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Increased input of circumpolar deep water-borne detritus to the glacial SE Atlantic Ocean

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[1] Analysis of radiogenic isotopes in marine sediments can provide useful information on the provenance and transport of detrital material, directly relevant to paleoceanographic investigations. Here we show that the detrital Nd isotopic composition of recent SE Atlantic marine sediments matches the complex modern-day hydrography. In these same cores, glacial-interglacial isotopic variations are consistent with previous investigations (using different paleoceanographic proxies), which have shown that the relative influence of North Atlantic Deep Water (NADW) into the South Atlantic was reduced during glacial periods. In a novel departure, however, we also calculate the mass accumulation rates of terrigenous material delivered by each of Circumpolar Deep Water (CDW) and NADW to demonstrate that the accumulation of detritus delivered by CDW was enhanced significantly in the glacial South Atlantic. This enhanced transport flux could be explained by an increased flow of CDW into the glacial South Atlantic and/or an increased concentration of suspended terrigenous material transported by glacial CDW.

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1. Introduction

[2] Thermohaline circulation plays a major role in climate change [*Broecker and Denton*, 1989]. At present, the formation of North Atlantic Deep Water feeds a 'global conveyor belt' which redistributes heat around the Earth. Atlantic deep-water progresses south toward the Southern Ocean, where it mixes with Circumpolar Deep Water and flows onward into the Indian and Pacific Oceans [*Broecker*, 1991]. The SE Atlantic Ocean, and the Cape Basin in particular, are therefore regions where fluctuations in the global influences of NADW and CDW can be monitored well [*Charles and Fairbanks*, 1992].

[3] Previously, various proxies have been used to investigate the general pattern of deep-water circulation during the last glacial maximum [*Broecker and Denton*, 1989; *Charles and Fairbanks*, 1992; *Bickert and Wefer*, 1996; *Boyle and Rosenthal*, 1996; *Dieckmann et al.*, 1996; *Rutberg et al.*, 2000]. In the South Atlantic, however, the use of these proxies has led to conflicting results, indicating that additional tracers of deep-water circulation were needed. Records of $\delta^{13}C$ [*Charles and Fairbanks*, 1992; *Bickert and Wefer*, 1999] and carbonate dissolution [*Bickert and Wefer*, 1996] have indicated that the chemical properties of glacial bottom-water in the South Atlantic resembled contemporaneous deep-water in the Pacific Ocean, implying a strong reduction of the export of NADW to the glacial Southern Ocean. However, other proxies such as Cd/Ca and Ba/Ca records from benthic foraminifers have argued for the presence of a strong NADW component mixed into glacial southern water masses [*Lea and Boyle*, 1990; *Boyle*, 1992]. Similarly, sedimentary $^{231}Pa/^{230}Th$ ratios measured in Atlantic sediments have suggested that the glacial analog of NADW continued to export vigorously to the Southern Ocean during the last glacial maximum [*Yu et al.*, 1996; *Marchal et al.*, 2000]. The divergence of these interpretations has been ascribed to problems related to (1) dissolution of carbonates (Cd/Ca; Ba/Ca [*McCorkle*, 1995]) and, (2) productivity effects, which may either overprint the "seawater signal" recorded in the shell of benthic foraminifers in high-productivity areas ($\delta^{13}C$ [*Mackensen et al.*, 1993; *Bickert and Wefer*, 1999]) or influence the scavenging rate of reactive particles; ($^{231}Pa/^{230}Th$ [*Marchal et al.*, 2000]). Recently, *Rutberg et al.* [2000] resolved part of this controversy by analyzing the Nd isotopic composition of the hydrogenous Fe-Mn oxide component in marine sediments; a new potential proxy which is not thought to be affected by productivity or dissolution effects. Their results, from the southern Cape Basin, provide a clear indication that the relative influence of NADW was markedly reduced in the Southern Ocean during the last glacial maximum. These Fe-Mn oxyhydroxide phases, just like most "traditional" paleoceanographic proxies (e.g., $\delta^{13}C$, Cd/Ca and Ba/Ca), act as direct archives of the chemical composition of past water masses. In the South Atlantic and adjacent Southern Ocean, those tracers can provide information on the relative degree of mixing between Atlantic and southern water masses during the Late Quaternary. A proxy which would allow one to reconstruct the independent behavior of each of NADW and CDW, however, would offer an interesting complementary insight to our understanding of deep-water circulation in the glacial South Atlantic Ocean.

[4] In marine sediments, detrital clays and other silicate minerals retain their Nd isotopic signature during all of: continental weathering, sediment transport and diagenesis. Isotopic analyses of these terrigenous fractions, therefore, can provide direct and quantitative information on the provenance of the sediment under investigation [*McCulloch and Wasserburg*, 1978; *Grousset et al.*, 1988; *Jones et al.*, 1994; *Revel et al.*, 1996; *Innocent et al.*, 1997; *Hemming et al.*, 1998; *Asahara et al.*, 1999; *Walter et al.*, 2000]. Measuring the Nd content and $^{143}Nd/^{144}Nd$ ratios of detrital fractions offers a further potential advantage over proxies which only record past seawater compositions: knowing the total accumulation rate of detrital sediment at any site one can, in principle, calculate the mass accumulation rate associated with each contributing detrital source. This, in turn, offers the potential to determine past variations associated with each transport mechanism, independently.

[5] The transport of terrigenous particles to the deep-sea is controlled by a complex system of atmospheric, hydrographic, glacial and topographic conditions [*Biscaye*, 1965]. With increasing distance from source areas, advection of fine-grained particles by deep-water currents becomes the most important mode of detrital transport to deep-sea sediments [*Biscaye*, 1965; *Petschick et al.*, 1996]. For example, studies in the North Atlantic area show clearly that the Nd isotopic composition of surface sediments matches the pathway of deep currents remarkably closely [*Revel et al.*, 1996; *Innocent et al.*, 1997]. In the deep South Atlantic, although surface currents have also been shown to influence the local isotopic composition of deep-sea terrigenous sediments (i.e., in the southern Cape Basin [*Rutberg et al.*, 2002]), fine-grained sediment transport and distribution remains primarily controlled by the deep-water advection of Circumpolar Deep Water and North Atlantic Deep Water [*Dieckmann et al.*, 1996; *Petschick et al.*, 1996; *Gingele and Schmiedl*, 1999; *Walter et al.*, 2000; *Kuhn and Dieckmann*, 2002]. At present, they are three main potential sources of detritus to the deep southeast Atlantic ocean (Figure 1a): (1) clays delivered to the equatorial Atlantic by the Congo River and transported southward by NADW; (2) material from the southwestern Atlantic province advected northward by CDW; (3) aeolian dust blown from the Namib Desert by SE Trade winds [*Petschick et al.*, 1996; *Dieckmann et al.*, 1996]. Present-day sedimentation in the SE Atlantic is also strongly influenced by the presence of the Walvis Ridge, which almost completely prevents CDW from entering the Angola Basin (Figure 1b). In this study, we have analysed the Nd isotopic composition of detrital fractions from four sediment cores from the southeast Atlantic Ocean (NAUSICAA–IMAGES II cruise (Figure 1a)) to investigate variations in the accumulation of detritus transported by each of CDW and NADW to this region during the Late Quaternary.

2. Sampling and Methods

[6] Two of our cores were raised from the northern Cape Basin (Figure 1a). These cores were chosen specifically to investigate the vertical structure of the deep SE Atlantic water column during the Late Quaternary: MD96-2086 (3606 m) was collected from the present-day boundary between NADW and Lower CDW while MD96-2098 (2910 m) was taken from nearer to the core of present-day NADW [*Reid*, 1989] (Figure 1b). We have also investigated the Nd isotopic composition of two further cores, MD96-2091 from the Angola Basin and MD96-2085 from the central Cape Basin, which lie north and south of the northern Cape Basin cores, along the southward flowing trajectory of modern-day NADW (Figure 1b).

[7] Apart from carbonate-rich core MD96-2085 (>85% $CaCO_3$ [*Bayon*, 2002]), lithologies are variable down-core, exhibiting changes in the relative amounts of carbonate ooze, biogenic silica (mainly diatoms and sponge spicules), and the terrigenous fraction [*Bertrand et al.*, 2002a, 2002b]. Lowering of sea level during glacial times might be expected to have exposed the Namibian continental shelf to erosion and potentially enhanced transport of detrital particles to the deep-sea. However, no evidence for turbidite or slump deposition is observed in any of the cores studied [*Bertrand et al.*, 2002a] and clay mineral studies in other sediment cores studied from the same area indicate that erosion of the shelf has not contributed significantly to base-of-slope sedimentation, even during periods of low sea level [*Dieckmann et al.*, 1996; *Gingele and Schmiedl*, 1999].

[8] Detrital fractions were isolated according to the procedure described in *Bayon et al.* [2002], which involves the separation of carbonates, Fe-Mn oxyhydroxides and organic compounds from the detrital sediment phase. In this work, Nd isotopic compositions were determined for the entire detrital fraction rather than any specific grain-size fraction. In all sediments, this detritus comprised predominantly fine-grained material (<20 μm) with glacial sediments containing an additional coarser sand fraction (G. Bayon, unpublished data, 2002). An age model for core MD96-2091 (Angola Basin) has been established based on $\delta^{18}O$ analyses in bulk carbonate fractions. Age models for cores MD96-2086 [*Bertrand et al.*, 2002a], -2085 [*Chen*

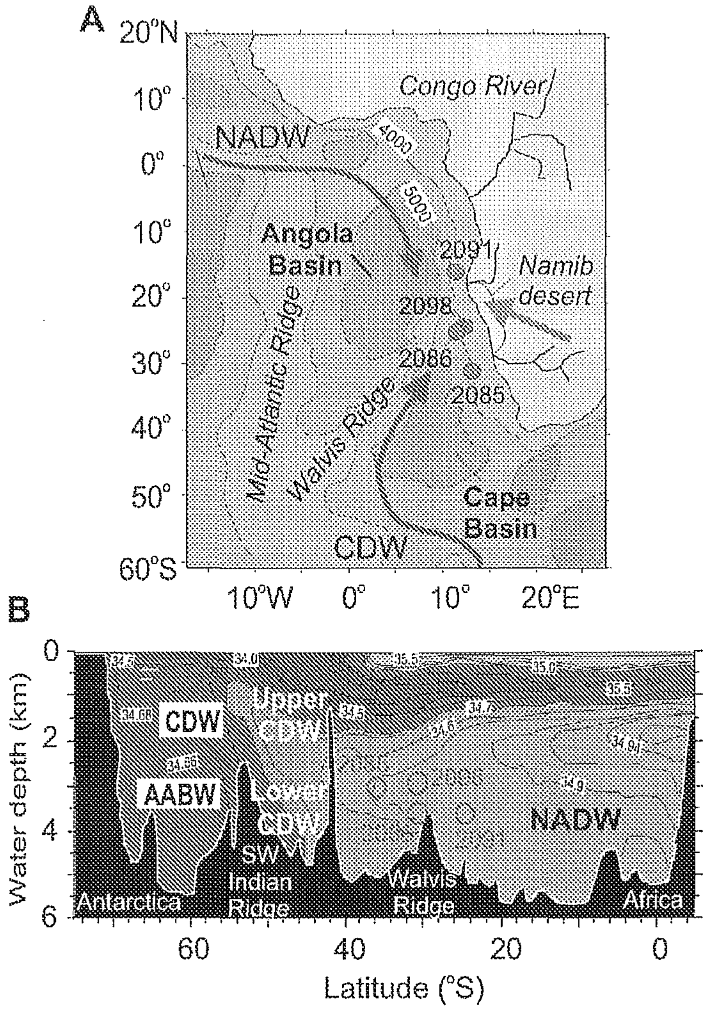

Figure 1. Map and N-S cross-section of our South East Atlantic study area. (a) Location map showing positions of core analyzed for this study. Cores MD96-2098 and -2086 were raised from the northern Cape Basin. Core MD96-2091 and -2085 were collected from further north and south, in the Angola Basin and central Cape Basin, respectively. NADW (red arrow) transports clays delivered to the Equatorial Atlantic by the Congo River, whereas advection of CDW (blue arrow) carries detritus from the SW Atlantic province. Southeasterly trade winds (orange arrow) deliver aeolian dusts from the Namib Desert. (b) Cross-section of salinity for the present-day South East Atlantic Ocean along the Greenwich meridian (modified from *Reid* [1989]). The depths and latitudes of the sediment cores analyzed in this study are represented schematically as red circles.

et al., 2002] and -2098 (R. Schneider, unpublished data, 1998) are derived from benthic foraminiferal $\delta^{18}O$ stratigraphies. These stratigraphies were correlated to the $\delta^{18}O$ reference curve of *Martinson et al.* [1987], assuming linear sedimentation rates between selected age control points. Accumulation rates of material from each of the three different detrital sources have been determined by combining the percentage contribution from each source, calculated from Nd isotope data (see later), and with bulk accumulation rates for the total terrigenous fraction. Uncertainties in these absolute terrigenous accumulation rates, derived from $\delta^{18}O$ stratigraphies depend upon the age difference between any two control points from which a linear sedimentation rate has been assumed. Those uncer-

Table 1. Nd Isotope Data of Detrital Fractions and Terrigenous Accumulation Rates (MAR)[a]

					Detrital sources, %			Terrigenous MAR (g/cm2/kyr)			
Depth in Core, cm	Age, kyr	Isotopic Stage	ε_{Nd}[b]	[Nd], ppm	Namib Winds	Congo River	SW Atlantic	Total	Congo, source (1)	SW Atlantic, source (2)	Ratio (2)/(1)
MD96-2091 (Location: Angola Basin – 14°53′S, 10°23′E, depth = 3569 m)											
2	1.6	Hol	−21.89 ± 0.12	28.4	32	68	0	-	-	-	-
21	7.2	Hol	−21.95 ± 0.14	25.6	40	60	0	1.5	0.9	0	0
41	9.6	Hol	−20.34 ± 0.08	22.5	53	47	0	3.8	1.8	0	0
61	**12.0**	**Hol/2**	**−18.22 ± 0.08**	**23.6**	**53**	**44**	**4**	**3.6**	**1.6**	**0.1**	**0.08**
81	**15.5**	**2**	**−18.08 ± 0.08**	**24.6**	**48**	**45**	**7**	**2.8**	**1.3**	**0.2**	**0.15**
121	**24.7**	**2/3**	**−16.99 ± 0.08**	**21.9**	**57**	**36**	**7**	**2.3**	**0.8**	**0.2**	**0.19**
321	**65.0**	**4**	**−16.97 ± 0.08**	**24.3**	**46**	**41**	**13**	**2.4**	**1.0**	**0.3**	**0.31**
341	**68.8**	**4**	**−17.30 ± 0.08**	**21.5**	**59**	**36**	**4**	**2.8**	**1.0**	**0.1**	**0.12**
361	72.5	4/5	−18.26 ± 0.10	22.4	58	41	0	2.7	1.1	0	0.01
381	76.3	5	−18.61 ± 0.08	23.7	54	45	1	2.3	1.0	0	0.03
511	105.0	5	−18.43 ± 0.08	19.0	66	34	0	2.4	0.8	0	0
611	117.7	5	−20.03 ± 0.14	26.5	44	56	0	4.0	2.2	0	0
641	122.0	5.5	−20.01 ± 0.12	27.0	42	58	0	3.8	2.2	0	0
651	126.8	5	−19.60 ± 0.18	27.2	42	57	2	1.1	0.6	0	0.03
661	**131.7**	**6**	**−19.59 ± 0.10**	**29.9**	**30**	**63**	**7**	**1.1**	**0.7**	**0.1**	**0.11**
681	**141.3**	**6**	**−18.71 ± 0.20**	**24.2**	**52**	**47**	**2**	**1.1**	**0.5**	**0**	**0.04**
701	**151.0**	**6**	**−18.69 ± 0.14**	**24.1**	**52**	**46**	**1**	**1.3**	**0.6**	**0**	**0.03**
761	**166.0**	**6**	**−16.52 ± 0.10**	**23.2**	**49**	**37**	**14**	**1.9**	**0.7**	**0.3**	**0.37**
961	219.5	7	−18.34 ± 0.10	26.1	42	49	9	1.8	0.9	0.2	0.18
1041	**253.0**	**8**	**−19.27 ± 0.08**	**25.8**	**47**	**52**	**1**	**1.3**	**0.7**	**0.0**	**0.02**
1082	**263.0**	**8**	**−17.22 ± 0.08**	**22.8**	**53**	**39**	**8**	**2.1**	**0.8**	**0.2**	**0.21**
1141	**295.3**	**8**	**−18.65 ± 0.10**	**22.2**	**58**	**42**	**0**	**0.8**	**0.3**	**0**	**0**
1161	**303.6**	**8/9**	**−18.02 ± 0.10**	**24.1**	**50**	**44**	**6**	**0.8**	**0.3**	**0.0**	**0.14**
1201	320.2	9	−20.07 ± 0.08	26.7	43	57	0	1.1	0.6	0	0
MD96-2098 (Location: Northern Cape Basin – 25°36′S, 12°38′E, depth = 2910 m)											
0	6.0	Hol	−12.95 ± 0.21	12.0	91	9	0	-	-	-	-
25	7.0	Hol	−13.30 ± 0.16	16.2	75	17	9	3.4	0.6	0.3	0.52
110	11.4	Hol/2	−11.98 ± 0.16	-	-	-	-	-	-	-	-
171	**14.4**	**2**	**−11.14 ± 0.10**	**14.5**	**80**	**10**	**11**	**5.3**	**0.5**	**0.6**	**1.12**
201	**16.0**	**2**	**−10.53 ± 0.16**	**17.5**	**62**	**12**	**27**	**5.1**	**0.6**	**1.4**	**2.34**
231	**17.6**	**2**	**−10.55 ± 0.16**	**17.3**	**63**	**11**	**26**	**5.3**	**0.6**	**1.4**	**2.29**
MD96-2086 (Location: Northern Cape Basin – 25°49′S, 12°8′E, depth = 3606 m)											
46	0.4	Hol	−11.84 ± 0.12	20.6	48	19	33	1.0	0.2	0.3	1.79
86	7.5	Hol	−11.33 ± 0.12	23.1	32	20	47	1.3	0.3	0.6	2.35
121	10.6	Hol/2	−10.12 ± 0.41	26.0	12	19	69	2.4	0.5	1.6	3.60
161	**15.2**	**2**	**−9.87 ± 0.16**	**23.5**	**26**	**16**	**58**	**2.7**	**0.4**	**1.6**	**3.73**
469	48.3	3	−10.83 ± 0.10	15.8	72	10	18	1.8	0.2	0.3	1.73
609	**62.2**	**4**	**−9.56 ± 0.08**	**17.9**	**57**	**9**	**34**	**3.8**	**0.4**	**1.3**	**3.54**
748	81.7	5	−10.85 ± 0.08	16.4	68	11	21	1.7	0.2	0.4	1.85
962	122.0	5.5	−11.86 ± 0.10	18.1	62	16	23	0.5	0.1	0.1	1.47
1009	126.1	5/6	−11.26 ± 0.10	16.3	70	12	18	2.9	0.3	0.5	1.51
1072	**131.0**	**6**	**−7.67 ± 0.16**	**10.5**	**97**	**0**	**4**	**2.1**	**0**	**0**	**0**
1421	**181.6**	**6**	**−9.99 ± 0.10**	**20.4**	**44**	**13**	**43**	**3.7**	**0.5**	**1.4**	**3.08**
1441	**184.7**	**6/7**	**−10.05 ± 0.18**	**19.3**	**50**	**12**	**38**	**4.1**	**0.5**	**1.3**	**2.80**
1481	190.9	7	−10.87 ± 0.14	18.1	59	13	28	3.7	0.5	0.8	1.74
1501	193.1	7	−10.71 ± 0.10	-	-	-	-	-	-	-	-
1516	195.5	7	−10.67 ± 0.20	16.4	68	11	21	0.4	0.0	0.1	1.37
MD96-2085 (Location: Central Cape Basin – 29°42′S, 12°56′E, depth = 3001 m)											
0	0.5	Hol	−11.39 ± 0.27	21.6	41	19	41	-	-	-	-
20	3.8	Hol	−10.90 ± 0.12	26.1	15	22	63	0.4	0.1	0.2	2.88
50	8.4	Hol	−11.59 ± 0.14	25.6	20	24	56	0.4	0.1	0.2	2.34
60	10.0	Hol	−10.92 ± 0.14	21.5	40	17	43	0.4	0.1	0.2	2.52
90	**14.6**	**2**	**−10.85 ± 0.18**	**26.9**	**10**	**23**	**67**	**0.5**	**0.1**	**0.3**	**2.96**
110	**18.8**	**2**	**−9.79 ± 0.12**	**21.5**	**37**	**14**	**50**	**0.5**	**0.1**	**0.3**	**3.67**

[a] Bold represents samples from glacial periods.
[b] Errors given are in-run errors (2 s.e). Note that these are generally lower than the external reproducibility (2 s.d. = ±0.16 ε units).

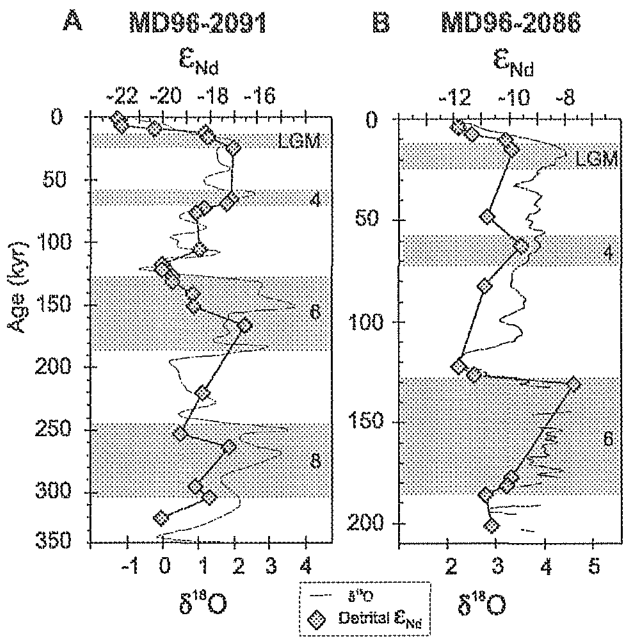

Figure 2. Nd isotopic compositions of detrital fractions and $\delta^{18}O$ record versus age (left side) and marine isotope stages (right side). Nd isotope data follow the $\delta^{18}O$ climatic signal, with terrigenous fractions from both (a) MD96-2091 and (b) -2086 cores showing a trend toward more radiogenic ε_{Nd} values in glacial versus interglacial periods. Cores -2098 and -2085 also exhibits a similar trend (Table 1).

tainties can be important in our study (i.e., from ±ca. 5% for the longest episodes to ±*ca.* 75% for the shortest ones [*Bertrand et al.*, 2002a]).

[9] Nd concentrations were analysed by ICP-MS on a VG Plasmaquad II+ instrument with an external accuracy of 5% (2 s.d.) and an internal precision better than 3% (2 s.e.). For isotopic analyses, Nd was separated by standard chromatographic methods and $^{143}Nd/^{144}Nd$ ratios were determined using dynamic mode data collection on a VG Sector 54 thermal ionization mass spectrometer. Isotope ratios were normalized to $^{146}Nd/^{144}Nd = 0.7219$. Analysis of the Nd-standard JNdi-1 gave $^{143}Nd/^{144}Nd = 0.512108 \pm 8$ (2 s.d., n = 14), during the run period (3 months).

3. Results and Discussion

[10] In cores MD96-2091 (Angola basin) and MD96-2086 (northern Cape Basin), the Nd isotopic compositions of the detrital fractions follow the $\delta^{18}O$ climatic signal (Table 1; Figure 2) with terrigenous fractions of both cores exhibiting more radiogenic (higher) ε_{Nd} values during glacials than interglacials. The two other cores from the northern (MD96-2098) and central (MD96-2085) Cape Basin also exhibit a trend toward more radiogenic ε_{Nd} values from the Holocene to the LGM (Table 1).

3.1. ε_{Nd} Values of Recent Clay-Rich Fractions: A Record of Present-Day Hydrography

[11] In Figure 3a, ε_{Nd} data are plotted against 1/Nd concentrations to investigate whether the Nd isotopic composition of recent (interglacial) detrital fractions accurately record the present-day hydrography of the deep southeast Atlantic. All Nd isotopic compositions and concentrations for the end-members are based on data from the literature or from this study. Nd concentrations and isotopic compositions of the three detrital end-members are given in Table 2. The source of sediment in the Angola Basin (core MD96-2091) is clearly dominated (>50%) by highly unradiogenic Congo River

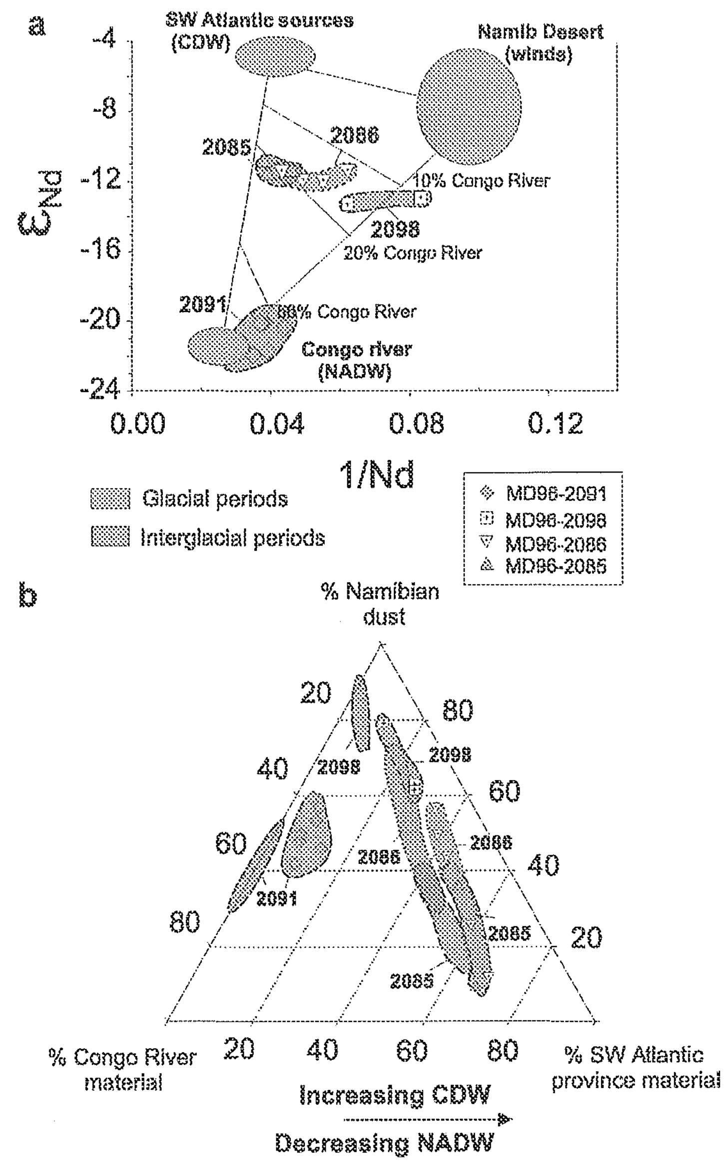

Figure 3. (a) Plot of ε_{Nd} versus 1/Nd for detrital fractions from recent (and interglacial) periods. The three potential sources of terrigenous material to the South Atlantic are plotted for comparison, with their modes of transport indicated in parentheses. Mixing lines between the three end-members are shown, together with mixing lines corresponding to sediments which contain 10%, 20% and 50% Congo River clays. Nd concentrations and isotopic data for these end-members are from the literature (see Table 2). (b) Ternary diagram showing the relative percentages of detritus from the SW Atlantic province, Congo River and Namibian dust in our studied samples (relative percentages calculated using a simple three-component mixing model).

material, whereas Namibian dust and southwestern Atlantic clays more strongly influence Cape Basin sedimentation (<20% Congo River clay input). Holocene detrital fractions from MD96-2098, situated near the core of present-day NADW, consist of a mixture of Congo River and Namib Desert material alone. By contrast, core MD96-2086, which samples the boundary between present-day NADW and lower CDW, and core MD96-2085, located further south, are also enriched in material

Table 2. Three-Component Mixing Model: εNd and [Nd] Values of End-Members[a]

	ε_{Nd}	[Nd] ppm
Congo River material	−22[b] (−22[b]; −16[c])	40[d]
SW Atlantic clay	−5[e] (−6.5 to −3.5)[e]	25 (15 to 28)[e]
Namibian dust	−8[b,f] (−11.5 to −4.5)[b,f]	10[b]

[a] Values between brackets indicate the measured range.
[b] This work.
[c] *Allègre et al.* [1996], suspended river loads.
[d] *Dupré et al.* [1996], suspended river loads.
[e] *Walter et al.* [2000], SW Atlantic clay-size detritus.
[f] *Grousset et al.* [1992], Aeolian and sand samples.

transported north by CDW from the SW Atlantic province. Recent detrital fractions in core MD96-2085, located south of the Namib Desert, plot close to the mixing line between Congo River and SW Atlantic material alone (Figure 3a). All these features match the modern-day circulation of deep-water in the Cape Basin remarkably well (Figure 1b). This is important because it provides reassurance that analysis of the Nd isotopic records preserved down-core within our SE Atlantic marine sediments should yield an accurate record of past variations in deep-water circulation in this region.

3.2. Detrital Sedimentation in the Glacial SE Atlantic

[12] Before pursuing any interpretation of the Nd isotopic record in SE Atlantic sediments, however, it is important to consider whether the Nd concentration and isotopic composition of any of the three major potential detrital sources might have fluctuated during the Late Quaternary. For Nd isotopes, weathering products from various types of rock tend to be homogenized thoroughly during both transport - whether by wind or rivers - and deposition - as desert sand or loess [e.g., *Asahara et al.*, 1999]. Therefore, major changes in the Nd isotopic composition of dust loads from the Namib Desert are not anticipated to have arisen between cold and warm stages. For the Congo River, there is evidence that discharge increased during past interglacials and periods of enhanced monsoon activity [*Schneider et al.*, 1997; *Gingele et al.*, 1998]. However, the Congo River drains an extensive platform, mainly occupied by the Central African Shield, which integrates the lithological and chemical diversity of the continental crust. As a consequence, the Nd isotopic composition of clays delivered by the Congo River has probably remained quite constant over the Late Quaternary. Therefore, although changes in weathering regime in the Congo River catchment basin may have affected the clay mineralogy of the river's suspended load [*Gingele et al.*, 1998], the Sm-Nd isotope systematics of this clay fraction should not be altered significantly. Finally, the Nd isotope ratios of both glacial and interglacial sediments from the Scotia Sea all fall within a limited range ($-3.5 > \varepsilon_{Nd} > -6.5$ [*Walter et al.*, 2000]), suggesting that the isotopic signature of clays transported by CDW has not varied drastically between cold and warm climatic stages, either. In addition, the range of Nd concentrations in terrigenous SW Atlantic sediments over interglacial/glacial periods is small when compared to variations between our three different end-members [*Walter et al.*, 2000]. This suggests that major changes in the Nd content of the three end-members are also unlikely to have occurred between glacial and interglacial stages. To a first approximation, we assume therefore that all three "end-member" sources have remained invariant, with respect to Nd concentrations and isotopes, throughout the glacial and interglacial stages investigated. Next, we investigate past detrital ε_{Nd} variations, down-core.

[13] We have calculated percentage contributions of our three "end-member" components (Congo River, SW Atlantic province and Namib Desert) to the detrital phase of all four cores studied (Table 1; Figure 3b). During glacial times, the contribution of Congo River material was reduced in both the Angola Basin (from ~60% to ~40%) and the Cape Basin (from ~20% to ~10%), while the percentage of clays from the southwestern Atlantic increased (Table 1; Figure 3b). This trend is consistent across all four cores, providing further reassurance of the validity of our approach and indicating that this represents a feature common throughout SE Atlantic sedimentation in the Late Quaternary. The data are consistent with previously reported evidence that the relative influence of NADW was greatly reduced in the South Atlantic during glacial periods, as demonstrated from studies using more

established paleoceanographic proxies [*Charles and Fairbanks*, 1992; *Bickert and Wefer*, 1996; *Boyle and Rosenthal*, 1996; *Dieckmann et al.*, 1996; *Rutberg et al.*, 2000]. In the next section, we extend this study further and calculate mass accumulation rates for each detrital source, to infer past variations in supply of detrital material associated with CDW and NADW, respectively.

3.3. Variations in Terrigenous Material Transport by NADW and CDW

[14] Using the simple three-component mixing calculations employed to construct Figure 3, we have also computed mass accumulation rates (MARs) for Namibian dust; Congo River clays and SW Atlantic province detritus. Calculated mass accumulation rates of Congo River material have remained relatively constant throughout the Late Quaternary (Table 1). For core MD96-2091, with the exception of two marked peaks at 10 kyr and 120 kyr (~2 g/cm^2/kyr), our calculated MARs for Congo River material have remained quite constant (0.8 ± 0.5 g/cm^2/kyr; Figure 4a). Such is also the case for core MD96-2086 (0.3 ± 0.2 g/cm^2/kyr; Figure 4b). This indicates that an efficient transport of this material, by the glacial analog of NADW, must have persisted under glacial conditions; a finding which is in agreement with prior independent ^{231}Pa/^{230}Th studies [*Yu et al.*, 1996; *Marchal et al.*, 2000].

[15] In contrast, calculated MARs for SW Atlantic detritus in all four cores appear much higher for glacial periods than interglacials. For example, accumulation rates for SW Atlantic fine-grained detritus in core MD96-2086 increased from 0.2 ± 0.2 g/cm^2/kyr, during interglacial periods, to 1.4 ± 0.2 g/cm^2/kyr during glacial times (Figure 4b). With the exception of core MD96-2085, glacial MARs for SW Atlantic material are 300–550% higher than interglacial values. These variations are always much larger than the relative uncertainty in the calculated MARs for this end-member (ca. ±75%). To further confirm the validity of our approach, we have also tested the sensitivity of our calculated MARs to changes in ε_{Nd} and [Nd] values (within the full range of cited literature values; Table 2) for our three end-members. An important first result is that, however the ε_{Nd} or [Nd] value used in our calculations is changed, the same interglacial to glacial variations observed in Figure 4 are maintained. By changing the absolute values of ε_{Nd} by ±2 units, or by changing [Nd] for any end-member by ±5 ppm, a maximum MAR error of ±95% is calculated. Again, these errors remain small when compared to the 300–550% MAR enrichments observed in glacial vs. interglacial periods, further confirming the validity of our conclusion: namely that mass accumulation of CDW transported material has been significantly greater during glacial rather than interglacial periods.

[16] Two mechanisms could account for the changes in terrigenous input observed: (1) a source effect, i.e., a change in the amount of material transported by each of NADW or CDW, due to variations in the Congo River discharge, for example; (2) a transport effect, i.e., a change in the deep-water masses, such as a weakening or strengthening of NADW and/or CDW. Below, we investigate to what extent either or both of these effects could account for the observed changes in terrigenous input to our Late Quaternary sediments.

[17] Core MD96-2091, in the Angola Basin, was raised from close to the mouth of the Congo River and, therefore, is probably more sensitive to direct changes in Congo River discharge rather than variations in NADW flow. This is confirmed, apparently, by the strong increases in mass accumulation rate of Congo River material observed at 10 kyr and 120 kyr (Figure 4a), coincident with periods of enhanced monsoon activity (i.e., enhanced chemical weathering) both within the Holocene and during MIS 5 [*Schneider et al.*, 1997]. No similarly marked MAR increases are observed for Congo River clays in the Cape Basin cores (Table 1; Figure 4b), suggesting that these variations in Congo River input must have been attenuated strongly, further south, away from the mouth of the river.

[18] In the Southern Ocean, previous studies of deep-sea sediment cores have routinely shown that accumulation rates of terrigenous material increased significantly during glacial periods

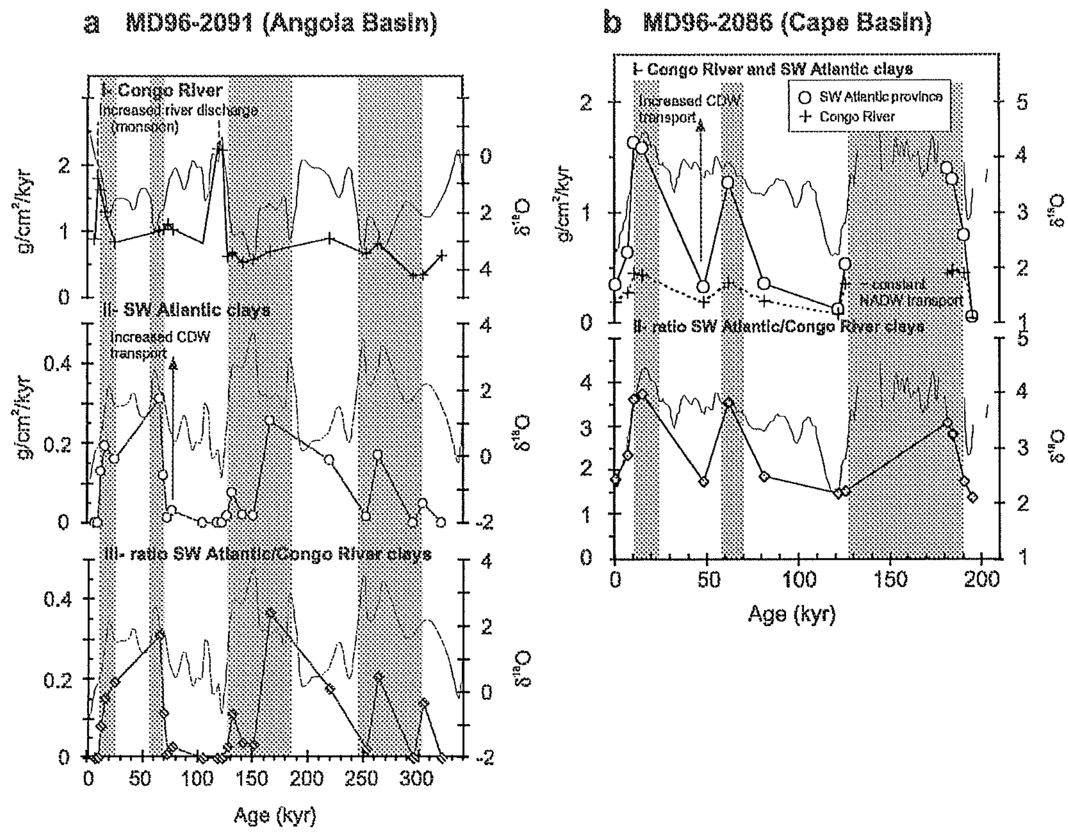

Figure 4. Accumulation rates of Congo River and southwestern Atlantic material, respectively, versus age in (a) core MD96-2091 (Angola Basin) and (b) MD96-2086 (Cape Basin). The $\delta^{18}O$ climatic signal is shown for comparison. Glacial periods are represented by shaded areas. In core MD96-2091, accumulation of Congo River material was higher during periods of enhanced monsoon activity (10 and 120 kyr [*Schneider et al.*, 1997]) but remained relatively constant throughout the Late Quaternary. Accumulation of SW Atlantic material increased greatly during glacial periods. The ratio SW Atlantic/Congo River clays is high during all glacial periods and can be interpreted as a decrease in the relative influence of NADW (see text for discussion).

[e.g., *Dieckmann et al.*, 1996; *Walter et al.*, 2000; *Bareille et al.*, 1994]. These greater MARs result, primarily, from intensified erosion of the southern American shelf [*Walter et al.*, 2000] coupled with more intensive supply of glaciogenic detritus to the open ocean [*Kanfoush et al.*, 2000]. Compared to those sources, any enhanced input of wind-blown particles from the southeastern American continent is considered to be relatively minor [*Walter et al.*, 2000]. Therefore, the higher MARs of SW Atlantic material calculated for our SE Atlantic sediment cores (Table 1; Figure 4) could derive, in part, from enhanced glacial inputs of detritus to the Southern Ocean, yielding an increased concentration of suspended material, per unit volume, transported northward by glacial Circumpolar Deep Water.

[19] Simultaneously, however, changes in the deep-water circulation could also account for the varying mass accumulation rates of SW Atlantic detritus and Congo River clays that we have calculated. During glacial stages, the fraction of detritus delivered by CDW to core MD96-2098 (close to the core of modern NADW; ~20% SW Atlantic clays) was still lower than that delivered to (deeper) core MD96-2086 (~30–70%; Figures 1b and 3b). This is consistent with previous studies [*Sarnthein et al.*, 1994; *Oppo and Horovitz*, 2000] and indicates that stratification of the South Atlantic water column,

similar to the present-day (Figure 1b), must still have been present during the last glacial maximum. In addition, however, the significant increases in accumulation rates for SW Atlantic material during the last glacial maximum provide clear evidence that transport of these sediments to the SE Atlantic by CDW must have been significantly enhanced at that time. This can be observed particularly clearly in the ratios of SW Atlantic:Congo mass accumulation rates which increase systematically from interglacial to glacial periods (Table 1; Figure 4b). One explanation for these enhanced SW Atlantic detritus MARs could be that CDW flow increased during glacial periods.

[20] Certainly, previous studies using the deposition rates of highly particle reactive ^{230}Th have shown that sediment redistribution by bottom currents has been a widespread phenomenon in the Southern Ocean [e.g., *Francois et al.*, 1993, 1997; *Kumar et al.*, 1995; *Frank et al.*, 1996, 1999; *Dezileau et al.*, 2000]. More specifically, in the eastern Atlantic sector of the Southern Ocean, glacial sediment focusing was generally higher than during interglacial periods, indicating a change in the bottom-water flow at that time [*Frank et al.*, 1996, 1999]. That independent ^{230}Th evidence for a change in the bottom-water flow, taken together with our calculations of enhanced glacial SW Atlantic detritus accumulation would be entirely consistent with our hypothesis that the northward flow of CDW increased during glacial periods. Finally, we note that, during glacial periods, even core 2091 in the deep Angola Basin, north of the Walvis Ridge appears to have received SW Atlantic province material (Figures 2 and 3b). This, again, would be consistent with overspill of a more intense northward flow of glacial CDW.

4. Conclusions

[21] Analysis of the Nd isotopic composition of detrital fractions in SE Atlantic marine sediments has provided a novel approach for studying the behaviour of each of NADW and CDW, independently, throughout the Late Quaternary. Our data accurately reproduce the complex modern-day hydrography of the SE Atlantic Ocean and provide an independent confirmation of the relative variations in NADW and CDW at the Last Glacial Maximum.

[22] Importantly, and in agreement with ^{231}Pa/^{230}Th studies, our new data suggest that an efficient transport of fine-grained material by the glacial analog of NADW, similar to present-day conditions, must have persisted during glacial periods. By contrast, these same data also indicate that the accumulation of SW Atlantic terrigenous material transported northward by CDW increased significantly under glacial conditions. If correct, the data presented here would reconcile tracers of ocean flux (i.e., sedimentary ^{231}Pa/^{230}Th ratios), which argue for a continuous export of NADW during glacial periods, with proxies of past seawater composition (e.g., δ^{13}C, ^{143}Nd/^{144}Nd of Fe-Mn oxide coatings), indicating a strong reduction of the relative NADW influence in the glacial South Atlantic. One possible interpretation of our data would be that the apparent decreased in the influence of NADW during glacial periods could be due, in part, to an increased flow of CDW rather than any major weakening of NADW, itself. What remains to be resolved, however, is to what extent our observations reflect fluctuations in the volume fluxes of each of NADW and CDW or, conversely, are the result of variations in the suspended loads carried by each of these water masses over glacial-interglacial cycles.

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