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► **To cite this version:**

Brian M. Chase, Eva M Niedermeyer, Arnoud Boom, Andrew Carr, Manuel Chevalier, et al.. Orbital controls on Namib Desert hydroclimate over the last 50,000 years. *Geology*, 2019, 47 (9), pp.867-871. <10.1130/G46334.1>. <hal-02933383>

HAL Id: hal-02933383

<https://hal.umontpellier.fr/hal-02933383v1>

Submitted on 8 Sep 2020

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35 **ABSTRACT**

36 Despite being one of the world's oldest deserts, and the subject of decades of research, evidence
37 of past climate change in the Namib Desert is extremely limited. As such, there is significant
38 debate regarding the nature and drivers of climate change in the low latitude drylands of
39 southwestern Africa. Here we present data from stratified accumulations of rock hyrax urine that
40 provide the first continuous high-resolution terrestrial climate record for the Namib Desert
41 spanning the last 50,000 years. These data, spanning multiple sites, show remarkably coherent
42 variability that is clearly linked to orbital cycles and the evolution and perturbation of global
43 boundary conditions. Contrary to some previous predictions of southwestern African climate
44 change, we show orbital-scale cycles of hydroclimatic variability in the Namib Desert region are
45 in phase with the northern tropics, with increased local summer insolation coinciding with
46 periods of increased aridity. Supported by climate model simulations, our analyses link this to

47 variations in position and intensity of atmospheric pressure cells modulated by hemispheric and
48 land-sea temperature gradients. We conclude that hydroclimatic variability at these time scales is
49 driven by the combined influence of direct low latitude insolation forcing and the influence of
50 remote controls on the South Atlantic Anticyclone, with attendant impacts on upwelling and sea-
51 surface temperature variations.

52 **INTRODUCTION**

53 Past climate change at low latitudes in Africa is generally considered to be driven at orbital
54 timescales by precessional variations in summer insolation (Collins et al., 2014; Kutzbach and
55 Street-Perrott, 1985; Partridge et al., 1997), which affect the position and extent of the tropical
56 African rainbelt (Partridge et al., 1997; Schefuß et al., 2011). In the northern and eastern African
57 tropics, the influence of direct orbital forcing is well-documented (Chevalier and Chase, 2015;
58 Kutzbach and Street-Perrott, 1985; Partridge et al., 1997; Schefuß et al., 2011; Shanahan et al.,
59 2015; Tierney et al., 2017; Tierney et al., 2008). In southwestern Africa (defined here as between
60 $\sim 17^{\circ}\text{S}$ - 30°S , and extending eastward from the coast to $\sim 20^{\circ}\text{E}$), where the influence of the South
61 Atlantic Anticyclone (SAA) and Benguela upwelling system play a significant role in driving
62 regional aridity, their role is unclear (Chase et al., 2009; Collins et al., 2014; Lim et al., 2016).
63 Here, low precipitation and strongly seasonal rainfall regimes have restricted the development of
64 lakes and wetlands that could provide longer term records of climate change. Long marine
65 sediment records from the adjacent southeast Atlantic have been interpreted as indicating a
66 strong positive relationship between summer insolation and precipitation in southwestern Africa
67 (Collins et al., 2014) and across the wider subcontinent (Daniau et al., 2013). These findings,
68 however, contrast with interpretations based on the limited terrestrial palaeoenvironmental
69 evidence from the Namib Desert (Chase et al., 2010; Lim et al., 2016; Scott et al., 2004) and, as a

70 result, there is no clear understanding of the nature of orbital-scale climate change and its
71 underlying drivers in one of the world's most arid regions.

72 **MATERIALS AND METHODS**

73 To study past climate change in the Namib Desert we have employed a unique
74 palaeoenvironmental archive, rock hyrax middens, stratified accumulations of the petrified urine
75 (hyraceum) of the rock hyrax (*Procavia capensis*). From these we have derived a 50,000-year
76 terrestrial record of palaeoclimate for southwestern Africa. Optimally preserved in dryland
77 environments, hyrax middens provide unprecedentedly detailed hydroclimate evidence in their
78 stable isotope records (Chase et al., 2015a; Chase et al., 2017; Chase et al., 2009; Chase et al.,
79 2012). For this study, we deployed a transect of three sites (Spitzkoppe: 15.20°E, 21.83°S;
80 Zizou: 15.97°E, 24.07°S; Pella: 19.14°E, 29.00°S) along a 900 km north-south transect of the
81 Namib Desert (Fig. 1). Situated along the steep zonal hydroclimate gradient that forms a
82 continuum from the arid to hyperarid Namib Desert in the west from the semi-arid to dry sub-
83 humid environments to the east (Fig. 1), the sites were selected to assess climate change trends
84 and events at a regional scale. Combined, eight middens from the three sites comprise a total of
85 208 cm of hyraceum accumulation, from which 1792 samples were analysed for their stable
86 nitrogen isotope composition ($\delta^{15}\text{N}$). To achieve a more comprehensive understanding of
87 regional hydroclimates, plant leaf wax *n*-alkanes were also extracted from the Spitzkoppe
88 middens (93 samples spanning 32,500 years) and analysed for their hydrogen isotope
89 composition (δD). A chronology was established with ^{14}C accelerator mass spectrometry ages
90 from the hyraceum to build a composite sequence (Fig. 2, S1, S2). For details on these methods,
91 please refer to the Supplementary Information.

92 Over the last 50 kyr, significant variability is apparent in the hyraceum $\delta^{15}\text{N}$ values
93 (13.5‰) (Fig. S1, S2). Despite the spatial range of the sites and the differences in accumulation
94 rates, strong orbital-scale similarities are apparent between the trends in the records obtained
95 (Fig. S2, S3), and a regional composite was created using Gaussian kernel smoothing (Rehfeld et
96 al., 2011) to the combined datasets (Fig. S2).

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

105 **DISCUSSION**

106 Overall, our $\delta^{15}\text{N}$ record indicates that the last glacial period was generally more humid
107 than the Holocene (Fig. 2). We consider temperature to be an important factor in defining this
108 trend, with lower temperatures during the last glacial period limiting potential evapotranspiration
109 and increasing water availability (Chevalier and Chase, 2016; Lim et al., 2016). Orbital-scale
110 variability within and across the Holocene and late Pleistocene in both, $\delta^{15}\text{N}$ and δD records,
111 conforms to precessional cycles, particularly during the last 36,000 years (Fig. 2). Our composite
112 record indicates that humidity in the Namib Desert region is generally negatively related to
113 summer insolation. This contrasts with an inferred positive relationship between summer
114 insolation and southern African precipitation (through the invigoration of tropical atmospheric

115 circulation systems) from records obtained from marine archives from off the Namibian coast
116 (Collins et al., 2014; Daniaux et al., 2013). Comparing our results with climate model simulations
117 (He et al., 2013) (Fig. 3) and evidence for intensifications of the SAA from wind and upwelling
118 proxies (Fig. 2), we conclude that this cycle of variability is determined by two interrelated
119 factors. The first is the inverse influence of high northern latitude summer insolation. Austral
120 summer insolation maxima correlate with boreal summer insolation minima, which induce
121 phases of global cooling, increasing latitudinal intra-hemispheric temperature gradients (Rind,
122 1998), and intensifying the SAA and related Benguela upwelling (Farmer et al., 2005; Little et
123 al., 1997b; Pichevin et al., 2005; Stuut et al., 2002). This serves to limit regional atmospheric
124 convection, block the incursion of moisture-bearing systems, and promote the advection of dry
125 air eastward. The second is the influence of austral summer insolation on land-sea temperature
126 and pressure gradients in southwestern Africa (Fig. 3). While global temperatures cool during
127 periods of low boreal summer insolation, coeval increases in austral summer insolation raise
128 summertime continental temperatures and enhance the land-sea pressure gradient, further
129 increasing southerly air flow, and augmenting coastal upwelling (Fig. 3). This combined
130 influence of high and low latitude precessional forcing results in interhemispheric synchrony in
131 orbital-scale patterns of climate change between the Namib Desert and the northern and eastern
132 African tropics across the last 50,000 years (Fig. 2).

133 The apparent contradiction between the records from marine (Collins et al., 2014; Daniaux
134 et al., 2013) and terrestrial archives from the region (compare Fig. 2 b, c and g) may reflect either
135 1) regional differentiation of climate signals, with marine records being predominantly
136 influenced by sediment sourced in central southern Africa, as suggested by Collins et al. and
137 Daniaux et al., or 2) the role of aeolian transport in determining the distinct patterns of variability

138 in the marine records. As a significant vector for the deposition of terrestrial components in
139 marine records (Dupont and Wyputta, 2003; Stuut et al., 2002), the extent and strength of the
140 SAA has the potential to significantly change the source area of these components. This is
141 implied by the inclusion of pollen from increasingly remote sources during periods of intensified
142 upwelling (Lim et al., 2016; Shi et al., 2001). Regional climate gradients are such that any
143 expansion of the source area away from the arid continental margin will promote the inclusion of
144 material from relatively humid areas (Fig. 1). Thus, inferred positive correlations between
145 precipitation and regional summer insolation may reflect the response of regional wind fields to
146 orbital forcing rather than conditions in the Namib Desert itself (Fig. 2).

147 During the Holocene, the influence of Northern Hemisphere ice sheets and ice rafting
148 events (Chase et al., 2015a) on the position of the African rainbelt (apparent in the midden record
149 as the discrete humid episodes during Heinrich stadials 1-3 [Fig. 2, Supplementary Information,
150 Fig. S2]) diminished. Direct insolation forcing became the dominant control on multi-millennial
151 variability of precipitation in the eastern tropics of southern Africa, resulting in a progressive
152 increase in summer rainfall (Chevalier and Chase, 2015; Schefuß et al., 2011) (Fig. 2). In
153 contrast, conditions in the Namib Desert are characterised by progressive aridification (with the
154 late Holocene being the driest period of the last 50,000 years). This is consistent with patterns of
155 change observed in the western (Collins et al., 2010; Garcin et al., 2018; Schefuß et al., 2005;
156 Shanahan et al., 2015; Weldeab et al., 2007) and northern (Stager et al., 2003; Tierney et al.,
157 2017) tropics. Similar to the dynamics described for the late Pleistocene, model simulations
158 indicate that orbital scale hydroclimatic variability during the Holocene was determined by the
159 combined influences of reduced high northern latitude insolation and increased southern low
160 latitude summer insolation (Fig. 3). This has broader implications: from the early Holocene

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

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

181

182 ¹GSA Data Repository item 201Xxxx, the hyraceum $\delta^{15}\text{N}$, leaf wax δD and radiocarbon and
183 sampling data that support the findings of this study, is available online at

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

186

187 **ACKNOWLEDGMENTS**

188 The research leading to these results has received funding from the European Research Council
189 under the European Union's Seventh Framework Programme (FP7/2007-2013), ERC Starting
190 Grant “HYRAX”, grant agreement no. 258657.

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327 **FIGURE CAPTIONS**

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

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

343 water). **d, e**, Namib Desert palaeotemperature estimates from noble gases from the Stampriet
344 Aquifer (Stute and Talma, 1998) and a pollen-based temperature index (values in uncalibrated
345 degrees Celsius) from the Pella rock hyrax midden (Lim et al., 2016). **f**, Composite record for
346 wind strength in the Benguela upwelling region derived from sediment and foraminifera records
347 (Farmer et al., 2005; Little et al., 1997a; Pichevin et al., 2005; Stuut et al., 2002). **g**, Leaf wax δD
348 record from Namibian coastal marine core MD08-3167 (Collins et al., 2014). **h**, δD record from
349 Lake Tanganyika, East Africa (Tierney et al., 2008). **i**, δD record from marine core GeoB 6518-
350 1, from off the Congo River mouth (Schefuß et al., 2005). **j**, Leaf wax δD record from Lake
351 Barombi, Cameroon (Garcin et al., 2018). **k**, Leaf wax δD record from Lake Bosumtwi, Ghana
352 (Shanahan et al., 2015). Records of hydroclimate have been oriented with the y-axis indicating
353 increases or decreases in humidity and/or precipitation.

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

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