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Supporting Online Material for

155,000 Years of West African Monsoon and Ocean Thermal Evolution

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Supporting Online Material

Material and Method

Sample preparation and measurement of Mg/Ca and Ba/Ca:

25-30 individuals of *G. ruber* variety pink were picked from the 250-300 µm fraction for each analysis. Shell samples were gently crushed and cleaned using the UCSB standard foraminifera cleaning procedure without the DTPA step *(1, 2)*. Dissolved samples were analyzed by the isotope dilution/internal standard method described in (*2*) using a Thermo Finnigan Element2 sector field ICP-MS. Analytical reproducibility of Mg/Ca and Ba/Ca, assessed by analyzing consistency standards (n=137) matched in concentration to dissolved foraminifera solutions and analyzed over the course of entire study (900 samples), is estimated at 0.6 % and 1.8 %, respectively.

Sample preparation and determination of $^{18}O/^{16}O$ (expressed as $\delta^{18}O$)

For the analysis of stable isotopes, we selected from each sample approximately 30 tests of the surface water dweller *G. ruber* (pink) from the size fraction of 250-300 µm. Oxygen isotope measurements were made with the Finnigan MAT 251 mass spectrometer at the Leibniz Laboratory, Kiel University. The instrument is coupled online to a Carbo-Kiel Device (Type I) for automated CO_2 preparation from carbonate samples for isotopic analysis. Samples were reacted by individual acid addition. The mean external error and reproducibility (1σ) of carbonate standards is better than ±0.07% and ±0.05% for $\delta^{18}O$ and $\delta^{13}C$, respectively. Results were calibrated using carbonate isotope standard NBS 20 and in addition NBS 19 and 18, and are reported on the Peedee belemnite (PDB) scale.

Age model for MD03-2707

The age model for the MD03-2707 record was developed using 24 ^{14}C-AMS datings measured at the Lawrence Livermore National Laboratory (Livermore, USA) and at the Leibniz-Laboratorium für Altersbestimmung und Isotopenforschung, Universität Kiel (Kiel, Germany) (Table S1). ^{14}C ages are converted to calendar age using the software "Calib" version 5.0.1 (*3*) and Marine data set (*4*) assuming a reservoir age of 400 years. For ^{14}C-dates beyond the calibration range of the "Calib" software, we use the online software "Fairbanks0805 calibration curve" (*5*). The final age model for the ^{14}C dated interval is based on two polynomial fits (Fig. S3). For the age interval between 54,850 and 120,300 years BP, the age model is developed by alignment of planktonic foraminiferal $\delta^{18}O$ in MD03-2707 with the $\delta^{18}O$ of NGRIP ice core (*6*). For ages older than 119,500 yr BP, the age model is developed by aligning benthic foraminiferal $\delta^{18}O$ in MD03-2707 (see Fig. S2 A) with the $\delta^{18}O$ of the stack record "LR04" (*7*).

Planktic foraminiferal Ba/Ca

Beyond 127,500 yr BP, planktic foraminiferal Ba/Ca is not shown due to post-depositional alteration, as indicated by values exceeding 3 mmol/mol with progressively higher values deeper in the core. This is independently confirmed by benthic foraminiferal Ba/Ca that also shows unusually high values in samples older than 127.500 yr BP. Ba/Ca in *G. ruber* between 120,000 and 127,500 yr BP might be elevated by 10-15% due to diagenetic complications.

Spectral analyses

We have run spectral analyses for the Mg/Ca SST and $\delta^{18}O$ (not shown) using the Arand software (developed by Philip Howell at Brown University). The SST record reveals strong 100 kyr cycles and less pronounced 23 kyr cycles. The $\delta^{18}O$ record shows all obital cycles (100 kyr, 41 kry, and 23 kyr) integrating high and low latitude forcings. The overall cross-correlation between SST and $\delta^{18}O$ is r = 0.83.

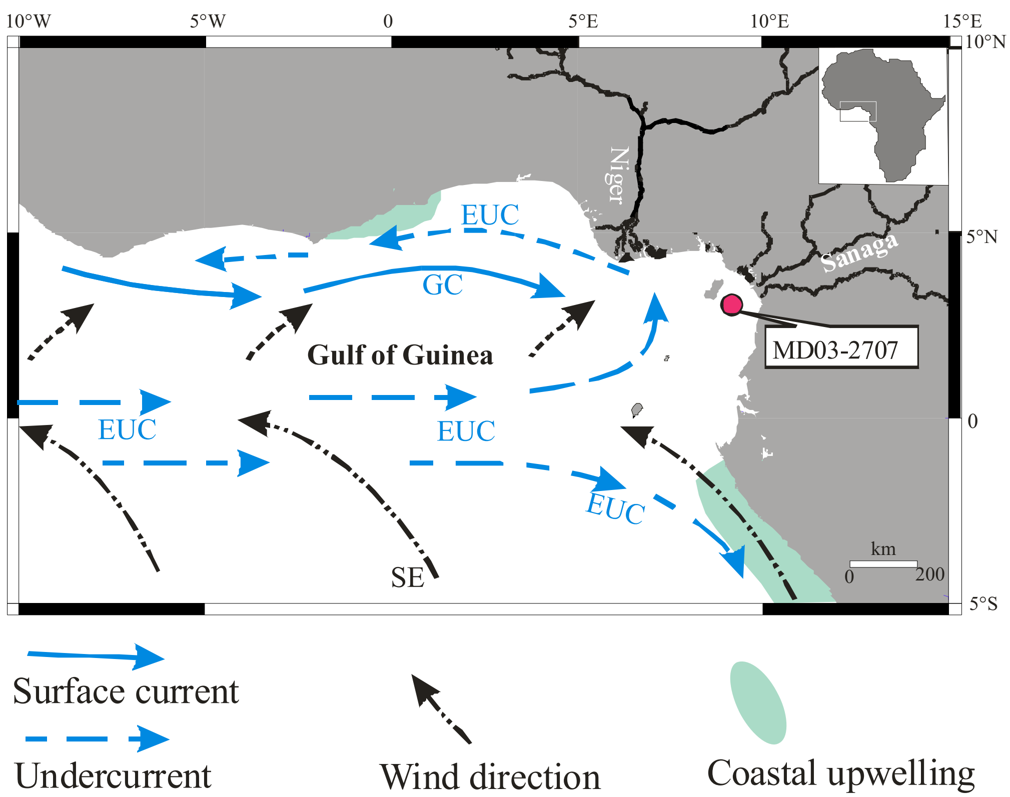

Figure S1: Surface current, subsurface current, and wind direction affecting the hydrography of the Gulf of Guinea (modified redraw from (*8, 9*) and adopted from (10)). GC: Guinea Current; EUC: Equatorial Undercurrent; SE: southeasterly trade winds (south of equator). Note that the upwelling along the east-west trending western equatorial Africa is not related to the local current and/or wind direction, but related to shoaling of the EUC in response to remote forcing of the western equatorial Atlantic (*8, 9*).

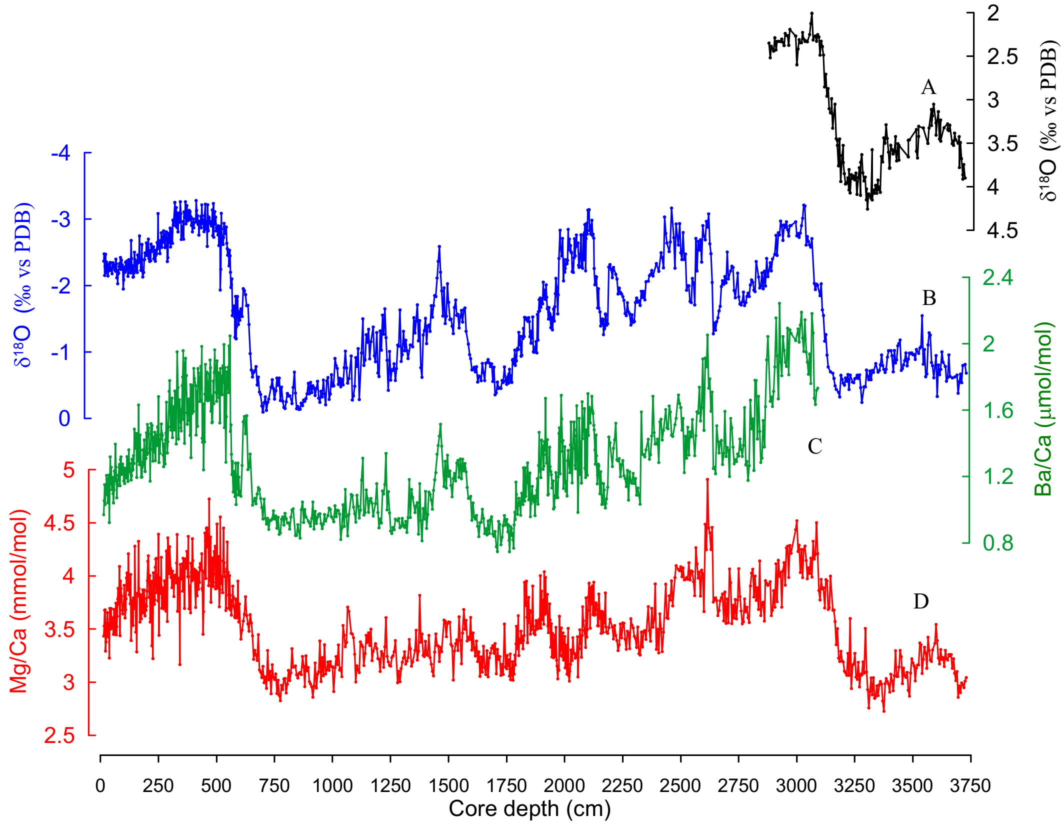

Figure S2: Mg/Ca (D), (C) Ba/Ca, (B) $\delta^{18}O$ in *G. ruber* test*, and* (A) benthic foraminiferal ^{18}O (*Cibicidoides pachydermus*) (black line) versus depth (cm) in MD03-2707.

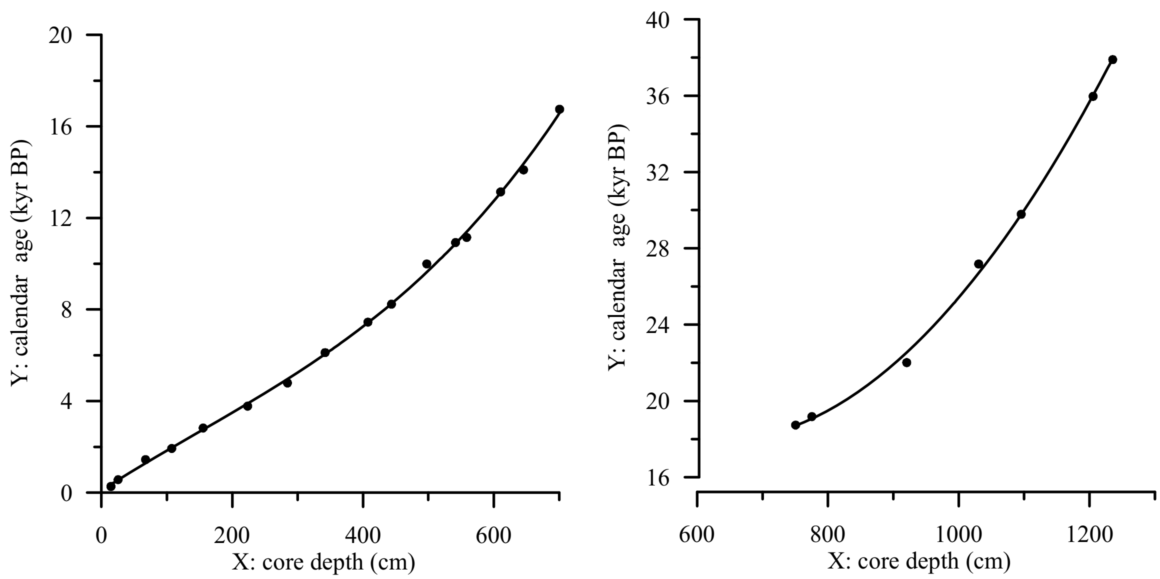

Figure S3: Age model for the ^{14}C-dated interval of MD03-2707 (0-1295.5 cm) obtained using two polynomial fits of calendar age versus core depth (see Table S1 and S2)

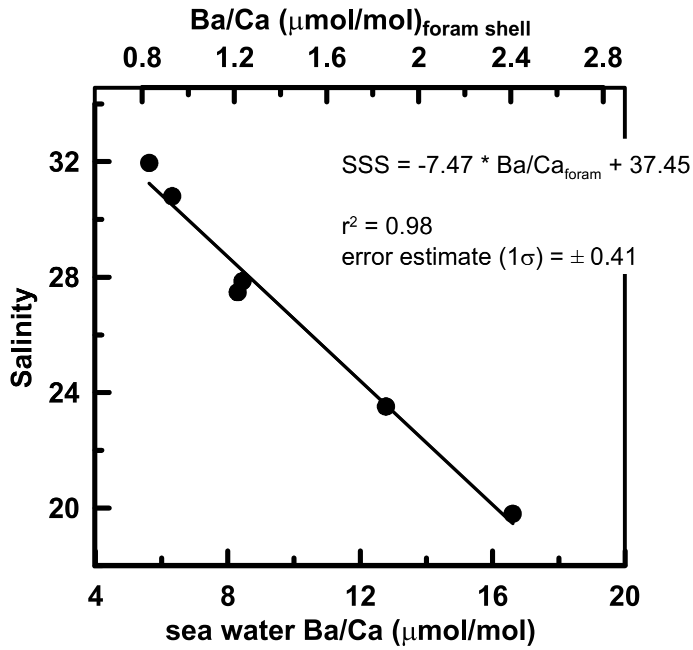

Figure S4: Ba/Ca in sea water and corresponding (calculated) Ba/Ca in planktonic foraminifer versus salinity. Ba/Ca in sea water is obtained using measured Ba and salinity from sites off Congo River (*10*). The corresponding Ca has been calculated assuming conservative behavior of Ca and linear relationship of Ca with salinity (assumption a salinity of 35 psu corresponds to 10.2 mmol/kg). Ba/Ca in planktonic foraminifer is calculated from Ba/Ca (μmol/mol) in sea water using the partition coefficient of D_{Ba}=0.147 (*11*) ($(Ba/Ca)_{sea\ water}$* D_{Ba}=$(Ba/Ca)_{forams}$). We estimate past sea surface salinity (SSS) using variation of planktonic foraminiferal Ba/Ca and the modern SSS-Ba/Ca relationship (see inset in Figure S4).

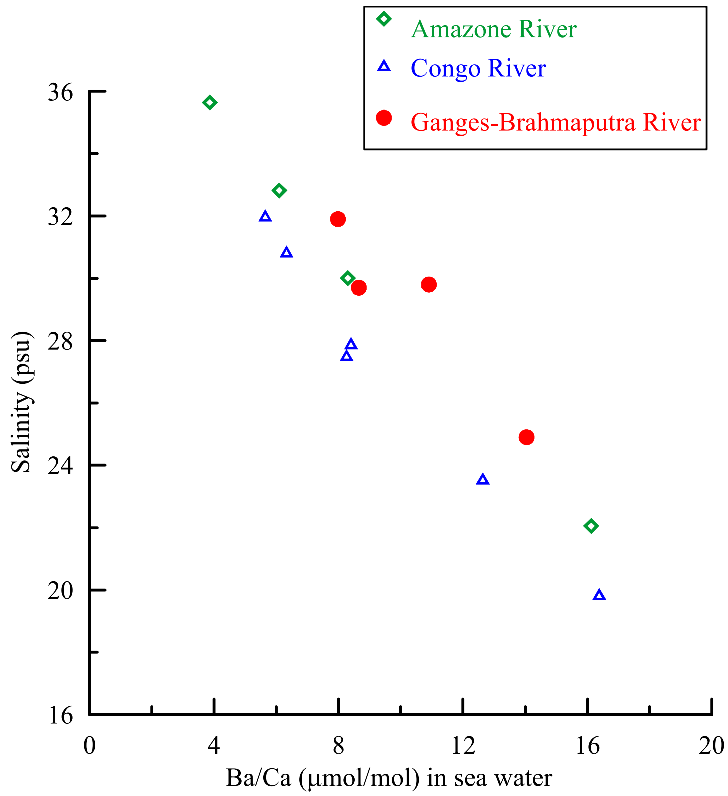

Figure S5: Relationship of sea surface salinity and Ba/Ca in sea water from three large tropical rivers: Congo (*10*), Amazone (*10*), and Ganges-Brahmaputra (*12*).

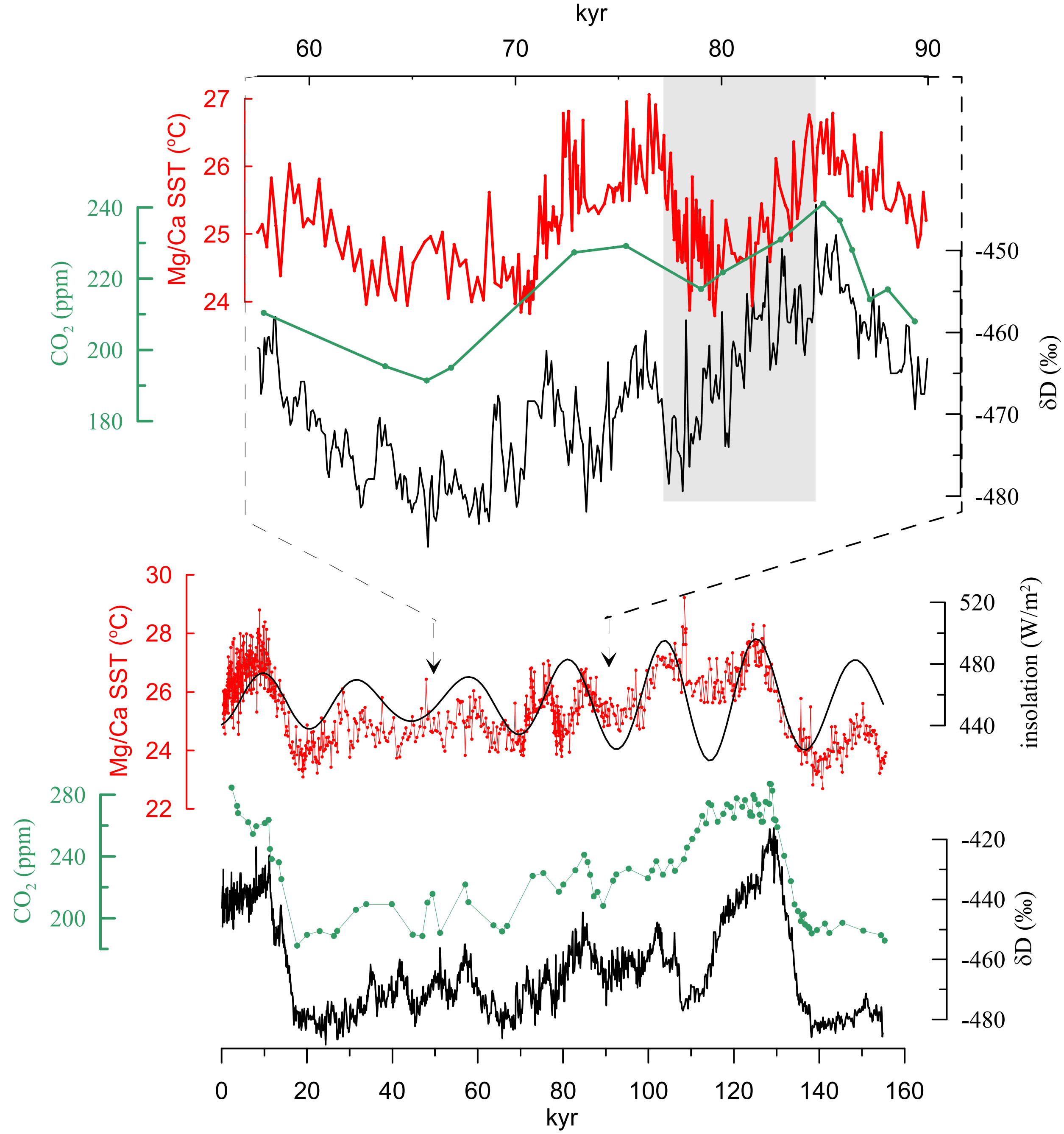

Figure S6: Mg/Ca-based SST estimate in the MD03-2707 record in comparison to mid-summer solar insolation at 15ºN, δD and CO_2 in Vostok ice core, Antarctica, (*13*). Grey area in the blow up points out the cooling interval discussed in the main text.

Table S1: ^{14}C-AMS dates used for establishing the age model of MD03-2707

Lab #	Core	Core depth (cm)	^{14}C age (yr BP)	14C age: ±	Calendar age range (1 σ)	calib. Age (yr, BP)
KIA 31010	MD2707	14.5	620	25	250-293	270
KIA 31011	MD2707	25.5	975	25	533-600	570
KIA 31012	MD2707	67.5	1900	25	1402-1488	1450
KIA 31013	MD2707	107.5	2320	25	1892-1972	1930
KIA 31014	MD2707	155.5	3070	30 / -25	2781-2869	2830
KIA 31015	MD2707	223.5	3835	35	3722-3838	3780
KIA 31016	MD2707	284.5	4585	40	4733-4853	4790
KIA 31017	MD2707	342.0	5700	35	6057-6177	6120
KIA 31018	MD2707	407.5	6945	35	7416-7482	7450
KIA 31019	MD2707	443.5	7755	60	8165-8298	8230
KIA 31020	MD2707	497.5	9170	45	9897-10085	9990
KIA 31021	MD2707	541.5	9950	50	10802-11047	10920
KIA 31022	MD2707	558.5	10125	45	11117-11181	11150
CAMS 126572	MD2707	610.5	11640	35	13100-13178	13140
CAMS 126573	MD2707	645.5	12650	35	14045-14153	14100
CAMS 12838	MD2707	700.5	14450	45	16551-16943	16750
CAMS 12839	MD2707	750.5	15775	45	18681-18789	18740
CAMS 126574	MD2707	775.5	16420	50	19082-19274	19180
CAMS 126575	MD2707	920.5	18795	50	21895-22127	22010
CAMS 127306	MD2707	1030.5	23080	180		27180 ±210
CAMS 126576	MD2707	1095.5	25280	110		29780 ±370
CAMS 126577	MD2707	1205.5	31430	180		35970 ±280
CAMS 127307	MD2707	1235.5	33370	630		37890 ±820
CAMS 127308	MD2707	1295 .5	36960	980		41680 ±600

Table S1: ^{14}C-AMS date used for the chronology of MD03-2707. ^{14}C ages are converted to calendar age using Calib v. 5.0.1 (*3*) and Data set (*4*). For samples that exceed that calibration range of Calib v. 5.0.1, the online "Fairbanks0805 calibration curve" (*5*) has been applied. Samples with prefix CAMS and KIA were analyzed at the Lawrence Livermore National Laboratory (Livermore, USA) and at the Leibniz-Laboratorium für Altersbestimmung und Isotopenforschung, Universität Kiel (Kiel, Germany), respectively.

Table S2: Polynomial fits and tie points used for establishing the age model of MD03-2707

core depth (cm)	cal age (kyr)	polynomial fits to individual cal. age (kyr)e	core depth (cm)	tie points*
14.50	0.27	0.36	1470.50	54.85
25.50	0.57	0.56	1586.90	60.00
67.50	1.45	1.29	1771.60	70.50
107.50	1.93	1.96	1846.05	72.92
155.50	2.83	2.76	1865.50	73.34
223.50	3.78	3.89	1878.78	74.64
284.50	4.79	4.96	1889.00	74.98
342.00	6.12	6.05	1921.87	77.08
407.50	7.45	7.42	1954.45	78.15
443.50	8.23	8.26	1980.50	78.63
497.50	9.99	9.63	2030.50	79.92
541.50	10.92	10.88	2125.50	85.39
558.50	11.15	11.40	2132.50	85.72
610.50	13.14	13.10	2190.50	88.44
645.50	14.10	14.37	2283.85	90.94
700.50	16.75	16.58	2520.50	104.47
750.50	18.74	18.70	2562.93	106.07
775.50	19.18	19.07	2620.50	108.61
920.50	22.01	22.54	2641.84	108.89
1030.50	27.18	26.70	2725.50	115.40
1095.50	29.78	29.77	2739.89	115.57
1205.50	35.97	36.02	2835.50	119.54
1235.50	37.89	37.95	3150.50	129.00
1295 .5	41.68	42.10	3210.50	135.00
			3370.50	140.59
			3730.50	155.63

Table S2: Polynomial fit of individual cal. age is used to develop age model for ^{14}C-AMS-dated interval (14.5-1295.5 cm). *Tie points: For depth intervals from 1470.5 to 2835.5 cm and from 3150.5 to 3730.5 cm, the age model was developed by aligning the δ^{18}O of G. ruber in MD03-2707 to the δ^{18}O record of NGRIP ice core (*6*) and by aligning the δ^{18}O of benthic foraminifera (Fig. S1) in MD03-2707 to the benthic foraminiferal δ^{18}O stack record “LR04” (*7*).

Cited references

S1. D. W. Lea, D. K. Pak, H. J. Spero, *Science* **289**, 1719 (2000).
S2. P. A. Martin, D. W. Lea, *Geochemistry Geophysics Geosystems* **3**, doi: 10.1029/2001GC000280 (2002).
S3. M. Stuiver, P. J. Reimer, *Radiocarbon* **35**, 215 (1993).
S4. K. A. Hughen *et al.*, *Radiocarbon* **46**, 1059 (2004).
S5. R. G. Fairbanks *et al.*, *Quaternary Science Reviews* **24**, 1781 (2005).
S6. K. K. Andersen *et al.*, *Nature* **431**, 147 (2004).
S7. L. Lisiecki, M. Raymo, *Paleoceanography* **20**, doi: 10.1029/2004PA001071 (2005).
S8. N. J. Hardmann-Mountford, J. M. McGlade, *International Journal of Remote sensing* **24**, 3247 (2003).
S9. J. Picaut, *Journal of Physical Oceanography* **13**, 18 (1983).
S10 S. Weldeab, R. R. Schneider, P. J. Mueller, Geochemistry Geophysics Geosystems (in press)
S11. J. M. Edmond, E. D. Boyle, D. Drummond, B. Grant, T. Mislick, *Netherlands Journal of Sea Research* **12**, 324 (1978).
S12. D. W. Lea, H. Spero, *Paleoceanogrphy* **9**, 445 (1994).
S13. J. Carroll, k. K. Falkner, E. T. Brown, W. S. Moore, *Geochimica et Cosmochimica Acta* **57**, 2981 (1993).
S13. J. R. Petit *et al.*, *Nature* **399**, 429 (1999).