Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation

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The covariation of carbon dioxide (CO2) concentration and temperature in Antarctic ice-core records suggests a close link between CO2 and climate during the Pleistocene ice ages. The role and relative importance of CO2 in producing these climate changes remains unclear, however, in part because the ice-core deuterium record reflects local rather than global temperature. Here we construct a record of global surface temperature from 80 proxy records and show that temperature is correlated with and generally lags CO2 during the last (that is, the most recent) deglaciation. Differences between the respective temperature changes of the Northern Hemisphere and Southern Hemisphere parallel variations in the strength of the Atlantic meridional overturning circulation recorded in marine sediments. These observations, together with transient global climate model simulations, support the conclusion that an antiphased hemispheric temperature response to ocean circulation changes superimposed on globally in-phase warming driven by increasing CO2 concentrations is an explanation for much of the temperature change at the end of the most recent ice age.

Global temperature

We calculate the area-weighted mean of 80 globally distributed, high-resolution proxy temperature records to reconstruct global surface temperature during the last deglaciation (Methods and Fig. 1). The global temperature stack shows a two-step rise, with most warming occurring during and right after the Oldest Dryas and Younger Dryas intervals and relatively little temperature change during the Last Glacial Maximum (LGM), the Bølling–Allerød interval and the early Holocene epoch (Fig. 2a). The atmospheric CO2 record from the EPICA Dome C ice core12, which has recently been placed on a more accurate timescale13, has a similar two-step structure and is strongly correlated with the temperature stack ($r^2 = 0.94$ (coefficient of determination), $P = 0.03$; Fig. 2a). Lag correlations quantify the timing of change in the temperature stack relative to CO2 from 20–10 kyr ago, an interval that spans the period during which low LGM CO2 concentrations increased to almost pre-industrial values. Our results indicate that CO2 probably leads global warming over the course of the deglaciation (Fig. 2b). A comparison of the global temperature stack with Antarctic temperature provides further support for this relative timing, in showing that

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Figure 1 | Proxy temperature records. a, Location map. CBT, cyclization ratio of branched tetraethers; MBT, methylation index of branched tetraethers; TEX$_{86}$, tetraether index of tetraethers consisting of 86 carbon atoms; U$^{13}$C, alkenone unsaturation index. b, Distribution of the records by latitude (grey histogram) and areal fraction of the planet in 5° steps (blue line).

although the structure of the global stack is similar to the pattern of Antarctic temperature change, it lags Antarctica by several centuries to a millennium throughout most of the deglaciation (Fig. 2a). Thus, the small apparent lead of Antarctic temperature over CO$_2$ in the ice-core records does not apply to global temperature. An additional evaluation of this result comes from an objective identification of inflection points in the CO$_2$ and global temperature records, which suggests that changes in CO$_2$ concentration were either synchronous with or led global warming during the various steps of the deglaciation (Supplementary Table 2). An important exception is the onset of deglaciation, which features about 0.3°C of global warming before the initial increase in CO$_2$ ~17.5 kyr ago. This finding suggests that CO$_2$ was not the cause of initial warming. We return to this point below. Nevertheless, the overall correlation and phasing of global temperature and CO$_2$ are consistent with CO$_2$ being an important driver of global warming during the deglaciation, with the centennial-scale lag of temperature behind CO$_2$ being consistent with the thermal inertia of the climate system owing to ocean heat uptake and ice melting.

Although other mechanisms contributed to climate change during the ice ages, climate models suggest that their impacts were regional and thus cannot explain the global extent of temperature changes documented by our stacked record alone. This conclusion is supported by the distinct differences, relative to the temperature stack, in the temporal variabilities of other likely climate change agents (Fig. 3). For example, insolation is a smoothly varying sinusoid that is in antiphase between the hemispheres and sums to near zero globally at the top of the atmosphere (Fig. 3f). Although spatial and temporal asymmetries in albedo could convert insolation to a non-zero forcing at Earth’s surface, it is unlikely to account for much of the step-like structure and global nature of the temperature stack.

Similarly, although ice-sheet extent and its associated albedo (from ice cover and emergent continental shelves) and orographic forcing decreased through the deglaciation, global ice volume and area changed only slowly or not at all during intervals of pronounced global warming such as the Oldest Dryas and Younger Dryas, and the greatest volume of ice cover and emergent continental shelves) and orographic forcing decreased through the deglaciation, global ice volume and area changed only slowly or not at all during intervals of pronounced global warming such as the Oldest Dryas and Younger Dryas, and the greatest volume of

Figure 2 | CO$_2$ concentration and temperature. a. The global proxy temperature stack (blue) as deviations from the early Holocene (11.5–6.5 kyr ago) mean, an Antarctic ice-core composite temperature record (red), and atmospheric CO$_2$ concentration (refs 12, 13; yellow dots). The Holocene, Younger Dryas (YD), Bølling–Allerød (B–A), Oldest Dryas (OD) and Last Glacial Maximum (LGM) intervals are indicated. Error bars, 1σ (Methods); p.p.m.v., parts per million by volume. b. The phasing of CO$_2$ concentration and temperature for the global (grey), Northern Hemisphere (NH; blue) and Southern Hemisphere (SH; red) proxy stacks based on lag correlations from 20–10 kyr ago in 1,000 Monte Carlo simulations (Methods). The mean and 1σ of the histograms are given. CO$_2$ concentration leads the global temperature stack in 90% of the simulations and lags it in 6%.

Our results, therefore, do not preclude an important contribution to global warming from ice-sheet retreat, but suggest that much of this warming was spatially restricted and may be inherently under-represented owing to the lack of suitable palaeotemperature records from and proximal to areas formerly covered by ice.
land and ocean proxy records during the last deglaciation, but that the timing may be slightly earlier in the marine records\cite{20} (Supplementary Fig. 4). Likewise, the pattern of temperature changes at upwelling sites, where reservoir ages may be more variable, is similar to that at non-upwelling sites but again seems somewhat older (Supplementary Fig. 4). These relationships imply that marine reservoir corrections may have been underestimated, which would shift the temperature stack to later times in some intervals and increase its average lag relative to CO\(_2\). We also evaluated the EPICA Dome C CO\(_2\) chronology\cite{21} by comparing the Dome C methane record on this timescale with the more precisely dated Greenland composite methane record on the GICC05 timescale\cite{22}. This comparison suggests that the EPICA Dome C CO\(_2\) age model may be one to two centuries too young during parts of the deglaciation (Supplementary Fig. 7), which would further increase the lead of CO\(_2\) over global temperature. We thus regard the lag of global temperature behind CO\(_2\) reported here as conservative.

### Hemispheric temperatures

The lead of Antarctic temperature over global temperature indicates spatial variability in the pattern of deglacial warming. To examine this spatial variability further, we calculated separate temperature stacks for the Northern Hemisphere and Southern Hemisphere and found that the magnitude of deglacial warming in the two hemispheric stacks is nearly identical (Fig. 4b). Given that greater LGM cooling probably occurred in the areas affected by the Northern Hemisphere ice sheets\cite{9,17}, this result provides additional support for our inference that the proxy network under-represents the regional impact of the ice sheets. Each hemispheric stack also shows a two-step warming as seen in the global stack and the CO\(_2\) record (Fig. 4a). Otherwise, the hemispheric stacks differ in two main ways. First, lag correlations suggest that whereas Southern Hemisphere temperature probably leads CO\(_2\), consistent with the Antarctic ice-core results\cite{12}, Northern Hemisphere temperature lags CO\(_2\) (Fig. 2b). Second, the Northern Hemisphere shows modest coolings coincident with the onset of Southern Hemisphere warmings, and the warming steps are concave-up in the north but are concave-down in the south (Fig. 4b).

Calculating the temperature difference, \(\Delta T\), between the two hemispheric stacks yields an estimate of the heat distribution between the hemispheres, and reveals two large millennial-scale oscillations that are one-quarter to one-third of the glacial–interglacial range in global temperature (Fig. 4d). We attribute the variability in \(\Delta T\) to variations in the strength of the AMOC and its attendant effects on cross-equatorial heat transport\cite{22,23}. A strong correlation of \(\Delta T\) with a kinematic proxy (Pa/Th, the protactinium/thorium ratio) for the strength of the AMOC\(^{24}\) \((r = 0.79, P = 0.03)\) supports this interpretation (Fig. 4g). We find that \(\Delta T\) decreases during the Oldest Dryas and Younger Dryas intervals, when the Pa/Th record suggests that the AMOC is weak and heat transfer between the hemispheres is reduced, and that \(\Delta T\) increases during the LGM, the Bølling–Allerød and the Holocene, when the AMOC is stronger and transports heat from the south to the north. Recalculating \(\Delta T\) for Atlantic-only records yields the same relations, but they are more pronounced and better correlated with Pa/Th\(^{(2)}(r = 0.86, P = 0.01)\), as would be expected given the importance of the AMOC in this ocean (Fig. 4d). We note that this seesawing of heat between the hemispheres explains the contrast between the lead of Antarctic temperature over CO\(_2\) and the lag of global (and Northern Hemisphere) temperature behind CO\(_2\).

### Transient modelling

We evaluate potential physical explanations for the correlations between temperature, CO\(_2\) concentration and AMOC variability in three transient simulations of the last deglaciation using the Community Climate System Model version 3 (CCSM3; ref. 25) of the US National Center for Atmospheric Research. The first simulation (ALL) runs from 22 to 6.5 kyr ago and is driven by changes in greenhouse gases, insolation, ice sheets and freshwater fluxes (the last of which is adjusted iteratively.
forcing. We sample the model output at the locations of the 80 proxy records, recording sea surface temperatures for the marine records and surface air temperatures for the land records, and stacking these sampled model time series just as we did the data. We also correct sea surface temperature time series from the ALL simulation for sea-level changes by scaling the eustatic sea-level curve\textsuperscript{26} to a warming by 0.32 °C at the LGM lowstand\textsuperscript{27}. To simulate uncertainties in the model results comparable to those of the data, we generated 1,000 Monte Carlo simulations in which the modelled time series were perturbed with random age-model ($\pm 300$ yr, 1σ) and temperature ($\pm 1$ °C, 1σ) errors at each site.

The ALL model temperature stack from the 80 sites is similar to the global mean temperature from the model ($r^2 = 0.97$), suggesting that the proxy sites represent the globe fairly well, although the amplitude of warming is slightly smaller in the stack (Fig. 3e and Supplementary Fig. 12). The ALL model stack is also similar to the CO2 model stack in shape and amplitude ($r^2 = 0.98$; Fig. 3e). Because the CO2 model stack reflects a response to only greenhouse gas forcing, its similarity to the ALL stack suggests that greenhouse gases can explain most of the mean warming at these 80 sites. The ORB model stack, by contrast, shows only minor warming, consistent with a modest role for orbital forcing in directly driving global temperature changes.

Calculating the difference in model temperature between the Northern Hemisphere and the Southern Hemisphere at the proxy sites in the three simulations yields $\Delta T$ time series that are strongly correlated with variations in modelled AMOC strength in each simulation ($r^2 = 0.95$ for ALL, 0.98 for CO2; Fig. 4f). Only $\Delta T$ for the ALL simulation, however, shows millennial-scale variability similar to that seen in the proxy $\Delta T$ time series and the Pa/Th record (Fig. 4d, e, g). These results suggest that ocean circulation changes driven primarily by freshwater flux, rather than by direct forcing from greenhouse gases or orbits, are plausible causes of the hemispheric differences in temperature change seen in the proxy records. Furthermore, in the ALL simulation the Southern Hemisphere temperature stack leads in temperature change seen in the proxy records. Moreover, in the ALL simulation the Southern Hemisphere temperature stack leads Northern Hemisphere (and global) temperature during the J-reg warming steps (Fig. 4c), supporting our inference that AMOC-driven internal heat redistributions explain the Antarctic temperature lag and global temperature lag relative to CO$_2$. Lag correlations from 20–10 kyr ago suggest that the modelled global temperature lags CO$_2$ concentration by 120 yr, which is within the uncertainty range of the proxy-based lag.

**The trigger for deglacial warming**

The proxy database provides an opportunity to explore what triggers deglacial warming. Substantial temperature change at all latitudes (Fig. 5b), as well as a net global warming of about 0.3 °C (Fig. 2a), precedes the initial increase in CO$_2$ concentration at 17.5 kyr ago, suggesting that CO$_2$ did not initiate deglacial warming. This early global warming occurs in two phases: a gradual increase between 21.5 and 19 kyr ago followed by a somewhat steeper increase between 19 and 17.5 kyr ago (Fig. 2a). The first increase is associated with mean warming of the northern mid to high latitudes, most prominently in Greenland, as there is little change occurring elsewhere at this time (Fig. 5 and Supplementary Fig. 20). The second increase occurs during a pronounced interhemispheric seesaw event (Fig. 5), presumably related to a reduction in AMOC strength, as seen in the Pa/Th record and our modelling (Fig. 4f, g). Tropical and Southern Hemisphere warming seem to have more than offset northern extratropical cooling, however, perhaps as a result of an asymmetry in the response of feedbacks such as Southern Ocean sea ice or tropical water vapour, leading to the global mean response. Alternatively, this non-zero-sum response may reflect proxy biases, as tropical warming is not equally evident in all proxies (Supplementary Fig. 20). In any event, we suggest that these spatiotemporal patterns of temperature change are consistent with warming at northern mid to high latitudes, leading to a reduction in the AMOC at ~19 kyr ago, being the trigger for the
global deglacial warming that followed, although more records will be required to confirm the extent and magnitude of early warming at such latitudes. A possible forcing model to explain this sequence of events starts with rising boreal summer insolation driving northern high-latitudes, while global temperature was in phase with or slightly lagged CO2. Furthermore, our results support an interhemispheric seesawing of heat related to AMOC variability and suggest that these internal heat redistributions explain the lead of Antarctic temperature over CO2 while global temperature was in phase with or slightly lagged CO2. Lastly, the global proxy database suggests that parts of the northern mid to high latitudes were the first to warm after the LGM, which could have initiated the reduction in the AMOC that may have ultimately caused the increase in CO2 concentration.

**METHODS SUMMARY**

The data set compiled in this study contains most published high-resolution (median resolution, 200 yr), well-dated (n = 636 radiocarbon dates) temperature records from the last deglaciation (see Supplementary Information for the full database). Sixty-seven records are from the ocean and are interpreted to reflect sea surface temperatures, and the remaining 13 record air or lake temperatures on land. All records span 18–11 kyr ago and ~85% of them span 22–6.5 kyr ago. We recalibrated all radiocarbon dates with the IntCal04 calibration (Supplementary Information) and converted proxy units to temperature using the reservoir corrections and proxy calibrations suggested in the original publications. An exception to this was the alkenone records, which were recalibrated with a global core-top calibration. The data were projected onto a 5° × 5° grid, linearly interpolated to 100-yr resolution and combined as area-weighted averages. We used Monte Carlo simulations to quantify pooled uncertainties in the age models and proxy temperatures, although we do not account for analytical uncertainties or uncertainties related to lack of global coverage and spatial bias in the data set. In particular, the records are strongly biased towards ocean margins where high sedimentation rates facilitate the development of high-resolution records. Given these issues, we focus on the temporal evolution of temperature through the deglaciation rather than on its amplitude of change. The global temperature stack is not particularly sensitive to interpolation resolution, areal weighting, the number of proxy records, radiocarbon calibration, infilling of missing data or proxy type. Details on the experimental design of the transient model simulations can be found in ref. 25. The temperature stacks and proxy data set are available in Supplementary Information.

Full Methods and any associated references are available in the online version of the paper at www.nature.com/nature.

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Author Contributions J.D.S. designed the study, synthesized and analysed data, and wrote the manuscript with P.U.C. Z.L. and B.O.-B. did the transient modelling. S.A.M. and A.C.M. contributed to data analysis. A.S. helped interpret AMOC–CO₂ linkages. E.B. provided data and discussion on the radiocarbon calibration. All authors discussed the results and provided input on the manuscript.

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METHODS

Age control. All radiocarbon dates were recalibrated using Calib 6.0.1 with the IntCal04 calibration and the reservoir corrections suggested in the original publications. Age models based on tuning were left unchanged from the original publications. We used the GICC05 timescale for NGRIP and GRIP, the timescale of ref. 13 for EDML and Dome C, and glaciological age models for the Dome F and Vostok ice cores.

Proxy temperatures. We converted proxy units to temperature for all alkenone, Mg/Ca and TEX86 records using the calibrations suggested by the original authors for Mg/Ca and Tex86 and the global core-top calibration for alkenone records\(^5\). We used the published temperature reconstructions for Antarctic ice-core, pollen, microfossil assemblages and MBT/CBT records and the GISP2 borehole calibration for the Greenland ice cores\(^3\). Missing data values near the beginning and end of the −15% of records not spanning the entire study interval were infilled using the method of regularized expectation maximization\(^6\).

Stacking. The proxy data were projected onto a 5° × 5° grid, linearly interpolated to 100-yr resolution and combined as area-weighted averages. We do not otherwise account for spatial biases in the dataset or lack of global coverage.

Uncertainty analysis. There are two main sources of uncertainty in the proxy records: age models and temperature calibration. We used a Monte Carlo approach to generate 1,000 realizations of each proxy temperature record after perturbing the records with chronological and temperature errors. These perturbed records were then averaged to yield 1,000 realizations of the global and hemispheric temperature stacks. The error bars on the temperature stacks represent the standard deviations of these 1,000 realizations, which provide an estimate of the propagated uncertainty due to uncertainties in the individual proxy records.

A similar approach was applied to the transient model output to develop the modelled temperature stacks and error bars. We developed continuous uncertainty estimates for radiocarbon-based chronologies, taking into account radiocarbon date errors as well as interpolation uncertainty between dates using a random walk model\(^7\). Age-model uncertainties for tuned records, the Dome F and Vostok ice cores, and regional temperature reconstructions for Beringia\(^8\) were assumed to be 2% (1σ). We used the Dome C and EDML ice-core age-model uncertainties\(^9\) and GICC05 maximum counting errors\(^10,11\) as 2σ uncertainties for the NGRIP and GRIP ice cores as suggested in ref. 50. We used the following 1σ temperature calibration uncertainties: alkenones, \(T = (U_5^T - 0.044 ± 0.016)/(0.033 ± 0.001)\) (ref. 41); Mg/Ca = ±0.02 ± 0.04 (ref. 42); TEX86 = ±1.7°C (ref. 52); ice cores, ±10% (ref. 53); pollen, microfossil assemblages and MBT/CBT, ±1.5°C. We did not account for analytical uncertainties in proxy measurements. Chronological errors in the Monte Carlo simulations were temporally autocorrelated but were random in space (but this does not account for systematic errors among the proxy records due to uncertainties in the radiocarbon calibration), whereas temperature errors were assumed to be random in space and time. We note that our study is concerned with temperature anomalies and is thus sensitive to relative but not absolute temperature errors in a proxy record. See Supplementary Information for more details and examples. Age-model uncertainties for the Antarctic Dome C CO2 record related to methane synchronization to Greenland were estimated on the basis of the combined uncertainties associated with Greenland layer counting, Greenland ice-age/gas-age differences and methane tuning to Antarctica. These uncertainties were used to generate 1,000 realizations of the CO2 record, which together with the 1,000 temperature stack realizations yield the 1,000 temperature-concentration lead–lag estimates shown in Fig. 2b.

Robustness of results. We evaluated how well the proxy sites represent the globe by subsampling the twentieth-century instrumental temperature record and our transient modelling output of the deglaciation at the 80 proxy sites. Both approaches suggested that the mean of the proxy sites approaches the global mean fairly well. We recalculated the stack after interpolating the records to 500-yr resolution but this did not change the time series or its uncertainty. Differences in areal weighting affect the glacial–interglacial amplitude of the stack but have little impact on its structure. Jackknifing suggests that the stack is not particularly sensitive to the number of records used. A leave-one-out proxy jackknifing approach suggests that the correlation (r² = 0.90–0.95) and lead–lag relation (300–600-yr temperature lag) between global temperature and CO2 concentration are not sensitive to proxy type. Statistical infilling of missing data values has negligible impact on the results. Although we here use the IntCal04 radiocarbon calibration, we tested the sensitivity of our results to this choice by recalibrating radiocarbon dates using the IntCal09 calibration. This makes the global stack up to 350 yr older during the Heinrich 1 interval, and shifts the overall phase lag relative to CO2 concentration from 460 ± 340 to 350 ± 340 yr. We consider the IntCal04 calibration to be more accurate for the reasons discussed in Supplementary Information. Lag correlations suggest that Antarctic temperature led CO2 concentration slightly throughout the deglaciation, whereas global temperature led CO2 concentration at the onset of deglaciation but lagged behind it thereafter. The lead–lag relation between CO2 concentration and the global temperature stack is not significantly changed by detrending the time series to remove the glacial-ramp in each proxy record. The raw modelled AMOC time series (Fig. 4f, thin lines) were effectively smoothed with a Monte Carlo approach similar to the one used to develop the modelled temperature stacks (Fig. 4e), to facilitate direct comparison of the two. More specifically, the smoothed AMOC time series (Fig. 4f, bold lines) are the means of 1,000 realizations of the raw AMOC time series generated by perturbing them with 300–600-yr (1σ) age-model errors.


