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Title:

A framework to estimate and track remaining carbon budgets for stringent climate targets

Preface

Research 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 a remaining carbon budget; the finite total amount of anthropogenic carbon dioxide that can still be emitted into the atmosphere while holding the global average temperature increase to the temperature limit set by the Paris climate agreement. A wide range of estimates for the remaining carbon budget have been reported, which limits its effectiveness for setting emission reduction targets consistent with the Paris temperature limit. Here we present a framework that enables tracking and understanding how remaining carbon budget estimates improve over time as scientific knowledge advances. We propose that the application of the framework can help reconcile differences in remaining carbon budget estimates and can provide a basis for narrowing uncertainties in the range of future estimates.

Text

Since the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report[1], the concept of a carbon budget has risen to prominence as a tool in guiding climate policy[2]. We here define remaining carbon budgets as the finite total amount of CO_2 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 system[3]. 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 CO_2 emissions produced by human activities since the industrial revolution[4-13]. This literature has allowed to define the linear relationship between warming and cumulative CO_2 emissions as the transient climate response to cumulative emissions of CO_2 (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 CO_2 – could potentially be reduced to a roughly linear relationship would allow scientists to draw clear and easy-to-communicate implications. However, additional processes that influence and are influenced by future warming, like the thawing of the permafrost, have recently been included in Earth-system models. These new additions add uncertainty and can change our understanding of this linear relationship. Moreover, global warming is not driven by emissions of CO_2 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 and estimating remaining carbon budgets thus also implies making assumptions about these non-CO_2 contributions. This complicates the relationship between future CO_2 emissions and global warming.

Carbon budgets still became a powerful tool for communicating the challenge we face when aiming to hold warming to 1.5°C and well-below-2°C – the limits of global average temperature increase set in the UN Paris Agreement[14-17]. First, every tonne of CO_2 emitted into the atmosphere by human activities adds to warming, and it hence does not matter whether this tonne of CO_2 is emitted today, tomorrow, or yesterday. This also implies that to limit temperature increase to any level, global CO_2 emissions produced by human activities have to 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 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 CO_2 emissions are brought to zero, warming would stabilize but would not disappear or be reversed[18-21]. 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 CO_2 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 vehicle 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-CO_2 forcers. These studies most often focus on requirements for holding warming to the internationally agreed 1.5°C or 2°C limits[14-16]. Despite all aiming to evaluate the same quantity, the use of different definitions and non-CO_2 climate forcing assumptions, as well as methodological and model differences have led to a wide variety of carbon budget estimates being reported 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 remaining carbon budgets and has therewith tempered the initial enthusiasm about their usefulness as guides 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.

[Insert Box1 here]

Here we present a conceptual framework which allows one to track, understand, update and explain estimates of remaining carbon budgets over time. The framework's structure enables the assessment of individual contributing factors, including historical warming, the TCRE, the zero emissions commitment (ZEC), and non-CO_2 contributions to future warming. It integrates suggestions made in earlier literature[12,47] and is a generalisation and extension of the framework used in the IPCC's Special Report on Global Warming of 1.5°C (ref. 48).

Remaining carbon budget framework

As indicated above, the remaining carbon budget can be defined as the remaining amount of CO_2 emissions that can still be emitted while keeping 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).

Estimates of the remaining carbon budget (RB_{lim}) for a specific temperature limit (T_{lim}) change 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-CO_2 contribution to future temperature rise (T_{nCO2}), the zero emissions commitment (T_{ZEC}), the *TCRE*, and an adjustment term for unrepresented Earth system feedbacks (E_{ESfb}). These terms are visualized in Figure 1 and are described and discussed in turn below.

$$RB_{lim} = (T_{lim} - T_{hist} - T_{nCO2} - T_{ZEC}) \times TCRE^{-1} - E_{ESfb} \qquad \text{Eq. (1)}$$

[INSERT FIGURE 1 HERE]

Arguably the most central term to estimating remaining carbon budgets is the **transient climate response to cumulative emissions of carbon dioxide** (*TCRE*, [°C $GtCO_2^{-1}$], Eq. 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 remaining allowable warming is the result of various contributions shown in Figure 1 and discussed below. The TCRE can be estimated from several lines of evidence, including the observational record[10,12,49-51], CO_2-only[10], and multi-gas simulations[12,31,49-53] with Earth system models of varying complexity. In its latest assessment[54], the IPCC reported the TCRE to fall within the 0.2–0.7 x 10^{-3} °C $GtCO_2^{-1}$ range with at least 66% probability. TCRE, and hence the linear proportionality of warming to cumulative emissions of CO_2, has also been found a robust feature for the domain up to about 7300 $GtCO_2$ of cumulative emissions[54,55], and probably more[56]. This domain of application easily spans the range of 1.5°C- and 2°C-consistent carbon budgets.

After TCRE, the combined remaining allowable warming (represented by $T_{lim} - T_{hist} - T_{nCO2} - T_{ZEC}$) is the next central determinant for estimating remaining carbon budgets. Its first term is the specific **temperature limit of interest** relative to preindustrial levels (T_{lim}, [°C], Eq. 1), while its second term represents the **historical human-induced warming** (T_{hist}, [°C], Eq. 1). The latter is the amount of human-induced warming since preindustrial times until a more recent reference period, for example, the 2006–2015 period.

The estimation of T_{hist} is a central factor affecting the size of remaining carbon budgets, because it determines how far we currently are from policy-relevant temperature limits (e.g. 1.5° 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]. The same is true for T_{lim}, and in case T_{lim} intends to represent an internationally agreed climate goal in line with the Paris Agreement it should do so by definition[15]. 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 is exploring 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 period[60], 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 also plays an important role. Studies analysing climate model simulations or observational products can use different metrics to estimate global mean temperature change (see also 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 CO_2 (ref. [59]). IPCC has typically specified carbon budgets based on globally area-averaged change in surface air temperature[48,66] (SAT). Other studies, however, have also used different metrics and at times even change metrics between observations and projections (Supplementary Table 1). This limits the comparability of these budget estimates[59] – a situation this new framework attempts to avoid.

A further term affecting the remaining allowable warming is the **non-CO_2 contribution to future global temperature rise** (T_{nCO2}, [°C], in Eq. 1, Fig. 1). Current and future warming depends on both CO_2-induced warming and warming due to non-CO_2 forcers. Future non-CO_2 warming might be considerable in light of the unmasking of warming due to reducing emissions of sulphur dioxide[67] and the knowledge that no obvious mitigation options have been identified to completely eliminate several important sources of non-CO_2 greenhouse gases[68,69]. For inclusion in the remaining carbon budget framework, the non-CO_2 warming contribution between a recent reference period (e.g., the same period as T_{hist}) and a specific time in the future has to be estimated. We suggest that this non-CO_2 contribution to future temperature rise is estimated from internally consistent multi-gas scenarios[36,70-74] and at the moment at which global CO_2 emissions reach net zero[48]. Estimating the non-CO_2 warming contribution at that moment in time reflects a situation in which global cumulative emissions of CO_2 are effectively capped and hence allows to directly inform the question of how much CO_2 can be emitted while keeping warming to a given temperature level. If non-CO_2 warming is estimated at other moments in time, its usefulness for informing mitigation requirements would potentially be strongly reduced.

Besides the future evolution of non-CO_2 emissions, the non-CO_2 warming contribution also depends on estimates of the corresponding radiative forcing, including potential changes in surface albedo[43]. Non-CO_2 forcing and warming can be estimated with the help of simple climate models[43,75,76], inferred from more complex climate model runs[77], or taken from the literature[37,48]. Importantly, non-CO_2 emissions would continue to affect warming levels after the time of net CO_2 reach zero, which creates uncertainty in methods that estimate budgets by integrating changes over time and after an overshoot (e.g., see refs. 36,43, and Box 1). These uncertainties are reduced in the here proposed framework by focusing on the time of reaching net zero CO_2 emissions and by considering internally consistent non-CO_2 emissions. Under these assumptions, non-CO_2 emissions are projected to result in a constant or declining forcing and warming after the time of net-zero CO_2.[48,73] However, if under alternative assumptions one would project non-CO_2 warming to continue to increase irrespective of the level of CO_2 emissions[78], this further increase should also be accounted for in T_{nCO2} as it would add to future peak warming.

The **zero emissions commitment (ZEC)** (T_{ZEC}, [°C]) is the next term in the remaining carbon budget framework represented by Equation 1. The ZEC is defined as the additional contribution to peak warming that is still to be expected after a complete cessation of CO_2 emissions[79,80], and hence provides a correction term for the instantaneous linearity postulated by the concept of the TCRE. This ZEC can be either positive or negative, or zero. For estimates of the remaining carbon budget, the ZEC when CO_2 emissions go towards net zero levels is of particular interest. In more general terms, this could also be formulated as an assessment of the lag in CO_2-induced warming at current and declining emissions rates[50,79]. When the ZEC is positive, not all warming will be experienced by the time global CO_2 emissions reach net zero. The estimated additional warming would hence also have to be reduced from the allowable remaining temperature increase. Currently, the ZEC is most often neglected in carbon budget studies (see Supplementary Table 1, with exceptions only hypothesizing the effect of its contribution[37]) and hence implicitly assumed to be zero or negative. Several studies suggest, however, that there might be a smaller[80-83] or larger[84,85] lag between the time when CO_2 emissions are ceased and the time of maximum warming from those emissions. Instead of being accounted for as a separate term, the ZEC could also be integrated in the assessment of TCRE, although a dedicated methodological framework to do so is currently lacking.

Finally, emissions reductions due to **unrepresented Earth system feedbacks** (E_{ESfb}, [$GtCO_2$], Eq. 1) are the last term in the proposed remaining carbon budget framework. Any Earth system feedbacks that are not yet incorporated in estimates of the TCRE or would reduce the applicability of TCRE should be assessed in addition, and accounted and communicated through this term. These feedbacks have typically been related to permafrost thawing[40-42,86] and the associated long-term release of CO_2 and CH_4. However, also other Earth system feedbacks that can affect remaining carbon budgets have been identified[42], including changes in vegetation CO_2 uptake linked to nitrogen availability[87-89]. If an unrepresented feedback results in a direct CO_2 emission from an ecosystem, the translation to the E_{ESfb} term is direct. However, because of the diverse nature of Earth system feedbacks[42], accounting for them through an adjustment in CO_2 emissions is not always straightforward. For example, if a feedback results in the release of other greenhouse gases or affects the Earth system through changes in processes like surface albedo, clouds, or fire regimes, its contribution needs to be translated into an equivalent CO_2 correction term (see refs. [90,91] for two examples). Because most of these Earth system feedbacks are either sensitive to rising CO_2 or to variations in climate parameters, it is expected that these contributions are scenario dependent, non-linear, and in some cases realized over longer time-scales only[40,41,86,92-99]. This adds to the complexity of the translation into a CO_2 equivalent correction term, and makes E_{ESfb} an uncertain contribution. E_{ESfb} could be estimated either for the time at which global net CO_2 emissions become zero, but also, for example, until the end of the century or beyond, assuming anthropogenic CO_2 emissions are kept at net-zero levels but feedbacks continue to change over time[41,86,93,94,98]. Finally, scenario-independent Earth system feedbacks that scale linearly with global average temperature increase could also be incorporated by adjusting the TCRE, as long as they are 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 here propose, 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 impact budget estimates. It also allows 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 remaining carbon budgets.

The road from geosciences to climate policy is long and winding. However, carbon budgets provide one of the simplest and most transparent means to connect geophysical limits imposed by the Earth system to implications for climate policy. For example, they provide the geophysical foundation for setting global net zero targets[6,100] which have recently been picked up by policy scholars for potentially being more effective in guiding policy towards a more actionable climate change mitigation goal[101]. When combined with models that simulate possible transformations to a low-carbon society[102], they can also help inform other 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 precise language exists to describe the nature of the various uncertainty contributions[103] (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 and will only gradually be reduced over time. In other cases, terms are not used consistently throughout the literature resulting in confusion and inconsistencies of carbon budget estimates (Table 1, Supplementary Table 1, Fig. 2). This is the case for the choice of global temperature metric or the time period over which remaining carbon budgets are computed. For increased comparability and flexibility, it would be useful if global surface air temperature (SAT) values would be routinely estimated for observational products, and climate model projections would report both metrics. Some uncertainties represent policy choices[44]. An example of such uncertainty is the estimate of the non-CO_2 emissions contribution to future warming. Future non-CO_2 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 emitting non-CO_2 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 by using a scenario-based approach. For some of the Earth system feedbacks which 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.

[INSERT TABLE 1 HERE]

The overview of assumptions made in carbon budget studies (shown in Fig. 2, and Supplementary Table 1 and 2) can already provide a first step in understanding relative differences between estimates. For example, bar the most recent IPCC assessment[48], none of the estimates available in the literature simultaneously apply consistent global warming metrics for historical and projected temperatures together with a non-CO_2 warming contribution reflecting a future that is in line with the Paris Agreement (Fig. 2, Supplementary Table 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 a formal representation of the uncertainty in TCRE, and studies typically do not include all currently identified Earth system feedbacks, although the impact of some has been described in dedicated studies[40-42,86].

Comparing estimates that are the same in all but their inclusion of some of the unrepresented Earth system feedbacks (from refs [41,48]) suggests that the inclusion of additional Earth system feedbacks could consistently reduce estimates of remaining carbon budgets – something to be kept in mind when future studies that use the latest generation of Earth system models will become available[104]. A further insight is that estimates that apply temperature metrics other than global surface-air temperatures (SAT, see earlier, Fig. 2, and Supplementary Text 2) consistently suggest larger remaining carbon budgets compared to estimates that use SAT 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, estimates using temperature metrics other than global averaged SAT usually suggest larger remaining carbon budgets but also come with clear climate change consequences: a relatively hotter Earth. A sound rationale thus needs to accompany the choice of temperature metric. We strongly recommend using global average SAT as temperature metric because it is computed from invariable fields across models, model runs, and over time. Global average SAT would also allow to easily link findings from new studies to the Paris Agreement temperature goal[59]. More detailed comparisons are complicated or impossible at this stage because the quantifications of the various contributing factors by the original studies are lacking. Hence this call to the research community. Unless studies provide a quantitative discussion of assumptions and factors contributing to their remaining carbon budget estimates, it is often virtually impossible to determine them ex post.

In the future, this framework can hence play a role in contextualizing new estimates, even if they use alternative methods. As science represents a continuous endeavour for deeper understanding, this framework can be used in combination with expert judgment to anticipate potential surprise changes in remaining carbon budgets. Finally, application of the framework presented here also allows to make a more independent assessment of remaining carbon budgets by drawing on multiple lines of evidence. A simplified version of this framework was also already applied in the recent IPCC Special Report on Global Warming of 1.5°C[48] (see Box 2).

[INSERT FIGURE 2 HERE]

Towards more robust carbon budget estimates

The decomposition of remaining carbon budgets in their contributing factors also allows one to identify a set of promising avenues for future research. A first area of research that can help the advancement of this field is a closer look at TCRE. Future research is anticipated to narrow the range of best estimates of TCRE as well as clarify the shape of the uncertainty distribution surrounding this value, the influence of a potential lag of CO_2 warming on estimating TCRE, the validity of the TCRE concept for annual emission rates approaching net zero, or during episodes of global net CO_2 removal. For example, at present there are no dedicated studies explicitly analysing 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 remaining carbon budgets (see Fig. 2, Supplementary Table 1). A second promising area of research is the study of the interdependence between factors and their uncertainties, for example, between uncertainties in T_{hist} and T_{nCO2}. This could be pursued through the development of methods that allow robust estimates of recent levels of human-induced warming and allow to link them to internally consistent projections of future non-CO_2 warming. For example, methodological developments with reduced-form climate models could prove useful to this end[57,75,105], as they can flexibly and timely 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. Currently, each factor of the presented framework comes with its own uncertainties, and a method to formally combine these uncertainties is lacking at present.

Finally, an important uncertainty in determining remaining carbon budgets continues to be the quantification of uncertain and ill-constrained Earth system feedbacks that feed into the assessment of TCRE or E_{ESfb}. Besides affecting carbon budgets consistent with limiting maximum warming to a specific temperature threshold, they could be of particular importance 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 CO_2 removal (see the Threshold Return Budget definition 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 enhance the robustness of our understanding of carbon budget estimates, and would be invaluable input in the on-going assessment of carbon budgets for the 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 check-list): the surface temperature measure and historic warming used, what is assumed for TCRE, and how non-CO_2 warming and Earth system feedbacks are accounted for. A systematic understanding of remaining carbon budget estimates and how they can evolve as science advances will be essential for consolidating their use for target setting and communicating the climate change mitigation challenge.

Tables

Table 1 | Key choices or uncertainties of terms affecting estimates of remaining carbon budgets. *They are listed for each of the terms in Equation 1. The last column indicates the authors' assessment of the current level of understanding of the various uncertainty components.*

Term	**Symbol**	**Key choices or uncertainties**	**Type**	**Level of understanding**
Temperature limit	T_{lim}	Metrics used to express global warming.	Choice	Medium to high
Historical human-induced warming	T_{hist}	Choice of different temperature metrics to express global warming, and consistency with global climate goals.	Choice	Medium to high
Historical human-induced warming	T_{hist}	Incomplete coverage in observational datasets, and methods to estimate human-induced component.	Uncertainty	Medium to high
Non-CO_2 contribution to future global warming	T_{nCO2}	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_{nCO2}	Climate response to non-CO_2 forcers, 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, 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): Linearity, value and distribution of TCRE for decreasing cumulative CO_2 emissions.	Uncertainty	Low
Unrepresented Earth system feedbacks	E_{ESfb}	Timescale and magnitude of permafrost thawing and methane release from wetlands and their representation in Earth system models, as well as other potential feedbacks.	Uncertainty	Very low

Figures

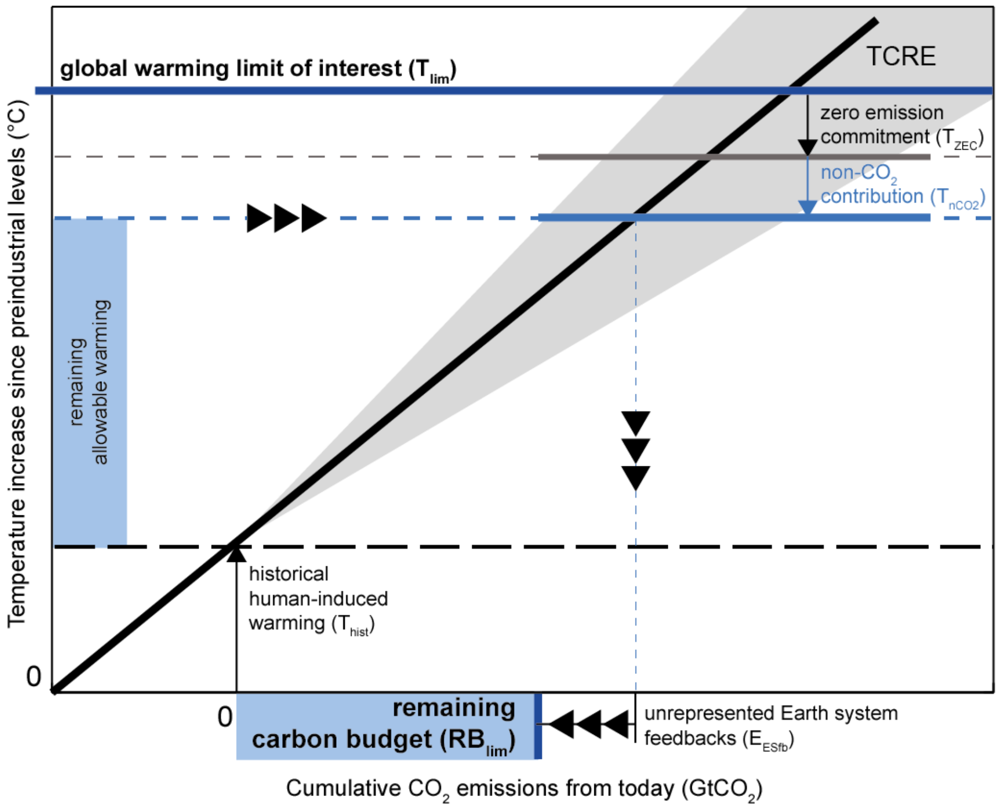

Figure 1 | Schematic of factors contributing to the quantification of a remaining carbon budget. *The schematic shows how the remaining carbon budget can be estimated from various independently assessable quantities, including the historical human-induced warming, the zero emission commitment, the contribution of future non-CO_2 warming (consistent with global net zero CO_2 emissions or otherwise), the transient climate response to cumulative emissions of carbon (TCRE), and further correcting for unrepresented Earth system feedbacks. Besides estimating remaining carbon budgets, the framework can also be applied to understand, decompose and discuss estimates of carbon budgets calculated with other methods.*

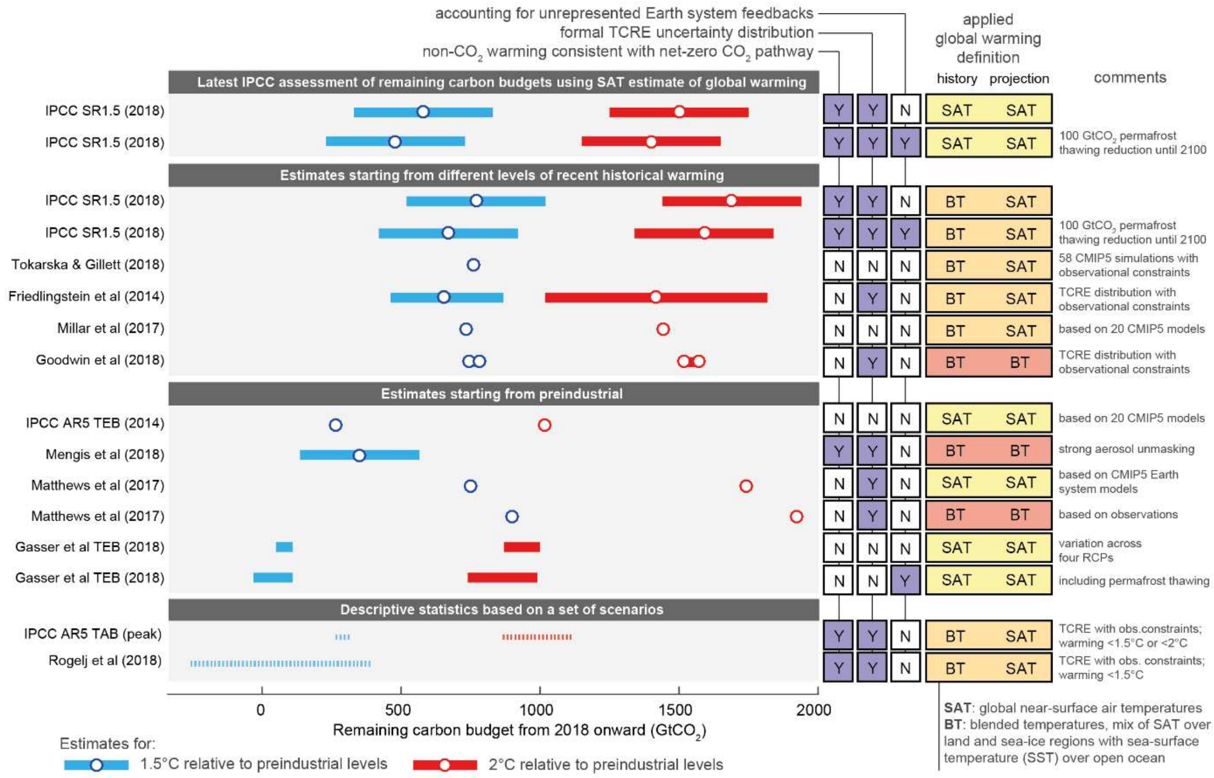

Figure 2 | Comparison of recent remaining carbon budget estimates for limiting global warming to 1.5°C and 2°C relative to preindustrial levels, and overview of factors affecting their variation. *Estimates are shown for a 50% probability of limiting warming to the indicated temperature levels, while 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. Obs. constraints: observational constraints. TEB: threshold exceedance budget[37]; TAB: threshold avoidance budget[37]; The listed studies are: IPCC Special Report on Global Warming of 1.5°C (SR1.5, ref. 48), Tokarska & Gillett[32], Friedlingstein et al[39] (with values for 1.5°C based on own calculations with the same method), Millar et al[30], Goodwin et al[31], IPCC Fifth Assessment Report (AR5, ref. 28), Mengis et al[43], Matthews et al[12], Gasser et al[41], and Rogelj et al[36]. The latest IPCC assessment of remaining carbon budgets assumes 0.97°C of historical warming until 2006–2015, while other estimates can assume either higher or lower warming for that period (Supplementary Table 1). Background and values for all studies are provided in Supplementary Tables 1 and 2.*

Boxes

Box 1 | Commonly used carbon budget definitions

Studies differ in how they define carbon budgets, and these differences affect the accuracy, size, and usefulness of reported estimates. This box provides an overview of five ways 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 in the main text of this paper.

Peak temperature budgets (PTB) or maximum temperature budgets (MTB) are defined as the cumulative amount of net CO_2 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 CO_2 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 CO_2 emissions consistent with achieving international temperature goals[48].

Threshold return budgets (TRB) are defined as the cumulative amount of net CO_2 emissions until a specific level of warming is achieved, 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 CO_2 and hence need to account for potential additional non-linearities in the Earth system response[106]. Supplementary Text 1 clarifies how the framework presented in the main text can be adjusted to suit this definition.

Threshold exceedance budgets (TEB) are defined as the cumulative amount of net CO_2 emissions until the time temperature projections for a given pathway exceed a temperature threshold of interest[37]. This method has been regularly 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 CO_2 emissions consistent with achieving international temperature goals but can still be discussed and understood with the framework presented in the main text of this paper, for example, by explicitly clarifying assumptions regarding historical warming, non-CO_2 warming at the time the temperature threshold is exceeded, and assumed ZEC and TCRE.

Threshold avoidance budgets (TAB) are derived from emissions pathways that avoid crossing a temperature threshold of interest[37]. Their main drawback is that their definition leaves a lot of room for interpretation. First, in contrast to previous budget definitions, no unambiguous point in time is available for TABs until when net CO_2 emissions should be summed, thus requiring additional assumptions[37,39]. Second, any scenario that limits warming below a threshold of interest – be it only barely or by a much larger margin – could be included in a TAB estimate[71]. This makes TAB estimates imprecise, very variable, and difficult to compare across studies. However, even here the framework presented in the main of this paper can help structure discussions.

Finally, some studies report **descriptive statistics** of emissions pathways, like **cumulative CO_2 emissions** until 2050 or 2100, instead of estimates of remaining carbon budgets. These statistics are not directly selected based on their temperature outcome[36,71] and should not be interpreted as geophysical carbon budget requirements.

Box 2 | Example application of remaining carbon budget framework

With the framework at hand (see Equation 1), remaining carbon budgets in line with limiting warming to 1.5°C or 2°C can be estimated by drawing on information available in the literature. We here 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[48].

Definition of temperature metric: Global warming estimated as globally area-averaged SAT change for historical warming and future projections so that T_{lim} is defined by a single consistent metric.
Preindustrial reference period: The 1850–1900 period is taken as a proxy for preindustrial levels.

$\boldsymbol{T_{hist}}$: 0.97°C until 2006–2015 since 1850–1900, derived as the average over four observational datasets[60,107-111] (0.87°C) corrected for by the ratio between SAT and BT informed by models. This level of warming is attributed to climate forcers emitted by human activities and hence accounts for the influence of natural (internal and natural forced) variability of the climate.
$\boldsymbol{T_{nCO2}}$: Estimated from integrated pathways that include all climate forcers emitted by human activities and derived at the time global total CO_2 emissions reach net-zero levels[73,74]. It is estimated[75,76] at about 0.1°C (0–0.2°C, 90% range) in scenarios that reach net-zero CO_2 and limit warming to 1.5°C and at about 0.2°C (0.1–0.4°C, 90% range) in scenarios limiting warming to 2°C.
$\boldsymbol{T_{ZEC}}$: Zero emission commitment is assumed to be zero or negative, and thus to not further impact the remaining allowable warming.

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

TCRE: Assumed to be normally distributed[66] with a 1-sigma range of 0.2–0.7°C x 10^{-3} $GtCO_2^{-1}$

$\boldsymbol{E_{ESfb}}$: Estimated based on literature that explicitly quantifies the effect of permafrost thawing on additional CO_2 release[40,41,86,94] and that translates the effect of other unrepresented feedbacks into a CO_2 equivalent correction[42]. Estimated to reduce the remaining carbon budget by about 100 $GtCO_2$ over the course of the 21st century, but subject to very low confidence (Table 1).

The combination of all terms in the here presented framework, and subtracting 290 $GtCO_2$ for global CO_2 emissions since 2011, results in a median remaining carbon budget RB_{lim} of 480 $GtCO_2$ with a 33–66% range of 740–320 $GtCO_2$ for a global warming limit of 1.5°C and 1400 $GtCO_2$ with a 33–66% range of 1070–1930 $GtCO_2$ for a 2°C limit. In the IPCC report[48], reported numbers are 100 $GtCO_2$ larger as E_{ESfb} is reported separately. In addition, also the impact of varying levels of success in reduction non-CO_2 emissions can be estimated from the variation in T_{nCO2}, suggesting a variation of about ±250 $GtCO_2$ for the remaining carbon budget for 1.5°C and -500 to +250 $GtCO_2$ for the remaining carbon budget for 2°C.

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Author Contributions

All authors contributed significantly to the development of the framework, its description and presentation, and the writing of the paper. CJS produced Supplementary Figure 1. JR coordinated the paper, carried out the comparison of remaining carbon budgets, produced Figures 1 and 2, and led the writing of the paper.

Competing interests

The authors declare no competing interests.