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## **A 25,000-year record of climate and vegetation change from the southwestern Cape coast, South Africa**

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1 A 25,000-year record of climate and vegetation change from  
2 the southwestern Cape coast, South Africa

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25 **Abstract**

26 The southwestern Cape of South Africa is a particularly dynamic region in terms of long-term climate  
27 change. We analysed fossil pollen from a 25,000-year sediment core taken from a near-coastal wetland

28 at Pearly Beach that revealed that distinct changes in vegetation composition occurred along the  
29 southwestern Cape coast. From these changes, considerable variability in temperature and moisture  
30 availability are inferred. Consistent with indications from elsewhere in southwestern Africa, variability in  
31 Atlantic meridional overturning circulation (AMOC) was identified as a strong determinant of regional  
32 climate change. At Pearly Beach this resulted in phases of relatively drier conditions (~24-22.5 cal ka BP  
33 and ~22-18 cal ka BP) demarcated by brief phases of increased humidity from ~24.5-24 cal ka BP and 22.5-  
34 22 cal ka BP. During glacial Termination I (~19 – 11.7 ka), a marked increase in coastal thicket pollen from  
35 ~18.5-15.0 cal ka BP indicates a substantial increase in moisture availability, coincident, and likely  
36 associated with, slowing AMOC and a build-up of heat in the southern Atlantic. With clear links to glacial  
37 and deglacial Earth system dynamics and perturbations, the Pearly Beach record represents an important  
38 new contribution to a growing body of data, providing insights into the patterns and mechanisms of  
39 southwestern African climate change.

#### 40 **Keywords**

41 Last Glacial Maximum; Heinrich stadial 1; Atlantic meridional overturning circulation; climate change;  
42 vegetation dynamics; South Africa

#### 43 **INTRODUCTION**

44 The southwestern Cape of South Africa is a particularly dynamic region in terms of long-term climate  
45 change as it is situated at the nexus of the three dominant climate systems in southern Africa: the South  
46 Atlantic anticyclone, the temperate westerlies and the tropical easterlies (Tyson, 1986; Taljaard, 1996;  
47 Tyson and Preston-Whyte, 2000; Chase and Meadows, 2007). While most of the subcontinent experiences  
48 summer rainfall as a result of perturbations in the tropical easterlies, the southwestern Cape presently  
49 receives the majority of its rainfall during the austral winter, when the southern westerly storm track  
50 migrates northward (Tyson, 1986; Taljaard, 1996; Tyson and Preston-Whyte, 2000). In contrast, during

51 the austral summer, the westerlies and the South Atlantic Anticyclone shift southward limiting the  
52 influence of both frontal systems and tropical moisture sources (Tyson and Preston-Whyte, 2000; Reason  
53 et al., 2006). These spatially-distinct precipitation patterns led to the classification of the winter rainfall  
54 zone (WRZ) (*sensu* Chase and Meadows, 2007; >66% of annual precipitation in winter), the summer  
55 rainfall zone (SRZ; >66% of annual precipitation in summer) and a transitional zone of limited seasonality  
56 between the WRZ and SRZ, the aseasonal or year-round rainfall zone (ARZ) (Fig. 1).

57         The southwestern Cape is also where the warm Agulhas Current and the cold Benguela Current  
58 meet and, the region is thus also particularly dynamic from an oceanographic perspective. Both currents  
59 are key components of the global ocean “conveyor belt” (thermohaline circulation) (Lutjeharms, 1996;  
60 Rahmstorf, 2006) and therefore contribute not only to climatic variability within the southwestern Cape  
61 but also play a role in global climate dynamics (Walker, 1990; Walker and Shillington, 1990; Cohen and  
62 Tyson, 1995; Reason, 2001; Biastoch et al., 2009; Beal et al., 2011).

63         The climatic setting of the southwestern Cape has played an important part in the development  
64 of the vegetation of the Cape Floristic Region (CFR) and is thought to have fostered the region’s  
65 extraordinary botanical diversity (Goldblatt, 1978; Linder et al., 1992; Cowling and Lombard, 2002; Linder,  
66 2005; Bradshaw and Cowling, 2014; Cowling et al., 2015). While long-term climatic stability during the  
67 Pliocene and Pleistocene is hypothesised to be one of the key factors for the diversification of the Cape  
68 flora (Cowling et al., 1997; Cowling and Lombard, 2002; Linder, 2005; Bergh and Cowling, 2014; Cowling  
69 et al., 2015), little direct evidence is available. Furthermore, species diversity within the CFR is not  
70 homogeneous and at finer spatial and temporal scales the concept of climatic stability driving diversity  
71 and species richness becomes more complex (Cowling, 1992; Cowling et al., 1997; Cowling and Lombard,  
72 2002). Palaeoclimatic records from the western montane region of the CFR provide evidence for steep

73 palaeoenvironmental gradients and highlight the need for more research to be conducted to assess the  
74 role of palaeoclimatic change in biodiversity patterns (Chase et al., 2019a).

75         Despite the challenges of conducting Quaternary paleoenvironmental studies in arid – semi-arid  
76 areas (see Chase and Meadows, 2007), considerable progress has been made over the last decade in terms  
77 of the generation of high-resolution palaeoclimatic records for the southwestern and southern Cape  
78 regions (e.g. Neumann et al., 2011; Stager et al., 2012; Chase et al., 2013; Valsecchi et al., 2013; Chase et  
79 al., 2015a; Quick et al., 2018; Wündsche et al., 2018; Chase et al., 2019a; Chase et al., 2020; Kirsten et al.,  
80 2020). This emerging regional dataset is enabling a more refined understanding of the spatial and  
81 temporal complexity of climate and vegetation responses to a range of forcing mechanisms, and suggests  
82 that substantial variability in inferred climatic trends/trajectories occurs across relatively short distances  
83 (e.g. Chase et al., 2015a; Chase et al., 2017; Chase and Quick, 2018; Chase et al., 2020). Even though more  
84 – and indeed more detailed – records are now available, most of these records only cover the Holocene  
85 (11.7 – 0 cal ka BP) or portions thereof. In particular, greater spatial and temporal coverage is still needed  
86 to fully document the Last Glacial Maximum (LGM; 19 – 26.5 ka (Clark et al., 2009)) and last glacial  
87 termination (Termination I; the period from the end of the Last Glacial Maximum to the early Holocene,  
88 ~19 – 11.7 ka).

89         During Termination I, one of the primary internal drivers of global change was variability in  
90 Atlantic meridional overturning circulation (AMOC), a key component of the thermohaline circulation (Mix  
91 et al., 1986; Crowley, 1992; Broecker, 1998; Stocker, 1998; Stocker and Johnsen, 2003). AMOC transports  
92 heat from the Southern Hemisphere to the North Atlantic basin. Perturbations in the strength of the  
93 AMOC thus impact climate in both hemispheres, with stronger AMOC resulting in net cooling (warming)  
94 in the Southern (Northern) Hemisphere, and weaker AMOC resulting in a build-up of heat in the Southern  
95 Hemisphere while the Northern Hemisphere cools, a dynamic referred to as the bipolar seesaw (Broecker,

1998; Stocker and Johnsen, 2003). Massive ice and freshwater discharges in the North Atlantic, known as Heinrich events, exerted a significant influence on AMOC, resulting, for example, in its near shut-down during Heinrich stadial 1 (HS1; ~18-14.6 ka) (Broecker, 1998; McManus et al., 2004; Ritz et al., 2013; Ng et al., 2018; Bendle et al., 2019).

100           In the southwest African sector, the influence of weaker AMOC is manifested in a general warming  
101 of southeast Atlantic sea-surface temperatures (SSTs) (Kim and Schneider, 2003; Farmer et al., 2005), a  
102 poleward shift of the Subtropical Front (Barker et al., 2009), and thus likely an increase in Agulhas leakage  
103 (Gordon, 1986; Peeters et al., 2004; Caley et al., 2012; Rühls et al., 2019). As an example, the abrupt slow-  
104 down in AMOC during HS1 is consistent as the underlying driver for the distinct humid phase registered  
105 at sites along the western continental margin in the Namib Desert (Lim et al., 2016; Chase et al., 2019b)  
106 and the Cederberg mountains in the southwestern Cape (Chase et al., 2015a), as well as further afield in  
107 the continental interior (Chase et al., 2017; Chevalier and Chase, 2015). It remains to be determined,  
108 however, how these changes in AMOC affected Africa's southern/southwestern Cape coast, particularly  
109 in the context of the emerging evidence for spatial complexity in the regional climatic response (Chase  
110 and Quick, 2018; Chase et al., 2019a; Chase et al., 2020). This brings into question the utility of the simple  
111 widely-used binary models that indicate or infer a coeval inverse relationship between the WRZ and SRZ  
112 (van Zinderen Bakker, 1976; Cockcroft et al., 1987) and thus how climate changes related to AMOC may  
113 have manifested in the region.

114           To investigate the potential influence of AMOC variability at the interface of the Agulhas and  
115 Benguela currents and at the margin of the WRZ, here we present a new record of fossil pollen, charcoal  
116 and sediment grain-size from a 25,000-year sediment core taken from Pearly Beach 1, a near-coastal  
117 wetland site situated on the eastern coastal boundary of the present-day WRZ (Figs. 1 and 2). Data from  
118 the core presents a rare opportunity to consider vegetation/climate responses through this major global

119 climate transition. The record reveals distinct changes in vegetation composition occurred along the  
120 southwestern Cape coast during the LGM, Termination I and Holocene. From these data, we infer  
121 considerable variability in temperature and moisture availability over the last 25 000 years and link these  
122 changes to glacial and interglacial boundary conditions, and particularly, to the perturbations and  
123 dynamics in the Earth system that characterised the process of deglaciation.

## 124 REGIONAL SETTING

125 In 2007, a sediment core (Pearly Beach 1, referred to hereafter as PB1, 34° 38.880'S; 19° 30.300'E, 5 m  
126 a.s.l., 2.5 km from the current coastline (Fig. 2)) was extracted from wetlands 2 km north of the coastal  
127 town of Pearly Beach, ~200 km southeast of Cape Town. The site is situated on the boundary of the  
128 modern WRZ (*sensu* Chase and Meadows, 2007; >66% of annual precipitation falling in MJJAS), receiving  
129 68% of its mean annual average of ~450 mm of rainfall during the winter (Climate System Analysis Group,  
130 2021). Temperatures are moderate (monthly-averaged daily mean of 17 °C), snow has not been recorded  
131 and frost appears to be absent from the area as well.

132 The Pearly Beach wetland complex is situated on a low-lying undulating coastal plain that is  
133 bounded to the north by Bredasdorp Group limestone (calcarenite) ridges and Table Mountain Group  
134 sandstone outcrops of Peninsula Formation (Malan, 1989). The wetlands derive their waters from the  
135 limestone uplands to the northeast of the site via both runoff and throughflow from spring seeps.  
136 Transverse coastal dunes, currently invaded by extensive alien vegetation, stretch along the southern and  
137 western boundaries of the wetland adjacent to the ocean. Relict deflated parabolic dunes can be  
138 identified within the landscape towards the northwest and southeast of the site. The coastal platform is  
139 underlain by unconsolidated aeolian calcareous Quaternary sediments of the Strandveld Formation with  
140 partially consolidated calcrete lenses found in some patches along the coast and further inland (Gresse  
141 and Theron, 1992). Alluvial deposits characterise the wetlands of the area. On the limestone ridges, soils

142 are shallow, alkaline and calcareous, whereas the lower slopes are characterised by more acidic, colluvial  
143 soils with evidence of early stages of podsolisation (Rebelo et al., 1991). The young coastal dune sands are  
144 associated with deeper calcareous, alkaline soils in comparison to the soils found on the slopes.

#### 145 Contemporary vegetation

146 The study area (Fig. 2) is home to the *Groot Hagelkraal* farm – a registered private nature reserve and a  
147 South African Nature Foundation Natural Heritage Site. The Groot Hagelkraal area harbours six local-  
148 endemic and 21 regional-endemic plant species, and has been lauded as the world’s “hottest” biodiversity  
149 hotspot and foremost conservation priority in the CFR (Cowling, 1996; Willis et al., 1996; Jones et al.,  
150 2002). The surrounding landscape is dominated by 1) sclerophyllous, Mediterranean-type shrublands of  
151 the fynbos biome, found on both the lowlands and uplands, 2) subtropical thickets that occupy parts of  
152 the near-coastal dune fields adjacent to the site, and 3) pockets of forest vegetation in more sheltered  
153 sites (Cowling et al., 1988; Mucina and Rutherford, 2006). Where surface water is perennially or seasonally  
154 available, lowland areas also support riparian and wetland habitats (Mustart et al., 2003).

155 The azonal vegetation associated with wetland systems around Pearly Beach and the upper  
156 reaches of the Groot Hagelkraal River is broadly classified as Cape Lowland Freshwater Wetlands (Mucina  
157 et al., 2006b). These systems are dominated by the reed, *Phragmites australis* (Poaceae), and the rushes  
158 *Juncus kraussii* and *J. capensis* (Juncaceae). Sedges, especially *Ficinia nodosa* (Cyperaceae), form dense  
159 stands along the margins of the vlei, while *Typha capensis* and *Isolepis prolifera* (Cyperaceae) inhabit the  
160 open water and shallower margins, together with obligate aquatics like *Aponogeton distachyos* and  
161 *Nymphaea nouchali*.

162 Three broad types of fynbos vegetation occur in the study area, each associated with a specific  
163 edaphic substrate (Thwaites and Cowling, 1988). Agulhas Limestone Fynbos occurs in fragmented patches  
164 inland of the Pearly Beach site on shallow, alkaline sands that accumulate in depressions over Bredasdorp



165 Group limestone pavements (Cowling et al., 1988; Mustart et al., 2003; Rebelo et al., 2006). This mid-high,  
166 moderately dense shrubland contains tall, emergent proteoids and is characterised by the presence of  
167 *Protea obtusifolia* and *Leucadendron meridianum*. The restioid component is poorly developed, but the  
168 widespread species *Elegia microcarpa* and *Restio leptoclados*, and the more restricted *Thamnochortus*  
169 *fraternus*, are typical of this fynbos type. Typical ericoid shrubs include *Aspalathus calcarea* (Fabaceae),  
170 *Metalasia calcicola* (Asteraceae), *Phyllica selaginoides* and *Passerina paleacea*, as well as several local- and  
171 regional-endemic species of the Ericaceae (e.g. *Erica calciphila*) and Rutaceae (e.g. *Diosma haelkraalensis*)  
172 (Mustart et al., 2003; Rebelo et al., 2006).

173           Similar to Agulhas Limestone Fynbos, Agulhas Sand Fynbos is associated with Bredasdorp Group  
174 limestones, but this vegetation type occurs on deep colluvial, neutral sands that fringe the base of  
175 limestone outcrops (Cowling et al., 1988; Mustart et al., 2003; Rebelo et al., 2006). Overstorey proteoids  
176 that characterise this vegetation type are *Protea susannae* and *Leucadendron coniferum*. Typical ericoid  
177 shrubs include *Erica discolor*, *E. plukenetii* subsp. *lineata*, *Metalasia densa* and *Passerina corymbosa*, as  
178 well as the Hagelkraal-endemic, *Spatalla ericoides* (Mustart et al., 2003; Rebelo et al., 2006). Commonly  
179 occurring restioids are *Elegia filacea*, *E. tectorum*, *Restio triticeus*, *Thamnochortus erectus* and *T. insignis*.

180           Overberg Sandstone Fynbos occurs on the rolling uplands where it is associated with deep  
181 colluvial, infertile acid sands derived from Table Mountain Group sandstones (Thwaites and Cowling,  
182 1988; Cowling et al., 1988; Rebelo et al., 2006) (Fig. 2). *Protea compacta* is the dominant and characteristic  
183 overstorey proteoid, while *Leucadendron xanthoconus* is also common. Restioids can be locally abundant,  
184 with *Ceratocaryum argenteum*, *Hypodiscus argenteus*, *Mastersiella digitata* and *Staberoha multispicula*  
185 being typical species.

186           The deep, well-drained alkaline sands of coastal dunes in the study area support Overberg Dune  
187 Strandveld, a mosaic-type vegetation comprising small clumps of subtropical thicket in a matrix of

188 asteraceous fynbos (Cowling et al., 1988; Rebelo et al., 2006). The dune-fynbos component is dominated  
189 by non-ericaceous ericoid shrubs, especially *Acmadenia obtusata* (Rutaceae), *Agathosma collina*  
190 (Rutaceae), *Metalasia muricata* (Asteraceae), *Muraltia satureioides* (Polygalaceae), *Passerina paleacea*  
191 and *Phyllica ericoides* (Mustart et al., 2003). Restioids are not abundant in the dune fynbos; this group is  
192 typically represented by only two species, *Elegia microcarpa* and *Restio eleocharis*. A conspicuous  
193 difference between the fynbos component of Overberg Dune Strandveld and the other fynbos vegetation  
194 types occurring in the study area is the absence of proteoids in the former (Cowling et al., 1988). While  
195 subtropical thicket shrubs occur throughout Overberg Dune Strandveld, dune thicket clumps are best  
196 developed in moist, wind- and fire-protected dune slacks where their structure and composition approach  
197 that of coastal forests (see below). Characteristic dune thicket shrubs include *Carissa bispinosa*  
198 (Apocynaceae), *Euclea racemosa*, *Morella cordifolia*, *Myrsine africana*, *Lauridia tetragona* (Celastraceae),  
199 *Olea exasperata*, *Robsonodendron maritimum* (Celastraceae), *Pterocelastrus tricuspidatus* (Celastraceae)  
200 and *Searsia glauca* (Cowling et al., 1988; Mustart et al., 2003; Rebelo et al., 2006).

201         The azonal vegetation associated with coastal strands, rocky shorelines and mobile dune cordons  
202 in the study area is classified as Cape Seashore Vegetation (Mucina et al., 2006a). Sandy areas typically  
203 host the grasses *Ehrharta villosa* and *Thinopyrum distichum* (both Poaceae), the succulent shrubs  
204 *Tetragonia decumbens* and *Carpobrotus acinaciformis* (both Aizoaceae), several herbaceous species like  
205 *Arctotheca populifolia* (Asteraceae), *Dasispermum suffriticosum* (Apiaceae), *Senecio elegans* (Asteraceae)  
206 and *Silene crassifolia* (Caryophyllaceae), and the shrubs *Hebenstreitia cordata* (Scrophulariaceae), *Morella*  
207 *cordifolia* and *Passerina rigida* (Mustart et al., 2003; Mucina et al., 2006a). The more stabilised dunes half  
208 a kilometre inland of the littoral zone are predominantly vegetated by *Osteospermum moniliferum*  
209 (Asteraceae), which, together with other woody species like *Searsia crenata*, form small pockets of wind-  
210 pruned thicket. Along rocky shores, the vegetation comprises low grasslands of salt-tolerant species like  
211 *Sporobolus virginicus* and *Stenotaphrum secundatum*, or succulent herblands where *Dimorphotheca*

212 *fruticosa* (Asteraceae), *Drosanthemum intermedium* (Aizoaceae), *Mesembryanthemum vanrensburgii*  
213 (Aizoaceae) and *Plantago crassifolia* are typical.

214 There are small, isolated patches of Southern Coastal Forest to the west of the site which are  
215 dominated by *Sideroxylon inerme*. Other trees and shrubs present in these patches include *Cassine*  
216 *peragua* (Celastraceae), *Chionanthus foveolatus* (Oleaceae), *Robsonodendron maritimum* (Celastraceae),  
217 *Maytenus procumbens* (Celastraceae), *Olea capensis*, *Polygala myrtifolia*, *Pterocelastrus tricuspidatus*  
218 (Celastraceae) and *Tarchonanthus littoralis* (Asteraceae) (Mustart et al., 2003; Mucina and Geldenhuys,  
219 2006).

## 220 MATERIALS AND METHODS

### 221 Chronology

222 The age-depth model for the PB1 core was constructed from eight radiocarbon ages (Table 1). Subsamples  
223 of approximately 1 g were taken from various positions along the PB1 core and sent to *Beta Analytic Inc*  
224 for AMS radiocarbon dating. These ages were calculated using the Libby half-life of 5568 years following  
225 Stuiver and Polach (1977). The ages were corrected for isotope fractionation using the AMS-measured  
226  $\delta^{13}\text{C}$ , which accounts for both natural and machine fractionation.

227 The age-depth model was developed in the software package *rbacon* (v. 2.3.6; Blaauw and  
228 Christen, 2011). Using a Bayesian framework, Bacon divides the core into sections and models the  
229 accumulation rate for each section through multiple Markov Chain Monte Carlo (MCMC) iterations. The  
230 ages were calibrated with the SHCal13 data (Hogg et al., 2013).

### 231 Particle size analysis

232 Particle size analysis was conducted at the Department of Geography, Friedrich-Schiller-University, Jena,  
233 Germany. Subsamples of ~5 g were pre-treated to remove organic material with hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>)  
234 while carbonates were removed with hydrochloric acid (HCl). Sodium pyrophosphate (Na<sub>4</sub>P<sub>2</sub>O<sub>7</sub>) was added  
235 as deflocculant. The particle size distributions were detected using a Beckman Coulter LS 13 320 Laser  
236 Diffraction Particle Size Analyzer, the single wavelength Aqueous Liquid Module (ALM). Measurements  
237 were carried out in several runs until a reproducible signal was obtained.

### 238 Pollen and microcharcoal analyses

239 Pollen and microcharcoal subsamples (1 cm-thick) were initially taken at 5 cm intervals. This was followed  
240 by finer resolution subsampling at targeted locations along the core that were identified by the initial  
241 pollen results as representing periods of significant vegetation change.

242 Palynomorphs were concentrated and extracted following Moore et al. (1991) with specific  
243 adaptations for dense media separation from Nakagawa et al. (1998). This involved 30% HCl treatment to  
244 remove carbonates, 10% KOH digestion to disaggregate the samples and remove humic acids and heavy  
245 liquid mineral separation using ZnCl<sub>2</sub> to separate the pollen grains from the non-pollen matrix (Faegri and  
246 Iversen, 1989; Moore et al., 1991; Nakagawa et al., 1998). Samples were acetolysed and mounted in  
247 *Aquatex*, an aqueous mounting agent. Three slides were produced per sample and absolute pollen  
248 concentrations were calculated via the addition of *Lycopodium* spores as per Stockmarr (1973). Pollen  
249 counts of 500 grains per sample were carried out at 400x magnification for routine identification and  
250 1000x for specific identification. Non-pollen palynomorphs (NNPs) were counted but not included in the  
251 total pollen sum. The University of Cape Town pollen reference collection and published resources (van  
252 Zinderen Bakker, 1953, 1956; van Zinderen Bakker and Coetzee, 1959; Scott, 1982) were used for the  
253 identification of pollen taxa. The pollen and microcharcoal diagram was constructed in Tilia (version

254 2.1.1)(Grimm, 1991) and was divided into statistically significant pollen assemblage zones based on a  
255 CONISS (Constrained Incremental Sum of Squares) (with square root transformation) analysis (Grimm,  
256 1987).

257 Charcoal particles were identified and counted on the same microscope slides produced for the  
258 pollen analysis. Only particles that were black, opaque and angular were considered charcoal fragments  
259 (Patterson et al., 1987; Mooney and Tinner, 2011). Charcoal fragments were classified and counted  
260 according to two size categories based on the long axis of each fragment; 10–100  $\mu\text{m}$  and  $>100 \mu\text{m}$ .  
261 Particles less than  $75 \mu\text{m}^2$  (or  $\sim 10 \mu\text{m}$  long) were not counted due to the risk of false identification  
262 (Mooney and Tinner, 2011). Therefore, the charcoal signal primarily relates to the regional (10–100  $\mu\text{m}$ )  
263 and local ( $>100 \mu\text{m}$ ) fire signals and excludes extra-regional fires ( $<10 \mu\text{m}$ ). Absolute charcoal abundances  
264 were calculated in the same manner as pollen concentrations (Stockmarr, 1973).

## 265 Defining plant-climate relationships

266 To objectively define the plant-climate relationships associated with the Pearly Beach pollen assemblage,  
267 we used the CREST (Climate REconstruction SofTware) method and software (Chevalier et al., 2014;  
268 Chevalier, 2019). For our analyses, we used botanical data obtained from the Global Biodiversity  
269 Information Facility (GBIF) database (Global Biodiversity Information Facility, <https://www.gbif.org/>),  
270 specifically the curated dataset of Chevalier (2020), and we used a regional subset of the Worldclim 2  
271 climatology (Fick and Hijmans, 2017).

## 272 RESULTS

### 273 Stratigraphy and chronology

274 The particle size analysis results indicate that the 250 cm core predominantly comprises sands and silty  
275 sands with three distinct zones of pale coarser-textured sands at the top (0 – 25 cm), middle (130 – 160

276 cm) and base (235 – 250 cm) of the core (Figs. 3 and 4, Appendix A). They are bounded by relatively  
277 homogeneous organic-rich silty sands. The exception being a thin lens of light-coloured coarser sand  
278 situated between 175 and 180 cm (Fig. 3).

279 The core spans the period ~25.3 cal ka BP to present (Fig. 3), encompassing much of the LGM (19-26.5  
280 cal ka BP), Termination I (~19 - 11.7 cal ka BP) and the Holocene (11.7 - 0 cal kBP).

### 281 Pollen and microcharcoal

282 A total of 102 pollen taxa were identified from the 78 samples analysed. The pollen, non-pollen  
283 palynomorphs, microcharcoal and particle size data (Fig. 4, Fig. 5, Appendix A) were divided based on  
284 CONISS analysis results and assemblage variability into four pollen assemblage zones (and three  
285 subzones). Pollen concentrations range between  $2 \times 10^3$  and  $33 \times 10^3$  grain  $g^{-1}$ , with peaks in concentration  
286 22.5 – 19 cal ka BP and 14 – 12 cal ka BP. No pollen was preserved from 11.6 – 8.5 cal ka BP.

287 The overall assemblage is characterised by variations in fynbos taxa (e.g. Proteaceae, Ericaceae,  
288 Restionaceae, *Cliffortia* and *Stoebe*-type), coastal thicket elements (such as *Euclea*, *Morella* and  
289 *Canthium*<sup>1</sup>), succulent/drought-resistant elements (e.g. Aizoaceae, *Crassula* and *Euphorbia*) and local  
290 wetland vegetation (predominantly Cyperaceae, Juncaceae and Haloragaceae) as well as more  
291 cosmopolitan pollen types such as Asteraceae and Poaceae. Ericaceae pollen is most prominent at the  
292 base of the sequence (pollen assemblage zone PB1-A; 25 – 21 cal ka BP), coinciding with the only  
293 significant presence of *Passerina*, relatively elevated proportions of *Stoebe*-type (which includes various  
294 *Stoebe* and *Elytropappus* spp.) and low percentages of Proteaceae and Restionaceae. A further  
295 distinguishing feature of PB1-A is the generally greater proportions of coastal thicket taxa, particularly  
296 *Euclea* and Santalaceae, as well as discrete, relatively high, peaks in *Dodonaea* and *Morella* from 22.5 –

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<sup>1</sup> The *Canthium* pollen type includes *Canthium mundianum* which has been renamed *Afrocanthium mundianum* (Lantz and Bremer, 2004).

297 21.5 cal ka BP. The isolated peaks in *Dodonaea* and *Morella* coincide with a large spike in *Crassula* (14%)  
298 and a smaller peak in Aizoaceae. Just prior to this phase, the highest counts and greatest concentrations  
299 of microcharcoal were recorded (from 23 – 22 cal ka BP). There is a small peak in Juncaceae percentages  
300 at the base of the sequence and peaks in Cyperaceae around 22 cal ka BP, although wetland taxa  
301 percentages are generally somewhat reduced for PB1-A.

302 For PB-1B (21 - 14.5 cal ka BP) we observe significantly elevated percentages of Restionaceae  
303 within the sand layer dating to ~20 - 15.5 cal ka BP (Fig. 4 and Fig. 5), coinciding with generally reduced  
304 succulent/drought-resistant taxa and fynbos elements relative to PB1-A. The highest peak in the aquatic  
305 taxon Haloragaceae for the sequence (12%) and peaks in the coastal thicket taxa *Canthium* and *Morella*  
306 also characterise PB1-B. While *Dodonaea* reappears near the top of PB1-B, this taxon is recorded in more  
307 significant proportions within PB1-C (14.5 - 12 cal ka BP), together with relatively elevated percentages in  
308 other coastal thicket indicators (e.g. *Canthium* and *Morella*) and the afrotemperate forest taxon *Clutia*.  
309 Fynbos (Ericaceae, Restionaceae, Proteaceae and *Stoebe*-type) proportions remain relatively high for this  
310 period. The succulent/drought-resistant taxa *Crassula*, *Euphorbia* and *Ruschia* all exhibit prominent peaks  
311 within this PB1-C.

312 Pollen was not found in sediments dating to the early Holocene (11.7 – 8 cal ka BP). For most of  
313 the mid- to late Holocene (PB1-D; ~7.7 - 0 cal ka BP), other than Restionaceae which remains relatively  
314 high, fynbos elements (particularly Ericaceae and *Passerina*) are represented in much lower proportions  
315 in comparison to the previous zones. The halophytic taxon Amaranthaceae peaks from 6 - 5 cal ka BP and  
316 is generally represented in high proportions within the whole of PB1-D. Coinciding with the peak in  
317 Amaranthaceae are peaks in *Ruschia*, *Crassula* and microcharcoal concentrations. Microcharcoal  
318 concentrations and amounts (for both size classes) peak again from 2 - 1 cal ka BP. Asteraceae percentages  
319 are generally higher within PB1-D compared to the previous zones and reach a maximum for the sequence

320 (38%) at ~4.2 cal ka BP. Wetland taxa generally exhibit no clear trends/changes other than a small peak in  
321 Blechnaceae at base of the zone, at ~7.7 cal ka BP and peaks in Cyperaceae at ~5.8 and ~1.9 cal ka BP.

322 The most recent portion of the record, the last 500 years (PB1-D3), is substantially different from  
323 the rest of the Holocene section, being characterised by exceptionally high percentages of Proteaceae (up  
324 to 26%), distinct peaks in *Cliffortia*, Amaranthaceae, *Euclea*, *Morella* and *Dodonaea*, and the appearance  
325 of *Sideroxylon* pollen.

## 326 DISCUSSION

327 The pollen results from the Pearly Beach sediment core reveal that distinct changes in vegetation  
328 composition occurred along the southwestern Cape coast since the onset of the LGM. The analysis of  
329 contemporary climatic constraints on the identified taxa (Figs. 6 and 7) provides a framework for the  
330 interpretation of this record. Considerable variability in temperature and moisture availability may be  
331 inferred from these results, which are of particular importance in shedding new light on the LGM and  
332 Termination I in the region. The Holocene portion of the record is of significantly lower resolution, but it  
333 provides important context for understanding the climate and vegetation history of the site. As the site is  
334 located 2.5 km from the modern coastline, and ~28.5 km from the LGM coastline (Spratt and Lisiecki,  
335 2016; Group, 2020), the potential impact of changing sea-level should be considered when considering  
336 the Pearly Beach data. The gradient of the adjacent shelf is low and regular, and the coastline is predicted  
337 to have encroached upon the site at a rate of ~1.6 km/ka since the LGM, achieving its current position at  
338 ~5 ka. Considering the position and palaeo-landscape of the site, factors such as increased continentality  
339 are unlikely to have been a significant factor, and a related progressive increase in moisture availability  
340 with reduced distance to the coast is not indicated by the pollen record, as will be described (Fig. 5).  
341 Similarly, rising sea-levels would have raised base-level and associated groundwater levels, but again the  
342 records do not indicate an increase in water-availability with a rise in base-level. Sea-level changes and



343 the position of the site relative to the coast may also have had an impact on sedimentation regimes, with  
344 marine transgression resulting in an increase in marine and aeolian sands. Grain size results from the  
345 sediment core (Fig 4.), however, indicate no pattern that can be readily associated with sea-level change,  
346 such as an increase in the coarse sediment fraction. Thus, in the absence of specific evidence for a strong  
347 marine impact, the record is presently interpreted primarily in terms of climate.

#### 348 The Last Glacial Maximum (LGM; ~25.3-19 cal ka BP)

349 Pollen from cold-tolerant fynbos taxa (*e.g.* *Stoebe*-type, *Passerina* and Ericaceae) indicate that these  
350 plants were dominant features of the Pearly Beach landscape from 25.3 – 22.5 cal ka BP (Figs. 5, 6 and 7).  
351 This is consistent with other evidence of cooler conditions throughout southern Africa during the last  
352 glacial period and LGM in particular (Heaton et al., 1986; Talma and Vogel, 1992; Stute and Talma, 1998;  
353 Truc et al., 2013; Chevalier and Chase, 2015). However, the presence of *Dodonaea* pollen, a relatively frost  
354 intolerant taxon (Valsecchi et al., 2013) (Fig. 6), suggests that frost — if it occurred — was not common.

355 During this period, the coastal thicket group is dominated by a relatively high abundance of *Euclea*  
356 and Santalaceae pollen (likely *Thesium*, based on associations with increased fynbos representation at this  
357 time), which, coupled with the co-occurrence of *Ruschia* pollen, may reflect a relatively xeric coastal  
358 thicket composition (Boucher and Moll, 1981; Boucher, 1987; Cowling et al., 1999). While more mesic  
359 taxa such as *Morella*, *Canthium*, and the afrotemperate taxa *Podocarpus/Afrocarpus* and *Myrsine* are  
360 present, they are found only in relatively low proportions (Figs. 5, 6 and 7). Cooler conditions at this time  
361 thus do not seem to be associated with either a significant decline in moisture availability (as has been  
362 inferred from charcoal data from Boomplaas Cave (Deacon et al., 1984; Scholtz, 1986)). Nor however do  
363 they seem to reflect substantially wetter conditions during the LGM, as indicated in some palaeoclimate  
364 model simulations (Engelbrecht et al., 2019), and has been inferred from evidence elsewhere in the WRZ,  
365 such as Elands Bay Cave (Cartwright and Parkington, 1997; Cowling et al., 1999; Parkington et al., 2000).

366 Considered in the context of the record as a whole, *Euclea* does exhibit a general positive relationship  
367 with microcharcoal concentrations (Fig. 5), suggesting that fire may also be a factor contributing to the  
368 dominance of *Euclea* in the coastal thicket at this time. *Euclea* (e.g. *E. racemosa*) may have been able to  
369 exert a competitive advantage over more mesic, less fire-adapted thicket taxa under a regime of more  
370 regular fire occurrence (Nzunda and Lawes, 2011).

371 The period from ~22.5-22 cal ka BP is characterised by high levels of succulent/drought-resistant  
372 pollen and decreased levels of both coastal thicket and afrotemperate forest taxa, indicating a period of  
373 relatively dry conditions (Fig. 5 and Fig. 8). High percentages of *Stoebe*-type pollen suggest this interval  
374 was also perhaps the coolest of the last 25 kyr. At ~22 cal ka BP, this phase of cool and relatively dry  
375 conditions is disrupted abruptly by an episode of increased temperatures and humidity, as indicated by  
376 strong increases in *Morella* and *Dodonaea* pollen (Fig. 5 and Fig. 6). While brief, the timing of this event is  
377 consistent with episodes of increased humidity in other regional records, at Seweweekspoort (Chase et  
378 al., 2017) and along the southwest African margin (Chase et al., 2019b).

379 The late LGM, from ~22-19 cal ka BP, is characterised by a further decline in coastal thicket and  
380 afrotemperate forest taxa and a dominance of Restionaceae pollen in association with greater  
381 contributions of medium and coarse-grained sands (Figs. 4 and 5). These trends may reflect the ceding of  
382 the thicket niche to Restionaceae species that are more tolerant of summer drought (e.g. *Thamnochortus*,  
383 which is common on dunes along the arid, winter-rain dominated west coast (Linder and Mann, 1998;  
384 SANBI, 2003)). The thicket taxa *Morella* and *Canthium* begin to become more prominent at ~20 cal ka BP,  
385 suggesting the beginning of an increase in humidity that accelerates rapidly (reflected in substantial  
386 increases in these taxa) with the onset of Southern Hemisphere warming at ~19 ka.

387 In terms of drivers of the patterns of vegetation change observed in the Pearly Beach pollen record,  
388 the data are consistent with indications from elsewhere in southwestern Africa (e.g. Chase et al., 2015a;

389 Chase et al., 2019b) that AMOC was a strong modulator of global LGM conditions. At Pearly Beach,  
390 changes in the pollen record – while complex – are in accord with results from Namib Desert rock hyrax  
391 middens, which indicate phases of relatively drier conditions (~24-22.5 cal ka BP and ~22-18 cal ka BP)  
392 demarcated by brief phases of increased humidity from ~24.5-24 cal ka BP and 22.5-22 cal ka BP prior to  
393 the beginning of Termination I (Chase et al., 2019b) (Fig. 9).

394 At variance with the inference that the cool/cold boundary conditions of the terminal Pleistocene  
395 created relatively humid conditions in the southwestern Cape (van Zinderen Bakker, 1976; Cockcroft et  
396 al., 1987; Cowling et al., 1999), the Pearly Beach record suggests that phases of increased humidity  
397 correlate positively with increased temperature (Figs. 9 and 8). This likely relates to a combination of  
398 factors linked to a progressive build-up of heat in the South Atlantic and high southern latitudes associated  
399 with weaker AMOC (Stocker and Johnsen, 2003; McManus et al., 2004; Ng et al., 2018). This warming -  
400 including the Southeast Atlantic and oceans surrounding the southwestern Cape (Kim et al., 2003; Farmer  
401 et al., 2005; Dyez et al., 2014) - may have influenced regional climates through: 1) a southerly shift of the  
402 Atlantic Intertropical Convergence Zone (ITCZ) and African rainbelt (Broccoli et al., 2006), including a  
403 weakening of the SE Trade Winds and a southerly shift of the Angola-Benguela Front (Kim et al., 2003)  
404 (Fig. 1), 2) a poleward displacement of the Subtropical Front and westerlies storm track (Lee et al., 2011;  
405 Menviel et al., 2018) (likely also enabling increased Agulhas leakage into the SE Atlantic (Peeters et al.,  
406 2004; Caley et al., 2012)), but a warming of the Southwest Atlantic and waters upstream from the  
407 southwestern Cape, increasing moisture uptake by the frontal systems that bring winter rains to the Cape  
408 (Reason et al., 2002; Reason et al., 2006), and 3) increased evaporation and advection of moisture from  
409 southern coastal waters, fostering the development of localised precipitation systems (Jury et al., 1993;  
410 Jury et al., 1997). All of these factors could result in a less seasonal rainfall regime and a shorter/less  
411 intense drought season in the southwestern Cape (Chase et al., 2015b). At the subcontinental scale, it has  
412 been observed that warm events in the Southeast Atlantic off Angola and Namibia are associated with

413 increased rainfall along southern Africa's western margin, and that these anomalies may extend inland  
414 significantly, particularly if easterly flow off the Indian Ocean is also high (Rouault et al., 2003). A critical  
415 dynamic may have thus been fostered between the warming and southward displacement of the Angola-  
416 Benguela Front (Fig. 1) and the increased moisture uptake of westerly frontal systems.

417 Today, cloud bands known as tropical-temperate troughs (TTTs) account for a significant proportion  
418 of southern Africa's summer rainfall and are a major mechanism for the poleward transfer of energy (Todd  
419 and Washington, 1999). The potential of TTTs and other forms of tropical temperate interactions (TTIs) to  
420 have been an important factor in determining synoptic-scale climate dynamics in southern Africa during  
421 the last glacial period has been highlighted, and considered to be a possible explanation for similarities in  
422 patterns of climate change across the continental interior (Chase, 2010; Chase et al., 2017). These types  
423 of synoptic systems have been identified as having an important influence on modern southern Cape  
424 climates (Engelbrecht et al., 2015), and similarities evident between the Pearly Beach record and records  
425 of climate change from sites in the Namib Desert (Chase et al., 2019b) (Fig. 9) suggest that the interactions  
426 between tropical and temperate regions may have been enhanced during periods of elevated southeast  
427 Atlantic SSTs, and associated cloud bands and other related disturbances may have formed further to the  
428 southwest than is common today.

#### 429 Termination I (~19-11.7 cal ka BP)

430 At Pearly Beach, the onset of Southern Hemisphere warming and the end of the LGM is associated with  
431 more abundant moisture, as indicated by the development of coastal thicket vegetation and a reduction  
432 in succulent/drought resistant pollen from ~19 – 13 cal ka BP (Figs. 5 and 8). In contrast to the thicket  
433 composition of the early LGM, *Canthium* is the dominant taxon at ~18.4 cal ka BP (Fig. 5). *Canthium* is  
434 most prevalent in humid coastal regions from the Knysna region eastward (SANBI, 2003), and at Pearly  
435 Beach it is a clear indicator of warmer, moister conditions (Fig. 7), likely implying significant contributions

436 of summer rainfall as a result of the climate system dynamics described above. Interestingly, *Canthium*  
437 quickly cedes dominance to *Morella*, which establishes itself as the most prominent thicket taxon for the  
438 period 18-14.5 cal ka BP, broadly coincident with the Heinrich stadial 1 chronozone (HS1; ~18.5-14.6 cal  
439 ka BP).

440 *Morella* and *Canthium* occupy very similar climatic niches, and the progression from *Canthium* to  
441 *Morella* dominance in the thicket taxa pollen spectrum may have been due to non-climatic mechanisms  
442 related to vegetation succession, as has been noted at other southern Cape sites (cf. Quick et al. 2016).  
443 *Morella* species likely do occur at the site (e.g. *M. quercifolia*) and are associated with stabilised sand  
444 dunes. *Canthium inerme* and *Afrocanthium mundianum* are associated with coastal forests and dune  
445 thicket but may have a closer association to active stream networks than *Morella*. The landscape  
446 surrounding Pearly Beach, comprises a low relief coastal platform (<30 m.a.s.l.) occupied by alluvial and  
447 aeolian sediments – including an extensive semi-active to primarily dormant dunefield – and a significant  
448 stream network associated with upland catchments to the north and northeast. The landscape dynamics  
449 of the immediate region therefore have potential to create a complex and changing mosaic of ecological  
450 niches. Therein, the observation that peaks in *Canthium* effectively bracket phases of *Morella* dominance  
451 may be associated with differences in the response time between fluvial systems and dunefields to  
452 changes in rainfall. While dune stabilisation under more humid conditions may be a protracted process,  
453 increased rainfall would have a much more immediate impact on fluvial activity and the development of  
454 riparian zones, thus potentially favouring the early establishment of *Canthium* over *Morella*. Once the  
455 dunefields became more stable, *Morella* would have become more prevalent. Conversely, increased  
456 aridity may have a more immediate impact on dunefield vegetation, as fluvial networks may continue to  
457 be fed by rainfall in the adjacent uplands and through groundwater discharge, maintaining higher levels  
458 of water availability at seeps and along channels.

459           Regardless of successional or landscape/hydrologic dynamics, the marked increase in *Canthium*  
460 and *Morella* pollen – and indeed coastal thicket taxa as a group – at ~18.5 cal ka BP indicating a substantial  
461 increase in moisture availability, is coincident, and perhaps associated with slowing AMOC (McManus et  
462 al., 2004; Ng et al., 2018) and a build-up of heat in the southern Atlantic (Fig. 9). As has been noted  
463 elsewhere (Chase et al., 2015a; Chase et al., 2019b), the response in terrestrial environments in  
464 southwestern Africa to changes in AMOC associated with HS1 is not predicted to be immediate. The rapid  
465 slow-down in AMOC at the beginning of HS1 resulted in a relatively slow, progressive build-up of heat in  
466 the South Atlantic and high southern latitudes, which culminates in maximum temperatures being  
467 reached at the very end of HS1, at ~14.6 cal ka BP (Kim and Schneider, 2003; Farmer et al., 2005; Jouzel  
468 et al., 2007; Pedro et al., 2011)(Fig. 9). As has been described for the LGM, these changes in SSTs in the  
469 Southeast Atlantic and oceans surrounding the southwestern Cape may have resulted in a less seasonal  
470 rainfall regime. At such times increased summer rainfall may have been derived from both localised  
471 precipitation systems (Jury et al., 1993; Jury et al., 1997) and the development of the aforementioned  
472 larger synoptic scale TTTs /TTIs (Todd and Washington, 1999), which may have been more prevalent in  
473 the region given elevated west coast SSTs (Fig. 9). At Pearly Beach these changes are reflected by high  
474 coastal thicket taxa pollen percentages and a strong increase in *Dodonaea* pollen (Fig. 5), indicating warm,  
475 humid conditions under a less seasonal rainfall regime.

476           Similarities with the deglacial record from Pearly Beach are observed across a wide range of  
477 terrestrial records not only from the southern and southwestern Cape (Chase et al., 2015a; Quick et al.,  
478 2016) and the western margin of southern Africa (Chase et al., 2015a; Lim et al., 2016; Chase et al., 2019b)  
479 – regions under the immediate influence of the South Atlantic anticyclone and the westerlies – but also  
480 from the ARZ (Scholtz, 1986; Chase et al., 2017) and the SRZ (Chevalier and Chase, 2015), emphasising the  
481 subcontinental-scale influence of the slow-down of AMOC during HS1 (Fig. 9).

482 HS1 ended at 14.6 ka, and at Pearly Beach this transition is marked by variable, declining levels of  
483 coastal thicket pollen and increases in pollen from xeric taxa such as *Ruschia* (Fig. 5). Coupled with  
484 increases in pollen from plants favouring cool/cold conditions — such as *Stoebe*-type and Ericaceae  
485 between ~13.9-12.6 cal kBP, the evidence seems to suggest that the increased AMOC strength (Ng et al.,  
486 2018) that triggered cooling in the southeast Atlantic (Kim and Schneider, 2003; Farmer et al., 2005) and  
487 the high southern latitudes (e.g. Jouzel et al., 2007) – the Antarctic Cold Reversal (Pedro et al., 2016) –  
488 resulted in relatively cool, dry conditions at Pearly Beach (Fig. 9). The subsequent Younger Dryas period is  
489 characterised by slight increases in pollen from both cool/cold and coastal thicket taxa, perhaps indicating  
490 a modest increase in winter rainfall. As has been noted elsewhere (Chase et al., 2015a), the magnitude of  
491 forcing associated with the Younger Dryas was substantially less than it was for HS1, and left an  
492 accordingly less distinct signature in most southwestern Africa records, with greater spatial heterogeneity.

#### 493 [The Holocene \(7.8 – 0.3 cal ka BP\)](#)

494 No pollen was preserved in the sediments dating to ~12-7.8 cal ka BP in the Pearly Beach core. It could be  
495 speculated that the limited preservation of pollen within the Pearly Beach core during the early Holocene  
496 was a response to increased aridity, as inferred from micromammalian data from Byneskranskop, an  
497 archaeological site 8 km northwest of Pearly Beach (Faith et al., 2018, 2020; Thackeray, 2020). Indications  
498 of relatively low moisture availability are also evident from further east within the Wilderness embayment  
499 (Martin, 1968; Quick et al., 2018), and the summer-rainfall zone (e.g. Holmgren et al., 2003), related, in  
500 part, to increased drought stress under warmer Holocene temperatures (Chevalier and Chase, 2016).

501 The resolution of the Holocene record allows for the identification of multi-millennial trends, but  
502 it lacks the detail required to make definitive inferences regarding the primary mechanisms driving climate  
503 change. As a whole, coastal thicket pollen percentages are relatively low until the recent past, when a  
504 strong increase is observed at ~ 0.3 cal ka BP. This suggests generally drier Holocene conditions compared

505 to the Late Pleistocene, with a modest, but notable increase in apparent humidity in the mid-Holocene,  
506 from ~6-4 cal ka BP (Figs. 5 and 9).

507           The recovery of high resolution records from the southwestern Cape, from Katbakkies Pass (Chase  
508 et al., 2015b) and Pakhuis Pass (Chase et al., 2019a) have enabled correlations with records for Southern  
509 Ocean SSTs and sea-ice extent (Nielsen et al., 2004) during the Holocene. These have been interpreted to  
510 indicate a phase of increased westerly influence during the mid-Holocene, which may account for the  
511 increased humidity at Pearly Beach. However, when considered in the context of other comparable  
512 records from the region, a pattern of marked spatial heterogeneity is observed (Chase et al., 2015a; Chase  
513 et al., 2019a), particularly between coastal and interior sites (Chase and Quick, 2018; Quick et al., 2018).  
514 Furthermore, the mid-Holocene in the Cape is a period of significant climatic variability, and while efforts  
515 have been made to establish diagnostic patterns of change that can be used to infer specific drivers (Chase  
516 et al., 2017; Chase and Quick, 2018; Chase et al., 2020), the Pearly Beach record currently lacks the  
517 requisite resolution to draw meaningful conclusions in this regard. What is evident, is that at Pearly Beach  
518 there are significant changes in the overall vegetation composition between the deglacial and Holocene,  
519 with a clear shift from ericaceous fynbos in the late Pleistocene to other structural types of fynbos  
520 (proteoid, restioid and asteraceous) in the middle and late Holocene. These changes are likely in response  
521 to increased Holocene temperatures and relatively drier conditions as compared to HS1 and at least some  
522 phases of the LGM.

523           The last 500 years is characterised by a significant increase in coastal thicket (e.g. *Euclea*, *Morella*  
524 and *Sideroxylon*, as well as *Dodonaea*, comparable to the peaks during HS1) and represents the  
525 culmination of the steady rise in Proteaceae percentages across the Holocene (Fig. 5). While the above  
526 mentioned taxa suggest more humid conditions, consistent with coeval increases in temperature and  
527 humidity as indicated by the record as a whole, there is also an increase in Amaranthaceae and *Ruschia*



528 pollen, suggesting at least some phases of more arid conditions, and probably an increase in climate  
529 variability. The sharp increase in thicket taxa in the sample dated to  $\sim 0.3$  cal ka BP is consistent with  
530 marked changes in inferred water availability in higher resolution records from Bo Langvlei (du Plessis et  
531 al., 2020), Seweweekspoort (Chase et al., 2017) and the Namib region (Chase et al., 2019b). Again,  
532 however, the resolution of this portion of the Pearly Beach record – in terms of both pollen and  
533 radiocarbon samples – does not allow for a clearer attribution of this increase in thicket pollen to either  
534 an increase in summer rainfall following the Little Ice Age (0.1-0.7 cal ka BP), as speculated at Bo Langvlei  
535 (du Plessis et al., 2020), or an increase in winter rainfall during the LIA, as inferred from diatom data at  
536 Verlorenvlei, on the west coast (Stager et al., 2012).

## 537 CONCLUSIONS

538 In this paper we present new fossil pollen, microcharcoal and sediment particle size data from a 25,000-  
539 year sediment core taken from a wetland at Pearly Beach, southwestern Cape coast of South Africa. The  
540 results reveal considerable variability in vegetation composition and by inference climate - along the  
541 southwestern Cape coast since the onset of the LGM. We find that the Pearly Beach record is generally  
542 consistent with indications from elsewhere in southwestern Africa (Chase et al., 2015a; Lim et al., 2016;  
543 Chase et al., 2019b) that AMOC through its impact on regional oceanic and atmospheric circulation  
544 systems was potentially a strong modulator of global LGM boundary conditions, resulting in phases of  
545 relatively drier conditions ( $\sim 24$ - $22.5$  cal ka BP and  $\sim 22$ - $18$  cal ka BP) demarcated by brief phases of  
546 increased humidity from  $\sim 24.5$ - $24$  cal ka BP and  $22.5$ - $22$  cal ka BP. During Termination I, the marked  
547 increase in coastal thicket pollen at  $\sim 18.5$  cal ka BP indicates a substantial increase in moisture availability,  
548 coincident, and likely associated with slowing AMOC and a build-up of heat in the southern Atlantic during  
549 HS1. The resolution of the Holocene portion of the record does not allow for definitive inferences  
550 regarding the primary mechanisms driving climate change, but it is evident that there are significant

551 changes in the overall vegetation composition between the deglacial and Holocene, with a clear shift from  
552 ericaceous fynbos in the late Pleistocene to other structural types of fynbos (proteoid, restioid and  
553 asteraceous) in the middle and late Holocene. These changes are likely in response to increased Holocene  
554 temperatures and relatively drier conditions.

555 Overall, the Pearly Beach record represents an important new contribution to a growing body of data that  
556 provides evidence for great spatial complexity in regional climatic responses, and more specifically,  
557 provides evidence that AMOC variability influence extended eastwards along the southwestern Cape  
558 coast at least as far as the modern boundary of the WRZ. It also provides a rare look at the response of  
559 lowland sectors of the mega-diverse Cape Floristic Region to major long-term climatic transitions.

## 560 Data Availability

561 The full pollen, charcoal and particle size datasets are given in Appendix A (Supplementary data) and will  
562 also be available on the Neotoma Palaeoecology data archive (<https://www.neotomadb.org/>) as a  
563 contribution to the African Pollen Database.

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571 Figures and figure captions

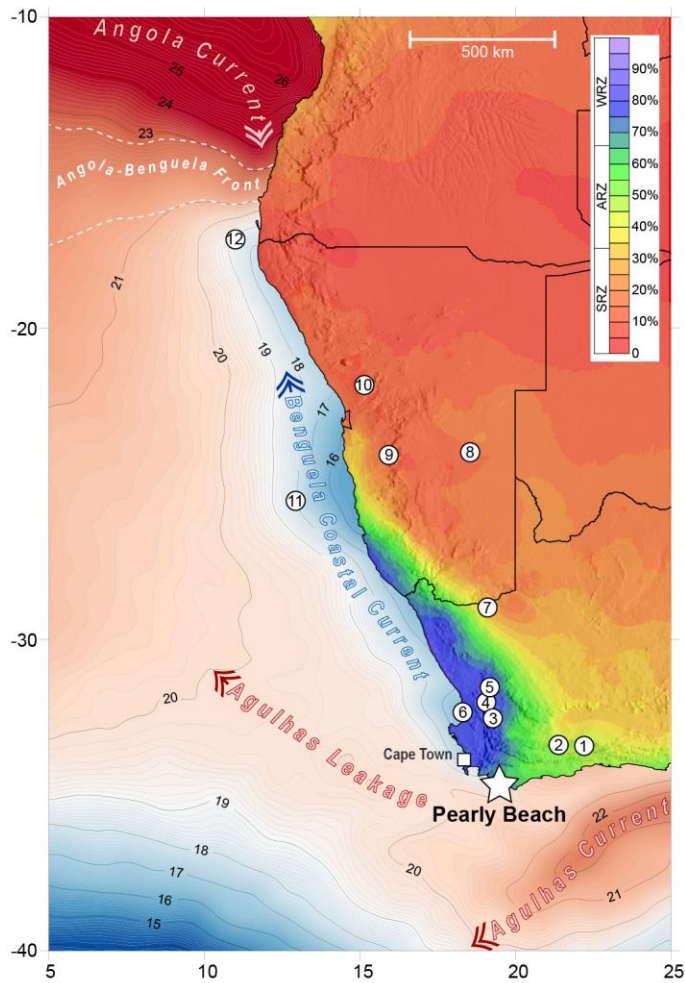
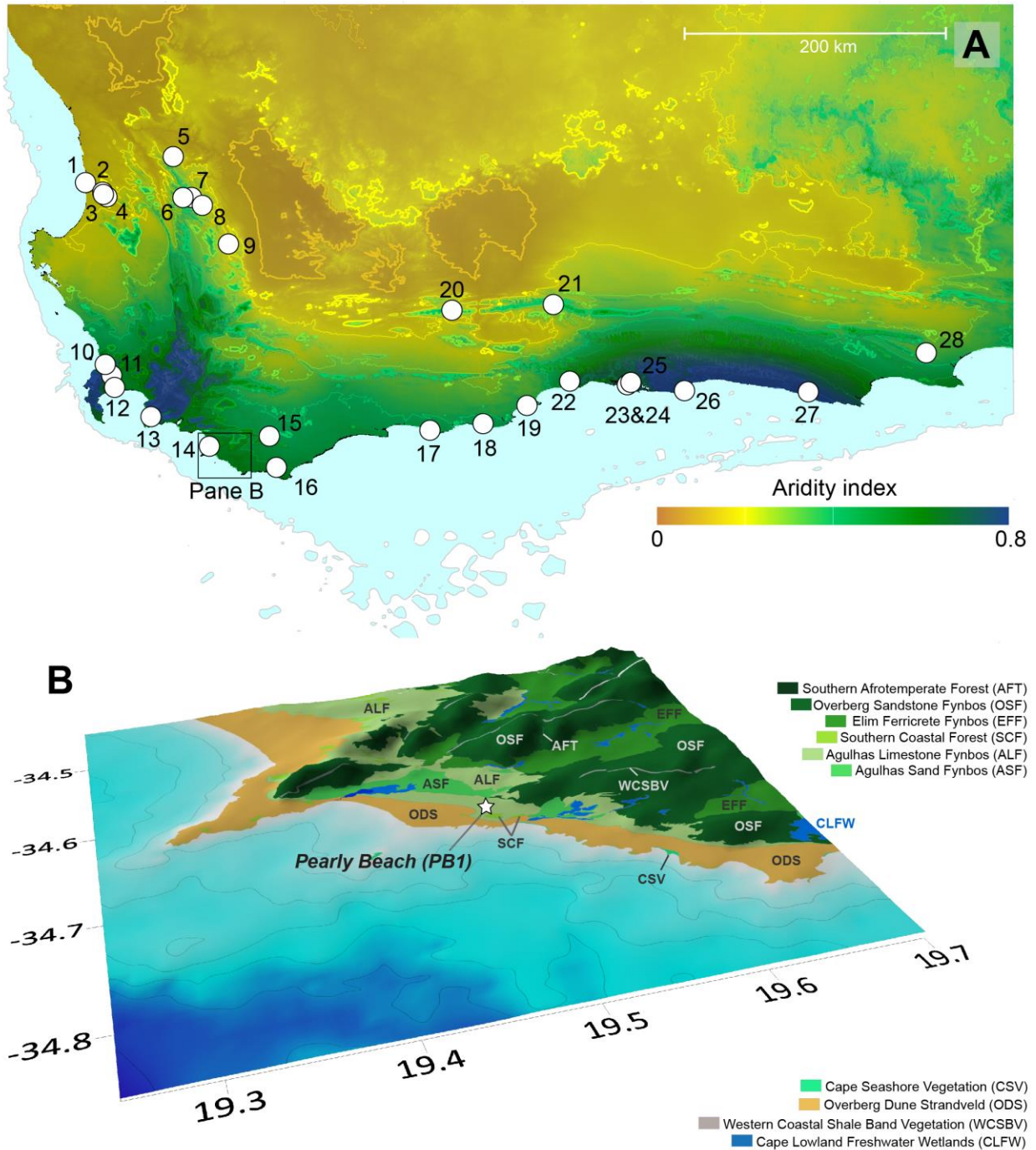


Figure 1. Map of the southwestern margin of Africa showing seasonality of rainfall and sharp climatic gradients dictated by the zones of summer/tropical (red) and winter/temperate (blue) rainfall dominance. The major oceanic circulation systems (the cold Benguela current and the warm Agulhas and Angola currents, temperatures shown in °C (Reynolds et al., 2007)) are indicated as well as the position of Pearly Beach (star) in relation to key palaeoclimatic records (1 – Cango Caves (Talma and Vogel, 1992), 2 – Seweweekspoort (Chase et al., 2013; Chase et al., 2017), 3- Katbakkies Pass (Meadows et al., 2010; Chase et al., 2015b), 4 – De Rif (Chase et al., 2011; Quick et al., 2011; Valsecchi et al., 2013; Chase et al., 2015a), 5 – Pakhuis Pass (Scott and Woodborne, 2007c, a; Chase et al., 2019a), 6 – Elands Bay Cave (Cowling et al.,

591 1999; Parkington et al., 2000), 7 – Pella (Lim et al., 2016; Chase et al., 2019b), 8 – Stampriet Aquifer (Stute  
 592 and Talma, 1998), 9 – Zizou (Chase et al., 2019b), 10 – Spitzkoppe (Chase et al., 2009; Chase et al., 2019b),  
 593 11 – ODP 1084B (Farmer et al., 2005), 12 – GeoB 1023-5 (Kim et al., 2003).

594



595

596 Figure 2. Pane A: Aridity index map of the southwestern Cape (data: Zomer et al., 2008) , with lower values

597 indicating drier conditions. Peripheral blue shading indicates position of shoreline at Last Glacial Maximum

598 low-stand (-130 m). The locations of published palaeoenvironmental and archaeological records from the

599 region are shown: 1 – Elands Bay Cave (Parkington et al., 1988; Cowling et al., 1999; Parkington et al.,

600 2000), 2 – Grootdrift (Meadows et al., 1996), 3 – Verlorenvlei (Kirsten et al.; Stager et al., 2012; Carr et al.,

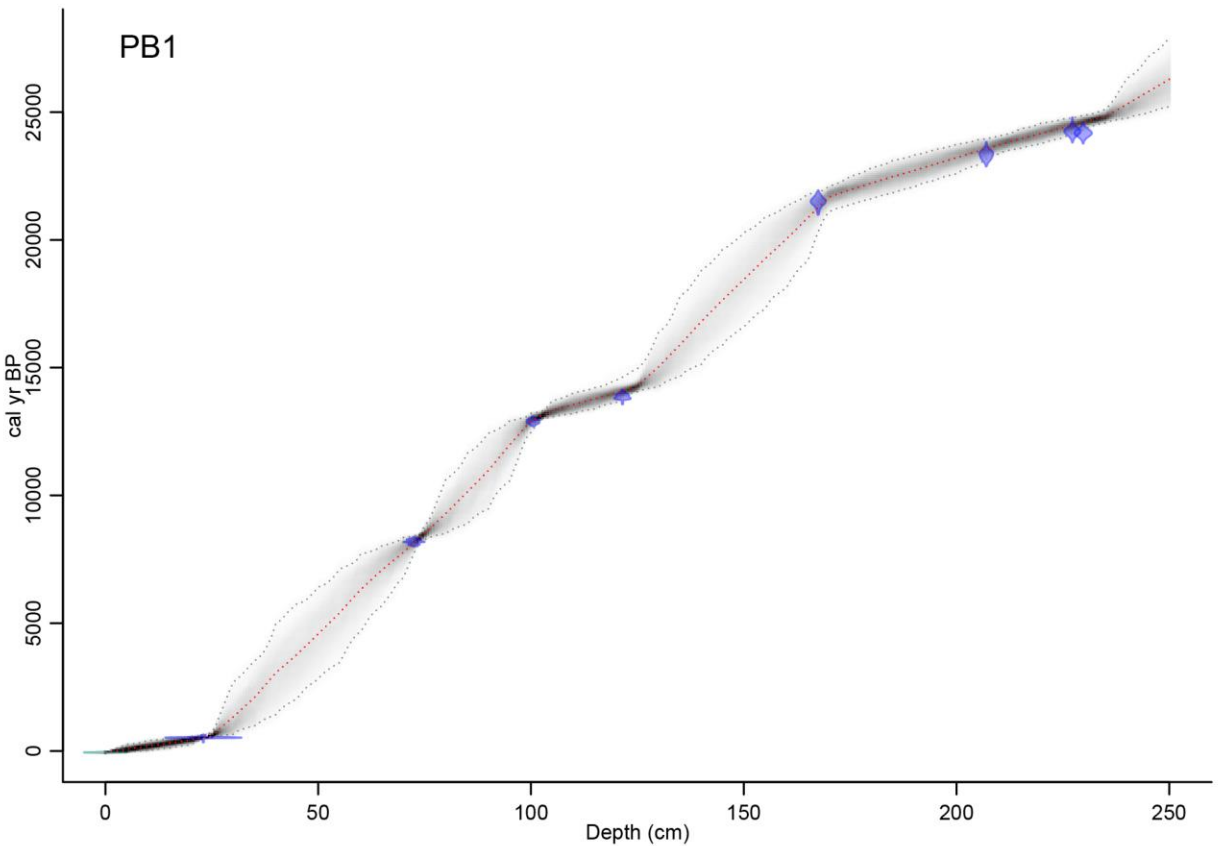
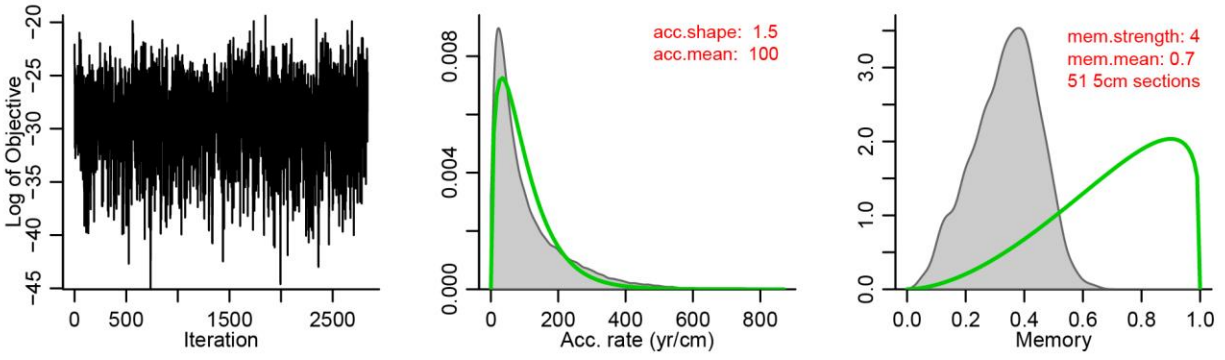
601 2015), 4 – Klaarfontein Springs (Meadows and Baxter, 2001), 5 – Pakhuis Pass (Scott and Woodborne,

602 2007b, c), 6 – Sneeuberg Vlei and Driehoek Vlei (Meadows and Sugden, 1991), 7 – De Rif (Chase et al.,  
603 2011; Quick et al., 2011; Valsecchi et al., 2013; Chase et al., 2015a), 8 – Truitjes Kraal (Meadows et al.,  
604 2010), 9 Katbakkies (Meadows et al., 2010; Chase et al., 2015b), 10 Rietvlei (Schalke, 1973), 11 – Cape  
605 Flats (Schalke, 1973), 12 – Princess Vlei (Neumann et al., 2011; Kirsten and Meadows, 2016; Cordova et  
606 al., 2019), 13 – Cape Hangklip (Schalke, 1973), 14 – Die Kelders (Klein and Cruz-Urbe, 2000), 15 –  
607 Bynekranskop (Schweitzer and Wilson, 1982; Faith et al., 2018), 16 – The Agulhas Plain vleis and lunettes  
608 (Soetendalsvlei, Voëlvlei, Renosterkop and Soutpan) (Carr et al., 2006a; Carr et al., 2006b), 17 – Blombos  
609 Cave (Henshilwood et al., 2001), 18 – Rietvlei-Still Bay (Quick et al., 2015), 19 – Pinnacle Point (Marean,  
610 2010; Rector and Reed, 2010), 20 – Seweweekspoort (Chase et al., 2013; Chase et al., 2017), 21 – Congo  
611 Cave (Talma and Vogel, 1992) and Boomplaas Cave (Deacon et al., 1984), 22 – Norga peats (Scholtz, 1986),  
612 23 – Eilandvlei (Kirsten et al., 2018; Quick et al., 2018; Wündsche et al., 2018) and Bo Langvlei (du Plessis  
613 et al., 2020), 24 – Groenvlei (Martin, 1968; Wündsche et al., 2016), 25 – Vankervelsvlei (Irving and  
614 Meadows, 1997; Quick et al., 2016), 26 – Nelson Bay Cave (Cohen and Tyson, 1995), 27 – Klasies River  
615 Mouth (Deacon et al., 1986) and 28 Uitenhage Aquifer (Heaton et al., 1986; Stute and Talma, 1998).

616 Pane B: Location of Pearly Beach 1 sediment coring site in relation to the current distribution of dominant  
617 vegetation types [Data: South African National Biodiversity Institute (2006-). The Vegetation Map of South  
618 Africa, Lesotho and Swaziland, Mucina, L., Rutherford, M.C. and Powrie, L.W. (Editors), Online,  
619 <http://bgis.sanbi.org/SpatialDataset/Detail/18>, Version 2018]. Bathymetry contours are at 20 m intervals  
620 (GEBCO, 2012) and 0.1° grid intervals equate to ~9.2 km at this latitude.

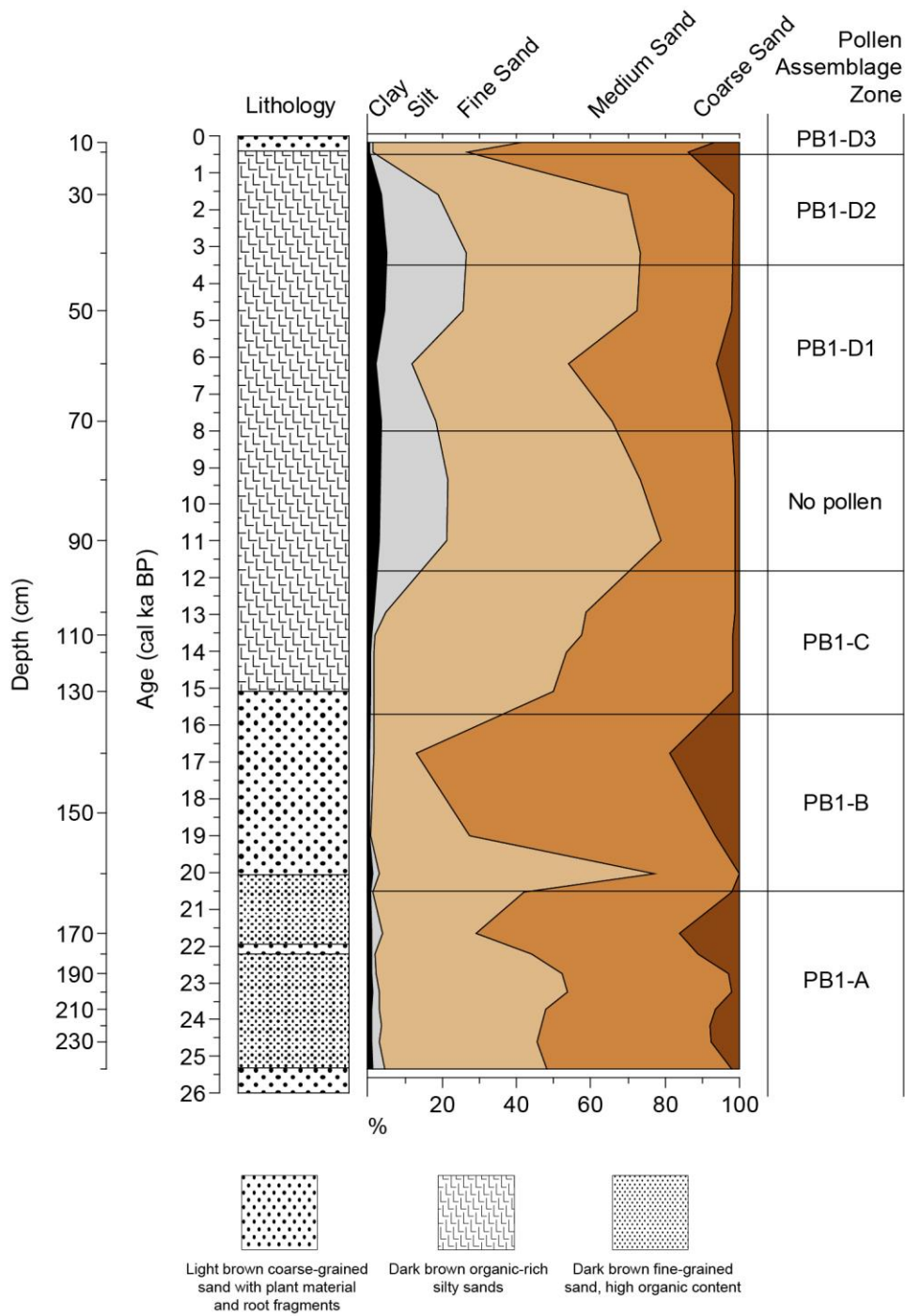
621





622  
 623 Figure 3. Age-depth model for Pearly Beach (PB1) using the *Bacon* software package (Blaauw and Christen,  
 624 2011). The blue areas represent the  $2\sigma$  probability distributions of the calibrated  $^{14}\text{C}$  ages, the grey-scales  
 625 indicate all likely age-depth models, grey dotted lines show the 95% confidence intervals and the red  
 626 dotted line shows the single 'best' model based on the median age for each depth.

627

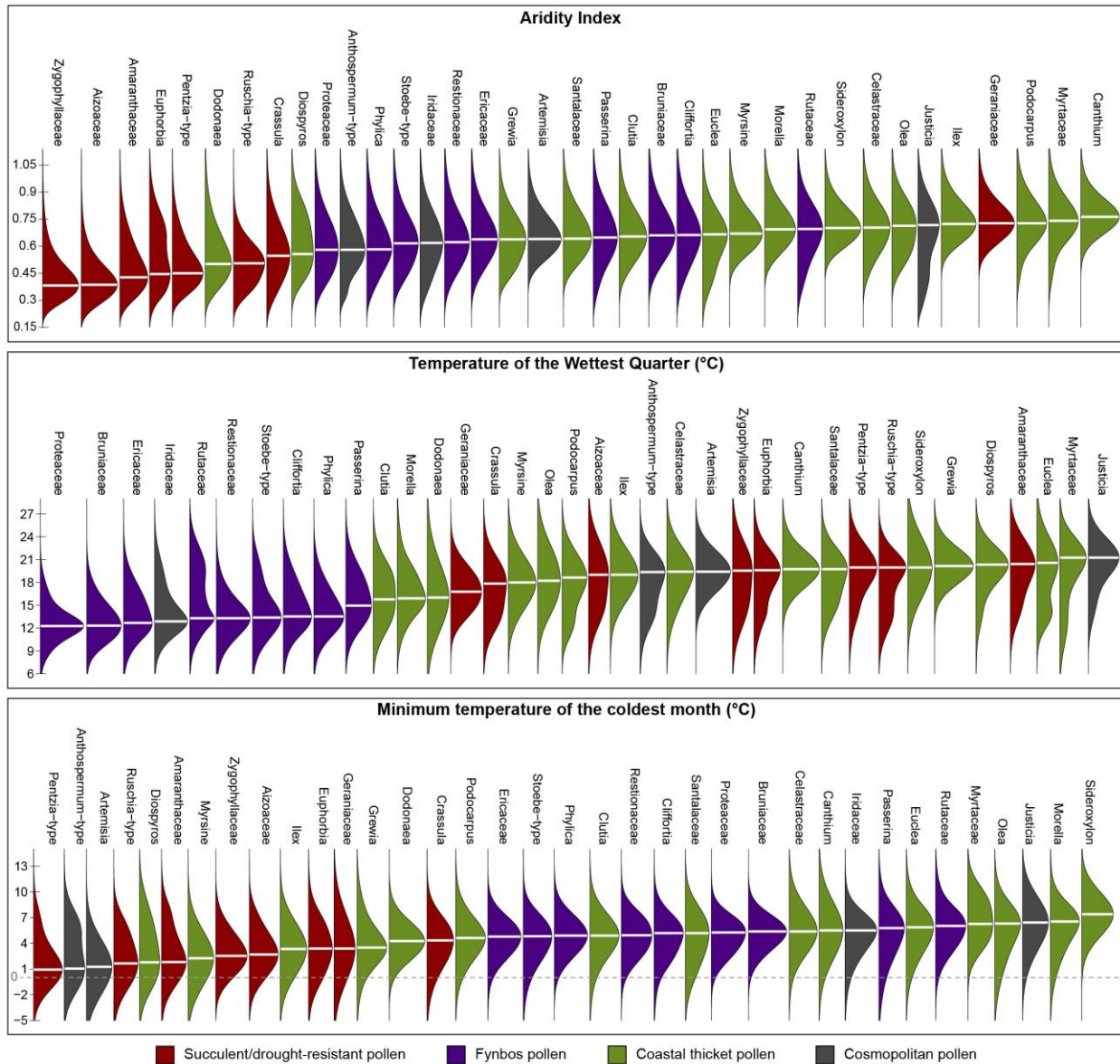


628

629 Figure 4: Pearly Beach 1 (PB1) particle size analysis data displayed as percentages of clay (0 – 2 μm), silt  
 630 (2 – 20 μm), fine sand (20 – 200 μm), medium sand (200 – 500 μm) and coarse sand (500 – 2000 μm)  
 631 plotted against interpolated age (cal kBP) and composite depth (cm) with pollen assemblage zones  
 632 indicated on the far right.







640  
 641 Figure 6: Probabilistic responses of the pollen taxa to three important regional climate determinants:  
 642 Aridity index (Zomer et al., 2008; Trabucco and Zomer, 2019) and the temperature of the wettest quarter  
 643 (used as a proxy for the temperature of the growing season) and the minimum temperature of the coldest  
 644 month (Fick and Hijmans, 2017). These responses were calculated following the probability density  
 645 function (pdf) approach of Chevalier et al. (2014) and using data from the SANBI database (SANBI, 2003),  
 646 restricted to the plant species that currently live in the study area (defined here as a box between 17° and  
 647 29°E and between 32° and 35°S).

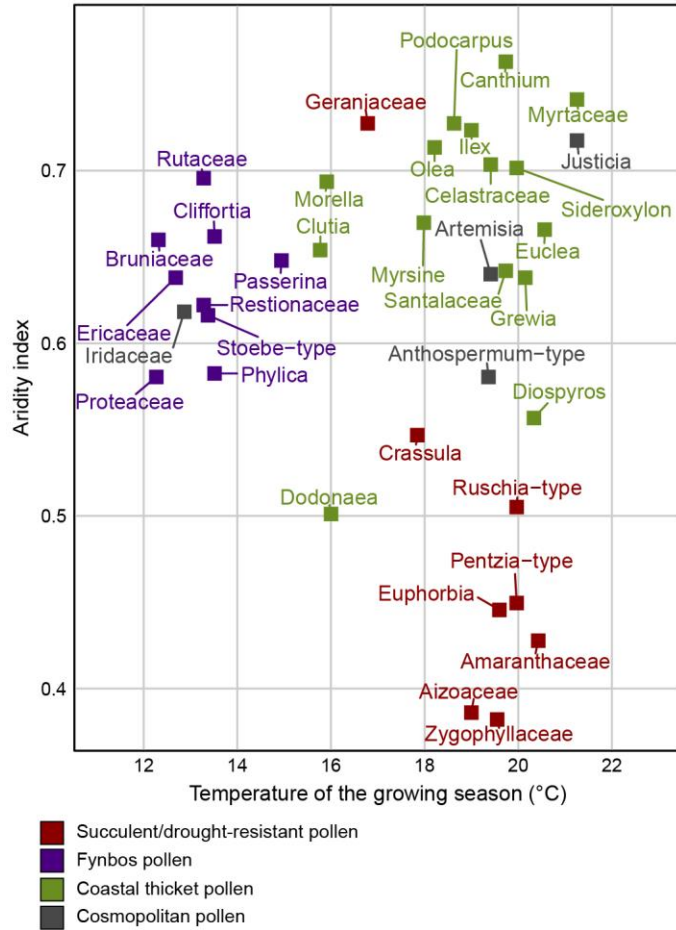


Figure 7: Biplot representing the climate optima (*i.e.* the climate value with the highest probability of presence) of the studied taxa for the temperature of the growing season (x-axis) (as represented by temperature of the wettest quarter) and aridity (y-axis; larger values associated with more humid conditions).

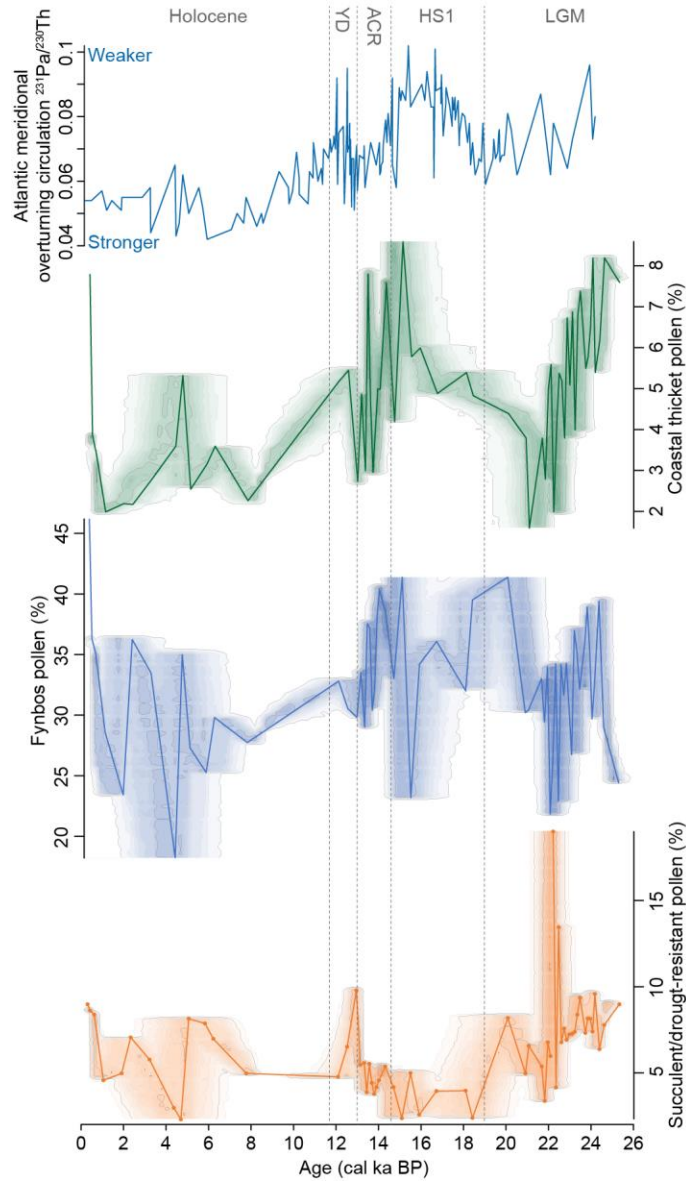


Figure 8: Primary pollen groups from Pearly Beach (PB1). Associated shading was obtained from proxy ghost analysis using *rbacon* software (v. 2.3.6; Blaauw and Christen, 2011) to express chronological uncertainties. The Holocene, Younger Dryas (YD), Antarctic Cold Reversal (ACR) and Last Glacial Maximum (LGM) chronozones are indicated.

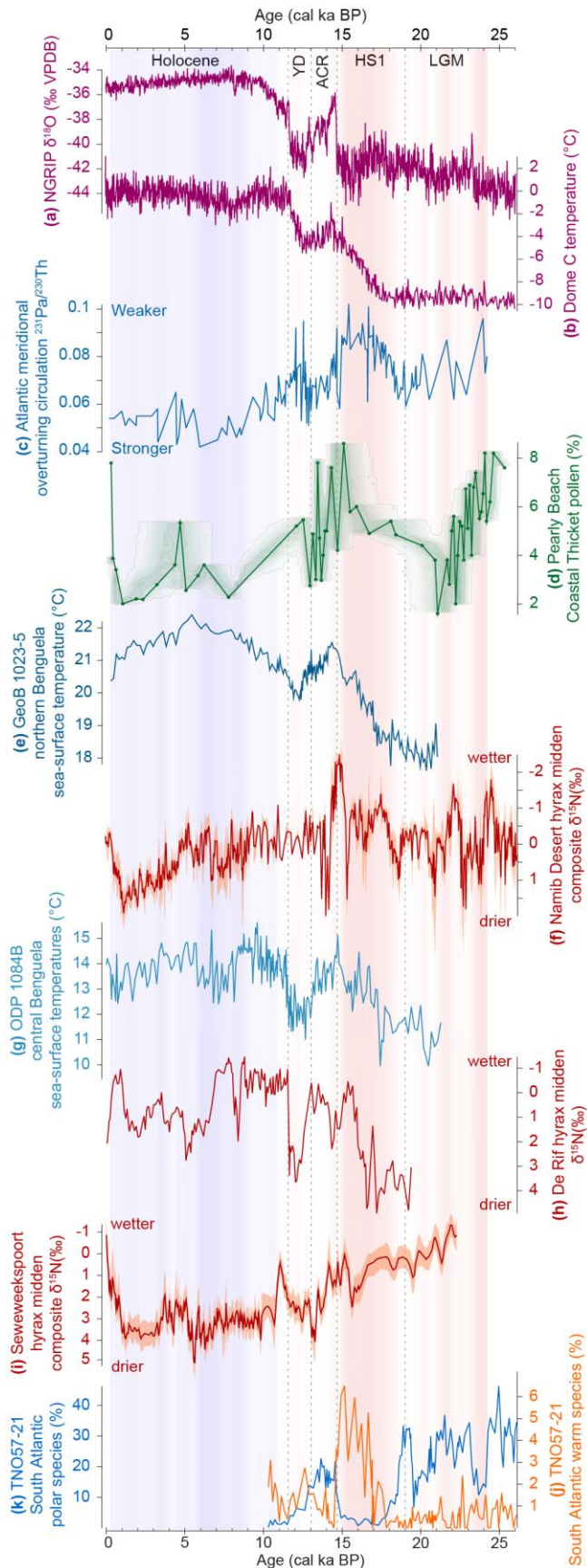


Figure 9. Comparison of records relevant to the context and climate dynamics associated with the changes observed in the Pearly Beach record. The Last Glacial Maximum (LGM), Heinrich stadial 1 (HS1), Antarctic Cold Reversal (ACR), Younger Dryas (YD) and Holocene chronozones are indicated. Shading has been added to indicate the strength of Atlantic overturning circulation relative to the 25 kyr mean (red = weaker, blue = stronger). Records shown are: **a)** North Greenland NGRIP oxygen isotope record (North Greenland Ice Core Project North Greenland Ice Core Project members, 2004), **b)** Antarctic temperature record from Dome C (Jouzel et al., 2007), **c)** record of Atlantic overturning circulation strength (Ng et al., 2018), **d)** the coastal thicket pollen record from Pearly Beach, shading from proxy ghost analysis using *rbacon* software (v. 2.3.6; Blaauw and Christen, 2011) to express chronological uncertainties, **e)** sea-surface temperature record from the GeoB 1023-5 marine core (Kim et al., 2003), **f)** Namib Desert rock hyrax midden nitrogen isotope record (Blaauw and Christen, 2011), **g)** sea-surface temperature record from ODP 1084B marine core (Farmer et al., 2005), **h)** De Rif rock hyrax midden nitrogen isotope record (Chase et al., 2011; Chase et al., 2015a), **i)** Seweweekspoort rock hyrax midden nitrogen isotope record (Chase et al., 2017), **j,k)** percentages of polar and warm water foraminiferal species in South Atlantic core TNO57-21 (Barker et al., 2009).



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