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Climate of the Past

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

J. C. Stager[1,2], P. A. Mayewski[2], J. White[1], B. M. Chase[3,4], F. H. Neumann[5,6], M. E. Meadows[7], C. D. King[1], and D. A. Dixon[2]

[1]Natural Sciences, Paul Smith's College, Paul Smiths, NY 12970, USA
[2]Climate Change Institute, University of Maine, Orono, ME 04473, USA
[3]Institut des Sciences de l'Evolution de Montpellier, Département Paléoenvironnements et Paléoclimats (PAL), UMR5554, Université Montpellier 2, Montpellier cedex 5, France
[4]Department of Archaeology, History, Culture and Religion, University of Bergen, P.O. Box 7805, 5020, Bergen, Norway
[5]Forschungsstelle für Paläobotanik, Westfälische Wilhelms-Universität Münster, 48143 Münster, Germany
[6]Bernard Price Institute for Palaeontological Research, University of the Witwatersrand Private Bag 3, Wits 2050, South Africa
[7]Department of Environmental and Geographical Science, University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa

Correspondence to: J. C. Stager (cstager@paulsmiths.edu)

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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 retreat of the austral westerlies with future warming, but the available paleoclimate records that might test these models have been limited to South America and New Zealand, are not fully consistent with each other and may be complicated by influences from other climatic factors. Here we present the first high-resolution diatom and sedimentological records from the winter rainfall region of South Africa, representing precipitation in the equatorward margin of the westerly wind belt during the last 1400 yr. Inferred rainfall was relatively high ∼1400–1200 cal yr BP, decreased until ∼950 cal yr BP, and rose notably through the Little Ice Age with pulses centred on ∼600, 530, 470, 330, 200, 90, and 20 cal yr BP. Synchronous fluctuations in Antarctic ice core chemistry strongly suggest that these variations were linked to changes in the westerlies. Equatorward drift of the westerlies during the wet periods may have influenced Atlantic meridional overturning circulation by restricting marine flow around the tip of Africa. Apparent inconsistencies among some aspects of records from South America, New Zealand and South Africa warn against the simplistic application of single records to the Southern Hemisphere as a whole. Nonetheless, these findings in general do support model projections of increasing aridity in the 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 westerlies tends to increase rainfall in those regions on both seasonal (winter) and millennial time scales (Shulmeister et al., 2004; Reason and Roualt, 2005). Many climate models suggest that the westerlies will move poleward in response to anthropogenic warming during this century (Boko et al., 2007; Toggweiller and Russell, 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). Aridity is, therefore, expected to increase in the austral winter rainfall zones (WRZ), with potentially serious consequences for centres 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 widely expected to cause a poleward drift of the westerlies and aridity in the associated WRZs, cooling might, therefore, be expected to have produced the opposite changes during the Little Ice Age (LIA, ∼1400–1800 AD; Mayewski et al., 2004). Despite the climatic and oceanographic importance of the westerlies, however, few records of their late Holocene history have yet been developed for locations outside of midlatitude South America. Several records of variable temporal resolution indicate wetter conditions in Chile and Argentina that were related to the westerlies during the LIA (Jenny et al., 2002; Lamy et al., 2001, 2010; Moy et al., 2008; Borromei et al., 2010; Elbert et al., 2011), but some discrepancies exist among these records. In addition, marine sediment records from fjords in New Zealand may indicate inconsistent relationships between precipitation regimes on opposite sides of the Pacific basin during the late Holocene (Knudson et al., 2011). The possible influences of complicating factors such as topography or uncertain carbon reservoir effects on the radiocarbon age models of marine cores, in addition to regionally variable climatic factors such as meridional and zonal changes in westerly flow patterns or the El Niño/Southern Oscillation system (ENSO), still leave important aspects of the history of the westerlies unresolved (Knudson et al., 2011). Additional information, particularly from other sectors of the Southern Hemisphere, is, 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 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 latitudinal drift of the westerlies. In southwestern Africa, the conceptual model of reduced westerly influence during periods of relative warmth is commonly applied, and surveys of what little evidence is available generally support this approach (Tyson and Lindesay, 1992; Tyson et al., 2000; Chase and Meadows, 2007). However, none of the records considered in these surveys from the South African WRZ are sufficiently well-dated or of suitable resolution to fully define regional climatic conditions during the late Holocene.

We present here the first high-resolution, continuous lacustrine diatom records from the South African WRZ (Fig. 1), representing decade-scale rainfall variability over the last 1400 yr that was associated with the equatorward margin of the westerlies. The climatic history of Lake Verlorenvlei is based upon diatom time series that are remarkably consistent among multiple cores, and the exceptionally strong chronology is based upon ^{137}Cs, exotic pollen, geochemical stratigraphy and more than two dozen accelerator mass spectrometry (AMS) dates on both terrestrial and lacustrine materials. Linking these African data to other Southern Hemisphere 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 drift 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 El Niño-Southern Oscillation (ENSO) system (Reason and Roualt, 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 sill and a narrow outlet channel (Sinclair et al., 1986). Roughly 80 % of the rainfall in the catchment ($<300\,\mathrm{mm\,yr^{-1}}$) 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

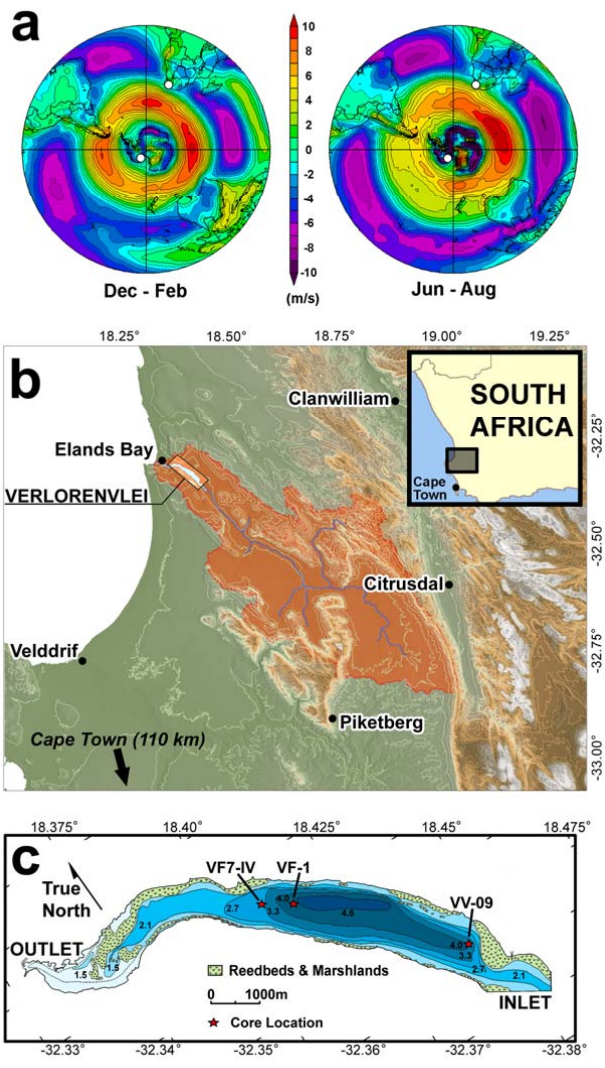

Fig. 1. Location maps. **(a)** Seasonal variations in the extent and speed of the austral westerlies, with Verlorenvlei and Siple Dome indicated (white dots). **(b)** Verlorenvlei watershed, with location in South Africa (insert). **(c)** Verlorenvlei bathymetry with coring sites indicated (stars).

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 during 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 the 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. The primary use of the % LOI and % CO_3 profiles from the cores was for stratigraphic purposes, including documentation of the loss of the mud-water interface from core VF7-IV (Fig. 2), selection of calendar ages within the 2-sigma brackets derived from AMS dates and support for the interpretation of changes in the diatom series as indicators of synchronous, lake-wide events.

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 centimetre 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; Taylor et al., 2007; EDDI database, http://craticula.ncl.ac.uk).

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 mostly planktonic, dilute-water diatoms (*Aulacoseira granulata*, *A. ambigua*, *Nitzschia lacuum*, *Synedra* cf. *delicatissima*) were taken to represent periods of increased runoff and river inputs to the lake under relatively wetter climatic conditions. The upper limit

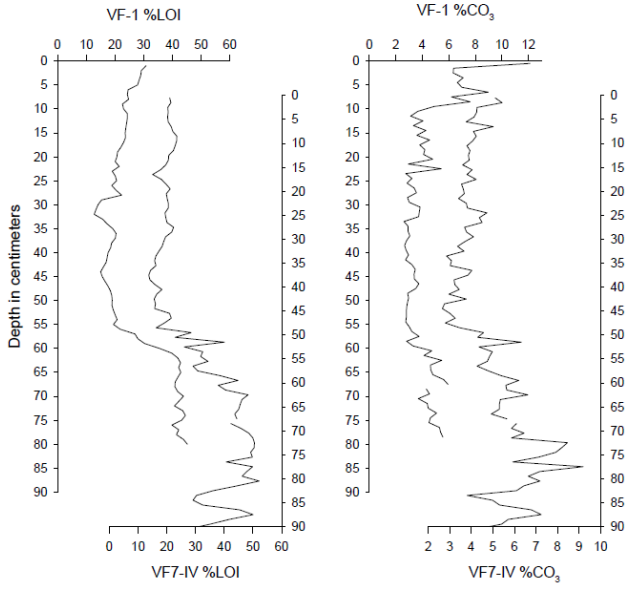

Fig. 2. Alignment of % LOI and % CO_3 profiles in cores VF-1 and VF7-IV from the western end of Verlorenvlei, showing evidence for the loss of ca. 8 cm from the top of VF7-IV.

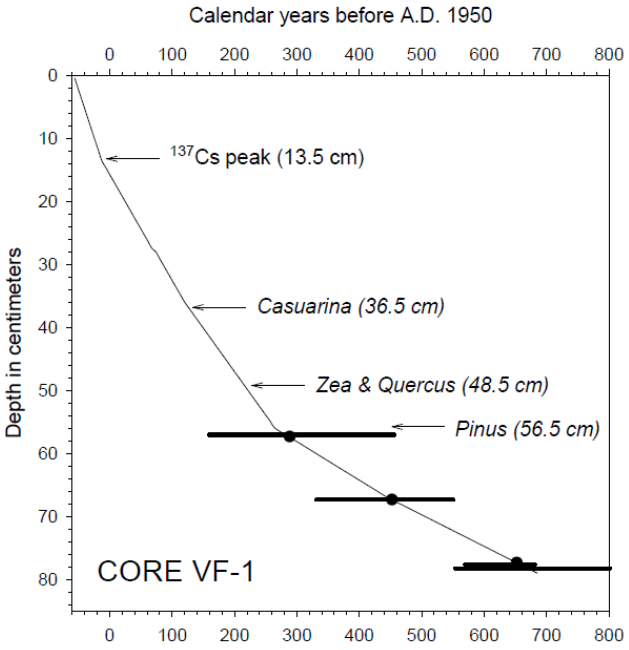

Fig. 3. Age-depth model for core VF-1. Peak concentration of ^{137}Cs is taken to represent atmospheric bomb testing peak in 1963 AD. First appearances of exotic pollen are indicated with arrows. The 2-sigma calendar age ranges for AMS dates on plant remains (black bars). The sediment-water interface was intact, so the curve meets the origin. A basal date on bulk sediment (see Table 1) lies off the time scale and is, therefore, not shown.

of the conductivity tolerance range for planktonic *Cyclotella meneghiniana* is an order of magnitude higher than for *A. granulata* (EDDI database), and high percentages of *C. meneghiniana* were taken to represent more brackish conditions and moderately reduced P-E. High percentages of littoral taxa, particularly epiphytic *Epithemia* and *Cocconeis* spp., represented low lake levels and marsh development under relatively dry conditions, but these taxa also persist in littoral habitats today and are, therefore, less useful qualitative ecological indicators than, for example, the *Aulacoseira* species which are most likely to become abundant under dilute, open-water conditions associated with higher P-E.

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.

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 determined 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 1963 AD and by the first appearances of exotic pollen. The ages assigned to the depth intervals in which *Pinus*, *Zea*, *Quercus* and *Casuarina* 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 metre is less well-supported than the younger intervals which

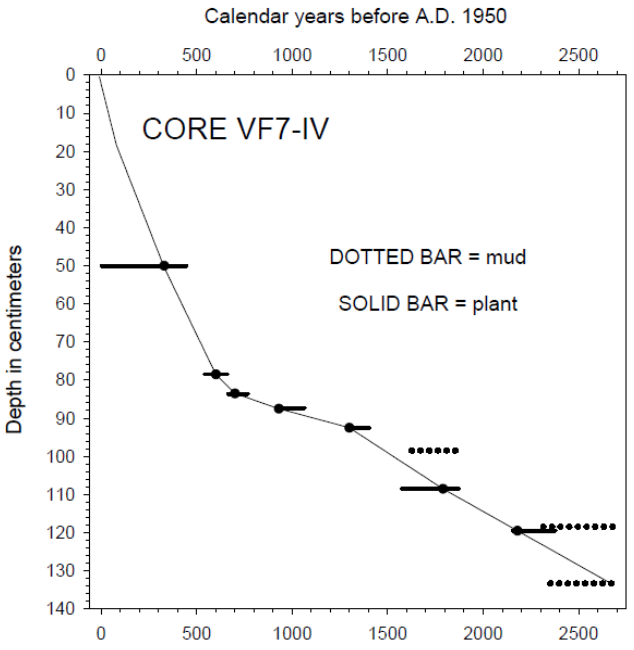

Fig. 4. Age-depth model for core VF7-IV. The 2-sigma calendar age ranges for AMS dates on plant remains (black bars) and bulk sediment (dotted). The uppermost 8 cm were lost during collection.

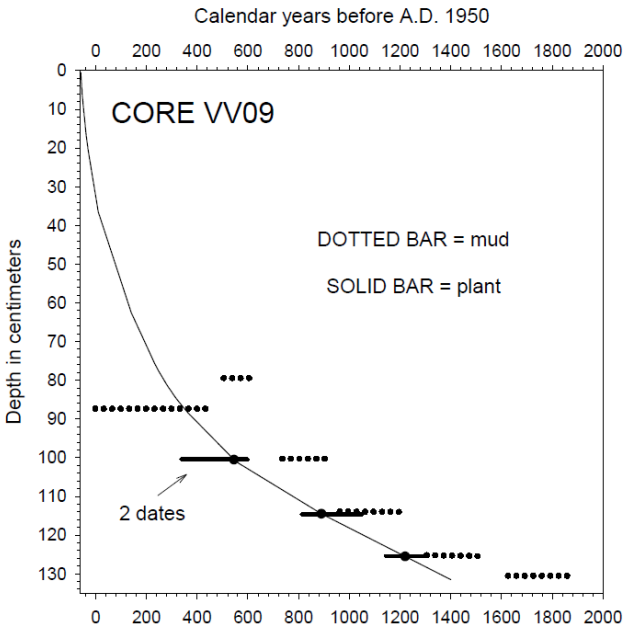

Fig. 5. Age-depth model for core VV09. The 2-sigma calendar age ranges for AMS dates on plant remains (black bars) and bulk sediment (dotted). The sediment-water interface was intact, so the curve meets the origin.

include more ages on terrestrial plant remains 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 metre of the core, but increased in the upper half metre (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 these sedimentary records do represent major ecological events in the lake as a whole (Fig. 7).

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 *A. 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–

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

Sample depth (cm)	Material	^{14}C age	cal yr 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)

Table 1. Continued.

Sample depth (cm)	Material	^{14}C age	cal yr range *(2-sigma probability)*
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)

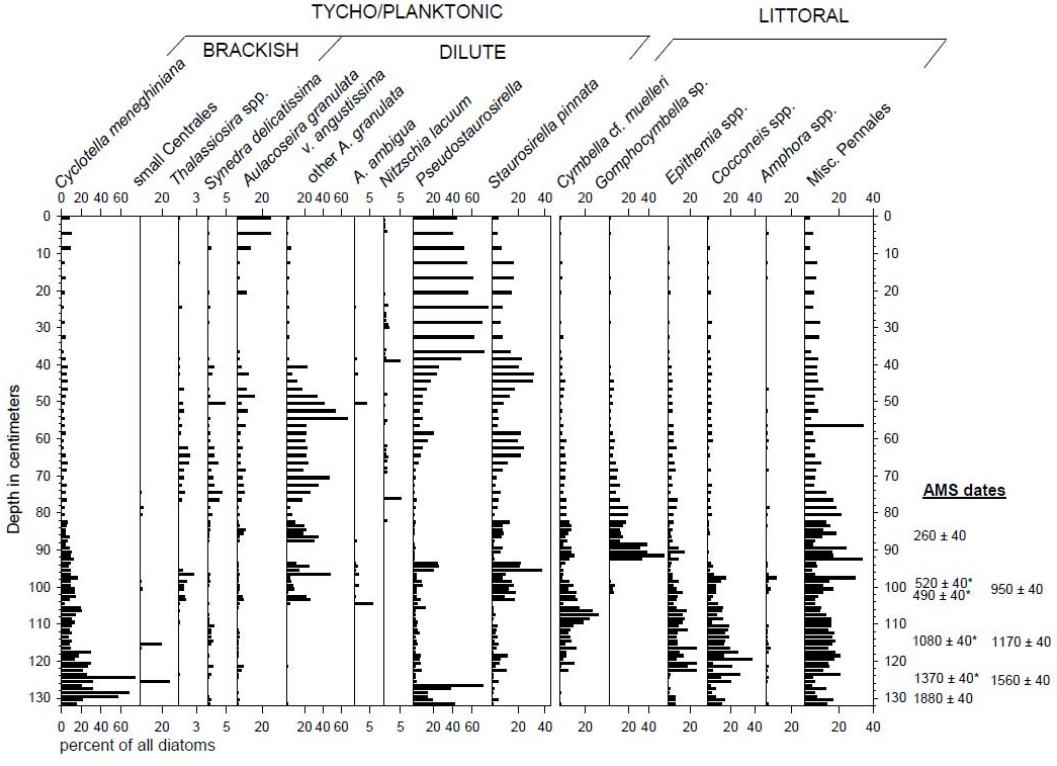

Fig. 6. Diatom assemblages in core VV09 versus depth, with AMS dates on plant remains (with asterisk) and bulk sediments.

124 cm; Fig. 8d). Percentages of epiphytic diatoms were most abundant ~1100–960 cal yr BP (122–116 cm), declining gradually thereafter (Fig. 8e). Percentages of tychoplanktonic (but normally benthic) *Pseudostaurosirella* and *Staurosirella* increased notably during the last century (upper 40 cm; Fig. 6).

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 centred 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.

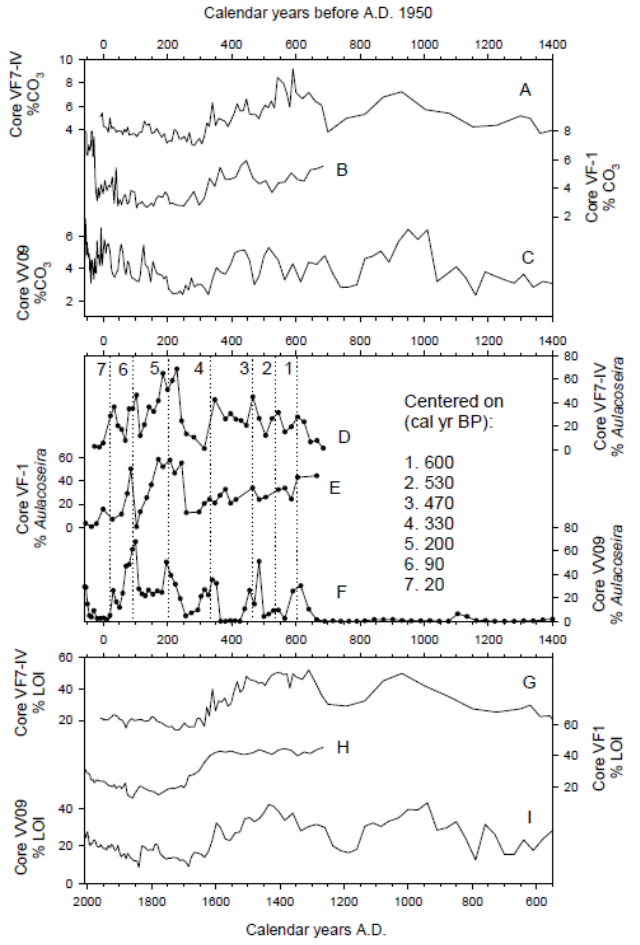

Fig. 7. Comparison of time series from the three Verlorenvlei cores. (A–C) % carbonate in VF7-IV, VF-1 and VV09, respectively. (D–F) % *Aulacoseira* diatoms, showing similar peaks approximately centred on the dates listed. (G–I) % LOI. The similarity of the profiles from opposite ends of the lake supports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

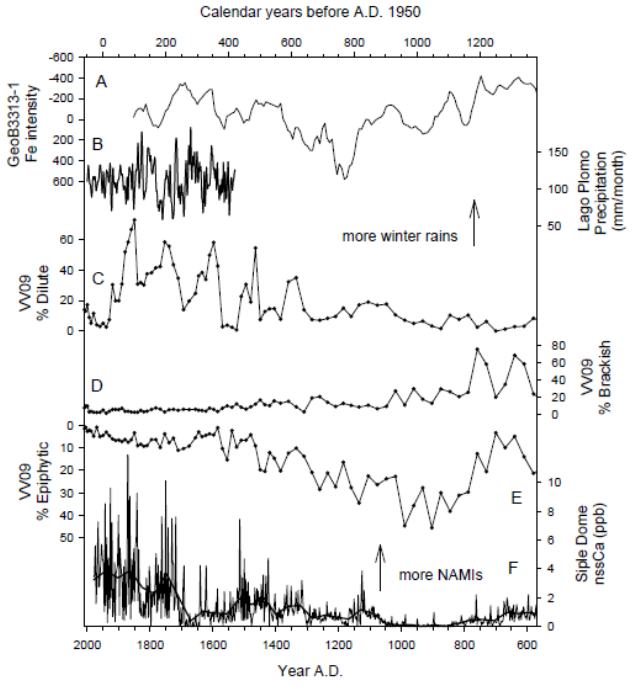

Fig. 8. Comparison of records from Southern Africa with records from Antarctica and Chile. (A) Iron intensity series from Chilean marine core GeoB 3313-1, five-point average in counts per second; lower intensity indicates more humid conditions along the coast (Lamy et al., 2001); data courtesy of F. Lamy. (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.

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 local vegetation and hydrology only during the last 300 yr 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 enhanced sediment delivery to the lake, most likely due to intensification and/or northward drift of the equatorward margin of the westerlies.

High percentages of moderately brackish-water diatoms ~1340–1190 cal yr BP (Fig. 8d) indicate slightly increased *P-E* that was sufficient to favour planktonic forms over littoral assemblages, but not large enough to favour 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 under relatively arid conditions during the Medieval Climate Anomaly (MCA: ~900–1400 AD). 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, 90 and 20 cal yr BP.

Increases in % LOI and % *Staurosirella* and *Pseudostaurosirella* during the last century or so, in addition to a

moderate increase in % *Aulacoseira* in recent decades, might reflect cultural eutrophication of the lake rather than climatic changes (Figs. 6, 7). The water today 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 lakeshore residences, the town of Eland's Bay, and 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 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 drift of the westerlies may have increased the poleward transport of dust due to expanded contact of prevailing wind tracks with southern landmasses, despite the increase of potentially dust-suppressing precipitation during the winter months.

4.3 Links to other Southern Hemisphere sites

Most sites throughout the WRZ of Chile and Argentina generally registered declining P-E during the MCA and rising P-E during the LIA (Jenny et al., 2002; Lamy et al., 2001, 2010; Moy et al., 2008; Borromei et al., 2010). In coastal marine core GeoB3313-1, for example, iron intensity values indicate declining P-E from 1400 to 800 cal yr BP followed by an overall wetting trend through the LIA (Fig. 8a; Lamy et al., 2001, 2010). However, a 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 somewhat from those indicated in the GeoB3313-1 and Verlorenvlei records.

Stable isotope records from New Zealand fjords (ca. 45° S) are thought to indicate major regional-scale differences in P-E when compared to the GeoB3313-1 series that may be due in part to both zonal and meridional distortions of the westerlies (Knudson et al., 2011). However, uncertainties in the reservoir corrections applied to the radiocarbon chronologies of these marine records also make it difficult to rule out the possibility that at least some of the inconsistencies might reflect dating methodologies more than regional climatic differences. Knudson et al. (2011) also proposed that a widening or equatorward shift of the westerly wind belt might have occurred over New Zealand 1100–750 cal yr BP followed by poleward drift of the northern margin of the wind belt 600–200 cal yr BP, but our findings show that such changes did not occur in the South African WRZ at those times.

Although we find general similarities among most P-E reconstructions from mid-latitude South America, New Zealand and South Africa (e.g., overall MCA drying trend, LIA wetting trend), apparent differences in the timing of decadal-scale climatic fluctuations in these different austral WRZs may reflect many possible factors, including choice of age models, regional distortion of wind tracks by topography and atmospheric pressure cells, or the influences of ENSO and sea surface temperatures (Lamy et al., 2010; Knudson et al., 2011). Such inconsistencies highlight the need for multiple time series from many locations to support the presumed history of large climatic systems such as the westerlies and urge caution in the interpretation of single records. Nonetheless, the occurrence of generally decreasing P-E during much of the MCA and increasing P-E during the LIA in these multi-proxy reconstructions from different continents suggests a common causal source for the underlying pattern of long-term change: the austral westerlies.

4.4 Links to marine circulation

Equatorward drift of the northern margin of the westerly wind belt during the wet episodes in the South 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, 90, and 20 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 a poleward drift of the westerlies (Boko et al., 2007; Toggweiler and Russell, 2008). Some model simulations project annual runoff reductions of

10–30 % in South African's WRZ by 2050 AD, which could threaten major centres 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 in the northern margin of the westerlies would also be likely to enhance Agulhas through-flow around the South African Cape, with possible widespread effects on SST patterns and associated climatic conditions within the Atlantic and Indian Ocean basins.

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References

Bate, G. C., Adams, J. B., and van der Molen, J. S.: Diatoms as indicators of water quality in South African river systems, Water Resources Commission Report 814/1/02, 2002.

Baxter, A. J. and Meadows, M. E.: Evidence for Holocene sea level change at Verlorenvlei, Western Cape, South Africa, Quatern. Int., 56, 65–79, 1999.

Biastoch, A. S., Böning, C. W., and Lutjeharms, J. R. E.: Agulhas leakage dynamics affects decadal variability in Atlantic overturning circulation, Nature, 456, 489–492, 2008.

Biastoch, A., Böning, C. W., Schwarzkopf, F. U., and Lutjeharms, J. R. E.: Increase in Agulhas leakage due to poleward shift of Southern Hemisphere westerlies, Nature, 462, 495–498, 2009.

Boko, M., Niang, I., Nyong, A., Vogel, C., Githeko, A., Medany, M., Osman-Elasha, B., Tabo, R., and Yanda, P.: Africa. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Parry, M. L., Canziani, O. F., Palutikof, J., van der Linden, P. J., and Hanson, C. E., Cambridge University Press, Cambridge UK, 433–468, 2007.

Borromei, A. M., Coronato, A., Franzén, L. G., Ponce, J. F., Sáez, J. A. L., Maidana, N., Rabassa, J., and Candel, M. S.: Multiproxy record of Holocene paleoenvironmental change, Tierra del Fuego, Argentina, Palaeogeogr. Palaeocl., 286, 1–16, 2010.

Chase, B. M. and Meadows, M. E.: Late Quaternary dynamics of southern Africa's winter rainfall zone, Earth-Sci. Rev., 84, 103–138, 2007.

Cocquyt, C.: Diatoms from the northern basin of Lake Tanganyika, Bibliotheca Diatomologica, Band 39, J. Cramer, Berlin, Stuttgart, 1998.

Cohen, A. L. and Tyson, P. D.: Holocene sea surface temperatures on the south coast of Africa: implications for terrestrial climate and rainfall, Holocene, 5, 304–312, 1995.

Cronin, T. M., Dwyer, G. S., Kamiya, T., Schwede, S., and Willard, D. A.: Medieval Warm Period, Little Ice Age, and 20th century temperature variability from Chesapeake Bay, Global Planet. Change, 36, 17–19, 2003.

Dixon, D. A., Mayewski, P. A., Goodwin, I. D., Marshall, G. J., Freeman, R., Maasch, K. A., and Sneed, S. B.: An ice core proxy for Northerly Air Mass Incursions (NAMI) into West Antarctica, Int. J. Climatol., online first: doi:10.1002/joc.2371, 2011.

Elbert, J., Grosjean, M., von Gunten, L., Urrutia, R., Fischer, D., Wartenberger, R., Ariztegui, D., Fujak, M., and Hamann, Y.: Quantitativehigh-resolution winter (JJA) precipitation reconstruction from varved sediments of Lago Plomo 47° S, Patagonian Andes, AD 1530–2002, Holocene, 22, 465–474, doi:10.1177/095968361 1425547, 2011.

Gasse, F.: East African diatoms: Taxonomy, ecological distributions, Bibliotheca Diatomologica, J. Cramer, Berlin, 1986.

Jenny, B., Valero-Garces, B. L., Urrutia, R., Kelts, K., Veit, H., Appleby, P. G., and Geyh, M.: Moisture changes and fluctuations of the Westerlies in Mediterranean Central Chile during the last 2000 years: The Laguna Aculeo record (30°50′ S), Quatern. Int., 87, 3–18, 2002.

Knudson, K. P., Hendy, I. L., and Neil, H. L.: Re-examining Southern Hemisphere westerly wind behavior: insights from a late Holocene precipitation reconstruction using New Zealand fjord sediments, Quaternary Sci. Rev., 30, 3124–3138, 2011.

Lamy, F., Hebbeln, D., Roehl, U., and Wefer, G.: Holocene rainfall variability in southern Chile: a marine record of latitudinal shifts of the Southern Westerlies, Earth Planet. Sc. Lett., 185, 369–382, 2001.

Lamy, F., Kilian, R., Arz, H. W., Francois, J.-P., Kaiser, J., Prange, M., and Steinke, T.: Holocene changes in the position and intensity of the southern westerly wind belt, Nat. Geosci., 3, 695–699, 2010.

Lund, D. C., Lynch-Stieglitz, J., and Curry, W. B.: Gulf Stream density structure and transport during the past millennium, Nature, 444, 601–604, 2006.

Martínez-Méndez, G.: Surface and Deep Circulation off South Africa: Agulhas Leakage Influence on the Meridional Overturning Circulation During the Last 345 kyr, Doctoral Dissertation, Autonomous University of Barcelona, 2008.

Mayewski, P. A., Rohling, E. E., Stager, J. C., Karlén, W., Maasch, K. A., Meeker, L. D., Meyerson, E. A., Gasse, F., van Kreveld, S., Holmgren, K., Lee-Thorp, J., Rosqvist, G., Rack, F., Staubwasser, M., Schneider, R. R., and Steig, E. J.: Holocene climate, Quaternary Res., 62, 243–255, 2004.

Mayewski, P. A., Maasch, K. A., White, J. W. C., Meyerson, E., Goodwin, I., Morgan, V. I., van Ommen, T., Curran, M. A. J., Souney, J., and Kreutz, K.: A 700 year record of Southern Hemisphere extra-tropical climate variability, Ann. Glaciol., 39, 127–132, 2005.

McCormac, F. G., Hogg, A. G., Blackwell, P. G., Buck, C. E., Higham, T. F. G., and Reimer, P. J.: ShCal04 Southern Hemisphere Calibration, 0–11.0 Cal Kyr BP, Radiocarbon, 46, 1087–1092, 2004.

Meadows, M. E.: Global change and southern Africa, Geogr. Res., 44, 135–145, 2006.

Mitchell, P. J.: The Quaternary archaeological record in southern Africa, in: The Cenozoic of Southern Africa, edited by: Maud, R. and Partridge, T., Ch. 22, Oxford Press, 2000.

Moy, C. M., Dunbar, R. B., Moreno, P. I., Francois, J.-P., Villa-Martínez, R., Mucciarone, D. M., Guilderson, T. P., and Garreaud, R. D.: Isoptic evidence for hydrologic change related to the westerlies in SW Patagonia, Chile, during the last millennium, Quaternary Sci. Rev., 27, 1335–1349, 2008.

Neumann, F., Stager, C., Scott, L., Venter, H. J. T., and Weyhenmeyer, C.: Holocene vegetation and climate records from Lake Sibaya, KwaZulu-Natal (South Africa), Rev. Palaeobot. Palyno., 152, 113–128, 2008.

Philippon, N., Roualt, M. Richard, Y., and Favre, A.: The influence of ENSO on winter rainfall in South Africa, Int. J. Climatol., online first: doi:10.1002/joc.3403, 2011.

Reason, C. J. C. and Rouault, M.: Links between the Antarctic Oscillation and winter rainfall over western South Africa, Geophys. Res. Lett., 32, L07705, doi:10.1029/2005GL022419, 2005.

Shulmeister, J., Goodwin, I., Renwick, J., Harle, K., Armand, L., McGlone, M. S., Cook, E., Dodson, J., Hesse, P., Mayewski, P., and Curran, M.: The Southern Hemisphere westerlies in the Australasian sector over the last glacial cycle: a synthesis, Quatern. Int., 118–119, 23–52, 2004.

Sinclair, S. A., Lane, S. B., and Grindley, J. R.: Verlorenvlei. Report 32 in Estuaries of the Cape, edited by: Heydorn, A. E. F. and Morant, P. D., CSIR Research Report 431, 1986.

Speich, S., Blanke, B., and Cai, W.: Atlantic meridional overturning circulation and the southern hemisphere supergyre, Geophys. Res. Lett., 34, L23614, doi:10.1029/2007GL031583, 2007.

Taylor, J. C., Harding, W. R., and Archibald, C. G. M.: An illustrated guide to some common diatom species from South Africa, Water Research Commission Report TT 282/07, 2007.

Thomas, C. D., Cameron, A., Green, R. E., Bakkenes, M., Beaumont, L. J., Collingham, Y. C., Erasmus, B. F. N., de Siquiera, M. F., Grainger, A., Hannah, L., Hughes, L., Huntley, B., van Jaarsveld, A. S., Midgley, G. F., Miles, L., Ortega-Hurta, M. A., Peterson, A. T., Phillips, O. L., and Williams, S. E.: Extinction risk from climate change, Nature, 427, 145–148, 2004.

Toggweiler, J. R. and Russell, J.: Ocean circulation in a warming climate, Nature, 451, 286–288, 2008.

Turpie, J., Winkler, H., Spalding-Fecher, R., and Midgley, G.: Economic Impacts of Climate Change in South Africa: A Preliminary Analysis of Unmitigated Damage Costs, Southern Waters Ecological Research and Consulting, Energy and Development Research Centre, University of Cape Town, 2002.

Tyson, P. D. and Lindesay, J. A.: The climate of the last 2000 years in southern Africa, Holocene, 2, 271–278, 1992.

Tyson, P. D., Karlen, W., Holmgren, K., and Heiss, G. A.: The Little Ice Age and medieval warming in South Africa, S. Afr. J. Sci., 96, 121–126, 2000.