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Climate of the Past Discussions

Precipitation variability in the winter rainfall zone of South Africa during the last 1400 yr linked to the austral westerlies

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Abstract

The austral westerlies strongly influence precipitation and ocean circulation in the southern temperate zone, with important consequences for cultures and ecosystems. Global climate models anticipate poleward contraction of the austral westerlies with future warming, but the available paleoclimate records that might test these models have been largely limited to South America, are not fully consistent with each other, and may be complicated by influences from other climatic factors. Here we present the first fine-interval diatom and sedimentological records from the winter rainfall region of South Africa, representing precipitation during the last 1400 yr. Inferred rainfall increased ∼1400–1200 cal yr BP and most notably during the Little Ice Age with pulses centered on ∼600, 530, 470, 330, 200, and 90 cal yr BP. Synchronous fluctuations in Antarctic ice core chemistry strongly suggest that these variations are linked to changes in the westerlies. Partial inconsistencies among South African and South American records warn against the simplistic application of local-scale histories to the Southern Hemisphere as a whole. Nonetheless, these findings in general do support model projections of increasing aridity in austral winter rainfall zones with future warming.

1 Introduction

Winter storms borne on the austral westerlies are a major source of precipitation over the southernmost sectors of Africa, Australia-New Zealand, and South America, and intensification and/or equatorward migration of the northern margin of the westerlies tends to increase rainfall in those regions on both seasonal (winter) and millennial time scales (Shulmeister et al., 2004; Reason and Rouault, 2005). Many climate models suggest that the westerlies will contract poleward in response to anthropogenic warming during this century (Boko et al., 2007; Toggweiller, 2008), a trend that has already been observed in recent decades as a result of both warming and ozone depletion (Biastoch et al., 2008, 2009; Dixon et al., 2011). As a result, aridity is expected to increase in the southern winter rainfall zones (WRZ), with potentially serious consequences for centers of endemism, fire frequency, agriculture, and public water resources (Turpie et al., 2002; Thomas et al., 2004; Meadows, 2006).

In addition, because the warm, salty Agulhas Current flows westward in a narrow zone along the South African coast, resistance to Agulhas through-flow from the Indian Ocean to the South Atlantic increases (decreases) when the northern margins of the westerlies shift equatorward (poleward) in winter (summer) (Biastoch et al., 2008, 2009; Chase and Meadows, 2007). Therefore, latitudinal shifts in the westerlies can also influence a critical choke point in the meridional overturning circulation system (MOC) and affect salinity and sea surface temperatures in the Atlantic and Indian Ocean basins (Biastoch et al., 2008, 2009).

Because global-scale warming in the future is expected to cause poleward contraction of the westerlies and aridity in the associated WRZs, widespread cooling might therefore be expected to have produced the opposite changes during the Little Ice Age (LIA, ∼AD 1400–1800; Mayewski et al., 2004). Despite the climatic and oceanographic importance of the westerlies, however, their late Holocene history is largely unknown outside of mid-latitude South America. Several records of variable temporal resolution indicate wetter conditions in and around Patagonia that were presumably related to the westerlies during the LIA (Jenny et al., 2002; Lamy et al., 2001, 2010; Elbert et al., 2011), but discrepancies among these records as well as the possible influences of additional factors such as topography or the El Niño/Southern Oscillation system (ENSO) still leave certain aspects of their climatic history unresolved. Information from other sectors of the Southern Hemisphere are therefore needed to determine how accurately these records reflect hemisphere-scale changes in the westerlies rather than other climatic systems or local-scale events.

Unfortunately, few records from the other temperate WRZs fully represent the last millennium, the period that is arguably most relevant to simulations of modern climates. This has also made it difficult to validate models that link past and future rainfall patterns to meridional drift of the westerlies.

We present here the first fine-interval, continuous lacustrine diatom record from the South African WRZ (Fig. 1a, b), representing decade-scale rainfall variability over the last 1400 yr. Linking these African data to the South American records helps to clarify the relative influences of the westerlies and other climatic factors on regional precipitation history. It also provides insights into possible wind-driven changes in MOC that might have occurred over that time period, with potentially far-reaching effects on sea surface temperatures (SST) and climates elsewhere. In addition, we use an ice core record from Siple Dome (Fig. 1a; Dixon et al., 2011) to show that increasing dust transport to West Antarctica by the westerlies accompanied periods of increasing wetness in the South African WRZ during the last millennium. Together, these findings support model projections of aridification in the southern WRZs that could accompany poleward contraction of the westerlies associated with future greenhouse warming.

2 Material and methods

2.1 Site description

Climatic conditions in the South African WRZ, which we define as the near-coastal region spanning the area from Cape Agulhas northwest to the Orange River (Chase and Meadows, 2007), have exceptionally clear linkages to the austral westerlies because the dominant influences on precipitation there come from frontal storm systems borne on westerly winds that strike the Cape during winter and early spring. It is only mildly influenced by the ENSO variability (Reason and Rouault, 2005; Chase and Meadows, 2007), although that influence may have increased in recent decades (Philippon et al., 2011).

Verlorenvlei, located in the Western Cape (32°19–23′ S, 18°21–27′ E; Fig. 1), is a slender, shallow (13 × 1.4 km, ~2–4 m mean depth), permanent, mesotrophic coastal lake situated in a formerly estuarine river valley whose seasonally fluctuating surface lies an average of 1 m above sea level and is separated from the Atlantic by a rocky

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sill and a narrow outlet channel (Sinclair et al., 1986). Roughly 80 % of the rainfall in the catchment (<300 mm yr^{-1}), occurs between April and September (Sinclair et al., 1986). Verlorenvlei has been isolated from the sea, apart from irregular outflows due to winter-spring flooding and minimal spillage effects of sporadic tidal or storm surge extremes, for the last 1500 yr or more (Baxter and Meadows, 1999). Salinity in the main body of the lake is low, normally <1 ppt (Sinclair et al., 1986), but lake levels fall and salinity increases due to evaporation between the dry seasons. The only sizeable tributary is the Verlorenvlei River, which drains the 1890 km^2 watershed into a marshy delta on the eastern shore (Fig. 1b).

Core VV09 (132 cm long) was collected in 2009 from 2 m water depth at the eastern end of the lake (Fig. 1c), using a single aluminum tube that was forced into the sediment by hand. Core VV07-IV (134 cm; also in aluminum tube) and gravity core VF-1 (80 cm) were collected from 2.0 and 1.5 m depths at the western end in 2007 and 2006, respectively, where the influence of sediment deposition by the Verlorenvlei River is reduced (Fig. 1c). The upper sections of VV09 and VF-1 were extruded vertically in the field in order to reduce disturbance of the most recent soft sediments. The uppermost ~8 cm of core VV07-IV were lost during collection and horizontal extrusion, an observation that was confirmed by alignment of the geochemical records of those cores (Fig. 2). In this paper, we focus on the diatom and sedimentological records of VV09 and use the other cores primarily to support the VV09 chronology.

2.2 Geochemical analyses

Subsamples for geochemical analyses were taken at 1 cm increments for each core. Organic content in the cores was estimated from weight loss on ignition (LOI) at 500 °C, and carbonate content was estimated by further combustion at 900 °C. Alignment of the %LOI and $\%CO_3$ profiles from the cores was used to document the loss of the mud-water interface from core VF7-IV (Fig. 2), and to assist in the selection of calendar ages within the 2-sigma brackets derived from AMS dates.

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2.3 Diatom analyses

Core VV09 was subsampled at variable depth intervals for diatom analysis because the age model showed that the time represented by each centimeter increased greatly with depth. Sampling at progressively wider intervals upwards in the core therefore produced more evenly spaced temporal increments in the diatom time series. Subsamples were taken every 1 cm in the lowest 50 cm of the core, every 2 cm from 36 to 82 cm, and every 4 cm in the 0–36 cm section. At least 300 valves were counted per sample. Ecological interpretations of the diatom assemblages were based upon plankton tows and surface sediment samples collected from across Africa by the first author, as well as standard literature (e.g., Gasse, 1986; Cocquyt, 1998; Bate et al., 2002).

Because water depth and salinity in this lake fluctuate considerably between rainy and dry seasons as well as from year to year, the diatom assemblages in Verlorenvlei's sediments integrate time periods of highly variable hydrology that make them unsuitable for standard quantitative water chemistry reconstructions. Because of this, and because we are most interested in qualitative changes in precipitation-evaporation (P-E) in this study, analysis was focused on the relative abundances of key taxa that most clearly represented limnological conditions indicative of paleo-rainfall regimes. Elevated percentages of tychoplanktonic to planktonic, dilute-water diatoms such as *Aulacoseira granulata* and *Nitzschia lacuum* were taken to represent periods of increased runoff and river inputs to the lake under relatively wetter climatic conditions. More salt-tolerant planktonic taxa such as *Thalassiosira* spp. and *Cyclotella meneghiniana* indicated intermediate P-E, and high percentages of littoral taxa, particularly epiphytic *Epithemia* and *Cocconeis* spp., represented low lake levels and marsh development under relatively drier conditions.

The diatom records of cores VF7-IV and VF-1 were examined in preliminary fashion in order to test the applicability of the VV09 record to the history of the lake as a whole. For this purpose, the percent abundance of *Aulacoseira* spp., the most common planktonic, dilute-water taxon, was determined in selected samples from those two cores.

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2.4 Chronology

Four AMS ages on plant matter from gravity core VF-1 were complemented by exotic pollen and ^{137}Cs activity profiles (Table 1; Fig. 3), seven AMS ages were obtained for plant remains from core VF7-IV (Table 1; Fig. 4), and four AMS ages were obtained for plant remains from core VV09 (Table 1; Fig. 5). Conversion of radiocarbon dates to 2-sigma calendar year age ranges was performed with the SHCal04 dataset in CALIB 5.0.1 (Table 1; McCormac et al., 2004). Comparison of radiocarbon age determinations on plant macrofossils to those on bulk lacustrine muds from equivalent depths in the cores indicated ancient carbon offsets of 100–300 yr, presumably due to hardwater effects and/or reworking of sediment deposits. Therefore, AMS ages of bulk sediments were not incorporated into the age models.

3 Results

3.1 Chronology

The selection of specific dates within the calibrated 2-sigma AMS age brackets on grass fragments in core VF-1 was supported by a maximum in ^{137}Cs concentrations at 13.5 cm that was taken to represent the peak of thermonuclear bomb testing in AD 1963, and by the first appearances of exotic pollen. The ages assigned to the depth intervals in which *Pinus*, *Zea*, *Quercus*, and *Casuarina* (full pollen analyses to be published elsewhere) first appeared were consistent with regional historical records of their arrival in South Africa (Neumann et al., 2008). These methods yielded a relatively smooth age-depth curve with a basal age of 685 cal yr BP (Fig. 3).

Our proposed age model for VF7-IV includes an interval of reduced sediment deposition at 80–90 cm depth (~1300–700 cal yr BP) which interrupted the otherwise smooth age-depth curve (Fig. 4). The chronology of the lowest half meter is less well supported than the younger intervals which include more ages on terrestrial plant remains

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and which overlap with records from the other cores. Bulk sediments yielded a basal age range of 2355–2705 cal yr BP, which may be offset by a century or more due to the aforementioned ancient carbon effects, but linear extrapolation from the older plant macrofossil ages intersects with the upper bound of that age range at 2676 cal yr BP (Table 1, Fig. 4). We tentatively selected 2676 cal yr BP for the basal age here but note that the last 1400 yr of the record are both more precisely dated and more relevant to this paper.

In our suggested chronology for the VV09 core, the age-depth relationship curved smoothly down to a basal age of 1400 calendar years (Fig. 5). The time intervals between diatom samples (Fig. 6) averaged 25–30 yr in the 132–100 cm interval (1400–545 cal yr BP), 10–15 yr in the 100–60 cm section (545–130 cal yr BP), and 3–10 yr in the upper 60 cm (130 to −59 cal yr BP).

3.2 Geochemistry

Most of core VV09 consisted of fine grey to brown mud in which the remains of marsh vegetation were fairly numerous. However, two intervals dating to ~1100–815 cal yr BP (121–111 cm) and ~715–350 cal yr BP (107–87 cm) were peat-rich with high %LOI and %CO_3 (Fig. 7). A band of fine, light grey mud with low %LOI and %CO_3 separated the two peat-rich sections (~815–715 cal yr BP; 111–107 cm). Organic content and %CO were also generally low in the upper meter of the core but increased in the upper half meter (the last 2 centuries).

Cores VF7-IV and VF-1 displayed similar variations, but at higher stratigraphic levels due to lower sediment accumulation rates at the western end of the lake. The inferred timing of high and low % LOI and % CO_3 episodes was similar to those in VV09, which indicates that they represented major ecological events in the lake as a whole (Fig. 7).

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3.3 Diatom records

The percentages of dilute-water diatoms in core VV09 (Figs. 6, 8c) displayed notable peaks around 615–590 cal yr BP (104–102 cm), 545–515 cal yr BP (101–98 cm), 485–440 cal yr BP (97–93 cm), 365–300 cal yr BP (89–83 cm), 240–140 cal yr BP (72–62 cm), 100–60 cal yr BP (55–46 cm), and 20 cal yr BP (30 cm). These assemblages were dominated by varieties of *Aulacoseira granulata* which forms clonal filaments whose irregular breakage may cause clumping in sample preparations that could account for some differences in the relative magnitudes of *Aulacoseira* peaks among the three sediment records. We therefore consider the timing of the pulses to be more reliable than their absolute magnitudes, and our inferences regarding rainfall fluctuations that they represent are qualitative in nature.

Percentages of planktonic taxa indicative of more brackish waters, primarily *C. meneghiniana*, were highest ~1340–1310 cal yr BP (130–128 cm) and 1220–1190 cal yr BP (126–124 cm; Fig. 8d). Percentages of epiphytic diatoms were most abundant ~1100–960 cal yr BP (122–116 cm), declining gradually thereafter (Fig. 8e).

The diatom records of cores VF7-IV and VF-1 registered peaks in % *Aulacoseira* during the last 600 yr that resembled those in the VV09 record, approximately centered on 600, 530, 470, 330, 200, 90, and 20 cal yr BP (Fig. 7d–f). Although the exact timing and magnitudes of peaks varied somewhat among the cores, this general consistency, along with similarities in the LOI and CO_3 records, supports our use of VV09 to represent the ecological history of the lake.

4 Discussion

4.1 Climatic interpretation

Humans have inhabited the Verlorenvlei region for tens of thousands of years (Mitchell, 2000), but heavy settlement and agricultural development have strongly influenced

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local vegetation and hydrology only during the last 3 centuries or so. Higher sediment accumulation rates and lower organic contents in the upper portions of the cores might in part reflect soil erosion since the early 18th century, but the decline in %LOI began long before major human impacts on the watershed occurred (Fig. 7g–i). The general increase of dilute-water diatoms and reduced %LOI suggest that increasing *P-E* and runoff during the last 600 yr have also enhanced sediment delivery to the lake, most likely due to intensification and/or northward drift of the westerlies.

High percentages of brackish-water diatoms ~1340–1190 cal yr BP (Fig. 8d) indicate moderately increased *P-E* that was sufficient to favor planktonic forms over littoral assemblages but not large enough to favor dilute-water taxa. Maximal percentages of epiphytic diatoms ~1100–960 cal yr BP (Fig. 8e), along with generally high %LOI (Fig. 7g, i) suggest encroachment of marsh on the coring site through lake level declines and/or movement of the river delta. In either case, reduced *P-E* would be a reasonable cause. Maximal percentages of dilute-water taxa indicate exceptionally wet conditions during most of the last 7 centuries, a time frame that includes the LIA. Inferred precipitation maxima occurred ~600, 530, 470, 330, 200, and 90 cal yr BP

Moderate but persistent increases in %LOI and % *Aulacoseira* during the last century might reflect cultural eutrophication of the lake rather than climatic changes (Figs. 6, 7). The water is generally turbid with phytoplankton, and cyanobacteria were at least as abundant as diatoms in tows collected by JCS in 2006 and 2009. Likely anthropogenic nutrient sources may include sediment, sewage, and/or fertilizers from residences, croplands, and ranches in the watershed.

4.2 Links to Antarctica

In order to test our assumption that the history of rainfall in South Africa's WRZ was linked to changes in the austral westerlies, we investigated ice core records of atmospheric circulation over Antarctica for evidence of synchronous fluctuations in wind patterns surrounding the south polar region. Higher non-seasalt calcium (nss-Ca) deposition at Siple Dome (Fig. 1a; 81° S, 148° W) represents increased frequency of

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northerly air mass incursions (NAMI), in which westerly winds transport dust from the mid-latitude continents to West Antarctica (Mayewski et al., 2005; Dixon et al., 2011). Decadal-scale peaks in the nss-Ca record indicate that more continental dust reached Siple Dome when rainfall increased in the WRZ, most notably during the last 7 centuries (Fig. 8f). This suggests that strengthening and/or equatorward expansion of the northern margins of the westerlies increased the poleward transport of dust due to enhanced contact of prevailing wind tracks with southern landmasses, despite the increase of potentially dust-suppressing precipitation during the winter months.

4.3 Links to South America

Several sites in the WRZ of Chile registered increasing winter rainfall much like that of the South African WRZ during the last 7 centuries (Jenny et al., 2002; Lamy et al., 2001, 2010). In coastal marine core GeoB3313-1, iron intensity values representing terrestrial runoff indicate declining *P-E* from 1400–800 cal yr BP followed by a long-term wetting trend (Fig. 8a; Lamy et al., 2001, 2010). Although this pattern of inferred *P-E* trends in recent centuries resembles that of Verlorenvlei in general, opposing trends during the earlier parts of the records and differences in the timing of multi-decadal scale fluctuations may reflect several possible factors, including variable radiocarbon dating offsets in marine sediments, local influences of ENSO, ocean currents, topography, or latitude, or meridional irregularities in westerly wind tracks. In addition, a varved lacustrine record from Lago Plomo (Fig. 8b; Elbert et al., 2011) yields a sequence of inferred wet-dry fluctuations during the last 4 centuries that differed from those indicated in the GeoB3313-1 and Verlorenvlei records. Such inconsistencies highlight the need for multiple time series from widely separated locations to support historical reconstructions of large-scale climate systems and urge caution in the interpretation of single records. Nonetheless, the occurrence of generally wet conditions after 700 cal yr BP in these multi-proxy reconstructions from different continents suggests a common causal source for the underlying pattern of long-term change; the austral westerlies.

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4.4 Links to marine circulation

Equatorward expansions of the westerlies during the wet episodes in the African WRZ would be likely to resist Agulhas flow around the Cape. This, in turn, could have altered oceanographic conditions in the Atlantic and Indian Oceans (Speich et al., 2007), including SST as far west as Argentina and poleward heat and salt transfer through the MOC system (Biastoch et al., 2008, 2009; Martínez-Méndez, 2008). Sea surface cooling on the eastern Agulhas Bank at the start of the LIA has previously been inferred from marine mollusk records (Cohen and Tyson, 1995), which suggests that Agulhas through-flow was indeed reduced then as enhanced rainfall in the WRZ would indicate. Our findings also suggest that large-scale MOC weakenings might have occurred ~600, 530, 470, 330, 200, and 90 cal yr BP. Rigorous testing of that hypothesis is beyond the scope of this paper, but MOC is thought to have weakened in the North Atlantic during much of the LIA (Cronin et al., 2003; Lund et al., 2006). Whether that change represented a response to constricted Agulhas through-flow, however, remains unclear.

4.5 Future trends

The Verlorenvlei record supports climate models which suggest that aridity should increase in the South African WRZ if warming during this century causes the westerlies to retreat poleward (Boko et al., 2007; Toggweiller, 2008). Some model simulations project annual runoff reductions of 10–30 % in South African's WRZ by AD 2050, which could threaten major centers of population and agriculture as well as many of the >5500 endemic plant species in the Succulent Karoo and Fynbos biomes (Turpie et al., 2002; Thomas et al., 2004; Meadows, 2006). Future poleward drift of the westerlies would also be likely to enhance Agulhas through-flow around the South African Cape, with possible effects on SST patterns and associated climatic conditions within the Atlantic and Indian Ocean basins.

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Table 1. Radiocarbon dates from the Verlorenvlei cores. Calendar year conversions (year before AD 1950) were calculated with CALIB 5.0.1, using the SHCal04 dataset (McCormac et al., 2004).

Sample depth (cm)	Material	^{14}C age	calyr range *(2-sigma probability)*
VV09 CORE			
125.5	leaf	1370 ± 40	1149–1156 (0.01) 1171–1306 (0.99)
114.5	leaf	1080 ± 40	809–868 (0.14) 902–1006 (0.80) 1029–1052 (0.06)
100.5	leaf	520 ± 40	475–480 (0.01) 486–554(0.99)
100.5	seed	490 ± 40	340–353 (0.03) 451–545 (0.98)
130.5	mud	1880 ± 40	1626–1668 (0.1) 1690–1871(0.92)
125.5	mud	1560 ± 40	1308–1445 (0.81) 1456–1517 (0.19)
114.5	mud	1170 ± 40	934–946 (0.02) 952–1094 (0.92) 1102–1140 (0.06) 1161–1168 (0.01)
100.5	mud	950 ± 40	738–913 (1.00)
87.5	mud	260 ± 40	74–81 (0.004) 108–111 (0.002) 142–226 (0.50) 252–330 (0.42) 369–441 (0.07)
79.5	mud	580 ± 40	504–565 (0.82) 599–631 (0.18)
VV07-IV CORE			
119.5	leaf	2260 ± 40	2117–2337 (1.00)
108.5	leaf	1850 ± 40	1573–1581 (0.01) 1603–1826 (0.98) 1851–1860 (0.01)
92.5	leaf	1490 ± 40	1288–1399 (1.00)
87.5	leaf	1120 ± 40	923–1059 (1.00)
83.5	leaf	830 ± 40	664–767 (1.00)
78.5	leaf	660 ± 40	547–656 (1.00)
50.0	leaf	260 ± 40	0–3 (0.002) 74–81 (0.004) 108–111 (0.002) 142–226 (0.502) 252–330 (0.42) 369–441 (0.07)
133.5	mud	2500 ± 40	2355–2551 (0.62) 2555–2618 (0.15) 2633–2705 (0.23)
118.5	mud	2420 ± 40	2312–2503 (0.89) 2529–2537 (0.003) 2595–2614 (0.02) 2637–2695 (0.08)
98.5	mud	1880 ± 40	1626–1668 (0.08) 1690–1871 (0.92)
VF1 CORE			
77.5	leaf	791 ± 88	549–807 (0.97) 870–901 (0.03)
77.5	seed	702 ± 33	559–615 (0.55) 620–667 (0.45)
67.5	leaf	493 ± 48	332–364 (0.07) 444–552 (0.93)
57.5	leaf	294 ± 33	153–172 (0.06) 178–208 (0.06) 277–333 (0.53) 362–444 (0.35)
79.5	mud	1210 ± 40	969–1173 (1.00)

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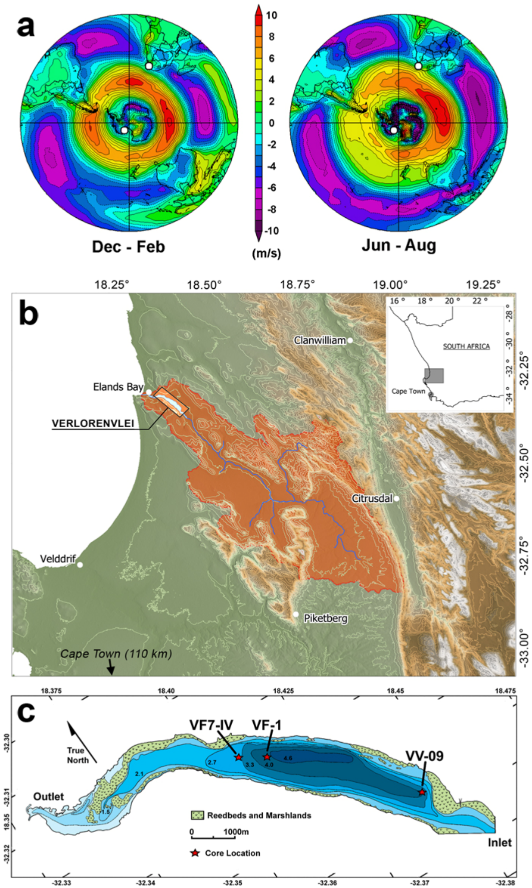

Fig. 1. Location maps. **(a)** Seasonal variations in the extent and speed of the austral westerlies, with Verlorenvlei and Siple Dome indicated (white dots). **(b)** Verlorenvlei watershed, with location in South Africa (insert). **(c)** Verlorenvlei bathymetry with coring sites indicated (stars).

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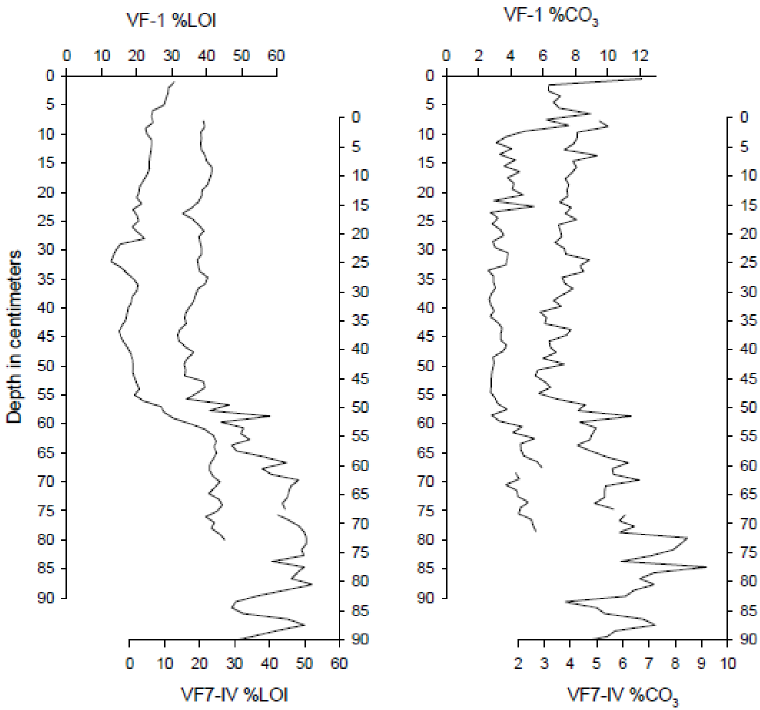

Fig. 2. Alignment of % LOI and % CO_3 profiles in cores VF-1 and VF7-IV from the western end of Verlorenvlei, showing evidence for the loss of ca. 8 cm from the top of VF7-IV.

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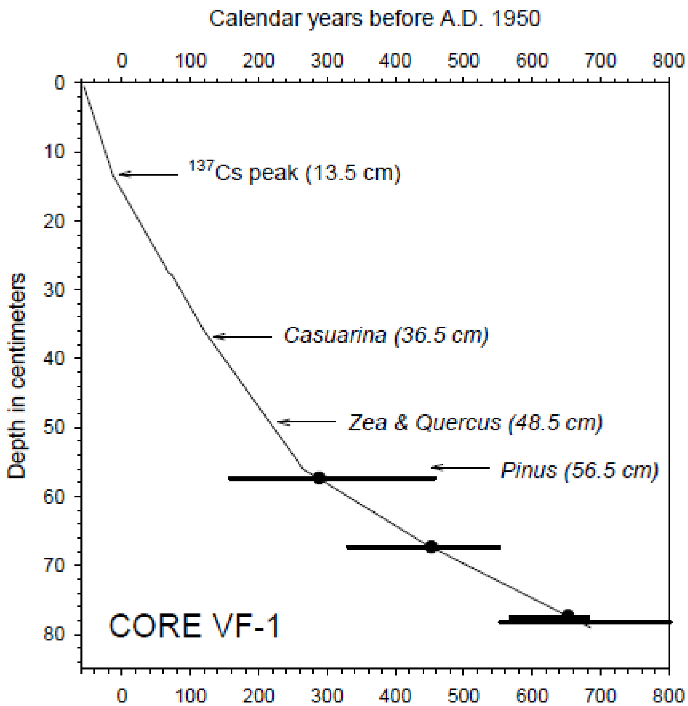

Fig. 3. Age-depth model for core VF-1. Peak concentration of ^{137}Cs is taken to represent atmospheric bomb testing peak in AD 1963. First appearances of exotic pollen are indicated with arrows. The 2-sigma calendar age ranges for AMS dates on plant remains (black bars) and bulk sediment (dotted). The sediment-water interface was intact, so the curve meets the origin.

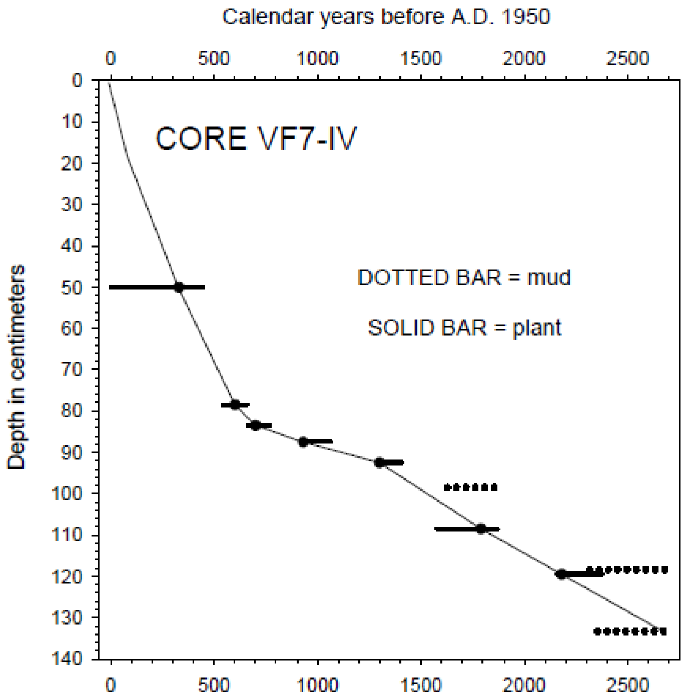

Fig. 4. Age-depth model for core VF7-IV. The 2-sigma calendar age ranges for AMS dates on plant remains (black bars) and bulk sediment (dotted). The uppermost 8 cm were lost during collection.

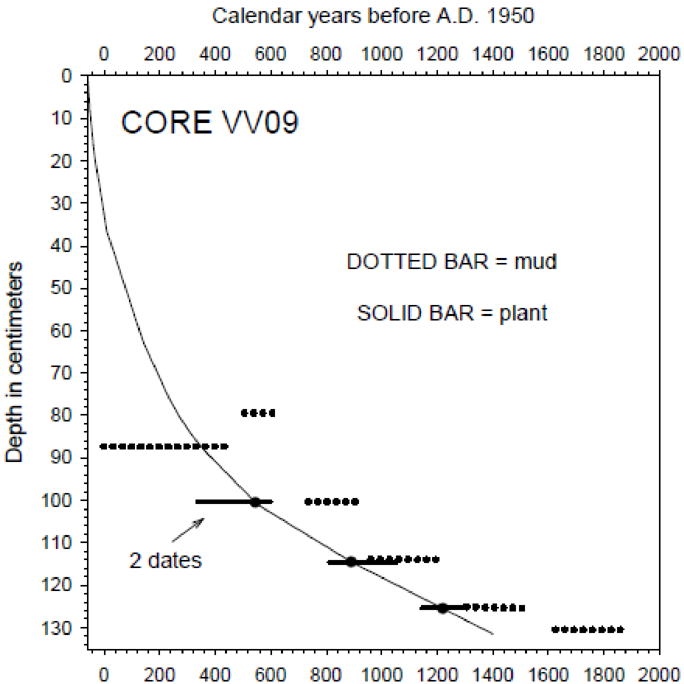

Fig. 5. Age-depth model for core VV09. The 2-sigma calendar age ranges for AMS dates on plant remains (black bars) and bulk sediment (dotted). The sediment-water interface was intact, so the curve meets the origin.

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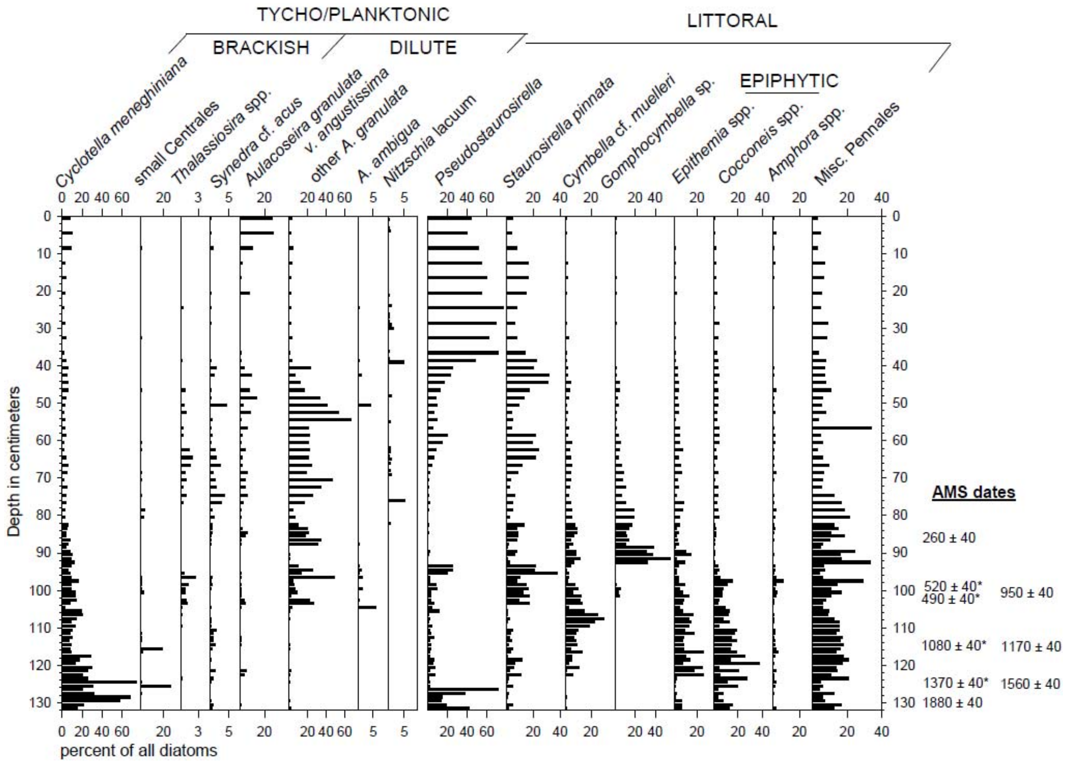

Fig. 6. Diatom assemblages in core VV09 versus depth, with AMS dates on plant remains (with asterisk) and bulk sediments.

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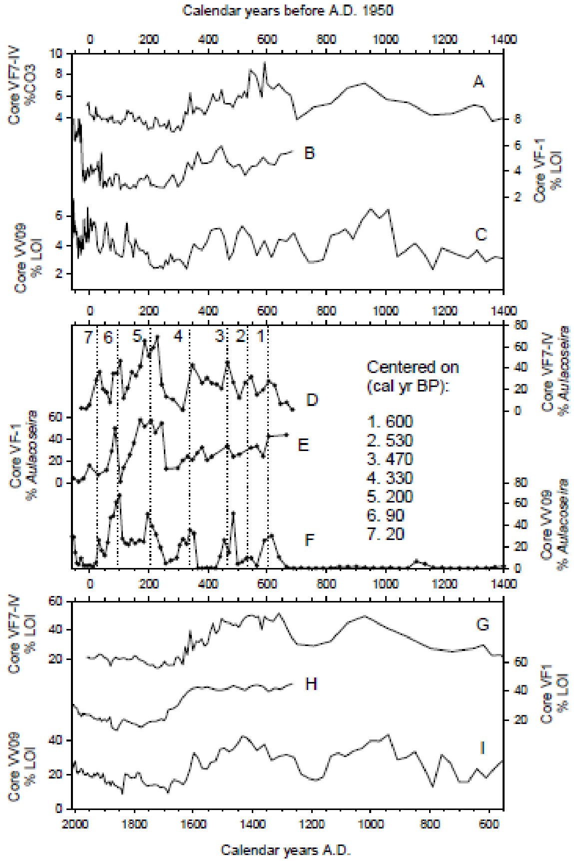

Fig. 7. Comparison of time series from the three Verlorenvlei cores. **(A–C)** % carbonate in VF7-IV, VF-1, and VV09, respectively. **(D–F)** % *Aulacoseira* diatoms, showing similar peaks approximately centered on the dates listed. **(G–I)** % LOI. The similarity of the profiles from opposite ends of the lake supports the respective age models and shows that the basic patterns of change in the cores represent lake-wide events.

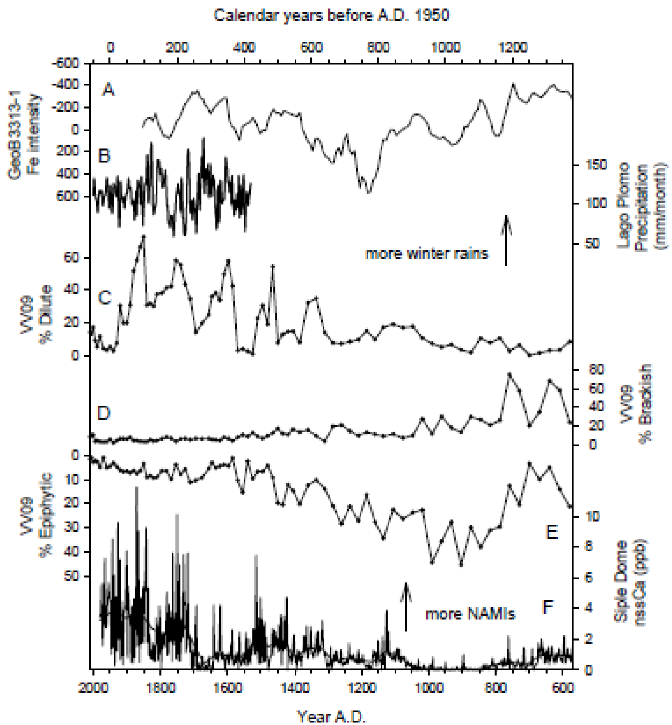

Fig. 8. Comparison of records from southern Africa with records from Antarctica and Chile. **(A)** Iron intensity series from Chilean marine core GeoB 3313-1, in counts per second; higher intensity indicates greater terrestrial runoff (Lamy et al., 2001, 2010). **(B)** Inferred winter precipitation from Lago Plomo (Elbert et al., 2011). **(C–E)** Diatom assemblages from Verlorenvlei core VV09 grouped as ecological indicators; profile of epiphytic taxa is shown with y-axis inverted. **(F)** Higher non-seasalt calcium concentrations at Siple Dome represent greater dust transport from austral mid-latitudes to West Antarctica by northern air-mass incursions (NAMI; Dixon et al., 2011). Profiles **(A–E)** are arranged to indicate increased winter precipitation upwards.