Climate and carbon budget implications of linked future changes in CO₂ and non-CO₂ forcing

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Abstract

The approximate proportional relationship between cumulative carbon emissions and instantaneous global temperature rise (the carbon budget approximation) has proven to be a useful concept to translate policy-relevant temperature objectives into CO₂ emissions pathways. However, when non-CO₂ forcing is changing along with CO₂ forcing, errors in the approximation increases. Using the GCAM model to produce an ensemble of ~3000 scenarios, we show that linked changes in CO₂ forcing, aerosol forcing, and non-CO₂ greenhouse gas (GHG) forcing lead to an increase in total non-CO₂ forcing over the 21st century across mitigation scenarios. This increase causes the relationship between instantaneous temperature and cumulative CO₂ emissions to become more complex than the proportional approximation often assumed, particularly for low temperature objectives such as 1.5 °C. The same linked changes in emissions also contribute to a near-term increase in aerosol forcing that effectively places a limit on how low peak temperature could be constrained through GHG mitigation alone. In particular, we find that 23% of scenarios that include CCS (but only 1% of scenarios that do not include CCS) achieve a temperature objective of 1.5 °C without temperature overshoot.

The stated aim of the Paris Agreement is to keep the global temperature increase in this century ‘well below’ 2 °C (compared to pre-industrial levels) and to ‘pursue efforts’ to limit the temperature increase to 1.5 °C. In understanding such objectives, the concept of a carbon budget linking temperature increases to cumulative CO₂ emissions has proven useful because it enables policy objectives (stated in terms of temperature increases) to be related to potential policy actions (stated in terms of CO₂ emissions reductions) (Matthews and Caldeira 2008, Allen et al 2009, Matthews et al 2009, Zickfeld et al 2009). This approximation is most valid when CO₂ emissions are the dominant climate forcing agent that is changing.

When non-CO₂ emissions are changing along with CO₂ emissions, the carbon budget relationship is more uncertain because the temperature response at a given point in time depends on the combination of forcing from CO₂ and non-CO₂ emissions. For this reason, recent studies have considered the role of non-CO₂ emissions explicitly. Some have focused on short-lived climate forcers, such as black carbon (BC) and methane, that have a warming effect (Shindell et al 2012, Bond et al 2013, Bowerman et al 2013, Smith and Mizrahi 2013, Rogelj et al 2014, Shindell et al 2017, Stjern et al 2017), while others have focused on aerosols that have a net cooling effect (Gillett and Salzen 2013, Baker et al 2015, Hienola et al 2018, Samset et al 2018). Other studies have considered a wider array of non-CO₂ forcers (greenhouse gases (GHGs) and aerosols) in various ways (Meinhsen et al 2009, Rogelj et al 2015, Rogelj et al 2016, Matthews et al 2017, Miller et al 2017, Mengis et al 2018, Tokarska and Gillett 2018, Tokarska et al 2018). This latter set of studies has primarily addressed non-CO₂ emissions using scenario analysis (Rogelj et al 2015, Mengis et al 2018,
Tokarska and Gillett 2018, Tokarska et al 2018), Monte Carlo ensemble approaches (Meinshausen et al 2009, Millar et al 2017), simplified approximations (Matthews et al 2017), or meta-analysis (Rogelj et al 2016).

Such approaches provide important insights about the sensitivity of the carbon budget relationship to non-CO₂ emissions and help to define the range of cumulative CO₂ emissions associated with particular temperature objectives. However, not all of these approaches fully capture the fact that CO₂ and non-CO₂ emissions abatement may be deliberately or inadvertently coupled in the real world. For example, in scenarios of rapid decarbonization, coal use declines markedly over the next several decades, leading to a commensurate reduction in SO₂ emissions (Wigley 1991). Similarly, changes in fossil fuel consumption driven by carbon pricing will lead to changes in other GHG emissions, if the pricing mechanism or relevant proxy policy is extended to those GHGs (and potentially even if it is not, since emissions of some GHGs will depend on changes in the energy system mediated by the carbon price).

Our study employs a large model ensemble, but does not conduct a formal Monte Carlo approach as do other studies (Meinshausen et al 2009, Millar et al 2017). In order to conduct a formal probabilistic analysis, Meinshausen et al (2009) consider a higher-dimensional parameter space, and when developing inputs related to non-CO₂ forcing, rely on a broad suite of available model results. Millar et al (2017) focus their probabilistic analysis on other climate system parameters, including equilibrium climate sensitivity and transient climate response, relying on non-CO₂ forcing information from the published Representative Concentration Pathways (RCPs) (Meinshausen et al 2011). In contrast to these studies, our study considers a set of endogenous non-CO₂ pathways that are directly linked to other GCAM scenario assumptions and outputs. In addition, both Meinshausen et al (2009) and Millar et al (2017) focus on carbon budgets associated with specific temperature objectives (2°C and 1.5°C, respectively), whereas our study focuses on a broader range of temperature objectives. Thus, by using an ensemble approach in which CO₂ and non-CO₂ emissions vary in a linked manner through the application of a universal carbon tax (UCT), our study is complementary to others. In addition, this scenario ensemble reveals new insights about the bounds of the climate system response and particular features of the carbon budget relationship that have not been previously highlighted.

Methods

We simulated ~3000 emissions pathways using the Global Change Assessment Model (GCAM). GCAM is an integrated assessment model that couples energy, economic, land use, and climate systems, reconciling these systems at each time step (Edmonds and Reilly 1985, Kim et al 2006, Clarke et al 2007, Kyle et al 2011, Wise et al 2014). GCAM balances supply and demand in all energy and agricultural commodity markets simultaneously across 32 geopolitical regions. The population and GDP growth assumptions follow the middle of the road scenario in Shared Socioeconomic Pathway 2 (Fricko et al 2017). All other assumptions and drivers are based on the standard GCAM 4.3 release. Non-CO₂ emissions, including other GHGs and aerosols, are calculated as the product of an activity rate calculated by GCAM (e.g. rice cultivation) and an emissions coefficient. Key climate variables are projected using a climate emulator, MAGICC 6 (Wigley and Raper 2001, Wigley et al 2009, Meinshausen et al 2011). MAGICC 6 parameters were held at their default values across all experiments, with an equilibrium climate sensitivity of 3 °C per CO₂ doubling. Importantly, MAGICC 6 includes a representation of both direct and indirect forcing from aerosols (Meinshausen et al 2011). Temperatures reported by MAGICC 6 throughout this paper are global mean surface temperatures.

The scenario suite is constructed by systematically varying a UCT applied to all GHG emissions everywhere. Non-CO₂ GHG emissions are taxed using their 100 year global warming potentials. Non-CO₂ GHG emissions have emissions abatement supply schedules that change the emissions coefficient for associated activities (EPA 2014). Aerosol emissions are neither taxed nor subsidized. Terrestrial carbon emissions are taxed at 10% of the fossil fuel carbon price to avoid unrealistic afforestation responses that would occur if land were priced at the same level as fossil fuels. In addition, 90% of unmanaged land is protected when cropland expands for agricultural or bioenergy production.

The UCT is first applied in 2025 and escalates exponentially up to a maximum value, after which time the carbon price remains fixed. Starting values were varied from $15 to $450 (in 2010 dollars) per metric ton CO₂, the escalation rate was varied from 1% per year to 10% real per year, and the maximum carbon price was varied from $1500 to $4500 per metric ton CO₂. Scenarios were run using a full suite of technology options including fossil fuels, wind, solar, geothermal, hydro, nuclear, bioenergy, and end-use technologies. 1500 tax paths were combined with two assumptions on carbon capture storage (CCS) availability (on or off) to generate a total of 3000 scenarios in addition to the Reference Case. The Reference Case

5 See https://github.com/IGCRI/gcam-core/releases/tag/gcam-v4.3. Current documentation for GCAM can be found on the GCAM wiki: http://igcri.github.io/gcam-doc/.

6 Climate response parameters in the default version of MAGICC 6 are calibrated to emulate the average response of the suite of CMIP3 models. The average equilibrium climate sensitivity from this suite is approximately 3 °C. In addition, the carbon cycle parameters in the default version of MAGICC 6 are calibrated to emulate the BERNcc model from C4MIP. MAGICC 6 includes a simplified representation climate-carbon cycle feedbacks. The calibration approach is discussed further in Meinshausen et al (2011).

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does not include an explicit price on GHGs, but it does include a representation of other existing policies that affect the energy system. When CCS is assumed to be available, bioenergy can be combined with CCS (BECCS) to produce negative emissions. The level of the UCT effectively sets a limit on bioenergy production and negative emissions from BECCS. Negative emissions can also be created by increasing the stock of terrestrial carbon stored in forests or by sequestering carbon in products derived from biomass feedstocks. Negative emissions create the potential for overshoot scenarios in which Earth’s average surface temperature is greater at some point in the century than at the end of the century. Negative emissions are a necessary—but not sufficient—condition for overshoot.

This study considers a wide range of emission scenarios in order to span a wide range of realized temperature outcomes, including those that achieve 1.5 °C. Because the emissions reductions are driven by the UCT, a wide range of carbon prices was applied to produce this range of emissions and temperature outcomes. This study does not assign likelihood to any scenario or range of scenarios (e.g. scenarios resulting in temperature rise below 2 °C or 1.5 °C), nor does it assign likelihood to any of the idealized policy assumptions in GCAM, including the level of the UCT (including the initial jump from zero) or the escalation rate. While the IPCC Special Report on Global Warming of 1.5 °C did not find that pathways to 1.5 °C were infeasible, it did find that such pathways ‘…would require rapid and far-reaching transitions in energy, land, urban and infrastructure (including transport and buildings), and industrial systems…’ and that for the transition in these systems there is ‘…no documented historic precedent for their scale…’ (IPCC 2018).

Results

Focusing on the scenarios that include CCS, the approach described in the methods section yields 1500 unique projections of CO₂ and other emissions, CO₂ concentrations, radiative forcing, and temperature change, in addition to the Reference Case, which represents a world without explicit GHG policy (see Methods). This approach provides several insights about the climate system response that would not be apparent using a small number of scenarios. We focus on two such observations here: (i) that temperature trajectories do not strongly deviate from the Reference Case until after about 2035 even though emissions deviate almost immediately after the carbon price is introduced (compare panel d to panel a in figure 1); and (ii) that the relationship between instantaneous temperature and cumulative CO₂ emissions (the carbon budget relationship) is more complex than the proportional approximation often assumed (panel f of figure 1).

The first of these effects can be explained by following the causal chain from GHG emissions to temperature change. First, CO₂ emissions decline immediately and very rapidly in the most stringent scenarios (shown as red trajectories in panel a of figure 1), and CO₂ concentrations (panel b of figure 1) also deviate from the Reference Case almost immediately in these cases. However, total forcing (panel c of figure 1), which includes the contribution from both CO₂ and other forcing agents, does not immediately deviate from the Reference Case and, to the extent that it does deviate, actually increases relative to the Reference Case. The primary reason for this effect is that SO₂ forcing is a mirror image of CO₂ emissions (compare panel a to panel e of figure 1), a consequence of the fact that CO₂ emissions are strongly correlated with SO₂ emissions (both are produced from the combustion of coal), but that the radiative forcing contribution from SO₂ emissions is negative. The temperature trajectories (panel d of figure 1) largely follow the total forcing trajectories.

The significant increase in SO₂ direct forcing (panel e of figure 1) and related indirect forcing constrains the feasibility of certain global temperature objectives. For example, in our scenario ensemble, which assumes default values for all climate parameters and an equilibrium climate sensitivity of 3 °C per CO₂ doubling (see Methods), we find that 23% of the scenarios (n = 342) achieve peak temperatures below 1.5 °C (within the allowed tolerance of 0.05 °C), and that carbon prices in those scenarios start at or above $240 (in 2010 dollars) per metric ton CO₂ and rise at 6% or more per year. In addition, all of these scenarios assume the availability of CCS, including bioenergy with CCS, which enables negative emissions. Without CCS, only 1% of scenarios (n = 14) achieve peak temperatures below 1.5 °C (within the allowed tolerance of 0.05 °C) (see figure S5). The initial carbon prices associated with the scenarios that do not include CCS are also higher than those associated with the scenarios that do include CCS (compare table S2 to table 1).

The second effect discussed above—the non-linearity of the carbon budget relationship—also follows from the behavior of non-CO₂ forcing. In panel (f) of figure 1, there is a period when the most stringent cases effectively move along a vertical trajectory before eventually moving leftward again at a higher temperature. This vertical offset is another way to visualize the commitment to a minimum temperature increase even when CO₂ emissions are assumed to phase out very quickly—cumulative CO₂ emissions soon reach a maximum as CO₂ emissions are rapidly reduced, but temperature continues to rise, largely due to non-CO₂ forcing, which continues to increase.7

7 The exact nature of the coupling between CO₂ and SO₂ is less important than the assumption that SO₂ emissions will be phased out rapidly in scenarios with stringent CO₂ mitigation. It has been noted that transient temperature response to aerosol forcing is greater than for well-mixed GHGs (Shindell et al 2014). The climate emulator used in this paper (MAGICC 6; see Methods) accounts for this effect (Smith et al 2014).
In addition, the complex shape of the relationship observed in panel (f) of figure 1 indicates the challenges in precisely defining a carbon budget, particularly for scenarios of rapid transformation associated with stringent temperature objectives. Table 1 shows the carbon budget associated with three temperature objectives (1.5, 2.0 and 2.5 °C) defined using two different definitions for each of the objectives. The first defines the temperature objective as a maximum temperature that is never exceeded in the simulation (shown as without overshoot in the table). The second defines the temperature objective as the temperature achieved in 2100 (shown as with overshoot in the table), since the temperature prior to 2100 may be higher than the temperature achieved in 2100. Scenarios that satisfy each objective within a certain tolerance (0.05 °C) are grouped together, and the relevant output metrics are reported for the relevant group as a range.

Two carbon budget metrics are included. The first metric is cumulative emissions of CO₂ in the year of net zero emissions, which is equal to the maximum cumulative net emissions of CO₂ over the century. For the without overshoot temperature objective, this is also approximately equal to the carbon budget achieved at the temperature objective, because the temperature maximum is achieved at approximately the same time as maximum cumulative net emissions. The second metric is the cumulative net CO₂ emissions by 2100. For the with overshoot temperature objective, this is also the carbon budget achieved at the temperature objective (since the temperature objective is achieved in 2100).

For two of the temperature objectives (2 and 2.5 °C), the range in the maximum budget for the without overshoot objective definition (1282–1507 GtCO₂ for 2 °C and 2462–2697 GtCO₂ for 2.5 °C) is close to the range in the 2100 budget for the with overshoot objective definition (1282–1538 GtCO₂ for 2 °C and 2445–2697 GtCO₂ for 2.5 °C), which implies that the budget is similar with and without overshoot of the temperature objective. For the 1.5 °C case, the similarity holds for the upper bound (585 GtCO₂ versus 506 GtCO₂), but does not hold as well for the lower bound (432 GtCO₂ versus 216 GtCO₂). Because the 1.5 °C without overshoot case achieves the temperature objective relatively early in the century (between 2035

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8 The definition of the without overshoot objective here is comparable to the definition of the ‘threshold avoidance budget’ used in Rogelj et al (2016).

9 The range associated with a particular temperature objective can stem from several factors, but the allowed tolerance around the objective likely explains most of the range. For example, if the carbon budget increases by ~2000 GtCO₂, as observed between the 1.5 °C and 2.5 °C cases in table 1, then the carbon budget would span about 200 GtCO₂ over a 0.1 °C interval, consistent with the tolerances allowed here.
Table 1. Metrics associated with three different temperature objectives defined in two different ways. The *without overshoot* definition includes scenarios that achieve the temperature objective (within allowed tolerance of 0.05 °C) without temperature overshoot. The *with overshoot* definition includes scenarios that achieve the temperature objective in 2100 (within allowed tolerance of 0.05 °C) and may overshoot temperature prior to that time. Two different carbon budget metrics are shown. *Cumulative CO₂ emissions in the year of net zero emissions* provides cumulative net CO₂ emissions from 2015 until the year in which net emissions are zero (equal to maximum cumulative net CO₂ emissions over the century), whereas *Cumulative CO₂ emissions by 2100* provides cumulative net emissions from 2015 until the end of the century, including the reduction from net negative emissions where applicable. Cumulative CO₂ emissions (including land use change emission) between 1870 and 2014 were 1941 GtCO₂. All CO₂ emissions reported in this table include emissions from land use change in addition to fossil and industrial emissions.

| Temperature Objective | 1.5 °C                  | 2.0 °C                  | 2.5 °C                  |
|-----------------------|-------------------------|-------------------------|-------------------------|
|                       | Without overshoot | With overshoot | Without overshoot | With overshoot | Without overshoot | With overshoot |
| Peak temperature (°C) | 1.5 | 1.55–1.94 | 2.0 | 1.97–2.28 | 2.5 | 2.45–2.54 |
| Year in which peak temperature is achieved | 2035–2048 | 2043–2065 | 2061–2100 | 2065–2100 | 2088–2100 | 2088–2100 |
| Year in which zero net CO₂ emissions are achieved | 2029–2042 | 2038–2060 | 2058–none | 2066–none | 2085–none | 2085–none |
| Cumulative CO₂ emissions in year of net zero emissions (GtCO₂) | 432–585 | 575–1349 | 1282–1507 | 1282–2023 | 2462–2697 | 2462–2697 |
| Cumulative CO₂ emissions by 2100 (GtCO₂) | –1158–159 | 216–506 | 597–1442 | 1282–1538 | 2445–2697 | 2445–2697 |
| Number of scenarios satisfying objective | 342 | 106 | 71 | 48 | 35 | 35 |
| Carbon price in 2025 (2010 $ per ton CO₂) | 240–450 | 45–450 | 45–420 | 15–420 | 15–375 | 15–240 |
and 2048), the temperature at the objective does not yet reflect the full non-CO₂ forcing commitment, and for this reason, the cumulative CO₂ emissions are higher than those associated with cases that have fully realized the non-CO₂ forcing commitment.

The budget estimates for 1.5 °C and 2 °C produced by GCAM are broadly similar to the budgets summarized in the IPCC Special Report on 1.5 °C (Rogelj et al 2018). The latter are estimated (for a 50% likelihood of achieving the temperature objective) to be 1500 GtCO₂ for 2 °C and 580 GtCO₂ for 1.5 °C, whereas the midpoints of the GCAM estimates shown in table 1 are 1410 GtCO₂ and 400 GtCO₂, respectively. These comparisons are approximate due to the differences in the IPCC Fifth Assessment Report (Stocker et al 2013). The carbon budgets from this study are lower than those from SR15, in part due to weaker non-CO₂ abatement in our GCAM scenarios (more non-CO₂ warming) than in scenarios from the IPCC SR15 database (see section S3). It is also worth noting that the carbon budgets associated with the GCAM cases that do not include CCS are somewhat higher than the carbon budgets associated with the cases that do include CCS (compare tables S2 to S1), due to differences in the non-CO₂ forcing pathways, which follow from differences in fossil energy deployment. Specifically, scenarios without CCS exhibit lower forcing from methane (due to less natural gas and coal primary energy) and lower (more negative) forcing from sulfate aerosols (due to greater coal use without CCS in the power sector), leading to less overall non-CO₂ warming.

The carbon budget approximation suggests that the instantaneous temperature anomaly is proportional to cumulative CO₂ emissions at all times with an approximate slope that is scenario-independent. When non-CO₂ forcing is introduced, the slope of the carbon budget relationship may depend on the scenario, because even if the non-CO₂ forcing trajectory is comparable across scenarios, it will be applied over a different range of cumulative CO₂ emissions. While a scenario-independent carbon budget relationship that applies at all times may not strictly hold when non-CO₂ forcing is changing, the relationship between achieved temperature in 2100 (or several decades in the future) may still hold, as long as non-CO₂ forcing has stabilized by such time. This explains why the cumulative emissions associated with different temperature objectives vary approximately linearly between 1.5 °C, 2.0 °C, and 2.5 °C in table 1. For example, the midpoints of the budget ranges associated with 1.5 °C, 2.0 °C and 2.5 °C temperature objectives are approximately 400, 1410, and 2570 GtCO₂, suggesting that the budget increases by ~1000 GtCO₂ for each 0.5 °C increase in the temperature objective. This effect is also apparent in panel (f) of figure 1, in which the upper envelope defined by all of the curves is approximately linear, while the carbon budget relationship for any given scenario may be strongly nonlinear.

### Discussion

The two key results explored above can be further explained by focusing on a smaller number of canonical scenarios. We chose to focus on three such scenarios, specifically those that achieve 1.5 °C, 2 °C and 2.5 °C in 2100 when the carbon price is assumed to rise at 3% real per year. The initial (2025) carbon price varies considerably between the cases, at $90, $195 and $435 (in 2010 dollars) per ton CO₂, respectively, for the three cases, and the maximum carbon price was capped at $1500 per ton CO₂ in each case. The first key insight identified above—the slower temperature divergence from the Reference Case, when compared to the CO₂ emissions divergence—is also visible in the canonical scenarios (panels a and d of figure 2).

A more quantitative assessment of this effect can be achieved by decomposing the total forcing into component terms. Table 2 shows the initial forcing from both CO₂ and non-CO₂ forcing agents and how these forcing terms evolve in the three canonical scenarios. The scenario in which CO₂ decreases most rapidly (1.5 °C scenario) is also the one in which total aerosol forcing increases most rapidly, because most of the CO₂ abatement in the near-term comes from reducing coal, which also reduces SO₂ emissions. Total forcing in 2030 is higher in the 1.5 °C scenario than in any other scenario, but lower in 2040 and beyond, suggesting that total forcing in the 1.5 °C scenario intersects the others between 2030 and 2040 (consistent with figure 2, panel c). Other anthropogenic forcing does not change significantly between the three canonical scenarios, although in each of these cases, it is lower than in the Reference Case, suggesting that non-CO₂ GHG abatement contributes significantly in the canonical scenarios, but by roughly equal amounts once a certain level of mitigation is achieved.

10 These comparisons are approximate due to the differences in approach, as well as different reference years for cumulative emissions (2015 in our study compared to 2018 in the IPCC SR15 Report). It should also be noted that the IPCC SR15 budgets are most comparable to our without overshoot objective definition. As the IPCC SR15 states, ‘The remaining carbon budgets assessed in this section are consistent with limiting peak warming to the indicated levels of additional warming. However, if these budgets are exceeded and the use of CDR… is envisaged to return cumulative CO₂ emissions to within the carbon budget at a later point in time, additional uncertainties apply...’ (Rogelj et al 2018).

11 In the IPCC SR15 Report, the carbon budget relationship was approximated by including the reference non-CO₂ temperature contribution (RNCTC) on top of the assessed transient climate response to emissions (TCRE) (Forster et al 2018). The relationship derived from such an approach is similar to the upper envelope in panel (f) of figure 1 in our study, which incorporates the non-CO₂ contribution from a single future year. The nonlinearity of the individual scenarios in panel (f) of figure 1 suggests that the actual transient climate response to emissions is more complex, due to simultaneously changing CO₂ and non-CO₂ emissions.
These results imply that, even if only a fraction of the carbon price were applied to non-CO2 GHGs, the amount of non-CO2 abatement in scenarios achieving low temperature objectives would not change significantly.

The second insight described above—the lack of a one-to-one mapping in the carbon budget relationship—is also visible in the canonical scenarios (figure 3, panel a). The relationship between temperature and cumulative CO2 emissions can be decomposed into four component relationships: (i) temperature change as a function of total forcing; (ii) total forcing as a function of CO2 forcing; (iii) CO2 forcing as a function of CO2 concentration; and (iv) CO2 concentration as a function of cumulative CO2 emissions (figure S1). The shapes of these relationships are discussed in the supplementary material (section S1). Importantly, the strong nonlinearity related to effects (i) and (iv) effectively cancel one another (Zickfeld et al 2016), meaning that the key driver of the nonlinearity and the lack of a one-to-one mapping in the carbon budget approximation follows primarily from the nonlinearity of total forcing as a function of CO2 forcing (figure 3, panel b).

In panel (b) of figure 3, the distance between each of the canonical scenarios and the $y = x$ line (black line in figure 3, panel b) is equivalent in the final year of the simulation, meaning that the net non-CO2 forcing approaches the same final value in each of these scenarios (also visible in table 2 by summing the total aerosol and other anthropogenic terms). A key difference between the scenarios is the rate at which this final value is approached. The 1.5°C scenario moves away from the $y = x$ line quickly due the rapid abatement of SO2 emissions, which is tied to the rapid abatement of CO2 emissions; the other scenarios move away from the $y = x$ line more slowly. To the extent that the forcing chart (figure 3, panel b) explains the carbon budget relationship (figure 3, panel a), it suggests that the lack of a one-to-one mapping in the carbon budget relationship is another consequence of the coupling between SO2 abatement and CO2 abatement and more generally the behavior of non-CO2 forcing.

Finally, it is instructive to compare the GCAM forcing scenarios to other scenarios common in the literature. Two of the RCPs—RCP 2.6 and RCP 4.5—achieve temperature outcomes comparable to our canonical scenarios. RCP 2.6 reaches approximately 1.6°C by 2100, while RCP 4.5 reaches approximately 2.4°C by 2100.
However, the evolution of non-CO2 forcing in these scenarios is different than it is in our canonical scenarios as shown in figure S2. Non-CO2 GHG forcing decreases as the stabilization objective is tightened in the RCPs, but it is approximately constant as the stabilization objective is tightened in our canonical scenarios. A comparison with scenarios in the IPCC 1.5 Report database yields consistent insights (section S3). The non-CO2 GHG forcing in GCAM scenarios stabilizes at ∼1.3 W per m2 (see table S1). The remaining forcing from non-CO2 GHGs is primarily from the agricultural sector. As GCAM only includes non-CO2 abatement from existing technologies and assumes no fundamental lifestyle changes related to diets, there is a limit on how far emissions can be reduced from high-emitting agricultural activities, such as meat and dairy, as well as rice cultivation. In addition, the growth of F-gas emissions from cooling in the GCAM Reference Case in this study is higher than the growth in other scenarios, including in any of the RCPs. These differences are discussed further in the supplementary material (sections S2 and S3).

These comparisons suggest that, if the evolution of non-CO2 forcing observed in our canonical scenarios is realistic (aerosol forcing increases and other non-CO2 forcing remains roughly constant), then an additional forcing of ∼0.5 W per m2 is effectively committed regardless of the stringency of CO2 mitigation. If abatement from non-CO2 GHGs is weaker, for example, in a world in which the UCT is not applied across GHGs, then forcing from non-CO2 GHGs would be even greater, further increasing the warming commitment and lowering the carbon budget associated with a given temperature objective. This forcing commitment implies that peak temperature could increase by an additional several tenths of a degree C above any warming attributed to CO2, which is a significant share of the total increase between the current temperature anomaly and stringent temperature objectives such as 1.5 °C or 2 °C. On the other hand, if non-CO2 GHG abatement could be increased beyond what is assumed here, due to measures not currently included in the marginal abatement supply schedules utilized in GCAM (EPA 2014), then the warming commitment could potentially be reduced (depending on when the abatement occurs) and carbon budgets for a given temperature objective could be increased. Generally, these results suggest that uncertainty in total non-CO2 forcing, due to uncertainty in how changes in aerosol and non-CO2 GHG forcing may offset one another.

Table 2. Midyear radiative forcing from anthropogenic, natural and all sources for the three canonical mitigation scenarios and the Reference Case. Anthropogenic forcing is further divided into CO2 forcing, aerosol forcing, and other anthropogenic (largely non-CO2 GHG) forcing. The first two columns show the absolute forcing in 2010 and 2020, respectively. The final four columns show differences between a specified future year and 2020. Table S1 provides the absolute radiative forcing for years between 2030 and 2100.

| RF Agent       | 2010  | 2020  | 2030–2020 | 2040–2020 | 2050–2020 | 2100–2020 |
|----------------|-------|-------|-----------|-----------|-----------|-----------|
| **Reference**  |       |       |           |           |           |           |
| Total anthropogenic | 1.92  | 2.32  | 0.50      | 1.05      | 1.56      | 4.00      |
| CO2            | 1.82  | 2.09  | 0.34      | 0.74      | 1.15      | 3.17      |
| Total aerosol  | −1.22 | −1.15 | 0.04      | 0.06      | 0.07      | 0.17      |
| Other anthropogenic | 1.31  | 1.38  | 0.11      | 0.24      | 0.34      | 0.66      |
| Total Natural  | 0.11  | 0.10  | 0.00      | 0.00      | 0.00      | 0.00      |
| Total          | 2.03  | 2.42  | 0.50      | 1.05      | 1.56      | 4.00      |

1.5 °C in 2100

| RF Agent       | 2010  | 2020  | 2030–2020 | 2040–2020 | 2050–2020 | 2100–2020 |
|----------------|-------|-------|-----------|-----------|-----------|-----------|
| **Total**      |       |       |           |           |           |           |
| Total anthropogenic | 0.50  | 0.54  | 0.47      | 0.47      | 0.47      | 0.47      |
| CO2            | 0.20  | 0.19  | 0.10      | 0.10      | 0.10      | −0.36     |
| Total aerosol  | 0.39  | 0.47  | 0.50      | 0.50      | 0.50      | 0.46      |
| Other anthropogenic | −0.09 | −0.12 | −0.13     | −0.13     | −0.13     | −0.05     |

2 °C in 2100

| RF Agent       | 2010  | 2020  | 2030–2020 | 2040–2020 | 2050–2020 | 2100–2020 |
|----------------|-------|-------|-----------|-----------|-----------|-----------|
| **Total**      |       |       |           |           |           |           |
| Total anthropogenic | 0.45  | 0.78  | 0.99      | 0.99      | 0.99      | 0.99      |
| CO2            | 0.27  | 0.50  | 0.64      | 0.64      | 0.64      | 0.64      |
| Total aerosol  | 0.20  | 0.30  | 0.38      | 0.38      | 0.38      | 0.38      |
| Other anthropogenic | −0.02 | −0.02 | −0.04     | −0.04     | −0.04     | −0.04     |

2.5 °C in 2100

| RF Agent       | 2010  | 2020  | 2030–2020 | 2040–2020 | 2050–2020 | 2100–2020 |
|----------------|-------|-------|-----------|-----------|-----------|-----------|
| **Total**      |       |       |           |           |           |           |
| Total anthropogenic | 0.44  | 0.83  | 1.17      | 1.17      | 1.17      | 1.17      |
| CO2            | 0.30  | 0.61  | 0.87      | 0.87      | 0.87      | 1.50      |
| Total aerosol  | 0.13  | 0.19  | 0.25      | 0.25      | 0.25      | 0.25      |
| Other anthropogenic | 0.01  | 0.03  | 0.05      | 0.05      | 0.05      | −0.02     |
another in the future, implies uncertainty in both the additional temperature commitment and the carbon budget associated with particular temperature objectives.

**Conclusions**

A key finding from this study is that the forcing from non-CO$_2$ emissions will generally increase in GHG mitigation scenarios due to SO$_2$ emissions reductions and because abatement of other non-CO$_2$ emissions is not sufficient to balance the aerosol-driven forcing increase. In scenarios of rapid energy system transformation, the change in temperature from a given change in non-CO$_2$ emissions occurs over a relatively small increase in cumulative CO$_2$ emissions, as CO$_2$ emissions are rapidly phased out in such scenarios. In such cases, the temperature increase due to the associated change in net aerosol forcing places an effective lower bound on peak temperature. In addition, the steep slope of the carbon budget relationship in such scenarios and the lack of a unique mapping between instantaneous temperature change and cumulative emissions highlight the challenges in using the carbon budget approximation in scenarios of rapid GHG mitigation.

Despite the limitations of the carbon budget approximation under certain conditions, the concept of a carbon budget is still useful if treated as a tool to relate temperature objectives achieved several decades into the future (as opposed to instantaneous temperatures) into cumulative CO$_2$ emissions, although uncertainty in the climate system response (considered more directly in other studies (Meinshausen et al 2009, Millar et al 2017)) still contributes uncertainty to the carbon budgets associated with particular temperature objectives. In GCAM scenarios, we find that the cumulative CO$_2$ emissions associated with the 2.0 $^\circ$C and 2.5 $^\circ$C objectives are similar regardless of whether the objective is defined as peak temperature or temperature in 2100. The same findings generally apply to the 1.5 $^\circ$C objective as well, except for greater variability in the low end of the estimated cumulative emissions range, a result of the fact that the temperature objective may be achieved while non-CO$_2$ forcing is still changing.

While GCAM considers changes in CO$_2$ forcing, aerosol forcing and other GHG forcing in an internally consistent manner by applying a UCT, there is significant uncertainty associated with such pathways, suggesting a number of areas for future study. First, there is a need to better understand future non-CO$_2$ GHG emissions growth trends. For example, growth in fluorinated gases (F-gases) and the associated growth in forcing could be larger than anticipated depending on the growth in global demand for space cooling (Velders et al 2009). Second, there is a need to better constrain and represent mitigation supply from various non-CO$_2$ GHGs, including methane and N$_2$O emissions (produced across multiple sectors) as well as

Figure 3. Panel (a) follows panel (f) of figure 1 for the three canonical scenarios. Panel (b) shows total forcing versus CO$_2$ forcing for the same scenarios. The solid black line is the $y = x$ line. The starting point of the blue line is offset from the $y = x$ line by the difference between total forcing and CO$_2$ forcing in 2010 (0.21 W per m$^2$). The dashed black line is offset from the $y = x$ line by the difference between total forcing and CO$_2$ forcing in 2100 (0.75 W per m$^2$). Movement off of the solid black line toward the dashed black line over time implies that the net forcing from non-CO$_2$ emissions is increasing over the projection period.
F-gases (Smith et al. 2013, Gernaat et al. 2015). Third, although models tend to agree on the importance of aerosol forcing, uncertainty in the magnitude of aerosol forcing (Myhre et al. 2013) and the lack of significant abatement from aerosol sources other than SO2 (such as black carbon) deserves greater scrutiny within integrated assessment models, particularly given the attention to black carbon mitigation as a potential policy measure (Shindell et al. 2012, Smith and Mizrahi 2013, Shindell et al. 2017).

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