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LETTERS

Ensemble reconstruction constraints on the global carbon cycle sensitivity to climate

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The processes controlling the carbon flux and carbon storage of the atmosphere, ocean and terrestrial biosphere are temperature sensitive[1–4] and are likely to provide a positive feedback leading to amplified anthropogenic warming[3]. Owing to this feedback, at timescales ranging from interannual to the 20–100-kyr cycles of Earth's orbital variations[1,5–7], warming of the climate system causes a net release of CO_2 into the atmosphere; this in turn amplifies warming. But the magnitude of the climate sensitivity of the global carbon cycle (termed γ), and thus of its positive feedback strength, is under debate, giving rise to large uncertainties in global warming projections[8,9]. Here we quantify the median γ as 7.7 p.p.m.v. CO_2 per °C warming, with a likely range of 1.7–21.4 p.p.m.v. CO_2 per °C. Sensitivity experiments exclude significant influence of pre-industrial land-use change on these estimates. Our results, based on the coupling of a probabilistic approach with an ensemble of proxy-based temperature reconstructions and pre-industrial CO_2 data from three ice cores, provide robust constraints for γ on the policy-relevant multi-decadal to centennial timescales. By using an ensemble of >200,000 members, quantification of γ is not only improved, but also likelihoods can be assigned, thereby providing a benchmark for future model simulations. Although uncertainties do not at present allow exclusion of γ calculated from any of ten coupled carbon–climate models, we find that γ is about twice as likely to fall in the lowermost than in the uppermost quartile of their range. Our results are incompatibly lower ($P < 0.05$) than recent pre-industrial empirical estimates of ~40 p.p.m.v. CO_2 per °C (refs 6, 7), and correspondingly suggest ~80% less potential amplification of ongoing global warming.

Approximately 40% of the uncertainty related to projected warming of the twenty-first century stems from the unknown behaviour of the carbon cycle[10], which is an important component of the global climate system[3,11]. Constraining slow oceanic processes, possible CO_2 fertilization of plants, and γ—which is proportional to the global CO_2/temperature feedback—is of key importance to reduce these uncertainties[11]. Coupled carbon–climate models show a wide range in feedback strength, with 20–200 p.p.m.v. of temperature-driven CO_2 by 2100 (ref. 8). The substantial anthropogenic perturbation of the carbon cycle and physical climate system characteristics limits possibilities of providing tight constraints during the recent (instrumental) period, while past glacial–interglacial CO_2 fluctuations are governed by currently poorly quantified processes[11]. This means that neither the interannual nor glacial–interglacial domains permit feedback quantification on timescales relevant for addressing amplification of anthropogenic global warming.

Highly resolved reconstructions of temperature and atmospheric CO_2 available for the past millennium (Fig. 1) provide significant potential for observational constraints[12,13]: the climate state is broadly stationary with respect to glacial–interglacial processes, and the multidecadal to centennial-scale periods within policymakers' horizons are met. Reconstructed long-term decreases in CO_2 concentration are indicative of positive feedbacks in the cooling transition from the Medieval Warm Period (MWP) into the Little Ice Age (LIA). The average correlation between individual temperature reconstructions and the mean CO_2 record is 0.47 over the pre-industrial 1050–1800 period (all years are AD), increasing to 0.57 with a 50-year CO_2 response lag—such timing is consistent with modelled CO_2 response to a temperature step change[12]. Relying upon temperature and CO_2 covariation, estimates for γ have been derived by regressing individual temperature reconstructions to a given CO_2 record[1,6,7]. Yet, great scatter in γ, from a few to more than 40 p.p.m.v. per °C, closely reflects the choice of the individual temperature and/or CO_2 estimates used for analysis[6,7].

Particularly relevant to constraining sensitivities of the Earth's coupled climate system is the amplitude of hemispheric to global-scale

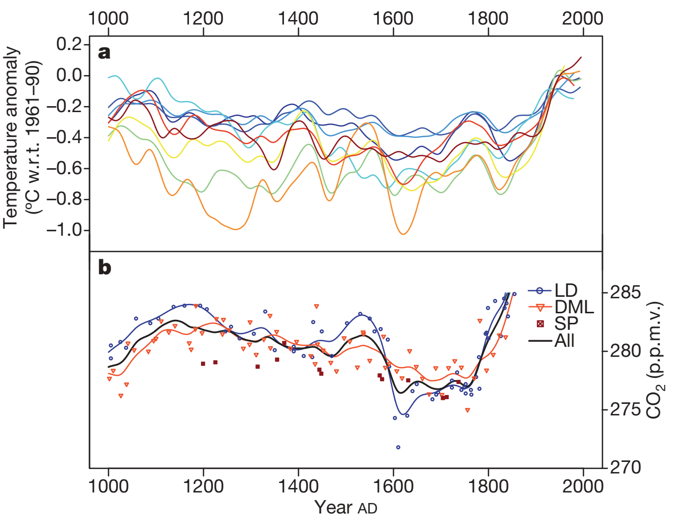

Figure 1 | Temperature and CO_2 variability over the past millennium. **a**, Large-scale reconstructions as originally calibrated (see Methods for details); records published before 2007 shown as in ref. 11. **b**, Variations in CO_2 concentration from three ice core records shown to 285 p.p.m.v. Measurements for Law Dome (LD) and Dronning Maud Land (DML) were sufficient to yield smoothed estimates for CO_2 evolution. Note broad long-term decline in CO_2 concentrations in the South Pole (SP) record. Records in **a** and **b** were smoothed with 80- and 50-year splines, respectively. These filters yield similar spectra owing to the lack of annual values and the smoothing effects of gaseous diffusion in **b** (see Supplementary Fig. 4).

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temperature change[12–14]. However, reconstructions presented in the 2007 IPCC report yield a wide amplitude range, with peak LIA conditions (1601–1630) about 0.3–1.0 °C cooler than present (1971–2000) (Fig. 1a). Statistical approaches that underestimate variability[15] and researcher specific decisions, including selection of calibration intervals and instrumental targets[14,16], contribute to this spread.

Reliable reconstruction of the small atmospheric CO_2 variations during the pre-industrial last millennium is also not without challenges. Analogous to temperature uncertainties, the amplitude of pre-industrial CO_2 changes differs among ice core records, with the Law Dome data showing more than 9 p.p.m.v. change, the Dronning Maud Land record less than 5 p.p.m.v., and the few South Pole data suggesting even smaller fluctuations (Fig. 1b; Methods). Artefacts of the ice archive[17,18] may lead to data scatter, while slow air enclosure into ice dampens atmospheric CO_2 variations[17,19]. Additionally, factors other than climate, such as anthropogenic emissions from land use[20,21] or century to millennial-scale carbon processes[22–25], may have contributed to atmospheric CO_2 variations.

Seeking to provide a comprehensive assessment of both temperature amplitude and γ, we use all available large-scale temperature reconstructions spanning the past millennium and contemporaneous estimates of CO_2 variation. We attempt to minimize the impact of potential limitations to the data sets and knowledge of carbon cycle processes by probabilistically considering different records, analysis periods, and data treatments. Climate reconstructions were recalibrated using methods shown to preserve the temperature amplitude[26]. Recognizing additional uncertainties related to the calibration interval[14] and target[16], we derive ensembles of past temperature change where we mitigate understood biases towards small amplitudes[26] and impacts of researcher specific calibration decisions that exist in the IPCC compilation (Supplementary Fig. 2).

Ensemble estimates (521) of past temperature variability were derived by calibrating nine reconstructions to annual Northern Hemisphere temperatures over all possible decadal intervals >40 years (Fig. 2; Methods), thus considering uncertainty in the intercept, slope and calibration period. On the basis of all ensemble members, we find the most recent climatological period (1971–2000) was 0.70 °C (median) warmer than the coldest episode of the past millennium (1601–1630), with 80% of the series yielding amplitudes between 0.52 and 0.99 °C. The warmest pre-anthropogenic period (1071–1100) was 0.38 °C warmer than 1601–1630, suggesting that recent anthropogenic influences have widened the last-millennium multi-decadal temperature range by ~75% and that late twentieth century warmth exceeds peak temperatures over the past millennium by 0.31 °C. A caveat to the latter conclusions is that more limited data[27] do not systematically bias MWP estimates.

We next use these ensembles of reconstructed temperature and CO_2 measurements to constrain γ (Methods). We consider different time-series smoothing approaches and three analysis periods: 1050–1800, 1050–1549 and 1550–1800. In comparison to previous investigations reporting only one or two estimates, here the numerous data sets, smoothings, and calibration and analysis periods result in 229,761 estimates of γ—thereby yielding distributions (and confidence intervals) for the first time. On the basis of all values, we obtain a mean (median) γ of 10.2 (7.7) p.p.m.v. per °C, with 80% of estimates between 1.7 and 21.4 p.p.m.v. per °C. Although carbon cycle sensitivities of 40 p.p.m.v. per °C or larger may be obtained from selected combinations of reconstructed temperature and CO_2 (refs 6, 7), such high upper tail sensitivities can be excluded at better than $P < 0.05$.

Values of γ for the early period (1050–1549) indicate a lower mean (4.3 p.p.m.v. per °C) and narrower distribution (s.d. = 3.5 p.p.m.v. per °C) than estimates for 1550–1800 (mean = 16.1; s.d. = 12.5 p.p.m.v. per °C), with distributions overlapping between 0.8 to 31.7 p.p.m.v. per °C (Fig. 3). If γ were to have been invariant during the pre-industrial past millennium, these distributions may permit γ to be more tightly constrained to 2.2–12.7 p.p.m.v. per °C (Methods). Yet owing to reconstruction uncertainties and a limited understanding of carbon cycle–climate processes and histories, we refrain from using this

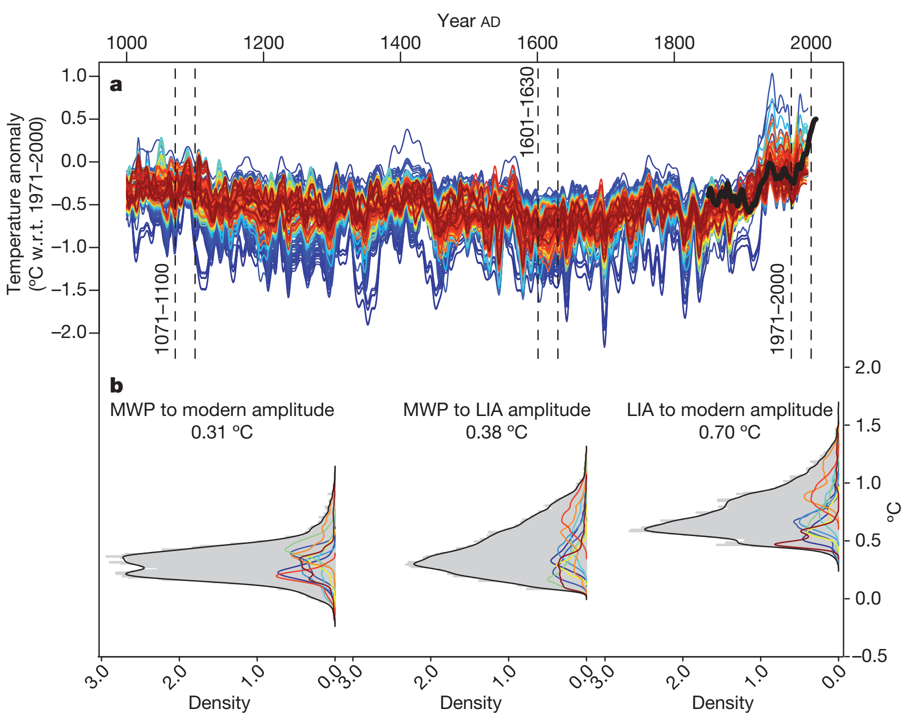

Figure 2 | Long-term temperature variation, amplitude and uncertainty. **a**, 521 estimates of hemispheric-scale temperature variability after 10-year smoothing calibrated to (smoothed) Northern Hemisphere annual land + ocean temperatures (thick black curve). The coldest climatological period of the past millennium (1601–1630) and the warmest instrumental (1971–2000) and pre-instrumental (1071–1100) climatological periods are indicated by vertical dashed lines. Colouring of ensemble members is based on distance from ensemble mean. **b**, Estimates of past millennium temperature amplitude. Gray histograms show all values between various reference periods, with separate density estimates for individual reconstructions indicated by coloured lines (colouring as in Fig. 1a).

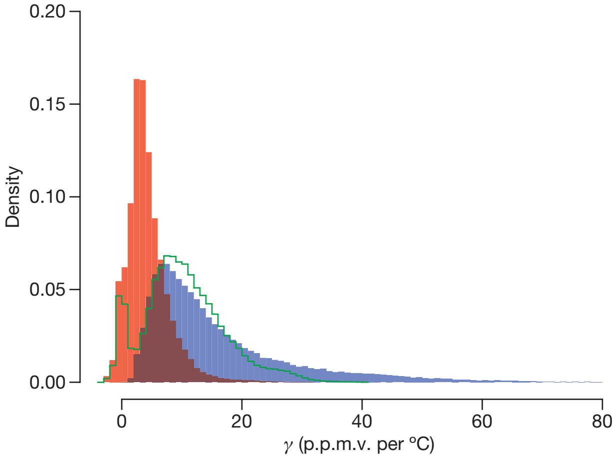

Figure 3 | Estimates for γ. Temporal dependence of γ estimates based on distributions derived from the early (1050–1549; red shading), late (1550–1800; blue shading) and full (1050–1800; green line) periods. The narrow (wide) distribution of the early (late) period reflects sensitivities implied by the small (large) changes in the CO_2 records (Fig. 1). Figure has been truncated at 80 p.p.m.v. per °C, thereby excluding 78 of 229,761 values.

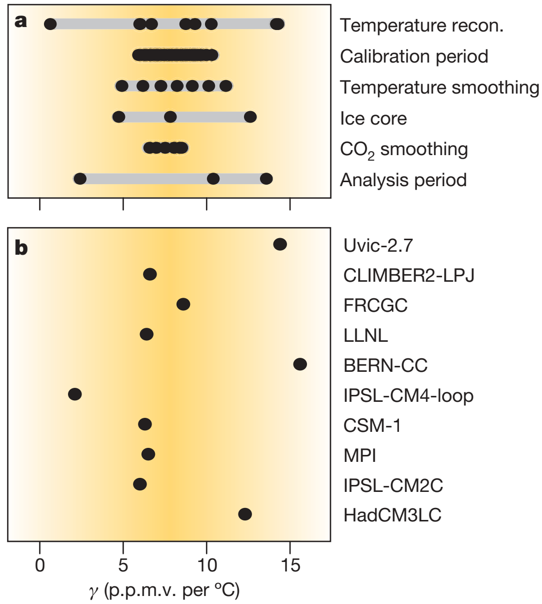

Figure 4 | Sensitivity in empirical and model estimates of γ. **a**, Range (grey shadows) and individual estimates (black dots) of median values of γ according to (top to bottom): the nine different temperature reconstructions shown in Fig. 1, possible temperature reconstruction calibration periods, smoothing of the temperature reconstructions, ice core records, smoothing of the CO_2 reconstructions, and analysis periods. See Methods for details. **b**, γ derived from ten coupled carbon cycle models for variations in temperature corresponding to the LIA – modern amplitude (Fig. 2b, Supplementary Table 3). Orange shading highlights central estimate of 7.7 p.p.m.v. per °C.

constraint. The distributional differences suggest that estimates are temporally biased, γ is not time invariant, and/or the mean climatic states during these two intervals are not comparable. The higher values for γ during the late period result from the strong LIA CO_2 dip around 1600, whereas the low values during the early period are associated with less variable CO_2 fluctuations. Although occurring around the coldest period of the past millennium (Fig. 2a), the LIA CO_2 decline is unique in the context of the past two millennia, both in magnitude and in its rate of change[19].

Contributions to the LIA CO_2 dip from factors other than large-scale temperature—such as shifts in oceanic[2] or atmospheric[28] states, artefacts in the ice core data[18], complex climatic–ecological interactions (for example, fire or biosphere inertia[24]), or changes in land use[21]—cannot easily be excluded as contributing noise in the estimation of γ. Moreover, the quality and independence of temperature reconstructions decrease back in time owing to the limited collection of proxy records[27]. Such decreased independence and increased noise might also act to decrease the values and variance of γ estimates during the 1050–1549 period (Methods). To assess biases from land use, we performed sensitivity tests by removing modelled variations in atmospheric CO_2 due to land-use change (derived from coupled climate–carbon cycle simulations) from ice-core reconstructed values before regression with temperature (Supplementary Fig. 11). Despite high uncertainties in land-use data, particularly towards the beginning of the past millennium, these first results suggest that land use had a small effect on γ quantification.

Estimates for γ, considering both data and methodological uncertainties, provide an integrated quantification of carbon cycle feedbacks over the past millennium. Nevertheless, intertwined vegetative, soil and oceanic processes—each with characteristic timescales, possible sensitivities, and physical and biological regulators—complicate a mechanistic understanding of carbon cycle feedbacks. Our conclusions of a pre-industrial carbon cycle sensitivity below ~20 p.p.m.v. per °C are supported by the lack of stronger correspondence between reconstructed temperature and CO_2 variation. A sensitivity assessment shows that γ estimates depend most significantly upon the temperature and CO_2 reconstructions used and the analysis period chosen (Fig. 4a). More complete palaeoclimatic reconstructions (including large-scale precipitation variation and oceanic circulation), as well as impacts of climatic extremes[29], a refined understanding of pre-industrial anthropogenic activities, and further progress in reconstructing CO_2 variation will contribute to improved quantification of γ. Large-scale changes in atmospheric and oceanic circulation that were associated with the MWP to LIA transition around 1400 led to teleconnected shifts in global temperature and precipitation regimes[28]. Such reorganizations could lead to decreased carbon storage in certain terrestrial regions and may also result in systematic differences for γ during the earlier and later past millennium.

A suite of ten coupled carbon cycle–climate models yields a mean γ of 8.5 p.p.m.v. per °C, and a range of 2.1–15.6 p.p.m.v. per °C (Fig. 4b; Supplementary Table 3) for a temperature amplitude comparable to that experienced during the past 1,000 years (Methods). On the basis of all empirical estimates, we find that γ between 2.1 and 8.5 p.p.m.v. per °C is about 1.6 times more likely than between 8.5 and 15.6 p.p.m.v. per °C. However, short simulation time spans and substantial internal model variability limit adequate comparison of model-derived and empirical estimates. Model development (for example, coupled nitrogen cycling[30]) and millennium-scale runs for a variety of simulations will be necessary to assess lagged effects and derive a comparable baseline carbon cycle–temperature sensitivity. Corroboration of empirical and modelled γ during the past millennium will increase confidence that basic carbon cycle processes and climate–carbon cycle interactions are well captured—perhaps a necessary prerequisite for reliable projections and a point emphasized by some recent simulations questioning the sign of γ (refs 9, 30). Reproduction of γ differences for the earlier and later epochs of the past millennium may represent a stringent test for next generation coupled climate models, or may additionally serve as a call for improved temperature and CO_2 reconstructions. The convergence of γ computed herein with other more moderate values quantified for interannual to Milankovitch[1,4,5] timescales suggests limited timescale dependence[1] and thus reduced possibilities for unwelcome surprises within the next century. However, as this indication is based on pre-industrial CO_2 concentrations and temperatures, possible threshold responses, transient behaviour, fertilization effects, and the role and rates of oceanic circulation and uptake and release from peatlands still need reconciliation in observational studies and climate-modelling efforts.

METHODS SUMMARY

Millennium-long temperature reconstructions were calibrated to annual Northern Hemisphere (land-ocean) instrumental data over numerous periods during the nineteenth to twentieth centuries with techniques shown to well preserve the full amplitude of climate variability[26]. This ensemble of reconstructions considers uncertainty in the individual records as well as the slope and intercept in proxy calibration (Methods). Regression between temperature and CO_2 variation[1,6,7] was used to estimate γ after optimizing lagged covariation[6,7]. Analyses were performed for variable smoothings (50, 75,…, 200), ice core records, temperature reconstructions, and for different pre-industrial time periods (1050–1800, 1050–1549, 1550–1800) to probabilistically consider temporal and frequency domain properties, yielding a total of 229,761 estimates for γ and full empirical distributions (Supplementary Figures) that now make it possible to assign likelihoods for γ. Coupled minus control runs for ten climate–carbon cycle simulations provided model estimates for γ for temperature amplitudes experienced over the past millennium (Methods and Supplementary Table 3).

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

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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METHODS

Temperature reconstructions. Analyses were performed using published temperature reconstructions with decadal or better resolution that extend to 1000. These records, their abbreviations, and the rainbow colour (from dark blue to dark red) shown in Fig. 1a are: Jones1998[31] (blue 3), Briffa2000[32] (blue 2), MannJones2003[33] (blue 1), Moberg2005[34] (light blue), DArrigo2006[35] (green), Hegerl2007[36] (yellow), Frank2007[37] (orange), Juckes2007[38] (red), Mann2008[39] (maroon). Most of these reconstructions are featured in the IPCC AR4 Figure 6.10. We replaced the reconstruction of ref. 40 with a methodological improvement to correct biases in the variance structure primarily resulting from changes in sample replication[37]. Additionally, we replaced the reconstruction from ref. 41 with the composite-plus-scaling reconstruction from ref. 39. For the ensemble calibration techniques, it is important that instrumental records are not spliced onto the end (that is, do not make up the modern portion) of proxy reconstructions, as this effectively results in a regression of a time series with itself (see below).

Instrumental data. The HADCRUT3 gridded $5^\circ \times 5^\circ$ data set[42] served as the instrumental target for calibration. Annual temperatures averaged over the Northern Hemisphere land and ocean areas were employed for primary analysis (Supplementary Fig. 3).

Calibration methods. To preserve the full amplitude of climate variability, both the instrumental data and large-scale temperature reconstructions were decadally smoothed with a cubic-smoothing spline[43]. The mean and variance of the smoothed temperature reconstructions were matched to those of the smoothed instrumental targets over the variable-length calibration periods (see below). Of the numerous calibration techniques tested using synthetic proxy data (so called pseudoproxies) and known target temperature histories generated by climate models[15], this calibration technique is among the simplest. However, it also tends to be among the methods least prone to variance underestimation[26] and is thus suitable for applications, such as estimation of the equilibrium temperature increase to a doubling of CO_2 (ref. 13) or evaluating the climate sensitivity of the carbon cycle, where accurate estimates for the absolute amplitude of past temperature variation are important.

We introduce ensemble calibration techniques to large-scale temperature reconstructions, whereby we calibrate each of the nine records to all possible decadal (beginning and ending in zero) intervals that are a minimum of 41 years in length. This results in between 36 and 66 calibration intervals for all temperature reconstructions when considering instrumental data back to 1850 and proxy records to their individual end years (ranging from 1960 to 1995). Calibration intervals range from 41 to 141 years in length. This technique overcomes biases in the choice of the calibration target and period[14] and also allows for uncertainty in the slope and intercept in the calibration procedure to be explicitly considered. Reconstruction calibration methods currently employed broadly suffer from poorly quantified proxy and target noise and their complicated noise structure (for example, non-Gaussian and also of variable magnitude in time). Advances in quantifying noise and improved reconstruction methodology may result in refinements for the temperature amplitude. Inhomogeneities in land[16] and sea-surface[44] temperatures which may still require correction will similarly affect future proxy calibration and model parameterization. The temporally variable proxy and instrumental noise components challenge preference of a particular calibration interval, and motivated us towards use of the calibration ensemble.

CO_2 data. Highly resolved CO_2 data spanning the past millennium were compiled from Antarctica. Three CO_2 histories were considered: one based on the Dronning Maud Land (DML[17]) data only, one based on the Law Dome (LD[45,46]) and one considering the combination of these data plus sparse measurements from the South Pole (SP[17]). For these three data sets, gas-ages were rounded to the nearest calendar year and then smoothed with a variety (see below) of cubic splines[43].

Empirical estimation of the carbon cycle climate sensitivity. We express the carbon cycle climate sensitivity, γ, in p.p.m.v. per °C as the increase (decrease) in atmospheric CO_2 concentrations given an increase (decrease) in temperature, here averaged over the Northern Hemisphere (Supplementary Fig. 3). Owing to the importance of temperature in regulating CO_2 solubility in the oceans, assimilation and respiration rates, and its high spatial autocorrelation, we follow convention and express γ in these terms, but note that other climatic factors such as precipitation can also affect the carbon cycle (see main text). Estimates of γ have previously been derived by contemporaneous changes in interannual to glacial–interglacial changes in temperature and CO_2 concentration[1,5–7]. Common to existing approaches is regression analysis of observational evidence alone[1,6] or in conjunction with coupled climate carbon cycle models to bridge the contemporary CO_2 rise, interannual variations, and LIA fluctuations[7]. We broadly follow these established regression methods on past millennium data[1,6,7], but attempt to more formally consider uncertainties that may arise due to different CO_2 and temperature reconstructions, time periods, and timescales of variability. Estimates were derived for three time windows (1050–1800, 1050–1549 and 1550–1800) by performing linear regression between the ensemble of reconstructed temperatures and the CO_2 records. To consider uncertainties in the response times of CO_2 to temperature change and make the temperature reconstructions compatible with the spectra of the ice archive (Supplementary Figs 4 and 5), all data sets were smoothed with a variety of splines (50, 75, …, 200 years) before regression. To avoid re-filtering data, the unsmoothed temperature reconstructions were rescaled in such a way that they would yield the amplitudes derived from the ensemble calibration were they simply to be decadally low-pass filtered. These unfiltered series were then smoothed (without recalibration) with the seven different low-pass filters for analysis. Before regression, the temperature and CO_2 reconstructions were lagged relative to each other within a $\pm$80-year search window to consider the response times and uncertainties of CO_2 changes driven by temperature variation. Consistent with expectation, in over 98.5% of all cases, CO_2 lagging behind temperature yielded the highest correlations. The negative lags occurred only during the first half of the past millennium which is in accordance with the apparently lower common signal, and thus the ability to determine precise relationships between the CO_2 and temperature records.

In detail, for all possible ensemble temperature and CO_2 estimates, least-squares regression was used to estimate γ as: $C = \gamma T + \varepsilon$, where C is the CO_2 concentration in p.p.m.v., T the calibrated temperature variation in °C, and ε is taken as random noise. Strong co-variation between temperature and CO_2 yields higher values of γ and as the common CO_2 and temperature signal approaches zero, so does γ. Understanding of the types, structure and time dependence of noise in both the CO_2 and temperature reconstructions would theoretically allow for application of different regression models and more robust estimation of γ. In practice, such modelling approaches are currently hindered by the ill-defined error structure. In addition to their likely non-Gaussian nature, errors (of an unknown magnitude) in large-scale temperature reconstructions increase back in time owing to declines in the absolute number and quality of proxy data[27]; whereas early industrial era changes in land use most probably contribute to increased uncertainties in the more recent CO_2 data (Supplementary Fig. 11). The lagging procedure to optimize fit between temperature and CO_2 reconstructions may act to positively bias γ. As noted previously, the fact that 98.5% of the lags were positive is consistent with physical expectation as well as decadal to centennial timescales suggested by modelling efforts[12,24]. However, the exact timescale for delays of carbon cycle processes is likely to depend on the particular sub-system under question and is not necessarily equivalent for warming and cooling. Conversely, if the noise in the temperature reconstructions is significantly greater than that in the CO_2 reconstructions, estimates of γ may be biased small. Potentially similar problems encountered in the calibration of temperature reconstructions (see main text) have been demonstrated on the basis of pseudo-proxy studies to be mitigated or overcome by smoothing time-series before calibration[26]. More research is needed to determine if the inherently smoothed nature of the ice archive and the necessary low-pass filtering of temperature data are advantageous or detrimental to the accurate estimation of γ.

Analysis of the early (1050–1549) and late (1550–1800) periods yielded distributions for γ with different characteristics. Under the hypothesis that γ is invariant across climatic states experienced during the past millennium, the independent early versus late periods could be used to find a distribution of γ that is consistent with both of these periods. We derive this distribution as $P(\gamma_{1050\text{-}1549}) \cdot P(\gamma_{1550\text{-}1800})$, where the probability, P, of γ is taken directly from the empirical distributions of the 76,587 estimates for both the early and late periods after binning in 0.1 p.p.m.v. per °C increments. The 2.5 and 97.5 percentiles of this distribution are used to estimate a 95% confidence interval. It however appears at this point premature to further constrain γ by the early and late period estimates until a more complete understanding of carbon-cycle processes and data and methodological limitations have been reached. Other hypotheses that may explain the differences in γ for the early versus late period are discussed in the main text.

Likelihoods and significance tests are based on the areas under the curves for the empirical distributions derived from all ensemble members.

Estimation of the carbon cycle feedback in models. We estimate γ using the simulations presented in ref. 8 (models used are given in their Table 1, except UMD as only global mean land temperatures are available). A control simulation without warming and a simulation with warming, both including CO_2 emissions, were available for each model. γ is obtained by calculating temperature and CO_2 differences in these simulations and estimating the regression coefficient between residual time-series. All data sets are smoothed with a variety of splines (50, 51, ..., 120-year filters) to damp internal variations and assess timescale dependencies. The median of this distribution is used as best estimate for the model and shown in Fig. 4.

In contrast to the authors of ref. 8, who estimated feedback parameters from twenty-first century results, we restrict our analysis to temperature changes associated with the amplitude over the past millennium (0.70 °C; Fig. 2). For most of the simulations, this constraint restricts analysis to roughly 1861–2000 (Supplementary Table 3). A further restriction to temperature changes ≤0.38 °C (the LIA to MWP amplitude) yields similar results for most of the models; however, models with a higher internal variability show greater spread in γ when compared with the 0.70 °C criterion.

Propagation of uncertainties. The ensemble approach introduced here allows a number of underlying uncertainties in the amplitude and course of temperature and CO_2 variation during the past millennium to be considered. The 521 ensemble calibration temperature reconstructions × 7 smoothings × 3 CO_2 reconstructions × 7 smoothings × 3 analysis periods yields 229,761 estimates for γ. Assessment of the sensitivity for these various possibilities, achieved by computing the median γ conditioned on the variable of interest as shown in Fig. 4, provides a rough idea of which factors contribute most to variation in γ. However, the different numbers of variables assessed (for example, nine temperature versus three CO_2 reconstructions) prohibit a definitive ranking. Similarly, the reduced numbers of proxy records available back in time, which tends to increase data overlap among reconstructions, also complicates a through estimation of error. Nevertheless, future, and ideally independent, CO_2 and temperature reconstructions can be incorporated into this framework to provide even more robust uncertainty estimates.

Large-scale temperature reconstructions are sometimes provided with uncertainty bounds related to unexplained temperature variance (for example, ref. 41), internal measures of signal quality (for example, ref. 40), and calibration uncertainties (for example, ref. 36, but also the ensemble approach applied herein). The typical provision of error (for example, two symmetrical time series of errors will yield identical regression coefficients as the mean reconstruction) are not readily, if at all, able to be incorporated in the present approach. We suspect that consideration of such errors will yield an increased absolute range in possible γ, but will have little if any influence on the mean, median, basic distributional properties of γ and associated likelihoods as the main parameters in the large-scale temperature-carbon cycle system have been well sampled. The derived distributions allow existing estimates of γ from the pre-industrial past millennium (such as 19 (ref. 1), 11 and 41 (ref. 6), and 40 (ref. 7) p.p.m.v. per °C), to be placed in the context of currently available data and assigned a likelihood. For example, in ref. 6 two distinct values for γ are presented, namely 11 and 41 p.p.m.v. per °C, with limited guidelines to prefer one estimate over the other. The distributions derived herein allow it to be determined that γ is ~27 times more likely to be between 10 and 12 p.p.m.v. per °C than between 40 and 42 p.p.m.v. per °C. Estimates of ~40 p.p.m.v. per °C are found to be possible from particular combinations of CO_2 and temperature data, albeit with a very low probability. Selection of (1) temperature reconstructions with a small calibrated amplitude, (2) CO_2 records with larger p.p.m.v. variation, (3) more (less) strongly smoothed temperature (CO_2) variation, and (4) performing analysis during the LIA dip, are all conducive to larger γ. Despite the use of recommended calibration methods, concerns that temperature amplitude might still be biased small and thus γ large, would make our conclusions for a moderate climate sensitivity of the carbon cycle conservative. Given uncertainties in the past temperature amplitude and difficulties in objectively preferring one record over another, it may be reasonable to report results from all available reconstructions in assessments of large-scale temperature variation, model data comparisons, and in quantifying sensitivities of the climate system. In addition, assigning higher weights to more likely estimates of past changes could result in reduced uncertainties. However, this would require a systematic and community-wide movement to evaluate existing records.

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