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Non-CO$_2$ forcing changes will likely decrease the remaining carbon budget for 1.5 °C

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One key contribution to the wide range of 1.5 °C carbon budgets among recent studies is the non-CO$_2$ climate forcing scenario uncertainty. Based on a partitioning of historical non-CO$_2$ forcing, we show that currently there is a net negative non-CO$_2$ forcing from fossil fuel combustion (FFC), and a net positive non-CO$_2$ climate forcing from land-use change (LUC) and agricultural activities. We perform a set of future simulations in which we prescribed a 1.5 °C temperature stabilisation trajectory, and diagnosed the resulting 1.5 °C carbon budgets. Using the historical partitioning, we then prescribed adjusted non-CO$_2$ forcing scenarios consistent with our model's simulated decrease in FFC CO$_2$ emissions. We compared the diagnosed carbon budgets from these adjusted scenarios to those resulting from the default RCP scenario's non-CO$_2$ forcing, and to a scenario in which proportionality between future CO$_2$ and non-CO$_2$ forcing is assumed. We find a wide range of carbon budget estimates across scenarios, with the largest budget emerging from the scenario with assumed proportionality of CO$_2$ and non-CO$_2$ forcing. Furthermore, our adjusted-RCP scenarios produce carbon budgets that are smaller than the corresponding default RCP scenarios. Our results suggest that ambitious mitigation scenarios will likely be characterised by an increasing contribution of non-CO$_2$ forcing, and that an assumption of continued proportionality between CO$_2$ and non-CO$_2$ forcing would lead to an overestimate of the remaining carbon budget. Maintaining such proportionality under ambitious fossil fuel mitigation would require mitigation of non-CO$_2$ emissions at a rate that is substantially faster than found in the standard RCP scenarios.

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INTRODUCTION

In the Paris agreement, adopted on December 12th 2015, 195 parties agreed to hold "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 above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change" (Article 2 1.(a) of the Paris Agreement[1]). Using the well-established finding of a linear climate response to cumulative carbon emissions (as measured by the Transient Climate Response to cumulative CO$_2$ Emissions (TCRE)[2-4]), we can estimate the total allowable CO$_2$ emissions associated with a 1.5 °C temperature target, the so-called 1.5 °C carbon budget. A robust estimate of the carbon budget for 1.5 °C would inform current political discussions surrounding what emissions targets are consistent with the goals of the Paris Agreement, and how the required mitigation effort should be shared among nations[5-7].

There is a growing number of estimates of the 1.5 °C remaining carbon budgets in recent literature, which collectively span a range of values that range from near zero to close to 20 years at current emissions rates. Across all of these studies, a key ambiguity is the question of how much non-CO$_2$ forcing is responsible for decreasing or increasing the estimated carbon budget. In a recent overview of studies assessing the 1.5 °C carbon budget, Rogelj et al.[8] showed that 9 out of 14 studies did not use non-CO$_2$ warming that is consistent with the assumed net-zero CO$_2$ emissions pathway. This includes some analyses that assumed a proportionality of future CO$_2$ and non-CO$_2$ forcing (i.e., that the relative contribution to future warming from non-CO$_2$ emission remains similar to today)[9,10], as well as others who prescribed non-CO$_2$ forcing from one or more representative concentration

pathway (RCP) scenarios[11-13]. Both approaches are problematic. In the case of prescribed RCP non-CO$_2$ forcing, the implied non-CO$_2$ emissions are not consistent with a scenario of decreasing fossil fuel CO$_2$ emissions as would be required for any plausible 1.5 °C scenario. Assuming proportionality of CO$_2$ and non-CO$_2$ forcing is itself a choice of a future scenario, but is one that is not consistent with the recent trend of increasing net non-CO$_2$ forcing, nor the likely independent mitigation of emissions from fossil fuels vs. LUC and agriculture.

The Special Report on Global Warming of 1.5 °C produced by the Intergovernmental Panel on Climate Change (IPCC SR1.5), recently provided an undated estimate of the remaining carbon budget for limiting warming to 1.5 °C[14]. For an additional warming of 0.53 °C above the 2006–2015 average (consistent with a total increase in global surface air temperature (GSAT) of 1.5 °C above 1850–1900), the IPCC SR1.5 estimated a remaining budget from 2018 onwards of 580 (420) GtCO$_2$, which correspond to the 50th (67th) percentile of the TCRE uncertainty distribution. In addition, the report provided ranges for the potential effects of different sources of uncertainty, such as non-CO$_2$ scenario uncertainty (±250 GtCO$_2$), non-CO$_2$ forcing and response uncertainty (−400 to 200 GtCO$_2$), uncertainty in the historical temperature (±250 GtCO$_2$) and uncertainty surrounding unrepresented Earth system feed-backs in state-of-the-art Earth system models (−100 GtCO$_2$)[8,14]. These numbers indicate that the non-CO$_2$ contribution to the remaining carbon budget is likely the largest uncertain factor affecting estimates of the remaining carbon budget for a 1.5 °C temperature target.

In a recent study, we estimated the effect of individual non-CO$_2$ forcing agents on the 1.5 °C carbon budget for a single emissions scenario[13] using an intermediate-complexity Earth system model,

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the University of Victoria Earth System Climate Model[15]. The large historical contribution of positive forcing from non-CO_2 greenhouse gases and the similarly large negative forcing from aerosols, create the conditions for a considerable amount of uncertainty surrounding how future non-CO_2 emission changes would affect the remaining carbon budget. We now extend this study, by first attributing current non-CO_2 forcing agents to their respective emission sources of (1) fossil fuel combustion, (2) land-use and agriculture and (3) other anthropogenic activities. We then use this partitioning to scale non-CO_2 forcing in the RCP scenarios to be consistent with our modelled 1.5 °C scenario in which fossil fuel CO_2 emissions are rapidly decreasing. Finally, we show that despite a large range in non-CO_2 contributions to the remaining carbon budget across our simulations, all scenarios produce the same budget when expressed in units of CO_2 forcing equivalents, which express non-CO_2 forcing as the amount of CO_2 emissions needed to achieve the equivalent amount of forcing. This highlights the potential of this approach to better represent the contribution of non-CO_2 forcing to the remaining carbon budget.

RESULTS

Partitioning of non-CO_2 forcing based on anthropogenic activities
Based on the partitioning of recent emissions data from single non-CO_2 forcing agents, we partition the current non-CO_2 forcing into three categories depending on the anthropogenic activities that cause the emissions: (1) fossil fuel combustion, (2) land-use changes and agriculture and (3) other human activities, such as emissions of ozone-depleting substances and other refrigerants. This allows us to assess the current net non-CO_2 effect of these human activities by combining all-forcing agents (see Methods).

It is noteworthy that the positive non-CO_2 forcing was almost perfectly compensated by an equivalent negative forcing throughout the historical period up until 1980 (Fig. 1). However, during the last 20 years the net non-CO_2 forcing has started to become increasingly positive and reaches a level of 0.26 W/m^2. This is in agreement with the upward trend of net non-CO_2 forcing shown by the FAIR and MAGICC simple climate models, which span a range of 0.1–0.45 W/m^2 at present-day (see Fig. 2.SM.2 of the IPCC SR1.5[14]). This trend can on the one hand, be attributed to

the increasing impact of non-CO_2 GHGs being emitted in association with the agricultural revolution (the so-called green revolution[16]), and on the other hand to the decreasing impact of cooling aerosols, whose emissions have been decreasing in response to associated health concerns[17]. This decrease of aerosol emissions due to health concerns is also represented in future projections, and is generally included in all RCP scenarios. The increasingly positive net non-CO_2 forcing indicates that it is likely problematic to assume compensation of positive and negative non-CO_2 climate forcing in future scenarios.

The partitioning of current non-CO_2 radiative forcing shows that LUC and agricultural (LUC+AGRIC) activities currently produce a net positive non-CO_2 climate forcing on the order of 0.34 W/m^2, whereas fossil fuel combustion (FFC) generates a net negative non-CO_2 climate forcing on the order of −0.4 W/m^2 (Fig. 1). The positive forcing from LUC+AGRIC activities results from high emissions of non-CO_2 GHGs such as CH_4 and N_2O, which are not compensated by equivalently high emissions of aerosols with negative climate forcing (Table 1): agricultural activities contribute more than a third of the total positive non-CO_2 forcing (0.53 W/m^2), but contribute less than a quarter of aerosol emissions that cause negative forcing (−0.23 W/m^2). In contrast, FFC co-emits a large amount of aerosols causing a large negative forcing (−0.88 W/m^2), which is more than twice as large as the positive forcing from co-emitted non-CO_2 GHGs (0.36 W/m^2). This non-compensatory behaviour in terms of non-CO_2 forcing from both FFC and LUC+AGRIC holds important implications for future forcing pathways: if FFC is to be reduced in compliance with ambitious mitigation targets this will eliminate a large part of the negative forcing from co-emitted aerosols. At the same time, the positive forcing from land-use and agricultural activities is expected to remain at current levels or even increase in the future, to comply with the projected increase in food demand in most scenarios[14]. In the absence of successful mitigation of agricultural emissions, these two effects could lead to an potentially large increase in future net non-CO_2 climate forcing.

Impact of non-CO_2 forcing scenarios on the CO_2-only carbon budget
The net non-CO_2 forcing for the RCP2.6/4.5/8.5 increased by 0.2/0.5/1.0 W/m^2 by 2050 (i.e., the time 1.5 °C is reached) relative
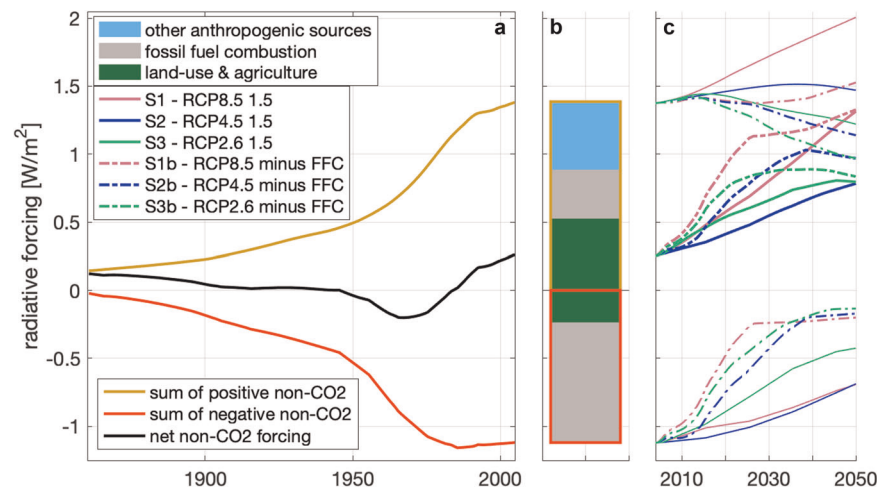

Fig. 1 Partitioning of historical non-CO_2 forcing and non-CO_2 forcing scenarios. a Simulated historical forcing from non-CO_2 greenhouse gases (GHGs) and aerosols. The black line shows the net non-CO_2 forcing, which starts to increase around 1970, due to increasing non-CO_2 GHGs (yellow line), and a reduced increase of the aerosols (red line). **b** Partitioning of current non-CO_2 forcing. The bars represent total positive and negative anthropogenic forcing. The colours then show the partitioning of the totals into the respective emissions source, that is fossil fuel combustion (grey shading), land-use changes (green shading), and other anthropogenic sources (blue shading). **c** Scenarios of future non-CO_2 forcing following the Representative Concentration Pathways 2.6, 4.5, and 8.5 (S1—RCP2.6, S2—RCP4.5 and S3—RCP8.5, respectively, solid lines) and the adjusted scenarios in which non-CO_2 forcing follows the respective diagnosed decline of fossil fuel combustion (FFC) in a prescribed 1.5 °C scenario (dashed lines).

Table 1. Partitioning of anthropogenic non-CO_2 forcing into their respective sources of emissions as % of total anthropogenic emissions, including uncertainty ranges if identified by the data source.

Non-CO_2 forcing agent	Fossil fuel	Agriculture + biomass burning (LUC)	Other anthropogenic activities
Methane (CH_4)	28 (25,31)	38 (35,40) + 11 (10,12)	23 (20,27)
Water vapour from (CH4ox)	28 (25,31)	38 (35,40) + 11 (10,12)	23 (20,27)
Nitrous oxide (N_2O)	10 (3,25)	60 (25,70) + 10 (3,15)	20 (9,65)
Tropospheric ozone (tropO3)	51	39	10
Fluorinated GHGs (F-gases)	0	0	100
Ozone-depleting substances (O3-depl.)	0	0	100
Stratospheric ozone (stratO3)	0	0	100
Organic carbon FFC-aerosol (OCI)	91 (86,95)	09 (5,14)	0
Black carbon FFC-aerosol (BCI)	91 (86,95)	09 (5,14)	0
Sulphate aerosol (SOXI)	97 (96,98)	3 (2,4)	0
Nitrate aerosol (NOXI)	74	26	0
Biomass-related aerosol (BM)	0	100	0
Mineral dust aerosol (MD)	0	100	0
Cloud-albedo effect (CLOUD-TOT)	78	22	0
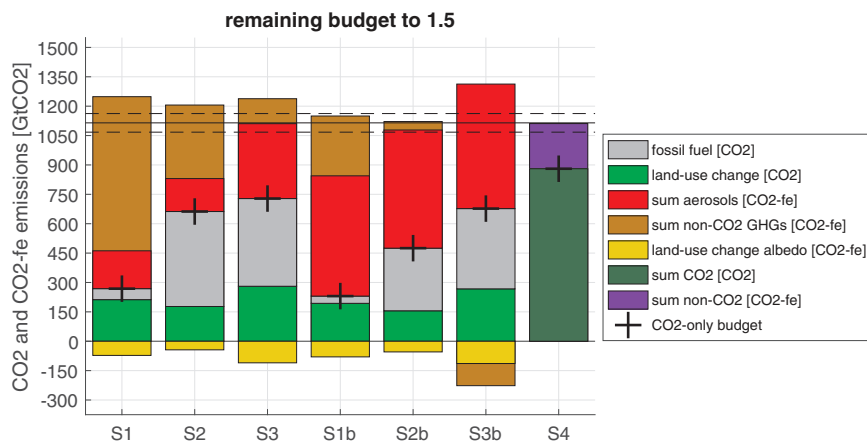
Fig. 2 Remaining carbon budgets between 2005 and 2050 for seven non-CO_2 forcing scenarios. Shown are the contributions from fossil fuel CO_2 emissions (grey), LUC CO_2 emissions (light green), and CO_2-fe emission estimates for non-CO_2 GHG forcing (brown), albedo changes from LUCs (yellow) and aerosol forcing (red). Scenario S4 specifies the total (FFC+LUC) CO_2 (olive) and non-CO_2 (purple) contributions. Black crosses indicate the sum of the CO_2-only remaining carbon budget (i.e., FFC+LUC), and the black line is the total CO_2+CO_2-fe budget with a value of 1115 ± 50 GtCO$_2$-fe across all scenarios.

to the beginning of the scenarios in 2005 (Fig. 1a). Removing positive and negative FFC-related non-CO_2 forcing from the default RCP scenarios (to regain consistency with simulated FFC CO_2 emissions decreases, see methods and Supplementary Sections 2–4) resulted in a larger increase in the net non-CO_2 radiative forcing (by 0.4/0.7/1.1 W/m^2 in the RCP2.6/4.5/8.5 minus FFC scenarios, respectively). This large range of non-CO_2 forcing scenarios in turn produced a wide range of remaining carbon budgets, of between 230 GtCO$_2$ and 720 GtCO$_2$ in total emissions from 2006 until the time 1.5 °C is reached in 2050 (black crosses Fig. 2). Finally, our scenario with assumed proportionality between future CO_2 and non-CO_2 forcing resulted in the largest remaining CO_2-only budget, of 880 GtCO$_2$. This range of remaining carbon budgets across scenarios is equivalent to about 17 years of current emissions (i.e., 10.7 PgC/yr equivalent to 39.2 GtCO$_2$/yr for 2007–16[18]), and also covers the range of 1.5 °C carbon budget estimates across recent studies[9,11–13].

Expressing the contributions by non-CO_2 climate forcers in CO_2-forcing equivalent emissions (see Method section for calculations), allows to directly compare their contributions and helps to clearly attribute reasons for the large discrepancies of the remaining

carbon budgets (Fig. 2). For example, it is clear that the large increase of non-CO_2 GHGs in S1 - RCP8.5 1.5, is the main reason for the low remaining carbon budget in this scenario. It is of course important to emphasise that this scenario, in addition to S1 and S2, include non-CO_2 forcing changes that are not consistent with the diagnosed CO_2 emissions. The strong increase in non-CO_2 forcing in S1 - RCP8.5 1.5, for example, is caused by the business-as-usual approach to FFC and LUC+AGRIC activities, which do not match the decreasing FFC CO_2 emissions that are required to meet our prescribed 1.5 °C temperature trajectory (Supplementary Section 1). In the 'adjusted' scenario S1b - RCP8.5 minus FFC (in which we subtracted the FFC-related non-CO_2 forcing so as to align correctly with diagnosed FFC-related CO_2 emissions), the contribution from non-CO_2 GHGs is smaller than in S1, though the contribution from reduced aerosols emissions is substantially larger. These two non-CO_2 contributions then compensate each other, which results in a similarly low remaining carbon budget. This indicates clearly that focussing only on fossil fuel emissions reductions, without also mitigating LUC-related CO_2 emissions and non-CO_2 GHG from LUC and agriculture, would likely result in an
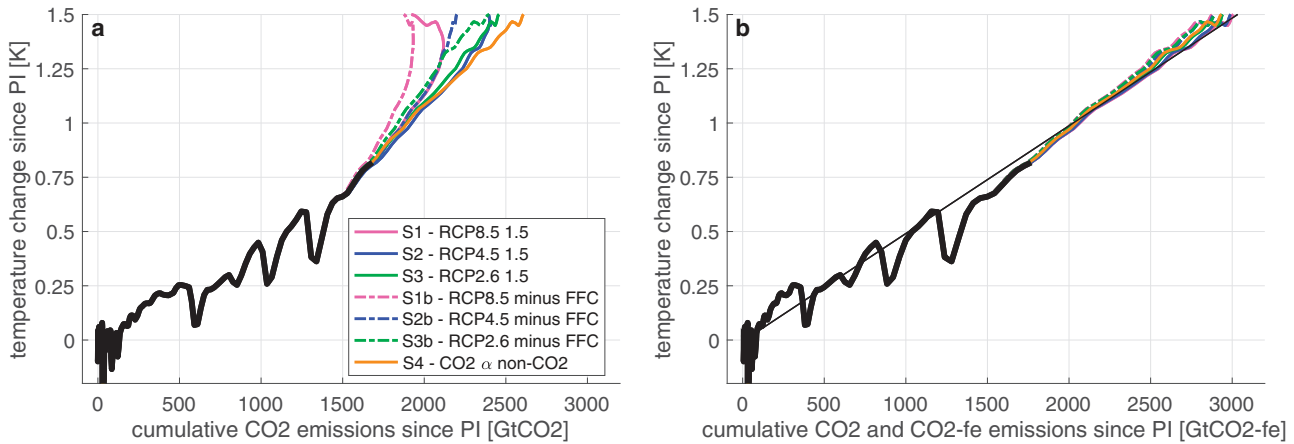
Fig. 3 **Effective transient climate response to cumulative CO_2 emissions ($TCRE_{eff}$) and to cumulative CO_2-fe emissions (TCRFE). a** Temperature change as a function of cumulative CO_2-only (FFC+LUC) emissions for the historical period (black) and the seven future scenarios. **b** Temperature change as a function of the sum of cumulative CO_2 (FFC+LUC) and CO_2-fe (aerosol+non-CO_2 GHGs+LUC albedo) budgets for the historical period (black) and the seven future scenarios.

impossibly small remaining fossil fuel carbon budget for the 1.5 °C target.

Among the three 'adjusted' scenarios, S2b - RCP4.5 minus FFC and S3b - RCP2.6 minus FFC (which include LUC CO_2 emissions and non-FFC non-CO_2 emissions from RCP2.6 and RCP4.5, respectively, combined with our scenario of decreasing FFC CO_2 and non-CO_2 emissions) are clearly the more 'realistic' 1.5 °C scenarios, in that they include internally consistent CO_2 and non-CO_2 emissions resulting from ambitious FFC decreases, combined with reasonably ambitious mitigation of other emission sources. The remaining carbon budget from these scenarios were 505 $GtCO_2$ and 775 $GtCO_2$ (from 2006 onwards), which corresponds to about 200 $GtCO_2$ and 465 $GtCO_2$, respectively, emitted from 2018 onwards. IPCC SR1.5 gave a best estimate of 580 $GtCO_2$ for the same time period. The difference between SR1.5 and our estimates is again likely due to different non-CO_2 contributions to future warming. The SR1.5 analysis was based on all available 1.5 °C scenarios from integrated assessment models, many of which included more ambitious non-FFC emissions mitigation than what is found in either RCP2.6 or RCP4.5. In addition, however, part of the reason for our smaller carbon budgets is that the aerosol forcing in our simulations decreases considerably more than in the simple climate models used to assess the non-CO_2 contribution to warming in SR1.5 (see Fig. 4 in the supplementary material). This difference in the aerosol forcing response to decarbonisation scenarios warrants additional attention, as it clearly has the potential to have a large influence on estimates of the remaining carbon budget.

These results show that if future non-CO_2 contributions are not clearly reported and accounted for in remaining carbon budgets estimates, this leads to widely-varying arbitrary carbon budget estimates, which almost entirely reflect the assumed non-CO_2 scenarios. It is noteworthy, however, that while the contributions from non-CO_2 GHG, aerosols, LUC and fossil fuel emissions vary throughout our scenarios, they all agree on a total remaining CO_2 + CO_2-fe budget of 1170 ± 35 $GtCO_2$-fe. This is in line with our expectations, and indicates that the remaining total climate forcing for a 1.5 °C target has to be the same in all scenarios.

Effective transient climate response to CO_2 and CO_2-fe emissions
The metric of the effective transient climate response to cumulative emissions ($TCRE_{eff}$) is used to express the temperature change caused by all emissions as a function of cumulative CO_2-only emissions. While this term ($TCRE_{eff}$) was only introduced recently by Matthews et al.[9], the concept was used in the 5th

assessment report of the IPCC (e.g., Fig. SPM.10[19]) as well as in more recent publications, e.g.[14,20], that plotted total temperature change from all-forcing model simulations as a function of cumulative CO_2 emissions. Unlike the transient climate response to cumulative CO_2 emissions (TCRE), which has been shown to be scenario-independent across a wide range of scenarios and emission quantities[21–24], the $TCRE_{eff}$ depends on the changing strength of non-CO_2 forcings, and is therefore not scenario-independent. The $TCRE_{eff}$ only remains constant in time for scenarios where CO_2 and non-CO_2 forcing are proportional. As a consequence, using the $TCRE_{eff}$ to estimate remaining carbon budgets (as done by e.g., refs. [9,10]) requires the (likely unjustified) assumption that the relative contribution of non-CO_2 forcing to future warming remains constant.

To illustrate the non-linearity of the $TCRE_{eff}$ across our scenarios, we show cumulative CO_2 emissions and the transient temperature response as diagnosed for varying non-CO_2 forcing scenarios (Fig. 3a). Note, that the linearity is conserved only in scenario S4, in which we assume proportionality between future CO_2 and non-CO_2 forcing. For other scenarios, and especially those with ambitious FFC mitigation, this proportionality is no longer valid, due to the increasing contribution from non-CO_2 climate forcers. For these scenarios, using the current $TCRE_{eff}$ to estimate the remaining carbon budget would results in a substantial overestimate of the budget.

In contrast to the large variation of the CO_2-only carbon budgets, there is good agreement in the 1.5 °C budgets when expressed as the sum of CO_2 and CO_2-fe emissions from all climate forcers, with a total budget of 1115 ± 50 $GtCO_2$-fe across all scenarios (Fig. 3b). This budget includes FFC and LUC CO_2 emissions, and in addition CO_2-fe from LUC albedo changes, and non-CO_2 forcing including aerosols and GHGs. This therefore represents an aggregated CO_2-fe budget that includes the contribution from all anthropogenic climate forcers. If expressed as the transient climate response to cumulative CO_2 forcing equivalent emissions (TCRFE, i.e., the slope of the lines in Fig. 3b), we find that the linearity and scenario-independence with respect to cumulative CO_2-fe is restored, with a value of TCRFE = 0.50 K/ 1000 $GtCO_2$-fe.

This metric now has a well-founded theoretical basis again: By construction, the CO_2-fe emissions give the same radiative forcing pathway and hence temperature response as the corresponding forcing agents from which they are computed[25]. In case of the $TCRE_{eff}$, the temperature change from an all-forcing simulation including non-CO_2 climate forcing is related to CO_2 emissions only, not accounting for the potential temperature response from

this additional forcing (Fig. 3a). In contrast, the TRCFE relates temperature change to cumulative emissions from all climate forcing expressed in CO_2 and CO_2-fe emissions (Fig. 3b). The same physical mechanism as for the TCRE[2–4,22,23] accordingly act to cause the linearity for the TCRFE. However, the non-CO_2 GHGs and aerosols in the real world would not interact with the carbon cycle, as they do per construction in our experiment. This interaction does in part cause the linearity of the TCRFE. The limits of the linearity for the TCRFE should accordingly be further investigated in future studies.

DISCUSSION

By partitioning the non-CO_2 contributions into different sources of anthropogenic activities, we show that today's LUC and agriculture non-CO_2 forcing contributions have a net warming effect, whereas FFC-related non-CO_2 forcing has a net cooling effect. This result holds some important implications. In ambitious mitigation scenarios in which fossil fuel combustion is to be strongly reduced, we would expect a strong decline in aerosol emissions, causing a shift towards more positive net non-CO_2 climate forcing. Of course, this shift could also occur in the absence of decreasing FFC CO_2 emissions, via the implementation or improvement of filter systems in response to health concerns[17].

Although historically the net non-CO_2 forcing contribution was close to zero, this is not a likely pathway for future non-CO_2 forcing in the context of ambitious mitigation action. All RCP scenarios show an increase in future non-CO_2 forcing, but when subtracting the FFC non-CO_2 forcing so as to align with faster decreases in FFC CO_2 emissions, we obtain an even steeper increase of future non-CO_2 forcing. This illustrates that the metric of the effective transient climate response to cumulative CO_2 emissions (TCRE$_{eff}$), is unlikely to remain constant even on relatively short time frames and especially not for scenarios with ambitious mitigation action. We recommend that this metric should not be applied to estimate the remaining CO_2 only budget under ambitious mitigation unless treated as a variable quantity that changes as a function of changing non-CO_2 emissions.

Our results suggest that the relative contribution of non-CO_2 forcing will likely increase in response to ambitious FFC mitigation actions, leading to a decrease in the remaining carbon budget for a 1.5 °C. Consequently, the assumption of future proportionality of CO_2 and non-CO_2 forcing is only plausible if we are considerably more successful in mitigating non-FFC-related non-CO_2 emissions (i.e., non-CO_2 forcing agents from LUC and agriculture and other anthropogenic activities) compared to what is represented by the range of RCP scenarios. When disregarding scenario S1b, which is a less likely realisation of future non-CO_2 forcing in line with a 1.5 °C temperature trajectory, our idealised, example scenarios show that depending on the assumed non-CO_2 forcing scenario, the size of the 1.5 °C CO_2-only budget varies by 410 GtCO$_2$. This range within budgets is larger than some estimates of the remaining budget itself, and in the range of the 67th percentile of the 1.5 °C budget presented in the IPCC's Special Report[14].

We find that in line with Allen et al.[25], adopting the metric of TCRFE (rather than, for example, TCRE$_{eff}$) would allow us to justifiably assume a linear temperature response to cumulative CO_2-fe emissions, leading to CO_2-fe budgets that are approximately scenario-independent. Using a more comprehensive carbon cycle model to diagnose CO_2-fe emissions associated with individual non-CO_2 climate forcers, we show that the framework introduced by Allen et al.[25] holds, and that we need to account explicitly for the non-CO_2 climate forcing to obtain an accurate estimate for the carbon budget for peak warming or climate stabilisation.

METHODS

Model description

For our study we used version 2.9 of the University of Victoria Earth System Climate Model (UVic ESCM), a climate model of intermediate complexity[26]. It includes schemes for ocean physics based on the Modular Ocean Model Version 2 (MOM2)[27], ocean biogeochemistry[28], and a terrestrial component including soil and vegetation dynamics represented by five plant functional types[29]. The atmosphere is represented by a two dimensional atmospheric energy moisture balance model, including a thermodynamic sea ice model[30,31]. All model components have a common horizontal resolution of 3.6° longitude and 1.8° latitude and the oceanic component has a vertical resolution of 19 levels, with vertical thickness varying between 50 m near the surface and 500 m in the deep ocean. The UVic ESCM is a well-established Earth system model with a good evaluation of its carbon cycle processes[15].

Diagnosed CO_2 and CO_2 forcing equivalent (CO_2-fe) emissions

For our simulations, we have prescribed a 1.5 °C temperature change scenario as the input to the UVic ESCM, and used the model to estimate the fossil fuel CO_2 emissions trajectory that is consistent with this temperature trajectory, as in Zickfeld et al.[3], Matthews et al.[32] and Mengis et al.[13] (see Supplementary Section 1 for the trajectory). When running the model in this mode, atmospheric CO_2 concentrations are adjusted dynamically by the model so as to achieve the prescribed temperature change, and the consistent fossil fuel CO_2 emissions are diagnosed as a function of simulated atmospheric CO_2 and land/ocean carbon sinks. Our prescribed temperature scenario followed the model-simulated temperature response to historical forcing up to the year 2015, and then stabilised at 1.5 °C above 1850–1879 temperature at about the year 2055 (Supplementary Fig. S1).

To estimate the cumulative CO_2 emissions that are equivalent to a given non-CO_2 forcing, the UVic ESCM was forced to follow the same temperature trajectory, while removing individual non-CO_2 forcings from the model input. To follow the temperature trajectory, the model therefore needed to adjust the diagnosed CO_2 emissions to account for the missing input forcing. The difference between the all-forced and the reduced-forced diagnosed cumulative CO_2 emissions represents the forcing equivalent CO_2 emissions (CO_2-fe) of the respective non-CO_2 forcing.

Given that we prescribed spatially changing land-use changes (LUC), land-use CO_2 emissions are generated internally by the model. Consequently, the compatible CO_2 emissions that result from our prescribed temperature scenarios are an estimate of fossil fuel CO_2 emissions only. Running the model with fixed pre-industrial land-use gives us the CO_2-fe emissions from both LUC-related CO_2 emissions, as well as the albedo effect from LUC. To estimate the LUC-only CO_2 emissions, we carried out another simulation with constant pre-industrial land-use conditions, but prescribing the CO_2 concentration increase from the changing land-use simulation, rather than prescribing the temperature trajectory. The difference between the total land carbon content of this prescribed-CO_2 no-LUC simulation and the changing-LUC simulation represents the LUC emissions[33]. Finally, the difference between this and the prescribed temperature no-LUC simulation estimates gives us the CO_2-fe emissions from albedo changes due to LUC.

Partitioning of non-CO_2 forcing

Based on the information from the fifth assessment report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) we partitioned non-CO_2 forcing agents as used in the Representative Concentration Pathways (RCPs) into three categories given the source of the respective forcing agent: (1) fossil fuel combustion, (2) agriculture and biomass burning including land-use change (LUC), and (3) other anthropogenic sources, which include sources of all halocarbon emissions, as well as other industrial activities such as waste disposal that are distinct from fossil fuel combustion and agriculture/LUC (Table 1).

28% of the anthropogenic methane sources are fossil fuel-based, 38% are attributed to agriculture, 11% are attributed to natural but mainly to anthropogenic biomass burning, and the remaining 23% are attributed to other anthropogenic activities such as waste disposal (Fig. 6.2 of the IPCC AR5 WGI[34]). This partitioning is in good agreement with the findings of the more recently published Global Methane Budget[35]. The same partitioning is assumed for the radiative forcing of water vapour from methane oxidation.

For N$_2$O, we attributed 10% of the global anthropogenic N$_2$O sources to fossil fuel combustion, 10% to biomass and biofuel burning, 60% to agriculture, and the remaining 20% to other anthropogenic sources, such as N$_2$O emissions from atmospheric depositions on ocean and land, or human excreta (Fig. 6.4c of the IPCC AR5 WGI[34]).

As tropospheric ozone is a by-product of the oxidation of carbon monoxide (CO), CH$_4$, and hydrocarbons (part of the F-gases) in the presence of nitrogen oxides (NOx), we calculated its partitioning as a weighted mean from the respective contributions of these gases. For CO, we used a partitioning of 48% from fossil fuel combustion and 52% from biomass burning (IPCC TAR WGI Chapter 4.2.3.1). We then weighted the partitioning of the respective forcing agents by their contribution to tropospheric ozone forcing, i.e., 0.235 W/m^2 from CH$_4$, −0.14 W/m^2 from F-gases, 0.075 W/m^2 from CO, 0.05 W/m^2 from OCI and 0.15 W/m^2 from NOXI, from IPCC AR5 WGI Fig. 8.17[34].

We attributed the forcing from fluorinated gases, ozone-depleting substances and the forcing from stratospheric ozone depletion to anthropogenic activities other than fossil fuel combustion, agriculture, and biomass burning. It is however noteworthy, that with the anticipated future decline of the predominant ozone-depleting substances, other gases, in particular N$_2$O will become important for stratospheric ozone depletion[36].

As black carbon and organic carbon (BCI and OCI, respectively) are byproducts of fossil and biofuel combustion, their partitioning is based on the carbon emissions partitioning, i.e., 9% of BCI and OCI is allocated to LUC and the remaining 91% is allocated to fossil fuel. The main source of anthropogenic sulphate aerosol is via SO$_2$ emissions from fossil fuel burning (about 97%), with a small contribution from biomass burning (about 3%) (IPCC AR4 WGI, Chapter 2.4.4.1[37]). The anthropogenic nitrate aerosol (NOXI) emissions can be partitioned into 74% from fossil fuel combustion and 26% from agriculture and biomass burning (Fig. 6.4b of the IPCC AR5 WGI[34]). Finally, biomass-related aerosols are 100% attributed to agriculture and LUC emissions.

Anthropogenic sources of dust, including road dust and mineral dust due to human land-use change, remain ill quantified. Recent satellite observations suggest the fraction of mineral dust due to the LUC could be 20–25% of the total (IPCC AR5 WGI Chapter 7.3.2.1[34]). We attribute 100% of the anthropogenic mineral dust forcing to LUC following Ginoux et al.[38].

The radiative forcing of the cloud-albedo effect is a theoretical construct that is not easy to separate from other aerosol cloud interactions. We assume that the partitioning of the direct aerosol forcing is representative of the partitioning of the indirect effect. Direct aerosol forcing from fossil fuel combustion in 2005 amounts to −0.3253 W/m^2 and from LUC to −0.0931 W/m^2. Accordingly, for the indirect effect we allocate 78% to fossil fuel combustion and the remaining 22% to LUC and agriculture.

Non-CO$_2$ forcing scenarios

Although we follow the same threshold avoidance temperature trajectory for all scenarios (Supplementary Fig. 1), we vary the non-CO$_2$ forcing following three Representative Concentration (RCP) scenarios, three alterations of the RCPs and one commonly used assumption of a non-CO$_2$ scenario (Fig. 1).

The RCP scenarios in this context purely represent different trajectories for the non-CO$_2$ climate forcers. The business-as-usual scenario (S1 - RCP8.5 1.5) assumes continuing high land-use change (LUC) and fossil fuel combustion (FFC) activity levels, and as a result has the largest increase in net non-CO$_2$ forcing. The middle-of-the-road scenario (S2 - RCP4.5 1.5) assumes a reduction of agricultural land area, resulting in lower LUC emissions, and at the same time, assumes that measures are taken to reduced the atmospheric aerosol burden. Lastly, the ambitious mitigation scenario (S3 - RCP2.6 1.5) assumes the implementation of bioenergy carbon capture and storage technology, while the negative forcing from aerosols is also reduced. Of these three, the latter two are more likely to represent 1.5 °C non-CO$_2$ forcing scenarios, however, in this first step, none of these non-CO$_2$ scenarios are consistent with the diagnosed CO$_2$ emissions trajectories for a 1.5 °C temperature target.

Therefore in a second step, we take the diagnosed FFC CO$_2$ emissions and scale the non-CO$_2$ climate forcers according to the respective FFC CO$_2$ trajectory, obtaining more consistent non-CO$_2$ scenarios for a 1.5 °C temperature target (S1b, S2b, and S3b, respectively). The adjusted scenarios now reflect the decrease of negative aerosol forcing that would follow stringent fossil fuel emissions mitigation measures or attempts for reduction of the atmospheric aerosol burden due to health concerns, while providing different scenarios for LUC and agricultural practices. This gives an idea of the impact of different LUC and agricultural practices on non-CO$_2$ climate forcers, and non-CO$_2$ GHGs in particular (because aerosols are mostly linked to FFC). Comparing scenarios S1b and S2b, for example, gives insights into the effect of non-CO$_2$ GHGs mitigation through reforestation (S2b) in contrast to continued deforestation (S1b).

Lastly, we wanted to explore the impact of assuming proportionality between CO$_2$ induced forcing to net non-CO$_2$ forcing. This is an assumption, made by several recent studies[9,10], of a constant future ratio between the net non-CO$_2$ forcing and the CO$_2$ induced forcing. For this implementation, we used the observed ratio of the net non-CO$_2$ forcing to the total CO$_2$ forcing for the 20 years period from 1995 to 2015, which gives a value of 0.26. Realising that the total CO$_2$-fe budgets are the same for all the forcing scenarios, we inferred the CO$_2$ and non-CO$_2$ forcing equivalent emissions for this scenario as using the following equation:

$$E_{total} = E_{non-CO_2} + E_{CO_2} = (0.26 + 1) * E_{CO_2}.$$

For more details on the assumptions behind the three RCP scenarios, the scaling of the Sxb scenarios with diagnosed FFC, and a comparison of the scenarios with the Shared Socioeconomic Pathways (SSPs) framework see Supplementary Sections 2–4.

DATA AVAILABILITY

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request, and will be made publicly available on https://thredds.geomar.de under 'Mengis and Matthews (2020), npj' upon acceptance of the manuscript.

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AUTHOR CONTRIBUTIONS

N.M. and H.D.M. conceived the experiment together, N.M. performed the literature review, model simulations, analysis, and wrote the manuscript with contributions from H.D.M. All authors approve of the final version of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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