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Abstract

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

Keywords

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

Highlights

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

1 Introduction

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

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

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

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

In terms of past climate change and its drivers, detailed, high resolution records from Seweweekspoort and Eilandvlei (Figure 1) indicate a surprising degree of spatial heterogeneity, implying strong hydroclimatic gradients existed over relatively short distances (<150 km) moving away from the coast, establishing and a coastal-interior dipole (Chase and Quick, 2018). From this, it has been hypothesised that the Agulhas Current may have a dominant, potentially highly localised, influence on near-coast environments (Chase and Quick, 2018), and may not extend northward beyond the coast-parallel orographic barrier of the Cape Fold Mountains (Jury et al., 1993), where macro-scale synoptic systems (e.g. tropical-temperate troughs (Hart et al., 2013; Washington and Todd, 1999)) dominate the climates and climatic variability of the continental interior (Chase et al., 2017). Fundamental questions remain, however, regarding the spatio-temporal distribution of climate change anomalies and it is clear that more data from a wider spatial range of sites is required before intra- and inter-regional long-term climate dynamics can be properly understood. The importance of understanding such gradients is significant in that the southern Cape coastal plain may have been mechanistically distinct in terms of its climate (Chase and Quick, 2018; Jury, 2015), as well as topographically and edaphically distinct from the Cape Fold Belt and the interior, which has implications for interpretation of the regional archaeological record.

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

1.1 Site description

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

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

The hyrax midden recovered for this study (Baviaanskloof-2-2 (BK-2-2); 33.53°S, 23.76°E, 800 m m.a.s.l.) was found on a northeast facing cliff in a tributary valley cut into the southern flank of Baviaanskloof (Figure 1c, 3). The vegetation in the area surrounding the site is a complex mosaic, reflecting the variable topography and geology of the region. The tributary valley itself is dominated by Groot Thicket (Mucina and Rutherford, 2006), a dense, shrubby vegetation characterised by succulent tree species such as *Aloe ferrox* and *Euphorbia tetragona* (Figure 3). Other trees and tall shrubs include *Vachellia* (*Acacia*) *karoo*, *Portulacaria afra*, *Pappea capensis*, *Boscia albitrunca*, *Grewia robusta*, *Dodonaea viscosa* and *Searsia* spp. Succulent *Crassula* shrubs are abundant, and grass cover in the valley itself is limited. To the north (~250 m), a small alluvial fan has developed at the junction with the main Baviaanskloof valley. Vegetation on the fan is much sparser than in the tributary valley, and grasses form a more important component of the vegetation. Above the site (~200 m), the surface of the plateau into which the tributary valley is incised supports a Baviaanskloof Shale Renosterveld vegetation (Mucina and Rutherford, 2006). *Aloe ferrox* and other smaller succulents are present, but the vegetation is dominated by *Elytropappus rhinocerotis* and grasses (including C_3 (*Agrostis*, *Melica*, *Stipa*) and C_4 (*Eragrostis*, *Eustachys* and *Themeda*) varieties). As rock hyraxes are generalist feeders (Carr et al., 2016; Fourie, 1990; Hoeck, 1975), the occurrence of C_4 and succulents presents the possibility that the diet of the hyraxes living at the site included non-C_3 plants.

2 Material and methods

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

Radiocarbon age determinations (n=7) were processed at the ^{14}CHRONO Centre, Queen's University Belfast using accelerator mass spectrometry (AMS) (Table 1; Figure 4). Samples were pre-treated with 2% HCl for one hour at room temperature to remove carbonates and dried at 60°C. They were then weighed into quartz tubes with an excess of CuO, sealed under vacuum and combusted to CO_2. The CO_2 was converted to graphite on an iron catalyst using the zinc reduction method (Slota et al., 1987). The radiocarbon ages were corrected for isotope fractionation using the AMS measured $\delta^{13}C$ and calibrated using the SHCal13 calibration data (Hogg et al., 2013). The Bayesian Bacon 2.3.6 software package (Blaauw and Christen, 2011) was used to generate all age-depth models (Figure 4). Considering the nature of the age model, the midden was considered to still be actively accumulating, and a surface age estimate of the year of collection (2013) was included in the construction of the age model.

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

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

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

3 Results

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

The $\delta^{15}N$ values of BK-2-2 range from 0.7 to 12.1‰ (Figure 5). The lowest values occur during the mid-Holocene (~5000 cal BP), with periods of generally higher values from 7200-6300 cal BP, 4600-3400 cal BP and ~3000 cal BP to present. The $\delta^{13}C$ values from the BK-2-2 midden vary from -20.6 to -25.5‰ (Figure 5). The lowest and least variable $\delta^{13}C$ values occur generally from 3000 cal BP to present, with higher values occurring from 7000-3000 cal BP. For much of the record, a degree of covariance is observed between the $\delta^{13}C$ and $\delta^{15}N$ values of the midden, which exhibit a positive correlation at multi-centennial to millennial timescales (wavelengths ~15-80 (750-4000 years); Figures 5, 6). However, at multi-millennial timescales (Figure 6; i.e. wavelengths >100 (>5000 years)) $\delta^{15}N$ and $\delta^{13}C$ are negatively correlated.

4 Discussion

4.1 Stable nitrogen and carbon isotopes

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

The midden $\delta^{13}C$ signal reflects animal diet and, in turn, two aspects of the response of vegetation to climate change: 1) plant photosynthetic pathway, i.e. C_3 (~-34 to -24‰), C_4 (~-16 to -10‰) and CAM (typically within the range -20 to -10‰) plants (Boom et al., 2014; Rundel et al., 1999; Smith, 1972; Smith and Epstein, 1971; Werger and Ellis, 1981), and 2) changes in C_3 plant water-use efficiency (Ehleringer and Cooper, 1988; Farquhar and Richards, 1984; Farquhar et al., 1989). At the BK-2-2 site, C_3 vegetation is abundant in the form of trees and shrubs, and the presence of both C_3 and C_4 grasses has been indicated (Mucina and Rutherford, 2006; Vogel, 1978). CAM plants are also abundant at the site (Figure 3), and as generalist feeders (Fourie, 1990; Hoeck, 1975) these can be part of the hyraxes' diet, although perhaps not in significant quantities (Carr et al., 2010a; Carr et al., 2016; Fourie, 1983).

In considering the isotope records from BK-2-2, we have identified variability at two primary timescales; multi-millennial variability (Figure 6; wavelengths >100 (>5000 years)), encompassing change across the whole of the record, and multi-centennial to millennial variability (wavelengths ~15-80 (750-4000 years)). At multi-millennial timescales, midden $\delta^{15}N$ and $\delta^{13}C$ are negatively correlated, with lower $\delta^{13}C$ values occurring under relatively drier conditions (indicated by higher $\delta^{15}N$ values) (Figure 6). This is most apparent during the late Holocene, after ~3000 cal BP (Figure 5), and might at first glance be associated with changes in temperature and/or rainfall seasonality. Available data from the region (Figures 7, 8), however, are not consistent with either of these mechanisms. For instance, lower $\delta^{13}C$ values would not be predicted with the strong increase in temperatures observed at ~3000 cal BP in the Cango Cave record (e.g. Epstein et al., 1997; Teeri and Stowe, 1976; Vogel, 1978). Similarly, warmer regional temperatures (Talma and Vogel, 1992), decreased Antarctic sea-ice presence, higher Southern Ocean sea-surface temperatures (SSTs) (Nielsen et al., 2004) and increased humidity at Eilandvlei (Quick et al., 2018) and Cold Air Cave (Holmgren et al., 2003) (both strongly influenced by tropical systems) are not consistent with a decrease in warm growing season C_4 grasses at this time. Rather, we propose that this relationship is a function of an ecological response to aridity thresholds at the site. Under generally drier conditions - due to either less/less regular rainfall or an extended drought season at the site - shallow rooting grasses may be less abundant (or less palatable (Carr et al., 2016)) relative to deeper rooting trees and shrubs, which may access more reliable water reserves (Gil-Romera et al., 2007; Holmgren et al., 2003; Lim et al., 2016).

At multi-centennial and millennial timescales, the BK-2-2 $\delta^{15}N$ record is positively correlated with palaeotemperature reconstructions obtained from speleothem $\delta^{18}O$ data from nearby Cango Cave (140 km west of BK-2-2) (Talma and Vogel, 1992) (Figure 7). This is perhaps due at least in part to the impact of reduced temperatures on evapotranspiration, rendering precipitation more effective (and $\delta^{15}N$ lower), as has been observed in other palaeoenvironmental reconstructions from the broader region (Chevalier and Chase, 2016). At these timescales (wavelengths of 60-100 (~3000-5000 years)) the midden $\delta^{15}N$ and $\delta^{13}C$ records are positively correlated (Figure 6). This is consistent with either changes in proportions in C_3 vs C_4 grasses as a function of temperature (increased cool growing season C_3 grasses under cooler conditions, which correlate with lower $\delta^{15}N$) or changes in water-use efficiency, which result in lower $\delta^{13}C$ values under more humid conditions (Figure 5, 6).

4.2 Patterns and drivers of changes in hydroclimate

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

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

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

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

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

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

5 Conclusions

The stable carbon and nitrogen isotope data from the rock hyrax midden at Baviaanskloof in South Africa's Eastern Cape provides valuable evidence from a climatically complex region. Strong correlations with palaeotemperature reconstructions from the nearby Cango Cave speleothems (Talma and Vogel, 1992) suggest that changes in temperature may have had a significant control on hydroclimate at the site. Similarities between BK-2-2 with SSTs and sea-ice presence in the Atlantic sector of the Southern Ocean (Nielsen et al., 2004) imply a clear link between changes in Antarctic sea ice extent, the southern westerlies and environmental conditions in the Cape Fold Mountains, with temperate circulation systems driving climatic variability at multi-millennial timescales. These results contrast with data from Eilandvlei on the southern Cape coast, which exhibit an anti-phase relationship with proxies for westerly influence, and express patterns of climate change similar to the southeast African tropics. Considered together, these data support the proposition that a steep climate response gradient has existed between the coast and adjacent uplands in the southern Cape (Chase and Quick, 2018; Quick et al., 2018).

At shorter multi-centennial to millennial timescales, however, temperate circulation systems do not appear to have been the dominant driver of climate change at Baviaanskloof. Rather, higher frequency hydroclimatic anomalies observed in the BK-2-2 record share strong similarities with records of variability in tropical climate systems, such as Cold Air Cave (Holmgren et al., 2003). The strength of influence of this tropical signal is temporally variable, being most prevalent – perhaps counter-intuitively – during the mid-Holocene phase of cooler Southern Ocean SSTs and increased Antarctic sea-ice extent. This is, however, consistent with the proposition that patterns of millennial-scale climate change in the Cape Fold Mountains are dictated by variability within the non-dominant component of the temperate/tropical dynamic that determines hydroclimatic variability in the region (Chase et al., 2017; Chase et al., 2015a; 2015b). Overall, the complex and dynamic nature of these relationships makes it clear that while the Baviaanskloof data provide important new evidence regarding spatio-temporal variability of climatic anomalies, more sites from both the terrestrial and marine realms are required before a reliable understanding of long-term environmental dynamics in the region is achieved.

6 Acknowledgements

Funding was received from the European Research Council (ERC) under the European Union's Seventh Framework Programme (FP7/2007-2013)/ERC Starting Grant “HYRAX”, grant agreement no. 258657. Two anonymous reviewers are thanked for constructive comments on an earlier version of this paper. This contribution is ISEM no. XXXX-XXX.

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8 Table captions

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

9 Figure captions

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

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

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

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

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

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

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

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

Figure 8: A comparison of the $\delta^{15}N$ **(a)** and $\delta^{13}C$ **(c)** records from the Baviaanskloof-2-2 rock hyrax midden (this paper), the palaeotemperature reconstruction from Cango Cave **(b)** (Talma and Vogel, 1992), **(d)** the Cold Air Cave $\delta^{13}C$ record (interpreted as higher δ13C values indicating more humid conditions; see Holmgren et al., 2003)**,** the $\delta^{15}N$ record from the Seweweekspoort rock hyrax middens **(e)** (Chase et al., 2017), the afrotemperate forest pollen record from Eilandvlei **(f)** (Quick et al., 2018), and proxies records relating to the position of the southern westerlies, including reconstructions of Southern Ocean summer sea-surface temperatures **(g)** and sea ice presence **(h)** (Nielsen et al., 2004).

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