ABSOLUTE PRODUCTION OF RADIOCARBON AND THE LONG-TERM TREND OF ATMOSPHERIC RADIOCARBON

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ABSTRACT. This paper presents simulations of the long-term trend of atmospheric radiocarbon, performed with the modified PANDORA model. The author shows that taking into account the outflow-supply carbon fluxes makes the decrease of D^{14}C between 40 and 0 ka BP larger by 40–80‰, not much depending on which data (sedimentary magnetism, archaeomagnetism or ^{10}Be) is used for the scenario of relative variations of ^{14}C production. This, together with the effect of CO$_2$ increase reasonably reconciles model-simulated and observed decline of atmospheric Δ^{14}C.

INTRODUCTION

It was recognized long ago that the secular variations of atmospheric radiocarbon concentration were related to changes of ^{14}C production in the Holocene (e.g. Stuiver et al. 1991) as well as in the Glacial (e.g. Bard et al. 1990). This relationship is mostly due to the screening effect of Earth's magnetic field on cosmic rays, which produce ^{14}C in the atmosphere.

During the last decade, studies of secular ^{14}C variations have been extensively developed. One line of development is the progress of ^{14}C calibration (Stuiver et al. 1993, 1998; Kitagawa and van der Plicht 1998; Schramm et al. 2000) which documents continuous decline of atmospheric ^{14}C over the last 40,000 years (Figure 1). The second one is an issue of independent data on cosmogenic production. These data include paleomagnetic reconstructions, based on archeomagnetic (McElhinny and Senanayake 1982) and sedimentary magnetic (e.g. Tric et al. 1992; Guyodo et al. 1996) studies, and more direct reconstructions of cosmic rays, which use ^{10}Be concentrations in sediments (Frank et al. 1997). Using such data and the global carbon cycle models, Mazaud et al. (1992) and Bard (1997a, 1998) concluded that the decline of Δ^{14}C is well explained by secular changes of cosmic-ray intensity.

The rate of Δ^{14}C decline, simulated in the studies above, was slower than that documented with the ^{14}C calibration data. That discrepancy was considered insignificant regarding uncertainty of proxy data. This uncertainty has been expressed (Figure 1a) with the bands representing range of "possible" Δ^{14}C. The upper and lower limits of those bands have been obtained with model simulations, using the highest and lowest possible values of ^{14}C production, deduced from the uncertainty of the proxy data.

However, influence of rapid fluctuations of ^{14}C production on atmospheric ^{14}C concentration is attenuated by the carbon cycle, which acts as a low-pass filter. Therefore rapid changes of Δ^{14}C within the bands in Figure 1a may require fluctuations of ^{14}C production larger that those allowed by the uncertainty of the production data. Such is the case of the ^{14}C record (Figure 1b). The deviation of the required ^{14}C production from that allowed by the proxy data is not large. However, between 20 ka and today, all the proxies consequently predict higher ^{14}C production than the required one. This may reflect some additional factor responsible for the secular changes of atmospheric ^{14}C concentration.

ABSOLUTE PRODUCTION RATE OF RADIOCARBON

The reservoir models of the global carbon cycle (e.g. Oeschger et al. 1975; Broecker et al. 1990; Bard 1997b) deal with relative changes of ^{14}C production and concentration. Here, the production rate is expressed in relation to the modern production, and ^{14}C concentration is expressed with rela-

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tion to the standard of modern biosphere. In the steady state, the models predict standard ^{14}C concentration in the atmosphere for the modern value of ^{14}C production.

However, the existing models do not properly explain the absolute value of ^{14}C production. This production should counterbalance radioactive decay of ^{14}C, which can be calculated using ^{14}C inventories in model reservoirs. That question has been raised by Damon (1988), and Damon and Sternberg (1989) pointed out that the model-calculated rate of ^{14}C decay is about 30% smaller than that determined using direct measurements of neutron fluxes in the atmosphere.

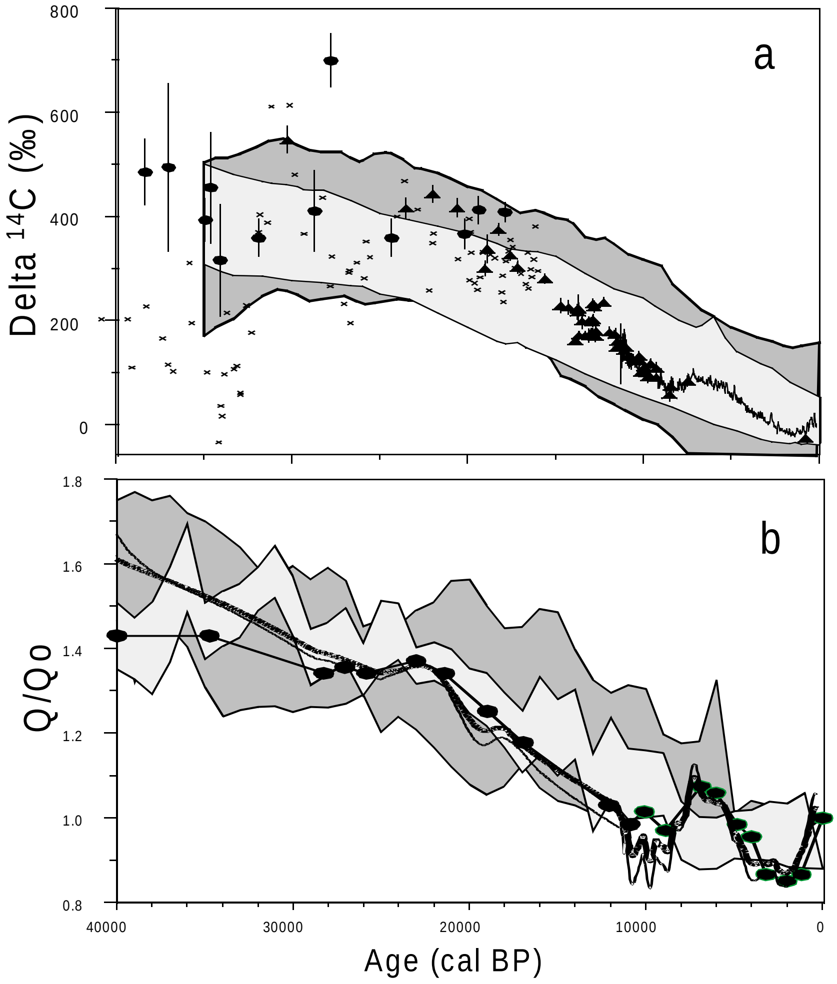

Figure 1*a* Atmospheric $\Delta^{14}C$ *vs*. time calculated using the ^{14}C calibration data from: ▲ = corals (Bard et al. 1998), — = European oak and pines (Stuiver et al. 1998), ✕ = Lake Suigetsu, Japan (Kitagawa and van der Plicht 1998), and ● = Lake Lisan, Israel (Schramm et al. 2000). Light and dark bands represent range of $\Delta^{14}C$ calculated by Bard (1997a, 1998) using the paleomagnetic (Guyodo et al. 1996) and the ^{10}Be (Frank et al. 1997) data, respectively. *b*: Changes of radiocarbon production rate (in relation to the present production) *vs*. time. Thin and thick lines = production rate required to explain the $\Delta^{14}C$ changes documented by the tree-ring and coral data, calculated with the PANDORA model without and with the E-I fluxes, respectively. Dark and light bands = ranges of ^{14}C production rate derived from the paleomagnetic (Guyodo et al. 1996) and the ^{10}Be (Frank et al. 1997) data, respectively. Line with solid circles = ^{14}C production rate derived from the archaeomagnetic data (McElhinny and Senanayake 1992).

Damon and Sternberg (1989) proposed that this apparent discrepancy is due to sedimentation of about 1.4 gigaton of carbon per year (GtC/yr), which transfers significant amounts of ^{14}C "out" of the usually considered carbon cycle. In their model, the main paths of carbon escape were deposition of carbonates at oceanic bottom (ca. 0.55 GtC/yr), and deposition of organic matter (ca. 0.7 GtC/yr) in coastal wetlands, deltas, lagoons, etc. with very long carbon residence time.

In the steady state, the escape must be balanced by inflow of ^{14}C-free or ^{14}C-depleted carbon. Damon and Sternberg (1989) assumed two fluxes of inactive carbon to the oceans, one (0.6 GtC/yr) from the atmosphere and the second one (ca. 0.8 GtC/yr) directly from the continents. To keep constant the atmospheric inventory, the atmospheric outflow must be balanced by release from continents (from decomposition of "very old" organic matter, volcanic eruptions, etc.)

The escape-inflow (E-I) fluxes have been usually neglected in model simulations of past ^{14}C levels. This seems well justified, as in the steady state, ^{14}C concentrations in all reservoirs are proportional to the production rate, independently of which model type (i.e. with and without the E-I) is used. So, as the ^{14}C concentrations and ^{14}C production rate are expressed in relative units (i.e. with respect to the concentration in the preindustrial atmosphere, and with respect to the modern production rate, respectively) the results of simulations with the two model types would be identical.

However, one must realize that by incorporating the E-I fluxes, we allow for 30% higher absolute changes of the production rate, while the amount of carbon in the atmosphere-ocean-biosphere system remains the same. Therefore, the response of ^{14}C concentration to given relative change of the production rate is stronger in the models with than without the E-I flux. The difference is strongest in the case of very quick changes, but may be significant even for changes with a time constant comparable to the half-life of ^{14}C.

MODELING THE E-I FLUXES

One of models used for calculations of past ^{14}C variations (Goslar et al. 1995, 1999, 2000) is the PANDORA model (Broecker et al. 1988). In these calculations, the sedimentation was being neglected. Nevertheless, if we assume that the specific ^{14}C activity in the preindustrial atmosphere (Δ^{14}C=0‰) was 14.1dpm/gC, the PANDORA model gives preindustrial steady-state ^{14}C decay rate of 1.66 dps/cm^2. This value is distinctly lower than the absolute production rate, which for the period 1964–1976 averaged at 2.2–2.35 at/cm^{2}s (compiled from Light et al. 1973; Korff and Mendel 1980; Castagnoli and Lal 1980; Lal 1988, 1992).

The ^{14}C production and decay may be balanced when we allow for an escape of 1.85GtC/yr "out" of the system. In fact, that value is independent of the form (i.e. whether organic or carbonate) of escaping carbon. It is worth to note, that bibliographic data on carbon fluxes to sediments are quite diverse (e.g. F_{org}= 0.4–1.3 GtC/yr—Baes et al. 1985; F_{org}= 1 GtC/yr—Olson et al. 1985; F_{carb}=0.4 GtC/yr and F_{org}= 0.35 GtC—Mackenzie et al. 1993; F_{org}= 2.2 GtC/yr—Wollast 1993; $F_{org+carb}$= 0.2GtC/yr—Siegenthaler and Sarmiento 1993).

In the standard PANDORA model, about 1.3 GtC/yr precipitates in the surface oceans in form of carbonates. Using the mean depth of the lysocline (4500 m; Broecker and Takahashi 1978), one can estimate that about 35% of that flux is ultimately deposited to sediments. So, the resulting sedimentary flux of carbonates (ca. 0.45 GtC/yr) is quite similar to that proposed by Damon and Sternberg (1989). Nevertheless, in previous ^{14}C simulations, the whole precipitating carbonate was assumed to dissolve in deeper reservoirs. In the E-I modification, the escape (total 1.85 GtC/yr) is provided by fluxes of carbon out of the surface ocean reservoirs (Figure 2).

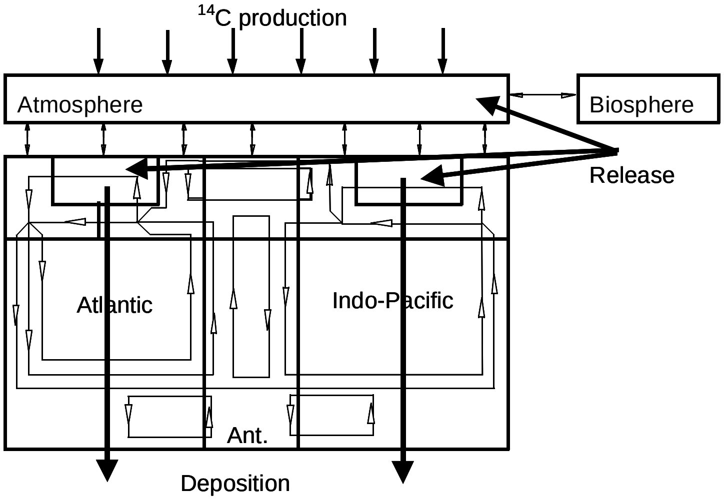

Figure 2 Schematic representation of the fluxes in the PANDORA model (Broecker et al. 1990). The fluxes introduced to balance the decay and production of radiocarbon are displayed with thick arrows.

The pathway of inflow of inactive carbon (which balances the escape) is meaningful for ^{14}C distribution between reservoirs, as the ^{14}C-free carbon dissolves ^{14}C in the recipient reservoir. This problem has not been analyzed before. In the model, I assumed that half of inactive carbon is supplied to the atmosphere, and the second half to the surface ocean (Figure 2). This would increase reservoir age of surface ocean by around 130–140 years, an effect which must be compensated by increased CO_2 exchange between oceans and atmosphere (from 15 mol/m^{2}yr to 19.5 mol/m^{2}yr). Such an increase, however, seems difficult to accept, since even the value of 15 mol/m^{2}yr is 15% higher than that calculated theoretically using known wind distribution over the oceans (Etcheto et al. 1991). Therefore, this problem requires further study.

MODELING THE LONG-TERM TREND OF ATMOSPHERIC ^{14}C

Recent simulations of long-term changes of atmospheric ^{14}C have been published by Bard (1997a, 1998), who used several scenarios of cosmogenic production. Two scenarios were based on the reconstructions of geomagnetic dipole moment, with the relationship between relative changes of geomagnetic field and production taken from Lal (1998). The third scenario used the measurements of ^{10}Be concentration in sediments. The changes of beryllium are proportional to the changes of cosmogenic production.

I used the same scenarios. To determine the effect of absolute ^{14}C production, each scenario was run on two versions of the PANDORA model i.e. without and with the E-I fluxes. The results obtained with the standard model (Figure 3) are very similar to those of Bard (1997a, 1998). All the scenarios predict decline of atmospheric D^{14}C distinctly slower than that documented by the ^{14}C calibration data. Taking into account the E-I fluxes makes the decline during the last 30 ka larger by 40–80‰, and closer to the real one. The increase of the rate of decline, caused by the E-I mechanism, is similar for all the scenarios of ^{14}C production.

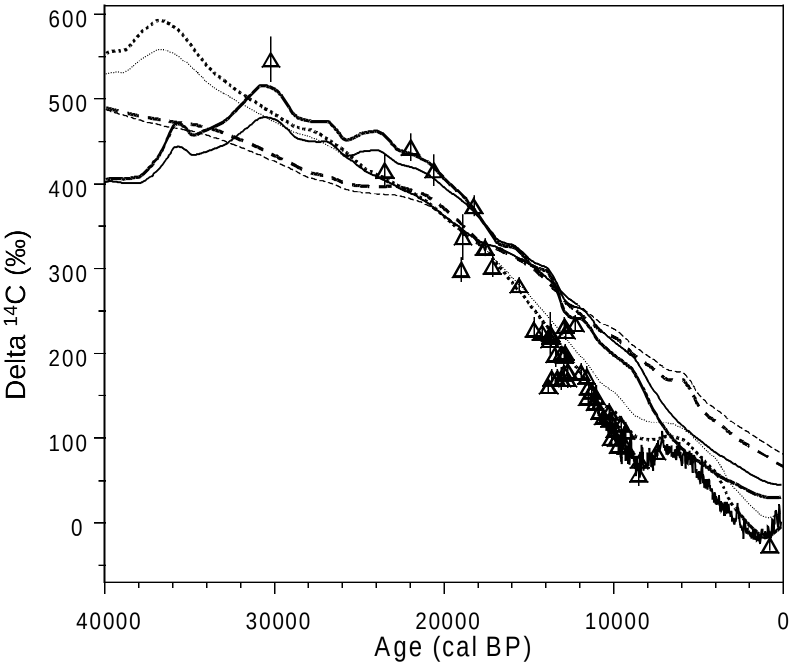

Figure 3 Results of simulations of atmospheric $\Delta^{14}C$ using the PANDORA model without (thin lines) and with (thick lines) the E-I fluxes. The line types differentiate input data on the cosmonuclide production. Dashed lines = sedimentary paleomagnetic data (Guyodo et al. 1996), solid lines = ^{10}Be data (Frank et al. 1997), dotted lines = archaeomagnetic data (McElhinny and Senanayake 1992). The values of $\Delta^{14}C$ calculated from Δ = corals (Bard et al. 1998) and — = European oak and pines (Stuiver et al. 1998) are shown for comparison.

CONCLUSION

Deposition of ^{14}C-bearing carbon in oceanic sediments, balanced by the release of ^{14}C-free carbon from the continents is a mechanism, which may reconcile the model-derived and measured absolute rates of modern ^{14}C production. Taking this (E-I) mechanism into account affects the results of model simulations of past ^{14}C concentration, making the decline of $\Delta^{14}C$ during the last 30 ka larger by 60‰. This diminishes discrepancy between observed long-term decline of atmospheric $\Delta^{14}C$ and that, which can be explained by the long-term changes of ^{14}C production rate.

Another factor is the increase of CO_2 concentration between the Glacial and the Holocene. This change would decrease atmospheric $\Delta^{14}C$ by around 25–35‰ (Lal and Revelle 1984; Keir 1983; Goslar et al. 1999), further increasing the rate of decline of $\Delta^{14}C$, towards the observed trend.

One serious problem of the E-I approach is that both the E and I fluxes could vary in time. Such variations are partly constrained by the known history of atmospheric CO_2 concentration, nevertheless, simultaneous changes of both E and I fluxes, which would affect atmospheric ^{14}C with no changing CO_2 concentration, are beyond control. This problem, however, is beyond the scope of this paper.

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