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Future aerosol emissions: a multi-model comparison

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Abstract This paper compares projections over the twenty-first century of SO_2, BC, and OC emissions from three technologically detailed, long-term integrated assessment models. The character of the projections and the response of emissions due to a comprehensive climate policy are discussed focusing on the sectoral level. In a continuation of historical experience, aerosol and precursor emissions are increasingly decoupled from carbon dioxide emissions over the twenty-first century due to a combination of emission controls and technology shifts over time. Implementation of a comprehensive climate policy further reduces emissions, although there is significant variation in this response by sector and by model: the response has many similarities between models for the energy transformation and transportation sectors, with more diversity in the response for the building and industrial sectors. Much of these differences can be traced to specific characteristics of reference case end-use and supply-side technology deployment and emissions control assumptions, which are detailed by sector.

1 Introduction

Aerosols, small particles in the atmosphere, are key climate-forcing agents, both positive and negative, with net aerosol cooling presently offsetting about 30 % of GHG warming (IPCC AR5 central values, Myhre et al. 2013). Aerosol emissions, therefore, form an essential component of

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projections used to explore future climate change (Taylor et al. 2012, Van Vuuren et al. 2011b). Climate mitigation strategies might also aim to manage future aerosols, such as reducing black carbon emissions, which have a positive contribution to warming. This can be a means of reducing short-term climate change (Unep 2011, Ramanathan and Xu 2010), although the scope for this may be more limited than previously thought (Smith and Mizrahi 2013, Rogelj et al. 2014).

It is important to understand the fundamental drivers of these emissions in future scenarios. Recently, Rose et al. (2014) examined the global aerosol forcing trends in projections from five integrated assessment models. This paper provides a more detailed sectoral examination of aerosol projections from three models, GCAM, IMAGE and MESSAGE, using projections produced for the Representative Concentration Pathway (RCP) scenarios process (Moss et al. 2010, Van Vuuren et al. 2011b). Understanding the emission trends in the RCPs is important as they have been widely used, including for CMIP5 climate model simulations (Taylor et al. 2012). Moreover, the current aerosol representations and model dynamics in these IAMs are similar to those in the model versions used to produce the RCPs (ESM §1, §2). We note that there have been new efforts by the IAMs to improve the representation of near-term pollution policies and linking efforts and degree of pollution control to socio-economic drivers. This is reflected in the recently developed SSP scenarios (Rao et al. 2016), which have a wider range of reference case emission pathways as compared to the RCP scenarios. However this range indicates the still substantial uncertainty in the future evolution of the key factors discussed here.

These IAM models simulate regional energy and land-use, their global interactions, and the greenhouse gas and pollutant emissions that result from these anthropogenic activities. They differ, however, in model structure and future assumptions for driving factors such as technology development and pollutant control levels. By comparing results from these three models in detail, we provide insight into how differences in model structure and assumptions impact pollutant emission projections. We examine both reference and corresponding climate policy scenarios from each model so that consistent changes due to climate policy can be examined. Further details on the scenarios and their development is provided in ESM §2.

This analysis focuses on century-scale emission projections for sulfur dioxide (SO_2), black carbon (BC), and organic carbon (OC), focusing on the energy and industrial emissions at the sectoral level. We single out these three compounds because these are the predominant sources and precursors of atmospheric aerosol particles.[1] For brevity, we will collectively refer to these as aerosol emissions below, noting that, physically, sulfur dioxide is an aerosol precursor.

The models and scenarios described elsewhere (Thomson et al. 2011, Riahi et al. 2011, Van Vuuren et al. 2011a), with a brief overview in the electronic supplementary material (ESM). Emissions in reference case projections that do not include a climate policy are examined in section 3. Section 4 examines how the projections change when a comprehensive climate policy is applied to the reference case scenarios. We conclude with a discussion and conclusions. The ESM contains comprehensive graphs of emissions and fuel use by sector, and regional emissions by sector.

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[1] Emissions of reactive gases such as nitrogen oxides, carbon monoxides, and volatile organic hydrocarbons also influence aerosol concentrations, however we focus here on SO_2, BC, & OC emissions.

2 Reference case emissions

2.1 Overall trends

We first consider emissions from the three reference case scenarios (solid lines in Figs. 1, 3, SM-3, SM-4, SM-7, etc.). Fossil energy use, one of the primary drivers of the emissions considered here, expands substantially in the reference cases. As a consequence, CO_2 emissions increase over the century in all three reference scenarios (ESM §5).

Global total anthropogenic emissions (exclusive of land-use) of SO_2, BC, and OC generally decline over the century (Fig. 1, ESM §7), as noted in previous work (Rose et al. 2014). SO_2 emissions trends are broadly similar in MESSAGE and GCAM, while the IMAGE emissions are much higher, which is largely due to different assumptions for the energy conversion sector. BC emissions are dominated by building and transport sectors. GCAM BC emissions increase until 2020, driven by increases in buildings and industry, and then decrease to around 3 Tg by the end of the century. MESSAGE BC emissions continuously decrease after 2005 to around 2 Tg, with near-term decreases in transportation offsetting flat or slightly increasing near-term emissions elsewhere. IMAGE BC emissions show a sharp decline in the last half of the century and decrease to very low values (< 1 Tg). These sectoral level details discussed further below.

Emission intensity tracks the aggregate sectoral impact of technology changes plus emission controls. BC and SO_2 emission intensity projections for each reference case are shown in Fig. 2. We define emission intensity as aerosol emissions per unit CO_2 emissions because a large portion of BC, OC, and SO_2 emissions originate from fossil-fuel combustion (there can be a slight bias in this metric depending on bioenergy accounting, but this is a small effect in most cases, see ESM).

Global emission intensity generally decreases by roughly an order of magnitude over the century (Fig. 2) as aerosol and precursor emissions progressively decouple from CO_2 emissions. BC emissions in GCAM and SO_2 emissions in IMAGE show the smallest intensity decrease, while SO_2 in MESSAGE and BC in IMAGE show the largest decreases. The divergence in emission intensity increases markedly in the second half of the century. The MESSAGE scenario has the lowest emission intensity values. In part, this is due to the MESSAGE scenario, broadly speaking, aiming to achieve similar air quality improvements

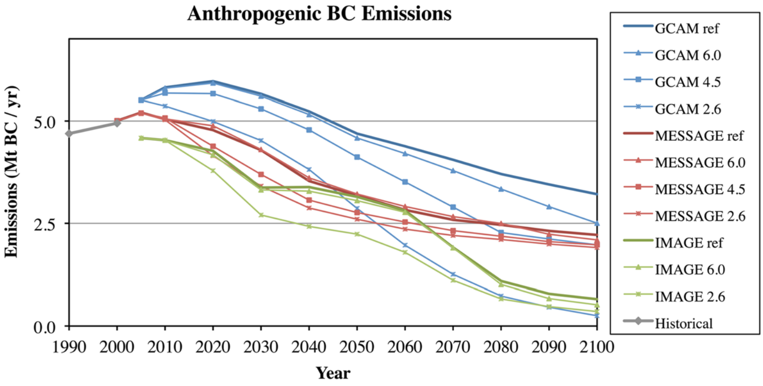


Fig. 1 Global anthropogenic black carbon (BC) emissions (*exclusive of land-use*). For each model, the thicker line is the reference scenario and the three thinner lines are the corresponding climate policy scenarios. The grey lines show historical emission estimates (Lamarque et al. 2010). Base-year emission differences are within estimated uncertainties are discussed further in the ESM

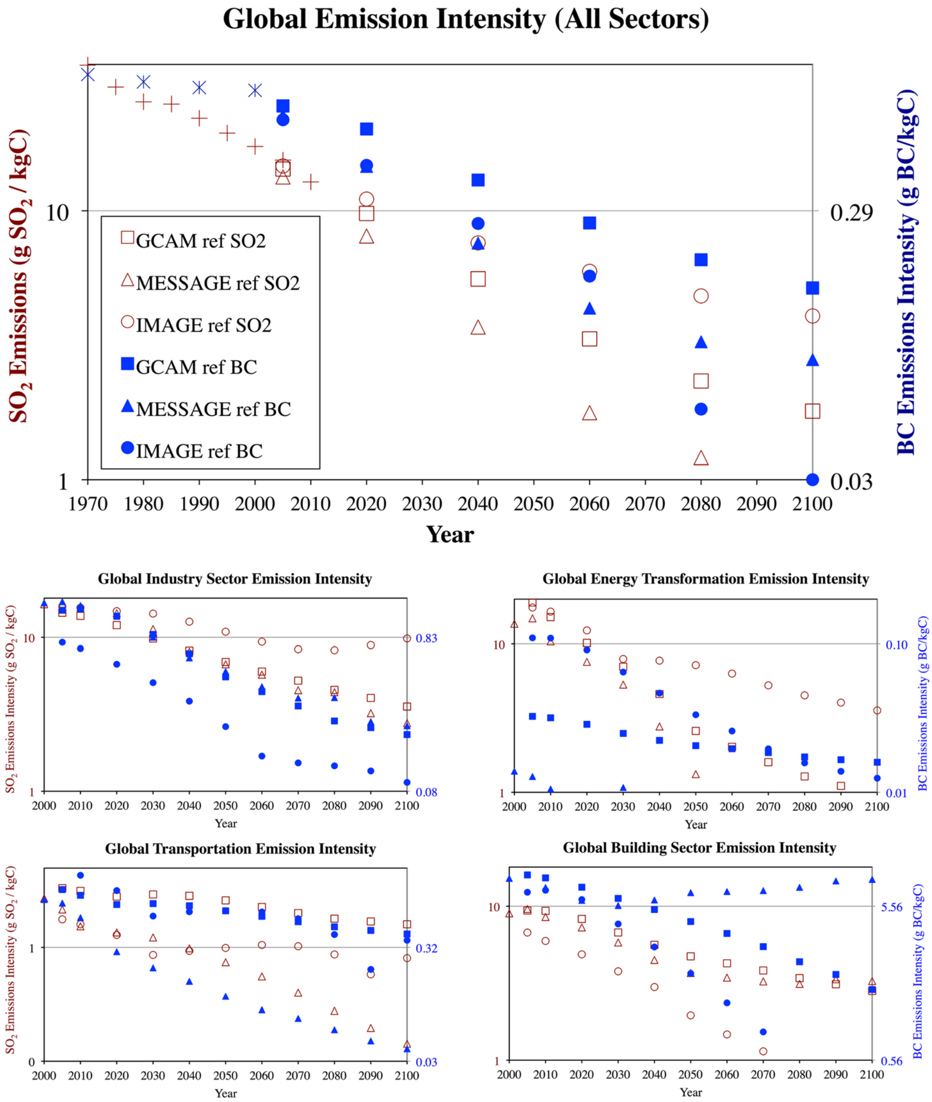


Fig. 2 BC and SO_2 emission intensities globally (*excluding land-use*) for reference (*ref*) scenarios. Top: for all sectors, and bottom: for the transportation, energy transformation, and industrial sectors separately. Intensities are in terms of reference scenario emissions per unit CO_2 emissions (in carbon units). Open, red symbols are for SO_2 (*left axis*), and closed, blue symbols are for BC (*right axis*). The vertical scale is logarithmic, and covers the same relative interval for BC and SO_2, although note the axis origin is different. Historical values from 1970 are also shown for global intensities. Note that non-combustion SO_2 emissions are included in the industrial sector, which increases this ratio (ESM §1.2). Building sector emission intensities are influenced by different accounting of CO_2 from biomass in the models

as in the other two models, in a scenario with higher fossil energy consumption, e.g. CO_2 emissions that are 30–40 % higher from 2050 to 2100. This requires a lower emission intensity to achieve a similar pollutant emissions outcome.

2.2 Emissions by sector

Figure 2 provides sectoral emission intensity trends, while the ESM provides comprehensive graphs for emissions and energy consumption by sector. The discussion below focuses on BC and SO_2. OC emissions at the sectoral level generally follow the trends for BC, and are briefly discussed in the supplement.

Transportation Transportation BC emissions and liquid fuel consumption are shown in Fig. 3. This sector is a substantial source of BC emissions through at least mid-century in all the models. By the end of the century transportation BC emissions in GCAM are only slightly lower than current estimates, while in MESSAGE these emissions have dropped substantially, and in IMAGE emissions are nearly zero by 2100. These differences are broadly reflected at the regional level as well (ESM §13). The end of century decrease in the IMAGE model is due to the widespread adoption of hydrogen-fueled vehicles. In GCAM, the global-average BC emission intensity falls by 60 % over the century (Fig. 2), which results in a modest reduction in total emissions from this sector given consumption increases. Transportation liquid fuel consumption in the MESSAGE model in 2100 is nearly twice that in the GCAM reference scenario (Fig. 3), however a much larger assumed decrease in emissions factors results in lower overall emissions. The MESSAGE scenario includes an increasing use of methanol in place of petroleum fuels, which is an inherently low sulfur fuel that would be compatible with the advanced particulate controls assumed in this scenario. These differences illustrate that assumptions about both technologies and the extent to which emission controls are implemented in the future can have a substantial impact on emission trajectories. See Riahi et al. (2012) and Chuwah et al. (2013) who examine how varying these assumptions impact future emission levels.

Buildings BC from this sector is primarily from residential buildings, and is initially higher in GCAM but then declines steadily after 2020. BC emissions in MESSAGE decline until mid-century mainly due to assumptions for fuel-shifting, but are then relatively constant to 2100 due largely to sustained use of traditional biomass in this scenario. The higher population and somewhat lower income levels in the MESSAGE scenario imply a larger rural population that continues to use traditional biofuels. Building BC emissions from IMAGE are lower in the base-year, and decline steadily over the century. Emissions from the buildings sector are driven more by assumptions about the penetration of modern energy forms, e.g., "energy access", than explicit pollution controls. Emissions, therefore, are closely linked to assumptions about the use of coal and traditional biomass fuels in residential buildings (ESM §8,9), which also impact sectoral emissions intensity. Regionally, these assumptions have the most impact in Africa and India (ESM §13).

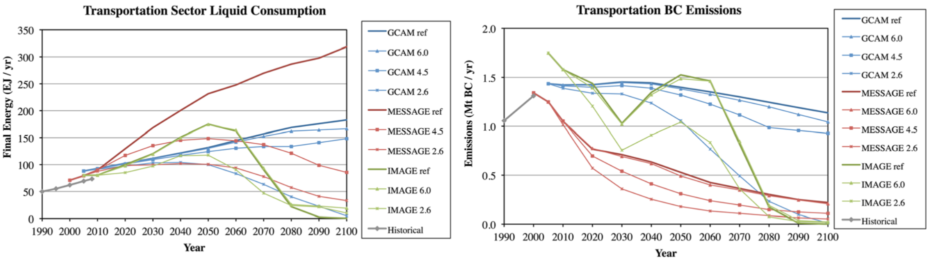


Fig. 3 Global liquid fuel use (*left*) and BC emissions (*right*) from the transportation sector

Industry The trajectory of industrial BC emissions is similar in all three models, flat or increasing initially, and then declining through the end of the century. Industrial BC emissions are largely from smaller, less efficient, industrial activities and would be impacted by both fuel substitution over time and emission factor assumptions. The global average emission intensity in this sector decreases substantially in all three models (Fig. 2). The assumed changes in emission factors in these models represent both general modernization of industries and implementation of explicit emission controls.

Energy transformation The energy transformation sector is currently dominated by electric power production. BC emissions from this sector are relatively low, at least for well-run modern power plants, while this sector is the dominant source of SO_2 emissions. Reference case total SO_2 emissions show substantial divergence, with the IMAGE reference scenario showing relatively constant global emissions after 2030 while emissions in the GCAM and MESSAGE scenarios gradually declining to 40 (GCAM) and 20 (MESSAGE) $TgSO_2$ by the end of the century.

These differences stem from assumptions for emission controls and technology choices. In the MESSAGE model, SO_2 emission trends in the near-term (to 2030) are derived from currently planned and legislated pollution limits (see SI) while in the long-term SO_2 emissions fall due to technology substitution processes, such as the installation of IGCC plants with inherently low pollutant emissions, which reaches 60 % of total fossil electric generation by 2050 and further increases to more than 80 % by the end of the century. IGCC penetration in the GCAM reference scenario reaches 50 % of coal-fired generation in 2050 and remains near that level throughout the century. Conventional coal plants in GCAM are assumed to be increasingly equipped with scrubbers over time as incomes increase.

The relatively high SO_2 emissions in the IMAGE scenario result from a rapid increase in the use of fossil fuels (in particular coal) that is only partially offset by a decline in emission factors (Fig. 2). It is possible that in some areas with high emissions (SE Asia, India, Africa; ESM §13), given the high population densities, surface air pollution levels would exceed recommended health guidelines (Smith et al. 2011, Rao et al. 2013). Long-term SO_2 emissions are lower in later versions of the IMAGE model. In all three models SO_2 emissions in 2100 are dominated by energy transformation and industrial sectors. Both emission control assumptions and technology assumptions, such as those for IGCC, can have a substantial impact on future emissions.

Land-use emissions of SO_2, BC, OC originate from natural and human-caused forest and grassland wildfires along with burning associated with deforestation. Reference case emissions from all three models are lower by 2100 than 2005 due to a reduction in deforestation and generally lower amounts of unmanaged land subject to wildfires. Emissions decline the most in IMAGE, with the decline largely complete by 2050 as a result of the land-use trends, while carbonaceous aerosol emissions in GCAM increase to 2050 due to increased deforestation before declining. Emissions in MESSAGE show a steady decline over the century reflecting a declining deforestation trend in combination with policies for fire prevention in the developing world in the long term. These different patterns reflect a diversity of underlying land-use trends and policies in the models.

These comparisons illustrate that future pollutant emissions pathways are a function of both assumptions about the evolution of pollutant emission controls and the evolution of technologies and energy systems. Ultimately, however, pollutant emission levels will be determined by preferences of future societies in terms of air pollutant concentrations, and the resources devoted to meeting these preferences.

3 Climate policy response

3.1 Overall response

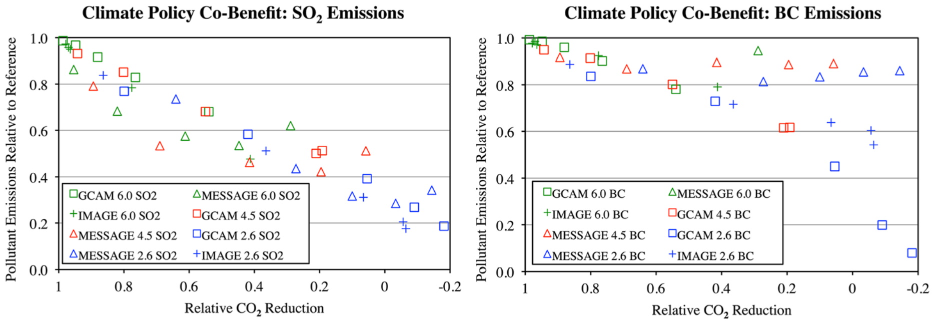
The reference case is the background upon which climate policies are applied. In each model a comprehensive climate policy is implemented in which a carbon price, or equivalent policy, is implemented throughout the global energy system in order to meet the specified radiative forcing target.

Meeting a climate forcing goal will require some combination of increased energy efficiency, decreased fossil-fuel consumption, increased use of carbon capture and storage, and land-use strategies. All of these options will tend to decrease emissions of aerosols and precursor compounds, although emission increases are occasionally seen as well. In aggregate aerosol emissions decrease, with reductions increasing with more stringent climate policies.

The response by emission and sector are discussed in more detail below. The emission responses to a carbon policy can generally be traced directly to changes in fuel consumption. Graphs of both emissions and fuel consumption are, therefore, provided in ESM §8, §9. A discussion of the response of land-use and international shipping emissions is provided in ESM §10.

The impact of a climate policy on aerosol emissions is summarized in Fig. 4, which shows the SO_2 and BC emissions reduction relative to the reference case as a function of CO_2 reduction. The relative aggregate response of SO_2 emissions to a climate policy is similar in all three models. This is due largely to coal combustion being a common source of both SO_2 and CO_2, and a similar relative response to a climate policy in the electric generation sector.

The BC emissions reduction in response to a carbon policy is smaller and more variable between the models. At moderate climate policy levels, with CO_2 emissions reduced by up to about 50 %, BC emissions are generally only reduced by 10–20 %. The models differ more substantially on the response to a very ambitious carbon policy, whereby emissions of carbon dioxide are net negative by the end of the century. BC reductions in the 2.6 scenario, relative to reference, range from no more than 20 % for MESSAGE, up to 40 % for IMAGE, and up to 80 % for GCAM, which are examined in more detail below.



Climate Policy Co-Benefit: SO_2 Emissions

Climate Policy Co-Benefit: BC Emissions

Fig. 4 Global SO_2 (*left*) and BC (*right*) climate policy co-benefit, shown as the aerosol emission level, relative to the reference scenario, as a function of CO_2 emissions reduction (also relative to the reference scenario). Note that net negative carbon dioxide emissions (negative reduction on the x-axis) are a feature of the most ambitious climate policy scenarios

3.2 Response by sector

Transportation All three models show a substantial reduction in BC emissions from the transportation sector. Liquid fuel consumption decreases relative to reference under a climate policy in all three models (Fig. 3), which decreases emissions. Transportation services shift to modern fuels: electricity in GCAM, hydrogen in IMAGE, and electricity, biomass-based liquids and hydrogen in MESSAGE. The level of the response in terms of fuel consumption also varies by climate policy target and the resulting carbon price. While GCAM has a relatively modest decrease in liquid fuel consumption in the 4.5 W/m^2 scenario, liquid fuel consumption for transport in MESSAGE is less than 1/3 of the reference case value in this scenario (due, in part, to the larger carbon price in MESSAGE, see ESM). Both GCAM and MESSAGE show large decreases in liquid fuel consumption and emissions in a 2.6 W/m^2 scenario by the end of the century. BC emissions in the IMAGE scenario are already small by the end of the century in the reference case due to the use of hydrogen in the transportation sector, with any climate response shifted upstream to the transformation sector.

A portion of these differences are due to baseline emission control assumptions. The much stronger transportation BC emission controls, coupled with substantial use of synthetic fuels, in the MESSAGE baseline scenario and resulting low emission levels, mean that, in absolute terms, there is less room for emissions to further decrease as liquid fuel consumption decreases under a climate policy. The larger reference case emissions in GCAM result in a potential for a larger relative reduction in the climate policy case.

Energy transformation The energy transformation sector is a relatively small source of BC emissions, and the response for BC and OC varies between the models. SO_2 emissions fall in all models as coal-fired electricity production either decreases or shifts to CCS technologies, which are assumed in all these models not to emit appreciable amounts of SO_2. Biomass energy with CCS (BECS) is included in all models. Similar to fossil power plants with CCS, BECS plants do not emit appreciable SO_2 or BC.

Industry IMAGE and GCAM have similar relative reductions in BC emissions, with the absolute reduction in GCAM larger due to larger initial emissions. There is only a very small response in the industrial sector BC emissions to climate policy in the MESSAGE model, due to the limited scope for reductions in this sector, the continued use of liquid fuels, and a requirement for some level of carbonaceous fuels.

The industrial sector is the second largest source of SO_2 at present, and emissions under a climate policy generally decrease in this sector, although the three models show different patterns. In absolute terms, the reduction in industrial SO_2 emissions is similar in IMAGE and GCAM, although overall emissions are lower in GCAM.

These differences in response in the industrial sector are due, in part, to different representations of industrial fuel demand in these models. Coal and liquid fuel consumption in the industrial sector shows a large response in GCAM and MESSAGE, with a much smaller response in IMAGE. Biomass consumption in the most stringent climate policy scenario increases in the near-term in GCAM and MESSAGE, but ultimately decreases to low levels by 2100 in both models, with a much smaller relative change in the IMAGE model.

Buildings The BC emissions response in the building sector is relatively small in IMAGE and MESSAGE, with a much more substantial response in the GCAM model. In all models a climate policy reduces coal and liquid fuel consumption, with this having a larger impact in GCAM due to higher reference scenario consumption. Most BC emissions, however, are associated with traditional bio-energy use. Traditional biomass consumption in the buildings sector is only mildly impacted by a climate policy in all of the models. Traditional biomass consumption increases slightly in IMAGE and GCAM under a climate policy as the cost of other fuels increases.

4 Discussion and conclusions

In this paper we document the state of three long-term integrated assessment models at the time the RCP scenarios were produced (Taylor et al. 2012, Van Vuuren et al. 2011b). Scenarios from all three models show two broad trends. As noted previously (Rose et al. 2014), aerosol emissions decline over the twenty-first century in the reference (no climate policy) scenarios as a result of combination of trends in energy technologies and air pollution policies. Emission intensity, measured relative to carbon dioxide emissions, decreases substantially in all three models, but the assumed rate of decrease varies by substance, sector, and model. These differences stem from different assumptions for pollution controls, technology characteristics, and model behavior at the sectoral level. Widespread adoption of inherently low emitting technologies, such as integrated gas combined cycle (IGCC) coal combustion or hydrogen fuel cell vehicles will result in low emissions, which can be an important factor motivating the adoption of such technologies.

Black carbon emissions are determined largely by assumptions in the transportation and buildings sectors. The higher black carbon emissions in the GCAM scenario are largely due to the assumption of less stringent emission controls for BC in the transportation sector. While there is significant uncertainty in the ability of many world regions to enforce emission controls. GCAM transportation emissions, for example, do not fall as rapidly as in recent more detailed projections (Yan et al. 2014), indicating that these projections might be too high. The somewhat modest decrease in BC emissions from MESSAGE in the last portion of the century is due to an assumption of continued reliance on traditional biofuels in developing countries in this scenario (See ESM).

SO_2 generally dominates the anthropogenic particulate fraction and is also the source of the largest aerosol climate forcing, the assumptions for sulfur dioxide emission controls in the electric power sector, and to a lesser extent in industry, are particularly important. The higher sulfur dioxide emissions in the IMAGE model, for example, are largely the result of an assumption of less stringent emission controls for energy transformation (Fig. 2).

A second common trend is a further reduction in emissions, relative to each model's reference case, under climate policy scenarios (Fig. 4). Reductions in sulfur dioxide and carbon dioxide are strongly coupled in all three models because coal combustion is a primary source of both SO_2 and CO_2. While reducing greenhouse gases also results in black carbon reductions, in general the reductions are smaller and there is a larger variation between the models in the response of BC emissions.

A number of trends in terms of aerosol reductions in response to a climate policy emerged at the sectoral level:

- In all three models, aerosol emissions from the *energy transformation* sector fall to low levels under a climate policy as energy transformation shifts to either renewable sources or technologies that use carbon capture and geologic storage (CCS), both of which have inherently low aerosol emission levels. This transition occurs relatively early, with energy sector emissions, particularly for SO_2, relatively low by mid-century under moderate (4.5 W/m^2) to strong (2.6 W/m^2) climate policies.

- For the *surface transportation* sector, projections vary between models due to different reference case assumptions. Under a stringent 2.6 W/m^2 scenario, however, the models agree that aerosol emissions become relatively small by the end of the century as liquid fuels are replaced by other options. Emissions by mid-century vary more substantially, even under a climate policy, with emission levels depending largely on reference-case emission control and fuel demand assumptions.
- There is considerable diversity in the climate policy response in the *industry* sector, driven in part by representations of this sector that are fairly aggregate (e.g., explicit technologies are often not represented), requiring styled assumptions to capture the relevant dynamics. Fossil-fuel use in the industrial sector comprises a wide range of uses, including process heat, internal combustion engines, and process-specific uses such as steel-making over a range of scales, from small plants and boilers to large manufacturing centers. In some models, off-road diesel consumption is also included in this sector. Historically, regulations on pollutant emissions can vary by industry, with inertia playing an important role. Fossil fuels can be difficult to replace in some industrial activities, such as those that need high temperature process heat. Some processes have quite specific requirements, such as steel making which requires a carbon-based input such as coal coke, which also differs in its pollutant emissions as compared to coal.
- *Building sector* emissions also show a range of responses. In all scenarios, aerosol emissions are lower by 2050 than in 2005, but the level varies substantially by model, even in the reference case. The response to policy also varies, with BC emissions changing little under a climate policy in two models, and reducing substantially in one model. Reference case assumptions can have a large impact in this sector. The MESSAGE reference case, for example, describes a world where a relatively large fraction of rural population in developing countries is still using traditional biofuels by the end of the century. The result is higher baseline black carbon emissions, from a sub-sector (traditional biofuels) that is also minimally responsive to climate policy.

In summary, the response of future aerosol emissions to the imposition of a comprehensive climate policy depends on both reference case scenario details and model structure (which is indicated by differences in sectoral climate policy response and carbon prices). A specific examination of the importance of model structure is given in the appendix, where comparable results are examined for a more recent version of the GCAM model that contains more end-use detail. Greater end-use detail results in a smaller aerosol emissions response to climate policy in this case (ESM §6).

Note that the analysis in this paper has focused on idealized model results. In all these scenarios, aerosol emissions factors and emission controls were assumed to be the same, at the level of individual technologies, in the climate policy scenarios as in the reference case. This simplifies the analysis but also implicitly assumes that additional reductions due to a climate policy would not result in relaxing pollutant emission controls elsewhere. In a pollutant cap and trade system, for example, at least some of the reductions in air pollutants resulting from a climate policy might be offset, at least in the near-term, by relaxed emission controls elsewhere. A recent health impact assessment (Rao et al. 2013), however, indicates that a combination of stringent policies on air pollution control, climate change mitigation and energy access would be important in achieving health objectives in the short-term for some regions. In the longer term (post 2050) climate policies result in large-scale technology shifts such that pollutant emissions from some sectors may become essentially zero. This trend is particularly strong in the electricity sector of all of the stringent mitigation scenarios assessed in this paper. Under strong climate policy mitigation scenarios, therefore, air pollutant control assumptions have a weaker impact in the long term.

5 Recommendations for future work

The relative sectoral contributions to future emissions are robust findings that will generally apply to all models, and points to the importance of analyzing future projections at the sectoral level. This also indicates where future model development could focus in order to better understand potential future pathways for aerosol emissions. These include how effective emissions controls will be in the transportation sector and how much traditional biofuel use might change in the future (often examined under the paradigm of energy access). Improving IAM resolution for the industrial sector, and off-road mobile emissions in particular, could also be a target for improvement.

While historical analysis should be used to improve future scenarios, there are data limitations. Assumptions for the use of traditional biomass, for example, have a large impact on black carbon emissions, however improvements here are particularly challenging since data on historical trends for these fuels are still quite uncertain (ESM §4). Historical emissions are also uncertain, particularly BC (Bond et al. 2007), and this uncertainty will also map directly to uncertainty in future projections.

Scenario development in these models has tended to focus on trends air pollution control policies and associated emissions, with pollutant control assumptions are informed by results from more detailed models (Amann et al. 2011, Chuwah et al. 2013). Instead of emissions, however, the ultimate policy objective is limiting impacts such as surface particulate concentrations and acidification. Research to incorporate more of the real-world tradeoffs, for example between pollution control costs and human exposure outcomes, while challenging, are needed. Improved application of methods that allow a connection between emissions and surface concentrations are need to improve the consistency of future scenarios (Smith et al. 2011, Rao et al. 2012, Chuwah et al. 2013). Additional challenges to modeling future air pollution policies include burgeoning megacities across the developing world and the increasing importance of long-distance pollutant transport, which makes achieving regional air pollution goals increasingly tied to actions elsewhere.

Finally, the impact of a climate policy on aerosol emissions depends on the sectoral level technology and service shifts. A better understanding of the reasons why models differ in this respect would be helpful. The industrial sector stands out in this analysis for such differences, and further examination of the potential response of the industrial sector to climate policies, particularly under stringent climate policies, seems warranted.

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