# The dynamic relationship between temperate and tropical circulation systems across South Africa since the Last Glacial Maximum

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14 Abstract

15 A fundamental and long-standing question of southern African palaeoclimatology is the way

16 tropical and temperate climate system dynamics have influenced rainfall regimes across the

17 subcontinent since the Last Glacial Maximum. In this paper, we analyse a selection of recently

18 published palaeoclimate reconstructions along a southwest-northeast transect across South Africa.

19 These records span the last 22,000 years, and encompass the transition between the region's winter

20 and summer rainfall zones. In synthesis, these records confirm broad elements of the dominant

21 paradigm, which proposes an inverse coeval relationship between temperate and tropical systems,

22 with increased precipitation in the winter (summer) rainfall zone during glacial (interglacial)

23 periods. Revealed, however, is a substantially more complex dynamic, with millennial-scale

24 climate change events being strongly – even predominantly – influenced by the *interaction and*

25 *combination* of temperate and tropical systems. This synoptic forcing can create same sign

26 anomalies across the South African rainfall zones, contrary to expectations based on the classic

27 model of phase opposition. These findings suggest a new paradigm for the interpretation of

28 southern African palaeoenvironmental records that moves beyond simple binary or additive

29 influences of these systems.

30

## Introduction

34 Southern African climate is strongly influenced by both temperate systems (associated with the

35 southern westerly storm track) and tropical easterly flow (Tyson, 1986). As a result, the region is

36 recognised as a particularly dynamic region in terms of long-term climate change (Chase and

37 Meadows, 2007; Gasse et al., 2008; Tyson, 1986). Seasonal variations in the position and strength

38 of these systems results in southwestern Africa receiving most of its rainfall during the austral

39 winter months, while most of the subcontinent experiences a primarily summer rainfall regime

40 (Figure 1). Over the last 40 years, most palaeoclimatic syntheses have generally concluded that:

41 1) the modern boundaries of these rainfall zones (often referred to as the winter and summer

42 rainfall zones, or WRZ and SRZ (see Chase and Meadows, 2007)) may have shifted significantly

43 over time, and 2) that the WRZ received more precipitation during cool/glacial periods, whereas

44 the SRZ received more precipitation during warm/interglacial periods (Chase and Meadows, 2007;

45 Cockcroft et al., 1987; Deacon and Lancaster, 1988; Heine, 1982; Partridge et al., 1999; Tyson,

46 1999; Tyson and Lindesay, 1992; van Zinderen Bakker, 1976).

47 In this paper, we explore this paradigm by considering a selection of recently published

48 well-dated, high-resolution palaeoclimate reconstructions along a southwest-northeast rainfall

49 seasonality gradient across South Africa spanning 22,000 years and encompassing the transition

50 between the WRZ and SRZ (Figure 1). Employed primarily are: 1) an newly expanded suite of

51 stable isotope data from rock hyrax middens recovered from Seweweekspoort, along the eastern

52 margin of the modern winter rainfall zone, and 2) precipitation reconstructions from South Africa's

53    northern and south-central summer rainfall zones (Chevalier and Chase, 2015). We focus on these

54    records as they are considered to primarily express variability in temperate and tropical moisture-

55    bearing systems respectively. We have excluded sites from western margins of South Africa such

56    as De Rif (Chase et al., 2015a; Chase et al., 2011; Quick et al., 2011; Valsecchi et al., 2013),

57    Pakhuis Pass (Scott and Woodborne, 2007a, b), Eksteenfontein (Scott et al., 1995) and Pella (Lim

58    et al., 2016), as records from these sites have been shown to be strongly influenced by the South

59    Atlantic Anticyclone, and not clear reflections of dynamics of either the westerly storm track or

60    tropical easterly flow. Through the resulting synthesis we seek to refine our understanding of South

61    African climate dynamics as a function of global change. The data enable us to identify a clear

62    patterning of climate anomalies that is consistent with trends and events observed in independent

63    records specifically indicative of temperate and tropical influences. We argue that along the

64    transect considered during the analysed time interval, singular dominance of temperate or tropical

65    systems is only relevant at orbital timescales, and it is only through considering how these

66    perceived end-members interact that much of the observed millennial-scale climate change in the

67    region can be understood.

68    Materials and Methods

69    *Rock hyrax middens*

70    Central to this study is a series of rock hyrax middens from Seweweekspoort (Figure 1). Rock

71    hyrax middens – the communal latrines of the rock hyrax (*Procavia capensis*) – accumulate over

72    thousands of years and preserve continuous records of past climate change (Chase et al., 2012).

73 Six middens from two sites within Seweweekspoort (SWP-1; 33.367°S, 21.414°E and SWP-3;

74 33.409°S, 21.403°E) were selected for analysis because they are composed almost entirely of

75 hyraceum (no visible faecal pellets). Our experience has demonstrated that such middens have

76 superior stratigraphic integrity compared to more pellet-rich middens (Chase et al., 2012).

### *Radiocarbon dating*

78 Representative portions of the middens were processed following Chase et al. (2013; 2012).

79 Radiocarbon age determinations (n=36) were processed at the [14]CHRONO Centre, Queen's

80 University Belfast using accelerator mass spectrometry (AMS) (Figure S1; Table S1). The

81 radiocarbon ages were corrected for isotope fractionation using the AMS measured $\delta^{13}C$ and

82 calibrated using the SHCal13 calibration data (Hogg et al., 2013). The Bacon 3.0.3 software

83 package (Blaauw and Christen, 2011) was used to generate all age-depth models (Figure S1).

84 Results indicate that these sequences continuously span the last 22,300 years.

### *Stable nitrogen and carbon isotopes*

86 The stable nitrogen (^{15}N) and carbon (^{13}C) isotope contents of 767 overlapping hyraceum samples

87 were measured at the Department of Archaeology, University of Cape Town following Chase et

88 al. (2010; 2009; 2011; 2012), with contiguous/overlapping samples obtained from two series of

89 offset 1 mm holes. For the stable isotope analyses, the standard deviation derived from replicate

90 analyses of homogeneous material was better than 0.2 ‰ for both nitrogen and carbon. Nitrogen

91 isotope results are expressed relative to atmospheric nitrogen (Figure S1, S2). Carbon isotope

92 results are expressed relative to Vienna PDB (Figure S3).

93    The carbon isotopic composition of the hyraceum is representative of vegetation around a

94    midden site (Carr et al., 2016) and provides information on 1) the relative contribution of $C_3$, $C_4$

95    and CAM plants (Smith, 1972) to the animals' diet, and 2) variations in plant water-use efficiency

96    (WUE) as a function of climate (Ehleringer and Cooper, 1988; Farquhar et al., 1989; Farquhar and

97    Richards, 1984; Pate, 2001). Throughout the broader region, the distribution of $C_3$ and $C_4$ grasses

98    tracks the proportion of winter versus summer rainfall (Vogel, 1978). At Seweweekspoort today,

99    grasses are a mosaic of $C_3$ and $C_4$ varieties (Rutherford et al., 2012; Rutherford et al., 2003;

100   SANBI, 2003), and where aspect and soil depth limit soil water content, succulent CAM plants

101   become increasingly abundant. As $C_3$ plants are depleted in $^{13}C$ compared with most CAM and all

102   $C_4$ plants, higher $\delta^{13}C$ values indicate more abundant warm season ($C_4$) grasses and/or CAM

103   plants, and generally warmer/more arid conditions. An additional potential control on the $\delta^{13}C$

104   signal is the deglacial increase in atmospheric $CO_2$ (Ehleringer and Cerling, 1995; Huang et al.,

105   2001). This, however, would result in higher glacial age $\delta^{13}C$ values, which is the opposite of what

106   we observe at Seweweekspoort (Figure 2). We thus conclude that either the changes in atmospheric

107   $CO_2$ did not significant impact the vegetation, or that it was over-ridden by the changes in water-

108   availability experienced at the site (Huang et al., 2001), as indicated by the $\delta^{15}N$ data (Figure 2).

109   Hyraceum $\delta^{15}N$ is an indicator of changes in ecosystem water-availability (Carr et al.,

110   2016; Chase et al., 2013; Chase et al., 2015b; Chase et al., 2009; Chase et al., 2011). A positive

111   relationship exists between aridity and $\delta^{15}N$ in soils, plants and hyraxes, with drier conditions

112   correlating with enriched $^{15}N$ (Carr et al., 2016). This most likely reflects denitrification processes

113   in arid/semi-arid soils (Handley et al., 1999; Handley et al., 1994; Hartman, 2011; Heaton, 1987;

114   Murphy and Bowman, 2006, 2009; Wang et al., 2010), and has been observed in other herbivores

115   in dryland regions (Ambrose and DeNiro, 1986; Hartman, 2011; Murphy and Bowman, 2006). In

116   hyraceum samples, the narrowly defined feeding range of the hyraxes (<60 m from the latrine;

117   Sale, 1965), and the accumulation rates of the middens (~20-60 years/sample in most cases)

118   enforces a spatio-temporal averaging that reduces the $\delta^{15}N$ variability observed in modern

119   ecosystem studies (Carr et al., 2016), and provides a more reliable index of past water variability

120   (Carr et al., 2016; Chase et al., 2012).

121        Results from each of the different Seweweekspoort rock hyrax middens overlap such that

122   they can be combined to create a 22,300-year composite records for the sites. To achieve this, the

123   stable isotope data were combined using Local Regression (LOESS) curve fitting of the combined

124   datasets (Figures S2 and S3). As individual middens under the same climate regime may exhibit

125   differences in their isotopic records due to microclimatic influences (Carr et al., 2016) on

126   individual foraging ranges (i.e. baseline $\delta^{15}N$ variability), prior to LOESS curve fitting we adjusted

127   the $\delta^{15}N$ to account for these differences. Using the SWP-1-1 and SWP-1-4b records as a datum,

128   an estimated offset of 1.5 ‰ was added to the $\delta^{15}N$ data from the SWP-3-1 to compensate for the

129   more humid microclimate in which the midden was found, and 0.5 ‰ and 1 ‰ were added to

130   SWP-1-5 and SWP-1-2a respectively to account for their more exposed positions. This accounts

131   for some, but not all, differences between the midden records. The $\delta^{15}N$ record from SWP-1-5, for

132   instance, presents an anomalous signal (Figure S2), which Chase et al. (2013) attribute to be

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133    primarily a function of both the position of the midden and the lower resolution of the record.

134    Overall, however, we find that the composite record created from these datasets is coherent at

135    orbital and millennial scales, and is suitable for the level of analysis addressed in this paper.

136    *Defining variability in temperate and tropical systems.*

137    To characterise variability in the temperate systems influencing South Africa, we employ the

138    Seweweekspoort hyrax midden records presented in this paper and data from the EPICA Dronning

139    Maud Land ice core (EDML; Fischer et al., 2007). We consider these to reflect respectively: 1)

140    the influence of the westerly storm track on southern Africa, and 2) an underlying driver of the

141    latitudinal position of the storm track through variations in sea-ice extent (Chase et al., 2013;

142    Fischer et al., 2007; Levine et al., 2014; Wolff et al., 2010). For tropical systems, new statistical

143    techniques (Chevalier et al., 2014; Truc et al., 2013) have recently been used to reconstruct

144    temperature, precipitation seasonality and aridity in the SRZ (Chevalier and Chase, 2015, 2016)

145    using pollen records from Tate Vondo (Scott, 1987a), Wonderkrater (Scott, 1982), Tswaing Crater

146    (Metwally et al., 2014; Scott, 1999), Rietvlei (Scott and Vogel, 1983), Blydefontein (Scott et al.,

147    2005), Braamhoek (Norström et al., 2009), Equus Cave (Scott, 1987b), Florisbad (Scott and

148    Nyakale, 2002) and lakes Eteza (Neumann et al., 2010; Scott and Steenkamp, 1996) and Mfabeni

149    (Finch and Hill, 2008) (Figure 1). Changes in the resulting aggregate record (Figure 2a, b, c) have

150    been linked to both remote and local forcing mechanisms (Chevalier and Chase, 2015). These

151    analyses have allowed for the identification of two broad climate regimes within the SRZ, one in

152    the far northeast that exhibits what may be considered a 'pure' (>85%) summer rain regime

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153   (northern summer rainfall zone (N-SRZ)), used in this study to indicate the general strength of

154   southeast African monsoon, and a second broader region that encompasses most of the interior

155   (southern-central summer rainfall zone (SC-SRZ)), and exhibits a more complex pattern of

156   variability (Chevalier and Chase, 2015).

## Orbital-scale changes in temperate and tropical climate systems since the LGM

158    The Seweweekspoort record shows substantial changes in both $\delta^{13}C$ and $\delta^{15}N$ over the last 22,300

159   years, indicating significant changes in climate and vegetation (Figure 2d, 2e, SI2, SI3) (Chase et

160   al., 2013; Chase et al., under review). Across this period, which encompasses the critical transition

161   between glacial and interglacial conditions, a strong trend is apparent, with cool, humid glacial

162   conditions (indicated by depleted $^{13}C$ and $^{15}N$) transitioning into warmer, but substantially drier

163   conditions during the Holocene (Figure 2). This aridification, while being in some part due to

164   increased potential evapotranspiration under warmer conditions (Chevalier and Chase, 2016;

165   Heaton et al., 1986; Talma and Vogel, 1992), coincides with the deglacial decline in Antarctic sea-

166   ice extent (EDML sea-salt sodium flux as a proxy) between 19-11 ka (Fischer et al., 2007; Levine

167   et al., 2014; Wolff et al., 2010) (Figure 2i), consistent with the hypothesis that related changes in

168   the circum-polar vortex and the position of the westerly storm-track had a strong influence on

169   climate variability in southernmost Africa (Chase et al., 2013; Chase and Meadows, 2007;

170   Cockcroft et al., 1987; Partridge et al., 2004; Stuut et al., 2004; van Zinderen Bakker, 1976).

171       Palaeoclimatic changes in the N-SRZ have been linked to 1) high northern latitude

172   mechanisms (affecting sea-surface (Otto-Bliesner et al., 2014) and continental temperatures, and

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173  the position of the ITCZ (Johnson et al., 2002; Schefuß et al., 2011)) and 2) to direct insolation

174  forcing. The former appear to dominate during cooler periods of increased glacial extent, while

175  the latter is more strongly expressed during the Holocene (Chevalier and Chase, 2015). This

176  dynamic resulted in significantly less precipitation in the SRZ during the LGM. It has also resulted

177  in a delayed onset of increased tropical precipitation (relative to global temperature trends) during

178  the early Holocene, as a result of low austral summer insolation, which peaked only in the late

179  Holocene (Chevalier and Chase, 2015).

180  Orbital-scale precipitation trends in both the N-SRZ and SC-SRZ exhibit a clear antiphase

181  relationship with the humidity record from Seweweekspoort (Figure 2a, b, d, e), indicating that

182  tropical systems did not play a dominant role in the southern Cape at these longer timescales. Data

183  from this transect of sites thus indicates that broad trends in climate change across South Africa

184  are generally consistent with the model of increased westerly influence during the last glacial

185  period and an invigoration of tropical systems concomitant with post-glacial warming into the

186  Holocene (Figure 3).

187  ## Millennial-scale variability

188  *The Last Glacial Maximum and Glacial-Interglacial Transition (22.3-11.7 cal kBP)*

189  Within the broad trends of deglacial aridification in the southern Cape and increasing humidity in

190  the SRZ, significant millennial-scale anomalies are evident in the regional records, particularly in

191  the transitional zone between the WRZ and N-SRZ (Figure 1, 2). Despite the strong orbital-scale

192  similarity between the Seweweekspoort $\delta^{15}$N record and the EDML sea-salt sodium record

193  (Fischer et al., 2007) (Figure 2e, i), comparison of the detrended datasets (i.e., removing orbital-

194  scale deglacial trends with a cubic polynomial; Figure 4) indicates that at millennial time scales

195  this relationship is in fact largely antiphase. During the last glacial-interglacial transition (LGIT;

196  ~18-11.7 cal kBP) and early Holocene, for example, two prominent episodes of wetter conditions

197  occur at Seweweekspoort, at 15.4-14.2 cal kBP and 11.8-10.7 cal kBP. The first of these episodes

198  – previously identified as being a period of exceptionally high effective precipitation in the

199  southern Cape (Scholtz, 1986) – corresponds with the warming of both high southern latitudes

200  (Stocker, 1998; Stocker and Johnsen, 2003) and the oceans surrounding southwestern Africa

201  (Barker et al., 2009; Farmer et al., 2005; Kim and Schneider, 2003) as a response to the slow-down

202  of Atlantic Meridional Overturning Circulation (AMOC) during Heinrich stadial 1 (HS1; ~18-14.6

203  ka) (McManus et al., 2004). Critically, this increase in precipitation was not limited to the zone of

204  immediate westerly influence as it is also clearly manifested in the SRZ, where southwest Indian

205  Ocean sea-surface temperatures (Sonzogni et al., 1998) and rainfall increase during HS1, peaking

206  near its termination between ~16-14.2 cal kBP (Chevalier and Chase, 2015)(Figure 2, 4).

207       This association of wetter conditions in the southern Cape during millennial-scale periods

208  of warmth, and an *in-phase* response with the SRZ (Figure 4), may be perceived as being contrary

209  to the paradigm of a coeval inverse relationship between the WRZ and SRZ. To explore the

210  mechanisms behind such episodes of millennial variability, we analysed the periodicity of the

211  dominant signals in the detrended southern Cape and SC-SRZ datasets (Figure 4), and their

212  relationship with records indicative of over-arching temperate and tropical systems/drivers (i.e.

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213    EDML sea-salt sodium flux and N-SRZ precipitation respectively). To assess correlations through

214    time, we calculated measures of correlation between the records using 2500 to 4500-year windows

215    at 500-year intervals (Figure 5). Results indicate that since the LGM the primary driver of

216    millennial-scale climate variability has evolved in concert with changing global boundary

217    conditions, but, rather than being the invigorated system that dominates (i.e. temperate (tropical)

218    systems during the last glacial (Holocene)) (Tyson, 1999), it is *variability in the weaker system*

219    that dictates the timing and direction of these millennial-scale climate change events (Figure 5).

220    This dynamic can be conceptualised in terms of limiting as opposed to dominant factors.

221    Under current conditions, interactions between temperate and tropical systems create composite

222    synoptic scenarios wherein disturbances in the easterlies and westerlies combine to create heavy,

223    widespread precipitation events (Tyson, 1986). A diversity of such composite synoptic types

224    exists, with a range of permutations of westerly and easterly waves and cut-off lows, and, perhaps

225    most importantly, the interaction of westerly and easterly disturbances to create cloud bands

226    known as temperate-tropical troughs (Lindesay, 1998; Tyson, 1986). As the resolution of the

227    palaeoclimatic record does not allow for the clear differentiation of these types, we will refer to

228    them generally here as temperate-tropical interactions (TTIs). Considered together, under modern

229    conditions TTIs are: 1) associated with large-scale rainfall events in southern Africa (Nicholson,

230    1986; Todd and Washington, 1999; Tyson, 1986), 2) account for most of the annual rainfall in the

231    interior, and 3) have the potential to create same sign signal in precipitation anomalies across South

232    Africa (Tyson, 1986). We propose that while changes in the strength and position of temperate and

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233    tropical systems may determine broad scale palaeoclimatic changes in the WRZ and SRZ

234    respectively, amplification or attenuation of these general trends has apparently been significantly

235    affected by variability in their counterpart, perhaps as a necessary element for the generation of

236    TTIs.

237        From this perspective, while the influence of the westerly storm track may have diminished

238    in the southern Cape after HS1, as the Subtropical Front shifted poleward (Barker et al., 2009),

239    increased evaporation from warmer oceans – including the southwest Indian Ocean after ~15.7 ka

240    (Sonzogni et al., 1998) – and the invigoration of the southern African monsoon system (sensu

241    Wang and Ding, 2008) (Figure 2) may have stimulated TTI development. Evidence for more

242    intense rainfall events, consistent with this type of precipitation system (Tyson, 1986), may

243    (caveats regarding differences in age models considered) be reflected in the Fe/K record from

244    marine core CD154-10-06P (Simon et al., 2015), off the southeast coast (Figure 4d) between 14.5-

245    13.3 cal kBP and 12-11.3 cal kBP, where peaks in terrigenous sediments exhibit a similar

246    patterning to the humid phases recorded at Seweweekspoort.

247        This early LGIT period of relatively humid conditions terminates abruptly at ~14.2 cal

248    kBP, concurrent with the post HS1 strengthening of AMOC (McManus et al., 2004) and the onset

249    of the Antarctic Cold Reversal, which resulted in an expansion of Antarctic sea ice (Fischer et al.,

250    2007), cooling in the adjacent Southern Ocean and an equatorward shift of the Subtropical Front,

251    (Barker et al., 2009). At this time, we observe a reduction in precipitation in the N-SRZ (Figure 2,

252    4). The implication is that while the westerly storm track is likely to have shifted equatorward, and

253     brought increased winter rainfall to the southern Cape during this period of southern mid- to high

254     latitude cooling (Pedro et al., 2016), the concurrent weakening of the southern African monsoon –

255     as the limiting factor in pre-Holocene TTI development - resulted in an aridification across the

256     whole of the study transect.

257     *The Early Holocene (11.7-8 cal kBP)*

258     The distinct humid episode at Seweweekspoort at the start of the Holocene, from 11.8-10.7 cal

259     kBP, corresponds with a sharp decline in sea ice extent, and the establishment of elevated

260     interglacial temperatures. Of note regarding this episode is its strength and its short duration, with

261     an abrupt shift to drier conditions at 10.7 cal kBP. These characteristics are shared by the record

262     of terrigenous sediment flux in marine core CD154-10-06P (Simon et al., 2015) (Figure 4d) and

263     data from the Drakensberg mountains (Norström et al., 2014) that indicate a period of increased

264     humidity and productivity associated with increased temperatures at ~10 cal kBP. Interestingly,

265     this episode appears to be restricted to the southern coastal margin, with no clear signal being

266     observed in the SRZ. Occurring during the transition between periods of relatively predictable

267     glacial and Holocene millennial-scale climate dynamics, this is the only interval of the last 22,000

268     years when the southern Cape and SC-SRZ are substantially out of phase (Figure 5c, d). At present,

269     it is unclear what drove this decoupling of the southern Cape and SC-SRZ, but certainly the LGIT

270     relationship between humidity at Seweweekspoort, temperature, and variability in summer

271     precipitation systems changed fundamentally after this period, and by ~9.5 cal kBP a positive

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272   relationship between humidity and Antarctic sea ice extent accounts for much of the observed

273   variability until the late Holocene (Figure 2, 4, 5).

*The Mid-Holocene (8-4 cal kBP)*

275   During the mid-Holocene, continental temperatures were relatively high and the southern African

276   monsoon was well-developed, bringing increased summer precipitation to the SRZ (Chevalier and

277   Chase, 2015; Figure 4). At Seweweekspoort, by contrast, the invigoration of tropical systems had

278   little apparent impact, and the Holocene as a whole was characterised by relative aridity. This anti-

279   phase response between the SRZ and the southern Cape is consistent with the prevailing model for

280   long-term palaeoclimatic dynamics in the region (Figure 3).

281         However, while the aggregate record derived from the SC-SRZ also indicates a general

282   pattern of increased summer precipitation across this period (Chevalier and Chase, 2015; Figure

283   4), it exhibits significantly more variability than the relatively muted signal in the N-SRZ (Figure

284   2, 4). Interestingly, these events are similar to those observed in both the $\delta^{13}$C record from

285   speleothems from Cold Air Cave in the N-SRZ (Chevalier and Chase, 2015; Holmgren et al., 2003)

286   and in the Seweweekspoort record, indicating strong spatial coherence across southern and eastern

287   South Africa during this period (Figure 4). Our analyses (Figure 5) show that these millennial-

288   scale climate change events are not linked to variability in tropical systems, but rather – as the

289   limiting factor in TTI development – are more closely linked to variations in Antarctic sea ice

290   extent and the southern westerlies, and humidity in the southern Cape and continental interior,

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291    with the nature of the composite synoptic systems again creating an in-phase dynamic across the

292    region (Figure 5).

293    *The late Holocene (4 cal kBP to present)*

294    After 4 cal kBP, sea ice again begins to retreat, and by 3 cal kBP conditions at Seweweekspoort

295    become more arid, similar to millennial-scale patterns observed in the SC-SRZ (Figure 4). These

296    findings are broadly consistent with previously identified episodes of mesic forest development in

297    the southern Cape between ~4.5-2.5 cal kBP (Martin, 1968) and a subsequent arid phase between

298    ~2.7-1.3 cal kBP recorded in both botanical (Scholtz, 1986) and geomorphological records (Carr

299    et al., 2006) from the region. In contrast, in the N-SRZ, a phase of increased precipitation and

300    humidity is observed between ~3.3 and 1.7 cal kBP, and the Cold Air Cave $\delta^{13}$C record indicates

301    relatively humid conditions. The establishment of this antiphase relationship between northern and

302    southern regions appears to reflect the dominance of local moisture bearing systems in each region,

303    and a reduction in the generation and influence of TTIs, which would tend to create same sign

304    responses across the continental interior. This dynamic persists during the last millennium,

305    wherein an abrupt shift to wetter conditions at Seweweekspoort is mirrored by marked aridification

306    at Cold Air Cave (Figure 4). These changes in inter-regional dynamics suggest that sensitive

307    thresholds exist in the relationship and interaction between temperate and tropical systems in South

308    Africa, and that slight variations in one or other may result in abrupt, significant changes in rainfall

309    regime at both local and subcontinental scales.

310    Conclusions

311     Consideration of records from this SW-NE rainfall seasonality transect across the continental

312     interior supports – in general terms, and over glacial-interglacial timescales - the basic long-

313     standing model of a coeval inverse response between southern Africa's temperate and tropical

314     moisture-bearing systems wherein colder (warmer) periods created wetter conditions in the

315     regions' winter (summer) rainfall zone over multi-millennial time scales. However, the complexity

316     of sub-orbital millennial-scale climate dynamics observed across the region since the LGM,

317     particularly during the LGIT and early Holocene, is not predicted by this simple model. Instead,

318     arid/humid climate anomalies often exhibit a coherent, *in-phase* spatio-temporal patterning across

319     the study transect. We hypothesise that such patterning reflects the importance of *interactions*

320     between temperate and tropical systems, with variability in the *weaker system* determining the

321     regional climate dynamics through control as a limiting factor on the development of TTIs. While

322     the influence of such synoptic forcings is clearly mediated by larger-scale changes in global

323     boundary conditions, and their influence on the position of the southern westerly storm

324     track/invigoration of the southern African monsoon, we propose that TTIs are a critical factor in

325     understanding an array of significant, abrupt changes in climate that have occurred across southern

326     Africa since the LGM.

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570

571 Figure captions

572 **Figure 1:** Map of southern Africa showing seasonality of rainfall and sharp climatic gradients dictated by

573 the zones of summer/tropical (red) and winter/temperate (blue) rainfall dominance. Winter rainfall is

574 primarily a result of storm systems embedded in the westerlies. Major atmospheric (white arrows) and

575 oceanic (blue arrows) circulation systems and the austral summer positions of the Inter-Tropical

576 Convergence Zone (ITCZ) and the Congo Air Boundary (CAB) are indicated. The location of Cold Air

577 Cave is shown (1), as are the key palaeoenvironmental sites used for the reconstruction of summer rainfall

578 zone climates (Northern region: 2) Tate Vondo, 3) Wonderkrater, 4) Tswaing Crater, 5) Reitvlei; and South-

579 central region: 6) Mfabeni, 7) Eteza, 8) Braamhoek, 9) Florisbad, 10) Equus Cave, 11) Blydefontein (see

580 Chevalier and Chase, 2015)), the sites at 12) Seweweekspoort and 13) Katbakkies Pass, which are strongly

581 influenced by the southern westerlies, and 14) the CD154-10-06P marine core.

582 **Figure 2:** Comparison of proxy records from the South African transect considered for this study. Heinrich

583 stadial 1 (HS1), the Younger Dryas cold reversal (YD) are highlighted by blue shading, and the Antarctic

584 Cold Reversal (ACR) shaded in red. Conditions in the summer rainfall zone are shown in wet season

585 precipitation reconstructions (PWetQ) for the north and south-central regions, and a region-wide mean

586 annual temperature reconstruction (a, b, c; Chevalier and Chase, 2015). Southern Cape conditions are

587 reflected in the $\delta^{13}C$ and $\delta^{15}N$ data from the Seweweekspoort rock hyrax middens (d, e), and data reflecting

588 important elements larger circulation systems affecting the region, such as the Atlantic Meridional

589 Overturning Circulation (AMOC) (f; McManus et al., 2004), conditions in the proximal South Atlantic (g,

590 h; Barker et al., 2009) sea salt sodium concentrations from the EPICA DML ice core in Antarctica indicating

591 sea-ice extent (i; Fischer et al., 2007) are shown.

592    **Figure 3:** Diagram of the prevailing conceptual model of southern African climate change (see Chase and

593    Meadows, 2007; van Zinderen Bakker, 1976), wherein a coeval inverse relationship exists between

594    temperate and tropical systems and warmer (colder) temperatures invigorate summer (winter) rainfall

595    systems. In support, the primary datasets considered in this paper are compared, and strong relationships

596    are shown between general trends in records from the southern-central summer rainfall zone (b) and the

597    southern Cape at Seweweekspoort (c) and records reflecting changes in tropical (northern summer rainfall

598    zone summer precipitation (PWetQ) anomalies; as reconstructed in Chevalier and Chase, 2015) and

599    temperate systems (sea salt sodium concentrations from the EPICA DML ice core in Antarctica; Fischer et

600    al., 2007).

601    **Figure 4:** Comparison of proxy records from the South African transect considered for this study. The data

602    have been detrended, removing orbital-scale deglacial trends (using cubic polynomials) to better highlight

603    the nature of millennial-centennial scale variability. Included are wet season precipitation reconstructions

604    (PWetQ) from the northern and south-central summer rainfall zone (a, c; Chevalier and Chase, 2015), the

605    $\delta^{13}C$ record from the Cold Air Cave speleothem (b, not detrended; Holmgren et al., 2003), the CD154-10-

606    06P marine core Fe/K record (d, not detrended; Simon et al., 2015), the Seweweekspoort rock hyrax midden

607    $\delta^{15}N$ record and sea salt sodium concentrations from the EPICA DML ice core in Antarctica (f; Fischer et

608    al., 2007).

609    **Figure 5:** Comparison of proxy records considered to primarily reflect trends in temperate (f; Fischer et al.,

610    2007) and tropical systems (a; Chevalier and Chase, 2015) as they influence records from the south-central

611    summer rainfall zone (c; Chevalier and Chase, 2015) and the southern Cape. To study millennial-scale

612    variability, panes (b) and (e) show measures of correlation (using 2500-4500-year windows at 500-year

613    intervals) between the south-central summer rainfall zone and southern Cape records and temperate (f) and

614    tropical records (a). For this analysis, all records were detrended to remove orbital-scale deglacial trends

615    (cubic polynomials) and highlight similarities in millennial-scale variability between the regions, as in

616    Figure 4. Results indicate that the weakened system has the strongest control over millennial-scale climate

617    variability in the region, and that this dynamic has evolved, inverting across the last glacial-interglacial

618    transition.