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Orbital controls on Namib Desert hydroclimate over the last 50,000 years

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ABSTRACT

Despite being one of the world's oldest deserts, and the subject of decades of research, evidence of past climate change in the Namib Desert is extremely limited. As such, there is significant debate regarding the nature and drivers of climate change in the low latitude drylands of southwestern Africa. Here we present data from stratified accumulations of rock hyrax urine that provide the first continuous high-resolution terrestrial climate record for the Namib Desert spanning the last 50,000 years. These data, spanning multiple sites, show remarkably coherent variability that is clearly linked to orbital cycles and the evolution and perturbation of global boundary conditions. Contrary to some previous predictions of southwestern African climate change, we show orbital-scale cycles of hydroclimatic variability in the Namib Desert region are in phase with the northern tropics, with increased local summer insolation coinciding with periods of increased aridity. Supported by climate model simulations, our analyses link this to variations in position and intensity of atmospheric pressure cells modulated by hemispheric and land-sea temperature gradients. We conclude that hydroclimatic variability at these time scales is driven by the combined influence of direct low latitude insolation forcing and the influence of remote controls on the South Atlantic Anticyclone, with attendant impacts on upwelling and sea-surface temperature variations.

INTRODUCTION

Past climate change at low latitudes in Africa is generally considered to be driven at orbital timescales by precessional variations in summer insolation (Collins et al., 2014; Kutzbach and Street-Perrott, 1985; Partridge et al., 1997), which affect the position and extent of the tropical African rainbelt (Partridge et al., 1997; Schefuß et al., 2011). In the northern and eastern African tropics, the influence of direct orbital forcing is well-documented (Chevalier and Chase, 2015; Kutzbach and Street-Perrott, 1985; Partridge et al., 1997; Schefuß et al., 2011; Shanahan et al., 2015; Tierney et al., 2017; Tierney et al., 2008). In southwestern Africa (defined here as between ~17°S-30°S, and extending eastward from the coast to ~20°E), where the influence of the South Atlantic Anticyclone (SAA) and Benguela upwelling system play a significant role in driving regional aridity, their role is unclear (Chase et al., 2009; Collins et al., 2014; Lim et al., 2016). Here, low precipitation and strongly seasonal rainfall regimes have restricted the development of lakes and wetlands that could provide longer term records of climate change. Long marine sediment records from the adjacent southeast Atlantic have been interpreted as indicating a strong positive relationship between summer insolation and precipitation in southwestern Africa (Collins et al., 2014) and across the wider subcontinent (Daniau et al., 2013). These findings, however, contrast with interpretations based on the limited terrestrial palaeoenvironmental evidence from the Namib Desert (Chase et al., 2010; Lim et al., 2016; Scott et al., 2004) and, as a result, there is no clear understanding of the nature of orbital-scale climate change and its underlying drivers in one of the world's most arid regions.

MATERIALS AND METHODS

To study past climate change in the Namib Desert we have employed a unique palaeoenvironmental archive, rock hyrax middens, stratified accumulations of the petrified urine (hyraceum) of the rock hyrax (*Procavia capensis*). From these we have derived a 50,000-year terrestrial record of palaeoclimate for southwestern Africa. Optimally preserved in dryland environments, hyrax middens provide unprecedentedly detailed hydroclimate evidence in their stable isotope records (Chase et al., 2015a; Chase et al., 2017; Chase et al., 2009; Chase et al., 2012). For this study, we deployed a transect of three sites (Spitzkoppe: 15.20°E, 21.83°S; Zizou: 15.97°E, 24.07°S; Pella: 19.14°E, 29.00°S) along a 900 km north-south transect of the Namib Desert (Fig. 1). Situated along the steep zonal hydroclimate gradient that forms a continuum from the arid to hyperarid Namib Desert in the west from the semi-arid to dry sub-humid environments to the east (Fig. 1), the sites were selected to assess climate change trends and events at a regional scale. Combined, eight middens from the three sites comprise a total of 208 cm of hyraceum accumulation, from which 1792 samples were analysed for their stable nitrogen isotope composition ($\delta^{15}N$). To achieve a more comprehensive understanding of regional hydroclimates, plant leaf wax *n*-alkanes were also extracted from the Spitzkoppe middens (93 samples spanning 32,500 years) and analysed for their hydrogen isotope composition (δD). A chronology was established with 86 ^{14}C accelerator mass spectrometry ages from the hyraceum to build a composite sequence (Fig. 2, S1, S2). For details on these methods, please refer to the Supplementary Information.

Over the last 50 kyr, significant variability is apparent in the hyraceum $\delta^{15}N$ values (13.5‰) (Fig. S1, S2). Despite the spatial range of the sites and the differences in accumulation rates, strong orbital-scale similarities are apparent between the trends in the records obtained (Fig. S2, S3), and a regional composite was created using Gaussian kernel smoothing (Rehfeld et al., 2011) to the combined datasets (Fig. S2).

Hyraceum $\delta^{15}N$ has been shown - through observation of modern middens and plants (Carr et al., 2016; Murphy and Bowman, 2006), as well as comparison with independent records and other proxies obtained from the same midden samples - to reflect environmental water availability, with higher $\delta^{15}N$ values occurring during more arid periods (Chase et al., 2015a; Chase et al., 2015b; Chase et al., 2009). At low latitudes, δD variability is often predominantly controlled by precipitation amount/intensity (Collins et al., 2014; Garcin et al., 2012), consistent with the similarities between the δD_{wax} and $\delta^{15}N$ records presented here (Fig. 2) (for a fuller discussion please refer to the Supplemental Information).

DISCUSSION

Overall, our $\delta^{15}N$ record indicates that the last glacial period was generally more humid than the Holocene (Fig. 2). We consider temperature to be an important factor in defining this trend, with lower temperatures during the last glacial period limiting potential evapotranspiration and increasing water availability (Chevalier and Chase, 2016; Lim et al., 2016). Orbital-scale variability within and across the Holocene and late Pleistocene in both, $\delta^{15}N$ and δD records, conforms to precessional cycles, particularly during the last 36,000 years (Fig. 2). Our composite record indicates that humidity in the Namib Desert region is generally negatively related to summer insolation. This contrasts with an inferred positive relationship between summer insolation and southern African precipitation (through the invigoration of tropical atmospheric circulation systems) from records obtained from marine archives from off the Namibian coast (Collins et al., 2014; Daniau et al., 2013). Comparing our results with climate model simulations (He et al., 2013) (Fig. 3) and evidence for intensifications of the SAA from wind and upwelling proxies (Fig. 2), we conclude that this cycle of variability is determined by two interrelated factors. The first is the inverse influence of high northern latitude summer insolation. Austral summer insolation maxima correlate with boreal summer insolation minima, which induce phases of global cooling, increasing latitudinal intra-hemispheric temperature gradients (Rind, 1998), and intensifying the SAA and related Benguela upwelling (Farmer et al., 2005; Little et al., 1997b; Pichevin et al., 2005; Stuut et al., 2002). This serves to limit regional atmospheric convection, block the incursion of moisture-bearing systems, and promote the advection of dry air eastward. The second is the influence of austral summer insolation on land-sea temperature and pressure gradients in southwestern Africa (Fig. 3). While global temperatures cool during periods of low boreal summer insolation, coeval increases in austral summer insolation raise summertime continental temperatures and enhance the land-sea pressure gradient, further increasing southerly air flow, and augmenting coastal upwelling (Fig. 3). This combined influence of high and low latitude precessional forcing results in interhemispheric synchrony in orbital-scale patterns of climate change between the Namib Desert and the northern and eastern African tropics across the last 50,000 years (Fig. 2).

The apparent contradiction between the records from marine (Collins et al., 2014; Daniau et al., 2013) and terrestrial archives from the region (compare Fig. 2 b, c and g) may reflect either 1) regional differentiation of climate signals, with marine records being predominantly influenced by sediment sourced in central southern Africa, as suggested by Collins et al. and Daniau et al., or 2) the role of aeolian transport in determining the distinct patterns of variability in the marine records. As a significant vector for the deposition of terrestrial components in marine records (Dupont and Wyputta, 2003; Stuut et al., 2002), the extent and strength of the SAA has the potential to significantly change the source area of these components. This is implied by the inclusion of pollen from increasingly remote sources during periods of intensified upwelling (Lim et al., 2016; Shi et al., 2001). Regional climate gradients are such that any expansion of the source area away from the arid continental margin will promote the inclusion of material from relatively humid areas (Fig. 1). Thus, inferred positive correlations between precipitation and regional summer insolation may reflect the response of regional wind fields to orbital forcing rather than conditions in the Namib Desert itself (Fig. 2).

During the Holocene, the influence of Northern Hemisphere ice sheets and ice rafting events (Chase et al., 2015a) on the position of the African rainbelt (apparent in the midden record as the discrete humid episodes during Heinrich stadials 1-3 [Fig. 2, Supplementary Information, Fig. S2]) diminished. Direct insolation forcing became the dominant control on multi-millennial variability of precipitation in the eastern tropics of southern Africa, resulting in a progressive increase in summer rainfall (Chevalier and Chase, 2015; Schefuß et al., 2011) (Fig. 2). In contrast, conditions in the Namib Desert are characterised by progressive aridification (with the late Holocene being the driest period of the last 50,000 years). This is consistent with patterns of change observed in the western (Collins et al., 2010; Garcin et al., 2018; Schefuß et al., 2005; Shanahan et al., 2015; Weldeab et al., 2007) and northern (Stager et al., 2003; Tierney et al., 2017) tropics. Similar to the dynamics described for the late Pleistocene, model simulations indicate that orbital scale hydroclimatic variability during the Holocene was determined by the combined influences of reduced high northern latitude insolation and increased southern low latitude summer insolation (Fig. 3). This has broader implications: from the early Holocene

Northern Hemisphere summer insolation maximum, substantial cooling is observed in both the northern (Sachs, 2007), eastern equatorial (Weldeab et al., 2007) and southeast Atlantic (Farmer et al., 2005) resulting in a progressive aridification of the whole western tropical margin, from the Namib Desert through the Gulf of Guinea (Garcin et al., 2018; Schefuß et al., 2005; Shanahan et al., 2015; Weldeab et al., 2007). In southwestern Africa, the impact was intensified by insolation driven warming of the continental interior, which enhanced the land-sea temperature gradient, resulting in stronger coastal upwelling (Fig. 3). Thus, this mechanism is shown to operate on/impact SW African climate under both glacial and interglacial boundary conditions.

Our results show that low latitude direct insolation forcing does not operate alone to produce a positive relationship between summer insolation and precipitation. Rather, the resulting low pressure that develops over the subcontinent reinforces the development of a strong east-west dipole. Enhanced tropical northerly flow increases precipitation over southeastern Africa, but coeval intensification of the South Atlantic Anticyclone and Benguela upwelling system result in the transport of dry air across southwestern Africa, resulting in markedly drier conditions. Contrary to previous postulations, long-term hydroclimatic variability in the Namib Desert is in phase with and strongly linked to high latitude Northern Hemisphere controls. These results provide a new benchmark for the evaluation of records obtained from southwestern Africa, offering a new perspective on past climate dynamics in the Southern Hemisphere low latitudes, and a novel model for understanding past climate dynamics in the southern subtropics.

[1] GSA Data Repository item 201Xxxx, the hyraceum δ^{15}N, leaf wax δD and radiocarbon and sampling data that support the findings of this study, is available online at

www.geosociety.org/pubs/ft20XX.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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FIGURE CAPTIONS

Figure 1. Modern hydroclimate and dominant circulation patterns of southern Africa. The rock hyrax midden sites at Spitzkoppe, Zizou and Pella, and the limits of the Namib Desert are indicated. The Aridity Index shown is that of Trabucco and Zomer (Trabucco and Zomer, 2009). Major ocean currents are indicated with bold arrows, and austral summer atmospheric circulation are indicated in white. Below, the distribution of the major Southern Hemisphere high pressure cells (Collins et al., 2006).

Figure 2. Records of environmental variability over the past 50,000 calibrated years BP. The Holocene, last glacial-interglacial transition and glacial periods are indicated with red, purple and blue shading respectively. The timing of the Last Glacial Maximum (LGM) is indicated, as are Heinrich stadials (HS) 1-5, which are more darkly shaded. For comparison or combination, some records have been normalized (norm.) using standard scores. **a**, Cycles of boreal (65°N) and austral (25°S) insolation. **b**, The composite δ^{15}N record from the Namib Desert rock hyrax middens, with the white zone indicating uncertainties associated with the creation of the regional composite record using Gaussian kernel smoothing (see SI; (Rehfeld et al., 2011)). **c,** Leaf wax δD record from the Spitzkoppe rock hyrax midden (VSMOW; Vienna standard mean ocean

water). **d, e,** Namib Desert palaeotemperature estimates from noble gases from the Stampriet Aquifer (Stute and Talma, 1998) and a pollen-based temperature index (values in uncalibrated degrees Celsius) from the Pella rock hyrax midden (Lim et al., 2016). **f,** Composite record for wind strength in the Benguela upwelling region derived from sediment and foraminifera records (Farmer et al., 2005; Little et al., 1997a; Pichevin et al., 2005; Stuut et al., 2002). **g**, Leaf wax δD record from Namibian coastal marine core MD08-3167 (Collins et al., 2014). **h**, δD record from Lake Tanganyika, East Africa (Tierney et al., 2008). **i**, δD record from marine core GeoB 6518-1, from off the Congo River mouth (Schefuß et al., 2005). **j**, Leaf wax δD record from Lake Barombi, Cameroon (Garcin et al., 2018). **k**, Leaf wax δD record from Lake Bosumtwi, Ghana (Shanahan et al., 2015). Records of hydroclimate have been oriented with the y-axis indicating increases or decreases in humidity and/or precipitation.

Figure 3. Orbital scale dynamics determining the phasing of Namib Desert hydroclimates. TraCE21ka simulations (He et al., 2013; Liu et al., 2009) of sea level pressure, precipitation and wind field changes between late to early Holocene (**a**; 1 ka minus 9 ka) and Last Glacial Maximum to early Holocene (**b**; 21 ka minus 9ka); **c**, TraCE21ka simulation (He et al., 2013; Liu et al., 2009) of the evolution of the land-sea pressure gradient from the Last Glacial Maximum to present day.