CARBON BUDGET

FACTSHEET

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The carbon budget is a powerful concept to quickly explain the climate challenge, but underneath the hood lies the complex dynamics of the climate system.

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Climate-Carbon Interactions in the Current Century

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THE CARBON BUDGET CONCEPT

The '**carbon budget**' concept has been around in some form for several decades (1), but did not really come to prominence until a series of papers published in the late 2000s (2-4). These papers all showed the strong relationship between temperature change and cumulative carbon dioxide (CO_2) emissions, with the implication that these emissions need to be reduced down to zero and thereby defining a finite 'carbon budget'.

The cumulative emissions relationship and carbon budget concepts have since dominated policy debates. The concepts have had high profile coverage in the 5th and 6th Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC), in addition to the Special Report on Global Warming of 1.5˚C. These concepts have likely influenced the recent growing interest and uptake of '**net zero**' emission pledges.

The carbon budget concept is an effective way to explain the climate challenge, particularly the need to get to zero emissions and the high costs of delaying mitigation actions. Despite the robustness of the concept, it is often misunderstood and the uncertainties are often overlooked. In this factsheet, we explain the background of the carbon budget, its uncertainties, and how to use it.

TEMPERATURE AND CUMULATIVE CO_2 EMISSIONS

The global climate system is complex, with many interacting non-linear components spanning multiple scales, from clouds to oceans. Given this complexity, it is quite remarkable that there is an essentially linear relationship between global surface temperature change and the total cumulative CO_2 emissions (Fig. 1).

The surface temperature change is driven by multiple factors, of which CO_2 emissions are the dominant one. Some factors, such as methane (CH_4) emissions, are more potent on a per unit mass basis, but their effects are short-lived as they remain in the atmosphere for relatively short periods of time (e.g. 10 years). CH_4-induced warming does not relate to cumulative CH_4 emissions, but rather the rate of CH_4 emissions (5). By contrast, CO_2 has a long lifetime and its effects linger essentially indefinitely, leading to the near linear relationship between CO_2-induced warming and cumulative CO_2 emissions.

The relationship between total temperature change from all components and cumulative CO_2 emissions is therefore still dominated by the CO_2-induced temperature change, with a small adjustment due to non-CO_2 emissions (Fig. 1).

The 'carbon budget' is the cumulative CO_2 emissions up to a given temperature level. It is defined for CO_2 emissions only, which means it is necessary to make an adjustment to account for non-CO_2 emissions. This non-CO_2 adjustment is one of the biggest uncertainties in the carbon budget. It is possible to construct carbon budgets for all greenhouse gases (6), but this cannot be done using CO_2-equivalent emissions with Global Warming Potentials (GWPs).

CARBON BUDGET

The focus on temperature change and cumulative CO_2 emissions seems somewhat removed from the carbon budget, but the two concepts are essentially equivalent. Any additional emissions lead to additional temperature change (Fig. 1); the temperature increases when moving from left to right towards higher cumulative emissions. The temperature stops rising when CO_2 emissions reach zero, and therefore the cumulative emissions stop growing. The illustrative carbon budget for 1.5˚C shows a gap between the shaded region for a 1.5˚C carbon budget and the black vertical line for CO_2-induced warming (Fig. 1), demonstrating that the carbon budget is smaller when non-CO_2 emissions are included.

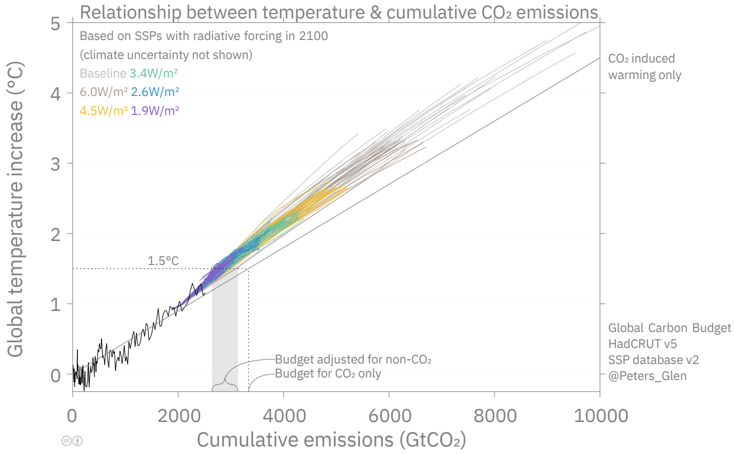


Figure 1. The relationship between temperature change and cumulative CO_2 emissions. The black squiggly line shows historical data, while the coloured lines show different emission scenarios reaching different levels of radiative forcing in 2100 (W/m^2), with each radiative forcing level corresponding to a different temperature level in 2100. All values are medians. The plotted temperature change is due to both CO_2 and non-CO_2 warming, but the temperature change is dominated by CO_2, indicated by the straight diagonal black line for CO_2-induced warming. The difference between the straight diagonal black line and the plotted data is the non-CO_2-induced warming. The horizontal dotted line at 1.5°C, and the shaded patch, is an approximate method to show the carbon budget for 1.5°C of warming.

The relationship between CO_2-induced warming and cumulative CO_2 emissions is known as the Transient Climate Response to cumulative CO_2 Emissions (TCRE), and has a value of 0.45˚C per 1,000 gigatonnes of CO_2 ($GtCO_2$), with a likely range 0.27-0.63˚C (diagonal black line in Fig. 1). The TCRE can be inverted to show that a 0.1˚C of CO_2-induced warming would result from 220 $GtCO_2$ cumulative emissions. This simple rule of thumb is useful for describing the differences in emissions between different warming levels.

Another concept, known as the Zero Emission Commitment (ZEC), relates the warming at a point in time after zero CO_2 emissions are reached and maintained (see 4C Science Summary). The ZEC explains temporal deviations away from the TCRE relationship as the system moves towards equilibrium. The value of ZEC, defined as the temperature change at 50 years after CO_2 emissions reach zero, was found to be -0.07˚C with a range -0.36 to 0.29˚C across a range of models (7). An implication is that exactly zero CO_2 emissions may not be needed, instead it could be slightly positive or negative, with the current best estimate suggesting that positive CO_2 emissions of +2.2 $GtCO_2$/yr could maintain zero additional warming (5–95th range spans –7.3-6.2 $GtCO_2$/yr) (8).

The carbon budget is often split into two components, a historical component and a future component. Today, the term “Remaining Carbon Budget” is used for the future component, while the term “Total Carbon Budget” is used for the combination of the historical and future component. Confusingly, the balance of sources and sinks in the carbon cycle is also called the ‘carbon budget’, but sometimes more explicitly as the ‘Historical Carbon Budget’. The use of the same term for different concepts obviously gives potential for confusion, but is hard to avoid as both terms are used extensively in the respective research and policy communities.

MULTIPLE DEFINITIONS OF THE CARBON BUDGET

There have been multiple definitions of the carbon budget, and multiple papers to explain these definitions (9,10). The carbon budget has been derived using Earth system models and integrated assessment models (IPCC AR5 Synthesis Report, Table 2.2), and the different approaches have different definitions and uncertainties. The carbon budget has variously been defined at the time a temperature target is exceeded, cumulative CO_2 emissions at the year of peak temperature when a temperature level is avoided, the cumulative CO_2 emissions until 2100 in a given scenario, and most recently, at the time CO_2 emissions reach zero (IPCC AR6 WGI Chapter 5). Each definition leads to slightly different estimates of the carbon budget.

In most emission scenarios, after the point of net zero CO_2 emissions the emissions become net negative. In these scenarios, the cumulative CO_2 emissions begin to decline from the point of net zero CO_2 emissions (until the scenario ends, often in 2100). This ‘peak-and-decline’ behaviour is commonly referred to as an ‘overshoot’ scenario, which exceeds a prescribed temperature level like 1.5˚C before returning below that temperature level.

The overshoot behaviour of many emission scenarios can lead to confusion over carbon budgets. The Remaining Carbon Budgets defined in AR6 WGI would imply zero emissions around 2040 with a linear decline in emissions to reach 1.5˚C, but most 1.5˚C scenarios reach zero CO_2 emissions around 2050. This means those scenarios actually exceed 1.5˚C, and in fact, most reach around 1.6˚C at the point of zero CO_2 emissions. The temperature in those scenarios then declines to be under 1.5˚C in 2100, meaning the cumulative CO_2 emissions in 2100 is smaller than the Remaining Carbon Budget defined in the point of zero CO_2 emissions. Many 1.5˚C scenarios have 0.1-0.2˚C of declining temperature from the peak temperature until 2100, with a part of that due to net negative CO_2 emissions, a part of that due to declining non-CO_2 emissions, and a part due to the behaviour of the climate model (11).

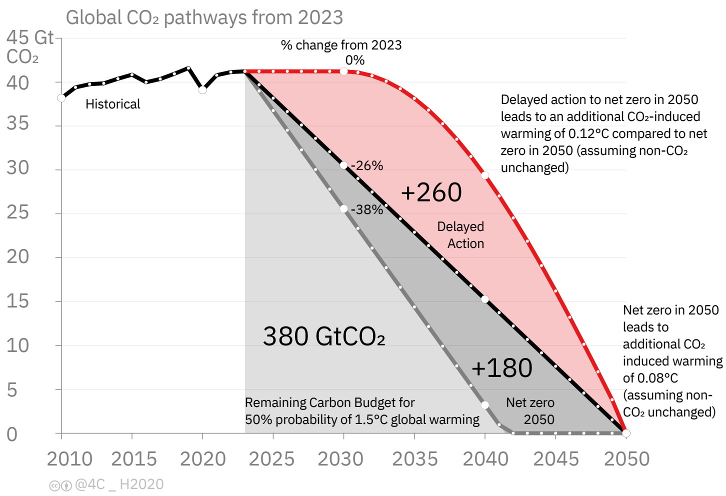


Figure 2. A linear decline in CO_2 emissions using a Remaining Carbon Budget of 1.5°C (AR6), showing the difference with a linear decline to zero CO_2 emissions in 2050 leading to around 1.6°C warming, and an extreme scenario where there is delay in mitigation, but net zero is still reached in 2050, leading to 1.7°C of warming. All these scenarios would have different warming levels in 2100, depending on the extent of net negative CO_2 emissions assumed from 2050 to 2100.

DISTRIBUTING A CARBON BUDGET OVER TIME

The carbon budget concept is particularly useful to show simple heuristics of distributing the carbon budget over time. The carbon budget, cumulative CO_2 emissions, is simply the area under the CO_2 emission curve. The simple relationship makes it easy to demonstrate the difference between scenarios with and without overshoot. It is possible to construct pathways with the same level of cumulative CO_2 emissions in 2100, but reach that point in different ways (Fig. 3):

- One option is to avoid overshoot by keeping CO_2 emissions above zero and staying within a Remaining Carbon Budget of 500 $GtCO_2$. This is equivalent to around 1.6˚C of warming in 2100. It is still possible to have emissions and removals, as long as the net CO_2 emissions do not go below zero.

- Another option is to have the same cumulative CO_2 emissions in 2100 of 500 $GtCO_2$, but exceed this value before 2100. The Remaining Carbon Budget, defined at the point of zero CO_2 emissions, is 770 $GtCO_2$ or 1.7˚C. Thus, the cumulative emissions are 270 $GtCO_2$ lower in 2100 than at net zero CO_2 emissions. This is the pathway in most 1.5˚C emission scenarios.

The concept of cumulative CO_2 emissions, works on a net basis (Fig. 3). The net emissions are the gross positive anthropogenic emissions into the atmosphere minus the gross negative anthropogenic removals from the atmosphere: net equals emissions minus removals. The 'net' concept is sometimes controversial as it places focus on removals, which some actors misuse as an alternative to emission reductions. Mathematically, zero and net zero CO_2 emissions are equivalent.

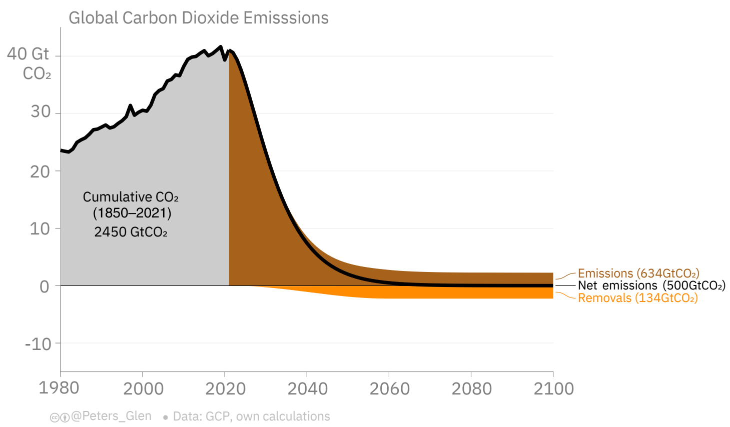
HOW MANY YEARS LEFT?

The Remaining Carbon Budget is often divided by the current levels of emissions to indicate the amount of time before the budget is exhausted assuming constant emissions (Fig. 4). While this is a defensible method to explain the size of the budget, it does not correlate to the time that the temperature level consistent with the budget might be exceeded.

The Remaining Carbon Budget is defined at the point of zero CO_2 emissions, and thus, the pathway from today to zero CO_2 emissions, with consistent reductions in non-CO_2 emissions, would lead to the temperature level being exceeded. Holding emissions flat, and making consistent assumptions on non-CO_2 emissions, is inconsistent with the definition of the Remaining Carbon Budget, and more akin to the earlier definition of an 'exceedance' budget, for which the emissions and temperature are expected to continue to rise after the budget is exceeded.

Therefore, care needs to be taken interpreting the years to exhaust the budget with the year a temperature target is exceeded. Even though the two may occur within a few years of each other, the concepts are inconsistent. Alternative methods are needed to determine when a temperature level is crossed.

The Remaining Carbon Budget can also be compared to the CO_2 emissions that are projected over the lifetime of existing fossil fuel infrastructure, assuming no additional abatement. The total cumulative CO_2 emissions from existing infrastructure already exceeds the Remaining Carbon Budget for 1.5˚C (>50%). If planned infrastructure is included, the exceedance becomes larger.



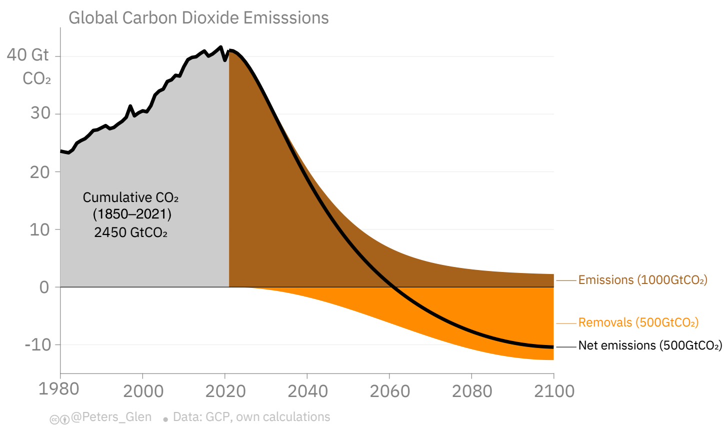


Figure 3. Two pathways reaching the same cumulative CO_2 emissions in 2100, but following different pathways: a balance between CO_2 emissions and removals so that net CO_2 emissions are positive (left) and an overshoot pathway with substantial net-negative CO_2 emissions (right). In both cases, net CO_2 emissions are the sum of emissions and removals.

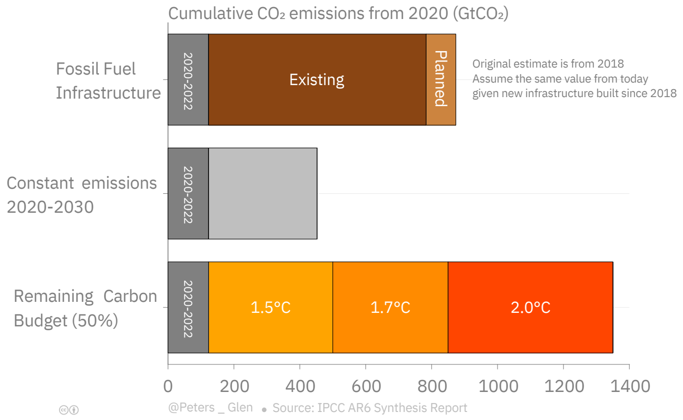


Figure 4. The cumulative CO_2 emissions for different existing and planned infrastructure if they run to their assumed end-of-life, over the period 2020-2030 assuming constant current emissions, and for different remaining carbon budgets (IPCC AR6). The dark grey part are historical emissions that occurred over the period 2020-2022.

PROBABILITIES AND UNCERTAINTIES

The Remaining Carbon Budgets are often reported for different likelihoods at different temperature levels (Fig. 5). The likelihoods refer to the uncertainty distribution of the TCRE. Further uncertainties, driven by different mechanisms, come in addition to the TCRE uncertainty. Uncertainty in non-CO_2 temperature change is the most notable, and in fact, the Remaining Carbon Budget for 1.5˚C has a decent chance of being negative when considering these uncertainties (12).

There is no right or wrong way to choose the relevant Remaining Carbon Budget for your needs, other than noting the background for the choice and the inherent uncertainties. There are some relevant connections across budgets: an 83% chance of keeping below 2˚C is coincidentally equivalent to a 17% chance of 1.5˚C.

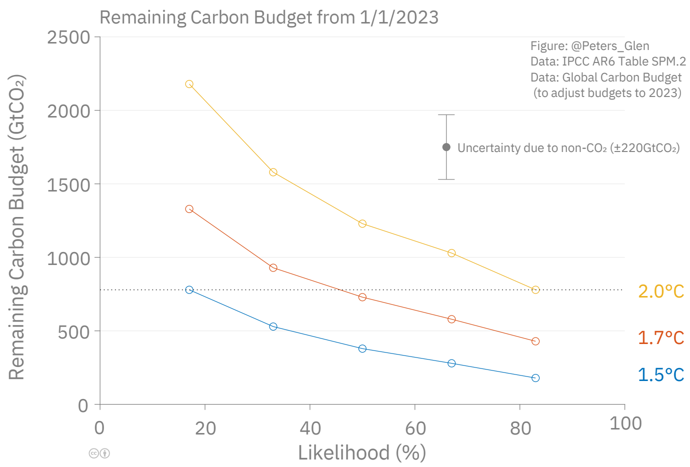


Figure 5. The Remaining Carbon Budget from the IPCC AR6 WGI SPM, Table 2, showing three different temperature levels and different likelihoods due to the probability distribution of the TCRE. With each of these budgets, there is an additional uncertainty due to assumptions on different non-CO_2 emission pathways. All these budgets are updated from AR6, by deducting the CO_2 emissions in 2020, 2021, and 2022.

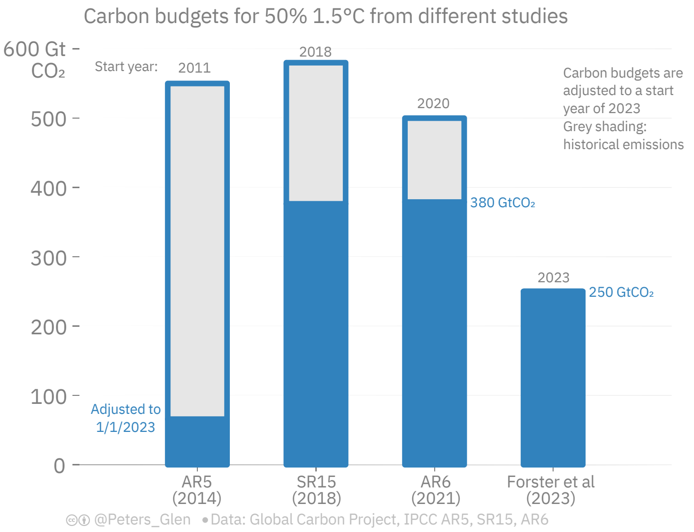
The likelihoods are due to the uncertainty in the TCRE. The Remaining Carbon Budget for a 50% chance of 1.5˚C is 380 $GtCO_2$, as of 1/01/2023, though the likely range (17-83%) is 180-780 $GtCO_2$. If the non-CO_2 uncertainty is added to this, then the budget for 1.5˚C is 380±220 $GtCO_2$, as of 2023, with a likely range (17%-83%) of -40 to +1000 $GtCO_2$, indicating negative budgets are already possible for some combinations of parameters.

CHANGE IN ESTIMATED CARBON BUDGETS OVER TIME

Various carbon budget estimates have been made over the years, most prominently in IPCC AR5, IPCC SR15, and IPCC AR6. The AR6 estimates were again updated in a journal publication (13). The methods have also evolved during each report, with the method used for IPCC AR5 differing the most. Improvements in methods and understanding since IPCC AR5 led to more robust and consistent estimates in IPCC SR15. IPCC SR15 and IPCC AR6 are the most consistent, but differ in how some feedbacks are included, such as permafrost feedbacks.

In IPCC AR6, the Remaining Carbon Budgets were estimated in WGI, but had to rely on emission scenarios from IPCC SR15. In IPCC AR6 WGIII, Box 3.4, a reference was made to an update of the WGI Remaining Carbon Budgets using the latest understanding of the climate and updated emissions scenarios from WGIII. Forster et al. (2023) carried out this update more formally, updating the IPCC AR6 estimate with the latest data, but using the same methodology as in IPCC AR6. To compare how the budgets have changed over time also requires adjusting for emissions that have occurred since the estimates were published (Fig. 6).

There now exist two Remaining Carbon Budgets stemming from IPCC AR6: the estimates published in IPCC AR6 and the estimates published in Forster et al. (2023). While the original IPCC AR6 estimate may have greater authority, since it is based on the IPCC process, it will eventually need to be updated. While Forster et al. 2023 does an update, other literature and estimates are expected to appear in the literature. This emerging literature will not be assessed until the next IPCC report, perhaps another five years away. Arguably, there has been too much focus placed on single numbers for the Remaining Carbon Budget (14), and instead focus should be placed on full uncertainty ranges. Based on IPCC AR6, the Remaining Carbon Budget for 1.5˚C has a median value of 500 $GtCO_2$ with a likely range of 300-900 $GtCO_2$ from 1/1/2020.



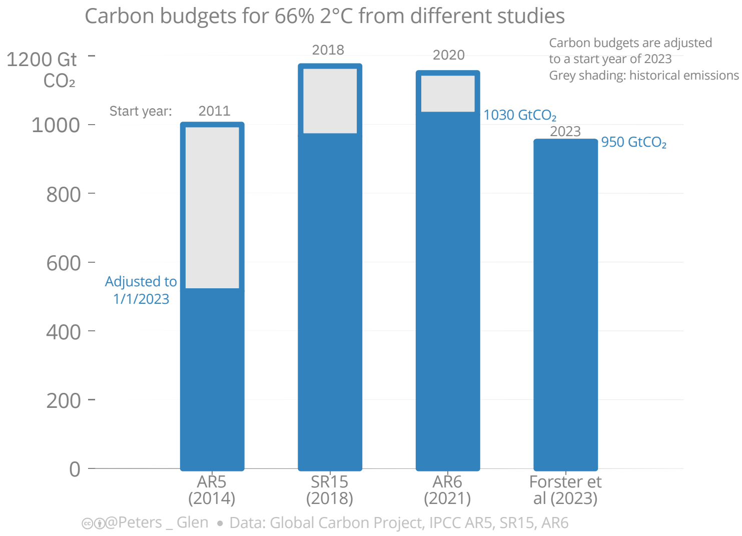


Figure 6. The Carbon Budgets as published in different IPCC reports and updated in Forster et al (2023). The total bar shows the published carbon budget and start date, the grey shading are historical emissions, and the blue bars are the carbon budgets as adjusted to 1/1/2023.

When updated to a start date of 1/1/2023, that reduced to 380 $GtCO_2$ with a likely range of 180-780 $GtCO_2$, which captures the updated estimate published in Forster et al 2023. This range only includes uncertainty in the climate system, with non-CO_2 emissions adding an additional 200 $GtCO_2$ uncertainty.

SUMMARY

Global warming is dominated by the near-linear relationship between the global average temperature increase and cumulative CO_2 emissions. This relationship helps define a 'carbon budget', with uncertainties relating to the climate system and society through non-CO_2 emission pathways.

The carbon budget has been an extremely powerful concept to quickly and succinctly explain the climate challenge, such as making comparisons with our current emissions to illustrate the urgency of short-term mitigation. Whilst seemingly simple, the concept also has many layers of complexity, such as the incorporation of uncertainty, the role of non-CO_2 emissions, and continual updates due to scientific improvements and our continued emissions.

The carbon budget concept will remain a useful communication tool, but some of its shortcomings may be exposed as the remaining carbon budget for 1.5˚C will soon be exhausted.

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