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22 **Title:**

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

24 **Preface**

25 Research during the past decade has shown that global warming is roughly proportional to the total
26 amount of carbon dioxide released into the atmosphere. This makes it possible to estimate a
27 remaining carbon budget; the finite total amount of anthropogenic carbon dioxide that can still be
28 emitted into the atmosphere while holding the global average temperature increase to the
29 temperature limit set by the Paris climate agreement. A wide range of estimates for the remaining
30 carbon budget have been reported, which limits its effectiveness for setting emission reduction
31 targets consistent with the Paris temperature limit. Here we present a framework that enables
32 tracking and understanding how remaining carbon budget estimates improve over time as scientific
33 knowledge advances. We propose that the application of the framework can help reconcile
34 differences in remaining carbon budget estimates and can provide a basis for narrowing
35 uncertainties in the range of future estimates.

36 **Text**

37 Since the Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment Report¹, the concept
38 of a carbon budget has risen to prominence as a tool in guiding climate policy². We here define
39 remaining carbon budgets as the finite total amount of CO₂ that can be emitted into the atmosphere
40 by human activities while still holding global warming to a desired temperature limit. This is not to be
41 confused with another concept, the historical carbon budget, which describes estimates of all major
42 past and contemporary carbon fluxes in the Earth system³. The idea of a remaining carbon budget is
43 grounded in well-established climate science. A series of studies over the past decade has clarified
44 and quantified why the rise in global average temperature increase is roughly proportional to the
45 total cumulative amount of CO₂ emissions produced by human activities since the industrial
46 revolution⁴⁻¹³. This literature has allowed to define the linear relationship between warming and
47 cumulative CO₂ emissions as the transient climate response to cumulative emissions of CO₂ (TCRE).
48 Once established, the appeal of this concept became immediately evident: the possibility that the
49 response of an enormously complex system – such as the response of planet Earth to our emissions
50 of CO₂ – could potentially be reduced to a roughly linear relationship would allow scientists to draw
51 clear and easy-to-communicate implications. However, additional processes that influence and are
52 influenced by future warming, like the thawing of the permafrost, have recently been included in
53 Earth-system models. These new additions add uncertainty and can change our understanding of this
54 linear relationship. Moreover, global warming is not driven by emissions of CO₂ only. Other
55 greenhouse gases (such as methane, fluorinated gases, or nitrous oxide) and aerosols and their
56 precursors (including soot or sulphur dioxide) affect global temperatures and estimating remaining
57 carbon budgets thus also implies making assumptions about these non-CO₂ contributions. This
58 complicates the relationship between future CO₂ emissions and global warming.

59 Carbon budgets still became a powerful tool for communicating the challenge we face when aiming
60 to hold warming to 1.5°C and well-below-2°C – the limits of global average temperature increase set
61 in the UN Paris Agreement¹⁴⁻¹⁷. First, every tonne of CO₂ emitted into the atmosphere by human
62 activities adds to warming, and it hence does not matter whether this tonne of CO₂ is emitted today,
63 tomorrow, or yesterday. This also implies that to limit temperature increase to any level, global CO₂
64 emissions produced by human activities have to be reduced to net zero levels at some point in time
65 and, on average, stay at net zero levels thereafter. Furthermore, when aiming to limit warming below

66 a specific limit, a finite carbon budget also implies that the more we emit in the coming years, the
67 faster emissions will have to decline thereafter to stay within the same budget – simple arithmetic.
68 Finally, once net CO₂ emissions are brought to zero, warming would stabilize but would not
69 disappear or be reversed¹⁸⁻²¹. Any amount by which a carbon budget compatible with a desired
70 temperature limit is missed or exceeded would thus have to be actively and permanently removed
71 from the atmosphere in later years. This could be achieved through measures that result in net
72 negative CO₂ emissions, which come with their own technical and social complications²²⁻²⁷. Besides
73 its role as a communication tool, the carbon budget concept also provides a vehicle to exchange
74 knowledge across disciplines. For example, such knowledge exchange is already happening for
75 climate change mitigation requirements between the geoscience community and other disciplines
76 that study climate change from a more societal angle^{28,29}.

77 **Diversity that may confuse**

78 Unfortunately, all that glitters is not gold. Over the past five years, a plethora of studies have been
79 published^{12,30-44} further exploring and estimating the size of carbon budgets while in some way
80 accounting for non-CO₂ forcings. These studies most often focus on requirements for holding warming
81 to the internationally agreed 1.5°C or 2°C limits¹⁴⁻¹⁶. Despite all aiming to evaluate the same quantity,
82 the use of different definitions and non-CO₂ climate forcing assumptions, as well as methodological
83 and model differences have led to a wide variety of carbon budget estimates being reported to
84 achieve temperature goals that are nominally the same (see Box 1 for an overview of carbon budget
85 estimation approaches). This variation seems to have decreased instead of increased the broader
86 understanding of remaining carbon budgets and has therewith tempered the initial enthusiasm
87 about their usefulness as guides for policy making and target setting^{45,46}. This confusion is avoidable,
88 however. Differences in remaining carbon budget estimates can be understood if a set of potential
89 contributing factors are carefully taken into account.

90 *[Insert Box1 here]*

91 Here we present a conceptual framework which allows one to track, understand, update and explain
92 estimates of remaining carbon budgets over time. The framework's structure enables the assessment
93 of individual contributing factors, including historical warming, the TCRE, the zero emissions
94 commitment (ZEC), and non-CO₂ contributions to future warming. It integrates suggestions made in
95 earlier literature^{12,47} and is a generalisation and extension of the framework used in the IPCC's Special
96 Report on Global Warming of 1.5°C (ref. 48).

97 **Remaining carbon budget framework**

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

104 Estimates of the remaining carbon budget (RB_{lim}) for a specific temperature limit (T_{lim}) change as a
105 function of five terms that represent aspects of the geophysical and coupled human-environment
106 system (Equation 1): the historical human-induced warming to date (T_{hist}), the non-CO₂ contribution
107 to future temperature rise (T_{ncO_2}), the zero emissions commitment (T_{ZEC}), the $TCRE$, and an
108 adjustment term for unrepresented Earth system feedbacks (E_{ESfb}). These terms are visualized in
109 Figure 1 and are described and discussed in turn below.

110
$$RB_{lim} = (T_{lim} - T_{hist} - T_{nCO2} - T_{ZEC}) \times TCRE^{-1} - E_{ESfb} \quad \text{Eq. (1)}$$

111 [INSERT FIGURE 1 HERE]

112 Arguably the most central term to estimating remaining carbon budgets is the **transient climate**
113 **response to cumulative emissions of carbon dioxide** ($TCRE$, [$^{\circ}\text{C GtCO}_2^{-1}$], Eq. 1). In essence, the
114 remaining carbon budget is estimated by multiplying the remaining allowable warming with the
115 inverse of the $TCRE$, where the magnitude of remaining allowable warming is the result of various
116 contributions shown in Figure 1 and discussed below. The $TCRE$ can be estimated from several lines
117 of evidence, including the observational record^{10,12,49-51}, CO_2 -only¹⁰, and multi-gas simulations^{12,31,49-53}
118 with Earth system models of varying complexity. In its latest assessment⁵⁴, the IPCC reported the
119 $TCRE$ to fall within the $0.2\text{--}0.7 \times 10^{-3} \text{ }^{\circ}\text{C GtCO}_2^{-1}$ range with at least 66% probability. $TCRE$, and hence
120 the linear proportionality of warming to cumulative emissions of CO_2 , has also been found a robust
121 feature for the domain up to about 7300 GtCO_2 of cumulative emissions^{54,55}, and probably more⁵⁶.
122 This domain of application easily spans the range of 1.5°C - and 2°C -consistent carbon budgets.

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

129 The estimation of T_{hist} is a central factor affecting the size of remaining carbon budgets, because it
130 determines how far we currently are from policy-relevant temperature limits (e.g. 1.5° or 2°C). The
131 assessment of T_{hist} should adequately isolate the human-induced warming signal from the effects of
132 natural forcing and variability^{57,58}. The same is true for T_{lim} , and in case T_{lim} intends to represent an
133 internationally agreed climate goal in line with the Paris Agreement it should do so by definition¹⁵.
134 Two additional choices play an important role in determining or setting T_{hist} and T_{lim} : the choice of the
135 preindustrial reference period and the temperature metric for determining global average
136 temperature increase. Neither the preindustrial reference period nor the specific warming metric are
137 explicitly defined by the Paris Agreement and recent literature is exploring the implications and
138 interpretations of this ambiguity^{34,35,59}.

139 The 1850–1900 period is often used as a proxy for preindustrial levels because observational
140 temperature records stretch back to the beginning of that period⁶⁰, and key scientific reports that fed
141 into the Paris Agreement also used this proxy^{1,59,61,62} (see Supplementary Text 2 for more details).
142 Other periods have been suggested⁶³⁻⁶⁵, but ultimately the crux lies in that T_{hist} and T_{lim} should always
143 be expressed relative to the same preindustrial reference period to avoid introducing erroneous
144 changes to the remaining allowable warming and therewith the remaining carbon budget. Besides
145 defining an appropriate preindustrial reference period, the choice of metric by which warming is
146 estimated from that period also plays an important role. Studies analysing climate model simulations
147 or observational products can use different metrics to estimate global mean temperature change
148 (see also Supplementary Text 2). The impact of this metric choice has been highlighted recently with
149 studies^{34,59} showing that this choice can result in variations in the estimated global warming of the
150 order of 10% (Supplementary Fig. 1), leading to a potential variation in remaining carbon budget
151 estimates of more than 400 billion tonnes of CO_2 (ref. ⁵⁹). IPCC has typically specified carbon budgets
152 based on globally area-averaged change in surface air temperature^{48,66} (SAT). Other studies,
153 however, have also used different metrics and at times even change metrics between observations
154 and projections (Supplementary Table 1). This limits the comparability of these budget estimates⁵⁹ –
155 a situation this new framework attempts to avoid.

156 A further term affecting the remaining allowable warming is the **non-CO₂ contribution to future**
157 **global temperature rise** (T_{nCO_2} , [°C], in Eq. 1, Fig. 1). Current and future warming depends on both
158 CO₂-induced warming and warming due to non-CO₂ forcers. Future non-CO₂ warming might be
159 considerable in light of the unmasking of warming due to reducing emissions of sulphur dioxide⁶⁷ and
160 the knowledge that no obvious mitigation options have been identified to completely eliminate
161 several important sources of non-CO₂ greenhouse gases^{68,69}. For inclusion in the remaining carbon
162 budget framework, the non-CO₂ warming contribution between a recent reference period (e.g., the
163 same period as T_{hist}) and a specific time in the future has to be estimated. We suggest that this non-
164 CO₂ contribution to future temperature rise is estimated from internally consistent multi-gas
165 scenarios^{36,70-74} and at the moment at which global CO₂ emissions reach net zero⁴⁸. Estimating the
166 non-CO₂ warming contribution at that moment in time reflects a situation in which global cumulative
167 emissions of CO₂ are effectively capped and hence allows to directly inform the question of how
168 much CO₂ can be emitted while keeping warming to a given temperature level. If non-CO₂ warming is
169 estimated at other moments in time, its usefulness for informing mitigation requirements would
170 potentially be strongly reduced.

171 Besides the future evolution of non-CO₂ emissions, the non-CO₂ warming contribution also depends
172 on estimates of the corresponding radiative forcing, including potential changes in surface albedo⁴³.
173 Non-CO₂ forcing and warming can be estimated with the help of simple climate models^{43,75,76},
174 inferred from more complex climate model runs⁷⁷, or taken from the literature^{37,48}. Importantly, non-
175 CO₂ emissions would continue to affect warming levels after the time of net CO₂ reach zero, which
176 creates uncertainty in methods that estimate budgets by integrating changes over time and after an
177 overshoot (e.g., see refs. 36,43, and Box 1). These uncertainties are reduced in the here proposed
178 framework by focusing on the time of reaching net zero CO₂ emissions and by considering internally
179 consistent non-CO₂ emissions. Under these assumptions, non-CO₂ emissions are projected to result
180 in a constant or declining forcing and warming after the time of net-zero CO₂.^{48,73} However, if under
181 alternative assumptions one would project non-CO₂ warming to continue to increase irrespective of
182 the level of CO₂ emissions⁷⁸, this further increase should also be accounted for in T_{nCO_2} as it would
183 add to future peak warming.

184 The **zero emissions commitment (ZEC)** (T_{ZEC} , [°C]) is the next term in the remaining carbon budget
185 framework represented by Equation 1. The ZEC is defined as the additional contribution to peak
186 warming that is still to be expected after a complete cessation of CO₂ emissions^{79,80}, and hence
187 provides a correction term for the instantaneous linearity postulated by the concept of the TCRE.
188 This ZEC can be either positive or negative, or zero. For estimates of the remaining carbon budget,
189 the ZEC when CO₂ emissions go towards net zero levels is of particular interest. In more general
190 terms, this could also be formulated as an assessment of the lag in CO₂-induced warming at current
191 and declining emissions rates^{50,79}. When the ZEC is positive, not all warming will be experienced by
192 the time global CO₂ emissions reach net zero. The estimated additional warming would hence also
193 have to be reduced from the allowable remaining temperature increase. Currently, the ZEC is most
194 often neglected in carbon budget studies (see Supplementary Table 1, with exceptions only
195 hypothesizing the effect of its contribution³⁷) and hence implicitly assumed to be zero or negative.
196 Several studies suggest, however, that there might be a smaller⁸⁰⁻⁸³ or larger^{84,85} lag between the
197 time when CO₂ emissions are ceased and the time of maximum warming from those emissions.
198 Instead of being accounted for as a separate term, the ZEC could also be integrated in the
199 assessment of TCRE, although a dedicated methodological framework to do so is currently lacking.

200 Finally, emissions reductions due to **unrepresented Earth system feedbacks** (E_{ESfb} , [GtCO₂], Eq. 1) are
201 the last term in the proposed remaining carbon budget framework. Any Earth system feedbacks that
202 are not yet incorporated in estimates of the TCRE or would reduce the applicability of TCRE should be

203 assessed in addition, and accounted and communicated through this term. These feedbacks have
204 typically been related to permafrost thawing^{40-42,86} and the associated long-term release of CO₂ and
205 CH₄. However, also other Earth system feedbacks that can affect remaining carbon budgets have
206 been identified⁴², including changes in vegetation CO₂ uptake linked to nitrogen availability⁸⁷⁻⁸⁹. If an
207 unrepresented feedback results in a direct CO₂ emission from an ecosystem, the translation to the
208 E_{ESfb} term is direct. However, because of the diverse nature of Earth system feedbacks⁴², accounting
209 for them through an adjustment in CO₂ emissions is not always straightforward. For example, if a
210 feedback results in the release of other greenhouse gases or affects the Earth system through
211 changes in processes like surface albedo, clouds, or fire regimes, its contribution needs to be
212 translated into an equivalent CO₂ correction term (see refs. ^{90,91} for two examples). Because most of
213 these Earth system feedbacks are either sensitive to rising CO₂ or to variations in climate parameters,
214 it is expected that these contributions are scenario dependent, non-linear, and in some cases
215 realized over longer time-scales only^{40,41,86,92-99}. This adds to the complexity of the translation into a
216 CO₂ equivalent correction term, and makes E_{ESfb} an uncertain contribution. E_{ESfb} could be estimated
217 either for the time at which global net CO₂ emissions become zero, but also, for example, until the
218 end of the century or beyond, assuming anthropogenic CO₂ emissions are kept at net-zero levels but
219 feedbacks continue to change over time^{41,86,93,94,98}. Finally, scenario-independent Earth system
220 feedbacks that scale linearly with global average temperature increase could also be incorporated by
221 adjusting the TCRE, as long as they are not double-counted in both E_{ESfb} and TCRE.

222 **Tracking and explaining scientific progress**

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

231 The road from geosciences to climate policy is long and winding. However, carbon budgets provide
232 one of the simplest and most transparent means to connect geophysical limits imposed by the Earth
233 system to implications for climate policy. For example, they provide the geophysical foundation for
234 setting global net zero targets^{6,100} which have recently been picked up by policy scholars for
235 potentially being more effective in guiding policy towards a more actionable climate change
236 mitigation goal¹⁰¹. When combined with models that simulate possible transformations to a low-
237 carbon society¹⁰², they can also help inform other targets.

238 Nevertheless, adequately characterizing and communicating the uncertainties that surround carbon
239 budget estimates is a challenge that will remain. These uncertainties are not unfathomable,
240 however, and precise language exists to describe the nature of the various uncertainty
241 contributions¹⁰³ (Table 1, Fig. 2). In some cases, uncertainties exist because of our imprecise
242 knowledge of certain processes or lack of precise measurements. This uncertainty is applicable to all
243 terms in our framework and will only gradually be reduced over time. In other cases, terms are not
244 used consistently throughout the literature resulting in confusion and inconsistencies of carbon
245 budget estimates (Table 1, Supplementary Table 1, Fig. 2). This is the case for the choice of global
246 temperature metric or the time period over which remaining carbon budgets are computed. For
247 increased comparability and flexibility, it would be useful if global surface air temperature (SAT)
248 values would be routinely estimated for observational products, and climate model projections
249 would report both metrics. Some uncertainties represent policy choices⁴⁴. An example of such

250 uncertainty is the estimate of the non-CO₂ emissions contribution to future warming. Future non-CO₂
251 emissions depend on future socio-economic developments and deployment of mitigation measures,
252 and these are influenced by policy and societal choices today, for example, regarding how much
253 emitting non-CO₂ greenhouse gases is penalized or which sectors are targeted when promoting
254 innovation for climate change mitigation. These policy-driven uncertainties and ambiguities can be
255 understood, quantified, and explained by using a scenario-based approach. For some of the Earth
256 system feedbacks which are not fully represented in models, a quantification of their impact remains
257 difficult. Expert judgment can be applied in this case to provide an estimate of its importance.

258 *[INSERT TABLE 1 HERE]*

259 The overview of assumptions made in carbon budget studies (shown in Fig. 2, and Supplementary
260 Table 1 and 2) can already provide a first step in understanding relative differences between
261 estimates. For example, bar the most recent IPCC assessment⁴⁸, none of the estimates available in
262 the literature simultaneously apply consistent global warming metrics for historical and projected
263 temperatures together with a non-CO₂ warming contribution reflecting a future that is in line with
264 the Paris Agreement (Fig. 2, Supplementary Table 1 and 2). Several estimates also infer the chance of
265 limiting warming to 1.5°C from ad-hoc frequency distributions of model results, instead of a formal
266 representation of the uncertainty in TCRE, and studies typically do not include all currently identified
267 Earth system feedbacks, although the impact of some has been described in dedicated studies^{40-42,86}.

268 Comparing estimates that are the same in all but their inclusion of some of the unrepresented Earth
269 system feedbacks (from refs ^{41,48}) suggests that the inclusion of additional Earth system feedbacks
270 could consistently reduce estimates of remaining carbon budgets – something to be kept in mind
271 when future studies that use the latest generation of Earth system models will become available¹⁰⁴. A
272 further insight is that estimates that apply temperature metrics other than global surface-air
273 temperatures (SAT, see earlier, Fig. 2, and Supplementary Text 2) consistently suggest larger
274 remaining carbon budgets compared to estimates that use SAT only. The reasons underlying this
275 perceived shift are well-understood (see Supplementary Text 2) and can be identified as an artefact
276 of a methodological choice. To be sure, estimates using temperature metrics other than global
277 averaged SAT usually suggest larger remaining carbon budgets but also come with clear climate
278 change consequences: a relatively hotter Earth. A sound rationale thus needs to accompany the
279 choice of temperature metric. We strongly recommend using global average SAT as temperature
280 metric because it is computed from invariable fields across models, model runs, and over time.
281 Global average SAT would also allow to easily link findings from new studies to the Paris Agreement
282 temperature goal⁵⁹. More detailed comparisons are complicated or impossible at this stage because
283 the quantifications of the various contributing factors by the original studies are lacking. Hence this
284 call to the research community. Unless studies provide a quantitative discussion of assumptions and
285 factors contributing to their remaining carbon budget estimates, it is often virtually impossible to
286 determine them ex post.

287 In the future, this framework can hence play a role in contextualizing new estimates, even if they use
288 alternative methods. As science represents a continuous endeavour for deeper understanding, this
289 framework can be used in combination with expert judgment to anticipate potential surprise changes
290 in remaining carbon budgets. Finally, application of the framework presented here also allows to
291 make a more independent assessment of remaining carbon budgets by drawing on multiple lines of
292 evidence. A simplified version of this framework was also already applied in the recent IPCC Special
293 Report on Global Warming of 1.5°C⁴⁸ (see Box 2).

294 *[INSERT FIGURE 2 HERE]*

295 **Towards more robust carbon budget estimates**

296 The decomposition of remaining carbon budgets in their contributing factors also allows one to
297 identify a set of promising avenues for future research. A first area of research that can help the
298 advancement of this field is a closer look at TCRE. Future research is anticipated to narrow the range
299 of best estimates of TCRE as well as clarify the shape of the uncertainty distribution surrounding this
300 value, the influence of a potential lag of CO₂ warming on estimating TCRE, the validity of the TCRE
301 concept for annual emission rates approaching net zero, or during episodes of global net CO₂
302 removal. For example, at present there are no dedicated studies explicitly analysing the uncertainty
303 distribution surrounding TCRE resulting in limited evidence to support the choice of a particular
304 formal distribution (be it normal, lognormal, or otherwise^{10,31,54}) when estimating remaining carbon
305 budgets (see Fig. 2, Supplementary Table 1). A second promising area of research is the study of the
306 interdependence between factors and their uncertainties, for example, between uncertainties in T_{hist}
307 and T_{nCO_2} . This could be pursued through the development of methods that allow robust estimates of
308 recent levels of human-induced warming and allow to link them to internally consistent projections
309 of future non-CO₂ warming. For example, methodological developments with reduced-form climate
310 models could prove useful to this end^{57,75,105}, as they can flexibly and timely incorporate most up-to-
311 date observations and forcing estimates. This also ties into a larger question of trying to understand
312 the overall, combined uncertainties affecting remaining carbon budgets. Currently, each factor of the
313 presented framework comes with its own uncertainties, and a method to formally combine these
314 uncertainties is lacking at present.

315 Finally, an important uncertainty in determining remaining carbon budgets continues to be the
316 quantification of uncertain and ill-constrained Earth system feedbacks that feed into the assessment
317 of TCRE or E_{ESfb} . Besides affecting carbon budgets consistent with limiting maximum warming to a
318 specific temperature threshold, they could be of particular importance to inform the risks that would
319 be incurred by exhausting and exceeding a specific carbon budget and temperature limit, and
320 attempting to return warming afterwards to lower levels through global net CO₂ removal (see the
321 Threshold Return Budget definition in Box 1). Challenges here lie in covering the full range of
322 responses of these highly uncertain components, including high-risk low-probability outcomes.

323 Advancements in any of these areas would enhance the robustness of our understanding of carbon
324 budget estimates, and would be invaluable input in the on-going assessment of carbon budgets for
325 the Sixth Assessment Report of the IPCC. A systematic understanding of remaining carbon budget
326 estimates is possible if studies improve their reporting. We recommend that future studies
327 estimating the remaining carbon budget report the factors considered within this framework (see
328 Supplementary Text 3 for a check-list): the surface temperature measure and historic warming used,
329 what is assumed for TCRE, and how non-CO₂ warming and Earth system feedbacks are accounted for.
330 A systematic understanding of remaining carbon budget estimates and how they can evolve as
331 science advances will be essential for consolidating their use for target setting and communicating
332 the climate change mitigation challenge.

333

334 **Tables**

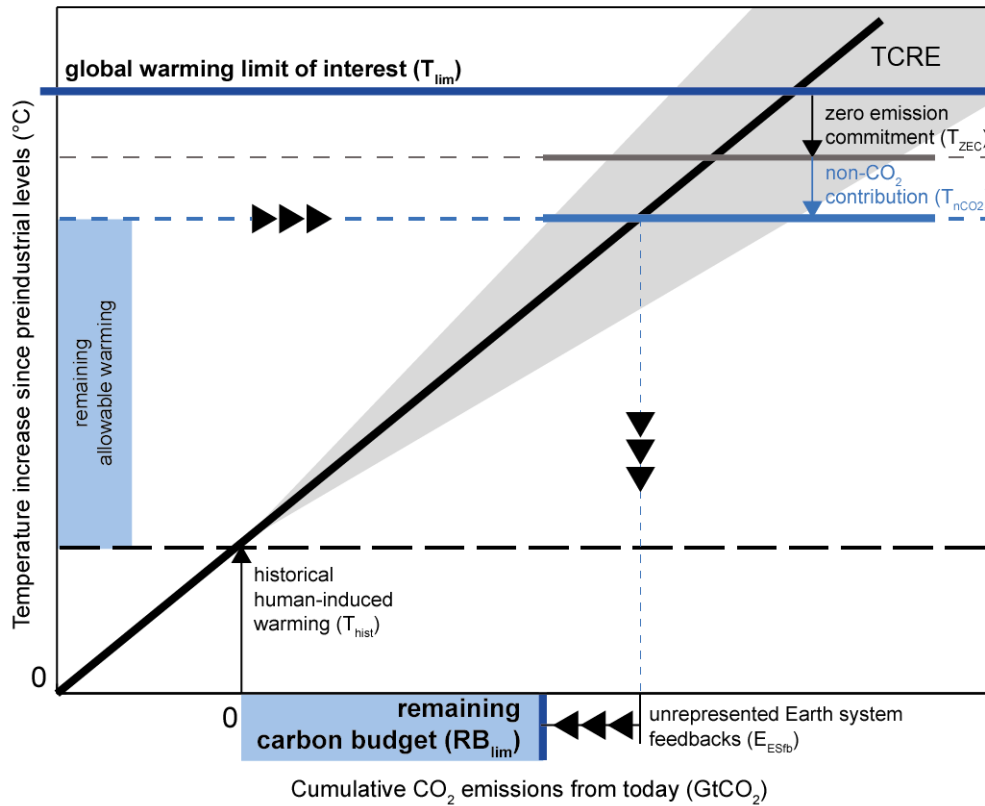
335 **Table 1 | Key choices or uncertainties of terms affecting estimates of remaining carbon budgets.**
 336 *They are listed for each of the terms in Equation 1. The last column indicates the authors' assessment*
 337 *of the current level of understanding of the various uncertainty components.*

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_{nCO_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_{nCO_2}	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

338

339

340 **Figures**

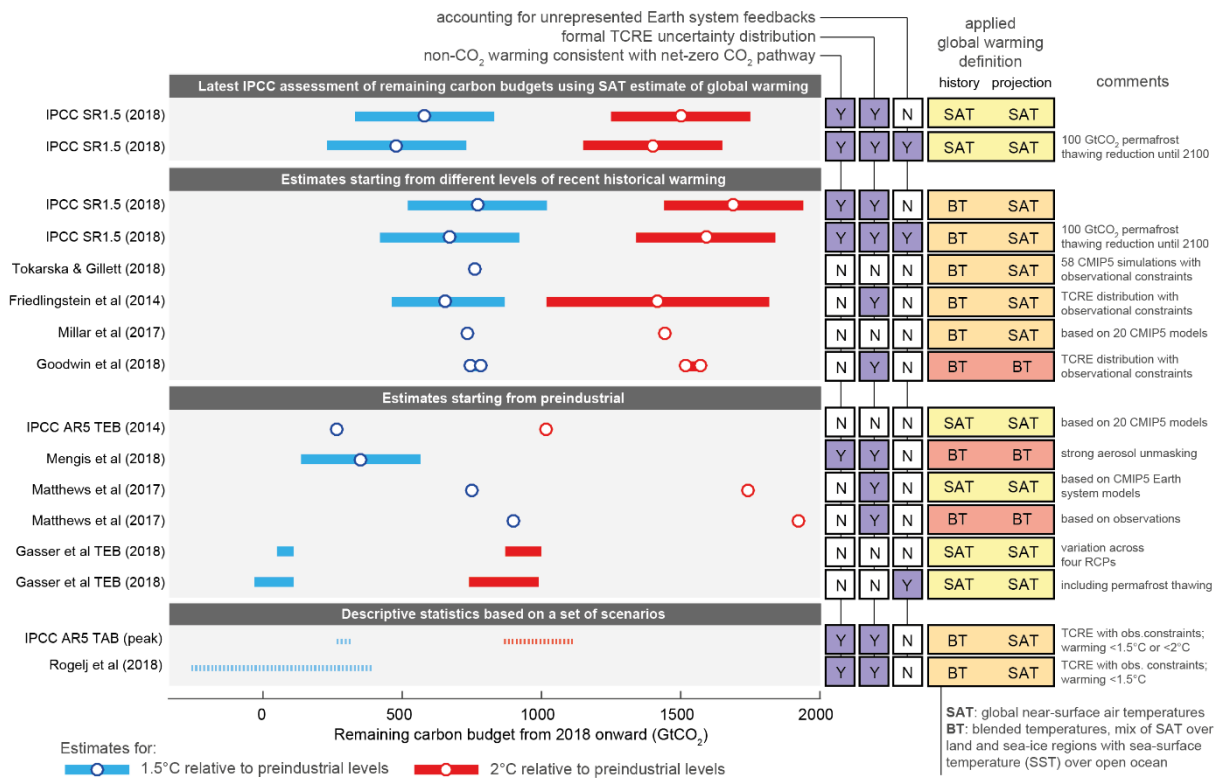


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342 **Figure 1 | Schematic of factors contributing to the quantification of a remaining carbon budget.**

343 *The schematic shows how the remaining carbon budget can be estimated from various independently*
344 *assessable quantities, including the historical human-induced warming, the zero emission*
345 *commitment, the contribution of future non-CO₂ warming (consistent with global net zero CO₂*
346 *emissions or otherwise), the transient climate response to cumulative emissions of carbon (TCRE), and*
347 *further correcting for unrepresented Earth system feedbacks. Besides estimating remaining carbon*
348 *budgets, the framework can also be applied to understand, decompose and discuss estimates of*
349 *carbon budgets calculated with other methods.*

350



352

353 **Figure 2 | Comparison of recent remaining carbon budget estimates for limiting global warming to**
 354 **1.5°C and 2°C relative to preindustrial levels, and overview of factors affecting their variation.**

355 *Estimates are shown for a 50% probability of limiting warming to the indicated temperature levels,*
 356 *while additional estimates for a 66% probability are provided in Supplementary Table 2. Several*
 357 *studies do not report formal probabilities, but report the frequency distribution across model*
 358 *simulations instead. The latter estimates are marked N in the “formal TCRE uncertainty distribution”*
 359 *column. Estimates shown with dashed lines indicate carbon budget estimates with an imprecise level*
 360 *of implied global warming, for example, because they were reported for a radiative forcing target*
 361 *instead. Obs. constraints: observational constraints. TEB: threshold exceedance budget³⁷; TAB:*
 362 *threshold avoidance budget³⁷; The listed studies are: IPCC Special Report on Global Warming of 1.5°C*
 363 *(SR1.5, ref. 48), Tokarska & Gillett³², Friedlingstein et al³⁹ (with values for 1.5°C based on own*
 364 *calculations with the same method), Millar et al³⁰, Goodwin et al³¹, IPCC Fifth Assessment Report*
 365 *(AR5, ref. 28), Mengis et al⁴³, Matthews et al¹², Gasser et al⁴¹, and Rogelj et al³⁶. The latest IPCC*
 366 *assessment of remaining carbon budgets assumes 0.97°C of historical warming until 2006–2015,*
 367 *while other estimates can assume either higher or lower warming for that period (Supplementary*
 368 *Table 1). Background and values for all studies are provided in Supplementary Tables 1 and 2.*

369

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 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 consistent with achieving international temperature goals⁴⁸.

Threshold return budgets (TRB) are defined as the cumulative amount of net CO₂ 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 CO₂ and hence need to account for potential additional non-linearities in the Earth system response¹⁰⁶. 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 CO₂ emissions until the time temperature projections for a given pathway exceed a temperature threshold of interest³⁷. 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 CO₂ 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-CO₂ 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 interest³⁷. 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 CO₂ 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 estimate⁷¹. 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 CO₂ 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°C⁴⁸.

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.

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.

T_{nCO_2} : Estimated from integrated pathways that include all climate forcers emitted by human activities and derived at the time global total CO₂ 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 CO₂ 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.

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 distributed⁶⁶ with a 1-sigma range of 0.2–0.7°C x 10⁻³ GtCO₂⁻¹

E_{ESfb} : Estimated based on literature that explicitly quantifies the effect of permafrost thawing on additional CO₂ release^{40,41,86,94} and that translates the effect of other unrepresented feedbacks into a CO₂ equivalent correction⁴². Estimated to reduce the remaining carbon budget by about 100 GtCO₂ 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 GtCO₂ for global CO₂ emissions since 2011, results in a median remaining carbon budget RB_{lim} of 480 GtCO₂ with a 33–66% range of 740–320 GtCO₂ for a global warming limit of 1.5°C and 1400 GtCO₂ with a 33–66% range of 1070–1930 GtCO₂ for a 2°C limit. In the IPCC report⁴⁸, reported numbers are 100 GtCO₂ larger as E_{ESfb} is reported separately. In addition, also the impact of varying levels of success in reduction non-CO₂ emissions can be estimated from the variation in T_{nCO_2} , suggesting a variation of about ±250 GtCO₂ for the remaining carbon budget for 1.5°C and -500 to +250 GtCO₂ for the remaining carbon budget for 2°C.

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700 **Author Contributions**

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

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706 **Competing interests**

707 The authors declare no competing interests.

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