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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

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ABSTRACT

In southeast Africa – a region for which few palaeoenvironmental records are available – the fossil pollen record from the Wonderkrater spring mound has contributed substantially to our understanding of past vegetation change since the Last Glacial Maximum (LGM; 21 ka). Multivariate analysis of the pollen data by Scott and Thackeray (1987) provided environmental reconstructions suggesting relatively mesic LGM conditions, with warm and dry conditions during the early Holocene (11–6 cal kBP). This conforms to predicted patterns of precipitation change in the southern African tropics in response to Northern Hemisphere cooling and orbital forcing. Subsequent data from the Cold Air Cave speleothems and a sea-surface temperature record from the Mozambique Channel, however, indicate that conditions during the early to mid-Holocene may have been wetter than present in the Wonderkrater region. To explore this question further, we have created a series of botanical–climatological transfer functions based on a combination of modern climate and plant distribution data from southern Africa. Applying these to the Wonderkrater fossil pollen sequence, we have derived quantitative estimates for temperatures during the cold and warm quarters, as well as precipitation during the wet and dry quarters. In addition, a species-selection method based on Bayesian statistics is outlined, which provided a parsimonious choice of likely plant species from what are otherwise taxonomically broad pollen-types.

We do not propose that our findings invalidate the previous principal component analyses, but they do have the advantage of being based more clearly on the relationship between modern plant distributions and individual climatic variables. Results indicate that temperatures during both the warm and cold seasons were 6 ± 2 °C colder during the LGM and Younger Dryas, and that rainy season precipitation during the Last Glacial Maximum was ~50% of that during the mid-Holocene. Our results also imply that changes in precipitation at Wonderkrater generally track changes in Mozambique Channel sea-surface temperatures, with a steady increase following the Younger Dryas to a period of maximum water availability at Wonderkrater ~3–7 ka. These findings argue against a dominant role of a shifting Intertropical Convergence Zone in determining long-term environmental trends, and indicate that the northern and southern tropics experienced similar climatic trends during the last 20 kyr.

1. Introduction

Late Quaternary climate variability in the Southern Hemisphere is a matter of significant debate, with a range of hypotheses invoking different forcing climatic mechanisms to explain observed patterns of change. In the southern tropics and subtropics of Africa, the most

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commonly posited phenomenon is latitudinal adjustment in the mean annual position of the Intertropical Convergence Zone (ITCZ). This is potentially driven by high latitude Northern Hemisphere cooling (e.g. Flohn, 1981; Johnson et al., 2002) and/or direct insolation forcing (e.g. Kutzbach, 1981; COHMAP, 1988; Liu et al., 2003; Braconnot et al., 2008; Marzin and Braconnot, 2009). Both hypotheses imply an inter-hemispheric anti-phase relationship, that is, aridification in northern tropics would be expected to coincide with humidification in the southern tropics (Scott, 1993; Street-Perrott and Perrott, 1993; Partridge et al., 1997; Schefuß et al., 2011). To date, however, no irrefutable evidence supporting either hypothesis has been found in southern Africa (cf. Chase et al., 2010).

In this context, southern Africa is a key region in which to investigate vegetation and climate dynamics, which may support, modify or falsify hypotheses concerning the Quaternary dynamics of the ITCZ. The region is highly sensitive to perturbations in the Earth's climate system, both at regional and global scales (cf. Chase and Meadows, 2007; Dupont et al., 2011) due to its position at the juncture of temperate, subtropical and tropical climate systems (Fig. 1). However, this region is also characterised by a lack of reliable, well-dated proxy records, and palaeoecological evidence is particularly sparse and often difficult to interpret.

One record that has played a particularly important role in shaping our understanding of past vegetation changes in southeast Africa during the late Quaternary is the fossil pollen sequence from the Wonderkrater spring mound (Scott, 1982; Scott and Thackeray, 1987; Scott, 1999; Thackeray, 1999). Notably, the record has been interpreted as indicating a cool, but moist, Last Glacial Maximum (LGM)/last glacial–interglacial transition (LGIT) and a dry early Holocene (Scott and Thackeray, 1987; Scott et al., 2003). These findings support both the hypothesis of a southward shift of the ITCZ due to Northern Hemisphere cooling and that of direct insolation forcing in response to precessional changes in the Earth's orbit.

As other records have been obtained from the region, however, certain paradoxes have become evident in the aggregate regional dataset. For example, high resolution stable isotope records from the Cold Air Cave speleothem spanning the last 25 kyr imply that the early to mid-Holocene was more humid than the LGM at Wonderkrater (Lee-Thorp et al., 2001; Holmgren et al., 2003). More recently, a longer, but lower resolution pollen record for the last 340 kyr from off the Limpopo River mouth suggests that warmer periods are generally more humid in the region (Dupont et al., 2011). The physical mechanism for this is thought to be the strong positive relationship between sea-surface temperatures (SSTs) in the Mozambique Channel (Sonzogni et al., 1998; Caley et al., 2011) and continental humidity in eastern South Africa, both under present conditions (Goddard and Graham, 1999), and over multi-millennial timescales (Chase et al., 2010; Dupont et al., 2011), with warmer SSTs favouring increased evaporation and moisture transport. A question therefore arises as to whether the principal components extracted from the Wonderkrater pollen sequence discretely reflect temperature and humidity, as has been proposed.

The aim of this paper is to develop a new approach for interpreting the pollen data and investigating this paradox, in order to improve our understanding of the forcing mechanisms driving regional climate variability since the LGM. To explore this question, we use plant distribution and climate data to define the specific climatic requirements of the plant taxa comprising the primary pollen-types in the Wonderkrater sediment core, and to develop botanical–climatological transfer functions based on probability density functions (*pdfs*). As well as addressing a critical topic in southern African palaeoclimatology, this paper also describes the methods by which quantitative, rather than qualitative, estimates of past climatic parameters can be obtained from southern African fossil pollen records. This represents a significant step in this region, and it promises to provide the basis for more robust comparisons of palaeoenvironmental data and general circulation model simulations.

1.1. Study area and regional settings

This study primarily considers trends in past vegetation and climate in the vicinity of the Wonderkrater spring mound (24.4390°S, 28.7507°E) in northeastern South Africa. However, the transfer function techniques applied necessitate a broader analysis of the distribution of plant taxa across southern Africa, including South Africa, Lesotho, Swaziland, Botswana and Namibia (17°–34°S and 11°–32°E) (Fig. 2). The wider study area is characterised by strong heterogeneity in terms of its topography, geology and climate. The complexity of this landscape, and the oceanic and atmospheric circulation systems that determine the region's climate have resulted in strong environmental gradients that have a clear influence on plant distributions.

Considering southern Africa as a whole, precipitation is associated with two major circulation systems, viz.: (1) tropical systems, including easterly flow from the Indian Ocean and northwesterly flow from the tropical Atlantic Ocean. These develop with seasonal heating of the continent, both of which are related to annual migrations of the ITCZ; (2) temperate systems, which influence the region as frontal systems embedded in the westerly storm-track that migrates equatorward in winter months (cf. Chase and Meadows, 2007) (Fig. 1). Mean annual rainfall ranges from c. 800 mm per annum in south east South Africa, to <50 mm per annum in Namibia. Isohyets are orientated in a broadly east–west manner in more tropical latitudes, but become increasingly north–south orientated in central and south-west South Africa, which reflects the increasing significance of the mid-latitude anticyclones and temperate systems relative to the Intertropical Convergence Zone (ITCZ) in driving atmospheric (in)stability and rainfall patterns (cf. Tyson and Preston-Whyte, 2000). The alternating seasonal dominance of these systems therefore results in a strong seasonality gradient in precipitation across the subcontinent, manifested as a summer rainfall zone in the eastern part of the sub-continent (SRZ, >66% of mean annual precipitation falling between Oct and Mar), a winter rainfall zone in the southwest (WRZ, >66% of mean annual precipitation falling between Apr and Sept) and a transitional zone sometimes referred to as the year-round rainfall zone (YRZ), which receives both winter and summer precipitation (cf. Chase and Meadows, 2007). Both of these broad climate regions are highly variable in terms of temperature and precipitation, with mean annual values ranging from 6.5 °C–24.4 °C and 10–1380 mm yr^{-1} in the SRZ, and 10.8 °C–19.9 °C and 25–970 mm yr^{-1} in the WRZ (Hijmans et al., 2005).

At local and region scales both temperature and precipitation are strongly influenced by topography, and the diversity of vegetation types is also influenced by edaphic conditions. Generally, vegetation in the SRZ is composed of a variety of subtropical savannas, shrublands, grasslands and woodland (Rutherford and Westfall, 1986). In contrast, the WRZ is associated with Mediterranean shrublands (known as fynbos and renosterveld).

The Wonderkrater site is located within the SRZ (Fig. 1), with mean annual rainfall of ~550 mm. It is characterised by wet summers (DJF; ~285 mm) and very dry winters (JJA; ~15 mm) (data from Hijmans et al., 2005). Mean seasonal temperatures are 23 °C and 13.5 °C during summer and winter respectively. The vegetation at the site is part of the Central Bushveld known as the Springbokvlakte Thornveld (Mucina and Rutherford, 2006). This vegetation is an open to dense savannah dominated by various species of *Acacia* or shrubby grassland. Important trees and shrubs include *Acacia karroo*, *Acacia leuderitzii*, *Acacia mellifera*, *Acacia nilotica*, *Ziziphus mucronata*, *Boscia foetida*, *Boscia albitrunca*, *Euclea undulata*, *Searsia* (*Rhus*) *engleri*, *Dichrostachys cinerea*, *Diospyros lycioides*, *Grewia flava* and *Tarchonanthus camphoratus*, while the grasses are primarily comprised of *Aristida bipartita*, *Aristida canescens*, *Dichanthium annulatum*, *Iscaenum afrum*, *Setaria incrassata* and *Brachiaria eruciformis* (Mucina and Rutherford, 2006).