Tree rings and ice cores reveal ^{14}C calibration uncertainties during the Younger Dryas

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The Younger Dryas interval during the Last Glacial Termination was an abrupt return to glacial-like conditions punctuating the transition to a warmer, interglacial climate. Despite recent advances in the layer counting of ice-core records of the termination, the timing and length of the Younger Dryas remain controversial. Also, a steep rise in the concentration of atmospheric radiocarbon at the onset of the interval, recorded primarily in the Cariaco Basin, has been difficult to reconcile with simulations of the Younger Dryas carbon cycle. Here we discuss a radiocarbon chronology from a tree-ring record covering the Late Glacial period that has not been absolutely dated. We correlate the chronology to ice-core timescales using the common cosmic production signal in tree-ring ^{14}C and ice-core ^{10}Be concentrations. The results of this correlation suggest that the Cariaco record may be biased by changes in the concentration of radiocarbon in the upper ocean during the early phase of the Younger Dryas climate reversal in the Cariaco basin. This bias in the marine record may also affect the accuracy of a widely used radiocarbon calibration curve over this interval. Our tree-ring-based radiocarbon record is easily reconciled with simulated production rates and carbon-cycle changes associated with reduced ocean ventilation during the Younger Dryas.

The Late Glacial time interval, from approximately 14,500 to 11,600 cal years BP, is of great interest in palaeoclimate research because of the strong climate variability found in various archives, for example in ice cores[1,2], lacustrine sediments[3], speleothems[4], marine sediments[5,6] and tree rings[7,8]. Accurate and independent dating of the various records is a prerequisite to understand the causes and effects of this climate variability, and there is still a relatively large disagreement between the different determinations of the length of the Younger Dryas (YD) cold period. From detailed ^{14}C dating of terrestrial macrofossils in European Late Glacial lake sequences it can be concluded that the onset of YD is dated to 10,800–10,600 ^{14}C years BP (refs 9,10 and references therein) and that the end is dated to 10,000–10,050 ^{14}C years BP (refs 9,10). Whereas the latter age is situated at the onset of a 200-year-long ^{14}C plateau, the former is from a period when ^{14}C ages rapidly decline. However, the definition of YD, especially its onset, is not unequivocal; a gradual transition of many proxies for a century or so is followed by a sudden entry into YD conditions. This probably reflects collapsing ecosystems as the extreme YD winter conditions had set in, and this first clear YD indication is usually dated to approximately 10,600 ^{14}C years BP. An age of 11,000 ^{14}C years BP has been assigned to the start of the YD[9], but this boundary has been defined by a tephra (from the Laacher See eruption), and the actual pollen zone change occurs at around 10,600 ^{14}C years BP. This makes YD 600–700 ^{14}C years long, but its length in calendar years is considerably longer. The recently developed annually counted ice-core timescale GICC05 shows that it may have lasted 1,193 ± 39 yr (ref. 11). For the GICC05 timescale the onset of the YD was defined by an abrupt shift in the deuterium excess[11]. Depending on the definition we could infer a considerably shorter duration of the YD if the $\delta^{18}O$ signal (Fig. 1(i)) is used. The GISP2 ice-core timescale indicates a longer duration (by approximately 70 yr (ref. 12)) compared with GICC05, whereas the dating of the Cariaco Basin sediments points to a YD length of about 1,300 yr (ref. 13). Three varved lake records in Germany and Poland suggest the length to be 1,090–1,140 yr (ref. 3). All these numbers depend on the definitions of start and end of the YD in the respective archive. The different durations at these locations could point to dating errors but they could also point to a sequence of climate changes that are not synchronous.

RADIOCARBON DURING THE YOUNGER DRYAS

Ocean circulation changes are hypothesized to control many climate sequences, especially the strong and rapid cooling in Greenland at the onset of YD, and there is evidence for changes

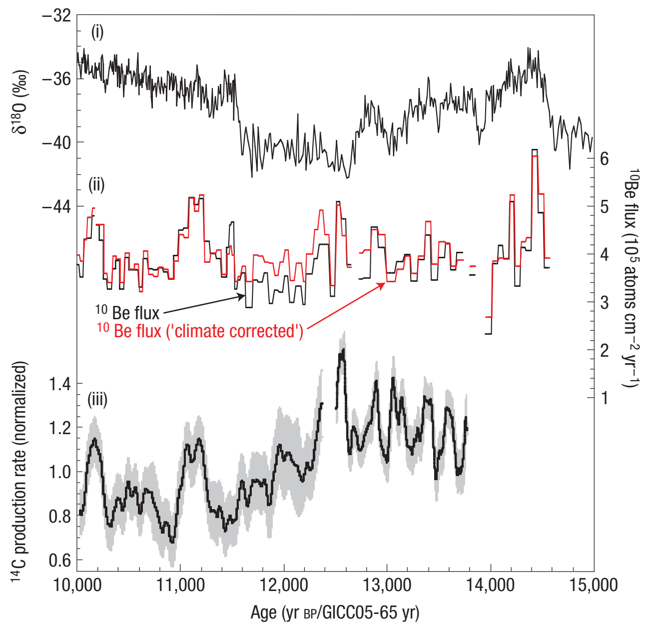

Figure 1 **δ^{18}O (ref. 36), ^{10}Be flux and ^{14}C production rate for the period from 15,000 to 10,000 yr BP.** The ice-core data (i), (ii) are on the basis of the new GICC05 timescale corrected for the 65 yr difference between ^{14}C and ^{10}Be during the Preboreal. The floating ^{14}C record (iii) is placed according to the best agreement with the ^{10}Be data. The ^{14}C production data show 50 yr averages, which correspond to the average time resolution of the ^{10}Be data. The 1σ errors of the ^{14}C data are assessed with Monte Carlo simulations.

in North Atlantic overturning[14], yet a detailed understanding is still lacking. Here, ^{14}C can provide insight because the atmospheric ^{14}C level (expressed as Δ^{14}C, which denotes the ^{14}C/^{12}C ratio with respect to a standard[15]) is affected by changes in the carbon cycle, that is, the distribution of ^{14}C among the atmospheric, biospheric and ocean reservoirs. Several studies have followed this approach[16–21]. However, atmospheric Δ^{14}C reconstructions on the basis of tree-ring ^{14}C data do not yet cover the complete YD because the absolutely dated tree-ring chronology currently starts at 12,410 cal BP (refs 22,23). Therefore, Δ^{14}C relies on more indirect marine ^{14}C sequences for the early YD (ref. 23). This complicates the interpretation of Δ^{14}C, because marine ^{14}C sequences are likely to also show fluctuations in the ocean reservoir age[24], that is, the ^{14}C age difference between atmosphere and ocean mixed layer.

Beyond the absolutely dated tree-ring chronologies, several pine chronologies have been built[7,25], which are 'floating'. This means that a connection to the absolutely dated tree-ring chronologies has not yet been possible[26]. Nevertheless, floating chronologies have the potential to significantly increase our knowledge about atmospheric ^{14}C variations and its determining factors. Initially, the floating sections were anchored to the Δ^{14}C data from the Cariaco basin[26], which assumes that these data provide the best timescale and Δ^{14}C data. In the following we will show that a connection to an absolute age scale can be achieved through comparison with ^{10}Be data measured in ice cores.

COSMOGENIC RADIONUCLIDES

^{10}Be and ^{14}C are both produced in the atmosphere by the cascade of nuclear reactions induced by the high-energy galactic cosmic rays[27]. Therefore, ^{10}Be and ^{14}C are both influenced by the variable solar activity and geomagnetic field intensity that modulate the incoming galactic cosmic ray intensity[27]. This common signal can be used to synchronize ^{10}Be and ^{14}C records and thereby connect the timescales of the ice cores and tree rings. This is facilitated by the recent progress in ice-core dating by multiproxy measurements in ice cores[11]. It allows the identification of the annual layers back to 42,000 yr in the NGRIP ice core[28]. In particular, the very accurate differential dating[29] of the ice-core timescales should lead to an improved accuracy of the placement of the floating ^{14}C chronologies. Therefore, ^{10}Be in well-dated ice cores can bridge the gap between the absolutely dated and floating tree-ring ^{14}C chronologies.

Previous studies showed that ^{10}Be measurements in the GRIP and GISP2 ice cores provide good estimates for solar activity and geomagnetic field intensity changes in the past[30–34]. In particular, solar peaks are well defined and allow the synchronization of ice-core and tree-ring timescales[21,35]. During the early part of the Holocene, the so-called Preboreal period, comparison of ice-core ^{10}Be with the tree-ring ^{14}C record points to a difference of approximately 65 yr between GICC05 and the tree-ring timescale (see Fig. 1). The age difference of 65 yr is most likely attributable to uncertainties in the ice-core timescale because the ^{14}C chronology is absolutely dated back to 12,410 yr BP with multiple replication[22]. The suggested 65 yr difference is well within the confidence limit of the ice-core timescales, which amounts to 99 yr at the YD/Preboreal transition[11]. Using GICC05 (corrected for the 65 yr difference) and the corresponding accumulation rate, we obtain the ^{10}Be flux shown in Fig. 1.

The comparison of ^{10}Be, geomagnetic-field and ^{14}C records indicates that the ^{10}Be flux is dominated by production-rate changes. However, a residual climate influence cannot be excluded. For example, there is a dependence of the ^{10}Be flux on the climate proxy δ^{18}O (ref. 36) if we use the new GICC05-based accumulation rate. This effect is of the order of 10%, but was not present in the ^{10}Be flux inferred from the older dating and accumulation-rate model (ss09 model)[21]. Following Alley *et al.*[37], this dependence should be removed to obtain a climate-corrected signal that follows more closely the ^{10}Be production rate changes. The main features of the ^{10}Be record are not affected by the uncertainties in the accumulation rates and the required correction for a possible climate influence (Fig. 1(ii)). The short-term changes (decadal to century scale), which are only slightly influenced by this correction, will mainly determine the placement of the floating tree-ring record with respect to the GICC05 timescale. In the following we will compare the climate-corrected estimate of past changes in ^{10}Be production rate with the ^{14}C production estimate inferred from the floating tree-ring record.

^{14}C–^{10}Be COMPARISON

Assuming that carbon-cycle changes have not significantly influenced Δ^{14}C allows us to calculate the ^{14}C production-rate changes from the floating tree-ring chronology (see the Methods section). The ^{14}C production rate can then be compared with the ^{10}Be flux inferred from ice cores. Perfect agreement between ^{10}Be flux and ^{14}C production rate cannot be expected owing to (1) uncertainties in the measured data and the relative dating, (2) potentially uncorrected climatic influence on the ^{10}Be deposition and (3) changes in the carbon cycle that could influence Δ^{14}C via changes in the distribution of ^{14}C between the major carbon reservoirs, most notably between ocean and atmosphere. Figure 1(iii) shows the reconstructed ^{14}C production rate depending on the dating as suggested by the comparison with the ^{10}Be data (Fig. 2). This dating is shifted by approximately 300 yr towards younger ages compared with the tentative age scale in ref. 26, which anchored the floating ^{14}C record to the ^{14}C data

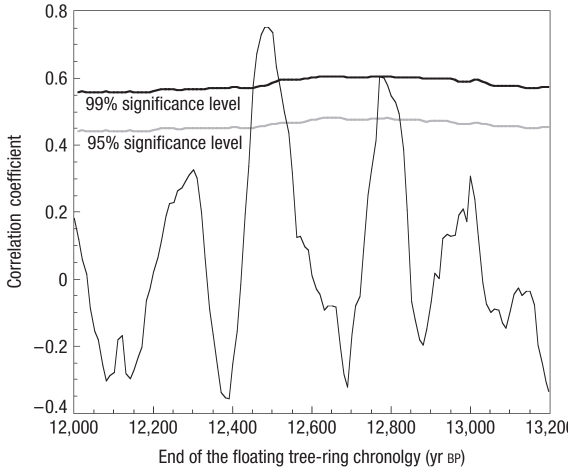

Figure 2 Correlation coefficient for a linear correlation between the ^{14}C production rate from the floating tree-ring record and the climate-corrected ^{10}Be flux to Summit. The best agreement is obtained when the floating tree-ring record ends at an age of 12,500 yr BP.

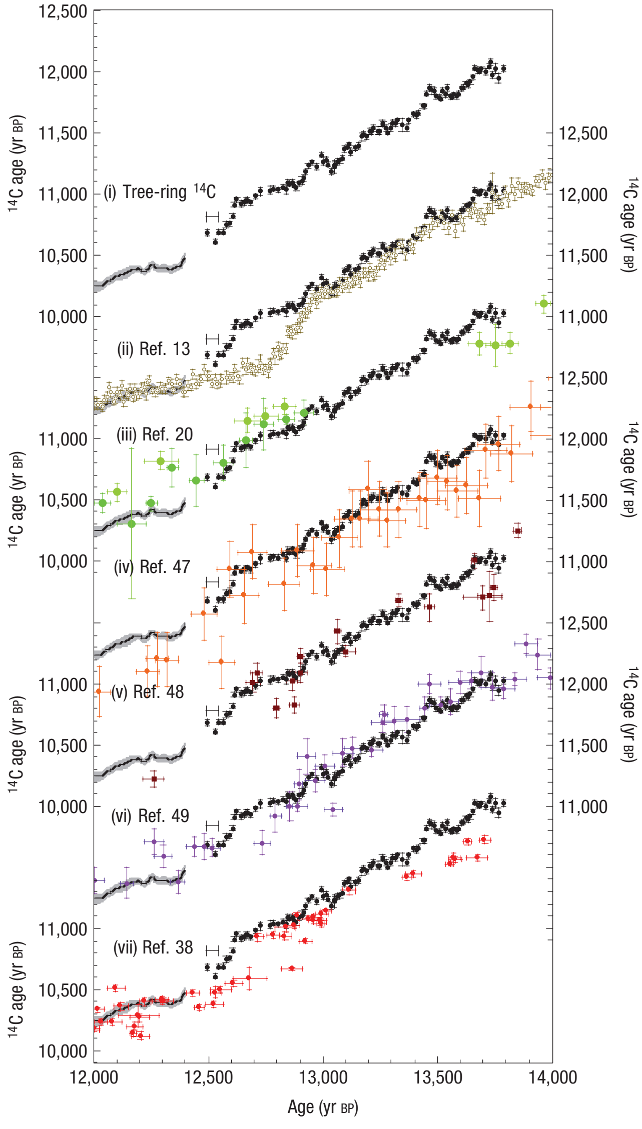

Figure 3 Comparison of tree-ring-based ^{14}C ages versus calendar ages with several independent calibration records. (i) Tree-ring-based ^{14}C ages versus calendar ages; (ii)–(vii) independent calibration records, which are from the Cariaco basin[13] (ii), from Lake Gosciaz and Lake Perespilno[20] (data were averaged into 100 yr bins) (iii), from stalagmites from the Bahamas[47] (iv), from corals from Tahiti and Barbados[48] (v), from Lake Suigetsu in Japan[49] (vi) and from pristine corals[38] (measurements on the same sample are averaged) (vii), including the 1σ errors. The marine records have been corrected for an assumed constant reservoir age. The bar above the tree-ring chronology shows the error in the age determination due to uncertainties in the ice-core dating.

from the Cariaco basin[13]. Only if the floating tree-ring chronology ends at approximately 12,500 yr BP does the significance level for the linear correlation between ^{10}Be flux and ^{14}C production rate exceed 99%. Therefore, if we postulate optimal agreement between ^{10}Be and ^{14}C the floating tree-ring chronology has to be shifted significantly towards a younger age. In consequence, there would be only a relatively short gap between the floating tree-ring chronology and the absolutely dated ^{14}C calibration curve. We could choose other placements with lower (but still significant) positive correlation between ^{10}Be and ^{14}C. However, such placements would lead to contradictions with the dating of a volcanic time marker in European lakes and the majority of independent ^{14}C data (see below).

COMPARISON WITH OTHER ^{14}C RECORDS

Figure 3 shows different independent ^{14}C-age–calendar-age reconstructions for the time period from 14,000 to 12,000 yr BP compared with the repositioned tree-ring chronology. Around late Allerød/early YD there are substantial discrepancies between the tree-ring and the Cariaco record, which is an important part of the IntCal04 calibration curve[23] (Fig. 3(ii)). This adds to the observation of timescale differences between ice cores, European lakes and the sediments from the Cariaco basin, exemplified by the differences in length of the YD. However, taking into account the age uncertainties, there is good agreement with the ^{14}C record from the Cariaco basin[13] for the older part of the record. This suggests that the deviations around the early YD are not caused by timescale uncertainties alone. In addition, regardless of the position of the floating tree-ring $\Delta^{14}C$ record, there are clear indications for changes in the reservoir age in the Cariaco basin around the end of Allerød and beginning of YD (ref. 26). Data from stalagmites and corals seem to be in reasonable agreement with the tree-ring data, although some data from ref. 38 deviate from our ^{14}C–calendar-age relationship. An older age, therefore, was assumed for the floating tree-ring chronology in ref. 39. However, some of the data in ref. 38 are in good agreement with the ^{10}Be-adjusted tree-ring record before the start of the YD. Because the tree-ring data are supposed to have perfect relative dating, it is difficult to explain partial agreement and partial disagreement. This may suggest that some of the coral data suffer from, for example, reservoir-age uncertainties. Figure 3 shows no conclusive picture that would exclude our placement, because all of the records have their own chronological uncertainties, also involving redeposition of organic material in lakes and unknown reservoir changes in marine samples. However, a 300-yr-older placement, as suggested by the second-highest correlation coefficient (Fig. 2), would lead to calibrated ages that are too old compared with the majority of the data shown in Fig. 3.

The uncertainties of the new GICC05 timescale should not be ignored in this discussion. The optimal placement of the floating

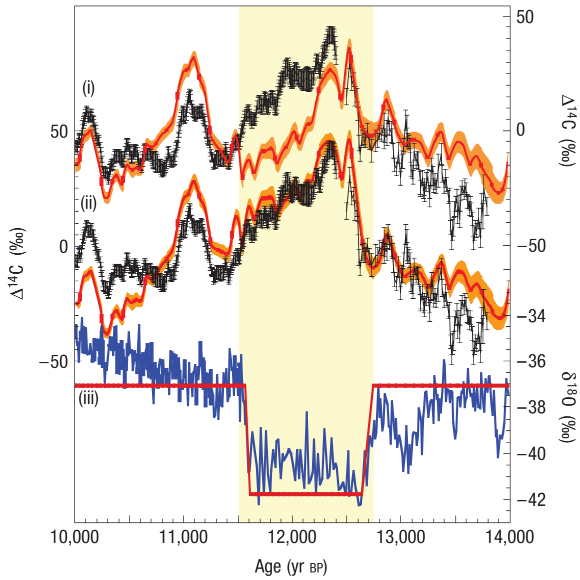

Figure 4 Modelled and measured $\Delta^{14}C$ and $\delta^{18}O$ during the YD. (i) The tree-ring $\Delta^{14}C$ data compared with the ^{10}Be-based $\Delta^{14}C$ calculated under the assumption of a constant carbon cycle. (ii) The results where we assumed a 30%-decreased ocean ventilation (ocean diffusion constant) during the YD (red line in (iii)). (iii) $\delta^{18}O$ from the GRIP ice core. The data are plotted on the GICC05 timescale after subtracting a constant offset of 65 yr. Monte Carlo simulations were carried out to assess the error (1σ) of the modelled $\Delta^{14}C$ record.

$\Delta^{14}C$ chronology shifts by 55 yr towards older ages if we add all the uncertain years to the GICC05 timescale during Bölling/Allerød and YD. In addition, the correlation coefficient between ^{14}C production rate and ^{10}Be flux increases slightly from 0.75 to 0.78, which could be an indication that years in the GICC05 timescale are systematically undercounted during Bölling/Allerød and YD. The tree-ring chronology would shift a similar number of years if we used the GISP2 timescale for the ^{10}Be record[35]. Irrespective of the applied ice-core timescale, this comparison suggests significant differences from the currently applied ^{14}C calibration curve at the onset of YD.

CARBON CYCLE DURING THE YOUNGER DRYAS

A combination of production and ocean-circulation changes have been suggested as an explanation for the $\Delta^{14}C$ changes during the YD. However, the strong $\Delta^{14}C$ increase during the early YD as seen in the data from the Cariaco basin has never been satisfactorily explained[24]. This is due to the fact that the annual ^{14}C production is small compared with the large ^{14}C reservoirs in the atmosphere, biosphere and ocean. If this combined ^{14}C system becomes effectively smaller (owing to decreased ocean ventilation), it still needs time to build up ^{14}C in the remaining system by the relatively small ^{14}C production rate. With the new placement of the tree-ring ^{14}C record, the origins of the $\Delta^{14}C$ changes have to be re-evaluated. Figure 4 shows a comparison of tree-ring-based $\Delta^{14}C$ and modelled $\Delta^{14}C$ during the YD. Assuming that the GICC05-based and climate-corrected ^{10}Be flux represents the global ^{10}Be production rate, we can infer a ^{14}C production rate, which can then be included in the modelling of $\Delta^{14}C$ with a carbon-cycle model. Figure 4(i) shows the results obtained under the assumption of a constant carbon cycle. Figure 4(ii) shows the modelled $\Delta^{14}C$ if we include 30%-reduced ocean ventilation during the YD (ref. 21). The agreement between modelled and tree-ring-based $\Delta^{14}C$ validates earlier results concerning the carbon-cycle changes during the YD, but with even better accuracy. Long-term differences between ^{10}Be and ^{14}C records still remain unresolved[40], and are responsible for the differences between modelled and measured $\Delta^{14}C$ around 10,000 yr BP (Fig. 4(ii)).

THE LAACHER SEE TEPHRA

The repositioning of the tree-ring record is further confirmed by the Laacher See Tephra (LST). This volcanic time marker can be found in European lakes at an age of 12,880 yr BP (refs 3,41). In the floating tree-ring ^{14}C record the position of the Laacher See eruption is known because trees were found buried *in situ* by this volcanic eruption and could be both ^{14}C 'wiggle matched' and dendro-cross-dated with the tree-ring chronology[26]. In addition, the climate impact of this eruption is visible in the tree rings of the Scots pines from Dättnau, near Winterthur, Switzerland, by a growth disturbance lasting at least 7 yr (refs 42,43). The ^{10}Be-based placement of this chronology assigns it an age of 12,830 yr BP. The remaining age difference can be attributed to uncertainties in ice-core dating from the LST to the end of the YD. Thus far, efforts to identify the LST in the Greenland ice cores have been unsuccessful[44]. However, the ^{10}Be–^{14}C comparison gives new information on where this excellent additional tie point might be found in the ice cores.

OUTLOOK

The ^{10}Be and ^{14}C comparison is promising for further studies of past climate change. Because radionuclide records show a truly external signal, they provide numerous fixed points to synchronize different climate records. This will allow detailed studies of leads and lags in climate change. The end of the YD is a good example. Our synchronization reveals that the two-step increase in temperature at the end of the YD is a synchronous feature in both ice-core $\delta^{18}O$ and tree-ring widths[8,36,45].

Tree-ring-based $\Delta^{14}C$ reconstructions have the advantage that they represent the ^{14}C concentration in the atmosphere. In addition, the dating is extremely well constrained owing to the existence of annual rings. We consider the comparison with ice-core ^{10}Be records an important step in this context, because this comparison can (1) help to determine the absolute age of floating tree-ring chronologies and (2) give estimates of the ^{14}C production rate, which can then be used to infer the carbon-cycle-related influences on the atmospheric ^{14}C concentration. We expect that this method can soon be applied to new floating tree-ring $\Delta^{14}C$ records, for example from the Kauri trees from New Zealand, which has the potential to provide an atmospheric ^{14}C calibration record that covers the complete range of ^{14}C dating.

METHODS

The ^{14}C production rate can be calculated from the ^{14}C-age–calendar-age relationship. A steep drop in the ^{14}C ages relative to the calendar ages indicates an increase in atmospheric ^{14}C concentrations, which is caused by an increased ^{14}C production rate, and vice versa for a rather constant ^{14}C-age–calendar-age relationship ('^{14}C age plateau'). This situation can be quantitatively modelled with a carbon-cycle model. We use a box-diffusion carbon-cycle model to calculate the ^{14}C production rate[33,46]. Because the scatter in the raw ^{14}C data would lead to unrealistic jumps in the ^{14}C production rate we low-pass filtered (cut-off frequency of $1/10\,yr^{-1}$) the tree-ring ^{14}C data before the calculation. The errors are inferred from 100 individual Monte Carlo calculations that include the measurement errors of the ^{14}C data. Changes in the carbon cycle can influence the outcome of the calculation of the ^{14}C production rate. We assumed a constant carbon cycle for this calculation. A YD-type change in ocean circulation (−30% in the oceanic diffusion constant in our case) would result in a ^{14}C production-rate decrease of about 16% if Δ^{14}C were kept constant. This change occurs within 150 yr and decreases slightly afterwards. Such a scenario at the beginning of the YD would diminish the reconstructed ^{14}C production rate increase but it does not remove it. The position of the optimal placement is not affected by this result. The reconstructed ^{14}C production rate is slightly influenced by the assigned age of the floating tree-ring chronology. For our calculation we used the age determination based on ^{10}Be. However, using the original placement in ref. 26 leads to a very similar ^{14}C production rate and the same results as shown in Fig. 2.

To calculate the correlation coefficient between ^{10}Be flux and the ^{14}C production rate, we inferred the average values of the ^{14}C production rate corresponding to the time intervals of the ^{10}Be values. Gaps in the ^{10}Be record, therefore, produce corresponding gaps in the ^{14}C production rate and do not influence the calculation. In consequence, a varying number of data points can enter the calculation of the correlation coefficient (depending on the start of the floating chronology), which is the reason for the varying significance levels. For this comparison the GISP2 ^{10}Be data were transferred to the GICC05 timescale via the common, volcanically derived, electrical-conductivity spikes in the Greenland ice cores[11]. The spacing of the electrical-conductivity time markers is relatively dense (roughly every 6 m/100 yr on average) for the period of interest.

For all carbon-cycle calculations the same model start-up is chosen (equilibrium ^{14}C distribution with pre-industrial carbon cycle). Therefore, independent of the applied carbon-cycle changes the ^{10}Be-based Δ^{14}C records yield the same result before the YD. However, the linear trend fitted to the modelled Δ^{14}C curve depends on the complete modelled Δ^{14}C record. As a result, the detrended Δ^{14}C records can also show different values before the YD.

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Author contributions

R.M. proposed the ^{10}Be–^{14}C link, initiated the paper and did the calculations. Each co-author contributed especially to his own field of expertise. B.K., M.F. and K.F.K. were the main contributors for the development of the floating tree-ring ^{14}C record. A.S. provided details on the ice-core dating and accumulation rate. S.B. and J.S. provided background and input on the climate, dating and correlation discussion. J.S. suggested a similar placement of the floating tree-ring chronology at the Second Carlsberg Dating Conference in Copenhagen. R.M. wrote the paper, with comments and input provided by all other authors.