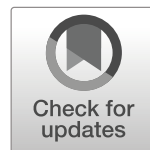# Co-benefits of black carbon mitigation for climate and air quality

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Abstract

Mitigation of black carbon (BC) aerosol emissions can potentially contribute to both reducing air pollution and climate change, although mixed results have been reported regarding the latter. A detailed quantification of the synergy between global air quality and climate policy is still lacking. This study contributes with an integrated assessment model-based scenario analysis of BC-focused mitigation strategies aimed at maximizing air quality and climate benefits. The impacts of these policy strategies have been examined under different socio-economic conditions, climate ambitions, and BC mitigation strategies. The study finds that measures targeting BC emissions (including reduction of co-emitted organic carbon, sulfur dioxide, and nitrogen dioxides) result in significant decline in premature mortality due to ambient air pollution, in the order of 4 to 12 million avoided deaths between 2015 and 2030. Under certain circumstances, BC mitigation can also reduce climate change, i.e., mainly by lowering BC emissions in the residential sector and in high BC emission scenarios. Still, the effect of BC mitigation on global mean temperature is found to be modest at best (with a maximum short-term GMT decrease of 0.02 °C in 2030) and could even lead to warming (with a maximum increase of 0.05 °C in case of a health-focused strategy, where all aerosols are strongly reduced). At the same time, strong climate policy would improve air quality (the opposite relation) through reduced fossil fuel use, leading to an estimated 2 to 5 million avoided deaths in the period up to2030. By combining both air quality and climate goals, net health benefits can be maximized.

Keywords Black carbon · Climate policy · Air quality · Short-lived climate forcers (SLCFs)

1 Introduction

Climate policy is mostly focused on the control of emissions of long-lived greenhouse gases (LLGHGs) like carbon dioxide (CO_2). These gases accumulate in the atmosphere and are the

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primary cause of long-term climate change. However, the emissions of short-lived climate forcers (SLCFs), gases, and aerosols with an atmospheric lifetime of years/decades (methane (CH_4) and hydrofluorocarbons (HFCs)) or days/weeks (tropospheric ozone (O_3) and black carbon (BC)) can significantly influence the near-term global mean temperature (GMT). Therefore, mitigation policy that specifically reduces SLCF emissions can potentially lead to a significant and rapid decrease of GMT change. Moreover, reducing SLCFs also leads to less air pollution and related health impacts (Anenberg et al. 2012; Haines et al. 2017; Shindell et al. 2012). For this reason, there is a need to assess the potential impact of SLCF mitigation policies on both climate- and air pollution–related health addressing costs and benefits across these dimensions, with the goal of maximizing synergies (Rafaj et al. 2018).

Here, we focus specifically on the mitigation of black carbon, an aerosol commonly called soot, which is emitted through the combustion of fossil fuels and (solid) biofuels. Policies targeting BC emissions could be of particular interest. Due to both its solar absorption and cloud forming properties, BC has a potentially large but uncertain effect on the global climate. Earlier studies indicated that BC could possibly be the second largest individual warming agent after carbon dioxide for current forcing (Bond et al. 2013; Bond and Sun 2005; Jacobson 2000; Sato et al. 2003). However, more recent studies indicate that the effect of BC on GMT is very likely lower than originally found (Samset et al. 2014; Samset et al. 2018; Stjern et al. 2017), especially when also accounting for the emissions of co-emitted aerosols (Baker et al. 2015; Rogelj et al. 2014; Smith and Mizrahi 2013; Stohl et al. 2015). Notably sulfur dioxide (SO_2) and organic carbon (OC) cool the atmosphere through the scattering of light and alteration of cloud properties, which can offset the climate benefits of BC mitigation.

As many air pollutants and greenhouse gases originate from similar sources, mitigation policies lead to reduction of multiple species simultaneously. The primary goal of this study is therefore not to assess the effects of BC only but to assess the effects of BC-focused mitigation strategies. Only the latter is interesting from a policy perspective and requires analyzing the effects of both BC and co-mitigated species.

The effects of BC mitigation on air quality are more certain than the climate effects. BC, OC, SO_2, and nitrogen dioxides (NO_x), are major components or precursors of fine particulate matter ($PM_{2.5}$). $PM_{2.5}$ causes an estimated yearly 2.9 million premature deaths due to ambient air pollution and another yearly 2.9 million deaths due to household or indoor air pollution from solid fuel use (worldwide in 2013) (Forouzanfar et al. 2015; WHO 2016). While ambient air pollution impacts both low- and high-income regions (with two thirds of premature deaths in Asia), the majority of indoor air pollution occurs in developing countries, where access to modern fuels for cooking and heating is limited.

Several recent studies investigated these linkages between climate, air quality, and health (see supplement S7 for a more complete overview). Some of these emphasized the short-term climate benefit of measures that aim to reduce BC emissions (CACC 2016; Shindell et al. 2012; UNEP/WMO 2011). Other studies focused on the opposite relation: the large co-benefits of climate policy on reducing air pollutants, including BC. Climate policy aimed at reducing LLGHGs (notably CO_2) reinforces air pollution control, mainly through reduced fossil fuel use, makes air quality targets easier to reach (Braspenning Radu et al. 2016; Rao et al. 2016; Reis et al. 2018; Smith et al. 2016) and reduces air quality policy costs (McCollum et al. 2013; Rafaj et al. 2018). The indirect monetized air quality benefits of stringent climate policy (aimed at 1.5 °C or 2 °C targets) are found to largely (Kitous et al. 2017) or fully (Markandya et al. 2018) outweigh climate policy costs, via avoided deaths and diseases, and agricultural productivity improvement.

To date, an exhaustive assessment of the costs and impacts of BC mitigation under various potential future conditions is lacking in the current literature (see supplement S7). Earlier assessments have either covered the full suite of SLCFs or pollutants (making it difficult to understand the effect of BC-focused mitigation), focused on specific aspects of BC mitigation (only climate or only health impacts), excluded air pollution mitigation costs, or looked at only one potential future reference scenario.

This study presents a first comprehensive cost-based analysis of BC mitigation policy. It aims to answer: "What are the global consequences of BC-focused mitigation policies for climate change and air pollution, under different potential future conditions in the short-term (up to 2030) and in the long-term (up to 2100)"? In addition to the environmental policy impacts (GMT change and air pollution–related deaths), we also consider the economic costs of climate and air pollution policy. In a separate analysis, air quality health benefits are also expressed in a monetized benefit using value of statistical life (VSL). The scenario analysis covers different potential socio-economic developments (representing different air pollution control reference cases), climate policy ambitions, and BC mitigation strategies.

2 Methods

2.1 Scenarios

The scenarios have been developed using the IMAGE 3.0 integrated assessment modeling framework, which simulates global and regional environmental consequences of changes in human activities (Stehfest et al. 2014) (see supplement S1 for more information).[1] The model has high coverage of low carbon energy technologies, endogenous land-use dynamics, and includes all major greenhouse gases (GHGs) and pollutants relevant to climate, health, and agricultural production. Climate policy costs, calculated by the model, are first order investment costs and do not include secondary effects on the economy. Optimization of climate policy occurs in a dynamic recursive process that selects the least (integrated discounted) costs scenario, when assuming a 5% social discount rate.

The scenarios are based on the shared socio-economic pathways (SSPs). The SSPs consist of different narratives that describe the drivers of how the future might unfold in terms of population growth, governance efficiency, inequality across and within countries, institutional factors, technology change, and environmental conditions (Riahi et al. 2017). As such, this scenario framework facilitates addressing key questions related to climate policy research and helps identifying the effectiveness, trade-offs, and synergies of mitigation strategies.

In this study, we applied the socio-economic assumptions of SSP2 and SSP3 as developed with the IMAGE model and described by Van Vuuren et al. (2017). SSP2 is a middle of the road scenario with moderate assumptions for all socio-economic dimensions. In contrast, in SSP3, the challenge for mitigation and adaption is high due to moderate economic growth, rapid population expansion, slow technological change, high inequality, and a highly regionalized world. SSP3 was used here to

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[1] This research is part of 30th energy modeling forum EMF (2019) Energy Modeling Forum (EMF)-30 Study on Short-Lived Climate Forcers (SLCF) and Air Quality., a multi-model comparison to assess strategies for SLCF mitigation. This single model study, performed with IMAGE, provides a more in-depth analysis of BC mitigation.

Table 1 Scenario setup

	SSP2		SSP3	
	No-climate policy	2.6 W/m^2	No-climate policy	3.4 W/m^2
Current air pollution policy *	SSP2	SSP2_26	SSP3	SSP3_34
Maximized health	SSP2_Health	SSP2_26_Health	SSP3_Health	SSP3_34_Health
Maximized climate	SSP2_Climate	SSP2_26_Climate	SSP3_Climate	SSP3_34_Climate

*The assumptions in the SSPs for pollution emission factors of BC, OC, CO, NOx, SO$_2$, and VOC are as follows. In 2030, SSP2, GAINS current legislation (CLE); SSP3, CLE*1.1. In 2100, SSP2, GAINS stringent legislation (SLE) as in Western Europe; SSP3, SLE (note that MFR BC mitigation policy goes beyond SLE)

Left column indicates the type of BC mitigation policy. The second and third row show the underlying SSP scenarios with climate mitigation targets

examine the possibly higher potential for ambitious BC mitigation measures in a world where emissions are generally higher due to the larger mitigation challenges.

The SSPs offer a wide range of possible future climate scenarios, by combining the different socio-economic assumptions with a range of climate targets. Here, we compare the no-climate policy baselines (SSP2 and SSP3) and the most stringent, achievable mitigation cases (in 2100, 2.6 W/m^2 in SSP2 and 3.4 W/m^2 in SSP3), see Table 1. Note that GHG mitigation differs across mitigation scenarios to compensate for differences in pollutant emissions (BC and others) in order to precisely reach the climate targets.

A set of 12 scenarios has been developed by combining the SSP references cases with three levels of BC mitigation:

- *Current air pollution policy.* In these scenarios, future emission factors for air pollutants have been set in accordance with the SSP storylines (Rao et al. 2017) making use of the emission factor database and air quality policy assumptions in the GAINS model (Amann et al. 2011; Klimont et al. 2017) (see footnote Table 1 for a more detailed description).
- *Maximized health benefits.* These scenarios include maximum feasible reduction (MFR)[2] of BC and co-emitted species (OC, SO$_2$, and NOx)[3] in all major emitting sectors (residential and commercial, transport, industry, and power generation). Note that this scenario goes beyond BC measures only, particularly in the power sector, where BC and OC emissions are low (1–2% of total BC and OC emissions), but SO$_2$ and NOx emissions are high. Scenarios are denoted by "health."
- *Maximized BC climate benefits.* These scenarios assume MFR of BC and co-emitted species (OC, SO$_2$, and NOx), exclusively in the residential/commercial and transport sectors, as BC mitigation in these sectors is found to have a net cooling effect (Bond et al. 2013; Stohl et al. 2015), due to a beneficial ratio of BC and climate cooling agents (OC, SO$_2$). In all other sectors, default air pollution policy as in respective SSPs is assumed. This is the same setup as in the EMF30 multi-model exercise. Scenarios are denoted by "climate."

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[2] MFR values are derived from the GAINS model (Amann et al. 2011) and are defined as the lowest technically feasible emission levels achievable without regarding policy cost limitations.
[3] No MFR measures have been assumed for volatile organic carbon (VOC) emissions. However, VOC emission factors in IMAGE are in accordance with the SSP storylines (Rao et al. 2017), and VOC emissions are reduced under climate policy.

Land-use mitigation measures (reduced forest and savannah burning) are assumed to be driven by CO_2 mitigation (and biodiversity protection), rather than by BC-focused policy. Therefore, they have only been included in the SSP2_26-based scenarios, following the land-use assumptions as described by Van Vuuren et al. (2017) (land-use mitigation is not assumed in SSP3_34; therefore, the land-use emissions in SSP3_34 are largely the same as in SSP3; only small differences occur indirectly due to mitigation activities in SSP3_34). Also, due to a high OC/BC ratio in emissions from this sector, the land-use mitigation measures have a net warming effect (Myhre et al. 2013) and are therefore beneficial for public health reasons only.

2.2 BC mitigation measures

(See supplement S1 for a more extensive description of this section)

The potential for further application of the air pollution control technologies in the scenarios has been based on emission factor data from the GAINS model (Amann et al. 2011). GAINS has been a widely used source for such projections (Braspenning Radu et al. 2016; Rao et al. 2016, 2017; Shindell et al. 2012; Stohl et al. 2015). Pollution control measures are expressed as region-/sector-/technology-/fuel-specific emission factors and include several hundreds of measures. These represent the reduction of BC emissions and co-emitted pollutants (included here are OC, SO_2, and NOx, as these are most relevant in terms of climate and health impact).

The main sectoral mitigation measures included in the health and climate scenarios are based on the ECLIPSE project database (V5a) (Klimont et al. 2017; Stohl et al. 2015). In GAINS, emissions of all air pollutants were computed for 174 regions/countries, based on international energy and industrial statistics, emission inventories, and national emission reporting. For this study, these have been aggregated to the 26 world regions in IMAGE.

The main sectoral mitigation measures (MFR) include:

> *Residential and commercial*. (1) A phase-out of the end-use of coal and biomass consumption for cooking and heating by 2030 (note that this is the only measure not realized via emission factors, in accordance with the EMF30 scenario setup) and (2) replacement of kerosene wick lamps with LED lamps.
> *Transport*. (1) Eliminating high-emitting vehicles and (2) widespread Euro VI equivalent emission standards (incl. particle filters on diesel engines).
> *Transformation*. (1) Modernized (mechanized) coke ovens.
> *Industry*. (1) Replacement of artisanal brick kilns with more efficient and cleaner kilns (e.g., zigzag, vertical shaft kiln, Marquez kiln).
> *Power sector*. 1) Coal plants with high-efficiency particle filters, desulfurization, and deNOx technology. Note that the power sector is a relatively small BC and OC source (1–2% of total emissions) but a large SO_2 (± 50%) and NOx source (± 25%). These measures are mainly impactful from a health point of view.

Air pollution policy costs, calculated in GAINS, represent the total annualized costs of mitigation measures and thus include the mitigation of all included pollutants: BC, OC, SO_2, and NOx. Costs in all scenarios are scaled with sectoral total final energy activities in IMAGE compared with GAINS.

2.3 Climate impacts

Climate impacts have been calculated using the simple climate model MAGICC 6.3 (Meinshausen et al. 2011), which is soft-linked to the IMAGE framework (providing climate projections based on the emission pathways generated by IMAGE). This model emulates the relations found by complex climate models, to simulate the effect of changing emissions on atmospheric composition, radiative forcing (RF), and GMT.

To better understand differences in scenarios, we have analyzed the climate impact of BC mitigation by sector (based on a global average, regional differences have not been included). For this, the RF difference between BC mitigation in the health scenarios and the baselines (SSP2, SSP3) in 2030 (when the RF change is projected to be the largest) was allocated to the sectors. Global emissions by sector were multiplied with the species-attributable RF efficiency (i.e., RF normalized per emission unit) by taking into account all relevant RF effects per species (e.g., in the case of BC: direct forcing, indirect cloud forcing and altered albedo forcing of BC on snow). The GMT impact of BC measures (in the Climate and Health cases) was assessed by comparing these to their respective default scenario without additional BC mitigation.

2.4 Health impacts

In order to assess the impact of pollutant emissions (from IMAGE) via atmospheric concentrations of $PM_{2.5}$ (particulate matter smaller than 2.5 μm) and tropospheric ozone (O_3) to human health impacts, we applied the TM5-FASST model (TM5-FAst Scenario Screening Tool, from here referred to as FASST) (Van Dingenen et al. 2018). It is a global reduced form air quality source–receptor model that has been designed to compute ambient (outside) air pollutant concentrations as well as a wide range of pollutant-related impacts. The model emulates linearized emission-concentration sensitivities derived with the full global atmospheric transport and chemistry model TM5 (Huijnen et al. 2010) and is found to represent these well (Van Dingenen et al. 2018).

Health impacts from ambient $PM_{2.5}$ and O_3 are calculated as the number of annual premature mortalities from five causes of death, following the global burden of disease (GBD) methodology (Lim et al. 2012): ischemic heart disease, chronic obstructive pulmonary disease, stroke, lung cancer, and acute lower respiratory airway infections. Based on this approach, FASST uses grid maps of pollutant exposure metrics. These are weighted by population, in our assessment by using the population grid maps from the IMAGE scenarios.

2.5 Combined results and monetized impacts of health benefits

The combined climate and air quality policy costs (i.e., direct economic costs of (1) GHG mitigation measures and (2) air pollutant controls) and benefits (reduced GMT change and avoided air pollution mortality) are presented in a single overview to identify synergies and trade-offs between the policy goals and costs (see Fig. 6). Results are shown for the 2015–2030 and 2015–2100 periods. All policy costs are provided in billion $(2015)/year to allow for comparison with costs between policy goals, using a 5% (common social) discount rate (see Table S5.1 in the supplement).

In a separate analysis, the health impacts have been compared with the total policy costs in monetized terms (this analysis is shown in supplement S2). Note that this additional analysis

should be seen as indicative as well as conservative, as it excludes the benefits from reduced indoor air pollution and reduced climate change impacts. To estimate the health benefits, the avoided deaths (compared with the baseline cases SSP2 and SSP3) have been expressed in a monetized benefit, using the value of statistic life (VSL) as an indication, based on the method by Markandya et al. (2018). The VSL is defined as the monetized value of (or society's willingness to pay for) a relative change in air pollution–related mortality risk reduction. Note that the VSL benefits cannot directly be equated to economic benefits, so they can only serve as an indicative comparison with economic costs. The method by Markandya et al. takes the widely accepted VSL of the OECD in 2005 in as a reference and derives the VSL in a given region and year by its difference in GDP/capita compared with the OECD in 2005 (in our case, with data from the IMAGE scenarios). As in Markandaya et al., we applied the OECD guideline and assumed morbidity costs to be 10% of the mortality costs. Morbidity costs represent costs that result from negative health effects other than premature death. These include losses arising from disability and loss of earnings, as well as direct market costs". See supplement S2 for the derived VSL data.

3 Results

3.1 Emissions

Figure 1 shows the projected BC emissions for the SSP2, SSP3, SSP2_26, and SSP3_34 scenarios (without additional BC mitigation). The base year (2015) BC emissions in IMAGE can be considered relatively high compared with the EMF30 model average (8 Mt), since it is calibrated with CEDS (Hoesly et al. 2018) and (van Marle et al. 2017), which includes the most recent updates in emission factors and estimates that are comparable with, but generally slightly higher than existing global inventories (see supplement S3 for a literature comparison). Differences in global inventories also indicate a relatively high uncertainty sectoral BC emissions.

BC emissions are projected to decline toward the end of the century under current air quality legislation in the SSP2 and, to a lesser extent, SSP3 scenario. In addition, climate policy has the co-benefit of reducing air pollutants (notably SO_2 and NOx, see supplement S4) in most sectors (e.g., transportation, industry, transformation), due to the replacement of fossil fuels by low emission renewable energy, also referred to as "CO_2-SLFC linkages" (Rogelj et al. 2014). For BC, this is illustrated by the lower total emissions in SSP2_26, compared with SSP2.

BC emissions in the residential sector are an exception. These are projected to increase in the mitigation cases (both in SSP2 and SSP3), as a result of increased traditional biomass use (a consequence of the phase-out of coal use for cooking and heating in developing countries). For this reason, by 2100, a total global BC emissions are even larger in SSP3_34 (4.7 Mt) than in SSP3 (4.4 Mt), thus presenting a trade-off between climate and air quality benefits.

Land-use emissions are projected to decline by the end of the century in all scenarios after an early century peak. Reduced deforestation (from land-use CO_2 mitigation) in SSP2_26 leads to an early century decline in forest burning emissions (around 1 Mt in 2030). In contrast, in SSP3_34, reduced deforestation is not included, and thus, the increased bioenergy production leads to slightly higher emissions than in SSP3 around 2040–2045. In all scenarios, land-use expansion for food production is decreasing. As a result, forest burning emissions are
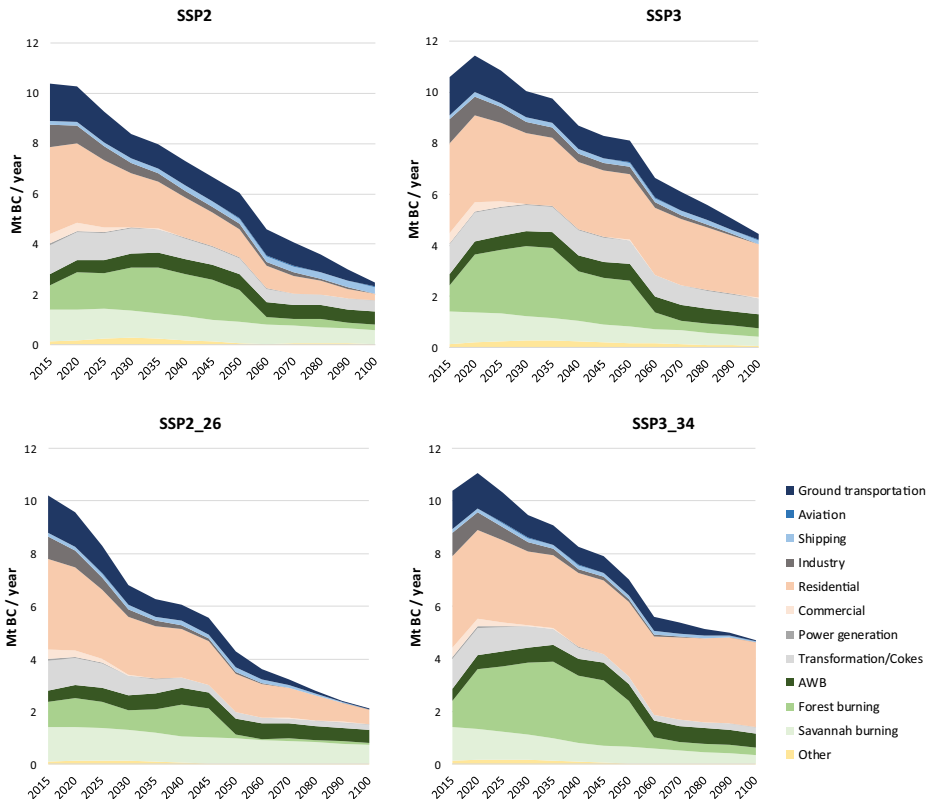
Fig. 1 Global sectoral BC emissions in the four SSP reference scenarios (excluding additional ambitious BC mitigation, i.e., SSP2, SSP3, SSP2_26, SSP3_34). See supplement S4 for emissions of OC, SO₂, and NOx. Scenario data is available as an additional supplementary document

projected to be strongly reduced in the last four decades. Also, savannah burning is projected to slowly decline over the whole century. Agricultural waste burning (AWB) is projected to remain relatively stable (around 0.5–0.7 Mt/year) across all scenarios.

Figure 2 shows the emissions and avoided emissions in 2030 and 2100. For each scenario, both the sectoral emissions and the avoided sectoral emissions compared with the respective baseline scenario (SSP2, SSP3) are shown (the latter as negative values).

In 2030, emissions in the SSP2 scenarios are lower than in the SSP3 scenarios, as are therefore the absolute emission reductions from BC mitigation (with up to 2.7 Mt or 32% reduction in SSP2_Health, compared with 3.3 Mt or 32% in SSP3_Health). In the mitigation cases, emission reductions are largest (almost halved) in SSP2_26, as forest burning and associated BC emissions are reduced (with up to 4.1 Mt or 49% reduction in SSP2_26_Health and 3.7 Mt or 36% in SSP3_34_Health).

Residential emission reductions are dominant in all BC mitigation scenarios. This means that the differences between the climate and health cases are modest (6 to 9 percentage points of the relative reductions). These differences result from the stronger mitigation assumptions in the industry and transformation (coke ovens and brick kilns) sectors in the health scenarios.

In 2100, the low emissions in SSP2 obviously imply there are little remaining emissions to mitigate (up to 1.2 Mt or 46% in SSP2_26_Health). In a SSP3 world, BC mitigation in the
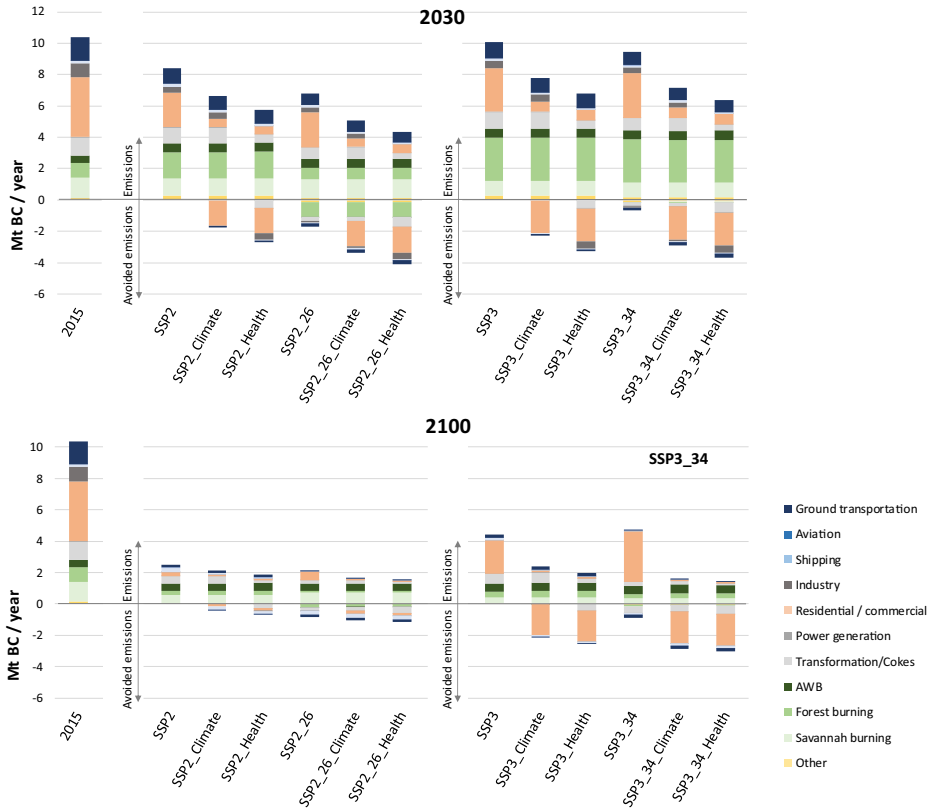
Fig. 2 Global sectoral BC emissions and avoided emissions in 2030 (upper panels) and 2100 (lower panels). 2015 emissions are shown as a reference (left). SSP2-based (center panels) and SSP3-based (right panels) scenario emissions as shown as positive values. Avoided emissions are the differences with the baseline scenarios (SSP2, SSP3) and are presented as negative values. See supplement S4 for emissions of OC, SO₂ and NOx. Scenario data is available as an additional supplementary document

long term can be much more significant, due to a very high reduction potential in the residential sector, in both the baseline (with a reduction of 2.5 Mt or 56% in SSP3_Health) and mitigation case (with 3.0 Mt or 68% in SSP3_34_Health).

The mitigation of OC in the different scenarios generally follows a similar pattern of that of BC (see supplement S4) but with a different distribution across sectors (e.g., very low in transportation, much higher in open burning categories). Note that the emissions of SO₂ and NOx are much more dependent on the climate policy stringency (and resulting reduction of fossil fuels in the transportation and power sector), rather than the on the ambition level of BC mitigation.

3.2 Climate impacts

Figure 3 shows the impact of BC mitigation measures by sector in 2030 on emissions (on the x-axis) and climate (indicated by RF changes, on the y-axis). Changes here refer to the difference between the SSP2/3 and SSP2/3_Health cases, except for the land-use sources, where the difference between SSP2/3 and the mitigation cases are shown. When including all relevant RF effects of all (co-)mitigated pollutants, we find that only measures in the residential

and commercial sector significantly contribute to reducing RF. Reductions in transportation could potentially lead to a RF reduction (as is the case in SSP3), but are too small to have a major effect, as pollutant control measures are already relatively stringent in the baselines. In all other sectors, the co-mitigation of climate cooling agents leads to a net sectoral contribution to global warming.

The net effect of BC and broader air quality measures on GMT for each scenario is shown in Fig. 4. The upper graph illustrates the general GMT paths and how the differences between the climate, health, and respective default scenarios are relatively small compared with the GMT change over the century. In the lower panels, these differences are shown in more detail. Both the climate- and health-focused emissions reductions have the largest GMT impact in the scenarios without climate policy (SSP2, SSP3), where pollutant emissions are generally higher than in the mitigation cases (SSP2_26, SSP3_34). However, the difference in the mitigation scenarios is also partly smaller by design, as all mitigation scenarios are forced to reach the same RF target in 2100. This mainly plays a role in SSP3_34_Climate where BC mitigation leads to additional cooling compared with SSP3_34 in 2100 (± 0.1 W/m^2), which allows for less stringent GHG climate policy (to a lesser extent, this is also the case for SSP3_34_Health and SSP2_26_Climate). Note that this also leads to lower climate policy costs (see Section 3.4).

The GMT reducing effect in the climate scenarios is limited (up to 0.03 °C in SSP3, and in the order of 0.01 °C in the other scenarios). Despite this low value and the large uncertainties in aerosol radiative forcing, it is likely that some cooling effect could result from climate-focused BC mitigation, based on an uncertainty analysis with MAGICC6 (see Discussion and Supplement S6).

The projected GMT reducing effects are also largely temporary; up to 2040/2050 in most cases, except in SSP3. The reason for this temporary effect is that the relative share of BC reduction in total aerosol reduction becomes smaller toward the end of the century, due to lower residential BC emissions in the reference case (SSP2). In SSP2_Climate, NOx reduction (mainly in transport) and the resulting reduction in nitrate aerosols therefore constitute a larger
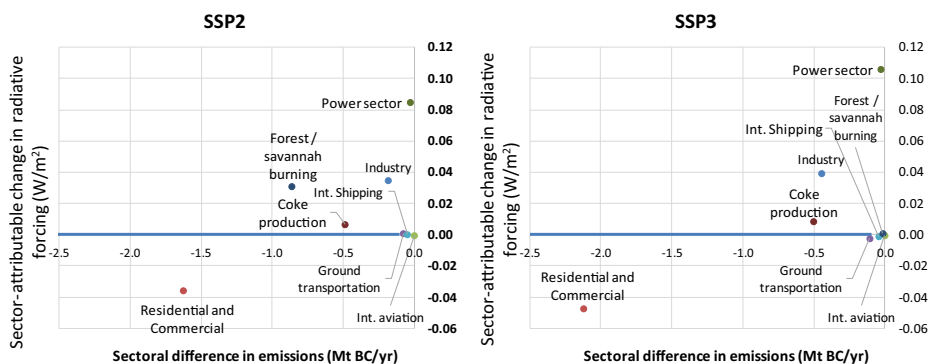

Fig. 3 Radiative forcing change attributable to sector-specific BC measures vs. sectoral BC emission reductions in 2030. Shown for SSP2 and SSP3 taking into account maximum feasible reduction of BC, OC, SO$_2$, and NOx. Values represent difference between the SSP2/3 and SSP2/3_Health cases, except for the land-use sources, where the difference between SSP2/3 and the mitigation cases (SSP2_26 and SSP3_34) are shown. All measures are end-of-pipe, except forest/savannah burning, which is realized by natural land preservation. From a climate policy standpoint, only sectors below the blue line are attractive, since this could lead to a reduction in GMT (clearly the case in the residential and commercial sector, in SSP3 also for transportation). Colors used to distinguish between sectors
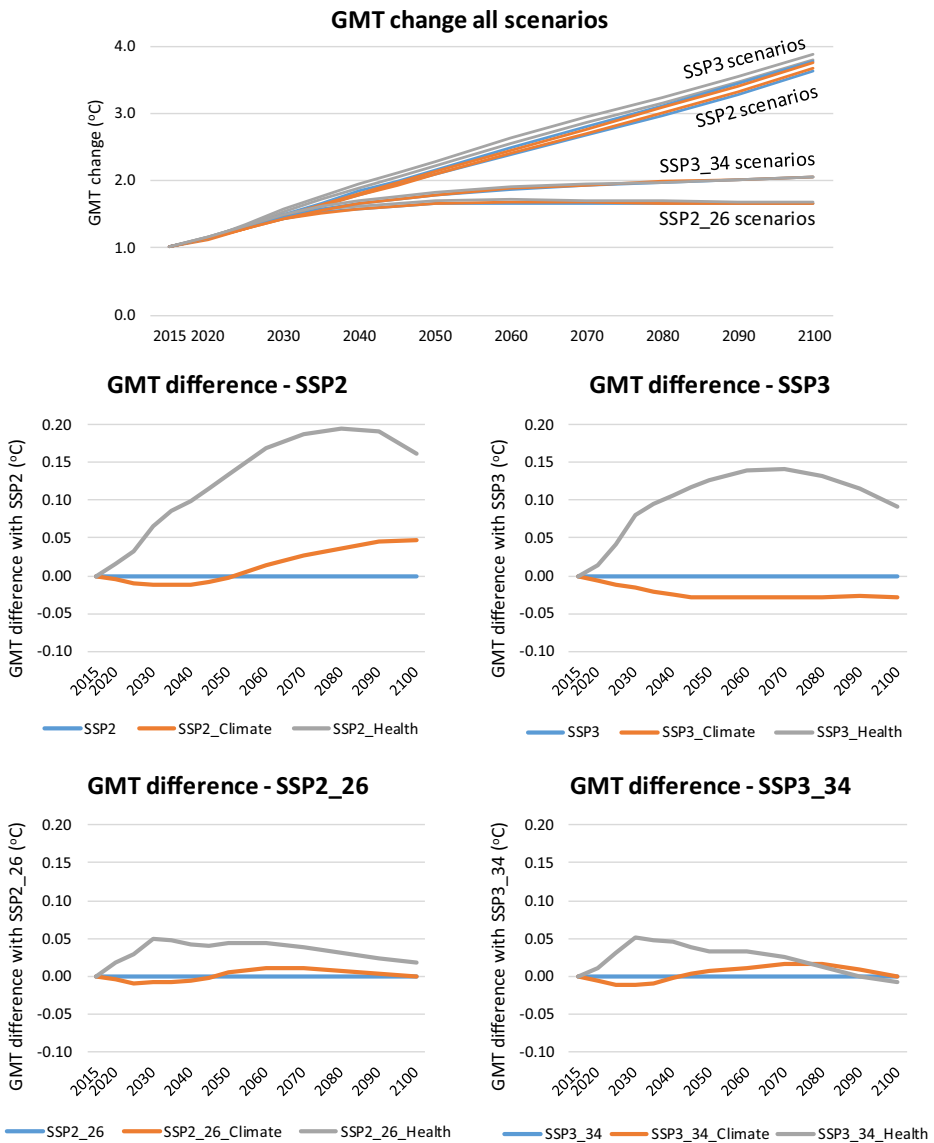
Fig. 4 GMT change. Upper panel: General overview of GMT change compared to pre-industrial values in all scenarios. Lower four panels: GMT difference between scenarios with default BC mitigation (SSP2, SSP3 (center panels), SSP2_26, SSP3_34 (lower panels), and their "health" and "climate" counterparts (value = GMT in scenario – GMT in reference)

share in total aerosol reduction, leading to a projected net warming effect from BC measures. In SSP3, this plays a smaller role, as residential emissions (and thus the BC mitigation potential in SSP3_Climate) remain high. Mitigation measures in the health scenarios lead to an increase in GMT (up to 0.05 °C in the mitigation cases, largely resulting from SO_2 mitigation); although in the mitigation scenarios, this effect can also be considered temporary (SSP3_34) or modest (SSP2_26) in the long term.

Note that the GMT reducing potential found here is much lower than the earlier estimate by Shindell et al. (2012) and UNEP/WMO (2011). The reason is that, in these studies, (1) BC emissions in the reference cases were assumed to be higher (both with and without climate policy, as the status of legislation was very different about a decade ago and so large part of the BC mitigation potential is now in the baseline) and that (2) the climate model used (GISS-PUCCINI) attributed high RF to BC indirect cloud forming and BC on snow (Harmsen et al. 2015), in line with the studies' GMT projections. In recent studies, as in this one, the effect of BC mitigation is found to be much lower for similar reasons (Rogelj et al. 2014; Smith and Mizrahi 2013; Stohl et al. 2015).

3.3 Health impacts

Figure 5 shows the mortality and avoided mortality per pollutant ($PM_{2.5}$ or tropospheric O_3, upper panels) and region (lower panels, only avoided mortality) in the scenarios for the periods 2015–2030 and 2015–2100. In order to assess the effect of BC/pollutant control, in both a no-climate policy and mitigation case, all policy scenarios are compared with baseline scenarios without climate policy and additional air quality policy: SSP2 or SSP3. Although O_3-related mortality is not the focus of this study (since BC is not a O_3 precursor), it is included in the overview to have a more complete estimate of all air pollutant–related mortality. The estimated cumulative number of premature deaths without policy (climate and air quality) in the period up to 2030 is 67 million in SSP2 and 72 million in SSP3 (i.e., 4.5 to 5 million per year) but with large uncertainties (range: 29 to 102 million in both SSP cases combined). These large projected ranges mainly arise from uncertainties in cause-effect relations (Van Dingenen et al. 2018). Another source of uncertainty in FASST is regional population growth, but that is partly captured here by different SSP assumptions. The highest health benefits can be realized by combining climate and air quality policy, an estimated 17% or approximately 11 million in both SSP cases. Up to 2100, the health benefit can be much higher: 34% (or 140 of 267 million) in SSP2 and 46% (or 187 of 347 million) in SSP3.

The short-term impact of BC measures only is roughly in line with Anenberg et al. (2011), with 1.0 million avoided deaths per year in SSP2_Health for all $PM_{2.5}$. O_3-related mortality in the scenarios constitutes between 10 and 15% of total mortality, consistent with Silva et al. (2016). O_3 levels are strongly dependent on the concentration of the precursor CH_4 and are therefore mainly lower in the mitigation cases.

Avoided mortality is predominantly realized in Asia (70 to 89% of total), where about two-thirds of ambient air pollution currently occurs (Forouzanfar et al. 2015; WHO 2016) and improvements are relatively easy to realize. Reduced mortality is mainly projected to occur in China and India (the latter more in longer term, as China is expected to improve pollutant control more in the default air pollution case).

The results presented here are likely an underestimation of total health benefits resulting from BC mitigation measures, as the impact of reduced indoor air pollution is not included. Especially in the health scenarios, the total avoided mortality could be more than 50% higher (notably realized in developing regions in Africa and Asia), following the estimate of Rafaj et al. (2018), 1.5 million yearly potentially avoided deaths from indoor air pollution in 2040. Note that the presented health benefit of climate policy alone (i.e., without additional air quality policy) might be an overestimation, since this is projected to lead to increased pollutant emissions in the residential sector, especially in SSP3_34.
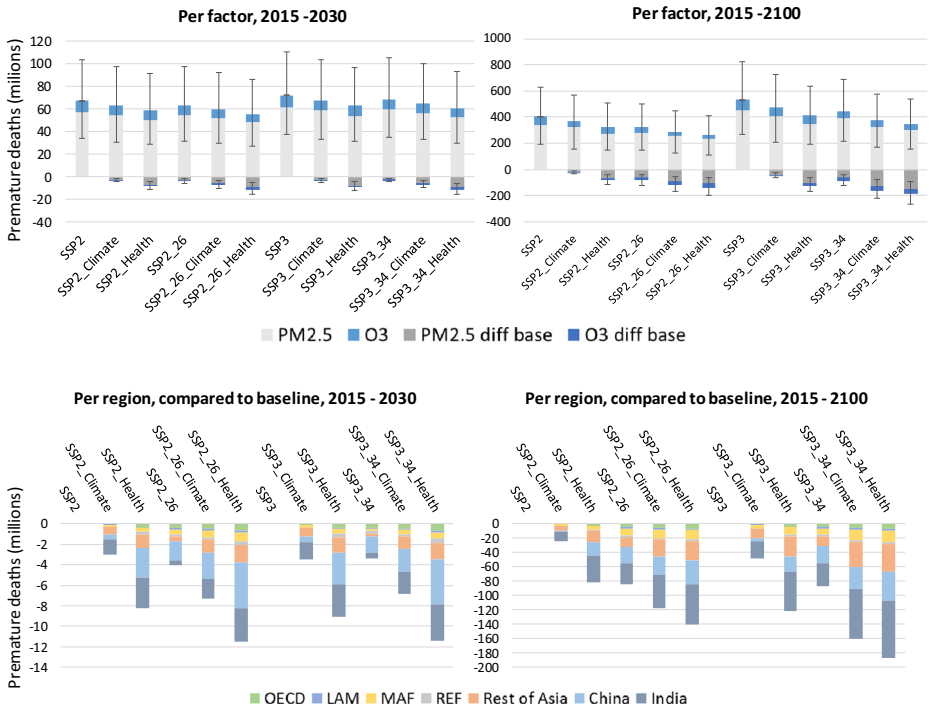
Fig. 5 Cumulative premature mortality in the 2015–2030 period (left) and 2015–2100 period (right). Upper panels: Premature deaths per pollutant (PM$_{2.5}$ or tropospheric O$_3$), shown by the column section above the zero line. Column section below zero represents difference with baseline (SSP2, SSP3). Whiskers indicate uncertainty in projected mortality: max/min total deaths (top side) and max/min difference with baseline ("diff base," bottom side). Lower panels: Avoided premature deaths per region compared with the baseline (this corresponds with the below zero part of the columns in the upper panels). LAM, Latin America; MAF, Middle-East and Africa; REF, Former Soviet Union and reforming economies of Eastern Europe. Note: different scales on the y-axes

3.4 Policy costs

Table S5.1 in the supplement gives an overview of the global sectoral air quality policy costs and climate policy costs. These represent cumulative discounted totals in the 2015–2030 and 2015–2100 periods with a 5% discount factor (see Table S5.2 for the yearly cost estimates in 2030 and 2100). In all scenarios, pollutant control measures are by far the most costly in transportation (65 to 95% of total air quality costs, mainly in road transport). Note that this is already largely the case in scenarios without additional BC mitigation. In the other sectors, there is a larger potential for improvement, indicated by the higher difference in costs between the cases with and without BC mitigation. In the climate policy cases (2.6 and 3.4 W/m^2 scenarios), air quality policy costs are reduced in all sectors, as fossil fuel–based activities are reduced, particularly in 2100.

Climate policy costs constitute the largest share of total policy, particularly as policy becomes more stringent toward the end of the century (with costs an order of magnitude larger than those of air quality policy). In several cases, climate policy stringency and thus costs are lowered by BC mitigation. In SSP3_34_Climate, with a high BC reduction potential in the residential sector, climate policy costs are considerably lower than in the absence of additional BC mitigation (in SSP3_34), both in 2030 and 2100. In SSP2_26_Climate, this is

also the case but with a smaller difference in cost, particularly in the long term. In SSP2_26_Health, climate impacts are similar as in SSP2_26.

The total discounted policy costs (i.e., from both climate and air quality policy) in the mitigation scenarios range from 0.7 to 1% of total global gross domestic product[4] (note that although the climate target in SSP2_26 is more stringent than in SSP3_34, the policy costs are only about 50% higher).

Regionally, projected policy costs can differ considerably (see also supplement S2). These are the high test in the OECD and in China. Depending on the scenario, these two world regions together account for between 56 and 93% of all projected policy costs. These regions also have the highest costs on a per-capita basis, together with the REF region (Former Soviet Union and reforming economies of Eastern Europe) (not shown). In all regions, climate policy costs are higher than air quality policy costs (on average 5 times as high over the 2015–2100 period), when considering scenarios that include both climate and air quality policy. Air quality policy costs in the OECD are projected to be particularly high (up to only slightly below climate policy costs in the SSP3_34_Health case), because of a relatively high share of high-cost measures.

3.5 Trade-offs and synergies

Figure 6 combines the previous sections' results regarding climate effects (temperature change on the y-axis), health effects (avoided premature deaths on the x-axis) and the cumulative discounted costs (indicated by a label, in trillion $(2015), and proportional to the size of the marker), for each SSP2- and SSP3-based scenario in the periods 2015–2030 and 2015–2100.

In the short term (long-term health impacts 2030), mitigation measures aimed at reducing pollutants in all sectors (i.e., health scenarios) slightly increase GMT, by up to 0.07 °C in the baseline cases. BC measures in the residential and transportation sectors only (i.e., climate scenarios) reduces GMT by up to 0.02 °C, which is mainly translated into lower short-term climate policy costs (e.g., with 2% and 6% lower costs in SSP2_26_Climate and SSP3_34_Climate, respectively, compared with SSP2_26 and SSP3_34).

Climate policy alone already has substantial short-term health co-benefits (with in SSP2_26 in the 2015–2030 period: 4 million avoided deaths compared with SSP2 or about a third of what is maximally realized in SSP_26_Health. In SSP3_34, this is similar). Air pollution mitigation further reduces mortality, roughly by 4 million more in the health scenarios than in the climate scenarios, in the 2015–2030 period. There is a clear trade-off between the two different air pollution mitigation strategies (e.g., between SSP2_26_Climate and SSP2_26_Health, indicated by the relative diagonal positions and different bubble sizes). The health scenario has higher policy costs (overall costs are 17% higher in SSP2_26_Health in 2030) and a lower short-term climate benefit (0.06 °C higher in 2030) but leads to a higher number of air pollution–related avoided deaths (11.5 million in the period up to 2030, i.e., 4.1 million more than in SSP2_26_Climate).

In the long term (up to 2100), CO_2 and other GHG mitigation are the dominant factor that determines GMT change. However, BC mitigation can still lead to a small GMT reducing effect, leading to lower climate policy costs. This mainly plays a role in SSP3_34_Climate where BC mitigation leads to strong BC reductions in the residential sector and therefore

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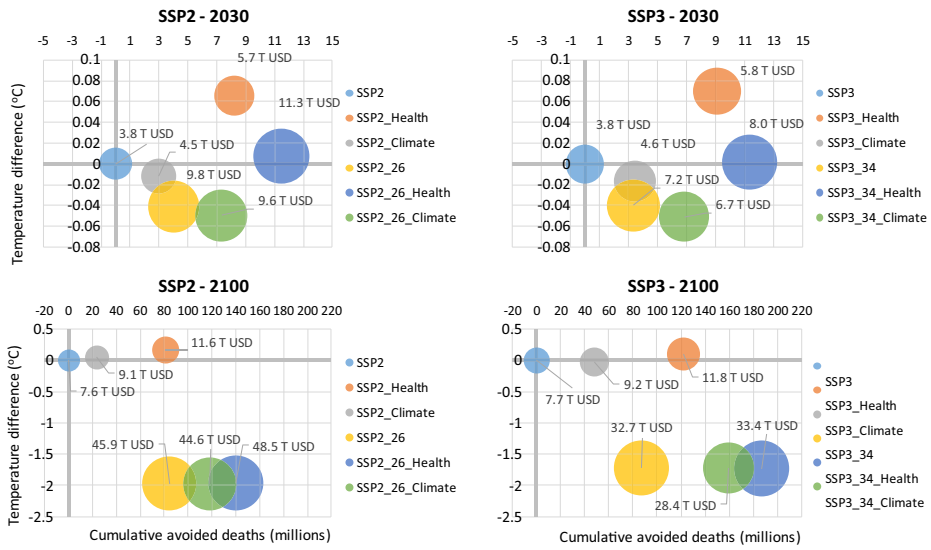[4] This value is higher when considering individual years (up to 2.8% in 2100, supplement S5)

Fig. 6 Combined global results. Upper panels: 2030 results for SSP2 and SSP3. Lower panels: 2100 results for SSP2 and SSP3. *X*-axes represent cumulative avoided premature deaths between 2015 and the target year (2030 or 2100) compared with the no-climate policy baselines (SSP2 or SSP3). *Y*-axes represent temperature difference compared to the no-climate policy baselines (SSP2 or SSP3) (notice different scales in upper and lower panels). Area of the bubbles and labels represent the cumulative integrated policy costs (air quality + climate, from Table S5.1) between 2015 and the target year (2030 or 2100) in trillion $(2015) (bubble sized between panels cannot be compared)

allows for less stringent climate policy than in SSP3_34 (indicated by a smaller bubble for SSP3_34_Climate).

Long-term health impacts resulting from increased tropospheric O_3 abundance are larger than in the short term, since $PM_{2.5}$-related pollutants are expected to be reduced considerably in the baselines (especially in SSP2), whereas the emissions of CH_4, an important O_3 precursor, are expected to increase. This explains the relatively larger long-term health benefits in all mitigation scenarios, with higher benefits in the SSP3 cases, where CH_4 reductions are larger. In the SSP2_26 scenarios, due to highly reduced pollutant emissions, additional air quality measures lead to a smaller increase of avoided deaths, compared with in SSP3_34. The long-term overview clearly shows that the combination of climate and air quality leads to attractive outcomes, with more avoided deaths and equal GMT change at similar or lower costs than climate policy alone.

In supplement S2, the monetized health benefits using VSL are compared with the policy costs, by world region. With a medium VSL, the health benefits from ambitious BC measures are found to outweigh all global policy costs (climate and air quality), especially for all health scenarios but also in the climate scenarios. This is similar for the short and long term. The net global benefits are mostly realized in China and India. In scenarios that reach a higher GMT than the reference cases (notably SSP2_Health and SSP3_Health), this result does not necessarily mean that all benefits exceed policy costs from a global standpoint, since the climate impacts are not monetized in this study.

The monetized air quality health benefits in SSP2_26 and SSP3_34 (excluding additional air quality policy) are found to be (25–27%) lower than the total policy cost. When applying the lower, conservative value of the VSL, health benefits from ambitious BC measures in the

baseline cases (SSP2_Health, SSP3_Health, SSP2_Climate, SSP3_Climate) are still larger than the policy costs (i.e., health benefits outweigh air quality costs), with the net benefits almost exclusively realized in China, India, and the rest of Asia. In a sensitivity analysis of the discount rate, a lower value of 2% (roughly similar to global economic growth) is shown to not affect this general image.

4 Discussion

The air pollutant mitigation measures considered are stringent. The alternative air quality strategies in this study assume a complete implementation of the MFR technology worldwide in 2030. This can be considered very ambitious, and the results should therefore be interpreted as an exploration of the maximum theoretical impact of air pollutant mitigation. However, the reduced long-term potential relies on the assumption that pollutant emissions will decrease considerably even without additional, stringent MFR measures in the baseline. In case this assumption will prove too optimistic, i.e., with limited air pollution control in the reference case (as in SSP3), stringent air pollution toward the MFR-bounded values would have a larger effect in terms of health and climate than currently estimated.

Estimates of the air pollutant mitigation costs are generally scarce and relatively uncertain. While the GAINS dataset is considered the most comprehensive source in that respect, these cost results mainly represent an indication of the order of magnitude. Despite uncertainties, studies with GAINS show that the costs of air quality policy are relatively modest compared with the energy system transformation needed for stringent climate policy (Rafaj et al. 2018). In addition, the societal benefits due to improved air quality and human health are found to be worth several times more than the additional costs.

The impact of BC on radiative forcing is uncertain. Recent model and field studies suggest that the forcing (Samset et al. 2014; Stohl et al. 2015) and effective forcing (proportional to GMT change) (Baker et al. 2015; Stjern et al. 2017) of BC and co-emitted species are likely lower than originally thought; however, uncertainty is still high.[5] The potentially lower climate impact could mean that the GMT reducing effect of BC mitigation might be lower than the already modest effect that is found here. Note that the high uncertainty also applies to OC forcing, as well as to the emissions of both species. Supplement S6 provides an uncertainty analysis of the climate-focused BC measures in SSP2 and SSP3 to determine the GMT reduction under different climate assumptions. In a Monte Carlo analysis, SSP2, SSP3, SSP2_Climate, and SSP3_Climate have been run with a probabilistic version of MAGICC6 (Meinshausen et al. 2011) with 171 cases per scenario that represent alternate configurations of 82 climate model parameters resulting in a range of possible GMT changes. It is shown that, although the uncertainty in GMT for individual scenarios is very large (in 2030: larger than 0.3 °C for all scenarios), the range in GMT difference (i.e., uncertainty in the effect of climate-focused BC measures) is much smaller. In the SSP2 case, this amounts from − 0.009 to − 0.014 °C in 2030. In SSP3, the range in GMT difference is projected to be − 0.013 to − 0.022 °C in 2030. The GMT estimates as projected with the default version of MAGICC6 used

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[5] Some results in short: Samset et al. estimated direct BC forcing to be 25% lower than estimated (now estimated at 0.17 W/m^2). Stjern et al. estimated present day BC emissions to have contributed to 0.07 °C warming (approximately 7% of total warming). Baker et al. concluded that the combination of BC and OC mitigation does not necessarily lead to a discernible climate response at a global level.

in this study fit well within these ranges. The analysis suggests that, despite uncertainties in climate parameters, there is likely a small temperature-reducing potential from the climate-focused BC measures considered in this study. However, this is likely not much higher than presented here.

Temperature effects of BC (and other aerosols) can differ considerably across regions. Among models, there is a reasonable agreement among that BC warming is concentrated in the Northern Hemisphere with some polar amplification and a general higher impact in snow-covered regions (Arctic and Himalayas) (Bond et al. 2013). However, large uncertainties remain regarding smaller regional scales. For the purpose of this study—understanding how BC mitigation can potentially contribute to global climate policy—GMT change is considered an appropriate indicator.

As the health analysis showed, the premature mortality impact from air pollution is uncertain in the long term (due to uncertain cause-effect relations and uncertain population growth). However, it is clear that increased pollutant emissions lead to higher mortality (Burnett et al. 2014), implying that pollutant emission reductions in any scenario would lead to beneficial health effects. In addition, this study takes a conservative approach by only including ambient air pollution in this assessment, making an underestimation of the actual health benefits in the presented scenarios more likely.

5 Conclusions

This study assesses the effectiveness of additional, beyond currently committed, BC mitigation policies on climate change and health. Policy interactions have been analyzed under different socio-economic conditions and climate policy levels.

Ambitious air quality policy (in the absence of climate policy) can lead to a reduction of 4 to 12 million air pollution–related premature deaths in the period up to 2030. Most of the avoided premature deaths occur in Asia. Reduction of air pollution and associated health benefits can be considered the primary motivation for BC abatement measures.

Reducing BC emissions can also contribute to reduction of near-term climate change. However, the maximum GMT reducing effect of BC measures is found to be modest: 0.01 °C in a stringent mitigation case. If, in contrast, air pollutant measures are taken in all sectors (to reduce health impacts), this is found to lead to a GMT increase of 0.05 °C. BC mitigation can have a positive impact on climate change, but this strongly depends on the impact of mitigation measures on other climate forcers (co-mitigation), which highly differs per sector. Targeting BC emissions from traditional cooking and heating in the residential sector can lead to less climate change, while reducing pollutant emissions in other sectors may lead to additional warming. The positive impact on climate is found to be small under a default assumption (SSP2) and is more substantial under a failed air pollution control case (SSP3). The tool used here to evaluate BC mitigation (MAGICC) shows a relatively small response to reducing BC emissions, but this is consistent with several recent studies on BC forcing (Samset et al. 2014; Stohl et al. 2015). In an uncertainty analysis, we showed that the small temperature-reducing potential from the climate-focused BC measures considered in this study seems robust.

There is a clear co-benefit of stringent climate policy on reducing air pollutant emissions and thus on improving health. This could lead to an estimated 2 to 5 million avoided premature deaths in the period up to 2030. This health benefit can be strongly reinforced by

additional air pollutant reduction measures, at similar policy costs, especially in case of a high air pollution baseline case (SSP3).

The two different air pollutant mitigation strategies represent a trade-off: ambitious measures in all sectors to improve health lead to a lower number of air pollution–related deaths but require higher total policy costs (climate and air quality) and could lead to a negative near-term climate impact. In a maximized health benefit case, with air pollution policy in all key sectors, additional health benefits compared with climate-focused BC measures only amount to an estimated 4 million additional avoided deaths globally in the period up to 2030. However, in this period, the overall policy costs are estimated to be 17% higher compared with a maximized climate benefit case (when combined with stringent climate policy), and GMT is projected to be 0.06 °C higher in 2030.

The benefits of maximized air quality policy, expressed in value of statistical life (VSL), outweigh climate and air quality policy costs, when considered from a global perspective. The health benefits of air quality policy are larger than the costs of air pollution and climate policy combined. The net global benefits are mostly realized in China and India. When applying a more conservative value of the VSL, health benefits from ambitious air pollutant measures in the baseline cases (i.e., without climate policy) are still larger than the air pollution control costs.

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