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Increased aridity in southwestern Africa during the last-interglacial warmest periods

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Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

We use pollen analysis of marine sediments from core MD96-2098 to produce a paleoenvironmental record spanning from 190 to 24.7 ka (thousand years before present) from southern Africa. Our interpretations of the pollen record are supported by an analysis of present day pollen spectra for the region. We apply canonical correspondence analysis (CCA) and detrended correspondence analysis (DCA) on pollen spectra from terrestrial surface samples to investigate pollen spectra-climate relationships. We identify pollen taxa that are suitable indicators for the different South African biomes, and assess in detail the distribution and potential interpretation of Poaceae pollen signals in marine sediments along the southwestern African coast.

The pollen record from MD96-2098 documented major increases of Poaceae pollen percentages, that are interpreted as expansions of semi-arid southwestern African biomes (i.e. the Nama-Karoo and fine-leaved savannas) during Marine Isotope Stage (MIS) 5e, 5c and 5a substages. These expansions coincided with minima in precession and global ice volume. They likely resulted from a combination of reduced Benguela upwelling; expanded subtropical high pressure and reduced austral-summer precipitation due to a northward shift of the Intertropical Convergence Zone (ITCZ); and a southern displacement of the westerlies and decreased austral-winter precipitation. During glacial isotopic stages MIS 6, 4 and 3, Fynbos expanded at the expense of semi-arid biomes. Stage and substage transitions were characterised by small but rapid increases in *Podocarpus* indicating a humidity increase. Increased millennial-scale variability in the vegetation and climate of southern Africa is also suggested for the last 100 ka.

1 Introduction

Southern Africa is recognised as a climatic (Giorgi, 2006), biodiversity and conservation hotspot (Myers et al., 2000) and as a region of crucial importance for the

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



development of early modern humans (Henshilwood and Dubreuil, 2011). Vegetation and climate changes are potential triggers of cultural innovations. Understanding the processes involved in the evolution of southern African (SAfr) environments is hence relevant both for human and climate sciences.

Southern Africa is influenced by tropical and subtropical atmospheric circulation linked to ITCZ shifts, and by both the Indian and the Atlantic Oceans (Tyson and Preston-Whyte, 2000). The water exchange between the two oceans is termed the Agulhas leakage and is documented to vary significantly during glacial vs. interglacials (Peeters et al., 2004). The Agulhas leakage is also suggested as a potential trigger of changes in the meridional overturning circulation (Beal et al., 2011), hence the importance of SAfr for Earth's climate. Climate in southwestern Africa (SWAfr) is also affected by the Benguela upwelling system (BUS), whose strength determines the extent of the coastal Namib Desert (Cowling et al., 1997b).

Vegetation and climate changes have been documented for SAfr at orbital and sub-orbital timescales based on a few marine (Dupont, 2011) and fragmentary terrestrial pollen sequences (Scott et al., 2012; Meadows et al., 2010). Putting together a comprehensive picture of paleoenvironmental conditions in SAfr has been hence controversial. Previous reconstructions point to expansions of the Fynbos biome (Shi et al., 2001) and the winter-rainfall zone during glacial periods (Chase and Meadows, 2007), and to a contracting (Shi et al., 2000) and relatively humid (Scott et al., 2012) Namibian Desert during the Holocene. It is also suggested that savannas expanded southwards during the Holocene climate optimum (Dupont, 2011), and that the SAfr summer-rainfall zone expanded during interglacials due to a strengthening of the walker circulation and an increased dominance of the ITCZ (Tyson, 1999). Contrastingly, significant reductions of austral-summer precipitation in SAfr are suggested to coincide with precession minima both during glacials and interglacials (Partridge et al., 1997), and are independently supported by reductions of grass-fuelled fires in the subcontinent (Daniau et al., 2013).

To disentangle these contrasting hypotheses, we conduct the pollen analysis of marine sequence MD96-2098 collected 200 km off the Namibian coast. In arid

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



environments like those of SWAfr, marine sequences can provide continuous records of vegetation change at the regional scale, and help unravel climatic signals obscured by local effects in terrestrial sequences. Furthermore, marine pollen sequences permit to correlate directly changes on land to changes in oceanic circulation and ice dynamics. Marine sequences are therefore pivotal to understanding vegetation and climate dynamics at orbital and suborbital timescales. Additionally, we improve the interpretation of the marine pollen record by performing a pollen-vegetation-climate calibration. We analyse a north-south transect of 31 pollen samples that are integrated to the marine and terrestrial surface samples compiled by Dupont and Wyputta (2003) and Gajewski et al. (2002), respectively. The present-day pollen-vegetation-climate spatial results are used to infer precipitation variations in SWAfr through time. We correlate these variations with independent climatic markers from the same sample set, along with other regional records for oceanic conditions and global ice dynamics, to reconstruct atmospheric and oceanic configurations around SAfr at orbital timescales.

2 Modern environmental setting

Climate in SAfr is influenced by oceanic circulation both in the Indian and the Atlantic Oceans and by tropical and subtropical atmospheric circulation (Tyson and Preston-Whyte, 2000). In the Atlantic Ocean, the influence of the cold Benguela current and offshore-wind driven upwelling results in aridity on the adjacent continent (Stuut and Lamy, 2004). In the Indian Ocean, warm waters from the Agulhas current (Beal and Bryden, 1999) and austral-summer heat allow evaporation and relatively high precipitations in southeastern Africa and the interior of the continent (Fig. 1). Austral-summer precipitations are also linked to the position of tropical low pressure systems (i.e. ITCZ) and reduced subtropical high pressure (Tyson and Preston-Whyte, 2000). As tropical low pressure systems migrate northwards during the austral winter, subtropical high pressure significantly reduces austral-summer precipitation in SAfr. The southwestern part of the continent is influenced by the seasonal migration of the subtropical front and

the southern westerlies that bring precipitation during the austral-winter months (Beal et al., 2011).

Biomes of SAfr were initially classified by White (1983), and later revisited and described into seven units by Rutherford (1997). These include the Succulent-Karoo, Nama-Karoo, Desert, savanna, Fynbos, Grassland, and forest (Fig. 1). The Succulent-Karoo receives between 20 and 290 mm yr⁻¹ of which more than 40 % falls during the austral-winter months (Rutherford, 1997). The two most abundant succulent families are Crassulaceae and Mesembryanthemaceae, and non-succulents are Anacardiaceae, Asteraceae, and Fabaceae (Milton et al., 1997). C4 perennial grasses (Poaceae) have relatively low abundance in the Succulent-Karoo (Milton et al., 1997).

The Nama-Karoo receives precipitations from 60 to 400 mm yr⁻¹ falling primarily during the austral summer (Palmer and Hoffman, 1997). Vegetation is characterized as dwarf open shrubland with high abundance of Asteraceae, Poaceae, Aizoaceae, Mesembryanthemaceae, Liliaceae and Scrophulariaceae (Palmer and Hoffman, 1997; Milton et al., 1997). The Nama- and Succulent-Karoo are structurally similar but influenced by different seasonal precipitations (Rutherford, 1997). To the northwest, the Nama-Karoo biome transitions into the Desert, where mean annual precipitation can be as low as 20 mm yr⁻¹ (Jurgens et al., 1997). The Desert reaches 300 km inland and its extent is linked to the intensity of BUS (Lutjeharms and Meeuwis, 1987).

High precipitation seasonality and austral-summer rainfall characterize the savanna. It represents a continuum that includes shrublands, dry forests, lightly-wooded Grasslands, and deciduous forests (Scholes, 1997). At the landscape scale however, the savanna can be subdivided into the fine- and broad-leaved savannas based on moisture conditions and soils (Scholes, 1997). The fine-leaved savanna (Fn-LSav) is associated with arid and fertile environments (between 400 and 800 mm yr⁻¹), and the broad-leaved savanna (Bd-LSav) is associated with nutrient-poor and moist environments (up to 1500 mm yr⁻¹) (Scholes, 1997). Additionally, in the Fn-LSav fuel load and fire frequency are very low, while the Bd-LSav has high fuel load and fire frequency (Scholes, 1997; Archibald et al., 2010). The Fn-LSav is found to the northeast of the

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Nama-Karoo biome (Fig. 1), known as the Kalahari Highveld transition zone (Cowling and Hilton-Taylor, 2009). Due to the transitional character of the Fn-LSav, some of its outer parts can be included in the Grassland or Nama-Karoo biomes. The composition of the Fn-LSav can be similar to that of the Nama-Karoo, with dominance of C4 grasses (Poaceae) and succulent plants, however it differs in having scattered trees (Cowling et al., 1994). The Bd-LSav is characterized by broad-leaved trees from the Caesalpinaceae and Combretaceae families and an under growing dominated by grasses (Scholes, 1997).

The Grassland biome is dominated by C4 grasses and non-grassy forbs as *Anthospermum* sp., *Lycium* sp., *Solanum* sp. and *Pentzia* sp. (O'Connor and Bredenkamp, 1997). In the high elevations the biome is dominated by C3 grasses. In the Grasslands, precipitation is highly seasonal with mean annual rainfall ranging between 750 and over 1200 mm, and falling primarily during the austral-summer months (O'Connor and Bredenkamp, 1997) (Fig. 1).

The southernmost part of Africa is dominated by the Fynbos biome, a fire-prone vegetation form dominated by Ericaceous and Asteraceae shrubs, diverse Proteas and Restionaceae herbs (Cowling et al., 1997a). The Fynbos biome is subject to low precipitation seasonality and relatively high annual precipitation (1200 mm per year) concentrated during the austral-winter months (Rutherford, 1997). The coastal forest biome is found in the eastern coast of the subcontinent and often occurs in small patches with high abundance of *Podocarpus* (Rutherford, 1997).

3 Material and methods

3.1 Surface-sample collection and analysis

A total of 31 surface samples were collected in a transect from Cape Town (South Africa) to Lüderitz (Namibia) during two weeks of field work in February 2011. The sampling area extended from latitudes 26.5 to 34.5° S and from longitudes 15 to 23.8° E

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(Fig. 1) and was designed to cover the four major biomes of SWAfr (Table 1 in the Supplement): Desert, Fynbos, Nama- and Succulent-Karoo. Although we did not conduct a vegetation survey at each sampling site, the surrounding vegetation was determined based on detailed descriptions and maps of SWAfr biomes (Mucina et al., 2007). We were also able to collect one sample in the coastal forest biome. While we did not intend to characterize the pollen spectra from coastal forests, including this sample in the dataset allowed to increase the variability of pollen spectra. Sediment samples were collected from small, probably ephemeral, water-logged depressions where pollen preservation was likely. When we found moss attached to rocks or soil, we collected pitches from several spots within a five meter radius. Water samples were also collected from small streams or rivers when neither water-logged depressions nor moss were found. As a result, our sample set included 12 sediment, 8 moss, and 11 water samples (Table 1 in the Supplement).

Surface samples were concentrated down to pellets using a manual and portable centrifuge in the field. Pellets were treated with standard acetolysis in the laboratory (Faegri and Iversen, 1989) and residues were mounted in glycerol and scanned under the microscope at 400 and 1000 magnification. Pollen sums were greater than 300 grains, and spores were quantified but excluded from this total. Four out of 31 surface samples had such low pollen concentration that their spectra were excluded from the analysis (Table 1 in the Supplement).

Pollen identification was aided by the pollen reference collection of the Department of Plant Sciences at University of the Free State, Bloemfontein, South Africa, the African Pollen Database (APD) (<http://medias3.mediasfrance.org/pollen>), the Universal Pollen Collection (<http://www.palyno.org/pollen>), and pollen descriptions published by Scott (1982). Pollen grains from the Asteraceae family were grouped into three pollen taxa: *Artemisia*-type, *Stoebe*-type and other morphotypes were classified into Asteraceae-other. *Artemisia*-type likely corresponds to the Asteraceae-low spine reported by other authors (Meadows et al., 2010). *Stoebe*-type may include pollen from *Tarchonanthus* sp. due to similarities in their pollen morphology. Pollen

percentages from more than one morphotype were grouped into the families Acanthaceae, Chenopodiaceae-Amaranthaceae, Crassulaceae, Cyperaceae, Ericaceae, Myrtaceae, Ranunculaceae, Restionaceae, and Solanaceae.

Canonical correspondence analysis (CCA) was used to summarize changes in pollen spectra from surface samples and explore their relationship with bioclimatic variables (McCune and Grace, 2002). Four temperature and four precipitation bioclimatic variables were extracted for each sampling point from the WorldClim Global Climate dataset (Hijmans et al., 2005), but only variables with the most constraining powers were preserved. Ordinations were run filtering out aquatic taxa to remove local effects and taxa that only occurred in one sample to avoid overweighting rare taxa. We also used previously published pollen spectra from 150 additional surface samples collected between 22 and 35° latitude south (African Pollen Database, APD, Gajewski et al., 2002) to assess the pollen-percentage distribution, and potential as indicators of large biomes, of seven abundant pollen taxa over SAfr. These taxa included *Artemisia*-type, Asteraceae-other, Chenopodiaceae-Amaranthaceae, Poaceae, *Podocarpus*, Restionaceae, and *Stoebe*-type. ArcGIS 10 was used to draw iso-lines of pollen percentages by interpolating values from a total of 178 surface samples through the natural neighbour method. Maps of bioclimatic variables were also drawn for comparison.

3.2 Marine core description and pollen analysis

Pollen analysis was conducted on the marine core MD96-2098 (25°36' S, 12°38' E). This giant CALYPSO core was collected during the IMAGES II-NAUSICAA cruise at a 2910-m water depth from the Lüderitz slope in the Walvis Basin, approximately 500 km northwest of the Orange River mouth (Fig. 1). The sediments of this 32-m long core were composed of calcium carbonates (foraminifera), biogenic silica (nannofossil mud), clays and organic matter (Bertrand et al., 1996). The core was sampled every 10 cm between 450 and 1940 cm (uncorrected depth) for pollen analysis. Additionally, two marine pollen samples from the upper part of core MD96-2098 (5 and 10 cm depth) were

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



analysed and compared with the pollen signal of the modern vegetation to evaluate how well marine sediments represent the vegetation of the adjacent landmasses, and to aid interpretation of the pollen record. Sample volumes were estimated by water displacement and pollen concentrations per unit volume were calculated based on a known spike of exotic *Lycopodium* spores added to each sample. Pollen extraction techniques included treatment with Hydrofluoric and Hydrochloric acids, and sieving through 150 and 10- μ m filters. This filtration allowed eliminating small non-palynomorph particles and concentrating pollen grains and spores. An independent test of this protocol showed that the use of a 10- μ m sieve had no effect on the pollen composition of marine samples, i.e. comparison of filtered and unfiltered samples confirmed that neither Poaceae nor other taxa were selectively filtered out during pollen preparation and concentration (see <http://www.ephe-paleoclimat.com/ephe/Lab%20Facilities.htm> for a detailed pollen preparation protocol). To summarize changes in the fossil pollen record over time, detrended correspondence analysis (DCA) was used in tandem with Non-metric multidimensional scaling (NMDS) as parametric and non-parametric alternatives. Results from the DCA ordination were preferred when NMDS was unable to reach a stable solution after several random starts, and when stress levels were too high to allow a meaningful interpretation (McCune and Grace, 2002). These ordinations were run filtering out taxa that only occurred in one sample to avoid overweighting rare taxa.

3.3 Marine core chronology

An age model based on 16 marine isotope events (MIE) from the *Cibicidoides wuellerstorfi* $\delta^{18}\text{O}$ benthic record of MD96-2098 (Bertrand et al., 2002) and 14 Accelerator Mass Spectrometer radiocarbon ages (AMS ^{14}C) produced at the Laboratoire de Mesure du Carbone 14 from mixed planktonic foraminifera was established for the core (Table 2 in the Supplement). One single ^{14}C date showed an age reversal and was therefore excluded from the chronology on the principle of parsimony. AMS ^{14}C ages were calibrated using the marine09.14c curve (Hughen et al., 2004) from CALIB REV6.0.0 (Stuiver and Reimer, 1993). We applied a 400-yr global reservoir

correction factor and a weighted mean Delta R of 157 yr derived from 9 regional reservoir error values from the Marine Reservoir Correction Dataset (Dewar et al., 2012; Southon et al., 2002). MIE ages were derived from LR04 global stack (Lisiecki and Raymo, 2005) and additional sources (Henderson and Slowey, 2000; Drysdale et al., 2007; Waelbroeck et al., 2008; Masson-Delmotte et al., 2010; Sanchez Goñi and Harrison, 2010) (Fig. 1 in the Supplement). Sample ages were calculated using a linear interpolation between AMS ^{14}C ages and MIE using the R package PaleoMAS (Correa-Metrio et al., 2010).

4 Results and discussion

4.1 Present-day pollen-vegetation-climate relationships in southern Africa

Asteraceae-other, Chenopodiaceae-Amaranthaceae, Poaceae and Restionaceae add up to 80 % of the pollen sums and are found in all surface samples (Fig. 2 in the Supplement). Cyperaceae pollen is also found in all but one of our surface samples. High Cyperaceae percentages probably reflect local abundances of sedges growing around small waterlogged depressions or along rivers as we deliberately targeted sites where pollen preservation was likely. As a result, we excluded Cyperaceae pollen percentages from ordination analyses.

In the surface samples collected in the Desert, Asteraceae-other percentages are up to 20 % and Chenopodiaceae-Amaranthaceae percentages are less than 10 %. Poaceae and Cyperaceae show up to 45 % and between 50 and 60 %, respectively. The source of Poaceae, Asteraceae-other and Chenopodiaceae-Amaranthaceae pollen in the Desert can be perennial grasses growing on dunes (Jurgens et al., 1997). Our results show that pollen spectra from the Desert are more similar to spectra from the Succulent-Karoo than to any other biome (Fig. 2a), suggesting that Desert surface samples receive pollen from Succulent-Karoo transitional patches.

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



composition of pollen spectra from the Fynbos biome in the DCA ordination is clearly distinguished from pollen spectra from other biomes (Fig. 2a). The classification of sample Fy22 near samples from the Nama-Karoo likely results from the relatively high abundance of Poaceae pollen in Fy22 compared to other Fynbos samples (Fig. 2 in the Supplement).

The spatial variability of pollen spectra from biomes in SWAfr is closely associated with precipitation variability and seasonality (Fig. 2b). Desert pollen spectra are linked to precipitation seasonality (PS), and plot in the opposite direction of all other precipitation variables. Similar to Desert samples, the Succulent-Karoo pollen spectra are associated with PS and somewhat linked to PCQ (coldest quarter precipitation), although less than Fynbos pollen spectra. Fynbos pollen spectra are linked to all precipitation variables except PS. Pollen spectra from the Nama-Karoo are correlated with PS, are somewhat linked to warmest quarter precipitation (PWQ) and clustered opposite PCQ.

The four temperature bioclimatic vectors plot in the same ordination quadrant (Fig. 3 in the Supplement), indicating they are correlated. In addition, Nama-Karoo pollen spectra are linked to all of these temperature bioclimatic variables. These results indicate that temperature does not appear to have as much constraining power as precipitation bioclimatic variables when classifying pollen spectra from SWAfr biomes, except in the case of the Nama-Karoo.

Some individual taxa are associated with the clustering of pollen spectra from the SWAfr biomes in the DCA ordination (Fig. 2a), suggesting their potential as indicators of specific biomes. For instance, Poaceae, Crassulaceae and *Tribulus* obtain the highest loadings to classify the pollen spectra from the Nama-Karoo. Asteraceae-other, Chenopodiaceae-Amaranthaceae and *Euphorbia* obtain high loadings to cluster Succulent-Karoo and Desert samples. Pollen taxa that characterize the Fynbos pollen spectra include Anacardiaceae, *Artemisia*-type, Ericaceae, *Myrica*, *Passerina*, *Protea*, *Stoebe*-type. *Podocarpus* characterizes the pollen spectra from coastal forests and Fynbos biomes.

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Pollen percentage iso-lines drawn for six of these abundant taxa using our pollen surface samples and those of the APD complement the picture of pollen percentage distribution in the subcontinent (Fig. 3). These six taxa are abundant both in terrestrial and marine pollen sequences (Dupont, 2011; Scott et al., 2012) and can therefore be valuable for the interpretation of fossil pollen records. The pollen iso-lines of Asteraceae-other show 25 % near the transition of the Nama-Karoo and the Grassland, and 40 % in part of the Succulent-Karoo (Fig. 3). Chenopodiaceae-Amaranthaceae pollen percentages are as high as 40 % in the Nama-Karoo and Desert biomes, and are also found up to 40 % in the transition between the Nama-Karoo and the Grasslands. This pollen distribution indicates that Chenopodiaceae-Amaranthaceae and Asteraceae-other high pollen percentages can be characteristic of the Succulent-Karoo, Nama-Karoo and Desert biomes of SWAfr.

High *Podocarpus* pollen percentages in surface samples from SAfr show a localized pattern in areas with high precipitation, namely coastal forest and in the eastern part of the Fynbos biome (Fig. 3) and in the eastern highlands. Consistently, Gajewski et al. (2002) reports maxima of *Podocarpus* pollen percentages in African regions where precipitation is at least 1000 mm per year.

Restionaceae plants are found mostly in the Fynbos biome (Cowling et al., 1997b) and its pollen has been used as a Fynbos indicator (Shi et al., 2001). However, the distribution of its pollen in our surface samples is only partly related to the distribution of the Fynbos biome (less than 5 %) (Fig. 3). Up to 4 % of Restionaceae pollen is found in surface samples from the Nama-Karoo, Succulent-Karoo and the Desert (Fig. 3), suggesting that these pollen grains are the result of long-distance transport. Restionaceae are wind pollinated (Honig et al., 1992), hence its pollen is likely transported by wind far from the vegetation source (Fig. 1). Due to this inconsistency between the vegetation source and the spatial distribution of Restionaceae pollen, it would be difficult to discern whether increases in Restionaceae pollen in palaeoenvironmental reconstructions are the result of wind strengthening or due to Fynbos vegetation expansions, without an independent tracer for past wind strength.

The distribution of pollen percentages from *Artemisia*-type and *Stoebe*-type are concentrated in the Fynbos biome (Fig. 3), and are positively correlated with PCQ (Fig. 2). Pollen signals from *Artemisia*-type and *Stoebe*-type, along with other taxa characteristic of the Fynbos vegetation (i.e. Ericaceae, *Protea* and *Passerina*, Fig. 2 in the Supplement) might therefore be good tracers for past expansions of the biome.

4.2 Poaceae pollen percentage distribution in terrestrial and marine surface samples and its interpretation

Occurrence of Poaceae pollen in all surface samples corresponds to the presence of grass species in virtually all SAfr biomes (Cowling et al., 1997b). However, the spatial distribution of Poaceae pollen percentages appears to be essential information to distinguish major biomes from their pollen spectra.

In the center part of SAfr, Poaceae pollen percentages in terrestrial surface samples up to 60 % in the Nama-Karoo and Fn-LSav, and in the transition between the Fn-LSav and the Grassland (Fig. 4). This suggests an overrepresentation of Poaceae in the pollen rain of the Nama-Karoo biome where grasses can be abundant but are not necessarily dominant. Poaceae is likely to be well represented in other parts of the Fn-LSav, but the paucity of surface samples North of 25° S within this biome hinder drawing further conclusions. In the Namib Desert where abundance of grasses in the vegetation is low, Poaceae pollen percentages are as high as 30 %, comparable to 20 % reported from hyrax dung (Scott et al., 2004). In the eastern and northeastern part of SAfr, the highest percentages of Poaceae pollen (up to 90 %) are found in the pollen rain of the Bd-LSav. We recognize that the number of terrestrial surface samples available for this calibration is limited, specially for the savanna biome. However, we are able to characterize the pollen spectra from the SWAfr biomes that are most likely recorded in our marine record.

Grazing and agriculture could artificially increase the abundance of Poaceae in surface samples from SAfr, thus complicating the usage of Poaceae pollen to discriminate biomes. We are unable to discard this bias from surface samples extracted from the

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



APD. However, we have no record of cultivated Poaceae pollen (i.e. cereals) in the surface samples we analysed. We also collected samples well outside grazing zones.

In marine surface samples along the SWAfr coast, Poaceae pollen percentages are as low as 10 % in samples collected in front of the Bd-LSav at around 15° S (Fig. 4).

Poaceae pollen percentages increase to the South and the highest values (40 %) are found between 20 and 25° S (Dupont and Wyputta, 2003) and correspond well with the distribution of the Desert and the Fn-LSav on the continent. The Poaceae pollen percentages from the two core-top samples from MD96-2098 dating to the last millennium extend the iso-lines drawn by Dupont and Wyputta (2003) to 25.5° S, and show that Poaceae pollen percentages are between 30 and 40 % in front of the Desert, Nama-Karoo and Fn-LSav biomes. As Poaceae pollen percentages in Desert surface samples are less than 25 %, high percentages of grass pollen in marine sediments in the SWAfr margin should be interpreted as indicator of the Nama-Karoo and the Fn-LSav, where Poaceae is as high as 60 % in terrestrial surface samples.

4.3 Pollen preservation and sources in marine core MD96-2098

Pollen sums excluding spores range from 100 to 240 grains in 141 samples analysed from core MD96-2098, with a mean of 21 taxa per sample. Total pollen concentration changes importantly over the record, ranging between ca. 300 and 16 000 grains cm⁻³ during most of MIS 6, 5 and 3 and increasing up to 48 000 grains cm⁻³ during MIS 4 (Fig. 4 in the Supplement). The pollen concentrations are relatively low when compared with terrestrial sites, even though BUS facilitates preservation of pollen grains and other organic microfossils at this site (Bertrand et al., 2003). The low net primary productivity that characterizes SWAfr (Imhoff et al., 2004) is partly due to reduced low annual precipitations (Cowling et al., 1997b) and can explain our relatively low pollen concentrations (Fig. 4).

Pollen grains are part of the fine sediment fraction and can be transported by two main vectors: aeolian or fluvial (Hooghiemstra et al., 1986; Heusser and Balsam, 1977). Dupont and Wyputta (2003) modelled present-day wind trajectories for marine core

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



locations between 6 and 30° S along the coastline of SAfr. They suggest aeolian pollen input to the Walvis area (23° S) via the south-east trade winds during austral summer, and dominant east-to-west wind directions during the austral fall and winter. These winds transport of pollen and other terrestrial particles from the Namib Desert, southern Namibia and western South Africa and suggest the Namib Desert and the semi-Desert (corresponding to the Nama-Karoo and Succulent-Karoo areas) as the main vegetation sources of pollen in the Walvis area (Dupont and Wyputta, 2003). The authors also infer that south of 25° S wind directions are predominantly west to east and aeolian terrestrial input very low. Marine site MD96-2098 is located less than a degree south of the area determined by Dupont and Wyputta (2003) to be dominated by terrestrial aeolian input, and given that this threshold was established using only two marine sites located far apart at 23°26' (GeoB1710-3) and 29°27' (GeoB1722-1), it is difficult to conclude that MD96-2098 only receives wind-transported pollen.

Sedimentological analyses of the Orange River delta and plume indicate that fine muds are transported both northwards and southwards (Rogers and Rau, 2006). The authors also infer that the fine fraction of the Orange River plume travels northwards of the mouth aided by oceanic currents. The input of terrestrial particles, including pollen, to marine site MD96-2098 from the Orange River catchment area is hence likely.

The contribution of both aeolian and fluvial processes is likely even during past glacial and interglacial periods. Analyses of aeolian vs river-transported clays from MD96-2098 show that both mechanisms were active and that their contribution varies over time independently of glacial and interglacial conditions (Daniau et al., 2013).

Scott et al. (2004) argue that pollen in marine sediments can be the result of long-distance transport by ocean currents, suggesting that pollen assemblages in marine sediments do not reflect accurately past changes in vegetation and climate. However, the highest pollen influx in marine sediments along this margin is not found along the paths of oceanic currents (i.e. Benguela Current), but near the coast and the vegetation source (Dupont et al., 2007). Additionally, analyses of pollen transport vs. source in northwestern Africa show that pollen grains can sink rapidly in the water column

(Hooghiemstra et al., 1986) before they can be carried away by ocean currents. As a result, influence of oceanic currents on the composition of pollen assemblages is probably negligible. The marine site MD96-2098 might therefore receive both aeolian and fluvial pollen input from the vegetation located east and southeast of the site. In addition, the pollen composition of two core-top samples from core MD96-2098 are dominated by Poaceae (30 and 40 %), Cyperaceae (20 %) and Chenopodiaceae-Amaranthaceae (20 and 30 %) (Fig. 4 in the Supplement). This composition corresponds well with the pollen spectra from the three major biomes, Desert, Nama-Karoo and Fynbos (Figs. 3 and 4) occupying today the adjacent landmasses (Fig. 1a). Pollen percentages from Fynbos are less than 10 %. These results support the assumption that the main pollen source from marine core MD96-2098 is the vegetation east and southeast of the site.

4.4 Southwestern Africa vegetation and climatic changes from MIS 6 to 2

The pollen record presented here spans from 24.7 to 190 ka. A log transformation of concentration values results in a curve remarkably similar to that of $\delta^{18}\text{O}_{\text{benthic}}$ values (Fig. 5). Relative increases in pollen concentration might indicate an increase of pollen arrival to the site during low sea-level stands when the vegetation source was closest (i.e. during glacial stages). However, this is unlikely because of the width of the Walvis continental Shelf (i.e. steep slope in a few kilometres). An increase of pollen concentration might indicate instead an increase in aeolian and riverine pollen input during glacials, and/or an increase in pollen preservation linked to upwelling enhancement as suggested by Pichevin et al. (2005). Nonetheless, these glacial–interglacial pollen concentration variations have no effect on the pollen record because vegetation changes are reconstructed based on standardized pollen abundances.

The axis scores on DCA1 reveal changes in the composition of pollen assemblages that also resemble variations in the $\delta^{18}\text{O}_{\text{benthic}}$ record. DCA1 axis scores from MIS 5 and 3 are overall positive in value, while scores from MIS 6 and 4 are negative. A series of large-magnitude changes in DCA1 axis scores (i.e. when adjacent sample scores switch from positive to negative values) are also visible and increase in amplitude after

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



c. 100 ka. Such changes in DCA Axis1 scores are also observed during MIS 6 but are of lesser magnitude. Changes in DCA axis scores suggest significant changes in vegetation composition from one time step to the next (i.e. adjacent samples).

Poaceae pollen percentages are up to 60 % during MIS 5 and display three percentage peaks that correspond with $\delta^{18}\text{O}_{\text{benthic}}$ and precession minima (Fig. 5a). These Poaceae percentage peaks are centred at 125, 107 and 83 ka. Pollen percentage of Acanthaceae, Aizoaceae and *Tribulus* are low, but consistent with changes in Poaceae pollen percentages (Fig. 4 in the Supplement). The composition of pollen spectra from warm marine substages, MIS 5e, 5c and 5a, is similar to the core-top samples (dating the last millennium). Additionally, Poaceae pollen percentages in these samples are relatively low compared to their maximum during MIS 5e (Fig. 5b). During MIS 6 and 4, Poaceae percentages are reduced and co-vary with $\delta^{18}\text{O}_{\text{benthic}}$ values. Pollen percentages of Chenopodiaceae-Amaranthaceae and Asteraceae-other are relatively high and increased along with enriched $\delta^{18}\text{O}_{\text{benthic}}$ values during MIS 6 and at the end of MIS 4 (Fig. 4 in the Supplement). Cyperaceae pollen percentages vary importantly throughout the record and are as high as 40 % during MIS 4. Fynbos indicators including *Artemisa*-type and *Stoebe*-type show relative increases in pollen percentage during MIS 6, 4 and 3 (Fig. 5b). Ericaceae, *Passerina*, *Anthospermum*, *Cliffortia*, and *Protea* pollen percentages are low but consistent with abundance changes of *Artemisa*-type and *Stoebe*-type (Fig. 4 in the Supplement). Pollen percentages of Restionaceae increase after the 105-ka $\delta^{18}\text{O}_{\text{benthic}}$ minimum and remain abundant during the rest of MIS 5 through MIS 3, despite a relative decrease during MIS 4. *Podocarpus* percentages are lower than 10 % but show increases at stage boundaries around 135 ka (MIS 6/5), 100 ka (5c/5b), 75 ka (MIS 5a/4), 60 ka (MIS 4/3), and around 27 ka (MIS 3/2) (Fig. 4 in the Supplement).

Based on the observed present-day distribution of Poaceae pollen percentages from marine and terrestrial surface samples, we infer that increases of Poaceae pollen percentages during MIS 5 warm substages correspond to expansions of the Nama-Karoo

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



and Fn-LSav biomes in SWAfr (Fig. 4). These increases of Nama-Karoo and Fn-LSav during MIS 5e, 5c and 5a likely resulted from expansions in three directions.

The Nama-Karoo and Fn-LSav probably expanded to the northwest into the present-day area of the coastal Namib Desert as the intensity of BUS weakened during MIS 5 warm substages. This weakening has been documented through alkenone-based SST from marine core GeoB1711-3 (Kirst et al., 1999) (Fig. 5c), foraminifera-assemblage based SST (Chen et al., 2002) and grain-size end-member modelling (Stuut et al., 2002). Stuut and Lamy (2004) also suggested reduced atmospheric circulation and weakening of trade winds during interglacials compared to glacials, resulting in a reduction of the upwelling. A weakened wind-driven upwelling and the associated relative increase in humidity likely led to a colonization of Desert areas by Nama-Karoo or Fn-LSav (Fig. 6a). Comparable contractions of the Namib Desert linked to increased SSTs and weakening of BUS during the present interglacial are documented by Shi et al. (2000).

To the south, the Nama-Karoo and Fn-LSav likely expanded at the expense of the Succulent-Karoo and Fynbos. Increased Antarctica temperatures recorded during warm substages compared to MIS 1 (EPICA, 2006) would drive the southern westerlies polewards (Ruddiman, 2006), contributing to the ventilation of deep CO₂-rich waters in the southern Ocean (Toggweiler and Russell, 2008). This mechanism would explain the paralleling trends observed between MIS 5 Nama-Karoo and Fn-LSav expansions in SAfr and the atmospheric CO₂ record (Petit et al., 1999; Bereiter et al., 2012) (Fig. 5). The increased Agulhas leakage documented in the Cape basin record during the last interglacial (Peeters et al., 2004) (Fig. 5c) would also be linked to a southward migration of the subtropical front and the westerlies, reducing austral-winter precipitation over SAfr. Such an atmospheric configuration would in turn favour the development of the Nama-Karoo at the expense of Succulent-Karoo and Fynbos biomes (Fig. 6a).

To the northeast, Nama-Karoo and Fn-LSav likely pushed the limit of Bd-LSav equatorward as austral-summer precipitation decreased (Fig. 5). Austral-summer

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



precipitation reductions in SAfr have been linked to reduced austral-summer insolation in the Pretoria saltpan (Partridge et al., 1997) and to reductions of grass-fuelled fires during precession minima reconstructed from MD96-2098 (Daniau et al., 2013) (Fig. 5b). Increased northern-hemisphere insolation during MIS5 warm sub-

stages would drive the ITCZ northwards while subtropical high pressure cells over the south Atlantic and the Indian Oceans would expand (Fig. 6a) (Ruddiman, 2006). Such changes in the tropical and subtropical pressure systems would allow the expansion of the Nama-Karoo and Fn-LSav to the northeast.

In contrast with the results presented here, previous studies report poleward interglacial expansions of savanna and are based on the increase of Poaceae pollen percentages in marine sediments along the SWAfr coast (Dupont, 2011). This interpretation could be related to two oversights. First, Dupont (2011) omits the possibility that high Poaceae percentages in SWAfr margin sediments could be an indicator of the Fn-LSav and Nama-Karoo on the adjacent continent. Secondly, Dupont (2011) does not differentiate between the broad-leaved and fine-leaved savannas, despite the significant climatic and structural differences between these two subdivisions of the biome. The Bd-LSav is influenced by fire and receives a considerable amount of precipitation during the austral summer (Scholes, 1997). The Fn-LSav is structurally and climatically more similar to the Nama-Karoo biome, as it receives very low austral-summer precipitation and does not burn (Archibald et al., 2010) despite being under a regime of significant precipitation seasonality (Scholes, 1997). Such lack of fires in the Fn-LSav and the Nama-Karoo are probably associated with low biomass and fuel load. If high Poaceae pollen percentages during MIS 5 warm substages in our record were related to expansions of the Bd-LSav and increased summer precipitation, the fire activity should also increase during these substages. Instead, an independent charcoal record from the same marine sequence MD96-2098 (Fig. 5b) documents reductions of grass-fuelled fires and a decrease in austral-summer precipitation during MIS-5 precession minima (Daniau et al., 2013).

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Our results suggest that the Bd-LSav retreated equatorwards during MIS 5 precession minima. Accordingly, up to 70 % pollen percentage of Poaceae during MIS 5 compared to 35 % in the core-top samples – bearing in mind that the last millennium is characterized by precession maxima – suggested that the Nama-Karoo and Fn-LSav likely expanded during MIS 5 warm substages and covered a surface area larger than at present. Altogether, such results point to an overall increase in aridity in SWAfr during the warmest periods of the last interglacial.

During glacial isotopic stages, contractions of the Nama-Karoo and Fn-LSav would result from the following atmospheric configuration (Fig. 6b): a southward migration of the ITCZ and the associated South African monsoon (Daniau et al., 2013; Partridge et al., 1997) increasing austral-summer rainfall over SAfr. An intensification of BUS and decreased SST off the Namibian coast (Stuut and Lamy, 2004; Kirst et al., 1999) leading to aridification of coastal areas. Lastly, an equatorward migration of the westerlies increasing austral-winter precipitation and allowing a northward expansion of the winter-rain zone in SAfr (Chase and Meadows, 2007).

The pollen record from MD96-2098 also suggested glacial expansions of Fynbos (Fig. 5b) as pollen percentages of *Artemisia*-type, *Stoebe*-type, *Passerina* and *Eriaceae* were higher during MIS 6, 4 and 3 than in the core-top samples (Fig. 4 in the Supplement). These results were consistent with glacial northward expansions of Fynbos documented in other palaeoenvironmental records from SAfr (Shi et al., 2000; Dupont et al., 2007). Our record also documented a large peak in Fynbos indicators (mostly *Artemisia*-type) that coincided with a fast decrease in Poaceae pollen percentages at the MIS 5e/5d transition (c. 117 ka), a precession and eccentricity maxima (Laskar, 1990), and an accelerated cooling in Antarctica (EPICA, 2006; Masson-Delmotte et al., 2010). As pollen percentages of *Artemisia*-type obtained from surface samples were associated with the Fynbos biome and austral-winter precipitation, it cannot be discarded that this resulted from a rapid and short-lived expansion of in the winter-rain zone of SAfr. Transitions MIS 6/5 and 4/3 were characterized by small but rapid increases in *Podocarpus*, indicating an overall increase in precipitation.

Such increases in *Podocarpus* have also been documented in other records from SAfr (Dupont et al., 2011; Dupont, 2011).

Finally, the amplitude of millennial-scale vegetation changes increased between ca. 100 and 25 ka and was highlighted by switches from negative to positive DCA1 scores (Fig. 5b) and increased variability of Restionaceae pollen percentages (Fig. 4 in the Supplement). This increased variability could indicate enhanced trade-wind variability or Fynbos vegetation expansions. Other Fynbos indicators did not display such trend, suggesting that Restionaceae variability between 100 and 25 ka were more likely the result of enhanced variability of southeast trade winds. Restionaceae pollen percentage data from a record 2° N of our marine site also showed increased amplitude of millennial-scale changes (Shi et al., 2001). Grain-size wind strength tracers from the Walvis Ridge also suggested enhanced millennial-scale variability, although only after ca. 80 ka (Stuut et al., 2002). Lastly, an analysis of BUS dynamics over the past 190 ka found increased millennial-scale variability of wind strength after ca. 100 ka and the windiest conditions in this zone during MIS 4 and 3 (Stuut et al., 2002). Such millennial-scale atmospheric reorganisations may also have resulted in rapid biome shifts in SWAfr.

5 Conclusions

The pollen spectra from SWAfr biomes were clearly differentiated based on qualitative and quantitative analyses. Pollen spectra spatial variability was closely associated with precipitation variability and seasonality. Pollen percentage iso-lines drawn for seven abundant taxa complemented the picture of pollen percentage distribution in the sub-continent. Our study showed that the most likely vegetation sources of high Poaceae pollen percentages in terrestrial surface samples from SWAfr were the Nama-Karoo and Fn-LSav. Poaceae pollen percentage distribution in marine surface sediments along the SWAfr coast supported this observation.

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The pollen record from core MD96-2098 documented expansions of the Nama-Karoo and Fn-LSav during MIS 5e, 5c and 5a warm substages. Northwestern expansions of the Nama-Karoo and Fn-LSav into Desert areas likely resulted from the reduction of BUS and a relative increase in humidity. In its eastern boundary, the Nama-Karoo and Fn-LSav likely expanded at the expense of Bd-LSav and Grasslands as a result of increased subtropical high pressure, northward shift of the ITCZ, and reduced austral-summer precipitation. Nama-Karoo and Fn-LSav expansions to the southern boundary probably resulted from a southern displacement of the westerlies and the subtropical front, decreasing austral-winter precipitation. Despite the relative increase in humidity associated with a weakened BUS, our results pointed to an overall increase in aridity in SWAfr during the last-interglacial warmest periods.

During glacial isotopic stages MIS 6, 4 and 3 the Fynbos biome likely expanded as the influence of the southern westerlies and austral-winter precipitation increased. Our pollen record also suggested that transitions between isotopic stages and substages were punctuated by short increases in humidity. Increase variability of vegetation changes at millennial timescales around 100 ka was also documented and could be associated with previously identified enhanced variability of the southeastern trade winds.

Interglacial-glacial SAfr biome dynamics were linked to atmospheric and oceanic dynamics resulting from changes in global ice volume and precession at orbital timescales. Atmospheric configurations with westerly winds shifted southwards relative to today have been suggested for other interglacials (Peeters et al., 2004) and are projected for the end of 21st-century under current global warming (Beal et al., 2011). This is likely to reduce austral-winter precipitation over SAfr and favour expansions of the Nama-Karoo at the expense of the winter-rain fed Fynbos and Succulent-Karoo biomes. However, taking the current orbital configuration alone, the Nama-Karoo and Fn-LSav in SAfr might naturally remain relatively reduced for several millennial ahead.

Supplementary material related to this article is available online at:
<http://www.clim-past-discuss.net/9/4323/2013/cpd-9-4323-2013-supplement.pdf>.

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References

- Archibald, S., Scholes, R. J., Roy, D. P., Roberts, G., and Boschetti, L.: Southern African fire regimes as revealed by remote sensing, *Int. J. Wildland Fire*, 19, 861–878, doi:10.1071/WF10008, 2010.
- Beal, L. M. and Bryden, H. L.: The velocity and vorticity structure of the Agulhas Current at 32   S, *J. Geophys. Res.-Oceans*, 104, 5151–5176, doi:10.1029/1998jc900056, 1999.
- Beal, L. M., De Ruijter, W. P. M., Biastoch, A., and Zahn, R.: On the role of the Agulhas system in ocean circulation and climate, *Nature*, 472, 429–436, doi:10.1038/nature09983, 2011.

CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

    

    

  

  

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Bereiter, B., Lüthi, D., Siegrist, M., Schüpbach, S., Stocker, T. F., and Fischer, H.: Mode change of millennial CO_2 variability during the last glacial cycle associated with a bipolar marine carbon seesaw, *P. Natl. Acad. Sci.*, 109, 9755–9760, doi:10.1073/pnas.1204069109, 2012.
- Bertrand, P., Balut, Y., Schneider, R., Chen, M. T., Rogers, J., and Shipboard Scientific Party: Scientific report of the NAUSICAA-IMAGES II coring cruise. Les rapports de campagne à la mer à bord du Marion-Dufresne, URA CNRS 197, Université Bordeaux1, Département de Géologie et Oceanographie, Talence, France, 382 pp., 1996.
- Bertrand, P., Giraudeau, J., Malaize, B., Martinez, P., Gallinari, M., Pedersen, T. F., Pierre, C., and Vénec-Peyré, M. T.: Occurrence of an exceptional carbonate dissolution episode during early glacial isotope stage 6 in the Southeastern Atlantic, *Mar. Geol.*, 180, 235–248, doi:10.1016/s0025-3227(01)00216-x, 2002.
- Bertrand, P., Pedersen, T. F., Schneider, R., Shimmield, G., Lallier-Verges, E., Disnar, J. R., Massias, D., Villanueva, J., Tribovillard, N., Huc, A. Y., Giraud, X., Pierre, C., and Vénec-Peyre, M.-T.: Organic-rich sediments in ventilated deep-sea environments: Relationship to climate, sea level, and trophic changes, *J. Geophys. Res.*, 108, 3045, doi:10.1029/2000JC000327, 2003.
- Chase, B. M. and Meadows, M. E.: Late Quaternary dynamics of southern Africa's winter rainfall zone, *Earth-Sci. Rev.*, 84, 103–138, doi:10.1016/j.earscirev.2007.06.002, 2007.
- Chen, M.-T., Chang, Y.-P., Chang, C.-C., Wang, L.-W., Wang, C.-H., and Yu, E.-F.: Late Quaternary sea-surface temperature variations in the southeast Atlantic: a planktic foraminifer faunal record of the past 600 000 yr (IMAGES II MD962085), *Mar. Geol.*, 180, 163–181, doi:10.1016/s0025-3227(01)00212-2, 2002.
- Cowling, R. M., Esler, K. J., Midgley, G. F., and Honig, M. A.: Plant functional diversity, species diversity and climate in arid and semi-arid southern Africa, *J. Arid Environ.*, 27, 141–158, 1994.
- Cowling, R. M., Richardson, D. M., and Mustart, P. J.: Fynbos, in: *Vegetation of Southern Africa*, edited by: Cowling, R. M., Richardson, D. M., and Pierce, S. M., Cambridge University Press, Cambridge, UK, 99–130, 1997a.
- Cowling, R. M. and Hilton-Taylor, C.: Phytogeography, flora and endemism, in: *The Karoo, Ecological Patterns and Processes*, edited by: Dean, W. R. J. and Milton, S., Cambridge University Press, Cambridge, UK, 42–56, 2009.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Daniau, A.-L., S'anchez Goñi, M. F., Martinez, P., Urrego, D. H., Bout-Roumazielles, V., Desprat, S., and Marlon, J. R.: Orbital-scale climate forcing of grassland burning in southern Africa, *P. Natl. Acad. Sci.*, 110, 5069–5073, doi:10.1073/pnas.1214292110, 2013.

Dewar, G., Reimer, P. J., Sealy, J., and Woodborne, S.: Late-Holocene marine radiocarbon reservoir correction (ΔR) for the west coast of South Africa, Holocene, doi:10.1177/0959683612449755, in press, 2012.

Drysdale, R. N., Zanchetta, G., Hellstrom, J. C., Fallick, A. E., McDonald, J., and Cartwright, I.: Stalagmite evidence for the precise timing of North Atlantic cold events during the early last glacial, *Geology*, 35, 77–80, 2007.

Dupont, L. M.: Orbital scale vegetation change in Africa, *Quaternary Sci. Rev.*, 30, 3589–3602, doi:10.1016/j.quascirev.2011.09.019, 2011.

Dupont, L. M. and Wyputta, U.: Reconstructing pathways of aeolian pollen transport to the marine sediments along the coastline of SW Africa, *Quaternary Sci. Rev.*, 22, 157–174, 2003.

Dupont, L. M., Behling, H., Jahns, S., Marret, F., and Kim, J.-H.: Variability in glacial and Holocene marine pollen records offshore from west southern Africa, *Veg. Hist. Archaeobot.*, 16, 87–100, doi:10.1007/s00334-006-0080-8, 2007.

Dupont, L. M., Caley, T., Kim, J.-H., Castañeda, I., Malaizé, B., and Giraudeau, J.: Glacial–interglacial vegetation dynamics in South Eastern Africa coupled to sea surface temperature variations in the Western Indian Ocean, *Clim. Past*, 7, 1209–1224, doi:10.5194/cp-7-1209-2011, 2011.

EPICA: One-to-one coupling of glacial climate variability in Greenland and Antarctica, *Nature*, 444, 195–198, doi:10.1038/nature05301, 2006.

Fægri, K., and Iversen, J.: *Textbook of Pollen Analysis*, 4th Edn., Wiley, Chichester, 328 pp., 1989.

Gajewski, K., Lézine, A.-M., Vincens, A., Delestan, A., and Sawada, M.: Modern climate–vegetation–pollen relations in Africa and adjacent areas, *Quaternary Sci. Rev.*, 21, 1611–1631, doi:10.1016/s0277-3791(01)00152-4, 2002.

Giorgi, F.: Climate change hot-spots, *Geophys. Res. Lett.*, 33, L08707, doi:10.1029/2006gl025734, 2006.

Henderson, G. M. and Slowey, N. C.: Evidence from U-Th dating against Northern Hemisphere forcing of the penultimate deglaciation, *Nature*, 404, 61–66, doi:10.1038/35003541, 2000.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



▶

▶

[Back](#)

Close

Full Screen / Esc

[Printer-friendly Version](#)

Interactive Discussion



- Henshilwood, C. S. and Dubreuil, B.: The Still Bay and Howiesons Poort, 77–59 ka: Symbolic Material Culture and the Evolution of the Mind during the African Middle Stone Age, *Curr. Anthropol.*, 52, 361–400, doi:10.1086/660022, 2011.
- Heusser, L. and Balsam, W. L.: Pollen distribution in the northeast Pacific Ocean, *Quaternary Res.*, 7, 45–62, doi:10.1016/0033-5894(77)90013-8, 1977.
- Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A.: Very high resolution interpolated climate surfaces for global land areas, *Int. J. Climatol.*, 25, 1965–1978, 2005.
- Honig, M. A., Linder, H. P., and Bond, W. J.: Efficacy of Wind Pollination: Pollen Load Size and Natural Microgametophyte Populations in Wind-Pollinated *Staberoha banksii* (Restionaceae), *Am. J. Bot.*, 79, 443–448, 1992.
- Hooghiemstra, H., Agwu, C. O. C., and Beug, H.-J.: Pollen and spore distribution in recent marine sediments: a record of NW-African seasonal wind patterns and vegetation belts, *Meteor. Forschungs-Ergebnisse C*, 40, 87–135, 1986.
- Hughen, K., Baillie, M., Bard, E., Bayliss, A., Beck, J., Bertrand, C., Blackwell, P., Buck, C., Burr, G., Cutler, K., Damon, P., Edwards, R., Fairbanks, R., Friedrich, M., Guilderson, T., Kromer, B., McCormac, F., Manning, S., Ramsey, C. B., Reimer, P., Reimer, R., Remmele, S., Southon, J., Stuiver, M., Talamo, S., Taylor, F., v. d. Plicht, J., and Weyhenmeyer, C.: Marine04 Marine radiocarbon age calibration, 26–0 ka BP, *Radiocarbon*, 46, 1059–1086, 2004.
- Imhoff, M. L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R., and Lawrence, W. T.: Global patterns in human consumption of net primary production, *Nature*, 429, 870–873, 2004.
- Jurgens, N., Burke, A., Seely, M. K., and Jacobson, K. M.: Desert, in: *Vegetation of Southern Africa*, edited by: Cowling, R. M., Richardson, D. M., and Pierce, S. M., Cambridge University Press, Cambridge, 189–214, 1997.
- Kirst, G. J., Schneider, R. R., Müller, P. J., von Storch, I., and Wefer, G.: Late Quaternary Temperature Variability in the Benguela Current System Derived from Alkenones, *Quaternary Res.*, 52, 92–103, doi:10.1006/qres.1999.2040, 1999.
- Laskar, J.: The chaotic motion of the solar system: A numerical estimate of the chaotic zones, *Icarus*, 88, 266–291, 1990.
- Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}\text{O}$ records, *Paleoceanography*, 20, PA1003, doi:10.1029/2004pa001071, 2005.
- Lutjeharms, J. R. E. and Meeuwis, J. M.: The extent and variability of South-East Atlantic upwelling, *S. Afr. J. Mar. Sci.*, 5, 51–62, doi:10.2989/025776187784522621, 1987.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Masson-Delmotte, V., Stenni, B., Pol, K., Braconnot, P., Cattani, O., Falourd, S., Kageyama, M., Jouzel, J., Landais, A., Minster, B., Barnola, J. M., Chappellaz, J., Krinner, G., Johnsen, S., Röthlisberger, R., Hansen, J., Mikolajewicz, U., and Otto-Bliesner, B.: EPICA Dome C record of glacial and interglacial intensities, *Quaternary Sci. Rev.*, 29, 113–128, 2010.

5 McCune, B. and Grace, J. B.: Analysis of Ecological Communities, MjM, Gleneden Beach, Oregon, 300 pp., 2002.

Meadows, M. E., Chase, B. M., and Seliane, M.: Holocene palaeoenvironments of the Cederberg and Swartuggens mountains, Western Cape, South Africa: Pollen and stable isotope evidence from hyrax dung middens, *J. Arid Environ.*, 74, 786–793, doi:10.1016/j.jaridenv.2009.04.020, 2010.

10 Milton, S. J., Yeaton, R. I., Dean, W. R. J., and Vlok, J. H. J.: Succulent karoo, in: Vegetation of Southern Africa, edited by: Cowling, R. M., Richardson, D. M., and Pierce, S. M., Cambridge University Press, Cambridge, 131–166, 1997.

Mucina, L., Rutherford, M. C., and Powrie, L. W.: Vegetation Map of South Africa, Lesotho and Swaziland, 2nd Edn., South African National Biodiversity Institute Pretoria, 2007.

15 Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A., and Kent, J.: Biodiversity hotspots for conservation priorities, *Nature*, 403, 853–858, 2000.

O'Connor, T. G. and Bredenkamp, G. J.: Grassland, in: Vegetation of Southern Africa, edited by: Cowling, R. M., Richardson, D. M., and Pierce, S. M., Cambridge University Press, Cambridge, UK, 215–257, 1997.

20 Palmer, A. R. and Hoffman, M. T.: Nama-Karoo, in: Vegetation of Southern Africa, edited by: Cowling, R. M., Richardson, D. M., and Pierce, S. M., Cambridge University Press, Cambridge, 167–188, 1997.

Partridge, T. C., Demenocal, P. B., Lorentz, S. A., Paiker, M. J., and Vogel, J. C.: Orbital forcing of climate over South Africa: A 200,000-year rainfall record from the pretoria saltpan, *Quaternary Sci. Rev.*, 16, 1125–1133, doi:10.1016/S0277-3791(97)00005-X, 1997.

25 Peeters, F. J. C., Acheson, R., Brummer, G.-J. A., de Ruijter, W. P. M., Schneider, R. R., Ganssen, G. M., Ufkes, E., and Kroon, D.: Vigorous exchange between the Indian and Atlantic oceans at the end of the past five glacial periods, *Nature*, 430, 661–665, doi:10.1038/nature02785, 2004.

30 Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J.-M., Basile, I., Bender, M., and Chappellaz, J.: Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica, *Nature*, 399, 429–436, 1999.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Pichevin, L., Martinez, P., Bertrand, P., Schneider, R., Giraudeau, J., and Emeis, K.: Nitrogen cycling on the Namibian shelf and slope over the last two climatic cycles: Local and global forcings, *Paleoceanography*, 20, PA2006, doi:10.1029/2004pa001001, 2005.

Rogers, J. and Rau, A. J.: Surficial sediments of the wave-dominated Orange River Delta and the adjacent continental margin off south-western Africa, *Afr. J. Mar. Sci.*, 28, 511–524, doi:10.2989/18142320609504202, 2006.

Ruddiman, W. F.: Orbital changes and climate, *Quaternary Sci. Rev.*, 25, 3092–3112, 2006.

Rutherford, M. C.: Categorization of biomes, in: *Vegetation of Southern Africa*, edited by: Cowling, R. M., Richardson, D. M., and Pierce, S. M., Cambridge University Press, Cambridge, UK, 1997.

Sanchez Goñi, M. F. and Harrison, S. P.: Millennial-scale climate variability and vegetation changes during the Last Glacial: Concepts and terminology, *Quaternary Sci. Rev.*, 29, 2823–2827, 2010.

Scholes, R. J.: Savanna, in: *Vegetation of Southern Africa*, edited by: Cowling, R. M., Richardson, D. M., and Pierce, S. M., Cambridge University Press, Cambridge, UK, 258–277, 1997.

Scott, L.: Late Quaternary fossil pollen grains from the Transvaal, South Africa, *Rev. Palaeobot. Palynol.*, 36, 241–268, 1982.

Scott, L., Marais, E., and Brook, G. A.: Fossil hyrax dung and evidence of Late Pleistocene and Holocene vegetation types in the Namib Desert, *J. Quaternary Sci.*, 19, 829–832, doi:10.1002/jqs.870, 2004.

Scott, L., Neumann, F. H., Brook, G. A., Bousman, C. B., Norström, E., and Metwally, A. A.: Terrestrial fossil-pollen evidence of climate change during the last 26 thousand years in Southern Africa, *Quaternary Sci. Rev.*, 32, 100–118, doi:10.1016/j.quascirev.2011.11.010, 2012.

Shi, N., Dupont, L. M., Beug, H.-J., and Schneider, R.: Correlation between Vegetation in South-western Africa and Oceanic Upwelling in the Past 21,000 Years, *Quaternary Res.*, 54, 72–80, doi:10.1006/qres.2000.2145, 2000.

Shi, N., Schneider, R., Beug, H.-J., and Dupont, L. M.: Southeast trade wind variations during the last 135 kyr: evidence from pollen spectra in eastern South Atlantic sediments, *Earth Planet. Sc. Lett.*, 187, 311–321, doi:10.1016/s0012-821x(01)00267-9, 2001.

Southon, J., Kashgarian, M., Fontugne, M., Metivier, B., and Yim, W. W.-S.: Marine reservoir corrections for the Indian Ocean and Southeast Asia, *Radiocarbon* 44, 167–180, 2002.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

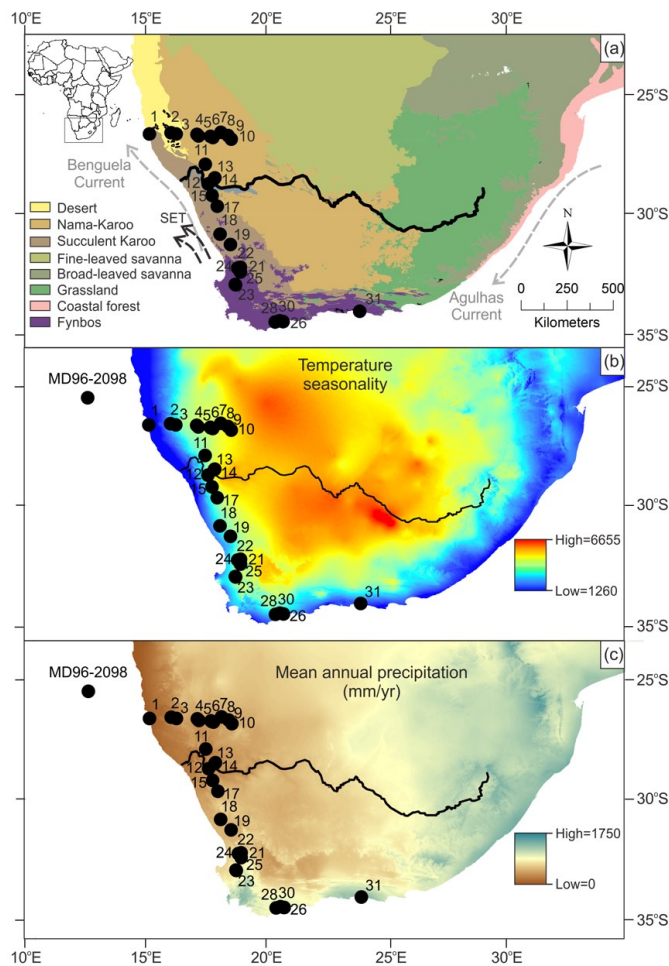
Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Stuiver, M. and Reimer, P. J.: Extended ^{14}C database and revised CALIB radiocarbon calibration program, *Radiocarbon*, 35, 215–230, 1993.
- Stuut, J.-B. W. and Lamy, F.: Climate variability at the southern boundaries of the Namib (south-western Africa) and Atacama (northern Chile) coastal deserts during the last 120,000 yr, *Quaternary Res.*, 62, 301–309, doi:10.1016/j.yqres.2004.08.001, 2004.
- Stuut, J.-B. W., Prins, M. A., Schneider, R. R., Weltje, G. J., Jansen, J. H. F., and Postma, G.: A 300-kyr record of aridity and wind strength in southwestern Africa: inferences from grain-size distributions of sediments on Walvis Ridge, SE Atlantic, *Mar. Geol.*, 180, 221–233, doi:10.1016/s0025-3227(01)00215-8, 2002.
- Toggweiler, J. R. and Russell, J.: Ocean circulation in a warming climate, *Nature*, 451, 286–288, 2008.
- Tyson, P. D.: Atmospheric circulation changes and palaeoclimates of southern Africa, *S. Afr. J. Sci.*, 95, 194–201, 1999.
- Tyson, P. D. and Preston-Whyte, R. A.: The weather and climate of southern Africa, Oxford University Press Southern Africa, Cape Town, 396 pp., 2000.
- Waelbroeck, C., Frank, N., Jouzel, J., Parrenin, F., Masson-Delmotte, V., and Genty, D.: Transferring radiometric dating of the last interglacial sea level high stand to marine and ice core records, *Earth Planet. Sc. Lett.*, 265, 183–194, 2008.
- White, F.: The vegetation of Africa: a descriptive memoir to accompany the Unesco/AETFAT/UNSO vegetation map of Africa, Paris, 1–356, 1983.



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Fig. 1. (a) Map of biomes of southern Africa based on Mucina et al. (2007) and modified using the savanna classification by Scholes (1997). The broad-leaved savanna distribution includes the Mopane and mixed savannas described by Scholes (1997). Location of the Orange River oceanic currents (grey arrows) and southeastern trade winds (black arrows). Temperature seasonality **(b)** and annual precipitation in mm yr⁻¹ **(c)** extracted from the WorldClim dataset (Hijmans et al., 2005). Black dots indicate location of marine core MD96-2098 and numbers indicate the location of surface sample collection points described in Table 1 in the Supplement.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

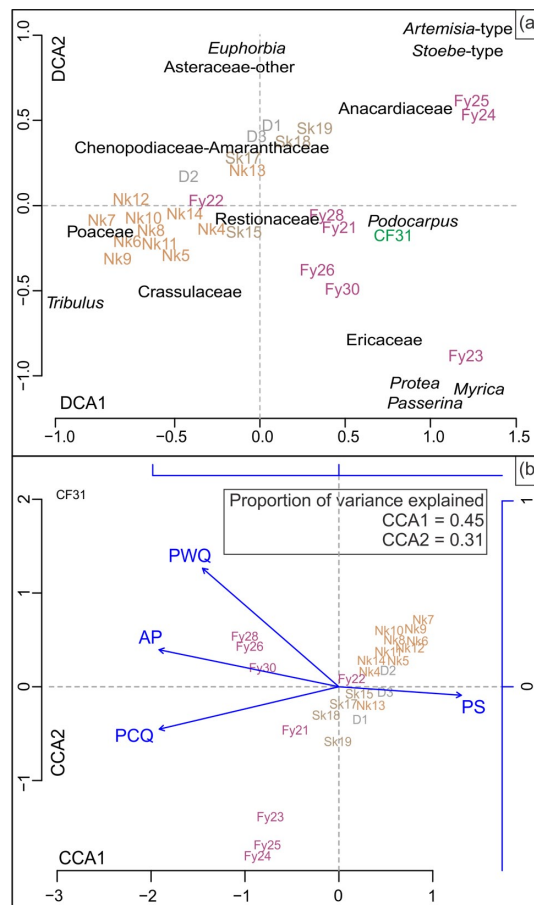


Fig. 2. (a) Detrended correspondence analysis summarizing changes in pollen spectra from surface samples collected in southwestern Africa. Sample labels indicate sample numbers and letters indicate biomes where samples were collected: D: Desert, Nk: Nama-Karoo, Sk: Succulent-Karoo Fy: Fynbos, CF: coastal forest. Rescaled species scores are shown for the 15 most abundant pollen taxa. **(b)** Canonical correspondence analysis (CCA) summarizing changes in pollen spectra from surface samples and precipitation bioclimatic variables extracted for individual collection points from the WorldClim dataset (Hijmans et al., 2005). PCQ: coldest quarter precipitation, PS: precipitation seasonality, AP: annual precipitation, PWQ: warmest quarter precipitation.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

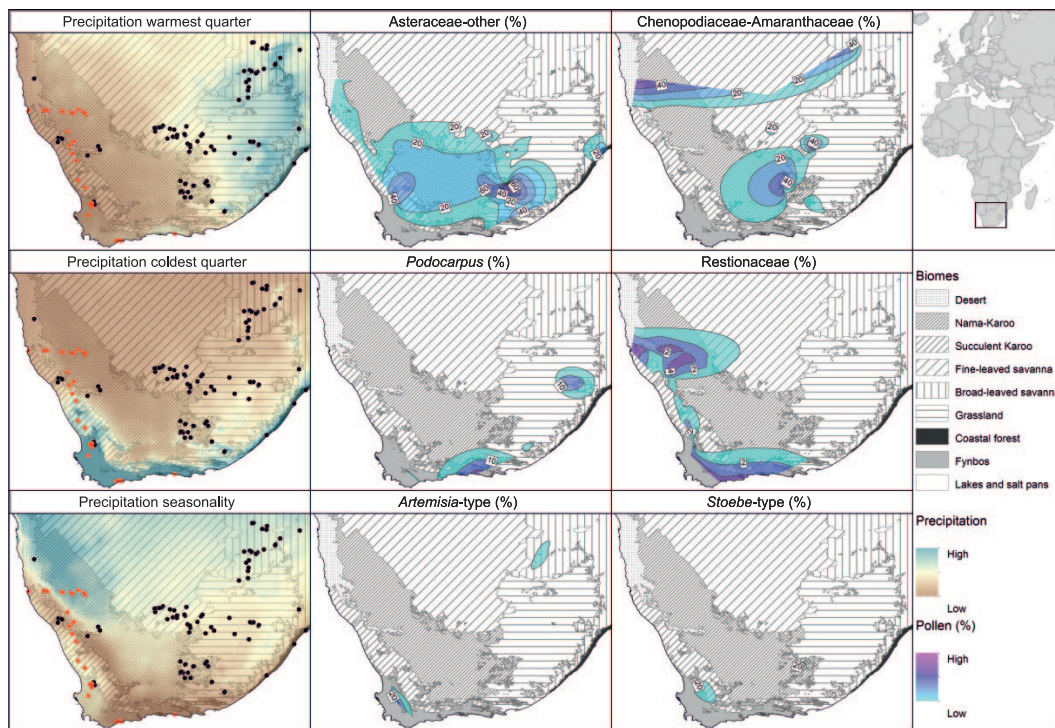


Fig. 3. Bioclimatic variables and pollen percentage iso-lines drawn over biome units of southern Africa (modified from Scholes, 1997; Mucina et al., 2007). The broad-leaved savanna distribution includes the Mopane and mixed savannas described by Scholes (1997). Iso-lines are plotted based on pollen percentage data from surface samples analysed in this study (red dots) and pollen spectra from other samples previously published and extracted from the African Pollen Database (black dots) (Gajewski et al., 2002). Numbers and lines represent pollen percentages and are shown for taxa discussed in the text: Asteraceae-other, Chenopodiaceae-Amaranthaceae, *Podocarpus*, Restionaceae, *Artemisia*-type, and *Stoebe*-type.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Increased aridity in southwestern Africa

D. H. Urrego et al.

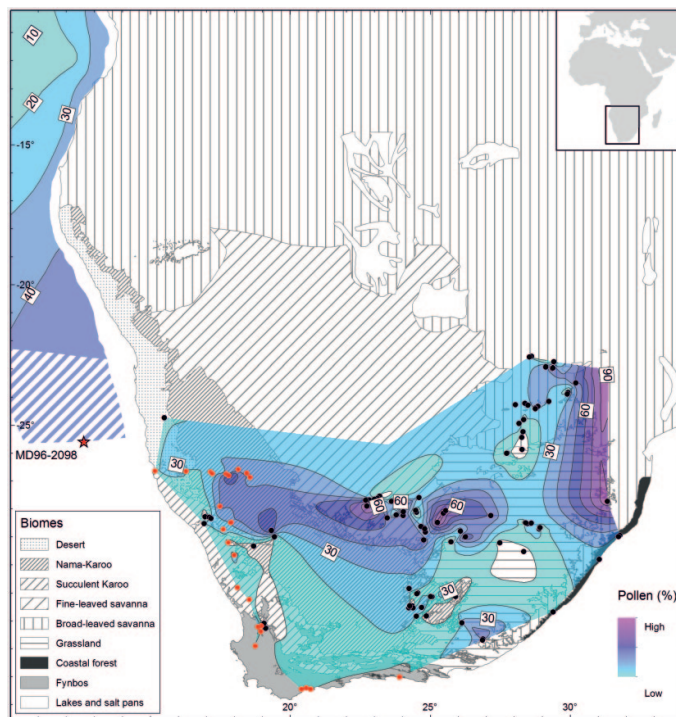


Fig. 4. Poaceae pollen percentage iso-lines drawn over biome units of southern Africa (modified from Scholes, 1997; Mucina et al., 2007). The broad-leaved savanna distribution includes the Mopane and mixed savannas described by Scholes (1997). Iso-lines are plotted based on pollen percentage data from surface samples analysed in this study (red dots) and pollen spectra from other samples previously published and extracted from the African Pollen Database (black dots) (Gajewski et al., 2002). Poaceae pollen percentage in the marine domain are redrawn from Dupont and Wyputt (2003) and extended beyond latitude 25° S using two MD96-2098 core-top samples (hatched).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

I◀

▶I

◀

▶

Back

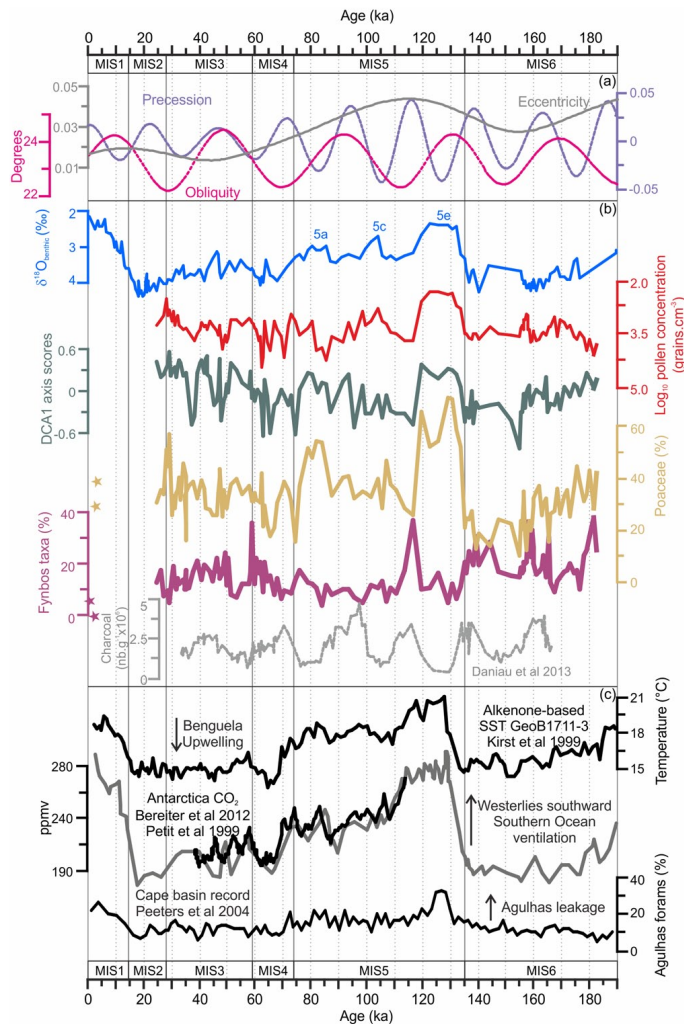
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





CPD

9, 4323–4363, 2013

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Fig. 5. Comparison of terrestrial, atmospheric and oceanic markers for southern Africa between 190 and 24.7 ka. **(a)** Orbital parameters plotted for latitude 25°36' S using La2004 (Laskar et al., 2004). **(b)** Stable Oxygen profile of benthic foraminifera *Cibicidoides wuellerstorfi* (Bertrand et al., 2002), log-transformed total pollen concentration, detrended correspondence analysis Axis1 scores, pollen percentages of indicator taxa for Nama-Karoo and fine-leaved savanna (Poaceae) and Fynbos (*Artemisia*-type, Ericaceae, Passerina, *Protea*, and *Stoebe*-type) and charcoal concentrations in number of particles per gram (nb g^{-1}) all from marine core MD96-2098 and plotted against age in ka (thousands of calibrated/calendar years before present). Stars on the left correspond to percentage of pollen taxa in two top-core samples dating 530 and 1060 calibrated years before present. **(c)** Independent climatic records discussed in the text. Stage boundary ages for 3/2, 4/3, and 5/4 from Sanchez Goñi and Harrison (2010) and 6/5 from Henderson and Slowey (2000).

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Fig. 6. Schematic and simplified configuration of vegetation, atmospheric, and oceanic systems over southern Africa during **(a)** the MIS 5 warm substages, and **(b)** glacial isotopic stages. Rainfall is illustrated as the current configuration of tropical and subtropical convection systems using average austral-summer **(a)** and austral-winter **(b)** precipitation data between 1979–1995 from the International Research Institute for Climate Prediction (<http://iri.ldeo.columbia.edu>). L: tropical low-pressure systems, H: subtropical high-pressure cells, SET: southeast trade winds, SW: southern westerlies, AL: Agulhas leakage. Stars indicate the location of marine records discussed in the text and blue arrows indicate direction of migration of pressure systems.

Increased aridity in southwestern Africa

D. H. Urrego et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

