Climate of the Past

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Discussions

Supplement of

South-western Africa vegetation responses to atmospheric and oceanic changes during the last climatic cycle

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1   *Methods for surface-sample collection and analysis*

2   A total of 31 surface samples were collected along a transect from Cape Town (South Africa)

3   to Lüderitz (Namibia) during two weeks of fieldwork in February 2011. The sampling started after the

4   first rains that followed a seven-year long drought. The area extended from latitudes 26.5^o to 34.5^oS

5   and from longitudes 15° to 23.8^oE (Fig.1) and was designed to cover the four major biomes of

6   southwestern Africa (Supplementary-Table1): Desert, Fynbos, Nama- and Succulent-Karoo. Although

7   we did not conduct a vegetation survey at each sampling site, the surrounding vegetation was

8   determined based on detailed descriptions and maps of southwestern Africa biomes (Mucina et al.,

9   2007). We were also able to collect one sample in the coastal forest biome. While we did not intend

10   to characterize the pollen spectra from coastal forests, including this sample in the dataset allowed

11   increasing the variability of pollen spectra. Sediment and water samples were collected from

12   ephemeral water puddles that developed after rainy episodes and small permanent waterlogged

13   depressions where pollen deposition and preservation was likely. When we found moss attached to

14   rocks or soil, we collected pitches from several spots within a five-meter radius. As a result, our

15   sample set included 12 sediment, 8 moss, and 11 water samples (Supplementary-Table1).

16   Surface samples were concentrated down to pellets using a manual and portable centrifuge

17   in the field. Pellets were treated with standard acetolysis in the laboratory (Faegri and Iversen, 1989)

18   and residues were mounted in glycerol and scanned under the microscope at 400 and 1000x

19   magnification. Pollen sums were greater than 300 grains and spores were quantified but excluded

20   from this total. Four out of 31 surface samples had such low pollen concentration that their spectra

21   were excluded from the analysis (Supplementary-Table1).

22   We used previously published pollen spectra from 150 additional surface samples collected

23   between 22° and 35° latitude south (APD, Gajewski et al. 2002) to assess the distribution of pollen

24   percentages and potential as indicators of large biomes of seven abundant pollen taxa. These taxa

25   included *Artemisia*-type, Asteraceae-other, Chenopodiaceae-Amaranthaceae, Poaceae, *Podocarpus*,

26   Restionaceae, and *Stoebe*-type. ArcGIS 10 was used to draw iso-lines of pollen percentages by

27   interpolating values from a total of 178 surface samples through the natural neighbour method.

28   Maps of bioclimatic variables were also drawn for comparison.

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31 **Supplementary Table 1.** Description of surface samples collected in southwestern Africa and used to
32   characterize the pollen spectra of four southwestern African biomes. Sample number and codes
33   correspond to those of Fig. 1 and 2, and Supplementary Figures 2 and 3. Samples with low pollen
34   concentration were not assigned a sample code and were not included in the analyses.

| Sample number	Sample code	Latitude	Longitude	Biome	Sample type	Location
1	D1	-26.66	15.17	Desert	Sediment	Luderitz
2	D2	-26.61	16.08	Desert	Water	Namibia semi-desert
3	D3	-26.66	16.28	Desert	Water	Aus savanna
4	Nk4	-26.69	17.15	Nama-Karoo	Water	Buchholzbrunn
5	Nk5	-26.75	17.22	Nama-Karoo	Water	Konkiep
6	Nk6	-26.76	17.71	Nama-Karoo	Sediment	Bethanie
7	Nk7	-26.81	17.81	Nama-Karoo	Water	Seehein
8	Nk8	-26.59	18.14	Nama-Karoo	Sediment	Grunau 2
9	Nk9	-26.73	18.45	Nama-Karoo	Water	Grunau 3
10	Nk10	-26.88	18.57	Nama-Karoo	Sediment	Grunau 4
11	Nk11	-27.92	17.49	Nama-Karoo	Sediment	Fish river canyon
12	Nk12	-28.48	17.90	Nama-Karoo	Sediment	Noodower
13	Nk13	-28.50	17.87	Nama-Karoo	Water	Namibian border
14	Nk14	-28.74	17.61	Nama-Karoo	Sediment	Orange
15	Sk15	-29.21	17.78	Succulent-Karoo	Water	Namaqualand 23
16	-	-29.20	17.78	Succulent-Karoo	Sediment	Swart Doring
0.	Sk17	-29.66	18.00	Succulent-Karoo	Moss	Goegab
18	Sk18	-30.82	18.12	Succulent-Karoo	Sediment	Olifant mouth
19	Sk19	-31.25	18.54	Succulent-Karoo	Moss	Namaqualand
20	-	-31.50	18.31	Succulent-Karoo	Water	Olifant river
21	Fy21	-32.19	18.96	Fynbos	Moss	Cederberg
22	Fy22	-32.23	18.85	Fynbos	Sediment	Typha swamp
23	Fy23	-32.39	18.95	Fynbos	Moss	Citrusdal
24	Fy24	-32.91	18.75	Fynbos	Moss	Piketberg 2
25	Fy25	-32.91	18.75	Fynbos	Moss	Piketberg 1
26	Fy26	-34.41	20.57	Fynbos	Sediment	De Hoop East
27	-	-34.49	20.39	Fynbos	Water	De Hoop reserve
28	Fy28	-34.45	20.40	Fynbos	Moss	De Hoop reserve
29	-	-34.30	20.31	Fynbos	Water	Bree river
30	Fy30	-34.45	20.73	Fynbos	Sediment	Klipdrift river
31	CF31	-34.02	23.90	Coastal forest	Moss	Tsitsikamma-Stormriver

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Supplementary Table 2. Chronological control for marine core MD96-2098 based on unpublished
Accelerator Mass Spectrometer radiocarbon dates (AMS[14]C) and marine isotope events (MIE)
identified in the δ^{18}O record from the record of benthic foraminifera *Cibicidoides wuellerstorfi*
(Pichevin et al., 2005a; Pichevin et al., 2005b). Calibration details and sources for MIE ages are
also shown.

Uncorrected depth (cm)	Corrected depth[1] (cm)	Sample code	AMS[14]C age/MIE	95.4% (2s) cal age ranges[2]/calendar age (yr BP)	Calibration data[3]/ Source for MIE age
22.5	22.5	SacA 24476	2850±30	2310-2490	Hughen et al. (2004)
65	65	SacA 23251	6105±30	6280-6430	Hughen et al. (2004)
100	100	SacA 26970	8495±40	8750-9020	Hughen et al. (2004)
150	150	SacA 24477	10775±40	11,730-12,080	Hughen et al. (2004)
200	200	SacA 26971	13970±60	16,050-16,860	Hughen et al. (2004)
241	241	SacA 23252	15300±50	17,650-18,070	Hughen et al. (2004)
275	275	SacA 26972	15880±50	18,230-18,290	Hughen et al. (2004)
331	331	SacA 23253	18010±60	20,420-21,220	Hughen et al. (2004)
430.5	430.5	SacA 26973	19150±70	21,850-21,930	Hughen et al. (2004)
481	481	SacA 24478	24200±120	27,990-28,710	Hughen et al. (2004)
561	561	SacA 24479	28890±180	31,910-33,230	Hughen et al. (2004)
601	601	SacA 26974	31870±240	35,130-36,450	Hughen et al. (2004)
647	647	SacA 24480	30430±210*	33,960-34,990	Hughen et al. (2004)
719	704	SacA 23254	40010±520	42,740-44,410	Hughen et al. (2004)
740	725		3.3	46,000	Lisiecki and Raymo (2005)
970	807		3.31	51,000	Lisiecki and Raymo (2005)
1000	837		4	57,000	Lisiecki and Raymo (2005)
1120	957		4.23	64,000	Lisiecki and Raymo (2005)
1195	1032		MIS 5/4	73,500	Sanchez Goñi and Harrison (2010)
1250	1087		5.1	82,000	Lisiecki and Raymo (2005)
1280	1117		5.2	87,000	Lisiecki and Raymo (2005)
1360	1197		5.3	103,800	Drysdale et al. (2007)
1400	1237		5.4	110,400	Drysdale et al. (2007)
1460	1297		Onset of MIS 5	129,000	Masson-Delmotte et al. (2010), Waelbroeck et al. (2008)
1500	1337		MIS 6/5	135,000	Henderson and Slowey (2000)
1560	1397		6.2	140,000	Lisiecki and Raymo (2005)
1600	1437		6.3	155,000	Lisiecki and Raymo (2005)
1730	1567		6.4	160,000	Lisiecki and Raymo (2005)
1800	1637		6.41	166,000	Lisiecki and Raymo (2005)
2020	1857		7.1	192,000	Lisiecki and Raymo (2005)

[1]Corrected depth for gaps reported in stratigraphic log; [2]rounded up to nearest 10 yr; [3]Marine09.14c curve,
reservoir age correction = 157 (local delta R) + 400 (Global); *rejected age.
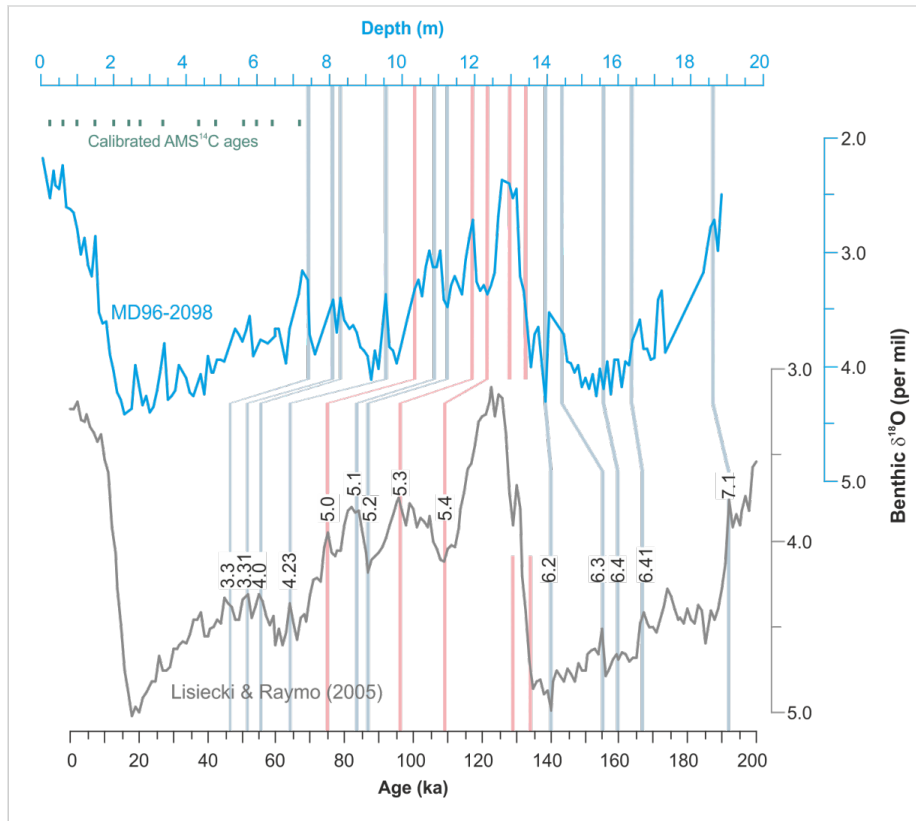
Supplementary Figure 1. Age control of core MD96-2098 based on 14 calibrated Accelerator Mass Spectrometer radiocarbon (AMS ^{14}C) ages (green dots) and 16 Marine Isotopic Events (MIE, grey and pink bars) from stable Oxygen profile of benthic foraminifera (Bertrand et al., 2002). Radiocarbon ages were calibrated using the Marine09.14c calibration (Hughen et al., 2004; Stuiver and Reimer, 2005), a delta R of 157 years, and global reservoir age of 400 years. Gray bands indicate MIE control points and ages derived from LR04 global stack (Lisiecki and Raymo, 2005). Pink bars indicate MIE ages derived from other chronologies: (Sanchez Goñi and Harrison, 2010), (Drysdale et al., 2007), (Masson-Delmotte et al., 2010; Waelbroeck et al., 2008), (Henderson and Slowey, 2000).
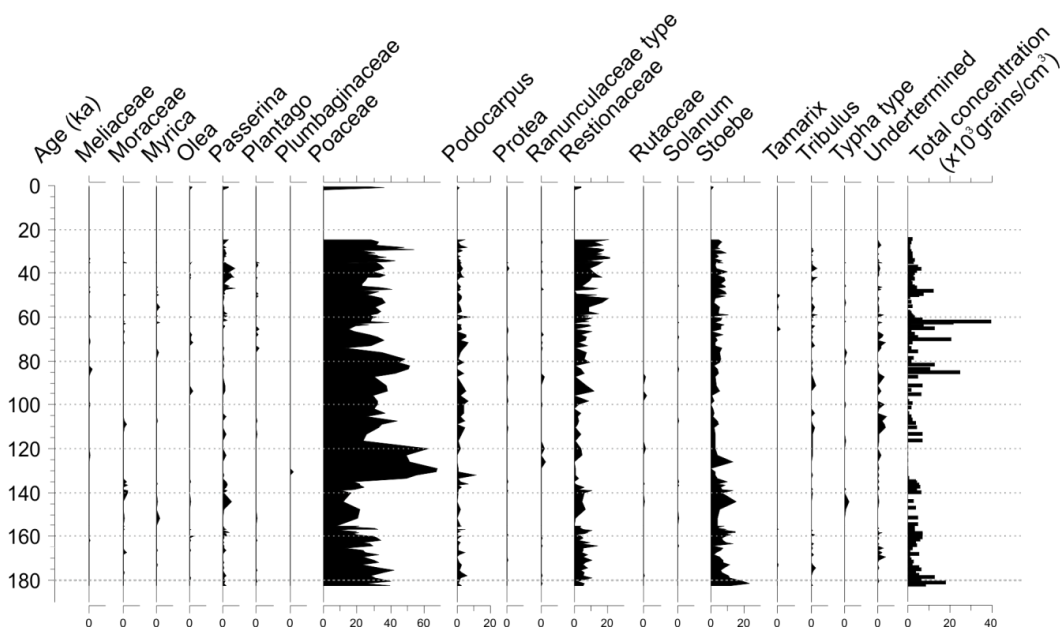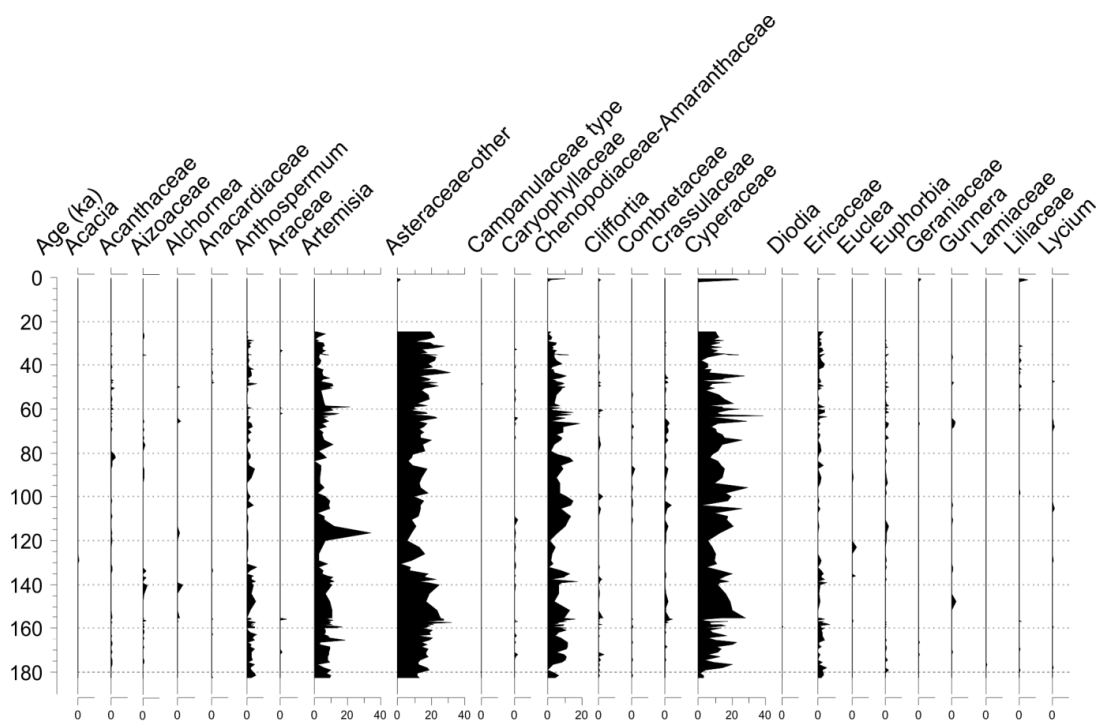
Supplementary Figure 2. Complete pollen record and total pollen concentrations from MD96-2098. Percentages from the following families group more than one morphotype: Acanthaceae, Aizoaceae, Anacardiaceae, Asteraceae-other, Chenopodiaceae-Amaranthaceae, Crassulaceae, Cyperaceae, Ericaceae, Liliacaee, and Restionaceae.
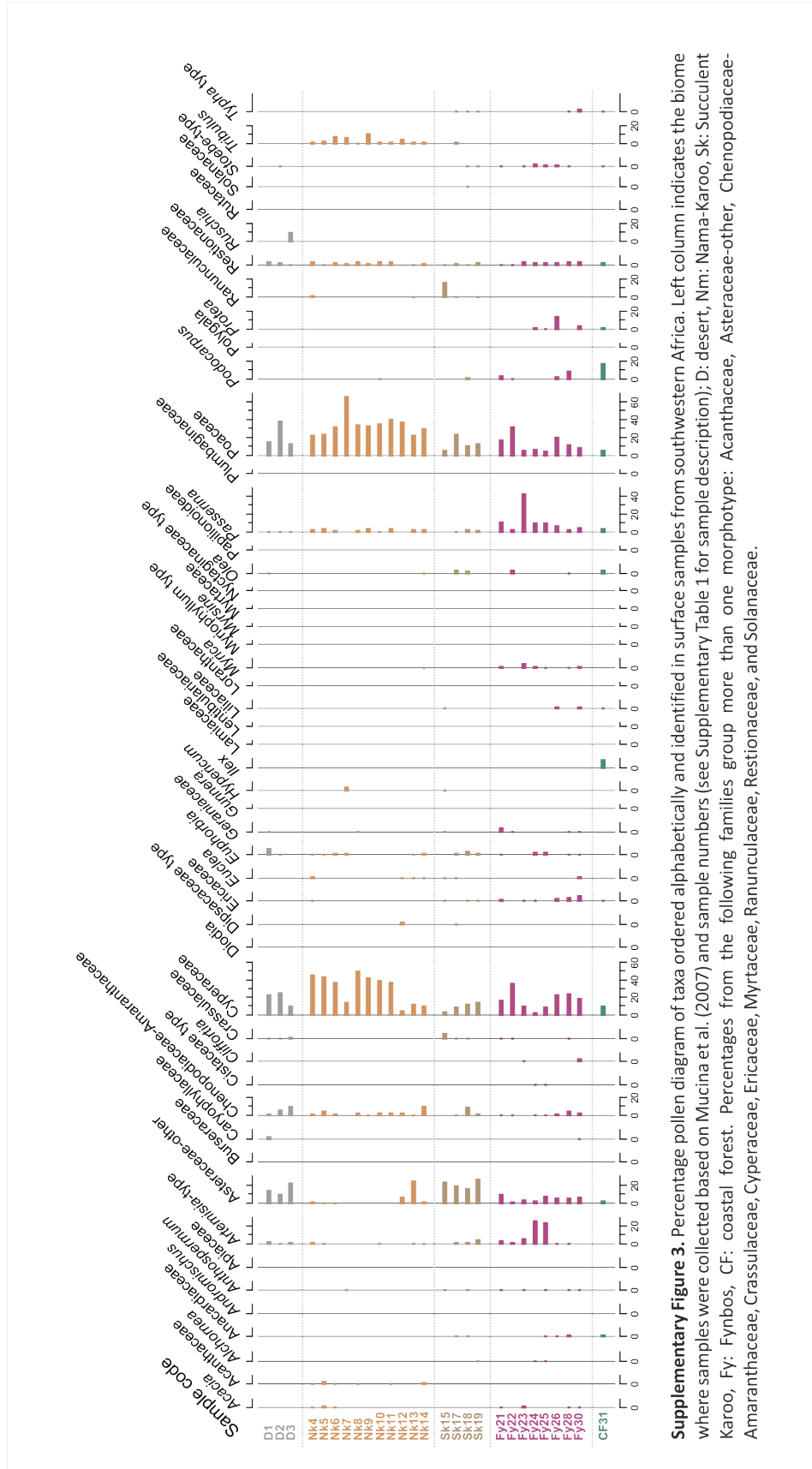
63 ***Present-day pollen-vegetation-climate relationships in southern Africa***

64   Asteraceae-other, Chenopodiaceae-Amaranthaceae, Poaceae and Restionaceae add up to

65 80% of the pollen sums and are found in all surface samples (Supplementary-Fig.3). Cyperaceae

66 pollen is also found in all but one of our surface samples. High Cyperaceae percentages are observed

67 in samples collected from permanent small, waterlogged depressions or along rivers. As a result, we

68 excluded Cyperaceae pollen percentages from ordination analyses.

69   We decided to include the grasses (Poaceae) in our pollen calibration analysis because they

70 are important components of the southern African vegetation, and not just concentrated around

71 wet areas. Grasses are an incredibly successful group of plants that can be found in many vegetation

72 types around the world, and southern Africa is not an exception. Numerous works on the

73 composition of semi-desert vegetation support this assertion. For instance, Born et al. (2007) reports

74 that the Karoo Region can be distinguished from the other regions by the high proportion of grasses

75 (Poaceae). Cowling and Hilton-Taylor (2009) also describe grasses as being one of the 10 top most

76 abundant families in the Namib-Karoo region. Additionally, Jurgens et al. (1997) reports on the

77 abundance of perennial grasses growing on dunes in the Namibian desert, and Desmet (2007)

78 highlights the dominance of grasses on sandy soils on the Karoo. Our field observations also support

79 this view as we observed large grass-dominated vegetation in the Nama-Karoo areas of southern

80 Africa (Fig.2).

81   In the surface samples collected in the Desert, Asteraceae-other percentages are up to 20%

82 and Chenopodiaceae-Amaranthaceae percentages are less than 10%. Poaceae and Cyperaceae show

83 up to 45% and between 50 and 60%, respectively. The source of Poaceae, Asteraceae-other and

84 Chenopodiaceae-Amaranthaceae pollen in the Desert can be perennial grasses growing on dunes

85 (Jurgens et al., 1997). Our results show that pollen spectra from the Desert are more similar to

86 spectra from the Succulent-Karoo than to any other biome (Supplementary-Fig.4), suggesting that

87 Desert surface samples receive pollen from Succulent-Karoo transitional patches.

Supplementary Figure 3. Percentage pollen diagram of taxa ordered alphabetically and identified in surface samples from southwestern Africa. Left column indicates the biome where samples were collected based on Mucina et al. (2007) and sample numbers (see Supplementary Table 1 for sample description); D: desert, Nm: Nama-Karoo, Sk: Succulent Karoo, Fy: Fynbos, CF: coastal forest. Percentages from the following families group more than one morphotype: Acanthaceae, Asteraceae-other, Chenopodiaceae-Amaranthaceae, Crassulaceae, Cyperaceae, Ericaceae, Myrtaceae, Ranunculaceae, Restionaceae, and Solanaceae.

89   In the Nama-Karoo surface samples, Poaceae pollen reaches percentages up to 60%

90   (Supplementary-Fig.3). Asteraceae-other pollen percentages are null in northern samples but

91   increase to 20% in samples collected near the Succulent-Karoo. Chenopodiaceae-Amaranthaceae

92   pollen percentages are up to 10%. *Tribulus* and Acanthaceae pollen are only found in the Nama-

93   Karoo samples and reach up to 12%, consistent with their abundance in the vegetation source. On

94   the other hand, Crassulaceae and *Euphorbia* pollen occur at low percentages in samples from Nama-

95   Karoo despite having been described as common in the vegetation (Honig et al., 1992). The pollen

96   spectra from samples collected in the Nama-Karoo form a tight cluster in the DCA ordination and are

97   clearly separated from samples from other biomes (Supplementary-Fig.4).

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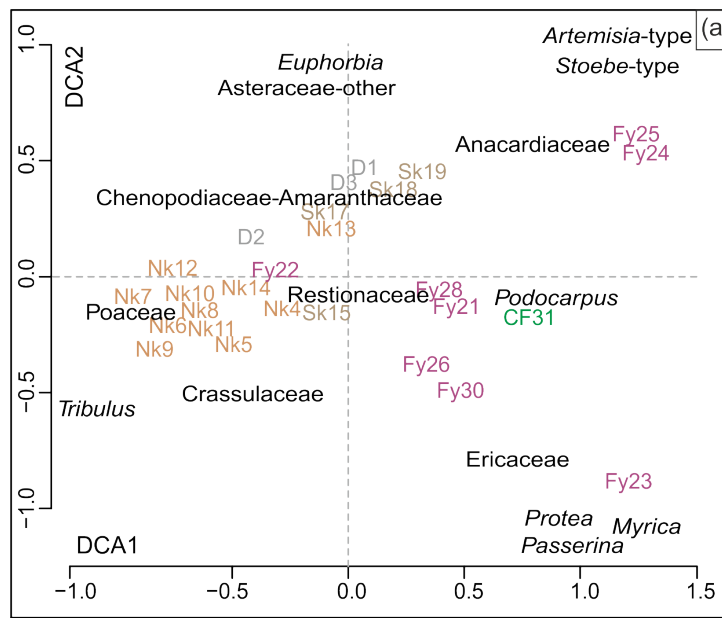
100   **Supplementary Figure 4.** Detrended correspondence analysis summarizing changes in pollen spectra
101   from surface samples collected in southwestern Africa. Sample labels indicate sample
102   numbers and letters indicate biomes where samples were collected: D: Desert, Nk: Nama-
103   Karoo, Sk: Succulent-Karoo Fy: Fynbos, CF: coastal forest. Rescaled species scores are
104   shown for the 15 most abundant pollen taxa.

105

106   Surface samples collected in the Succulent-Karoo are characterized by pollen percentages of

107   Asteraceae-other up to 20% and Poaceae between 15 and 20% (Supplementary-Fig.3). This result

108   corresponds with the abundance of species from the Asteraceae family in this biome, and the

109   relatively less abundance of C4 grasses compared to the Nama-Karoo (Cowling and Hilton-Taylor,

110   2009). Small percentages of *Olea* and *Podocarpus* also found in the pollen spectra of the Succulent-

111   Karoo could be the result of long-distance wind transport. The DCA ordination groups the Succulent-

112   Karoo pollen spectra near Desert samples, and this clustering is constrained by Asteraceae-other,

113   *Euphorbia* and Chenopodiaceae-Amaranthaceae (Supplementary-Fig.4).

114   In surface samples collected within the Fynbos biome, Anacardiaceae, *Anthospermum*,

115   *Artemisia*-type, Ericaceae, *Passerina*, *Protea* and *Stoebe*-type reach highest percentages

116   (Supplementary-Fig.3). These pollen abundances reflect well the composition of the vegetation

117   source described by (Cowling et al., 1997a), as species of Ericaceae, *Passerina* and *Protea* are

118   particularly characteristic of the Fynbos biome. Up to 10% *Podocarpus* pollen percentages found in

119   the Fynbos likely originate from small forest patches within the area. Poaceae pollen percentages

120   are below 20% in the Fynbos and in the coastal forest sample. *Ilex* pollen is found in the sample from

121   the coastal forest at approximately 5% and *Podocarpus* pollen is up to 18%, consistent with their

122   abundance in the vegetation source. Except for sample Fy22, the composition of pollen spectra from

123   the Fynbos biome in the DCA ordination is clearly distinguished from pollen spectra from other

124   biomes (Supplementary-Fig.4). The classification of sample Fy22 near samples from the Nama-Karoo

125   likely results from the relatively high abundance of Poaceae pollen in Fy22 compared to other

126   Fynbos samples (Supplementary-Fig.3).

127   Some individual taxa are associated with the clustering of pollen spectra from the SWAfr

128   biomes in the DCA ordination (Supplementary-Fig.4), suggesting their potential as indicators of

129   specific biomes. For instance, Poaceae, Crassulaceae and *Tribulus* obtain the highest loadings to

130   classify the pollen spectra from the Nama-Karoo. Asteraceae-other, Chenopodiaceae-

131   Amaranthaceae and *Euphorbia* are important in the Succulent-Karoo and Desert. Pollen taxa that

132   characterize the Fynbos pollen spectra include Anacardiaceae, *Artemisia*-type, Ericaceae, *Myrica*,

133   *Passerina*, *Protea*, *Stoebe*-type. *Podocarpus* characterizes the pollen spectra from coastal forests and

134   Fynbos biomes.

135   Pollen percentage iso-lines drawn for six of the most abundant taxa in southern Africa are

136   shown in Supplementary-Fig.5. These six taxa are also abundant both in terrestrial and marine pollen

137   sequences (Dupont, 2011; Scott et al., 2012) and can therefore be valuable for the interpretation of

138   fossil pollen records. The pollen iso-lines of Asteraceae-other show 25% near the transition of the

139   Nama-Karoo and the Grassland, and 20% in part of the Succulent-Karoo (Supplementary-Fig.5).

140   Chenopodiaceae-Amaranthaceae pollen percentages are as high as 35% in the Nama-Karoo and are

141   also found up to 50% in a relatively small area of the Desert. This pollen distribution indicates that

142   Chenopodiaceae-Amaranthaceae and Asteraceae-other high pollen percentages can be

143   characteristic of the Succulent-Karoo, Nama-Karoo and Desert biomes of southwestern Africa.
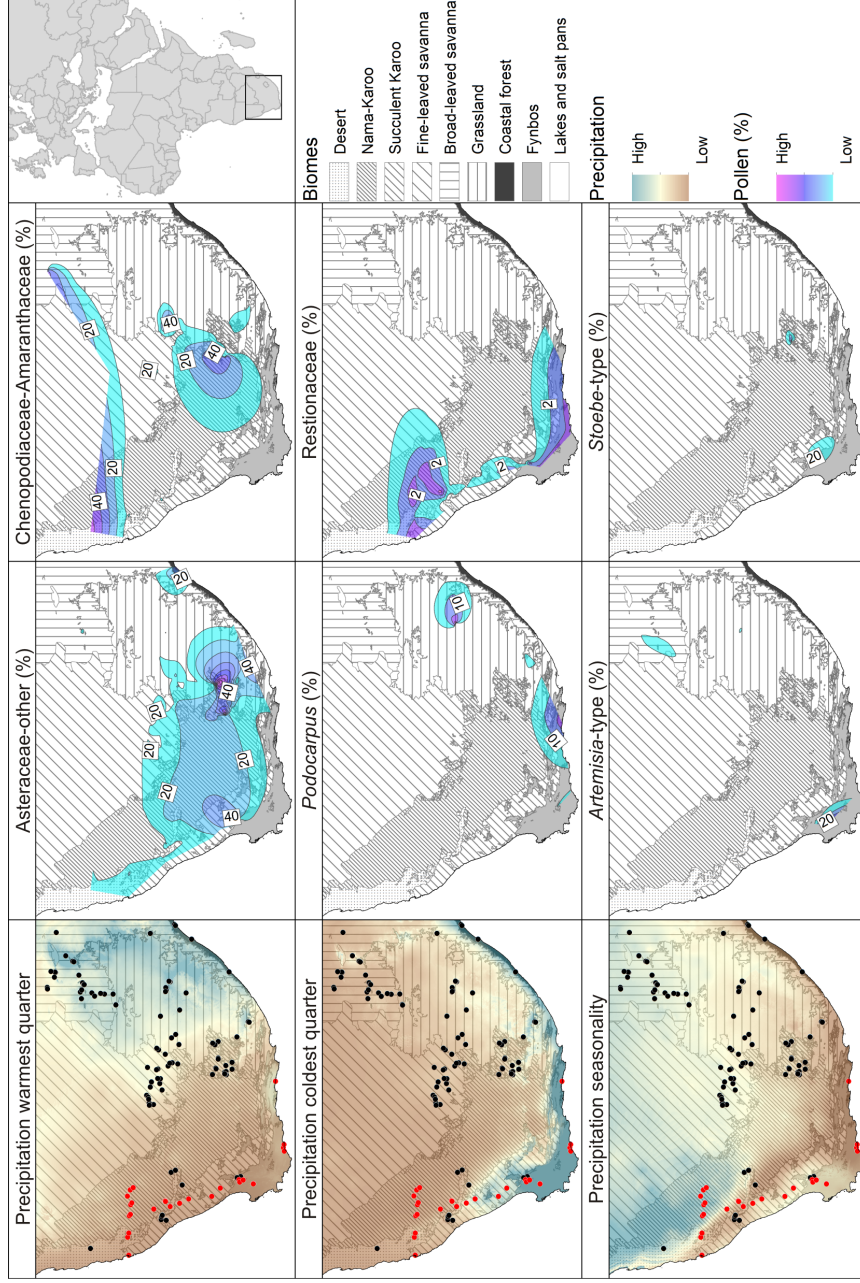
Supplementary Figure 5. Bioclimatic variables and pollen percentage iso-lines drawn over biome units of southern Africa (modified from Scholes (1997); Mucina et al. (2007)). The broad-leaved savanna distribution includes the Mopane and mixed savannas described by Scholes (1997). Iso-lines are plotted 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.

151

152   *Podocarpus* pollen percentages in surface samples from southern Africa show a localized

153   pattern in areas with high precipitation, namely coastal forest and in the eastern part of the Fynbos

154   biome (Supplementary-Fig.5). Consistently, (Gajewski et al., 2002) reports maxima of *Podocarpus*

155   pollen percentages in African regions where precipitation is at least 1000 mm per year.

156   Restionaceae plants are found mostly in the Fynbos biome (Cowling et al., 1997b) and its

157   pollen has been used as a Fynbos indicator (Shi et al., 2001). However, the distribution of its pollen

158   in our surface samples is only partly related to the distribution of the Fynbos biome (less than 5%)

159   (Supplementary-Fig.5). Up to 5% of Restionaceae pollen is found in surface samples from the Nama-

160   Karoo, Succulent-Karoo and the Desert (Supplementary-Fig.5). Restionaceae are wind pollinated

161   (Honig et al., 1992),suggesting that these pollen grains are the result of long-distance transport.

162   (Fig.1). Due to this inconsistency between the vegetation source and the spatial distribution of

163   Restionaceae pollen, it would be difficult to discern whether increases in Restionaceae pollen in

164   palaeoenvironmental reconstructions are the result of wind strengthening or due to Fynbos

165   vegetation expansions without an independent wind tracer.

166   The distribution of pollen percentages from *Artemisia*-type and *Stoebe*-type are

167   concentrated in the Fynbos biome (Supplementary-Fig.5), and are positively correlated with PCQ

168   (Supplementary-Fig.4). Pollen signals from *Artemisia*-type and *Stoebe*-type, along with other taxa

169   characteristic of the Fynbos vegetation (i.e. Ericaceae, *Protea* and *Passerina* Supplementary-Fig.3)

170   might therefore be good tracers for past expansions of the biome.

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