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Southeast African records reveal a coherent shift from high- to low-latitude forcing mechanisms along the east African margin across last glacial–interglacial transition

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A B S T R A C T

Late Quaternary climate variability in the southern African subtropics is still only poorly resolved, with significant complexity and apparent contradictions in the regional dataset. To more effectively interpret and synthesize key regional records, we reanalysed the data from 13 pollen sequences from the summer rainfall zone of South Africa spanning the last 45,000 years, obtaining directly comparable quantitative reconstructions of mean annual temperature and summer rainfall. Temperature reconstructions from across the region provide consistent results, with all sites reflecting trends observed in southwest Indian Ocean sea-surface temperatures in the adjacent Mozambique Channel. Precipitation reconstructions are more heterogeneous, with two distinct subregions being identified. In the northeast, long-term trends in precipitation are determined by sea-surface and continental temperature trends, revealing a positive relationship between temperature and rainfall. This long-term pattern appears to be primarily driven by high northern latitude mechanisms, with direct local insolation being subordinate. Their relative impact reversed during terminal glacial period/early Holocene, at which time direct insolation forcing became the main driver of rainfall variability. Further south, in central South Africa, precipitation variability appears also to be influenced by the latitudinal position of the Southern Hemisphere westerlies, which combine with tropical flow to create tropical-temperate trough, advecting moisture into the interior. In this region, periods of maximum precipitation coincide with periods of elevated SSTs and equatorward expansions of the westerly storm track. This study allows for a fully constrained understanding of climate dynamics along the eastern African margin for the last 45,000 years, linking dynamics to drivers and describing how the climate systems evolved across the last glacial–interglacial transition.

1. Introduction

The patterns and causes of late Quaternary climate variability in the subtropics of southeastern Africa remain the subject of significant debate. To explain the variability observed in individual or discrete subsets of records, different mechanistic models have been proposed. The most widely accepted models involve migrations of the mean position of the Intertropical Convergence Zone (ITCZ) as 1) a function of direct insolation forcing (Braconnot et al., 2008; Joussaume et al., 1999; Kutzbach and Street-Perrott, 1985; Kutzbach, 1981; Peyron et al., 2006) and/or 2) expansions of Northern Hemisphere (NH) continental ice sheets (Arbuszewski et al., 2013; Broecker and Putnam, 2013).

Extensive studies have been conducted in the East African lakes such as Lake Challa (Barker et al., 2011; Sinninghe Damsté et al., 2011; Tierney et al., 2011b; Verschuren et al., 2009), Lake Victoria (Johnson et al., 1996), Lake Tanganyika (Tierney et al., 2008), Lake Rukwa (Vincens et al., 2005) and Lake Malawi (Castañeda et al., 2009, 2007; Johnson et al., 2002), all of which broadly indicate reduced rainfall at the end of the last glacial period and a strong imprint of direct insolation forcing (Tierney et al., 2008; Verschuren et al., 2009). Implicit in these models, however, is an anti-phase relationship between the northern and southern tropics, with one tropic getting drier while the other is getting wetter (Braconnot et al., 2008; Castañeda et al., 2007; Partridge et al., 1997). As the majority of evidence from eastern Africa comes from sites located

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north of the modern southern position of the ITCZ (~13–14°S, Fig. 1), it has been difficult to fully evaluate the impact of possible ITCZ migrations, or determine that this has been the sole/dominant driver of long-term climate change along the eastern African margin.

In southeastern Africa south of the maximum austral summer limit of the ITCZ, evidence for an anti-phase relationship supporting the model of a shifting ITCZ has been ambiguous. Early evidence from Tswaing Crater (Partridge et al., 1997), tuned to the precessional cycle, did identify an anti-phase relationship, but significant limitations in the chronology, and the lack of a clear precessional signal during the last 45 kyr has led to questions regarding the reliability of the record. Shorter records from Wonderkrater (Scott, 1999, 1989, 1982a; Truc et al., 2013) and Cold Air Cave (Holmgren et al., 2003, 1999; Lee-Thorp et al., 2001) spanning the last precessional cycle (23 kyr) have been interpreted in different, sometimes contradictory ways. While in some cases support has been found for an antiphase interhemispheric relationship, debate regarding the significance of the proxies has left the evaluation of the model unresolved.

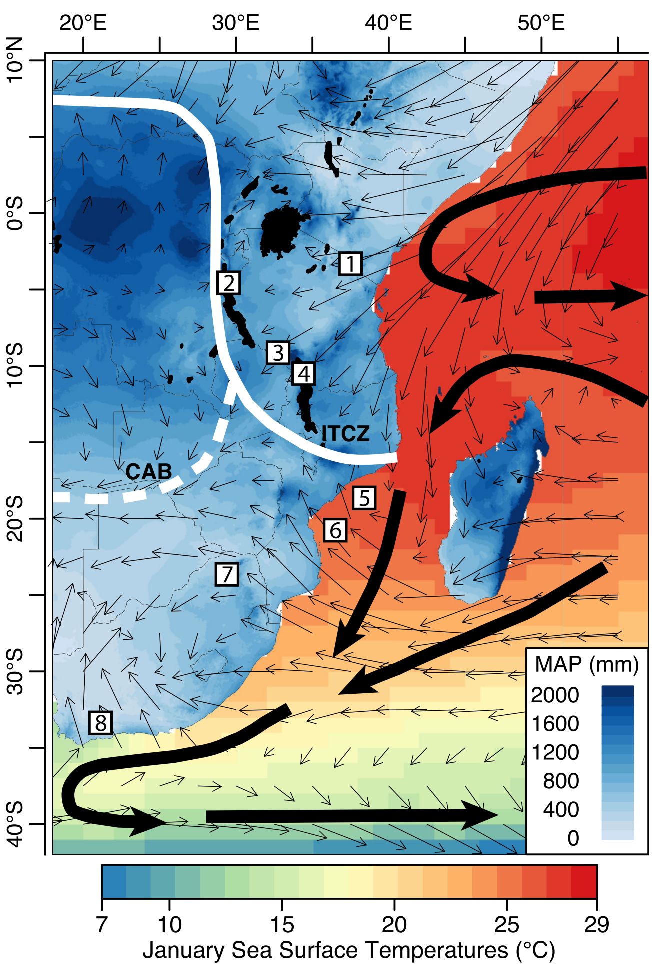

Fig. 1. Map of the major atmospheric and oceanic circulation systems, convergence zones (the Intertropical Convergence Zone (ITCZ) and the Congo Air Boundary (CAB)), mean annual precipitation (MAP, Hijmans et al., 2005), sea surface temperatures (Reynolds et al., 2002) and the mean summer windfield (NCEP/NCAR reanalysis, Kalnay et al., 1996). The primary sites considered, but not analysed, in this study are numbered from north to south: 1) Lake Challa (Sinninghe Damsté et al., 2011), 2) Lake Tanganyika (Tierney et al., 2008), 3) Lake Masoko (Garcin et al., 2006a), 4) Lake Malawi (Castañeda et al., 2007), 5) marine core GeoB9307 (Zambezi river mouth, Schefuβ et al., 2011), 6) marine core MD79257 (Bard et al., 1997; Sonzogni et al., 1998), 7) Cold Air Cave speleothem (Holmgren et al., 2003, 1999; Lee-Thorp et al., 2001) and 8) Seweekspoort hyrax midden (Chase et al., 2013, 2012).

Many recent works from across the subcontinent have failed to identify a dominant signal related to direct insolation forcing south of the modern ITCZ (Chase et al., 2010, 2009; Dupont et al., 2011; Stager et al., 2011; Truc et al., 2013), with a majority of records indicating interhemispheric synchrony, rather than asynchrony as the conceptual models predict. It has been suggested that the influence of insolation may be significantly modulated by variations in continental and sea-surface temperatures (SSTs), which - as determinants of the amount of evaporation and advection of moisture - appear to be important/dominant factors in driving precipitation variability during the late Quaternary (Stager et al., 2011; Tierney et al., 2008; Truc et al., 2013). The spatial homogeneity and temporal variability of the significance of these patterns and drivers remain open questions, with the possibility existing that shifts in the mean position of the ITCZ did occur according to changes in direct insolation forcing and NH ice sheet extent, bringing increased precipitation to parts of southeastern Africa (Schefuβ et al., 2011; Thomas et al., 2009), but that they were dominant only in a spatially restricted area, between no more than 15°S–21°S (Truc et al., 2013).

In this study, we focus on constraining key elements of this debate in southeastern Africa through the quantitative reconstruction and comparison of summer rainfall amount (PWetQ) and mean annual temperature (MAT) at 11 sites (13 pollen sequences) from the South African summer rainfall zone (SRZ; sensu Chase and Meadows, 2007) using the methodologies developed in the CREST software package (Chevalier et al., 2014). By distilling estimates of specific climatic variables from the palaeobotanical data, we 1) render the diverse data directly comparable, and 2) isolate for discussion those climatic elements that are most-directly linked to the moisture-bearing systems related to the ITCZ and tropical circulation systems. This has allowed the identification of similar records and, through a Monte Carlo framework, their combination into regionally representative records that preserve the most robust signals present in the individual datasets. Comparing these records with data from sites along Africa's eastern margin has allowed for a more holistic evaluation of the models of long-term climate variability across the region, and revealed the complex patterning and evolution of dominance in key climatic drivers during the last 45,000 years.

2. Regional setting

Spanning the subtropics, southern African climates are diverse, with warm mesic conditions dominating the east, arid to semi-arid climates across much of the interior and west, and a narrow zone of Mediterranean climate in the extreme southwest (Fig. 1, Tyson and Preston-White, 2000; Tyson, 1986). Temperatures are primarily defined by a combination of latitude and elevation, with the coldest values found in the Drakensberg Mountains (Fig. 2b), and by proximity to the warm Indian Ocean. Considered in terms of precipitation seasonality and the circulation systems that determine moisture transport, most of the subcontinent experiences a distinct summer rainfall regime, with moisture being advected from the tropical Indian and Atlantic Oceans. This has resulted in strong moisture gradients across the continent, diminishing with distance from source. This distribution is modified by 1) the uplands of the Great Escarpment, which border the subcontinent and enhance local precipitation as a function of orographic effect, and 2) the South Atlantic Anticyclone, which blocks moisture transport to the western coastal margin (Nicholson, 2000; Tyson and Preston-White, 2000). The Mediterranean climate of the Cape region in the southwest is defined by rains falling primarily during the austral winter, as frontal systems associated with the westerly