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Influence of tropical easterlies in southern Africa's winter rainfall zone during the Holocene

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ABSTRACT

South Africa's southwestern Cape occupies a critical transition zone between Southern Hemisphere temperate (winter) and tropical (summer) moisture-bearing systems. In the recent geological past, it has been proposed that the relative influence of these systems may have changed substantially, but little reliable evidence regarding regional hydroclimates and rainfall seasonality exists to refine or substantiate the understanding of long-term dynamics. In this paper we present a mid-to late Holocene multi-proxy record of environmental change from a rock hyrax midden from Katbakkies Pass, located along the modern boundary between the winter and summer rainfall zones. Derived from stable carbon and nitrogen isotopes, fossil pollen and microcharcoal, these data provide a high resolution record of changes in humidity, and insight into changes in rainfall seasonality. Whereas previous work concluded that the site had generally experienced only subtle environmental change during the Holocene, our records indicate that significant, abrupt changes have occurred in the region over the last 7000 years. Contrary to expectations based on the site's location, these data indicate that the primary determinant of changes in humidity is summer rather than winter rainfall variability, and its influence on drought season intensity and/or length. These findings are consistent with independent records of upwelling along the southern and western coasts, which indicate that periods of increased humidity are related to increased tropical easterly flow. This substantially refines our understanding of the nature of temperate and tropical circulation system dynamics in SW Africa, and how changes in their relative dominance have impacted regional environments during the Holocene.

1. Introduction

Southwestern Africa lies at the boundary between Southern Hemisphere temperate and tropical climate systems (Tyson, 1986). Presently, much of the region's precipitation falls during the austral winter months, when expansions of the circumpolar vortex bring the westerly storm track and its associated frontal systems into closer contact with the subcontinent. Conversely, the region experiences a marked summer drought period, as (1) it lies distal to the primary tropical moisture source of the Indian Ocean, and (2) seasonal displacements the South Atlantic Anticyclone intensify upwelling along the west coast, blocking the westward propagation of easterly waves that bring summer rainfall to much of southern Africa. During the late Quaternary, the region is thought to be sensitive to long-term changes in these systems as a function of changes in global boundary conditions (see van Zinderen Bakker, 1976; Cockroft et al., 1988; Chase and Meadows, 2007). However, while the relative dominance of these climate systems may have changed significantly during the late Quaternary, the region's strongly seasonal climates generally preclude the preservation of organic material, and very little terrestrial evidence exists to refine our understanding of their past dynamics (e.g. Martin, 1968; Scholtz, 1986; Carr et al., 2006). Despite this constraint, records of environmental change can be obtained from archives that are not

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subject to deterioration by the region's climate. Notably, proxy records obtained from marine cores (Farmer et al., 2005; Weldeab et al., 2013) and stable isotope records from archaeological deposits (Cohen et al., 1992; Cohen and Tyson, 1995), although containing records of inherently contrasting temporal resolution, have provided some indications of changes in regional atmospheric circulation dynamics, particularly those manifested in variations in coastal upwelling regimes. Key among hypotheses derived from these data is the mechanistic model developed by Cohen and Tyson (1995), which posits that lower (higher) near-coastal SSTs along the south coast would be associated with increased (decreased) upwelling along the south coast, and increased tropical easterly (temperate westerly) flow. This variability was linked to overall wetter (drier) conditions in the continental interior, which is part of southern Africa's summer rainfall zone, and derives most its moisture from the tropical easterlies. Recent studies of rock hyrax middens from the southern Cape Fold Mountains (Chase et al., 2013) have lent some support this model, finding that regional trends in water availability during the Holocene correlate strongly with higher south coast SSTs, continental temperature records (Talma and Vogel, 1992 [chronology after Chase et al., 2013]), and remote evidence for shifts in the westerly storm track (Lamy et al., 2001), which in turn can be linked to changes in Antarctic sea-ice extent (Fischer et al., 2007; Wolff et al., 2010). These findings highlight the importance of temperate moisture-bearing systems in the southwestern and southern Cape, but lacking are records from the western interior that indicate the extent to which increases in easterly flow may have brought increased summer rainfall to regions distal to the primary Indian Ocean moisture source.

In this paper, we present fossil pollen, microcharcoal, and high resolution stable isotope ($\delta^{13}C$ and $\delta^{15}N$) records from a rock hyrax (*Procavia capensis*) midden from Katbakkies Pass in South Africa's Swartruggens Mountains, strategically located on the modern winter–summer rainfall zone boundary. These data provide detailed information regarding both past vegetation and hydroclimatic change, providing a first opportunity to assess the relative roles of temperate westerly and tropical easterly systems in driving climate change in southwestern Africa during the Holocene.

1.1. *Regional setting*

The Swartruggens Mountains are a southeastern subsidiary range of the Cederberg Mountains, which dominate the north–south axis of the Cape Fold Mountains to the east and northeast of Cape Town (Fig. 1). Extending for ~300 km parallel to the Atlantic Ocean (50–100 km to the west), this portion of the Cape Fold Belt is, in its northern portion, a significant divide between the relatively humid climates of the southwestern Cape and the arid Karoo, which dominates much of South Africa's western continental interior. The range also broadly marks the divide between southern Africa's two major climate regimes: the winter rainfall zone to the west and the summer rainfall zone to the northeast (cf. Chase and Meadows, 2007). The winter rainfall zone is defined by the seasonal intensification and northward expansion of the westerlies and associated frontal depressions that transport moisture to the region during the austral winter months. To the east, and across most of South Africa, tropical easterly flow transports moisture from the Indian Ocean during the austral summer (Fig. 1; Tyson, 1986; Tyson and Preston-Whyte, 2000). The Cederberg and adjacent ranges act as an orographic divide between these climate zones, with the mountains creating a distinct rainshadow for westerly derived rainfall. The higher elevations receive five times the precipitation of the lowlands to the east, but more importantly, while the mountains receive more than 75% of their rainfall during the winter, the

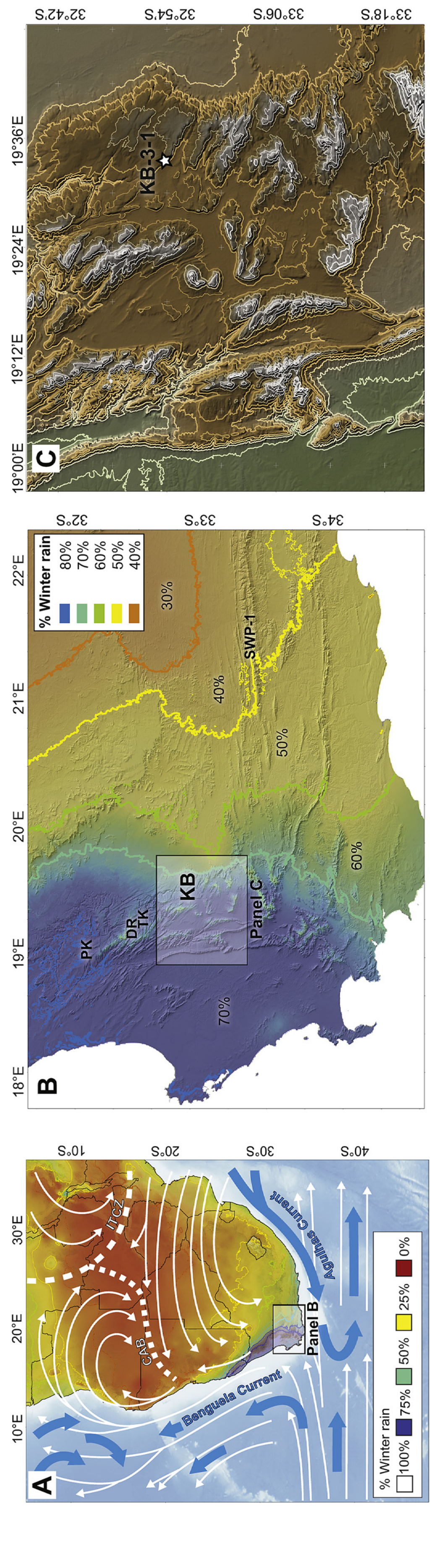

Fig. 1. (A) Map of southern Africa showing seasonality of rainfall and sharp climatic gradients dictated by the zones of summer/tropical (red) and winter/temperate (blue) rainfall dominance. Winter rainfall is primarily a result of storm systems embedded in the westerlies. Major atmospheric (white arrows) and oceanic (blue arrows) circulation systems and the austral summer positions of the Inter-Tropical Convergence Zone (ITCZ) and the Congo Air Boundary (CAB) are indicated. The location of the study site in the southwestern Cape region is shown. (B) Map of southwestern Cape with the Katbakkies Pass site and other hyrax midden sites indicated (PK, Pakhuis Pass (Scott and Woodborne, 2007a, b); DR, De Rif (Chase et al., 2011; Quick et al., 2011; Valsecchi et al., 2013); TK, Truitjes Kraal (Meadows et al., 2010); SWP-1, Seweweekspoort-1 (Chase et al., 2013)). (C) Topographical map of Katbakkies Pass (200 m contours), with the KB-3-1 site indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)