

Estimating and tracking the remaining carbon budget for stringent climate targets

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Research reported during the past decade has shown that global warming is roughly proportional to the total amount of carbon dioxide released into the atmosphere. This makes it possible to estimate the remaining carbon budget: the total amount of anthropogenic carbon dioxide that can still be emitted into the atmosphere while holding the global average temperature increase to the limit set by the Paris Agreement. However, a wide range of estimates for the remaining carbon budget has been reported, reducing the effectiveness of the remaining carbon budget as a means of setting emission reduction targets that are consistent with the Paris Agreement. Here we present a framework that enables us to track estimates of the remaining carbon budget and to understand how these estimates can improve over time as scientific knowledge advances. We propose that application of this framework may help to reconcile differences between estimates of the remaining carbon budget and may provide a basis for reducing uncertainty in the range of future estimates.

Since the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)¹, the concept of a carbon budget has risen to prominence as a tool in guiding climate policy². We here define the remaining carbon budget as the finite total amount of CO₂ that can be emitted into the atmosphere by human activities while still holding global warming to a desired temperature limit. This is not to be confused with another concept, the historical carbon budget, which describes estimates of all major past and contemporary carbon fluxes in the Earth system³. The idea of a remaining carbon budget is grounded in well established climate science. A series of studies over the past decade has clarified and quantified why the rise in global average temperature increase is roughly proportional to the total cumulative amount of CO₂ emissions produced by human activities since the industrial revolution^{4–13}. This literature has allowed scientists to define the linear relationship between warming and cumulative CO₂ emissions as the transient climate response to cumulative emissions of CO₂ (TCRE). Once established, the appeal of this concept became immediately evident: the possibility that the response of an enormously complex system—such as the response of planet Earth to our emissions of CO₂—could potentially be reduced to a roughly linear relationship would allow scientists to infer clear and easy-to-communicate implications. However, additional processes that influence and are influenced by future warming, such as the thawing of permafrost, have recently been included in models that simulate the Earth system. These additional processes add uncertainty and may change our understanding of this linear relationship. Moreover, global warming is not driven by emissions of CO₂ only. Other greenhouse gases (such as methane, fluorinated gases or nitrous oxide) and aerosols and their precursors (including soot or sulphur dioxide) affect global temperatures. Estimating the remaining carbon budget thus also implies making assumptions about these non-CO₂ contributions. This further complicates the relationship between future CO₂ emissions and global warming.

Carbon budgets nevertheless have become a powerful tool for communicating the challenges we face in aiming to hold warming to 1.5°C and to well below 2°C—the limits of global average temperature increase set out in the United Nations Paris Agreement^{14–18}. First, every tonne of



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CO₂ emitted into the atmosphere by human activities adds to warming, and it does not matter whether this tonne of CO₂ is emitted today, tomorrow or yesterday. This also implies that to limit temperature increase to any level, global CO₂ emissions produced by human

activities must be reduced to net-zero levels at some point in time and, on average, stay at net-zero levels thereafter. Furthermore, when aiming to limit warming to below a specific limit, a finite carbon budget also implies that the more we emit in the coming years, the faster emissions will have to decline thereafter to stay within the same budget—simple arithmetic. Finally, once net CO₂ emissions are brought to zero, warming would stabilize but would not disappear or be reversed^{19–21}. Any amount by which a carbon budget compatible with a desired temperature limit is missed or exceeded would thus have to be actively and permanently removed from the atmosphere in later years. This could be achieved through measures that result in net negative CO₂ emissions, which come with their own technical and social complications^{22–27}. Besides its role as a communication tool, the carbon budget concept also provides a way to exchange knowledge across disciplines. For example, such knowledge exchange is already happening for climate change mitigation requirements between the geoscience community and other disciplines that study climate change from a more societal angle^{28,29}.

Diversity that may confuse

Unfortunately, all that glitters is not gold. Over the past five years, a plethora of studies have been published^{12,30–44} further exploring and estimating the size of carbon budgets while in some way accounting for non-CO₂ climate forcing. These studies most often focus on requirements for holding warming to the internationally agreed 1.5°C or 2°C limits^{14–16}. Although all studies aim to evaluate the same quantity, the use of different definitions and non-CO₂ climate forcing assumptions, as well as methodological and model differences, have led to a wide variety of reported carbon budget estimates that aim to achieve temperature goals that are nominally the same (see Box 1 for an overview of carbon budget estimation approaches). This variation seems to have decreased instead of increased the broader understanding of

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the remaining carbon budget and has thus tempered the initial enthusiasm about its usefulness as a guide for policy making and target setting^{45,46}. This confusion is avoidable, however. Differences in remaining carbon budget estimates can be understood if a set of potential contributing factors are carefully taken into account.

Here we present a conceptual framework that allows one to track, understand, update and explain estimates of the remaining carbon budget over time. The framework's structure enables the assessment of individual contributing factors, including historical warming, the TCRE, the zero-emissions commitment and non-CO₂ contributions to future warming. It integrates suggestions made in earlier literature^{12,47} and is a generalization and extension of the framework used in ref.⁴⁸.

Remaining carbon budget framework

As discussed, the remaining carbon budget can be defined as the remaining amount of CO₂ emissions that can still be emitted while keeping the global average temperature increase due to human activities to below a specific temperature limit. The framework set out below applies to a situation in which one aims to limit peak (or maximum) warming and its associated impacts. It can, however, also be extended to apply to a situation where temperature rise has temporarily exceeded an intended temperature limit, often referred to as a temperature overshoot (see Supplementary Text 1).

We present in equation (1) an estimate of the remaining carbon budget (B_{lim}) for a specific temperature change limit (T_{lim}) as a function of five terms that represent aspects of the geophysical and coupled human–environment system (equation (1)): the historical human-induced warming to date (T_{hist}), the non-CO₂ contribution to future temperature rise (T_{nonCO_2}), the zero-emissions commitment (T_{ZEC}), the TCRE, and an adjustment term for sources of unrepresented Earth system feedback (E_{Esfb}). These terms are visualized in Fig. 1 and are described and discussed in turn below.

$$B_{\text{lim}} = (T_{\text{lim}} - T_{\text{hist}} - T_{\text{nonCO}_2} - T_{\text{ZEC}}) / \text{TCRE} - E_{\text{Esfb}} \quad (1)$$

Transient climate response to cumulative emissions

Arguably the most central term to estimating the remaining carbon budget is the TCRE (in units of °C per gigatonne of carbon dioxide (Gt CO₂); see equation (1)). In essence, the remaining carbon budget is estimated by multiplying the remaining allowable warming with the inverse of the TCRE, where the magnitude of the remaining allowable warming is the result of various contributions shown in Fig. 1 and discussed below. The TCRE can be estimated from several lines of evidence, including the observational record^{10,12,49–51}, CO₂-only simulations¹⁰ and multi-gas simulations^{12,31,49–53} with Earth system models of varying complexity. In its latest assessment⁵⁴, the IPCC reported the TCRE to fall within the range of 0.2–0.7 °C per 1,000 Gt CO₂ with a probability of at least 66%. TCRE, and hence the linear proportionality of warming to cumulative emissions of CO₂, has also been found to be robust up to about 7,300 Gt CO₂ of cumulative emissions^{54,55} and probably more⁵⁶. This domain of application easily spans the range of carbon budgets consistent with warming limits of 1.5 °C and 2 °C.

Historical and maximum temperature increase

After TCRE, the combined remaining allowable warming (represented by $T_{\text{lim}} - T_{\text{hist}} - T_{\text{nonCO}_2} - T_{\text{ZEC}}$) is the next key determinant for estimating the remaining carbon budget. Its first term is the specific temperature limit of interest relative to preindustrial levels (T_{lim} , in units of °C), and its second term represents the historical human-induced warming (T_{hist} , in units of °C); see equation (1). T_{hist} is the amount of human-induced warming since preindustrial times until a more recent reference period, such as the 2006–2015 period.

The estimation of T_{hist} is a central factor affecting the size of the remaining carbon budget, because it determines how far we currently are from policy-relevant temperature limits (1.5 °C or 2 °C). The assessment of T_{hist} should adequately isolate the human-induced warming signal from the effects of natural forcing and variability^{57,58}.

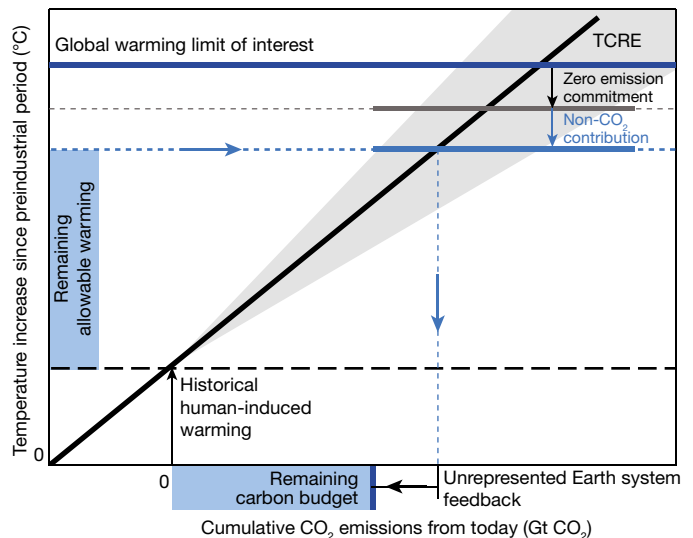


Fig. 1 | Schematic of factors contributing to the quantification of a remaining carbon budget. The schematic shows how the remaining carbon budget can be estimated from various independently assessable quantities, including the historical human-induced warming T_{hist} , the zero-emissions commitment T_{ZEC} , the contribution of future non-CO₂ warming (consistent with global net-zero CO₂ emissions or otherwise) T_{nonCO_2} , the transient climate response to cumulative emissions of carbon (TCRE), and further correcting for unrepresented Earth system feedback E_{Esfb} . The grey shading illustrates how uncertainty in TCRE propagates from the start point. Arrows and dashed lines are visual guides illustrating how the various factors combine to provide an estimate of the remaining carbon budget. Besides estimating the remaining carbon budget B_{lim} , the framework can also be applied to understand, decompose and discuss estimates of carbon budgets calculated by other methods. The relative sizes of the various contributions shown in this schematic are not to scale.

The same is true for T_{lim} , and if T_{lim} is intended to represent an internationally agreed climate goal in line with the Paris Agreement it should do so by definition¹⁵. Two additional choices play an important role in determining or setting T_{hist} and T_{lim} : the choice of the preindustrial reference period and the temperature metric for determining global average temperature increase. Neither the preindustrial reference period nor the specific warming metric are explicitly defined by the Paris Agreement and recent literature has explored the implications and interpretations of this ambiguity^{34,35,59}.

The 1850–1900 period is often used as a proxy for preindustrial levels because observational temperature records stretch back to the beginning of that period⁶⁰, and key scientific reports that fed into the Paris Agreement also used this proxy^{1,59,61,62} (see Supplementary Text 2 for more details). Other periods have been suggested^{63–65}, but ultimately the crux lies in that T_{hist} and T_{lim} should always be expressed relative to the same preindustrial reference period to avoid introducing erroneous changes to the remaining allowable warming and therewith the remaining carbon budget. Besides defining an appropriate preindustrial reference period, the choice of metric by which warming is estimated from that period is also important. Studies analysing climate model simulations or observational products can use different metrics to estimate global mean temperature change (see Supplementary Text 2). The impact of this metric choice has been highlighted recently with studies^{34,59} showing that this choice can result in variations in the estimated global warming of the order of 10% (Supplementary Fig. 1), leading to a potential variation in remaining carbon budget estimates of more than 400 billion tonnes of CO₂ (ref.⁵⁹). The IPCC has typically specified carbon budgets based on global area-averaged change in surface air temperature^{48,66}. Other studies, however, have used different metrics and at times have even changed metrics between observations and projections (Supplementary Table 1, Fig. 2). This limits the comparability of these budget estimates⁵⁹—a situation this new framework attempts to avoid.

Non-CO₂ contribution to future warming

Another term affecting the remaining allowable warming is the non-CO₂ contribution to future global temperature rise (T_{nonCO_2} , in units of °C) (see equation (1) and Fig. 1). Current and future warming depends on both CO₂-induced warming and warming due to non-CO₂ forcing. Future non-CO₂ warming might be considerable, given that reducing emissions of cooling sulphur dioxide causes warming⁶⁷ and the knowledge that no obvious mitigation options have been identified that can completely eliminate several important sources of non-CO₂ greenhouse gases^{68,69}. To include T_{nonCO_2} in the remaining carbon budget framework, the non-CO₂ warming contribution between a recent reference period (for example, the same period as T_{hist}) and a specific time in the future has to be estimated. We suggest that this non-CO₂ contribution to future temperature rise should be estimated from scenarios with an internally consistent evolution of greenhouse gases and other climate forcings^{36,70–74} and at the moment at which global CO₂ emissions reach net zero⁴⁸. Estimating the non-CO₂ warming contribution at that moment in time reflects a situation in which global cumulative emissions of CO₂ are effectively capped and hence allows us to directly inform the question of how much CO₂ can be emitted while keeping warming to a given temperature level. If non-CO₂ warming were to be estimated at other moments in time, its usefulness for informing mitigation requirements would potentially be strongly reduced.

Besides the future evolution of non-CO₂ emissions, the non-CO₂ warming contribution also depends on estimates of the corresponding radiative forcing, including potential changes in surface albedo⁴³. Non-CO₂ forcing and warming can be estimated with the help of simple climate models^{43,75,76}, inferred from more complex climate model runs⁷⁷, or taken from the literature^{37,48}. Importantly, non-CO₂ emissions would continue to affect warming levels after the time when net CO₂ reaches zero, which creates uncertainty in methods that estimate budgets by integrating changes over time and after an overshoot (for example, see refs^{36,43} and Box 1). These uncertainties are reduced in the framework proposed in this Perspective by focusing on the time of reaching net-zero CO₂ emissions and by considering internally consistent non-CO₂ emissions. Under these assumptions, non-CO₂ emissions are projected to result in a constant or declining forcing and warming after the time of net-zero CO₂ (refs^{48,73}). However, if under alternative assumptions one would project non-CO₂ warming to continue to increase irrespective of the level of CO₂ emissions⁷⁸, this further increase should also be accounted for within T_{nonCO_2} because it would add to future peak warming.

Zero-emissions commitment

The zero-emissions commitment, T_{ZEC} (in units of °C) is the next term in the remaining carbon budget framework represented by equation (1). T_{ZEC} is defined as the additional contribution to peak warming that is still to be expected after a complete cessation of CO₂ emissions^{79,80}, and hence provides a correction term for the instantaneous linearity postulated by the concept of the TCRE. T_{ZEC} can be positive, negative or zero. For estimates of the remaining carbon budget, the T_{ZEC} when CO₂ emissions approach net-zero levels is of particular interest. In more general terms, this could also be formulated as an assessment of the lag in CO₂-induced warming at current and declining emissions rates^{50,79}. When T_{ZEC} is positive, not all warming will have been experienced by the time global CO₂ emissions reach net zero. The estimated additional warming would hence also have to be reduced from the allowable remaining temperature increase. At present, T_{ZEC} is frequently neglected in carbon budget studies (see Supplementary Table 1, with exceptions only hypothesizing the effect of its contribution³⁷) and is hence implicitly assumed to be zero or negative. Several studies suggest, however, that there might be a smaller^{79–82} or larger^{83,84} lag between the time when CO₂ emissions have ceased and the time of maximum warming caused by those emissions. Instead of being accounted for as a separate term, the T_{ZEC} could also be integrated within the assessment of TCRE, although a dedicated methodological framework to do so is currently lacking.

Box 1

Frequently used carbon budget definitions

Studies differ in how they define the carbon budget, and these differences affect the accuracy, size and usefulness of reported estimates. This box provides an overview of five ways in which carbon budgets can be defined, and highlights some of their strengths and weaknesses as well as how they link to the remaining carbon budget framework introduced here.

Peak or maximum temperature budgets are defined as the cumulative amount of net CO₂ emissions that would hold maximum warming to a specific temperature limit. In most cases, peak warming roughly coincides with the timing of a pathway reaching net-zero CO₂ emissions, and peak temperature budgets are thus directly compatible with the framework proposed in this paper. They also provide a direct estimate of the amount of CO₂ emissions that is consistent with achieving international temperature goals⁴⁸.

Threshold return budgets are defined as the cumulative amount of net CO₂ emissions until a specific level of warming is reached, yet only after having temporarily exceeded that level by a certain amount and during a certain period of time earlier^{36,47}. By definition, they include a period of global net removal of CO₂ and hence must account for potential additional nonlinearities in the Earth system response¹⁰⁵. Supplementary Text 1 clarifies how the framework presented here can be adjusted to suit this definition.

Threshold exceedance budgets are defined as the cumulative amount of net CO₂ emissions until the time at which temperature projections for a given pathway exceed a temperature threshold of interest³⁷. This method has been often applied by studies that estimate carbon budgets from a limited set of simulations of complex Earth system models^{10,30,32,54}. They do not provide a direct estimate of the amount of CO₂ emission that is consistent with achieving international temperature goals, but can still be discussed and understood within the framework presented in this Perspective, for example, by explicitly clarifying assumptions regarding historical warming and non-CO₂ warming at the time the temperature threshold is exceeded, and assumed values for T_{ZEC} and TCRE.

Threshold avoidance budgets are derived from emissions pathways that avoid crossing a temperature threshold of interest³⁷. Their main drawback is that their definition leaves a lot of room for interpretation and variation. First, in contrast to previous budget definitions, no unambiguous point in time is available for threshold avoidance budgets until such time as net CO₂ emissions are summed, thus requiring additional assumptions^{37,39}. Second, any scenario that limits warming below a threshold of interest (whether slightly or by a much larger margin) could be included in a threshold avoidance budget estimate⁷¹. This makes these estimates imprecise, extremely variable and difficult to compare across studies. However, even here the framework presented in this Perspective can help to structure discussions.

Finally, some studies report descriptive statistics of emissions pathways, such as cumulative CO₂ emissions until 2050 or 2100, instead of estimates of remaining carbon budgets. These statistics are not directly selected on the basis of their temperature outcome^{36,71} and should not be interpreted as geophysical carbon budget requirements.

Unrepresented sources of Earth system feedback

Finally, reductions in emissions due to unrepresented Earth system feedback mechanisms (E_{Esfb} , in units of Gt CO₂), are the last term in the proposed remaining carbon budget framework (equation (1)). Any Earth system feedback that is not yet incorporated in estimates of the TCRE or that would reduce the applicability of TCRE should be assessed, and accounted for and communicated as part of E_{Esfb} .

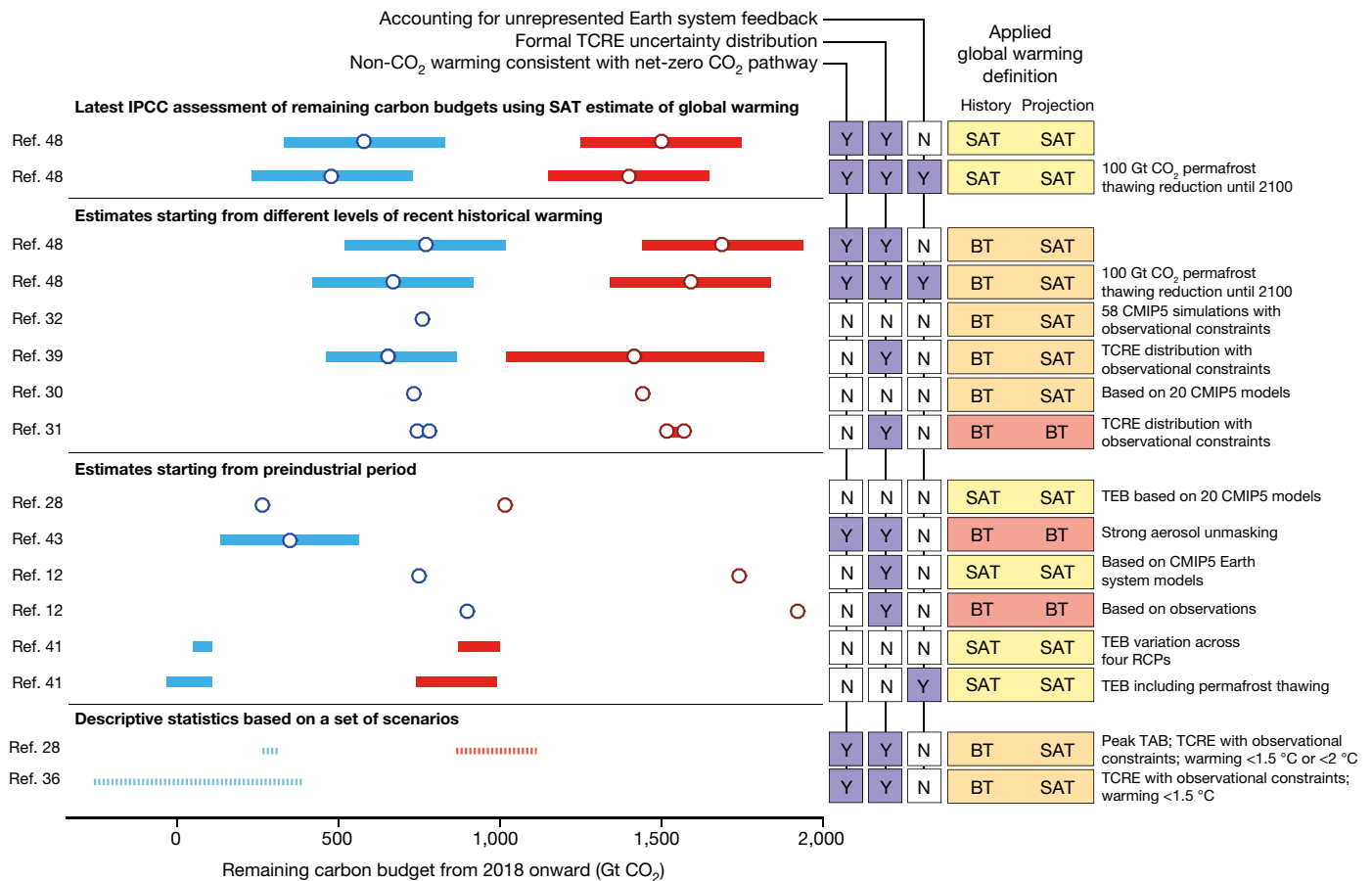


Fig. 2 | Comparison of recent remaining carbon budget estimates for limiting global warming to 1.5 °C (blue) and to 2 °C (red) relative to preindustrial levels, and overview of factors affecting their variation. Estimates are shown for a 50% probability of limiting warming to the indicated temperature levels (additional estimates for a 66% probability are provided in Supplementary Table 2). Several studies do not report formal probabilities, but report the frequency distribution across model simulations instead. The latter estimates are marked N in the ‘Formal TCRE uncertainty distribution’ column. Estimates shown with dashed lines indicate carbon budget estimates with an imprecise level of implied global warming, for example, because they were reported for a radiative forcing target instead. TEB means threshold exceedance budget³⁷; TAB means threshold avoidance budget³⁷ (see Box 1). Data are taken from the

These feedback processes have typically been related to permafrost thawing^{40–42,85} and the associated long-term release of CO₂ and CH₄. However, other Earth system feedback sources that can affect remaining carbon budgets have been identified⁴², including changes in vegetation CO₂ uptake linked to nitrogen availability^{86–88}. If unrepresented feedback results in a direct CO₂ emission from an ecosystem, the translation to the E_{ESfb} term is direct. However, because of the diverse nature of Earth system feedback⁴², accounting for it through an adjustment in CO₂ emissions is not always straightforward. For example, if a feedback system results in the release of other greenhouse gases or affects the Earth system through changes in surface albedo, clouds or fire regimes, for example, its contribution needs to be translated into an equivalent CO₂ correction term (see refs^{89,90} for example). Because most Earth system feedback is either sensitive to rising CO₂ or to variations in climate parameters, it is expected that these contributions are scenario-dependent, nonlinear, and in some cases realized over longer timescales only^{40,41,85,91–98}. This adds to the complexity of the translation into a CO₂-equivalent correction term, and makes E_{ESfb} an uncertain contribution. E_{ESfb} could be estimated either for the time at which global net CO₂ emissions become zero or until the end of the century or beyond, assuming anthropogenic CO₂ emissions are kept at net-zero levels but feedback mechanisms continue to change over

IPCC Special Report on Global Warming of 1.5 °C (ref. 48), ref. 39 (with values for 1.5 °C based on our own calculations using the same method), the IPCC Fifth Assessment Report (ref. 28) and refs^{12,30–32,36,41,43}. The latest IPCC assessment of the remaining carbon budget⁴⁸ assumes 0.97 °C of historical warming until 2006–2015, whereas other estimates assume either higher or lower warming for that period (Supplementary Table 1). The background and values for all studies are provided in Supplementary Tables 1 and 2. The assumptions made for each study are coloured (right-hand side of figure) for ease of visual grouping: N, no; Y, yes; SAT, global near-surface air temperatures; BT, blended temperatures (surface air temperature over land and sea-ice regions combined with sea surface temperature over open ocean); RCP, Representative Concentration Pathway; CMIP5, Phase 5 of the Coupled Model Intercomparison Project.

time^{41,85,92,93,97}. Finally, scenario-independent Earth system feedback that scales linearly with global average temperature increase could also be incorporated by adjusting the TCRE, as long as it is not double-counted in both E_{ESfb} and TCRE.

Tracking and explaining scientific progress

We are of the opinion that through conscientious and rigorous application of the framework we propose in this Perspective, much of the confusion surrounding the size and variation of remaining carbon budget estimates can be avoided. Our proposed framework allows scientists to identify, understand and track how the progression of science on multiple fronts can affect budget estimates. It also allows us to identify and discuss key uncertainties and choices related to each respective term (Table 1). Together, these two improvements can contribute to a more constructive and informed discussion of the topic, and better communication across the various disciplines and communities that research, quantify and apply estimates of the remaining carbon budget.

The road from the geosciences to climate policy is long and winding. However, carbon budgets provide one of the simplest and most transparent means of connecting geophysical limits imposed by the Earth system to implications for climate policy. For example, they provide

Table 1 | Key choices or uncertainties of terms affecting estimates of the remaining carbon budget

Term	Symbol	Key choices or uncertainties	Type	Level of understanding
Temperature limit	T_{lim}	Choice of temperature metrics used to express global warming, choice of preindustrial reference period, and consistency with global climate goals	Choice	Medium to high
Historical human-induced warming	T_{hist}	Choice of temperature metrics used to express global warming, choice of preindustrial reference period, and consistency with global climate goals	Choice	Medium to high
Historical human-induced warming	T_{hist}	Incomplete coverage in observational data sets, and methods to estimate human-induced component	Uncertainty	Medium to high
Non-CO ₂ contribution to future global warming	T_{nonCO_2}	The level of different non-CO ₂ emissions that are consistent with global net-zero CO ₂ emissions, which depends on policy choices but also on uncertain success of their implementation	Choice and uncertainty	Medium
Non-CO ₂ contribution to future global warming	T_{nonCO_2}	Climate response to non-CO ₂ forcings, particularly in the level of aerosol recovery and temperature reduction from lower methane emissions	Uncertainty	Low to medium
Zero-emissions commitment	T_{ZEC}	Sign and magnitude of zero-emission commitment at decadal time scales for current and near-zero annual CO ₂ emissions	Uncertainty	Low
Transient climate response to cumulative emissions of CO ₂	TCRE	Distribution of TCRE uncertainty, linearity of TCRE for increasing and stabilizing cumulative CO ₂ emissions, and impact of temperature metrics on TCRE estimate	Uncertainty	Low to medium
Transient climate response to cumulative emissions of CO ₂	TCRE	When extended beyond peak warming (Supplementary Text 1), uncertainty about linearity, value and distribution of TCRE for decreasing cumulative CO ₂ emissions	Uncertainty	Low
Unrepresented Earth system feedback mechanisms	E_{Estb}	Timescale and magnitude of permafrost thawing and methane release from wetlands and their representation in Earth system models, as well as other potential types of feedback	Uncertainty	Very low

Each of the terms in equation (1) is listed. 'Level of understanding' indicates our assessment of the current level of understanding of the various uncertainty components.

the geophysical foundation for setting global net-zero targets^{6,99}, which have recently been picked up by policy scholars as being potentially more effective in guiding policy towards a more actionable climate change mitigation goal¹⁰⁰. When combined with models that simulate possible transformations to a low-carbon society¹⁰¹, they can also help inform other, more specific, climate change mitigation targets.

Nevertheless, adequately characterizing and communicating the uncertainties that surround carbon budget estimates is a challenge that will remain. These uncertainties are not unfathomable, however, and language exists to describe the nature of the various uncertainty contributions¹⁰² (Table 1, Fig. 2). In some cases, uncertainties exist because of our imprecise knowledge of certain processes or lack of precise measurements. This uncertainty is applicable to all terms in our framework except for T_{lim} , and will only gradually be reduced over time. In other cases, terms are not used consistently throughout the literature, resulting in confusion and inconsistency between carbon budget estimates (Table 1, Supplementary Table 1, Fig. 2). This is the case for the choice of global temperature metric or for the time period over which remaining carbon budgets are computed. For increased comparability and flexibility, it would be useful if global surface air temperature values were routinely estimated for observational products and if climate model projections were to report both metrics. Some uncertainties represent policy choices⁴⁴. An example of such uncertainty is the estimate of the non-CO₂ emissions contribution to future warming. Future non-CO₂ emissions depend on future socio-economic developments and deployment of mitigation measures, and these are influenced by policy and societal choices today, for example, regarding how much the emission of non-CO₂ greenhouse gases is penalized or which sectors are targeted when promoting innovation for climate change mitigation. These policy-driven uncertainties and ambiguities can be understood, quantified and explained using a scenario-based approach. For sources of Earth system feedback that are not fully represented in models, a quantification of their impact remains difficult. Expert judgment can be applied in this case to provide an estimate of its importance.

The overview of assumptions made in carbon budget studies (Fig. 2 and Supplementary Tables 1 and 2) can already provide a first step in

understanding the relative differences between estimates. For example, except for the most recent IPCC report⁴⁸, none of the estimates available in the literature simultaneously apply consistent global warming metrics for historical and projected temperatures together with a non-CO₂ warming contribution reflecting a future that is in line with the Paris Agreement (Fig. 2, Supplementary Tables 1 and 2). Several estimates also infer the chance of limiting warming to 1.5 °C from ad hoc frequency distributions of model results, instead of from a formal representation of the uncertainty in TCRE. In addition, studies typically do not include all currently identified Earth system feedback, although the impact of some has been described in dedicated studies^{40–42,85}.

Comparing estimates that are the same in all but their inclusion of some of the unrepresented Earth system feedback mechanisms (from refs^{41,48}) suggests that the inclusion of additional Earth system feedback could consistently reduce estimates of the remaining carbon budget—something to bear in mind when future studies that use the latest generation of Earth system models become available¹⁰³. A further insight is that estimates that apply temperature metrics other than global surface air temperatures (Fig. 2 and Supplementary Text 2) consistently suggest remaining carbon budgets that are larger than estimates that use surface air temperature only. The reasons underlying this perceived shift are well understood (see Supplementary Text 2) and can be identified as an artefact of a methodological choice. To be sure, although estimates using temperature metrics other than global averaged surface air temperature usually suggest a larger remaining carbon budget, they also come with clear climate change consequences: a relatively hotter Earth, inconsistent with the long-term temperature goal of the Paris Agreement⁵⁹. A sound rationale therefore needs to accompany the choice of temperature metric. We strongly recommend using global average surface air temperature as the temperature metric because it is computed from invariable fields across models, model runs and over time. More detailed comparisons between published estimates of remaining carbon budgets are complicated or impossible at this stage because the quantifications of the various contributing factors by the original studies are lacking. Hence, we suggest that future studies should provide a quantitative discussion of assumptions and factors contributing to their remaining carbon budget estimates

Box 2

An application of the framework to determine the remaining carbon budget

Using the framework (equation (1)), remaining carbon budgets in line with limiting warming to 1.5 °C or to 2 °C can be estimated by drawing on information available in the literature. We now provide an example of how this could be done, starting from the assessment carried out in the context of the IPCC Special Report on Global Warming of 1.5 °C (ref. ⁴⁸).

The temperature metric is defined as follows: global warming is estimated as the global area-averaged surface air temperature change for historical warming and future projections so that T_{lim} is defined by a single consistent metric.

The preindustrial reference period is 1850–1900, as a proxy for preindustrial levels.

T_{hist} is taken to be 0.97 °C until 2006–2015 since 1850–1900. It is derived as the average over four observational datasets^{60,106–110} (0.87 °C), corrected for by the ratio between surface air temperature and blended temperatures (surface air temperature over land and sea-ice regions combined with sea surface temperature over open ocean) informed by models. This level of warming is attributed to climate forcing that is caused by human activities and hence accounts for the influence of natural (internal and natural forced) variability of the climate.

T_{nonCO_2} is estimated from integrated pathways that include all climate forcing caused by human activities and derived at the time that global total CO₂ emissions reach net-zero levels^{73,74}. It is estimated^{75,76} to be about 0.1 °C (0–0.2 °C, 90% range) in scenarios that reach net-zero CO₂ and limit warming to 1.5 °C and to be about 0.2 °C (0.1–0.4 °C, 90% range) in scenarios limiting warming to 2 °C.

T_{ZEC} is assumed to be zero or negative, and thus not to affect the remaining allowable warming.

The remaining allowable warming starting from the recent 2006–2015 period is hence about 0.4 °C and 0.8 °C for global temperature increase limits of 1.5 °C and 2 °C, respectively.

TCRE is assumed to be normally distributed⁶⁶ with a 1 σ range of 0.2–0.7 °C per 1,000 Gt CO₂.

E_{Estb} is estimated based on literature that explicitly quantifies the effect of permafrost thawing on additional CO₂ release^{40,41,85,93} and that translates the effect of other unrepresented feedback into a CO₂-equivalent correction⁴². It is estimated to reduce the remaining carbon budget by about 100 Gt CO₂ over the course of the twenty-first century, but this estimate has very low confidence attached to it (Table 1).

The combination of all terms in the framework presented here, and subtracting 290 Gt CO₂ for global CO₂ emissions since 2011, results in a remaining carbon budget B_{lim} of 480 Gt CO₂ for a 50% probability of limiting global warming to 1.5 °C (and with a B_{lim} of 740 and 320 Gt CO₂ for 33% and 66% probabilities, respectively). For a 2 °C limit, B_{lim} amounts to 1,400 Gt CO₂ for a 50% probability (and 1,930 or 1,070 Gt CO₂ for a 33% or 66% probability, respectively). In the IPCC report⁴⁸, reported numbers are 100 Gt CO₂ larger because E_{Estb} is reported separately. In addition, the impact of varying levels of success in reducing non-CO₂ emissions can be estimated from the variation in T_{nonCO_2} suggesting a variation of about ± 250 Gt CO₂ for the remaining carbon budget for a 1.5 °C limit and -500 to $+250$ Gt CO₂ for a 2 °C limit.

methods. In addition, this framework can be used in combination with expert judgment to anticipate potential changes in the remaining carbon budget. Finally, application of the framework presented here also allows us to make a more independent assessment of remaining carbon budgets by drawing on multiple lines of evidence. A simplified version of this framework has also already been applied in ref. ⁴⁸ (see Box 2).

Towards more robust carbon budget estimates

Decomposing the remaining carbon budget into its contributing factors also allows one to identify a set of promising avenues for future research. An area of research that could advance this field is a closer look at TCRE. Future research is anticipated to narrow the range of best estimates of TCRE as well as to clarify the shape of the uncertainty distribution surrounding this value, the influence of a potential lag of CO₂ warming on estimating TCRE, and the validity of the TCRE concept for annual emission rates approaching net zero or during episodes of global net CO₂ removal. For example, at present there are no studies dedicated to explicit analysis of the uncertainty distribution surrounding TCRE, resulting in limited evidence to support the choice of a particular formal distribution (be it normal, lognormal, or otherwise^{10,31,54}) when estimating the remaining carbon budget (see Fig. 2 and Supplementary Table 1).

Another promising area of research is the study of the interdependence between factors and their uncertainties, for example, between uncertainties in T_{hist} and T_{nonCO_2} . This could be pursued through the development of methods that allow robust estimates of recent levels of human-induced warming and allow us to link them to internally consistent projections of future non-CO₂ warming. For example, methodological developments with reduced-complexity climate models could be useful^{57,75,104}, because such models can flexibly and promptly incorporate most up-to-date observations and forcing estimates. This also ties into a larger question of trying to understand the overall, combined uncertainties affecting remaining carbon budgets. At present, each factor of the presented framework comes with its own uncertainties, and a method of formally combining these uncertainties is lacking.

Finally, an important uncertainty in determining the remaining carbon budget continues to be the quantification of uncertain and ill-constrained Earth system feedback processes that feed into the assessment of TCRE or E_{Estb} . Besides affecting carbon budgets that are consistent with limiting maximum warming to a specific temperature threshold, such feedback could help to inform the risks that would be incurred by exhausting and exceeding a specific carbon budget and temperature limit, and attempting to return warming afterwards to lower levels through global net CO₂ removal (see the definition of the threshold return budget in Box 1). Challenges here lie in covering the full range of responses of these highly uncertain components, including high-risk, low-probability outcomes.

Advancements in any of these areas would improve our understanding of carbon budget estimates, and would be invaluable in the ongoing assessment of carbon budgets for the forthcoming Sixth Assessment Report of the IPCC. A systematic understanding of remaining carbon budget estimates is possible if studies improve their reporting. We recommend that future studies estimating the remaining carbon budget report the factors considered within this framework (see Supplementary Text 3 for a checklist): the surface temperature measure and historic warming used, what is assumed for TCRE, and how non-CO₂ warming and Earth system feedback sources are accounted for. A systematic understanding of remaining carbon budget estimates and how they could evolve as science advances will be essential for effective target setting and for communicating the challenges of climate change mitigation.

Online content

Any Methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available in the online version of the paper at <https://doi.org/10.1038/s41586-019-1368-z>.

(Supplementary Text 3), without which it is often virtually impossible to determine them later.

In the future, this framework could play a part in contextualizing new estimates, even if such estimates are obtained using alternative

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Competing interests The authors declare no competing interests.

Additional information

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