Title:

Differences between carbon budget estimates unravelled

Authors:

Joeri Rogelj[1,2,*], Michiel Schaeffer[3,4], Pierre Friedlingstein[5], Nathan P. Gillett[6], Detlef P. van Vuuren[7,8], Keywan Riahi[1,9], Myles Allen[10,11], Reto Knutti[2]

* Corresponding author

Affiliations:

[1] ENE Program, International Institute for Applied Systems Analysis (IIASA)

Schlossplatz 1, A-2361 Laxenburg, Austria

[2] Institute for Atmospheric and Climate Science, ETH Zurich,

Universitätstrasse 16, CH-8092 Zürich, Switzerland

[3] Climate Analytics

Karl-Liebknechtstrasse 5, 10178 Berlin, Germany

[4] Environmental Systems Analysis Group, Wageningen University and Research Centre

PO Box 47, 6700 AA Wageningen, The Netherlands

[5] College of Engineering, Mathematics and Physical Sciences, University of Exeter

Exeter EX4 4QF, UK,

[6] Canadian Centre for Climate Modelling and Analysis, Environment Canada

University of Victoria, PO Box 1700, STN CSC, Victoria, BC, V8W 2Y2, Canada.

[7] PBL Netherlands Environmental Assessment Agency

PO Box 303, 3720 AH Bilthoven, The Netherlands

[8] Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University

Budapestlaan 4, 3584 CD Utrecht, The Netherlands

[9] Graz University of Technology

Inffeldgasse, A-8010 Graz, Austria

[10] ECI, School of Geography and the Environment, University of Oxford

Oxford OX1 3QY, UK

[11] Department of Physics, University of Oxford

Parks Road, Oxford OX1 3PU, UK

Preface:

Several methods exist to estimate the cumulative carbon emissions which would keep global warming to below a given temperature limit. We here review estimates reported by the IPCC and the recent literature, and discuss the reasons underlying their differences. The most scientifically robust number – the carbon budget for CO_2-induced warming only – is also the least relevant for real-world policy. Including all greenhouse gases and using methods based on scenarios that avoid instead of exceed a given temperature limit results in lower carbon budgets. To limit warming below the internationally agreed temperature limit of 2°C relative to preindustrial levels with >66% chance, the most appropriate carbon budget estimate is 590-1240 $GtCO_2$ from 2015 onward. Variations within this range depend on the probability of staying below 2°C and on end-of-century non-CO_2 warming. Current annual CO_2 emissions are about 40 $GtCO_2$/yr, and global CO_2 emissions thus have to be reduced urgently to keep within a 2°C-compatible budget.

<u>Main text:</u>

The ultimate objective of the international climate negotiations is to prevent dangerous anthropogenic interference with the climate system[1]. Since 2010, this objective has been interpreted as limiting global-mean temperature increase to below 2°C relative to preindustrial levels[2], although discussion remains whether it needs to be strengthened to 1.5°C (for example, see Ref. 3).

Over the past decade, a large body of literature has appeared which shows that the maximum global-mean temperature increase as a result of carbon dioxide emissions is nearly linearly proportional to the total cumulative carbon (CO_2) emissions[4-11]. Maximum warming is also influenced by the amount of non-CO_2 forcing leading up to the time of the peak[12-14]. This has culminated in the most recent assessment of the Intergovernmental Panel on Climate Change (IPCC) in the form of several estimates of emission budgets compatible with limiting warming to below specific temperature limits. Here, we first explain the underlying scientific rationale for such budgets and then continue with a detailed account of the strengths and limitations of the various budgets reported in both the IPCC Fifth Assessment Report (AR5) and the recent literature, and of the differences between them.

The purpose of budgets

The IPCC AR5 Working Group I (WGI) Report[15] indicated that the total net cumulative emission of anthropogenic CO_2 is the principal driver of long-term warming since preindustrial times. Therefore, to limit the warming caused by CO_2 emissions to below a given temperature threshold, cumulative CO_2 emissions from all anthropogenic sources need to be capped to a specific amount, sometimes referred to as carbon budget or quota (which, in the context of this paper, refers to global values and not to emission allowances of single countries).

The near-linearity between peak global-mean temperature rise and cumulative CO_2 emissions is the result of an incidental interplay of several compensating feedback processes in both the carbon cycle and the climate: the logarithmic relationship between atmospheric CO_2 concentrations and radiative forcing, the decline of ocean-heat-uptake efficiency over time, as well as the change of the airborne fraction of anthropogenic CO_2 emissions[15]. This compensating relationship is robust over a range of CO_2 emissions and over timescales of up to a few centuries, with very few exceptions[16]. Such a relationship is not generally available for other anthropogenic radiatively active species. An approximate proportionality exists for other long-lived greenhouse gases (GHG) for warming during this century[12], while for short-lived climate forcers the rate of emissions leading up to the time of peak warming is important[12-14].

The unique characteristics of the Earth system's response to anthropogenic carbon emissions allow the definition of a quantity called the transient climate response to cumulative emissions of carbon

(TCRE). TCRE is defined as global average surface temperature change per unit of total cumulative anthropogenic CO_2 emissions, typically 1000 PgC. The IPCC AR5 assessed TCRE to fall 'likely' (i.e. with greater than 66% probability[17]) between 0.8 to 2.5°C per 1000 PgC for cumulative CO_2 emissions less than about 2000 PgC and until the time at which temperature peaks.

The constancy of TCRE means that it can also be assessed for the real world by dividing an estimate of CO_2-induced warming to date by an estimate of anthropogenic CO_2 emissions[5,10]. Such an approach relies on a calculation of GHG-attributable warming using a regression of observed warming onto the simulated response to GHG and other forcings, and an estimate of the ratio of CO_2 to total GHG radiative forcing or temperature response. Alternatively TCRE may be assessed from observations by applying observational constraints to the parameters of a simple carbon-cycle climate model[7,8], and evaluating the ratio of warming to emissions for the constrained model.

For a carbon budget approach to make sense, TCRE must be reasonably independent of the pathway of emissions. Earlier studies have indeed shown that this is the case[7,8,18,19], at least for peak warming and monotonously increasing cumulative carbon emissions. If a set carbon budget limit is exceeded, CO_2 needs to be removed actively from the atmosphere afterwards[20-22] to bring emissions back to within the budget. Figure 1 illustrates this path independency (even for moderate amounts of net negative CO_2 emissions), and shows with the simple carbon-cycle and climate model MAGICC[7,23,24] that even with large variations in the pathway of CO_2 emissions during the 21st century, the transient temperature paths as a function of cumulative CO_2 emissions are very similar – a characteristic also found in other models[18,25]. Once all pathways achieve the same end-of-century cumulative CO_2 emissions, the temperature projections are virtually identical (Figure 1b).

Given these considerations, carbon budgets are a useful guide for defining and characterizing emissions pathways which limit warming to certain levels, such as 2°C relative to preindustrial.

An abundance of carbon budgets

Budget for CO_2-induced warming only

The most direct application of TCRE is to derive cumulative carbon budgets consistent with limiting CO_2-induced warming to below a specific temperature threshold. For instance, IPCC WGI indicates[26] that limiting anthropogenic CO_2-induced warming to below 2°C relative to 1861-1880 with an assessed probability of greater than 50% will require cumulative CO_2 emissions from all anthropogenic sources since that period to stay approximately below 4440 $GtCO_2$. Alternatively, doing so with a greater than 66% probability would imply a 3670 $GtCO_2$ budget. These values assume a normal distribution of which the standard-deviation (1-sigma) range is given by the assessed 'likely'

TCRE range of 0.8 to 2.5°C per 1000 PgC (i.e., about 3670 $GtCO_2$), and make use of the near-linearity of the ratio of CO_2-induced warming and cumulative CO_2 emissions[15].

While being the most robust translation of the TCRE concept into a cumulative carbon budget, it is at the same time also the least directly useful to policy-making. In the real world, non-CO_2 forcing also plays a role, and its global-mean temperature effect is superimposed on the CO_2-induced warming. A carbon budget derived from a TCRE-based estimate should thus not be used in isolation.

The near-linear relationship of TCRE does hence not necessarily apply to the ratio of total human-induced warming to cumulative carbon emissions (as might be suggested by Figure SPM.10 in Ref. 26). The latter relationship is scenario dependent, because, for example, the percentage contribution of non-CO_2 climate drivers to total anthropogenic warming increases in the future in many scenarios. Therefore, to take into account the influence of non-CO_2 forcing on carbon budgets, the TCRE-based approach can be extended using multi-gas emission scenarios. Multi-gas emission scenarios provide an internally consistent evolution over time of all radiatively active species of anthropogenic origin. They are often created with "integrated assessment models" (IAMs) which represent interactions within the global energy-economy-land system (for examples, see Refs. 27-29).

Threshold exceedance budgets

A first, straight-forward methodology to extend TCRE-based carbon budgets for CO_2-induced warming to budgets that also take into account non-CO_2 warming is here defined as *threshold exceedance budgets* (TEB) for multi-gas warming (see Table 1).

This approach uses multiple realisations of the simulated response to a multi-gas emission scenario. These realisations can either be multi-model ensembles or perturbed parameter ensembles. An example of the former would be simulations of the Representative Concentration Pathways[30,31] (RCP) by Earth-System Models (ESMs) that were contributed to the Fifth Phase of the Coupled Model Intercomparison Project[32] (CMIP5). An example of the latter would be the use of a simple climate model in a probabilistic setup[7,23,24], as used in the assessments of the IPCC[33-35] as well as in other recent studies[36-38]. From such multi-model or perturbed parameter ensembles, the carbon budget is estimated at the time a specified share (for example, 50% or one third) of realisations exceeds a given temperature limit (i.e., 50% or two thirds of the ensemble members remain below the limit, see orange scenario in Figure 2).

The TEB approach was used by IPCC WGI for determining carbon budgets that account for non-CO_2 forcing[15]. Applying this methodology to the CMIP5 RCP8.5 (Ref. 39) simulations of ESMs[10,40] and Earth-System Models of Intermediate Complexity[41] (EMICs), they found that compatible CO_2

emissions since 1870 are about 3010 $GtCO_2$ and 2900 $GtCO_2$ to limit warming to less than 2°C since the period 1861–1880 in more than 50% and 66% of the available model runs, respectively. Other recent studies[36] have used an extended version of this approach which computes TEBs based on perturbed parameter ensembles of a subset of scenarios from the IPCC AR5 Scenario Database (hosted at the International Institute for Applied Systems Analysis – IIASA, and available at https://secure.iiasa.ac.at/web-apps/ene/AR5DB/).

The results of a TEB approach are most useful if the warming due to non-CO_2 forcing as a function of cumulative CO_2 emissions is similar across scenarios, meaning that the conclusions are not strongly dependent on the scenario chosen. However, Figure 3a shows that there is quite a large variation in non-CO_2 forcing for a given level of cumulative CO_2 emissions when looking at all scenarios available in the IPCC AR5 Scenario Database. Caution is therefore advised when deriving carbon budgets based on one single multi-gas scenario (see more below). Finally, the use of TEBs for limiting warming to below a given temperature limit, assumes that non-CO_2 warming never increases beyond the level it reached at the time the TEB was computed (see Figure 2). Also non-CO_2 forcing thus needs to be kept within limits over time.

Threshold avoidance budgets

Carbon budgets defined in the previous section are derived at the time a given scenario exceeds a specific temperature threshold or limit. A complementary approach is to consider multiple emission scenarios and evaluate carbon budgets for the subset of scenarios that avoid crossing such a threshold with a given probability. We name these budgets *threshold avoidance budgets* (TAB, see Table 1). Because, by definition, such scenarios do not exceed the limit of interest at any specific point in time (with a given probability), a time horizon needs to be defined until when a budget is computed. This time horizon can either be a predefined period, for example the 2011-2050 or the 2011-2100 period, or more variable in nature, for example the time period until peak warming (see yellow scenario in Figure 2). Both of these approaches were used in the IPCC AR5, and more sophisticated approaches based on the TAB methodology have been used in the literature[7].

IPCC Working Group III (WGIII) computed TABs for the periods 2011-2050 and 2011-2100, by assessing the probabilistic temperature projections in 2100[34,35]. For this, WGIII categorized a large number of scenarios based on end-of-century CO_2-equivalent concentrations. The reported TAB values – for example, in Table 6.3 in the WGIII Report[35] or Table SPM.1 in the Synthesis Report[33,34] (SYR) – are therefore the result of an assessment of the exceedance probability outcomes found in each of the CO_2-equivalent concentration categories. Alternatively, scenarios could have been categorised on the basis of median temperature, probabilities to limit warming to below a specific temperature limit, or even carbon budgets. For scenarios that limit end-of-century warming to below

2°C with a 'likely' probability (greater than 66% chance), the IPCC AR5 WGIII assessment[34] reports that the TABs in terms of cumulative CO_2 emissions in the periods 2011-2050 and 2011-2100 are 150-1300 $GtCO_2$ and 630-1180 $GtCO_2$, respectively.

In the IPCC SYR[33] TABs are also computed based on the scenarios available in the IPCC AR5 Scenario Database – see Table 2.2 in Ref. 33. However, the SYR categorizes scenarios directly based on their probability of keeping peak warming to below a specific temperature threshold (1.5°C, 2°C, or 3°C) during the 21st century. For example, the IPCC SYR reports TABs for limiting warming to below 2°C with at least 66% chance of 2550-3150 $GtCO_2$ from 1870 until peak warming.

The numbers compared

To understand what the different approaches mean in terms of the actual values of carbon budgets, we compare the available budgets related to the 2°C limit. Table 2 provides an overview for all the numbers discussed in this section, relative to two common base years (2011 and 2015). Taking into account that about 2050 $GtCO_2$ (ca. 560 PgC) of CO_2 had already been emitted by the end of 2014 (Ref. 36), a CO_2-only budget approach would indicate that 1620 $GtCO_2$ (or 440 PgC) remain to have a >66% probability of limiting warming to below 2°C relative to preindustrial levels (here defined as the 1861-1880 period[26]). Using a TEB approach and assuming non-CO_2 forcing as in RCP8.5, this amount is reduced to 850 $GtCO_2$ (or 230 PgC). When assessed with the latter approach, a 1620 $GtCO_2$ budget would limit warming to below 2°C in less than 33% of the available models (Ref. 42).

It is worth noting that the IPCC assessment of the CO_2-only budget is based on an assessed uncertainty range of TCRE, drawing upon many lines of evidence. The IPCC WGI numbers including non-CO_2 forcing are based on CMIP5 simulations of the response to RCPs, which – although being a valid approach – provide a narrower scientific basis. At least for the four RCPs used by WGI, a similar warming as a function of cumulative CO_2 emissions is found (see Figure TFE.8 in Ref. 42), despite having different non-CO_2 evolutions (see Figure 3a). This counterintuitive result is explained further below.

When extensively varying the non-CO_2 assumptions for TEBs using a subset of baseline and weak mitigation scenarios from the IPCC AR5 Scenario Database (which all exceed the 2°C limit), a range of 850-1550 $GtCO_2$ (5^{th}-95^{th} percentile range across all TEB scenarios, from 2015 onward) is associated with limiting warming to below 2°C with 66% probability[36]. The difference between this range and the 850 $GtCO_2$ number quoted above is, on the one hand, caused by the different modelling frameworks and, on the other hand, by the fact that the non-CO_2 forcing evolution of RCP8.5 is situated amongst the highest percentiles of the non-CO_2 forcing in other high emission scenarios that exceed the 2°C threshold (see Figure 3).

When considering TAB until peak warming, based on the stringent mitigation scenarios of the IPCC AR5 Scenario Database, a range of 590-1240 $GtCO_2$ is found for limiting warming to below 2°C with >66% probability[33] (10^{th}-90^{th} percentile range, as reported by IPCC WGIII, from 2015 onward). Finally, for TAB calculated over the 2015-2100 period, an assessment of the stringent mitigation scenarios available in the IPCC AR5 Scenario Database and their temperature outcomes results in a range of 470-1020 $GtCO_2$ (10^{th}-90^{th} percentile range) for limiting warming to below 2°C with a 'likely' (greater than 66%) chance[35].

In conclusion, moving from a CO_2-only budget[42] to a multi-gas multi-scenario TEB budget[36] removes around 420 $GtCO_2$ (i.e., the average of the 70-770 $GtCO_2$ range) from the CO_2 budget from 2015 onward for limiting warming to below 2°C with 66% chance. Subsequently moving to a TAB budget until peak warming[33] or over the 2015-2100 period[35] and a >66% chance would additionally remove about 260-310 $GtCO_2$ and 380-530 $GtCO_2$, respectively. (Note that these values are illustrative as they are obtained by comparing ranges which are defined in different ways.)

In conclusion, the TAB range for limiting warming to below 2°C with greater than 66% probability of 470-1020 $GtCO_2$ for the 2015-2100 period is thus 35 to 70% below what would have been inferred from a CO_2-only budget with a TEB approach.

Strengths and limitations

The various approaches to computing carbon budgets each come with their respective strengths and limitations. Understanding what can lead to possible differences in budget estimates is critical to avoid misinterpretation of the numbers.

The budget type definition, the underlying data and modelling, the scenario selection, temperature response timescales and the accompanying pathway of CO_2 and non-CO_2 emissions are identified as possible key drivers of the difference between the various budget options discussed above.

That the **budget type definition** will have an influence on the resulting numbers is almost trivial. For example, when defining TABs from 2011 to 2100 instead of until peak warming, the cumulated net negative emissions which can be achieved until the end of the century will lead to consistently lower 2015-2100 TABs compared to TABs defined until peak-warming levels. Negative emissions occur when carbon dioxide is actively removed from instead of emitted into the atmosphere by human activities. For instance, for TABs compatible with limiting warming to below 2°C with >66% chance, the difference between TABs defined until peak warming and over the 2015-2100 period would be of the order of 120-220 $GtCO_2$. Furthermore, the budget type definition also influences other factors, like scenario selection, whose impact on the carbon budget is explained in more detail below.

Underlying data and modelling

Some of the differences between the quantitative budgets estimates are simply driven by differences in the underlying data and models. In general, these differences apply to TEB and TAB alike. For example, while the WGI CO_2-only budget is based on the interpretation of an assessed uncertainty range, the other TEB and TAB budgets were computed either from CMIP5 RCP results (in the WGI Report and the SYR) or from a simple climate model (MAGICC) in a probabilistic setup[7,23,24] (in the WGIII Report and the SYR).

Budget estimates can differ depending on whether a single-scenario multi-model ensemble is used (for example, all CMIP5 runs for RCP8.5) or alternatively a single-model multi-scenario perturbed parameter ensemble is used (for example, the IPCC AR5 WGIII approach which uses MAGICC). The former approach allows us to use information from a wide range of the most sophisticated models and incorporate state-of-the-art Earth-system interactions in the budget assessment. However, this approach comes at a high computational cost, resulting in only a limited ensemble of opportunity of model runs being available for any assessment. The latter method, on the other hand, uses a much simpler model, and hence comes with great computational efficiency which allows for hundreds if not thousands of realisations per scenario. This allows variations in scenario assumptions on the pathways and evolution of non-CO_2 forcing over time to be explored in more detail.

These differences in the underlying data and modelling can result in changes in the budget estimates. However, while a simple climate model does not provide the detail of ESMs, it can closely emulate their global-mean behaviour[43] and can represent the uncertainties in carbon-cycle and climate response in line with the assessment of the IPCC AR5 (Refs. 7,24,44). Of importance here is that the MAGICC setup applied in WGIII and the SYR is consistent with the CMIP5 ensemble for temperature projections and TCRE (Figure 12.8 in Ref. 15, and Figure 6.12 in Ref. 35). It is therefore expected that these differences are limited.

A final aspect related to the data and modelling is the interpretation of the nature of the uncertainties that accompany the various data. Uncertainty ranges can be the expression of a variety of underlying uncertainty sources[45], and they can be interpreted in different ways. In the context of the quantification of carbon budgets, at least three kinds of uncertainty ranges can be distinguished: (1) an uncertainty range resulting from an in-depth assessment of multiple lines of evidence (a so-called assessed uncertainty range); (2) an uncertainty range emerging from a sophisticated statistical sampling of the parameter space or; (3) an uncertainty range which represents the spread across an arbitrary collection of model results (a so-called ensemble of opportunity). Each of these uncertainty ranges can be interpreted in different ways, and they decline in robustness going from an assessed uncertainty range over targeted statistical approaches to ensembles of opportunities. These aspects thus also influence the robustness of any carbon budget estimates based on them. For example, the budget for CO_2-induced warming from WGI is derived from an assessed uncertainty range, while the WGI budgets that additionally take into account non-CO_2 forcing are based on an ensemble of opportunity, which makes them much less robust (see also Technical Focus Element 8 in Ref. 42).

Scenario selection

Applying the definition of TEB and TAB budgets to a large scenario ensemble for the assessment of CO_2 budgets in line with a particular temperature limit results in the selection of two disjoint subsets of emission scenarios: a subset of baseline and weak mitigation scenarios that exceed the temperature limit with a given probability in case of TEB budgets, and a disjoint subset of more stringent to very stringent mitigation scenarios that all keep warming to below the specified temperature limit with a given probability in case of TAB budgets.

A first implication of the use of these disjoint scenario sets results from only very few scenarios being available that have, for example, precisely a 66% probability for limiting warming to below a given temperature threshold. While TEBs are consistently computed for each scenario at the time a scenario exceeds a temperature limit with a given probability, the value of TABs is further driven by the choice of the range of probabilities that is used to select appropriate TAB scenarios. For example, the IPCC SYR selected all scenarios that have a 66 to 100% probability of limiting warming to below a given threshold (compared to exactly 66% for TEB). This resulted in an average probability of staying below 2°C across the subset of TAB scenarios that comply with the abovementioned selection criterion of about 75%. This can explain about one third to half of the 260-310 $GtCO_2$ difference between the TEB estimates from Friedlingstein *et al.* (Ref. 36) and the IPCC SYR TAB estimates. Moreover, for some temperature levels, for example around 3°C, the scenarios available in the IPCC AR5 Scenario Database do not sample the possible range extensively, which can lead to additional biases in the numbers obtained.

Temperature response timescales

A second aspect that is different in the disjoint scenario subsets are the CO_2 emission pathways and hence the annual CO_2 emissions at the time the compatible carbon budget is derived. In the TAB subset, CO_2 emissions will typically approach zero or become negative in order to stabilize global temperatures, and will thus be very low at the time of maximum warming during the 21st century. In the TEB subset this is not the case. Because of the timescales of CO_2-induced warming[46,47] this leads to differences in the carbon budget estimates.

Recent research indicates that, at current emission rates, maximum CO_2-induced warming only occurs about a decade after a CO_2 emission[46,47]. Thus, even in a CO_2-only world, TABs and TEBs with complementary probabilities (for example, a 66% probability to limit warming below 2°C and a 34% probability to exceed 2°C) would not be entirely identical. In case of the TEB approach, the maximum warming of the CO_2 emissions of the last decade before the temperature limit was exceeded has possibly not yet fully occurred. In a TAB approach the emissions in the last decade would be significantly lower, if not zero, and this would allow a much larger fraction of the warming to already be realized. The TEB approach thus leads to a consistent overestimate of the CO_2 budget compatible with a given temperature limit, while this is not the case with the TAB approach. At least one third of the approximately 260-310 $GtCO_2$ difference between the TEB estimates from Ref. 36 and the IPCC SYR TAB estimates can be explained by accounting for the approximately one decade delay between CO_2 emissions and their maximum warming.

Non-CO_2 warming contribution

A third and last aspect that differs between the two disjoint TEB and TAB scenario subsets is the mixture of CO_2 and non-CO_2 forcers. This mixture differs over time and therefore, depending on when the compatible carbon budget is determined, the TAB and TEB are derived under possibly very different non-CO_2 forcing (see Figure 3b). The relationship between CO_2 emissions and non-CO_2 forcing is complex, as it covers the total non-CO_2 forcing which results from both positive and negative climate forcers. Climate policy influences these non-CO_2 forcers both directly (via abatement measures) and indirectly (via changes induced in the energy system), which is captured in different ways in IAMs. For example, stabilizing and peaking global temperatures requires global CO_2 emissions to be reduced to close to net zero. Such very low CO_2 emissions are achieved through a fundamental transformation of the global energy-economy-land system[35], which in turn leads to changes in non-CO_2 emissions because of the phase-out of common sources of CO_2 and non-CO_2 emissions[14,48]. This can lead to important differences in non-CO_2 forcing as a function of total cumulative CO_2 emissions (Figure 3a). Figure 3b shows that median non-CO_2 forcing at the time which is of importance for deriving the carbon budget (i.e., the time of exceedance for TEBs, and peak warming for TABs) is about 0.2 W/m^2 higher in the subset of scenarios used for TEBs compared to the subset used for TABs.

However, the non-CO_2 forcing at either peak warming or the time of exceeding a given temperature threshold does not tell the entire story. When estimating the actual non-CO_2-induced warming at these time points of interest (see Box 1 on 'Non-CO_2 temperature contributions'), very little difference can be found between the TEB and TAB scenario subsets (Figure 3c). This thus suggests that, when a sufficiently large scenario sample is available, variations in non-CO_2 forcing cannot be used to explain the variations between TEB and TAB estimates for limiting warming to below 2°C. The precise influence of this difference on the carbon budgets has not been quantified.

Incidentally, this feature is not obviously visible when looking at the four RCPs only, because both the lowest, RCP2.6, and the highest, RCP8.5, are outliers in terms of non-CO_2 warming, at opposite sides of the scenario distribution (Figures 3b-c).

Finally, while non-CO_2 forcing does not provide a strong explanation for the variations between TEB and TAB estimates, it plays an important role for the variation within the TEB and TAB subsets. Figure 3d shows that respectively 70% and 50% of the variance within the TEB and TAB subsets can be explained by non-CO_2 warming at the time of determining the carbon budget.

Future non-CO_2 warming under stringent mitigation remains nonetheless very uncertain at present. Its magnitude will depend on the extent to which society will be successful in bringing about assumed future improvements in agricultural yields and practices or dietary changes[49], amongst many other factors. These are very uncertain. Furthermore, how much non-CO_2 forcing is reduced compared to CO_2 depends on the relative weight that is given to CO_2 and non-CO_2 emissions in mitigation scenarios, and also on other mitigation choices[50]. These weights are mostly constant in IAMs (for example, by using global warming potentials as a fixed exchange rate), but can also change over time and depend on the question posed.

Air pollution controls can influence the rate of near-term warming and, depending on the precise mix of air pollutants that is reduced by air pollution controls, non-CO_2 warming can be increased, decreased or stay constant[14]. The estimated effect of air pollution controls on carbon budgets, in particular on TABs, is very small[51]. This is important information for policy-making, as it can be used to consider trade-offs between the uncertainty in non-CO_2 mitigation, possibly larger CO_2 budgets, and a larger amount of committed warming at the multi-century scale due to larger cumulative CO_2 emissions.

Applicability

Earlier we indicated that budgets that only take into account CO_2-induced warming are scientifically best understood as – per definition – they do not depend on additional uncertainties associated with other forcings. However, at the same they are impractical and largely irrelevant for use in the real world, because of their obvious limitation of neglecting any contribution that is different from CO_2. The other approaches that go beyond this CO_2-only approach, might therefore be more practical. Using a CO_2-only approach estimate for real-word decision-making would lead to an overestimation of the allowable carbon budget, i.e. a very high risk of exceeding a given climate target when emitting that particular carbon budget.

The strength of TEBs is that they are easily comparable to TCRE-based budgets for CO_2-induced warming only. Hence the influence of non-CO_2 forcing on the size of carbon budgets can be assessed.

However, because of the limitations related to scenario selection (TEBs are derived from scenarios that fail in limiting warming to the temperature level of interest) and the timescales of the temperature response, TABs are preferred over TEBs. The strength of TABs lies exactly in their use of scenarios that represent our best understanding of how CO_2 and other radiatively active species would evolve over time when CO_2 emissions are stringently reduced.

Conclusions

Several possibilities are available to compute cumulative carbon budgets consistent with a particular temperature limit. We have shown that each of the CO_2 budget approaches has strengths but also comes with important limitations. The devil is in the detail here. The most scientifically robust number – the budget for CO_2-induced warming – is also the least practical in the real world. Selecting budgets based on multi-gas emission scenarios that actually restrict warming to below a given temperature threshold, results in the lowest, but most relevant CO_2 emission budgets in a real-world multi-gas setting. Any practical implementation of a carbon budget mitigation strategy would require parallel mitigation efforts for non-CO_2 agents.

At the time of the IPCC AR5, no established methodologies were available to ensure easy comparability of carbon budget estimates across working groups. In hindsight and anticipating future assessments, three recommendations can be formulated. First, insofar important topics can already be identified, coordinated model simulations, intercomparisons, and methods could be initiated at an early stage to ensure consistency and traceability. Second, consistency across – and collaboration and integration between – the IPCC working groups could be improved by setting up stronger ties between them. And third, IPCC reports should be clearer about the policy-applicability of the numbers they provide, without being policy prescriptive.

For limiting warming to below 2°C relative to preindustrial levels with greater than 66% probability, the remaining CO_2 budget from 2015 onwards for CO_2-induced warming only is 1620 $GtCO_2$. The corresponding TAB budget would be 590-1240 $GtCO_2$. The latter is equivalent to about 15 to 30 years of CO_2 emission at current (2014) levels (about 40 $GtCO_2$/yr, Ref. 52). No matter which approach is taken, the CO_2 budget for keeping warming to below 2°C always implies stringent emission reductions over the coming decades and net zero CO_2 emissions in the long term. For policymaking in the context of the UNFCCC, we suggest using the 590-1240 $GtCO_2$ estimate from 2015 onward, as this is derived from an assessment of scenarios that effectively limit warming to below the 2°C limit.

BOX 1: Non-CO_2 temperature contributions

The estimated temperature contributions of non-CO_2 forcing, shown in Figure 3c, are derived by the following equation, as described in the Supplementary Material to the IPCC AR5 Working Group I Chapter on 'Anthropogenic and Natural Radiative Forcing'[53] (equation 8.SM.13).

$$R_T(t) = \sum_{j=1}^{M} \frac{c_j}{d_j} exp\left(-\frac{t}{d_j}\right)$$

Where R_T is the climate response to a unit of forcing, c_j the component of the climate sensitivity, d_j the response times, and t the time. For the two-term approximation ($M=2$) presented by Ref. 54, values of c_1, c_2, d_1, and d_2 are taken from Table 8.SM.9 in Ref. 53. This estimate is to be considered an illustrative approximation of the non-CO_2 forcing's temperature effect.

END BOX 1

Figure captions:

Figure 1 | Proportionality of global-mean temperature increase to cumulative emissions of CO_2. Four CO_2 emission pathways with identical cumulative carbon emissions over the 21st century (panel **a**) and their corresponding temperature projections (panel **b**). The grey area in panel **b** shows the central 66 percent uncertainty range of temperature projections around the thick purple line. Panels are adapted from Figure 12.46 in Ref. 15.

Figure 2 | Illustration of the approach to compute threshold exceedance budgets (TEB) versus threshold avoidance budgets (TAB). In a first step (arrows labelled "1"), temperature outcomes are computed from multi-gas emission scenarios which either exceed (orange) or avoid (yellow) a given temperature threshold. Based on either the timing of exceeding the chosen threshold or the timing of peak warming, carbon budgets compatible with the chosen temperature threshold are computed in a second step (arrow labelled "2") by summing the carbon emissions of the underlying scenarios until the timing of exceeding the threshold or peak warming for TEB or TAB (arrow labelled "3"), respectively.

Figure 3 | Non-CO_2 forcing and cumulative CO_2 emissions. a, Non-CO_2 forcing as a function of cumulative CO_2 emissions from 2015 onwards for scenarios of the IPCC AR5 Scenario Database. Scenarios are split up into two subsets: (1) scenarios that limit warming to below 2°C relative to preindustrial with at least 66% probability (yellow-mustard, used for TAB) and (2) scenarios that lead to global-mean temperatures exceeding the 2°C relative to preindustrial limit with at least 34% (orange, used for TEB). **b**, Distribution of non-CO_2 forcing at the time point critical for deriving TEB (orange) and TAB (yellow-mustard) budgets, i.e., the moment the 2°C limit is exceeded for TEBs and peak warming for TABs. **c**, Distribution of the estimated temperature contribution from non-CO_2 forcing at the same time point as in panel **b** (see Box 1 on 'Non-CO_2 temperature contributions'). The four RCPs are also included for comparison. **d**, Variation within the TEB and TAB budget subsets as a function of the estimated temperature contribution from non-CO_2 forcing as in panel **c**. Numerical values in panel **d** are R^2 values for the two linear fits.

Tables:

Table 1 | Three different types of carbon budgets and their definition

Carbon budget type	Abbreviation	Definition and description
Budget for CO_2-induced warming	CO_2-only budget	Amount of cumulative carbon emissions that are compatible with limiting warming to below a specific temperature threshold with a given probability in the hypothetical case that CO_2 is the only source of anthropogenic radiative forcing. This budget can be inferred from the assessed range of TCRE.
Threshold Exceedance Budget	TEB	Amount of cumulative carbon emissions at the time a specific temperature threshold is exceeded with a given probability in a particular multi-gas emission scenarios. This budget thus takes into account the impact of non-CO_2 warming at the time of exceeding the threshold of interest.
Threshold Avoidance Budget	TAB	Amount of cumulative carbon emissions over a given time period of a multi-gas emission scenario that limits global-mean temperature increase to below a specific threshold with a given probability. This budget thus takes into account the impact of non-CO_2 warming at peak global-mean warming, which is approximately the time global CO_2 emissions become zero and global-mean temperature is stabilized.

Table 2 | Selection of carbon emission budgets related to a global temperature limit of 2°C relative to preindustrial levels from various sources. 1890 $GtCO_2$ were already emitted by 2011, and about 2050 $GtCO_2$ by 2015. All values are in $GtCO_2$, reported from 2011 and 2015 onwards, and rounded to the nearest 10. Budget types are defined in Table 1.

Source	Type	Specification	Value since 2011	Value since 2015
IPCC AR5 WGI	***CO_2-only budget***	To limit warming to less than 2°C since the period 1861-1880 with greater than 66% (or 50%) probability	1780 (or 2550)	1620 (or 2390)
IPCC AR5 WGI	***TEB***	To limit warming to less than 2°C since the period 1861-1880 in more than 66% (or 50%) of the model runs when accounting for the non-CO_2 forcing as in the RCP scenarios	1010 (or 1120)	850 (or 960)
IPCC AR5 WGIII	***TAB***	To limit warming in 2100 to below 2°C since 1850-1900 with a 'likely' (>66%) probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database*. (10%-90% range over scenarios in IPCC WGIII scenario category 1)	630 to 1180	470 to 1020
IPCC AR5 WGIII	***TAB***	To limit warming in 2100 to below 2°C since 1850-1900 with a 'more likely than not' (>50%) probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database*. (10%-90% range over scenarios in IPCC AR5 scenario category II without overshoot)	960 to 1430	800 to 1270
IPCC AR5 SYR	***TEB***	To limit warming to less than 2°C since the period 1861-1880 in more than 66% (or 50% or 33%) of the model runs of the CMIP5 RCP8.5 ESM and EMIC simulations. (These correspond to the IPCC AR5 WGI TEB budgets reported above)	1010 (1110 or 1410)	850 (960 or 1250)
IPCC AR5 SYR	***TAB***	To limit warming to below 2°C since 1861-1880 with 66-100% probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database. (10%-90% range)	750 to 1400	590 to 1240
IPCC AR5 SYR	***TAB***	To limit warming to below 2°C since 1861-1880 with 50-66% probability, accounting for the non-CO_2 forcing as spanned by the subset of stringent mitigation scenarios in the IPCC AR5 Scenario Database. (10%-90% range)	1150 to 1400	990 to 1240
Friedlingstein et al. (2014)	***TEB***	To limit warming to less than 2°C since 1850-1900 with a 66% probability, accounting for the non-CO_2 forcing as spanned by the subset of baseline and weak mitigation scenarios in the IPCC AR5 Scenario Database*. (5%-95% range)	1310 (1010 to 1710)	1150 (850 to 1550)
Friedlingstein et al. (2014)	***TEB***	To limit warming to less than 2°C since 1850-1900 with a 50% probability, accounting for the non-CO_2 forcing as spanned by the subset of baseline and weak mitigation scenarios in the IPCC AR5 Scenario Database*. (5%-95% range)	1610 (1210 to 2010)	1450 (1050 to 1850)

*: The temperature difference between the 1861-1880 and 1850-1900 is 0.02°C, based on Ref. 55

References:

1. UNFCCC. United Nations Framework Convention on Climate Change. 1992**:** 1-25.
2. UNFCCC. FCCC/CP/2010/7/Add.1 Decision 1/CP.16 - The Cancun Agreements: Outcome of the work of the Ad Hoc Working Group on Long-term Cooperative Action under the Convention. 2010**:** 31.
3. UNFCCC. FCCC/CP/2012/8/Add.1 - Report of the Conference of the Parties on its eighteenth session, held in Doha from 26 November to 8 December 2012 - Addendum - Part Two: Action taken by the Conference of the Parties at its eighteenth session. Doha, Qatar: UNFCCC; 2012. pp. 1-37.
4. Matthews HD, Caldeira K. Stabilizing climate requires near-zero emissions. *Geophysical Research Letters* 2008, **35**(4).
5. Matthews HD, Gillett NP, Stott PA, Zickfeld K. The proportionality of global warming to cumulative carbon emissions. *Nature* 2009, **459**(7248)**:** 829-832.
6. Zickfeld K, Eby M, Matthews HD, Weaver AJ. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proceedings of the National Academy of Sciences* 2009, **106**(38)**:** 16129-16134.
7. Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, Knutti R*, et al.* Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* 2009, **458**(7242)**:** 1158-1162.
8. Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, Meinshausen M*, et al.* Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* 2009, **458**(7242)**:** 1163-1166.
9. Gillett NP, Arora VK, Zickfeld K, Marshall SJ, Merryfield WJ. Ongoing climate change following a complete cessation of carbon dioxide emissions. *Nature Geosci* 2011, **4**(2)**:** 83-87.
10. Gillett NP, Arora VK, Matthews D, Allen MR. Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations. *Journal of Climate* 2013, **26**(18)**:** 6844-6858.
11. Knutti R, Rogelj J. The legacy of our CO2 emissions: a clash of scientific facts, politics and ethics. *Climatic Change* 2015**:** 1-13.
12. Smith SM, Lowe JA, Bowerman NHA, Gohar LK, Huntingford C, Allen MR. Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Clim Change* 2012, **2**(7)**:** 535-538.
13. Bowerman NHA, Frame DJ, Huntingford C, Lowe JA, Smith SM, Allen MR. The role of short-lived climate pollutants in meeting temperature goals. *Nature Clim Change* 2013, **3**(12)**:** 1021-1024.
14. Rogelj J, Schaeffer M, Meinshausen M, Shindell DT, Hare W, Klimont Z*, et al.* Disentangling the effects of CO2 and short-lived climate forcer mitigation. *Proc Natl Acad Sci U S A* 2014, **111**(46)**:** 16325-16330.
15. Collins M, R. Knutti, J. Arblaster, J.-L. Dufresne, T. Fichefet, P. Friedlingstein*, et al.* Long-term Climate Change: Projections, Commitments and Irreversibility. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2013, pp 1029-1136.
16. Frolicher TL, Winton M, Sarmiento JL. Continued global warming after CO2 emissions stoppage. *Nature Clim Change* 2014, **4**(1)**:** 40-44.
17. Mastrandrea MD, Field CB, Stocker TF, Edenhofer O, Ebi KL, Frame DJ*, et al.* Guidance Notes for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. IPCC; 2010. p. 5.
18. Zickfeld K, Arora VK, Gillett NP. Is the climate response to CO2 emissions path dependent? *Geophysical Research Letters* 2012, **39**(5)**:** L05703.

19. Van Vuuren DP, Meinshausen M, Plattner GK, Joos F, Strassmann KM, Smith SJ*, et al.* Temperature increase of 21st century mitigation scenarios. *Proceedings of the National Academy of Sciences* 2008, **105**(40)**:** 15258-15262.
20. Obersteiner M, Azar C, Kauppi P, Mollersten K, Moreira J, Nilsson S*, et al.* Managing climate risk. *Science* 2001, **294**(5543)**:** 786-787.
21. Azar C, Lindgren K, Obersteiner M, Riahi K, van Vuuren D, den Elzen K*, et al.* The feasibility of low CO2 concentration targets and the role of bio-energy with carbon capture and storage (BECCS). *Climatic Change* 2010, **100**(1)**:** 195-202.
22. Tavoni M, Socolow R. Modeling meets science and technology: an introduction to a special issue on negative emissions. *Climatic Change* 2013, **118**(1)**:** 1-14.
23. Meinshausen M, Raper SCB, Wigley TML. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos Chem Phys* 2011, **11**(4)**:** 1417-1456.
24. Rogelj J, Meinshausen M, Knutti R. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Clim Change* 2012, **2**(4)**:** 248-253.
25. Matthews HD, Solomon S, Pierrehumbert R. Cumulative carbon as a policy framework for achieving climate stabilization. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 2012, **370**(1974)**:** 4365-4379.
26. IPCC. Summary for Policymakers. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2013, pp 1-29.
27. Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M. International climate policy architectures: Overview of the EMF 22 International Scenarios. *Energy Econ* 2009, **31**(Supplement 2)**:** S64-S81.
28. Riahi K, Dentener F, Gielen D, Grubler A, Jewell J, Klimont Z*, et al.* Chapter 17 - Energy Pathways for Sustainable Development. *Global Energy Assessment - Toward a Sustainable Future*. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, 2012, pp 1203-1306.
29. Kriegler E, Weyant J, Blanford G, Krey V, Clarke L, Edmonds J*, et al.* The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. *Climatic Change* 2014, **123**(3-4)**:** 353-367.
30. Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP*, et al.* The next generation of scenarios for climate change research and assessment. *Nature* 2010, **463**(7282)**:** 747-756.
31. van Vuuren D, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K*, et al.* The representative concentration pathways: an overview. *Climatic Change* 2011, **109**(1-2)**:** 5-31.
32. Taylor KE, Stouffer RJ, Meehl GA. An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society* 2011, **93:** 485–498.
33. IPCC. Summary for Policymakers. *Climate Change 2014: Synthesis Report of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom, and New York, NY, USA, 2014, pp 1-32.
34. IPCC. Summary for Policymakers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K*, et al.* (eds). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom, and New York, NY, USA, 2014, pp 1-33.
35. Clarke L, Jiang K, Akimoto K, Babiker M, Blanford G, Fisher-Vanden K*, et al.* Assessing Transformation Pathways. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K*, et al.* (eds). *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate*

Change. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2014, pp 413-510.

36. Friedlingstein P, Andrew RM, Rogelj J, Peters GP, Canadell JG, Knutti R*, et al.* Persistent growth of CO2 emissions and implications for reaching climate targets. *Nature Geoscience* 2014, **7**(10)**:** 709-715.
37. Schaeffer M, Gohar L, Kriegler E, Lowe J, Riahi K, van Vuuren D. Mid- and long-term climate projections for fragmented and delayed-action scenarios. *Technological Forecasting and Social Change* 2015, **90, Part A**(0)**:** 257-268.
38. Rogelj J, Luderer G, Pietzcker RC, Kriegler E, Schaeffer M, Krey V*, et al.* Energy system transformations for limiting end-of-century warming to below 1.5°C. *Nature Clim Change* in press.
39. Riahi K, Rao S, Krey V, Cho C, Chirkov V, Fischer G*, et al.* RCP 8.5—A scenario of comparatively high greenhouse gas emissions. *Climatic Change* 2011, **109**(1)**:** 33-57.
40. Jones C, Robertson E, Arora V, Friedlingstein P, Shevliakova E, Bopp L*, et al.* Twenty-First-Century Compatible CO2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways. *Journal of Climate* 2013, **26**(13)**:** 4398-4413.
41. Zickfeld K, Eby M, Weaver AJ, Alexander K, Crespin E, Edwards NR*, et al.* Long-Term Climate Change Commitment and Reversibility: An EMIC Intercomparison. *Journal of Climate* 2013, **26**(16)**:** 5782-5809.
42. Stocker TF, Qin D, Plattner G-K, Alexander LV, Allen SK, Bindoff NL*, et al.* Technical Summary. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (ed). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2013, pp 33-115.
43. Meinshausen M, Wigley TML, Raper SCB. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: Applications. *Atmos Chem Phys* 2011, **11**(4)**:** 1457-1471.
44. Rogelj J, Meinshausen M, Sedláček J, Knutti R. Implications of potentially lower climate sensitivity on climate projections and policy. *Environmental Research Letters* 2014, **9**(3)**:** 031003.
45. Smith LA, Stern N. Uncertainty in science and its role in climate policy. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 2011, **369**(1956)**:** 4818-4841.
46. Ricke KL, Caldeira K. Maximum warming occurs about one decade after a carbon dioxide emission. *Environmental Research Letters* 2014, **9**(12)**:** 124002.
47. Zickfeld K, Herrington T. The time lag between a carbon dioxide emission and maximum warming increases with the size of the emission. *Environmental Research Letters* 2015, **10**(3)**:** 031001.
48. Rogelj J, Rao S, McCollum DL, Pachauri S, Klimont Z, Krey V*, et al.* Air-pollution emission ranges consistent with the representative concentration pathways. *Nature Clim Change* 2014, **4**(6)**:** 446-450.
49. Gernaat DEHJ, Calvin K, Lucas PL, Luderer G, Otto SAC, Rao S*, et al.* Understanding the contribution of non-carbon dioxide gases in deep mitigation scenarios. *Global Environmental Change* 2015, **33**(0)**:** 142-153.
50. Rogelj J, Reisinger A, McCollum DL, Knutti R, Riahi K, Meinshausen M. Mitigation choices impact carbon budget size compatible with low temperature goals. *Environmental Research Letters* 2015, **10**(7)**:** 075003.
51. Rogelj J, Meinshausen M, Schaeffer M, Knutti R, Riahi K. Impact of short-lived non-CO2 mitigation on carbon budgets for stabilizing global warming. *Environmental Research Letters* 2015, **10**(7)**:** 075001.

52. Le Quéré C, Moriarty R, Andrew RM, Peters GP, Ciais P, Friedlingstein P*, et al.* Global carbon budget 2014. *Earth Syst Sci Data Discuss* 2014, **7**(2)**:** 521-610.
53. Myhre G, D. Shindell, F.-M. Bréon, W. Collins, J. Fuglestvedt, J. Huang*, et al.* Anthropogenic and Natural Radiative Forcing. In: Stocker TF, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung*, et al.* (eds). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, United Kingdom and New York, NY, USA, 2013, pp 659-740.
54. Boucher O, Reddy MS. Climate trade-off between black carbon and carbon dioxide emissions. *Energy Policy* 2008, **36**(1)**:** 193-200.
55. Brohan P, Kennedy JJ, Harris I, Tett SFB, Jones PD. Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research-Atmospheres* 2006, **111:** D12106.

Acknowledgements

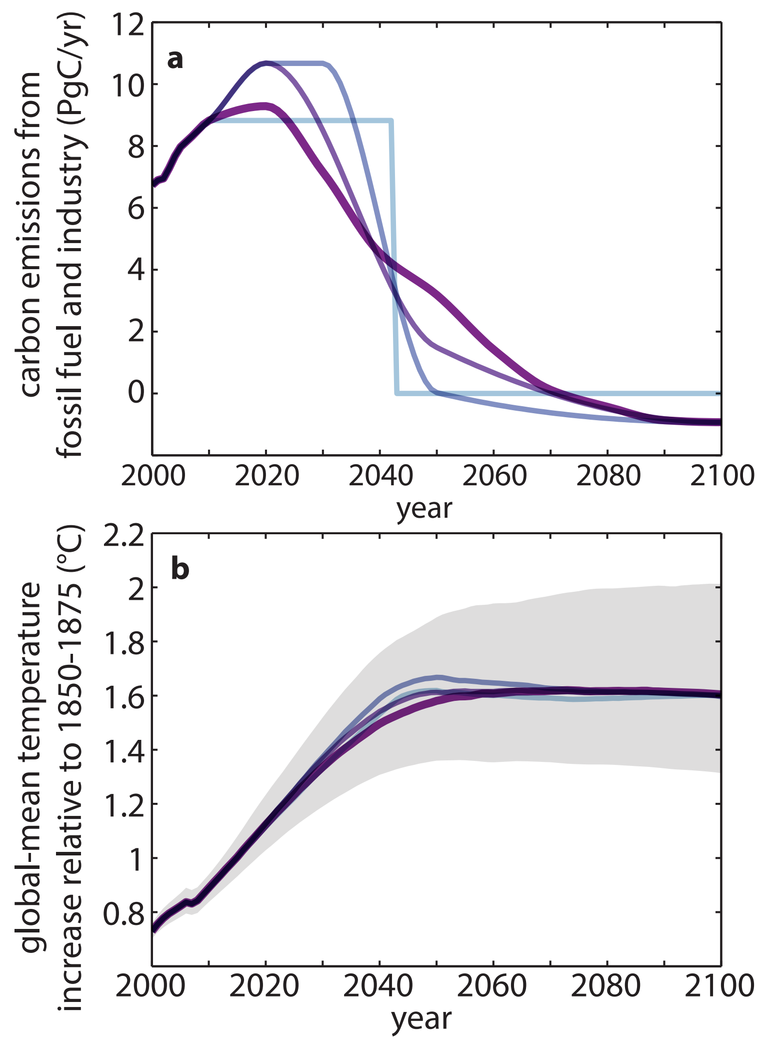
We acknowledge the work by IAM modellers that contributed to the IPCC AR5 Scenario Database and the climate modelling teams contributing to CMIP5. We thank IIASA for hosting the IPCC AR5 Scenario Database, and Malte Meinshausen for detailed comments and feedback on the manuscript.

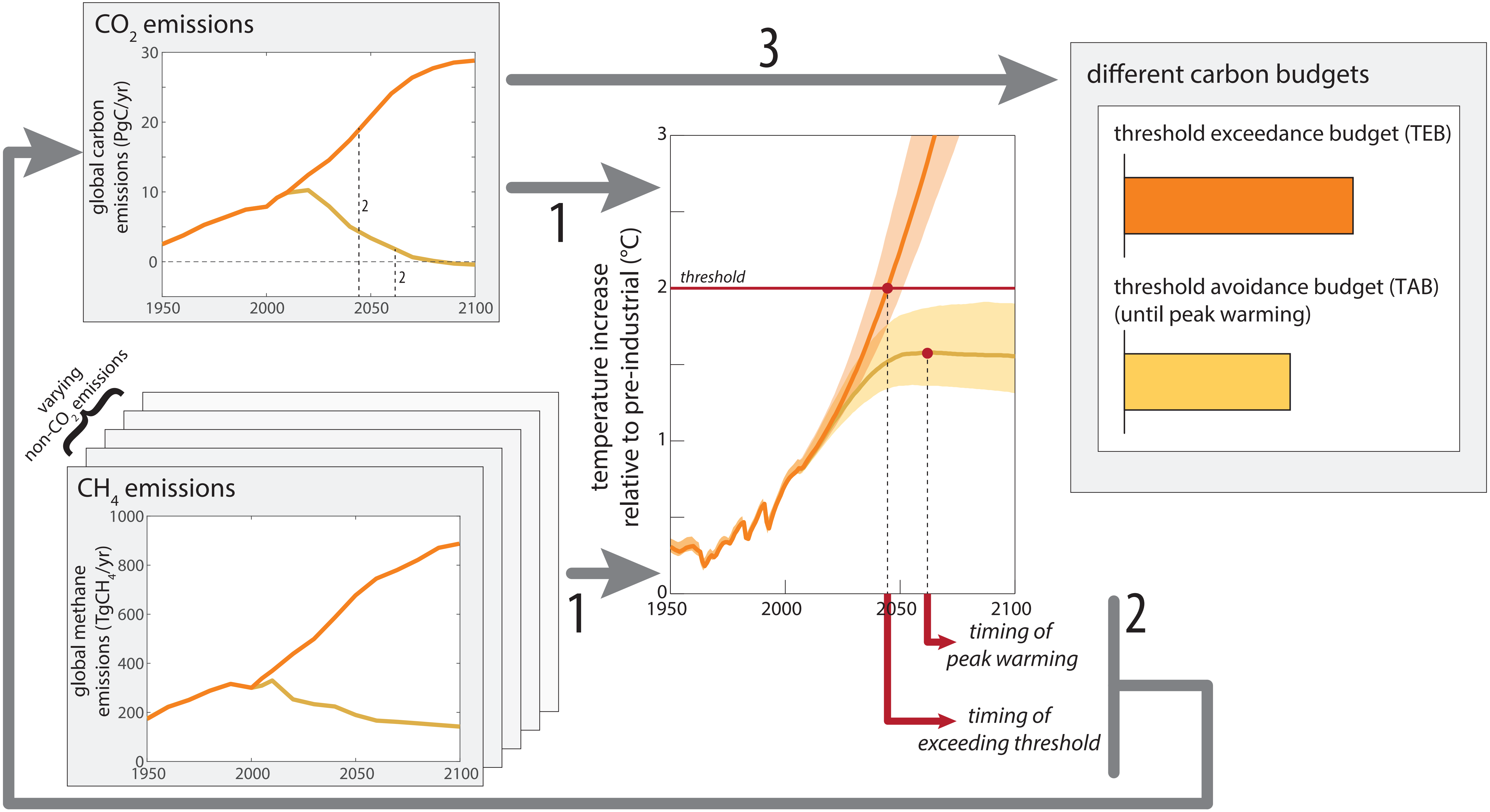
Author Information

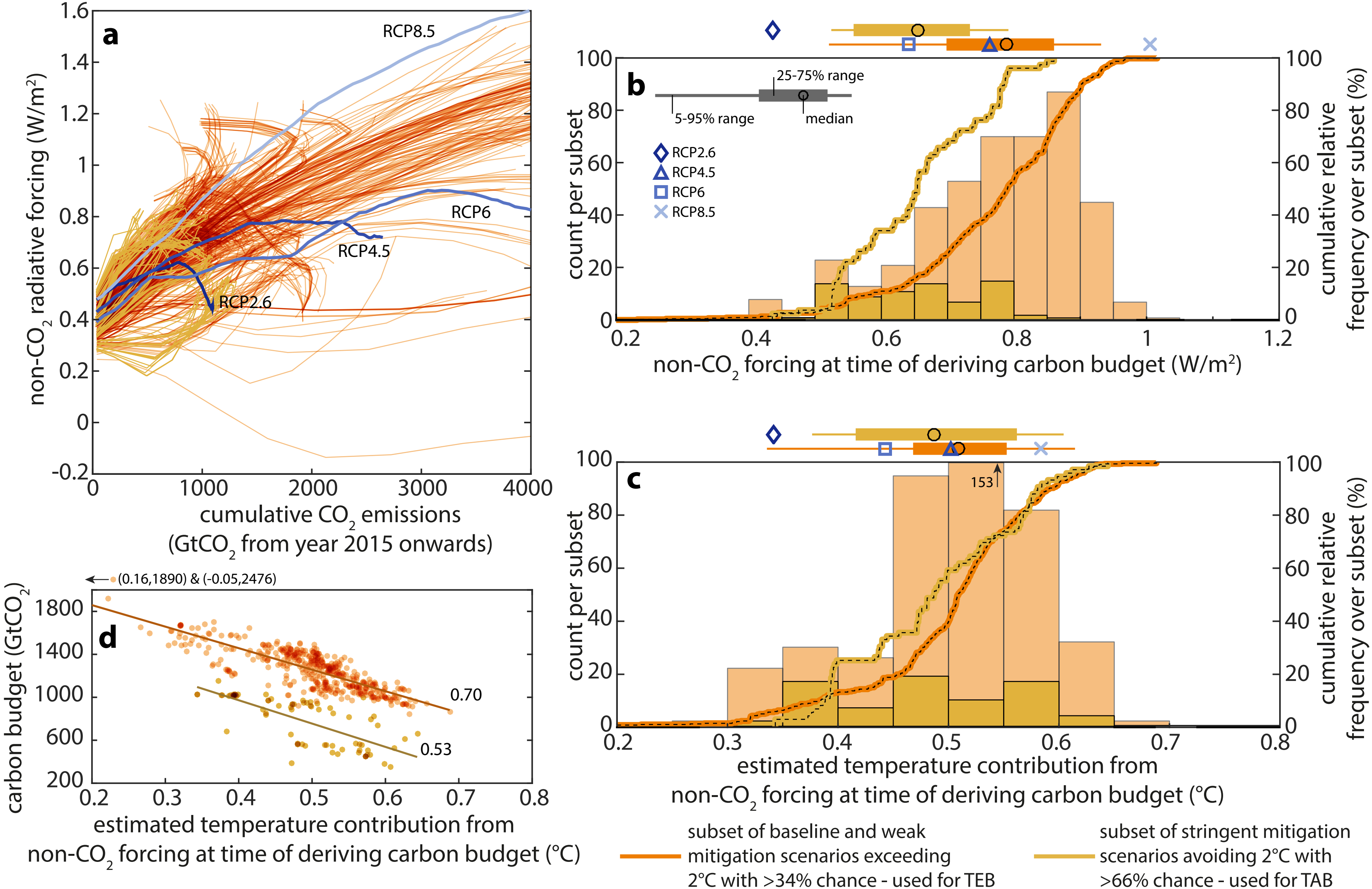
Correspondence and requests for materials should be addressed to JR (rogelj@iiasa.ac.at).

Author Contributions

All authors contributed to the underlying research during the writing process of the IPCC AR5. JR coordinated the conception and the writing of the paper. JR carried out the research with significant contributions from MS, and developed the TEB and TAB conceptual framework. JR produced the figures and wrote the first draft of the manuscript. All authors contributed to interpreting and discussing the results, and writing the paper.


a
carbon emissions from fossil fuel and industry (PgC/yr)
12
10
8
6
4
2
0
2000
2020
2040
2060
2080
2100
year
b
global-mean temperature increase relative to 1850-1875 (°C)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
2000
2020
2040
2060
2080
2100
year


CO2 emissions
global carbon emissions (PgC/yr)
30
20
10
0
1950
2000
2050
2100
2
2
varying non-CO2 emissions
CH4 emissions
global methane emissions (TgCH4/yr)
1000
800
600
400
200
0
1950
2000
2050
2100
1
1
3
temperature increase relative to pre-industrial (°C)
threshold
3
2
1
0
1950
2000
2050
2100
timing of peak warming
timing of exceeding threshold
2
different carbon budgets
threshold exceedance budget (TEB)
threshold avoidance budget (TAB) (until peak warming)



a
RCP8.5
RCP6
RCP4.5
RCP2.6
non-CO2 radiative forcing (W/m2)
cumulative CO2 emissions
(GtCO2 from year 2015 onwards)
b
25-75% range
5-95% range
median
RCP2.6
RCP4.5
RCP6
RCP8.5
count per subset
cumulative relative frequency over subset (%)
non-CO2 forcing at time of deriving carbon budget (W/m2)
c
153
count per subset
cumulative relative frequency over subset (%)
estimated temperature contribution from
non-CO2 forcing at time of deriving carbon budget (°C)
d
(0.16,1890) & (-0.05,2476)
0.70
0.53
carbon budget (GtCO2)
estimated temperature contribution from
non-CO2 forcing at time of deriving carbon budget (°C)
subset of baseline and weak mitigation scenarios exceeding 2°C with >34% chance - used for TEB
subset of stringent mitigation scenarios avoiding 2°C with >66% chance - used for TAB