LETTERS

The proportionality of global warming to cumulative carbon emissions

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The global temperature response to increasing atmospheric CO_2 is often quantified by metrics such as equilibrium climate sensitivity and transient climate response[1]. These approaches, however, do not account for carbon cycle feedbacks and therefore do not fully represent the net response of the Earth system to anthropogenic CO_2 emissions. Climate–carbon modelling experiments have shown that: (1) the warming per unit CO_2 emitted does not depend on the background CO_2 concentration[2]; (2) the total allowable emissions for climate stabilization do not depend on the timing of those emissions[3–5]; and (3) the temperature response to a pulse of CO_2 is approximately constant on timescales of decades to centuries[3,6–8]. Here we generalize these results and show that the carbon–climate response (CCR), defined as the ratio of temperature change to cumulative carbon emissions, is approximately independent of both the atmospheric CO_2 concentration and its rate of change on these timescales. From observational constraints, we estimate CCR to be in the range 1.0–2.1 °C per trillion tonnes of carbon (Tt C) emitted (5th to 95th percentiles), consistent with twenty-first-century CCR values simulated by climate–carbon models. Uncertainty in land-use CO_2 emissions and aerosol forcing, however, means that higher observationally constrained values cannot be excluded. The CCR, when evaluated from climate–carbon models under idealized conditions, represents a simple yet robust metric for comparing models, which aggregates both climate feedbacks and carbon cycle feedbacks. CCR is also likely to be a useful concept for climate change mitigation and policy; by combining the uncertainties associated with climate sensitivity, carbon sinks and climate–carbon feedbacks into a single quantity, the CCR allows CO_2-induced global mean temperature change to be inferred directly from cumulative carbon emissions.

We propose a new measure of the climate response to anthropogenic carbon dioxide emissions: the 'carbon–climate response' (CCR). The CCR is illustrated schematically in Fig. 1, which shows the progression from carbon emissions to climate change. The CCR incorporates the standard concept of climate sensitivity (the temperature response to increased atmospheric CO_2), in addition to a 'carbon sensitivity' (the amount by which atmospheric CO_2 concentrations increase in response to CO_2 emissions, as mediated by natural carbon sinks, and including also the effect of feedbacks between climate change and carbon uptake).

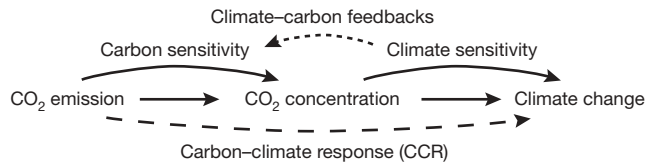

Figure 1 | Schematic representation of the progression from CO_2 emissions to climate change. We define 'carbon sensitivity' as the increase in atmospheric CO_2 concentrations that results from CO_2 emissions, as determined by the strength of natural carbon sinks. 'Climate sensitivity' is shown here as a general characterization of the temperature response to atmospheric CO_2 changes. Feedbacks between climate change and the strength of carbon sinks are shown as the upper dotted arrow (climate–carbon feedbacks). The CCR aggregates the climate and carbon sensitivities (including climate–carbon feedbacks) into a single metric representing the net temperature change per unit carbon emitted.

The CCR thus represents the net climate response to CO_2 emissions, and can be defined as $\Delta T/E_T$, where ΔT is the global mean temperature change over some period of time, and E_T is the total cumulative carbon dioxide emitted over that period. We assign units of trillion tonnes of carbon to E_T (1 Tt = 1 teratonne, or 10^{18} grams, of carbon, which is equivalent to 3.7 trillion tonnes of CO_2), so the CCR as defined here carries units of °C per Tt C emitted. CCR can be written as:

$$\mathrm{CCR} = \Delta T/\mathrm{E_T} = (\Delta T/\Delta C_A) \times (\Delta C_A/E_T)$$

where ΔC_A is the change in atmospheric carbon (in Tt C). Written in this way, CCR represents the product of the temperature change per unit atmospheric carbon increase ($\Delta T/\Delta C_A$) and the airborne fraction of cumulative carbon emissions ($\Delta C_A/\Delta E_T$). If defined under conditions of constant doubled pre-industrial atmospheric CO_2, ΔT is equal to the equilibrium climate sensitivity, and if defined under doubled CO_2 conditions in a simulation in which CO_2 increases at 1% per year, ΔT is equal to the transient climate response[1].

Both the airborne fraction of cumulative emissions and the temperature change per unit atmospheric carbon increase are dependent on the atmospheric CO_2 concentration and its rate of increase; however, the CCR (as the product of the two) shows a remarkable constancy with time. This can be seen in Fig. 2, which shows three model simulations using the University of Victoria Earth System Climate Model[9] (UVic ESCM, see Methods), an intermediate-complexity coupled climate–carbon model. In all simulations, we prescribed atmospheric CO_2 concentrations and used the model's interactive carbon sinks to diagnose the implied anthropogenic CO_2 emissions consistent with the prescribed concentration changes[10]. In the first simulation (Fig. 2a) we increased atmospheric CO_2 by 1% per year for 70 years; in the second and third simulations (Fig. 2b), atmospheric CO_2 was doubled (solid lines) or quadrupled (dashed lines) instantaneously and held constant for 1,000 years. In all simulations, the airborne fraction of cumulative emissions decreased over time, whereas the temperature change per unit change in atmospheric carbon increased with time. After an initial adjustment period of about a decade, the CCR remained almost constant at ~1.7 °C per Tt C emitted.

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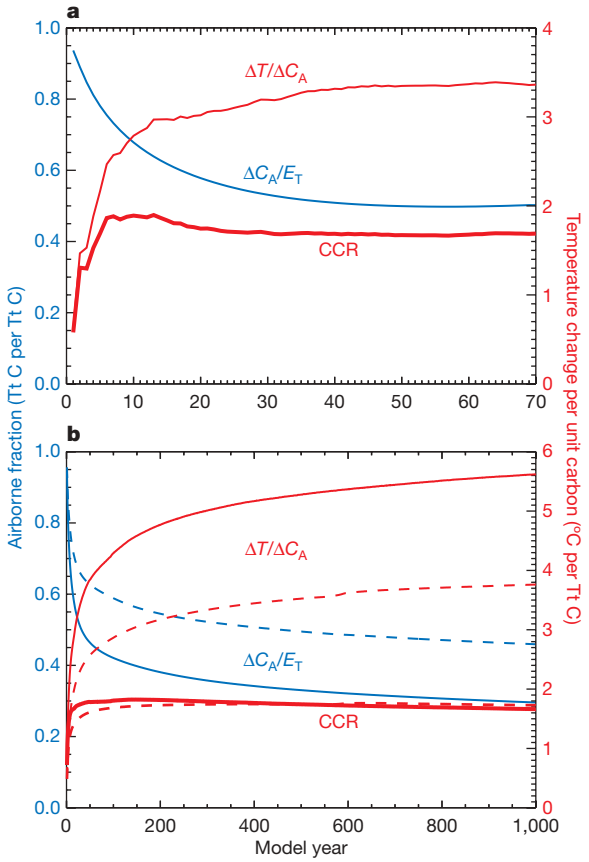

Figure 2 | Idealized model simulations of the CCR. a, Simulation with a 1% per year atmospheric CO_2 increase for 70 years, showing temperature change per unit atmospheric carbon increase ($\Delta T/\Delta C_A$: thin red line, right axis), airborne fraction of cumulative carbon emissions ($\Delta C_A/E_T$: thin blue line, left axis) and CCR (thick red line, right axis). In this simulation, cumulative airborne fraction decreased with time owing to a delayed carbon cycle response to a rapid prescribed rate of atmospheric CO_2 increase. This is consistent with saturating carbon sinks at higher atmospheric CO_2, which leads to an increased airborne fraction of annual emissions with increasing atmospheric CO_2. **b**, Simulations with an instantaneous doubling (solid lines) and quadrupling (dashed lines) of atmospheric CO_2 for 1,000 years (colours as in **a**). In all cases, the cumulative airborne fraction decreased with time, whereas the temperature change per unit atmospheric carbon increased with time; consequently, the CCR (defined as the product of these two quantities) remained constant in time.

In these simulations, the CCR is independent of both time and CO_2 emission (or concentration) scenario. At a given CO_2 concentration (see, for example, Fig. 2b), the time-independence of CCR arises from a cancellation of a decreasing airborne fraction of cumulative emissions, and an increasing temperature change per unit atmospheric CO_2 over time. This may relate in part to the uptake of heat and carbon by the ocean being driven by the same deep-ocean mixing processes on long timescales[3,7]. However, as can be seen in Fig. 2a and b, CCR is also independent of CO_2 concentration and, by extension, of the CO_2 emission scenario. This scenario independence emerges owing to the approximate cancellation of the saturation of carbon sinks and the saturation of CO_2 radiative forcing with increasing atmospheric CO_2. As a result, at higher atmospheric concentrations, a given CO_2 emission will lead to a larger increase in atmospheric CO_2, but the temperature change per unit change in atmospheric CO_2 will be smaller[2].

Even in the extreme case of instantaneous pulse emissions[8], the temperature change per unit carbon emitted in the UVic ESCM is found to be constant to within 10% on timescales of between 20 and 1,000 years, and for cumulative emissions of up to 2 Tt C (see Supplementary Fig. 1). As is seen, however, in Fig. 2a, we expect CCR to be more closely constrained in simulations in which cumulative emissions vary smoothly. Nonetheless, if used as a metric for model intercomparison, we recommend that CCR be defined under standard conditions, such as at the time of CO_2 doubling in a transient simulation with 1% CO_2 increase per year. Defined in this way, CCR generalizes previously proposed metrics (such as the temperature response to a small pulse or constant sustained emission[6]—see Supplementary Information for additional discussion) into a single robust and versatile quantity which can be easily estimated from current standard model experiments, and yet represents the climate response to a wide range of CO_2 emissions scenarios.

In a given model, CCR is approximately constant with respect to time and emissions scenario; however, we would expect the value of CCR to vary among models owing to differences in both climate and carbon sensitivities. Its time and scenario independence mean that the CCR can be estimated from any model simulation with either prescribed CO_2 emissions, or prescribed CO_2 concentrations and prognostic model carbon sinks. Consequently, the simulations performed as part of the Coupled Climate Carbon Cycle Model Intercomparison Project (C4MIP[11]) provide a means of estimating the range of CCR values among the current generation of coupled climate–carbon models.

Figure 3 shows results from the 11 C4MIP models and the ensemble mean, with global temperature change plotted as a function of cumulative carbon emissions (Fig. 3a) and temperature change per unit carbon emitted plotted as a function of time (Fig. 3b). Most models (and the ensemble mean) show a nearly linear relationship between temperature change and cumulative emissions (Fig. 3a), suggesting that this may be a robust property of the coupled climate–carbon system. Some models do deviate from linearity, particularly early in the simulations, which is at least partly due to the influence of decadal temperature variability. However, by the middle of the twenty-first century, all models converge to an intrinsic value of temperature change per unit carbon emitted, which remains approximately stable for the remainder of the simulation (Fig. 3b). CCR values calculated at the time of CO_2 doubling in each model simulation are given in Supplementary Table 1. Model values of CCR range from 1.0 to 2.1 °C per Tt C, with an ensemble mean value of 1.6 °C per Tt C (see Supplementary Information for additional discussion of model CCR values).

The CCR can also be estimated from historical carbon emissions data and observed temperature changes. To calculate CCR from observations, we first estimated decadal-mean CO_2-attributable warming relative to 1900–09 by scaling an estimate of greenhouse-gas-attributable warming[12] by the ratio of CO_2 to greenhouse-gas forcing. We then calculated CCR by dividing CO_2-attributable warming by cumulative anthropogenic CO_2 emissions between 1900–09 and each subsequent decade, including emissions from land-use change, fossil fuels and cement production (see Methods).

Figure 4 shows an estimate of CCR for 1990–99 of 1.0–2.1 °C per Tt C (5 to 95% confidence interval), with a best estimate of 1.5 °C per Tt C. Similar estimates of CCR, albeit with larger uncertainties, are obtained for previous decades. We note that these estimates are less contaminated with internal climate variability than those derived from single simulations in Fig. 3 because the greenhouse-gas-attributable warming is based on a scaled ensemble mean of 11 simulations. Nonetheless, assuming the simulated temporal evolution of the greenhouse gas response is realistic, these results provide further evidence for the constancy of CCR as a function of time.

Recent climate–carbon model experiments have shown that eliminating CO_2 emissions leads to approximately stable, or slowly decreasing global temperatures over time[3,7,13]; this implies that close to zero net anthropogenic carbon emissions are required to stabilize global mean temperature[3], and conversely that there may be negligible future warming commitment as a result of past CO_2 emissions[3,7,13]. Consequently, the CCR, defined here as the ratio of instantaneous temperature change to past CO_2 emissions, can also

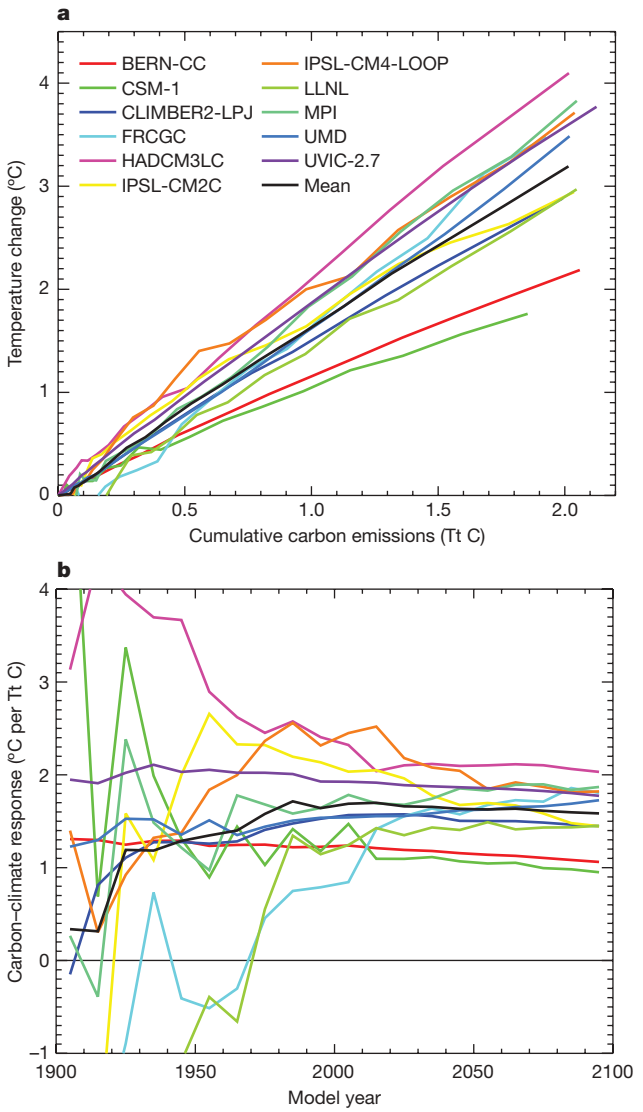

Figure 3 | CCR estimated from the C4MIP simulations[11]. **a**, Decadal-average temperature change plotted as a function of cumulative carbon emissions, showing a near-linear relationship for both individual models (coloured lines) and the ensemble mean (black line). **b**, Temperature change per cumulative carbon emitted for each decade from 1900 to 2100 relative to the first decade of each model simulation. Over most of the twenty-first century portion of the simulations, CCR values in each model are remarkably constant in time.

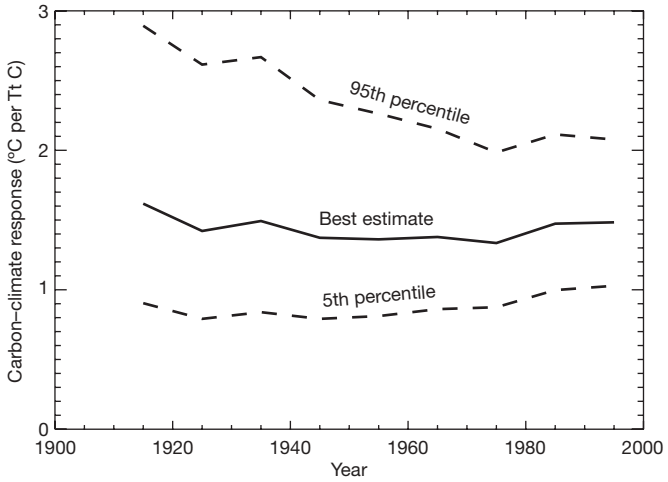

Figure 4 | Observational estimates of CCR. CCR was estimated for each decade of the twentieth century after 1910 by scaling an observationally constrained estimate of greenhouse-gas-attributable warming relative to 1900–09 by the ratio of CO_2 forcing to total greenhouse gas forcing, and dividing by cumulative anthropogenic carbon emissions over the same period. This observationally constrained estimate of CCR is both stable in time and consistent with the estimates derived from model simulations.

be used as an estimate of the centennial-scale temperature legacy of these emissions. As a result, our estimates of CCR can be inverted to estimate the total allowable anthropogenic carbon emissions per degree of long-term temperature change.

From our model-based estimate of CCR, we estimate allowable emissions of 1.25 Tt C (range, 0.95–2 Tt C) for 2 °C warming relative to pre-industrial temperature; our observationally based best estimate of allowable emissions for 2 °C of warming is 1.4 Tt C (5–95% confidence interval, 1.0 to 1.9 Tt C). Given total CO_2 emissions until now of approximately 0.5 Tt C from fossil fuels and land-use change[14,15], this implies that total future carbon emissions consistent with 2 °C of warming must be restricted to a best estimate of about 0.8 Tt C (0.7 Tt C based on the model ensemble mean; 0.9 Tt C based on observational constraints).

We emphasize, however, that the calculated uncertainty on this number is quite large (0.4 to 1.5 Tt C). Furthermore, we are unable to exclude the possibility of higher values of CCR (and consequently lower values of allowable emissions), owing particularly to poorly quantified uncertainties in historical land-use change emissions and structural uncertainties in the simulated sulphate aerosol response. For example, the allowable emissions for a particular warming target calculated by ref. 5 were lower, because they used a higher observational estimate of CO_2-attributable warming as well as a climate–carbon model which simulated non-negligible zero emissions commitment under conditions of high climate sensitivity. We note also that our analysis of allowable emissions applies specifically to CO_2-induced warming, and does not account for the effects of other greenhouse gases or aerosols.

The CCR is a simple, yet robust representation of the global temperature response to anthropogenic CO_2 emissions, and as such is directly relevant to current policy negotiations surrounding international climate mitigation efforts. The European Union has proposed restricting global warming to less than 2 °C above pre-industrial temperatures[16]; however, large uncertainty in equilibrium climate sensitivity[17] prevents confident estimates of the CO_2 stabilization level required to avoid 2 °C warming, and climate sensitivity alone provides no policy-useful information about the allowable CO_2 emissions for a given stabilization level. The CCR represents a synthesis of previous efforts to quantify the temperature response to anthropogenic CO_2 emissions by aggregating the uncertainties associated with climate sensitivity, carbon sinks and climate–carbon feedbacks into a single well-constrained metric of climate change that is related directly to cumulative carbon emissions.

METHODS SUMMARY

For the idealized model experiments (1% per year CO_2 increase; doubled/quadrupled CO_2) we used the UVic ESCM version 2.8 (refs 9, 18–20). The UVic ESCM is a computationally efficient coupled climate–carbon model, with interactive representations of three-dimensional ocean circulation, atmospheric energy and moisture balances, sea ice dynamics and thermodynamics, dynamic vegetation and the global carbon cycle (including land and both inorganic and organic ocean carbon). Version 2.7 of the UVic ESCM was one of the 11 participating models in C4MIP[11], in which models were driven by a common CO_2 emissions scenario and carbon sinks and atmospheric CO_2 concentrations were calculated interactively until the year 2100. From the C4MIP simulations, we estimated CCR using globally averaged temperature change and accumulated carbon emissions at the year of CO_2 doubling in each simulation.

Our observational estimate of CCR was derived using estimates of CO_2-attributable warming and cumulative CO_2 emissions for each decade of the twentieth century relative to 1900–09. We estimated CO_2-attributable warming using an estimate of greenhouse-gas-attributable warming[12], scaled by the ratio of CO_2 to

total greenhouse-gas forcing[21], where greenhouse-gas forcing was first scaled by an estimate of the mean efficacy of long-lived greenhouse gases[22]. We calculated uncertainties in greenhouse-gas-attributable warming, accounting for internal variability and inter-model uncertainty[12], and assumed normally and Student-*t* distributed uncertainties for radiative forcings and greenhouse-gas efficacy, respectively[22]. We calculated cumulative carbon emissions from fossil fuels and land-use change[13,14,23], and assumed a one-sigma systematic uncertainty on land-use emissions of ± 0.5 Pg C per year[24]. Our central estimates for CO_2-attributable warming and cumulative emissions at 1990–99 relative to 1900–09 were 0.492 °C and 0.338 Tt C, respectively. We calculated a probability density function for CCR based on the probability distributions of the constituent terms, which we used to estimate the mean and the 5th and 95th percentiles.

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

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1. Randall, D. A. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 589–845 (Cambridge University Press, 2007).
2. Caldeira, K. & Kasting, J. F. Insensitivity of global warming potentials to carbon dioxide emissions scenarios. *Nature* **366,** 251–253 (1993).
3. Matthews, H. D. & Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* **35,** L04705 (2008).
4. Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci. USA*. (submitted).
5. Allen, M. R. *et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458,** 1163–1166 (2009).
6. Shine, K. P., Fuglestvedt, J. S., Hailemariam, K. & Struber, N. Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases. *Clim. Change* **68,** 281–302 (2005).
7. Solomon, S., Kasper Plattner, G., Knutti, R. & Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. *Proc. Natl Acad. Sci. USA* **106,** 1704–1709 (2009).
8. Eby, M. *et al.* Lifetime of anthropogenic climate change: millennial time-scales of potential CO_2 and surface temperature perturbations. *J. Clim.* **22,** 2501–2511 (2009).
9. Weaver, A. J. *et al.* The UVic Earth System Climate Model: model description, climatology and applications to past, present and future climates. *Atmos. Ocean* **39,** 361–428 (2001).
10. Matthews, H. D. Emissions targets for CO_2 stabilization as modified by carbon cycle feedbacks. *Tellus* **55B,** 591–602 (2006).
11. Friedlingstein, P. *et al.* Climate-carbon cycle feedback analysis, results from the C4MIP model intercomparison. *J. Clim.* **19,** 3337–3353 (2006).
12. Huntingford, C., Stott, P. A., Allen, M. R. & Lambert, F. H. Incorporating model uncertainty into attribution of observed temperature change. *Geophys. Res. Lett.* **33,** L05710 (2006).
13. Plattner, G.-K. *et al.* Long-term climate commitments projected with climate-carbon cycle models. *J. Clim.* **21,** 2721–2751 (2008).
14. Marland, G., Boden, T. A. & Andres, R. J. Global, regional, and national fossil fuel CO_2 emissions. In *TRENDS, A Compendium of Data on Global Change* (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US DOE, 2008).
15. Houghton, R. A. Carbon flux to the atmosphere from land-use changes: 1850–2005. In *TRENDS, A Compendium of Data on Global Change* (Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US DOE, 2008).
16. European Commission. Limiting global climate change to 2 degrees Celsius: the way ahead for 2020 and beyond. (Commission of the European Communities, 2007).
17. Meehl, G. A. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 747–845 (Cambridge University Press, 2007).
18. Meissner, K. J., Weaver, A. J., Matthews, H. D. & Cox, P. M. The role of land-surface dynamics in glacial inception: a study with the UVic Earth System Climate Model. *Clim. Dyn.* **21,** 515–537 (2003).
19. Matthews, H. D., Weaver, A. J. & Meissner, K. J. Terrestrial carbon cycle dynamics under recent and future climate change. *J. Clim.* **18,** 1609–1628 (2005).
20. Schmittner, A., Oschlies, A., Matthews, H. D. & Galbraith, E. D. Future changes in climate, ocean circulation, ecosystems and biogeochemical cycling simulated for a businessas-usual CO_2 emissions scenario until year 4000 AD. *Glob. Biogeochem. Cycles* **22,** GB1013 (2008).
21. Gregory, J. M. & Forster, P. M. Transient climate response estimated from radiative forcing and observed temperature change. *J. Geophys. Res.* **113,** D23105 (2008).
22. Forster, P. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 129–234 (Cambridge University Press, 2007).
23. Denman, K. *et al.* in *Climate Change 2007: The Physical Science Basis* (eds Solomon, S. *et al.*) 129–234 (Cambridge University Press, 2007).
24. Canadell, J. G. *et al.* Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc. Natl Acad. Sci. USA* **104,** 18866–18870 (2007).

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

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Author Contributions H.D.M. proposed the study, carried out model simulations and analysis, and wrote most of the paper. N.P.G. proposed the inclusion of observational constraints, N.P.G. and P.A.S. carried out this analysis, and N.P.G. wrote the sections of the paper and methods describing these results. K.Z. provided additional model simulations and analysis as described in the Supplementary Information. All authors participated in discussions pertaining to interpretation and presentation of results.

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METHODS

UVic ESCM. The UVic ESCM is an intermediate-complexity coupled climate–carbon model. The climate component consists of a reduced-complexity energy–moisture balance atmosphere coupled to a general circulation ocean and dynamic/thermodynamic sea-ice model[9]. The carbon cycle component of version 2.8 consists of a biochemical dynamic vegetation model[18,19] and an organic/inorganic ocean carbon cycle model[20]. Version 2.7 of the UVic ESCM was one of the 11 participating models in the C4MIP[11], as well as a contributing model to the long-term climate and carbon cycle projections highlighted in ref. 17.

C4MIP. The C4MIP compared the simulated climate and carbon cycle changes from 11 coupled climate–carbon models (including seven atmosphere–ocean general circulation models, and four intermediate-complexity models)[11]. Models were driven by a common CO_2 emissions scenario (including specified emissions from both fossil fuels and land-use change), with carbon sinks and atmospheric CO_2 calculated interactively until the year 2100. To calculate the CCR for each model, we used globally averaged temperature changes from the coupled simulations, along with a running total of specified CO_2 emissions. The values of CCR presented here and in the Supplementary Information were calculated using a ten-year average of temperature increases and cumulative emissions, centred at the time of CO_2 doubling in each simulation.

Observationally constrained CCR estimate. We calculated observational estimates of CCR by taking the ratio of CO_2-attributable warming and cumulative emissions in the decade 1900–09 and each subsequent decade of the twentieth century. We began with a multi-model estimate of greenhouse-gas-attributable warming for each decade of the twentieth century. This was derived by scaling the mean simulated temperature response to prescribed historical well-mixed greenhouse-gas concentrations from HadCM3, GFDL and PCM to best-fit HadCRUT2v temperature observations, based on a multiple regression together with the response to sulphate aerosol and natural forcing[12]. The calculated uncertainty in this greenhouse-gas-attributable warming includes an estimate of internal variability based on control simulations and an estimate of model uncertainty based on inter-model differences in forcings and simulated responses[12].

We scaled the greenhouse-gas-attributable warming by the ratio of CO_2 forcing to total well-mixed greenhouse gas forcing, with all forcings expressed as differences between 1900–09 and subsequent decades of the twentieth century[21]. Before this scaling, we multiplied the well-mixed greenhouse-gas forcing by the mean efficacy for long-lived greenhouse gases (shown in figure 2.19 of ref. 22) to account for the larger temperature response per unit radiative forcing for other greenhouse gases compared to CO_2. Tropospheric ozone changes were not specified in the simulations used by ref. 12, so we did not include them in our estimate of total greenhouse gas forcing, under the assumption that the response to tropospheric ozone is spatially and temporally dissimilar to that due to the well-mixed greenhouse gases and is therefore unlikely to be aliased in the multiple regression (the inclusion of tropospheric ozone forcing in the total greenhouse-gas forcing estimate reduces our observational estimate of CCR to 0.9–1.8 °C per Tt C). Our calculation also assumes that climate forcings other than CO_2 emissions have had little influence on atmospheric CO_2 concentration. This is a reasonable assumption given a near-cancellation over the past century of positive non-CO_2 greenhouse-gas forcing and negative aerosol forcing.

Uncertainties in greenhouse-gas-attributable warming were calculated following ref. 12; uncertainties in radiative forcings were estimated from ref. 22 (FAQ 2.1, Fig. 2) and were assumed to be normally distributed; uncertainties in efficacies were estimated from figure 2.19 of ref. 22, and were assumed to be Student-*t* distributed. Land use, fossil fuel and cement emissions were taken from CDIAC[14,15]. A one-sigma uncertainty on fossil fuel and cement emissions of $\pm 5\%$ was assumed following ref. 23 and a one-sigma systematic uncertainty on land-use emissions of ± 0.5 Pg C per year was assumed following ref. 24; both were assumed to be normally distributed. A probability density function was calculated for CCR based on the probability density functions of the constituent terms, and this was used to derive the mean and the 5th and 95th percentiles. The uncertainty in land-use emissions was the largest single contributor to the overall uncertainty in CCR. Given this, we tested the sensitivity of our results to setting land-use emissions to zero; this gave an estimate of CCR for the decade 1990–99 of 1.6–2.7 °C per Tt C, though we emphasize that this should not be taken as a realistic upper bound for CCR, because zero land-use emissions are not consistent with observed atmospheric CO_2 increases. Uncertainties in the overall magnitude of aerosol forcing are fully accounted for in our estimate of greenhouse-gas-attributable warming; however, uncertainties in the temporal or spatial pattern of the response to aerosol forcing are only accounted for to the extent that they are sampled in the three global climate models we used, and errors in these patterns could lead to values of CCR outside our estimated uncertainty range.