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Estimating carbon budgets for ambitious climate targets

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Abstract

Carbon budgets, which define the total allowable CO₂ emissions associated with a given global climate target, are a useful way of framing the climate mitigation challenge. In this paper, we review the geophysical basis for the idea of a carbon budget, showing how this concept emerges from a linear climate response to cumulative CO₂ emissions. We then discuss the difference between a “CO₂-only carbon budget” associated with a given level of CO₂-induced warming, and an “effective carbon budget” associated with a given level of warming caused by all human emissions. We present estimates for the CO₂-only and effective carbon budgets for 1.5 and 2 °C, based on both model simulations and updated observational data. Finally, we discuss the key contributors to uncertainty in carbon budget estimates, and suggest some implications of this uncertainty for decision-making. Based on the analysis presented here, we argue that while the CO₂-only carbon budget is a robust upper bound on allowable emissions for a given climate target, the size of the effective carbon budget is dependent on the how quickly we are able to mitigate non-CO₂ greenhouse gas and aerosols emissions. This suggests that climate mitigation efforts could benefit from being responsive to a changing effective carbon budget over time, as well as to potential new information that could narrow uncertainty associated with the climate response to CO₂ emissions.

Introduction

An important recent development in climate science is the finding that warming responds approximately linearly to cumulative CO₂ emissions over time (Matthews et al. 2009; Allen et al. 2009; Gillett et al. 2013; Collins et al. 2013; Friedlingstein et al. 2014). This proportionality between cumulative emissions and global temperature change opens new avenues for how we approach climate mitigation (Matthews et al. 2012; Zickfeld et al. 2009), as well as our ability to predict the regional climate impacts associated with a given emission pathway (Leduc et al. 2016). Importantly, this allows us to estimate a global carbon budget, which represents the total quantity of CO₂ that can be emitted if we want to avoid exceeding a desired level of global temperature increase (Collins et al. 2013; Friedlingstein et al. 2014).

Setting a finite budget of allowable CO₂ emissions is a simple and easily understood way of framing the global climate challenge and the national emissions pathways that would be consistent with international climate targets (Gignac & Matthews 2015; Raupach et al. 2014). However, there is a high level of confusion surrounding the use and estimates of carbon budgets in the scientific literature, which hampers their utility for climate policy development. The confusion stems from inconsistent methodologies and definitions among published carbon budget estimates, as well as from fundamental scientific uncertainties associated with estimating the climate response to a given quantity of emissions (Rogelj et al. 2016). Furthermore, there has been virtually no research focussed on estimating carbon budgets for less than 2 °C of global warming; this is an urgent research gap that needs to be filled to support the Paris climate agreement's goal of "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C" (Article 2 of the Paris Climate Agreement, available at:

<https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf>).

In this paper, we review the scientific basis of carbon budget estimates, focusing on how the concept of allowable emissions can be inferred from known (though uncertain) geophysical constraints emerging from the climate response to cumulative CO₂ emissions. We begin by discussing the climate response to CO₂ emissions alone, and the resulting carbon budget estimates associated with a given amount of CO₂-induced warming. We then show how this CO₂-only budget can be adjusted to account for the effect of non-CO₂ greenhouse gas and aerosol emissions, which results in an “effective” estimate of the total CO₂ emissions associated with a given climate target. Finally, we discuss the important contributors to uncertainty in carbon budget estimates, and the implications of this uncertainty for emissions targets. Throughout, we focus on the climate targets of 1.5–2 °C above pre-industrial, as stipulated in the Paris Climate Agreement.

Geophysical basis for a carbon budget

The climate response to CO₂ emissions is well characterized by a linear temperature response to cumulative emissions of CO₂ over time (Matthews et al. 2009; Allen et al. 2009; Gillett et al. 2013; Collins et al. 2013; Friedlingstein et al. 2014; MacDougall & Friedlingstein 2015; MacDougall 2016). The slope of this relationship – the temperature change per unit emission of CO₂ – has now been defined as the “Transient Climate Response to cumulative CO₂ Emissions,” or TCRE (Gillett et al. 2013; Collins et al. 2013; Gregory et al. 2009). Analyses of the climate response to cumulative emissions have shown that the TCRE remains approximately constant for total emissions up to several thousand giga-tonnes of carbon (GtC), and is highly path-independent in that the value of the TCRE shows only a small variation across a wide range of CO₂ emission scenarios (Zickfeld et al. 2012; Matthews & Zickfeld 2012; Leduc et al. 2015; Tokarska et al. 2016).

Another important feature of the climate and carbon cycle system is the fast climate response to CO₂ emissions (Ricke & Caldeira 2014; Matthews & Solomon 2013;

Zickfeld & Herrington 2015). This response time was recently quantified by Ricke and Caldeira (2014) who showed that the peak warming occurs 10 years after a 100 GtC pulse emission of CO₂. Zickfeld and Herrington (2015) further showed that the climate response time varies as a function of the size of the emission pulse, such that larger pulse sizes as associated with a longer response time. By extension, the climate response to small changes in CO₂ emissions should be effectively instantaneous (Matthews & Solomon 2013).

This fast climate response time to small changes in CO₂ emissions supports a third important feature of the climate response to CO₂ emissions: that the unrealized warming associated with past CO₂ emissions is small (Matthews & Caldeira 2008). The future warming associated with past emissions is defined as the “Zero-Emissions Commitment” (ZEC), which represents the amount of additional warming that occurs after CO₂ emissions have been set to zero. Analyses of the ZEC across a range of different climate models suggest that there is little (if any) unrealized warming associated with past CO₂ emissions, but rather that global temperature remain approximately constant for several centuries after CO₂ emissions reach zero (Zickfeld et al. 2013; Matthews & Caldeira 2008; Matthews & Zickfeld 2012; Solomon et al. 2009; Lowe et al. 2009; Matthews & Weaver 2010; Gillett et al. 2011; Nohara et al. 2015). This arises as a result of the near-cancellation of opposing inertial effects associated with ocean heat and carbon uptake. In the case of constant atmospheric CO₂, ocean thermal inertia would lead to continued warming for decades to centuries; however, in the context of zero CO₂ emissions, the continued uptake of CO₂ by the ocean leads to declining atmospheric CO₂ concentrations which largely cancels the effect of ocean thermal inertia and results in near-constant global temperature over time (Matthews & Solomon 2013; Matthews & Weaver 2010). This relative balance of ocean thermal and carbon cycle inertia does vary among models, though while some models show larger amounts of unrealized warming (Frölicher & Paynter 2015), the occurrence of substantial continued warming after zero emissions is generally restricted to simulations driven by very high (>2000 GtC) levels of cumulative emissions (Frölicher et al. 2014; Zickfeld & Herrington

2015; Leduc et al. 2015; Nohara et al. 2013). This body of literature therefore suggests that the quantity of emissions produced to date is consistent with the CO₂-induced warming that has already occurred, with little additional expected future warming commitment, and also little recovery from current levels of warming on centennial timescales.

The concept of a carbon budget – the total allowable CO₂ emissions consistent with a given amount of global temperature increase – is therefore a robust measure of human-climate influence that emerges from these three properties of the climate-carbon cycle system: (1) that global temperature responds linearly to cumulative CO₂ emissions, as defined by the TCRE; (2) that the climate response time to CO₂ emission is fast; and (3) that the realized warming associated with total CO₂ emissions to date is approximately the same as the centennial-scale legacy of these same emissions. As a consequence, the total amount of CO₂ emissions as inferred from the TCRE is uniquely associated with remaining below a given level of CO₂-induced warming on timescales of 10 to several hundred years. This quantity has been defined as the “CO₂-only carbon budget” to represent the total allowable CO₂ emissions associated with a given amount of CO₂-only warming (Rogelj et al. 2016). And in the case of low temperature targets, the CO₂-only budget is consistent with both meeting and also not exceeding the targeted amount of CO₂-induced temperature change. That is, there is little difference here between the budgets associated with exceeding or avoiding 1.5–2 °C (i.e. the threshold exceedance or threshold avoidance budgets, as defined by Rogelj et al, 2016).

Estimates of CO₂-only carbon budgets

The CO₂-only carbon budget can be understood simply as the inverse of the TCRE. While the TCRE equals $\Delta T/E_T$ (where ΔT =global temperature change and E_T = cumulative emissions over time), the carbon budget per degree of warming = $E_T/\Delta T$. The CO₂-only carbon budget for a given climate target (T^*) is therefore $T^*/TCRE$. This simple relationship between the TCRE and the CO₂-only carbon budget is

shown in Figure 1.

The TCRE can be estimated from either Earth system models (ESMs) that include a dynamic representation of the global carbon cycle, or from the observational record. Across the current generation of climate models, as represented by the ESMs included in the CMIP5 model ensemble, the TCRE varies from 0.8–2.4 °C/1000 GtC (Gillett et al. 2013), with an median value of 1.6 °C/1000 GtC [calculated from CO₂-only simulations with CO₂ concentrations increasing by 1% per year].

Estimating the TCRE from the observational record requires first identifying the proportion of observed warming attributable to CO₂ alone, and then calculating the TCRE as a function of observed CO₂-induced warming and historical cumulative CO₂ emissions from fossil fuels and land-use change. Applying this approach, Gillett et al. (2013) estimated an observationally-constrained (5-95%) TCRE range of 0.7–2.0 °C/1000 GtC, with a best-estimate of 1.35 °C/1000 GtC.

The CO₂-only carbon budgets estimates associated with these TCRE values are summarized in Table 1. The model-average TCRE of 1.6 °C/1000 GtC suggests a global carbon budget of 625 GtC per degree, or 940 Gt C and 1250 Gt C for 1.5 and 2 °C of CO₂-induced warming, respectively. [Note: all carbon budget values are rounded to the nearest 5 GtC]. By contrast, the observationally-based TCRE of 1.35 °C/1000 GtC suggests a larger carbon budget of 740 GtC per degree, or 1110 GtC and 1480 GtC for 1.5 and 2 °C of CO₂-induced warming. It is clear that differences in the sensitivity of the climate system to CO₂ emission, as illustrated here by the difference between model- and observationally-based TCRE estimates, can have a large effect on the size of the CO₂-only carbon budgets for 1.5–2 °C.

Influence of non-CO₂ greenhouse gases and aerosols

The CO₂-only carbon budget is well grounded in the science of the climate system response to cumulative CO₂ emissions, and can be easily estimated from the TCRE.

However, the real climate system is also influenced by non-CO₂ greenhouse gas and aerosol emissions, as well as changes in surface albedo due to land-use. The effect of non-CO₂ emissions is complicated by the large number of individual forcing agents, which have widely varying atmospheric lifetimes that are in general considerably shorter than that of CO₂. While the climate response to CO₂ is well characterized by the TCRE, and similar relationships have been proposed for other long-lived greenhouse gases (Smith et al. 2012), there is no simple linear scaling factor that can be applied to all non-CO₂ emissions. Although scientifically robust, the CO₂-only carbon budget is not by itself enough to inform efforts to meet climate targets, as it does not account for the additional net warming expected from these other emissions. It is important therefore to adjust the CO₂-only carbon budget to account for non-CO₂ emissions and related warming.

According to the IPCC forcing estimates, non-CO₂ forcing – including the combined effect of all non-CO₂ greenhouse gases and aerosols – currently accounts for 23% of the total anthropogenic forcing (Myhre et al. 2013) [here, values from 1750-2011 from Myhre et al. (2013) were extended to 2015 using observations from the NOAA greenhouse gas index (<http://www.esrl.noaa.gov/gmd/aggi/aggi.html>) and adopting RCP6 percentage trends over 2011-2015 for the other anthropogenic forcing agents (Meinshausen et al. 2011); from 2011 to 2015 greenhouse gas forcing increased by 5% and non-greenhouse forcings changed very little]. Using the simplifying assumption that this ratio of forcings approximately represents the ratio of contributions to historical warming, we infer that about 77% of the observed warming up to the year 2015 can be attributed CO₂ forcing, with the remaining observed warming attributable to non-CO₂ emissions. We can then define an “effective TCRE” which represents the global temperature response to cumulative CO₂ emissions, adjusted to implicitly include the effect of non-CO₂ forcing.

The effective TCRE can be estimated from observations as: $TCRE_{eff} = \Delta T_{obs} / E_T$, where ΔT_{obs} is the observed human-induced global temperature change and E_T represents the cumulative historical CO₂ emissions from fossil fuels and land-use

change. To represent the human contribution to observed warming, we use the “Global Warming Index” (GWI) (Otto et al. 2015; Haustein et al. 2016), which allows us to remove the effect of particularly warm or cold individual years on the estimate of human-induced climate change. When updated to the end of 2015, the GWI gives an observed human-induced temperature increase of 0.99°C, relative to the 1861-1880 average (Haustein et al. 2016). Total historical CO₂ emissions between 1870 and 2015 are 555 GtC (Le Quéré et al. 2015), which gives a TCRE_{eff} of 1.78 °C/1000 GtC (0.99 °C / 555 Gt C).

The effective TCRE is therefore an estimate of the warming caused by a given quantity of CO₂ emissions, scaled upwards to account for the additional warming from non-CO₂ emissions. The ratio of TCRE to TCRE_{eff} should therefore be equal to the ratio of CO₂ to total anthropogenic forcing. Using the observationally-based best estimate for the TCRE of 1.35 °C/1000 GtC, we can see that the ratio of TCRE to TCRE_{eff} is $1.35/1.78 = 0.76$, which is consistent with the current ratio of CO₂ to total anthropogenic forcing taken from the IPCC forcing estimates (see Figure 2). Updated estimates of year-2015 anthropogenic warming, CO₂ emissions and anthropogenic forcing therefore support Gillett et al (2013)’s observationally constrained TCRE of 1.35 °C/1000 GtC, and a corresponding TCRE_{eff} of 1.78 °C/1000 GtC.

An alternate method to estimate the TCRE_{eff} would be to scale the CMIP5 model-based TCRE according to the ratio of CO₂ to total forcing as simulated by this model ensemble, again assuming that temperature response is approximately proportional to forcing. As plotted in Figure 2, CO₂ makes up about 86% of total anthropogenic forcing at the year 2015 in the CMIP5 models; this value is consistent with the ensemble-average for RCP scenarios 8.5, 4.5 and 2.6, noting that there is some variation in the ratio of CO₂ to total forcing among scenarios, and also among individual CMIP5 models for a particular RCP scenario (Meinshausen et al. 2011). Using the CMIP5 TCRE of 1.6 °C/1000 GtC, this results in a TCRE_{eff} of $1.6/0.86 = 1.86$ °C/1000 GtC. This model-based TCRE_{eff} suggests an observed warming of 1.03°C at the end of 2015 (1.86 °C/1000 GtC * 555 GtC) which, while slightly higher

than the GWI best estimate of 0.99°C for this date, is well within the 5-95% uncertainty range of the GWI (-0.14 to $+0.22^{\circ}\text{C}$) (Haustein et al. 2016). It is worth noting that the difference between the model-based and observationally-based estimate of the TCRE_{eff} (1.86 vs. $1.78^{\circ}\text{C}/1000$ GtC) is smaller than the difference for the CO_2 -only TCRE (1.6 vs. $1.35^{\circ}\text{C}/1000$ GtC). This smaller TCRE_{eff} difference is explained by a smaller total anthropogenic forcing (about 0.3 W/m^2) in the CMIP5 ensemble compared to the IPCC forcing estimate, which in turn reflects an overall larger negative aerosol forcing in the CMIP5 models compared to the IPCC forcing data. As a result, the ratio of CO_2 to total forcing is larger in the CMIP5 models than the IPCC forcing data, as can be seen in Figure 2. This highlights the important role of aerosol forcing uncertainty in particular as a constraint on our ability to validate TCRE_{eff} estimates against the observational record.

These estimates of the TCRE_{eff} can be used to estimate an effective carbon budget, which represents the total quantity of CO_2 emissions that is consistent with a given climate target, while allowing for additional non- CO_2 warming. Using the observationally-based TCRE_{eff} of $1.78^{\circ}\text{C}/1000$ GtC suggests an effective carbon budget of 560 GtC per degree, or 845 GtC for 1.5°C and 1125 GtC for 2°C . Using the model-based TCRE_{eff} of $1.86^{\circ}\text{C}/1000$ GtC results in an effective carbon budget of 540 GtC per degree, or 805 GtC for 1.5°C and 1075 GtC for 2°C (see Table 2).

These effective carbon budgets, as derived either from models or from historical data, are therefore a first-order estimate of the quantity of CO_2 that would be consistent with 1.5 or 2°C of global warming, allowing for a portion of this warming to come from additional non- CO_2 emissions. This calculation implicitly assumes that the ratio of CO_2 to total anthropogenic forcing will remain approximately constant as we approach these targets. There are important caveats to this assumption, however, that limit the utility of this simple TCRE-based derivation of effective carbon budgets.

In general, CO_2 forcing will continue to increase until the point that global CO_2

emissions drop below the level of natural sinks; at the point that we reach 1.5 or 2 °C of global warming, the level of CO₂ in the atmosphere will therefore necessarily be higher than today. The assumption of a constant ratio of CO₂ to total forcing would only be consistent with a scenario of a net increase in non-CO₂ forcing, at a rate comparable to the rate of increase in CO₂ forcing. This is a plausible assumption for the next decade or two, as expected decreases in global aerosol emissions (and associated negative forcing) are likely to result in a near-term increase in net non-CO₂ forcing. However, it is unlikely that non-CO₂ forcing will continue to increase, given that efforts to curb greenhouse gas emissions are unlikely to be applied only to CO₂ and not also to other non-CO₂ greenhouse gases. We therefore argue that in the context of ambitious mitigation scenarios that are consistent with 1.5–2 °C climate targets, it is very likely that by the time we reach 1.5 or 2 °C of climate warming, net non-CO₂ forcing will be smaller than today, and consequently that the ratio of CO₂ to total anthropogenic forcing will increase over time (as is the case for the RCP2.6 scenario, as shown in Figure 2).

This in turn means that the effective carbon budget for 1.5–2 °C will likely increase over time, becoming larger than the values given in Table 2; for example, if we were successful in mitigating non-CO₂ emissions rapidly enough such the ratio of CO₂ to total forcing were to increase to 0.93 (the maximum value in RCP2.6), this would imply an effective carbon budget of 580 GtC per degree (870 GtC for 1.5 °C; 1165 GtC for 2 °C) based on the model-based TCRE of 1.6 °C/1000 GtC and the resulting TCRE_{eff} of 1.72 °C/1000 GtC at the time that we reach 1.5 or 2 °C. We suggest therefore that the TCRE_{eff}, and associated effective carbon budget, be treated as quantities that will change over time in response to our own climate policy decisions regarding non-CO₂ mitigation. This time and scenario-dependence of the effective carbon budget is plotted in Figure 3, which shows that the range of non-CO₂ mitigation across the RCP scenarios results in an effective carbon budget range of 90 GtC per degree, or about 17% of the estimate based on year-2015 forcing ratios.

Key contributions to carbon budget uncertainty

The values given above represent best estimates of the TCRE and associated $TCRE_{eff}$ based on currently-available model output and observational data. While the observationally-constrained estimates could arguably be considered to be the more reliable of the two (Gillett et al. 2013), the model-based estimates are also consistent with the range of uncertainty associated with observed temperature changes and should therefore be considered to be a similarly plausible representation of the climate response to cumulative human CO₂ emissions. We therefore suggest here that the range of values between the observationally- and model-based estimates shown in Table 2 should be taken as a range of best estimates of the effective carbon budgets for 1.5–2 °C. These values are considerably larger than most previous carbon budget estimates (IPCC 2014; Friedlingstein et al. 2014; Rogelj et al. 2016), though are consistent with a recent reassessment of CMIP5 model results in light of observed temperature changes (Millar, Fuglestedt, et al. 2016).

However, in the context of setting emissions targets for a given level of global temperature increase, these best estimates are only consistent with a 50% chance of remaining below the desired level of global warming. Given the large uncertainty in the climate response to emissions, increasing the confidence level associated with meeting a climate target (e.g. to a 67% chance) can result in a substantial decrease in allowable emissions. For example, if the model-based range of TCRE is assumed to represent a Gaussian distribution with 5th and 95th percentiles of 0.8 and 2.4 °C/1000 GtC, this would mean that the TCRE has a 67% chance of being less than 1.8 °C/1000 GtC and a 90% chance of being less than 2.2 °C/1000 GtC. The increase in confidence from a 50 to 67% chance in remaining below the desired climate target requires using a 12.5% higher value for the TCRE, and results in a corresponding decrease in the carbon budget for a given climate target (i.e. by 70 GtC per °C of target). Similarly, increasing the confidence from 50 to 90% decreases the carbon budget by about 27% (170 GtC per degree). For comparison, the

difference between the model-based CO₂-only and effective carbon budgets (reflecting the effect of accounting for non-CO₂ warming) is 85 Gt C (Table 1 vs. Table 2).

This idea of assigning a likelihood of meeting a climate target given some carbon budget has been used in most previous assessments of carbon budgets associated with different levels of climate change (Friedlingstein et al. 2014; Rogelj et al. 2016). However, the method accounts for only one source of quantified uncertainty: the uncertainty associated with the climate response to CO₂ emissions. This implicitly includes the contribution of climate sensitivity (or more precisely, transient climate response) uncertainty, as well as the uncertainty associated with the uptake of anthropogenic CO₂ by land and ocean carbon sinks (which further includes the uncertainty associated with climate-carbon feedbacks that govern how carbon sinks are affected by CO₂ (or non-CO₂)-induced warming). It also indirectly accounts for uncertainty associated with observed temperature change and the present-day strength of non-CO₂ forcing, in that a higher TCRE would have to be associated with smaller net non-CO₂ forcing (e.g. due to stronger negative aerosol forcing) in order to remain consistent with the observational record.

These above likelihood values do not, however, account for the uncertainty associated with future non-CO₂ emission pathways, and therefore do not account for the critical question of how strong non-CO₂ forcing will be at the time that we are approaching 1.5–2 °C of climate warming. Given that the majority of the non-CO₂ forcing is the result of gases and aerosols with short atmospheric lifetimes – so-called “short-lived climate forcers” or SLCFs – the strength of non-CO₂ forcing is primarily determined by the annual rate of emissions, rather than (as is the case for CO₂) the total accumulated emissions over time (Smith et al. 2012). Consequently, the level of non-CO₂ emissions several decades from now will have a very large influence on the effective carbon budget associated with 1.5–2 °C of climate warming. And unlike the likelihood values associated with the climate response uncertainty above, there are no equivalent likelihood values that have been

estimated for future non-CO₂ emissions pathways. Previous analyses have therefore considered the range of non-CO₂ forcing strengths across the RCP scenarios as a plausible range, and have used these values to estimate a range of effective carbon budgets, without assigning any additional likelihood values to this range (Rogelj et al. 2016; Friedlingstein et al. 2014). This has resulted in a very large range of “likely” (i.e. 67% chance of remaining below the target) carbon budgets, which limits their usefulness to climate policy.

While there is no immediate solution to the problem of how to apply likelihood values to the mitigation decisions that will determine future non-CO₂ forcing, we here attempt to clarify what these human decisions mean for carbon budget estimates. First, for any climate target in the range of 1.5–2 °C it seems highly unlikely that non-CO₂ emissions will follow a business-as-usual trajectory, with human mitigation effort concentrated solely on decreasing CO₂ emissions. This then suggests that the lower-end of the RCP non-CO₂ forcing range (which makes up between 7 and 15% of total forcing during the second half of this century as shown in Figure 2) is much more likely than the higher non-CO₂ forcing in RCP8.5. This in turn implies that effective carbon budgets based on the current strength of non-CO₂ forcing (as in Table 2) should be taken as conservative estimates with a high likelihood that the eventual effective carbon budget will be closer to (but lower than) the CO₂-only carbon budgets listed in Table 1. Second, the implication that emerges here for climate mitigation decision making is that while the size of CO₂-only carbon budget is governed entirely by geophysical constraints, the *difference* between CO₂-only and effective carbon budgets depends primarily on *human* decisions. If we decide to aggressively mitigate non-CO₂ emission such that non-CO₂ forcing at the time we reach 1.5–2 °C is small, then this will enlarge the effective carbon budget, thereby increasing the amount of cumulative CO₂ emissions that would be consistent with the desired target.

It is worth commenting briefly on a third source of uncertainty, which is associated with the climate response time to emissions. As argued above, there is evidence to

suggest that the climate response time to CO₂ emissions is small (Ricke & Caldeira 2014), implying that CO₂-induced temperature change remains relatively stable once emissions are stopped (Matthews & Weaver 2010). For non-CO₂ agents, however, global temperature does change after the elimination of emissions, leading to non-negligible positive or negative ZECs associated with current emissions of different short-lived species. This is well illustrated by the case of aerosols emissions, which include a range of individual aerosol types that both warm and cool the climate. On balance, aerosols currently produce a net negative forcing, and decreased emissions would therefore warm the climate, though this effect would of course vary depending on the relative effectiveness of mitigating different aerosol types. In the case of short-lived greenhouse gases (such as methane or tropospheric ozone), decreased emissions would result in cooling in response to declining forcing. Matthews and Zickfeld (2012) estimated the ZEC associated with both CO₂ and non-CO₂ emissions, showing that an abrupt elimination of all emissions would lead to a warming of a few tenths of a degree over about a decade, followed by a gradual cooling that returned global temperatures to close to present-day levels over the course of about two centuries. This result implies that complete elimination of current non-CO₂ emissions would likely cause a small initial warming as aerosol forcing abruptly dissipates, and would then gradually reverse in line with eventually declining non-CO₂ greenhouse gas forcing. Again, however, this potential warming response depends primarily on human mitigation decisions, and not on any inherent geophysical constraints.

A final source of uncertainty relates to the potential effect of important processes that are still missing from, or poorly represented in, the current generation of Earth system models. For example, accounting for CO₂ release from thawing permafrost would decrease the size of the CO₂-only carbon budget, though like other carbon cycle feedbacks, the effect of permafrost melt does not invalidate the concept of a carbon budget and the associated linear relationship between warming and cumulative CO₂ emissions (MacDougall et al. 2015). Changing fire dynamics could also have a important consequences for the carbon cycle (Landry et al. 2015) and

therefore for carbon budget estimates. In general however, the uncertainty surrounding human decisions has much greater bearing on future warming estimates than do these geophysical uncertainties (Hawkins & Sutton 2009; Fyke & Matthews 2015). And as outlined above, human decision uncertainty is also an important direct contributor to the differences in effective carbon budget estimates, which emphasizes the critical importance of effective climate mitigation decision-making that reflects and accommodates for fundamental geophysical uncertainty.

Conclusions

Despite the large uncertainty range on any estimate of a carbon budget for a given climate target, the idea that there is a finite amount of CO₂ that is allowed to be emitted remains an appealing way of framing the climate mitigation challenge. CO₂-only carbon budgets represent a simple and robust quantity that emerges from a set of increasingly well-understood processes that govern the climate response to cumulative CO₂ emissions. Effective carbon budgets, which define the allowable CO₂ emissions for a given climate target while allowing for additional warming from non-CO₂ emissions, are less robust because they are less governed by geophysical constraints. This means that the eventual size of the effective carbon budget will be highly influenced by human decisions and in particular by our ability to mitigate emissions of short-lived greenhouse gases and aerosols.

This responsiveness of the size of effective carbon budgets to human decisions implies the need for climate mitigation strategies that are able to adapt to new information about the climate response to emissions (Millar, Allen, et al. 2016), as well as to our success or failure at aggressively mitigating emissions of short-lived species. It may therefore be less important to precisely estimate the size of the effective carbon budget now, as it is to implement strong non-CO₂ emission mitigation policies that would enlarge the carbon budget, in parallel with efforts to mitigate emissions of CO₂ themselves. However, it is also crucial that efforts to curb non-CO₂ emissions do not replace mitigation of CO₂, as this would increase both

peak and long-term warming (Pierrehumbert 2014). While the CO₂-only budget represents a firm (if uncertain) upper limit on total allowable emissions, the smaller effective carbon budget is a quantity that will become more clear only as we move forward with ambitious climate mitigation efforts aimed at limiting climate warming to the 1.5–2 °C range committed to in the Paris Climate Agreement.

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Table 1: Best-estimates of the TCRE (Transient Climate Response to cumulative CO₂ Emissions) from climate models and observational data, with corresponding estimates of the CO₂-only carbon budgets associated with a given amount of CO₂-induced global temperature increase. Values in parentheses are in units of CO₂ rather than C, where 1 tonne of C = 3.67 tonnes of CO₂, and all carbon budget values are rounded to the nearest 5 Gt.

	TCRE	CO ₂ -only Carbon budgets		
		per °C	1.5 °C	2 °C
CMIP5 models	1.6 °C / 1000 GtC (0.44 °C / 1000 GtCO ₂)	625 GtC (2290 GtCO ₂)	940 GtC (3445 GtCO ₂)	1250 GtC (4585 GtCO ₂)
Observations	1.35 °C / 1000 GtC (0.37 °C / 1000 GtCO ₂)	740 GtC (2715 GtCO ₂)	1110 GtC (4070 GtCO ₂)	1480 GtC (5425 GtCO ₂)

Table 2: Best-estimates of the TCRE_{eff} (“effective TCRE,” representing the climate response to cumulative CO₂ emissions, scaled upwards to account for additional non-CO₂ warming) from climate models and observational data, with corresponding estimates of the effective carbon budgets associated with a given amount of global temperature increase resulting from all human emissions. Values in parentheses are in units of CO₂ rather than C, where 1 tonne of C = 3.67 tonnes of CO₂, and all carbon budget values are rounded to the nearest 5 Gt.

	Effective TCRE	Effective Carbon budgets		
		per °C	1.5 °C	2 °C
CMIP5 models	1.86 °C / 1000 GtC (0.51 °C / 1000 GtCO ₂)	540 GtC (1980 GtCO ₂)	805 GtC (2950 GtCO ₂)	1075 GtC (3940 GtCO ₂)
Observations	1.78 °C / 1000 GtC (0.49 °C / 1000 GtCO ₂)	560 GtC (2055 GtCO ₂)	845 GtC (3100 GtCO ₂)	1125 GtC (4125 GtCO ₂)

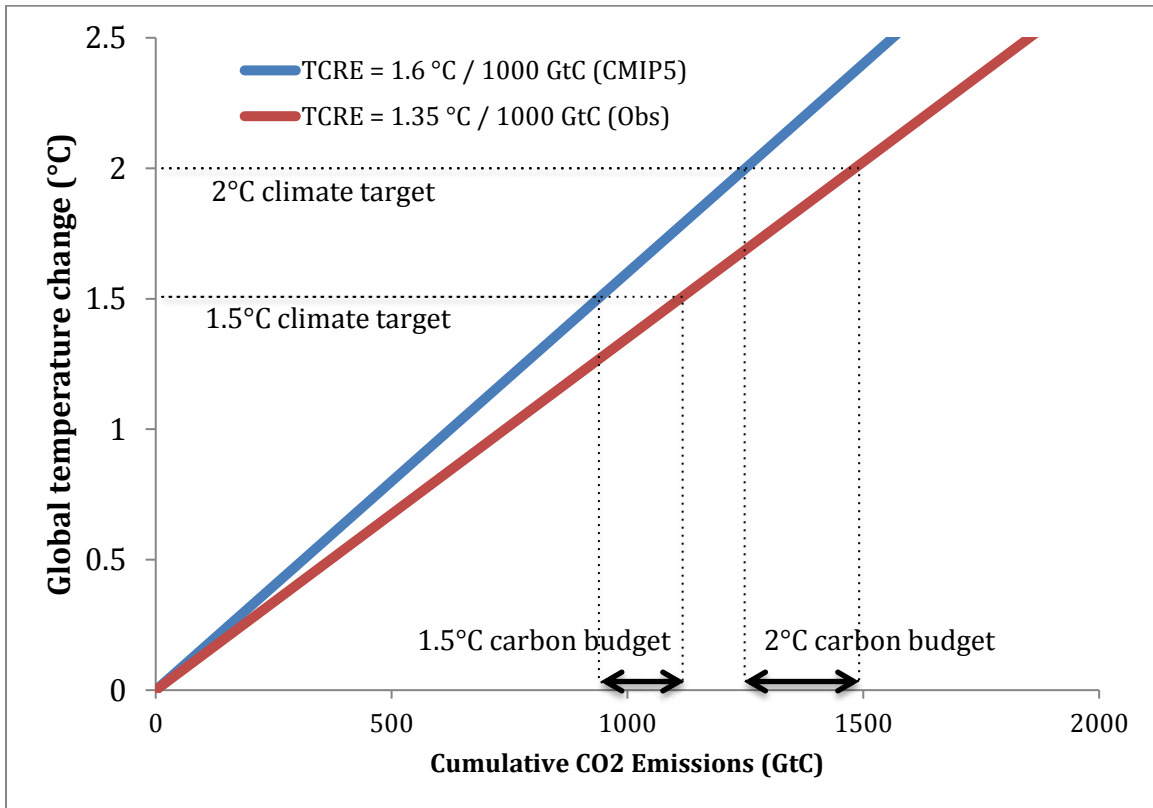


Figure 1 Relationship between the cumulative CO₂ emissions and CO₂-induced temperature change for two different estimates of the TCRE. CO₂-only carbon budget ranges for 1.5–2 °C associated with this range of TCRE values are marked on the horizontal axis. The two values of the TCRE illustrated here are the median of the ensemble of CMIP5 Earth-system models (1.6 °C/1000 GtC; blue line) and the observationally-constrained best estimate (1.35 °C/1000 GtC; red line) (Gillett et al. 2013).

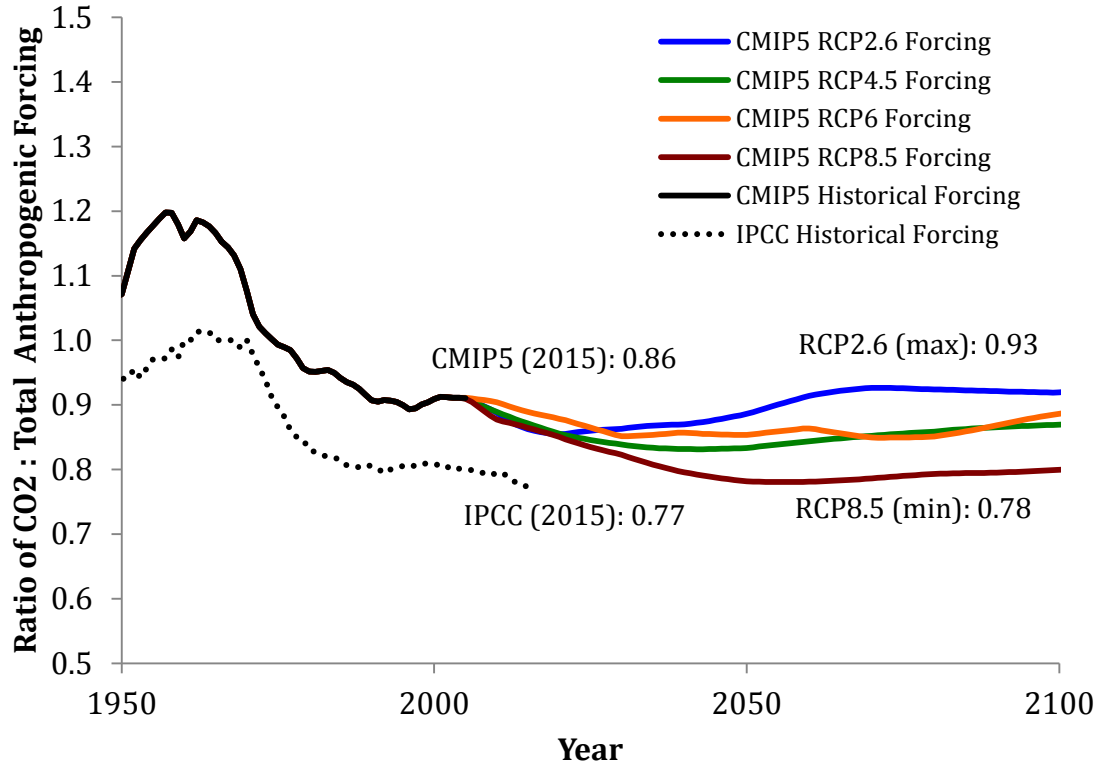


Figure 2: Ratio of CO₂ to total anthropogenic forcing from the IPCC forcing estimates (dotted line) and the CMIP5 model ensemble (solid lines). IPCC forcing data is calculated according to Myhre et al. (2013), updated to the year 2015. CMIP5 forcing data is approximated here using forcing data from Meinshausen et al. (2011), which gives forcing estimates using the MAGICC model, scaled to match the mean response of the CMIP5 model ensemble.

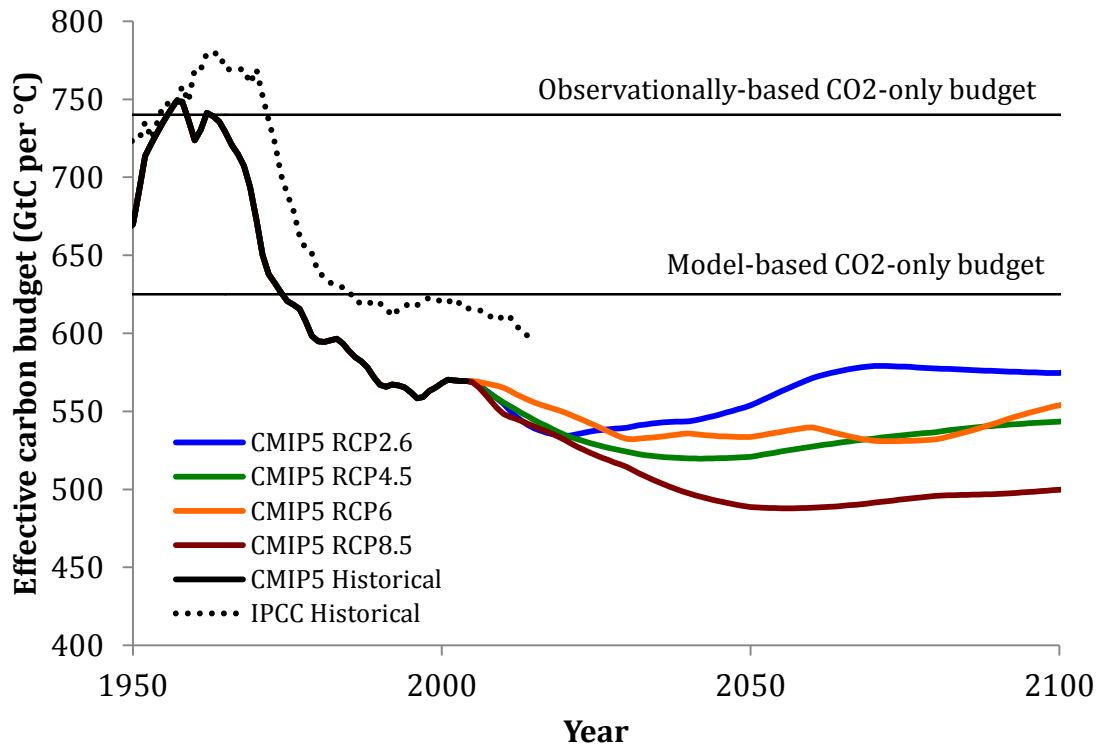


Figure 3: Effective carbon budget estimates (per 1 °C), based on a constant CO₂-only budget scaled using the ratios of CO₂ to total anthropogenic forcing shown in Figure 2. Both model-based (solid lines) and observationally-based (dashed line) estimates of the effective carbon budgets are shown, calculated using their respective CO₂-only budget estimates from Table 1 (thin horizontal lines). Values in Table 2 correspond to the year-2015 values taken from these time-series (where the model-based estimate for 2015 is consistent with the RCP2.6, RCP4.5 and RCP8.5 scenarios, rather than with RCP6 which shows a slightly higher year-2015 effective carbon budget).