

1 **A LATE QUATERNARY RECORD OF SEASONAL SEA SURFACE TEMPERATURES OFF SOUTHERN**
2 **AFRICA**

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13

14 **ABSTRACT**

15 The southern Cape coastal region is important for understanding both the behavioural history of
16 modern humans, and regional and global climate dynamics, because it boasts a long archaeological
17 record and occupies a key geographical location near the intersection of two major oceans. The
18 western boundary Agulhas Current, implicated in global heat exchange dynamics, is an important
19 modulator of southern African climates and yet we understand its past behaviour only broadly as the
20 Current itself scours the coastal shelf and marine sediment core records necessarily provide little
21 detail. Numerous archaeological sites from both the late Pleistocene and Holocene provide the
22 opportunity for reconstruction of near-shore seasonal SST records, which respond both to localized
23 wind-driven upwellings and Agulhas temperature shifts, corresponding in turn with terrestrial
24 precipitation trends in the near-coastal and summer rainfall regions. Here we present a record of
25 seasonal SSTs extending over MIS5, MIS4, and the Holocene, from serial $\delta^{18}\text{O}$ measurements of a
26 single gastropod species, *Turbo sarmaticus*. The results show that mean SST shifts accord well with
27 global SST trends, although they are larger than those recorded in the Agulhas Current from coarser-
28 scale marine sediment records. Comparison with a record of Antarctic sea-ice suggests that annual
29 SST amplitude responds to Antarctic sea-ice extent, reflecting the positioning of the regional wind
30 systems that drive upwelling dynamics along the coast. Thus, near-shore SST seasonality reflects the
31 relative dominance of the westerly and easterly wind systems. These data provide a new climate
32 archive for an important but understudied climate system.

33 **Keywords:** Late Pleistocene; Holocene; palaeoclimatology; southern Africa; Agulhas Current; oxygen
34 isotopes; mollusc shells; westerly winds

35 **Abbreviations**

36 AC – Agulhas Current; BNK1 – Byneskranskop1; HRC – Hoffman’s Robberg Cave; KRM –
37 Klasies River Main site; NBC – Nelson Bay Cave; PP5-6 – Pinnacle Point 5-6; SST – sea surface
38 temperature.

39 1 Introduction

40 The climate of southern Africa is strongly seasonal, with a summer-rainfall climate extending over
41 much of the eastern and northern parts of the subcontinent, and grading into a Mediterranean-like,
42 winter-rainfall climate in the south-west (see Figure 1; Tyson and Preston-Whyte, 2000). The
43 southern Cape lies between these two dominant precipitation regimes and experiences a gradient of
44 rainfall seasonality along its length, and is thus sensitive to shifts in the rain-bearing easterly and
45 westerly wind systems. The coastline, a mixture of rocky and sandy shores subject to high-energy
46 wave action, is adjacent to a large coastal plain, currently submerged but exposed to various degrees
47 in the past depending on global sea levels (van Andel, 1989). Numerous late Pleistocene and
48 Holocene archaeological sites along the coastline of the modern high-sea stand attest to the
49 importance of this coastal shelf region for the history of modern humans.

50 The Agulhas Current (AC), with an estimated annual transport volume of c. 65 Sverdrup, is the
51 largest western boundary current in the Southern Hemisphere (Lutjeharms, 2006), and forms part of
52 the wind-driven circulation of warm tropical waters in the south Indian Ocean. The Current flows
53 from approximately 25°S, along the South African coastal shelf to the southern tip of Africa, where it
54 abruptly retroflects southwards and flows east as the Agulhas Return Current (see Figure 1). At the
55 retroflection, large eddies and rings of warm, salty water occlude off and travel northwards into the
56 South Atlantic Ocean. This leakage of warm Agulhas water into the Atlantic is an important process
57 in the global redistribution of energy via the Atlantic Meridional Overturning Circulation (Beal et al.,
58 2011). The AC is fed mostly by water from a South West Indian Ocean sub-gyre, which circulates in
59 the Agulhas Basin. Some water is also fed in via the Mozambique Current and the East Madagascar
60 Current in the form of intermittent eddies and rings, which contribute to a seasonal signal in the
61 flow of the Agulhas Current (Lutjeharms, 2006).

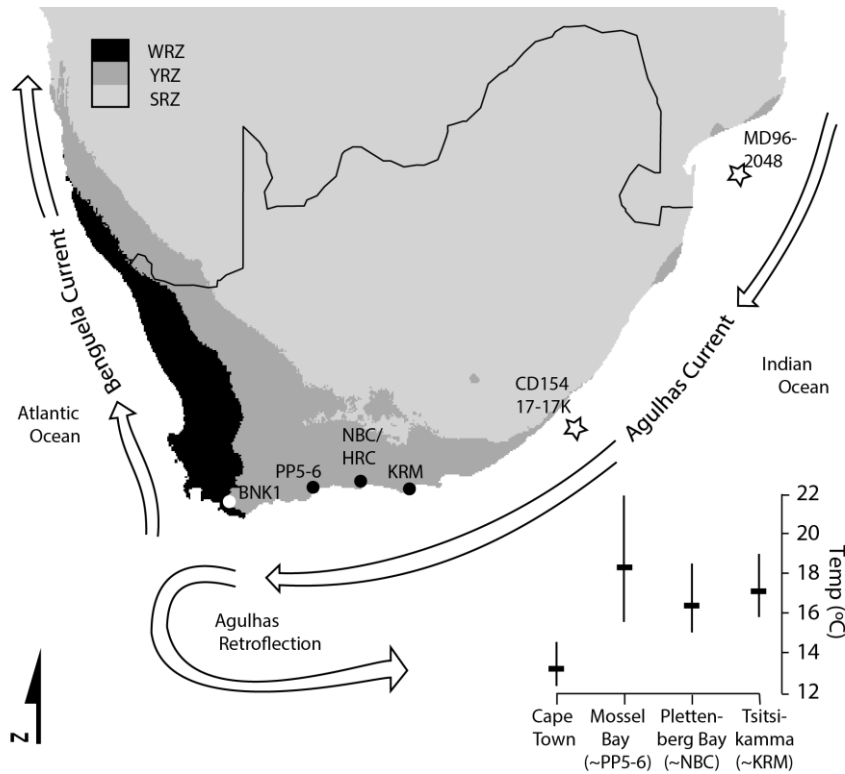
62 Cohen and Tyson (1995) presented a theoretical model to interpret near-shore sea surface
63 temperature (SST) records along the southern cape, based on an understanding of the main
64 influences on the regional climate and oceanic systems as reflected in marine mollusc records.
65 According to the model, during periods of increased westerly winds, such as the austral winter when
66 the circumpolar vortex is displaced equator-ward and westerly systems are forced northwards over
67 the southern Cape (Cockcroft et al., 1987), the flow of the Agulhas is weakened and warm waters are
68 advected onshore. At the same time, atmospheric circulation over the southwest Indian Ocean is
69 also weakened and less warm, and moist air is advected over the subcontinent. Consequently, the
70 model predicts that warm surface waters in the Agulhas system and near-shore zone are associated
71 with dry conditions in the interior, summer rainfall zone ("dry-spell mode" – although note that the
72 winter rainfall region will receive more rainfall from the northwards-shifted westerly systems).
73 Conversely, during summer-like conditions when the zone of westerly winds is forced polewards,
74 there is an increased frequency of alongshore easterly-component winds, and surface waters are
75 advected away from the coast by Ekman transport processes. Cooler bottom waters upwell along
76 the in-shore edge of the Agulhas Current, causing the thermocline to rise and leading to rapid drops
77 in coastal SSTs that typically persist for several days (Schumann, 1999; Schumann et al., 1995). These
78 easterly component winds advect warm, moist air over the eastern half of the subcontinent, and
79 bring rainfall to this region. Consequently, the model predicts that cool surface waters along the
80 southern coast during the summer are associated with wet conditions in the summer rainfall zone
81 ("wet-spell mode"). Given the seasonal dimension of this mechanism, with summer SSTs primarily
82 affected by the upwelling processes, shifts in seasonal amplitude can distinguish upwelling-driven
83 SST fluctuations in the near-shore zone from global SST shifts due to glacial/interglacial dynamics.

84 Cohen and Tyson (1995) also produced a relatively modest dataset of Holocene SST estimates from
85 oxygen isotope analyses of limpet shells preserved at Nelson Bay Cave (see Figure 1) and noted that
86 this dataset seemed consistent with the model described above.

87 The behaviour of the AC over longer timescales is as yet only poorly understood, despite its
88 important role in global and regional climates. This is in part due to the scarcity of long, finely-
89 resolved archives, as the AC itself scours away much of the sediment from the coastal shelf. Even
90 fewer records reveal details of seasonal conditions in the past, yet seasonality is an important
91 dimension of regional climates, and structures much of the ecological patterning across the
92 subcontinent. The best possibilities for records with the required temporal resolution and
93 chronological control come from material within stratified archaeological sites. Serial oxygen isotope
94 analysis of mollusc shell increments is one of the few proxies of palaeo-SSTs capable of providing
95 robust measures of intra-annual SSTs outside of the tropics (e.g. Carré et al., 2005; Ferguson et al.,
96 2011).

97 The oxygen isotope composition ($\delta^{18}\text{O}$) of calcium carbonate shells reflects both seawater
98 temperature and seawater $\delta^{18}\text{O}$ during formation (Urey et al., 1951). Serial sampling of incremental
99 growth layers supplies a record of shifts in marine conditions throughout the growth of the shell. In
100 regions where there are no fluctuations in seawater $\delta^{18}\text{O}$, the sequence largely records SST shifts.
101 Mollusc shells are a common component of archaeological sites along the south coast of South
102 Africa, collected by foraging people for food and discarded as refuse that has gradually accumulated
103 in rockshelter and cave deposits. Importantly, such assemblages span tens of thousands of years of
104 occupation in the region, with the same species represented throughout at many sites. The shells
105 are dated by association with the stratified archaeological deposits, which in many cases provides
106 better chronological control than other types of climate archive.

107 In order to address the gap in our understanding of seasonal variability of Agulhas SSTs over the late
108 Pleistocene and Holocene and the implications for coastal climates, we use archaeological *Turbo*
109 *sarmaticus* shells from five sites located along the south coast (see Figure 1) to derive seasonally
110 resolved records of near-shore SSTs across the last glacial cycle. Serial $\delta^{18}\text{O}$ measurements across the
111 *T. sarmaticus* operculum have been shown to reliably capture mean SST parameters, including the
112 mean annual SST value and the mean annual SST amplitude (Galimberti et al., 2016). Contrasting
113 mean annual SST estimates with the annual SST amplitude (or difference between average SSTs of
114 warmest and coolest months) allows one to distinguish annual SST shifts driven by global climate
115 changes (i.e. glacial/interglacial dynamics) and seasonal effects due to changes in the upwelling
116 regime (described above). The SST record presented here partitions into three broad periods: the
117 first spans much of Marine Isotope Stage (MIS) 5; the second spans the MIS5/4 transition and the
118 final period spans the terminal Pleistocene and the entire Holocene. Thus, this dataset samples both
119 glacial and interglacial conditions and two periods of global climatic transition, providing information
120 about AC seasonal dynamics during large global climate fluctuations.



121

122 **Figure 1** Map of southernmost Africa, showing the locations of the five archaeological sites in this
 123 study (filled circles). Also shown are the modern rainfall zones receiving most (> 66%) annual
 124 precipitation in summer (SRZ) and winter (WRZ), and the year-round rainfall zone (YRZ). The major
 125 currents are shown schematically, and the position of two off-shore cores is indicated (stars). The
 126 plot in the right-hand corner shows the annual mean SSTs at locations along the coast, with the
 127 mean annual SST amplitude (mean SST of warmest month – coolest month) indicated by the
 128 vertical bar. All SST data 2000-2010 (morning measurements), except at Plettenberg Bay, where
 129 1990-2000 only was available. Data is from the South African Weather Service
 130 (www.weathersa.co.za/climate).

131 **2 Material and Methods**

132 **2.1 Archaeological sites**

133 Samples were obtained from five archaeological sites that span c. 500 km of the southernmost coast
 134 of South Africa. The distribution of the archaeological sites along the southernmost coast ensures
 135 that the temperature records at each are differentially influenced by the oceanographic gradients
 136 along this coast (see Figure 1). Samples are from the MIS1 and 2 levels at Nelson Bay Cave (NBC:
 137 Deacon, 1986), Hoffman’s/Robberg Cave (HRC: Kyriacou 2009) and Byneskranskop 1 (BNK1:
 138 Schweitzer and Wilson 1982) and the MIS4 and MIS5 levels of Pinnacle Point 5-6 (PP5-6: Fisher et al.,
 139 2015) and Klasies River main site (KRM: Deacon and Geleijnse, 1988; Wurz, 2002). NBC and HRC are
 140 located on the same side of the Robberg Peninsula, about 800m apart, and reflect similar
 141 environmental conditions. These sites are all caves or rock-shelters located at the modern coastline,
 142 except BNK1 which lies c. 10 km inland. Deposits are mostly a series of human occupation layers
 143 interbedded with aeolian sands, and each site contains well preserved organic material, including
 144 shells and faunal remains.

145 The sites were excavated over the last four decades and the shells used here were largely obtained
 146 from museum collections – precise spatial information for each shell is available only at PP5-6,
 147 where excavations are ongoing. Thus, samples were aggregated according to broad time periods or

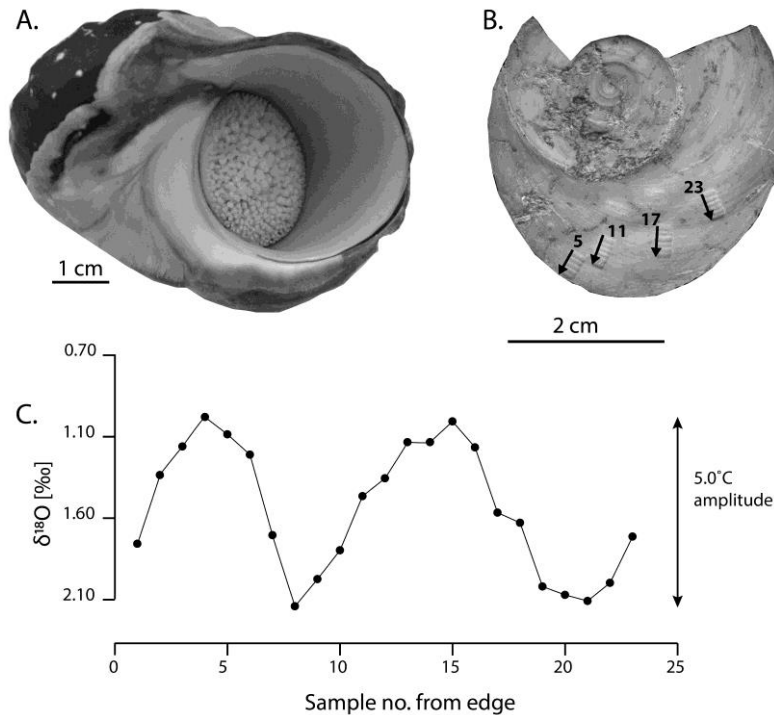
148 depositional contexts defined by technological or sedimentological features (see Table 1). The
149 archaeological sequences of NBC and BNK1 span the terminal Pleistocene and Holocene (although
150 well-preserved shells are found only in the upper deposits at BNK1), and the chronologies of these
151 two sites are securely underpinned by Bayesian modelled suites of conventional and accelerator
152 radiocarbon dates (Loftus et al., 2016). The recent radiocarbon research at NBC has considerably
153 improved the site's chronology since the study of Cohen and Tyson (1995). Radiocarbon dates from
154 HRC show that the part of the sequence investigated thus far spans only a couple of thousand years
155 in the late Holocene (Kyriacou, 2009). Samples from the three Holocene/ terminal Pleistocene sites
156 are aggregated according to broad time divisions in the Holocene – early (c. 12-8 ka), middle (c. 8 – 4
157 ka) and later (<4 ka), and the terminal Pleistocene (c. 12 – 14 ka). The KRM deposits are dated by a
158 variety of methods (e.g. optically stimulated luminescence [OSL], electron-spin resonance and U-Th
159 dating), but are constrained only very broadly to periods within MIS5 and samples are aggregated
160 according to the technological units identified by Wurz (2002). The PP5-6 deposits, dated by OSL
161 methods on sediments to periods within MIS5 and MIS4, are well constrained: samples are
162 aggregated according to the depositional units, which are each dated to within a few thousand years
163 (Karkanas et al., 2015).

164 **2.2 *Turbo sarmaticus* ecology and temperature record**

165 *Turbo sarmaticus* (or giant periwinkle, common name alikreukel) is a member of the globally
166 distributed Turbinidae family known as turban shells, which are characterized by a hard, disc-like,
167 aragonitic operculum that fits into the aperture of the topshell for protection from predators (see
168 Figure 2A). A comparatively large macro-algal grazer endemic to the southern and eastern coasts of
169 South Africa, *T. sarmaticus* is a common component of rocky shore communities along this coastline
170 (Foster, 1997). The species inhabits the lower littoral (intertidal) and sublittoral regions to depths of
171 approximately 8m (Branch et al., 2007). Typically, individuals occupy well-flushed locations and the
172 high energy wave dynamics of this coastline ensure thorough water mixing.

173 One of the few studies of the life history of *T. sarmaticus* reports a growth rate among wild animals
174 of approximately 25 mm/yr for the topshell and 9 mm/yr for the operculum during the first three
175 years (Foster et al. 1999). The growth rate slows dramatically after this, to c. 5 mm/yr and 2 mm/yr
176 for the topshell and operculum respectively. Animals can live up to 10 years (Bruton et al., 1991).
177 The value of *T. sarmaticus* for palaeoenvironmental research derives from the robustness and good
178 preservation of the operculum compared with other shells found in archaeological sites. *T.*
179 *sarmaticus* opercula are frequently preserved largely intact, unlike thin-shelled topshells, bivalves
180 and limpets, and form a significant component of south coast archaeological assemblages spanning
181 the last glacial cycle (e.g. Langejans et al. 2012).

182 The *T. sarmaticus* operculum does however present challenges for seasonal-resolution sampling as
183 many commonly used sclerochronological methods cannot be applied. The portion of the operculum
184 with regular growth increments is just a few millimetres thick, so the operculum cannot be sectioned
185 or polished prior to sampling and must be sampled directly from the ridged surface. Annual growth
186 patterns are not clearly identifiable, and the growth of the opercula is slow relative to many species
187 used in similar studies, limiting the number of samples per annual cycle and the possibility of using
188 statistical curve-fitting approaches to reconstruct seasonality. Additionally, the direction of growth
189 changes abruptly throughout life as the animal rotates the operculum to better fit the aperture of
190 the coiling topshell during growth (see Figure 2).



191

192 **Figure 2 (A) *Turbo sarmaticus* shell with operculum pulled into aperture; (B) Inner surface of**
 193 **broken archaeological *T. sarmaticus* operculum from PP5-6 (ID PP131492 from context SADBS, 71**
 194 **\pm 3 ka) with 23 micromilled samples (numbered), arrows indicating the changing direction of**
 195 **growth and sampling path; and (C) $\delta^{18}\text{O}$ measurements of PP131492, showing the seasonal SST**
 196 **signal, with the annual SST amplitude indicated.**

197 Notwithstanding the complexity of the growth patterns, earlier studies have indicated the utility of
 198 this species for archaeological research and palaeotemperature reconstruction. Shackleton (1982)
 199 analysed $\delta^{18}\text{O}$ of a small number of opercula from KRM; his purpose was to establish a chronology
 200 for the shell midden based on the global sea-level curve. Henshilwood (2008) measured
 201 archaeological *T. sarmaticus* $\delta^{18}\text{O}$ to explore changes in the seasonal timing of shellfish harvesting
 202 during the Holocene. Most recently, Galimberti et al. (2016) undertook a systematic study of modern
 203 *T. sarmaticus* opercula, collected from Mossel Bay between 2004-2007, to determine the reliability
 204 of temperature records from this species. The data show that *T. sarmaticus* precipitate their shells in
 205 equilibrium with water temperature and the Grossman and Ku (1986) palaeotemperature equation
 206 for all carbonates (as modified by Hudson and Anderson (1989) to account for the 0.2‰ difference
 207 between SMOW and average marine water) is most appropriate for this species:

208
$$T (^{\circ}\text{C}) = 19.7 - 4.34 * (\delta^{18}\text{O}_{\text{aragonite}} - \delta^{18}\text{O}_{\text{water}}),$$

209 where the $\delta^{18}\text{O}_{\text{water}}$ value is 0.52‰, as established by modern measurements at Mossel Bay
 210 (Galimberti et al., 2016).

211 The modern data of Galimberti et al. (2016) show that although single individuals do not necessarily
 212 capture the full annual temperature amplitude recorded by *in situ* thermometers, *mean* SST
 213 parameters that represent typical conditions are accurately represented across a set of opercula.
 214 Thus, the average shell-derived maximum (22.3°C) and minimum (15.6°C) SSTs match well with the
 215 actual mean temperatures of the warmest and coolest months at Mossel Bay between 2000-2007
 216 (Jan = 22.4°C; Jul = 15.6°C). Consequently, the amplitude of SSTs from each shell averaged across the

217 full set of shells, 6.7°C, corresponds well with the average seasonal range of measured SSTs at
218 Mossel Bay (6.8°C; i.e. the difference between the mean temperatures of the warmest and the
219 coolest months).

220 Although it has been suggested that a truncated SST amplitude recorded in individual modern *T.*
221 *sarmaticus* opercula might reflect physiological temperature limits for *T. sarmaticus* (i.e.
222 temperatures above and below which they cannot grow), examination of archaeological data from
223 an MIS5 site (Pinnacle Point 13b) suggests that this is not the case as these shells record cooler
224 temperatures than the modern lower limit (data reported in a doctoral thesis; Galimberti, 2010).
225 Additionally, the modern habitat of *T. sarmaticus* extends to the markedly cooler Atlantic waters
226 around the Cape Point peninsula (annual average SST = 13.3°C; Branch et al., 2007). These
227 observations suggest that the attenuated SST amplitude recorded in individual opercula might
228 reflect either a physiological limit on time spent growing driven by their biological clocks, and that
229 the animals can in fact shift their temperature tolerances to some degree, or rather that the
230 sampling resolution of the Galimberti et al. (2016) study was simply inadequate to capture periods
231 of slower growth during stressful growth seasons.

232 The approach taken here, where data from several archaeological opercula per context is
233 aggregated to determine mean SST statistics, offers improved potential to capture the general
234 environmental conditions compared with studies based on single shells per time unit, where
235 microhabitat signals or stressful events in the life-histories of individual molluscs may introduce bias.
236 Where climate is considered as the average state of environmental conditions aggregated over
237 several decades, palaeoclimate records from high-resolution but short-lived archives such as mollusc
238 shells require appropriately conservative interpretation.

239 **2.3 Shell selection and sampling**

240 *T. sarmaticus* precipitate their opercula as aragonite, a polymorph of CaCO₃ that is metastable under
241 atmospheric conditions and is more vulnerable to dissolution and recrystallization than calcite, thus
242 erasing the original oxygen isotope record in the process. Aragonitic shells provide an inherent
243 advantage over calcitic shells for palaeoclimate reconstructions in that, while the potential for
244 dissolution and recrystallisation is greater, the detection of calcite provides an unambiguous
245 indication of recrystallization and altered shells can be removed from analysis. A greater challenge
246 for this study is the patchy occurrence of diagenesis over the exposed surface of the opercula from
247 which the growth increments are sampled. This variability of preservation within a single operculum
248 demands a highly resolved assessment of recrystallization across the entire drilling path. In order to
249 overcome this problem we applied a method based on Fourier transform infrared spectroscopy with
250 an attenuated reflectance attachment (FTIR-ATR) to small aliquots (c. 0.5 mg) of powdered sample
251 to test for and quantify the presence of calcite in several samples from each operculum (Loftus et
252 al., 2015). Opercula were pre-screened using this method, whereupon approximately a quarter of
253 the opercula were discarded, although this varied between the older, Pleistocene sites and the
254 Holocene-aged sites where preservation was generally better. Upon micromill sampling,
255 approximately every 4th or 5th milled sample (i.e. 2 - 3 mm) was screened with FTIR-ATR, and if
256 recrystallisation was detected along the drilling path then the series of powdered samples
257 continuing past the altered patch were discarded. Approximately a fifth of the milled samples from
258 all sites were discarded in this way.

259

260 **Table 1 All sample contexts, correction for global changes in oceanic $\delta^{18}\text{O}$ averaged across the age**
 261 **range for each context (based on Waelbroeck et al., 2002), and the numbers of samples analysed.**
 262 **Holocene sub-contexts from NBC, BNK1 or HRC are distinguished by the first letter N, B or H,**
 263 **respectively. Calibrated radiocarbon dates for NBC and BNK1 in Loftus et al. (2016), and for HRC in**
 264 **Kyriacou (2009). OSL ages for PP5-6 in Karkanis et al. (2015), KRM dated with various methods,**
 265 **see Wurz (2002). Welch's unequal variances t-test results for significant differences between**
 266 **opercula from the same sub-context are indicated (*: $p < 0.05$; **: $p < 0.001$; data were tested for**
 267 **normality).**

Context	Sub-contexts	Date (ka)	$\delta^{18}\text{O}$ correction (‰)	No. of opercula	No. of $\delta^{18}\text{O}$ samples
	Sub-total			7	104
Late Holocene < 4.2 ka	B_1_Eva	1.7-1.9	0	1	
	N_EIII	2.5	0	2	
	B_4_Dud	3.7-4.0	0	2	
	H_RR_P	4.0-4.3	0	2	
	Sub-total			9	159
Mid Holocene c. 4.2 - 8.2 ka	B_5_Inge	3.9-6.1	0.03	1	
	N_Ivan**	4.9-6.6	0.03	2	
	B_6_Hilary	6.1-6.6	0.04	1	
	N_Glen	5.9-7.0	0.06	1	
	B_9_Mort**	6.4-7.4	0.06	2	
	N_RiceA	6.8-9.2	0.15	2	
	Sub-total			8	165
Early Holocene c. 8.2 - 11.9 ka	N_RiceB*	9.2-9.7	0.21	2	
	N_Jake	9.5-11.4	0.30	4	
	N_BSBJ**	10.9-11.9	0.48	2	
End Pleistocene	N_GSL**	12.0 - 14.9	0.75	3	65
PP5-6	DBCS	62 ± 3	0.54	1	20
	OBS1	69 ± 3	0.64	5	80
	SADBS	71 ± 3	0.58	8	151
	ALBS	72 ± 3	0.51	5	74
	LBSR	81 ± 4	0.22	5	74
KRM	MSA II Upper	c. 80 - 85	0.22	7	104
	MSA II Lower	c. 90 - 95	0.32	8	112
	MSA I	c. 115-120	0.07	6	67
Total			72	1175	

268

269 After pre-screening, opercula were micromilled using a New Wave Merchantek micromill with
 270 tungsten carbide dental burrs (0.8 mm – overlapping of samples allows for c. 0.6 mm resolution).
 271 Samples were taken in a nested series of curved lines that lie perpendicular to the direction of
 272 growth. This sampling strategy is unlike previous sampling efforts: continuous, curving arcs of
 273 individual holes that followed the mid-line of the operculum (Galimberti et al., 2016; Henshilwood,
 274 2008; Shackleton, 1982). Rather, the direction of sampling is shifted in accordance with the direction
 275 of growth changes, forming sets of discontinuous, but overlapping, samples (see Figure 2B). The
 276 number of analytical samples per operculum ranges from 5 to 26, depending on size and
 277 preservation of the shell.

278 Twenty-seven opercula were sampled from the three Holocene sites (including the terminal
 279 Pleistocene deposits at NBC), and 45 from the Late Pleistocene sites, 24 from PP5-6 and 21 from
 280 KRM (see Table 1). Table 1 also shows the age for each context and sub-context where this can be
 281 resolved, and the correction applied for changes in global ocean $\delta^{18}\text{O}$ across the glacial cycle
 282 according to Waelbroeck et al. (2002). The error of the correction is a result of the age uncertainty of
 283 the sample in each case.

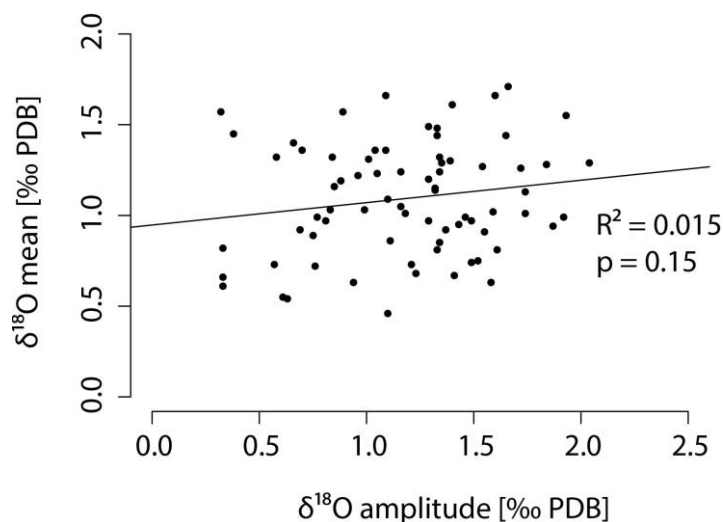
284 **2.4 Analyses**

285 Carbonate samples with < 10% calcite were analysed on one of three systems (indicated in Table
 286 SM1) - a Kiel Device coupled to a Delta V Advantage isotope mass spectrometer in the Earth Science
 287 Department, University of Oxford (external reproducibility of 0.10‰ for $\delta^{18}\text{O}$); an automated
 288 Thermo GasBench II device, coupled to a Thermo Delta V Advantage isotope mass spectrometer at
 289 the Division of Archaeological, Geographical and Environmental Sciences of the University of
 290 Bradford (external reproducibility of 0.30‰ for $\delta^{18}\text{O}$); and a Multiprep device coupled to a GV
 291 Isoprime isotope mass spectrometer at the NERC Isotope Geosciences Facilities at the British
 292 Geological Survey, Keyworth (external reproducibility of <0.10‰ for $\delta^{18}\text{O}$). In each case CO_2 was
 293 produced by 100% phosphoric acid hydrolysis, and the solid-gas fractionation of the samples is
 294 corrected using an aragonite specific factor with appropriate corrections for reaction temperature
 295 (1.00906 at 71°C [Kiel and Gasbench], 1.00854 at 90°C [Isoprime]; Kim et al., 2007). For the
 296 calculation of temperatures from a carbonate palaeotemperature equation (Grossman and Ku,
 297 1986), however, the $\delta^{18}\text{O}$ values are adjusted for solid-gas fractionation using a calcite-specific factor
 298 (1.00868 at 71°C, 1.00813 at 90°C; Kim et al., 2007) as the Grossman and Ku (1986) study did not
 299 take into account the differing fractionation factors (see also Füllenbach et al., 2015) – accordingly,
 300 both sets of $\delta^{18}\text{O}$ values are reported to aid comparison between studies. The samples were
 301 calibrated against internal calcite standards calibrated in turn to international standards (NBS19:
 302 $\delta^{18}\text{O} = -2.20\text{‰}$). Results are reported in the delta-notation relative to V-PDB, according to the
 303 equation:

304
$$\delta^{18}\text{O} (\text{‰}) = \left\{ \left(\frac{R_{\text{SAMPLE}}}{R_{\text{STANDARD}}} \right) - 1 \right\} \times 1000,$$

305 where R_{SAMPLE} and R_{STANDARD} is the $^{18}\text{O}/^{16}\text{O}$ ratio of the sample and reference materials.

306 **Figure 3 Scatterplot showing linear regression model of mean $\delta^{18}\text{O}$ value for each shell against the**
 307 **amplitude of $\delta^{18}\text{O}$ values per shell.**



308

309 **Table 2** Summary statistics for *Turbo sarmaticus* $\delta^{18}\text{O}$ data from all archaeological contexts (see
310 supplementary table for data), with reconstructed temperatures using the Grossman and Ku (1986)
311 equation for all data (as modified by Hudson and Anderson (1989)). $\delta^{18}\text{O}$ values are shown adjusted
312 for solid-gas fractionation using an aragonite specific factor, and a calcite factor for application in the
313 palaeotemperature (PT) equation, (resulting in values c. 0.4‰ more positive). The $\delta^{18}\text{O}_{\text{water}}$ value for
314 the equation is 0.52‰, adjusted by the change in global ocean $\delta^{18}\text{O}$ for each context, as recorded in
315 Table 1. Also shown are the data from modern opercula collected by Galimberti et al. (2016) and the
316 departures between the modern and archaeological data. The averaged parameters from each level
317 are calculated from the maximum, minimum and amplitude of each operculum from that level (see
318 section 2.2), and so cannot be calculated for DBCS at PP5-6, where only one operculum was
319 available.

		Number of analyses	Number of shells	Mean	Ave. max $\delta^{18}\text{O}$ / Ave. min T(°C)	Ave. min $\delta^{18}\text{O}$ / Ave. max T(°C)	Ave. ampli- tude	
Modern	$\delta^{18}\text{O}$ (‰)	327	16	+0.69	+1.47	-0.07		
	T(°C) conversion			19	15.6	22.3	6.7	
Late Holocene	$\delta^{18}\text{O}$ (‰)	104	7	+1.06	+1.56	+0.46		
	PT $\delta^{18}\text{O}$ (‰)			+1.44	+1.96	+0.85		
	T(°C) conversion			15.7	13.5	18.3	4.8	
	T(°C) dep. from modern			-3.3	-2.1	-4.0	-1.9	
Mid Holocene	$\delta^{18}\text{O}$ (‰)	159	9	+1.27	+1.70	+0.73		
	PT $\delta^{18}\text{O}$ (‰)			+1.67	+2.09	+1.11		
	T(°C) conversion			14.7	12.9	17.1	4.2	
	T(°C) dep. from modern			-4.3	-2.7	-5.1	-2.5	
NBC, BNK1 and HRC	$\delta^{18}\text{O}$ (‰)	165	8	+1.58	+2.16	+0.91		
	PT $\delta^{18}\text{O}$ (‰)			+1.96	+2.55	+1.29		
	T(°C) conversion			13.4	10.9	16.3	5.4	
	T(°C) dep. from modern			-5.5	-4.7	-5.9	-1.2	
Late Pleistocene	$\delta^{18}\text{O}$ (‰)	65	3	+2.03	+2.78	+1.21		
	PT $\delta^{18}\text{O}$ (‰)			+2.38	+3.17	+1.60		
	T(°C) conversion			11.6	8.2	15.0	6.8	
	T(°C) dep. from modern			-7.3	-7.4	-7.3	0.1	
DBCS	$\delta^{18}\text{O}$ (‰)	20	1	+1.48				
	PT $\delta^{18}\text{O}$ (‰)			+1.89	-	-		
	T(°C) conversion			13.8	-	-	-	
	T(°C) dep. from modern			-5.2	-	-	-	
OBS1	$\delta^{18}\text{O}$ (‰)	80	5	+1.66	+2.38	+0.91		
	PT $\delta^{18}\text{O}$ (‰)			+2.07	+2.79	+1.32		
	T(°C) conversion			13.0	9.9	16.2	6.4	
	T(°C) dep. from modern			-6.0	-5.7	-6.0	-0.3	
PP5- 6	$\delta^{18}\text{O}$ (‰)	151	8	+1.34	+1.99	+0.75		
	PT $\delta^{18}\text{O}$ (‰)			+1.75	+2.40	+1.16		
	T(°C) conversion			14.3	11.5	16.9	5.4	
	T(°C) dep. from modern			-4.6	-4	-5.3	-1.3	
ALBS	$\delta^{18}\text{O}$ (‰)	74	5	+1.49	+1.81	+1.04		
	PT $\delta^{18}\text{O}$ (‰)			+1.90	+2.22	+1.45		
	T(°C) conversion			13.7	12.3	15.7	3.4	
	T(°C) dep. from modern			-5.2	-3.3	-6.6	-3.3	
LBSR	$\delta^{18}\text{O}$ (‰)	74	5	+1.02	+1.53	+0.48		
	PT $\delta^{18}\text{O}$ (‰)			+1.43	+1.94	+0.89		
	T(°C) conversion			15.7	13.5	18.1	4.6	
	T(°C) dep. from modern			-3.2	-2.1	-4.2	-2.1	
KRM	MSAII	$\delta^{18}\text{O}$ (‰)	104	7	+1.57	+2.27	+0.91	

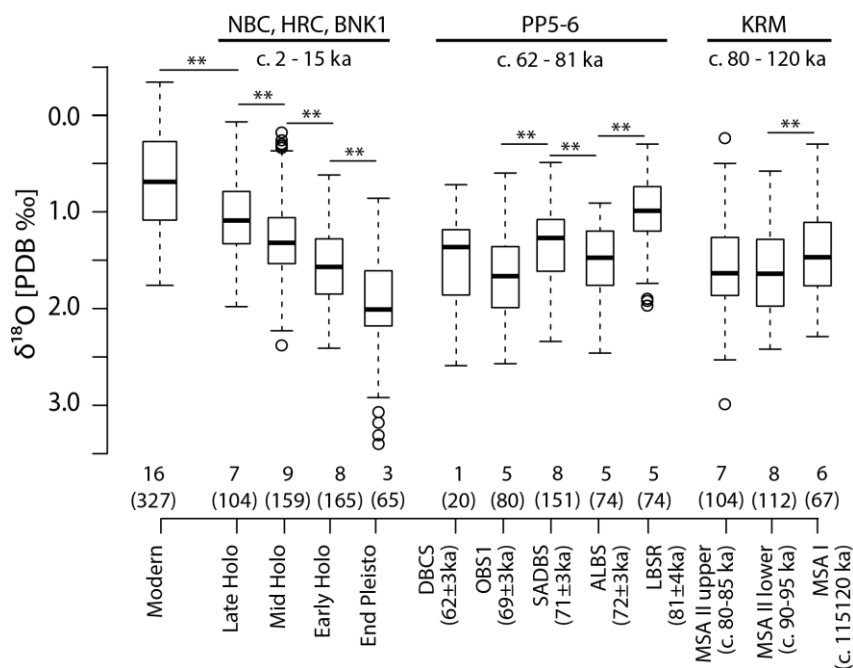
upper	PT $\delta^{18}\text{O}$ (‰)			+1.98	+2.68	+1.32	
	T(°C) conversion			13.3	10.3	16.2	5.9
	T(°C) dep. from modern			-5.6	-5.3	-6.0	-0.8
MSAII	$\delta^{18}\text{O}$ (‰)	112	8	+1.60	+2.09	+0.96	
	PT $\delta^{18}\text{O}$ (‰)			+2.01	+2.50	+1.37	
	T(°C) conversion			13.2	11.1	16.0	4.9
lower	T(°C) dep. from modern			-5.7	-4.5	-6.2	-1.7
	$\delta^{18}\text{O}$ (‰)	67	6	+1.43	+1.88	+0.76	
	PT $\delta^{18}\text{O}$ (‰)			+1.84	+2.29	+1.17	
MSAI	T(°C) conversion			14.0	12.0	16.9	4.9
	T(°C) dep. from modern			-5.0	-3.6	-5.4	-1.8

320

321 3 Results

322 A total of 1175 $\delta^{18}\text{O}$ samples from 72 archaeological opercula were analysed (Table 1). The raw
 323 isotope measurements, uncorrected for changes in global ocean $\delta^{18}\text{O}$, but corrected for solid-gas
 324 fractionation using both aragonitic and calcitic (for palaeotemperature conversions) appropriate
 325 correction factors are provided in supplementary material (Table SM1 and SM2). The serial isotope
 326 profiles of many opercula produce seasonal cycles as expected (see Figures 2, SM1, SM2 and SM3).
 327 The key $\delta^{18}\text{O}$ and converted temperature statistics for each context are provided in Table 2. Figure 3
 328 shows average $\delta^{18}\text{O}$ values for each shell compared with the total $\delta^{18}\text{O}$ amplitude for that shell using
 329 raw $\delta^{18}\text{O}$ values. The lack of a strong relationship (adjusted $R^2 = 0.015$; p-value = 0.1494) between
 330 mean SST and SST amplitude per shell supports the hypothesis that there is no bias against growth
 331 under cool climate conditions and allows interpretation of changes in seasonal amplitude across the
 332 glacial cycle.

333 **Figure 4 Boxplots of *Turbo sarmaticus* $\delta^{18}\text{O}$ values from each archaeological context (Table 2) with**
 334 **sites indicated. Numbers of shells are shown below each box, with the number of analytical**
 335 **samples in brackets. Note the left-hand scale has been reversed so that the top of the graph**
 336 **reflects higher temperatures. Significant results for pairwise statistical comparisons are indicated**
 337 **by ** ($p < 0.001$; Post-hoc TukeyHSD test).**



338

340 **3.1 Glacial-interglacial shifts in near-shore seasonal SST record**

341 The aggregated $\delta^{18}\text{O}$ measurements for each stratigraphic excavation unit are shown in Figure 3. The
 342 data show clear shifts in mean SST and annual SST amplitude. Across the terminal Pleistocene and
 343 Holocene, the shell-derived SSTs reflect a steady warming of 4.1°C (see also Figure 5), while a more
 344 variable pattern of SST change is recorded across the MIS5/4 transition, with SSTs declining by 2.7°C
 345 overall from the oldest level at PP5-6, LBSR (82 ± 4 ka), to level OBS1 (82 ± 3 ka). At KRM, the SST
 346 record is considerably more stable, reflecting less than 1°C change across the three time periods.

347 The record also shows shifts in seasonality as recorded in the annual SST amplitude. During all three
 348 periods of the Holocene, mean minimum temperatures differ less from the modern dataset of
 349 Galimberti et al. (2016) than do the mean maximum temperatures. For example, during the late
 350 Holocene, the averaged minimum recorded SSTs are 2.1°C cooler than recorded by the modern
 351 dataset, but the averaged maximum recorded SSTs are 4.0°C cooler. This asymmetry in the
 352 departures between maximum and minimum temperatures suggests that during this period cooler
 353 summer SSTs had more of an effect on the overall temperature shifts than did the cooler winter
 354 SSTs. Arguably, this pattern of cooler maximum SSTs could simply reflect biased growth trends of *T.*
 355 *sarmaticus*, as the species might sufficiently slow its growth under cool conditions so that winter SST
 356 values are underrepresented. However, this interpretation is directly challenged by the data from
 357 the terminal Pleistocene levels, where the departure from modern was approximately equal (c.
 358 7.3°C) in the averaged maximum and minimum SSTs, indicating that at this time the cooling was
 359 more or less equally distributed throughout the year.

360 Figure 7(F) shows the annual average SST amplitude across all the data, which, for the terminal
 361 Pleistocene/Holocene dataset, is lowest during the mid-Holocene (4.2°C) and highest during the
 362 terminal Pleistocene (6.8°C). The situation is mirrored for the MIS5/4 data from PP5-6, where the
 363 annual SST amplitude is high in the glacial MIS4 assemblage in context OBS1 (69 ± 3 ka: 6.4°C) and
 364 lower during the interglacial MIS5 assemblages in contexts LBSR (81 ± 4 ka: 4.6°C) and ALBS (72 ± 3
 365 ka: 3.4°C) especially (date ranges in Karkanis et al., 2015). Similar to the Holocene dataset, the low
 366 annual amplitudes in the PP5-6 dataset are driven by cooler maximum temperatures during both
 367 LBSR and ALBS, which are depressed by approximately twice as much as the minimum temperatures
 368 compared with modern values. During early MIS4 glacial OBS1, SSTs are depressed by c. 5.7 – 6.0°C
 369 year round, which is similar to the SST depression observed during the terminal Pleistocene.

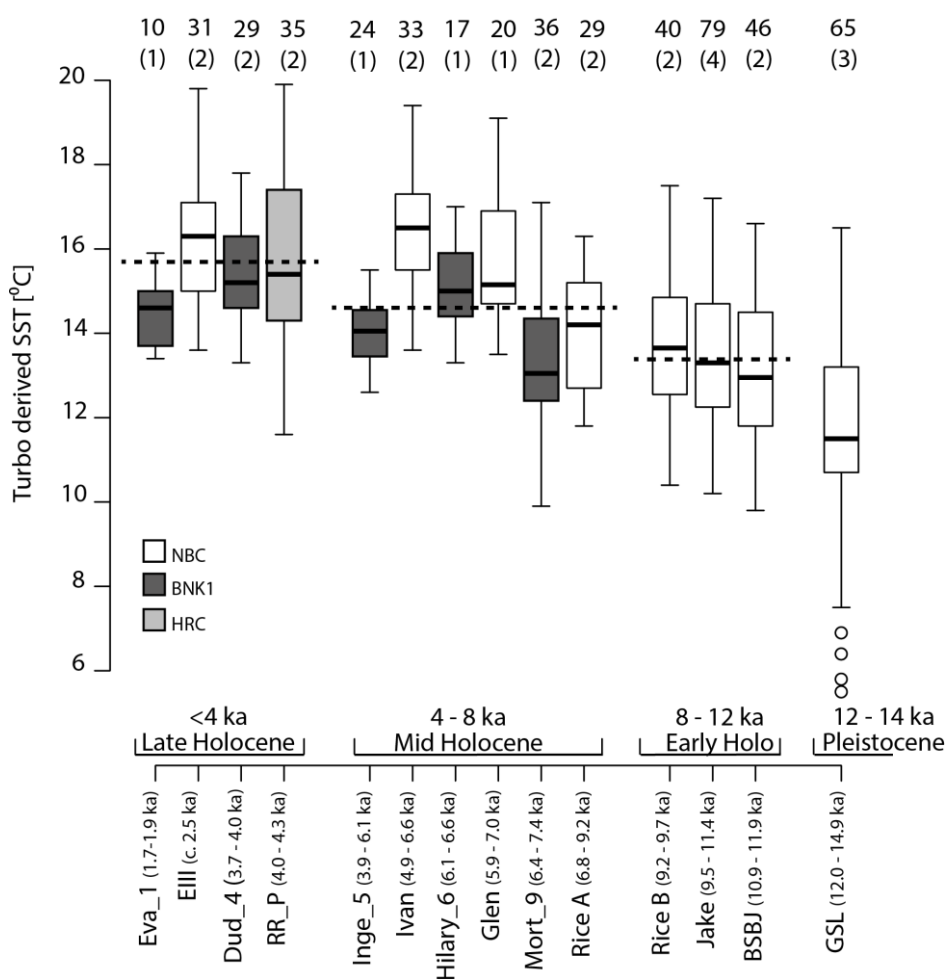
370 **3.2 Intra-context variability**

371 Chronological control among the Holocene-aged samples is sufficient to permit $\delta^{18}\text{O}$ correction
 372 according to the age of the sub-context (see Table 1), allowing exploration of variability in SST
 373 estimates at finer timescales. More than one shell was measured from a single stratigraphic
 374 excavation unit or sub-context in ten instances (see Table 1), and significant differences are
 375 observed in five cases (with Welch two sample t-test for unequal sample sizes: significant results
 376 indicated in Table 1). These differences may reflect climatic changes occurring within the timespan
 377 represented by the stratigraphic sub-context or micro-scale differences in the habitats of individual
 378 *T. sarmaticus*. It is worth noting that only in one of these ten sub-contexts, where age estimates can
 379 span thousands of years, does the standard deviation among $\delta^{18}\text{O}$ analyses exceed that recorded
 380 among all sixteen modern shells collected over just a few years (0.52‰, versus that of 0.56‰ during
 381 the terminal Pleistocene), and where the standard deviation presumably results from small
 382 differences in annual SSTs and microhabitat. Where two or more shells from a single depositional

unit reflect similar mean temperatures, one can infer with greater confidence that the shells record average environmental parameters rather than microhabitat conditions. Yet, as demonstrated by the modern study of Galimberti et al. (2016), analysis of multiple shells allows for more accurate reconstruction of parameters such as mean SST and seasonal amplitude.

Figure 5 shows the shell-derived SSTs for the Holocene and terminal Pleistocene dataset, according to sub-context. The same overall trends are evident as in Figure 4, although the magnitude of SST shifts within each context are now clear. For example, during the mid-Holocene, SSTs at NBC fluctuate by over 2°C from sub-context Rice A (14.0°C; 6.8-9.2 kcalBP, n=29) to Ivan (16.4°C; 4.9-6.6 kcalBP, n=33), whereas SSTs change less than 1°C across the early Holocene from sub-context BSBJ (13.1°C; 10.9-11.9 kcalBP, n=46) to Rice B (13.7°C; 9.2-9.7 kcalBP, n=40), suggesting that the mid-Holocene witnessed more dynamic conditions in the near-shore zone that did the early Holocene. Similar assessments of intra-context variability will be possible further back in time at KRM and PP5-6, as ongoing dating efforts at these sites improve the age estimates for the depositional contexts and allow for more precise and accurate corrections for changes in ocean $\delta^{18}\text{O}$.

Figure 5 Boxplots of *Turbo sarmaticus* shell $\delta^{18}\text{O}$ derived temperatures by sub-unit and site for Holocene and terminal Pleistocene aged samples (see Table 1 for contextual information). Dotted horizontal lines indicate average temperature for the entire period. Number of analytical samples and number of shells (in brackets) per unit is shown above each unit. Temperatures calculated using the Grossman and Ku (1986) equation for all carbonates, as modified by Hudson and Anderson (1989).

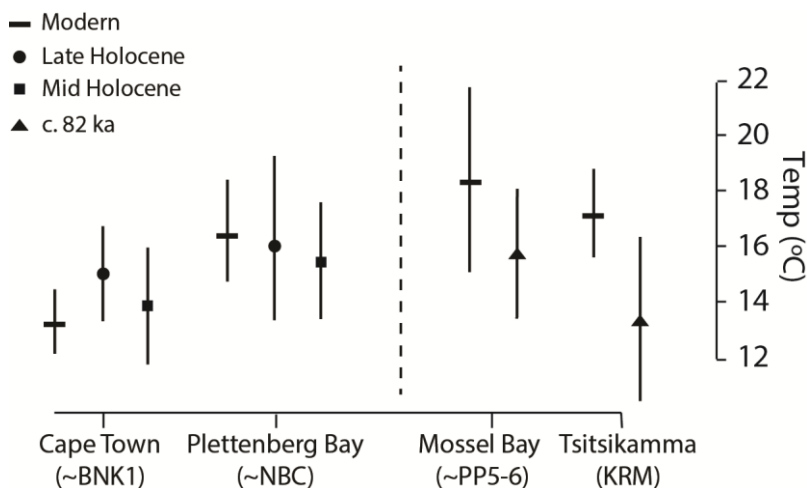


404 **3.3 Spatial variation in near-shore SSTs**

405 Along-shore SST trends can be reconstructed for the mid-late Holocene and at c. 82 ka, as data from
406 two geographically separated sites overlaps during these intervals. In the mid and late Holocene,
407 shell-derived SSTs from the Robberg Peninsula (NBC and HRC) are consistently higher than those
408 from BNK1, consistent with modern SST gradients between Plettenberg Bay (see Figure 6:
409 instrumental mean SST = 16.4°C; annual range = 3.6°C) and Cape Town, to the west of BNK1
410 (instrumental mean SST = 13.3°C; annual range = 2.3°C: data available on request from South African
411 Weather Service). During the mid-Holocene, reconstructed mean annual SSTs at BNK1 are 13.9°C
412 and on the Robberg Peninsula 15.4°C; the average amplitude at both locations is the same (4.2°C).
413 During the late Holocene, the mean annual SST at BNK1 is 15.1°C, while that at Robberg is 16.0°C.
414 The average amplitude differs sharply between BNK1 (3.4°C) and the Robberg Peninsula (5.9°C).

415 At c. 82 ka, SSTs at KRM are 13.3°C, while those at PP5-6 are 15.7°C. This, too, is consistent with the
416 modern SST gradient, as instrumental temperatures recorded at Tsitsikamma, near to KRM, today
417 average 17.1°C, while those at Mossel Bay average 18.4°C. However, the average amplitude is only
418 4.6°C in level LBSR at PP5-6, while it is 5.9°C in the MSA II upper level at KRM. To contrast, the
419 modern annual SST range at Mossel Bay is 6.7°C and that at the Tsitsikamma SST station is 3.1°C. The
420 large SST range at Mossel Bay today is driven largely by very warm summer SSTs: conversely, the
421 high SST amplitude at KRM at 82 ka appears to be largely a result of very low winter SSTs, averaging
422 10.3°C at this time.

423 **Figure 6 Mean shell-derived SST values by location along the south coast and by time period, with**
424 **modern SSTs (*in-situ* measurements available on request from South African Weather Service).**
425 **The mean annual temperature amplitude (i.e. difference between averaged maximum and**
426 **minimum temperatures) for each dataset is indicated by the vertical lines.**



427

428 **4 Discussion**

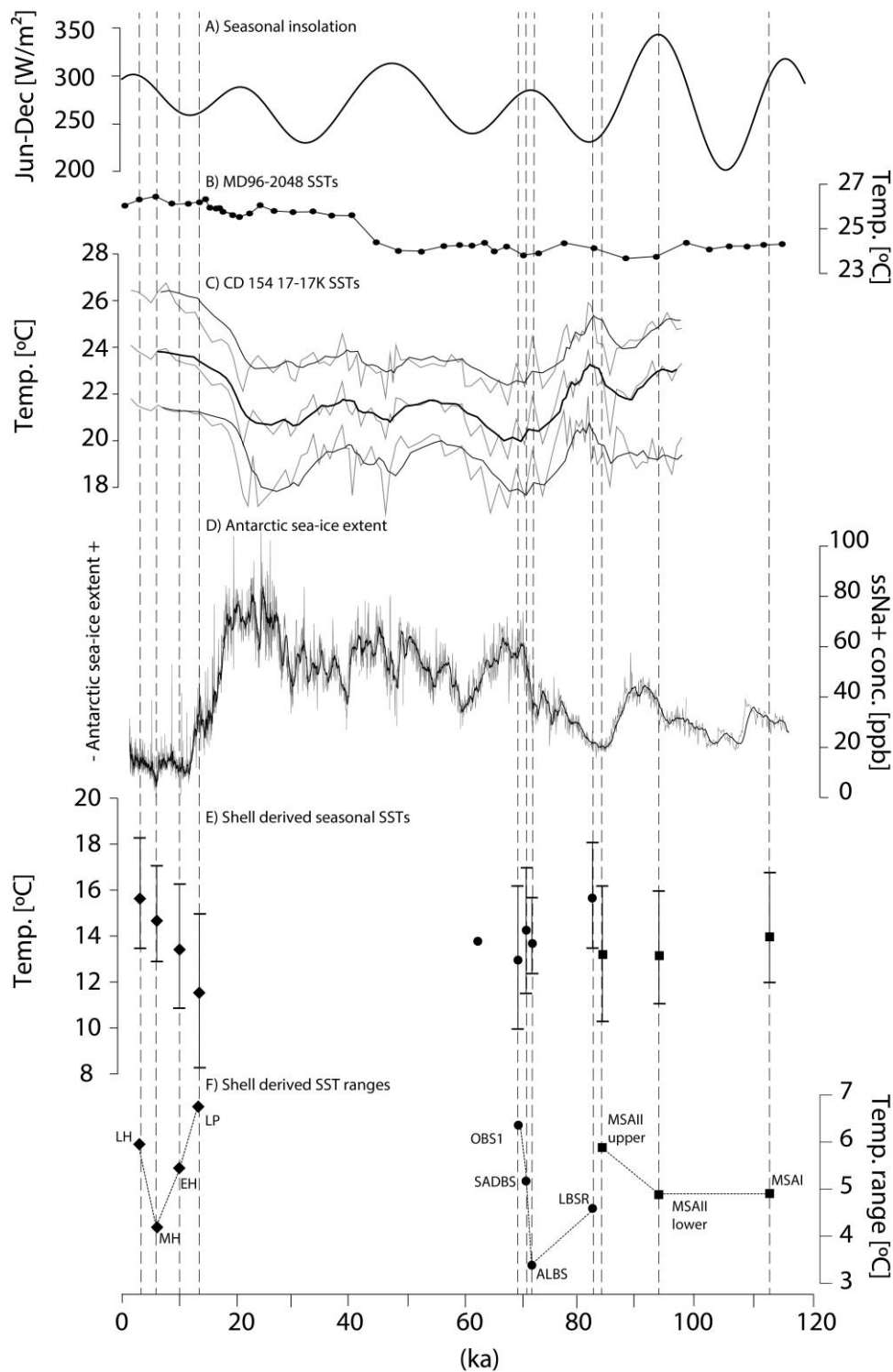
429 **4.1 Agulhas Current and near-shore SST trends**

430 The spatial patterns between the sites and the temporal shifts in temperature match well with both
431 the modern spatial temperature gradient along this coastline, and global climate shifts across MIS5
432 through the late Holocene, although our data represent but a small number of annual seasonal
433 cycles across each depositional unit. The clearest SST trend is the steady rise in temperatures from
434 the terminal Pleistocene through the Holocene. The PP5-6 data shows a gradual decline in
435 temperatures between 82 ± 4 ka (LBSR) and 69 ± 3 ka (OBS1), although the trend is not linear,

436 suggesting that fluctuations in local SST and oceanographic conditions accompanied the transition
437 from interglacial to glacial conditions between MIS5 and MIS4. In contrast, the MIS5 dataset from
438 KRM shows relatively little change between the three levels. This stability might indicate that the site
439 was occupied only during MIS5 interstadials, which is consistent with the broad dates for the
440 deposits.

441 Figure 7 shows a measure of regional climate seasonality (the difference between June and
442 December insolation; Berger and Loutre, 1991), alongside a stacked record of AC SSTs for the last
443 115 ka from marine sediment core MD96-2048, located in the formation region of the AC adjacent
444 to the Delagoa Bight (Caley et al., 2011); and a record of AC SSTs for the last 100 ka derived from
445 marine sediment core CD154 17-17K located in the main trajectory of the AC (Simon et al., 2013).
446 The SST estimates by Simon et al. (2013) are derived via a similarity index transfer function based on
447 modern analogue foraminiferal assemblages, which allows for the estimation of summer and winter
448 SSTs in addition to an annual average. Both the MD96-2048 and CD154 17-17K temperature
449 estimates are for off-shore locations closer to the Indian Ocean, and so are not directly comparable
450 with the shell-derived records of this study, which, in addition to responding to the SST shifts of the
451 larger AC system, are also influenced by near-shore processes such as upwelling. These core records,
452 however, provide information about the long-term behaviour of the Agulhas system (Caley et al.,
453 2011), and their juxtaposition with the shell-derived SST records allows us to discern global and
454 regional processes. Also shown in Figure 7 is an Antarctic record of sea salt sodium concentrations, a
455 measure of polar sea-ice extent, which effects the position of the hemispheric wind belts (Fischer et
456 al., 2007). These measures of seasonality, Agulhas Current conditions and hemisphere-wide
457 atmospheric dynamics are displayed alongside the shell-derived mean SST reconstructions (mean,
458 maximum and minimum per context) and shell-derived SST amplitudes (see Table 2).

459 **Figure 7 Shell-derived SSTs by depositional unit against: A) insolation seasonality (June-December**
 460 **insolation) at 30°S (Berger and Loutre, 1991); B) AC SSTs derived from Mg/Ca ratios and alkenone**
 461 **and tetraether indices from marine core MD96-2048 (26° 10.0'S, 34° 1.0'E; Caley et al., 2011); C)**
 462 **planktic foraminifera derived AC seasonal SSTs from marine sediment core CD154 17-17K (33°**
 463 **19.2'S, 29° 28.2'E; Simon et al., 2013) with five point running averages overlaid, and D) sea salt**
 464 **sodium concentrations from EPICA DML ice-core as a measure of sea ice extent (Fischer et al.,**
 465 **2007). E) Shell-derived SSTs are shown with average maximum and minimum values and the F)**
 466 **range between these values is plotted below. Robberg sites (NBC and HRC only: BNK1 values not**
 467 **included here): diamonds; PP5-6: circles; and KRM: squares. Note that the data from PP5-6 unit**
 468 **DBCS are not shown as they derive from only a single shell.**



470 Neither the shell-derived average SSTs nor the annual SST amplitudes correspond with seasonal
471 insolation, suggesting that other mechanisms drive the large shifts in SST and seasonality in the
472 Agulhas and near-shore zone. While reconstructions of AC SSTs from offshore cores are considerably
473 warmer than those reflected in the shell records, the magnitude of SST shifts is muted in the main
474 Agulhas system compared with the near-shore zone (SSTs are displayed at the same scale in Figure
475 5). Moreover, the fluctuations in seasonal temperature amplitudes reported by Simon et al. (2013)
476 are more constrained (between 4.0 - 5.6°C) compared to those from shell records (3.4 - 6.8°C),
477 suggesting that seasonal amplitude in the main AC may be buffered from the processes that
478 influence SST shifts and seasonal amplitude in the near-shore SST record. Admittedly, the marine
479 core records are likely to be time averaged from mixing and bioturbation processes, dampening any
480 large changes in annual SST.

481 The seasonal amplitude of nearshore SSTs corresponds well with a record of sea-ice extent from
482 Antarctica (Fischer et al., 2007). During the terminal Pleistocene, when sea-ice was more extensive
483 than during the Holocene, the larger seasonal amplitude of near-shore SSTs indicates summer
484 upwelling was reduced. As sea-ice extent is known to affect the position of the dominant wind
485 systems around southern Africa (Chase et al., 2015), this relationship suggests that the south coast
486 experienced reduced frequency of the easterly winds that drive summer upwelling of cooler, deeper
487 water, as the austral westerly wind systems were forced equatorwards over the southern part of
488 South Africa. Conversely, during the mid-Holocene, the low amplitude of the near-shore SST
489 reconstructions argues for enhanced summer upwelling, when sea-ice extent in the Atlantic sector
490 of the Southern Ocean is most diminished (Fischer et al., 2007). Sea-ice extent around Antarctica
491 subsequently expanded about 5 ka through the late Holocene (Fischer et al., 2007), when the higher
492 late Holocene shell-derived SST annual amplitude again indicates reduced summer upwelling and an
493 increased influence of westerly winds.

494 A similar pattern is observed in the trend of SST amplitudes over the MIS5/4 transition. Increasing
495 sea-ice extent across the transition is accompanied by increasing annual SST amplitudes in the near-
496 shore SST reconstructions at PP5-6. During levels LBSR (82 ± 4 ka) and ALBS (72 ± 3 ka) at PP5-6,
497 annual SST amplitudes were lower than in the subsequent SADBS (71 ± 3 ka) and OBS1 (69 ± 3 ka)
498 levels, suggesting a decrease in summer upwelling and an increased importance of westerly winds
499 along the south coast, driven by expanded Antarctic sea-ice. However, the same pattern does not
500 appear to hold in the MIS5 assemblages from KRM. While the two earliest assemblages (MSA I [115-
501 120 ka] and MSA II lower [90 – 95 ka]) have equivalent annual SST amplitudes, the annual SST
502 amplitude of MSA II upper (80 - 85 ka) is higher, suggesting a decrease in summer upwelling, yet sea-
503 ice extent declines slightly across this period. However, the age ranges for the KRM deposits are not
504 as well established as those of the other sites here – it is possible that ongoing dating studies at KRM
505 will provide more precise and accurate age estimates for the deposits.

506 **4.2 Near-shore SSTs and terrestrial precipitation trends**

507 According to the Cohen and Tyson (1995) model, shifts in near-shore SST seasonality respond to
508 seasonal, wind-driven upwelling (e.g. decreased seasonality as a result of decreased summer SSTs
509 linked to wind-driven upwelling). The low annual SST amplitude during the mid-Holocene indicates
510 that upwelling intensity was greatest during the mid-Holocene, which would correspond with
511 increased summer rainfall. Environmental records from the summer rainfall region show that the
512 mid-Holocene was indeed a time of generally moister conditions (Scott et al., 2012; Scott and Lee-
513 Thorp, 2004). Warmer, moister conditions in the northern savanna region are reflected in the
514 Makapansgat T7 speleothem between 6.4 – 5.1 ka (Holmgren et al., 2003; Lee-Thorp et al., 2001),

515 and high water levels are recorded in pans to the south, in the highveld grassland around Florisbad
516 (Scott and Nyakale, 2002). Pollen records from the coastal Lake Eteza, at the eastern edge of the
517 subcontinent, capture a moist episode between c. 7 – 4 ka, which Scott et al. (2012) hypothesise is
518 linked to the warming of the Agulhas: instead, we suggest here that it reflects increased easterly
519 winds that are also recorded in the seasonal SST record of upwelling.

520 In contrast, during the terminal Pleistocene Younger Dryas event from c. 13 – 11.5 ka, generally dry
521 conditions prevailed across the southern African interior (Scott et al., 2012), and this is consistent
522 with the SST record of increased seasonality which suggests a low frequency of summer upwelling
523 and easterly component winds at this time. Similarly, Scott et al. (2012) note lower moisture levels
524 recorded in pollen records from several sites in the SRZ during the late Holocene, c. 3.5 - 1.5 ka,
525 which is also suggested by the rise in seasonality seen in the late Holocene shell SST record. The
526 Holocene SST record thus aligns well with the expectations of the Cohen and Tyson (1995) model for
527 the SRZ.

528 Detailed records of SRZ precipitation are scarce for earlier periods, but the similarity between the
529 pattern of increasing SST amplitude recorded across the MIS5/4 transition with the mirrored trend
530 for the terminal Pleistocene/Holocene, suggests a decrease in summer rainfall in the interior across
531 the MIS5/4 transition. One of the few archives that spans this period, the Tswaing crater
532 sedimentary record (Partridge et al., 1997) shows a decrease in summer rainfall between MIS5/4. An
533 off-shore record of terrestrial run-off, situated off the east coast of South Africa, shows spikes in
534 summer rainfall during late MIS5 (Ziegler et al., 2013). However, the nature of that record is such
535 that it does not capture periods of increased aridity.

536 An indirect line of evidence for drying in the SRZ during MIS4 comes from off-shore records along
537 the western coast that show increasing proportions of rainfall in the WRZ, particularly from c. 73 –
538 57 ka (Chase, 2010). An increase in winter rainfall would result if the westerly wind system was
539 forced northwards, which is consistent with the increased seasonality seen in the shell SST record. A
540 confounding factor for reconstructing precipitation from terrestrial archives is the effect of global
541 temperature shifts on aridity across this time – although summer rainfall may have decreased during
542 MIS4, the year-round rainfall region remained generally humid due to the cooler temperatures and
543 larger amounts of winter rainfall (Chase, 2010; Chevalier and Chase, 2016).

544 **5 Conclusions**

545 Seasonal near-shore SSTs as reconstructed from serial $\delta^{18}\text{O}$ measurements of *Turbo sarmaticus*
546 opercula collected from archaeological sites along the southernmost coast of South Africa
547 correspond closely with global SST trends across MIS5, MIS4, the terminal Pleistocene and the
548 Holocene. Largely stable SSTs across the interstadial periods of MIS5 are followed by sudden
549 fluctuations in average SST across the MIS5/4 transition. From the terminal Pleistocene, average
550 SSTs rise steadily through to the late Holocene, by a total of c. 4°C.

551 While seasonal insolation does not appear to correspond with the seasonality of near-shore SSTs,
552 shifts in the annual SST amplitude may reflect wind-driven upwelling intensity, apparently in
553 response to Antarctic sea-ice forcing of the westerly wind belt. Increased upwelling (as reflected in a
554 low annual SST amplitude) during the mid-Holocene corresponds with increased precipitation in the
555 summer rainfall region. Both increased upwelling intensity and summer precipitation amounts are
556 predicted responses to an increased frequency of easterly component winds which bring moisture
557 from the warm Agulhas and Indian Ocean. Conversely, reduced near-shore upwelling during the

558 terminal Pleistocene (as reflected in a high annual SST amplitude), when sea-ice was more extensive
559 and the westerly wind systems were shifted equatorwards, corresponds with drier conditions over
560 the summer rainfall zone. Similar, but mirrored, SST trends are observed across the MIS5/4
561 transition, in the PP5-6 assemblage. Increasing annual SST amplitude across the transition suggests a
562 decrease in summer upwelling as sea-ice expanded around Antarctica. Such an expansion would
563 force the westerly wind belt north, reducing the frequency of easterly component winds over the
564 south coast and resulting in reductions in summer rainfall from MIS5 through to the start of MIS4.

565 This study augments the range of seasonal climate archives from a globally-important but poorly-
566 understood system. More broadly, the approach taken here demonstrates the value of seasonally
567 resolved near-shore SST records from archaeological marine molluscs for connecting marine and
568 terrestrial climate systems. Oceanographic processes that primarily affect near-shore contexts
569 should be distinguished from trends in the open ocean, as SST records from the two contexts are not
570 equivalent. In this study, we link near-shore upwelling dynamics, as revealed in seasonal SST records,
571 with regional precipitation trends, via latitudinal shifts in the rain-bearing wind systems (Cockcroft et
572 al., 1987; Cohen and Tyson, 1995). Currently, the number of annual seasonal SST cycles represented
573 in each depositional context is small for the purpose of defining average climate states, but given the
574 large numbers of archaeological sites with well-preserved shell material along the South African
575 coastline, the approach taken here offers good possibilities for developing detailed records of SST
576 and precipitation shifts across the last glacial period for this region.

577 **Acknowledgments**

578 This work was supported by the South African Research Chairs Initiative of the Department of
579 Science and Technology and the National Research Foundation of South Africa; Merton College,
580 Oxford; a Quaternary Research Association New Research Worker's Award, the Palaeontological
581 Scientific Trust and a NERC Isotopes Geosciences Facilities Steering Committee Award (grant number
582 IP-1543-0515). Permissions for export and sampling were obtained from the curator of the
583 archaeological collections at Iziko Museum, Heritage Western Cape (case number
584 14072110GT0730E) and the Eastern Cape Provincial Heritage Resources Agency (permit number
585 2/2/APM-PERMIT/14/09/003). Grateful acknowledgments to Curtis Marean and Sarah Wurz for help
586 accessing the collections from PP5-6 and KRM. Thanks are also due to Gideon Henderson for access
587 to sampling equipment in the Department of Earth Sciences, Oxford and especially to Chris Day,
588 Peter Ditchfield, Hilary Sloane, Chris Richardson and Andy Gledhill for help with analyses.

589 **6 References**

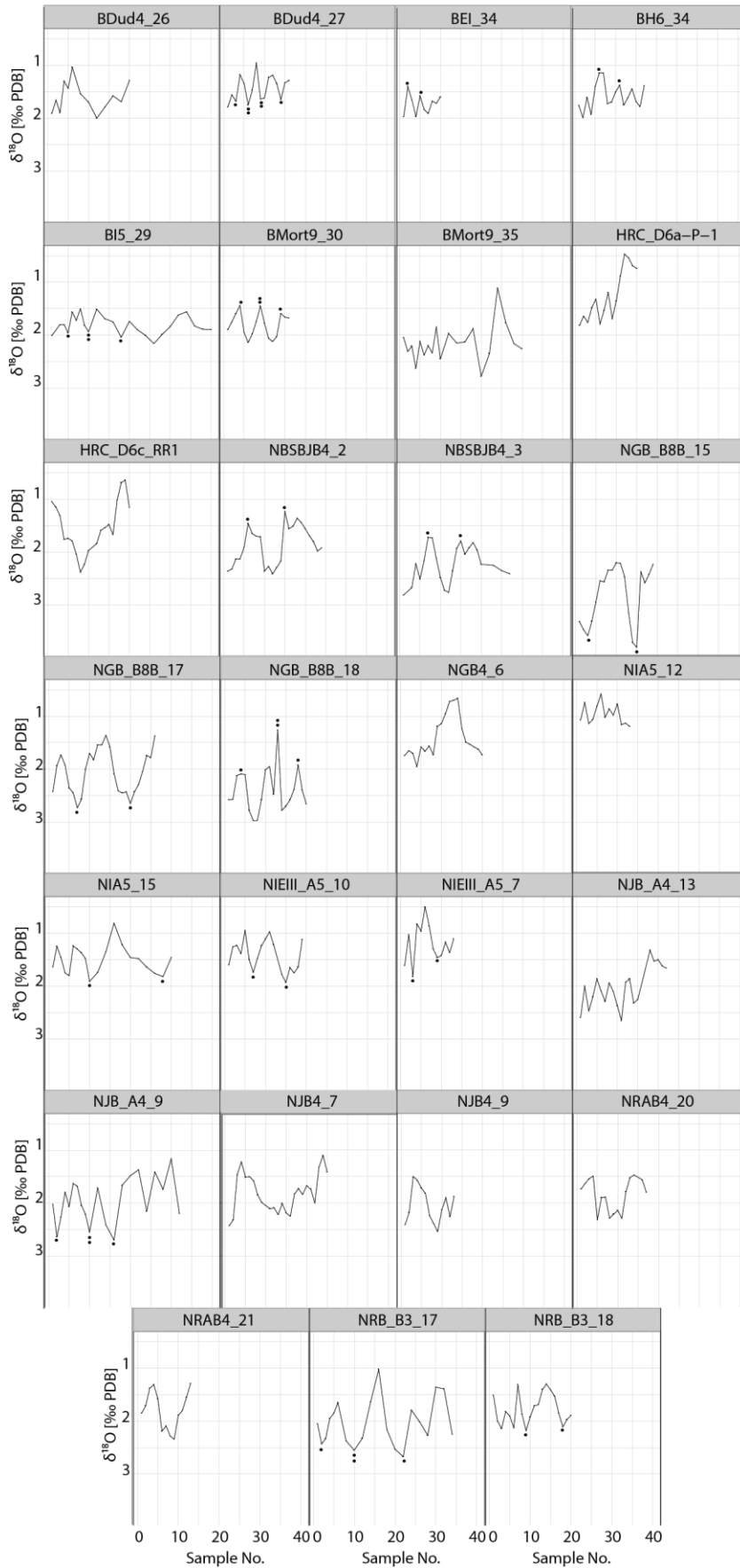
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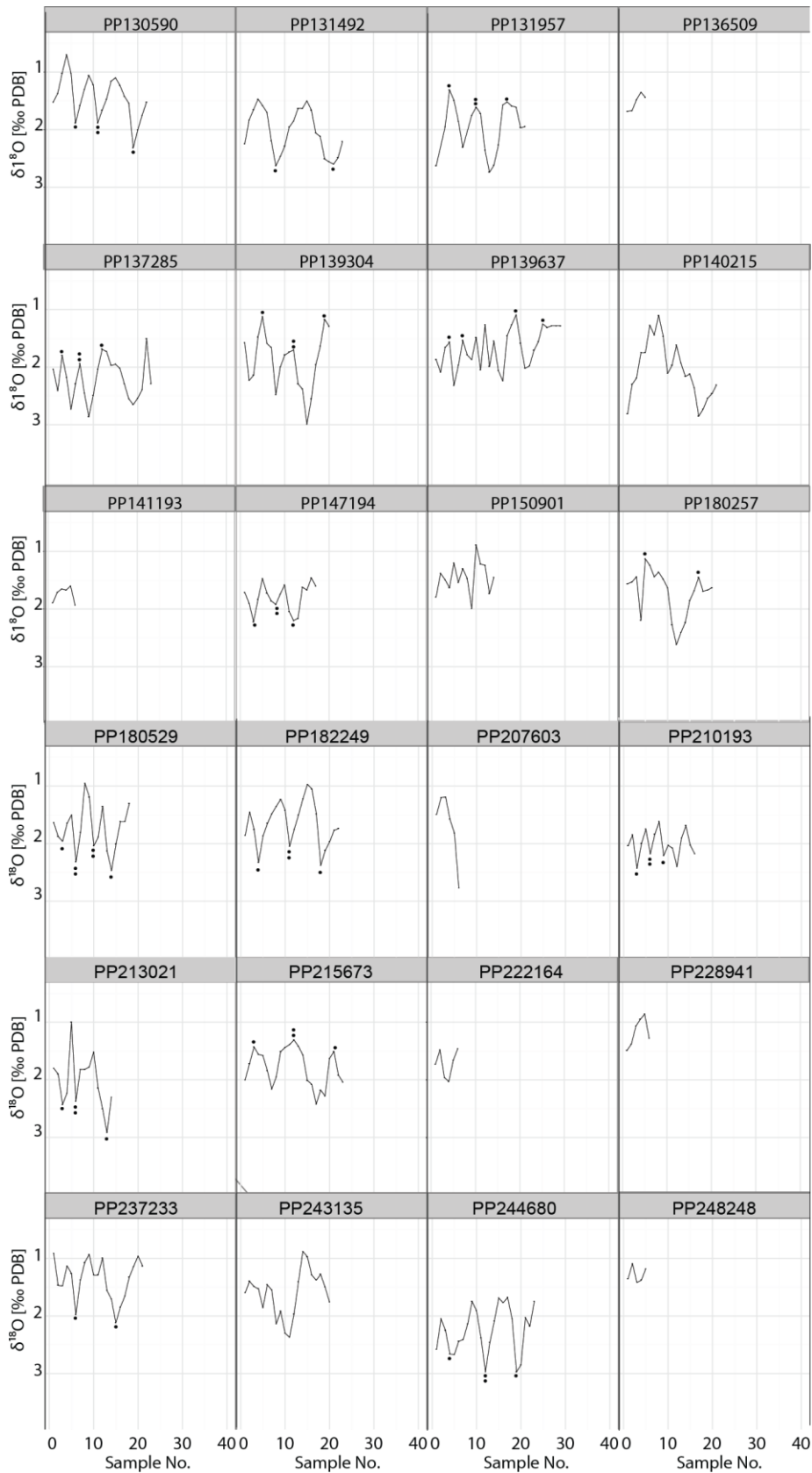
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719

720 **7 Supplementary figures**



721

722 **SM Figure 1** Serial $\delta^{18}\text{O}$ sequences from twenty-seven Holocene and Pleistocene aged *Turbo*
 723 *sarmaticus* opercula (see Table 1 for context).

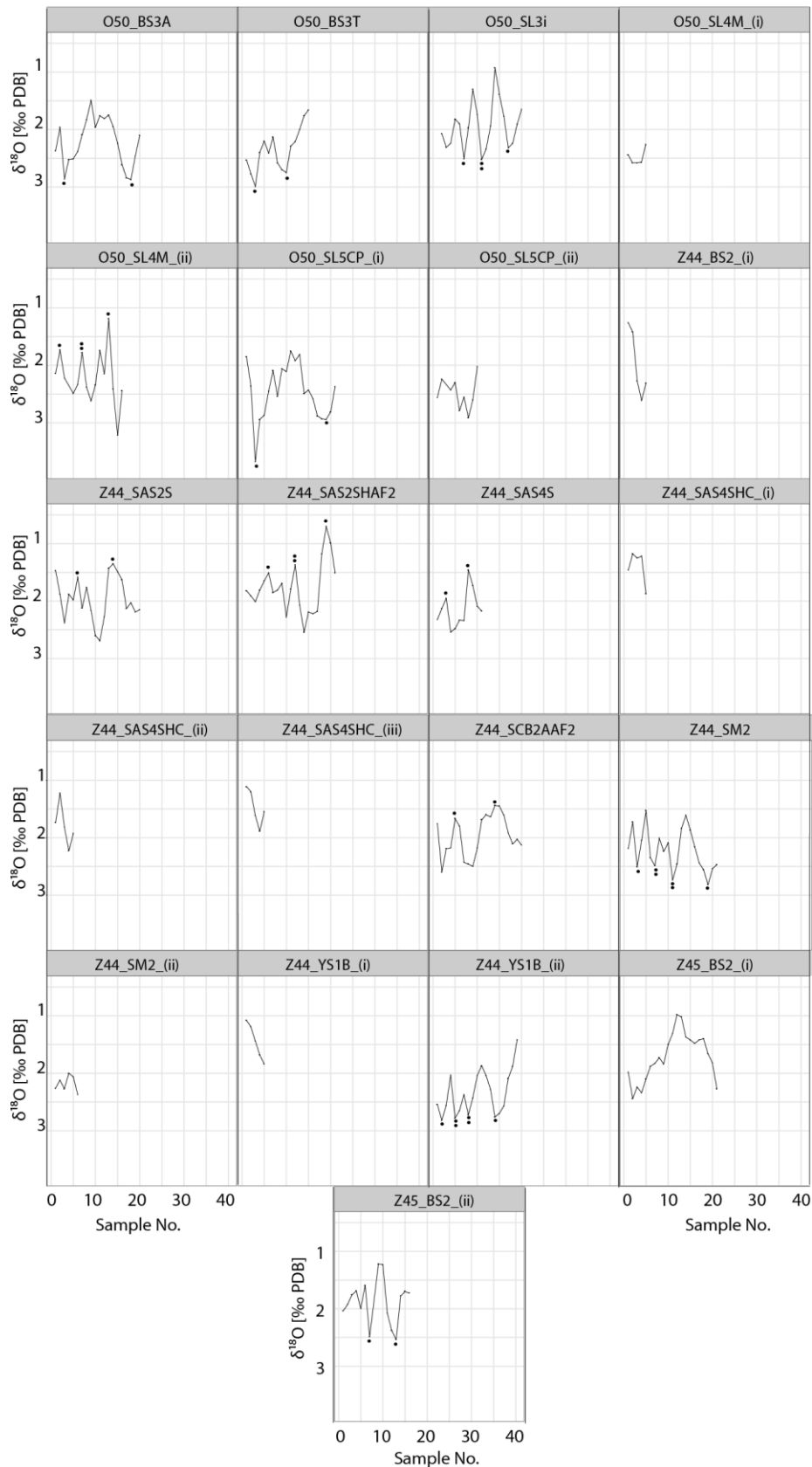


724

725 **SM Figure 2** Serial $\delta^{18}\text{O}$ sequences from twenty-four *Turbo sarmaticus* opercula from Pinnacle Point
 726 5-6 (see Table 1 for context of each shell).

727

728



729

730 **SM Figure 3** Serial $\delta^{18}\text{O}$ sequences from twenty-one *Turbo sarmaticus* opercula from Klasies River
 731 main site (see Table 1 for context of each shell).