PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

^{10}Be and ^{14}C in the Earth System [and Discussion]

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^{10}Be and ^{14}C in the Earth system

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In a very short period of time, ^{10}Be data have significantly improved our knowledge in various fields of Earth and planetary sciences. Examples are:

(*a*) solar modulation of isotope production, revealed in ^{10}Be ice-core profiles;

(*b*) geomagnetic modulation of isotope production, revealed in ^{10}Be ice-core (from the past 10 ka) and ocean-sediment profiles (geomagnetic reversals);

(*c*) climatic effects reflected in ^{10}Be profiles in loess and polar ice cores (^{10}Be behaviour in atmosphere);

(*d*) comparison of ^{10}Be and ^{14}C variations (tree rings) from carbon-cycle models and information on ocean circulation history from ^{14}C measurements on benthic and planktonic Foraminifera in ocean sediments.

An overview on work in collaboration with the Zürich AMS facility (with Professor W. Wölfli) is given.

Introduction

Studies of the impact of Man on the environment have clearly shown the complex interactions between the different parts of the Earth system (ES), like the atmosphere, biosphere, ocean, cryosphere, and lithosphere. In September 1986, the International Council of Scientific Unions (ICSU) implemented the International Geosphere–Biosphere Programme 'A study of global change'. The central focus is 'to describe and understand the interactive physical, chemical and biological processes that regulate the total earth system, the unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions'.

In such a holistic study, radioactive and stable isotopes play a major role. As an example, ^{14}C produced by cosmic rays and oxidized to $^{14}CO_2$, marks the pathways of the carbon that is in exchange with atmospheric CO_2 and gives information on the dynamics of carbon cycling. It is especially helpful in the determination of oceanic circulation and mixing times.

^{10}Be follows a different pathway in the ES; after attachment to aerosol particles it is deposited on the ground. Its concentration in such precipitation reflects not only the production by cosmic radiation in the atmosphere, but also meteorological effects, like atmospheric transport and deposition.

Accelerator mass spectrometry (AMS) enables us to significantly extend the field of application of ^{10}Be and ^{14}C to study the solar–terrestrial relation and ES processes at present and in the past. Before the introduction of AMS, ^{10}Be measurements on rain, snow or ice were not practical because of the large samples required for radioactive-decay counting. The sample size for ^{14}C measurements was of the order of a few grams of carbon, and the reduction of the sample size to about 1 mg of carbon opened up the possibility of studies on specially selected inorganic and organic sediment constituents.

In this paper, we summarize recent work on ^{10}Be and ^{14}C from ES samples and the present status of the interpretation of the results in the context of the history of solar parameters, of

carbon-cycle dynamics, carbon-cycle variations and climate history. This work is the result of collaborations with Professor W. Wölfli and his group at ETH Zürich; Professor C. C. Langway, SUNY Buffalo, Professor W. Dansgaard, Geophysics Institute, Copenhagen; and Professor W. Broecker, Lamont, N.Y., and their co-workers. The AMS data presented here were obtained with the tandem accelerator at ETH Zürich.

The carbon cycle and its isotopic labelling

Figure 1 shows the main reservoirs of the carbon system with the carbon contents and the exchange fluxes between the reservoirs. The rapidly exchanging reservoirs are the atmosphere, the ocean and the biomass. The carbon contents and fluxes represent the undisturbed carbon-cycle state, before the atmospheric CO_2 concentration started to rise as a result of biomass destruction and fossil-fuel consumption, in the 19th century.

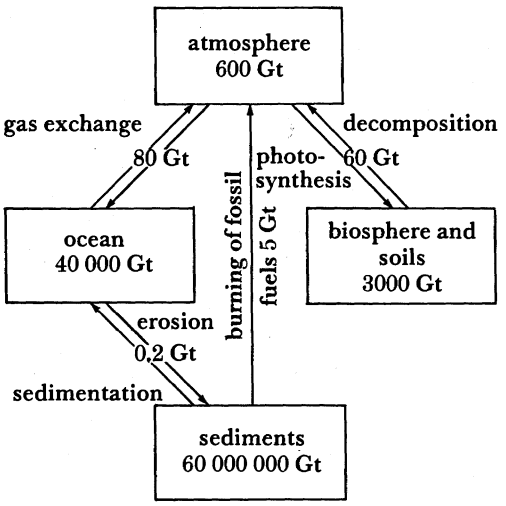

Figure 1. Global carbon system main reservoirs and fluxes. The reservoir amounts and annual fluxes are in units of gigatonnes of carbon.

Natural carbon consists of the two stable isotopes ^{12}C (98.9 %) and ^{13}C (1.1 %). The radioactive carbon isotope ^{14}C is produced in the atmosphere by cosmic radiation mainly through $^{14}N(n,p)^{14}C$ reactions. Its half-life is 5730 years, and it is also found in the ocean and biomass reservoirs and young sediments. The $^{13}C:^{12}C$ ratio is slightly changed by chemical reactions and diffusion processes.

Figure 2 shows the atmosphere–ocean part of the carbon cycle with the relative concentrations of carbon, the $^{13}C:^{12}C$ ratios, expressed as the deviations per mile $\delta^{13}C$ from a standard, and the $^{14}C:C$ ratios, normalized to 100 % in the well-mixed atmospheric reservoir. The values reflect the undisturbed Holocene state of the system. Because of radioactive decay, the $^{14}C:C$ ratio is lower, the slower the exchange with the atmosphere. For most of the ocean surface water, it is 95 %. In the subsurface ocean, because of the ageing of the circulating water masses, it varies between 90 % and 80 %, with an estimated average of 84 %. The exchange with the living biomass is relatively rapid, and its $^{14}C:C$ ratio is therefore close to that of the atmosphere. These $^{14}C:C$ ratios enable us to estimate the CO_2 exchange flux between atmosphere and ocean,

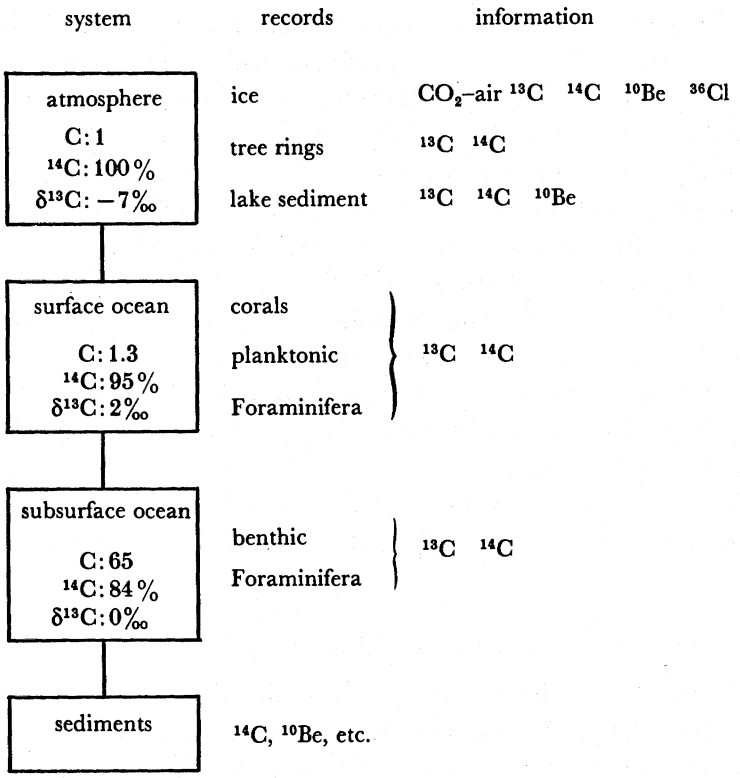

FIGURE 2. Information on the CO_2 system. The radioisotopes are partly or entirely measured by AMS.

and the mixing and circulation rate of the subsurface ocean water. As an example, based on the ratio of 84%:95% for ^{14}C:C in the subsurface and the surface ocean, an apparent ^{14}C age for the subsurface ocean water of *ca.* 1000 years can be calculated.

The mean δ^{13}C of the carbonate system of the surface ocean is slightly higher than that of the subsurface ocean. The difference is a result of isotopic fractionation during the formation of organic matter. Detailed δ^{13}C studies in the ocean and the sediments give valuable information on the biological processes in the ocean, reflecting also ocean dynamics and their history (see, for example, Broecker & Peng 1982). In this paper, we will concentrate on carbon-system studies with radioactive ^{14}C, especially measurements on small samples.

THE INFORMATION ON THE CARBON CYCLE AND ITS HISTORY IN ICE, SEDIMENTS AND ORGANIC MATTER

Natural archives, such as ice, organic matter and sediments, record continuously the important parameters reflecting the state of the carbon cycle, and indirectly the ocean and climate systems. Even the solar phenomena are imprinted on the carbon system through the modulation of cosmic radiation and thus of ^{14}C production.

Polar ice is the natural archive that is most directly coupled to the atmosphere. It records not only information on the water cycle, as ^{18}O:^{16}O and ^{2}H:^{1}H variations in the water molecule, and on particulate and soluble matter, it even contains, in the form of air bubbles,

physically occluded samples of the ancient atmosphere. Ice cores, obtained by drilling through polar ice sheets and glaciers thus allow the reconstruction of the time histories of the atmospheric CO_2 content and of the $^{13}C:^{12}C$ ratio of the occluded CO_2. Thanks to AMS, measurements of the $^{14}C:C$ ratio and of the ^{10}Be and ^{36}Cl concentrations have also become possible (see, for example, A. Litherland, this symposium). ^{10}Be and ^{36}Cl are produced in a way similar to ^{14}C by the interaction of cosmic radiation with atomic nuclei in the atmosphere, essentially by spallation reactions on N and O in the case of ^{10}Be, and on ^{40}Ar in that of ^{36}Cl. After production, these isotopes are attached to aerosols and, unlike ^{14}C, are deposited with precipitation.

The $^{13}C:^{12}C$ and $^{14}C:C$ ratios of atmospheric CO_2 are further recorded in trees, peat and lake sediments (in $CaCO_3$ and plant macrofossils). Also, the isotopic ratios of the carbonate system of the surface and the deep ocean are continuously preserved in the shells of surface-dwelling planktonic and bottom-dwelling benthic Foraminifera, and AMS allows us to measure a few hundred hand-picked shells of a single Foraminifera species from an ocean sediment core (Andrée *et al.* 1986*a*, *b*).

In the following section, we give examples of studies of isotopic records in ice and sediments that give information on the glacial, the glacial–postglacial and the Holocene Earth system periods.

Information on the Holocene Earth system

During the Holocene, before the human impact in the 19th century, the system parameters introduced above were relatively constant. Ice-core measurements show atmospheric CO_2 concentrations in the range of 280 ± 10 p.p.m. (by volume) (Neftel *et al.* 1985). Variations in the atmospheric $^{14}C:C$ ratio may be unambiguously determined by measurements on tree rings, the absolute age being independently determined by dendrochronology (Suess 1971; Stuiver & Quay 1980).

In figure 3, the deviations of ^{14}C from a standard, corrected for radioactive decay, are given. The curve is based on data from M. Stuiver (personal communication, 1986) and Linick *et al.* (1985). Essentially, two types of variations exist.

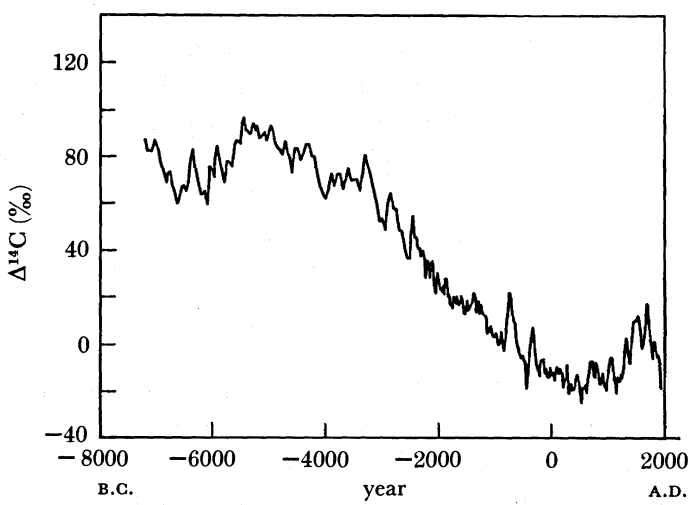

Figure 3. Atmospheric $^{14}C:C$ variations expressed in deviations per mil from standard, determined dendrochronologically dated tree rings, compiled from M. Stuiver (personal communication, 1986) and Linick *et al.* (1985).

1. Short-term fluctuations (wiggles) of *ca.* 20–30‰ (peak to peak) that, during certain time intervals, show a periodicity of *ca.* 200 years (Neftel *et al.* 1981).

2. A long-term trend, showing (on the negative time axis) a slight decrease to *ca.* −15‰, around AD 500, followed by an increase to a maximum of +100‰, around 5000 BC.

The short-term fluctuations are generally attributed to variations in the production rate of ^{14}C due to solar modulation of cosmic radiation (Suess 1971; Stuiver & Quay 1980). The long-term trend is generally considered to be caused by changes in ^{14}C production due to a variation in the magnetic shielding of the Earth from cosmic radiation (Suess 1971; Damon & Linick 1986), but it might also show a change in the carbon-cycle dynamics (Siegenthaler *et al.* 1980).

Additional information on the causes of the variations in ^{14}C can be obtained from records of other isotopes produced by cosmic rays, for example ^{10}Be in ice.

Comparison of ^{10}Be and ^{14}C fluctuations

It can be assumed that in a first-order ^{10}Be and ^{14}C production variations are proportional. When comparing the ^{14}C (tree-ring) and ^{10}Be (ice-core) variations, one has to take into account the different geochemical pathways of the elements. Whereas ^{10}Be is deposited, on average, about 1–2 years after production, newly produced ^{14}C is oxidized to $^{14}CO_2$, then mixed with the atmospheric CO_2 and later with the carbon in the ocean and in the biomass. Carbon-cycle models simulate this spreading into the carbon system. Thus, assuming proportionality of the ^{10}Be and ^{14}C production variations and neglecting climatic effects, the atmospheric ^{14}C variations corresponding to the ^{10}Be ice-core fluctuations can be calculated and compared with actually observed fluctuations.

This study has been performed on two ice cores from Greenland. The first core drilled at Station Milcent in central Greenland covers the past 780 years. It has been dated by counting seasonal δ^{18}O variations (Hammer *et al.* 1978) with an uncertainty of the order of 1%. Figure 4*a* shows the observed ^{10}Be concentration profile measured on samples covering 3–7 years (Beer *et al.* 1983). A first observation is the generally large differences between adjacent samples. They are, in most cases, larger than the experimental error of ±5–10%, and reflect meteorological effects and probably also production variations (Beer *et al.* 1985). Second, a grouping of high values is observed for the second half of the 17th century and the beginning of the 18th century. This period coincides with the so-called Maunder minimum period of the quiet Sun (Eddy 1976), during which the heliomagnetic shielding of cosmic radiation probably was minimal. Figure 4*b* shows the model-calculated (^{10}Be-based) Δ^{14}C curve together with the Δ^{14}C curve determined on tree rings by Stuiver & Quay (1980). The agreement between the two curves is satisfactory. The three periods of high Δ^{14}C (corresponding to the Maunder, Spörer and Wolf solar minima) also appear in the model-calculated Δ^{14}C. However, whereas the ^{10}Be-based Δ^{14}C maximum during the Wolf minimum agrees in amplitude with the measured Δ^{14}C, during the Spörer minimum it underestimates and during the Maunder minimum it overestimates it. The following conclusions can be drawn.

1. The ^{14}C variations observed in tree rings covering the period AD 1200–1800 correspond, in a first approximation, to the ^{10}Be variations determined in the Milcent core from Greenland covering this period. The variations do reflect fluctuations in the production rate of these isotopes.

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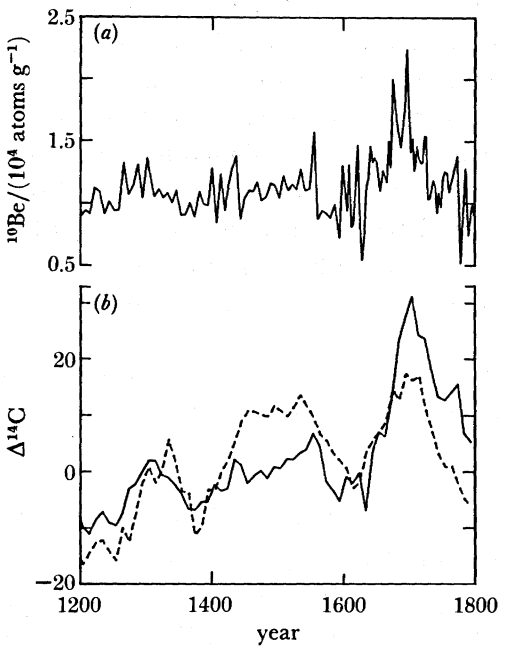

FIGURE 4. (*a*) ^{10}Be concentrations measured on an ice core from Station Milcent, central Greenland. (*b*) Comparison of measured ^{14}C (broken line) (Stuiver & Quay 1980) and carbon-model calculated ^{14}C, assuming that the observed ^{10}Be variations in (*a*) reflect production variations, and that the production variations of ^{10}Be and ^{14}C are proportional.

2. Considering the meteorological effects on the ^{10}Be concentrations, the carbon-cycle model reproduces well the dampening and phase shift expected for the atmospheric ^{14}C variations as a result of mixing in the atmosphere and parts of the oceanic and biomass carbon reservoirs.

3. The difference between the measured and the deduced Δ^{14}C curves is mainly attributed to changing meteorological conditions at Station Milcent, and in the northern polar region in general. As an example, during the Maunder minimum period, the humidity in this region might have been somewhat lower with the result of higher ^{10}Be concentration values in precipitation.

Next we will discuss what ^{10}Be can tell us regarding the cause of the long-term ^{14}C trend. Is it also the result of a trend in radioisotope production, e.g. is it caused by a change in the geomagnetic shielding against cosmic radiation, or does it reflect a carbon-cycle effect, like an increase of the mixing between surface and subsurface water that brings the ^{14}C:C of the surface ocean and of the atmosphere closer to that of the subsurface ocean, by far the largest reservoir of exchanging carbon?

An ice core from Camp Century in northwestern Greenland, drilled in 1966 by a team of U.S. engineers and scientists (Ueda & Garfield 1969), served to study the long-term ^{10}Be behaviour. The ^{10}Be data obtained for this ice core are plotted in figure 5. At a height above bedrock of *ca.* 250 m there is the transition from the Younger Dryas cold phase to the Holocene, corresponding to about 10000 ^{14}C years BP.

The direct comparison with the tree-ring Δ^{14}C record shows that the major wiggles find their counterparts in the ^{10}Be record. Higher ^{10}Be concentrations are observed for the period 6000–4000 B.C., in accordance with the bump in the ^{14}C record. The comparison of the

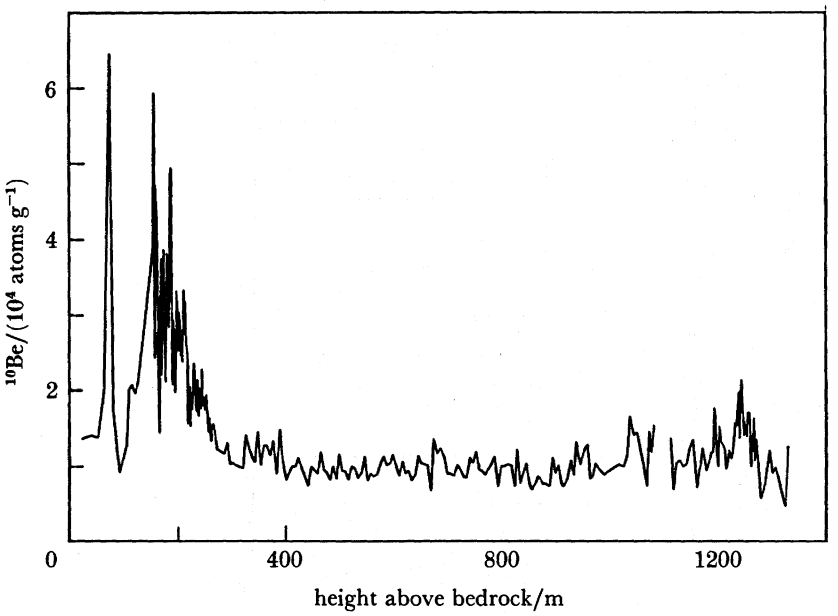

FIGURE 5. ^{10}Be concentrations in the ice core from Camp Century, northwestern Greenland. The transition from Glacial to Holocene (10000 ^{14}C years BP) is observed at 250 m above bedrock and corresponds to a decrease of the ^{10}Be concentration.

long-term ^{14}C and ^{10}Be records with a carbon cycle model are discussed in detail by Beer *et al.* (1984; and unpublished results).

One problem is the fact that, when approaching the transition to the glacial, significant changes in the ES affect both the ^{10}Be concentrations and the atmospheric ^{14}C:C ratio, and rather than production changes, these records reveal information on the processes during the glacial–interglacial change.

There is, however, an independent possibility of checking whether the decrease in ^{14}C from *ca.* 8 ka–2 ka BP does not reflect a carbon-cycle change. There are reasons to believe that the amounts of carbon in the different reservoirs did not vary much during the Holocene; one indication is the relatively constant CO_2 concentrations in the air occluded in ice cores. As stated above, an increasingly rapid oceanic turnover would lead to a smaller difference between subsurface and surface ocean ^{14}C:C. The atmospheric ^{14}C:C ratio would follow the ocean surface trend. When discussing figure 2, we emphasized that planktonic and benthic Foraminifera reflect in their shells the ^{14}C:C ratios of the carbonate system in ocean-surface on ocean-bottom water. Thus in high-accumulation deep-sea cores, where bioturbation only little affects stratigraphy, samples of co-existing, contemporaneously deposited, Foraminifera of the two types can be collected for AMS ^{14}C analysis. Such a study has been successfully performed on a sediment core from the South China Sea (Andrée *et al.* 1986*a*, *b*). First results show that the apparent age difference between the two Foraminifera species during the Holocene remained essentially constant within the error limits (figure 6). Based on the information on this part of the ocean, no change in ocean dynamics that could produce the Holocene atmospheric ^{14}C:C long-term trend is indicated. This supports its explanation as the result of a higher ^{14}C production during the end of the last glaciation and the early Holocene.

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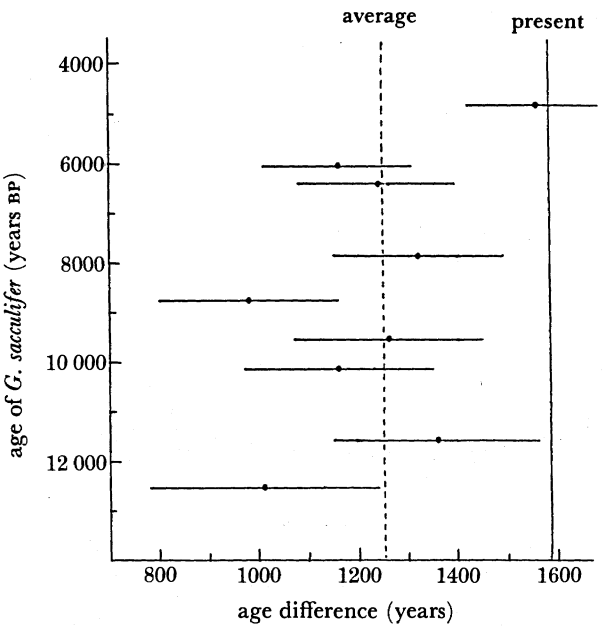

FIGURE 6. Deviation of the age of *G. sacculifer* from the age of mixed benthics against the age of *G. sacculifer*. The solid line marks the present-age deviation. The broken line indicates the mean value of the measured points. Measured average: 1250±60 years; present: 1585±150 years.

INFORMATION ON THE GLACIAL AND THE GLACIAL–POSTGLACIAL TRANSITION

As indicated in the Camp Century ^{10}Be data during the glacial period, with a few exceptions the concentrations were higher by a factor of 2–4. This most probably reflects low snow accumulation in the north polar area, corresponding to a lower dilution of the cosmic ray ^{10}Be flux. ^{10}Be concentrations are indeed used to estimate accumulation rates (Yiou *et al.* 1985).

Measurements of CO_2 concentrations in the air occluded in glacial ice cores from Greenland and Antarctica (Stauffer *et al.* 1985; Neftel *et al.* 1982) indicate CO_2 concentrations ranging from 180–200 p.p.m. (by volume) for the coldest periods.

First extensions of the Foraminifera ^{14}C studies into last glaciation indicate, for the Tropical Pacific and Tropical Atlantic Ocean, an age difference between surface and bottom water that is by about 800 years greater than during the Holocene, corresponding to a slower oceanic turnover (W. S. Broecker & M. Andrée, personal communication). These data still need confirmation.

Based on Greenland ice core, in the North Atlantic area and lake sediment, as well as pollen information in peat, the transition to the Holocene occurred in two rapid pronounced steps. A first warming occurred around 12500 ^{14}C years BP. This Bølling–Allerød warm period ended 11000 ^{14}C years BP and was followed by the Younger Dryas cold Period, which lasted about 1000 ^{14}C years. The final transition to the postglacial warm period occurred around 10000 ^{14}C years BP. These rapid climatic oscillations can be correlated with movements of the deglacial North Atlantic polar front, as deduced from faunal studies on ocean sediments. The transition of glacial CO_2 concentrations of 180–200 p.p.m. (by volume) to Holocene values of 280±10 p.p.m. (by volume) occurred during this transition period. Greenland ice-core data indicate that the change occurred in two steps, in phase with the climatic transition. However,

this stepwise change could not yet be confirmed in the Antarctic cores and a more gradual change during a few thousand years cannot be excluded.

During the transition, the average ocean-surface temperature increased by *ca.* 2.5 K, the salinity decreased because of the melting of ice sheets, and the total carbon in the ocean decreased because organic matter was formed on the continents and $CaCO_3$ was precipitated and preserved on the sea floor.

All these changes must be reflected in the atmospheric ^{14}C:C ratio. Unfortunately, it is difficult to find preserved fossil trees through the entire glacial–postglacial transition to construct a continuous dendrochronological and ^{14}C record back into the last glaciation. This problem can be overcome by ^{14}C studies on plant macrofossils, deposited in lake sediments, especially if these are varved and thus show countable annual layers. Data obtained for Lake Lobsigen, a small lake on the Western Swiss Plateau, are shown in figure 7 (Andrée *et al.* 1986*a*,*b*). Surprising results of this ^{14}C profile are the comparatively constant ages of the macrofossils during the early Preboreal and Bølling periods. The Preboreal age plateau confirms earlier ^{14}C studies on a peat bog from Wachseldorn by Oeschger *et al.* (1980), who reported a sequence of almost constant ^{14}C age, corresponding to a peat growth of *ca.* 500 years during that period.

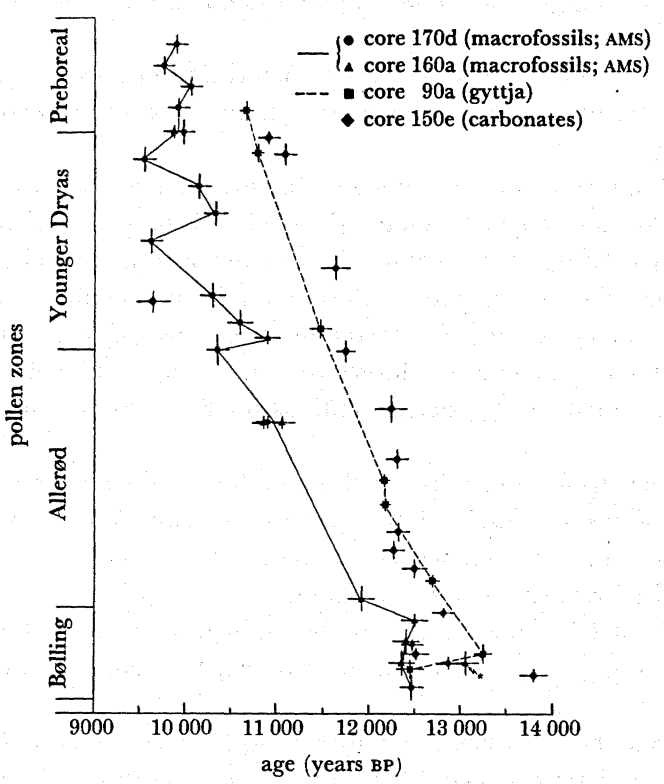

FIGURE 7. Plot of ^{14}C ages against pollen zones for measurements on Lake Lobsigen. The points are plotted according to the depth scales of the individual cores. These have been correlated by using local pollen-zone boundaries. The horizontal bars indicate standard measurement error, the vertical bars show the depth span of the sample.

Both the Bølling and the Preboreal ^{14}C plateaux (as well as the turbulent Younger Dryas age sequence) probably reflect carbon-system changes as a decrease in atmospheric ^{14}C:C due to the evasion of ^{14}C-older CO_2 from the ocean, the speeding up of ocean circulation, and the general shift of the carbon cycle to a new steady state.

This observation of a carbon-cycle parameter trend goes in parallel with the development of carbon-cycle models simulating changes in total CO_2 and CO_2 partitioning among the reservoirs, and trends in the dynamic parameters.

Conclusions

AMS studies of isotopes produced by cosmic rays discussed here allow a deep insight into ES processes and their history. They range from the reconstruction of the histories of solar phenomena, terrestrial magnetism, atmosphere–ocean interaction, oceanic mixing, to that of the amount of carbon cycling in the atmosphere–biosphere–ocean system and its partitioning among these different reservoirs.

Although these studies are only just beginning, answers to some fundamental questions have already been obtained or seem within reach during the next few years.

1. Combining the ^{14}C tree-ring and ^{10}Be ice-core records enables us to unambiguously reconstruct major fluctuations of solar magnetism. Parallel to the solar magnetism, other solar parameters having some impact on the Earth climate might have changed, and correlations between ^{14}C and ^{10}Be changes and climatic fluctuations might help to identify a solar influence on climate.

2. The ocean-circulation pattern and its characteristic times seem to have been essentially constant during the Holocene; but there are strong indications for slower oceanic mixing during the last glaciation.

3. Together with studies of other parameters measured in polar ice, ocean and lake sediments (beside geomorphological evidence), a more-detailed and complete picture of the climatic and environmental events at the end of last glaciation and the transition to the Holocene is emerging.

4. To synchronize the ES evolution, information from the different archives and from geomorphological evidence dating is a prerequisite. Because of the requirement of only little sample material, AMS has significantly enlarged the field of application of the ^{14}C dating method, as has been demonstrated by age determinations on single Foraminifera species and plant macrofossils.

5. Most of the new applications discussed here relate to the assessment of the present and the reconstruction of past ocean-circulation patterns. Ocean circulation and mixing is one of the most important ES processes for several reasons.

(*a*) It helps to distribute energy over the globe.

(*b*) The atmospheric CO_2 concentration is determined by the partial pressure of CO_2 in the ocean surface depending, in turn, on biological processes steered, for example, by the ocean dynamics.

(*c*) It interacts in a very complex way with atmospheric circulation. This nonlinear system at present seems to oscillate between different modes of operation (El Niño phenomenon).

(*d*) During the glacial and the transition to the postglacial, the interaction of the ocean with the cryosphere played an important role, indicating the sensitivity of ocean dynamics to changing boundary conditions.

(*e*) Related to Man's impact on the environment, the ocean acts as the main sink for anthropogenic CO_2 and, because of its heat capacity, dampens changes of the energy balance at the Earth's surface induced by the increase of greenhouse gases. An open question remains as to whether it will operate during this period of global change as it did during the past decades and centuries.

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(f) With models of different hierarchies an attempt is made to describe the present oceanic behaviour and a possible change due to changing boundary conditions. Such models also should be capable of describing past oceanic events as reconstructed with the new analytical techniques. It is this interaction between theoretical and analytical approaches that promises progress toward an integrated understanding of the complex mechanisms governing climate and environment.

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Discussion

U. Fehn (*University of Rochester, New York, U.S.A.*). I have a question about the production changes related to the Maunder minimum and to two previous minima in solar activity. If you look at the ^{14}C record it seems that three minima were produced by amplitude changes of approximately the same size, but in ^{10}Be the Maunder minimum is dominant. The two earlier minima are hardly visible. I wonder if Professor Oeschger could comment on that.

H. Oeschger. The comparison of the ^{14}C variations calculated by the ^{10}Be-based model with the measured variations shows a good agreement for the Wolf minimum; the Spörer minimum is underestimated, whereas the Maunder minimum is overestimated. We are aware of the meteorological noise in the ^{10}Be record, caused by variations in atmospheric mixing and dilution with water vapour. We try to normalize the ^{10}Be information by using continuous records or chemical constituents and isotopic ratios (δ^{18}O). Also the comparison of detailed ^{10}Be profiles from different locations in Greenland and on other ice sheets may help to distinguish between production variations and terrestrial effects.

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P. DAMON (*University of Arizona, Arizona, U.S.A.*). I noticed that the ^{10}Be seems to correlate closely with ^{18}O. Is this perhaps because the dominant influence is climatic?

H. OESCHGER. In the Camp Century (northeast Greenland) ice core, δ^{18}O shows low values, coinciding with the Maunder minimum ^{10}Be peak. In the Milcent (central Greenland) this correlation is much less pronounced, if it exists at all. As mentioned above, the possibility of separating terrestrial effects on the ^{10}Be concentration by using additional information is being studied. The ^{10}Be–^{14}C comparison is rather convincing, and we believe that, at least regarding the short-term (200 year) variations, the cosmic-ray signal is dominant.

U. FEHN. There is no correlation between the short-term variation of δ^{18}O and ^{10}Be. There is a correlation over the long term, and especially at the end of the last glaciation. The short-term variations are only correlated with the ^{14}C wiggles.

G. RAISBECK. I noticed that there were some very large ^{10}Be concentrations during the last ice age in your Camp Century data. Would Professor Oeschger care to comment on them?

H. OESCHGER. There have been large ^{10}Be changes (by a factor of 1.5–2.5) observed during the Wisconsin. They are correlated with changes in δ^{18}O and anions, and can be explained by variations in the accumulation rate. In the Camp Century ice-core record, however, there is one value outside the range of these variations that is of mainly climatic origin. Without additional measurements we would not like to speculate on its cause.

W. HENNING. I have a question with respect to Professor Oeschger's 11 year cycle. How is Professor Oeschger going to try to check the constancy of sidereal effects? If he uses a Fourier-type analysis, will he have enough data; and also in view of some differences in the wiggles of fine structure between different sites, does Professor Oeschger think that he will still be able to get reliable information on the 11 year cycle, which is of course very interesting?

H. OESCHGER. It will be difficult but not impossible. In a pit study on the Greenland ice cap, a series of parameters has been studied on approximately monthly samples covering 5 years. Whereas δ^{18}O and ^{3}H in the water show nice and smooth seasonal variations, parameters like anions, ^{10}Be and ^{210}Pb show strong variations from sample to sample, probably reflecting variations in the aerosol contents and origins. We have to learn to interpret this information to correct for terrestrial effects on ^{10}Be concentrations.

E. BARD (*Centre de Faibles Radioactivites, France*). What does Professor Oeschger think about the effects of bioturbation on the age difference between planktonic and benthic Foraminifera?

H. OESCHGER. Bioturbation causes problems that till now can only be overcome in high accumulation ocean sediment cores as the one from the South China Sea, as discussed in this paper.

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