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Evolving southwest African response to abrupt deglacial North Atlantic climate change events

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Highlights

- 19.4 kyr multi-proxy records from a rock hyrax midden from SW Africa.
- Aridification events at 34˚S concurrent with the Younger Dryas and 8.2 ka events.
- Influence of bipolar-seesaw replaced by atmospheric teleconnection after 14.6 ka.

Abstract

Climate change during the last deglaciation was strongly influenced by the 'bipolar seesaw', producing antiphase climate responses between the North and South Atlantic. However, mounting evidence demands refinements of this model, with the occurrence of abrupt events in southern low to mid latitudes occurring in-phase with North Atlantic climate. Improved constraints on the north-south phasing and spatial extent of these events are therefore critical to understanding the mechanisms that propagate abrupt events within the climate system. We present a 19,400 year multi-proxy record of climate change obtained from a rock hyrax midden in southernmost Africa. Arid anomalies in phase with the Younger Dryas and 8.2 ka events are apparent, indicating a clear shift in the influence of the bipolar seesaw, which diminished as the Earth warmed, and was succeeded after ~14.6 ka by the emergence of a dominant interhemispheric atmospheric teleconnection.

Keywords: southern Africa, palaeoclimate, hyrax middens, bipolar seesaw, Atlantic Overturning Meridional Circulation

Introduction

While some studies have reported interhemispheric synchrony and symmetry during extreme climate disturbances such as the Younger Dryas cold reversal (YD; 12.9-11.6 ka (Lowe et al., 2008)) (Denton and Hendy, 1994; Goede et al., 1996), abrupt changes in Northern Hemisphere climates (North Greenland Ice Core Project members, 2004) have also been associated with anti-phase responses in the Southern Hemisphere (Kaplan et al., 2010; Putnam et al., 2010). Such antiphase responses are hypothesised to be driven by the oceanic Atlantic Overturning Meridional Circulation (AMOC), which draws heat from the Southern Hemisphere into the North Atlantic, but which is sensitive to disruption by ice and freshwater discharges (Broecker, 1998; McManus et al., 2004). Reduction and intensification of ocean heat transport during northern stadial (cold) and interstadial (warm) intervals leads to the alternating build-up and extraction of Southern Hemisphere heat; the so-called bipolar seesaw (Broecker, 1998; Stocker, 1998; Stocker and Johnsen, 2003).

An increasing number of records suggest that the relative warmth of the Northern Hemisphere's Bølling-Allerød interstadial coincided with the Antarctic Cold Reversal (ACR; 14.7-13.0 ka) (Pedro et al., 2011; Putnam et al., 2010), and that the marked northern cooling of the YD was a period of rising temperatures and glacial retreat in the southern high (Pedro et al., 2011) to mid-latitudes (Kaplan et al., 2010). However, a lack of reliable evidence from the low southern latitudes has still prevented a full assessment of the bipolar seesaw hypothesis, including the location of its ‘fulcrum’. Such information is vital to test simulations, which are currently showing no consensus on the spatial extent of past (or future) abrupt climate change events (Kageyama et al., 2010).

To address this problem, we explore the regional impact of key perturbations in the North Atlantic using a multi-proxy record from the arid SW Cape region of South Africa (Fig. 1). The region lies at the juncture between southern Africa's three dominant climate systems: the South Atlantic anticyclone, the tropical easterlies, and the austral westerlies (Tyson, 1986). Approximately 75% of the region's precipitation falls during winter, when the westerlies and their related cold fronts migrate northward, advecting moisture from the southern Atlantic to the mountains of the SW Cape (Reason et al., 2006). In the dry summer months, the westerlies and the South Atlantic Anticyclone shift southward, limiting frontal system influence and blocking tropical moisture-bearing systems from the Indian Ocean and tropical Atlantic (Reason et al., 2006).

Little is known about SW Africa's environmental history, mainly due to its aridity and marked rainfall seasonality, which allows for few wetland sediment records. Rock hyrax (*Procavia capensis*) middens have emerged in this setting as valuable archives of palaeoenvironmental information (Carr et al., 2010; Chase et al., 2013; Chase et al., 2015; Chase et al., 2009; Chase et al., 2011; Chase et al., 2012; Meadows et al., 2010; Quick et al., 2011; Scott and Bousman, 1990; Scott et al., 2005; Scott and Vogel, 2000; Scott and Woodborne, 2007). As hyraxes use discrete locations as latrines, deposits of sub-fossilised urine (hyraceum) accumulate in their shelters, much like stalagmites in a cave. These finely laminated amber-like deposits preserve a wide range of proxies, including pollen, charcoal, and stable isotopes, all of which can provide insight into past environmental conditions (Chase et al., 2011; Valsecchi et al., 2013) (see Supplementary Information).

Results

The records presented here were obtained from two sections of a 53 cm thick midden collected from De Rif, in the Driehoek Valley of the Cederberg Mountains (32°26′45″S, 19°13′15″E, 1151 m amsl.) (Chase et al., 2011; Valsecchi et al., 2013). Chronologies spanning the past 19,400 years were established using 29 ^{14}C AMS dates (see Supplementary Information). Together, the De Rif midden records reveal coherent patterns of marked environmental variability since the Last Glacial Maximum (LGM; Fig. 2). Highlighted here are aspects of the records that primarily reflect changes in hydroclimate. In a region dominated by C_3 plants, the hyraceum $\delta^{13}C$ record primarily reflects variations in water-use efficiency (Chase et al., 2012; Ehleringer and Cooper, 1988; Farquhar et al., 1989; Farquhar and Richards, 1984; Pate, 2001), although a long-term enrichment in is evident across the mid- to late Holocene. This is consistent with increased water use efficiency of C_3 plants, and an increasing abundance of $\delta^{13}C$ enriched drought-resistant succulent CAM plants under drier conditions (Smith, 1972; Valsecchi et al., 2013). These data are supported by the hyraceum $\delta^{15}N$ record, which also reflects water-availability (Chase et al., 2012; Handley et al., 1999; Handley et al., 1994; Hartman, 2011; Heaton, 1987; Murphy and Bowman, 2006, 2009; Wang et al., 2010), as well as by fossil pollen data (Valsecchi et al., 2013) and derived reconstructions of relative palaeo-aridity. Each of these proxy records expresses variability similar to that observed in regional marine core records, confirming that they are reflecting variability in a tightly coupled climate system (Fig. 3).

Although De Rif lies within the core of the winter rainfall zone, our data show that changes in the duration or intensity of the summer drought season were important drivers of environmental change at this site for much of the last 19 kyr. Whereas increases in winter rainfall would result in a net increase in annual rainfall, increased precipitation in the summer drought season would have a significantly greater impact on reducing drought-stress in the region (Chase et al., 2015). This is reflected by trends in the percentage of drought-tolerant and intolerant taxa (Valsecchi et al., 2013) and aridity index reconstructions (Fig. 2d). While a degree of variability is evident between these records as a function of their specific sensitivities, each reflects aspects of changes in drought season length and/or intensity, and corresponds well with overall changes in water availability inferred from the $\delta^{13}C$ and $\delta^{15}N$ records (Fig. 2). These findings are supported by the CCSM3 TraCE-21ka general circulation model (GCM) simulations, which show qualitative agreement between austral summer precipitation in the region and the proxy records from the De Rif middens (He et al., 2013).

The De Rif data, particularly the higher resolution $\delta^{15}N$ and $\delta^{13}C$ records, highlight the impact of three major freshening events: HS1, the YD and the 8.2 ka events. We observe two primary phases in the region's deglacial climatic evolution: (1) a general increase in moisture availability and reduced seasonality from the terminal LGM to the end of HS1 at ~14.6 ka (Fig. 2b, c), and (2) a late deglacial/early Holocene period from ~14.6 to 7 ka marked by significant, clear arid episodes synchronous with the YD and 8.2 ka event (Fig. 2b, c).

Discussion

The early deglacial period is defined by the abrupt decline of the AMOC during HS1 (Fig. 3b), and the slow build-up of South Atlantic heat from ~18-14.6 ka that is registered in Antarctic ice cores (Jouzel et al., 2007; Pedro et al., 2011) (Fig. 3h), SE Atlantic sea-surface temperatures (SSTs) (Farmer et al., 2005; Kim and Schneider, 2003) and resulted in increased humidity at De Rif (Fig. 3d, e). While these changes likely affected the Subtropical Front (Barker et al., 2009) (Fig. 3h), resulting in a poleward shift of the moisture-bearing systems associated with the westerly storm track, we interpret that compensating factors such as increased flow of warm Agulhas Current waters into the SE Atlantic and reduced northward heat transport in the AMOC favoured warming SSTs and increasing advection influence of tropical easterlies in the southwestern Cape(Reason et al., 2006). This would have resulted in an increase in summer rain and a shorter/less intense drought season (Chase et al., 2015; He et al., 2013).

At ~14.6 ka, the rapid increase of AMOC created an immediate cooling response in the South Atlantic, as the Subtropical Front shifted equatorward at least as far as ~41°S (Barker et al., 2009). In SW Africa, however, the impact was more muted (Fig. 3). In the northern (Kim et al., 2002) and central (Farmer et al., 2005) Benguela system, this period marked the end of the warming trend that began at ~19 ka, but the subsequent cooling was relatively slow, similar to southern (Pedro et al., 2011) and northern(North Greenland Ice Core Project members, 2004) polar records during the Bølling-Allerød interstadial ~14.7-12.9 ka (Lowe et al., 2008). In the SW Cape, the response to these changes was a clear reduction in humidity (Fig. 3f, g). This aridification, however, was short-lived, lasting only through the Bølling interstadial (14.7-14.1 ka (Lowe et al., 2008)), whereas the Allerød interstadial (14.1-12.9 ka (Lowe et al., 2008)) saw increased water availability at De Rif. Compared to the regionally coherent HS1 signal, the spatial heterogeneity of responses during this time suggests a restructuring of Earth's climate system, with the increasing influence of the South Atlantic Anticyclone in the southern subtropics across the last deglaciation.

This restructuring is underscored by the regional response to the subsequent YD. While the Northern Hemisphere cooling coincides with a distinct decrease in AMOC, the SE Atlantic and SW African response is in sharp contrast to the HS1 signal, with an abrupt drop in SSTs (Farmer et al., 2005; Kim et al., 2002) and marked aridity at De Rif. In contrast with the slow build-up of heat during HS1 the immediate response during the YD implies a dominant atmospheric interhemispheric teleconnection (cf. Moreno et al., 2001), inconsistent with the oceanic controls related to the bipolar seesaw. The De Rif records further reveals an significant (cf. Morrill and Jacobsen, 2005) and abrupt drying signal relating to the 8.2 ka event (Barber et al., 1999), indicating that even relatively small fresh water pulses in the North Atlantic (Clarke et al., 2004) produced immediate responses in SW Africa, resulting in significant aridification events in the region (Fig. 3g, h).

This dramatic contrast in response to perturbations in the North Atlantic (more humid at De Rif during the AMOC slow-down of HS1 and more arid during the slow-downs of the YD and 8.2 ka events) challenges any systematic application of the bipolar-seesaw model of north-south phasing during abrupt climate perturbations and raises questions on the relative roles of oceanic and atmospheric teleconnections in driving SE Atlantic and SW African climate. Of particular importance here is the influence of the South Atlantic Anticyclone, which dominates atmospheric circulation in the SE Atlantic basin and has a significant impact on oceanographic conditions through its regulation of upwelling intensity (Farmer et al., 2005; Kim and Schneider, 2003; Kim et al., 2003).

Either alternatively or in concert with the potential influence of a bipolar seesaw, a weakening South Atlantic Anticyclone during HS1 would have reduced upwelling intensity and raised SSTs in the Benguela system. After ~14 ka, however, the impact of the bipolar seesaw as a driver of climatic variability was apparently not expressed in the SE Atlantic. The rapidity and direction of the SW African responses to the changes in the North Atlantic that induced the YD and 8.2 ka events (Barber et al., 1999; Murton et al., 2010) strongly implicate an atmospheric rather than oceanic interhemispheric teleconnection, and the acute sensitivity of this relationship is illustrated by the influence of the relatively minor freshwater outburst that triggered the cooling of the 8.2 ka event (Barber et al., 1999). This implies that an early dominance of the bipolar seesaw was replaced - perhaps as a result of diminishing high latitude ice sheets and a related reduction in the intensity and impact of declines in AMOC (McManus et al., 2004; Ritz et al., 2013) - in favour of more immediate atmospheric teleconnections, (Fig. 3b). This effectively displaced the boundary between positive and negative SST anomalies related to perturbations in the North Atlantic by at least 24°, shifting the 'fulcrum' of the bipolar seesaw poleward of the African continent, where at 41°S, and contrary to conditions in the SE Atlantic, warmer SSTs occurred during the YD (Barker et al., 2009). These findings pose an exciting challenge as they call for closer consideration of the spatiotemporal influence of the bipolar seesaw, and identify areas for refinement of Earth System Models, which may lead to a more complete understanding of global climate dynamics.

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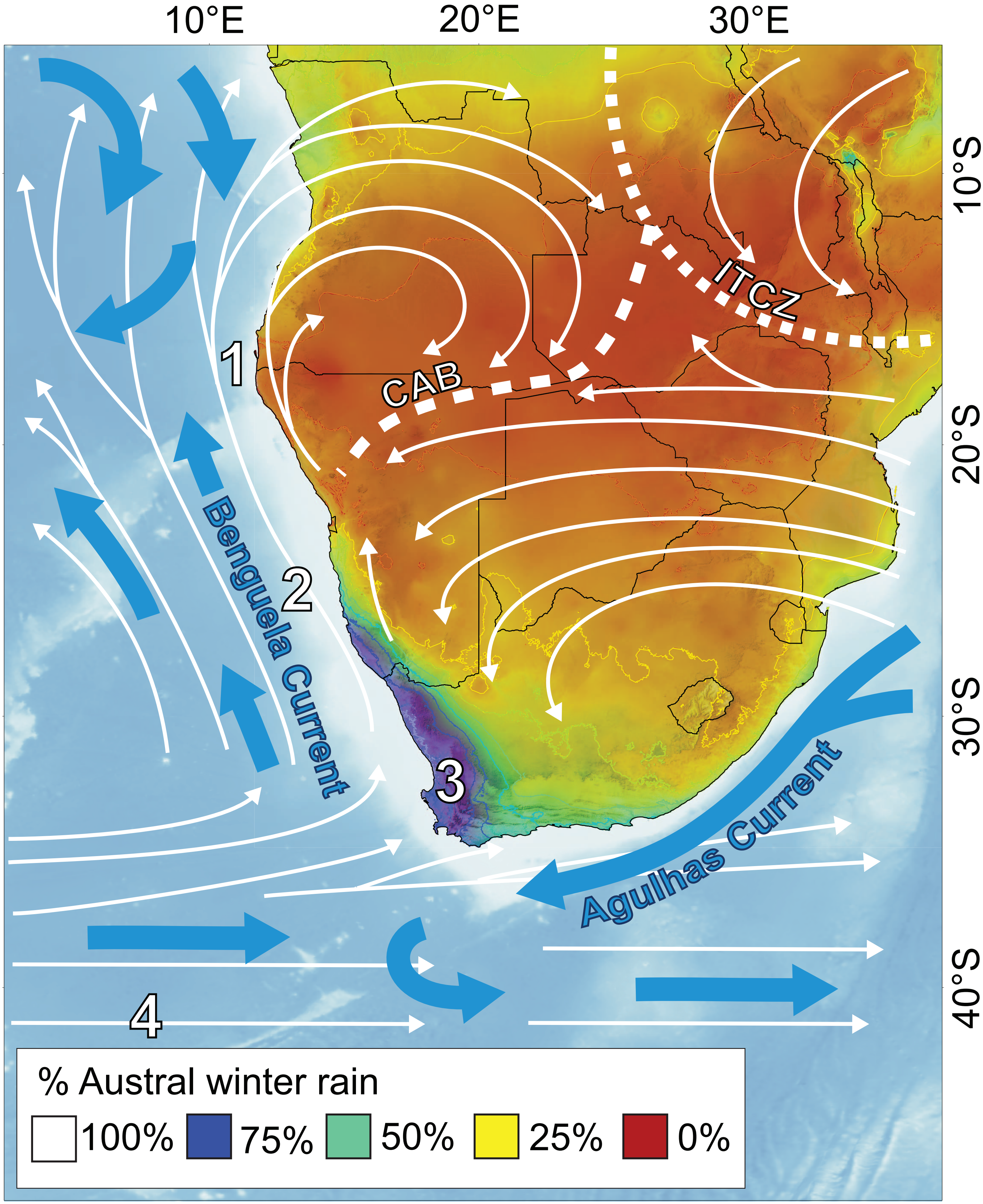
Figure captions

Fig. 1. Map of study region indicating generalised atmospheric (white arrows) and oceanic (blues arrows) circulation systems and the seasonal distribution of rainfall as indicated by the percent of the total mean annual rainfall received during the austral winter months of April-September. The convergence zones of the Congo Air Boundary (CAB) and the Intertropical Convergence Zone (ITCZ) are shown in the austral summer positions. Key sites discussed in the manuscript are indicated by number: 1) GeoB1023-5 (Kim and Schneider, 2003; Kim et al., 2003); 2) ODP1084b (Farmer et al., 2005); 3) the De Rif rock hyrax midden; and 4) TNO57-21 (Barker et al., 2009).

Fig. 2. Comparison of proxy records from the De Rif rock hyrax midden and general circulation model (GCM) simulation data for the region. Radiocarbon ages shown as triangles along x-axis (DR2010 section in red, DR-2 section in blue). Heinrich stadial 1 (HS1), the Younger Dryas cold reversal (YD) and 8.2 ka event are highlighted by blue shading, and the Bølling (B) and Allerød (A) interstadials are shaded in red. Stable nitrogen (b) and carbon (c) records from the middens primarily reflect water-availability in the environment and water-use efficiency of plants respectively. These data are confirmed by pollen analysis of the De Rif midden (Valsecchi et al., 2013) and an aridity index reconstruction using a *pdf*-based modelling technique (Chevalier et al., 2014) applied to the De Rif pollen assemblage (d; shading indicates 20% and 50% errors), which indicate the importance of drought season intensity and length in determining environmental change in the region. First-order similarities between results from the CCSM3 TraCE-21ka transient GCM simulation (He et al., 2013) of austral summer (DJF) (a), and the proxy records support these conclusions, but the lack of a significant Younger Dryas signal in the simulation suggests that the model may not be capturing certain important elements of the global deglacial climate system.

Fig. 3. Comparison of proxy records from the De Rif rock hyrax midden with independent regional and extra-regional records reflecting changes in a series of related climate systems during the last 20,000 years. Radiocarbon ages shown as triangles along x-axis (DR2010 section in red, DR-2 section in blue). Heinrich stadial 1 (HS1), the Younger Dryas cold reversal (YD) and 8.2 ka event are highlighted by blue shading, and the Bølling (B) and Allerød (A) interstadials are shaded in red. Climatic perturbations in the North Atlantic basin are recorded in the NGRIP ice core record from Greenland (a) (North Greenland Ice Core Project members, 2004) and have been observed to have a significant impact on the Atlantic Meridional Overturning Circulation (AMOC) and the northward oceanic transport of heat (b) (McManus et al., 2004), resulting in an antiphase relationship between northern (a) and southern (i) hemisphere temperatures (Broecker, 1998; Stocker, 1998). This is indicated by records from the South Atlantic (g, h) (Barker et al., 2009) and the southern polar regions (i) (Jouzel et al., 2007; Pedro et al., 2011). While from ~18-14.6 ka this trend may have been expressed in SE Atlantic (c, d) (Farmer et al., 2005; Kim and Schneider, 2003; Kim et al., 2003) and SW Africa (e, f), variability in the intensity of the South Atlantic Anticyclone (c, d) (Farmer et al., 2005; Kim and Schneider, 2003; Kim et al., 2002; Kim et al., 2003) provide a coherent complimentary (Kim et al., 2002) mechanism, and highlight the increasing importance of atmospheric teleconnections with the North Atlantic in driving SW African climate change across the deglacial period.

*Figure 1



10°E
20°E
30°E
10°S
20°S
30°S
40°S
ITCZ
CAB
1
2
3
4
Benguela Current
Agulhas Current
% Austral winter rain
100%
75%
50%
25%
0%

*Figure 2 REVISED

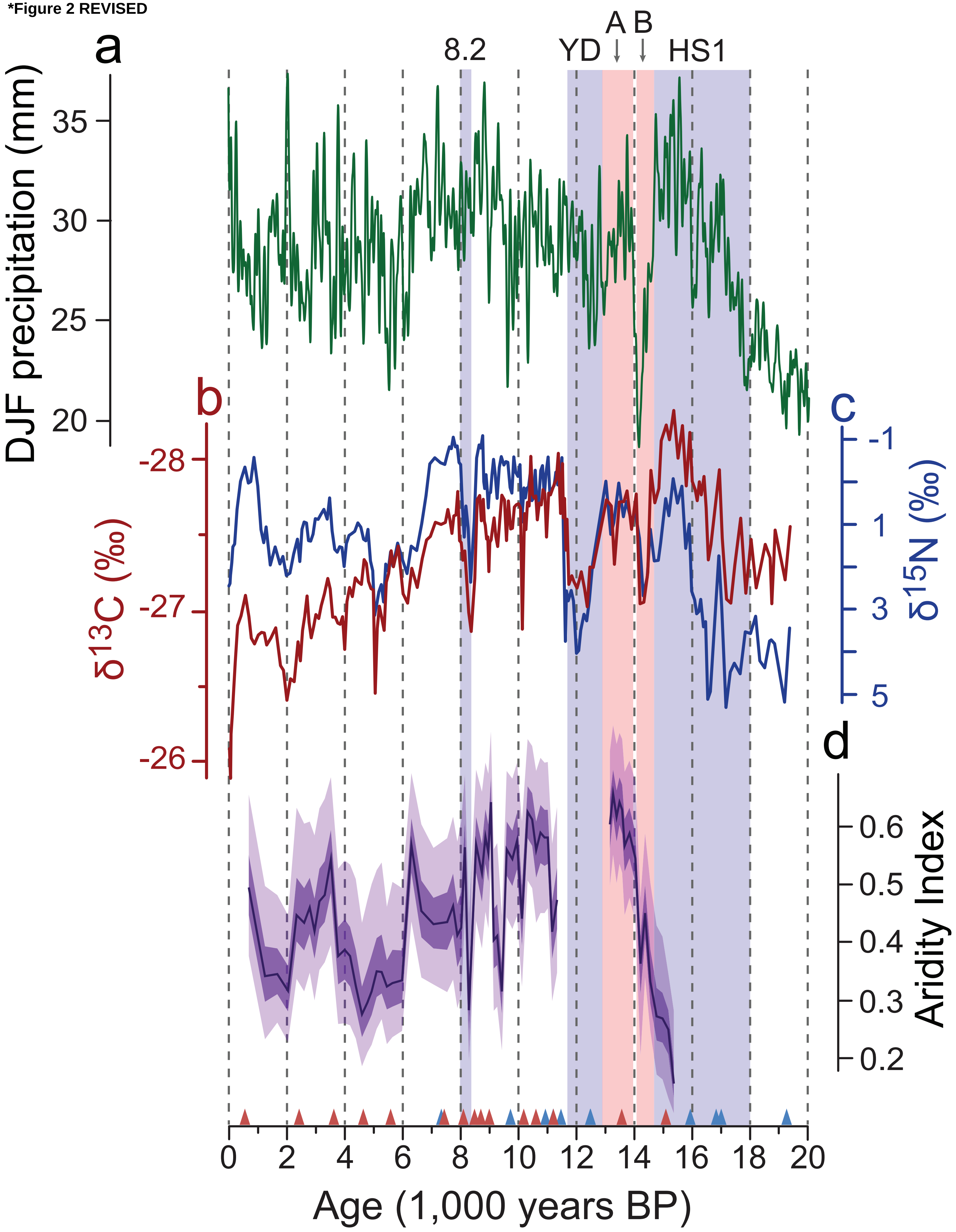
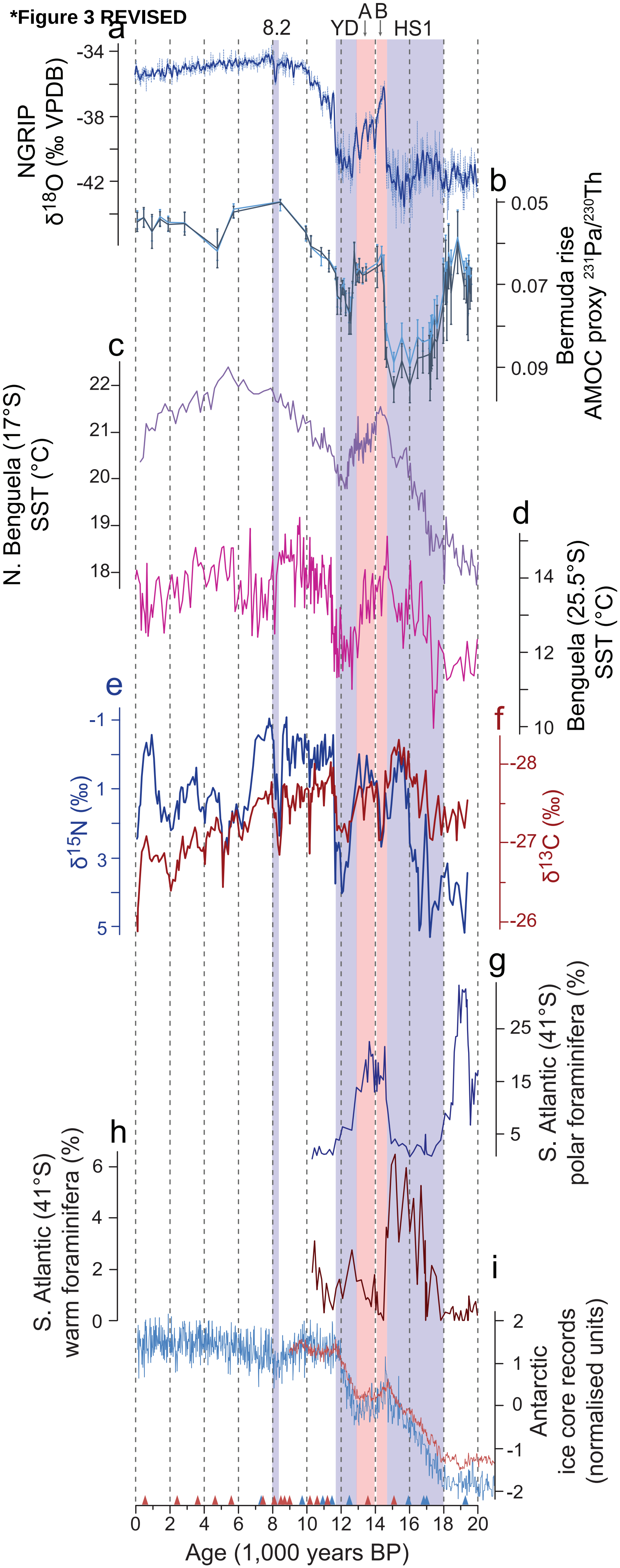


*Figure 3 REVISED



Supplementary Data

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Table S1

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Supplementary Data

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Supplementary Data

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