Relationship between Antarctic sea ice and southwest African climate during the late Quaternary

Jan-Berend W. Stuut
Research Center Ocean Margins (RCOM), Universität Bremen, Klagenfurterstraße, 28359 Bremen, Germany
Xavier Crosta
Département Géologie et Océanographie, UMR-CNRS 5805 EPOC, Université Bordeaux I, Avenue des Facultés, 33405 Talence, France
Klaas van der Borg
R.J. Van de Graaff Laboratory, Utrecht University, Princetonlaan 4, 3584 CD Utrecht, Netherlands
Ralph Schneider
Département Géologie et Océanographie, UMR-CNRS 5805 EPOC, Université Bordeaux I, Avenue des Facultés, 33405 Talence, France

ABSTRACT

Here we compare late Quaternary southwest African climate records from the west coast of southern Africa (published winter rainfall and trade wind intensity records from a core off the coast of Namibia) to records of Antarctic sea-ice extent. This comparison reveals coherent changes between Antarctic sea-ice extent and the southwest African winter rain region since 45 k.y. B.P., with enhanced winter rainfall and trade-wind vigor during periods of increased sea-ice presence. We propose an oceanic and atmospheric coupling between Antarctic sea ice and the winter rainfall zone of southwest Africa that may lead to increased desertification in the region if global warming persists.

Keywords: late Quaternary, aridity, trade wind strength, grain size, dust, end-member modeling, sea ice, diatoms.

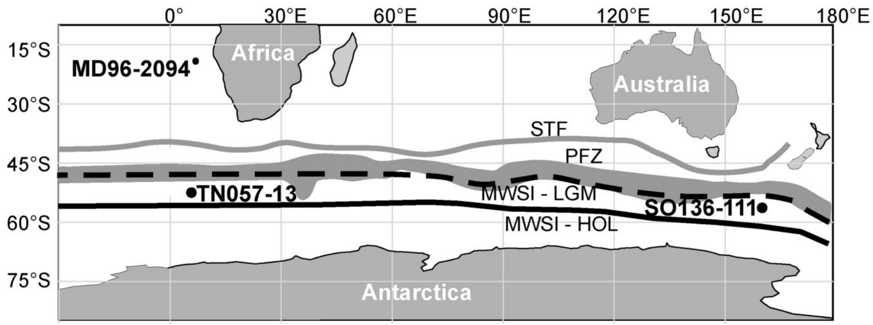
INTRODUCTION

The nature of late Quaternary climate variability in the southern part of the African continent has been the subject of many studies focusing on terrestrial records from proxy data sources such as dune activity (e.g., Thomas et al., 2000), pollen (Meadows et al., 1996), micromammals (Avery, 1999), and *Hyrax* middens (Scott and Vogel, 2000). However, continuous continental climate records from the subcontinent are scarce (Meadows, 2001). Eastern South African late Quaternary climate, as inferred from lake sediments, was suggested to vary with precessional (~23 k.y.) frequency, showing that the driving mechanisms for climate variability in eastern South Africa are most likely tied to changes in the Indian Ocean monsoonal system (Partridge et al., 1997). In contrast, deep-sea sediments recovered off the coast of Namibia revealed that the driving mechanisms of the southwest African winter rainfall region probably have to be sought at high latitudes instead, because of a prominent obliquity (~41 k.y., Stuut, 2001) signature in the climate records. The present-day major difference between the eastern and western parts of southern Africa is the timing of rainfall. The larger part of southern Africa is characterized by summer rainfall (>60% of the mean annual precipitation) from the Indian monsoon (d'Abreton and Tyson, 1994), whereas a small part, along the southwestern coast and the adjacent escarpment, is typified by winter rainfall (>70% of the mean annual precipitation, Tyson, 1986). Annual precipitation in the winter rainfall zone varies from >2 m in the southern mountains to <50 mm in the Namib Desert. The subhumid Mediterranean climate of the southwestern cape has resulted in the distinct Fynbos flora (e.g., Cowling et al., 1997), whereas the dunes of the hyperarid Namib are nearly devoid of vegetation.

A very similar sharp north-south precipitation gradient can be observed at about the same latitudes in present-day South America, where the winter rainfall area that exists along the coast west of the Andes mountains grades from the extremely wet climate of Patagonia in the south into the hyperarid Atacama Desert in the north (e.g., Lamy et al., 2001). Late Quaternary rainfall variability in western South America is suggested to be related to the latitudinal position and intensity of the southern westerlies, in response to an enhanced pole-to-equator thermal gradient (Heusser, 1989b; Lamy et al., 2001) and the accompanying enhanced polar vortex (Thompson and Solomon, 2002). On the basis of a conceptual model, Van Zinderen Bakker (1976) proposed a similar mechanism (an expanded Antarctic anticyclone causing an equatorward shift of the westerlies and increased winter precipitation) for late Quaternary southernmost Africa as well. However, because of the fact that the winter rainfall region in southwestern Africa is largely restricted to semiarid to hyperarid climates where terrestrial proxy data sources are not readily preserved, evidence from the region to test this model has remained elusive.

Here we propose that during the late Quaternary, precipitation in the winter rain region of southwestern Africa was ultimately related to Antarctic sea-ice extent via its impact on the latitudinal position of the oceanic and atmospheric fronts in the Southern Ocean (Fig. 1). We compare two late Quaternary (since 45 ka) sea-ice presence records from sediment cores located south of the Polar Front to a trade-wind intensity and winter rainfall record from a sediment core off southwest Africa (Stuut et al., 2002) (Fig. 2). The sea-ice presence records are derived from a modern analogue technique (MAT) applied to fossil diatom assemblages from the Southern Ocean (Crosta et al., 1998). Sea-ice extent can be deduced from sea-ice presence because there is a quasi-linear relationship between sea-ice presence at one location and ice concentration

Figure 1. Schematic representation of large-scale fronts in Atlantic and Indian parts of Southern Ocean (after Naval Oceanography Command Detachment, 1985; Peterson and Stramma, 1991; Belkin and Gordon, 1996; Crosta et al., 1998). Positions of discussed cores are indicated. STF—Subtropical Front; PFZ—Polar Frontal Zone; MWSI-LGM—maximum winter sea ice during Last Glacial Maximum; MWSI-HOL—maximum winter sea ice during Holocene.



and extent in the direct vicinity. Changes in southwest African trade-wind intensity and winter rainfall were inferred from the terrigenous sediment fraction in core MD96–2094, collected from offshore Namibia (Stuut et al., 2002). An end-member algorithm (Weltje, 1997) was applied to unmix grain-size distributions of the terrigenous sediment fraction into different sediment populations that were ascribed to eolian- and fluvial-transport mechanisms (Stuut et al., 2002). Downcore proportions of the coarse and fine eolian subpopulations were taken as a measure of wind strength. Downcore proportions of the eolian versus fluvial subpopulations were taken as a measure of continental humidity, which, in this region, is dominated by winter rainfall.

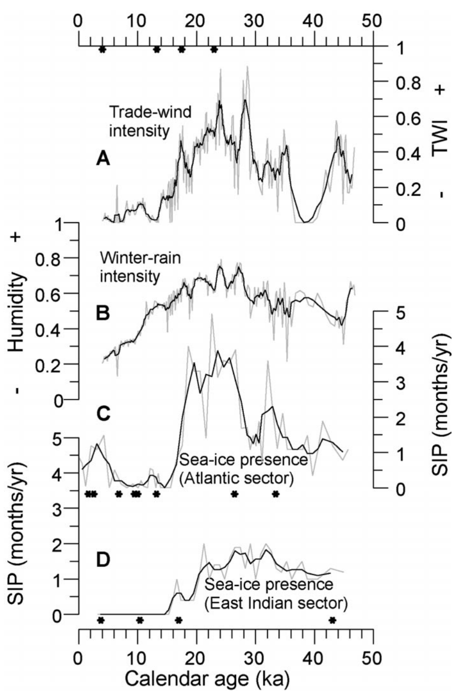


Figure 2. Relationship between Antarctic sea ice and climate variability in southwestern Africa since 45 ka. A: Southwest African trade-wind intensity (TWI) record. B: Winter rainfall record, derived from core MD96-2094 (Stuut et al., 2002) (gray line—raw data; black line—five-point moving average). C and D: Records of Antarctic sea-ice presence (SIP) in Atlantic and Indian sectors of Southern Ocean (C—core TN057-13; D—core SO136-111) (gray lines—raw data, black lines—three-point moving average). Accelerator mass spectrometer ^{14}C control points of records denoted by asterisks (see Table 1).

MATERIAL AND METHODS

The sediment core (MD96-2094), from which the southwest African margin paleoclimate records were reconstructed, was taken to represent the sedimentation patterns on Walvis Ridge, based on chemical data from a transect of seven cores over the ridge (Stuut, 2001). Stuut et al. (2002) stated that the terrigenous fraction of the sediments on Walvis Ridge originates from the southwest African continent and is transported to the southeast Atlantic Ocean by the southeast trade winds and by the perennial Orange River and several ephemeral rivers. The aridity and wind-strength records inferred by Stuut et al. (2002) are used here to compare with the sea-ice records from the Southern Ocean.

Stratigraphy

Age models of the three sediment cores are based on stable oxygen isotope data (Stuut et al., 2002) plus 4 (MD96-2094), 10 (TN057-13, Kanfoush et al., 2000; Hodell et al., 2001; Shemesh et al., 2002), and 4 (SO136-111, Crosta et al., 2004) additional accelerator mass spectrometry (AMS) ^{14}C dates (Table 1). For core MD96-2094 (Stuut et al., 2002), four ^{14}C ages were determined on monospecific samples of *G. ruber*. The AMS ^{14}C ages were corrected for a reservoir age of 400 yr as the mean value for the South Atlantic Ocean at lat 20°S (Bard, 1988) and subsequently converted to calendar years with the Calib 4 software (Stuiver and Reimer, 1993). For core SO136-111 (Crosta et al., 2004), four ^{14}C ages were determined on monospecific samples of *N. pachyderma* (sinistral). The AMS ^{14}C ages were corrected for a reservoir age of 800 yr as the mean value for the Indian sector of the Southern Ocean (Bard, 1988) and converted to calendar years with the Calib 4 software (Stuiver and Reimer, 1993).

Modern Analogue Technique

February sea-surface temperatures (SSTs) and sea-ice cover reconstruction were estimated by applying the MAT to fossil diatom assemblages. The MAT compares the com-

TABLE 1. ACCELERATOR MASS SPECTROMETRY ^{14}C DATES TO CONSTRAIN THE AGE-DEPTH MODEL FOR CORES MD96-2094, TN057-13, AND SO136-111

Core and depth (cmbsf)	Age (^{14}C ka ± 1σ)	Calibrated age	Reference cited
MD96-2094			
3	4.130 ± 0.050	4.175	(Stuiver and Reimer, 1993)
83	11.940 ± 0.080	13.310	(Stuiver and Reimer, 1993)
128	15.150 ± 0.090	17.540	(Stuiver and Reimer, 1993)
188	19.870 ± 0.120	22.990	(Stuiver and Reimer, 1993)
TN057-13			
20	1.590 ± 0.080	0.720	(Stuiver et al., 1998)
63	2.630 ± 0.060	1.830	(Stuiver et al., 1998)
256	6.850 ± 0.060	6.930	(Stuiver et al., 1998)
449	9.340 ± 0.060	9.540	(Stuiver et al., 1998)
473	9.370 ± 0.080	9.600	(Stuiver et al., 1998)
536	10.050 ± 0.040	10.310	(Stuiver et al., 1998)
741	13.140 ± 0.050	14.400	(Bard et al., 1998)
919	26.360 ± 0.150	29.130	(Bard et al., 1998)
970	33.420 ± 0.250	36.990	(Bard et al., 1998)
SO136-111			
1	3.715 ± 0.050	3.163	(Stuiver et al., 1998)
31	10.235 ± 0.060	10.414	(Stuiver et al., 1998)
56	16.860 ± 0.100	19.045	(Bard et al., 1998)
111	43.120 ± 1.870	43.120	(Bard et al., 1998)

Note: cmbsf—centimeters below seafloor.

position of downcore sediment samples to a database of core-top analogues with known modern parameters. Here, modern February SST values are from the *World Ocean Atlas* (Levitus and Boyer, 1994), and modern values of sea ice are from the Naval Oceanography Command Detachment (1985). The estimate is a simple average of the parameter values associated to the five closest analogues chosen by the MAT and consequently assumed to represent the climate at the core locality when the fossils of the downcore sample were produced.

DISCUSSION

The wind strength and winter rainfall records from core MD96-2094 (Figs. 2A, 2B) show a coherent pattern from 45 ka to the present; trade-wind intensity and humidity were generally higher during the glacial interval, and drier conditions with lower trade-wind strengths were the rule during the Holocene. The contemporaneous increased humidity in the winter rain region and increased trade-wind intensity during the glacial interval apparently seem to be contradictory but fit well in the conceptual model of increased latitudinal temperature and pressure gradients during glaciation, leading to increased winter rainfall along the western margin of southern Africa and intensified atmospheric circulation (Stuut et al., 2002). Wetter conditions in the southwestern cape region are confirmed by the regional synthesis by Meadows and Baxter (1999). The inferred increase in rainfall in the Namibian sector of the winter rainfall region during the Last Glacial Maximum (LGM) is corroborated by the timing of groundwater aquifer formation in Namibia (Stute and Talma, 1998) and pollen data (Dupont and Wyputta, 2003). The latter showed that under LGM conditions, Restionaceae pollen (characteristic for the winter rain Fynbos vegetation of South Africa) were found farther to the north, while an atmospheric circulation model showed that trade-wind directions did not change to more zonal paths. The inferred equatorward expansion of the Fynbos vegetation during the LGM was thus related to more humid conditions compared to those of the Holocene, consistent with the results from our grain-size data.

The two sea-ice presence records from the Southern Ocean (Figs. 2B, 2C) also show a coherent pattern during the past 45 k.y.; sea-ice presence increased during the glacial period and decreased during the early Holocene. The sea-ice presence signature from the Atlantic sector shows higher amplitudes compared to the one from the East Indian part of the Southern Ocean. This result can be explained by the greater formation of ice in the Weddell Sea and by its northward advection by the Weddell Gyre, which causes the winter sea-ice edge to be closer to the Antarctic Polar Front (APF) in the Atlantic sector than in the East Indian sector (Crosta et al., 1998, 2004). We interpret the gradual change in signature in the East Indian sea-ice presence record as representative of variations in sea-ice extent around the whole Antarctic, whereas the record from the Atlantic sector reflects an additional high-amplitude signature caused by the larger formation of sea ice in the Weddell Gyre (Crosta et al., 1998). The high reactivity of sea ice—it appeared and disappeared in ~2 k.y.—is consistent with modeling studies (Gildor and Tziperman, 2000, 2001).

The nature of the proxy records only allows for a broad comparison between the records and not for a peak-to-peak correlation. Differences between the records can be ascribed, for example, to differences in their temporal resolutions and age models, as well as lags that may be caused by changes in vegetation in the source areas of the terrigenous sediments. Nevertheless, the Southern Ocean sea-ice presence records and grain-size–based trade-wind intensity and humidity records for the southwestern margin of Africa show a coherent pattern during the past 45 k.y. Low sea-ice presence values between 45 and 25 ka coincided with relatively low trade-wind intensity and winter rainfall, whereas greater sea-ice presence between 25 and 18 ka occurred with increased trade-wind intensity, as well as winter rainfall (Fig. 2). After 12 ka, low sea-ice presence occurred again with low trade-wind intensity and low winter rainfall. In general it can be observed that the high-amplitude trade-wind intensity record better resembles the sea-ice presence record from the Atlantic sector, whereas the more gradually changing winter rainfall record better resembles the sea-ice presence record from the East Indian sector (Fig. 2). Beside the aforementioned differences in age models and resolutions of the different proxy records, we interpret these observations as a difference in response time of the involved processes to retreating ice edge. During glacial onset, the northward displacement of the oceanic and atmospheric frontal zones is relatively instantaneous, because by definition these fronts cannot be located underneath the ice. However, response of continental systems to increased moisture availability will not cause instantaneous increased supply of eolian and fluvial sediments owing to the aforementioned terrestrial lags.

A comparable increase in winter rainfall during the LGM has been inferred from sediment and pollen records in South America (Heusser, 1989a; Lamy et al., 1998, 2001). Moreover, speleothem records from the easternmost winter rain region of Australia also show an increase in humidity related to glacial intervals during the past 500 k.y. (Ayliffe et al., 1998). However, Hesse et al. (2004) argued that in southeastern Australia the proxy records give an unclear picture of continental aridity during the Quaternary, and there is also evidence for increased aridity during glacial times (for an extensive review of Quaternary Australian climate, see Shulmeister et al., 2004). Nevertheless, considering the similar latitudinal positions of the aridity records, and their location in the winter rain climate zones of the three continents, we hypothesize that the mechanism for humidity increases during glacial intervals could potentially be the same.

Although we are aware of the uncertainties and pitfalls in the interpretation of the proxy records, we propose that climate in the winter rainfall region of southwestern Africa is linked to Antarctic sea ice through the impact that the sea-ice movements have on the position of oceanic and atmospheric fronts. Extended Antarctic sea ice during the glacial period caused an increase of the polar high and therefore an expansion of the polar vortex, leading to a northward shift of the fronts and moisture-bearing air masses, resulting in enhanced precipitation in the winter rain region of southwestern Africa. Retreat of sea ice during warm periods caused a decrease of the polar vortex and a poleward shift of the oceanic and atmospheric frontal zones. This effect, in turn, led to reduced precipitation along the continent's western margin. If our proposed hypothesis is true and if the Southern Ocean gets warmer in the future in response to global temperature rise, we may expect a further decline of Antarctic sea-ice cover and a southward migration of oceanic and atmospheric frontal zones. On the basis of this hypothesis we speculate further that these changes may lead to reduced precipitation and therefore to enhanced desertification over southwestern Africa. It appears that such a scenario may have existed during the last interglacial interval (ca. 128 ka), which was warmer than today (e.g., Vimeux et al., 1999) and was a time in which the Southern Ocean frontal zones were farther south than they are today (Brathauer and Abelmann, 1999) and in which more arid climate conditions prevailed in southwestern Africa (Stuut et al., 2002).

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