

Carbon budgets for the 1.5°C limit

Carl-Friedrich Schleussner, Katarzyna B. Tokarska, Martin Stolpe, Peter Pfleiderer, Quentin Lejeune, Bill Hare

Summary

The concept of carbon budgets is rooted in physics and has proven itself very useful to communicate the urgency to act on climate change. However, it has its own challenges and uncertainties, i.e. linked to definitional issues, accounting non-CO₂ emissions and/or Earth system feedbacks. These uncertainties increase in relative relevance if the available budget is small, as it is the case for 1.5°C. If the size of these uncertainties is of the order of the remaining central budget estimate, it is questionable whether this concept is still informative.

Recent publications using a reference period over the recent decade for observed and modelled warming and cumulative carbon emissions have argued that the remaining “carbon budget” available to meet the Paris agreement long-term temperature goal is larger than previously estimated by the IPCC in its Fifth Assessment Report (Millar et al 2017, Tokarska and Gillett 2018, Leach et al 2018), which has given rise to a lot of confusion and discussion.

This briefing examines the estimates of the remaining warming that have been used in the IPCC AR5 and in recent studies and evaluate the consequences for carbon budget estimates to limit warming to 1.5°C. The main basis for a bigger budget is that CMIP5 models show a stronger warming between 1986-2005 and 2006-2015 than has been identified in temperature observations. Adjusting model results for the observed decadal warming increases the level of warming remaining to reach 1.5°C by about 0.16°C. For reference, an increase (decrease) of 0.1°C in the level of warming remaining to reach 1.5°C adds (subtracts) about 200 gigatons of CO₂ to the budget.

However, it is questionable whether or not the 2006-2015 warming mismatch between models and observations is systematic in nature, or the result of climate forcing differences, natural variability and methodological differences. In fact, we show that accounting for all of these effects allows us to reconcile models and observations over this period. This implies that a part of the budget increase might be an artefact resulting from the choice of the reference period and warming product used, rather than a real finding.

We find that the temperature rebasing effect explains about 60-80% of the estimated increase in carbon budgets in recent studies compared to the IPCC AR5 estimates. The remainder is linked to differences in diagnosed historical CO₂ emissions in the models. IPCC mitigation benchmarks are not informed by carbon budgets, but by emission reduction pathways quantified by temperature alone. Therefore, they are independent from any uncertainties arising from historical cumulation CO₂ emissions. Assessments for mitigation targets would only change as a result of changes in the reference period warming, which

lacks a solid foundation as discussed above. Therefore, there is no direct policy relevance in updated carbon budgets beyond the discussion around global mean temperature. Independently of these updated estimates, it needs to be emphasized that any notion of “more time” for climate protection is completely ill advised. In order to be in line with 1.5°C, global GHG emissions need to peak as soon as possible and then reduce by 50% in 2030 (and equally 50% below current NDC level). Instead of ‘more time’ to delay climate action, we have no time to lose to achieve 1.5°C.

Carbon budgets and Global Mean Temperature estimates

Estimating the level of present day anthropogenic climate warming is a central methodological challenge in climate science. Policy makers need to know how ‘far’ the world is from warming limits such as the Paris Agreement’s 1.5°C limit. This limit refers to a 1.5°C global average climatological warming above a pre-industrial base line caused by human activities. The definition of climate change under the UNFCCC only links to the anthropogenic warming component (Rogelj *et al* 2017). With a human attributable warming of about 1°C above pre-industrial levels (Haustein *et al* 2017) even seemingly minor methodological differences can have a strong effect.

This issue has acquired more relevance since several recent publications have argued that the carbon budget, the amount of CO₂ that can still be emitted in compliance with the temperature goal, for 1.5°C might be bigger than estimated in the AR5 (Millar *et al* 2017, Tokarska and Gillett 2018, Leach *et al* 2018). In relation to estimating carbon budgets an increase (decrease) 0.1°C in the level of warming remaining to reach 1.5°C adds (subtracts) about 200 gigatons of CO₂ to the budget, which can add or subtract a sizeable proportion of the small budget remaining.

To understand the sources of these differences we need to first step back and briefly describe the method which is taken to estimate remaining warming to 1.5°C. It is not as simple as taking the observational record and working out how much warming has occurred to date above the preindustrial reference period. We also need to know what component of the observed warming is due to human activities, or to natural variability or volcanic effects on the climate system. In other words, we need to know the attributable warming from the pre-industrial to a recent period. To do this, climate models are our best tool and have been used for several decades now to make future projections. In order to overcome intrusive differences between models and observational datasets, future warming is estimated against a common recent reference period. Whilst it has benefits, this also means that care must be taken to disentangle decadal natural variability and volcanic effects and the anthropogenic signal when looking at future warming estimates.

The Paris Agreement temperature goal is based on the science of the time: the IPCC’s Fifth Assessment Report (AR5) and its assessments of impacts at different warming levels that have informed the UNFCCC (UNFCCC 2015). It is clear that science will progress and new approaches will become available. However, assessments on the progress towards the Paris Agreement goals, including on carbon budgets, should be linked back to the science that underpinned those goals – the AR5 and the global mean temperature indicators used therein (Pfleiderer *et al* 2018).

The AR5 estimated global mean surface air temperature (GMT) increase relative to a 1986-2005 reference period based on observed warming using the HadCRUT4 dataset. This

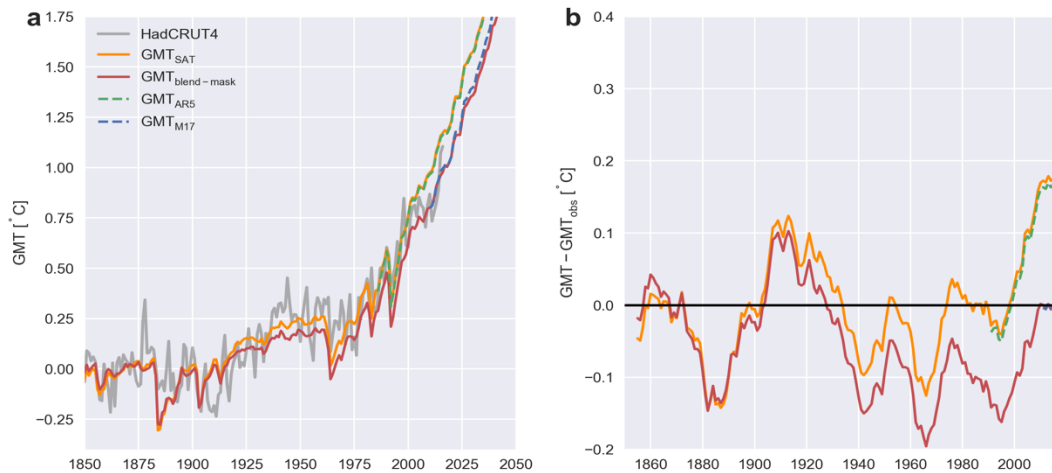


Figure 1 | a, Observed GMT from HadCRUT4 (gray) and model-based GMT for the different GMT metrics relative to the 1861-1880 reference period. The following metrics are shown:

- GMT_{SAT}: modelled surface air temperature (SAT) warming since 1861-1880 in dark yellow,
- GMT_{AR5}: HadCRUT4 warming from 1850-1900 until 1986-2005 and modelled warming thereafter in green,
- GMT_{M17}: like GMT_{AR5} with an updated attributable observational record until 2015 (as in Millar *et al.* (2017)) in blue,
- GMT_{blend-mask}: modification of modelled SAT warming to resemble masking and blending effects as in HadCRUT4. Future projections assume constant coverage of the years 1986-2016.

b, difference between HadCRUT4.6 observations and the different GMT metrics presented as a 10-year running mean. From Pflaiderer *et al* (2018).

dataset shows a 0.6°C warming compared to its 1861-1880 pre-industrial based period. Note that different choices of the pre-industrial period may also alter the warming above pre-industrial (Hawkins *et al* 2017). Projections for future warming in the AR5 from 2006 onwards were based on warming from climate models from the CMIP5 model ensemble.

The composite nature of this GMT_{AR5} product is of relevance in light of methodological differences between modelled and observed GMT estimates linked to limited observational coverage in some regions (masking) and treatment of sea-surface and surface air temperature over sea ice regions (blending). This leads to a sizeable mismatch between observed and modelled GMT products (Fig. 1 a) that also varies over time (Fig. 1 b). Due to an increased sea-ice melt and strong polar warming over the recent decades, this mismatch has increased to almost 0.2°C since the late 1990s. This implies that model-based and observed GMT products cannot be directly compared without accounting for the methodological differences.

The IPCC also used modelled warming from pre-industrial only (GMT_{SAT}). Climate models in the AR5 have been driven by historical forcing until 2005 and by climate scenarios since then. Those scenarios will deviate from observed emissions since then which may result in different temperature trajectories. At the same time, they do not account for observed non-anthropogenic climate forcing such as volcanic activity and solar irradiance, and cannot capture decadal natural variability that will influence the observed warming trajectory (Medhaug *et al* 2017). Unpacking these issues and how they apply for the AR5 reference period (1986-2005), and the updated reference period (2006-2015) used to generate recent estimates of larger carbon budgets, can help resolve the budget estimate differences.

	1850-1900 to 2006-2015	1850-1900 to 1986-2005	1986-2005 to 2006-2015
HadCRUT4.6	0.84 [0.79—0.89]	0.60 [0.57—0.66]	0.22 [0.21—0.23]
Berkeley	0.98	0.73	0.25
CMIP5 GMT_{SAT}	0.99 [0.65—1.37]	0.62 [0.38—0.94]	0.38 [0.24—0.62]
CMIP5 GMT_{blend-masked}	0.86 [0.54—1.18]	0.50 [0.31—0.79]	0.34 [0.19—0.54]

Table 1: Observed (HadCRUT4.6 and Berkeley Earth Surface Temperature analysis) and modelled warming since 1850-1900 relative to two reference periods: 1986-2015 and 2006-2015. CMIP5 blend-mask is derived following (Richardson *et al* 2016, Cowtan *et al* 2015). The 5-95% uncertainty range is given in square brackets.

Origins of modelled and observed warming mismatches

Table 1 shows observed warming for the HadCRUT4 dataset as well as different GMT products (see Figure 1) since the 1850-1900 pre-industrial period for the 1986-2005 and 2006-2015 period. Since the blended-masking correction is applied based on HadCRUT4, only this observational dataset is shown. Other observational products estimate a stronger absolute warming and less 1986-2005 vs 2006-2015 difference than HadCRUT4, but lead to qualitatively similar results. Rebased projections to the observed attributable warming until 2015 as in (Millar *et al* 2017, GMT_{M17}) will result in a downwards of GMT correction of about 0.18°C compared to the definition of warming used in the AR5 (GMT_{AR5}, see Figure 1). We show below that this difference is not however due to human activity but rather due to systematic differences in the applied forcing, methodological differences, and natural variability in the climate system. Two different sources or mismatches are of relevance when comparing modelled and observed GMT products and their relevance for the remaining carbon budget.

CMIP5 blended-masking correction

The correction for the blended-masking of observational sea surface and surface air temperature (SST/SAT) products and full globe SAT-only modelled GMT leads to a downwards correction of warming since the pre-industrial period (compare Fig. 1). The blended-masking effect (yellow vs. red line in Fig 1b) varies over time and is increasing with warming (Schurer *et al* 2018). For present day warming, the blended-masked CMIP5 GMT matches well with the HadCRUT4.6 observational temperature record (Richardson *et al* 2016). Applying a blended masking correction to the CMIP5 models over the historical period, however, would result in a temperature increase of 0.5°C for the 1986-2005 period compared to 1850-1900 (compare Table 1), about 0.1°C lower than in HadCRUT4. The blended-masking correction, however, can only partly explain the increased modelled vs. observational warming between 1986-2005 and 2006-2015 (mean estimates GMT_{SAT}: 0.38°C, GMT_{blend-mask}: 0.34°C vs. HadCRUT4.6: 0.22°C, see Table 1).

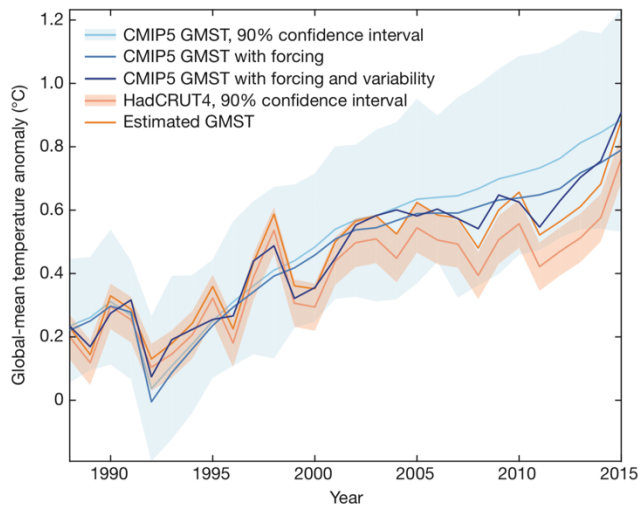


Figure 2: Reconciling observed and modelled temperatures from (Medhaug *et al* 2017). Ensemble-GMTs from 84 simulations by 36 CMIP5 models (historical plus Representative Concentration Pathway (RCP) 8.5 after 2005) is shown (light blue line) with the 90% confidence interval (shading). The CMIP5 ensemble mean when adjusted with updated forcings (intermediate blue line), and with updated forcings and corrected for Pacific variability (dark blue line) are also shown. Observed HadCRUT4 GMT is shown in light orange, together with the 90% confidence interval (shading). The uncertainty is based on a 100-member ensemble of the HadCRUT4 dataset. The blend-mask corrected GMT based on HadCRUT4 is depicted by the dark orange line. The values are given relative to the mean of 1961–1990.

Non-anthropogenic forcing and natural variability

To understand the apparent warming mismatch for the 1986–2005 vs 2006–2015 period, factors related to the modelling protocol as well as natural variability characteristics need to be considered. This has been done in a recent comprehensive review (Medhaug *et al* 2017) that provides the basis for the following analysis.

- Non-anthropogenic forcing:** Until 2005, CMIP5 models have been forced with observed anthropogenic and non-anthropogenic forcing (the ‘historical’ runs). This includes observed solar irradiance cycles as well as volcanic activity. From 2006 onwards, however, projections of the Representative Concentrations Pathways (RCPs) are deployed. In the RCPs solar forcing repeats solar cycle 23 (the one observed over the 1996–2008 period) indefinitely. However, this was an abnormal cycle from a historical perspective. It lasted longer and the minimum was lower than recorded in almost 100 years. Also, solar cycle 24 (from 2008 onwards) had an abnormal low maximum. This leads to the assumed solar forcing in the model projections after 2008 being too high (Medhaug *et al* 2017, Huber and Knutti 2014). At the same time, a series of moderate volcanic eruptions have led to an increase in stratospheric aerosols by around 4–10% between 2000 and 2009 (Medhaug *et al* 2017), while the background volcanic aerosol forcing assumed in the RCPs projections is near zero. Correcting models to account for the effects of non-anthropogenic forcing differences results in about 0.06°C less warming between 1986–2005 and 2006–2015 period (Medhaug *et al* 2017). Similar results are found by (Schmidt *et al* 2014) and (Santer *et al* 2017).
- Natural variability:** Another factor that has been discussed prominently in the context of the ‘warming hiatus’ (a period of small observed warming between 1998 and 2012 affecting both reference periods assessed here) is linked to the presence of natural variability, in particular of multi-decadal modes in the Pacific (Douville *et al* 2015, Kosaka and Xie 2013, Medhaug *et al* 2017). The strength of these effects is considerably uncertain and some estimates (Douville *et al* 2015, Kosaka and Xie 2013, Watanabe *et al* 2014, Kosaka and Xie 2016) find it to be strong enough to link most if not all of the apparent CMIP5 – observational mismatch to natural variability

alone. Following (Medhaug *et al* 2017), correcting for Pacific variability leads to a reduction of about 0.03°C in warming between 1986-2005 and 2006-2015.

in [°C]	1986-2005 to 2006-2015
CMIP5 GMT _{SAT}	0.38 [0.24—0.62]
Blended- Masking	- 0.04
Forcing	- 0.06
Natural variability	-0.03
Corrected GMT _{SAT}	0.25

Table 2: CMIP5 modelled warming between 1986-2005 and 2006-2015 and applied corrections following a methodology introduced in Medhaug et al. (2017, see Text). Taken together, these adjustments yield a warming difference about 33% lower than the uncorrected

Reconciling model projections and observations

Taken together, the effects of blended-masking, non-anthropogenic forcing and natural variability may account for 0.04°C+0.06°C+0.03°C = 0.13°C, explaining most of the documented ‘mismatch’ between CMIP5 and observed warming for the 1986-2005 and 2006-2015 reference period. Note that the direct sum of all contributions is not fully appropriate as the estimates for blended-masking and forcing corrections and variability corrections are done independently of each other and accounting for the cross-correction effects may result in slightly different estimates. However, since all estimates come with considerable uncertainty this might serve as an estimate of the overall effect.

In sum this implies that observed and modelled warming differences between the two periods can be reconciled using only factors not linked to anthropogenic activity. Shifting the baseline from the 1986-2005 period to 2006-2015 while not accounting for necessary corrections can thereby lead to unintended consequences for GMT products and related carbon budget estimates.

These consequences could imply an unintended shift in goalposts¹ of the Paris Agreement’s Article 2 as impacts previously assessed to occur at 1.5°C in the AR5 would occur at lower levels of warming (below 1.4°C) with such a shifted baseline. Such unintended consequences should be avoided in order not to misguide policy makers and the public alike (Pfleiderer *et al* 2018).

¹ <https://www.carbonbrief.org/guest-post-dont-shift-the-goalposts-of-paris-agreements-temperature-limits>

² Threshold exceedance budgets: 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-CO₂ warming at the time of exceeding the threshold of interest. From (Rogelj *et al* 2016)

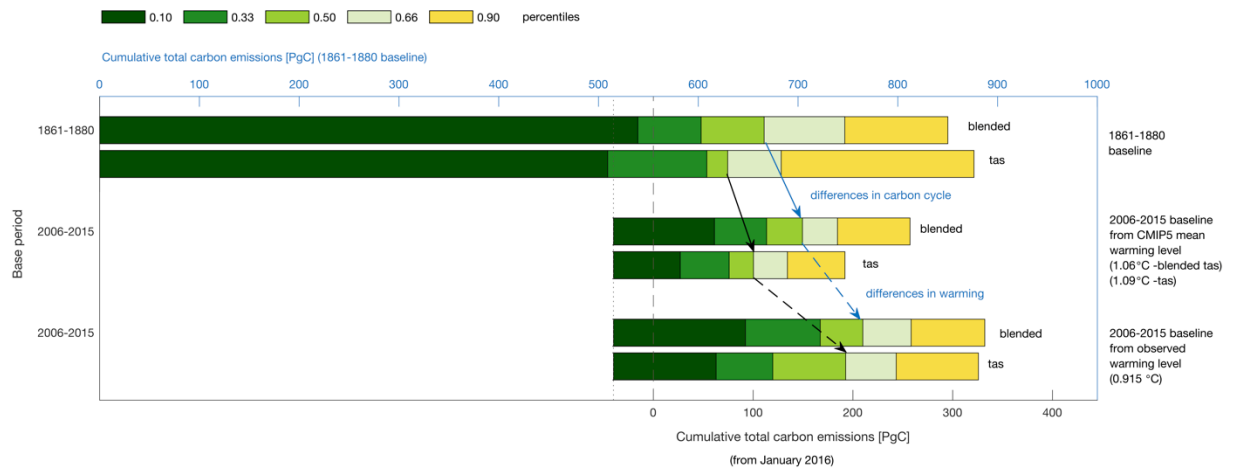


Figure 4. (Adapted from Tokarska and Gillett, 2018). Cumulative frequency distributions consistent with the 1.5 °C global warming target, based on CMIP5 models (RCP 4.5 and 8.5 scenarios) for CMIP5 modelled GMT (tas) and blended corrected model data (blended). The grey dashed line indicates the observational total cumulative carbon emissions for the period 1870–2015, with a median value of 555 PgC, the dotted line indicates cumulative carbon emissions up to the end of 2010. The top bars show carbon budgets relative to 1861–1880 (blue x axis), in PgC. The remaining bars show carbon budgets relative to the recent decade 2006–2015, offset by the IPCC estimate of the cumulative carbon emissions up to the end of 2010. The lower (black) x axis shows carbon budgets from January 2016. The effects of changing the baseline for carbon budget estimates to the 2006-2015 base period are investigated for modelled (middle bars) and observed warming (bottom bars) separately.

Implications for carbon budget estimates

A change in GMT of 0.1°C would alter carbon budget estimates by about 200 Gt CO₂ (Pfleiderer *et al* 2018). Reconciling models and observations as shown above would thereby lead to a sizeable difference in the estimates of the remaining carbon budget. Here we have assessed these effects making use of the Threshold Exceedance Budgets (TEBs)² as defined in the IPCC AR5 WG1. The IPCC AR5 Working Group 1 budget estimates have been based on the linear relationship between cumulative carbon emissions and temperature since the 1861-1880 period in climate models (CMIP5). The aim of the AR5 method was not to derive carbon budgets for political relevant targets, but to illustrate the linear relationship between cumulative emissions and global mean temperature increase.

However, uncertainties related to modelled cumulative emissions and temperature response increase over time and so does the uncertainty in carbon budget estimates. In order to reduce that uncertainty, Tokarska and Gillett (2018), similarly to Millar *et al* 2017, have performed a rebasing to a more recent 2006-2015 period, offset by the observed amount of warming and reported CO₂ emissions. The changes in the remaining carbon budgets after rebasing and offsetting GMT and cumulative CO₂ emissions to a more recent period arise predominantly from the following two effects: (1) differences in the carbon cycle between models and observations (Figure 4, solid arrows), and (2) differences in warming between models and observations (Figure 4, dashed arrows). Here we disentangle both effects.

² Threshold exceedance budgets: 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-CO₂ warming at the time of exceeding the threshold of interest. From (Rogelj *et al* 2016)

In order to do so, warming over the 2006-2015 period is inferred for different temperature records -using solely the model warming for the historical period (Fig. 4 middle bars), or using the observed GMT level (Fig.4. bottom bars). For these warming levels, cumulative carbon emissions are calculated from the model responses, offset by the reported amount of CO₂ emissions, and the remaining TEB budget is calculated until 1.5°C level is reached. Since models have systematically underestimated cumulative carbon emissions over the historical period (e.g. Tokarska and Gillet, 2018), this leads to bigger remaining budgets compared to carbon estimates calculated from an earlier baseline (1861-1880, Fig.4. top bars), due to differing carbon cycle responses between models and the real world. Accounting for this carbon cycle contribution, leads to a bigger remaining budget of around 40 and 25 PgC more (or 140 and 90 Gt CO₂, for blended and regular bars, respectively; Figure 4, solid arrows, middle bars).

Rebasing GMT to the observed record over the 2006-2015 period rather than modelled warming adds about another 60 and 90 PgC (or 220 and 330 Gt CO₂) (for blended and regular bars, respectively; Figure 4, dashed arrows, bottom bars), due to apparent differences in warming between models and observations. However, if modelled and observed GMT increase can be reconciled as outlined above, this contribution would disappear.

Despite the apparent mismatch between modelled and observed historical emissions, these results do not change considerably when the model ensembles are constrained by observations (Tokarska and Gillet, 2018). This implies that likely other non-CO₂ related effects play an important role here.

‘Near-term’ carbon budgets are subject to considerable uncertainty related to global carbon cycle feedbacks (Lowe and Bernie 2018) i.e. related to permafrost melt (Comyn-Platt *et al* 2018, McGuire *et al* 2018). Similarly, land use change emissions are uncertain from observations and future projections (Le Quéré *et al* 2017). These cumulative emission budget estimates will further be affected strongly by future trajectories of non-CO₂ emissions (Tokarska *et al* 2018, Mengis *et al* 2018).

Implications for emission reduction targets

Emission reduction targets in the IPCC have not been inferred from WG1 carbon budgets, but from emission pathways in WG3 in line with certain temperature targets (IPCC 2014). They are based on pathways from Integrated Assessment Models, which account for technology dynamics and inertia in socio-economic systems. These models also account for sources of non-CO₂ greenhouse gas emissions, and in most cases require negative-CO₂ emissions in order to limit warming to defined temperature levels. These emission pathways are ‘forward looking’ in time and thereby not affected by historical uncertainties related to cumulative carbon emissions. This means that changes in the carbon budget resulting from adjustments related to historic cumulative emissions do not affect reduction targets. For temperature, however, the case is different. The temperature response for those pathways has been derived based on reduced complexity probabilistic climate models calibrated to observations and complex climate models relative to a reference period. Pathways have been classified according to their warming trajectory and emission targets derived based on this classification. If GMT was revised over the reference period, this would inevitably also lead to adjustment in the classification of emission pathways and thereby affect the reduction targets. Whether or not such adjustments are warranted is, however, questionable as discussed above.

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