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## High-resolution record of Holocene climate change dynamics from southern Africa's temperate-tropical boundary, Baviaanskloof, South Africa

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## 26 **Abstract**

27 South Africa's southern Cape is a highly dynamic climatic region that is influenced by changes in  
28 both temperate and tropical atmospheric and oceanic circulation dynamics. Recent research  
29 initiatives suggest that the major elements of the regional climate system have acted both  
30 independently and in combination to establish a mosaic of distinct climate regions and  
31 potentially steep climate response gradients across the southern Cape. To consider this further,  
32 we present new high resolution  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  data from a rock hyrax (*Procavia capensis*)  
33 midden from Baviaanskloof, in the Cape Fold Mountains of South Africa's Eastern Cape  
34 Province. Spanning the last 7200 years, these data provide detailed information regarding  
35 environmental changes in the mid- and late Holocene. These allow us to assess the spatio-  
36 temporal nature of climate change anomalies across the wider region. Across the full duration  
37 of the record, a negative correlation between humidity and palaeotemperature reconstructions  
38 from nearby Cango Cave is observed. In conjunction with correlations with Southern Ocean sea-  
39 surface temperatures and sea-ice presence, we infer a dominant influence of the southern  
40 westerlies in determining multi-millennial scale hydroclimate variability. At shorter, multi-  
41 centennial to millennial timescales, the Baviaanskloof data indicate a clearer expression of  
42 tropical influences, highlighting a delicate balance between the mechanisms driving regional  
43 climate dynamics across timescales, and the sensitivity of the region to changes in global  
44 boundary conditions.

45 **Keywords**

46 Palaeoclimate; Holocene; South Africa; rock hyrax middens; stable isotopes

47 **Highlights**

- 48 • New high resolution  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  data from a rock hyrax midden from South Africa's  
49 southern Cape.
- 50 • A strong negative relationship between temperature and humidity in the region.
- 51 • The influence of temperate and tropical climate drivers appear to operate at distinct  
52 timescales.
- 53 • Dominant influence of westerly storm tracks on climate at multi-millennial timescales.
- 54 • Millennial-scale change suggest significant influence of tropical circulation systems.

## 55 1 Introduction

56 Southern African climates are primarily defined by hemispheric-scale changes in pressure fields  
57 that determine: 1) the position and extent of the circum-polar vortex, and 2) land-sea-pressure  
58 gradients that modulate the advection of moisture from the tropical Atlantic and Indian oceans  
59 (Tyson and Preston-Whyte, 2000). This dynamic has created strongly seasonal rainfall regimes  
60 across southern Africa. The southwestern Cape receives much of its precipitation during the  
61 austral winter months as the westerly storm track associated with the circum-polar vortex shifts  
62 northward. By contrast, much of the rest of southern Africa experiences a summer rainfall  
63 regime, as the continent warms during the austral summer months and the tropical easterly  
64 flow strengthens and shifts southward (Crétat et al., 2012; Reason and Rouault, 2005; Reason  
65 et al., 2002; Tyson, 1986; Tyson and Preston-Whyte, 2000) (Figure 1a). These spatial distinctions  
66 in rainfall regimes have given rise to the classification of a winter rainfall zone (WRZ), an  
67 aseasonal or year-round rainfall zone (ARZ or YRZ) and a summer rainfall zone (SRZ), defined in  
68 terms of the percentage of mean annual rain falling between October and March (>66% = WRZ,  
69 66%-33% = ARZ/YRZ, <33% = SRZ) (*sensu* Chase and Meadows, 2007). During the late  
70 Quaternary, changes in global boundary conditions are considered to have modulated these  
71 seasonal patterns, with glacial periods experiencing an increased influence of frontal systems  
72 embedded in the westerly storm track as they migrate equatorward due to expanded Antarctic  
73 sea ice and changing temperature gradients. Conversely, interglacial periods experience  
74 stronger convection over the continent and enhanced advection of tropical moisture (Cockcroft  
75 et al., 1987; van Zinderen Bakker, 1976; see review of literature by Chase and Meadows, 2007).

76 In this context, South Africa's southern Cape coast is situated within the ARZ, the  
77 transition between zones of temperate and tropical climate system dominance, which receives  
78 precipitation from moisture-bearing systems related to both (Figure 1a, b). Additionally, the  
79 southern Cape coast is influenced by the temperature and proximity of the Agulhas Current,  
80 which flows along the coast from the Mozambique Channel (Jury et al., 1993; Rouault et al.,  
81 2002). As a result of this combination of factors, the region is currently characterised by mesic  
82 conditions, but it has been suggested that the changes in their relative dominance could have a  
83 profound impact on climate regimes, rendering the region particularly sensitive to changes in  
84 global boundary conditions, and shifts in the boundaries of the WRZ and SRZ at longer  
85 timescales (see Carr et al., 2016; Chase and Meadows, 2007; Cowling, 1992; Deacon and  
86 Lancaster, 1988; Meadows and Baxter, 1999).

87 Despite being one of the most data-rich regions of southern Africa, there is still a  
88 relatively limited understanding of past environmental change from this region (see Chase and  
89 Meadows, 2007; Deacon and Lancaster, 1988). Known for its rich record of human prehistory,  
90 much of the evidence for Holocene environmental change has been recovered from  
91 archaeological deposits at sites such as Boomplaas (e.g. Deacon et al., 1984; Klein, 1978;  
92 Scholtz, 1986) and Nelson Bay caves (e.g. Butzer, 1973; Deacon, 1978; Klein, 1972). Subsequent  
93 work and the application of evolving analytical techniques has further contributed to the  
94 wealth of data obtained from these sites (e.g. Avery, 2003; Chase et al., 2018; Cohen and Tyson,  
95 1995; Faith, 2011; Faith, 2013; Faith et al., 2018; Loftus et al., 2016; Sealy et al., 2016; Sealy and  
96 Thackeray, 1998), but as anthropogenic deposits they are often fundamentally constrained in  
97 terms of both their taphonomy and their continuity.

98           A number of other palaeoenvironmental archives also exist in the region, with the most  
99   notable early work being that of Martin (1959; 1968) who conducted palynological analyses on  
100   the lacustrine sediments from Groenvlei, within the Wilderness embayment. These data were  
101   later complimented by work on the Norga peats by Scholtz (1986), speleothems from Congo  
102   Cave by Talma and Vogel (1992), and most recently by evidence from rock hyrax middens from  
103   Seweweekspoort (Chase et al., 2013; Chase et al., 2017). Recent initiatives have also explored  
104   the potential of other lakes within the Wilderness region (Kirsten et al., 2018; Quick et al., 2018;  
105   Quick et al., 2016; Wündsche et al., 2018; Wündsche et al., 2016) and adjacent coastal margin  
106   (Carr et al., 2010b; Quick et al., 2015) (Figure 1b).

107           In terms of past climate change and its drivers, detailed, high resolution records from  
108   Seweweekspoort and Eilandvlei (Figure 1) indicate a surprising degree of spatial heterogeneity,  
109   implying strong hydroclimatic gradients existed over relatively short distances (<150 km)  
110   moving away from the coast, establishing and a coastal-interior dipole (Chase and Quick, 2018).  
111   From this, it has been hypothesised that the Agulhas Current may have a dominant, potentially  
112   highly localised, influence on near-coast environments (Chase and Quick, 2018), and may not  
113   extend northward beyond the coast-parallel orographic barrier of the Cape Fold Mountains  
114   (Jury et al., 1993), where macro-scale synoptic systems (e.g. tropical-temperate troughs (Hart et  
115   al., 2013; Washington and Todd, 1999)) dominate the climates and climatic variability of the  
116   continental interior (Chase et al., 2017). Fundamental questions remain, however, regarding  
117   the spatio-temporal distribution of climate change anomalies and it is clear that more data  
118   from a wider spatial range of sites is required before intra- and inter-regional long-term climate  
119   dynamics can be properly understood. The importance of understanding such gradients is

120 significant in that the southern Cape coastal plain may have been mechanistically distinct in  
121 terms of its climate (Chase and Quick, 2018; Jury, 2015), as well as topographically and  
122 edaphically distinct from the Cape Fold Belt and the interior, which has implications for  
123 interpretation of the regional archaeological record.

124 In this paper, we present high resolution  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  data from a new rock hyrax  
125 (*Procapra capensis*) midden – an accumulation of dried urine and faecal pellets (see Chase et al.,  
126 2012 for full description) – from Baviaanskloof, in South Africa’s Eastern Cape Province (Figure  
127 1). Situated along the divide between the arid interior and relatively mesic coastal margin,  
128 these data provide valuable information regarding long-term changes in hydroclimate and  
129 vegetation and enable a more comprehensive analysis of the spatial distribution of Holocene  
130 climate change anomalies and their likely drivers. Key questions concern whether the steep  
131 coastal-inland climate gradient inferred to have existed between Seweweekspoort and  
132 Eilandvlei (Chase and Quick, 2018) exists in this eastern sector, and if differences can be  
133 observed between Seweweekspoort and Baviaanskloof that might highlight the nature of the  
134 gradient between tropical and temperate circulation systems in this region.

### 135 **1.1 Site description**

136 Baviaanskloof is an east-west trending valley situated between the Baviaanskloofberge and the  
137 Kougaberge mountains, both of which are part of the Cape Fold Mountains. The valley extends  
138 parallel to the coast, which lies ~55 km to the south. Over its ~60 km length, Baviaanskloof  
139 descends from an elevation of approximately 800 m.a.s.l. in the west to 250 m.a.s.l. in the east,  
140 with the flanking mountains rising to form orographic barriers between 1000-1700 m.a.s.l.



141 Combined, the Cape Fold Mountains present a significant climatic divide between the coast and  
142 the arid Lower Karoo to the north (Figures 1, 2).

143 The hyrax midden recovered for this study (Baviaanskloof-2-2 (BK-2-2); 33.53°S, 23.76°E,  
144 800 m m.a.s.l.) was found on a northeast facing cliff in a tributary valley cut into the southern  
145 flank of Baviaanskloof (Figure 1c, 3). The vegetation in the area surrounding the site is a  
146 complex mosaic, reflecting the variable topography and geology of the region. The tributary  
147 valley itself is dominated by Groot Thicket (Mucina and Rutherford, 2006), a dense, shrubby  
148 vegetation characterised by succulent tree species such as *Aloe ferrox* and *Euphorbia tetragona*  
149 (Figure 3). Other trees and tall shrubs include *Vachellia (Acacia) karoo*, *Portulacaria afra*,  
150 *Pappea capensis*, *Boscia albitrunca*, *Grewia robusta*, *Dodonea viscosa* and *Searsia* spp.  
151 Succulent *Crassula* shrubs are abundant, and grass cover in the valley itself is limited. To the  
152 north (~250 m), a small alluvial fan has developed at the junction with the main Baviaanskloof  
153 valley. Vegetation on the fan is much sparser than in the tributary valley, and grasses form a  
154 more important component of the vegetation. Above the site (~200 m), the surface of the  
155 plateau into which the tributary valley is incised supports a Baviaanskloof Shale Renosterveld  
156 vegetation (Mucina and Rutherford, 2006). *Aloe ferrox* and other smaller succulents are  
157 present, but the vegetation is dominated by *Elytropappus rhinocerotis* and grasses (including C<sub>3</sub>  
158 (*Agrostis*, *Melica*, *Stipa*) and C<sub>4</sub> (*Eragrostis*, *Eustachys* and *Themeda*) varieties). As rock hyraxes  
159 are generalist feeders (Carr et al., 2016; Fourie, 1990; Hoeck, 1975), the occurrence of C<sub>4</sub> and  
160 succulents presents the possibility that the diet of the hyraxes living at the site included non-C<sub>3</sub>  
161 plants.

## 162 **2 Material and methods**

163 To ensure stratigraphic integrity and regular accumulation rates, middens with high hyraceum  
164 contents are favoured for analysis. The BK-2-2 midden was selected because it is composed  
165 entirely of hyraceum, with no visible pellets. A representative portion of the midden (measuring  
166 186 mm in depth) was cut perpendicular to the stratigraphy using an angle grinder, and  
167 sections were cleaned using progressively finer grades of sandpaper.

168 Radiocarbon age determinations (n=7) were processed at the <sup>14</sup>CHRONO Centre,  
169 Queen's University Belfast using accelerator mass spectrometry (AMS) (Table 1; Figure 4).  
170 Samples were pre-treated with 2% HCl for one hour at room temperature to remove  
171 carbonates and dried at 60°C. They were then weighed into quartz tubes with an excess of CuO,  
172 sealed under vacuum and combusted to CO<sub>2</sub>. The CO<sub>2</sub> was converted to graphite on an iron  
173 catalyst using the zinc reduction method (Slota et al., 1987). The radiocarbon ages were  
174 corrected for isotope fractionation using the AMS measured  $\delta^{13}\text{C}$  and calibrated using the  
175 SHCal13 calibration data (Hogg et al., 2013). The Bayesian Bacon 2.3.6 software package  
176 (Blaauw and Christen, 2011) was used to generate all age-depth models (Figure 4). Considering  
177 the nature of the age model, the midden was considered to still be actively accumulating, and a  
178 surface age estimate of the year of collection (2013) was included in the construction of the age  
179 model.

180 The stable nitrogen isotope composition of 203 hyraceum samples (approx. 2 mg) were  
181 measured at the School of Geography, Geology and the Environment, University of Leicester,  
182 with contiguous/overlapping samples obtained from two offset tracks using a 1 mm drill.

183 Isotope ratios were measured on a Sercon 20-20 continuous flow isotope ratio mass  
184 spectrometer. For the stable isotope analyses, the standard deviation derived from replicate  
185 analyses of homogeneous material was better than 0.2‰ for both carbon and nitrogen. Carbon  
186 isotope results are expressed relative to Vienna PDB. Nitrogen isotope results are expressed  
187 relative to atmospheric nitrogen (Figure 5).

188 To explore the variability of, and correlations between the BK-2-2  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  records  
189 at a range of frequencies, the data were analysed using continuous Morlet wavelet transforms  
190 and semblance analysis (Cooper and Cowan, 2008). For these analyses, the records were  
191 resampled to a common 50-year resolution using linear interpolation.

### 192 **3 Results**

193 AMS radiocarbon dating of the BK-2-2 midden indicates that it was deposited between 7240 cal  
194 (calibrated) BP and present. The age-depth model suggests regular, continuous deposition with  
195 no apparent hiatuses (Figure 4). Accumulation rates average  $\sim 40 \mu\text{m yr}^{-1}$ , which translates to  
196 each 1 mm isotope sample integrating approximately  $\sim 40$  years of hyraceum.

197 The  $\delta^{15}\text{N}$  values of BK-2-2 range from 0.7 to 12.1‰ (Figure 5). The lowest values occur  
198 during the mid-Holocene ( $\sim 5000$  cal BP), with periods of generally higher values from 7200-  
199 6300 cal BP, 4600-3400 cal BP and  $\sim 3000$  cal BP to present. The  $\delta^{13}\text{C}$  values from the BK-2-2  
200 midden vary from -20.6 to -25.5‰ (Figure 5). The lowest and least variable  $\delta^{13}\text{C}$  values occur  
201 generally from 3000 cal BP to present, with higher values occurring from 7000-3000 cal BP. For  
202 much of the record, a degree of covariance is observed between the  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  values of the  
203 midden, which exhibit a positive correlation at multi-centennial to millennial timescales

204 (wavelengths ~15-80 (750-4000 years); Figures 5, 6). However, at multi-millennial timescales  
205 (Figure 6; i.e. wavelengths >100 (>5000 years))  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  are negatively correlated.

## 206 **4 Discussion**

### 207 **4.1 Stable nitrogen and carbon isotopes**

208 The BK-2-2 records provide detailed information regarding environmental change, enabling us  
209 to consider the records from South Africa's southern Cape in a broader regional context. The  
210  $\delta^{15}\text{N}$  signal from BK-2-2 is considered to primarily indicate changes in water-availability. As  
211 described in previous works, and supported by strong correlations with independent climate  
212 records (Chase et al., 2015a; Chase et al., 2015b; Chase et al., 2010; Chase et al., 2009; Chase et  
213 al., 2012), this reflects aridity-driven changes in soil nitrogen pools, with drier conditions  
214 inducing more N flow to inorganic pools that are subject to gaseous loss of  $^{15}\text{N}$  depleted  
215 products (Austin and Vitousek, 1998; Handley et al., 1999; Murphy and Bowman, 2009). Plants  
216 growing in the resulting  $^{15}\text{N}$ -enriched soils exhibit higher  $\delta^{15}\text{N}$  values (Craine et al., 2009;  
217 Hartman and Danin, 2010), as do the tissues – and in the case of hyrax middens, the excreta - of  
218 animals that consume them (Carr et al., 2016; Hartman, 2011; Murphy and Bowman, 2006).

219 The midden  $\delta^{13}\text{C}$  signal reflects animal diet and, in turn, two aspects of the response of  
220 vegetation to climate change: 1) plant photosynthetic pathway, i.e.  $\text{C}_3$  (~-34 to -24‰),  $\text{C}_4$  (~-16  
221 to -10‰) and CAM (typically within the range -20 to -10‰) plants (Boom et al., 2014; Rundel et  
222 al., 1999; Smith, 1972; Smith and Epstein, 1971; Werger and Ellis, 1981), and 2) changes in  $\text{C}_3$   
223 plant water-use efficiency (Ehleringer and Cooper, 1988; Farquhar and Richards, 1984; Farquhar  
224 et al., 1989). At the BK-2-2 site,  $\text{C}_3$  vegetation is abundant in the form of trees and shrubs, and

225 the presence of both C<sub>3</sub> and C<sub>4</sub> grasses has been indicated (Mucina and Rutherford, 2006;  
226 Vogel, 1978). CAM plants are also abundant at the site (Figure 3), and as generalist feeders  
227 (Fourie, 1990; Hoeck, 1975) these can be part of the hyraxes' diet, although perhaps not in  
228 significant quantities (Carr et al., 2010a; Carr et al., 2016; Fourie, 1983).

229 In considering the isotope records from BK-2-2, we have identified variability at two  
230 primary timescales; multi-millennial variability (Figure 6; wavelengths >100 (>5000 years)),  
231 encompassing change across the whole of the record, and multi-centennial to millennial  
232 variability (wavelengths ~15-80 (750-4000 years)). At multi-millennial timescales, midden  $\delta^{15}\text{N}$   
233 and  $\delta^{13}\text{C}$  are negatively correlated, with lower  $\delta^{13}\text{C}$  values occurring under relatively drier  
234 conditions (indicated by higher  $\delta^{15}\text{N}$  values) (Figure 6). This is most apparent during the late  
235 Holocene, after ~3000 cal BP (Figure 5), and might at first glance be associated with changes in  
236 temperature and/or rainfall seasonality. Available data from the region (Figures 7, 8), however,  
237 are not consistent with either of these mechanisms. For instance, lower  $\delta^{13}\text{C}$  values would not  
238 be predicted with the strong increase in temperatures observed at ~3000 cal BP in the Congo  
239 Cave record (e.g. Epstein et al., 1997; Teeri and Stowe, 1976; Vogel, 1978). Similarly, warmer  
240 regional temperatures (Talma and Vogel, 1992), decreased Antarctic sea-ice presence, higher  
241 Southern Ocean sea-surface temperatures (SSTs) (Nielsen et al., 2004) and increased humidity  
242 at Eilandvlei (Quick et al., 2018) and Cold Air Cave (Holmgren et al., 2003) (both strongly  
243 influenced by tropical systems) are not consistent with a decrease in warm growing season C<sub>4</sub>  
244 grasses at this time. Rather, we propose that this relationship is a function of an ecological  
245 response to aridity thresholds at the site. Under generally drier conditions - due to either  
246 less/less regular rainfall or an extended drought season at the site - shallow rooting grasses may

247 be less abundant (or less palatable (Carr et al., 2016)) relative to deeper rooting trees and  
248 shrubs, which may access more reliable water reserves (Gil-Romera et al., 2007; Holmgren et  
249 al., 2003; Lim et al., 2016).

250 At multi-centennial and millennial timescales, the BK-2-2  $\delta^{15}\text{N}$  record is positively  
251 correlated with palaeotemperature reconstructions obtained from speleothem  $\delta^{18}\text{O}$  data from  
252 nearby Cango Cave (140 km west of BK-2-2) (Talma and Vogel, 1992) (Figure 7). This is perhaps  
253 due at least in part to the impact of reduced temperatures on evapotranspiration, rendering  
254 precipitation more effective (and  $\delta^{15}\text{N}$  lower), as has been observed in other  
255 palaeoenvironmental reconstructions from the broader region (Chevalier and Chase, 2016). At  
256 these timescales (wavelengths of 60-100 (~3000-5000 years)) the midden  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  records  
257 are positively correlated (Figure 6). This is consistent with either changes in proportions in  $\text{C}_3$  vs  
258  $\text{C}_4$  grasses as a function of temperature (increased cool growing season  $\text{C}_3$  grasses under cooler  
259 conditions, which correlate with lower  $\delta^{15}\text{N}$ ) or changes in water-use efficiency, which result in  
260 lower  $\delta^{13}\text{C}$  values under more humid conditions (Figure 5, 6).

## 261 **4.2 Patterns and drivers of changes in hydroclimate**

262 As the site is located in the ARZ, and influenced by temperate and tropical circulation systems,  
263 we have compared the midden  $\delta^{15}\text{N}$  record with proxies reflecting changes in each system. At  
264 multi-millennial timescales, the BK-2-2  $\delta^{15}\text{N}$  record is negatively correlated with tropically-  
265 dominated records from Cold Air Cave (Holmgren et al., 2003) and Eilandvlei (Chase and Quick,  
266 2018; Quick et al., 2018). It is also positively correlated with Southern Ocean sea-ice and SST  
267 records (Nielsen et al., 2004) - proxies for the position of the southern westerlies - and with the

268  $\delta^{15}\text{N}$  record from Seweweekspoort (Chase et al., 2013; Chase et al., 2017), which is most  
269 strongly influenced by the westerlies at these timescales (Figure 8). This suggests that - at its  
270 broadest scale – long-term Holocene hydroclimatic change at BK-2-2 is dominated by the  
271 influence of temperate circulation systems and winter rainfall, as has been previously  
272 suggested for this region (Chase et al., 2013; Chase et al., 2017). It also supports the proposition  
273 that coastal sites such as Eilandvlei experience climate regimes that are distinct from sites in  
274 the Cape Fold Mountains and interior, perhaps as a result of the highly localised influence of  
275 the Agulhas Current and the related onshore flow of moist air (Chase and Quick, 2018).

276 Chase et al. (2017) suggest that while the model of increased winter rainfall during  
277 glacial periods and increased summer rainfall during interglacial periods (Cockcroft et al., 1987;  
278 van Zinderen Bakker, 1976) may reasonably describe southern African climate change at multi-  
279 millennial and glacial-interglacial timescales, shorter-term multi-centennial to millennial-scale  
280 climate change may be driven by variability in the *non-dominant* system. For instance, in the  
281 continental interior during the Holocene, when convective potential has been generally high as  
282 a result of elevated continental and sea-surface temperatures (Chevalier and Chase, 2015;  
283 Heaton et al., 1986; Simon et al., 2015; Sonzogni et al., 1998; Stute and Talma, 1998; Talma and  
284 Vogel, 1992), changes in the position of the westerlies and associated frontal systems – which  
285 are relatively weak in comparison with glacial periods – may be critical for inducing multi-  
286 centennial to millennial scale changes in regional hydroclimates (Chase et al., 2017). This may  
287 be the result of additive processes, such as the contribution of rainfall during the drought  
288 season (Chase et al., 2015a; Chase et al., 2015b), or integrative processes such as the

289 development of composite synoptic systems as in the case of tropical-temperate troughs  
290 (Chase et al., 2017).

291 Evidence that this dynamic manifests at Baviaanskloof during the Holocene may be seen  
292 in the relationships between the BK-2-2  $\delta^{15}\text{N}$  record, the Cold Air Cave  $\delta^{13}\text{C}$  (Holmgren et al.,  
293 2003), the Eilandvlei afrotemperate forest pollen records (Quick et al., 2018), and the TN057-17  
294 record for Antarctic sea-ice presence (Nielsen et al., 2004). At multi-millennial timescales, there  
295 is a strong positive relationship between humidity at Baviaanskloof and Antarctic sea-ice  
296 presence (Figure 8), and these trends are anti-phased with the tropically dominated records  
297 from Cold Air Cave and Eilandvlei (Figure 8). When multi-millennial trends are removed,  
298 however, the isolated shorter-term multi-centennial and millennial modes of variability  
299 commonly indicate same-sign anomalies (Figure 9). These similarities are particularly strong  
300 between ~6500 cal BP to 3000 cal BP, when Southern Ocean SSTs are at their Holocene  
301 minimum and Antarctic sea-ice is best developed (Figure 8). This is consistent with the  
302 proposition of Chase et al. (2017) that between temperate and tropical influence it is the non-  
303 dominant system that drives multi-centennial to millennial scale climate change anomalies; *i.e.*  
304 when the westerlies are in a more stable equatorward position it is changes in tropical potential  
305 that may determine higher frequency variability.

306 These findings highlight a complex dynamic that likely requires a fuller regional dataset  
307 to adequately characterise. Compared with Seweweekspoort, 235 km to the east of BK-2-2  
308 (Chase et al., 2013; Chase et al., 2017), there are some broad similarities, but also some  
309 significant differences (Figure 8). At both sites, early mid-Holocene conditions (~7000-5500 cal



310 BP) are relatively dry (higher  $\delta^{15}\text{N}$ ), and a rapid change towards more humid conditions is  
311 registered between 5500-5000 cal BP. At Seweweekspoort, this generally humid period lasts  
312 until ~3500 cal BP, while at BK-2-2 it extends until ~3000 cal BP and is more clearly bimodal,  
313 with periods of maximum humidity at ~5000 and ~3000 cal BP. A more distinct difference is  
314 apparent in the late Holocene (from ~1000 cal BP), when the Seweweekspoort record indicates  
315 a strong increase in humidity, while at BK-2-2 conditions remain relatively dry. As the only two  
316 palaeo-humidity records currently available from this axis of the Cape Fold Mountains, it  
317 remains to be seen whether the differences between these records indicate changes in the  
318 relative dominance of temperate/tropical circulation systems along environmental gradients or  
319 distinct micro- to meso-scale phenomena. The influence and interactions of temperate and  
320 tropical systems combined with the spatial heterogeneity of climate change anomalies  
321 engendered by the region's strong topographic variability has been highlighted in the  
322 identification of marked climate response gradients from across the region (Chase et al., 2019;  
323 Chase et al., 2015b; Chase and Quick, 2018). The records presented here from Baviaanskloof  
324 are consistent with this growing body of evidence, presenting strong indications for the  
325 influence of the underlying climate drivers, but expressing anomalies that suggest a complex -  
326 and as yet unresolved - spatio-temporal dynamic.

## 327 **5 Conclusions**

328 The stable carbon and nitrogen isotope data from the rock hyrax midden at Baviaanskloof in  
329 South Africa's Eastern Cape provides valuable evidence from a climatically complex region.  
330 Strong correlations with palaeotemperature reconstructions from the nearby Cango Cave

331 speleothems (Talma and Vogel, 1992) suggest that changes in temperature may have had a  
332 significant control on hydroclimate at the site. Similarities between BK-2-2 with SSTs and sea-ice  
333 presence in the Atlantic sector of the Southern Ocean (Nielsen et al., 2004) imply a clear link  
334 between changes in Antarctic sea ice extent, the southern westerlies and environmental  
335 conditions in the Cape Fold Mountains, with temperate circulation systems driving climatic  
336 variability at multi-millennial timescales. These results contrast with data from Eilandvlei on the  
337 southern Cape coast, which exhibit an anti-phase relationship with proxies for westerly  
338 influence, and express patterns of climate change similar to the southeast African tropics.  
339 Considered together, these data support the proposition that a steep climate response gradient  
340 has existed between the coast and adjacent uplands in the southern Cape (Chase and Quick,  
341 2018; Quick et al., 2018).

342         At shorter multi-centennial to millennial timescales, however, temperate circulation  
343 systems do not appear to have been the dominant driver of climate change at Baviaanskloof.  
344 Rather, higher frequency hydroclimatic anomalies observed in the BK-2-2 record share strong  
345 similarities with records of variability in tropical climate systems, such as Cold Air Cave  
346 (Holmgren et al., 2003). The strength of influence of this tropical signal is temporally variable,  
347 being most prevalent – perhaps counter-intuitively – during the mid-Holocene phase of cooler  
348 Southern Ocean SSTs and increased Antarctic sea-ice extent. This is, however, consistent with  
349 the proposition that patterns of millennial-scale climate change in the Cape Fold Mountains are  
350 dictated by variability within the non-dominant component of the temperate/tropical dynamic  
351 that determines hydroclimatic variability in the region (Chase et al., 2017; Chase et al., 2015a;  
352 2015b). Overall, the complex and dynamic nature of these relationships makes it clear that

353 while the Baviaanskloof data provide important new evidence regarding spatio-temporal  
354 variability of climatic anomalies, more sites from both the terrestrial and marine realms are  
355 required before a reliable understanding of long-term environmental dynamics in the region is  
356 achieved.

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606

## 607 8 Table captions

608 **Table 1:** Radiocarbon ages and calibration information for the Baviaanskloof-2-2 rock hyrax  
609 midden.

## 610 9 Figure captions

611 **Figure 1: (A)** Map of southern Africa showing seasonality of rainfall and sharp climatic gradients  
612 dictated by the zones of summer/tropical (red) and winter/temperate (blue) rainfall  
613 dominance. Winter rainfall is primarily a result of storm systems embedded in the westerlies.  
614 Major atmospheric (white arrows) and oceanic (blue arrows) circulation systems are indicated.  
615 The location of the study site in the southern Cape region is shown. **(B)** Map of southern Cape  
616 with the Baviaanskloof site and other palaeoenvironmental sites indicated. **(C)** Topographical  
617 map of the region surrounding the Baviaanskloof site.

618 **Figure 2:** Elevation (black), mean annual precipitation (blue) and precipitation seasonality (red;  
619 higher values = greater seasonality) data for a north-south transect (23.73-23.78°E, 34-32.85°S)  
620 oriented to include the Baviaanskloof-2 hyrax midden site and indicating the decline in rainfall  
621 and increase in seasonality with distance from the coast. Data from the NASA Shuttle Radar  
622 Topographic Mission (SRTM v.4.1; Jarvis et al., 2008) and WorldClim 1.4 (Hijmans et al., 2005).

623 **Figure 3:** Photograph looking south into the narrow valley where the Baviaanskloof-2 site was  
624 found. The site itself is indicated in the white circle.

625 **Figure 4:** The age-depth model for the Baviaanskloof-2-2 midden section, established using the  
626 computing package Bacon v2.3.6 (Blaauw and Christen, 2011).

627 **Figure 5:** The  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  data from the Baviaanskloof-2-2 (BK-2-2) rock hyrax midden.

628 **Figure 6:** Results of wavelet-based semblance analysis (Cooper and Cowan, 2008) of the BK-2-2  
629  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  records. The records were interpolated to a common 50-year sample interval  
630 prior to analysis. In the upper two panes, red indicates large positive anomalies while blue  
631 indicates large negative anomalies. In the lower semblance pane, red indicates a semblance of  
632 +1 (positive correlation), and blue indicates a semblance of -1 (negative correlation).

633 **Figure 7:** Comparison of  $\delta^{15}\text{N}$  and  $\delta^{13}\text{C}$  variability from the Baviaanskloof-2-2 (BK-2-2) rock hyrax  
634 midden with the Cango Cave palaeotemperature reconstruction (Talma and Vogel, 1992). The  
635 central pane shows real-value variability in the 400-600 yr frequency band obtained using

636 continuous Morlet wavelet transforms of each record interpolated to a common 50-yr  
637 resolution.

638 **Figure 8:** A comparison of the  $\delta^{15}\text{N}$  **(a)** and  $\delta^{13}\text{C}$  **(c)** records from the Baviaanskloof-2-2 rock  
639 hyrax midden (this paper), the palaeotemperature reconstruction from Cango Cave **(b)** (Talma  
640 and Vogel, 1992), **(d)** the Cold Air Cave  $\delta^{13}\text{C}$  record (interpreted as higher  $\delta^{13}\text{C}$  values indicating  
641 more humid conditions; see Holmgren et al., 2003), the  $\delta^{15}\text{N}$  record from the Seweweekspoort  
642 rock hyrax middens **(e)** (Chase et al., 2017), the afrotemperate forest pollen record from  
643 Eilandvlei **(f)** (Quick et al., 2018), and proxies records relating to the position of the southern  
644 westerlies, including reconstructions of Southern Ocean summer sea-surface temperatures **(g)**  
645 and sea ice presence **(h)** (Nielsen et al., 2004).

646 **Figure 9:** A comparison of the Baviaanskloof-2-2  $\delta^{15}\text{N}$  record, the afrotemperate forest pollen  
647 record from Eilandvlei (Quick et al., 2018), and the Cold Air Cave  $\delta^{13}\text{C}$  record (interpreted as  
648 higher  $\delta^{13}\text{C}$  values indicating more humid conditions; see Holmgren et al., 2003). Records were  
649 normalised using standard scores. Multi-millennial trends have been removed from each record  
650 using 3<sup>rd</sup>-order polynomials to isolate multi-centennial and millennial scale anomalies. Shading  
651 is derived from anomalies observed in the Baviaanskloof-2-2 record, with red indicating relative  
652 aridity and blue indicating relative humidity.