


# Impact of methane and black carbon mitigation on forcing and temperature: a multi-model scenario analysis

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## Abstract

The relatively short atmospheric lifetimes of methane (CH<sub>4</sub>) and black carbon (BC) have focused attention on the potential for reducing anthropogenic climate change by reducing Short-Lived Climate Forcer (SLCF) emissions. This paper examines radiative forcing and global mean temperature results from the Energy Modeling Forum (EMF)-30 multi-model suite of scenarios addressing CH<sub>4</sub> and BC mitigation, the two major short-lived climate forcers. Central estimates of temperature reductions in 2040 from an idealized scenario focused on reductions in methane and black carbon emissions ranged from 0.18–0.26 °C across the nine participating models. Reductions in methane emissions drive 60% or more of these temperature reductions by 2040, although the methane impact also depends on auxiliary reductions that depend on the economic structure of the model. Climate model parameter uncertainty has a large impact on results, with SLCF reductions resulting in as much as 0.3–0.7 °C by 2040. We find that the substantial overlap between a SLCF-focused policy and a stringent and comprehensive climate policy that reduces greenhouse gas emissions means that additional SLCF emission reductions result in, at most, a small additional benefit of ~0.1 °C in the 2030–2040 time frame.

**Keywords** Climate change · Air pollution · Radiative forcing · Black carbon · Methane

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## 1 Introduction

While the predominant driver of anthropogenic climate change is fossil fuel carbon dioxide (CO<sub>2</sub>) emissions, emissions of other greenhouse gases (GHGs) and air pollutants also impact the climate (Myhre et al. 2013). Interest has focused lately on forcing agents with shorter atmospheric lifetimes, so-called short-lived climate forcers (SLCFs), mitigation of which offers the potential for near-term climate-mitigation. SLCF policies are potentially important because they could contribute to mitigating global warming in the short term and, to some extent, offset climate system inertia.

When evaluating the relative importance of different emission species, it is important to consider both direct effects on climate and various indirect effects. The two most important warming SLCFs are methane (CH<sub>4</sub>) and black carbon (BC), as shown in Table 1 adapted from Myhre et al. (2013). Methane is the second most important greenhouse gas in terms of its current contribution to radiative forcing. The direct forcing from methane is amplified due to increases in tropospheric ozone and stratospheric water vapor (Table 1). Black carbon, often referred to as soot, also increases warming, although the magnitude of its effect is highly uncertain (Bond et al. 2013) and could be smaller than currently estimated (Stjern et al. 2017).

While SLCF analysis has often focused on emissions that result in warming, whose reduction would reduce temperature changes, it is critical to include all emissions species since some co-emitted species have cooling effects that could offset reductions in methane and black carbon. The combination of sulfur dioxide and aerosol-cloud indirect forcing may have a cooling effect that is of the same order of magnitude as the forcing from black carbon and methane combined (Table 1). Co-emitted air pollutants also contribute additional net positive forcing through increases in tropospheric ozone and carbon dioxide concentrations, which is offset somewhat by a net decrease in methane lifetime.

Early estimates of the potential climate impact of SLCF reductions (UNEP 2011; Ramanathan and Xu 2010; Shindell et al. 2012; Hu et al. 2013) indicated that a focus on reducing SLCF emissions could reduce warming by around 0.5 °C. These estimates not only drew on different reference scenarios with higher SLCF mitigation potentials (addressing also BC sources in addition to transport and residential sectors) but also used simple impulse models for climate response, or made simplified assumptions about the development of some species beyond 2030 (see discussion in Smith and Mizrahi 2013). Subsequent analysis, e.g., using integrated assessment models together with simple climate models (Smith and Mizrahi 2013; Rogelj et al. 2014a), and updated reference and mitigation scenarios in a study using multiple atmospheric models (e.g., Stohl et al. 2015) found smaller temperature changes for

**Table 1** Radiative forcing (*ERF* effective radiative forcing) by emitted compound over 1750–2011 from Fig. 8.17 of Myhre et al. (2013). *ERF<sub>aci</sub>* is aerosol-cloud interactions (also termed cloud indirect effects). See SM §D for additional details

Emission	Forcing (ERF W/m <sup>2</sup> )
CO <sub>2</sub>	1.68
CH <sub>4</sub>	0.97
Other GHGs	0.38
BC + OC	0.35
SO <sub>2</sub> , NH <sub>3</sub> , and <i>ERF<sub>aci</sub></i>	− 0.92
Reactivities	0.18
Total	2.64

SLCF reductions, especially with respect to the global mean temperature response to BC mitigation.

There is a need, therefore, to examine the emissions and climate system responses to SLCF-focused reductions across a range of both emission projection models and climate system responses. This paper examines the radiative forcing and temperature impact of methane- and black carbon-focused reductions within the multi-model suite of idealized scenarios developed as part of the Energy Modeling Forum (EMF)-30 model comparison project focusing on Short-Lived Climate Forcers and Air Quality (hereafter EMF-30).<sup>1</sup> Radiative forcing is the energy imbalance at the top of the atmosphere, relative to pre-industrial conditions, that is caused by a change in atmospheric concentrations. Examining radiative forcing is a useful method of comparing the relative contributions of various greenhouse gases and other forcing agents such as aerosols. For example, we compare the impact of changes in CO<sub>2</sub> emissions, methane emissions, and aerosol emissions.

Ultimately, however, we are interested not in changes in forcing, but climate changes that might impact human and natural systems. Therefore, we also examine global surface temperature changes. Changes in other quantities, such as precipitation and changes in extremes or regional temperature, might also be of interest but would require other tools. We note that for black carbon, the relationship between forcing and surface temperature changes is particularly uncertain, an issue that we return to in the discussion.

This analysis centers on a subset of scenarios that illustrate the potential impact of methane- and black carbon-focused reductions separately, then jointly, and finally in combination with comprehensive reductions in greenhouse gas emissions. The use of multiple integrated assessment models is a key feature of this study as this allows the examination of self-consistent scenarios where components of the system interact with each other. This is particularly important when considering the interplay between SLCF-focused and GHG-focused policies. The multi-model analysis of this suite of scenarios allows us to identify results that are robust across the models and assess underlying factors that cause model results to differ. Our analysis uses a comprehensive methodology from emissions to global climate so that the impacts of all emitted species can be considered (Table 1), along with uncertainty.

While we focus in this analysis on SLCF emissions, it is important to note that reducing the level of future climatic changes requires reductions in carbon dioxide emissions. Unlike SLCFs, carbon dioxide accumulates in the atmosphere, meaning that stabilizing radiative forcing means ultimately reducing net carbon dioxide emissions to zero. We, therefore, also include scenarios with comprehensive greenhouse gas reductions in the analysis as discussed below.

The role of SLCF emissions in a longer-term context has recently been reviewed by Rogelj et al. (2018) as part of the IPCC special report on 1.5° warming. They note that both geophysical uncertainties (e.g., parameter uncertainties we explore below) and uncertainty in long-term SLCF mitigation potential can have a significant impact on the allowable carbon dioxide emissions budget for 1.5° warming. In contrast, we focus here on the impact of SLCF emission reductions over the next several decades and will return to this point in the discussion.

This analysis of radiative forcing and temperature results is accompanied by other topical papers in this special issue including analysis of scenarios that reduce methane (Harmsen et al. 2019a, this issue) and an analysis of the potential for SLCF-focused reductions to contribute toward meeting climate targets as an adjunct to nationally determined contributions (NDCs)

<sup>1</sup> <https://emf.stanford.edu/projects/emf-30-short-lived-climate-forcers-air-quality>

(Harmsen et al. 2019b, this issue). An overview paper (Smith et al., in prep, this issue) will present the overall study design and a synthesis of results from both topical papers and additional analysis papers by individual modeling groups.

The scenarios and a brief overall description of the models are provided in the next section. A more comprehensive description of the EMF-30 exercise and the associated models is provided in the supplementary material (SM). The remaining sections of this paper examine results for forcing and then surface temperature change. Given the substantial uncertainty in climate parameters, the results from a probabilistic analysis are also presented. The paper concludes with a discussion.

## 2 Methods

The nine models participating in the EMF-30 exercise are as follows: AIM/CGE, DNE21+v.14, ENV-Linkages, GCAM4, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND, and WITCH (see SM). These models span a range of computational methodologies and model structures. All the model versions used in this study incorporate emissions of the major greenhouse gases ( $\text{CO}_2$ ,  $\text{CH}_4$ ,  $\text{N}_2\text{O}$ ), and a suite of air pollutant and precursor emissions including nitrogen oxides ( $\text{NO}_x$ ), carbon monoxide ( $\text{CO}$ ), non-methane hydrocarbons (NMVOC), sulfur dioxide ( $\text{SO}_2$ ), black carbon (BC), and organic carbon (OC).

All radiative forcing and temperature calculations presented in this work use a common version of the simple climate model MAGICC6 (Meinshausen et al. 2011a,b). MAGICC6 incorporates representations of the relevant gas cycles and radiative forcing for each species. Critically, MAGICC6 includes a multi-region representation of forcing and climate responses. This results in a more rapid response of the climate system to aerosol forcings, located predominately over land and in the northern hemisphere such as sulfate and black carbon (Schwarber et al. 2018), as also seen in earth system models (Shindell 2014). The use of a common climate model eliminates spurious differences due to different climate model versions and parameter assumptions used by individual modeling groups. We specifically report here MAGICC6 results for top of the atmosphere forcing after stratospheric adjustment (see supplementary material, SM, §C for further discussion).

Models participating in the EMF-30 exercise implemented a wide range of scenarios, some of which are more fully explored in other papers in this special issue (Harmsen et al. 2019a). Each model first produces a reference scenario, generally following socio-economic assumptions similar to the SSP2 storyline (O'Neill et al. 2017), representing future conditions without additional climate policies. Each model's reference case also includes some representation of on-going efforts to limit air pollutant emissions. Differences in reference case trajectories, which are not harmonized between the models, contribute to differences in model results. This is a useful feature as we seek robust results across this diversity of models.

Under the EMF-30 exercise, a common set of scenarios was implemented in nine models that span a range of methodologies. We focus in this analysis on the differences from the reference case scenario for five scenarios, summarized in Table 2. The first two scenarios target mitigation of selected SLCFs: **CH4-Only**—incorporates only policies to reduce methane emissions; **BCOC-EndU**—explores BC and OC reductions achievable by application of best available technology in the transportation sector and the phase-out of direct use of biomass and coal in the residential and commercial buildings sector. These two sectors represent the majority of anthropogenic emissions of BC and OC worldwide for nearly all

**Table 2** Overview of scenarios used in this work. See Supplemental Material (SM) for further details

Scenario name	General description	SLCF assumptions
Reference	Reference case without additional climate policies.	Air pollutant emission controls evolve according to either a <i>reference scenario</i> or <i>current legislation</i> (CLE) approach (see discussion in SM), with no specific focus on SLCF emissions.
CH4-Only	Maximal feasible reductions in methane (CH <sub>4</sub> ) emissions	Implements a CH <sub>4</sub> price that ramps up from zero in 2015 to \$4250/tCH <sub>4</sub> by 2030, constant thereafter. This policy is considered to be of sufficient magnitude to induce near maximal reductions in methane emissions. <sup>a</sup>
BCOC-EndU	Maximal reductions of BC and OC emissions from transportation and building sectors	Phase out end-use coal and biomass consumption in buildings (roughly equivalent to 100% penetration of clean cook-stoves and heating). Begin implementation of advanced emission controls in transportation for all regions, starting after 2015 similar to LIMITS Maximal Feasible Reduction (MFR) 2030 in OECD regions. <sup>b</sup>
SLCF	Both BCOC-EndU and CH4-Only policies	As above for both CH <sub>4</sub> in all sectors and BC OC in buildings and transportation.
ClimPolicy	Global policy to reduce greenhouse gas (GHG) emissions	Global cumulative fossil CO <sub>2</sub> emissions constraint of 1000 GtCO <sub>2</sub> from 2011 to 2100. This budget corresponds to the upper end of emission budgets of scenarios in the 430–480 ppm category of likely 2 °C scenarios and is also used in the ADVANCE/IAMC community diagnostics exercise. <sup>c</sup>
ClimPolicy+SLCF	ClimPolicy and SLCF scenarios together	Both SLCF and ClimPolicy scenarios applied.

<sup>a</sup> For reference, this is equal to \$50/tCO<sub>2</sub> and methane index of 85 (= 20-year AR5 GWP), or also equal to \$170/tCO<sub>2</sub> and a methane index of 25 (= 100-year AR4 value). The GWP is given for reference only—whatever index or other formulation for CO<sub>2</sub> equivalence implemented within each model has been used <sup>b</sup> Both building and transport policies are completed by 2030. The intention of this scenario is that all road vehicles in use by 2030 would be in compliance with strict emission controls with no super-emitters. Energy system feedbacks (e.g., energy technology replacement to provide the services formally supplied by coal and biomass) are included in the results <sup>c</sup> Carbon price is also applied, as implemented for each model, to non-CO<sub>2</sub> GHG emissions. Models vary in how CO<sub>2</sub> emission policies are applied to land-use CO<sub>2</sub> emissions. Models with a time horizon until 2050 also applied a 2011–2050 budget of 1000 GtCO<sub>2</sub>, implicitly assuming carbon neutrality for the 2nd half of the century

regions and are also well represented in the models. Finally, the large BC/OC ratio in the transportation sector makes this potentially an even more attractive target for climate mitigation. In order to assess the impact of strong reduction of methane and black carbon jointly, the **SLCF** scenario is evaluated—it combines CH<sub>4</sub>-Only and BCOC-EndU. For comparison, we include an idealized climate policy scenario (**ClimPolicy**) in which emissions of all GHGs, including CH<sub>4</sub>, are reduced such that cumulative CO<sub>2</sub> emissions over 2011–2100 are equal to 1000 Gt CO<sub>2</sub>, generally sufficient to limit warming below 2 °C with > 67% probability (Luderer et al. 2018). Finally, in the **ClimPolicy+SLCF** scenarios, both GHG reductions and SLCF-focused reductions are applied so we can evaluate the additional impact of SLCF reductions relative to the ClimPolicy scenario.

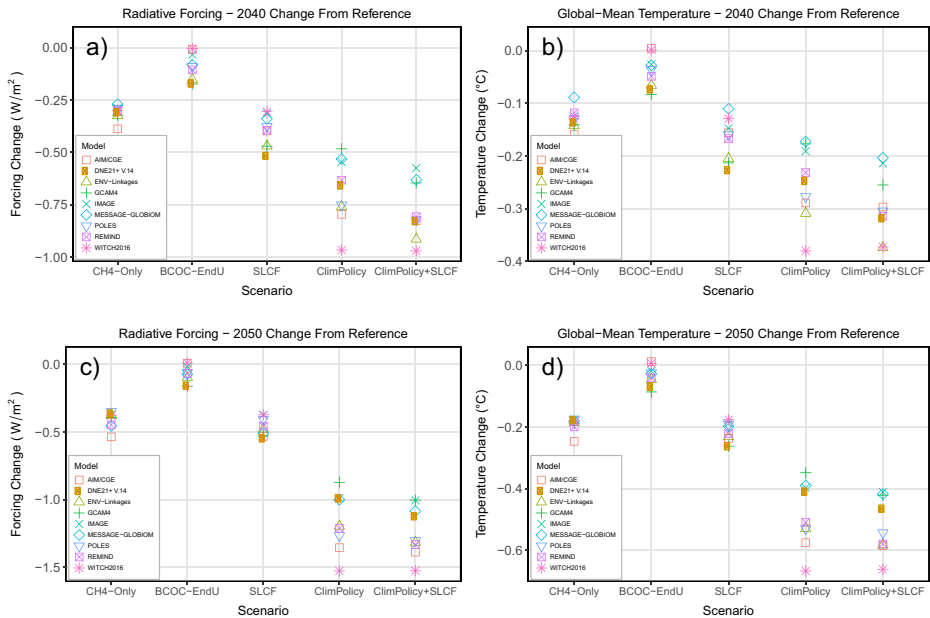
### 3 Radiative forcing changes

#### 3.1 Overall results

Figure 1a shows 2040 and 2050 changes in global radiative forcing for each scenario relative to each model's reference scenario using central climate model parameters (see SM for 2030 and 2050). As found in previous work (Smith and Mizrahi 2013; Rogelj et al. 2014b), the major SLCF contributor to radiative forcing changes is methane reductions (e.g., the CH<sub>4</sub>-Only scenario). The BCOC-EndU scenario, focused on BC reductions, results in a net reduction in most models; however, they are significantly smaller than for CH<sub>4</sub>-Only. There is little sectoral or species overlap in the CH<sub>4</sub>- and BC-reduction scenarios, with the sum of CH<sub>4</sub>-Only and BCOC-EndU forcing reductions close to the reductions in combined SLCF scenario.

The reduction in total forcing from the SLCF scenario is similar to that from the ClimPolicy scenario in 2030 (see SM), but from 2040 onward, the ClimPolicy scenario results in much larger forcing reductions. There is considerable overlap in terms of sectoral and emission species reduction between the ClimPolicy and SLCF scenarios, which will be examined in the temperature change section below.

We split our analysis of forcing changes into consideration of the direct forcing changes, which are the forcing changes from the targeted emission species, and auxiliary reductions, which are defined as the sum of all other forcing changes that occur in other species (see SM). We now examine results for the CH<sub>4</sub> and BC emission reduction scenarios below.



**Fig. 1** **a** (left) Total radiative forcing and **b** (right) global-mean temperature changes relative to the corresponding reference scenario for the five central EMF-30 scenarios in 2040 and for 2050 (**c** and **d**). Each symbol represents the result from an individual model. All results estimated consistently using the same version of the MAGICC6 simple climate model. Similar figures for years 2030 and 2100 can be found in the SM, as well as larger versions of these figures

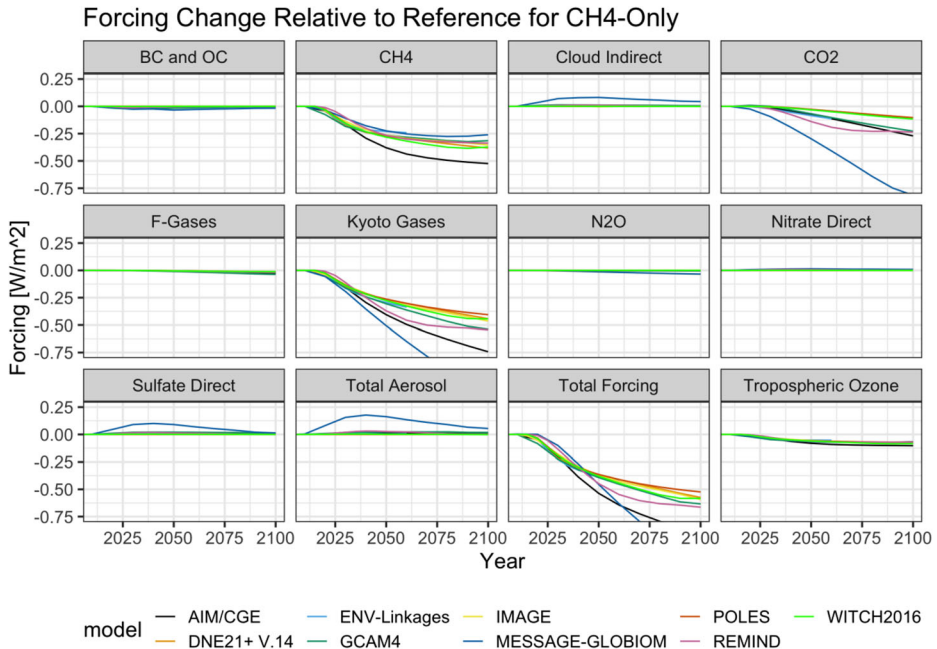
### 3.2 CH<sub>4</sub>-Only—methane-focused reductions

In the CH<sub>4</sub>-Only scenario, a methane price is phased in from 2015 to 2030 and has been set to a magnitude sufficient to induce near-maximal reductions in methane emissions (SM §A). The methane emission reductions in the CH<sub>4</sub>-Only scenario result in an average 2040 CH<sub>4</sub> forcing a reduction of 0.23 W/m<sup>2</sup>, with relatively little scatter other than one model (Fig. 2). Further analyses of methane emission reductions are provided in Harmsen et al. (2019a), although see SM for a note on differences in the CH<sub>4</sub> scenario definition between these two works.

There are also significant auxiliary forcing reductions that are in addition to the change in CH<sub>4</sub> forcing itself. The largest are reductions in CO<sub>2</sub> and tropospheric ozone forcing (Fig. 2). Neglecting one outlier model whose results in this case are due to a specific model configuration, total auxiliary forcing reductions amplify the direct CH<sub>4</sub> emission reductions by 30–50% in 2040 and 35–70% in 2050. The MESSAGE model is an outlier here due to the inclusion of land-use-related CO<sub>2</sub> emission reductions in the CH<sub>4</sub> reduction case. (see discussion in SM.)

The auxiliary CO<sub>2</sub> reductions vary across the models with one group of models showing relatively small reductions (< 0.02 W/m<sup>2</sup> in 2040) with the second group showing much larger reductions, which range from 15 to 20% of the direct reduction in CH<sub>4</sub> forcing in 2040, and 20–50% in 2050. The relative impact of these auxiliary CO<sub>2</sub> reductions increases with time as CO<sub>2</sub> concentration changes accumulate in the atmosphere.

There are two sets of mechanisms for these auxiliary effects. The first set of mechanisms are economic auxiliary effects, which are reductions due to economic feedbacks and technology



**Fig. 2** Radiative forcing change for the CH<sub>4</sub>-Only scenario by component relative to the reference scenario ( $F_{\text{CH}_4\text{-only}} - F_{\text{Reference}}$ ). The sum of all forcing components is shown as “Total Forcing” and all aerosols as “Aerosol”. Negative values indicate net cooling in the CH<sub>4</sub>-Only scenario as compared with the reference scenario. See SM for forcing variable definitions



shifts induced by the CH<sub>4</sub> emission reduction policy. In some models, the methane emission price has an economic impact on the cost of activities that produce methane. As the methane price increases, those activities become more expensive and their consumption is reduced, which also can reduce other emissions such as CO<sub>2</sub>. For example, reductions in (1) fossil fuel and (2) beef production, two sectors with substantial methane emissions, would tend to reduce net CO<sub>2</sub> emissions through reducing (1) fossil fuel consumption and (2) land-use change. The strength of these reductions will depend on model structure and the extent to which the CH<sub>4</sub> price is passed through to consumers. Note that in some cases, these economic feedbacks can be a modeling choice and in other cases, it is inherent to the structure of the model (see model descriptions in the SM).

In four of the models, there are limited or no economic feedbacks from a methane reduction policy. This can be thought of as a CH<sub>4</sub> policy formulation where CH<sub>4</sub> reductions are incentivized and this is assumed to occur in a revenue neutral manner with respect to the CH<sub>4</sub>-producing activity. This might represent, for example, an offset or best available technology (BAT) regulation regime where the direct costs of methane mitigation activities are compensated but any non-mitigatable emissions are not priced. While there may still be economic feedbacks in such a regime in reality, these can be of a different magnitude (e.g., general equilibrium effects instead of direct effects at the technology level) or simply not be included in the model formulation.

A second set of auxiliary reduction mechanisms are physical effects related to changing methane concentrations. Decreasing methane emissions decreases temperatures, the oxidation of CH<sub>4</sub> to CO<sub>2</sub>, the production of tropospheric ozone, and the production of stratospheric water vapor (all included in MAGICC). All of these forcing mechanisms contribute to the auxiliary forcing reductions and their magnitude is quantified in the lower set of model auxiliary results noted above (e.g.,  $\sim 0.03$  W/m<sup>2</sup> in 2050). The largest contributor to the CO<sub>2</sub> decrease is smaller carbon-cycle feedbacks due to decreased global temperatures. Note that there is additional forcing uncertainty for some of these mechanisms as compared with methane forcing itself. We also note that in the configuration used here, all anthropogenic methane is assumed to be oxidized to CO<sub>2</sub>, where in reality only fossil CH<sub>4</sub> emissions should be considered to add to atmospheric CO<sub>2</sub> concentration (Boucher et al. 2009), which will lead to an overestimate of the effect of CH<sub>4</sub> oxidation.

Consideration of these auxiliary effects is clearly a potentially important element of a policy focused on CH<sub>4</sub> emission reductions. The economic auxiliary effects are the dominant contributor, where these are included, which continue to increase throughout the century as CO<sub>2</sub> accumulates in the atmosphere. We note that this scenario included a relatively high CH<sub>4</sub> emission price. A different scenario formulation, with a more modest CH<sub>4</sub> price, will result in a lower level of economic auxiliary emission reductions.

### 3.3 BCOC-EndU—black carbon-focused reductions

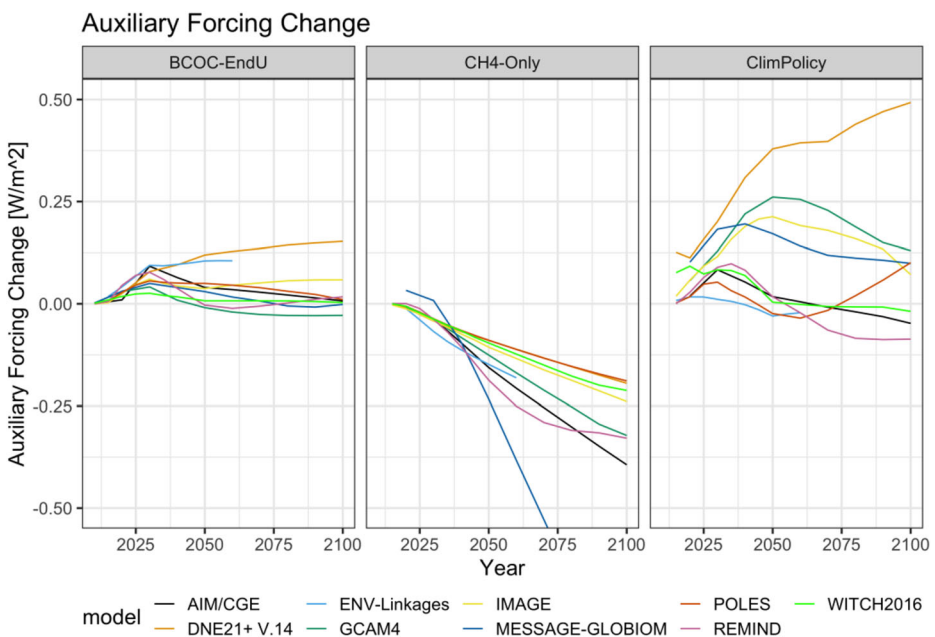
The BCOC-EndU scenario includes two policies targeting emission sectors with high BC emissions: a complete phase-out of end-use coal and traditional biomass in the buildings sector and the imposition of stringent particulate emission controls on vehicles, both by 2030. These BC-focused reductions show a wide range of results across the models, with a total forcing reduction relative to reference that peaks in 2030 and ranges from 0.06–0.29 W/m<sup>2</sup>. The reasons for the range in BC and OC emission reductions are discussed further by Smith et al. (in prep, this issue), so we concentrate here on examining the various radiative forcing components.



BC and OC are emitted together, although in different proportions depending on the source. Because the SLCF scenario focuses on BC-rich sources, the impact of OC emissions is relatively low in these scenarios, with the magnitude of the OC forcing differences (BCOC-EndU—reference) ranging from 10 to 20% of the BC forcing differences.

For the BCOC-EndU scenario, we define all forcing changes other than direct BC and OC to be auxiliary reductions. The largest auxiliary changes are cloud indirect effects, which act to reduce the forcing impact of the BC emission reductions while tropospheric ozone changes add to the forcing reductions. Overall, up until about 2050, auxiliary forcing changes are net positive, reducing the impact of the BC and OC forcing reductions by up to 50% (Fig. 3, Fig. S9, S10). Auxiliary forcing changes in the BCOC-EndU scenario generally peak in 2030 and decrease in absolute magnitude thereafter. The two models with the largest auxiliary forcing (DNE21+ and ENV-Linkages) also have the largest reductions in BC forcing, so their total forcing impact is still among the highest among these models.

Note that one factor that was not included in these models was that the sulfur content of road diesel fuel would need to be reduced to very low levels in order to facilitate the operation of the particulate control devices necessary to achieve low BC emission levels from the transportation sector. This would further reduce the temperature impact of BC-focused reductions (Smith and Mizrahi 2013). Overall, given the role of auxiliary reductions, we conclude that it is important to include a comprehensive representation of air pollutant and GHG emission changes when examining the impact of potential BC-focused policies.



**Fig. 3** Auxiliary radiative forcing changes—the sum of all forcing changes (e.g., Fig. 2, and SM figures) other than the primary target(s) of each policy (see text for definition) for the CH4-Only, BCOC-EndU, and ClimPolicy scenarios. Changes are expressed as absolute differences from the reference scenario

## 4 Temperature changes

### 4.1 Results using central climate model parameters

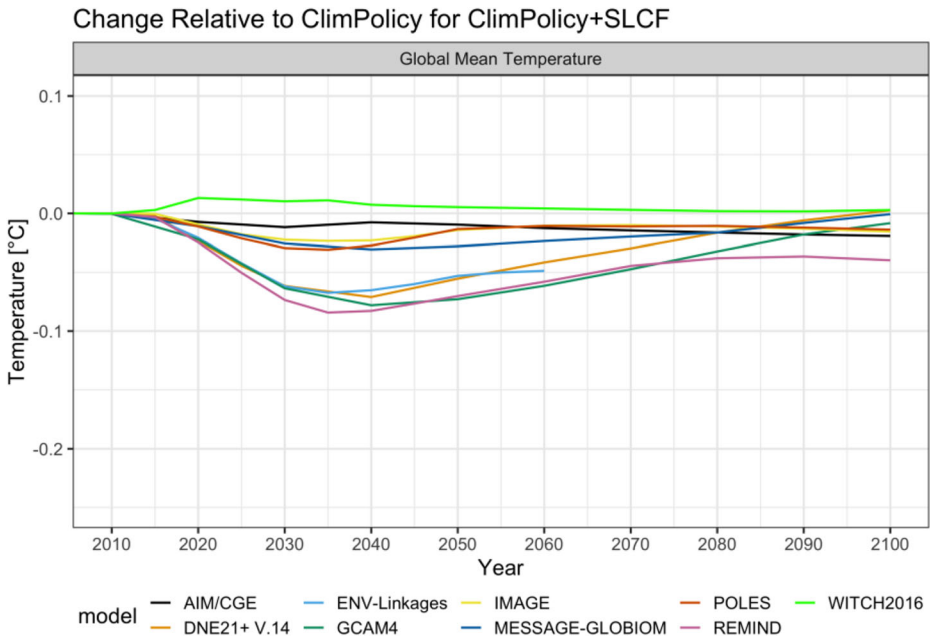
As shown in Fig. 1b, the relative size of temperature changes generally mirrors that of the forcing changes, although there is not a 1:1 correspondence since greenhouse gases and aerosols have different efficacies and response timescales. Temperature reductions in the SLCF scenario show a relatively wide spread in 2030, from 0.04–0.15 °C below the reference scenario with the relative range narrowing by 2050 to 0.18–0.26 °C. The inter-model variation is largest for the BC reductions, with significant variation also in CH<sub>4</sub> impacts.

In 2030, the contribution of BC emissions reductions ranges from 0 to 50% of the temperature change, depending on the model. The relative impact of the BC reductions is smaller by 2050, with one set of models showing very little net contribution (AIM/CGE, IMAGE, WITCH), another set (DNE21+, GCAM4, ENV-Linkages) showing 20–30% contribution, and the remainder showing a 10% contribution (POLES, MESSAGE-GLOBIOM, REMIND).

We can also examine the extent to which SLCF reductions might augment a climate policy by comparing temperature changes in the ClimPolicy scenario with those in the ClimPolicy+SLCF scenario (Fig. 4). Relative to the ClimPolicy scenario, the simultaneous SLCF policy results in additional cooling from BC, CH<sub>4</sub>, CO<sub>2</sub>, and tropospheric ozone, offset by changes in cloud indirect and nitrate forcing (Fig. S15). The maximum additional benefit of the SLCF reductions, applied in addition to the comprehensive climate policy, is in 2040 for most models. The magnitude of the additional SLCF temperature reduction varies from near zero to 0.07°/0.08 °C in 2030/2040 (similar to that found in Harmsen et al. 2019b). This is much smaller than the reduction due to the SLCF policy in isolation, since much of the methane reductions and some of the BC-oriented reductions also occur under a comprehensive climate policy. The SLCF policy has a larger relative impact at earlier times, but the absolute impact varies by model. By 2040, two models (AIM/CGE, WITCH) show almost no additional temperature benefit while the remainder finds 20–50% of SLCF-only temperature reduction still occurs if coupled with the climate policy scenario.

### 4.2 Uncertainty analysis

The above forcing and temperature results were generated using central assumptions for aerosol forcing and other climate system parameters. Aerosol forcing in particular is quite uncertain and this uncertainty will impact results. We conduct here an uncertainty analysis using the uncertainty range from a Monte Carlo setup of MAGICC6 following the approach outlined in Meinshausen et al. (2009), with the distribution of equilibrium climate sensitivity set to be consistent with the assessment of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change as described in Rogelj et al. (2012, 2014a). The uncertainty analysis consists of 600 cases that sample across a range of 82 climate model parameters selected such that the model matches historical temperature change within a specified accuracy. The parameters varied including climate sensitivity, ocean heat diffusion rate, and strength of aerosol forcing by species (i.e., sulfate direct, BC direct, OC direct, cloud indirect) as detailed in Table S1 of Meinshausen et al. (2009). This parameter distribution, therefore, represents uncertainty in how the physical system would respond to changes in SLCF and



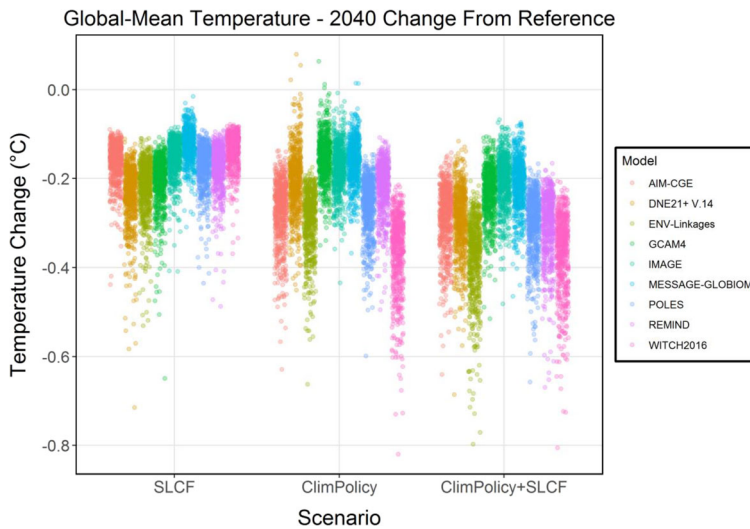
**Fig. 4** Additional global temperature change due to SLCF emission reductions when applied to the ClimPolicy scenario for central climate model parameters (ClimPolicy+SLCF scenario–ClimPolicy scenario). Negative values represent an additional reduction in global temperature change due to the SLCF reductions.

GHG emissions, with parameter combinations constrained such that the results are consistent with historical observations.

As shown in Fig. 5, uncertainty in climate model parameters, primarily aerosol forcing strengths (see SM), result in a large temperature range, due to parametric uncertainty. Overall, this parametric uncertainty has a larger impact on results than the selection of an IAM. For example, the range in central temperature change relative to reference across the IAM models for the BCOC-EndU scenario is 0.12 °C (Fig. 1b), while the range in any single IAM model due to parametric uncertainty is 3–5 times the range across IAMs.

We note that the parametric uncertainty range varies by a factor of 2 across models, or 0.29–0.60 °C. The distribution is skewed with a tail of cases with temperature reductions that are more than twice the central value. The five parameters that most influence these high tail cases are as follows: ocean vertical diffusivity, climate sensitivity, methane forcing per unit concentrations, tropospheric ozone forcing, and the land/ocean warming ratio. The role of climate sensitivity is straightforward; this affects all results. The importance of the methane and ozone parameters is due to methane’s role as the largest SLCF component and its role as a precursor of background tropospheric ozone. Both ocean diffusivity and the land/ocean contrast play key roles in determining climate response timescales. These parameters, therefore, determine how fast the climate system responds to a short-timescale forcing change (see SM for further details).

Note, however, that the larger temperature increases in the uncertainty analysis are often also associated with larger reference scenario temperature changes (Figs. S23–25). That means that these larger temperature reductions do not necessarily reflect a larger proportionate reduction in temperature change. The strength of the relationship between SLCF scenario



**Fig. 5** Uncertainty analysis for 2040 temperature change, relative to reference scenario, by model. Each colored cloud represents results for the specified IAM sorted left to right and identified by color as indicated in the legend. These results are analogous to Fig. 1b but are showing the implications of climate parameter uncertainty. Horizontal jitter within results for each model added for clarity; only the vertical position of each point has meaning

reduction and reference case temperature varies by model, with the models with higher SLCF scenario reductions generally having a stronger relationship.

In 2030, the range in temperature reduction due to parametric uncertainty is similar for the SLCF and ClimPolicy scenarios, except that there are more cases with a near-term increase in global-mean temperatures for the ClimPolicy scenarios, i.e., a temporary dis-benefit. This is because, under a climate policy, there is a larger reduction in cooling from sulfur dioxide emissions (Fig. S13) compared with the SLCF scenario (Fig. S12). If cooling forcing per unit sulfate emissions is high, one of the possibilities covered in the uncertainty ensemble, then there is a possibility of a near-term temperature dis-benefit. By 2050, the parametric uncertainty range is much larger for ClimPolicy and there are no longer any cases with a dis-benefit (Fig. S22).

## 5 Discussion

Estimates of temperature reductions from SLCF scenarios relative to reference scenarios in 2050 ranged from 0.18–0.26 °C across the nine models (from 0.11–0.23 °C in 2040), using a central set of climate and aerosol assumptions. The models varied substantially in the extent to which BC-focused mitigation contributed to this reduction while methane drives 70% or more of the temperature reductions by 2050, which is consistent with previous studies.

We note that it is important to examine the effect of potential policy actions relative to realistic reference scenarios since background conditions such as GHG concentrations and air pollutant emissions will certainly change over time. Using a multi-model approach, we can better identify what results are robust with respect to differing energy-economic models.

We also find that the economic assumptions related to how methane reductions are implemented in a model can have a large influence on the size of auxiliary forcing reductions, defined as forcing reductions from species other than those primarily targeted by the policy. Auxiliary reductions of carbon dioxide emissions play an increasing role as time goes on in models where the value of methane emissions is allowed to impact economic decision-making.

We find that there is a substantial overlap between a SLCF policy and a comprehensive climate policy that reduces greenhouse gas emissions. When both SLCF and GHG reduction policies are considered together, the additional benefit from a SLCF policy ranges from zero in some models to a maximum of 0.07°/0.08 °C in 2030/2040 in other models. This is much smaller than the reduction from the SLCF-focused policy alone. We, therefore, find limited near-term additional global climate forcing reduction from SLCF-focused policies when combined with comprehensive GHG reductions in these scenarios.

These comparisons reinforce the importance of GHG-focused emission reductions, particularly CO<sub>2</sub>, for long-term temperature decreases relative to the reference scenario. The temperature impact of BC-focused emission reductions peaks in 2030–2040, while the impact of methane-focused reductions continues to increase through to 2100 (Fig. S18). However, only comprehensive GHG reductions produce temperature reductions relative to reference larger than ~0.4 °C by 2050 (using central climate system parameters).

The temperature reduction is strongly dependent on uncertain climate model parameters. This parametric uncertainty is far larger than the differences between models. If climate sensitivity is high and methane and timescale-related parameters are in a certain range (see §4.2 and SM), then the SLCF scenario could reduce temperatures up to 0.5–1.0 °C by 2050 for end-case parameter choices. On the other end of the uncertainty range, temperature reductions could be half of the central case results, or even result in additional warming.

Note that we have used a single simple climate model in this work. This model has been shown to provide results similar to an ensemble of more complex models (Meinshausen et al. 2011). With respect to SLCF scenarios, we note that the results of Stohl et al. (2015) using more complex models were nearly identical to those from Smith and Mizrahi (2013) using an earlier version of the MAGICC simple model used here. While our uncertainty analysis covers a range of parametric uncertainty, there is likely additional structural uncertainty due to the use of a single climate model.

We note in particular that there is substantial scientific uncertainty in the mechanisms by which black carbon emissions would impact surface temperatures, and this uncertainty is not necessarily reflected in current multi-model assessments or in the simple climate model used here. A set of experiments removing all anthropogenic BC from four coupled model simulations found temperature effects that were inconsistent both between models and between ensemble members of the same model (Baker et al. 2015). Recent work has noted that rapid adjustments to BC-atmospheric effects act to reduce the net impact of black carbon on surface temperature (Stjern et al. 2017), leading the community toward the use of a new definition of radiative forcing that includes rapid adjustments. This might reduce estimates of BC temperature impact in future assessments; however, large differences between model responses remain. We also note that the temperature response to a change in BC emissions in the MAGICC6 model used here (Schwarber et al. 2018) is different in character to the response shown in a step emission experiments in two coupled climate model experiments (Sand et al. 2015; Yang et al. 2019), further emphasizing the uncertainty in climate responses to BC emissions in particular. Overall, therefore, results for the impact of black carbon on surface temperature should be considered indicative.

We note also that changes in GHG and aerosol emissions will impact not only global mean-temperature but also regional temperature changes and precipitation; however, methods to examine these changes in simple climate models do not yet exist and are, therefore, not addressed in this study.

Results for methane are more robust, although uncertainties remain (Harmsen et al. 2019b). Methane contributes the largest amount to temperature reduction in the SLCF scenarios considered here with central case temperature reductions of around 0.2 °C by mid-century. Recent findings (Etminan et al. 2016; Modak et al. 2018) suggest that a  $\pm 14\%$  uncertainty in methane efficacy may underestimate the uncertainty in methane forcing.

This analysis focused on the impacts of policy scenarios, that is, reductions as compared with a reference scenario produced by the same model. While we find a fair amount of consistency in the methane forcing *reductions* across models (Fig. 2), there is still a substantial range in the absolute level of emissions that remain after mitigation measures have been put into place. This is particularly true for methane. As noted in Harmsen et al. (2019a), there is a range of  $\sim 150$  Mt in global methane emissions between models in both 2050 and 2100 even under strong methane mitigation assumptions. Lower methane emissions would both lower near-term climate change and also increase the allowable long-term carbon budget (Rogelj et al. 2018). Continued refinement of methane emission projections and mitigation potentials should remain an important area for future research. Given our findings on the impact of auxiliary reductions on forcing reductions from the stylized methane scenarios considered here, further consideration of how methane-focused reductions might be most realistically simulated in IAMs from an economic perspective is also warranted.

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