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EDITORIAL

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The Energy Modeling Forum (EMF)-30 study on short-lived climate forcers: introduction and overview

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1 Introduction

Anthropogenic climate change is driven largely by changes in atmospheric energy balance, termed radiative forcing. Carbon dioxide is the dominant driver of these changes, but a suite of other greenhouse gases, air pollutants, and land-use changes also impact the climate (Myhre et al. 2013). While changes in carbon dioxide emissions have impacts ranging over decades to centuries, there are a number of species that impact the climate primarily in the nearer term due to shorter atmospheric lifetimes. These short-lived climate forcers (SLCFs) include methane, aerosols, HFCs, and tropospheric ozone (and precursor emissions).

Because, by definition, SLCFs have a relatively short atmospheric lifetimes, there has been a growing interest in developing strategies to reduce their emissions and consequently mitigate near-term climate change. See Harmsen et al. (2019b, 2020) and Smith et al. (2020) in this issue for literature review and discussion of previous work. Many of the SLCFs are also air pollutants or air pollution precursors so reducing SLCF emissions will generally lead to reductions in air pollutant–related mortality and economic impacts, as also examined in this special issue.

The Energy Modeling Forum inter-comparison study on short-lived climate forcers (EMF-30) focuses on black carbon (BC) and methane (CH_4), two of the most important warming SLCFs. The study is aimed at quantifying the potential impact of methane and BC-focused reductions on climate change and at comparing the impact of idealized SLCF reductions as compared to idealized GHG reduction policies of the type long-analyzed by the modeling community.

The EMF-30 study takes a multi-model approach that includes nine integrated assessment models. Analysis of the interaction between dedicated SLCF and GHG reduction policies and

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the systematic implementation of stylized scenarios allows an assessment of the role of forcers individually and as they interact with different policy options. The multi-model analysis allows an assessment of how robust results are across different models and background scenario assumptions.

The special issue consists of this overview, three cross-cutting papers that focus on different aspects of the multi-model analysis results (Harmsen et al. 2019a, b, Smith et al. 2020), and four papers expanding on this topic largely using individual models (Chantret et al. 2020; Harmsen et al. 2020; Rauner et al. 2020; Vandyck et al. 2020). The next section provides an overview of the EMF-30 study, followed by a summary of study results, and ending with a conclusion section.

2 Study overview

The EMF-30 study uses a scenario approach in which a coordinated suite of scenarios is used to explore how stylized global policies to reduce SLCFs impacts emissions, concentrations, radiative forcing, and global temperature change. The SLCF reduction scenarios focus on methane across all sectors and black carbon from transportation and buildings. Greenhouse gas (GHG) mitigation scenarios are also considered, including the combination of GHG and SLCF mitigation.

2.1 Scenarios

The analysis starts with a reference case, which generally follows socio-economic assumptions similar to the SSP2 storyline (O'Neill et al. 2017) with no additional policies focusing specifically on greenhouse gases. Each model incorporates a representation of the future evolution of air pollutant emission controls. Beyond the broad socio-economic assumptions provided by the SSP2 storyline, reference case trajectories are not harmonized between models, which is a useful feature as we seek to determine how robust results are across this diversity of models and reference scenarios.

The first two policy scenarios examine the impact of SLCF-focused reductions of methane (*CH4-Only*) and black/organic carbon (*BCOC-EndU*). The *SLCF* scenario is the combination of the CH4- and BC-focused scenarios and allows analysis of the combined impact of SLCF reductions.

The CH4-Only scenario simulates a policy to reduce methane emissions through a global price on methane. Methane is the second largest source of positive climate forcing (Myhre et al. 2013) and has a relatively short (~decadal) atmospheric lifetime, making it a key SLCF species.

The BCOC-EndU scenario explores the impact of BC and OC emission 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 building sector (including cooking and heating). These scenarios, therefore, represent maximal (as foreseen in each of the models) emission reductions in those sectors over the near term. These sectors were chosen because they comprise the bulk of global anthropogenic black carbon emissions (3/4 of the global emissions in Klimont et al. 2017), are the target of many national and regional policies across the globe, and are represented explicitly in the models used in this analysis. We note that there are additional sectors that could be targeted to reduce black carbon emissions, such as agricultural and construction machinery, diesel generators, traditional coal coke production, gas flaring, open burning of agricultural residues, and brick kilns. These sources were not included because the models used here generally do not have sufficient detail to represent these technologies, and some of these sources are more likely to cause net cooling due to lower ratios of BC to OC emissions.

A central point of interest in this study was to examine how SLCF emission reductions interact with climate policies. For comparison with the SLCF-focused scenarios, we include an idealized climate policy scenario (*ClimPolicy*) in which cumulative CO_2 emissions over 2011–2100 are limited to 1000 Gt CO_2. For CH_4, N_2O, and fluorinated gases, the same emission pricing in terms of GWP-100 CO_2 equivalents as for CO_2 was applied, ensuring similar policy stringency across all greenhouse gases covered by the Kyoto protocol. These emission constraints are generally sufficient to limit warming below 2 °C with > 67% probability (Clarke et al. 2014; Luderer et al. 2018). Finally, to examine the interaction between SLCF and climate policies, we have the *ClimPolicy+SLCF* scenario in which both GHG reductions and SLCF-focused reductions are applied, which allows analysis of overlap between the two strategies. With this scenario, we can evaluate the additional impact of SLCF reductions relative to the ClimPolicy scenario.

A summary of the core EMF-30 scenarios is provided in Table 1.

Table 1 Overview of the core EMF-30 scenarios. See Smith et al. SI (Table S1) for further details. See Harmsen et al. (2019b) for a discussion of scenarios involving National Determined Contributions (NDCs) and hydrofluorocarbons (HFCs)

Scenario name	General description	SLCF assumptions
Reference	Reference case without additional climate policies	Air pollutant emission controls evolve according to either a *reference scenario* or *current legislation* (CLE) approach to air pollutant emission controls (see discussion), with no specific focus on SLCF emissions.
CH4-Only	Maximal feasible reductions in methane (CH_4) emissions	Implements a CH_4 price that ramps up from zero in 2015 to $4250/tCH4 by 2030, constant thereafter. This policy is considered to be of sufficient magnitude to induce near maximal reductions in methane emissions.
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 cookstoves 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.
SLCF	Both BCOC-EndU and CH4-Only policies	As above for both CH_4 in all sectors and BC/OC in buildings and transportation.
ClimPolicy	Global policy to reduce greenhouse gas (GHG) emissions	Global cumulative fossil CO_2 emission constraint of 1000 $GtCO_2$ 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 diagnostic exercise.
ClimPolicy+SLCF	ClimPolicy and SLCF scenarios together	Both SLCF and ClimPolicy scenarios applied.

2.2 Participating IA models

There were nine models participating in the EMF-30 exercise: AIM/CGE, DNE21+v.14, ENV-Linkages, GCAM4, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND, and WITCH (see also Table S1.1 in Harmsen et al. 2019a and supplemental section B in Smith et al. 2020). These models span a range of computational methodologies and model structures. Overall, these models project medium- to long-term energy system structures, including end-use and energy transformation sectors, resulting in projections of GHG and SLCF emissions. Using multiple models allows us to examine if results are robust with respect to modeling methodology. All the model versions used in this study incorporate emissions of the major greenhouse gases (CO_2, CH_4, N_2O) and a suite of air pollutant and precursor emissions, including nitrogen oxides (NO_x), carbon monoxide (CO), non-methane hydrocarbons (NMVOC), sulfur dioxide (SO_2), black carbon (BC), and organic carbon (OC).

2.3 GAINS data

The EMF-30 exercise was also an opportunity to incorporate air pollutant emissions into some of these models or stimulate improved representations in others. To facilitate this process, the GAINS (Greenhouse gas–Air pollution Interactions and Synergies) model framework (Amann et al. 2011; Höglund-Isaksson 2012; Klimont et al. 2017) was used to produce historical and near-term emission data for the air pollutant emission species mentioned above that were used by many modeling groups to calibrate their historical emission values and also used by some groups as future emission factor trajectories. The approach used in EMF-30 builds on the experience developed during the multi-model EU-funded study LIMITS (Rao et al. 2016) and earlier collaboration between the MESSAGE and GAINS modeling groups at IIASA (e.g., Riahi et al. 2012). GAINS data was provided to the modeling groups with a source sector protocol with higher granularity data for transport and building sectors in order to allow accurate use of GAINS data by Integrated Assessment Models (IAMs).

The GAINS dataset used in EMF-30 relies on exogenous projections of energy use and industrial production (IEA 2012) and agricultural activities (Alexandratos and Bruinsma 2012) which were translated into GAINS structure and resolution. The baseline GAINS current legislation case (CLE) assumes effective implementation of environmental policies committed before 2015. The maximum technical feasible reduction (MFR) case assumes implementation of all technologies in the GAINS database beyond the CLE, which can be used to identify low emission pathways. These, and other compatible, datasets were used in the ECLIPSE project (Stohl et al. 2015) and are available from the GAINS website as ECLIPSE V5a. The baseline (CLE) and maximum mitigation (MFR) sets of sectoral and regional emission factors were developed for use within the EMF-30 study; these were calculated for a set of common source sectors satisfying the harmonized needs of the global IAMs. Figure 1 shows the global average emission factor trajectories developed in the GAINS model for road diesel vehicles and residential fuel use in the CLE and MFR cases.

2.4 Climate model: MAGICC

All radiative forcing and temperature calculations presented below and in the EMF-30 cross-cut papers use a common version of the simple climate model MAGICC6 (Meinshausen et al. 2011). The MAGICC6 model incorporates representations of the relevant gas cycles and

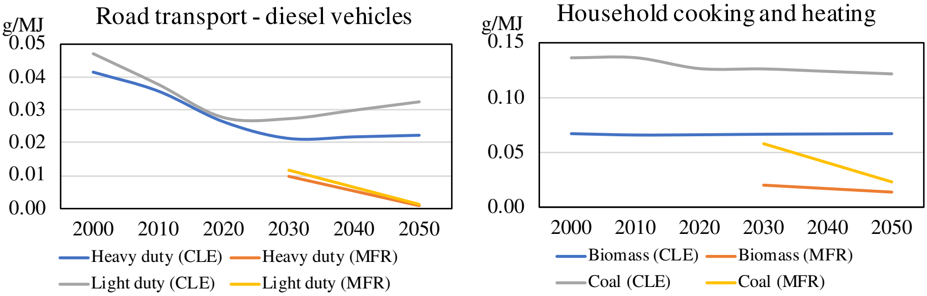

Fig. 1 Evolution of the baseline (CLE) and mitigation (MFR) case black carbon emission factors (at a global level) in the GAINS ECLIPSE V5a scenarios for two key sectors addressed in the BCOC-EndU scenario

radiative forcing for each relevant species and produces radiative forcing estimates similar to those from more complex models (Harmsen et al. 2015). Critically, MAGICC6 includes a multi-region representation of forcing and climate responses which results in a more rapid response to aerosol forcing as compared to well-mixed greenhouse gases such as sulfate and black carbon that are preferentially felt over land and in the northern hemisphere (Meinshausen et al. 2011; Smith et al. 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. The MAGICC model also was used to examine the impact on results of parametric uncertainty in the climate system.

3 Overview of study results

Global mean temperature change is often used as a metric to examine the effectiveness of climate mitigation policies, and we also do so here, recognizing that other metrics such as changes in regional climate, precipitation, and extremes can be important for specific impacts. Global temperature is reduced by 0.18–0.26 °C in 2050 (0.11–0.23 °C in 2040) by the SLCF (CH4 plus BC)-focused reductions examined in the EMF-30 scenarios (Smith et al. 2020), with similar results in Harmsen et al. (2019b). Harmsen et al. (2019b) also find that SLCF reductions can have a somewhat larger relative reduction (up to 15%) on the rate of temperature change. These results are for central climate model assumptions, and the range represents inter-model differences in reference case emission projections and different model dynamics. When climate parameter uncertainty is included, this broadens the uncertainty range considerably to 0.29–0.60 °C, with higher SLCF changes tending to occur in scenarios with higher reference case climate change (Smith et al. 2020, Figures 5, S23–S25).

Reductions in methane emissions contribute the largest portion of the temperature change reduction seen in the SLCF scenarios (60–100% of the total in 2040 and 70–100% in 2050). As discussed in Harmsen et al. (2019a), methane emissions increase in reference scenarios, even when models assume that economically favorable methane reductions are taken (e.g., capturing methane to use as an energy source). Applying maximum methane reductions in the CH4-Only scenario reduces emissions in 2050 and 2100 below 2010 levels. The impact of these reductions on climate includes direct forcing from methane but also additional reductions in tropospheric ozone and other species due to methane's impact on atmospheric oxidation capacity (Harmsen et al. 2019a) and auxiliary reductions due to economic effects in some models (see below).

The impact of BC-focused reductions in the transportation and building sectors is smaller and more variable between models with global-mean temperature change in 2050 across the models ranging from essentially no change to a reduction of 0.09 °C. The diversity in outcomes is due largely due to model-specific differences in reference case trajectories. For road transport, emission trajectories show similar features with increasing fuel use and steady reduction of emissions (consistent with the CLE development of emission factors—see Fig. 1) in the reference case and a sharper decline in the BC-OC-EndU scenario. However, transport sector reductions typically represent less than one-third of total BC mitigation in this scenario. Most of the inter-model difference originates from reference case implementations of residential sector biomass, and to some extent also coal, use across the models, with 2050 building BC emissions ranging from 15 to 80% of 2010 values. Models with larger reference case building emissions by 2050 will, therefore, have larger mitigation potential from implementation of energy access and clean cookstove policies.

The relative range in forcing and temperature outcomes due to climate model parametric uncertainty from the BC-focused reductions is much higher than that for methane due to the much higher uncertainty in the climate effects of aerosols in general and BC in particular. As noted above, there are additional BC/OC emissions from sectors other than buildings and transportation that were not considered in this work that could increase somewhat the impact of BC -focused reductions (e.g., Stohl et al. 2015).

A third category of SLCFs includes shorter-lived hydrofluorocarbons (HFCs). Maximal reductions in HFC emissions could constitute an estimated 6% of SLCF radiative forcing reduction in 2030 on average (Harmsen et al. 2019b).

One advantage of using an integrated modeling approach is that economic and physical interactions across sectors and emission species can be estimated. Auxiliary forcing changes, which are defined here as changes in forcing beyond the targeted species in a given scenario, were significant in general, although these vary quite substantially across models. These can either enhance (additional forcing reduction) or offset the primary effect. In general, auxiliary changes were offsetting for BCOC-EndU (reduced cooling), enhancing for CH4-Only (additional forcing reduction), and offsetting for ClimPolicy (see Smith et al. 2020 Figure S17). These results emphasize the importance of considering all emitted species in a consistent manner when analyzing emission reduction scenarios.

The EMF-30 scenarios also revealed that model structure plays a role in determining the magnitude of auxiliary reductions from a methane reduction policy. For the set of models that pass a methane price to methane-producing technologies, additional auxiliary reductions occur as economic activities shift to less methane-intensive activities (Smith et al. 2020).

A substantial overlap between SLCF and Climate policies was found, primarily due to CH_4 emission reductions in both scenarios. Combining the ClimPolicy scenario, focused on GHG reductions, with SLCF-focused reductions results in a 0.07°/0.08° additional global mean temperature reduction in 2030/2040 relative to ClimPolicy alone (Smith et al. 2020) and a slightly larger benefit relative to estimated Nationally Determined Contributions (NDCs) under the United Nations Framework Convention on Climate Change (Harmsen et al. 2019b). The strong SLCF policy, when added to NDCs, has a more significant impact on the rate of temperature change (Harmsen et al. 2019b).

Individual modeling groups expanded on the above results with more in-depth analysis focusing on health impacts. Rauner et al. (2020) and Vandyck et al. (2020) find substantial monetized co-benefits from the reductions in air pollution that occur under imposition of a climate policy regionally and globally. Using the REMIND model, Rauner et al. (2020) find that the monetized benefits of the air pollutant emission reductions that occur under GHG mitigation, consistent with a 2° temperature pathway out to 2050, are larger than the cost of the GHG abatement, particularly for China and India. Vandyck et al. (2020) find, using the POLES-JRC model, that the total magnitude of air pollution co-benefits increases when climate mitigation ambition is strengthened from 2 to 1.5°. Examining the EMF-30 multi-model results, they find that global air quality co-benefits, when quantified in terms of CO_2 equivalent GHG emissions, range from \$8 to \$40 per tonne of greenhouse gases abated in 2030, with a median across models and scenarios of \$18/tCO_2e, with strong differentiation across regions and sectors.

The above studies quantify air pollution co-benefits using the value of statistical life, which reflects an estimate of the "aggregate dollar amount that a large group of people would be willing to pay for a reduction in their individual risks of dying in a year, such that we would expect one fewer death among the group during that year on average" (US EPA 2020). Chantret et al. (2020) add an important element to this analysis by also estimating the market impacts of air pollution on additional health expenditures, changes in labor productivity, and crop yield losses using the ENV-Linkages model. These specific direct impacts propagate through the economy resulting in indirect impacts that accumulate over time to dominate long-term economic effects. Overall, they find global market impacts, under a continued legislation (CLE) scenario, of 0.43% of global GDP which reduce to 0.21% under maximum technically feasible air pollutant emission reductions (MFR). These relative impacts are much larger in the OECD region (0.90% for CLE) as compared to the non-OECD region (0.18% for CLE).

Finally, Harmsen et al. (2020) present a detailed examination comparing BC-focused and health-focused mitigation scenarios using the IMAGE model, looking across two contrasting reference-case pathways with central (SSP2) and higher (SSP3) air pollutant emissions. A BC-focused policy results in reduced mortality in 2030 in both reference scenarios, together with a modest, although uncertain, climate benefit (e.g., global temperature reduction). A health-focused policy with deeper emission reductions across air pollutant species has a larger climate dis-benefit (temperature increase) but stronger health benefits.

4 Conclusion

The results in this EMF-30 special issue highlight the need for integrated analysis of SLCF reduction strategies. From a climate mitigation standpoint, methane emerges as the key component of near-term forcing reductions. This highlights the need to move beyond quantification of the technical potential for methane emission reductions, as assumed in the EMF-30 scenarios, but to understand the barriers to implementing mitigation and to better understand the pace at which deep emission reductions could actually be put into place (van den Berg et al. 2015, Höglund et al. 2020). A key determinant of long-term future methane emission levels under a strong mitigation regime will be the amount of mitigation possible for agricultural sources, particularly from waste management and ruminant livestock (Harmsen et al. 2019a; Höglund et al. 2020).

From a health standpoint, while reducing methane emissions also reduces background tropospheric ozone levels, the largest health benefits in the near term will come from reduction of particulate matter (PM) emissions (including BC) and precursor gases of ambient PM such as sulfur dioxide. While there is a potential climate benefit from BC-focused reductions, global mitigation focused more broadly on improving air quality will generally result in a global temperature disbenefit as cooling aerosols (sulfates, nitrates) are reduced (e.g., Harmsen et al. 2020). Given the high priority placed on improving air quality around the world, as embedded in the UN sustainable development goals (SDGs), it is not clear to what extent BC-focused reductions would be implemented without implementation of measues reducing emissions of multiple air pollutant species as well.

There is substantial overlap between the SLCF and climate policies in terms of climate mitigation, which means that care must be taken not to simply add any benefits from a SLCF-focused policy with those from a broader GHG reduction policy. Both the policies examined here were idealized in terms of sectoral and geographical scope, which tends to maximize their impact. While different results might be found in an analysis of less idealized policies, the overall magnitude of climate benefits would also be smaller.

Within the overall conclusions summarized above, the structure and setup of individual models also have an impact on the detailed results. Larger reference case emissions will tend to result in larger estimates of future mitigation potential. The characteristics of the reference scenario has a significant impact on mitigation results. One key differentiation between models in this study is the choice of a current legislation (CLE) or a long-term reference (Ref) scenario setup for air pollutant emission controls. Under a CLE setup, here taken from the GAINS model, only currently in place legislation is considered. Under a long-term reference setup, emission controls continue to strengthen throughout the modeling time horizon, consistent with the recent and historical trends, especially for road transport. Several models in this study use a hybrid approach, following GAINS CLE trajectories in the near term, with additional controls assumed over the longer term. As a result, a pure CLE approach would overestimate future emissions in a region that puts into place additional regulations in the near future and underestimate emissions in a region where current regulations are not effectively implemented. Note that the current level of compliance with existing regulations is often difficult to determine, even in high-income countries with robust scientific and regulatory infrastructures.

The finding that auxiliary forcing reductions of methane can increase over time (Smith et al. 2020) is important since methane is the largest contributor to SLCF climate forcing reductions. This effect follows directly from model structure. Models that allow a methane price to have an economic impact on methane-emitting technologies show significant non-methane emission reductions, largely CO_2, from the increasing methane price in the EMF-30 scenarios. This model structure effect relates directly to how methane reduction policies are implemented. The way models represent a methane-focused policy might not represent how any such policy would be implemented in reality.

All of the model-specific papers in this special issue use the reduced-form TM5-FASST source-receptor model (Van Dingenen et al. 2018) to calculate surface concentrations of particulate matter and ozone as well as respective health and crop loss impacts. This points to the utility of using such models to perform integrated analysis. There is substantial uncertainty in many portions of the chemistry and atmospheric transport calculations that feed into a source-receptor model that are not reflected in these results, although differences between scenarios, particularly for particulate matter concentrations, are likely more robust than absolute values. The limitations inherent in any specific source-receptor model need to be kept in mind when interpreting results.

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Data availability Data are available as described in individual special issue papers.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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