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LETTERS

Warming caused by cumulative carbon emissions towards the trillionth tonne

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Global efforts to mitigate climate change are guided by projections of future temperatures[1]. But the eventual equilibrium global mean temperature associated with a given stabilization level of atmospheric greenhouse gas concentrations remains uncertain[1–3], complicating the setting of stabilization targets to avoid potentially dangerous levels of global warming[4–8]. Similar problems apply to the carbon cycle: observations currently provide only a weak constraint on the response to future emissions[9–11]. Here we use ensemble simulations of simple climate-carbon-cycle models constrained by observations and projections from more comprehensive models to simulate the temperature response to a broad range of carbon dioxide emission pathways. We find that the peak warming caused by a given cumulative carbon dioxide emission is better constrained than the warming response to a stabilization scenario. Furthermore, the relationship between cumulative emissions and peak warming is remarkably insensitive to the emission pathway (timing of emissions or peak emission rate). Hence policy targets based on limiting cumulative emissions of carbon dioxide are likely to be more robust to scientific uncertainty than emission-rate or concentration targets. Total anthropogenic emissions of one trillion tonnes of carbon (3.67 trillion tonnes of CO_2), about half of which has already been emitted since industrialization began, results in a most likely peak carbon-dioxide-induced warming of 2 °C above pre-industrial temperatures, with a 5–95% confidence interval of 1.3–3.9 °C.

Under conventional climate stabilization scenarios, greenhouse gas emissions are reduced until atmospheric composition approaches a stabilization level consistent with a desired equilibrium warming and are then adjusted to hold concentrations stable thereafter[5]. If climate system and carbon cycle properties were known, this would be straightforward: we could reliably map emissions to temperatures and vice versa. For example, if the climate system were to follow the response of a simple model with most likely values of key parameters (see Methods Summary and Supplementary Information), the emissions scenario highlighted by the solid red line in Fig. 1a would bring atmospheric carbon dioxide (CO_2) concentrations towards 490 p.p.m. (parts per million) by the end of the twenty-first century (solid red line in Fig. 1b). Under the '490 p.p.m. stabilization scenario' shown by the dotted red lines, rapid reductions cease after 2070, with smaller subsequent adjustments causing concentrations to converge to 490 p.p.m.

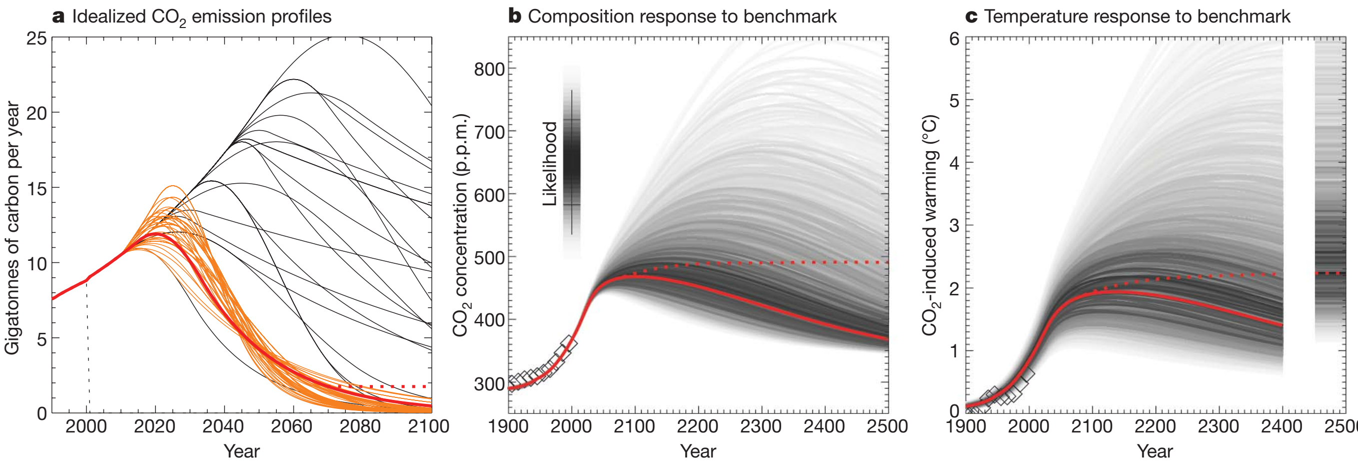

Figure 1 | Idealized carbon dioxide emission scenarios and response to benchmark scenario. a, Emissions, including zero emissions after 2000 (dotted black line). Solid red and orange lines show scenarios with cumulative emissions 1750–2500 within 1% of 1 Tt C. Solid red line shows benchmark case and dotted red line shows the '490 p.p.m. stabilization' scenario. **b**, CO_2 concentration response to benchmark scenario with best-fit combination of simple climate model parameters (solid red line) and with random parameter combinations shaded by likelihood (grey plume). The vertical scale bar shows the corresponding likelihood profile for a normally distributed quantity, with black line showing 5–95% (horizontal tickmarks: 17–83%) confidence interval. The dotted red line shows best-fit response to stabilization scenario. **c**, Temperature response to benchmark scenario from simple model: best fit in red and likelihood profile in grey. Bar on right shows likelihood profile for peak warming response to '490 p.p.m. stabilization' emissions scenario: in cases where temperatures are still rising in 2500, equilibrium warming response to 2500 CO_2 concentration is plotted. Diamonds in **b** and **c** show observed CO_2 concentrations and temperatures (relative to 1900–1920), respectively.

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over the following century[5]. With most likely values of key parameters in this model (including an Equilibrium Climate Sensitivity, or ECS, of 2.8 °C for doubling atmospheric CO_2) these emissions cause a warming of 2.2 °C above pre-industrial by 2500, but much higher responses (shown by the shaded bar on the right of Fig. 1c) are also consistent with current uncertainties in ECS[1,2] and carbon cycle[9–11]. The shading shows the range arising solely from known uncertainties in current feedbacks: the true uncertainty is greater, particularly for long timescales and higher responses, because feedbacks may change as the climate changes[3]. In practice, our descendants would be unlikely to adhere to this specific emissions scenario in the event that both CO_2 and temperature overshoot the original targets, but this illustrates the 'stabilization dilemma': either we specify a temperature or concentration target and accept substantial uncertainty in the emissions required to achieve it or we specify emissions and accept even more uncertainty in the temperature response.

There is, however, no intrinsic reason why emissions must be adjusted to maintain a target concentration, particularly if temperatures then look likely to overshoot. Instead, we could assume that once the current rate of increase in emissions starts to fall, it declines until it reaches a maximum annual percentage rate of decrease which is subsequently maintained indefinitely (see Methods and Supplementary Fig. S3a). Varying both the timing of the transition and the maximum rate of decrease gives idealized emission profiles (solid lines in Fig. 1a) which can reproduce the essential features of most mitigation scenarios over the next few decades. Unlike conventional stabilization and overshoot scenarios[5,12,13], the integrals under these 'containment scenarios', or cumulative total carbon dioxide emissions over the entire 'anthropocene' period, are bounded. For integrals less than two trillion tonnes of carbon (Tt C) almost all emissions occur before 2200. The solid red line in Fig. 1a is one such containment scenario with an integral of 1 Tt C: with most likely values of climate system properties applied to the simple climate model, it suggests that both carbon dioxide levels and temperatures peak (at 470 p.p.m. and almost exactly 2 °C above pre-industrial respectively) and then decline thereafter (solid red lines in Fig. 1b and c). Substantially higher responses to this benchmark scenario are also consistent with current observations, as shown by the spread of the grey shaded plumes, but even the most pessimistic show temperatures declining within a couple of centuries, unlike the response to the dotted 'stabilization scenario' emissions, under which CO_2 levels and temperatures could continue rising for centuries if the climate turns out to be more sensitive than our current best estimate.

The maximum warming under concentration overshoot scenarios[12,13] is better constrained by observations than the long-term response to a stabilization scenario[14], but such overshoot scenarios appear to require at least three specified targets: the final concentration, the size of the overshoot and its duration. A simpler target is suggested by Fig. 2, which plots peak carbon-dioxide-induced warming against the total carbon dioxide released over the entire period 1750 to 2500, expressed as Tt C, for 250 containment scenarios (a subset of which are shown by the solid black lines in Fig. 1a). Each white cross in Fig. 2 shows maximum warming under one scenario in the simple climate model with most likely values of model parameters. The black–grey–white shading denotes the relative likelihood of different levels of warming for the same total carbon dioxide released, allowing for uncertainty in modelled carbon cycle, atmosphere and ocean. The crosses all lie close to a single curve despite the fact that peak emission rates differ by up to a factor of two for the same cumulative carbon release. The total emissions determine peak CO_2-induced warming under a containment scenario, not the peak emission rate or other details of the emission pathway. We focus here on peak warming, but we find this result also applies to average warming over the 2000–2500 period or indeed warming by any given date after emissions have substantially declined (see Supplementary Information).

This conclusion is supported by an independent model and approach. The coloured diamonds in Fig. 2 show peak warming as a function of cumulative CO_2 emissions as simulated by different versions of the Hadley Centre Simple Climate-Carbon-Cycle Model (HadSCCCM1)[10] for a subset of these 250 containment scenarios. Different colours show the impact of adjusting HadSCCCM1 parameters to fit the behaviour of the eleven coupled Earth System Models (ESMs)[15] in the Coupled Climate Carbon Cycle Model Intercomparison (C^4MIP) experiment[16]. The fit becomes less reliable for temperatures more than 0.5 °C above the range simulated by the corresponding C^4MIP simulation: hence diamonds are plotted only where peak warming is inside this range. Again, symbols corresponding to each particular ESM fall close to a single line: peak warming is independent of the shape of the emissions path and depends only on the cumulative total.

This insensitivity to the timing of future emissions suggests we can define the Cumulative Warming Commitment (CWC) as the peak

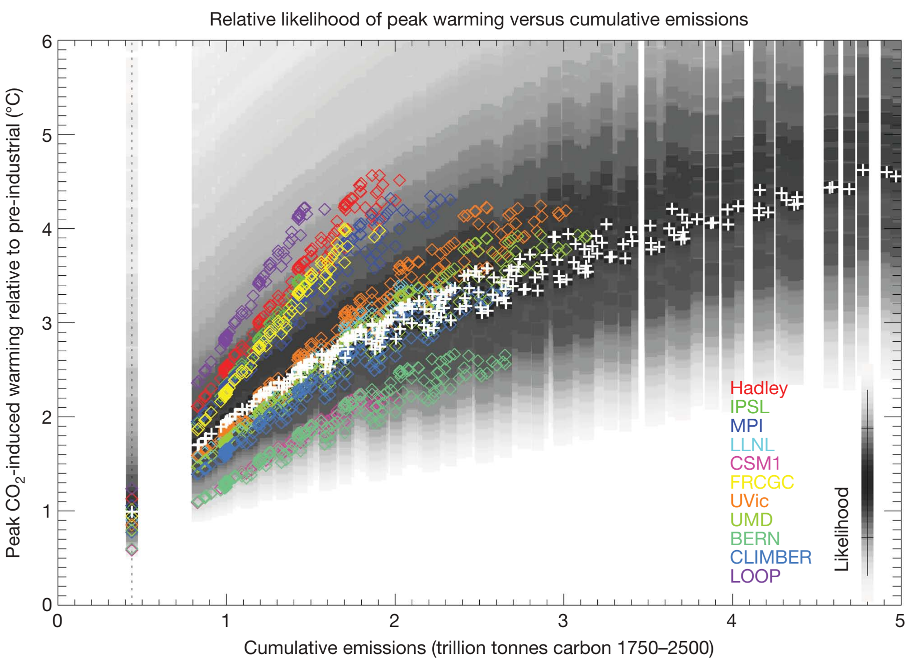

Figure 2 | Peak CO_2-induced warming as a function of total cumulative emissions 1750–2500 for 250 idealized emission scenarios. (A subset is plotted as black lines in Fig. 1a.) White crosses correspond to best-fit values of simple climate model parameters, with each cross corresponding to a single scenario. Grey shading shows relative likelihood of other parameter combinations, plotted in order of increasing likelihood, showing the uncertainty in peak warming arising from parameter uncertainty in the simple model. Coloured diamonds show responses of the HadSCCCM1 model with parameters fitted to ESMs in the C^4MIP experiment, with colours indicating the corresponding ESM. Diamonds are plotted only where temperatures remain within 0.5 °C of the range of the tuning data set (the SRES A2 scenario) to ensure a valid emulation. Bar and symbols at 0.44 Tt C show peak warming assuming zero emissions after 2000. Likelihood scale bar as in Fig. 1b.

warming response to a given total injection of CO_2 into the atmosphere following our best estimate of anthropogenic emissions to date and any future emissions pathway that is smooth, positive and ends in exponential decline. CWC provides a simple measure of climate system response to scenarios in which CO_2 concentrations peak and decline. Unlike ECS, CWC relates emissions right through to temperature, so a range on CWC also incorporates uncertainty in the carbon cycle.

The coloured diamonds in Fig. 2 suggest that the ratio of CWC per trillion tonnes of carbon emitted, or normalized CWC, is approximately constant across the range of responses over which we can calibrate HadSCCCM1 against the C^4MIP ensemble (the lines are nearly straight), although it does depend on which member of the C^4MIP ensemble we emulate. The white crosses generated by the simple model suggest that this ratio declines slightly for cumulative emissions exceeding 2 Tt C. For the highest scenarios, emissions continue beyond 2500 and all results for high emission totals should be treated with caution: warmer temperatures increase the likelihood of strongly nonlinear feedbacks in the climate system[17] that might be represented only in more comprehensive models[18].

Figure 3 shows an analysis of uncertainty in CWC for the specific case of 1 Tt C total anthropogenic emission of CO_2. The 49 solid red and orange curves (superimposed and almost indistinguishable) show 'likelihood profiles'[19] for peak warming response to the red and orange containment scenarios plotted in Fig. 1a, all of which represent cumulative emissions over 1750–2500 that fall within 1% of 1 Tt C. These show the relative likelihood of the most likely versions of the simple climate model out of the subset that gives the values of peak warming shown on the horizontal axis, where likelihoods are computed from the constraints detailed in Supplementary Figs S1 and S2. The overall best-fit (most likely) value of the 1 Tt C CWC is 2 °C, and the 5–95% confidence interval (given by the range over which likelihoods exceed the corresponding threshold[19]) is 1.3–3.9 °C, again independent of which scenario is used to estimate it. The black dotted curve shows the likelihood profile for peak warming in response to the '490 p.p.m. stabilization scenario': the higher emissions in this scenario after 2070 have little impact on the most likely peak warming (they prolong the peak rather than raising it), but they double the likelihood of warming in the 3–6°C range because CO_2 levels and temperatures continue to rise in more sensitive versions of the model.

Coloured symbols in Fig. 3 show CWC under these 49 1 Tt C containment scenarios predicted by HadSCCCM1 emulating the C^4MIP ESMs. The horizontal spread of each set of coloured symbols is small, reiterating that CWC does not depend on the shape of the emission pathway. The variation in emission pathway is illustrated by the vertical position of coloured symbols, showing the fractional reduction in emissions from 2010 to 2050 (right axis) for each of the 49 scenarios. The large vertical spread shows that very different emission pathways with the same cumulative total give the same peak warming: reductions by 2050 only matter insofar as they affect the total CO_2 released.

The black horizontal error bar in Fig. 3 shows a 5–95% Bayesian posterior probability interval for 1 Tt C CWC estimated from an additional independent model and approach detailed in ref. 20 using their representative distribution for climate system properties and our benchmark scenario. Corresponding intervals for the other 48 1 Tt C containment scenarios are almost identical, providing further evidence that the timing of emissions has no impact on CWC. The lower bound is consistent with the other two approaches detailed here. The upper bound is lower primarily because the posterior upper bound on past CO_2-attributable warming implied by ref. 20, although consistent with typical inter-model ranges for Transient Climate Response[1], is lower than the upper bound used to constrain the simple model, which is more consistent with observationally constrained confidence intervals for the transient response[1,14,21].

The need to limit the total amount of carbon dioxide released into the atmosphere has been noted before[4,22–24]: the concept of CWC

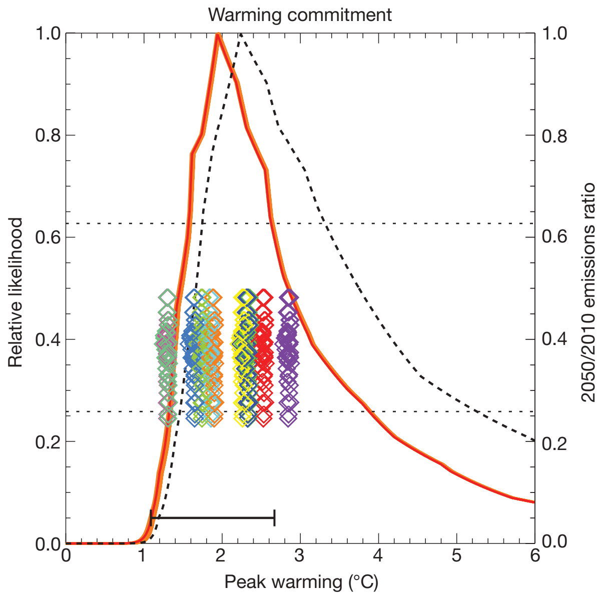

Figure 3 | Warming commitment for selected scenarios shown in Fig. 1a. **Red and orange curves (superimposed) show likelihood profiles for cumulative warming commitment (CWC) under 49 scenarios with total emissions within 1% of 1 Tt C estimated with the simple climate-carbon-cycle model; dotted black curve shows likelihood profile for peak warming under '490 p.p.m. stabilization' scenario. Horizontal dotted lines show thresholds for the 17–83% and 5–95% confidence intervals[19]. The horizontal location of coloured symbols shows corresponding 1 Tt C CWCs predicted by HadSCCCM1 fitted to the ESMs in the C^4MIP ensemble. The vertical location and right-hand axis shows fractional decrease in emissions 2010 to 2050 for each of the 49 emissions scenarios. Solid error bar shows 5–95% Bayesian posterior probability interval (1.1–2.7 °C) for 1 Tt C CWC based on an independent model and approach[20].**

could provide the scientific basis for such limits. Because of its emissions path independence, CWC is a relatively simple quantity for policy discussions[25]. It is also easier to constrain with observations than either the ECS or the emissions required to achieve a given stabilization target. The CWC is closely related to the response to a pulse injection used to define the Global Temperature Potential (GTP)[26,27] and to the Zero Emissions Commitment (ZEC)[18,28], or additional warming that occurs after a sudden and complete cessation of emissions. GTP is defined for a particular timescale and background scenario, so CWC may be thought of as a 'peak GTP' averaging over scenarios. If we assume CWC is linear in cumulative emissions, then the sum of the CO_2-attributable warming in 2000 (0.85 °C with a 5–95% range of 0.6–1.1 °C) and the ZEC in 2000, both divided by best-guess cumulative emissions to 2000 (0.44 Tt C), could provide an estimate of normalized CWC. If we could further assume that the ZEC were negligible, then the first term alone, which corresponds to the 'Carbon-Climate Response' of ref. 25 and is independent of our simple models, implies a best-guess normalized CWC of 1.9 °C per TtC with a 5–95% range of 1.4–2.5 °C per TtC.

Hence, the asymmetry in our full range for CWC (Fig. 3) primarily arises from the possibility of a substantial ZEC. This emerges in our simple models because both CO_2 and temperatures take many decades to fall after emissions cease even for values of ECS around 3 °C, consistent with results from some more complex models[4,18,28,29]. With the longer response times associated with higher, but still not particularly unlikely, values of ECS (for example, 4.5 °C), temperatures can rise substantially even after emissions are set to zero. Hence we argue that CWC allowing for a non-zero ZEC provides a more conservative basis for policy than the CWC neglecting ZEC, as proposed by ref. 25, unless further research rules out a substantial ZEC (in which case the upper bound on CWC would fall considerably). Reducing uncertainty in past warming attributable to greenhouse gases would also reduce uncertainty in CWC[21,30], but similar-magnitude reductions in uncertainty in ocean heat uptake[30] and long-term carbon cycle properties have less impact (see Supplementary Table and Supplementary Discussion). We can therefore expect uncertainty in CWC to decline as the attributable warming signal strengthens (results here only use data to 2000).

CO_2-induced warming only equals total anthropogenic warming if the net effect of non-CO_2 anthropogenic climate forcing agents is relatively small. This may be the case at present, but it is unlikely to remain so. Another study[20] argues that non-CO_2 forcing reduces the budget of CO_2 emissions consistent with a best-guess total anthropogenic warming of 2 °C to just under 0.4 Tt C for the 2000–2050 period, compared with a budget for this period of 0.4–0.5 Tt C in the scenarios that we find give a most likely warming of 2 °C due to CO_2 alone. The balance of warming and cooling by non-CO_2 climate drivers is, however, strongly scenario-dependent. Defining a timescale- and scenario-independent method of combining the impact of short- and long-lived climate forcing agents is impossible[27] because emission rates determine the impact of agents with atmospheric lifetimes shorter than a few decades (the thermal response time of the climate system), whereas cumulative emissions drive the impact of CO_2. CO_2 emission rates, within the same cumulative total, have little impact on projected warming. A simpler policy framework might therefore be to limit emission rates of shorter-lived agents to avoid dangerous rates of warming and to use the concept of CWC to limit cumulative emissions of CO_2 (and other very-long-lived agents) to avoid a dangerous total warming commitment.

METHODS SUMMARY

We generate idealized carbon dioxide emission scenarios by continuously varying the fractional rate of change in emissions to give a smooth transition from exponential growth to exponential decline: see Supplementary Fig. S3a. With the exception of the coloured symbols in Figs 2 and 3, all results are based on a simple coupled climate carbon-cycle model detailed in the Supplementary Information with five free parameters: climate sensitivity; ocean thermal diffusivity; ocean/biosphere carbon uptake diffusivity; rate of advection of carbon into the deep ocean; and feedback parameter for carbon released by surface warming. These are subject to five constraints: warming attributable to greenhouse gases over the twentieth century[21]; effective ocean/troposphere heat capacity[14,30]; observed net airborne fraction over the 1960–2000 period[31]; contribution of temperature–carbon-cycle feedbacks to net airborne fraction 1750–2100, based on the C^4MIP ensemble[16]; and rate of uptake of carbon into the deep ocean based on current ESMs[29]. Parameters are varied at random and the likelihood of each parameter combination is evaluated as the product of the likelihoods with respect to the individual constraints normalized to unity at the best-fit value. Relative likelihoods can then be plotted against any variable simulated by the model, and the outline, or likelihood profile[19], evaluated against standard thresholds to give confidence intervals. The grey-shaded points in Figs 1 and 2 are plotted in order of increasing likelihood to visualize the evolution of the likelihood profile as a function of time or total CO_2 emissions. The coloured symbols in Figs 2 and 3 represent 11 versions of the HadSCCCM1 model[10,15] fitted to the ESMs in the C^4MIP study[16], with the ESM name indicated by the legend in Fig. 2. The spread illustrates the range of behaviour of current ESMs but it is not a comprehensive measure of model uncertainty.

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

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