201 equivalent grit size down to ca. 3 μ m) and polished using a neoprene cloth and a 3 μ m diamond
202 solution. Aragonite powder samples of between 10 μ g and 400 μ g were then drilled from the
203 growth increments of a subset of shells that had been previously dated, by means of crossdating,
204 into the master *G. glycymeris* sclerochronology. The samples were drilled using a 300 μ m
205 tungsten carbide drill bit coupled to a Merchantek (New Wave) micromill system. This system
206 permits visualisation of the growth increments prior to drilling through a digital camera system
207 embedded in the micromill facilitating the robust determination of the target growth increments
208 (Figure 2). Shell samples were drilled using two strategies to facilitate the generation of ultra-
209 high resolution sub-annual and annual resolution samples. Figure 2C provides a schematic of
210 each of the sampling strategies employed. All the samples were drilled from the outer shell
211 layer from the ventral margin to the umbone sections, rather than in the tooth, as this was the
212 only region of the shell with growth increments of sufficient width for sampling.

213

214 For the sub-annual sampling, initially a pit was drilled into the outer shell layer prior to the
215 position of the first sampling location and the material discarded. The pit was required to
216 remove aragonite material that was not in the target increment but would have otherwise been
217 sampled due to the width of the drill bit (300 μ m) being greater than the targeted sampling
218 width (150 μ m). Samples were then drilled using a sequential sampling strategy with each
219 sample being 150 μ m in width; the samples were drilled using between 10 and 15 passes each
220 of 100 μ m to provide a total sample swath of between 1-1.5 mm. The width of all sub-annually
221 resolved samples was kept constant at 150 μ m to facilitate the application of statistical
222 techniques to assess seasonal changes in growth rates. Given that the growth increments vary
223 in width from year to year the sub-annual sampling methodology generated a mean of 13.7
224 (± 3.7 , 1 σ) samples per year over the time interval from 1954-2010. The samples were drilled
225 from a total of eight *G. glycymeris* shells.

226

227 For the annually resolved sampling, single samples were drilled from each growth increment.
228 Whilst the sample swath of each sample was kept constant (1mm) the width of each sample
229 was dictated by the width of the corresponding growth increment to ensure that each sample
230 captured shell material spanning the entire period of the annual shell growth (black dashed
231 parallelograms in Figure 2C). The drilling technique of using multiple passes, rather than
232 drilling one deep line, ensured that the shell powder was thoroughly homogenised. This is

233 particularly important for the annual samples as often the drilling process results in a large
234 volume of material being collected and therefore only a sub-sample of the resulting material
235 from each annual increment is actually analysed for stable isotopes. We analysed the $\delta^{18}\text{O}_{\text{shell}}$
236 composition of 107 replicate sub-samples from 13 individual shells to assess the
237 homogenisation of the carbonate powder ($1\sigma = <0.10\text{‰}$).

238

239 All carbonate samples were analysed using a Kiel IV carbonate device coupled to a Thermo
240 Finnigan MAT 253 mass spectrometer (Cardiff University). The shell carbonate samples were
241 analysed alongside internal standard Carrara marble (no less than six standards per 40 shell
242 carbonate samples) and calibrated against NBS-19 international standard relative to VPDB.
243 The samples were analysed using 100% orthophosphoric acid at 70°C for 300 seconds. To
244 make our isotope data comparable to the Royer et al., (2013) study, which applied a phosphoric
245 acid fractionation factor for calcite (Thebault pers. comm. 2017), we also did not apply a
246 specific aragonite phosphoric acid fractionation factor (e.g., Kim et al., 2007). The external
247 precision (1σ) for the $\delta^{18}\text{O}$ analyses, based on replicate measurements of laboratory reference
248 sample (Carrera marble) was $\leq 0.05\text{‰}$.

249

250 To test whether the modern $\delta^{18}\text{O}_{\text{shell}}$ data is significantly different to that occurring during the
251 previous two centuries, the mean and standard deviation of the annually resolved $\delta^{18}\text{O}_{\text{shell}}$ data
252 were calculated within discrete ten year non-overlapping bins. These data were tested for
253 normality using the Shapiro-Wilk test. The independent sample (student) t-test was then used
254 to compare the mean $\delta^{18}\text{O}_{\text{shell}}$ values over the period from 2001-2010 (modern) with the ten
255 year binned data over the previous two centuries.

256

257 **3.3 Seawater temperature calibration**

258 The annual and sub-annual $\delta^{18}\text{O}_{\text{shell}}$ series were converted to SWTs using (i) the Grossman and
259 Ku (1986) aragonite palaeotemperature equation (Equ. 1) and (ii) the Royer et al. (2013)
260 empirically derived *G. glycymeris* species-specific palaeotemperature equation (Equ. 2). Both
261 equations require the $\delta^{18}\text{O}$ of ambient seawater ($\delta^{18}\text{O}_{\text{sw}}$) to be known to convert the $\delta^{18}\text{O}_{\text{shell}}$
262 ratios into absolute SWTs. Over the instrumental period we applied the Cage and Austin,
263 (2010) local $\delta^{18}\text{O}_{\text{sw}}$ vs. salinity mixing line equation (Equ. 3) to estimate $\delta^{18}\text{O}_{\text{sw}}$ from the local
264 observational seawater temperature and salinity time series. As the Tiree Passage salinity
265 record is relatively short (Inall et al., 2009) we also derived SSS data from the EN4 gridded

266 SSS dataset (Good et al., 2013) estimated from a $10^{\circ}\times 10^{\circ}$ grid box centred on the Tiree Passage.
 267 In both calibrations we subtracted 0.27‰ to convert the $\delta^{18}\text{O}_{\text{sw}}$ values from Vienna Standard
 268 Mean Ocean Water (VSMOW) to Vienna Pee Dee Belemnite (VPDB) scales (Hut, 1987). The
 269 reconstructed SWTs are hereafter referred to as $T\delta^{18}\text{O}_{\text{shell}}$.

270

$$271 \text{ Equ. 1. } T\delta^{18}\text{O}_{\text{shell}} (^{\circ}\text{C}) = 20.60 - 4.34 * (\delta^{18}\text{O}_{\text{shell}} (\text{VPDB}) - (\delta^{18}\text{O}_{\text{w VSMOW}} - 0.27))$$

$$272 \text{ Equ. 2. } T\delta^{18}\text{O}_{\text{shell}} (^{\circ}\text{C}) = 18.11 - 2.66 * (\delta^{18}\text{O}_{\text{shell}} (\text{VPDB}) - (\delta^{18}\text{O}_{\text{w VSMOW}} - 0.27))$$

$$273 \text{ Equ. 3. } \delta^{18}\text{O}_{\text{sw}} = 0.18 * \text{salinity} - 6.00$$

274

275 As there are currently no independent salinity or $\delta^{18}\text{O}_{\text{sw}}$ records that extend beyond the modern
 276 instrumental period, from either the northeast Atlantic or on the Hebridean shelf, we adopted
 277 two approaches to quantify the associated salinity/ $\delta^{18}\text{O}_{\text{sw}}$ uncertainty on the corresponding
 278 $T\delta^{18}\text{O}_{\text{shell}}$ estimates. In the first approach we quantified the mean squared error (MSE) between
 279 two $T\delta^{18}\text{O}_{\text{shell}}$ series, over the time interval from 1954-2007, in which in one of the
 280 reconstructions the $\delta^{18}\text{O}_{\text{sw}}$ values were kept constant and the second reconstruction the $\delta^{18}\text{O}_{\text{sw}}$
 281 values varied based on the conversion of EN4 SSS data to $\delta^{18}\text{O}_{\text{w}}$ values using Equ. 3. In the
 282 second approach, we quantified the difference between two $T\delta^{18}\text{O}_{\text{shell}}$ reconstructions generated
 283 using two constant salinities that are representative of (i) open ocean Atlantic water (salinity =
 284 35.0) and (ii) surface coastal waters (salinity = 33.5). Though these differences reflect the
 285 maximum potential influence of salinity on the SWT reconstruction, such a high amplitude
 286 change in salinity is highly unlikely at the shell sampling location in Tiree Passage.

287

288 Whereas oceanographic mooring data indicate that the Tiree Passage has a salinity of ~ 34.5 ,
 289 the more coastal locality of Keppel Pier has salinities of ~ 33.5 (Inall et al., 2009). Therefore,
 290 in order to test the skill of $T\delta^{18}\text{O}_{\text{shell}}$ series for reconstructing Keppel Pier SWTs we used (i) a
 291 constant salinity value of 33.5 and (ii) a variable salinity record (EN4 SSS; Good et al., 2013)
 292 which also has a mean of 33.5. The salinity of 33.5 was only used for the comparison of the
 293 $T\delta^{18}\text{O}_{\text{shell}}$ series against the Keppel Pier observations. For the final $T\delta^{18}\text{O}_{\text{shell}}$ reconstruction of
 294 SWTs in the Tiree Passage a salinity value of 34.5 was used. While varying the salinity constant
 295 does not change the structure of variability within the reconstruction, using the lower salinity
 296 of 33.5 would result in the $T\delta^{18}\text{O}_{\text{shell}}$ overestimating Tiree Passage SWTs, and so the more
 297 accurate local value of 34.5 was used.

298

299 To define the growing season of the *G. glycymeris* population in the Tiree passage the sub-
300 annually resolved $T\delta^{18}O_{shell}$ data were compared against seasonal SWTs recorded from both
301 Keppel Pier and Tiree Passage. The comparisons were made using both the Grossman and Ku
302 (1986) and the Royer et al. (2013) paleotemperature equations to determine independent
303 growing seasons. The monthly resolution of the instrumental SWT data restricts our ability to
304 provide a complete assessment of whether the sub-annual growth rate of *G. glycymeris* is linear
305 or non-linear. However, to take potential variations in the rate of *G. glycymeris* seasonal growth
306 into account we applied both a linear and non-linear growth rate model to assign calendar
307 positions, within each absolutely dated growth increment, to the sub-annually resolved
308 $T\delta^{18}O_{shell}$ data. Supplementary Figure 2 shows a schematic detailing the linear and non-linear
309 growth rate models applied. The linear and non-linear growth rate models were also applied to
310 generate weighted mean growing season instrumental SWT series that were used, in addition
311 to arithmetic mean growing season and arithmetic mean summer (June to August) SWTs, as
312 targets for the calibration of the annually resolved $T\delta^{18}O_{shell}$ data.

313

314 We adopted the standard dendrochronological and sclerochronological reduction of error (RE),
315 coefficient of efficiency (CE) and percentage variance (R^2 , North, 2000) statistical techniques
316 for assessing the skill of the $T\delta^{18}O_{shell}$ series, generated using both the variable and constant
317 salinity approaches together with both palaeotemperature equations, at reconstructing SWT
318 variability in the instrumental SWT time series. The Keppel Pier SWT dataset was used for
319 this comparison rather than the Tiree Passage mooring data because, while the Tiree Passage
320 mooring is more proximal to the shell collection site, the observation period of the dataset is
321 considerably shorter (1981-2006) and it is also discontinuous as it contains several annual gaps
322 (Inall et al., 2009). In comparison, the Keppel Pier dataset spans from 1953-2007 and provides
323 a continuous monthly record of SWT data that, despite being located around 150 km further
324 south than the Tiree Passage shell collection site, has been shown to contain SWT variability
325 that is coherent with the Tiree Passage (Reynolds et al., 2013). While the R^2 statistic provides
326 an indication of the degree of variance replicated by the target proxy series, the RE and CE
327 statistics assess the sensitivity of the reconstruction relative to subtle shifts in the target variable
328 mean between the independent calibration and verification periods (North, 2000). Given the
329 duration of the Keppel Pier instrumental dataset we used the time intervals of 1980-2007 and
330 1954-1979 for the calibration and verification periods respectively.

331

332 Spatial correlation analyses were conducted, using the KNMI Climate Explorer Facility
333 (Trouet and Van Oldenborgh, 2013), between the $T\delta^{18}\text{O}_{\text{shell}}$ series and gridded environmental
334 data sets over the calibration period. This period was used as it is the period represented by the
335 satellite measurements providing the broadest coverage of instrumental data over the North
336 Atlantic region whilst still providing sufficient data to provide a robust statistical test. Prior to
337 this period the spatial coverage of instrumental data becomes increasingly sparse (Hurrell and
338 Trenberth, 1999; Smith and Reynolds, 2004). Spatial correlations were calculated between the
339 raw and linear detrended $T\delta^{18}\text{O}_{\text{shell}}$ series and HadISST1 gridded sea surface temperatures
340 (SSTs; Rayner et al., 2003) and EN4 gridded SSS (Good et al., 2013). Whilst it is important to
341 assess the degree of coherence across all frequency domains, to account for the high degree of
342 autocorrelation in both the $T\delta^{18}\text{O}_{\text{shell}}$ series and the instrumental datasets, which can lead to an
343 overestimate of the significance of the correlation between the two series, we examined the
344 correlations using both the raw non-detrended data and linear detrended data. Additionally, we
345 applied the Ebisuzaki Monte Carlo bootstrapping methodology, which takes into account the
346 degree of autocorrelation in each of the datasets, to provide a more robust assessment of the
347 significance of the correlations (Ebisuzaki, 1997).

348

349 **3.4 Multi-proxy analyses**

350 The $T\delta^{18}\text{O}_{\text{shell}}$ series was compared with contemporaneous proxy archives from the Tiree Passage and
351 adjacent Loch Sunart. For the comparison with the co-registered *G. glycymeris* growth increment width
352 master sclerochronology, constructed from the same shells used to derive the $\delta^{18}\text{O}_{\text{shell}}$ series, the
353 $T\delta^{18}\text{O}_{\text{shell}}$ data were also detrended using a 100 year first order loess high pass filter. This was necessary
354 as the construction of the growth increment width chronology is based on detrended data, required to
355 remove the biological growth trends (Schöne et al., 2013). In all other comparison no statistical
356 detrending of the $\delta^{18}\text{O}_{\text{shell}}$ isotope record was used. The Loch Sunart $\delta^{18}\text{O}$, which is derived from the
357 analysis of benthic foraminifera (Cage and Austin, 2010), was linear interpolated to annual resolution
358 to facilitate a linear regression analysis to be performed against the $T\delta^{18}\text{O}_{\text{shell}}$ series. This interpolation
359 was necessary as the Loch Sunart $\delta^{18}\text{O}$ series contains variable sampling resolution. Running correlation
360 analysis was used to evaluate the stability of the correlation between the $T\delta^{18}\text{O}_{\text{shell}}$ series and the *G.*
361 *glycymeris* growth increment width sclerochronology.

362

363 A multiple linear regression model was used to investigate the possibility that variability contained in
364 the *G. glycymeris* growth increment width chronology is driven by the combined influence of variability
365 in SWT and biological productivity (specifically primary productivity and zooplankton abundance).

366 The analyses were conducted using the R-statistics V3.47.1 package. The analyses were repeated three
367 times, initially incorporating the Keppel Pier SST record and seasonal primary productivity (measured
368 as the greenness of the water column and diatom abundance) and zooplankton abundance (measured as
369 the abundance of copepods). The analyses were then repeated omitting the SST series to evaluate solely
370 the coherence between the growth increment width chronology and primary productivity and
371 zooplankton abundance. Finally, the model was run using only the measures of primary productivity.
372 The primary productivity and zooplankton abundance data were obtained from the Continuous Plankton
373 Recorder (CPR) survey dataset from the grid box 55-60°N by 0-10°W (www.sahfos.ac.uk/ DOI:
374 10.7487/2017.216.1.1072).

375

376 **4. Results**

377 **4.1 Raw isotope data**

378 **4.1.1 Sub-annual $\delta^{18}\text{O}_{\text{shell}}$ data**

379 In total, we derived the $\delta^{18}\text{O}_{\text{shell}}$ values of 1052 sub-annually resolved aragonite samples from
380 the growth increments of eight independently sampled shells (Figure 3). The sub-annual data
381 span the time interval from 1954-2010. The number of samples derived from each growth
382 increment varied from 3 to 22 per year, with a mean 13.7 (± 3.7 , 1σ) samples per year. The
383 number of samples per increment was variable due to the fixed width of the drilled samples
384 (150 μm) and the highly variable width of the growth increments, resulting in the overall
385 reduction in samples drilled from narrower growth increments. The sub-annual $\delta^{18}\text{O}_{\text{shell}}$ series
386 shows a strong sinusoidal-like curve with values, across all increments, ranging from 0.84 to
387 2.64‰ (Figure 3). This 1.80‰ $\delta^{18}\text{O}_{\text{shell}}$ range equates to a SWT range of $\sim 7.7^\circ\text{C}$, assuming a
388 4.3°C change in temperature per 1‰ in $\delta^{18}\text{O}$ and no influence of varying salinity.

389

390 As the sampling resolution of each increment was not constant, due to the variable width of the
391 growth increments and the constant width of the drilled sample (150 μm), in order to quantify
392 the offsets between shells, and derive the inter-shell $\delta^{18}\text{O}$ and corresponding SWT uncertainty,
393 the sub-annual isotopic values for each increment were arithmetically averaged to derive an
394 annually resolved record for each shell. The standard deviation was then calculated between
395 the $\delta^{18}\text{O}$ ratios in 19 years replicated across 41 increments in the eight sampled shells. These
396 analyses indicated a 1σ uncertainty of 0.14‰; this level of uncertainty equates to SWT
397 uncertainty of $\pm 0.6^\circ\text{C}$.

398

399 **4.1.2 Annually-resolved $\delta^{18}\text{O}_{\text{shell}}$ data**

400 We derived the $\delta^{18}\text{O}_{\text{shell}}$ values of 441 annually resolved aragonite samples from seven
401 independently sampled *G. glycymeris* shells spanning the time interval from 1799-2010.
402 Replicate samples drilled from growth increments representing the same years in multiple
403 shells provide an assessment of the inter-shell variability (Figure 4). These replicates indicate
404 an inter-shell variability (mean of the 1σ standard deviation of the 396 replicates across the 181
405 replicated years) of $\pm 0.12\text{‰}$. This equates to a SWT uncertainty of $\pm 0.5^\circ\text{C}$. The standard
406 deviation of all the available replicated annually resolved increments, including the annual
407 average of the sub-annual resolution $\delta^{18}\text{O}_{\text{shell}}$ data combined with the actual annually sampled
408 $\delta^{18}\text{O}_{\text{shell}}$ data, provides a total estimate of the inter-shell variability. These data include a total
409 of 473 independent growth increments representing 185 unique years, contain a 1σ uncertainty
410 of $\pm 0.13\text{‰}$, equivalent to a temperature uncertainty of $\sim \pm 0.6^\circ\text{C}$.

411

412 The annually resolved $\delta^{18}\text{O}_{\text{shell}}$ series is characterised by two distinct intervals (Figure 5). From
413 1799 to ~ 1900 -1910 the $\delta^{18}\text{O}_{\text{shell}}$ series contains an increasing trend, with the shells becoming
414 heavier at a rate of $+0.0025\text{‰yr}^{-1}$. Between 1890 and 1920 the $\delta^{18}\text{O}_{\text{shell}}$ remains stable at \sim
415 $1.76\pm 0.09\text{‰}$. However, over the time interval from 1920-2010, the 19th century trend in the
416 $\delta^{18}\text{O}_{\text{shell}}$ series reverses with the shells gradually become lighter at a rate of -0.004‰yr^{-1} . These
417 long term $\delta^{18}\text{O}_{\text{shell}}$ gradients equate to a cooling trend (assuming 4.3°C per 1 ‰ change in
418 $\delta^{18}\text{O}_{\text{shell}}$) of $\sim 0.10^\circ\text{C}$ per decade over the 19th century and a warming trend of $\sim 0.17^\circ\text{C}$ per
419 decade over the period from 1920-2010.

420

421 Examination of the decadal binned $\delta^{18}\text{O}_{\text{shell}}$ data (Figure 5), with zero years overlap between
422 bins, indicates that the time interval of 2001-2010 as being significantly different to any other
423 10-year period over the reconstruction period from 1799-2010 ($P < 0.001$; for full student t-test
424 results see Supplementary Table 1).

425

426 **4.2 Environmental analyses**

427 **4.2.1 Sub-annual data**

428 The sub-annually resolved $T\delta^{18}\text{O}_{\text{shell}}$ data contains temperatures that range from 8.8 - 16.6°C and
429 9.3 - 16.2°C using the Grossman and Ku (1986) and the Royer et al., (2013) paleotemperature
430 equations respectively (Figure 6 and 7). Comparison of the sub-annually resolved $T\delta^{18}\text{O}_{\text{shell}}$
431 data with the seasonal SWT curves from both Keppel Pier and the Tiree Passage (Figure 6) as

432 well as monthly HadISST1 SSTs (Figure 7), derived from a $10^\circ \times 10^\circ$ grid box (50° - 60° N 0° -
433 10° W), demonstrates that $T\delta^{18}\text{O}_{\text{shell}}$ series corresponds to SWT over the period from May to
434 October using the Grossman and Ku (1986) equation and from June to September using the
435 Royer et al., (2013) equation (Figure 6). The $T\delta^{18}\text{O}_{\text{shell}}$ data, generated using both equations
436 and applying both linear and non-linear growth models, indicates that peak reconstructed
437 temperatures are temporally synchronous and match in amplitude (within error) the peak
438 summer SWTs in the monthly HadISST1 SSTs. None of the $T\delta^{18}\text{O}_{\text{shell}}$ data appear to match
439 SWTs during the months of November to April.

440

441 **4.2.2 Annually resolved data**

442 Significant positive correlations were identified between the $T\delta^{18}\text{O}_{\text{shell}}$ series, generated using
443 both calibration equations and constant and variable approaches to salinity variability, and
444 mean summer, arithmetic and weighted mean growing season SWTs (Table 1). The $T\delta^{18}\text{O}_{\text{shell}}$
445 data generated using the Grossman and Ku (1986) equation explained between 29% and 49%
446 of the variance in arithmetic mean summer SWT and 25% to 52% of the variance in mean
447 growing season (May-October) SWT. The variable salinity approach to converting the $\delta^{18}\text{O}_{\text{shell}}$
448 data to SWTs contains marginally lower R^2 values against all three target parameters ($R^2=0.36$
449 to 0.52 compared to 0.25 to 0.50 for constant and variable salinity approaches respectively).
450 The $T\delta^{18}\text{O}_{\text{shell}}$ data generated using the Royer et al. (2013) equation explained between 29%
451 and 49% of arithmetic mean summer SWT variance and 23% to 47% of the growing season
452 (June-September) SWT variance. As with the Grossman and Ku derived $T\delta^{18}\text{O}_{\text{shell}}$ series the
453 reconstructed temperatures derived using the Royer et al. (2013) equation using the variable
454 salinity approach explain marginally less variance in the target parameters than those where
455 the constant salinity was applied ($R^2=0.35$ to 0.49 compared to 0.23 to 0.47 for constant and
456 variable salinity approaches respectively).

457

458 The examination of the reconstructions MSE, RE and CE statistics indicate that only the
459 Grossman and Ku (1986) based reconstructions of arithmetic mean summer SWT and weighted
460 growing season SWT (using both approaches to salinity) contain significant skill (RE and
461 $\text{CE} \geq 0$, $P < 0.001$; Table 1). However, despite the significant Pearson correlation and RE
462 statistics, the Grossman and Ku (1986) based reconstructions of arithmetic mean growing
463 season, using both approaches to salinity, do not contain significant CE statistics ($\text{CE} < 0$). In
464 contrast, whilst the Royer et al. (2013) derived $T\delta^{18}\text{O}_{\text{shell}}$ series performed well over the

465 calibration period against all three target parameters each of the reconstructions contain non-
466 significant CE statistics ($CE < 0$) over the verification period.

467

468 Examination of the spatial correlations calculated between the $T\delta^{18}O_{shell}$ series and the
469 HadIST1 SST and EN4 SSS gridded data over the time interval 1980-2007 (Figure 10)
470 indicates that the $T\delta^{18}O_{shell}$ series correlates with variability over broad regions of the North
471 Atlantic. Highly significant positive correlations were identified with the raw (un-detrended)
472 HadISST1 SST dataset over regions spanning from the equatorial Atlantic from the west coast
473 of Africa to the Gulf of Mexico and tracking the trajectory of the southern, eastern and northern
474 boundary currents of the SPG including in the Labrador Sea. However, no significant
475 correlations were identified with SSTs in the central region of the SPG. The spatial correlation
476 patterns between the linear detrended $T\delta^{18}O_{shell}$ series and HadISST1 SSTs were constrained
477 to the east and northern boundary currents of the SPG (Figure 10B). The spatial correlation
478 analyses between the $T\delta^{18}O_{shell}$ series and EN4 gridded SSS data indicates no significant
479 correlation with salinity on the Hebridean Shelf. However, the correlation analyses do indicate
480 significant positive correlations with salinity variability in the Labrador Sea and in the central
481 regions of the North Atlantic. The correlations with the Labrador Sea SSS are consistent using
482 both the raw (un-detrended) and the linear detrended datasets, although are somewhat more
483 spatially constrained using the linear detrended data (Figure 10C-D).

484

485 **4.3 Multi-proxy analyses**

486 Linear regression analyses identified a significant positive correlation between the $T\delta^{18}O_{shell}$
487 and the linear interpolated Loch Sunart benthic $\delta^{18}O$ series ($R=0.23$, $P<0.05$, calculated over
488 the period 1799-2001; Cage and Austin, 2010). However, examination of the coherence
489 between the co-registered $T\delta^{18}O_{shell}$ series and the *G. glycymeris* growth increment width
490 sclerochronology using 20 year running correlations indicates a variable relationship between
491 shell growth and the $T\delta^{18}O_{shell}$ data (Figure 11). Over the instrumental period (1950-2000) and
492 early 19th century the $T\delta^{18}O_{shell}$ data and *G. glycymeris* chronology exhibit positive correlations.
493 However, during the late 19th and early 20th century the $T\delta^{18}O_{shell}$ series and *G. glycymeris*
494 chronology exhibit negative to negligible coherence.

495

496 Significant correlations were identified between the *G. glycymeris* growth increment width
497 sclerochronology and primary productivity on the Hebridean shelf ($R=0.44$, $P<0.1$, calculated

498 over the period 1958-2010). The correlation between the *G. glycymeris* and zooplankton
499 abundance was found to be non-significant ($R=0.38$, $P=0.14$, calculated over the period 1958-
500 2010). Multiple linear regression model analyses indicated that biological productivity
501 (phytoplankton and zooplankton abundance) and SWT variability can explain 68% ($F= 4.02$,
502 $P<0.001$) of the variability in the *G. glycymeris* growth increment width chronology. The
503 multiple linear regression model indicated that biological productivity alone (excluding SWT
504 variability) can explain 48% ($F = 2.74$, $P<0.05$) of the variability in the *G. glycymeris* growth
505 increment width chronology. The multiple linear regression model indicates that primary
506 productivity can explain 39% ($F = 2.09$, $P<0.05$) of the variability in the *G. glycymeris* growth
507 increment width chronology.

508

509 **5. Discussion**

510 **5.1 Sub-annual analyses**

511 The sub-annual sequential sampling strategy, which generated continuous carbonate samples
512 throughout a series of growth increments from eight independent shells, provides data that
513 facilitates the assessment of the seasonal timing of shell growth and the formation of the growth
514 line. Previous assessments, which assumed a linear sub-annual growth rate, have suggested
515 that the growth check (line) forms during the winter months with growth predominantly
516 occurring during the spring and summer months (Royer et al., 2013). Although there were
517 differences in the duration of the suggested growing season between the sub-annually resolved
518 $T\delta^{18}O_{shell}$ data derived using the Grossman and Ku (1986) and Royer et al. (2013) equations
519 (May-October and June-September respectively) both approaches indicate that the growth
520 check in the *G. glycymeris* population in the Tiree Passage likely starts to form shortly after
521 peak SWTs are reached in autumn with little, if any, growth occurring over the winter months.
522 Whilst the sub-annual $T\delta^{18}O_{shell}$ data does not incorporate any reconstructed SWTs that would
523 be characteristic of winter SWTs these data do not unequivocally indicate that the *G.*
524 *glycymeris* shells do not grow during the winter months. As has been shown in some *A.*
525 *islandica* populations, it could be the case that *G. glycymeris* continues to grow at a greatly
526 reduced rate over the winter months (Schöne, 2013). However, the reduced growth rate over
527 the winter interval must be sufficiently slow that the winter growth makes up a relatively small
528 percentage of the 150 μ m sampling resolution used for the sub-annual analyses. As such the
529 remaining portion of the sample, which would have formed as growth rates increase during
530 spring, would mask any winter signal thus leading to the first sample containing a reconstructed

531 SWT corresponding to spring water temperatures. However, whilst developing a more detailed
532 understanding of the absolute timing of the *G. glycymeris* growing season in the Tiree Passage
533 is an important future objective, the priority with the current analyses is to determine the likely
534 seasonal bias of the annually resolved $\delta^{18}\text{O}_{\text{shell}}$ data. The coherence between the sub-annually
535 resolved $\text{T}\delta^{18}\text{O}_{\text{shell}}$ series with the Tiree Passage, Keppel Pier and HadISST1 SST datasets from
536 Northwest Scotland (Figure 6 and 7) strongly indicates that the peak growing season of the
537 Tiree Passage *G. glycymeris* population is likely from late spring through to late summer, which
538 is in agreement with other *G. glycymeris* populations (Royer et al., 2013). As with other marine
539 bivalves however, it is likely that the precise seasonality of growth is associated with local
540 environmental conditions and thus the growing season may differ across study localities with
541 different environmental settings.

542

543 The suggested duration of the *G. glycymeris* growing season (approximately six and four
544 months using the Grossman and Ku (1986) and the Royer et al. (2013) palaeotemperature
545 equations respectively) and maximum sub-annual sampling resolutions (22 samples per
546 increment) suggests that it is possible to reconstruct up to sub-weekly resolution SWT
547 variability in the Tiree Passage. The mean sub-annual sampling resolution (13.7 samples per
548 increment) corresponds to approximately fortnightly resolution.

549

550 **5.2 Sub-annual growth rate assessment**

551 Despite the high temporal resolution of the sub-annually resolved $\text{T}\delta^{18}\text{O}_{\text{shell}}$ data the fact that
552 the instrumental observations from this region are only available at monthly resolution limits
553 our ability to provide a thorough assessment of the suggestion that the rate of sub-annual *G.*
554 *glycymeris* shell growth is constant throughout the growing season. However, the application
555 of both arithmetic and weighted mean growing season SWT series as target environmental
556 parameters provided an opportunity to evaluate the likelihood of whether *G. glycymeris* sub-
557 annual shell growth forms at a constant rate throughout the growing season. In theory, if the
558 shell forms at constant rate throughout the growing season then the annually resolved $\text{T}\delta^{18}\text{O}_{\text{shell}}$
559 reconstruction should perform best against the arithmetic mean growing season SWT target
560 parameter as each month used to compute the mean SWT is equally weighted. Our analyses
561 however indicate that, using both the Grossman and Ku (1986) and the Royer et al. (2013)
562 equations, the $\text{T}\delta^{18}\text{O}_{\text{shell}}$ reconstructions perform better against the weighted mean growing
563 season SWTs than against the arithmetic mean growing season SWTs (Table 1). Given the

564 weighting function applied was Gaussian corresponding to a peak weighting during August to
565 September and reduced weighting at the onset and end of the growing season (see
566 supplementary information), these results strongly support the suggestion that *G. glycymeris*
567 seasonal growth is not constant. These results and the frequency distribution of the sub-
568 annually resolved $T\delta^{18}O_{\text{shell}}$ data (Figure 6), which show a predominant bias towards the
569 summer SWTs, suggests that the sub-annual shell growth of *G. glycymeris* in the Tiree Passage
570 is likely to be greatest during the summer with slower rates of growth in early spring and at the
571 end of the peak growing season (autumn).

572

573 **5.3 Thermal threshold of growth**

574 It has previously been proposed that *G. glycymeris* has a minimum thermal threshold for growth
575 of 12.9°C (Royer et al., 2013), which could limit the application of *G. glycymeris* records for
576 reconstructing SWTs through intervals characterised by colder climate conditions, such as the
577 so called Little Ice Age (~1450-1850), or in more northerly, cooler, regions of the North
578 Atlantic. Our data, however, suggests reconstructed SWTs in the sub-annual $T\delta^{18}O_{\text{shell}}$ series
579 extend down to minimum values of 8.8°C and 9.3°C, using the Grossman and Ku (1986) and
580 the Royer et al. (2013) equations respectively. These data therefore indicate that *G. glycymeris*
581 shell growth does occur in SWT's below the suggested 12.9°C growth threshold. Nonetheless,
582 with these currently available data we are not able to firmly rule out the possibility that a
583 thermal threshold on growth does exist in *G. glycymeris*, and a much broader study
584 incorporating samples from a wider spectrum of environments would be required to test this
585 hypothesis.

586

587 **5.4 Reconstruction calibration**

588 Whilst it was not the primary scope of this paper to conduct an assessment of Grossman and
589 Ku (1986) and the Royer et al. (2013) palaeotemperature equations, comparison of the sub-
590 annual and annually resolved $T\delta^{18}O_{\text{shell}}$ series converted using each equation does provide
591 scope for a preliminary assessment of the validity of both calibrations in reconstructing past
592 SWT variability. The comparison between the annually resolved $T\delta^{18}O_{\text{shell}}$ series against the
593 three target SWT series (arithmetic mean summer and arithmetic and weighted mean growing
594 season, with independent growing seasons applied to the Grossman and Ku (1986) and Royer
595 et al. (2013) derived reconstructions) highlighted that the $T\delta^{18}O_{\text{shell}}$ series can explain a
596 significant proportion of observed SWT variability of the instrumental time interval (Table 1).

597 Over the calibration period both palaeotemperature equations resulted in $T\delta^{18}\text{O}_{\text{shell}}$ data that
598 contained significant skill at reconstructing SWT variability over the calibration period (1980-
599 2007; $\text{RE}>0$; Table 1). However, only the $T\delta^{18}\text{O}_{\text{shell}}$ data derived using the Grossman and Ku
600 (1986) equation contained significant skill over both the calibration and verification periods
601 (RE and $\text{CE}>0$; Table 1). The $T\delta^{18}\text{O}_{\text{shell}}$ data derived using the Royer et al. (2013) equation
602 over the verification period was on average $0.7\pm 0.06^\circ\text{C}$ too warm across the three target
603 parameters. The differences between the reconstructed SWT data using the Grossman and Ku
604 (1986) and Royer et al. (2013) equations are due to differences in the gradients (sensitivity) of
605 the empirically derived equations, with the Grossman and Ku (1986) equation generating a
606 reconstruction with a higher amplitude of variability due to its greater sensitivity.

607

608 Royer et al. (2013) derived the *G. glycymeris* species-specific palaeotemperature equation to
609 account for an offset in their reconstructed SWTs, derived using the Grossman and Ku (1986)
610 equation, from the instrumental SWTs at their sampling site. In their study Royer et al. (2013)
611 assumed that *G. glycymeris* had a constant rate of growth during the growing season. Our data
612 however suggests that such an assumption is likely incorrect. The difference in skill of the
613 $T\delta^{18}\text{O}_{\text{shell}}$ reconstructions using the Grossman and Ku (1986) equation when compared to
614 arithmetic mean growing season and weighted growing season reconstructions suggests that
615 the failure to take into account a non-linear growth rate over the growing season could account
616 for a significant proportion of the offset between the reconstructed SWTs. For instance, the
617 $T\delta^{18}\text{O}_{\text{shell}}$ data, generated using the Grossman and Ku (1986) equation when calibrated against
618 weighted mean growing season SWTs, contains significant RE and CE statistics (RE and
619 $\text{CE}>0$; Table 1). However, the Grossman and Ku (1986) derived $T\delta^{18}\text{O}_{\text{shell}}$ data reconstruction
620 of arithmetic mean growing season SWTs contains a mean offset from the instrumental data of
621 $+0.7^\circ\text{C}$, comparable to the offset we find when using the Royer et al. (2013) equation. In
622 addition, the $T\delta^{18}\text{O}_{\text{shell}}$ reconstruction of arithmetic mean growing season SWTs has a non-
623 significant CE statistic and a MSE over the verification period more than two to three times
624 that of the weighted mean SWT reconstruction ($\text{MSE} = 0.79^\circ\text{C}$ and 0.98°C compared to 0.26°C
625 and 0.32°C respectively; Table 1). Whilst the application of the two palaeotemperature
626 equations does not change the overall patterns of variability contained in the raw $\delta^{18}\text{O}_{\text{shell}}$ data,
627 the equations do generate differences in the quantitative reconstruction of absolute SWTs. It is
628 therefore clear from these analyses that future studies need to adopt approaches to evaluate the

629 nature of sub-annual growth rates to accurately derive the seasonal bias captured by the
630 annually resolved $\delta^{18}\text{O}_{\text{shell}}$ series.

631

632 **5.5 Salinity/ $\delta^{18}\text{O}_w$ uncertainty**

633 Given the lack of observational $\delta^{18}\text{O}_w$ data, required for reconstructing past SWT variability
634 from $\delta^{18}\text{O}_{\text{shell}}$ records, the effects of varying salinity and therefore $\delta^{18}\text{O}_w$ data was evaluated
635 over the instrumental period. The comparison between the $T\delta^{18}\text{O}_{\text{shell}}$ series derived using
636 constant and variable salinity values over the instrumental period, as well as examining the
637 calibration verification statistics, provided two ways of assessing the $\delta^{18}\text{O}_w$ uncertainties. The
638 low MSE (0.02°C) calculated between the $T\delta^{18}\text{O}_{\text{shell}}$ series derived using the Grossman and Ku
639 (1986) equation using both the constant and variable salinity approaches over the calibration
640 period suggests that uncertainties associated with salinity variability are negligible in our
641 $T\delta^{18}\text{O}_{\text{shell}}$ series. The significant RE and CE statistics (Table 1) for the $T\delta^{18}\text{O}_{\text{shell}}$
642 reconstructions, derived using both the constant and variable salinity values, and the negligible
643 difference in reconstructed SWTs calculated using the two salinity approaches, indicates that
644 variability in the $\delta^{18}\text{O}_{\text{shell}}$ record is dominated by SWT variability with SSS playing only a
645 negligible role. We argue therefore that using a constant salinity based approach to convert
646 $\delta^{18}\text{O}_{\text{shell}}$ record into absolute SWTs in the Tiree Passage can produce a robust and skilful SWT
647 reconstruction over, at least, the past two centuries. Using the modern salinity range between
648 ~33.5 and 35 across the Hebridean shelf (Inall et al., 2009) suggests a corresponding SWT
649 uncertainty of $\pm 0.59^\circ\text{C}$.

650

651 **5.6 Broad scale variability**

652 Physical and geochemical variability across the Sea of the Hebrides are closely coupled to that
653 of the wider North Atlantic with variations in local currents (e.g. ESC) reflecting variations in
654 local wind stress, SPG dynamics and broader changes in the AMOC (Inall et al., 2009;
655 Huthnance et al., 2009; Holliday et al., 2015; Xu et al., 2015; Marsh et al., 2016). The
656 examination of the sensitivity of the $T\delta^{18}\text{O}_{\text{shell}}$ series against North Atlantic SWTs and SSSs
657 indicates that the variability contained in the Tiree Passage *G. glycymeris* shells reflect the
658 connectivity of the local hydrographic setting to the wider North Atlantic system (Figure 10).
659 The spatial pattern of the correlations between the $T\delta^{18}\text{O}_{\text{shell}}$ series and North Atlantic SWTs,
660 broadly coincides with the eastern boundary currents of the SPG system suggesting that the

661 variability contained in the $T\delta^{18}O_{shell}$ series is reflecting SWT variability across the Sea of the
662 Hebrides and the adjacent northeast Atlantic waters.

663

664 Intriguingly, whilst no significant correlations were identified between the $T\delta^{18}O_{shell}$ series and
665 local salinity variability, highly significant correlations were identified between the $T\delta^{18}O_{shell}$
666 series and SSS variability over the western region of the SPG and in the Labrador Sea (Figure
667 10). The Labrador Sea is a key area of deepwater formation, contributing around one third
668 towards the deep limb of the AMOC and drives changes in the North Atlantic surface
669 hydrography, mainly the SPG circulation (e.g., Rhein et al., 2002; Talley, 2003). The positive
670 correlations identified between the $T\delta^{18}O_{shell}$ series and SSS variability over the broader
671 Labrador Sea region suggests that periods characterised by high (low) salinity (and presumably
672 density) here coincide with periods of warm (cold) conditions in the Northeast Atlantic and the
673 Sea of the Hebrides. Given that increases (decreases) in seawater density across the Labrador
674 Sea region are associated with an increases (decreases) in the production of Labrador Sea Water
675 (LSW; Marshall and Schott, 1999), this pattern of correlations would implicate that a proportion
676 of the variability contained in the $T\delta^{18}O_{shell}$ series likely reflects the local SWT variability that
677 is brought about by changes in SPG circulation pattern of the North Atlantic associated with
678 the LSW formation. This interpretation is supported by the pattern of the spatial correlations
679 between the $T\delta^{18}O_{shell}$ series and North Atlantic SWTs with the correlations broadly following
680 the distribution of the surface boundary currents of the SPG across the Northeast Atlantic
681 region. It should be noted however, that given the coastal locality of the $T\delta^{18}O_{shell}$ series the
682 variability captured in the reconstruction clearly reflects a proportion of local scale variability
683 coupled with that of the broader North Atlantic region. Thus it would be inappropriate to
684 interpret the single $T\delta^{18}O_{shell}$ series as a direct reconstruction of changes in North Atlantic
685 circulation dynamics.

686

687 **5.7 Multi-proxy analyses**

688 The availability of three independent proxy records from the Tiree Passage and adjacent Loch
689 Sunart (the new $T\delta^{18}O_{shell}$ series presented here, the *G. glycymeris* growth increment width
690 chronology (Reynolds et al., 2013) and the Loch Sunart benthic foraminifera $\delta^{18}O$ record (Cage
691 and Austin, 2010; Figure 11) provides the opportunity for a more detailed analysis of the past
692 environmental variability in this region. However, while the three records have each been
693 robustly and independently calibrated to reconstruct past SWT variability, which should

694 suggest an element of coherence between the records, the comparison of the three records is
695 complicated by subtle differences in seasonality, temporal resolution and the frequency
696 domains captured by each reconstruction. For example, the $T\delta^{18}O_{\text{shell}}$ series and the *G.*
697 *glycymeris* growth increment width chronology, which were built from the same *G. glycymeris*
698 shell material, capture different frequency domains. The growth increment width chronology
699 contains only the high frequency component of variability due to the application of detrending
700 techniques during the construction of the chronology (Reynolds et al., 2013). Given that no
701 detrending techniques were applied to the $T\delta^{18}O_{\text{shell}}$ series the variability it contains should
702 more closely reflect that of the environment. Furthermore, as the low frequency variability
703 contained in the growth increment width chronology is a function of the mean segment length,
704 related to the mean longevity of the shells contained in the chronology, which is variable
705 through time, portions of the chronology that contain shells with greater (lower) mean
706 longevities contain a higher (lower) degree of low frequency variability (Cook et al., 1995). In
707 contrast, the benthic foraminifera $\delta^{18}O$ record, which is generated by the analysis of a sediment
708 core, is relatively deficient in the high frequency domain, due to the relatively lower temporal
709 sampling resolution, and therefore captures a greater proportion of the low frequency
710 variability.

711

712 Despite these potential complications, the $T\delta^{18}O_{\text{shell}}$ and the Loch Sunart benthic $\delta^{18}O$ series
713 (Cage and Austin, 2010) show significant, albeit weak, coherence over the last two centuries
714 ($R=0.23$, $P<0.05$, 1799-2001). Differences between the $T\delta^{18}O_{\text{shell}}$ series and SWTs
715 reconstructed from the benthic $\delta^{18}O$ series could be due to a multitude of factors such as
716 environmental differences between Loch Sunart main basin and the Tiree Passage, varying
717 sedimentation rates and/or variable seasonality in the benthic $\delta^{18}O$ record due to foraminiferal
718 migration within the water column. Due to the age uncertainties in the benthic $\delta^{18}O$ record the
719 generation of a longer-term $T\delta^{18}O_{\text{shell}}$ series from the Tiree Passage is required to provide a
720 more robust evaluation of the mechanisms behind the differences in the two records.

721

722 Whilst significant correlations were identified between the $T\delta^{18}O_{\text{shell}}$ series and the *G.*
723 *glycymeris* growth increment width chronology over some time intervals, e.g. from 1950-2010,
724 the relationship is highly variable (Figure 11). The variable coherence between the two series
725 provides insights into the possible drivers of the variability in both the proxy archives and in
726 the Tiree Passage.

727

728 Hitherto the biological mechanism that drives the growth increment variability in *G. glycymeris*
729 is not known. The examination of the relationships between the *G. glycymeris* chronology and
730 SST variability, phytoplankton abundance and zooplankton abundance on the Hebridean shelf
731 provides the opportunity to evaluate the biological mechanisms that drive *G. glycymeris* shell
732 growth and reconcile the differences between the chronology and the $T\delta^{18}O_{\text{shell}}$ series.
733 Although the growth increment widths have been shown to be sensitive to SWT variability
734 (Brocas et al., 2013; Reynolds et al., 2013) it is likely that SWT is a secondary driver of growth,
735 with the growth increments primarily driven by primary productivity dynamics (quantity and
736 nutritious value of the food supply) which are in turn related to SWT, as has been demonstrated
737 in other temperate marine bivalves such as *Arctica islandica* (Witbaard et al., 2003;
738 Wanamaker et al., 2009). The significant, albeit relatively weak, relationship between the *G.*
739 *glycymeris* and the phytoplankton abundance indicates that primary productivity likely plays a
740 significant role in driving *G. glycymeris* shell growth in the Tiree Passage. However, the results
741 of the multiple linear regression model analyses and linear regression analyses indicate that
742 primary productivity is unlikely to be the sole biological mechanism that influences *G.*
743 *glycymeris* shell growth. For instance, the multiple linear regression model incorporating total
744 biological productivity (zooplankton and phytoplankton abundance) can explain 48% ($P < 0.05$)
745 of the variability in *G. glycymeris* shell growth compared to 38% ($P < 0.05$) that could be
746 explained by primary productivity alone. The stronger relationship of the growth increment
747 chronology with biological productivity is likely due to the model incorporating the reduction
748 in food quality and/or quantity associated with an increase in zooplankton abundance leading
749 to an overall negative impact on shell growth. Similar relationships have been reported between
750 *A. islandica* populations and zooplankton abundance in the North Sea (Witbaard et al., 2003).
751 Visually examining the relationship between primary productivity, zooplankton abundance and
752 the *G. glycymeris* chronology highlights this pattern (Figure 12). For instance, over the interval
753 1980-1990 primary productivity is at a relatively low level, albeit with a slight increasing trend.
754 Over this interval zooplankton abundance (copepods) exhibits a pronounced spike. The
755 enhanced level of competition for the relatively low level of food over this period leads to the
756 *G. glycymeris* shells having their worst period of shell growth recorded over the instrumental
757 period. The likely mechanism linking zooplankton abundance and *G. glycymeris* shell growth
758 is that the zooplankton reduce the abundance of high quality food from the water column and
759 lead to an increase in the level of low quality food sources (faecal matter). The negative

760 correlation between zooplankton and *G. glycymeris* shell growth indicates that the reduced
761 food quality combined with the reduced level of higher quality food is the likely biological
762 mechanism driving *G. glycymeris* shell growth. The fact that the multiple linear regression
763 model combining biological productivity and SST variability improves the correlation over
764 both the biological productivity and primary productivity models (68% compared to 48% and
765 38% respectively) indicates that SWT variability is likely still a dominant mechanism in driving
766 *G. glycymeris* shell growth.

767

768 Given the relationship between the *G. glycymeris* growth increment width chronology and
769 biological productivity and SSTs, differences between the variability in the *G. glycymeris*
770 growth increment width chronology and the $T\delta^{18}O_{\text{shell}}$ series could therefore be driven by
771 several mechanisms. Firstly, we discount the possibility that these differences are associated to
772 ontogenetic (age related) shifts in the seasonality of *G. glycymeris* shell growth. The fact that
773 shells of different ontogenetic ages have been successfully crossdated (Reynolds et al., 2013;
774 Brocas et al., 2013) and the $\delta^{18}O_{\text{shell}}$ data, derived from increments of different ontogenetic
775 ages, contain coherent variability suggests the *G. glycymeris* has a constant growing season
776 throughout the lifetime of each specimen. Given primary productivity is greatest at the sea
777 surface, associated with SST variability (Richardson and Schoeman, 2004), SSS variability
778 (Mollmann et al., 2003) and circulation patterns (Reid et al., 2003), and the $\delta^{18}O$ variability
779 contained in the *G. glycymeris* shells corresponds to that of the ambient water surrounding the
780 shell on the sea bed (~24-55 m water depth), differences in the relationship between the growth
781 increment width chronology and $\delta^{18}O_{\text{shell}}$ derived proxies is likely related to differences
782 between seafloor and sea surface environmental conditions and/or changes in biological
783 productivity.

784

785 **6. Conclusions**

786 In this study we demonstrate that sub-annual and annually resolved $\delta^{18}O$ analyses derived from
787 the growth increments of the long-lived marine bivalve *G. glycymeris* can reconstruct past
788 summer SWTs on sub-annual to multi-centennial timescales. The resulting reconstruction,
789 which passes statistical tests of significance and skill, can therefore be used to quantify the
790 amplitude and frequency of past SWT variability that will ultimately lead to the development
791 of a better understanding of the mechanisms and drivers of the coupled ocean-atmosphere
792 system. Analyses of the reconstructed SWTs with the *G. glycymeris* growth increment width

793 chronology and records of biological productivity highlight that *G. glycymeris* shell growth is
794 likely driven by the combined influence of SST variability and the abundance and quality of
795 food supply. The availability of fossil *G. glycymeris* shell material from western Scotland
796 dating back to at least the early Holocene and the apparent sensitivity of the reconstruction to
797 broad scale variability across the Northeast Atlantic region indicates these methods could
798 facilitate the reconstruction of past marine variability, at seasonal to millennial timescales,
799 spanning the entire Holocene period.

800

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 994

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1001

1002 **Data availability**

1003 These stable isotope data presented in this study is available at
 1004 <https://www.ncdc.noaa.gov/paleo/study/22621>.

1005

1006 **Table 1:** Comparison between Pearson correlation, percentage variance, mean squared error
 1007 (MSE), reduction of error (RE) and coefficient of efficiency (CE) statistics calculated over the
 1008 calibration and verification periods between the $T\delta^{18}O_{shell}$ series generated using both the Royer
 1009 et al. (2013) and Grossman and Ku (1986) palaeotemperature equations. The data were
 1010 calibrated over the time interval from 1980-2007 and verified using the independent
 1011 instrumental data over the period 1954-1979. The $T\delta^{18}O_{shell}$ data were calibrated against
 1012 arithmetic mean summer (June-August) and arithmetic and weighted mean growing season
 1013 SWTs in the Keppel Pier instrumental record. The reconstruction is deemed robust if the RE
 1014 and CE statistics are >0 .

1015

Grossman and Ku (1986)	Arithmetic mean summer			Arithmetic mean growing season			Weighted mean growing season			RE	CE				
	R	R ²	MSE	R	R ²	MSE	R	R ²	MSE						
Constant salinity															
Calibration	0.70	0.49	0.47	RE	0.32	0.72	0.52	0.42	RE	0.26	0.67	0.45	0.42	RE	0.20
Verification	0.61	0.37	0.42	CE	0.31	0.57	0.33	0.79	CE	-0.96	0.60	0.36	0.26	CE	0.35
Variable salinity															
Calibration	0.68	0.47	0.53	RE	0.23	0.71	0.50	0.40	RE	0.28	0.65	0.42	0.47	RE	0.10
Verification	0.54	0.29	0.48	CE	0.21	0.50	0.25	0.93	CE	-1.29	0.50	0.25	0.32	CE	0.39
Royer et al., (2013)															
Constant salinity															
Calibration	0.70	0.49	0.41	RE	0.40	0.68	0.47	0.41	RE	0.26	0.64	0.41	0.33	RE	0.32
Verification	0.61	0.37	1.03	CE	-0.69	0.60	0.36	0.91	CE	-1.16	0.59	0.35	0.67	CE	-0.77
Variable salinity															
Calibration	0.68	0.47	0.41	RE	0.41	0.66	0.44	0.40	RE	0.28	0.63	0.39	0.33	RE	0.33
Verification	0.54	0.29	1.11	CE	-0.83	0.51	0.26	1.00	CE	-1.37	0.48	0.23	0.75	CE	-0.98

1016

1017

1018 **Figure Captions**

1019 **Figure 1:** Map showing the major currents of A) the North Atlantic and B) the continental
1020 shelf of northwest Scotland. Shell samples were collected from the Tiree Passage (TP).
1021 Oceanographic data were obtained from oceanographic instrumental moorings at both Keppel
1022 Pier (KP) and TP. Red arrows denote warm saline currents, blue arrows represent cold fresh
1023 currents, and yellow and orange arrows denote coastal currents flowing north along the British
1024 coast. The black arrows denote the general circulation pattern of the Sub-polar Gyre (SPG).
1025 Shaded contours spaced at 100m depth intervals. GS/NAC = Gulf Stream/North Atlantic
1026 Current; EGC = East Greenland Current; PF = Polar Front. Figure adapted from Reynolds et
1027 al. (2016) and Inall et al. (2009)

1028 **Figure 2:** A) Illustration demonstrating the line of section along the axis of maximum growth
1029 from the umbone to the ventral margin in a single *G. glycymeris* valve (dashed line on lower
1030 photograph) and the resulting cross section. U and V denote the positions of the umbone and
1031 the ventral margin portions of the shell respectively. B) A digital photomosaic of the tooth
1032 (enlargement of box B in plate A) and a single photomicrograph from the mosaic illustrating
1033 the clarity of the growth increment series in *G. glycymeris* shells. Panel C illustrates the
1034 sampling strategy employed for micro-drilling the annually and sub-annually resolved shell
1035 samples. The dashed red lines indicate the position of the annual growth check; the dashed
1036 green lines indicate the position of the periostracum and boundary between the outer and inner
1037 shell layers. The dashed black and blue parallelograms indicate the idealised drilling position
1038 of the annual and sub-annually resolved samples respectively. The black lines labelled SW
1039 denote the width of the drilled sample, with the annual samples this is equivalent to the width
1040 of the growth increment, whilst in the sub-annual samples is 150 μ m. Panels A and B modified
1041 from Reynolds et al. (2013).

1042

1043 **Figure 3:** A) sub-annually resolved $\delta^{18}\text{O}_{\text{shell}}$ data plotted for each absolutely dated year sampled
1044 over the period from 1954-2010. The sub-annual data are plotted relative to sampling position
1045 within the growth increment and not based on a seasonal growth model. B) Standard deviation
1046 calculated between $\delta^{18}\text{O}_{\text{shell}}$ data derived from the same year across multiple shells. C) Number
1047 of independent samples analysed per growth increment sampled. Different coloured lines
1048 represent each individual shell sampled.

1049

1050 **Figure 4:** A) Comparison between the annually resolved $\delta^{18}\text{O}_{\text{shell}}$ data, and the annual mean
 1051 of the sub-annually resolved $\delta^{18}\text{O}_{\text{shell}}$ data, from all *G. glycymeris* shells independently
 1052 sampled (black lines) with the mean $\delta^{18}\text{O}_{\text{shell}}$ series shown in red.. B) The solid black line
 1053 shows the standard deviation of the $\delta^{18}\text{O}_{\text{shell}}$ data calculated between samples replicated
 1054 between independent shells. The dashed black line denotes the mean standard deviation
 1055 across all replicated years ($1\sigma = 0.13\text{‰}$). C) Number of shells sampled in each given year.

1056

1057 **Figure 5:** A) Annually resolved $\delta^{18}\text{O}_{\text{shell}}$ data (red line) fitted with uncertainty envelope
 1058 calculated using the sum of the inter-shell variability and external precision (shaded grey area).
 1059 B) Ten-year binned mean $\delta^{18}\text{O}_{\text{shell}}$ data (black lines), with zero years overlap between bins,
 1060 fitted with 95% confidence intervals (shaded grey boxes).

1061

1062 **Figure 6:** Comparison between the sub-annually resolved $T\delta^{18}\text{O}_{\text{shell}}$ data, calibrated using the
 1063 Grossman and Ku (1986; plots A, C and E) and Royer et al., 2013; plots B, D and F)
 1064 palaeotemperature equations, and mean seasonal SWTs recorded in the Keppel Pier and Tiree
 1065 Passage instrumental timeseries. A and B) Plot of the $T\delta^{18}\text{O}_{\text{shell}}$ data (red circles) plotted with
 1066 respect to the relative sampling position (given as percentage of cumulative growth). The red
 1067 line shows the polynomial best fit generated excluding the first and last sample of each
 1068 increment. Supplementary Figure 1 shows all the sub-annually resolved data including the first
 1069 and last sample from each increment. C and D) Frequency histograms demonstrating the
 1070 distribution of the sub-annually resolved $T\delta^{18}\text{O}_{\text{shell}}$ data. E and F) Comparison between the sub-
 1071 annual $T\delta^{18}\text{O}_{\text{shell}}$ data, plotted assuming linear seasonal growth, and the arithmetic mean ($\pm 2\sigma$)
 1072 seasonal SWT curves from the Tiree Passage (Blue line with shaded blue envelope) and Keppel
 1073 Pier (black line with shaded grey envelope). For the comparison between $T\delta^{18}\text{O}_{\text{shell}}$ data plotted
 1074 using linear and non-linear growth models and seasonal SWTs see Supplementary Figure 3.

1075

1076 **Figure 7:** Sub-annually resolved $T\delta^{18}\text{O}_{\text{shell}}$ data generated using A) the Grossman and Ku
 1077 (1986) and B) the Royer et al. (2013) paleotemperature equations, plotted against monthly
 1078 HadISST1 SSTs (grey line) from a $10^\circ \times 10^\circ$ grid box ($50^\circ\text{-}60^\circ\text{N } 0^\circ\text{-}10^\circ\text{W}$). Each shell sampled
 1079 is represented with a different coloured line. For the comparison between $T\delta^{18}\text{O}_{\text{shell}}$ data plotted
 1080 using linear and non-linear growth models and seasonal SWTs see Supplementary Figure 3.

1081

1082 **Figure 8:** Comparison of the $T\delta^{18}\text{O}_{\text{-shell}}$ series derived using A) the Grossman and Ku (1986)
 1083 and B) the Royer et al., (2013) palaeotemperature equations using both variable and constant
 1084 salinity approaches (black and red lines respectively). The green lines show arithmetic mean
 1085 summer (June to August) SWTs whilst the blue and orange lines show the arithmetic and
 1086 weighted mean growing season SWTs respectively.

1087

1088 **Figure 9:** Reconstructed SWTs ($T\delta^{18}\text{O}_{\text{-shell}}$) over the time interval 1799-2010 (black line). The
 1089 shaded grey area represents a 1σ error envelope corresponding to the sum of the salinity
 1090 uncertainty, inter-shell $\delta^{18}\text{O}_{\text{-shell}}$ variability and external precision. Calibration equation MSE
 1091 $=\pm 0.3^\circ\text{C}$, external precision $=\pm 0.2^\circ\text{C}$, mean inter-shell variability $=\pm 0.6^\circ\text{C}$.

1092

1093 **Figure 10:** Spatial correlation analyses between the annually resolved $T\delta^{18}\text{O}_{\text{shell}}$ record and A)
 1094 raw and B) linear detrended mean May to October HadISST1 gridded sea surface temperatures;
 1095 and C) raw and D) linear detrended mean May to October EN4 SSS gridded sea surface salinity;
 1096 Correlations calculated over the calibration period from 1980-2007. All correlations shown are
 1097 significant at $P < 0.1$. Correlations calculated using KNMI Climate Explorer Facility (Trouet
 1098 and Van Oldenborgh (2013).

1099

1100 **Figure 11:** Comparison between A) the $\delta^{18}\text{O}_{\text{-shell}}$ data; B) Reconstructed SWTs from the Loch
 1101 Sunart $T\delta^{18}\text{O}$ -foram record (Cage and Austin, 2010); C) 100-year high pass filtered $\delta^{18}\text{O}_{\text{-shell}}$
 1102 data; D) the *G. glycymeris* Arstan growth increment width chronology index (Reynolds et al.,
 1103 2013). E) 20-year running correlations calculated between the 100 year high pass filtered
 1104 $\delta^{18}\text{O}_{\text{shell}}$ data and the Arstan growth increment width chronology index.

1105

1106 **Figure 12:** Comparison between the Arstan *G. glycymeris* growth increment width
 1107 chronology and biological productivity on the Hebridean shelf. A) The annually resolved
 1108 Arstand *G. glycymeris* growth increment width sclerochronology (Reynolds et al., 2013). B)
 1109 Level of primary productivity measured by the greenness of samples. C) Copepod abundance.
 1110 D) The annually resolved $\delta^{18}\text{O}_{\text{shell}}$ series. Primary productivity and copepod abundance
 1111 recorded across the 55-60°N by 0-10°W grid box from the Continuous Plankton Recorder (CPR)
 1112 survey dataset (<https://www.sahfos.ac.uk/> DOI: 10.7487/2017.216.1.1072).

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