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Shifting westerlies and precipitation patterns during the Late Pleistocene in southern Africa determined using glacier reconstruction and mass balance modelling

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ABSTRACT

South Africa experiences a range of different climatic regimes and is thus an ideal region to investigate Late Pleistocene environmental and climate change. However, detailed quantifiable palaeoclimate data are sparse in the region. In particular, reliable palaeoclimatic data are essential to resolve ongoing controversies regarding temperature depression and moisture availability during glacial periods in the sub-continent. Small glaciers close to the glaciation threshold are highly sensitive to changes in temperature and precipitation and are therefore ideal indicators of past climatic conditions during their existence. This paper derives some of the first quantitative data on Last Glacial Maximum (LGM) palaeoprecipitation in southern Africa, based on glacier reconstruction and mass balance modelling for the Lesotho Highlands.

The reconstruction of former glaciers and their dynamics enables the determination of glacier viability under specific climatic envelopes. Glacier reconstructions at five sites in the Lesotho Highlands yield palaeoglaciers with Equilibrium Line Altitudes (ELAs) ranging from 3095 to 3298 m a.s.l., and reconstructed steady-state mass balance and flow dynamics are comparable with modern analogues. Topoclimatic factors are investigated, with temperature-radiation-index modelling indicating that topographic shading was an important factor determining the existence of small glaciers in this region. The occurrence of glaciation in the Drakensberg during the LGM suggests a potential increase in precipitation and change in its seasonality. Such trends are likely associated with an increased frequency of westerly wave (cold front) disturbances due to the northward shift of pressure belts, which would also increase precipitation as snow at higher altitudes. The application of a high resolution climate model (HadAM3h) to test this, displays a change in the seasonal timing of precipitation during the Last Glacial cycle, with a decrease in precipitation evident during the summer months. This is likely to have had important implications for the mass balance and survival of small niche glaciers in the region, with more precipitation falling during the spring – winter – autumn months as snow.

1. Introduction

Southern Africa is uniquely positioned at the junction of three of the world's oceans. During glacial periods, the expansion of Antarctic sea ice forces both oceanic and atmospheric frontal systems of the Southern Ocean to move northwards (Stuut et al., 2004; Bard and Rickaby, 2009), which in turn may lead to significant changes in the climate of southern Africa. The southern hemisphere westerlies are thought to be a key component of global climate change and at present only affect the far southwestern regions of southern Africa. Considerable debate has focussed on whether these were displaced pole-wards or equator-wards during glacial periods (Lamy et al., 1998; Wyrwoll et al., 2000; Sugden et al., 2005) and Global Circulation Models (GCMs) aiming to derive the position and intensity of the westerlies during the Last

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Glacial Maximum (LGM) have failed to do so convincingly (Rojas et al., 2009). Terrestrial records therefore provide an opportunity to quantify temperature and precipitation changes which can calibrate/constrain model outputs.

Proxy data providing detailed palaeoclimate records are relatively scarce in the southern hemisphere, relative to those available from the northern hemisphere. Although the climate of southern Africa does not typically lend itself to the preservation of long uninterrupted terrestrial records (Chase and Meadows, 2007), well dated records are becoming increasingly available from both terrestrial and offshore environments (see Gasse et al., 2008 for a review). Coldest terrestrial temperatures during the Last Glacial cycle inferred from combined pollen data for southern Africa are believed to have occurred at ~24 and ~17 ka (Scott et al., 2012). Temperatures derived from dissolved gas records from aquifers (Heaton et al., 1986), speleothem $\delta^{18}O$ (Talma and Vogel, 1992; Holmgren et al., 2003) and pollen records (Scott, 1999), indicate a mean annual temperature decrease of 5–7 °C at the LGM over southern Africa. Seasonal variations from this have been inferred using pollen-based reconstructions and suggest temperature depressions of 10–15 °C for the coldest month, with more subdued temperature depressions during the warmest month in the summer rainfall region of southern Africa (Wu et al., 2007), implying an overall temperature depression coupled with a significant increase in seasonality.

The suggested temperature depressions proposed offer support to climate-based arguments for the existence of Late Pleistocene glaciers in the highest altitude regions of southern Africa. Despite this, there has been ongoing scientific debate, now spanning some 40 years, on the evidence for Pleistocene glaciations in southern Africa. Most recently, the primary concern has focussed on the suggestion that palaeoprecipitation may have been too low to sustain any glaciers during the LGM (Hall, 2004). Evidence for past glaciation was first presented by Sparrow (1967) and subsequently stimulated considerable debate and further work (e.g. Marker and Whittington, 1971; Marker, 1991; Grab, 1996; Boelhouwers and Meiklejohn, 2002; Mills and Grab, 2005; Mills et al., 2009a,b; Hall, 2010). Recent work based on a multi-method approach proposes small scale glaciation in the Lesotho Highlands during the LGM (Mills and Grab, 2005; Mills et al., 2009a,b). The occurrence of restricted glaciation during the LGM in southern Africa has now become more widely accepted (Mark and Osmaston, 2008; Hall and Meiklejohn, 2011). Importantly, with the confirmation of such marginal glacial phenomena, palaeoglacier dynamics can be used to constrain the palaeoclimate during the LGM.

In this paper, glacier reconstruction and mass balance modelling is applied to constrain the palaeoclimate of the Lesotho Highlands during the LGM. The importance of local topography and shading on accumulation and ablation is considered using snowblow and temperature-radiation-index modelling. This permits a fine-tuned palaeoclimatic reconstruction (notably palaeoprecipitation), which is then compared against the HadCM3 and higher resolution HadAM3h climate models for the region.

2. Regional setting

The highest mountains in southern Africa are situated in Lesotho, where altitudes rise to 3482 m a.s.l. at Thabana Ntlenyana (Fig. 1). Contemporary temperatures at high altitudes in Lesotho are characterised by cool to mild summers (mean = 10 °C) and cold winters (mean = 0 °C), with a Mean Annual Air Temperature (MAAT) for the higher peaks estimated at 4 °C (Grab, 1999).

The Great Escarpment of southern Africa, a product of post-Gondwana uplift, is a primary control on moisture dispersal across south-eastern Africa, particularly blocking the advection of moist Indian Ocean air into the western interior (Gasse et al., 2008). Southern Africa may be categorized into three precipitation zones (Fig. 2). The winter rainfall zone covers the western part of the country where over 66% of precipitation falls between April and September, primarily through frontal systems associated with westerly wave disturbances (Tyson and Preston-Whyte, 2000). By contrast, the summer rainfall zone receives over 80% of its mean annual precipitation between October and April (Killick, 1976; Sene et al., 1998), associated with the seasonal movement of high-pressure cells, whilst less than 10% falls between May and August (Tyson et al., 1976). A narrow zone receiving year-round precipitation is located across the Eastern Cape Province and adjacent Karoo, and eastern parts of the Western Cape regions of South Africa.

The altitudinal zone of maximum precipitation along the main escarpment is estimated between 2300 and 2900 m a.s.l., but precipitation decreases rapidly westwards of the escarpment (Killick, 1963). Snowfalls occur on average five to ten times per annum during the cooler seasons over the highest regions (typically above 2800 m a.s.l.) and are usually associated with cold fronts (Sene et al., 1998).

The study sites discussed in this paper are located in the summer precipitation zone of eastern Lesotho; along the Tsatsa-La-Mangaung, Sekhokong and Leqooa mountain ranges (Fig. 1). Landforms and sediments of interpreted glacial origin have been identified along the south-facing slopes of these mountain ranges, and all occur within a few kilometres west of the escarpment. The geomorphology, sedimentology and micromorphology of these deposits have previously been described in detail (see Mills and Grab, 2005; Mills et al., 2009a,b) and are therefore not elaborated on in this paper.

3. Methods

The extent of former glaciation at four of the five sites was determined through geomorphological mapping, whilst moraines have been dated to the LGM based on ^{14}C AMS ages obtained from soil organic matter (Mills and Grab, 2005; Mills et al., 2009a,b). In addition, the landforms at a fifth site (Leqooa Site 2) were mapped, and although no direct dating has been undertaken, the moraine is assumed to be of similar age to those from adjacent sites; such an assumption is based on the similar state of weathering of surface boulders making up the deposits.

3.1. Glacier reconstruction and equilibrium line altitudes

3.1.1. Glacier reconstruction

The existence of mapped and dated moraines allows individual palaeoglacier surfaces to be reconstructed. The lateral margins of the palaeoglaciers were defined by the crest lines of the moraines and the confining topography, whilst the upper limits were positioned approximately 30 m below the confining headwall (Gray, 1982). Due to the relative lack of confining terminal moraines, with the exception of Leqooa Site 2, a 'minimal reconstruction' is undertaken. Palaeoglacier form and ice surfaces at 25 m contour intervals were reconstructed in a geographical information system (ArcGIS). Ice surface contours were reconstructed based on contemporary glaciers which display a distinct contour pattern, with contours becoming increasingly concave below and convex above the ELA, whilst remaining almost straight at the approximate mean altitude of the glacier (Porter, 1975; Carr and Coleman, 2007; Carr et al., 2010).

3.1.2. Equilibrium line altitude

The ELA of a glacier represents the area where net accumulation equals net ablation. A variety of methods are available to reconstruct former ELAs, the most precise are based on the three-