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

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A B S T R A C T

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.

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,

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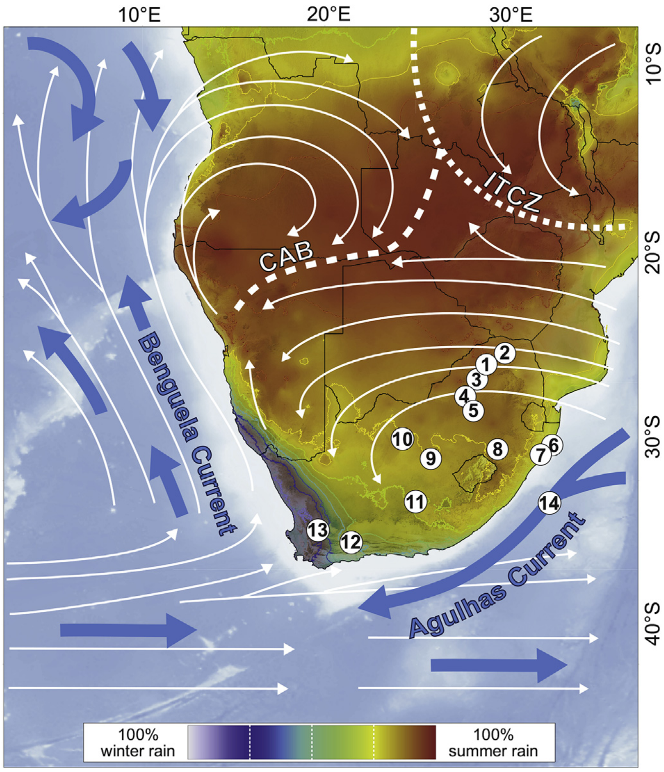

Fig. 1. Map of southern Africa showing seasonality of rainfall and sharp climatic gradients dictated by the zones of summer/tropical (red) and winter/temperate (blue) rainfall dominance. Winter rainfall is primarily a result of storm systems embedded in the westerlies. Major atmospheric (white arrows) 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) Rietvlei; 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 timescales, 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}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 $\delta^{13}C$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ 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 $\delta^{13}C$ 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 significant 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 $\delta^{15}N$ data (Fig. 2).

Hyraceum $\delta^{15}N$ 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 $\delta^{15}N$ 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;