



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  $\mu\text{m}$  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 $^{18}\text{O}/^{16}\text{O}$ (expressed as $\delta^{18}\text{O}$ )

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  $\mu\text{m}$ . 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  $\text{CO}_2$  preparation from carbonate samples for isotopic analysis. Samples were reacted by individual acid addition. The mean external error and reproducibility ( $1\sigma$ ) of carbonate standards is better than  $\pm 0.07\%$  and  $\pm 0.05\%$  for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , respectively. Results were calibrated using carbonate isotope standard NBS 20 and in addition NBS 19 and 18, and are reported on the Pee Dee belemnite (PDB) scale.

#### Age model for MD03-2707

The age model for the MD03-2707 record was developed using 24  $^{14}\text{C}$ -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).  $^{14}\text{C}$  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  $^{14}\text{C}$ -dates beyond the calibration range of the “Calib” software, we use the online software “Fairbanks0805 calibration curve” (5). The final age model for the  $^{14}\text{C}$  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  $\delta^{18}\text{O}$  in MD03-2707 with the  $\delta^{18}\text{O}$  of NGRIP ice core (6). For ages older than 119,500 yr BP, the age model is developed by aligning benthic foraminiferal  $\delta^{18}\text{O}$  in MD03-2707 (see Fig. S2 A) with the  $\delta^{18}\text{O}$  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  $\delta^{18}\text{O}$  (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  $\delta^{18}\text{O}$  record shows all orbital cycles (100 kyr, 41 kyr, and 23 kyr) integrating high and low latitude forcings. The overall cross-correlation between SST and  $\delta^{18}\text{O}$  is  $r = 0.83$ .

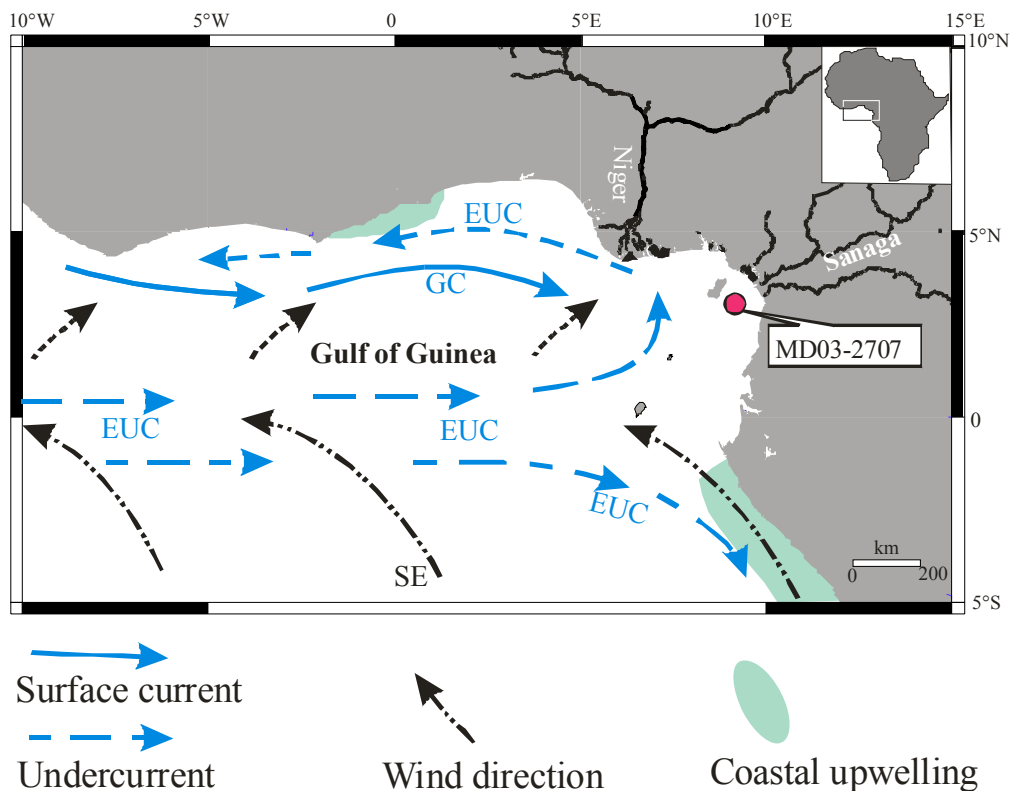


Figure S1: Surface current, subsurface current, and wind direction affecting the hydrography of the Gulf of Guinea (modified redraw from (8, 9) and adopted from (10)). GC: Guinea Current; EUC: Equatorial Undercurrent; SE: southeasterly trade winds (south of equator). Note that the upwelling along the 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).

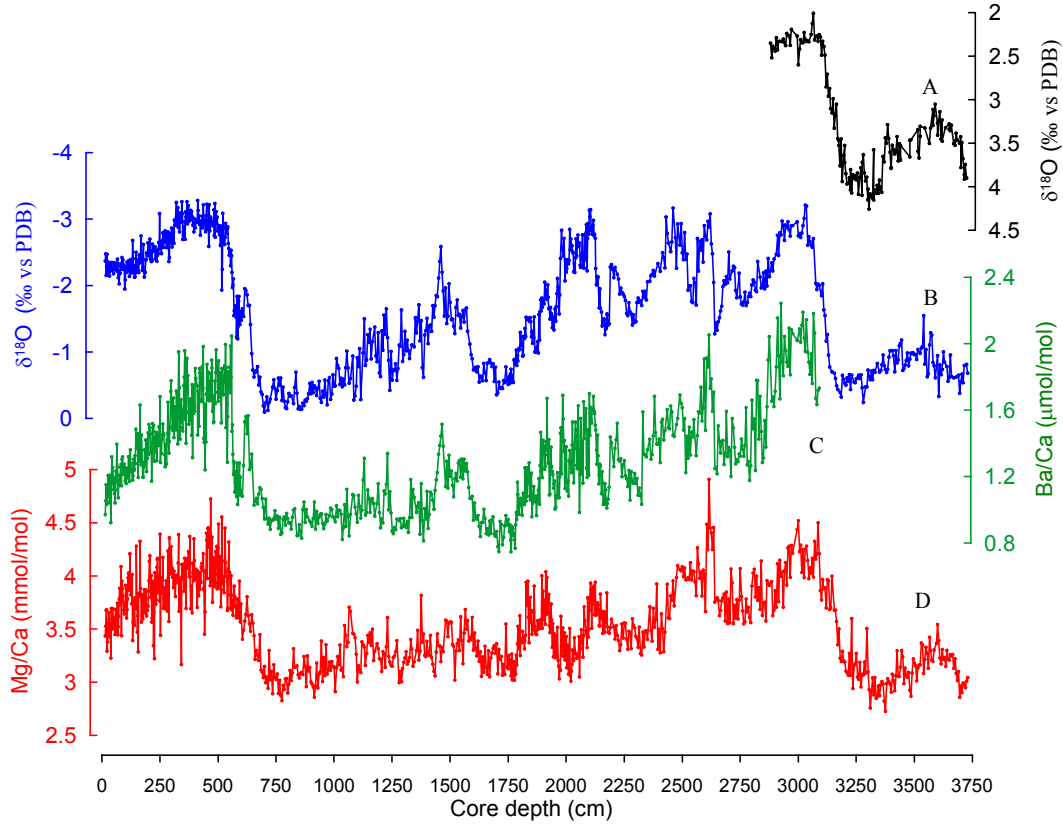


Figure S2: Mg/Ca (D), (C) Ba/Ca, (B)  $\delta^{18}\text{O}$  in *G. ruber* test, and (A) benthic foraminiferal  $^{18}\text{O}$  (*Cibicoides pachydermus*) (black line) versus depth (cm) in MD03-2707.

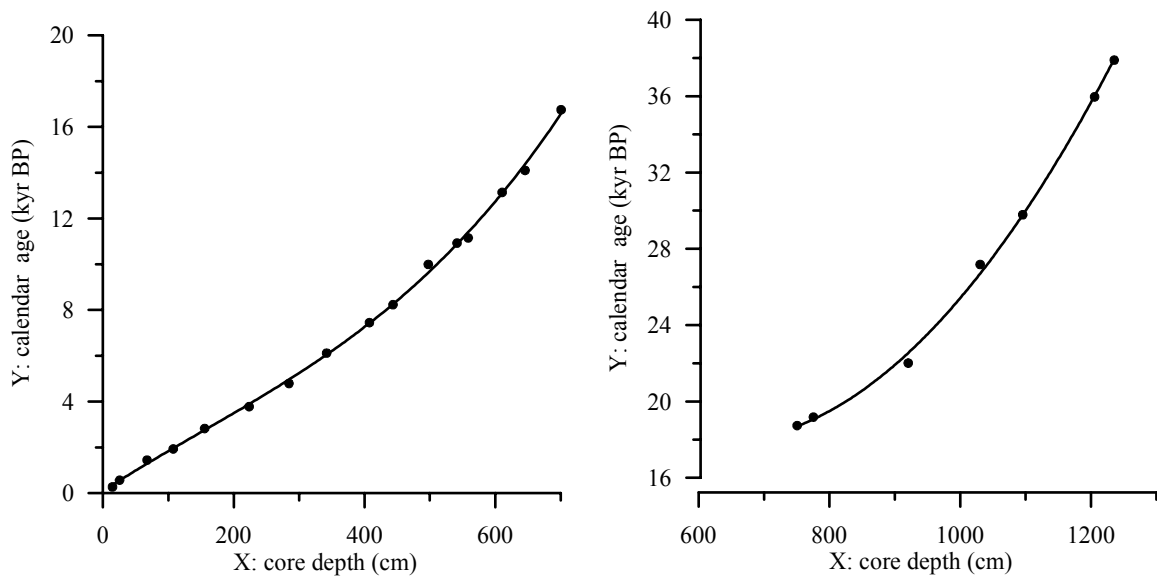


Figure S3: Age model for the  $^{14}\text{C}$ -dated interval of MD03-2707 (0-1295.5 cm) obtained using two polynomial fits of calendar age versus core depth (see Table S1 and S2)

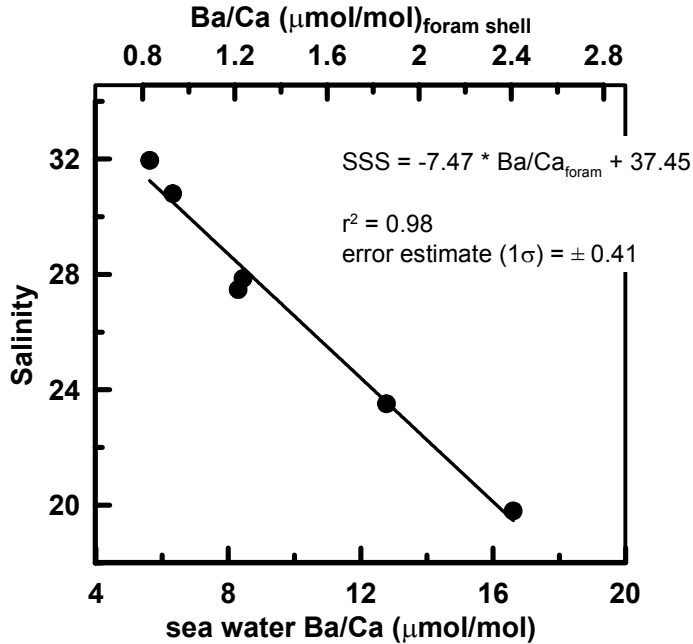


Figure S4: Ba/Ca in sea water and corresponding (calculated) Ba/Ca in planktonic foraminifer versus salinity. Ba/Ca in sea water is obtained using measured Ba and salinity from sites off Congo River (10). The corresponding Ca has been calculated assuming conservative behavior of Ca and linear relationship 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 ( $\mu\text{mol/mol}$ ) in sea water using the partition coefficient of  $D_{\text{Ba}}=0.147$  (11) ( $(\text{Ba/Ca})_{\text{sea water}} * D_{\text{Ba}}=(\text{Ba/Ca})_{\text{forams}}$ ). 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).

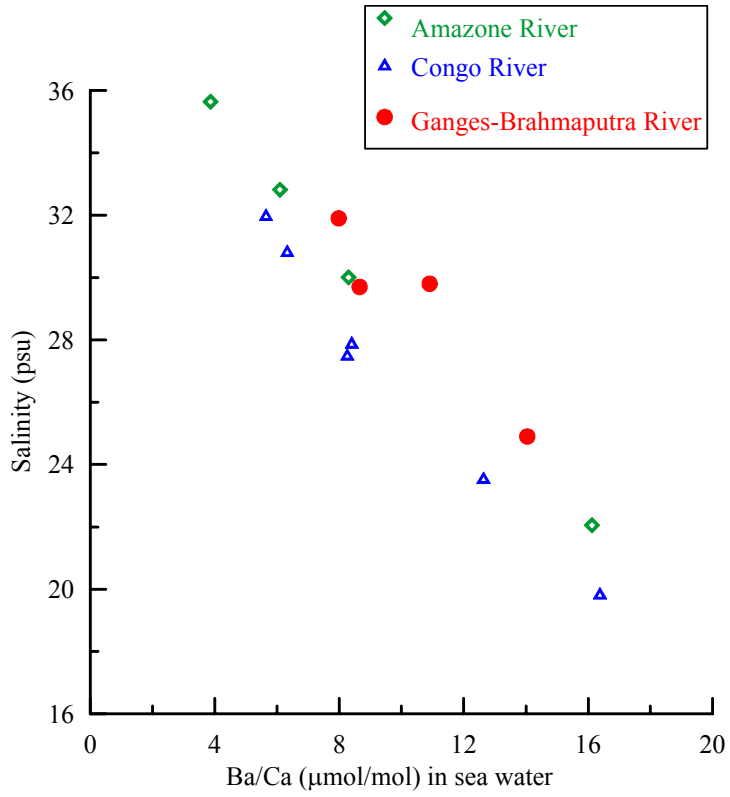


Figure S5: Relationship of sea surface salinity and Ba/Ca in sea water from three large tropical rivers: Congo (10), Amazon (10), and Ganges-Brahmaputra (12).

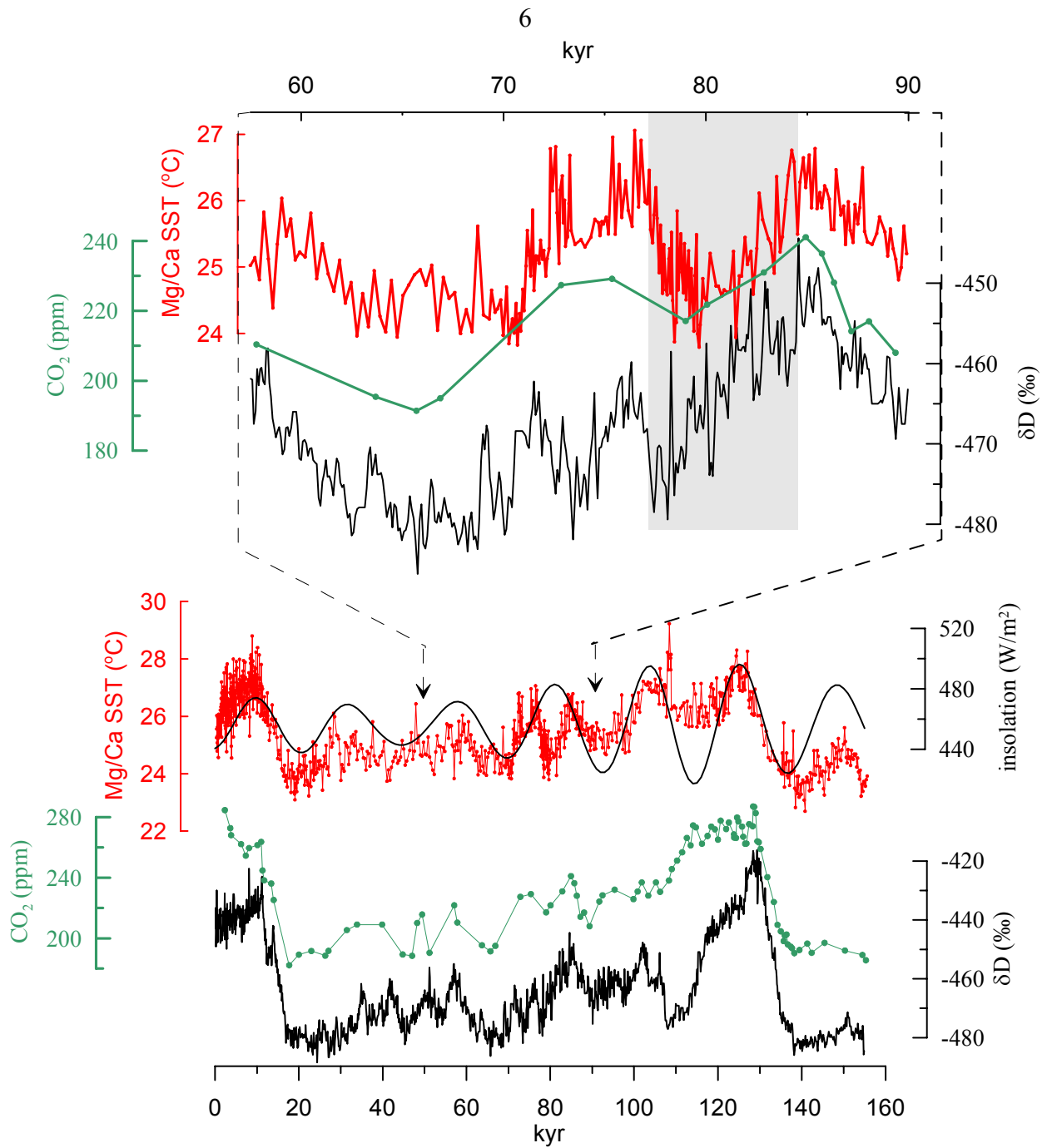


Figure S6: Mg/Ca-based SST estimate in the MD03-2707 record in comparison to mid-summer solar insolation at 15°N,  $\delta D$  and  $CO_2$  in Vostok ice core, Antarctica, (13). Grey area in the blow up points out the cooling interval discussed in the main text.

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

Lab #	Core	Core depth (cm)	$^{14}\text{C}$ age (yr BP)	$^{14}\text{C}$ age: $\pm$	Calendar age range ( $1\sigma$ )	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 $\pm$ 210
CAMS 126576	MD2707	1095.5	25280	110		29780 $\pm$ 370
CAMS 126577	MD2707	1205.5	31430	180		35970 $\pm$ 280
CAMS 127307	MD2707	1235.5	33370	630		37890 $\pm$ 820
CAMS 127308	MD2707	1295.5	36960	980		41680 $\pm$ 600

Table S1:  $^{14}\text{C}$ -AMS date used for the chronology of MD03-2707.  $^{14}\text{C}$  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 (cm)	depth 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  $^{14}\text{C}$ -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  $\delta^{18}\text{O}$  of *G. ruber* in MD03-2707 to the  $\delta^{18}\text{O}$  record of NGRIP ice core (6) and by aligning the  $\delta^{18}\text{O}$  of benthic foraminifera (Fig. S1) in MD03-2707 to the benthic foraminiferal  $\delta^{18}\text{O}$  stack record “LR04” (7).

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