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The greening of Arabia: Multiple opportunities for human occupation of the Arabian Peninsula during the Late Pleistocene inferred from an ensemble of climate model simulations

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ABSTRACT

Climate models are potentially useful tools for addressing human dispersals and demographic change. The Arabian Peninsula is becoming increasingly significant in the story of human dispersals out of Africa during the Late Pleistocene. Although characterised largely by arid environments today, emerging climate records indicate that the peninsula was wetter many times in the past, suggesting that the region may have been inhabited considerably more than hitherto thought. Explaining the origins and spatial distribution of increased rainfall is challenging because palaeoenvironmental research in the region is in an early developmental stage. We address environmental oscillations by assembling and analysing an ensemble of five global climate models (CCSM3, COSMOS, HadCM3, KCM, and NorESM). We focus on precipitation, as the variable is key for the development of lakes, rivers and savannas. The climate models generated here were compared with published palaeoenvironmental data such as palaeolakes, speleothems and alluvial fan records as a means of validation. All five models showed, to varying degrees, that the Arabia Peninsula was significantly wetter than today during the Last Interglacial (130 ka and 126/125 ka timeslices), and that the main source of increased rainfall was from the North African summer monsoon rather than the Indian Ocean monsoon or from Mediterranean climate patterns. Where available, 104 ka (MIS 5c), 56 ka (early MIS 3) and 21 ka (LGM) timeslices showed rainfall was present but not as extensive as during the Last Interglacial. The results favour the hypothesis that humans potentially moved out of Africa and into Arabia on multiple occasions during pluvial phases of the Late Pleistocene.

1. Introduction

The timing and spatial distribution of the dispersal of *Homo sapiens* out of Africa is the subject of intense and continued scientific debate (e.g. Oppenheimer, 2009; Frumkin et al., 2011; Boivin et al., 2013; Mellars et al., 2013). The consensus view is that genetic and archaeological evidence supports a major dispersal of

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human populations after 70,000 years ago (ka) during Marine Isotope Stage (MIS) 4 or early MIS 3 (Mellars et al., 2013). However, this has been challenged by recent archaeological discoveries and new genetic and environmental interpretations, which advocate multiple dispersals during MIS 5 (130–71 ka) and also later times (Boivin et al., 2013; Groucutt and Petraglia, 2014; Parton et al., 2015). Central to this debate is the need to understand the environmental context of human dispersals. In regions where secure palaeoenvironmental records are incomplete or under development this is a difficult task. Here we present a different approach and assess the degree to which global climate models can inform us about past climate change and human dispersals.

Climate models are sophisticated mathematical tools that have been used in similar contexts to address key questions such as the extinction of the Neanderthals and the arrival of modern humans in Europe (Davies et al., 2003), the identification of Neanderthal refugia in southern Iberia (Jennings et al., 2011) and the modelling of human populations structures in North Africa (Scerri et al., 2014a,b). Eriksson and colleagues (2012) have recently used one model to explore *H. sapiens* dispersals out of Africa but on a larger geographic scale than we now present. Instead, we focus solely on one key region, the Arabian Peninsula.

Those working in the Arabian Peninsula consider the region to be a critical area for understanding *H. sapiens* dispersals and demography (Petraglia and Alsharekh, 2003; Bailey, 2009; Marks, 2009; Parker, 2009; Parker et al., 2009; Armitage et al., 2011; Petraglia, 2011; Rose et al., 2011; Rosenberg et al., 2011, 2013; Groucutt and Petraglia, 2012, 2014; Crassard and Hilbert, 2013; Crassard et al., 2013). Yet, the Saharo-Arabian desert belt, a hyperarid–arid expanse at 14–35°N, has often been seen as a major biogeographical barrier for human range expansions out of Africa, with the Nile River hypothesised as a possible dispersal corridor (Van Peer, 1998; Vermeersch, 2001). However, over the last decade it has been shown that the Sahara was not always desert and that rivers, lakes and savanna grasslands developed during pluvial episodes, linked to changes in insolation (e.g. Drake et al., 2011, 2013; Larrasoaña et al., 2013). As research develops in the Arabian Peninsula, researchers are returning to ancient lakebeds previously investigated in the 1970s (e.g. Petraglia, 2011; Rosenberg et al., 2011, 2013; Crassard et al., 2013). Although these palaeolakes were once thought to date to MIS 3, evidence now indicates that the lakes formed during MIS 5 (Petraglia, 2011; Rosenberg et al., 2011). Speleothem growth, a sign of increased humidity, has also been dated to this period in caves in south and southeast Arabia (Fleitmann et al., 2004, 2007), while Late Quaternary fluvial deposits have been identified in the United Arab Emirates (UAE) (Atkinson et al., 2013).

Much of what we know about Arabia's past climate is currently undergoing extensive revision. Just as in the Sahara, the idea that the Arabian Peninsula was wetter during certain periods of the Pleistocene is rapidly developing into the null hypothesis. Recent discoveries of Middle Palaeolithic sites in stratified contexts on the shores of some of these aforementioned palaeolakes strongly suggests that *H. sapiens* populations, or possibly even Neanderthals, were in the interior of the Arabia Peninsula during MIS 5 (Groucutt and Blinkhorn, 2013; Petraglia et al., 2012; Crassard et al., 2013). If savanna grassland and lakes had developed 130 ka, the idea of solely a coastal dispersal around Arabia to explain human dispersals (cf. Mellars et al., 2013), in which the interior of Arabia was bypassed, seems highly unlikely. Instead, the presence of savanna habitats in the Arabian interior suggests that human populations could have dispersed into this region during humid phases between 130 and 78 ka, especially given that *H. sapiens* fossils at Skhul and Qafzeh in the Levant (Grün et al., 2005), and archaeological assemblages at Jebel Faya in SE Arabia (Armitage et al., 2011; Bretzke et al., 2013) and in East Africa (Basell, 2008) date to this time.

One of the key difficulties in testing the hypothesis that human populations inhabited the interior of Arabia during the Late Pleistocene is the lack of dated and stratified archaeological sites. For a landmass that is one quarter of the size of Europe, a small handful of dated lakebeds, speleothems and stratified sites do not provide enough evidence to link human presence to the palaeoclimatic framework. Here, we take a different approach and assess this data in the context of five climate models covering the Arabian Peninsula. We employ climate models because they are an informative way of developing insights into past climate change, especially where comprehensive palaeoclimate records are not available. Climate models take into account the major processes that shaped past climate change, such as astronomical forcing, ice sheet extent, sea-level, vegetation cover, and atmospheric greenhouse gas concentrations. The climate models provide spatial and temporal frameworks that can be tested using securely dated, independently derived sedimentological and palaeontological data (Braconnot et al., 2012; Heiri et al., 2014).

Here we focus on modelling precipitation, as this variable is a useful measure for determining the amount of rainfall that potentially fell across the Peninsula during the Late Pleistocene, as water would have undoubtedly been vital for the range expansion of our species (Finlayson, 2014). Multiple timeslices are examined, but with a particular focus on specific periods of MIS 5e, when rainfall levels are thought to have been at their highest (Parton et al., 2015). We first review the main weather systems bringing rainfall into the Peninsula today and describe the boundary conditions used in model experiments. Understanding both of these components is necessary before using palaeoenvironmental and archaeological evidence to assess the models and form hypotheses on human demography in the Arabian Peninsula during these periods.

2. Present day rainfall patterns in the Arabia Peninsula

The Arabian Peninsula supports some of the driest environments anywhere in the world. Areas of the Negev desert, north and northwest Saudi Arabia, and in the Rub Al-Khali, a vast expanse of sand desert in southern Saudi Arabia, receive mean annual rainfall levels of <60 mm per annum, placing them in hyper-arid bioclimatic zones (Almazroui et al., 2012). Rainfall is more varied elsewhere in the peninsula (Fig. 1), attaining an average of 75.4 mm in the Eastern Province of Saudi Arabia (with the highest yearly total recorded being 384 mm) (Barth and Steinkohl, 2004), up to 140 mm per annum in the UAE (Parker et al., 2006), 234 mm per annum in Bahrain (Elagib and Abdu, 2010) and up to 400 mm in the Al Jabal and Al Akhdar mountains of Oman (Kwarteng et al., 2009). High levels of rainfall are also known in the Yemen highlands and in southwest Saudi Arabia, where up to 400 mm per annum is recorded and it can rain during every month of the year (Al-Subyani, 2004; Al-Subyani, 2005; Almazroui, 2011; Furl et al., 2014). However, decadal averages across the peninsula do not typically exceed 200 mm per annum outside the upland areas of SW Saudi Arabia, Yemen and Oman (Almazroui et al., 2012) and as such, an arid to hyper-arid climate prevails across the vast majority of the peninsula.

An important reason for the observed rainfall variation in Arabia is orography, where rainfall increases with elevation. For instance, the Asir Mountains (3000 m above sea level) which run parallel to the Red Sea along the western side of the Peninsula, and the Hadramaut (1500 m above sea level) in the south of Arabia receive higher rainfall than interior areas. It has been noted that there are too few weather stations to record accurately precipitation levels in such regions owing to the complex orographic variability (Abo-Monasar and Al Zahrani, 2014). Elsewhere, at Wadi Yalalam in the west of Arabia, rainfall levels are higher in the wadi's upper reaches (220 mm), on the western slopes of the Hijaz escarpment, than at