



The dynamic relationship between temperate and tropical circulation systems across South Africa since the last glacial maximum



Brian M. Chase^{a,*}, Manuel Chevalier^b, Arnoud Boom^c, Andrew S. Carr^c

^a Centre National de La Recherche Scientifique, UMR 5554, Institut des Sciences de L'Evolution-Montpellier, Université Montpellier, Bat.22, CC061, Place Eugène Bataillon, 34095 Montpellier, Cedex 5, France

^b Institute of Earth Surface Dynamics, Geopolis, University of Lausanne, Quartier UNIL-Mouline, Bâtiment Géopolis, CH-1015 Lausanne, Switzerland

^c School of Geography, Geology and the Environment, University of Leicester, Leicester, LE1 7RH, UK

ARTICLE INFO

Article history:

Received 9 December 2016

Received in revised form

5 August 2017

Accepted 11 August 2017

Keywords:

Last glacial maximum

Holocene

Palaeoclimate

Climate dynamics

South Africa

Hyrax middens

Stable isotopes

ABSTRACT

A fundamental and long-standing question of southern African palaeoclimatology is the way tropical and temperate climate system dynamics have influenced rainfall regimes across the subcontinent since the Last glacial maximum. In this paper, we analyse a selection of recently published palaeoclimate reconstructions along a southwest-northeast transect across South Africa. These records span the last 22,000 years, and encompass the transition between the region's winter and summer rainfall zones. In synthesis, these records confirm broad elements of the dominant paradigm, which proposes an inverse coeval relationship between temperate and tropical systems, with increased precipitation in the winter (summer) rainfall zone during glacial (interglacial) periods. Revealed, however, is a substantially more complex dynamic, with millennial-scale climate change events being strongly – even predominantly – influenced by the *interaction and combination* of temperate and tropical systems. This synoptic forcing can create same sign anomalies across the South African rainfall zones, contrary to expectations based on the classic model of phase opposition. These findings suggest a new paradigm for the interpretation of southern African palaeoenvironmental records that moves beyond simple binary or additive influences of these systems.

© 2017 Published by Elsevier Ltd.

1. Introduction

Southern African climate is strongly influenced by both temperate systems (associated with the southern westerly storm track) and tropical easterly flow (Tyson, 1986). As a result, the region is recognised as a particularly dynamic region in terms of long-term climate change (Chase and Meadows, 2007; Gasse et al., 2008; Tyson, 1986). Seasonal variations in the position and strength of these systems results in southwestern Africa receiving most of its rainfall during the austral winter months, while most of the subcontinent experiences a primarily summer rainfall regime (Fig. 1). Over the last 40 years, most palaeoclimatic syntheses have generally concluded that: 1) the modern boundaries of these rainfall zones (often referred to as the winter and summer rainfall zones, or WRZ and SRZ (see Chase and Meadows, 2007)) may have shifted significantly over time, and 2) that the WRZ received more

precipitation during cool/glacial periods, whereas the SRZ received more precipitation during warm/interglacial periods (Chase and Meadows, 2007; Cockcroft et al., 1987; Deacon and Lancaster, 1988; Heine, 1982; Partridge et al., 1999; Tyson, 1999; Tyson and Lindesay, 1992; van Zinderen Bakker, 1976).

In this paper, we explore this paradigm by considering a selection of recently published well-dated, high-resolution palaeoclimate reconstructions along a southwest-northeast rainfall seasonality gradient across South Africa spanning 22,000 years and encompassing the transition between the WRZ and SRZ (Fig. 1). Employed primarily are: 1) a newly expanded suite of stable isotope data from rock hyrax middens recovered from Seweweekspoort, at the eastern margin of the modern winter rainfall zone, and 2) precipitation reconstructions from South Africa's northern and south-central summer rainfall zones (Chevalier and Chase, 2015). We focus on these records as they are considered to primarily express variability in temperate and tropical moisture-bearing systems respectively. We have excluded sites from western margins of South Africa such as De Rif (Chase et al., 2011, 2015a; Quick et al., 2011; Valsecchi et al., 2013), Pakhuis Pass (Scott and Woodborne,

* Corresponding author.

E-mail address: brian.chase@univ-montp.fr (B.M. Chase).

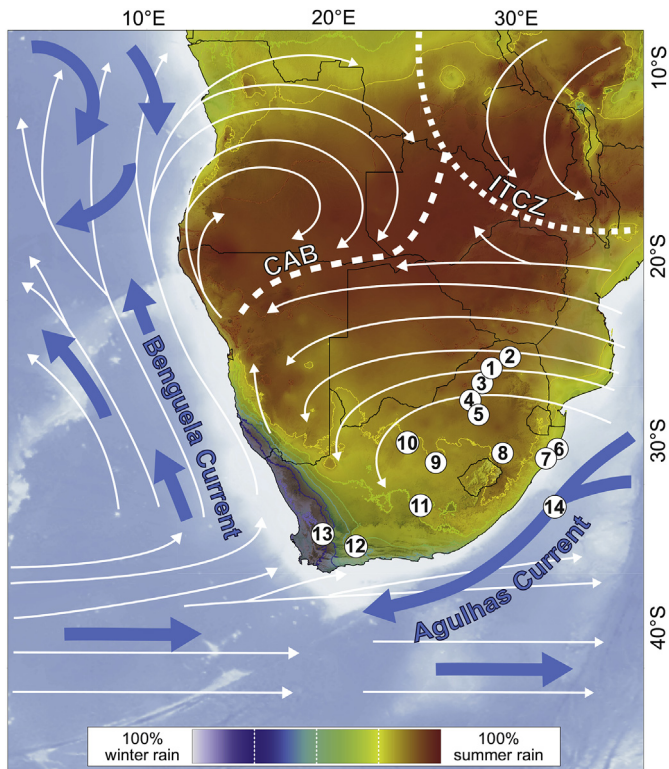


Fig. 1. Map of southern Africa showing seasonality of rainfall and sharp climatic gradients dictated by the zones of summer/tropical (red) and winter/temperate (blue) rainfall dominance. Winter rainfall is primarily a result of storm systems embedded in the westerlies. Major atmospheric (white arrows) and oceanic (blue arrows) circulation systems and the austral summer positions of the Inter-Tropical Convergence Zone (ITCZ) and the Congo Air Boundary (CAB) are indicated. The location of Cold Air Cave is shown (1), as are the key palaeoenvironmental sites used for the reconstruction of summer rainfall zone climates (Northern region: 2) Tate Vondo, 3) Wonderkrater, 4) Tswaing Crater, 5) Rietveld; and South-central region: 6) Mfabeni, 7) Eteza, 8) Braamhoek, 9) Florisbad, 10) Equus Cave, 11) Blydefontein (see [Chevalier and Chase, 2015](#)), the sites at 12) Seweweekspoort and 13) Katbakkies Pass, which are strongly influenced by the southern westerlies, and 14) the CD154-10-06P marine core. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2007a, b), Eksteenfontein ([Scott et al., 1995](#)) and Pella ([Lim et al., 2016](#)), as records from these sites have been shown to be strongly influenced by the South Atlantic Anticyclone, and are not clear reflections of dynamics of either the westerly storm track or tropical easterly flow. Through the resulting synthesis we seek to refine our understanding of South African climate dynamics as a function of global change. The data enable us to identify a clear patterning of climate anomalies that is consistent with trends and events observed in independent records specifically indicative of temperate and tropical influences. We argue that along the transect considered, during the analysed time interval, singular dominance of temperate or tropical systems is only relevant at orbital time-scales, and it is only through considering how these perceived end-members interact that much of the observed millennial-scale climate change in the region can be understood.

2. Materials and methods

2.1. Rock hyrax middens

Central to this study is a series of rock hyrax middens from Seweweekspoort ([Fig. 1](#)). Rock hyrax middens – the communal latrines of the rock hyrax (*Procavia capensis*) – accumulate over

thousands of years and preserve continuous records of past climate change ([Chase et al., 2012](#)). Six middens from two sites within Seweweekspoort (SWP-1; 33.367°S, 21.414°E and SWP-3; 33.409°S, 21.403°E) were selected for analysis because they are composed almost entirely of hyraceum (no visible faecal pellets). Our experience has demonstrated that such middens have superior stratigraphic integrity compared to more pellet-rich middens ([Chase et al., 2012](#)).

2.2. Radiocarbon dating

Representative portions of the middens were processed following [Chase et al. \(2013, 2012\)](#). Radiocarbon age determinations ($n = 36$) were processed at the $^{14}\text{CHRONO}$ Centre, Queen's University Belfast using accelerator mass spectrometry (AMS) ([Fig. S1](#); [Table S1](#)). The radiocarbon ages were corrected for isotope fractionation using the AMS measured $\delta^{13}\text{C}$ and calibrated using the SHCal13 calibration data ([Hogg et al., 2013](#)). The Bacon 3.0.3 software package ([Blaauw and Christen, 2011](#)) was used to generate all age-depth models ([Fig. S1](#)). Results indicate that these sequences continuously span the last 22,300 years.

2.3. Stable nitrogen and carbon isotopes

The stable nitrogen (^{15}N) and carbon (^{13}C) isotope contents of 767 overlapping hyraceum samples were measured at the Department of Archaeology, University of Cape Town following [Chase et al. \(2010, 2009; 2011; 2012\)](#), with contiguous/overlapping samples obtained from two series of offset 1 mm holes. For the stable isotope analyses, the standard deviation derived from replicate analyses of homogeneous material was better than 0.2‰ for both nitrogen and carbon. Nitrogen isotope results are expressed relative to atmospheric nitrogen ([Figs. S1 and S2](#)). Carbon isotope results are expressed relative to Vienna PDB ([Fig. S3](#)).

The carbon isotopic composition of the hyraceum is representative of vegetation around a midden site ([Carr et al., 2016](#)) and provides information on 1) the relative contribution of C_3 , C_4 and CAM plants ([Smith, 1972](#)) to the animals' diet, and 2) variations in plant water-use efficiency (WUE) as a function of climate ([Ehleringer and Cooper, 1988; Farquhar et al., 1989; Farquhar and Richards, 1984; Pate, 2001](#)). Throughout the broader region, the distribution of C_3 and C_4 grasses tracks the proportion of winter versus summer rainfall ([Vogel, 1978](#)). At Seweweekspoort today, grasses are a mosaic of C_3 and C_4 varieties ([Rutherford et al., 2003, 2012; SANBI, 2003](#)), and where aspect and soil depth limit soil water content, succulent CAM plants become increasingly abundant. As C_3 plants are depleted in ^{13}C compared with most CAM and all C_4 plants, higher $\delta^{13}\text{C}$ values indicate more abundant warm season (C_4) grasses and/or CAM plants, and generally warmer/more arid conditions. An additional potential control on the $\delta^{13}\text{C}$ signal is the deglacial increase in atmospheric CO_2 ([Ehleringer and Cerling, 1995; Huang et al., 2001](#)). This, however, would result in higher glacial age $\delta^{13}\text{C}$ values, which is the opposite of what we observe at Seweweekspoort ([Fig. 2](#)). We thus conclude that either the changes in atmospheric CO_2 did not significantly impact the vegetation, or that it was over-ridden by the changes in water-availability experienced at the site ([Huang et al., 2001](#)), as indicated by the $\delta^{15}\text{N}$ data ([Fig. 2](#)).

Hyraceum $\delta^{15}\text{N}$ is an indicator of changes in ecosystem water-availability ([Carr et al., 2016; Chase et al., 2009, 2011, 2013, 2015b](#)). A positive relationship exists between aridity and $\delta^{15}\text{N}$ in soils, plants and hyraxes, with drier conditions correlating with enriched ^{15}N ([Carr et al., 2016](#)). This most likely reflects denitrification processes in arid/semi-arid soils ([Handley et al., 1994, 1999; Hartman, 2011; Heaton, 1987; Murphy and Bowman, 2006, 2009;](#)

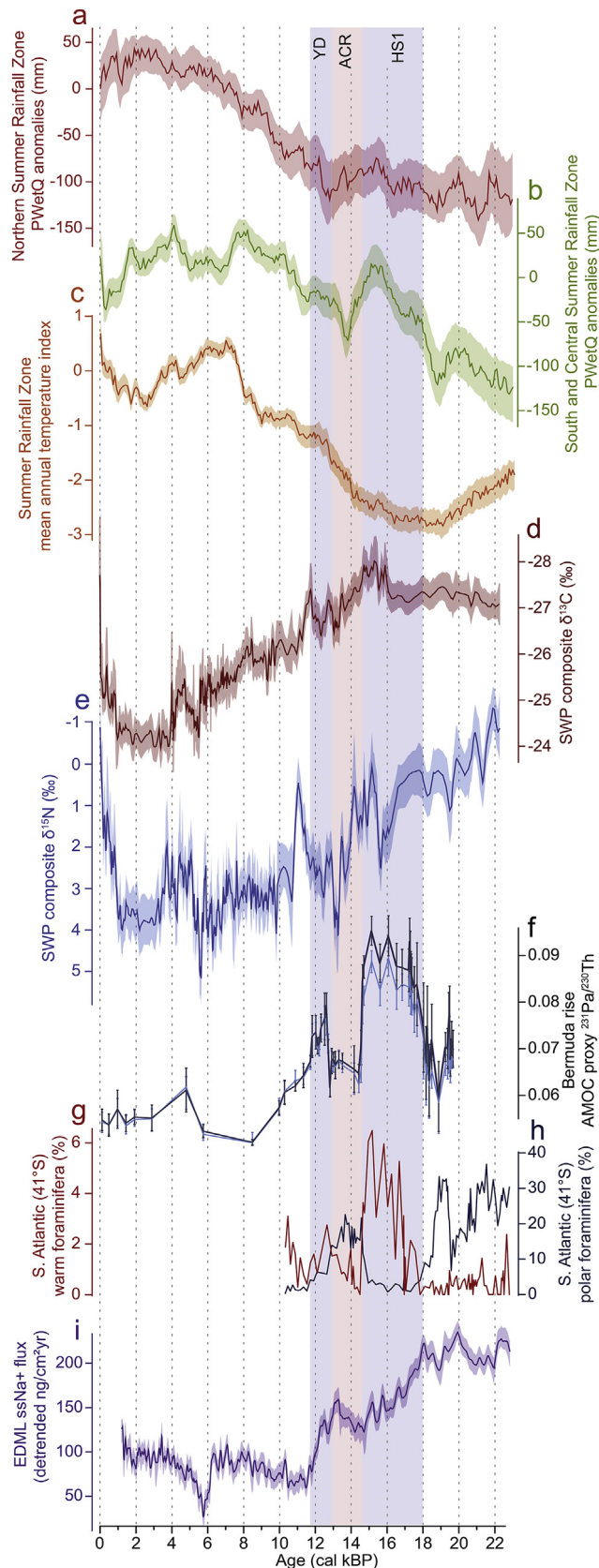


Fig. 2. Comparison of proxy records from the South African transect considered for this study. Heinrich stadial 1 (HS1), the Younger Dryas cold reversal (YD) are highlighted by blue shading, and the Antarctic Cold Reversal (ACR) shaded in red. Conditions in the summer rainfall zone are shown in wet season precipitation reconstructions (PWetQ) for the north and south-central regions, and a region-wide

Wang et al., 2010), and has been observed in other herbivores in dryland regions (Ambrose and DeNiro, 1986; Hartman, 2011; Murphy and Bowman, 2006). In hyraceum samples, the narrowly defined feeding range of the hyraxes (<60 m from the latrine; Sale, 1965), and the accumulation rates of the middens (~20–60 years/sample in most cases) enforces a spatio-temporal averaging that reduces the $\delta^{15}\text{N}$ variability observed in modern ecosystem studies (Carr et al., 2016), and provides a more reliable index of past water variability (Carr et al., 2016; Chase et al., 2012).

Results from each of the different Seweweekspoort rock hyrax middens overlap such that they can be combined to create a 22,300-year composite record for the sites. To achieve this, the stable isotope data were combined using Local Regression (LOESS) curve fitting of the combined datasets (Figs. S2 and S3). As individual middens under the same climate regime may exhibit differences in their isotopic records due to microclimatic influences (Carr et al., 2016) on individual foraging ranges (i.e. baseline $\delta^{15}\text{N}$ variability), prior to LOESS curve fitting we adjusted the $\delta^{15}\text{N}$ to account for these differences. Using the SWP-1-1 and SWP-1-4b records as a datum, an estimated offset of 1.5‰ was added to the $\delta^{15}\text{N}$ data from the SWP-3-1 to compensate for the more humid microclimate in which the midden was found, and 0.5‰ and 1‰ were added to SWP-1-5 and SWP-1-2a respectively to account for their more exposed positions. This accounts for some, but not all, differences between the midden records. The $\delta^{15}\text{N}$ record from SWP-1-5, for instance, presents an anomalous signal (Fig. S2), which Chase et al. (2013) attribute to be primarily a function of both the position of the midden and the lower resolution of the record. Overall, however, we find that the composite record created from these datasets is coherent at orbital and millennial scales, and is suitable for the level of analysis addressed in this paper.

2.4. Defining variability in temperate and tropical systems

To characterise variability in the temperate systems influencing South Africa, we employ the Seweweekspoort hyrax midden records presented in this paper and data from the EPICA Dronning Maud Land ice core (EDML; Fischer et al., 2007). We consider these to reflect respectively: 1) the influence of the westerly storm track on southern Africa, and 2) an underlying driver of the latitudinal position of the storm track through variations in sea-ice extent (Chase et al., 2013; Fischer et al., 2007; Levine et al., 2014; Wolff et al., 2010). For tropical systems, new statistical techniques (Chevalier et al., 2014; Truc et al., 2013) have recently been used to reconstruct temperature, precipitation seasonality and aridity in the SRZ (Chevalier and Chase, 2015, 2016) using pollen records from Tate Vondo (Scott, 1987a), Wonderkrater (Scott, 1982), Tswaing Crater (Metwally et al., 2014; Scott, 1999), Rietvlei (Scott and Vogel, 1983), Blydefontein (Scott et al., 2005), Braamhoek (Norström et al., 2009), Equus Cave (Scott, 1987b), Florisbad (Scott and Nyakale, 2002) and lakes Eteza (Neumann et al., 2010; Scott and Steenkamp, 1996) and Mfabeni (Finch and Hill, 2008) (Fig. 1). Changes in the resulting aggregate record (Fig. 2a, b, c) have been linked to both remote and local forcing mechanisms (Chevalier and Chase, 2015). These analyses have allowed for the identification of

mean annual temperature reconstruction (a, b, c; Chevalier and Chase, 2015). Southern Cape conditions are reflected in the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data from the Seweweekspoort rock hyrax middens (d, e), and data reflecting important elements larger circulation systems affecting the region, such as the Atlantic Meridional Overturning Circulation (AMOC) (f; McManus et al., 2004), conditions in the proximal South Atlantic (g, h; Barker et al., 2009) and sea salt sodium concentrations from the EPICA DML ice core in Antarctica indicating sea-ice extent (i; Fischer et al., 2007) are shown. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

two broad climate regimes within the SRZ, one in the far northeast that exhibits what may be considered a 'pure' (>85%) summer rain regime (northern summer rainfall zone (N-SRZ)), used in this study to indicate the general strength of southeast African monsoon, and a second broader region that encompasses most of the interior (southern-central summer rainfall zone (SC-SRZ)), and exhibits a more complex pattern of variability (Chevalier and Chase, 2015).

2.5. Orbital-scale changes in temperate and tropical climate systems since the LGM

The Seweweekspoort record shows substantial changes in both $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ over the last 22,300 years, indicating significant changes in climate and vegetation (Fig. 2d, e, SI2, SI3) (Chase et al., 2013, under review). Across this period, which encompasses the critical transition between glacial and interglacial conditions, a strong trend is apparent, with cool, humid glacial conditions (indicated by depleted ^{13}C and ^{15}N) transitioning into warmer, but substantially drier conditions during the Holocene (Fig. 2). This aridification, while being in some part due to increased potential evapotranspiration under warmer conditions (Chevalier and Chase, 2016; Heaton et al., 1986; Talma and Vogel, 1992), coincides with the deglacial decline in Antarctic sea-ice extent (EDML sea-salt sodium flux as a proxy) between 19 and 11 ka (Fischer et al., 2007; Levine et al., 2014; Wolff et al., 2010) (Fig. 2i), consistent with the hypothesis that related changes in the circum-polar vortex and the position of the westerly storm-track had a strong influence on climate variability in southernmost Africa (Chase et al., 2013; Chase and Meadows, 2007; Cockcroft et al., 1987; Partridge et al., 2004; Stuut et al., 2004; van Zinderen Bakker, 1976).

Palaeoclimatic changes in the N-SRZ have been linked to 1) high northern latitude mechanisms (affecting sea-surface and continental temperatures (Otto-Bliesner et al., 2014) and the position of the ITCZ (Johnson et al., 2002; Schefuß et al., 2011)) and 2) to direct insolation forcing. The former appear to dominate during cooler periods of increased glacial extent, while the latter is more strongly expressed during the Holocene (Chevalier and Chase, 2015). This dynamic resulted in significantly less precipitation in the SRZ during the LGM. It has also resulted in a delayed onset of increased tropical precipitation (relative to global temperature trends) during the early Holocene, as a result of low austral summer insolation, which peaked only in the late Holocene (Chevalier and Chase, 2015).

Orbital-scale precipitation trends in both the N-SRZ and SC-SRZ exhibit a clear antiphase relationship with the humidity record from Seweweekspoort (Fig. 2a, b, d, e), indicating that tropical systems did not play a dominant role in the southern Cape at these longer timescales. Data from this transect of sites thus indicate that broad trends in climate change across South Africa are generally consistent with the model of increased westerly influence during the last glacial period and an invigoration of tropical systems concomitant with post-glacial warming into the Holocene (Fig. 3).

3. Millennial-scale variability

3.1. The last glacial maximum and glacial-interglacial transition (22.3–11.7 cal kBP)

Within the broad trends of deglacial aridification in the southern Cape and increasing humidity in the SRZ, significant millennial-scale anomalies are evident in the regional records, particularly in the transitional zone between the WRZ and N-SRZ (Figs. 1 and 2). Despite the strong orbital-scale similarity between the Seweweekspoort $\delta^{15}\text{N}$ record and the EDML sea-salt sodium record (Fischer et al., 2007) (Fig. 2e, i), comparison of the detrended

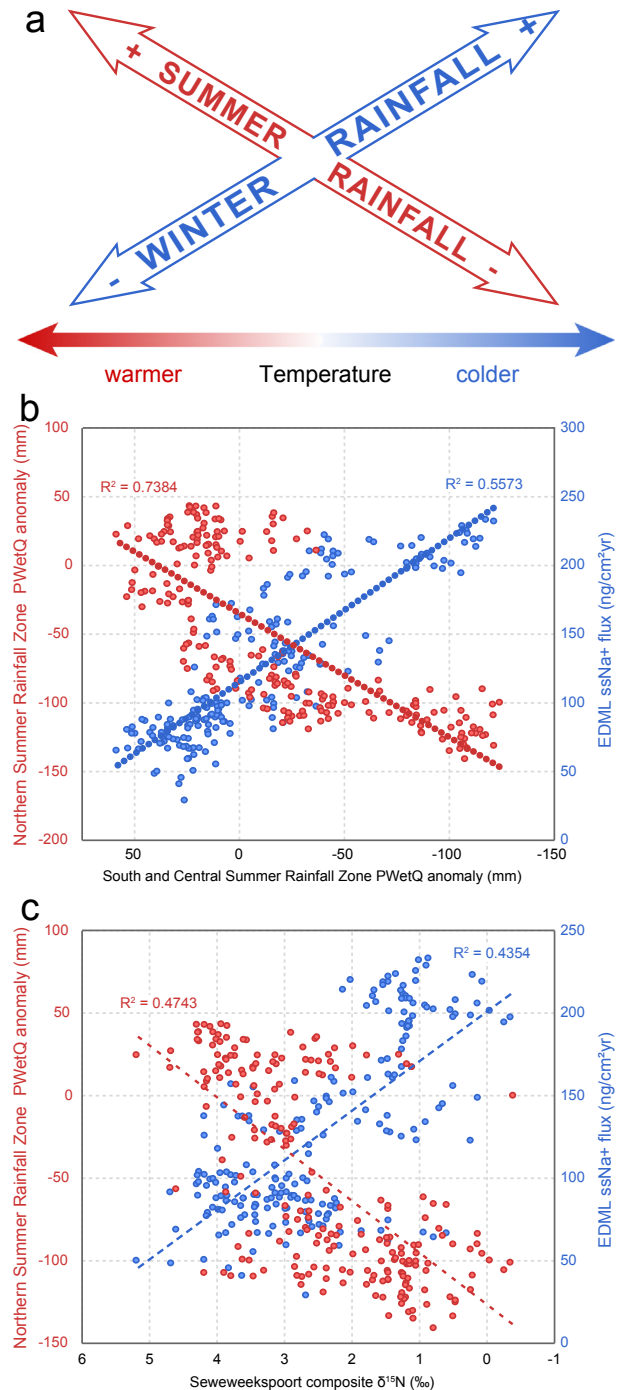


Fig. 3. Diagram of the prevailing conceptual model of southern African climate change (see Chase and Meadows, 2007; van Zinderen Bakker, 1976), wherein a coeval inverse relationship exists between temperate and tropical systems and warmer (colder) temperatures invigorate summer (winter) rainfall systems. In support, the primary datasets considered in this paper are compared, and strong relationships are shown between general trends in records from the southern-central summer rainfall zone (b) and the southern Cape at Seweweekspoort (c) and records reflecting changes in tropical (northern summer rainfall zone summer precipitation (PWetQ) anomalies; as reconstructed in Chevalier and Chase (2015) and temperate systems (sea salt sodium concentrations from the EPICA DML ice core in Antarctica; Fischer et al., 2007).

datasets (i.e., removing orbital-scale deglacial trends with a cubic polynomial; Fig. 4) indicates that at millennial time scales this relationship is in fact largely antiphase. During the last glacial-interglacial transition (LGIT; ~18–11.7 cal kBP) and early Holocene, for example, two prominent episodes of wetter conditions occur at Seweweekspoort, at 15.4–14.2 cal kBP and 11.8–10.7 cal kBP. The first of these episodes – previously identified as being a period of exceptionally high effective precipitation in the southern Cape (Scholtz, 1986) – corresponds with the warming of both high southern latitudes (Stocker, 1998; Stocker and Johnsen, 2003) and the oceans surrounding southwestern Africa (Barker et al., 2009; Farmer et al., 2005; Kim and Schneider, 2003) as a response to the slow-down of Atlantic Meridional Overturning Circulation (AMOC) during Heinrich stadial 1 (HS1; ~18–14.6 ka) (McManus et al., 2004). Critically, this increase in precipitation was not limited to the zone of immediate westerly influence as it is also clearly manifested in the SRZ, where southwest Indian Ocean sea-surface temperatures (Sonzogni et al., 1998) and rainfall increase during HS1, peaking near its termination between ~16–14.2 cal kBP (Chevalier and Chase, 2015) (Figs. 2 and 4).

This association of wetter conditions in the southern Cape during millennial-scale periods of warmth, and an *in-phase* response with the SRZ (Fig. 4), may be perceived as being contrary to the paradigm of a coeval inverse relationship between the WRZ and SRZ. To explore the mechanisms behind such episodes of millennial variability, we analysed the periodicity of the dominant signals in the detrended southern Cape and SC-SRZ datasets (Fig. 4), and their relationship with records indicative of over-arching temperate and tropical systems/drivers (i.e. EDML sea-salt sodium flux and N-SRZ precipitation respectively). To assess correlations through time, we calculated measures of correlation between the records using 2500–4500-year windows at 500-year intervals (Fig. 5). Results indicate that since the LGM the primary driver of millennial-scale climate variability has evolved in concert with changing global boundary conditions, but, rather than being the invigorated system that dominates (i.e. temperate (tropical) systems during the last glacial (Holocene)) (Tyson, 1999), it is *variability in the weaker system* that dictates the timing and direction of these millennial-scale climate change events (Fig. 5).

This dynamic can be conceptualised in terms of limiting as opposed to dominant factors. Under current conditions, interactions between temperate and tropical systems create composite synoptic scenarios wherein disturbances in the easterlies and westerlies combine to create heavy, widespread precipitation events (Tyson, 1986). A diversity of such composite synoptic types exists, with a range of permutations of westerly and easterly waves and cut-off lows, and, perhaps most importantly, the interaction of westerly and easterly disturbances to create cloud bands known as temperate-tropical troughs (Lindesay, 1998; Tyson, 1986). As the resolution of the palaeoclimatic record does not allow for the clear differentiation of these types, we will refer to them generally here as temperate-tropical interactions (TTIs). Considered together, under modern conditions TTIs are: 1) associated with large-scale rainfall events in southern Africa (Nicholson, 1986; Todd and Washington, 1999; Tyson, 1986), 2) account for most of the annual rainfall in the interior, and 3) have the potential to create same sign signal in precipitation anomalies across South Africa (Tyson, 1986). We propose that while changes in the strength and position of temperate and tropical systems may determine broad scale palaeoclimatic changes in the WRZ and SRZ respectively, amplification or attenuation of these general trends has apparently been significantly affected by variability in their counterpart, perhaps as a necessary element for the generation of TTIs.

From this perspective, while the influence of the westerly storm track may have diminished in the southern Cape after HS1, as the

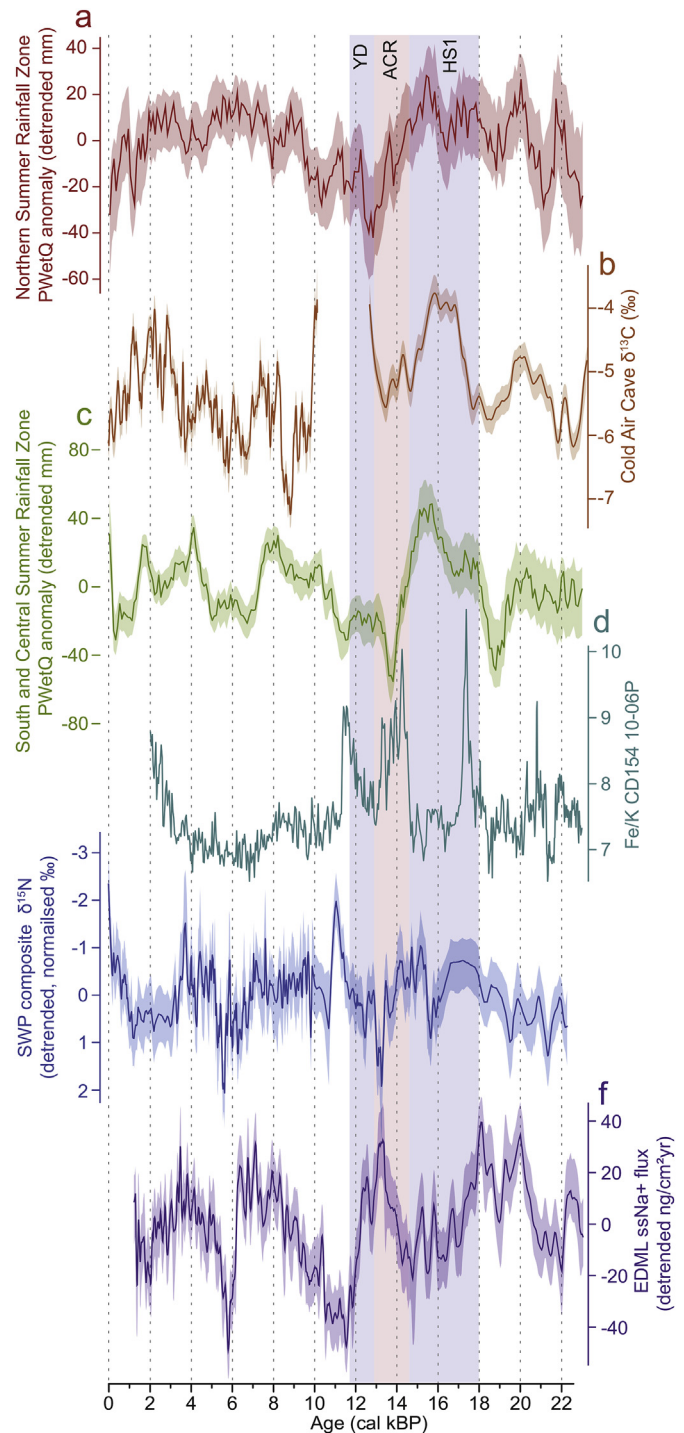


Fig. 4. Comparison of proxy records from the South African transect considered for this study. The data have been detrended, removing orbital-scale deglacial trends (using cubic polynomials) to better highlight the nature of millennial-centennial scale variability. Included are wet season precipitation reconstructions (PWetQ) from the northern and south-central summer rainfall zone (a, c; Chevalier and Chase, 2015), the $\delta^{13}\text{C}$ record from the Cold Air Cave speleothem (b, not detrended; Holmgren et al., 2003), the CD154-10-06P marine core Fe/K record (d, not detrended; Simon et al., 2015), the Seweweekspoort rock hyrax midden $\delta^{15}\text{N}$ record and sea salt sodium concentrations from the EPICA DML ice core in Antarctica (f; Fischer et al., 2007).

Subtropical Front shifted poleward (Barker et al., 2009), increased evaporation from warmer oceans – including the southwest Indian Ocean after ~15.7 ka (Sonzogni et al., 1998) – and the invigoration

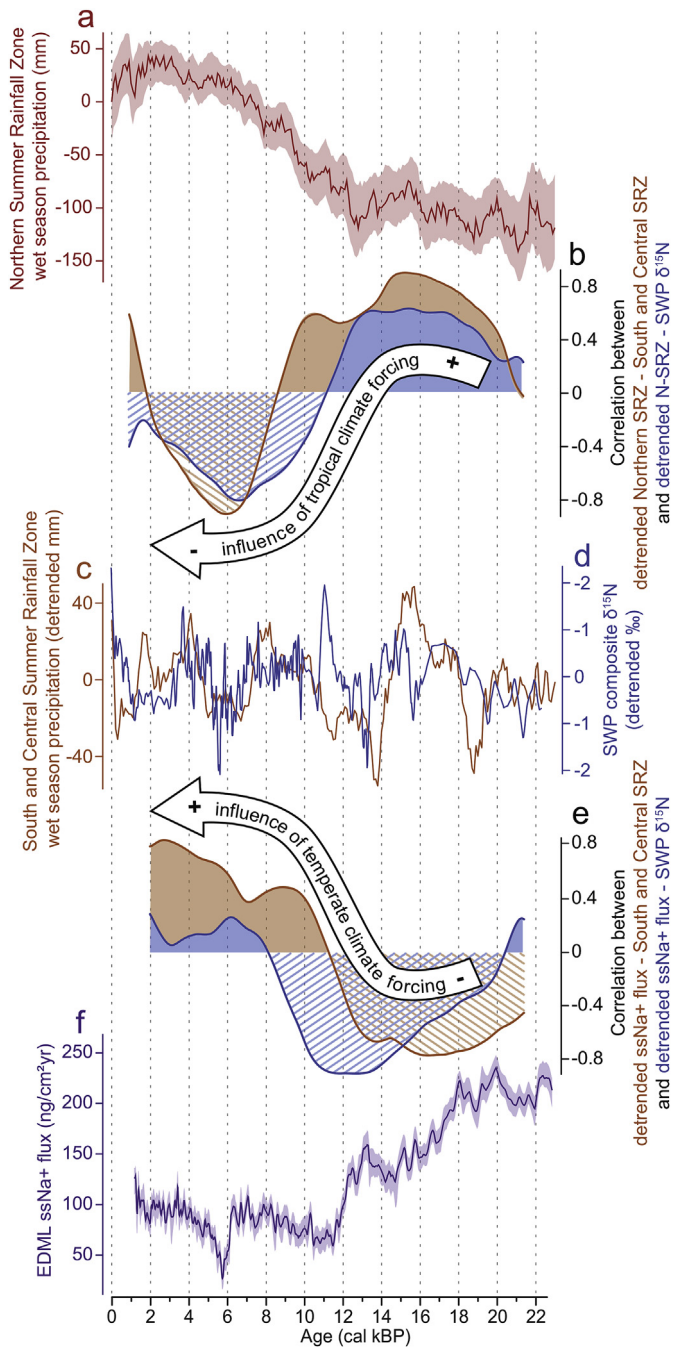


Fig. 5. Comparison of proxy records considered to primarily reflect trends in temperate (f; Fischer et al., 2007) and tropical systems (a; Chevalier and Chase, 2015) as they influence records from the south-central summer rainfall zone (c; Chevalier and Chase, 2015) and the southern Cape. To study millennial-scale variability, panes (b) and (e) show measures of correlation (using 2500–4500-year windows at 500-year intervals) between the south-central summer rainfall zone and southern Cape records and temperate (f) and tropical records (a). For this analysis, all records were detrended to remove orbital-scale deglacial trends (cubic polynomials) and highlight similarities in millennial-scale variability between the regions, as in Fig. 4. Results indicate that the weakened system has the strongest control over millennial-scale climate variability in the region, and that this dynamic has evolved, inverting across the last glacial-interglacial transition.

of the southern African monsoon system (sensu Wang and Ding, 2008) (Fig. 2) may have stimulated TTI development. Evidence for more intense rainfall events, consistent with this type of precipitation system (Tyson, 1986), may (caveats regarding differences in

age models considered) be reflected in the Fe/K record from marine core CD154-10-06P (Simon et al., 2015), off the southeast coast (Fig. 4d) between 14.5 and 13.3 cal kBP and 12–11.3 cal kBP, where peaks in terrigenous sediments exhibit a similar patterning to the humid phases recorded at Seweweekspoort.

This early LGIT period of relatively humid conditions terminates abruptly at ~14.2 cal kBP, concurrent with the post HS1 strengthening of AMOC (McManus et al., 2004) and the onset of the Antarctic Cold Reversal, which resulted in an expansion of Antarctic sea ice (Fischer et al., 2007), cooling in the adjacent Southern Ocean and an equatorward shift of the Subtropical Front, (Barker et al., 2009). At this time, we observe a reduction in precipitation in the N-SRZ (Figs. 2 and 4). The implication is that while the westerly storm track is likely to have shifted equatorward, and brought increased winter rainfall to the southern Cape during this period of southern mid-to high latitude cooling (Pedro et al., 2016), the concurrent weakening of the southern African monsoon – as the limiting factor in pre-Holocene TTI development – resulted in an aridification across the whole of the study transect.

3.2. The early holocene (11.7–8 cal kBP)

The distinct humid episode at Seweweekspoort at the start of the Holocene, from 11.8 to 10.7 cal kBP, corresponds with a sharp decline in sea ice extent, and the establishment of elevated interglacial temperatures. Of note regarding this episode is its strength and its short duration, with an abrupt shift to drier conditions at 10.7 cal kBP. These characteristics are shared by the record of terrigenous sediment flux in marine core CD154-10-06P (Simon et al., 2015) (Fig. 4d) and data from the Drakensberg mountains (Norström et al., 2014) that indicate a period of increased humidity and productivity associated with increased temperatures at ~10 cal kBP. Interestingly, this episode appears to be restricted to the southern coastal margin, with no clear signal being observed in the SRZ. Occurring during the transition between periods of relatively predictable glacial and Holocene millennial-scale climate dynamics, this is the only interval of the last 22,000 years when the southern Cape and SC-SRZ are substantially out of phase (Fig. 5c and d). At present, it is unclear what drove this decoupling of the southern Cape and SC-SRZ, but certainly the LGIT relationship between humidity at Seweweekspoort, temperature, and variability in summer precipitation systems changed fundamentally after this period, and by ~9.5 cal kBP a positive relationship between humidity and Antarctic sea ice extent accounts for much of the observed variability until the late Holocene (Figs. 2, 4 and 5).

3.3. The mid-holocene (8–4 cal kBP)

During the mid-Holocene, continental temperatures were relatively high and the southern African monsoon was well-developed, bringing increased summer precipitation to the SRZ (Chevalier and Chase, 2015, Fig. 4). At Seweweekspoort, by contrast, the invigoration of tropical systems had little apparent impact, and the Holocene as a whole was characterised by relative aridity. This anti-phase response between the SRZ and the southern Cape is consistent with the prevailing model for long-term palaeoclimatic dynamics in the region (Fig. 3).

However, while the aggregate record derived from the SC-SRZ also indicates a general pattern of increased summer precipitation across this period (Chevalier and Chase, 2015, Fig. 4), it exhibits significantly more variability than the relatively muted signal in the N-SRZ (Figs. 2 and 4). Interestingly, these events are similar to those observed in both the $\delta^{13}\text{C}$ record from speleothems from Cold Air Cave in the N-SRZ (Chevalier and Chase, 2015; Holmgren et al., 2003) and in the Seweweekspoort record, indicating strong

spatial coherence across southern and eastern South Africa during this period (Fig. 4). Our analyses (Fig. 5) show that these millennial-scale climate change events are not linked to variability in tropical systems, but rather – as the limiting factor in TTI development – are more closely linked to variations in Antarctic sea ice extent and the southern westerlies, and humidity in the southern Cape and continental interior, with the nature of the composite synoptic systems again creating an in-phase dynamic across the region (Fig. 5).

3.4. The late holocene (4 cal kBP to present)

After 4 cal kBP, sea ice again begins to retreat, and by 3 cal kBP conditions at Seweweekspoort become more arid, similar to millennial-scale patterns observed in the SC-SRZ (Fig. 4). These findings are broadly consistent with previously identified episodes of mesic forest development in the southern Cape between ~4.5–2.5 cal kBP (Martin, 1968) and a subsequent arid phase between ~2.7–1.3 cal kBP recorded in both botanical (Scholtz, 1986) and geomorphological records (Carr et al., 2006) from the region. In contrast, in the N-SRZ, a phase of increased precipitation and humidity is observed between ~3.3 and 1.7 cal kBP, and the Cold Air Cave $\delta^{13}\text{C}$ record indicates relatively humid conditions. The establishment of this antiphase relationship between northern and southern regions appears to reflect the dominance of local moisture bearing systems in each region, and a reduction in the generation and influence of TTIs, which would tend to create same sign responses across the continental interior. This dynamic persists during the last millennium, wherein an abrupt shift to wetter conditions at Seweweekspoort is mirrored by marked aridification at Cold Air Cave (Fig. 4). These changes in inter-regional dynamics suggest that sensitive thresholds exist in the relationship and interaction between temperate and tropical systems in South Africa, and that slight variations in one or other may result in abrupt, significant changes in rainfall regime at both local and subcontinental scales.

4. Conclusions

Consideration of records from this SW-NE rainfall seasonality transect across the continental interior supports – in general terms, and over glacial-interglacial timescales – the long-standing model of a coeval inverse relationship between southern Africa's temperate and tropical moisture-bearing systems wherein colder (warmer) periods created wetter conditions in the regions' winter (summer) rainfall zone over multi-millennial time scales. However, the complexity of sub-orbital millennial-scale climate dynamics observed across the region since the LGM, particularly during the LGIT and early Holocene, is not predicted by this simple model. Instead, arid/humid climate anomalies often exhibit a coherent, *in-phase* spatio-temporal patterning across the study transect. We hypothesise that such patterning reflects the importance of *interactions* between temperate and tropical systems, with variability in the *weaker system* determining regional climate dynamics as a limiting factor on the development of TTIs. While the influence of such synoptic forcings is clearly mediated by larger-scale changes in global boundary conditions, and their influence on the position of the southern westerly storm track/invigoration of the southern African monsoon, we propose that TTIs are a critical factor in understanding an array of significant, abrupt changes in climate that have occurred across southern Africa since the LGM.

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.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.quascirev.2017.08.011>.

References

- Ambrose, S.H., DeNiro, M.J., 1986. The isotopic ecology of East African mammals. *Oecologia* 69, 395–406.
- Barker, S., Diz, P., Vautravers, M.J., Pike, J., Knorr, G., Hall, I.R., Broecker, W.S., 2009. Interhemispheric Atlantic seesaw response during the last deglaciation. *Nature* 457, 1097–1102.
- Blaauw, M., Christen, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Anal.* 6, 457–474.
- Carr, A.S., Chase, B.M., Boom, A., Medina-Sanchez, J., 2016. Stable isotope analyses of rock hyrax faecal pellets, hyraceum and associated vegetation in southern Africa: implications for dietary ecology and palaeoenvironmental reconstructions. *J. Arid Environ.* 134, 33–48.
- Carr, A.S., Thomas, D.S.G., Bateman, M.D., 2006. Climatic and sea level controls on late Quaternary eolian activity on the Agulhas Plain, South Africa. *Quat. Res.* 65, 252–263.
- Chase, B.M., Boom, A., Carr, A.S., Carré, M., Chevalier, M., Meadows, M.E., Pedro, J.B., Stager, J.C., Reimer, P.J., 2015a. Evolving southwest African response to abrupt deglacial North Atlantic climate change events. *Quat. Sci. Rev.* 121, 132–136.
- Chase, B.M., Boom, A., Carr, A.S., Meadows, M.E., Reimer, P.J., 2013. Holocene climate change in southernmost South Africa: rock hyrax middens record shifts in the southern westerlies. *Quat. Sci. Rev.* 82, 199–205.
- Chase, B.M., Lim, S., Chevalier, M., Boom, A., Carr, A.S., Meadows, M.E., Reimer, P.J., 2015b. Influence of tropical easterlies in southern Africa's winter rainfall zone during the Holocene. *Quat. Sci. Rev.* 107, 138–148.
- Chase, B.M., Meadows, M.E., 2007. Late Quaternary dynamics of southern Africa's winter rainfall zone. *Earth-Science Rev.* 84, 103–138.
- Chase, B.M., Meadows, M.E., Carr, A.S., Reimer, P.J., 2010. Evidence for progressive Holocene aridification in southern Africa recorded in namibian hyrax middens: implications for african monsoon dynamics and the “african humid period”. *Quat. Res.* 74, 36–45.
- Chase, B.M., Meadows, M.E., Scott, L., Thomas, D.S.G., Marais, E., Sealy, J., Reimer, P.J., 2009. A record of rapid Holocene climate change preserved in hyrax middens from southwestern Africa. *Geology* 37, 703–706.
- Chase, B.M., Quick, L.J., Meadows, M.E., Scott, L., Thomas, D.S.G., Reimer, P.J., 2011. Late glacial interhemispheric climate dynamics revealed in South African hyrax middens. *Geology* 39, 19–22.
- Chase, B.M., Scott, L., Meadows, M.E., Gil-Romera, G., Boom, A., Carr, A.S., Reimer, P.J., Truc, L., Valsecchi, V., Quick, L.J., 2012. Rock hyrax middens: a palaeoenvironmental archive for southern African drylands. *Quat. Sci. Rev.* 56, 107–125.
- Chevalier, M., Chase, B.M., 2015. Southeast African records reveal a coherent shift from high- to low-latitude forcing mechanisms along the east African margin across last glacial–interglacial transition. *Quat. Sci. Rev.* 125, 117–130.
- Chevalier, M., Chase, B.M., 2016. Determining the drivers of long-term aridity variability: a southern African case study. *J. Quat. Sci.* 31, 143–151.
- Chevalier, M., Cheddadi, R., Chase, B.M., 2014. CREST (Climate REconstruction Software): a probability density function (pdf)-based quantitative climate reconstruction method. *Clim. Past* 10, 2081–2098.
- Cockcroft, M.J., Wilkinson, M.J., Tyson, P.D., 1987. The application of a present-day climatic model to the late Quaternary in southern Africa. *Clim. Change* 10, 161–181.
- Deacon, J., Lancaster, N., 1988. Late Quaternary Palaeoenvironments of Southern Africa. Clarendon Press, Oxford.
- Ehleringer, J.R., Cerling, T.E., 1995. Atmospheric CO₂ and the ratio of intercellular to ambient CO₂ concentrations in plants. *Tree Physiol.* 15, 105–111.
- Ehleringer, J.R., Cooper, T.A., 1988. Correlations between carbon isotope ratio and microhabitat of desert plants. *Oecologia* 76, 562–566.
- Farmer, E.C., deMenocal, P.B., Marchitto, T.M., 2005. Holocene and deglacial ocean temperature variability in the Benguela upwelling region: implications for low-latitude atmospheric circulation. *Paleoceanography* 20. <http://dx.doi.org/10.1029/2004PA001049>.
- Farquhar, G.D., Ehleringer, J.R., Hubick, K.T., 1989. Carbon isotope discrimination and photosynthesis. *Annu. Rev. Plant Physiology Plant Mol. Biol.* 40, 503–537.
- Farquhar, G.D., Richards, R.A., 1984. Isotopic composition of plant carbon correlates with water-use efficiency of wheat genotypes. *Aust. J. Plant Physiology* 11, 539–552.
- Finch, J.M., Hill, T.R., 2008. A late Quaternary pollen sequence from Mfabeni Peatland, South Africa: reconstructing forest history in Maputaland. *Quat. Res.* 70, 442–450.
- Fischer, H., Fundel, F., Ruth, U., Twarloh, B., Wegner, A., Udisti, R., Becagli, S., Castellano, E., Morganti, A., Severi, M., Wolff, E., Littot, G., Röthlisberger, R.,

- Mulvaney, R., Hutterli, M.A., Kaufmann, P., Federer, U., Lambert, F., Bigler, M., Hansson, M., Jonsell, U., de Angelis, M., Boutron, C., Siggaard-Andersen, M.-L., Steffensen, J.P., Barbante, C., Gaspari, V., Gabrielli, P., Wagenbach, D., 2007. Reconstruction of millennial changes in dust emission, transport and regional sea ice coverage using the deep EPICA ice cores from the Atlantic and Indian Ocean sector of Antarctica. *Earth Planet. Sci. Lett.* 260, 340–354.
- Gasse, F., Chalié, F., Vincens, A., Williams, M.A.J., Williamson, D., 2008. Climatic patterns in equatorial and southern Africa from 30,000 to 10,000 years ago reconstructed from terrestrial and near-shore proxy data. *Quat. Sci. Rev.* 27, 2316–2340.
- Handley, L.L., Austin, A.T., Stewart, G.R., Robinson, D., Scrimgeour, C.M., Raven, J.A., Heaton, T.H.E., Schmidt, S., 1999. The $\delta^{15}\text{N}$ natural abundance ($\delta^{15}\text{N}$) of ecosystem samples reflects measures of water availability. *Funct. Plant Biol.* 26, 185–199.
- Handley, L.L., Odee, D., Scrimgeour, C.M., 1994. $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ patterns in savanna vegetation: dependence on water availability and disturbance. *Funct. Ecol.* 8, 306–314.
- Hartman, G., 2011. Are elevated $\delta^{15}\text{N}$ values in herbivores in hot and arid environments caused by diet or animal physiology? *Funct. Ecol.* 25, 122–131.
- Heaton, T.H.E., 1987. The $^{15}\text{N}/^{14}\text{N}$ ratios of plants in South Africa and Namibia: relationship to climate and coastal/saline environments. *Oecologia* 74, 236–246.
- Heaton, T.H.E., Talma, A.S., Vogel, J.C., 1986. Dissolved gas paleotemperatures and ^{18}O variations derived from groundwater near Uitenhage, South Africa. *Quat. Res.* 25, 79–88.
- Heine, K., 1982. The main stages of the late Quaternary evolution of the Kalahari region, southern Africa. *Palaeoecol. Afr.* 15, 53–76.
- Hogg, A.G., Hua, Q., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M., Zimmerman, S.R.H., 2013. SHCal13 Southern Hemisphere Calibration, 0–50,000 Years Cal BP.
- Holmgren, K., Lee-Thorp, J.A., Cooper, G.R.J., Lundblad, K., Partridge, T.C., Scott, L., Sthaldean, R., Talma, A.S., Tyson, P.D., 2003. Persistent millennial-scale climatic variability over the past 25,000 years in Southern Africa. *Quat. Sci. Rev.* 22, 2311–2326.
- Huang, Y., Street-Perrott, F.A., Metcalfe, S.E., Brenner, M., Moreland, M., Freeman, K.H., 2001. Climate change as the dominant control on glacial-interglacial variations in C_3 and C_4 plant abundance. *Science* 293, 1647–1651.
- Johnson, T.C., Brown, E.T., McManus, J., Barry, S., Barker, P., Gasse, F., 2002. A high-resolution paleoclimate record spanning the past 25,000 years in southern East Africa. *Science* 296, 113–132.
- Kim, J.-H., Schneider, R.R., 2003. Low-latitude control of interhemispheric sea-surface temperature contrast in the tropical Atlantic over the past 21 kys: the possible role of SE trade winds. *Clim. Dyn.* 23, 337–347.
- Levine, J.G., Yang, X., Jones, A.E., Wolff, E.W., 2014. Sea salt as an ice core proxy for past sea ice extent: a process-based model study. *J. Geophys. Res. Atmos.* 119, 5737–5756.
- Lim, S., Chase, B.M., Chevalier, M., Reimer, P.J., 2016. 50,000 years of vegetation and climate change in the southern Namib Desert, Pella, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 451, 197–209.
- Lindesay, J.A., 1998. Past climates of southern Africa. In: Hobbs, J.E., Lindesay, J.A., Bridgman, H.A. (Eds.), *Climates of the Southern Continents: Present, Past and Future*. John Wiley & Sons, New York.
- Martin, A.R.H., 1968. Pollen analysis of Groenvlei lake sediments, Knysna (South Africa). *Rev. Palaeobot. Palynology* 7, 107–144.
- McManus, J.F., Francois, R., Gherardi, J.-M., Keigwin, L.D., Brown-Leger, S., 2004. Collapse and rapid resumption of Atlantic meridional circulation linked to deglacial climate changes. *Nature* 428, 834–837.
- Metwally, A.A., Scott, L., Neumann, F.H., Bamford, M.K., Oberhänsli, H., 2014. Holocene palynology and palaeoenvironments in the savanna biome at Tswaing Crater, central South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 402, 125–135.
- Murphy, B.P., Bowman, D.M.J.S., 2006. Kangaroo metabolism does not cause the relationship between bone collagen $\delta^{15}\text{N}$ and water availability. *Funct. Ecol.* 20, 1062–1069.
- Murphy, B.P., Bowman, D.M.J.S., 2009. The carbon and nitrogen isotope composition of Australian grasses in relation to climate. *Funct. Ecol.* 23, 1040–1049.
- Neumann, F.H., Scott, L., Bousman, C.B., van As, L., 2010. A Holocene sequence of vegetation change at Lake Eteza, coastal KwaZulu-Natal, South Africa. *Rev. Palaeobot. Palynology* 162, 39–53.
- Nicholson, S.E., 1986. The nature of rainfall variability in Africa south of the Equator. *J. Climatol.* 6, 515–530.
- Norström, E., Neumann, F.H., Scott, L., Smittenberg, R.H., Holmstrand, H., Lundqvist, S., Snowball, I., Sundqvist, H.S., Risberg, J., Bamford, M., 2014. Late Quaternary vegetation dynamics and hydro-climate in the Drakensberg, South Africa. *Quat. Sci. Rev.* 105, 48–65.
- Norström, E., Scott, L., Partridge, T.C., Risberg, J., Holmgren, K., 2009. Reconstruction of environmental and climate changes at Braamhoek wetland, eastern escarpment South Africa, during the last 16,000 years with emphasis on the Pleistocene-Holocene transition. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 271, 240–258.
- Otto-Bliessner, B.L., Russell, J.M., Clark, P.U., Liu, Z., Overpeck, J.T., Konecky, B., deMenocal, P., Nicholson, S.E., He, F., Lu, Z., 2014. Coherent changes of south-eastern equatorial and northern African rainfall during the last deglaciation. *Science* 346, 1223–1227.
- Partridge, T.C., Scott, L., Hamilton, J.E., 1999. Synthetic reconstructions of southern African environments during the last glacial maximum (21–18 kyr) and the Holocene althermal (8–6 kyr). *Quat. Int.* 57–8, 207–214.
- Partridge, T.C., Scott, L., Schneider, R.R., 2004. Between Agulhas and Benguela: responses of southern African climates of the late Pleistocene to current fluxes, orbital precession and the extent of the circum-Antarctic vortex. *Past Clim. Var. through Eur. Afr.* 45–68.
- Pate, J.S., 2001. Carbon isotope discrimination and plant water-use efficiency: case scenarios for C_3 plants. In: Unkovich, M., Pate, J., McNeill, A., Gibbs, D.J. (Eds.), *Stable Isotope Techniques in the Study of Biological Processes and Functioning of Ecosystems*. Kluwer Academic Publishers, Dordrecht, pp. 19–37.
- Pedro, J.B., Bostock, H.C., Bitz, C.M., He, F., Vandergoes, M.J., Steig, E.J., Chase, B.M., Krause, C.E., Rasmussen, S.O., Markle, B.R., Cortese, G., 2016. The spatial extent and dynamics of the Antarctic Cold Reversal. *Nat. Geosci.* 9, 51–55.
- Quick, L.J., Chase, B.M., Meadows, M.E., Scott, L., Reimer, P.J., 2011. A 19.5 kyr vegetation history from the central Cederberg Mountains, South Africa: palynological evidence from rock hyrax middens. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 309, 253–270.
- Rutherford, M.C., Mucina, L., Powrie, L.W., 2012. the South african national vegetation database: history, development, applications, problems and future. *South Afr. J. Sci.* 108.
- Rutherford, M.C., Powrie, L.W., Midgley, G.F., 2003. ACKDAT: a digital spatial database of distributions of South African plant species and species assemblages. *South Afr. J. Bot.* 69, 99–104.
- Sale, J.B., 1965. The feeding behaviour of rock hyraxes (genera *Procavia* and *Heterohyrax*) in Kenya. *Afr. J. Ecol.* 3, 1–18.
- SANBI, 2003. PRECIS (National Herbarium Pretoria (PRE) Computerized Information System) Database.
- Schefeuf, E., Kuhlmann, H., Mollenhauer, G., Prange, M., Patzold, J., 2011. Forcing of wet phases in southeast Africa over the past 17,000 years. *Nature* 480, 509–512.
- Scholtz, A., 1986. Palynological and Palaeobotanical Studies in the Southern Cape. University of Stellenbosch, Stellenbosch, South Africa.
- Scott, L., 1982. A late Quaternary pollen record from the Transvaal bushveld, South Africa. *Quat. Res.* 17, 339–370.
- Scott, L., 1987a. Late quaternary forest history in venda, southern Africa. *Rev. Palaeobot. Palynology* 53, 1–10.
- Scott, L., 1987b. Pollen analysis of hyena coprolites and sediments from Equus Cave, Taung, southern Kalahari (South Africa). *Quat. Res.* 28, 144–156.
- Scott, L., 1999. Vegetation history and climate in the Savanna biome South Africa since 190,000 ka: a comparison of pollen data from the Tswaing Crater (the Pretoria Saltpan) and Wonderkrater. *Quat. Int.* 57–8, 215–223.
- Scott, L., Bousman, C.B., Nyakale, M., 2005. Holocene pollen from swamp, cave and hyrax dung deposits at Blydefontein (Kikvorsberge), Karoo, South Africa. *Quat. Int.* 129, 49–59.
- Scott, L., Nyakale, M., 2002. Pollen indications of Holocene palaeoenvironments at Florisbad spring in the central free state, South Africa. *Holocene* 12, 497–503.
- Scott, L., Steenkamp, M., 1996. Environmental history and recent human influence at coastal Lake Teza, KwaZulu-Natal. *South Afr. J. Sci.* 92, 348–350.
- Scott, L., Steenkamp, M., Beaumont, P.B., 1995. Palaeoenvironmental conditions in South Africa at the Pleistocene-Holocene transition. *Quat. Sci. Rev.* 14, 937–947.
- Scott, L., Vogel, J.C., 1983. Late quaternary pollen profile from the transvaal highveld, South Africa. *South Afr. J. Sci.* 79, 266–272.
- Scott, L., Woodborne, S., 2007a. Pollen analysis and dating of late quaternary faecal deposits (hyraceum) in the cederberg, western Cape, South Africa. *Rev. Palaeobot. Palynology* 144, 123–134.
- Scott, L., Woodborne, S., 2007b. Vegetation history inferred from pollen in Late Quaternary faecal deposits (hyraceum) in the Cape winter-rain region and its bearing on past climates in South Africa. *Quat. Sci. Rev.* 26, 941–953.
- Simon, M.H., Ziegler, M., Bosmans, J., Barker, S., Reason, C.J.C., Hall, I.R., 2015. Eastern South African hydroclimate over the past 270,000 years. *Sci. Rep.* 5, 18153.
- Smith, B.N., 1972. Natural abundance of the stable isotopes of carbon in biological systems. *BioScience* 22, 226–231.
- Sonzogni, C., Bard, E., Rostek, F., 1998. Tropical sea-surface temperatures during the last glacial period: a view based on alkenones in Indian Ocean sediments. *Quat. Sci. Rev.* 17, 1185–1201.
- Stocker, T.F., 1998. The seesaw effect. *Science* 282, 61–62.
- Stocker, T.F., Johnsen, S.J., 2003. A minimum thermodynamic model for the bipolar seesaw. *Paleoceanography* 18.
- Stuut, J.-B.W., Crosta, X., Van der Borg, K., Schneider, R.R., 2004. On the relationship between Antarctic sea ice and southwestern African climate during the late Quaternary. *Gecy* 32, 909–912.
- Talma, A.S., Vogel, J.C., 1992. Late quaternary paleotemperatures derived from a speleothem from cango caves, Cape province, South Africa. *Quat. Res.* 37, 203–213.
- Todd, M., Washington, R., 1999. Circulation anomalies associated with tropical-temperate troughs in southern Africa and the south west Indian Ocean. *Clim. Dyn.* 15, 937–951.
- Truc, L., Chevalier, M., Favier, C., Cheddadi, R., Meadows, M.E., Scott, L., Carr, A.S., Smith, G.F., Chase, B.M., 2013. Quantification of climate change for the last 20,000 years from Wonderkrater, South Africa: implications for the long-term dynamics of the Intertropical Convergence Zone. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 386, 575–587.
- Tyson, P.D., 1986. *Climatic Change and Variability in Southern Africa*. Oxford University Press, Cape Town.
- Tyson, P.D., 1999. Atmospheric circulation changes and palaeoclimates of southern Africa. *South Afr. J. Sci.* 95, 194–201.
- Tyson, P.D., Lindesay, J.A., 1992. The climate of the last 2000 years in southern

- Africa. *Holocene* 2, 271–278.
- Valsecchi, V., Chase, B.M., Slingsby, J.A., Carr, A.S., Quick, L.J., Meadows, M.E., Cheddadi, R., Reimer, P.J., 2013. A high resolution 15,600-year pollen and microcharcoal record from the Cederberg Mountains, South Africa. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 387, 6–16.
- van Zinderen Bakker, E.M., 1976. The evolution of late Quaternary paleoclimates of Southern Africa. *Palaeoecol. Afr.* 9, 160–202.
- Vogel, J.C., 1978. Isotopic assessment of the dietary habits of ungulates. *South Afr. J. Sci.* 74, 298–301.
- Wang, B., Ding, Q., 2008. Global monsoon: dominant mode of annual variation in the tropics. *Dyn. Atmos. Oceans* 44, 165–183.
- Wang, L., D'Odorico, P., Ries, L., Macko, S.A., 2010. Patterns and implications of plant-soil $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values in African savanna ecosystems. *Quat. Res.* 73, 77–83.
- Wolff, E.W., Barbante, C., Becagli, S., Bigler, M., Boutron, C.F., Castellano, E., de Angelis, M., Federer, U., Fischer, H., Fundel, F., Hansson, M., Hutterli, M., Jonsell, U., Karlin, T., Kaufmann, P., Lambert, F., Littot, G.C., Mulvaney, R., Röthlisberger, R., Ruth, U., Severi, M., Siggaard-Andersen, M.L., Sime, L.C., Steffensen, J.P., Stocker, T.F., Traversi, R., Twarloh, B., Udisti, R., Wagenbach, D., Wegner, A., 2010. Changes in environment over the last 800,000 years from chemical analysis of the EPICA Dome C ice core. *Quat. Sci. Rev.* 29, 285–295.