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THE LAST DEGLACIATION IN THE SOUTHERN OCEAN

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*Abstract.* The isotopic and micropaleontological deglacial records of three deep-sea cores from 44°S to 55°S have been dated by accelerator mass spectrometry. The available records did not allow accurate dating of the initiation of the deglaciation. By 13,000 years B.P., sea surface temperatures reached values similar to the present values. A cool oscillation abruptly interrupted this warm phase between 12,000 and 11,000 years B.P. Initiation of this cooling therefore preceded the northern hemisphere Younger Dryas by approximately 1000 years. Complete warming was reached by 10,000 years B.P., more or less synchronous with the northeast Atlantic Ocean.

INTRODUCTION

The hydrological response of the surface ocean to the last glacial-Holocene transition has been recently the subject of numerous studies supported by detailed <sup>14</sup>C dating with accelerator mass spectrometry (AMS). Most are concentrated in the northern and eastern Atlantic ocean [Duplessy et al., 1986; 1989; Bard et al., 1987; Broecker et al., 1988] with few in the Pacific [Duplessy et al., 1989; Kallel et al., 1988; Shackleton et al., 1988]. Biostratigraphical studies seem to indicate that the surface waters warmed earlier (by few

thousand years) in the southern ocean than in the northern Atlantic, both for the last and the penultimate glacial-interglacial transitions [Hays, 1978; Morley and Robinson, 1980; CLIMAP Project Members, 1984]. Yet quantitative informations on the timing of the southern hemisphere deglacial records are still insufficient to explore the reasons for this lead and understand the interhemispheric teleconnections of climate. In this paper we document the timing of the changes in surface water temperature and foraminiferal isotopic ratio during the last deglaciation between 44°S and 54°S by <sup>14</sup>C AMS dating of planktonic foraminifera in three cores located in the Indian sector of the southern ocean, between Crozet and Heard islands (MD 73-025 at 43°49'S, 51°19'E, 3284 m; MD 84-527 at 43°49.3'S, 51°19.1'E, 3269 m, and MD 84-551 at 55°00.5'S, 73°16.9'E, 2230 m).

THE SOUTHERN OCEAN PALEOCLIMATIC RECORDS

Two types of climatic signals have been considered in this study: the oxygen isotope measurements ( $\delta^{18}\text{O}$  versus PeeDee Belemnites Standard (PDB)) and the sea surface temperatures (SST) estimated from foraminiferal-based transfer function (T. F.):

The fractionation between calcium carbonate and water during foraminiferal growth depends strongly on the seawater temperature. The  $\delta^{18}\text{O}$  of foraminifera shells is therefore a function not only of the global variations in the isotopic composition of the oceans due to changes in the volume of ice stored over the continents, but also of the seawater temperature. In the case of the last deglaciation the total ice volume effect is thought to account for  $\pm 1.1\text{‰}$  [Labeyrie et al., 1987]. The local seawater  $\delta^{18}\text{O}$  depends also upon salinity variations and meltwater discharges in the proximity of the Antarctic ice sheet [Labeyrie et al., 1986]. The temperature contribution to the foraminiferal  $\delta^{18}\text{O}$  signal may not, therefore, be calculated directly.

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SST are estimated by multivariate statistical analysis of planktonic foraminifera [Imbrie and Kipp, 1971]. The transfer function (F1-3 T. F.) which relates faunal changes to SST has been adapted from the F I-2 T. F. of Hutson and Prell [1980]. The modern reference data set has been adjusted to optimize the coverage throughout the southern ocean and increase sensitivity to the low SST range. We used as reference data base the 33 subpolar and polar core tops from Hutson and Prell [1980] completed by 16 new Holocene core tops from the Polar Front zone and the Antarctic ocean. This new T. F. is based on the abundance variations of the 21 planktonic foraminifera species present in the sample selection.

A Q-mode factor analysis, applied on the matrix of core top assemblages following the procedures described by Imbrie and Kipp [1971], produces five distinct faunal associations, the varimax factors. The three first factors (Table 1) account for over 97% of the variance of the species distribution. The communalities are always larger than 0.96. The varimax factor score matrix, which gives the statistical weight of the analyzed species for each of the first three factors, is given in Table 2.

We used a multicurvilinear regression by least-squares to relate the three major factors to modern SST; the reference winter and summer SST were obtained by interpolation from the 3-month average values given in the Southern Ocean Atlas data set [Gordon and Molinelli, 1986]. The water temperature

TABLE 1. Varimax Factor Matrix

Core	Latitude	Longitude	Depth (m)	Com.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
RC12-291*	42°35'S	17°48'W	3508	0.989	0.927	-0.013	0.264	0.146	0.197
V22-106*	46°08'S	10°54'W	3037	0.999	0.300	-0.949	0.092	-0.010	0.027
RC15-93*	46°06'S	13°14'W	2714	0.998	0.516	-0.799	0.175	-0.011	0.249
RC11-78*	50°52'S	9°52'W	3115	0.999	0.066	-0.995	0.012	0.015	-0.069
V22-107*	44°28'S	6°38'W	3998	0.997	0.974	-0.194	0.096	-0.037	-0.011
V22-108*	43°11'S	3°15'W	4171	0.996	0.986	-0.009	0.138	-0.060	-0.013
RC11-79*	49°00'S	4°36'W	3385	0.999	0.073	-0.994	0.025	0.020	-0.075
RC13-253*	46°36'S	7°38'E	2494	1.000	0.639	-0.762	0.049	0.017	0.088
RC13-275*	50°43'S	13°26'E	1984	1.000	0.072	-0.996	0.012	0.012	-0.052
RC8-39*	42°53'S	42°21'E	4330	0.992	0.910	0.015	0.289	0.276	0.055
RC8-40*	43°47'S	46°12'E	2540	0.990	0.799	-0.314	0.347	0.363	-0.019
V16-65*	45°00'S	45°46'E	1618	0.979	0.807	-0.506	0.235	0.127	-0.016
V16-64*	46°01'S	44°22'E	2202	0.976	0.821	-0.524	0.142	0.088	-0.012
RC8-41*	43°38'S	51°16'E	2897	0.995	0.678	-0.691	0.184	-0.129	-0.091
AR3-25*	39°44'S	67°53'E	4065	0.963	0.458	-0.003	0.867	-0.033	-0.037
AR4-63*	39°50'S	75°03'E	3768	0.943	0.371	-0.040	0.893	-0.081	-0.014
RC11-122*	38°02'S	83°29'E	3490	0.953	0.433	0.031	0.850	0.196	0.052
RC11-121*	39°43'S	82°15'E	3426	0.929	0.322	0.022	0.906	-0.055	0.014
RC8-50*	44°46'S	92°25'E	3219	0.998	0.872	-0.084	0.397	0.269	0.028
E49-22*	45°01'S	95°04'E	2717	0.984	0.833	-0.240	0.432	0.214	0.014
E49-23*	47°07'S	95°04'E	3207	0.997	0.916	-0.362	0.150	0.061	0.006
E49-25*	49°22'S	94°49'E	3335	0.998	0.887	-0.429	0.152	0.010	-0.071
E49-24*	47°59'S	95°02'E	3164	0.987	0.873	-0.442	0.104	0.136	-0.003
RC9-143*	41°22'S	114°08'E	4396	0.998	0.943	0.054	0.246	-0.207	-0.038
E45-81*	43°58'S	114°21'E	4158	0.995	0.917	-0.031	0.295	-0.252	-0.039
E45-77*	46°27'S	114°25'E	3740	0.995	0.983	-0.131	0.086	-0.047	-0.047
E45-73*	47°33'S	114°26'E	3690	1.000	0.954	-0.295	0.042	0.015	-0.021
E45-70*	48°30'S	114°28'E	3639	0.999	0.968	-0.244	0.055	0.006	-0.018
E44-27*	53°02'S	119°43'E	3508	1.000	0.509	-0.856	0.047	-0.017	-0.078
RC9-140*	45°25'S	121°07'E	4400	0.993	0.996	-0.021	0.021	-0.003	-0.023
RC9-139*	47°46'S	123°06'E	4158	0.997	0.995	-0.038	0.059	-0.028	-0.043
RC8-61*	46°32'S	125°34'E	4254	0.994	0.964	-0.106	0.181	-0.143	-0.020
RC8-62*	49°20'S	127°07'E	3875	0.98	0.975	-0.110	0.097	0.022	0.078
MD84-548	57°47'S	74°42'E	2390	1.000	0.061	-0.996	0.004	0.004	-0.064
MD84-552	54°55'S	73°50'E	1780	1.000	0.079	-0.996	0.012	0.008	-0.031
MD84-528	46°10'S	53°04'E	3408	0.998	0.737	-0.64	-0.021	0.105	0.161
MD84-551	55°00'S	73°17'E	2230	1.000	0.129	-0.983	0.005	0.012	0.132
MD84-550	56°46'S	71°23'E	4080	1.000	0.061	-0.995	0.004	0.005	-0.074
MD84-557	53°20'S	75°48'E	1084	1.000	0.065	-0.996	0.003	0.005	-0.064
MD84-553	54°41'S	76°33'E	1504	1.000	0.076	-0.997	0.001	0.005	-0.025
MD84-562	51°55'S	68°14'E	3553	1.000	0.221	-0.975	-0.008	0.035	0.002
MD84-563	50°43'S	68°09'E	1720	1.000	0.104	-0.985	0.007	0.012	0.137
MD84-560	53°07'S	72°10'E	950	1.000	0.107	-0.991	0.000	0.011	-0.073
MD84-568	48°36'S	72°40'E	2241	1.000	0.093	-0.944	0.010	-0.002	0.317
MD80-304	51°00'S	67°00'E	1950	1.000	0.058	-0.993	0.056	0.056	-0.061
MD24-K63	51°56'S	42°53'E	2550	1.000	0.069	-0.997	0.005	0.006	-0.019

TABLE 1 (continued)

Core	Latitude	Longitude	Depth (m)	Com.	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
MD82-424	54°06'S	0°21'W	2350	1.000	0.061	-0.995	0.004	0.005	-0.074
MD82-436	61°13'S	19°29'E	3620	1.000	0.061	-0.995	0.004	0.005	-0.074
MD73-026	44°59'S	53°17'E	3429	1.000	0.304	-0.903	-0.004	0.055	0.298
<b>Variance</b>					<b>42.297</b>	<b>46.216</b>	<b>8.489</b>	<b>1.259</b>	<b>0.927</b>

List and location of the core tops utilized to establish the transfert function, and results of the Varimax analysis: Communality (Com.) and statistical weight of the five first factors for each of the stations. The samples from Hutson and Prell [1980] are marked by asterisks.

TABLE 2. Varimax Score Matrix

Species	Factor 1	Factor 2	Factor 3
<i>G. pachyderma (left)</i>	0.061	-0.995	0.004
<i>G. pachyderma (right)</i>	-0.036	0.004	0.664
<i>G. bulloides</i>	0.955	0.061	-0.187
<i>G. quinqueloba</i>	0.039	-0.073	0.011
<i>G. scitula</i>	-0.001	0.000	0.023
<i>G. glutinata</i>	0.071	-0.004	0.176
<i>G. inflata</i>	0.266	0.016	0.674
<i>G. hirsuta</i>	-0.004	0.000	0.031
<i>G. truncatulinoides (left)</i>	0.076	0.018	0.148
<i>G. truncatulinoides (right)</i>	-0.005	-0.001	0.059
<i>G. aequilateralis</i>	-0.005	0.000	0.029
<i>G. falconensis</i>	0.006	0.002	0.002

range is -0.2°C to 15.5°C during summer and -2.2°C to 13°C during winter. Correlation coefficients are 0.983 for summer and 0.978 for winter. The standard error is ±1.27°C for summer and ± 1.38°C for winter within the selected temperature range. Yet as the foraminiferal population is monospecific (species *Neogloboquadrina pachyderma* s.) below a summer SST of +3°C, this temperature represents the lower limit for the foraminiferal T.F. The results of this T.F. applied to the foraminiferal specific distributions of core MD 73-025 and core MD 84-527 are reported in Table 3 and respectively in Figure 1c and 1g. The high communalities obtained during this calculation (always above 0.975) indicate that there is no distortion of the original information given by the modern reference. Core MD 84-551, located in the high southern

TABLE 3. Changes in the δ<sup>18</sup>O and Summer SST Measured on the Foraminifera From Cores MD 73-025, MD 84-527, and MD 84-551

MD 73-025					MD 84-527					MD 84-551		
depth	age	N. p.	Non.	SST	depth	age	N. p.	C. w	G. b.	SST	depth	N. p.
cm	kyr	δ18	δ18 *	°C	cm	kyr	δ18	δ18*	δ18	°C	cm	δ18
0	02.40	2.40	3.61	-	0	01.75	1.98	-	-	-	0	3.15
4	02.74	-	3.64	-	2	01.83	-	-	2.41	-	10	3.31
10	03.25	1.95	-	-	5	01.95	-	3.73	-	-	20	3.00
20	04.10	2.13	-	-	10	02.14	2.14	-	2.43	6.5	30	3.15
24	04.28	-	3.35	-	13	02.26	-	3.69	-	-	40	3.14
30	04.55	2.39	3.30	-	20	02.53	2.14	-	2.5	6.8	50	3.27
40	04.99	2.28	3.55	-	23	02.65	-	3.67	-	-	60	3.13
50	05.44	2.14	3.50	-	30	02.93	1.96	3.48	2.74	6.8	70	3.21
60	05.88	1.66	3.54	-	40	03.32	1.71	3.17	2.62	5.9	80	3.09
70	06.33	1.77	3.62	-	50	03.71	1.89	3.52	2.49	7.4	90	3.40
80	06.78	2.07	3.57	-	53	03.83	-	3.81	-	-	100	3.20
90	07.15	2.11	-	-	60	04.10	2.09	3.48	-	7.4	110	3.18
100	07.46	1.91	3.76	-	62	04.16	-	2.42	-	-	112	3.49
110	07.77	2.06	3.80	-	70	04.42	2.15	3.79	2.56	6.8	122	3.85
120	08.08	2.23	3.73	-	73	04.52	-	3.63	-	-	130	3.84
130	08.38	1.88	3.76	-	75	04.58	-	-	-	7.3	140	3.04
142	08.69	2.13	3.83	-	80	04.74	2.19	3.48	2.63	<-	142	3.53
150	09.00	1.95	-	-	83	04.84	-	3.59	-	-	150	4.08
160	09.16	1.96	3.96	-	90	05.07	2.23	3.53	2.43	-	155	4.74
170	09.31	1.83	-	-	100	05.39	2.01	3.66	-	-	160	4.78
180	09.47	1.92	4.03	-	102	05.45	-	-	2.74	-	162	4.45
190	09.62	2.01	-	-	110	05.71	1.90	3.37	2.52	6.8	172	4.10
200	09.83	2.24	3.89	-	113	05.81	-	3.83	-	-	182	4.25
210	10.10	2.28	4.14	-	120	06.03	2.14	-	2.32	6.1	192	4.29

TABLE 3. (continued)

MD 73-025					MD 84-527					MD 84-551		
depth	age	N. p.	Non.	SST	depth	age	N. p.	C. w	G. b.	SST	depth	N. p.
cm	kyr	$\delta^{18}$	$\delta^{18}$ *	$^{\circ}$ C	cm	kyr	$\delta^{18}$	$\delta^{18}$ *	$\delta^{18}$	$^{\circ}$ C	cm	$\delta^{18}$
212	10.15	-	-	12.4	130	06.36	1.80	3.29	2.31	4.9	200	4.11
220	10.36	2.33	4.30	-	138	06.61	-	3.77	-	-	202	4.17
222	10.41	-	-	11.1	140	06.68	2.02	-	2.28	4.3	210	4.06
230	10.70	2.38	4.32	-	143	06.77	-	3.67	-	-	220	4.05
232	10.82	-	-	11	150	07.00	2.26	3.73	2.37	6	230	3.82
240	11.30	2.94	4.38	-	160	07.39	1.89	3.85	-	5.4	240	3.68
242	11.42	-	-	4.5	170	07.78	2.36	3.94	2.39	4.1	250	4.00
250	12.00	2.85	4.40	-	180	08.18	2.14	3.90	2.79	7	260	3.51
252	12.01	-	-	4.6	190	08.57	1.98	-	2.37	8.3	270	3.78
260	12.04	3.20	4.42	-	200	08.96	2.07	-	2.38	8.2	280	3.83
262	12.04	-	-	4.8	210	09.26	1.64	4.06	2.60	-	290	3.86
270	12.07	3.06	4.77	-	215	09.41	-	-	-	8.5	300	3.81
272	12.08	-	-	6.8	220	09.55	1.85	4.20	2.31	-	310	3.55
280	12.60	2.67	5.12	-	225	09.70	-	-	-	9.3	316	3.85
282	12.87	-	-	7.1	230	09.85	1.63	4.38	2.68	7.9	320	3.48
290	14.71	4.00	5.10	-	240	10.16	1.69	4.43	2.82	7.6	326	3.80
292	15.20	-	-	4.4	250	10.46	2.32	4.54	2.74	6.8	340	3.83
300	17.16	4.01	5.20	4.5	260	10.98	2.06	4.60	2.65	5.9	346	3.80
310	19.61	4.86	5.13	2.8	270	11.54	2.22	4.61	-	3.3	350	3.67
320	22.06	4.13	-	4	280	12.10	2.41	5.13	3.54	5.3		
330	24.51	4.05	4.97	6	290	12.76	2.29	5.18	3.01	6.4		
340	28.30	4.34	4.79	2.2	293	12.84	-	5.04	-	-		
350	28.55	3.43	4.95	3.5	300	13.00	3.54	4.92	3.03	1.8		
					302	14.20	3.68	5.26	-	-		
					310	19.00	3.48	4.98	3.46	2.2		
					313	20.80	-	5.02	-	-		
					320	25.00	3.43	4.93	3.31	2.5		
					330	25.80	2.78	4.95	2.79	2.8		
					340	26.60	3.39	4.97	-	3.3		
					342	26.76	-	-	3.45-	-		
					350	27.19	3.31	4.94	-	2.6		

The isotopic analyses were done on a VG 602C mass spectrometer. The SST (summer sea surface temperatures) are estimated with the foraminiferal transfer function F 1.3 modified from Hutson and Prell [1980], as explained in the text. Analyses are reported versus depth : for core MD 73-025, ages,  $\delta^{18}\text{O}$  (versus PDB) of the planktonic species *Neogloboquadrina pachyderma* s., of the benthic species *Melonis pompilioides* (*Nonion*), and summer SST; for core MD 84-527, ages,  $\delta^{18}\text{O}$  of *N. pachyderma* s.,  $\delta^{18}\text{O}$  of the benthic species *Cibicides wuellerstorfi*,  $\delta^{18}\text{O}$  of the planktonic species *Globigerina bulloides* (250- to 315- $\mu\text{m}$  size fraction), and SST; for core MD 84-551,  $\delta^{18}\text{O}$  of *N. pachyderma* s.. Construction of the age scale is explained in the text.

\*Corrected for specific fractionation by +0.4‰ (*M. pompilioides* (*Nonion*)) or +0.64‰ (*G. bulloides*)

latitude waters (55°S) within the monospecific *N. pachyderma* s. assemblage zone, may not be studied by this transfer function.

The isotopic results are reported (as  $\delta^{18}\text{O}$  / PDB) versus depth in the cores in Table 3 and Figure 1. The oxygen isotopic ratios have been analyzed on the planktonic foraminifera polar species *N. pachyderma* s. in the three cores (Figures 1b, 1f, and 1j), and on the subpolar species *Globigerina bulloides* in core MD 84-527 (Figure 1e). The benthic foraminifera  $\delta^{18}\text{O}$  have been analyzed in core MD 73-025 (*Melonis pompilioides*, (Figure 1a)) and MD 84-527 (*Cibicides wuellerstorfi*, (Figure 1d)). Core MD 84-551 does not contain enough benthic foraminifera for the measurements.

#### CHRONOLOGICAL FRAMEWORK AND SEDIMENTATION RATES

The AMS  $^{14}\text{C}$  dates were obtained from monospecific planktonic foraminifera samples (Figure 1 and Table 4). All dates are calculated with the 5.568 years half-life, and corrected for a constant surface water age of 480 years, the estimated prebomb age of surface waters at 45°S [Bard et al., 1989]. The equivalent estimated prebomb age of surface waters at the location of core MD 84-551 is 100 to 300 years older [Bard et al., 1989]; however, we have no idea how this age changed with time, so the same correction is taken for all the cores. For the same reason, an exact comparison with dates made on

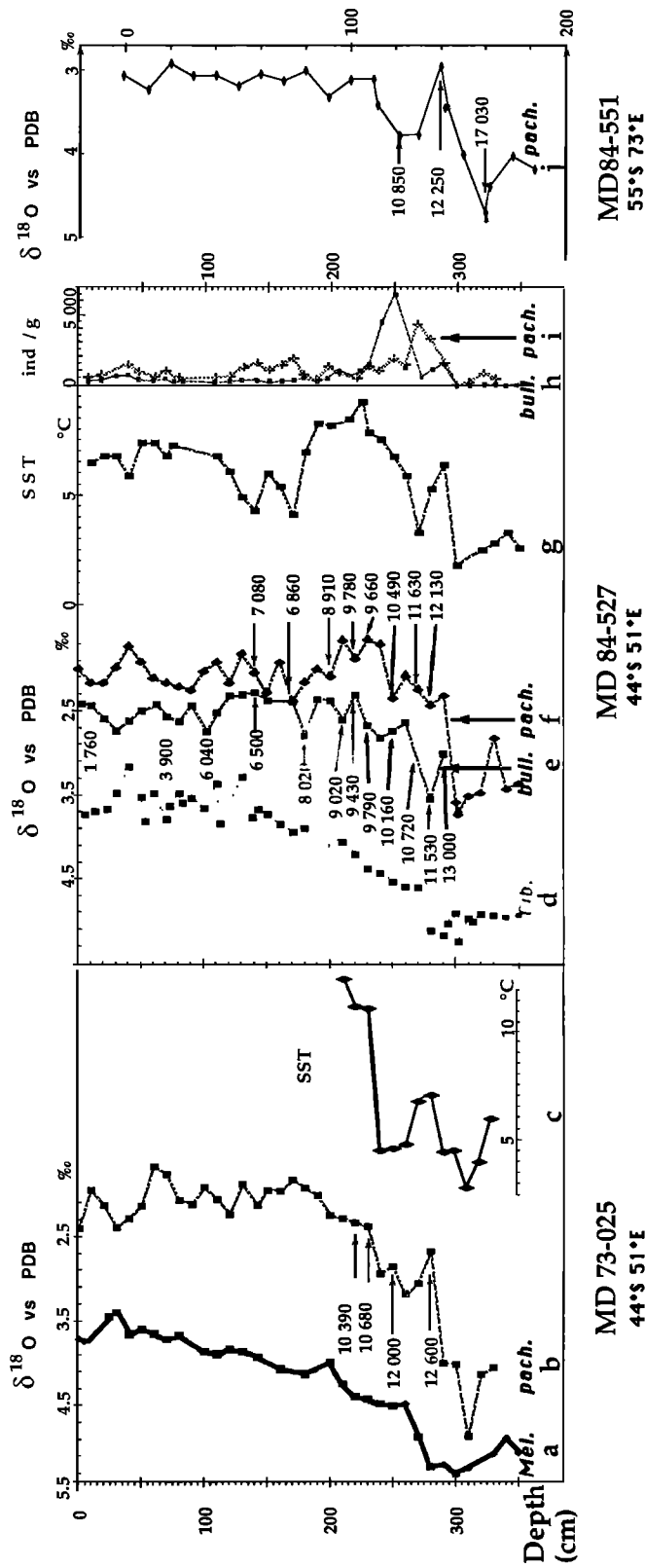


Fig. 1. Distribution with depth in the cores MD 84-527, MD 84-551, and MD 73-025, of (a)  $\delta^{18}\text{O}$  of *Melonis pompilioides* (*Nonion*) in core MD 73-025, (b)  $\delta^{18}\text{O}$  of *N. pachyderma* s. in core MD 73-025, (c) SST in core MD 73-025, (d)  $\delta^{18}\text{O}$  of *Cibicides wuellerstorfi* in core MD 84-527, (e)  $\delta^{18}\text{O}$  of *G. bulloides* in core MD 84-527, (f)  $\delta^{18}\text{O}$  of *N. pachyderma* s. in core MD 84-527, (g) SST in core MD 84-527, (h) abundance (in shells per gram) of *G. bulloides* in core MD 84-527, (i) abundance (shells per gram) of *N. pachyderma* s. in core MD 84-527, (j)  $\delta^{18}\text{O}$  of *N. pachyderma* s. in core MD 84-551. All ages are corrected by  $\sim 480$  years.

TABLE 4. AMS  $^{14}\text{C}$  Ages for Cores MD 84-527, MD 84-551, and MD 73-025

	depth	sp.	age BP	error ( $\pm$ )	age-480 years
MD 84-527	0-2	bull.	2,240	90	1,760
	60-62	bull.	4,380	100	3,900
	102-104	bull.	6,520	100	6,040
	142-144	bull.	6,980	100	6,500
	172-174	bull.	8,500	130	8,020
	200-202	bull.	9,500	120	9,020
	220-222	bull.	9,910	120	9,430
	230-232	bull.	10,270	140	9,790
	250-252	bull.	10,640	120	10,160
	270-272	bull.	11,200	120	10,720
	280-282	bull.	12,010	140	11,530
	290-292	bull.	13,480	160	13,000
	140-142	pach.	7,560	130	7,080
	170-174	pach.	7,340	110	6,860
	200-202	pach.	9,390	110	8,910
	220-222	pach.	10,260	160	9,780
	230-232	pach.	10,140	120	9,660
	250-252	pach.	10,970	160	10,490
	270-272	pach.	12,110	140	11,630
	280-282	pach.	12,610	180	12,130
	320-322	pach.	25,450	480	24,970
	342-344	pach.	27,800	510	27,320
	350-352	pach.	28,470	570	27,990
360-364	pach.	25,490	430	25,010	
380-382	pach.	28,830	550	28,350	
400-402	pach.	29,300	730	28,820	
440-442	pach.	31,260	730	30,780	
MD 84-551	120-122	pach.	11,330	170	10,850
	140-142	pach.	12,720	200	12,240
	160-162	pach.	17,510	160	17,030
MD 73-025	220-224	bull.	10,870	140	10,390
	230-234	bull.	11,160	140	10,680
	250-254	pach.	12,480	160	12,000
	280-284	bull.	13,080	160	12,600
	378-382	pach.	39,050	1,800	38,600
	388-392	pach.	36,470	1,300	36,000

Approximately 5 mg monospecific samples of foraminifera are prepared for each analysis, to allow for duplication. The species analyzed is either *G. bulloides* (bull) or *N. pachyderma* s. (pach). The correction of -480 years takes into account the present apparent ages of surface waters at 45°S. The errors correspond to  $1\sigma$ .

carbon from terrestrial plants would require more precise determination of the changes in ventilation of surface waters.

Two different species have been analyzed. *N. pachyderma* s. , the cold water species, was picked in the three cores; *G. bulloides*, the subpolar species, was picked only in core MD 84-527. The mean difference in the ages obtained for these two species at the same depths is not significant ( $170 \pm 230$  years).

A coherent picture of the changes in sedimentation rate with time at the location of neighbor cores MD 73-025 and MD 84-527 is given by the AMS dates (Figure 2): the sedimentation rate has been constant, around 30 cm/kyr, between 13 kyr B.P. and 2 kyr B.P.. This rate insures that bioturbation mixing has a negligible effect on the measured  $^{14}\text{C}$  dates during deglaciation. During the last glacial maximum, the sedimentation rate was much lower ( $\approx 3$  cm/kyr for core MD

84-527), and the records are not as reliable as during deglaciation. The only major difference in the age versus depth relationship occurs at the bottom of the analyzed records: Core MD 73-025 has a well-defined sedimentological unconformity at the base of a compact ash layer, at 370 cm. An age of 38.6 kyr B.P. was obtained for this core at 380 cm, whereas core MD 84-527 gives 28.4 kyr B.P. at the same depth, thus indicating that around 10 kyr may have been lost from the MD 73-025 record. The more southern core MD 84-551 (55°S) has a lower sedimentation rate during deglaciation (approximately 13 cm/kyr). We have no absolute dates to constrain how sedimentation was reduced during the last glacial. Comparison of the foraminiferal  $\delta^{18}\text{O}$  records between cores MD 84-551 and MD 84-527 would give an approximate age of 25 kyr B.P. at 170 cm, which corresponds to a sedimentation rate around 1.5 cm/kyr during the last glacial maximum.

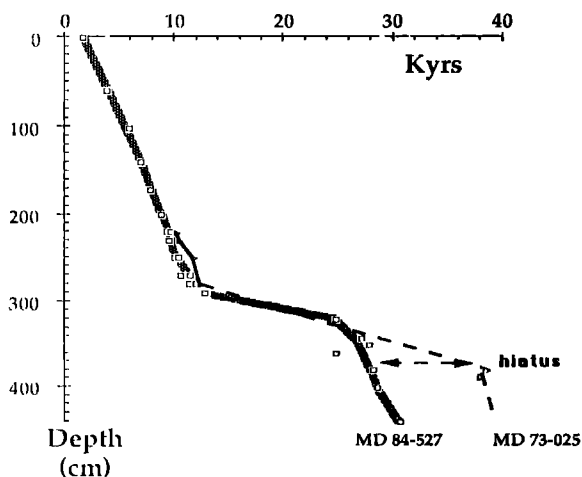


Fig. 2. Age-depth relations built using the AMS  $^{14}\text{C}$  datings of *N. pachyderma s.* in core MD 73-025 and *G. bulloides* and *N. pachyderma s.* in core MD 84-527. All ages are corrected by -480 years.

A composite graph of the changes versus time of the foraminiferal  $\delta^{18}\text{O}$  and summer SST has been reconstructed, to help comparison between the records of cores MD 73-025 and MD 84-527 (Figure 3). The proposed age scale was built in several steps: An optimum correlation was established between the isotopic and SST signals of both cores, serving as reference with the available  $^{14}\text{C}$  dates to build a common age-depth relationship (Table 5). The final age scale was estimated by linear interpolation between the representative levels (Table 3). This detailed correlation was complicated by small differences between the records, apparent by example around 250 cm in both cores for the *N. pachyderma*  $\delta^{18}\text{O}$  signal (Figures 1b and 1f) as well as the SST signals (Figures 1c and 1g). There is a larger difference around 300 cm, *N. pachyderma*  $\delta^{18}\text{O}$  being significantly more positive in core MD 73-025 than in core MD 84-527. Apparently, the different records of core MD 84-527 were slightly perturbed during handling of the core barrel on the ship deck. A small amount of sediment was lost during section of the core liner at 300 cm: the sediment at these latitudes contains between 50 and 90% diatoms, and fluidifies by tixotropy during core retrieval operations (especially when the core barrel is deposited horizontally on the deck for extraction and section). The larger core diameter of core MD 84-527 (10 cm, compared to 7 cm for core MD 73-025) facilitates differential settling of the heavier benthic foraminifera, and flowing along the core of the lighter planktonic foraminifera and diatoms, specially during the core section. As the number of foraminiferal shells per gram of sediment changes significantly along core MD 84-527 (Figures 1h and 1i.), the resulting transfer of some of the foraminifera shells from the high abundance levels (290 cm and above) to the low abundance levels (300 cm and below) may explain the disappearance of the last glacial maximum  $\delta^{18}\text{O}$  peak in this core.

#### THE BENTHIC FORAMINIFERAL $\delta^{18}\text{O}$ RECORDS

The  $\delta^{18}\text{O}$  records of the benthic foraminifera from cores MD 73-025 and MD 84-527 are presented versus depth (Figure 1a and Figure 1d respectively), and versus interpolated ages (Figure 3). The signals are very similar in both cores. The glacial/ interglacial isotopic shift, 1.6 to 1.7‰ is of the same order of magnitude as that in the equatorial Pacific ocean core V 19-30 [Shackleton et al., 1983]. About 0.5‰ of this shift is attributed to a warming of the deep water at the location of the cores during deglaciation [Labeyrie et al., 1987]. However, detailed comparison of these records with other AMS-dated high sedimentation rate cores from the Pacific ocean [Shackleton et al., 1988, Kallel et al., 1988] indicates that the southern ocean benthic  $\delta^{18}\text{O}$  records do not represent accurately the heavy values of the last glacial maximum. In fact, the first of the classically described two steps corresponding to the initiation of the deglaciation (transition 1-A [Duplessy et al., 1981; Ruddiman and Duplessy, 1985]), is absent from our records. This event is dated in the equatorial Pacific ocean core TRI63-31 between 14.9 and 13.4 kyr B.P. (ages with no reservoir correction [Shackleton et al., 1988,]). Its absence may be explained by the mechanism advocated for planktonic foraminifera, i.e., downcore mixing from the levels of high benthic foraminiferal abundance during deglaciation (between 260 and 280 cm in core MD 84-527) to the low abundance levels of the last glacial maximum (between 300 and 340 cm [Ippolito, 1985]). The quality of the isotopic records is much better in the high sedimentation rate section of the core, from 290 cm upwards. As in the other high sedimentation rate cores, the trend of the second of the classically described two steps (termination 1B) is not linear but starts abruptly around 280 cm in both cores (Figures 1a and 1d), and becomes progressively more gentle upwards. The estimated age for the beginning of this transition is 12.6 kyr B.P. for core MD 73-025 and 12.1 kyr B.P. for core MD 84-527. This age range is similar to the estimations realized in the North Atlantic Ocean [Duplessy et al., 1986; Bard et al., 1987] and in the Pacific Ocean [Kallel et al., 1988; Shackleton et al., 1988]. Holocene isotopic values are reached by 7 kyr B.P.

#### SEA SURFACE TEMPERATURE AND PLANKTONIC FORAMINIFERAL $\delta^{18}\text{O}$ RECORDS.

The SST changes during deglaciation exceed 7°C for core MD 73-025 (Figure 1c) and 5°C for core MD 84-527 (Figure 1g), due to the southward migration of the polar front, from north of 40°S during the last glacial maximum [CLIMAP Project members, 1981] to its present location, between 42° and 46°S in that area. The glacial values, below 4°C, are not reliable for the foraminiferal T.F.

Core MD 73-025 (Figure 1b) presents a maximum glacial/ interglacial isotopic shift of 3‰ for the polar planktonic foraminiferal species *N. pachyderma s.* The total amplitude is only around 2‰ in core MD 84-527. Yet the 3‰ figure is a minimum, if we take into consideration the possibility of downward flowing of foraminiferal shells from transition to glacial sediments. The detailed interpretation may begin in both cores MD 73-025 and MD 84-527 at 290 cm, the depth



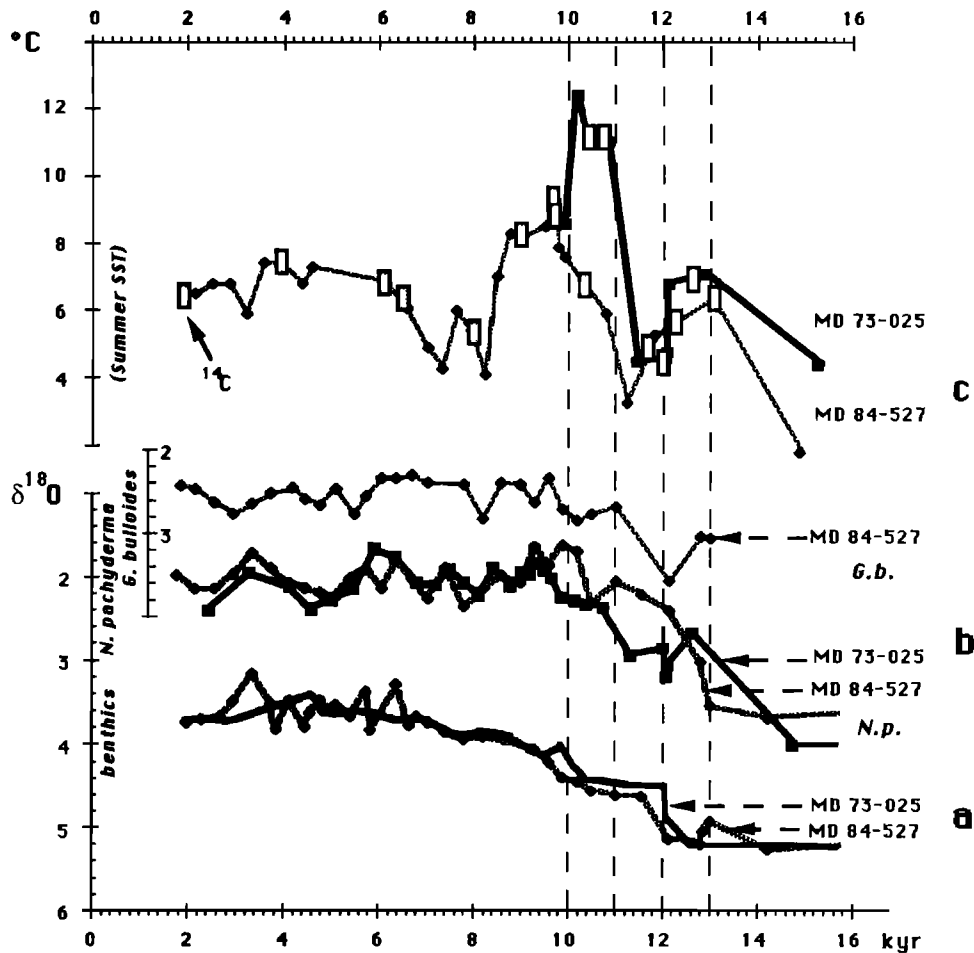


Fig. 3. Distribution versus calculated ages in cores MD 84-527 and MD 73-025, of (a)  $\delta^{18}\text{O}$  of the benthic foraminifera, (b)  $\delta^{18}\text{O}$  of the planktonic foraminifera (*N.p.*, *N. pachyderma s.*; *G.b.*, *G. bulloides*), and (c) summer SST.

at which we observe a significant increase in the number of shells (Figure. 1h and 1i for core MD 84-527). This corresponds to 150-cm depth in core MD 84-551.

Observation of core tops indicates that *N. pachyderma*  $\delta^{18}\text{O}$  are not far from isotopic equilibrium with water, considering a depth habitat of 50-100 m [Kellogg et al., 1978; Labeyrie and Duplessy, 1985], and spring hydrological conditions [Labeyrie et al., 1986]. The question is still open for *G. bulloides*, although unpublished results from our group indicate that in the north Atlantic the Holocene  $\delta^{18}\text{O}$  values are close to equilibrium if we follow the generally admitted concept that *G. bulloides* growth occurs during late spring and summer in surface temperate and subpolar waters, i.e., warmer waters than for *N. pachyderma s.*. The mean  $\delta^{18}\text{O}$  value of *G. bulloides* in core MD 84-527 is approximately 0.3‰ more positive than for *N. pachyderma s.*. There is a large isotopic gradient across the Antarctic polar front, with subtropical water heavier than polar waters by approximately 0.6‰ [Duplessy, 1970]. The simultaneous presence of both species in the core would be due to the seasonal and pluriannual oscillations of the polar

front above the core location. Yet this effect appears insufficient to explain the heavy isotopic values of *G. bulloides*, if this species lives effectively in warmer waters than *N. pachyderma*. However, W. Howard and W. Prell (personal communication 1988) have found by statistical analysis of core tops on a global basis that *G. bulloides* is associated with colder waters in the southern ocean than in the north Atlantic, an added argument to explain the relatively high  $\delta^{18}\text{O}$  values of *G. bulloides*.

The reliable record starts around 12.2 kyr B.P. for core MD 84-551 (140 cm), 12.6 kyr B.P. for core MD 73-025 (280 cm), and 13 kyr B.P. for core MD 84 527 (290 cm), where the planktonic foraminiferal  $\delta^{18}\text{O}$  and the SST transfer function indicate a warm event with temperatures equivalent to the modern conditions. This warm event was immediately followed by a cold episode, indicated in the foraminiferal  $\delta^{18}\text{O}$  of the different cores studied and the SST estimates. Detailed comparison of the  $^{14}\text{C}$  dates indicates, for the initial part of that episode, a transitory doubling of the mean sedimentation rate in core MD 73-025. This explains the

TABLE 5. Age-Depth Relationship Between Cores MD 84-527 and MD 73-025

MD 84-527, cm	MD 73-025, cm	age kyr
—	0	01.75
17	0	02.40
60	20	04.10
150	85	07.00
201	150	09.00
225	195	09.70
251	225	10.49
255	230	10.70
271	245	11.60
275	250	12.00
280	278	12.10
283	280	12.60
300	283	13.00
320	332	25.00
345	335	27.00
380	340	28.30
400	360	28.80
440	365	30.80
500	385	37.50
620	530	42.00
710	680	48.00

better recording of its coldest phase, between 12 kyr B.P. and 11 kyr B.P. (Figure 3). A plateau, with intermediate isotopic values and temperatures similar to or higher than those for the modern ocean followed the cold phase, between ~ 10.5 kyr B.P. and ~10 kyr B.P., before reaching the lightest  $\delta^{18}\text{O}$  values. The period with maximum of temperatures is dated between 10.3 kyr B.P. and 8.9 kyr B.P. in core MD 84-527. The SST record of core MD 73-025 would start this warm event around 11 kyr B.P.

#### IMPLICATIONS AND COMPARISON WITH OTHER RECORDS OF THE DEGLACIATION

Our data set indicates therefore that at least in the Indian sector of the southern ocean, the postglacial warming was well established at 12.5 to 13 kyr B.P. (Figure 3). These dates are not significantly different from the ages obtained in the northern hemisphere for the first large postglacial warming. They are concomitant with the decrease in Earth-Sun distance (increase in insolation) during summer over the high northern latitudes, i.e., during winter over the low southern latitudes (Bölling, dated between 13 and 12 kyr B.P. in northern Europe [Mangerüd et al., 1979]). However, in the high southern latitudes, this warm event was followed by a well-defined cold oscillation, which peaked around 12 to 11.5 kyr B.P. and lasted to approximately 10.5 kyr B.P. This period is therefore roughly synchronous with the succession of the Older Dryas, Alleröd, and Younger Dryas, continental chronozones described in Europe [Mangerüd et al., 1979]. However, the southern ocean records does not give any indication of the warm period characteristic of the Alleröd between 12 and 11 kyr B.P. As this age is supported both by the polar species *N. pachyderma* s. and by the subpolar species *G. bulloides*, which develop in well ventilated temperate waters, there is no reason to

hypothesize a significant underestimation of the correction to apply to the surface water ages.

There are no precisely dated continental records within the same polar to subpolar climatic zone in the southern hemisphere, which could help to generalize our conclusions. The exceptional pollen record of Alerce (Chile), located at 41°S, is influenced by the subtropical Pacific waters. Heusser and Streeter [1980] indicated in this record a first postglacial warm event peaking at 11,300 years B.P. ( $\pm 900$ ), followed by a pronounced cold period, before a second warm event (to temperatures higher than today's) dated between 9400 and 8600 years B.P. Their cold oscillation is therefore apparently synchronous with the northern hemisphere Younger Dryas. However, more recently, Heusser and Rabassa [1987] and Heusser [1989] evidenced a transitory cooling marked by a drop of pollen influx between 11,850 ( $\pm 50$ ) and 10,500 years B.P. ( $\pm 80$ ) in the southernmost South America. There is here a clearer correspondence with the dating of the cold event in the southern ocean records. Our results indicate therefore that the rapid succession of climatic oscillations described by the European palynologists, which culminated during the Younger Dryas, was different in the high southern latitudes. The early part of the cold oscillation, around 12 kyr B.P., appears synchronous with the cold Older Dryas in Europe, but it was not followed by a warming similar to the mild Bölling-Alleröd interstadial. The warming started only after 11 kyr B.P., apparently synchronous to the Younger Dryas cold in western Europe and northeast of America. This could highlight the Bölling-Alleröd period as anomalously warm, if we take into consideration the amount of continental ice still present in the Feno-Scandinavian and the Laurentide ice sheets.

The climatic optimum, around 10 kyr B.P. in the southern ocean (well defined also in Alerce), is better marked but in phase with the warming to Holocene temperatures observed in the northeast Atlantic Ocean [Duplessy et al., 1987].

The difference in the timing of the deglaciation appears therefore limited to the 12- to 10-kyr B.P. period, with an apparent 1-kyr lag of the northern hemisphere cold Younger Dryas compared to the southern ocean SST record. Such time constant indicates that continental ice, deep water circulation, and their consequences on atmospheric  $p\text{CO}_2$ , may be involved in this oscillatory behavior of the global climate system during the deglaciation. A quantitative reconstruction of the changes of climate at that period will have to wait for reliable climate models including interactive ocean, atmosphere, and ice. Yet taking into account the differences in the timings and local responses, other time series are necessary, especially in the poorly known southern hemisphere.

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