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ATMOSPHERIC RADIOCARBON AT THE END OF THE LAST GLACIAL: AN ESTIMATE BASED ON AMS RADIOCARBON DATES ON TERRESTRIAL MACROFOSSILS FROM LAKE SEDIMENTS

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ABSTRACT. The main purpose of this work is to reconstruct the atmospheric $\Delta^{14}C$ in the glacial-postglacial transition, 14,000 – 10,000 BP, a range not covered by the tree-ring calibration curve. We measured $^{14}C/^{12}C$ ratios on series of terrestrial macrofossils from sediments of two Swiss lakes. We selected exclusively plant remains of recognizable terrestrial origin that are not affected by hard water and thus reflect atmospheric ^{14}C concentration. Due to the scarcity of such material, we used accelerator mass spectroscopy. Cores of two lakes were measured to eliminate local effects and to check the reproducibility of results. This required a reliable, ^{14}C-independent correlation of the cores, obtained through local pollen zone boundaries. ^{14}C ages were obtained as a function of the depth in the cores. If sedimentation rates are known, ages can be converted into $\Delta^{14}C$ values. We also attempted estimating sedimentation rates; calculations are based on the Swedish varve chronology. Results were combined to form an entire data set. The $\Delta^{14}C$ curve shows an increase with time during the Allerød and decreases during Preboreal and Bølling periods. Probabilities for these ^{14}C variations are discussed.

INTRODUCTION

Results discussed here are based on several sediment cores taken in two Swiss lakes, Lobsigensee (47°02′N, 7°18′E) 514m asl and Rotsee (47°09′N, 8°20′E) 419m asl. Both lakes have small, closed or almost closed basins and thus show undisturbed sedimentation with little allochthonous input. Both sites were studied for pollen analysis and $\delta^{18}O$ measurements (Ammann *et al,* 1985; Lotter & Zbinden, 1989), so we can interpret our measurements with reference to other results.

MATERIAL AND METHODS

We measured $^{14}C/^{12}C$ ratios exclusively on terrestrial macrofossils, *ie,* plant remains of recognizable origin (mainly birch fruit). This type of material is not affected by hard water. Old carbon introduced into the water as dissolved rock carbonate may increase the ^{14}C age of, eg, gyttja by up to 1000 yr (Andrée *et al,* 1986a). The scarcity of terrestrial macrofossils made the application of accelerator mass spectrometry (AMS) necessary. Sample treatment consisted in cutting samples, washing out plant debris, acid treatment and identification of terrestrial material by the Systematic Geobotanic Institute, oxidation, cleaning of gases and reduction to elemental carbon using zinc reduction method (Andrée, 1984) by Oeschger's group (low level counting, LLC), AMS measurements (Bonani *et al*, 1986) by the ETH group and LLC and data evaluation.

TABLE 1

List of all ^{14}C dates from Lobsigensee and Rotsee

No.	Depth in core [cm]	Depth norm. 1)	Age	Error
Lobsigensee Core LL160a				
C495	853.0 - 855.0	700	9880	120
C496	887.0 - 889.0	794	10900	140
C497	901.0 - 903.0	828	10860	130
C760	903.0 - 905.0	833	11110	160
C754	905.0 - 907.5	838	10680	150
C755	907.5 - 910.0	844	10680	140
C717	910.0 - 912.5	850	11080	170
C756	912.5 - 915.0	856	10970	140
C719	915.0 - 917.5	862	11510	150
C723	917.5 - 920.0	868	11460	160
C722	920.0 - 922.5	874	11510	150
C757	922.5 - 925.0	880	11220	150
C718	925.0 - 927.5	885	11590	160
C758	927.5 - 930.0	891	11530	150
C499	930.0 - 932.5	897	11920	140
C493	932.5 - 936.5	906	12420	150
C533	936.5 - 939.5	915	12410	150
C501	939.5 - 943.5	924	12360	140
C759	1060.0 -1090.0	1061	12630	170
Lobsigensee Core LQ170d				
Ck77	738.0 - 740.0	621	8000	200
Ck76	740.0 - 742.0	630	8330	230
C1087	742.0 - 744.0	640	9270	170
C612	744.0 - 746.0	650	9910	120
C611	746.0 - 748.0	663	9770	120
C610	748.0 - 750.0	675	10060	120
C609	750.0 - 752.0	688	9930	120
C608	752.0 - 754.0	700	9980	120
C607	754.0 - 756.0	713	9550	130
C604	756.0 - 758.0	725	10150	130
C603	758.0 - 760.0	738	10330	130
Ck37	760.0 - 762.0	750	9620	130
Ck38	762.0 - 764.0	763	11640	160
C597	764.0 - 766.0	775	10300	140
C598	766.0 - 768.0	788	10600	140
C599	768.0 - 770.0	800	10350	120
C613	775.0 - 775.0	828	10900	130
Ck75	799.0 - 801.5	946	12360	320
C1088	830.0 - 850.0	1045	13360	280
Lobsigensee Core LL160b/LQ170c/LQ80				
C503	898.0 - 900.0	828	11060	140
C614	901.0 - 905.0	940	12470	140
C504	481.0 - 493.0	921	13060	150
Rotsee core RL305				
C846	904 - 908	642	9510	140
C847	908 - 912	650	9450	140
C848	912 - 916	658	9760	160
C852	916 - 918	667	9630	150
C853	920 - 924	675	10010	160
C854	924 - 928	683	10010	150
C859	928 - 932	692	10060	130
C864	932 - 936	700	10010	150
C869	936 - 940	714	9870	150
C874	940 - 944	729	10010	150
C889	944 - 948	743	10130	150
C909	948 - 952	757	10470	160
C904	952 - 956	767	10310	160
C905	956 - 960	778	10440	160
C901	960 - 964	789	10450	160
C910	964 - 968	800	11070	170
C914	968 - 972	820	10640	160
C915	972 - 976	838	11370	180
C919	976 - 980	853	11670	170
C978	976 - 980	853	11230	180
C920	980 - 984	869	11740	180
C934	984 - 988	884	11810	200
C939	988 - 992	900	12060	220
C935	992 - 996	914	12410	220
C940	996 - 1000	927	11160	160
C964	996 - 1000	927	10360	230
C792	1002.5- 1004	944	11560	160
C793	1004 - 1008	950	12730	190
C794	1008 - 1012	960	12600	170
C795	1012 - 1016	970	12570	180
C796	1016 - 1020	980	12800	190
C804	1020 - 1024	990	12280	190
C809	1024 - 1028	1000	12800	190
C805	1028 - 1032	1010	13350	210
C810	1032 - 1036	1020	13540	210
C814	1036 - 1040	1030	13290	200
C815	1040 - 1044	1040	12970	200
C818	1044 - 1048	1050	13600	220
C830	1048 - 1052	1060	13820	210
C831	1052 - 1056	1070	14000	210
C823	1056 - 1060	1080	14570	240
C837	1060 - 1064	1090	14240	220
C838	1064 - 1068	1100	13990	220
Ck63	1068 - 1076	1115	12390	350
Ck64	1076 - 1084	1135	10480	270
C836	1084 - 1100	1165	14170	230
Rotsee Core RL300				
C724	622.5 - 627.5	629	9450	140
C725	632.5 - 637.5	639	9380	130
C726	642.5 - 647.5	650	9770	130
C727	652.5 - 657.5	661	9780	140
C728	662.5 - 667.5	671	9360	130
C734	672.5 - 677.5	682	10020	120
C746	682.5 - 687.5	692	9840	140
C747	692.5 - 697.5	703	9360	130
C731	702.5 - 707.5	716	10120	140
C730	732.5 - 737.5	754	10000	130
C748	742.5 - 747.5	771	10920	170
C732	752.5 - 757.5	788	9750	130
C968	752.5 - 757.5	788	10730	150
C733	762.5 - 767.5	804	9680	130
C729	772.5 - 777.5	821	9490	130
C965	772.5 - 777.5	812	10160	130
C784	805.0 - 807.5	860	11440	140
C785	812.5 - 817.5	874	11460	140
C781	822.5 - 827.5	887	11970	150
C782	832.5 - 837.5	900	11870	150
C783	842.5 - 847.5	911	11800	140
C973	842.5 - 847.5	911	11640	190
C979	852.5 - 857.5	922	11880	150
C791	862.5 - 867.5	933	12580	170
Rotsee core RL300a				
C778	772.5 - 777.5	812	9870	120
C779	782.5 - 787.5	828	11260	140
C780	792.5 - 797.5	844	11270	140

1) normalized depth, see text

RESULTS, ERRORS AND CORE CORRELATION

Table 1 shows all results including those previously published (Andrée *et al,* 1986b). The given error includes the measurement accuracy (1σ) involving the statistical errors of sample and standard measurements and the long-term stability of the background as well as the error of the estimated $\delta^{13}C$ value of plant material according to Stuiver and Polach (1977).

Another error to be considered originates from the distribution of the single particles within the core section used as sample. The effective depth of the sample in the core cannot be determined precisely. This uncertainty in depth corresponds to an uncertainty in age in the range of 100 yr, depending on sample size and sedimentation rate.

To eliminate major errors due to disturbed sedimentation or other local effects, we measured several cores from two lakes. Thus, a reliable correlation of the cores was needed, for which, in principal, any recognizable feature in the core would be suitable. In our cores we found one excellent time marker, volcanic ash from Laach (LST). We also used the boundaries of local pollen assemblage zones (PAZ) to correlate within one lake and the boundaries of the regional PAZ to correlate between the two lakes. In our special case, $\delta^{18}O$ is not very suitable for a correlation, because the Lobsigen $\delta^{18}O$ curve shows rather atypical behavior and the resolution of the Rotsee curve is not satisfactory.

We constructed a normalized depth scale into which the depth scale of each core could be converted. The proportions of the PAZ lengths in the normalized scale correspond approximately to their average proportions in the single cores. Figure 1 shows the results of all cores plotted against the normalized depth. In general, the coincidence is satisfactory, except for the labeled values that are excluded in the final evaluation for the following reasons: 1) very small samples which required a special processing

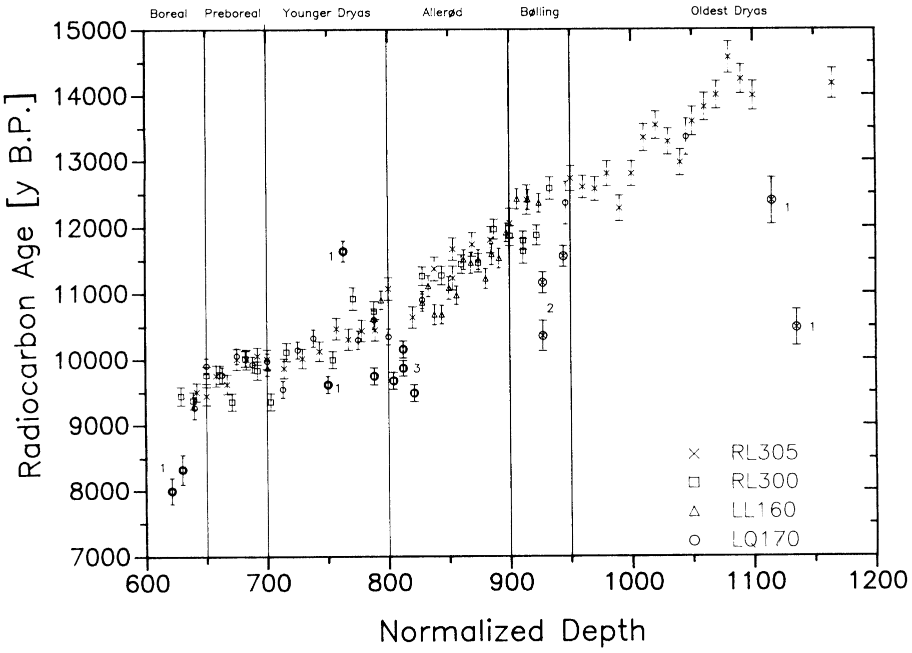

Fig 1. ^{14}C ages (BP) of the samples as a function of a normalized depth scale. Specified values (1–3), see text.

apparatus with an increased contamination problem. We lack experience to judge the reliability of these values; 2) those samples from the top of a core segment probably originate from younger material that fell into the borehole during the coring process; 3) those samples that are obviously too young for unknown reasons. It strikes us that the results of core RL300 generally show larger deviations from the average trend than those of the other cores. Thus, we have rejected all results from RL300.

HOW TO OBTAIN A RELIABLE TIME SCALE

From the shape of the curve in Figure 1, two periods of nearly constant ^{14}C age can be discerned. This could be due to either a decrease in the ^{14}C concentration or an increase in the sedimentation rate, or both. If we knew the sedimentation rate, we could determine the ^{14}C variations and *vice versa*. We tried to estimate mean sedimentation rates with linear regressions of the ^{14}C ages. As the sedimentation has probably been changing, the core can be divided into different segments with more likely constant sedimentation rates due to constant climatic conditions. On the other hand, the shorter these segments are, the more the result is affected by the ^{14}C variations. Thus, the selection of the segments influences the outcome. We tried linear regressions, once over the whole period and then over two parts, Preboreal – Younger Dryas and Allerød – Bølling. This was done for each core and with the determined sedimentation rates the duration of every pollen zone was calculated. The results are compared in Table 2. It becomes

TABLE 2

Comparison of the durations of the PAZ (D) [yr] and the sedimentation rates (S) [cm/100yr] with different calculations

	Preboreal		Younger Dryas		Allerød		Bølling	
	(D)	(S)	(D)	(S)	(D)	(S)	(D)	(S)
1. Regression								
RL 300	590	8.1	865	8.1	895	8.1	525	8.1
RL 305	750	3.2	1000	3.2	750	3.2	500	3.2
All values	470	x	940	x	940	x	470	x
2. Regression								
RL 300	450	10.6	660	10.6	1210	6.0	710	6.0
RL 305	470	5.1	630	5.1	1330	1.8	890	1.8
LL 160			1850	2.3	540	2.3		
LQ 170	350	2.3	700	2.3				
Varves								
RL 300	500	9.5	800	8.8	800	9.1	500	8.5
RL 305	500	4.8	800	4.0	800	3.0	500	3.2
LL 160	500	2.9	800	4.5	800	5.3	500	2.5
LQ 170	500	1.6	800	2.0	800	2.8	500	2.0

evident that there are considerable differences between the two approaches. As it is almost impossible to judge which partition of the core is admissible for the linear regression, another independent time scale is unquestionably necessary.

Counting varves, annual layers in the sediment, is one way to obtain a time scale. Since no varves are visible in our sediments, we refer to the Swedish varve chronology (Tauber, 1970) transferring it to our sites. Possible correlation marks that coincide are those PAZ boundaries corresponding to abrupt temperature changes that can clearly be observed in the records of both Swedish and Swiss lakes (Oldest Dryas/Bølling, Allerød/Younger Dryas and Younger Dryas/Preboreal). The varve chronology supplies the duration of these periods (Younger Dryas: 800 ± 50 yr, Bølling + Allerød: 1300 ± 50 yr). The specified errors concern the varve measurements, connections between different profiles and duplication or suppression of annual deposits according to Fromm (1970). There is also an error because the late glacial periods are not directly marked in the varve sequences. The varve ages of these periods are obtained by a more or less subjective equating of geomorphological features and halts or readvances of the ice front with the climatic changes reflected in the pollen diagrams. It seems that the localization of the Oldest Dryas/Bølling boundary is not uncontroversial, in contrast to the Younger Dryas (Tauber, 1970). The climate possibly changed quite synchronously in Switzerland and in Scandinavia, but the response of the vegetation to climatic changes is recorded with an unknown time lag. Finally, we have to consider the time resolution of the biological record. All these errors are difficult to estimate; the total error of the correlation could be in the range of 100–200 yr.

We assume the sedimentation rate to be uniform within the designated periods. The period including Bølling and Allerød is divided into its two parts according to the mean ratio of the lengths of the corresponding core segments from every core with known biostratigraphy. So we obtain 800 ± 70 yr for the length of the Allerød and 500 ± 70 yr for the length of the Bølling. The specified 70-yr error only concerns the scattering of the ratio; the total error is estimated at 200 yr.

The duration of the Preboreal was established similarly by comparing the length of the core segment with those of the other pollen zones. But the ratios show a systematic difference between the two lakes, so that the obtained value of 500 ± 200 yr is probably less reliable than the others.

Based on these durations, the normalized depth scale that equalizes minor variations in the individual cores can be converted into a time scale, assuming again uniform sedimentation within the PAZ. In Table 2, the mean sedimentation rates of the cores are calculated according to the ages estimated with the varve data. The sedimentation rates do not change excessively over the whole period, so the results seem to be quite reasonable.

Since there are no time marks in the Oldest Dryas, the time scale has to be extrapolated from the Bølling. Because the sediments changed (marl and gyttja instead of clay) the obtained values are not reliable.

The determination of an absolute time scale, *ie,* the determination of the absolute age of the zero level of the chronology is one of the main problems of the varve chronology. Strömberg (1985) estimates the absolute age of the Younger Dryas/Preboreal transition at 10,700 (+50, –150) yr, in good agreement with the 10,720 ± 150 yr obtained by Hammer *et al* (1986) dating an ice core from Dye 3, Greenland. We appoint 10,700 yr for the Younger Dryas/Preboreal boundary, the absolute ages of the other boundaries are determined according to the obtained durations of the PAZ (Table 3). A shift of the absolute time scale would cause a corresponding shift of $\Delta^{14}C$ curve but not alter the shape of the curve.

TABLE 3

The time scale according to the Swedish varve chronology, ^{14}C ages of the pollen zone boundaries

Pollenzone	Duration with estimated error	Absolute age of boundaries		^{14}C age
		PB/Bo	10,200 y cal BP	9,700 BP
Preboreal	500 ± 200 yr			
		YD/PB	10,700 y cal BP	10,000 BP
Younger Dryas	800 ± 150 yr			
		Al/YD	11,500 y cal BP	10,800 BP
Allerød	800 ± 200 yr			
		Bo/Al	12,300 y cal BP	12,000 BP
Bølling	500 ± 200 yr			
		OD/Bo	12,800 y cal BP	12,600 BP

INTERPRETATION OF THE $\Delta^{14}C$ CURVE

We can now calculate $\Delta^{14}C$ values using the absolute time scale obtained by the methods outlined above. Figure 2 shows $\Delta^{14}C$ values plotted against absolute age. The fitted curve is based on the calculation of running means over five values. Although the scattering of the values is considerable, the following striking features of the fitted curve can be perceived:

1) a dramatic increase of nearly 100‰ during the Allerød;

2) two drops of $\Delta^{14}C$ of ca 50‰ each time, once during the Bølling and again from the end of the Younger Dryas to the middle of the Preboreal.

Despite uncertainties in the time scale, we are convinced that the decreases are real. A horizontal segment in a ^{14}C age *vs* depth curve always implies a decrease of $\Delta^{14}C$ with time. The $\Delta^{14}C$ shift decreases when this period is shorter, but from the observed changes in the vegetation these periods might even last longer. The values in the Oldest Dryas are not reliable for the reasons mentioned above. So it cannot be excluded that the ^{14}C decrease of the Bølling begins earlier and thus is even larger.

The apparent ^{14}C increase in the Allerød is quite surprising. It could be due to an underestimation of the duration of the Allerød caused by an error in the varve chronology itself or in its transfer to our sites. If the Allerød lasted 200 yr (estimated error) longer, the increase would be reduced by ca 1/3 (30‰). To remove the whole increase, the Allerød should last 600 yr longer. We cannot definitely exclude an error of that order. On the other

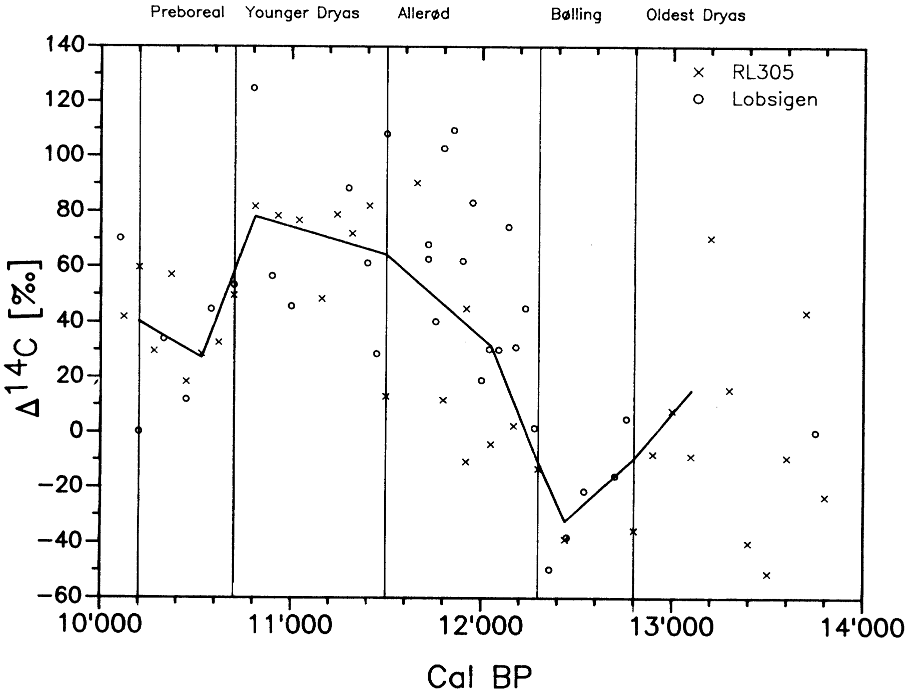

Fig 2. $\Delta^{14}C$ as a function of time. The fitted curve is based on running means over 5 values.

hand, we have additional evidence that confirms the 1300 yr obtained for the duration of Allerød and Bølling. In the Dye 3 ice core, the ratio between the accumulation in the Younger Dryas (≈ 10m) and Bølling + Allerød (≈16m) is 1:1.6. If we estimate 800 yr for the Younger Dryas, we obtain 1280 yr for Allerød and Bølling, assuming equal accumulation rates and compression of the annual layers. The accumulation rate is supposed to be lower by about a factor of 2 during the cold Younger Dryas, whereas the rheological thinning of the annual layers is lower only by a factor of 1.1 to 1.3 (a rough estimate, Schwander, pers commun), so the duration of Bølling and Allerød could be even shorter. However, the time scale is uncertain and we have to keep that in mind during further interpretations.

Stuiver *et al* (1986) established $\Delta^{14}C$ values reaching back to 13,500 cal BP using results from the varved Lake of Clouds and several ^{14}C ages from the Swedish varve series (Tauber, 1970). Between 13,000 and 10,000 cal BP he obtains five almost constant $\Delta^{14}C$ values of 100‰ by ^{14}C matching these dates to the known tree-ring record. Stuiver's generally higher values can be explained by the fact that with ^{14}C matching, the ^{14}C value representing the Younger Dryas/Preboreal transition is ca 11,200 cal BP. The 500-yr shift in the time scale causes ca 60‰ higher $\Delta^{14}C$ values.

PROBABLE CAUSES FOR THE STATED ^{14}C VARIATIONS

^{14}C variations are due to changes either in the isotope production rate or in the carbon cycle. Variations in atmospheric ^{14}C concentration during the abrupt climatic change at the end of the glacial period are likely due to changes in the global carbon cycle which is strongly coupled to the global climatic system. Principally, the observed changes in atmospheric ^{14}C concentration could be established by production variations, but the measured ^{14}C variations do not show the same characteristics as the ^{14}C variations in the Holocene that are believed to reflect production variations (eg, Suess wiggles). Although an extraordinary production change cannot be excluded, we restrict the following considerations to changes in the global carbon cycle.

The temperature development at the glacial-Holocene transition is known from $\delta^{18}O$ measurements of ice cores and lake sediments as well as from biological studies (Siegenthaler, Eicher & Oeschger, 1984). It is interesting to note that $\Delta^{14}C$ drops at the times of temperature increases at the beginning of the Bølling and at the end of the Younger Dryas cold phase. Atmospheric CO_2 was lower during the glacial than during the Holocene; the increase starts with the first warming, but further measurements are necessary to reconstruct the exact phase relation between $\delta^{18}O$ and CO_2. The Younger Dryas event cannot be identified in the CO_2 record (Neftel *et al,* 1988).

CO_2 increase is probably due to changes in the ocean circulation and chemistry. The mechanisms are not yet known in detail. Several scenarios have been suggested (Broecker & Peng, 1985). Wenk & Siegenthaler (1985) proposed the following mechanism: an increased upwelling of CO_2-rich deep water in regions where bioproductivity is not limited by the lack of nutrients would lead to a higher total carbon content in the surface water. Thus, CO_2 with low ^{14}C activity would be released to the atmosphere, raising CO_2 and reducing the ^{14}C concentration. Calculations with a 4-box model yield a ^{14}C increase of 35‰ for a 50% reduction of the exchange rate between the cold surface and the deep sea. Thus, an increased ventilation rate at the beginning of the Bølling could cause a ^{14}C decrease of about the amount we have measured.

The increase of the atmospheric ^{14}C concentration during the Allerød could be established by a reduction of the CO_2 exchange between atmosphere and the deep sea. The reason for such a reduction could be the influx of meltwater leading to a stable stratification of the surface water diminishing the vertical mixing of the ocean. A decrease of the ventilation rate of the deep sea by 50% leads to an atmospheric ^{14}C increase of ca 10‰ (Keir, 1983), *ie*, about the value we have measured. Of course, Keir's assumptions are arbitrary, but his calculations indicate that mechanisms of this kind could produce the observed ^{14}C increase.

To obtain the succession ^{14}C decrease – increase – decrease, it seems that the ocean has to switch between states of low and high ventilation rates. The Younger Dryas cold phase is supposed to be due to an interim transition of the system from the warm to the cold mode, possibly induced by a diversion of the discharge of Lake Agassiz meltwater from the Mississippi to the St Lawrence (Broecker *et al,* 1987). But in contrast to the ^{14}C decreases that are synchronous with warming, the ^{14}C increase occurs clearly before the Allerød (warm) – Younger Dryas (cold) transition. To understand the processes occurring at the glacial/postglacial transition, more detailed studies of the ocean circulation are needed. The first ^{14}C measurements on benthic and planktonic forams by Andrée *et al* (1986a) indicate that the ventilation rate was in fact lower during the glacial.

^{10}Be measurements on ice cores by Beer *et al* (1988) suggested that a 20% higher ^{14}C production rate for the last 10–15 kyr of the glacial than for the Holocene could be the reason for the long-term $\Delta^{14}C$ trend of the Holocene. To confirm this proposition, much higher $\Delta^{14}C$ values at the end of the glacial would be required than allowed by our study.

CONCLUSIONS

Measurements of ^{14}C on terrestrial macrofossils from lake sediments provide a method to reconstruct atmospheric $\Delta^{14}C$. The main problem is to obtain a reliable time scale, a problem that may only be solved satisfactorily if the sediments show annual layers. Despite all the difficulties with time control, we obtain a rough $\Delta^{14}C$ curve, which may be helpful for a correct interpretation of ^{14}C ages of this period. The determined ^{14}C variations are a hint to the behavior of the environmental system at the glacial/postglacial transition. Possible reasons for the observed ^{14}C changes have been mentioned, but we are far from fully understanding the mechanisms that occur.

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