Current level and rate of warming determine emissions budgets under ambitious mitigation

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Summary

Some of the differences between recent estimates of the remaining budget of carbon dioxide (CO_2) emissions consistent with limiting warming to 1.5°C arise from different estimates of the level of warming to date relative to pre-industrial conditions, but not all. Here we show that, for simple geometrical reasons, the combination of both the level and rate of human-induced warming provides a remarkably accurate prediction of remaining emission budgets to peak warming across a broad range of scenarios, if budgets are expressed in terms of CO_2-forcing-equivalent emissions. These in turn predict CO_2 emissions budgets if (but only if) the fractional contribution of non-CO_2 drivers to warming remains approximately unchanged, as it does in some ambitious mitigation scenarios, indicating a best-estimate remaining budget for 1.5°C of about 22 years' current emissions with a 'likely' (1-standard-error) range of 13-32 years. This provides a simple, transparent, and model-independent metric of progress towards an ambitious temperature stabilisation goal that could be used to inform the Paris Agreement stocktake process. It is less applicable to less ambitious goals. Alternate definitions of current warming and scenarios for non-CO_2 drivers give lower 1.5°C budgets. Lower budgets based on the MAGICC simple modelling system widely used in Integrated Assessment Studies reflect its relatively high simulated current warming rates.

Recent discussion[1,2,3,4] of the "carbon budget" to limit warming to below 1.5°C relative to pre-industrial levels highlights the impact of different geophysical constraints on emissions consistent with ambitious mitigation goals, including the definition of "preindustrial",[5] current level of warming,[6] committed warming due to past emissions,[7] interpretation of "exceedance",[8] and contribution of non-CO_2 forcing.[9,10] Many methods compute remaining carbon budgets as a residual, calculating an emission budget relative to some reference period and then subtracting estimated emissions since that time, which does not make optimal use of proximity to the target temperature. Differences in the estimated current level of warming explain discrepancies between budgets based on full-complexity climate models, but not between these budgets and those based on the MAGICC simple modelling system[11,12] which, by expressing temperatures relative to a recent reference period, simulates a current level of warming close to that observed. This has led to the suggestion[13] that the entire carbon budget concept is too uncertain to be relevant to very ambitious mitigation scenarios, and attention should focus instead on the pathway to achieving net zero emissions. This seems paradoxical, because the remaining Threshold Exceedance Budget[14] (TEB, or emissions to the time a temperature threshold is crossed) might be expected to become more, not less, certain as temperatures approach 1.5°C, being determined by the current rate of emissions and time remaining before the threshold is crossed, which in turn is determined by the current level and rate of human-induced warming.[15] Focussing attention on the current climate trajectory might therefore provide a simple metric of progress[16] approaching a temperature stabilisation goal[17] that becomes increasingly accurate as that goal is approached.

Since the proportionality of cumulative emissions to warming has only been established for CO_2, the existence of multiple forcing agents complicates estimates of emission budgets. One simple assumption is to calculate budgets conditioned on the assumption that the fractional contribution of non-CO_2 drivers to human-induced warming remains unchanged, allowing the proportionality between cumulative CO_2 emissions and CO_2-induced warming to be applied also to total anthropogenic warming.[18,19] Although currently available scenarios show a broad range of changes in this fraction, some of the most ambitious mitigation scenarios[20] show little change between the mid-2020s and peak warming, as reduced forcing by cooling aerosols is balanced by other reductions in short-lived climate forcers[21] (see Fig. S2c in the Supplementary Online Material, SOM). The scenario-dependence of this fraction should decline as peak warming is approached simply because less time would be available for it to change. A more comprehensive approach is to account for non-CO_2 drivers using CO_2-forcing-equivalent (CO_2-fe) emissions[22,23] that, by construction, yield the same temperature response as the corresponding emission of CO_2.

A contentious issue in any discussion of ambitious mitigation goals is the current level of warming. Here we primarily use a dataset and definition of pre-industrial consistent with the IPCC 5th Assessment Report (AR5) and guidance[24] (specifically the statement "climate-related impacts are prevalent at the current degree of warming of 0.85°C above the pre-industrial level"; this refers to total, not human-induced warming, but the natural contribution is small[25]) given to the negotiators of the Paris Agreement,[26] while also showing the implications of alternate definitions.[27] Any estimate of human-induced warming is subject to the caveat that internal variability may be correlated with the expected responses to external climate drivers, but there is no evidence for a systematic bias in estimates based, as here, on the past century as a whole (see Fig. S4 in the SOM).

Simple expressions for remaining emissions budgets under ambitious mitigation

Cumulative CO_2 emissions are proportional to CO_2-induced warming,[28,29] with less than 10 years' committed warming "in the pipeline" due to past CO_2 emissions.[30] This proportionality can be generalised to multi-forcing-agent pathways using CO_2-forcing-equivalent (CO_2-fe) emissions (the amount of CO_2 emissions that would give an identical radiative forcing pathway as a given multi-forcing-agent scenario)[22,23,31,32]. Total cumulative CO_2-fe emissions over a multi-decade period t_0 to t_1 are closely proportional to total human-induced warming ΔT over that period, because CO_2-fe behaves, by construction, like CO_2.[33] In this paper, CO_2-fe emissions are computed by inverting a simple carbon cycle model, but a simple heuristic approximation may be helpful: the contribution of non-CO_2 climate drivers to cumulative CO_2-fe emissions between t_0 and t_1 is approximately proportional to the net change, ΔF, in average non-CO_2 radiative forcing between the a 1-2 decade period prior to t_0 and the corresponding period prior to t_1. For slowly-varying forcing, the length of this averaging period is immaterial, and the approximation breaks down for sub-decadal changes.

Due to their definition, past CO_2-fe emissions also entail little committed warming, although socio-economic commitments to high future CO_2-fe emissions may exist due, for example, to increasing methane emissions or reducing emissions of aerosol precursors, driven by non-climate-related constraints on diet or air quality.[10] Hence:

$$\Delta T \equiv \int_{t_0}^{t_1} T'(t)\, dt = r\int_{t_0}^{t_1} E^{\mathrm{fe}}(t)\, dt \approx r\int_{t_0}^{t_1} E(t)\, dt + r\alpha\Delta F, (1)$$

where ΔT is the change in human-induced warming between t_0 and t_1, $T'(t)$ is the time rate of change of human-induced warming (we use primes to refer to time rates of change throughout, and Δ to refer to changes), $E^{\mathrm{fe}}(t)$ and $E(t)$ are the annual rates of CO_2-fe and CO_2 emissions respectively, r is the applicable Transient Climate Response to cumulative CO_2 Emissions (TCRE), and the constant of proportionality α is approximately 1200 $GtCO_2/(Wm^{-2})$ for representative mitigation scenarios.[33] If t_1 is the time at which temperatures peak, then $T'(t_1) \equiv 0$, allowing us to introduce an "adaptation/mitigation timescale", which we define as $\rho \equiv \Delta T / T'_0$, under ambitious mitigation (we use a subscript 0 to refer to the present-day value of a quantity throughout). This represents the threshold crossing time for temperatures to increase by ΔT if the current warming rate continues (constant $T' \Rightarrow \Delta T = T'_0(t_1 - t_0) \equiv T'_0\rho$ from (1)); the time available to halve the warming rate under a linear decline in $T'(t)$ that limits future warming to ΔT (a quadratic temperature stabilisation profile); or the required decay time under exponential stabilisation (see schematic Fig. S1 in the SOM). Note that for every year's delay in reducing emissions, as long as warming continues at the current rate, ρ falls by one year, and hence the time remaining to reduce the warming rate linearly to zero to meet any given temperature stabilisation goal (2ρ) falls by two years.[16]

The timescale ρ also determines remaining emission budgets. For CO_2-only scenarios ($\Delta F \equiv 0$), this is intuitively clear: if CO_2 emissions continue at their current rate, $E(t) = E_0$, and the TCRE r is constant, then temperatures will also increase at a constant rate $T_0' = rE_0$, and so the TEB for an additional ΔT ($\Delta T = r \int E_0 dt = r \times \mathrm{TEB}$) of warming is $\mathrm{TEB} = E_0 \rho$. Under a linear or exponential decline in emissions (and correspondingly declining warming rate) defined as above, this is also the budget to peak warming. Crucially, as the threshold is approached, and the rate of emissions falls, ρ may be less uncertain than the TCRE itself, which is formally defined in terms of the response to a hypothetical (relatively high) emissions scenario, and hence needs to account for the possibility of r changing over time due, for example, to changing carbon cycle feedbacks.[34] These feedbacks are less likely to change over a small number of decades as temperature approaches stabilisation. The largest differences between TEBs and budgets to peak warming emerge when TEBs are calculated from scenarios that are still warming rapidly as they pass the threshold. If the TEB is continuously recalculated as warming rates decline, it must eventually converge on the actual budget to peak warming. Committed warming due to past CO_2 emissions also falls as the CO_2-induced warming rate declines.

Since the temperature response to CO_2-fe emissions is, by construction, identical to the response to the same emissions (both amount and time-history) of CO_2, the current rate of CO_2-fe emissions $E_0^{\mathrm{fe}} = T_0'/r$, where T_0' refers to the current rate of warming due to all anthropogenic forcings combined, and the remaining CO_2-fe emissions budget for a further $\Delta T = r\int E^{\mathrm{fe}}dt = r\ \times\ \mathrm{TEB}^{\mathrm{fe}}$ of warming is:

$$\mathrm{TEB}^{\mathrm{fe}} = \int_{t_{\mathrm{now}}}^{t_{\mathrm{peak}}} E^{\mathrm{fe}}(t)\,dt = \frac{E_0^{\mathrm{fe}}\Delta T}{T_0'} \equiv E_0^{\mathrm{fe}}\rho. (2)$$

Note that, as in the CO_2 only case, this represents the TEB assuming constant emissions, or the budget to peak warming assuming linearly or exponentially declining CO_2-fe emissions. Furthermore, since $T_0' \approx r(E_0 + \alpha F_0')$, where T_0' is the current rate of total anthropogenic warming and F_0' is the current rate of change of non-CO_2 anthropogenic forcing (in W/m^2/year), then

$$\mathrm{TEB} = \int_{t_{\mathrm{now}}}^{t_{\mathrm{peak}}} E(t)\,dt \approx (E_0 + \alpha F_0')\frac{\Delta T}{T_0'} - \alpha\Delta F \leq \frac{E_0\Delta T}{T_0'} \equiv E_0\rho, (3)$$

where $E(t)$ and E_0 refer to CO_2 emissions and the inequality holds provided the fractional contribution of non-CO_2 forcing to total human-induced warming is either unchanged or increases in the future. This fraction is currently increasing[32] (since $F_0' > E_0/\alpha$), but stabilises after the mid-2020s in a number of ambitious mitigation scenarios (see Fig. S2c in the SOM).

Fig. 1a illustrates these points in an idealised quadratic approach to 1.5°C (black solid line), corresponding to a linear decline in total and CO_2-induced warming rates (Fig. 1b) and CO_2-fe and CO_2 emission rates (black and red dotted lines, right axes). Black and red solid lines in Fig. 1 correspond to best-estimate total anthropogenic and CO_2-induced warming up to 2017 estimated following ref. 10 and then computed using the FAIR simple climate model[35] from linearly declining CO_2-fe and CO_2 emissions. This assumes net non-CO_2 forcing remains proportional to CO_2 forcing as CO_2 emissions decline (so black and red lines decline together in panel b), stabilizing at $1Wm^{-2}$ at the time of peak warming (see Fig. S2b). The thin cyan lines show warming and warming rates in the AR5 WG3 scenarios[36] computed using the MAGICC simple climate model,[11] median response, retaining only scenarios with temperatures peaking before 2100 and consistent with 2016 CO_2 emissions and rate of change of non-CO_2 radiative forcing. One reason for the differences between MAGICC-based carbon budgets[12,36] and more recent estimates, both constrained to a similar level of current warming, is immediately evident: these MAGICC-simulated scenarios are warming, on average, by 0.25-0.32°C/decade at present due to a combination of high CO_2 airborne fraction, recovery from past low non-CO_2 radiative forcing and a relatively high Transient Climate Response. None of these are inconsistent with currently-accepted ranges of these quantities, but together they give, for a median climate response, a simulated median current rate of warming T_0' in the top tercile of the distribution of current warming rates estimated by ref. 15, and above the 0.3-0.7°C over 30 years of the AR5 near-term forecast[37] (grey shading).

Since expressions (2) and (3) are independent of the climate response provided the TCRE, r, remains unchanged, we can use this MAGICC ensemble[36] to test the validity of these expressions for remaining TEBs across a broad range of mitigation scenarios. Fig. 2 shows remaining cumulative emissions budgets to the time of peak warming plotted against predicted budgets calculated using MAGICC-simulated levels and rates of warming (cyan lines in Fig. 1) in 2020 (filled dots) and 2035 (open dots). Predicted remaining CO_2 budgets generally satisfy the inequality (3). Filled dots below the 1:1 line in Fig. 2a indicate the fractional contribution of non-CO_2 forcing increases relative to CO_2 forcing in most mitigation scenarios. As we approach peak warming, non-CO_2 forcing converges to its value at the peak, so ΔF in equation (1) declines and the open circles are closer to the 1:1 line. When non-CO_2 forcing is expressed as CO_2-fe emissions (Fig. 2b), all scenarios lie close to the 1:1 line, and closer still if temperatures are recalculated from CO_2 emissions and non-CO_2 forcing using the FAIR simple climate model (grey dots). Fig. 2c shows predicted CO_2 budgets to the time of peak CO_2-induced warming computed using MAGICC and FAIR, confirming that (3) becomes an approximate equality in the CO_2-only case ($\Delta F \equiv 0$). Departures from the 1:1 line in Figs. 2b and 2c indicate that the TCRE implied by the current rate of emissions and warming is different from the TCRE implied by the model-simulated budget to peak warming. Neither MAGICC nor FAIR is constrained to use a constant TCRE, so some discrepancies are expected, but these decline as peak warming is approached (predictions from 2035 are closer to the 1:1 line).

Estimating the current required rate of emissions reduction

The key metric, $\rho = \Delta T / T_0'$, accurately predicts not only the timescale over which warming rates need to be reduced to limit future warming to ΔT under a broad range of mitigation scenarios, but also the number of years of current emissions in remaining budgets to peak warming. Fig. 3 shows estimates of the current level and rate of human-induced warming from a range of observational and model sources, plotted over isolines of ρ for ΔT limiting remaining warming to 1.5°C. Estimating human-induced warming from the HadCRUT4 observational ensemble[38] (median indicated by orange diamond, distribution by greyscale histogram) we estimate that, to limit warming to 1.5°C, both the rate of anthropogenic warming and the rate of CO_2-fe emissions will have to fall, on average, by 4% per year from 2017 (median estimate, with a 17–83% "likely" range, approximating one-standard-error, of 3–8% per year), equivalent to a linear decline to zero over 45 (25–64) years, consistent with the linear decline to 2060 shown in Fig. 1b. If (but only if) the fractional contribution of non-CO_2

forcing to future warming does not substantially change (as is approximately the case in the scenarios considered by refs. 1-3, and the zero ΔF case of ref. 4), then these required rates of decline also apply to CO_2 emissions. Under this assumption, for a two-in-three chance of limiting warming to 1.5°C we find a remaining budget of 18 years' current emissions from 2017 (red line), which is broadly consistent with CO_2 budgets of refs. 1-4. Note that ΔT and T_0' are not independent, as is clear from the shape of the grey confidence region.

An advantage of this presentation is that is makes the implications of alternative estimates of the current state of the climate system very transparent. For example, Berkeley Earth[27] (the temperature reconstruction showing the highest level of present-day human-induced warming – green diamond in Fig. 3) indicates a smaller emissions budget for 1.5°C than HadCRUT4. If, however, the long-term temperature goal of the Paris Agreement is interpreted relative to the decade 2006-2015, which in turn was 0.84-0.89°C warmer than 1850-1900 in the datasets used in AR5, consistent with guidance given to the UNFCCC on the "current level of warming of 0.85°C" in 2015[24], the difference between Berkeley Earth and HadCRUT4 estimates is reduced (open diamonds). An alternate, forcing-independent, method[39] of estimating the current warming rate, removing known sources of internal variability rather than regressing onto expected responses to external forcing, provides a consistent estimate of the recent secular warming rate (0.18 (±0.04) °C/decade for 1979-2017, not shown on Fig. 3 but see Fig. S4 in the SOM) on the assumption this is entirely anthropogenic. This approach also provides no evidence that interdecadal modes of variability such as the Pacific Decadal Oscillation introduce a low bias into current estimates of anthropogenic warming.

Many CMIP5 general circulation models (red/blue dots, obtained simply by smoothing the model output, hence also making use of model-simulated near-term future temperatures in computing trends) show both high present-day levels and rapid rates of warming. This is consistent with human-induced warming estimated from these models in the same way that it has been estimated from observations (see Fig. S3 in the SOM) providing a 'perfect model' check on that calculation, and also with the fact that anthropogenic forcing dominates current warming in these simulations. The locations of these dots are consistent with small remaining CO_2 emissions budgets if estimated[12] relative to 1870, but inconsistent with the histogram of uncertainty in these quantities derived from HadCRUT4, and with the 2017 level and rate of warming implied by predicted near-term warming relative to 1986-2005 in ref. 37 (pink cross). Simulations of the MAGICC simple climate model (cyan dots – median climate response) show present-day rates of increase in human-induced warming substantially higher than the central value of the HadCRUT4-based attribution analysis. If warming relative to pre-industrial is interpreted consistently with guidance given to the UNFCCC, these simulations might be better interpreted as providing carbon budgets giving a probability closer to two-in-three rather than a close to even chance of temperatures remaining below 1.5°C, based on the observationally-based uncertainty analysis here.

There are four main sources of uncertainty in these estimates of remaining CO_2 budgets. First and most important is the uncertainty in the current level and rate of human-induced warming. The method in ref. 17 accounts for observational uncertainty, internal climate variability (using model-simulated variability) and forcing uncertainty, but these estimates remain contentious. Resulting estimates of the level and rate of human-induced warming are not independent but Fig. 3 shows that their principal axis of co-variability is orthogonal to isolines of ρ so this dependence should not result in an underestimate of uncertainty in ρ. Results are not sensitive to the timescale used to compute human-induced warming rate if (but only if) net anthropogenic forcings vary relatively slowly: sudden changes in short-lived climate forcers might confound this. Fig. 3 uses just one method of estimating human-induced warming rate, although we provide evidence of its reliability in a perfect-model context, and compare with an independent method, in the SOM. Second, the assumption of a constant TCRE to convert ρ into a CO_2-fe emissions budget depends on the assumption that no new carbon cycle feedbacks emerge between now and the time of peak warming, which is only justified for very ambitious mitigation pathways,[40] not for carbon budgets for 2°C or higher levels of warming. Third, although not relevant to CO_2-fe emission budgets themselves, the specification of future non-CO_2 forcing impacts the implications of CO_2-fe budgets for allowable CO_2 emissions: this, however, is not a simple uncertainty, since this forcing depends on future policy as well as Earth system uncertainties. Fourth, substantial uncertainties in current emission rates, particularly from land-use change, affect the conversion of ρ into an absolute emissions budget although not for budgets expressed in terms of "years of current emissions." The impact of committed warming after CO_2-fe emissions reach zero[41] is negligible provided CO_2-fe emissions are brought to zero over a timescale longer than a decade (the time to peak warming response to a pulse injection of CO_2), so for values of ρ shorter than a decade, this method would also break down. The choice of dataset and definition of "pre-industrial" also has an impact, although once a choice has been made, remaining emissions budgets would evolve predictably, so this source of ambiguity is less relevant provided a consistent definition is adopted.

Conclusions

We have shown that a simple predictor of remaining carbon budgets can be constructed from quantities that can be inferred from observed climate change to date. This method can be used to predict remaining CO_2-fe emissions budgets for retaining warming below a given threshold under the most ambitious mitigation pathways, and provides an indication of CO_2-only emissions budgets, on the assumption of only small deviations in the future fractional contribution of non-CO_2 forcing from the present-day fraction, which is only achieved under the most ambitious current scenarios for non-CO_2 mitigation. The key quantities determining the emission reductions required to stabilize temperatures at any given level are the current level and rate of global average human-induced warming. Current observations of global temperature allow a range of these quantities, and the timescale $\rho = \Delta T / T_0'$, together with different scenarios for future non-CO_2 mitigation, largely accounts for differences between estimates of remaining carbon budgets for ambitious temperature goals. This demonstrates the need to reduce uncertainties in, and improve the consistency of, methods for estimating human-induced warming and its rate of increase in the context of regular stocktakes of progress towards the long-term temperature goal of the Paris Agreement.

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Author Contributions

NL, RM & MRA conceived the study; NL produced all figures except S4; KH provided updated estimates of human-induced warming and performed the analysis generating figure S4; SJ contributed code for the calculation of CO2-fe emissions and EG helped with the analysis and checking of the IIASA MAGICC simulations. NL and MRA wrote the paper, with all authors contributing.

Figure Captions

Figure 1: **Emissions and temperatures in a 1.5°C stabilization scenario.** Orange and green lines in panel a show observed global average temperature increase relative to 1850-1900 from the HadCRUT4 and Berkeley temperature datasets. Black and red solid lines show anthropogenic and CO_2-induced warming to date relative to 1875, extended by reducing CO_2 emissions linearly to zero in 2060 and stabilizing non-CO_2 forcing at 1 W/m^2 over the same time-period. Black error bar shows 5-95% range of estimated anthropogenic warming in 2017. Dotted black line (right axis) shows

cumulative CO_2-fe emissions diagnosed from total anthropogenic forcing over the full period. Dotted red line shows cumulative CO_2 emissions relative to 1875, observed to 2017, linearly declining thereafter. Thin cyan lines show simulated temperatures from AR5 IIASA database scenarios, MAGICC median response. Panel b shows rates of change of quantities plotted in panel a. Grey shading: AR5 medium-range forecast of 0.3-0.7°C over 30 years from 1986-2005.

Figure 2: **Current level and rate of warming constrain emission budgets to peak warming. a)** Actual CO_2 emission budgets (vertical) to year of peak anthropogenic warming in AR5 scenarios as simulated by the MAGICC simple climate model versus predicted CO_2 budgets (horizontal) using RHS of (3) applied to total anthropogenic warming trajectories from 2020 (filled circles) and 2035 (open circles). Points below (on) the 1:1 line indicate net positive (zero) change in fractional contribution of non-CO_2 forcing in different scenarios. **b)** Actual CO_2-fe budgets to year of peak anthropogenic warming versus predicted CO_2-fe budgets using RHS of (2) applied to total anthropogenic warming trajectory. **c)** Actual CO_2 budgets to year of peak CO_2-induced warming versus predicted CO_2 budgets using RHS of (3) applied to CO_2-induced warming only. Grey dots in panels b and c computed using the FAIR simple climate model. Note the different axis scales.

Figure 3: **Implications of current level and rate of warming for emissions budgets for 1.5°C.** Greyscale 2-D histogram shows HadCRUT4-based distribution for current (2017) human-induced warming and warming rate including observational, internal variability and response-time uncertainties. The legend symbol indicates the shade for a “likely” range; 2/3^{rds} of ensemble members lie in bins of a darker shade than this symbol. Filled orange and green diamonds show best-fit human-

induced warming and warming rate derived from HadCRUT4 and Berkeley datasets. Unfilled diamonds show identical values of present-day warming and warming rate set relative to 2006-2015 mean plus 0.87°C (see Methods). Black solid lines show isolines of required reduction in warming rate or annual CO_2-fe emissions to limit peak warming to 1.5°C, or number of years of 2017 emissions in the remaining 1.5°C CO_2-fe emission budget. Red line shows the required reduction to maintain temperatures "likely below" 1.5°C for the HadCRUT4-based distribution. Small cyan dots indicate the 2017 warming and warming rate for the AR5 WG3 database MAGICC simulations, median response. Blue and red dots show warming and warming rate from the CMIP5 ensemble RCP2.6 and RCP8.5 experiments. Magenta cross indicates the AR5 medium-range forecast of 0.3-0.7°C over 30 years from 1986-2005 plus best-estimate HadCRUT4 warming for 1986-2005 relative to the chosen pre-industrial baseline period of 1850-1900.

Methods

Present-day level and rate of human-induced warming are estimated by a least-squares fit between observations of global mean surface temperature (GMST) and the expected responses to anthropogenic and natural forcings as described in ref. 15 (computed using FAIR, the relevant component of which is identical to the two-time-constant impulse-response model of AR5[42]) relative to the mid-point of the 1850-1900 pre-industrial reference period: HadCRUT4-based best-estimates in 2017 are 1.02°C, increasing at 0.215°C/decade when calculated over the 5-year period 2013-17. This is higher than the central estimate of 0.17°C/decade indicated by the forecast of 0.3-0.7°C over 30 years from 1986-2005 assessed in ref. 37, indicating recent acceleration of human-induced warming due to increasing anthropogenic forcing.

All detection and attribution studies, ref. 15 included, are subject to the caveat that natural modes of variability such as the Pacific Decadal Oscillation (PDO) may project onto the signal of human-induced warming. This possibility is accounted for in uncertainty estimates using model-simulated internal variability, and by fitting temperatures to expected responses to forcing over the past century, not simply to the most recent decades. Ref. 15 demonstrates that the short period of relatively cool years 2011-2014 had little impact on estimated human-induced warming because of this constraint. An empirical decomposition[39] of GMST into trend and known sources of natural variability provides no evidence that temperatures have been persistently below trend outside of that short period (see Fig. S4 in the SOM). The PDO has recently reverted to weakly negative after a strong positive phase, again providing no consistent indication of a bias. Hence although internal variability must be acknowledged as source of uncertainty in human-induced warming, there is no clear evidence that current estimates of human-induced warming based on temperatures over the full past century are systematically biased low.

Ref. 15 uses GMST responses computed using the AR5 two-time-constant impulse-response[42] model and demonstrates that the calculation is insensitive to the specification of the model used and also consistent with responses from much more complex models. More important is the specification of external forcings, particularly anthropogenic, since these determine the recent rate of acceleration. Forcing uncertainties, particularly aerosol-related, are accounted for in ref. 15 following recent assessments, but remain contested. Historical CO_2 emissions are obtained from the Global Carbon Project,[43] and non-CO_2 Effective Radiative Forcing (ERF) from ref. 42, updated.[44] CO_2-induced warming is obtained by assuming the same response to CO_2 forcing as the best-fit anthropogenic response to total anthropogenic ERF.

Future emissions in Fig. 1 are obtained by assuming a linear decline in CO_2 emissions to 2060 and linear reduction in the rate of increase of net non-CO_2 forcing, stabilizing at 1 Wm^{-2} in 2060. Temperatures and emissions for MAGICC simulations are obtained from the AR5 WG3 scenario database, retaining only those in which temperatures peak before 2100 and in which scenario CO_2 emissions and rate of change of non-CO_2 forcing are both within the 5-95% range of observations in 2016 (see Fig. S2 in the SOM). CO_2-fe emissions in Figs. 1 and 2b are diagnosed using the FAIR simple carbon cycle model with parameters tuned to provide 0.87°C mean warming and observed cumulative airborne fraction to 2006-2015 relative to 1850-1900 in Fig. 1 and tuned to reproduce the MAGICC carbon cycle in 2b. CO_2-induced warming in Fig. 2c is computed directly from scenario CO_2 emissions. Levels and rates of warming in CMIP5 simulations in Fig. 3 are computed relative to 1861-80, with 0.02°C added to reflect the offset from 1850-1900 in HadCRUT4, smoothed with a 5-year standard deviation Gaussian kernel. Open diamonds in Fig. 3 correspond to observations expressed relative to the period 2006-2015 plus 0.87°C, being the mean warming to 2006-2015 relative to 1850-1900 in the dataset spanning this period used in AR5 (HadCRUT4), scaled to the linear average trend from 1880-2012 of the three datasets used in AR5 (HadCRUT4, GISTEMP and NOAA), for consistency with the UNFCCC Structured Expert Dialogue. Warming rates are computed using simple first-differences in Figs. 1 and 2, while present day warming rates in Fig. 3 are taken as the average gradient over the period 2013-2017. For the MAGICC median temperature scenarios shown in Fig. 1, this reduces the warming rate versus a simple first-difference by a median value of 0.015 degrees/decade and a maximum of 0.022 degrees/decade.

Model Description

Calculations performed for this study have used the FAIR (Finite Amplitude Impulse Response) simple climate model,[35] a version of the IPCC impulse-response model[42] modified to account for carbon cycle feedbacks giving a much more realistic response to finite-amplitude perturbations. This incorporates a two-box thermal response to radiative forcing, and four carbon pools representing geological, deep ocean, biospheric and ocean thermocline, and rapid biospheric and ocean mixed-layer uptake of atmospheric CO_2. We make use of this model due to its simplicity and transparency, which allows us to invert both its thermal and carbon cycles, to diagnose CO_2-fe emissions for a given temperature or forcing scenario.[32] In addition, we show temperature responses to multiple forcing scenarios calculated using the MAGICC simple climate model,[11] primarily because both this system and these specific warming trajectories are very widely used in the Integrated Assessment Modelling (IAM) community. MAGICC responds very similarly to FAIR to both radiative forcing and CO_2 emissions, but in the set-up used by the IAM community, is run in a “hybrid” mode driven with observed concentrations (normally to 2005) followed by input emissions, accentuating the impact of this model’s relatively high current airborne CO_2 fraction on current warming rates. No inverse version of MAGICC is available for the computation of CO_2-fe emissions. CO_2-induced warming in figure 2c is obtained by providing only CO_2 as an external climate forcer to both the MAGICC and FAIR models with default (median response) parameters. All other MAGICC outputs used were pre-computed and are available from the AR5 WG3 database.

Code Availability

Code used will be available on request to the corresponding author.

Data Availability

GCP CO_2 emissions data used in this study are available at http://www.globalcarbonproject.org/carbonbudget/17/data.htm

MAGICC simulations from AR5 IIASA database scenarios are available at https://tntcat.iiasa.ac.at/AR5DB/dsd?Action=htmlpage&page=welcome

HadCRUT4 warming observation data are available at https://www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html

Berkeley Earth warming observation data are available at http://berkeleyearth.org/data/

Observational forcing data are available at http://www.globalwarmingindex.org/AWI/info_page.html

CMIP5 model output are available at https://esgf-node.llnl.gov/projects/esgf-llnl/

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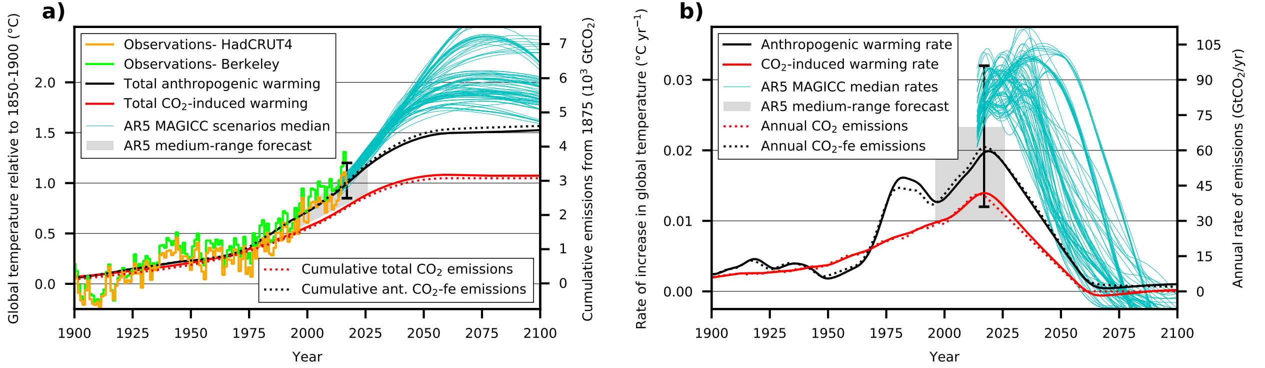
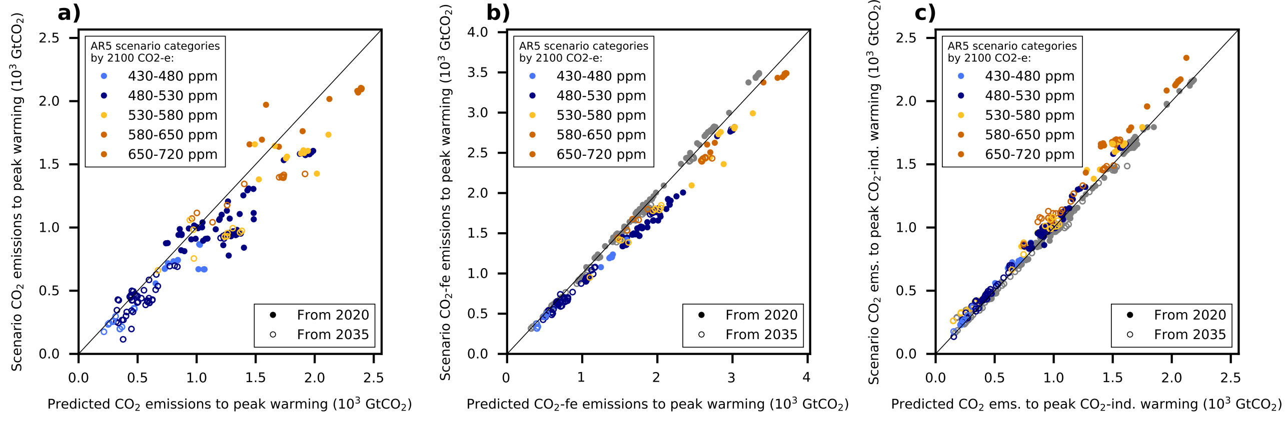
[43] Le Queré, C., *et al*: Global Carbon Budget 2016, *Earth Syst. Sci. Data*, **8**, 605-649 (2016).

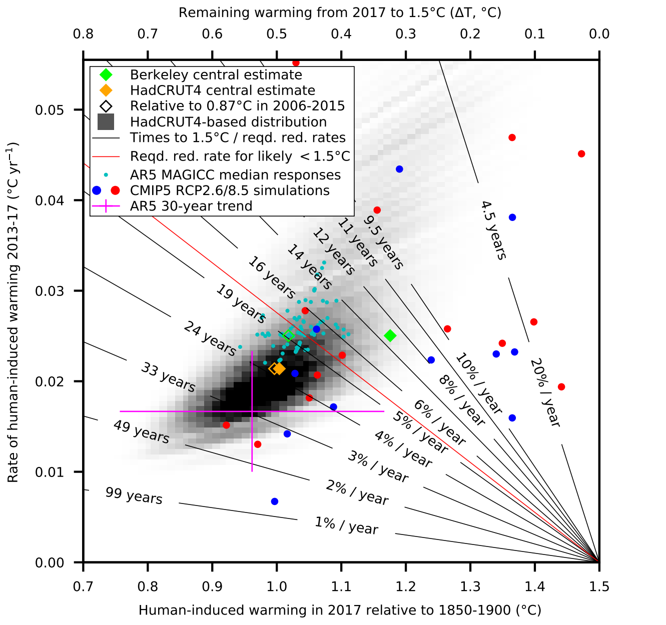
[44] Hoesly, R.M., *et al*, Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the Community Emissions Data System (CEDS), *Geosci. Model Dev.*, **11**, 369-408 (2018).



a)
Observations- HadCRUT4
Observations- Berkeley
Total anthropogenic warming
Total CO2-induced warming
AR5 MAGICC scenarios median
AR5 medium-range forecast
Cumulative total CO2 emissions
Cumulative ant. CO2-fe emissions
Global temperature relative to 1850-1900 (°C)
Cumulative emissions from 1875 (10^3 GtCO2)
Year
b)
Anthropogenic warming rate
CO2-induced warming rate
AR5 MAGICC median rates
AR5 medium-range forecast
Annual CO2 emissions
Annual CO2-fe emissions
Rate of increase in global temperature (°C yr^-1)
Annual rate of emissions (GtCO2/yr)
Year



a)
AR5 scenario categories
by 2100 CO2-e:
430-480 ppm
480-530 ppm
530-580 ppm
580-650 ppm
650-720 ppm
From 2020
From 2035
Scenario CO_2 emissions to peak warming (10^3 $GtCO_2$)
Predicted CO_2 emissions to peak warming (10^3 $GtCO_2$)
0.0
0.5
1.0
1.5
2.0
2.5
b)
AR5 scenario categories
by 2100 CO2-e:
430-480 ppm
480-530 ppm
530-580 ppm
580-650 ppm
650-720 ppm
From 2020
From 2035
Scenario CO_2-fe emissions to peak warming (10^3 $GtCO_2$)
Predicted CO_2-fe emissions to peak warming (10^3 $GtCO_2$)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
0
1
2
3
4
c)
AR5 scenario categories
by 2100 CO2-e:
430-480 ppm
480-530 ppm
530-580 ppm
580-650 ppm
650-720 ppm
From 2020
From 2035
Scenario CO_2 ems. to peak CO_2-ind. warming (10^3 $GtCO_2$)
Predicted CO_2 ems. to peak CO_2-ind. warming (10^3 $GtCO_2$)
0.0
0.5
1.0
1.5
2.0
2.5



Remaining warming from 2017 to 1.5°C (ΔT, °C)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Berkeley central estimate
HadCRUT4 central estimate
Relative to 0.87°C in 2006-2015
HadCRUT4-based distribution
Times to 1.5°C / reqd. red. rates
Reqd. red. rate for likely < 1.5°C
AR5 MAGICC median responses
CMIP5 RCP2.6/8.5 simulations
AR5 30-year trend
4.5 years
9.5 years
11 years
12 years
14 years
16 years
19 years
24 years
33 years
49 years
99 years
20% / year
10% / year
8% / year
6% / year
5% / year
4% / year
3% / year
2% / year
1% / year
Rate of human-induced warming 2013-17 (°C yr⁻¹)
0.00
0.01
0.02
0.03
0.04
0.05
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Human-induced warming in 2017 relative to 1850-1900 (°C)