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Title: Emission budgets and pathways consistent with limiting warming to 1.5℃

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Opening paragraph

The Paris Agreement has opened debate on whether limiting warming to 1.5℃ is compatible with current emission pledges and warming of about 0.9℃ from the mid- 19th-century to the present decade. We show that limiting cumulative post-2015 CO_2 emissions to about 200 GtC would limit post-2015 warming to less than 0.6℃ in 66% of Earth System Model members of the

CMIP5 ensemble with no mitigation of other climate drivers, increasing to 240GtC with ambitious non-CO_2 mitigation. We combine a simple climate-carbon-cycle model with estimated ranges for key climate system properties from the IPCC 5th Assessment Report. Assuming emissions peak and decline to below current levels by 2030 and continue thereafter on a much steeper decline, historically unprecedented but consistent with a standard ambitious mitigation scenario (RCP2.6), gives a likely range of peak warming of 1.2-2.0℃ above the mid-19th-century. If CO_2 emissions are continuously adjusted over time to limit 2100 warming to 1.5℃, with ambitious non-CO_2 mitigation, net future cumulative CO_2 emissions are unlikely to prove less than 250 GtC and unlikely greater than 540GtC. Hence limiting warming to 1.5℃ is not yet a geophysical impossibility, but likely requires delivery on strengthened pledges for 2030 followed by challengingly deep and rapid mitigation. Strengthening near-term emissions reductions would hedge against a high climate response or subsequent reduction-rates proving economically, technically or politically unfeasible.

Main text:

The aim of Paris Agreement is “holding the increase in global average temperature to well below 2℃ above pre- industrial levels and pursuing efforts to limit the temperature increase to 1.5℃ ”[1]. The Parties also undertook to achieve this goal by reducing net emissions “to achieve a balance between anthropogenic sources and removals by sinks of greenhouse gases in the second half of this century”, and hence implicitly not by geo-engineering planetary albedo. Under what conditions is this goal geophysically feasible?

Human-induced warming reached an estimated 0.93℃ (±0.13℃ ; 5-95 percentile range) above mid-19th-century conditions in 2015 and is currently increasing at almost 0.2℃ per decade [2]. Combined with the effects of El Niño and other sources of natural variability, total warming exceeded 1℃ for the first time in 2015 and again in 2016[3]. Average temperatures for the 2010s are currently 0.88℃ above 1861-80, which would rise to 0.93℃ should the y remain at 2015 levels for the remainder of the decade. With few exceptions[4,5], mitigation pathways that could achieve peak or end-of-century warming of 1.5℃ h ave thus far received little attention. Even the “Paris, increased ambition” scenario of ref. 6 results in CO_2 emissions still well above zero in 2100 and hence a low chance of limiting warming to 1.5℃.

Long-term anthropogenic warming is determined primarily by cumulative emissions of CO_2[7–10]: the IPCC 5th Assessment Report (IPCC-AR5) found that cumulative CO_2 emissions from 1870 had to remain below 615GtC for total anthropogenic warming to remain below 1.5℃ in more than 66% of members of the CMIP5 ensemble of Earth System Models (ESMs)[11] (see Fig. 1a). Accounting for the 545GtC that had been emitted by the end of 2014[12], this would indicate a remaining budget from 2015 of less than 7 years' current emissions, while current commitments under the Nationally Determined Contributions (NDCs) indicate 2030 emissions close to current levels[13].

The scenarios and simulations on which these carbon budgets were based, however, were designed to assess futures in absence of CO_2 mitigation, not the very ambitious mitigation scenarios and correspondingly small amounts of additional warming above present that are here of interest. Furthermore, many mitigation scenarios begin reductions in 2010 and are already inconsistent with present-day emissions, complicating the comparison with pledges for 2030.

Updating carbon budgets and scenarios for ambitious mitigation goals

The black cross on Fig. 1a shows an estimate of human-induced warming, which excludes the impact of natural fluctuations such as El Niño, in 2015 (0.93±0.13℃ relative to 1861- 80; 5-95 percentile range) and pre-2015 cumulative carbon emissions (545±75GtC since 1870; 1 standard deviation). While both quantities are individually consistent with the CMIP5 ensemble, in the mean CMIP5 response (coloured lines) cumulative emissions do not reach 545GtC until after 2020, by which time the CMIP5 ensemble-mean human-induced warming is over 0.3℃ warmer than the central estimate for human-induced warming to 2015. In estimating the outstanding carbon budget for 1.5℃, this is an important discrepancy. IPCC-AR5 also calculated the percentiles of the CMIP5 distribution that exceeded given thresholds of warming relative to the average of 1986-2005 (Table 12.3 of ref 14), adding a further 0.61℃ to express these relative to 1850-1900. However, this reference period and the GCM ensemble used in this table are not identical to the ESM ensemble used to derive estimates of the carbon budget, for which a volcano-free reference period is preferred, to focus on human-induced warming. Moreover, since the discrepancy in warming between ESMs and observations only emerges after 2000, expressing warming relative to the 1986-2005 reference period does not entirely resolve it and also does not address the small underestimate in cumulative emissions to date. Fig. 1b shows an alternative analysis of the CMIP5 ensemble to assess the remaining carbon budget for an additional 0.6℃ of warming beyond the current decade, a possible interpretation of ‘pursuing efforts to limit the temperature increase to 1.5°C’ in light of estimated human-induced warming to date. The median response of the CMIP5 models indicates allowable future cumulative emissions (threshold-exceedance budget or TEB[15]) of 223GtC for a further 0.6℃ warming above the 2010-2019 average, and a 204GtC remaining TEB from 2015 to keep warming likely below this value (meaning, by the time cumulative emissions from 2015 reach 204GtC, 66% of CMIP5 models have warmed less than 0.6℃ above the present decade, consistent with the methodology for assessing the 2℃ carbon budget in IPCC-AR5 [16]). Given uncertainty in attributable human-induced warming to date, differences between observational products and true global surface air temperature[17], and the precise interpretation of the 1.5℃ goal in the Paris Agreement (for example, the choice of pre-industrial reference period which temperatures are defined relative to[18]), budgets corresponding to a range of levels of future warming should also be considered – see Table 1 and the Supplementary Information.

TEBs are useful because peak CO_2-induced warming is a function (shown by the grey plume in figure 1) of cumulative CO_2 emissions and approximately independent of emission path, although threshold behaviour, such as sudden carbon release from thawing permafrost, might complicate this relationship[19]. This does not apply to non-CO_2 forcing, which is relatively more important for ambitious mitigation scenarios. The rapid warming from the 2000s to the 2030s in CMIP5 arises partly from strong increases in net non-CO_2 forcing over this period in the driving RCP scenarios, due to simulated rapid reductions in cooling aerosol forcing. It remains unclear whether this increase in non-CO_2 forcing will be observed if future reductions in aerosol emissions occur because present-day effective non-CO_2 forcing is still highly uncertain[20]. Table 2 shows budgets for thresholds of future warming in the CMIP5 ensemble under an RCP2.6 scenario, a stabilisation scenario in which non-CO_2 forcing across the rest of the century remains closer to the 2010-2019 average than in the RCP8.5 scenario. This allows more CO_2-induced warming for the same total, increasing the median TEB of the CMIP5 distribution for an additional 0.6℃ to 303GtC and the 66th percentile to 242GtC.

In many current ambitious mitigation scenarios (e.g. RCP2.6[21], dark blue lines in fig. 2), substantial CO_2 emission reductions begin in 2010, such that both emissions and forcing are already inconsistent with observed climate state and emission inventories to date. The thick dark green lines in Fig. 2 show an amended version of RCP2.6 that is more consistent with current emissions and estimated present-day climate forcing. This scenario, hereafter referred to as RCP2.6-2017, assumes the same proportional rates of change of emissions of both CO_2 and other anthropogenic forcing components as in the standard RCP2.6 scenario from 2010, but with the mitigation start date delayed by 7 years to 2017 (following the RCP8.5 scenario[22] between 2010-2017). This is more representative of a possible mitigation pathway from today: many nations are already planning on policy action to reduce emissions over the 2015-2020 period, in anticipation of achieving their NDC commitments in the future. Total anthropogenic radiative forcing peaks in 2050 (at 3.41 Wm^{-2}) in RCP2.6-2017, as opposed to in 2043 (at 3.00 Wm^{-2}) under RCP2.6. The grey lines represent emissions pathways from the IPCC 430-480ppm scenario category[23,24] but with proportional decreases in radiative forcing also delayed by 7 years to start in 2017.

Figure 2c shows the implications of these scenarios for future warming, evaluated with a simple climate model that reproduces the response of the CMIP5 models to radiative forcing under ambitious mitigation scenarios (Supplementary Material). Like other simple climate models, this lacks an explicit physical link between oceanic heat and carbon uptake. It allows a global feedback between temperature and carbon uptake from the atmosphere, but no direct link with net deforestation. It also treats all forcing agents equally, in the sense that a single set of climate response parameters are used in for all forcing components, despite some evidence of component specific responses[25,26]. We do not, however, attempt to calibrate the model directly against observations, using it instead to explore the implications of ranges of uncertainty in emissions[12], and forcing and response derived directly from the IPCC-AR5, which are derived from multiple lines of evidence and, importantly, do not depend directly on the anomalously cool temperatures observed around 2010. Non-CO_2 forcing and the transient climate response (TCR) co-vary within AR5 ranges to consistently reproduce present-day externally-forced warming (Methods), and as in figure 1b, we quote uncertainties in future temperatures relative to this level.

The limits of the green plume in Fig. 2c show peak warming under the RCP2.6-2017 scenario is likely between 1.24-2.03℃ (1.12-1.99℃ for 2100 warming) given a 2015 externally-forced warming of 0.92℃. The IPCC-AR5 did not propose a 'best-estimate' value of the TCR, but using a central value of 1.6℃ (the median of a log-normal distribution consistent with IPCC-AR5 likely ranges, the typical shape of most reported TCR distributions in ref. 16), RCP2.6-2017 gives a median peak warming of 1.55℃ above pre-industrial (1861-1880 mean) and 1.47℃ in 2100, approximately consistent with as likely as not (50% probability) of warming below 1.5℃ in 2100.

The shaded green bands show the central four probability sextiles of the distribution of responses to RCP2.6-2017 for a log-normal distribution for TCR (see Supplementary Material for alternative distributions). Under RCP2.6-2017, peak warming is likely below 2℃, and well below 2℃ by the end of the century. However, such a scenario cannot exclude a non-negligible probability of peak warming significantly in excess of 2℃, particularly given the possibility of non-linear climate feedbacks for which there is some evidence in more complex GCMs[27].

Emissions in Fig. 2a are diagnosed from radiative forcing in Fig. 2b using a version of the IPCC-AR5 carbon cycle impulse-response function[28], with a minimal modification to account for the change in the impulse response between pre-industrial and 21st century conditions due to atmospheric CO_2 and temperature-induced feedbacks on carbon uptake, as observed in Earth System Models[29]. This simple model reproduces the response of ESMs to ambitious mitigation scenarios (Supplementary Information) including, with best-estimate parameters, near-constant temperatures following a cessation of CO_2 emissions. The temperature response of the UVic Earth System Climate Model (UVic ESCM)[30–32] driven by the diagnosed RCP2.6-2017 emissions scenario and non-CO_2 forcing is shown in Fig. 2c (orange line), which is emulated well by the simple carbon-cycle-climate model with equivalent climate response parameters (thin green line, see Methods). Carbon-cycle feedback uncertainties (see Methods) only have limited scope to influence the allowable emissions under scenarios in which concentrations and temperatures peak at a relatively low level.

Since RCP2.6-2017 represents a scenario with ambitious CO_2 and non-CO_2 mitigation, it currently lies near the lower limit of 2100 anthropogenic forcing available in the literature[4,15], as shown by the grey lines in Figure 2. We have not assumed any additional non-CO_2 mitigation beyond RCP2.6, but uncertainties in mitigation technologies and demand reduction measures decades into the future mean that non-CO_2 mitigation may yet play a larger role than indicated here.

Adaptive mitigation paths and implications for carbon budgets

The Paris Agreement establishes a regime of continuously updated commitments informed by on-going scientific and policy developments and the overarching temperature and emission reduction goal. We therefore re-estimate carbon budgets, accounting for the present-day climate state and current uncertainty in the climate response, and assuming mitigation efforts are perfectly adapted over time to achieve a warming in 2100 of 1.5℃ for a range of possible realisations of the climate response[2,33]. Figure 3a shows a distribution of future temperature trajectories, for different climate responses, that are all consistent with observed attributable warming in 2015 and a smooth transition to 1.5℃ in 2100. The limits of the green plume show temperature trajectories associated with IPCC-AR5 likely ranges for TCR and equilibrium climate sensitivity (ECS), with bands delineating the central four sextiles of the distribution. These temperatures initially follow the responses to the RCP2.6-2017 scenario (the green plumes in Figure 2c) but are then smoothly interpolated over the coming century to the trajectory given by the best-estimate response (see Supplementary Methods). This provides a simple representation of goal-consistent pathways for a range of possible climate responses[34]. In contrast to a scenario-driven, forward-modelling approach (e.g. ref. 6 and Fig. 2), the temperature trajectories in Figure 3a define the scenario, from which corresponding CO_2 emission pathways (Figure 3b) are derived, similar to the temperature-tracking approach used by ref 10. This implicitly assumes that information on the emerging climate response is available and acted upon instantaneously. In reality, both resolving the response and adapting policies will be subject to delay, although the impact can be reduced if policies respond to both observed and decadal predictions of human-induced warming, which are much better constrained than long-term projections of, for example, ECS.

Green bands in Fig. 3b show emissions compatible with the goal-consistent temperature trajectories and climate responses of Figure 3a, computed using the modified IPCC-AR5 impulse-response function with carbon-cycle feedback uncertainty assumed positively correlated with TCR (see Methods). Such an assumption may be pessimistic, but uncertainty in these feedbacks may also be underestimated in CMIP5 – the impact of thawing permafrost, for example, is generally not represented.

Fig. 3c shows cumulative emissions (net carbon budgets) consistent with limiting warming to 1.5℃ warming in 2100 under the climate response uncertainty distribution and these goal-consistent pathways. The median *('as likely as not')* case corresponds to a cumulative budget of 370GtC (1400GtCO_2 - all carbon budgets given to 2 significant figures) from 2015 to 2100, including ~10GtC of net negative emissions in the final decades. Compared to this, higher cumulative CO_2 emissions budgets are associated with lower climate responses and vice versa (hence the ordering of the coloured bands in 3a and 3b). Assuming completely successful adaptive CO_2

mitigation to achieve a warming of 1.5℃ in 2100 (allowing for mid-century temperature overshoots, assuming non-CO_2 forcing following RCP2.6-2017, and imposing no restrictions on the rate of net carbon dioxide removal), the cumulative carbon budget from 2015 to 2100 is unlikely (<33% probability) to be less than 250GtC (920GtCO_2), in good agreement with the 242GtC TEB for the 66th percentile of the CMIP5 distribution for 0.6℃ warming above the 2010-2019 average in the RCP2.6 scenario (Table 2). Conversely, cumulative future emissions from 2015 compatible with a warming of 1.5℃ in 2100 are unlikely to be greater than 540GtC (the top of the 50-67% band in Figure 3c) even under such an idealised perfectly responsive mitigation policy. The relationship between CO_2-induced future warming compatible with the cumulative emissions shown in Fig. 3c is also broadly consistent that expected from the IPCC-AR5 likely range of TCRE (see Fig. S4), which, when combined with varying contributions from non-CO_2 forcing, informs the all-forcing budgets quoted here.

The small difference that varying TCR makes to warming between 2015 and 2030 (Fig. 3a) highlights both the importance of continuous quantifications of human-induced warming in any stock-take of progress to climate stabilization, and the need for a precautionary approach even under an adaptive mitigation regime[34]. Although more progress has been made on constraining TCR than ECS, uncertainties are unlikely to be resolved rapidly. Allowing emissions to rise in the hope of a low climate response risks infeasible subsequent reductions should that hope prove ill founded. Conversely, the risk of “over-ambitious” mitigation is low: the darkest green plume in fig. 3b shows that the difference between a TCR of 1.3℃ and 1℃ has a substantial impact on the allowable carbon budget for 1.5℃, but the probability of a TCR in that range is already assessed to be low. Since IPCC-AR5 a number of studies have suggested an increase in the lower bound on TCR towards 1.3℃ (e.g ref. [25]), whilst others indirectly support a 1.0℃ lower bound through upward revisions of radiative forcing[35,36]. Using a TCR likely range of 1.3-2.5℃ and an ECS likely range of 2.0-4.5℃ , the remaining budget for a 1.5℃ warming would be unlikely greater than 400GtC and unlikely less than 220GtC (see Supplementary Information figure S18).

Discussion and implications for the 'emissions gap'

Much recent policy discussion has centred on the 'emissions gap' between the NDCs emerging from the Paris Agreement and emission scenarios consistent with 1.5℃ and 2℃ [13,37]. The extent of any 'gap' depends on the uncertain climate response; the definition of the Paris Agreement goals; the interpretation, delivery and/or revision of the NDCs, and in particular the technical and/or socio-economic feasibility of subsequent emissions reductions.

Considerable uncertainties are associated with the NDCs themselves[13,38]. Modelling indicates that the NDCs could be consistent with global fossil fuel and land-use change CO_2 emissions in 2030 only slightly above 2015 values[6,13] (lower limit of the brown bar in Fig. 2a and 3b), close to the RCP2.6-2017 scenario. This would imply that if (i) NDCs are fully implemented (including all conditional elements), with plausible values for Chinese emissions in 2030, and (ii) RCP2.6-2017 mitigation rates are maintained after 2030, then the NDCs would still remain inconsistent with future scenarios projected to correspond to a peak warming likely below 2℃ and a 2100 warming as likely as not below 1.5℃. However, a modest strengthening of the pledges corresponding to an approximate 10% reduction in proposed 2030 emissions could achieve consistency with such scenarios. Hence the NDCs as they stand do not necessarily imply a commitment to a fundamentally different approach, such as resorting to solar radiation management (SRM), to achieve a warming of 1.5℃ in 2100 , if the climate response is close to or less than our central estimate and if emissions can be rapidly reduced after 2030. The RCP2.6-2017 scenario involves a smooth transition to slightly negative net CO_2 emissions after 2080, which may require challenging rates of deployment of CO_2 removal (CDR). Figure 3b shows that returning warming to 1.5℃ in 2100 under a higher climate response potentially requires very substantial rates of CDR, which may not be technically feasible or socio-economically plausible.

An additional caveat to assessments of a 2030 “emissions gap” is that most NDCs are formulated in terms of CO_2-equivalent (CO_2-eq) emissions, a composite metric of warming impact of different gases based on Global Warming Potentials (GWPs) from various IPCC reports. It is therefore impossible to assess precisely the 2030 emissions of CO_2 itself that are compatible with these pledges without additional assumptions, because CO_2-eq pledges could be attained through varying combinations of long-lived and short-lived forcer mitigation[39–41]. Separate reporting of long-lived and short-lived greenhouse gases in national pledges would help clarify their long-term implications[41,42].

Aside from scientific uncertainties and the interpretation of the NDCs, a crucial issue is the feasibility of achieving sufficient rates and levels of decarbonisation required by these ambitious mitigation scenarios. Rapid decarbonisation relies on societies being able to swiftly replace existing capital with new investments at massive scales. Inertia within the economic system is an important constraint on realisable mitigation pathways[43]. RCP2.6-like scenarios imply decarbonisation at over 0.3GtC/yr/yr in the 2030s and 2040s – or 4-6% per year sustained for multiple decades. If applied to gross CO_2 emissions, such rates of reduction have historically only been observed globally for short periods, such as in the 1930s Great Recession and the 2nd World War, and regionally in the collapse of the former Soviet Union[44]. Sustained decarbonisation at these rates, and the associated capital displacement (run-down and replacement of fossil-fuel infrastructure), would be historically unprecedented, though the parallel between intentional policy-driven decarbonisation in the future and historical rates remains unclear.

Longer-term deep decarbonisation also relies on many energy system innovations, including development and deployment on an unprecedented scale of renewable energy as well as, as yet undemonstrated, amounts of carbon capture and storage and CDR[45]. Given possible limits to rates of decarbonisation, near-term mitigation ambition and delays in mitigation start dates may strongly influence peak and 2100 warming. The purple dashed lines in Fig. 2 illustrate this point with a simple scenario in which CO_2 emissions reduce linearly (at 0.17GtC/yr/yr, about 0.6GtCO_2/yr/yr) from 2020 in order to achieve approximately the same warming as RCP2.6-2017 in 2100. Under this scenario, maximum rates of decarbonisation are much lower than in RCP2.6-2017, in both absolute and percentage terms, demonstrating the potential advantage of more ambitious near-term mitigation given the risk that subsequent RCP2.6-like rates of decarbonisation may be unachievable.

More ambitious near-term mitigation may be more feasible than previously thought. The rapid growth of global emissions 2000-2013 was dominated by increases in Chinese emissions[46], driven, at least in part, by unprecedented levels of debt-fuelled investment in carbon-intensive industries and capital stock[47]. Sustaining such expansion is likely to be neither necessary (the infrastructure is now built) nor feasible (the debt levels are likely to prove unsustainable)[47]. For these reasons, the possibility that both Chinese and global emissions are at or near their peak[46,48] and could reduce from 2020, seems less far-fetched than it did. This could allow for the required strengthening of the NDCs in the 2020 review towards an RCP2.6-2017 trajectory or beyond, more readily consistent a 1.5℃ goal.

Regular review of commitments is built in to the Paris Agreement. This stocktake should be extended to relate commitments directly to the long-term temperature goal. As human-induced warming progresses, the question must be asked: “Are we on track to reduce net emissions to zero to stabilise climate well below 2℃ as agreed in Paris ”? Regular updates of human-induced warming based on a standard and transparent methodology would allow countries to adapt commitments to the emerging climate response. Our analysis suggests that ‘pursuing efforts to limit the temperature increase to 1.5°C’ is not chasing a geophysical impossibility, but likely requires a significant strengthening of the NDCs at the first opportunity in 2020 in order to hedge against the risks of a higher-than-expected climate response and/or economic, technical or political impediments to sustained reductions at historically unprecedented[34] rates after 2030.

Tables

	Percentiles of CMIP5 models				
Warming above 2010-2019 average (°C)	90%	66%	50%	33%	10%
0.3	80	106	119	142	189
0.4	107	133	155	172	242
0.5	137	168	186	209	299
0.6	164	204	223	250	333
0.7	199	245	256	289	387
0.8	231	279	301	333	438
0.9	274	321	348	376	505
1.0	306	358	382	421	579
1.1	332	395	416	464	653

Table 1: Future cumulative budgets (GtC) from January 2015 for percentiles of the distribution of RCP8.5 simulations of CMIP5 models and various levels of future warming above the modelled 2010-2019 average. Percentiles correspond to the percentage of CMIP5 models that have greater cumulative emissions for the given level of warming.

	Percentiles of CMIP5 models				
Warming above 2010-2019 average (°C)	90%	66%	50%	33%	10%
0.3	89	106	118	133	245
0.4	106	152	173	193	NA
0.5	126	191	214	258	NA
0.6	143	242	303	NA	NA
0.7	170	291	NA	NA	NA
0.8	177	372	NA	NA	NA
0.9	277	NA	NA	NA	NA
1.0	468	NA	NA	NA	NA
1.1	NA	NA	NA	NA	NA

Table 2: Future cumulative budgets (GtC) from January 2015 for percentiles of the distribution of RCP2.6 simulations of CMIP5 models and various levels of future warming above the modelled 2010-2019 average. Percentiles correspond to the percentage of CMIP5 models that have greater cumulative emissions for the given level of warming. If an insufficient number of models warm above a particular threshold to calculate a given percentile of the total model distribution a value of NA is given.

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Author Contributions: RJM conducted the analysis and produced figures 2 and 3. JR conducted the CMIP5 analysis and produced Figure 1. HDM conducted the integrations with the UVic ESCM. RJM produced an initial draft of the manuscript along with JSF, MG, PF and MRA. All authors contributed to the experimental design, interpretation and revisions of the manuscript.

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Figures

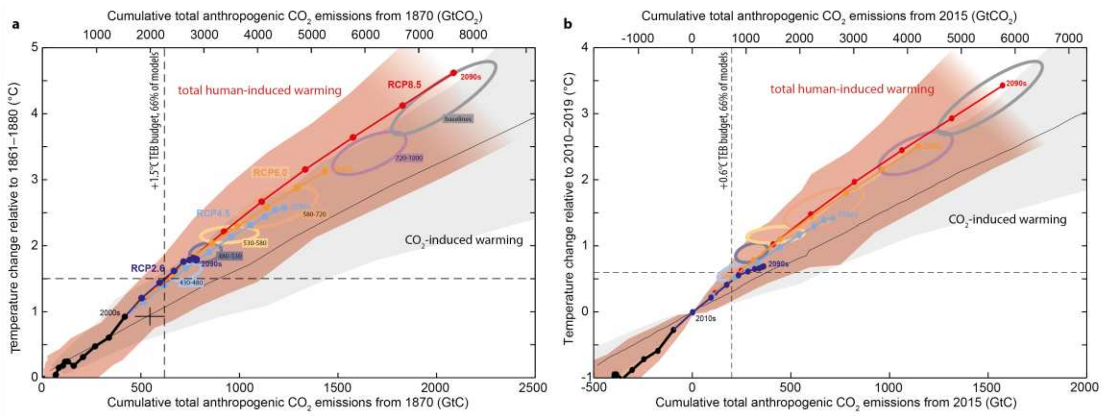

Figure 1: Warming as a function of cumulative CO_2 emissions in the CMIP5 ensemble. (a) Cumulative emissions since 1870 and warming relative to the period 1861-80, adapted from figure 2.3 of ref 11. The red and grey plumes show the 5-95% range of model response under the RCPs and 1% annual CO_2 increase scenarios respectively. Thick coloured lines show ensemble mean response to the RCP forcing scenarios. Ellipses show cumulative emissions and warming in 2100 for different categories of future emissions scenario. Black cross shows uncertainty in 2015 human-induced warming and observed cumulative emissions. (b) As for a) but with cumulative emissions given since January 2015 and warming relative to the period 2010-2019. Dashed vertical grey lines show the threshold exceedance budgets (TEBs) below which over 66% of models have warmed less than 1.5℃ above 1861-80 in panel (a), and less than 0.6℃ above 2010- 19 in panel (b).

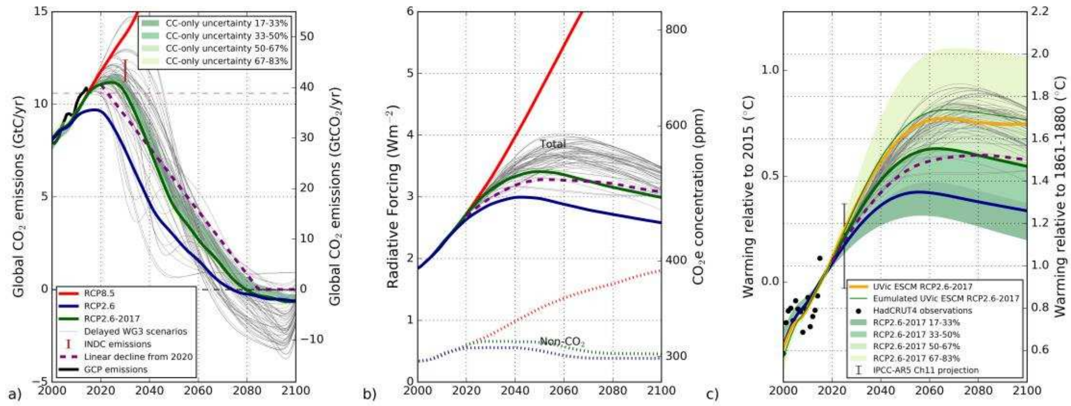

Figure 2: Emissions, forcing and temperature response associated with various mitigation scenarios. Solid lines in panel (b) show total anthropogenic forcing for RCP8.5 (red), RCP2.6 (dark blue), RCP2.6-2017 (dark green) and delayed IPCC-WG3 430-480ppm (grey) scenarios. Dotted lines show non-CO_2 forcing. Solid lines in panel (a) shows median diagnosed emissions, with

green shading showing the central 4 probability sextiles in the carbon-cycle feedbacks distribution. The brown bar denotes projected emissions in 2030 based on current NDCs. Solid lines in panel (c) show median temperature response, with green shading showing central 4 probability sextiles of response to RCP2.6-2017 radiative forcing. Black bar shows the likely range for the IPCC-AR5 scenario-independent projection for the average of the 2016-2035 period[49], while black dots represent HadCRUT4 observations (relative to right hand axis only). The response of the UVic ESCM (orange), and the simple climate model with identical climate response parameters (thin green), both driven by the diagnosed RCP2.6-2017 emissions scenario are shown in panel (c). These two lines correspond to the left hand axis only. Purple dashed lines in all panels show a hypothetical scenario with linear emissions decline from 2020 giving similar median warming in 2100 to RCP2.6-2017.

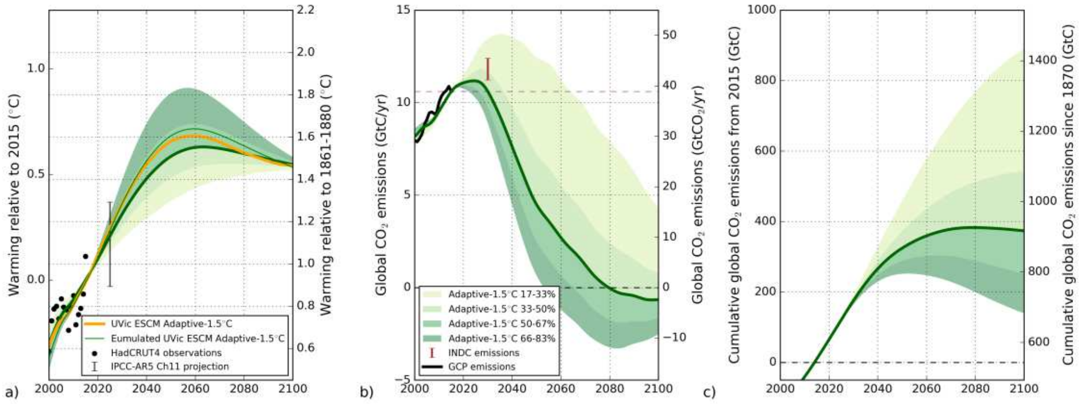

Figure 3: Temperature trajectories and associated emissions consistent with 1.5℃ warming in 2100 for a range of climate responses under an adaptive mitigation regime. Dark green line in panel (a) shows median response to RCP2.8-2017 scenario as in Fig. 2c, green plume shows temperature

trajectories corresponding initially to central 4 sextiles of the response to RCP2.6-2017, then smoothly interpolated over 2017-2117 to the median response. The orange line shows the response of the UVic ESCM driven by diagnosed emissions from the simple climate-carbon-cycle model consistent with the interpolated temperature trajectory corresponding to the UVic ESCM climate response parameters. The thin green line shows the response of the simple climate-carbon-cycle model driven by the same emissions as the UVic ESCM with identical climate response parameters to UVic ESCM and identical carbon-cycle parameters to the standard RCP2.6-2017 scenario in Fig 1a. These two lines correspond to the left hand axis only. Panel (b) shows diagnosed emissions consistent with temperature trajectories in panel (a) and the corresponding response percentile. Brown and black bars shows INDC emission range and near-term temperature projection as in Fig. 2. Panel (c) shows cumulative emissions from 2015, or relative to 1870 (right hand axis) assuming the observed best-estimate of 545GtC emissions 1870-2014.

Methods

We refer to "climate response" as a specified combination of TCR and ECS throughout this paper. Our median estimate climate response (TCR=1.6℃, ECS=2.6℃) is defined as the median of log-normal distributions consistent with IPCC-AR5 likely bounds on TCR and ECS (TCR: 1.0-2.5℃; ECS: 1.5-4.5℃). From this the likely above/below values are found from the 33rd and

66th percentiles of the distribution (TCR: 1.3-1.9℃; ECS: 2.0-3.3℃). The median TCR of this log-normal distribution is significantly lower than in the IPCC-AR5 ESM ensemble but is more consistent with observed warming to date than many ensemble members (see Supplementary Methods), indicative of the multiple lines of evidence used to derive the IPCC-AR5 uncertainty ranges. Although IPCC-AR5 did not explicitly support a specific distribution, there is some theoretical justification[50] for a log-normal distribution for a scaling parameter like TCR. Reconciling IPCC-AR5 best-estimate of attributable warming trend over 1951-2010 with the best-estimate effective radiative forcing requires a best-estimate TCR near to 1.6℃ under the simple climate model used here, consistent with a log-normal distribution. As a sensitivity study, we also assume a Gaussian distribution for TCR (see Supplementary Methods) that raises the 2015 attributable warming to 1.0℃ but only marginally affects the remaining carbon budget for a 1.5℃ warming above pre-industrial (the likely below budget is reduced to 240GtC).

The ECS distribution used here is derived directly from the IPCC-AR5 likely bounds that drew on multiple lines of evidence, so our conclusions are not directly affected by uncertainties in the efficacy of ocean heat uptake that affect purely observational constraints on ECS[51]. We are not here arguing for the revision of uncertainty estimates on any climate response parameters, although any such revision would of course affect our conclusions. The implications of an increased lower bound on the climate response are shown in figure S18.

Reproducing present day temperatures with differing values for both TCR and ECS requires these parameters to co-vary with present-day net anthropogenic radiative forcing[52]. In the best-estimate forcing case (Figure 2b), past and future effective radiative forcing components are individually scaled (multiplicatively) to match the respective best-estimate values for each component in 2011 as given in IPCC-AR5[25]. Figures 2 and 3 scale past and future anthropogenic aerosol effective radiative forcing (the most uncertain forcing component[28]), along with accounting for combined uncertainty in the non-CO_2 effective radiative forcing components that were assessed to have Gaussian distributed uncertainty in IPCC-AR5 (draws from this distribution are taken at a percentile equal to the TCR distribution draw). The aerosol radiative forcing scaling factor is chosen to give externally-forced warming above 1861-1880 equal to that under the median climate response (i.e. 0.92℃ in 2015) for all draws from the climate response distribution. In all cases shown the scaled 2011 aerosol forcing is within IPCC-AR5 assessed uncertainty bounds. A summary of climate system properties used is given in Table S1: in only one case (the TCRE value implied by the lowest, 17^{th}, percentile) are these outside the AR5 "likely" ranges, and this parameter combination is only used in the figures, not our headline conclusions.

Temperature anomalies are computed using a two-timescale impulse-response model from ref. [29] and [28], in which surface temperatures adjust to an imposed radiative forcing with a fast and slow timescale characterising the uptake of heat into the upper and deep ocean (set at 8.4 and 409.5 years respectively as in ref. [28]). The lower limit of the TCR likely range requires a total anthropogenic forcing of $3.54 Wm^{-2}$ in 2011, slightly greater than the upper bound of the IPCC-AR5 confidence interval ($3.33 Wm^{-2}$). Natural forcing is taken as given at http://www.pik-potsdam.de/~mmalte/rcps/ and is smoothed with a 10-year standard deviation Gaussian filter beyond 2015 in all scenarios.

In constructing temperature trajectories in Figure 3a, a smooth cosine interpolation of the CO_2-induced warming is applied over the period 2017 to 2117 between the response for a specific climate response parameter set to RCP2.6-2017 and the total warming under the RCP2.6-2017 median climate response (which meets the goal of 1.5℃ in 2100). Non- CO_2 warming remains as originally simulated under the climate response parameter set for RCP2.6-2017 and only CO_2-induced warming is adapted to force the total warming to asymptote towards the median response of RCP2.6-2017, corresponding to a scenario in which only CO_2 policy responds to the emerging signal.

CO_2 emissions in Figure 2a and 3b are derived using the simple carbon-cycle impulse-response formulation in ref. [28], modified to make airborne fraction a linear function of both warming and cumulative carbon uptake by terrestrial and ocean sinks[29]. Emissions in all figures are smoothed with a Gaussian filter with a standard deviation of 2 years: note that our use of an acausal filter implies that emissions are continuously adjusted to projected human-induced warming over this timescale in addition to warming to date. Cumulative emissions (Figure 3c) are more robust than emission rates in any given year, since rates depend on the method used to construct these goal-consistent pathways.

The strength of carbon cycle feedbacks (a single scaling factor applied to default r_T and r_C coefficients in ref. [29]) varies from 0-2, consistent with CMIP5 RCP2.6 ensemble (Sup. Info.). We assume that this scaling factor range corresponds to the 5-95 percentiles of a Gaussian distribution. In Figure 3, draws from this carbon-cycle feedback scaling factor distribution are taken at an equal percentile to that from the TCR distribution. This correlation between the TCR and carbon-cycle feedback distribution is chosen to maximise the range of carbon budgets calculated from Figure 3. For each carbon-cycle feedback strength, total airborne fraction is adjusted (via the r_0 parameter in ref. [29]) to reproduce observed CO_2 emissions in 2014 and leads to a range of historical cumulative CO_2 emissions of 467-598GtC (17^{th}-83^{rd} percentile of distribution), with a median estimate of 542GtC, under carbon-cycle only uncertainty.

Figures 2c and 3a show a version of the simple carbon-cycle-climate model (thin green lines) with thermal climate response parameters as represented in the UVic Earth System Climate Model (version 2.9 - TCR=1.9℃ and ECS=3.5℃) [31,32] and default carbon-cycle parameters given in ref. [29]. These parameters achieve a good emulation of the UVic ESCM response when driven with the RCP4.5 scenario (see Supplementary Methods). In Figure 2c, UVic ESCM and the UVic ESCM-emulation simple carbon-cycle-climate model version are driven by RCP2.6-2017 emissions, diagnosed from the simple climate-carbon-cycle model using the median climate response and carbon-cycle parameters (dark green line in Figure 2a) and RCP2.6-2017 non-CO_2 radiative forcing scaled as discussed previously, for a 1.9℃ TCR. In Figure 3a, UVic ESCM and the UVic ESCM-emulation simple carbon-cycle-climate model version are driven by diagnosed emissions corresponding to an interpolated temperature pathway at a 1.9℃ TCR, consistent with the method described previously.

We add an estimate of the 2030 land-use emissions in RCP2.6-2017 (2023 in RCP2.6) as derived from the MAGICC model[53] (http://www.pik-potsdam.de/~mmalte/rcps/), to the fossil fuel and industry emissions consistent with the NDCs from ref 12 for the brown bars in Figures 2 and 3.

In analysis of the CMIP5 ensemble budgets given in Table 1 and 2, budgets are calculated in an identical fashion to ref. [54] (both in terms of models and initial condition ensemble members used). Budgets are TEBs and are derived from percentiles of the distribution of decadal means of CMIP5 RCP8.5 integrations, linearly interpolating between adjacent rank-ordered ensemble members. In Table 2, where insufficient models cross a particular future warming threshold to calculate a particular percentile of the total model distribution at that threshold, no value is reported. For the grey (1%/yr CO_2 increase) plume in Figure 1, cumulative emissions and temperatures expressed from the beginning of the increase (1a) and relative to a ten-year period centred around the year in which concentrations reach the 2015 value of 398ppm (1b). Scenarios that peak and decline emissions were excluded from the red plume in Figure 1b.

Code availability: Code will be available on request to the corresponding author.

Data availability: RCP forcing data used in this study is available at http://www.pik-potsdam.de/~mmalte/rcps/

Supplementary Information: Supplementary methods are included with this submission.

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