Permafrost thawing as a possible source of abrupt carbon release at the onset of the Bølling/Allerød

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One of the most abrupt and yet unexplained past rises in atmospheric CO₂ (>10 p.p.m.v. in two centuries) occurred in quasi-synchrony with abrupt northern hemispheric warming into the Bølling/Allerød, ~14,600 years ago. Here we use a U/Th-dated record of atmospheric Δ¹⁴C from Tahiti corals to provide an independent and precise age control for this CO₂ rise. We also use model simulations to show that the release of old (nearly ¹⁴C-free) carbon can explain these changes in CO₂ and Δ¹⁴C. The Δ¹⁴C record provides an independent constraint on the amount of carbon released (~125 Pg C). We suggest, in line with observations of atmospheric CH₄ and terrigenous biomarkers, that thawing permafrost in high northern latitudes could have been the source of carbon, possibly with contribution from flooding of the Siberian continental shelf during meltwater pulse 1A. Our findings highlight the potential of the permafrost carbon reservoir to modulate abrupt climate changes via greenhouse-gas feedbacks.

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Changes in the global carbon cycle during the last deglaciation are so far not completely understood. However, based on the data and model-based interpretation, the emerging picture indicates that the rise in atmospheric CO$_2$ of $\sim$45 p.p.m.v. during the first half of the deglaciation ($\sim$1 p.p.m.v. per century) was probably fuelled by the release of old, $^{13}$C- and $^{14}$C-depleted deep ocean carbon. The processes responsible for CO$_2$ rise have changed dramatically with the beginning of the Bolling/Allerød (B/A) $\sim$14,600 years before present ($\sim$14.6 kyr BP). Here the abrupt CO$_2$ rise recorded in the EPICA Dome C (EDC) ice core was six times faster than before, about 10 p.p.m.v. in 180 years or $\sim$6 p.p.m.v. per century (Fig. 1). Atmospheric CH$_4$ rose by 150 p.p.b.v. between 18.5 and 14.6 kyr BP and then by the same amount again, but within centuries, around the onset of the B/A. The changes in both greenhouse gases (GHG) imply that a ratio of both changes $\Delta$CH$_4$/$\Delta$CO$_2$ is a factor of five larger around 14.6 kyr BP than during the previous four millennia. Such a change in the ratio $\Delta$CH$_4$/$\Delta$CO$_2$ might be the first indication that the wetlands identified as the main contributor to the rapid rise in CH$_4$ at the onset of the B/A might also have contributed to the abrupt rise in CO$_2$ at that time.

Although this analysis of CH$_4$ and CO$_2$ changes gives some first ideas on the potential cause of the abrupt CO$_2$ rise around the onset of the B/A, its ultimate source was so far not identified. The $^{13}$C signature of terrestrial or marine carbon sources are different and might allow some source detection. However, the data uncertainty and density of the atmospheric $^{14}$C record did so far not allow such an identification. A high-resolution U/Th-dated time series of atmospheric $^{14}$C derived from Tahiti corals over that event offers now some new and independent insights on the exact timing and magnitude of the carbon release event and brings some suggestions on its potential origin.

Here we show that the synchronous change in atmospheric $^{14}$C and CO$_2$ derived from the Tahiti and EDC data sets at the onset of the B/A can be explained by the same process and suggest permafrost thawing being this process. We finally examine the climate impact of the GHG changes around 14.6 kyr BP using a state-of-the-art-coupled Earth system model. Special focus of these investigations is the imprint of the GHG changes on the Antarctic temperature signature and the relevance of these changes for the interpretation of bipolar climate linkages during abrupt climate changes.

Results

Atmospheric $^{14}$C and ice core CO$_2$. The new coral-based atmospheric $^{14}$C record from Tahiti shows a prominent decline around 14.6 kyr BP, an anomaly not visible in the IntCal13 $^{14}$C stack (Fig. 2). For comparison, we briefly discuss specific details related to IntCal13 and what other $^{14}$C archives record at that point in time: After 13.9 kyr BP IntCal13 is based on tree rings and what other $^{14}$C archives record at that point in time: After 13.9 kyr BP IntCal13 is based on tree rings with very little variability. For older samples, however, the various archives differ by more than the measurement errors. A $^{14}$C anomaly similar to the Tahiti data can be seen in speleothems from Bahamas (Fig. 2). The anomaly is not seen in speleothems from the Hulu Cave or in the marine sediments from Cariaco (Fig. 2). The Cariaco record bears some problems—therefore, a part of it has been excluded by the IntCal13 group specifically during the Heinrich 1 event, that is, just before the B/A. Necessary corrections of speleothem $^{14}$C data for its dead carbon fraction (DCF) introduce large uncertainties to atmospheric $^{14}$C based on them. Furthermore, the DCF is not constant but depends itself on climate making the speleothems an archive difficult to interpret, especially during rapid climate changes. The signal might thus potentially be smoothed out in Hulu, as the DCF acts as a low-pass filter. The best recorder of atmospheric $^{14}$C available up to now might be the terrestrial plant material derived from Lake Suigetsu. Here no corrections for the reservoir effect or for DCF are necessary. The Lake Suigetsu data, however, are rather scattered over the time interval of interest, show a steeper decline in $^{14}$C than IntCal13, but neither strongly support IntCal13 nor Tahiti (Fig. 2). Altogether, the evidences from $^{14}$C data are mixed and further data are necessary for a conclusive interpretation.

The coral-based $^{14}$C record from Tahiti is corrected for a reservoir age of constantly 300 $^{14}$C years to be interpreted as atmospheric $^{14}$C. In principle, the reservoir age might change over time, mainly due to ocean circulation changes. However, simulations with three different models suggest that the
reservoir age is relatively stable in the central Pacific around Tahiti for various ocean circulation changes (see Supplementary Note 1 for details). We therefore assume that reservoir ages did not change over the last 15 kyr in the central low-latitude Pacific and the Δ¹⁴C signal based on Tahiti corals is not based on local effects but indeed a recorder of atmospheric Δ¹⁴C changes.

We date the start of this Δ¹⁴C decline seen in the Tahiti data with two different approaches (Fig. 2, methods) with a 1σ uncertainty of less than a century to 14.6 kyr BP and calculate a Δ¹⁴C decline of ~55% within 200 to 250 years. Having already changed exclusions in reservoir age, we are left with either a modified carbon cycle or reduced ¹⁴C production rates as potential process explaining the Tahiti Δ¹⁴C data. On the basis of available ¹⁸⁷⁷Be, data changes in ¹⁴C production rates cannot convincingly explain the Δ¹⁴C data (Supplementary Fig. 1, Supplementary Note 1). All our tests therefore indicate that the Tahiti Δ¹⁴C drop at 14.6 kyr BP is caused by carbon cycle changes. This is our working hypothesis on which all else is based and on, but note that its failure cannot entirely be ruled out.

Carbon cycle changes responsible for the Δ¹⁴C anomaly would also leave their imprints on atmospheric CO₂. We can therefore use the absolute U/Th-dated Δ¹⁴C from the Tahiti corals as an independent time constraint on the atmospheric CO₂ rise. This is a novel new approach to synchronize atmospheric Δ¹⁴C and atmospheric CO₂, because ice cores archive only a smoothed version of the atmospheric concentrations making an exact dating of the abrupt change in atmospheric CO₂ very difficult. Furthermore, firnification and gas enclosure are still not completely understood, and the age difference between ice matrix and embedded gases complicates gas chronologies. On the most recent chronology, AICC2012, CO₂ measured in situ in the EDC ice core rises by 10 p.p.m.v. between 14.81 and 14.68 kyr BP. This is more than a century faster when compared with previous chronologies (Figs 3a and 4b), but might in detail be revised even further once the most recent understanding of firnification is applied. Atmospheric changes in CO₂ need to have happened even more abruptly than what is recorded in ice cores.

Here we use the Tahiti Δ¹⁴C as an independent age constraint for the start of the carbon cycle changes (14.6 kyr BP). Recently, others have shown that the rise in atmospheric CH₄ and in temperature in Greenland are near synchronous (±25 years) at the onset of the B/A warming. From previous GHG records measured at the EDC ice core, it is known that CO₂ and CH₄ also rise synchronously at 14.6 kyr BP. Combining this information, we have to conclude that the rise in atmospheric CO₂ and CH₄ together with the rapid warming of the northern hemisphere (NH) happened at the same time, and started at 14.6 kyr BP. This is only 35 years later than the suggested age of the onset of the B/A (14.635 ± 0.186 kyr BP, ± 1σ) in the annual-layer counted NGRIP ice core, within the dating uncertainty of GICC05 (Fig. 5).
We assume a depletion in $^{14}$C of the released carbon with respect to the atmosphere ($\Delta (\Delta^{14}C)$) between $-50$ and $-1,250\%$. This range in the $^{14}$C anomalies covers carbon sources from the mean terrestrial biosphere potentially released by shelf flooding$^6$ ($-50\%$), suggested signatures of old carbon of Pacific intermediate waters as measured off Baja California$^{29}$ ($-400\%$) and Galápagos$^{30}$ ($-700\%$) to a maximum effect of $^{14}$C-free carbon ($-1,250\%$). The Shelf Flooding Hypothesis is explained in detail in the next section, and some more details on our assumptions on $^{14}$C are found in the methods.

The highest-simulated anomalies in atmospheric $\Delta^{14}C$ are obtained for short release times reaching $100\%$ for 50 years and the largest $\Delta (\Delta^{14}C)$ of $-1,250\%$ (Fig. 4c). The amplitudes drastically decline with longer release time towards less than $-35\%$. $^{14}$C anomalies are significantly smaller if $\Delta (\Delta^{14}C)$ was $-700\%$ or less (Fig. 4c). Because of the distinct dynamics of the $\Delta^{14}C$ data, release times shorter than $\sim 110$ years are at odds with the Tahiti $^{14}$C reconstruction. Simulated anomalies in atmospheric carbon records are nearly identical for Atlantic meridional overturning circulation (AMOC) in the strong or weak mode (Methods, Fig. 4c, Supplementary Fig. 3). Combining the information from both the ice core data and our analysis of the Tahiti $^{14}$C data leads to a range of scenarios with carbon release times between $\sim 110$ and 200 years in which model results and data agree (Fig. 4c). The range of possible scenarios fulfilling the data constraints also includes some with $\Delta (\Delta^{14}C)$ between $-700$ and $-1,250\%$, and so we cannot entirely exclude the possibility that the released carbon still contains some $^{14}$C. From these possible scenarios, we selected the one with the longest release time of 200 years to be our best-guess scenario, because short release times lead to higher amplitudes in atmospheric $^{14}$C, which are not supported by other ice core data. This scenario pinpoints to a $\Delta (\Delta^{14}C)$ of $-1,250\%$ resulting in peak amplitudes of $-42\%$ in atmospheric $^{14}$C (Fig. 4c) and of $+22\%$ p.p.m.v. in atmospheric $^{14}$C (Fig. 4d). The depletion in $^{14}$C necessary for the model output to agree with the data implies that the shelf flooding hypothesis connected with meltwater pulse 1A (MWP-1A)$^{6,31}$ seems at a first glance to be in disagreement with the Tahiti-based atmospheric $^{14}$C reconstructions (Fig. 4c). We discuss details on a potential contribution connected with MWP-1A further below. The release of deep ocean carbon, although so far not suggested to play a role during this rapid $^{14}$C rise, might only potentially be responsible here, if water masses are detected, which are even more depleted in $^{14}$C than what is known until now$^{29,30}$.

The Tahiti $^{14}$C data show an excursion from the long-term declining trend of IntCal13 (ref. 9) (Figs 1 and 4a). Depending on the time window of interest, IntCal13 might be approximated by a linear fit with a slope of $-0.04\%$ per year (the whole Mystery Interval, 19–14 kyr BP) or $-0.10\%$ per year (15.0–14.3 kyr BP), respectively. These long-term changes are probably caused by a mixture of changes in $^{14}$C production rate and the carbon cycle$^{32}$. While we are able to force our model with changing $^{14}$C production rates (Supplementary Fig. 4), all relevant processes in the carbon cycle are not yet identified. We therefore compare the $^{14}$C data with our original simulation results based on constant $^{14}$C production rate, but also with some results that are corrected for the trend seen in IntCal13. If corrected accordingly, our best-guess scenario finally meets the amplitude in the Tahiti $^{14}$C data (Fig. 4a,c).

**Evidence for permafrost thawing.** The synchronicity of the NH warming and the carbon cycle change together with our suggested hypothesis for the injection of nearly $^{14}$C-free carbon into the atmosphere make permafrost thawing and a subsequent release of
old soil carbon a prominent candidate to explain the atmospheric carbon records. The age of carbon stored in permafrost soils during glacial times is unknown. Throughout the last glacial cycle Greenland and the whole NH was perturbed by the rapid warming of Dansgaard-Oeschger (D/O) events. However, during the last 80 kyr, only D/O event 12 around 47 kyr BP reached in a temperature reconstruction for the site of the NGRIP ice core in Greenland similar high temperatures as the B/A (Fig. 6a). In this NGRIP, temperature time series D/O event 2 around 23 kyr BP was rather weak and short, but D/O event 3 at 28 kyr BP reached with −36 °C nearly the temperature of −33 °C of the B/A (Fig. 6b). We assume that most of the NH follow this temporal changes in temperature observed for Greenland, although with warmer temperatures closer to the freezing point further south. It might then be that large areas of the NH were permanently frozen after D/O event 3, thus about 13 kyr before thawing induced by the onset of the B/A. The Δ14C of that permafrost carbon would be depleted by −900‰ with respect to atmospheric Δ14C during release around 14.6 kyr BP (Fig. 6a). However, soil carbon might age significantly in high latitudes before freezing, for example, present day North American peatlands are up to 17-kyr old. Such soil ageing reduces 14C even further. If the precursor material of the permafrost soil carbon was photosynthetically produced during D/O event 12 around 47 kyr BP (the next preceding period comparable in temperature to the B/A, Fig. 6b), it would be essentially free of 14C and depleted with respect to atmospheric Δ14C by nearly −1,250‰ (Fig. 6a). Permafrost thawing would

**Figure 4 | Main carbon cycle simulation results.** The transient simulation results (left) showing the impact of a carbon release event on true atmospheric Δ14C and CO2 obtained with the carbon cycle model BICYCLE for the best-guess scenario are compared with the data. In sensitivity studies (right), the length of the release event and the radiocarbon signature Δ(Δ14C) of the released carbon are constrained by the data. (a) Atmospheric Δ14C data from Tahiti corals (magenta, mean ± 1σ in both age and Δ14C) and IntCal13 (grey areas) as function of length of carbon release in the non-linear model of the Tahiti data interpretation. The vertical black dashed line marks the estimated started of carbon release at 14.6 kyr BP based on a combination of different explanations. Best-guess simulation results of atmospheric Δ14C (blue) superimposed by a linear trend of either −0.04‰ per year (long dashed line) or −0.10‰ per year (solid line) (short dashed: no trend superimposed). (b) Atmospheric CO2. EDC ice core CO2 data (mean ± 1σ) on two different chronologies AICC2012 and Parrenin2013. Simulated true atmospheric CO2 rise (black bold line), and how the signal might be recorded in EDC (dashed red line) after filtering for gas enclosure and shifted by 50 years to meet the data. (c) Simulated peak height in atmospheric Δ14C (grey areas) as function of length of carbon release and of the Δ14C depletion. (d) Simulated peak height in atmospheric CO2 (dark blue area) as function of length of carbon release. In c, d simulations result with the AMOC in either a weak or a strong mode are combined spanning a range of results. Magenta square and circle in c, d mark results of our best-guess scenario for Δ14C and CO2, respectively. We colour coded the areas in the parameter space where simulation results agree with the EDC CO2 data (d, light blue) and with the interpretation of the Tahiti Δ14C data (c, black boxes). The latter are modified for background linear trends already contained in IntCal13 based on other processes.
then contain a depletion in $\Delta^{14}C$, which is more negative than for all other suggested processes\textsuperscript{6,29,30}. An alternative scenario based on the destabilization of gas hydrates, which also contain $^{14}C$-free carbon, can be rejected based on $CH_4$ isotopes\textsuperscript{35–37}.

For the present day, a rise in global mean temperature by 5 K, which because of polar amplification might represent a northern high latitude warming of 10 K, was proposed to lead to the release of more than 130 Pg of soil carbon from permafrost thawing within 200 years\textsuperscript{38}. Greenland ice core data\textsuperscript{33} and simulations\textsuperscript{39} suggest that temperatures in the B/A rose by 10–15 K to near preindustrial levels in central Greenland and throughout most of the NH land areas. A large inert terrestrial carbon pool consisting of permafrost soils containing 700 Pg more C at the Last Glacial Maximum (LGM) than at present day has been proposed\textsuperscript{40}, which needs to release its excess carbon during deglaciation. The areal extent of continuous permafrost at LGM (Fig. 7) was calculated from models\textsuperscript{41} in PMIP3 to 26 x 10\textsuperscript{12} m\textsuperscript{-2}, agrees with reconstructions\textsuperscript{42}, and is twice as large as for preindustrial times\textsuperscript{43}.

Previously, methane isotopes\textsuperscript{36} suggested that a rise in boreal wetland $CH_4$ emissions by $+32$ Tg CH$_4$ per year would explain the CH$_4$ rise into the B/A. These findings\textsuperscript{36} have been challenged by new methane isotope data\textsuperscript{37}, but so far no revised CH$_4$ emissions from boreal wetlands have been calculated for the B/A. An alternative interpretation\textsuperscript{3} of the CH$_4$ cycle based on its interhemispheric gradient suggests that the rise in CH$_4$ by 150 p.p.b.v. at the onset of the B/A was largely driven by the increase in CH$_4$ emissions from both tropical (+ 35 Tg CH$_4$ per year) and boreal (+ 15 Tg CH$_4$ per year) wetlands. The CH$_4$ change at the onset of the B/A is thus clearly dominated by tropical wetlands and its conclusive interpretation is beyond the scope of this study. However, the rise in CH$_4$ emissions from
Figure 7 | PMIP3 simulation results on the LGM permafrost extent. Results41 show a polar projection of the NH from 20°N northwards, based on soil temperature and distinguish land with ice (dark blue), permafrost (blue), seasonal frozen (light blue) and not frozen (red). Present day coastlines are sketched in thin black lines. Magenta points mark potential core sites (Siberian Shelf, Black Sea, Caspian Sea, Sea of Okhotsk) from which future 14C measurements on terrigenous material might verify the age of permafrost possible thawed around 14.6 kyr BP (suggested green areas).

boreal wetlands is nearly identical to the rise in emissions of up to + 14 Tg CH4 per year projected from deep permafrost thawing of the next century45. If this rise in the boreal CH4 flux is integrated over the 200-year time window of our carbon release scenario, a total of 3.0 Pg of CH4 (or 2.25 Pg C in the form of CH4) might have been released. This is ~2% of our total estimated carbon emissions of 125Pg C, and in line with an expert assessment on the future vulnerability of permafrost44 estimating that 2–3% of carbon released by thawing might enter to the atmosphere in the form of CH4. Although the contribution from boreal wetlands to the CH4 rises at the onset of the B/A is small, the nearly 14C-free signature connected with our proposed permafrost thawing might be tested by 14C measurements on CH4 derived from ice cores45.

So far, we suggested that NH permafrost is the responsible source of the released carbon. In the following, we hypothesize which region might have been affected in detail by permafrost thawing and how this can be tested in future studies. The PMIP3-based map on the LGM permafrost extent clearly indicates that the largest areas with continuous permafrost are found in northern Siberia (Fig. 7). Thus, evidences of permafrost thawing connected to the NH warming should be expected in outflow originated from the southern edge of the LGM permafrost area (around 40–50°N), which thawed first. A lot of these areas are drained via the Amur river into the Sea of Okhotsk and into coastal seas towards the south (Caspian and Black Sea). Indeed, a coastal erosion and sub-sea permafrost thermodynamically thawing at the southern edge of the permafrost area or to a contribution from flooding the Siberian Shelf during MWP-1A.

Discussion
The rapid CO2 rise at the onset of the B/A is contained with different amplitude in various ice cores (Fig. 3a). However, the uncertainty in the proposed age distribution of the CO2 in EDC is still large6 (Supplementary Fig. 2c) and the assumed carbon release history and the applied carbon cycle model influence the amplitude of the proposed true atmospheric CO2 rise. Future CO2 measurement from the WD ice core54 might refine some of these aspects. The WD ice core has an order of magnitude higher 14C in permafrost carbon on the shelf to decay and to produce a 14C (D14C) in the released carbon of down to ~ 900% (Fig. 6). Most recent sediment data48 on iceberg discharge in Antarctica during Termination I found a significant Antarctic contribution to MWP-1A. Fingerprint analysis49 of different water sources for MWP-1A indicate that sea level would rise locally by up to 50% above global average on the Siberian Shelf for freshwater released in Antarctica. When considering the source-depending overprint49, we calculate, based on the present day bathymetry50, a maximum areal extent of 0.4 x 1012 m$^{-2}$ of the Siberian Shelf, which might have been flooded by MWP-1A. This is the same order of magnitude as the present day Siberian Yedoma deposit extent51 from which an organic carbon content of 30–140 Pg C has been proposed51. Coastal erosion and sub-sea permafrost release in Arctic Siberia are also observed for modern times52 with a D14C signature of the released organic carbon as low as ~ 800%. Modern organic carbon content in Eurasian Arctic53 river runoff have D14C ages of up to 10 kyr. All these modern data indicate that old carbon in permafrost exists nowadays, and potentially was more abundant and older during glacial times.

In which region the thawing of permafrost finally happened might be verified by future 13C measurements on terrigenous organic material that are retrieved from marine sediments in the suggested coastal seas. It will then be possible to finally attribute the size of the released carbon to either a pure thermodynamically thawing at the southern edge of the permafrost area or to a contribution from flooding the Siberian Shelf during MWP-1A.
Termination II also contains\(^5^8\) an abrupt rise in CO\(_2\), synchronous to a rise in CH\(_4\). A massive drop in atmospheric \(\delta^{13}CO_2\) accompanying this event\(^5^9\) is consistent with the release of \(\delta^{13}C\)-depleted CO\(_2\) that might indicate a terrestrial source. However, new \(\delta^{13}CO_2\) data\(^5^9\) did not confirm this negative \(\delta^{13}C\) anomaly and the revised data give no indication on the source of this CO\(_2\) rise. A synchronous change in deuterium excess\(^6^0\), a proxy for moisture source shifts, has been used to suggest that abrupt shifts in southern westerlies might be connected with the CO\(_2\) rise\(^6^1\), but a compelling explanation remains elusive and further testing of permafrost thawing as a possible alternative interpretation is needed.

In conclusion, we here suggest that the processes responsible for the abrupt CO\(_2\) rise at the onset of the B/A is also the underlying cause for the drop seen in atmospheric \(\Delta^{14}C\) based on Tahiti corals. This connection offers a U/Th-dated tie point for the start of the massive release of carbon at 14.6 kyr BP. Using a carbon cycle model, and assuming the release of 125 Pg C of nearly \(14C\)-free carbon, we are able to explain observed anomalies in atmospheric CO\(_2\) and \(\Delta^{14}C\). On the basis of the \(\Delta^{14}C\) signature of the released carbon and the synchronicity to the warming of the NH, we suggest that the thawing of permafrost was this responsible process. A potential contribution from MWP-1A flooding the Siberian Shelf, which might have contained a large amount of permafrost, is also possible. Future \(\Delta^{14}C\) measurements on terrigenous material might further constrain the source region. Our interpretation not only provides conceptual insights into the source of the excursions in the atmospheric carbon records around 14.6 kyr BP, but also offers an alternative to explanations\(^6^2,^6^3\) for the interhemispheric timing of the B/A and the ACR as found in ice cores from both hemispheres. Taken together, our findings highlight a potential climate feedback that might be obtained from abrupt CO\(_2\) release during deglaciation. This analysis furthermore indicates that the proposed carbon cycle feedback from an anthropogenic driven permafrost thawing in the near future\(^3^8,^4^3,^4^4,^4^6\) may already have happened in a similar way in the past.

Methods

Analysis of the \(\Delta^{14}C\) data. For analysis of the drop in the atmospheric \(\Delta^{14}C\) data based on Tahiti corals, we used two different approaches (Fig. 2). First, we used a linear statistical model Breakfit\(^6^5\), which calculates the break points in time series. Breakfit searches for two linear functions that are joined at the break point. To determine the break points, the model is fitted to the data applying an ordinary least squares method with a bootstrap search for the break points. A measure of the uncertainty of the break points is based on 2,000-bootstrap simulations, applying a moving block bootstrap algorithm with a block length of 1. We were searching for two break points in the time intervals between 16 and 13 kyr BP. The two subintervals (one for each break point) were ranging from the outer boundary next to the break point of interest to the other break point. Subintervals were finally identified after at least two iterative applications to (in kyr BP): break point 1 [15,74, 14,45] and break point 2 [14,67, 13,16]. Breakfit identified the start in the \(\Delta^{14}C\) drop at 14.66 ± 0.07 kyr BP followed by its decline by 54 ± 8% within 207 ± 95 years. Because of the very distinct dynamics of atmospheric \(\Delta^{14}C\), including a rebound after its minimum (that is, after the carbon release in the atmosphere stopped), we also analysed the data more subjectively using a non-linear approach. Here we only calculated the mean time and mean \(\Delta^{14}C\) right at the start of the carbon cycle changes around 14.6 kyr BP (two data points) and at its minimum (eight data points) assuming that \(\Delta^{14}C\) followed a non-linear pathway between both and included a rebound thereafter. The \(\Delta^{14}C\) data then starts to decline at 14.59 ± 0.04 kyr BP and stop after 258 ± 53 years with a maximum drop of 58 ± 14% followed by a rebound of atmospheric \(\Delta^{14}C\). This non-linear dynamic is seen in the Tahiti data but also in our carbon cycle simulations (Figs 2 and 4a). Combining the linear and non-linear approach brings high confidence that the \(\Delta^{14}C\) drop started at around 14.6 kyr BP. All uncertainties are given as 1σ.

Possible \(\Delta^{14}C\) signature of permafrost carbon. The maximum possible \(\Delta(\Delta^{14}C)\) of carbon released from permafrost thawing is a function of age and of atmospheric \(\Delta^{14}C\) during time of production. From the \(\Delta^{14}C\) signature (IntCal13)\(^7^9\) of the precursor material (atmospheric CO\(_2\)), which varies before the B/A roughly between 250 and 550% (Fig. 6a), we first subtract the mean \(\Delta^{14}C\) value of...
terrestrial carbon at the LGM in the model (~50%) before a further reduction in \(\Delta^{14}C\) signature is realised by the radioactive decay of \(^{14}C\) (half-life time of 57,300 years).

**Carbon cycle model.** We use the carbon cycle box model BICYCLE in transient mode to simulate changes in atmospheric CO2 and \(\Delta^{14}C\). The model setup is identical to an earlier study, which already proposed the magnitude of the CO2 overshoot during the B/A4.

We simulate the release of 125 Pg of carbon into the atmosphere with a constant rate that varies inversely with the time length of the event between 0.42 Pg C per year (300 years) and 2.5 Pg C per year (50 years) and configured the AMOC in either its strong or its weak mode. Both AMOC configurations differ in the strength of the overturning cell in the Atlantic with 16 Sv deep water production in the North Atlantic in the strong mode and 2 Sv in the weak mode. We repeated our previous comparison of simulated atmospheric \(\Delta^{14}C\) to ice core data from the EDC because new \(\delta^{13}C\) data were published in the mean time.1 More details on these assumptions are found in our previous article.6

14C production rates are assumed to be constant and 15% higher than present day, leading to atmospheric \(\Delta^{14}C\) of +250% at 14.6 kyr BP in agreement with IntCal13 (ref. 9). Long-term trends in \(\Delta^{14}C\) production rate as suggested by the geomagnetic field data merely slightly impact our simulations (Supplementary Fig. 4).

For model evaluation, BICYCLE is (a) compared in its oceanic carbon uptake dynamic resulting in a model-specific air-sea fraction with other models, (b) used to simulate the Suess effect (years 1920–1950 AD), (c) the bomb \(\Delta^{14}C\) peak (years 1950–2000 AD) and (d) applied on CO2 release experiments for preindustrial background conditions. The model is compared with the results from another carbon cycle box model66 (Suess effect and for preindustrial conditions) and with output from the GENIE model,67 an Earth system model of intermediate complexity (preindustrial conditions). All details on this model evaluation are found in the Supplementary Note 2 including Supplementary Figs 6–8.

Filtering true atmospheric CO2 into signals recorded in EDC. The smoothing effect of the gas enclosure process in ice cores that transforms a potential true atmospheric \(\Delta^{14}C\) into a time series comparable to EDC ice core data is performed with a log-normal probability density function with an assumed mean value or width of 400 ± 80 years (mean ± 1σ)34 (Supplementary Fig. 2c):

\[
f(x) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(\ln(x/c0))^2}{2\sigma^2}}
\]

with \(x\) (in years) as the time elapsed since the last exchange with the atmosphere. From the two free parameters, \(\mu\) and \(\sigma\) of the equation, we chose for simplicity \(\sigma = 1\), which leads to \(E = e^{-\sigma^2}/\sigma\). The application of such a filter function for the transformation of true atmospheric signals into those that might be recorded in ice cores during rapid climate change was compared with results from firm densification models and extensively validated with CH4 data from both hemispheres6.

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Author contributions
All authors designed research, P.K. performed carbon cycle simulations with BICYCLE; E.B. performed carbon cycle simulations with other box models; G.K. performed climate simulations; P.K. drafted the manuscript with contributions from all co-authors.

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