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Non-Kyoto radiative forcing in long-run greenhouse gas emissions and climate change scenarios

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Abstract Climate policies must consider radiative forcing from Kyoto greenhouse gases, as well as other forcing constituents, such as aerosols and tropospheric ozone that result from air pollutants. Non-Kyoto forcing constituents contribute negative, as well as positive forcing, and overall increases in total forcing result in increases in global average temperature. Non-Kyoto forcing modeling is a relatively new component of climate management scenarios. This paper describes and assesses current non-Kyoto radiative forcing modeling within five integrated assessment models. The study finds negative forcing from aerosols masking (offsetting) approximately 25 % of positive forcing in the near-term in reference non-climate policy projections. However, masking is projected to decline rapidly to 5–10 % by 2100 with increasing Kyoto emissions and assumed reductions in air pollution—with the later declining to as much as 50 % and 80 % below today's levels by 2050 and 2100 respectively. Together they imply declining importance of non-Kyoto forcing over time. There are however

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significant uncertainties and large differences across models in projected non-Kyoto emissions and forcing. A look into the modeling reveals differences in base conditions, relationships between Kyoto and non-Kyoto emissions, pollution control assumptions, and other fundamental modeling. In addition, under climate policy scenarios, we find air pollution and resulting non-Kyoto forcing reduced to levels below those produced by air pollution policies alone—e.g., China sulfur emissions fall an additional 45–85 % by 2050. None of the models actively manage non-Kyoto forcing for climate implications. Nonetheless, non-Kyoto forcing may be influencing mitigation results, including allowable carbon dioxide emissions, and further evaluation is merited.

1 Introduction

There is international concern about climate change and policy interest in managing it. Recent international negotiations have indicated that policies would focus on avoiding a global mean temperature increase of two degrees Celsius above pre-industrial levels, with consideration of even lower targets (Cancun Agreement, 2010). To achieve such a goal, greenhouse gas emissions (GHG) would need to be significantly constrained. International GHG mitigation policies (e.g., Kyoto Protocol) have focused mainly on six GHGs. These gases, referred to as the Kyoto gases, are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF_6). However, total radiative forcing is determined by a variety of additional constituents—aerosols, tropospheric ozone, ozone depleting substances regulated under the Montreal Protocol, land albedo, etc. Together they determine the earth's radiative balance—the balance between radiant energy received by the earth and energy re-radiated to space. The difference between the two is radiative forcing. Increases in greenhouse gases and other forcings can affect this balance and thus change the planet's climate, causing higher global average temperatures and other climate related changes. The magnitude of transient climate response to radiative forcing is an uncertain function of forcing level, the sensitivity of climate to atmospheric concentrations changes, and climate system lags.

Central estimates suggest that increases in the concentrations of Kyoto GHGs are responsible for approximately 2.6 W/m^2 of historic increases in radiative forcing (1750–2005), while changes in non-Kyoto elements are responsible for net negative radiative forcing of approximately −0.8 W/m^2 (Forster et al. 2007), which is the result of negative and positive forcing central estimates of −1.6 and 0.8 W/m^2. There is significant uncertainty, in particular in aerosol forcing, with estimates of net direct and indirect aerosol forcing ranging from −0.9 to −0.1 W/m^2 and −1.8 to −0.3 W/m^2 respectively (Forster et al. 2007).[1] See the "Supplemental Material" for forcing by constituent from Forster et al. (2007). Some of these forcing estimates are undergoing substantial revision (e.g., Bond et al. 2013) and observational constraints suggest that very large negative forcings from aerosol indirect effects can potentially be ruled out (Murphy et al. 2009). The Intergovernmental Panel on Climate Change's forthcoming Fifth Assessment Report will provide revised estimates of historic forcing that consider these and other advances in knowledge. Integrated assessment models will have to consider the revised estimates in the future in their scenario work. Whether they impact the baseline and policy scenario results shown in this paper will depend on other revisions that together define relationships between forcing and forcing drivers.

[1] Aerosols can directly affect forcing as particles and indirectly affect forcing by facilitating formation of other elements that affect radiative forcing, such as clouds and troposhperic ozone.

Some precursors of non-Kyoto forcing elements, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulates such as black carbon (BC) and organic carbon (OC), carbon monoxide (CO) and volatile organic compounds (VOCs), are considered to be local and regional pollution emissions. These emissions are actively managed for non-climate benefits, such as air quality and ecosystem health. The stringency of their management varies by country, pollutant, and over time as a function of many factors, including scientific and epidemiological understanding, technology, and public and political will.

Integrated assessment modeling has evolved over time with policy and science from a concentration on energy CO_2 emissions (Hourcade et al. 2001), to Kyoto emissions (including land use) (Weyant et al. 2006), to Kyoto forcing (Clarke et al. 2009), and recently to Kyoto and non-Kyoto radiative forcing (van Vuuren et al. 2011). Modeling of non-Kyoto forcing however is young and developing, with only a few models to date representing non-Kyoto forcing agents. This modeling utilizes current scientific understanding of pollutant emissions, technologies, climate change, and atmospheric chemistry.

Given the estimated historical importance of non-Kyoto forcing and a policy interest in forcing and temperature outcomes, a community initiative emerged within the EMF-27 Study (Kriegler et al. 2013) to develop, evaluate, and advance integrated assessment modeling of non-Kyoto forcing. This paper is the product of that initiative. Specifically, a small number of modeling teams developed a subgroup to discuss and assess non-Kyoto forcing modeling, engage with other research communities regarding science and technology, improve modeling, and identify future development opportunities and priorities. This paper characterizes and compares current integrated assessment modeling of non-Kyoto forcing and evaluates the role non-Kyoto forcing plays in current results. By taking stock of current modeling and its implications, we hope to advance understanding and discussion, and stimulate future research in this area. Within this study, we explore the importance of non-Kyoto forcing in projections. We consider positive forcing masking from aerosols and the net forcing implications. We also evaluate the non-Kyoto emissions and forcing implications of climate policy, and the effects of non-Kyoto forcing on Kyoto gas mitigation. Note, however, that the scenarios that we consider do not jointly optimizing climate and air pollution, nor do they use air pollution to manage the climate.

We begin with an overview of the models considered from a non-Kyoto forcing perspective. We then present results quantifying the role of non-Kyoto forcing in reference and climate policy scenarios. We conclude with key insights and research directions.

2 Modeling

The overall EMF-27 study is an exploration into the cost and societal transformation implications of different technological and climate policy futures (see Kriegler et al. 2013). The EMF-27 study includes nineteen models. Our study considers only five of the models: GCAM (Kim et al. 2006; Calvin et al. 2012), IMAGE (MNP 2006), MERGE (Blanford et al. 2013), MESSAGE (Riahi et al. 2011), and REMIND (Luderer et al. 2013; Leimbach et al. 2010). These five integrated assessment models project non-Kyoto forcing, as well as Kyoto forcing. Integrated assessment models are designed to integrate socioeconomic and climate systems in order to evaluate potential socioeconomic and GHG emissions scenarios and their climate change implications. In particular, as in the EMF-27 study, integrated assessment models have been used to identify potential future energy systems and land-use associated with reduced levels of climate change.

A questionnaire was used during the course of this study to collect modeling information related to non-Kyoto forcing. Specifically, we collected details regarding the modeling of forcing and climate, technology and policy, and non-Kyoto forcing precursor emissions. See the "Supplemental Material" for the questions and responses. There are many non-Kyoto forcing related modeling similarities across the models; however, there are meaningful differences as well. All five models simulate direct aerosol forcings as proportional to the relevant emissions. Indirect cloud aerosol forcing, however, is simulated as a logarithmic function of emissions—either as a function of sulfur emissions only or a combination of aerosol emissions. In all models, tropospheric ozone forcing is a function of methane concentrations and NO_x, CO, and VOC emissions.

Air pollution policies manifest themselves in various ways within the models. First, aerosol and pollutant emissions factors associated with anthropogenic activities (e.g., emissions per unit fuel) are prescribed to change over time as a function of per capita income, as well as other factors that vary by model, including thresholds, technology vintage, and present and planned air quality policy. Declining emissions factors represent improvements in technology efficiency and/or pollution policy driven changes in technology (e.g., adoption and improvements in best available control technology). We explore these issues explicitly in the next section. Second, in addition to declining emissions factors, some models utilize pollutant emissions caps. Air pollution policy resolution varies by model as well, with assumptions varying by region, sector, type of emissions, fuel, and/or technology.

Pollutant emissions modeling also varies by model. All five of the models endogenously model SO_2, black carbon (BC), and organic carbon (OC). Four of the models also endogenously model NO_x, CO, and VOCs. The fifth model includes these emissions exogenously. Two of the models also model ammonia (NH_3). Energy system pollutant emissions are included in all the models based on fuel consumption. However, a variety of approaches are implemented for land and non-combustion process pollutant emissions and forcing.

It is important to note that, while the models are tracking pollution emissions and non-Kyoto forcing, they are not actively managed in the model's decision algorithms in developing cost-effective GHG mitigation portfolio projections for a climate target. The models pursue Kyoto emissions mitigation and sequestration, and non-Kyoto changes are a co-effect that affects the climate target level but not the mitigation technology choices. This approach reflects the assumption that pollution emissions are, and will continue to be, managed for near-term and local non-climate human health and ecosystem benefits.

3 Non-Kyoto forcing in scenarios

To elucidate and evaluate the role of non-Kyoto forcing within projections and across models, we consider three scenarios from each model: the model reference and two climate policy scenarios. From the reference scenarios, we elucidate the basic role of non-Kyoto forcing and the mechanics of the individual models. From the policy scenarios, we learn about the potential implications of climate policy for non-Kyoto emissions and forcing, as well as insights regarding the potential role of non-Kyoto forcing in achieving climate policy objectives.

The reference scenario represents business as usual without additional climate policy. For the climate policy scenarios, we consider 2100 radiative forcing targets of 3.7 and 2.8 W/m^2. The 3.7 W/m^2 policy does not allow the forcing target to be exceeded at any point in time, while the 2.8 W/m^2 target allows overshoot prior to 2100. The forcing targets apply to all forcing constituents except nitrate aerosols, mineral dust and land-use albedo changes. We refer to this concept of "total" forcing as *RCP forcing*, because it has its origins in the Representative Concentration Pathways (RCPs; van Vuuren et al. 2011). Focusing on RCP forcing allows us to be consistent with research community efforts to develop a common thread for a more integrated body of research (Moss et al. 2010).[2] The excluded constituents historically account for a negative forcing of around −0.4 W/m^2. The forcing of the three agents is speculative and some are treated exogenously, if at all, in integrated assessment models.

3.1 Reference scenarios

One of the most enticing questions regarding non-Kyoto forcing, is to what degree could the global cooling effects of aerosols mask warming? From Fig. 1 (left), we see that net aerosol forcing is masking approximately 25 % (22 to 27 %) of positive radiative forcing today from Kyoto GHGs and other constituents. However, all of the models show a rapid decline in masking over time (with the range of masking across models widening). In less than two decades, masking declines to 16 to 20 %, and, by 2050, to 10 to 16 %. By the end of the century, aerosols are masking only 5 to 11 % of positive forcing. Key uncertain assumptions, and differences, across models are driving this result.

The decline in masking is the net effect of a combination of increased Kyoto greenhouse gas positive forcing and decreased net aerosol negative forcing, the dynamics of which vary across models. The variation in masking across models over time, in part, contributes to variation in total RCP forcing over time—approximately 2.3 to 2.5 W/m^2 in 2010 and 7.0 to 7.8 W/m^2 in 2100 (Fig. 1 right). During the century there is up to a 1.1 W/m^2 difference across model reference scenarios. In Fig. 1, despite changes in various forcings, there is evidence that having lower or rapidly declining aerosol forcing masking implies higher RCP total forcing (GCAM and REMIND), and having greater masking implies lower RCP forcing (IMAGE, MERGE).

The large negative forcing uncertainty range in 2010 might seem surprising as 2010 is relatively close to historical base years. However, current aerosol forcing is highly uncertain; and, while the models rely on similar forcing input data for many constituents, they are not implementing it the same way. The base year differences in both Kyoto and non-Kyoto forcing constituents could have bearing on the projections as base year forcing levels define relationships with economic activity levels and precursor emissions that underlie forcing responses to socioeconomic growth. And, in climate policy scenarios, base year differences could influence costs. Base year uncertainty is an issue worthy of future analysis.

Changes in non-Kyoto forcing over time are not contributing equally over the century to total RCP forcing. Declining non-Kyoto forcing is contributing to the increase in total forcing during the first half of the century 2005–2050, but not during the second half (Supplemental Material). In the first half of the century, there is variation in total forcing growth across models, but driven by changes in non-Kyoto forcing, with four of the models exhibiting similar Kyoto forcing growth (1.54 to 1.59 % per year), but different total RCP forcing growth (1.61 to 1.86 % per year). In the second half of the century (2050–2100), Kyoto forcing growth is slower in all models, and is the sole driver of growth in total forcing.

Figure 2 provides a decomposition of the RCP and aerosol forcing for each model. Kyoto forcing dominates overall forcing, and increasingly so in the future, as net aerosol forcing declines (Fig. 2, left). As mentioned, the differences in 2010 are significant, but primarily in

[2] Note that the overall EMF-27 study refers to RCP total forcing as AN3A forcing—total anthropogenic forcing minus the three excluded constituents.

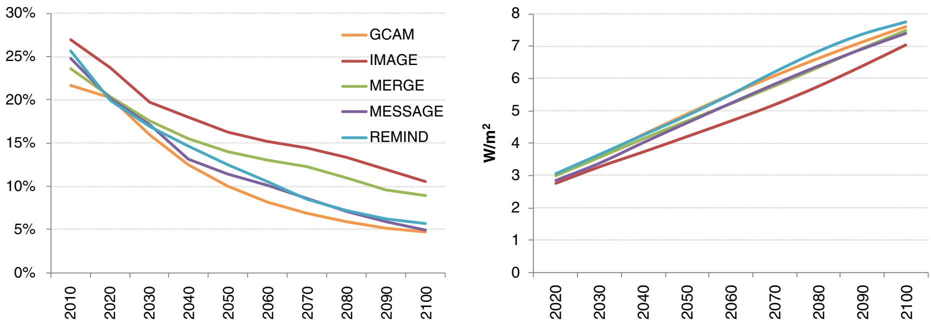

Fig. 1 Reference aerosol forcing masking of other forcing (*left*) and RCP total forcing (*right*)

non-Kyoto forcing elements, in particular aerosols. For example, aerosol forcing in 2010 ranges from −0.87 to −0.68 W/m^2, tropospheric ozone forcing from 0.33 to 0.39 W/m^2 and the direct forcing from Montreal gases from 0.30 to 0.36 W/m^2. The figure shows that the forcings from tropospheric ozone and Montreal gases are relatively modest, with the former stable over time, and the later declining.

In Fig. 2 (right), we see the negative and positive forcing components of net aerosol forcing. The masking effect is caused by the negative indirect cloud and sulfate direct forcings, as well as organic carbon direct forcing (included within Black and Organic Carbon). Across the models, there are dramatic differences in the reference aerosol story over the century as seen in the differences in the composition and dynamics of aerosol forcing. As noted, the differences start with 2010 net aerosol forcing (−0.87 to −0.68 W/m^2). By 2050, aerosol forcing ranges from −0.82 to −0.44 W/m^2, and by 2100, −0.83 to −0.26 W/m^2. Indirect cloud forcing is the largest component of aerosol forcing in all the models, with −0.73 to −0.50 W/m^2 in 2050, and −0.69 to −0.31 W/m^2 in 2100. Variation in the dynamics of cloud forcing across models is stark, with declining negative forcing in most models due to endogenous declining aerosol emissions, but significant variation in the magnitude and rate of cloud forcing decline through 2100. Variation in the direct forcing components across models—positive and negative—is also prominent. Overall, net negative aerosol forcing declines 1 to 37 % by 2050 from 2005 levels, and minus 1 to 63 % by 2100.

The differences in total and net aerosol forcing over time stem from differences in economic activity levels, technological change, and air pollution emissions control assumptions, as well as modeling structure and the differences in base forcing conditions—all of which determine future pollutant emissions. Projected changes in reference aerosol and precursor emissions vary widely across the models and pollutants (Fig. 3). In most models, and for most pollutants, global emissions levels decline by 2100, but across models the patterns are very different. Some models exhibit a large variation in growth across pollutants (IMAGE), while others exhibit less variation (MERGE, REMIND). Models differ in which pollutants decline the most and least. For example, in GCAM, BC, OC, and NO_x decline the least, and SO_2 declines the most, while for IMAGE, BC and OC decline the most, and SO_2 and NO_x decline the least (after a period of increase for NO_x). It is useful to recall that SO_2 is the sole determinant of indirect cloud aerosol forcing in some models, while a combination of emissions determines cloud forcing in others. Thus, a stronger reduction in sulfur emissions relative to other aerosol emissions would produce a more significant reduction in cloud forcing when sulfur is the sole consideration.

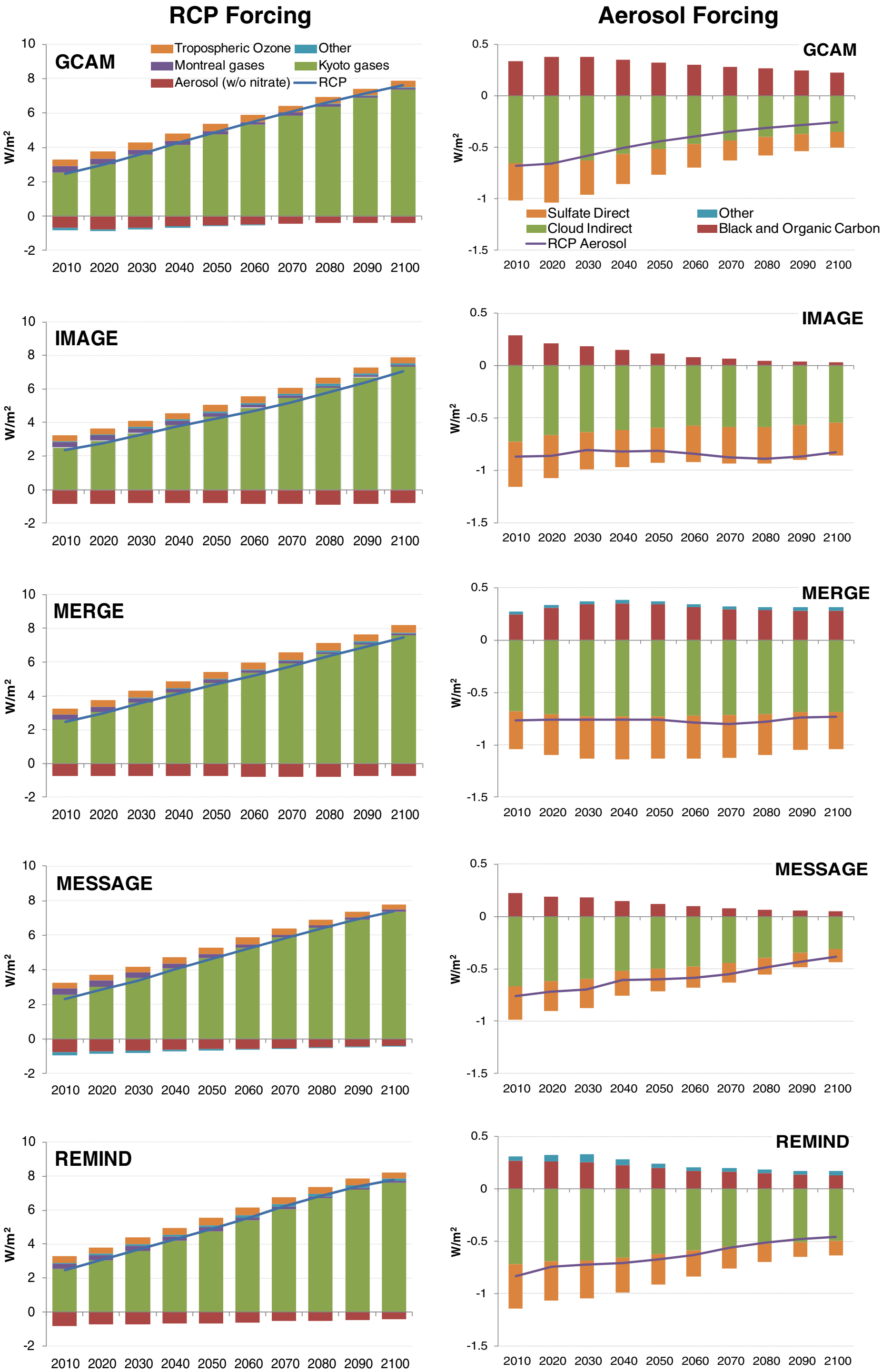

Fig. 2 Decomposition of reference RCP (*left*) and aerosol radiative forcing (*right*)

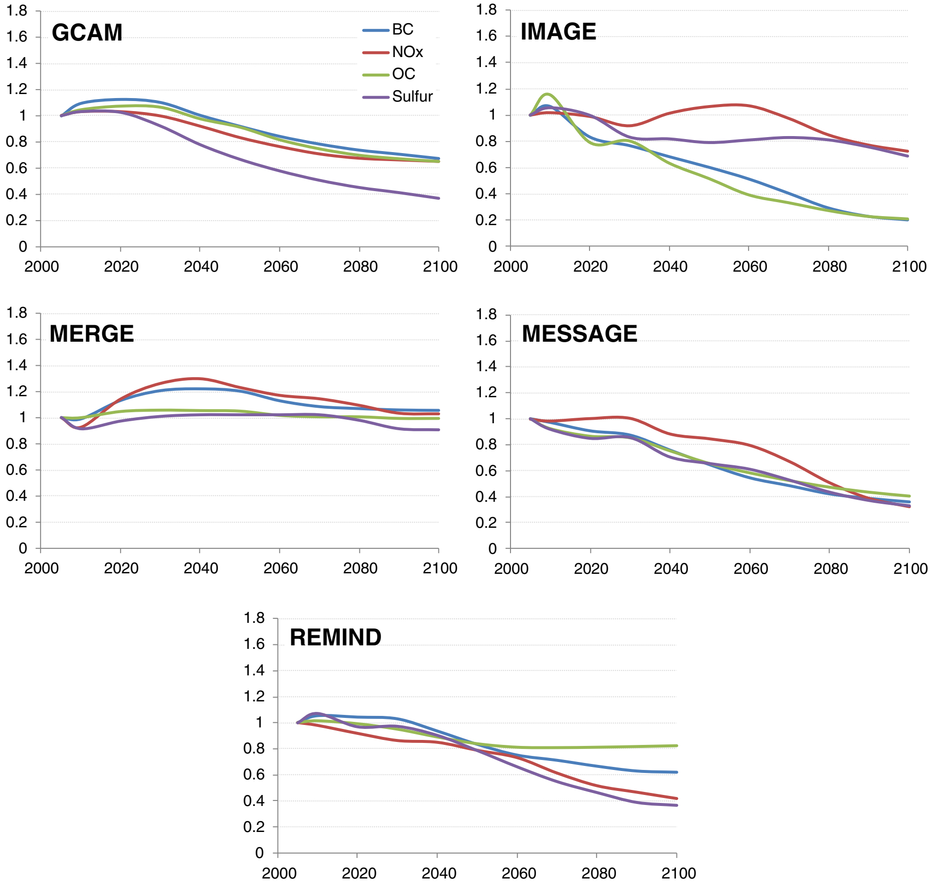

Fig. 3 Reference global SO_2, NO_x, BC, and OC emissions (2005=1)

Behind the differences in global aerosol emissions growth are variations in regional emissions (Supplemental Material). There are noteworthy differences in regional 2010 emissions that likely affect the emissions intensities of economic activities and subsequently projected emissions levels and growth. Non-OECD Asia is the largest regional source of SO_2 and NO_x at the beginning of the century in all the models, as well as BC in three of the models. By the end of the century, other developing and transitional economies are projected to dominate most aerosol emissions. The largest changes over time are in Asia, followed by the OECD. Asian SO_2 emissions are 20 to 80 % below today's emissions by 2100, while NO_x is 20 % above to 65 % below today's levels, and BC 5 % above to 80 % below. In the OECD, SO_2 is 45 to 90 % below today's emissions by 2100, NO_x is 35 to 80 % below, and BC is 25 to 85 % below. In the rest of the World, some models have little to no change from today by 2100, some show significant growth, and some project significant reductions (the later preceded by emissions growth during the century).

Overall, we found that the models have very different assumptions about air pollution policies, as well as resulting projected economies and energy systems. To understand these assumptions and the resulting model behavior, we explore emissions relationships—with income and with the energy system. With these we are able to look beyond differences in the level of emissions drivers, such as income and population, and explore comparable elements that are at the core of emissions, and radiative forcing, outcomes. Specifically, we evaluate relationships between income and aerosol emissions, aerosol emissions and CO_2 emissions, and aerosol emissions and energy use. The first relationship reveals the model implied income level at which per capita emissions peak and begin declining. The second reveals how readily aerosol emissions are decoupled from the energy system. The third allows us to decompose the second into changes in fuel mix versus pollution controls. Each is defined explicitly below. Due to space constraints, our presentation focuses on aerosols, and primarily SO_2 emissions.

Economic theory suggests that willingness to pay for environmental quality increases with income and that there is, as a result, a point at which environmental degradation peaks and declines as demand for environmental quality increases with additional income. This relationship, an inverted U-shaped correlation, is known as an Environmental Kuznets Curve (EKC). See, for instance, Frank and Bernanke (2005). The theory is that developing countries will follow a similar transition to environmental quality as developed countries. Empirical work suggests that, while there is a general tendency towards lower pollution emissions as incomes increase, there is not a single universal relationship between air pollutant levels, or emissions, and incomes that is relevant to all countries (Stern 2004, 2005; Carson 2010). This literature suggests that country-specific factors dominate.

All of the models evaluated here utilize hybrid EKC-based relationships to represent air pollution policy, some with country specific adjustments, such as for recent emissions trends and governance. In Fig. 4, we present the implied EKC relationships within the models for SO_2 emissions in China and India. These relationships are implied because they are derived from model results. In Fig. 4, per capita income growth is correlated with time. First, we note the substantial differences across models in projected per capita income levels by the end of the century. See the "Supplemental Material" for the reference projections for GDP per capita, GDP, and population for China and India. Note, that per capita income is higher when purchasing power (PPP) is considered, which reflects the value of domestic income given domestic prices versus the market exchange rate value of income (MER).[3] In China, there is large variation in initial per capita SO_2 emissions, which has implications for projected total emissions over time. China's per capita SO_2 emissions have declines significantly during the last decade due to the introduction of stricter emission limits followed by an ambitious program of installing flue gas desulfurization on power plants (Lu et al. 2010; Klimont et al. 2013). Per capita SO_2 in China peaks at different income levels across the models, ranging from less than \$1,700 to \$5,200 in MER per capita income, where the lower end of the range corresponds to two models that suggest that peak per capita SO_2 emissions have already passed in China at per capita income levels less than or equal to \$1,700 (MERGE, MESSAGE). In PPP terms, the peaks occur at higher per capita income levels, and are less pronounced, but are still very different across models (<\$4,100, \$6,100, and \$14,300). There is also significant variation in the rates of decline in per capita SO_2 in China following the peaks—the more rapid the decline, the more aggressive the assumed adoption of pollution policy and technologies with economic growth. Finally, per capita emissions never fall to zero. The lowest levels are reached at per capita income levels ranging from \$14,400 to over \$75,000 (MER), with some models having twice the per capita emissions as others.

[3] Not all models reported PPP based income. Differences in PPP per capita GDP in China by the end of the century are \$43,900 to \$116,900.

In India, we find a very different picture for per capita SO_2. First, per capita emissions are lower in general than in China due to the differences in population and SO_2 source composition and the resulting levels. The EKC peaks are also less prominent, and in some cases are barely evident (IMAGE). Overall, there is less agreement than in China regarding peaks, with per capita SO_2 peaks in India ranging from $3,600 to $22,200 in MER per capita income. In PPP terms, like with China, the peaks occur at higher per capita income levels, and are less pronounced ($12,000, $19,600, $40,800).

The lack of consensus in Fig. 4 is not unreasonable given that, as noted above, income is not a unique proxy for pollution policy. However, the uncertainty shown also illustrates that a range of pollution policy assumptions have been made in current projections, and therefore, subsequent analysis would be valuable. Next, we evaluate how reference aerosol emissions change with respect to the energy system. We do so by analyzing the ratio of global SO_2 emission to global energy and industry carbon dioxide emissions (E&I CO_2). Across models, we find a significant decline in the ratio over time, which represents a rapid decoupling of SO_2 from E&I CO_2 emissions (Fig. 5a). Most of the decoupling occurs by 2050. Specifically, by 2050, the ratio of SO_2 to E&I CO_2 is 30 to 40 % of 2005 ratios after average annual decreases of 2 to 3 % per year through 2050. How much of the decoupling is due to a change in fuel mix versus tighter pollution controls? We find that four out of the five models exhibit increased CO_2 energy intensity (CO_2 per unit biomass and fossil primary energy), which implies an increased share of carbon-intensive fossil fuels in primary energy (Fig. 5b). All of the models also exhibit decreases in aerosol emissions per unit biomass and fossil primary energy. Thus, almost all the models are supporting economic growth with a gradually increasing dependence on carbon-intensive fossil fuels and bioenergy, while substantially tightening pollution controls, with reduction rates tending to be larger for OC, BC, and SO_2. Note that BC and OC reductions are in large part a co-benefit of particulate matter controls, and substitution away from traditional biomass, which has a large emissions coefficient.

3.2 Climate policy scenarios

From the previous section we saw that non-Kyoto forcing, in particular aerosols, could mask significant positive radiative forcing in the reference scenario. It is therefore logical to ask what role does masking play under a climate policy; or, more generally, what happens to non-Kyoto forcing under a climate policy? In this section, we first explore the implications for emissions, and then for forcing. Greenhouse gas mitigation calls for a reduction in the net

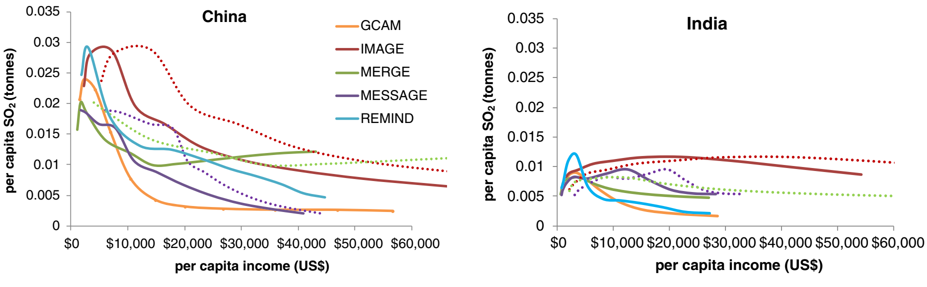

Fig. 4 Income-SO_2 relationships for China and India. Notes: *solid line* = GDP measured using market exchange rates, *dotted line* = GDP measured using regional purchasing power parity. IMAGE and MERGE PPP per capita income exceeds $60,000 (in 2100, it is $117,000 and $103,000 in IMAGE and MERGE respectively)

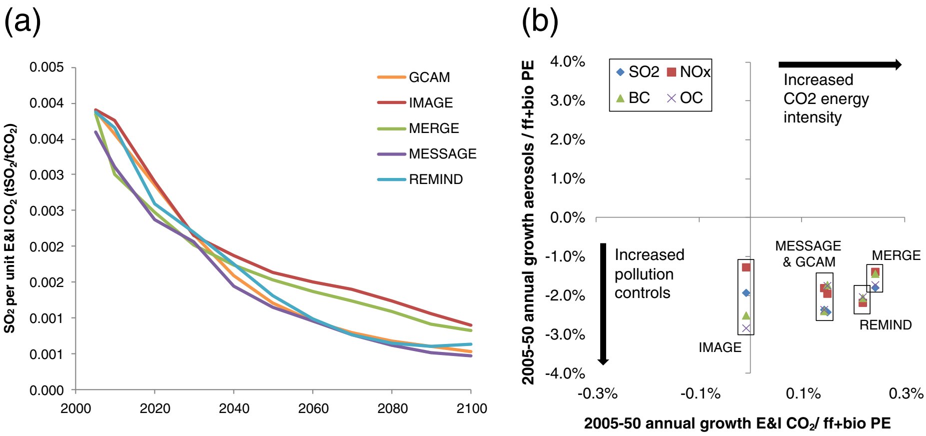

Fig. 5 Global SO_2 and energy system relationships – **a** SO_2 per unit energy and industry CO_2, and **b** growth in aerosol and energy and industry CO_2 emissions per unit fossil fuel plus biomass primary energy

emissions of carbon dioxide, and other GHGs, which requires a reduction in fossil fuel use, shifts towards high efficiency fossil fuel technologies, and use of carbon dioxide capture and geologic storage technologies (CCS), which lowers emissions of most local air pollutants. As a result, aerosol and tropospheric ozone precursor emissions also tend to be reduced as fossil fuel emissions are squeezed out of the economy. Specifically, total aerosol emissions are less under the climate policy than under the air pollution policy alone. In China, for instance, the 3.7 W/m^2 policy pushes SO_2 emissions to 15 to 55 % below reference levels by 2030 and 45 to 80 % below by 2050 (Supplemental Material). In the 2.8 W/m^2 policy, China SO_2 emissions are 30 to 70 % below reference levels by 2030, and 60 to 85 % below by 2050.[4] The deviations from reference in pollution emissions varies across models, as it is a function of the sectors where GHG mitigation occurs within each model and differences in sectoral aerosol emissions intensities. Note that pollution control technologies are still assumed for the remaining energy system.

The largest forcing changes under the climate policies are to Kyoto forcing (Fig. 6). However, non-Kyoto forcing changes are also a part of the story—potentially softening the mitigation challenge or making it more difficult. In Fig. 6, we separate non-Kyoto forcing into net aerosol forcing and other non-Kyoto forcing. The former is net negative and the later is net positive throughout the century. Thus, they are offsetting, with some models projecting net positive non-Kyoto forcing (net warming contribution), while others projecting net negative non-Kyoto forcing (net cooling contribution). The net effects vary with time and can switch sign.

Significant changes in non-Kyoto forcing from reference occur in the 3.7 W/m^2 scenarios. The 2.8 W/m^2 scenarios produce only modest additional changes. Changes in non-Kyoto forcing relative to Kyoto forcing are largest in the near-term and decline over time. In 2050, aerosol masking is reduced significantly from reference masking (10 to 60 %) with the residual aerosol masking with climate policy 5 to 12 % in 2050 under both policies and 3 to 8 % and 4 to 10 % in 2100 under the 3.7 and 2.8 policies respectively.

The implications of residual masking, and non-Kyoto forcing in total, are evident in the Kyoto forcing trajectories. For instance, in Table 1 for the 3.7 and 2.8 W/m^2 policies, the

[4] Whether SO_2 emission deviate from the reference starting in 2010 or 2020 depends on when the climate policy starts in each model.

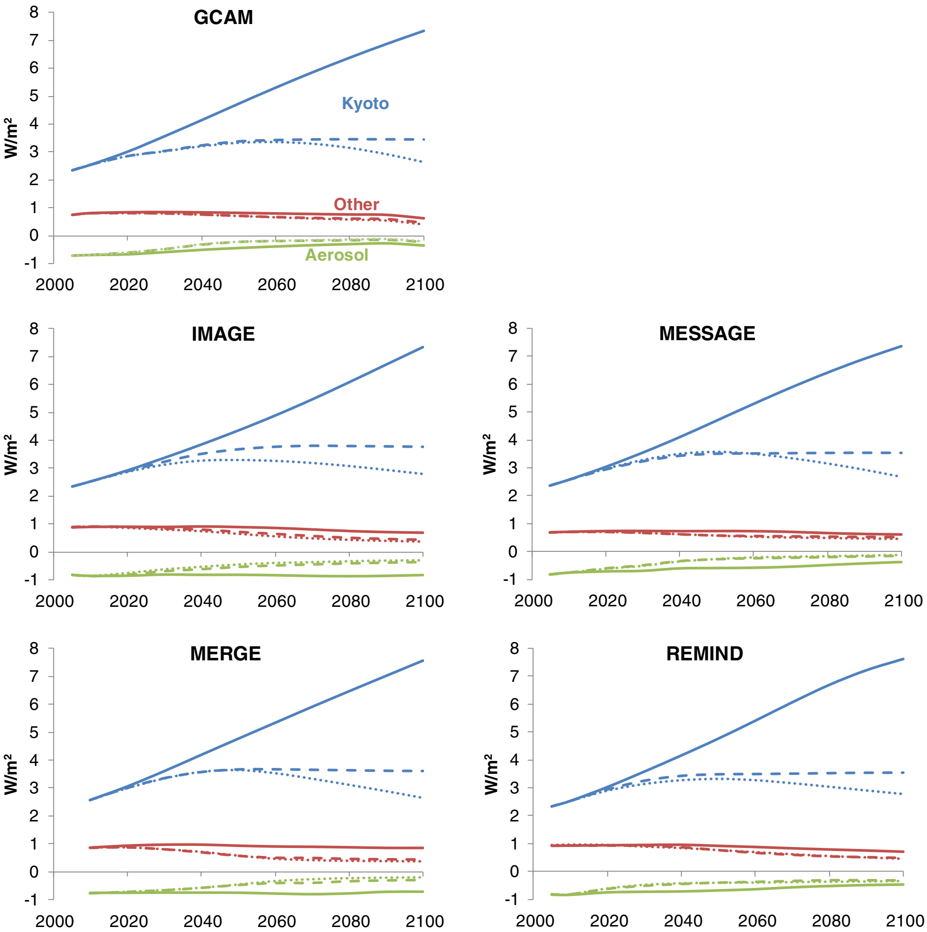

Fig. 6 Kyoto, aerosol, and other non-Kyoto RCP radiative forcing in reference and climate policy scenarios (*solid*/*dashed*/*dotted* = reference/3.7 W/m^2/2.8 W/m^2 scenarios)

Kyoto forcing pathways reflect the non-Kyoto pathways. Non-Kyoto forcing in 2050 ranges from 0.01 to 0.29 W/m^2 and 0.04 to 0.29 W/m^2 in the 3.7 and 2.8 scenarios respectively. For the most part, models with lower 2050 and 2100 Kyoto forcing have higher 2050 and 2100 non-Kyoto forcing. Furthermore, though only a fraction of total forcing, the remaining non-Kyoto forcing is defining total RCP forcing. For instance, two models—MESSAGE and REMIND—report identical 2100 Kyoto forcing for their 3.7 scenarios (3.55 W/m^2), but differences in non-Kyoto forcing result in differences in RCP forcing of 0.10 W/m^2 (3.61 vs. W/m^2). Similar outcomes are seen in the 2.8 results between IMAGE and REMIND, and also between GCAM and MERGE.

Finally, we note that the models are reaching the targets with a range of CO_2 emissions budgets—1466 to 2078 $GtCO_2$ and 848 to 1200 $GtCO_2$ from 2005–2100 for the 3.7 and 2.8 W/m^2 policies respectively. During the first half of the century, the CO_2 emission budgets range from 1062 to 1576 $GtCO_2$ and 1017 to 1323 $GtCO_2$ respectively. Thus, some models are allowing respectively as much as 50 % and 30 % more CO_2 emissions than other

Table 1 Radiative forcing, CO_2 concentration and cumulative CO_2 emissions for 2.8 and 3.7 W/m^2 scenarios

Model	Forcing (W/m^2)						CO_2 concentration		CO_2 emissions	
	RCP		Kyoto		Non-Kyoto		(ppm)		($GtCO_2$)	
	2050	2100	2050	2100	2050	2100	2050	2100	2005–2050	2005–2100
3.7 W/m^2 target										
GCAM	3.67	3.70	3.38	3.45	0.29	0.25	431	427	1062	1466
IMAGE	3.70	3.74	3.67	3.76	0.02	−0.02	469	470	1576	2078
MERGE	3.67	3.70	3.66	3.61	0.01	0.09	472	454	1393	1807
MESSAGE	3.62	3.71	3.52	3.55	0.10	0.17	444	432	1285	1653
REMIND	3.70	3.61	3.49	3.55	0.21	0.07	456	459	1394	1765
2.8 W/m^2 target										
GCAM	3.62	2.85	3.33	2.64	0.29	0.21	427	371	1017	848
IMAGE	3.34	2.77	3.29	2.79	0.06	−0.02	443	408	1270	1200
MERGE	3.69	2.80	3.65	2.64	0.04	0.16	465	381	1322	986
MESSAGE	3.67	2.81	3.56	2.68	0.11	0.14	447	378	1323	1064
REMIND	3.54	2.83	3.33	2.79	0.21	0.04	442	397	1219	923

models. There is some evidence of an inverse correlation between CO_2 budgets and non-Kyoto forcing (IMAGE vs. GCAM). Some of the models with more (less) cumulative CO_2 have smaller (larger) non-Kyoto forcing. In general, in the second half of the century, the models allow additional CO_2 emissions under the 3.7 policy and pursue net negative emissions under the 2.8 policy. However, we still see evidence of an inverse CO_2 budget and non-Kyoto forcing correlation, with the correlations stronger for the 3.7 policy.

Non-Kyoto forcing is not the only factor at play. Differences in carbon cycle modeling are clearly important as indicated by notable variation in cumulative CO_2 emissions over the century yet similar Kyoto forcing in 2100 in the 2.8 results. Also important are differences in emissions pathways and negative emissions technologies. An explicit, and more rigorous, evaluation of the relationship between Kyoto and non-Kyoto forcing, as well as these other factors, would be beneficial.

4 Conclusion

It is important to model non-Kyoto forcing for analyzing climate change scenarios. Integrated assessment models have begun to do so, but only a handful of models have developed this capability. Overall, modeling of non-Kyoto forcing is developing and beset with uncertainty. This modeling relies on scientific understanding regarding climatology and atmospheric chemistry. In this study, we present and evaluate current integrated assessment modeling of non-Kyoto forcing.

In evaluating scenarios, we find aerosols masking (offsetting) about 25 % of positive forcing today in reference scenarios. But, masking is projected to decline rapidly to approximately 10 to 15 % by 2050 and 5 to 10 % by 2100, with growth in Kyoto forcing over the century and reductions in non-Kyoto forcing primarily in the first half of the century. However, the composition of projected reference non-Kyoto forcing varies across models, as does projected precursor pollutant emissions, due to a variety of factors.

We find similarities in modeling, but also important differences that likely affect projections. There are differences in base forcing conditions and emissions inventories, economic activity, and population projections, as well as in pollution control assumptions. There are very different relationships across models between air pollutants and income and the energy system.

In climate policy scenarios, we find that pollutant emissions are driven by climate policy and reduced below levels dictated by air pollution policies alone. We also find non-Kyoto forcing diminished under climate policies, but affecting Kyoto emissions mitigation and total forcing outcomes, including allowable carbon dioxide emissions over the century.

We also conclude that internal model consistency is paramount for modeling long-run concentration, forcing, and temperature. The five models involved in this study are all unique, with model specific elements (assumptions and structure) abundant. Together, these elements define energy, economic, and biophysical relationships within a model that have implications for model responses and projection results.

Finally, it is important to acknowledge and consider uncertainties. Each model in this study provided only one realization of potential non-Kyoto forcing for each reference and policy scenario. However, there are prominent historical uncertainties regarding forcing, emissions, and socioeconomic relationships. There are also future uncertainties regarding socioeconomomics, technology, policy, and their relationships. For instance, there is uncertainty about the level of air pollution regions will be willing to tolerate, and the resulting implications for pollutant projections. These uncertainties need to be evaluated.

A number of additional research opportunities arise from this study. There are non-Kyoto forcing modeling issues regarding resolution, emissions to forcing translations, and pollution emissions modeling that could have implications for climate projections and policy. Unlike greenhouse gases, non-GHGs do not mix uniformly, and regional rates of aerosol and ozone formation as well as forcing per unit mass can vary. Thus, the forcing implications of non-GHG emissions can vary by location. Current integrated assessment modeling does not capture most of these complexities. In the future, physical estimates of the spatial forcing efficacy of non-GHG emissions may be important for improving the integrated assessment modeling representation of the relative forcing contributions of regional emissions over time. There are also other forcing elements to consider that contribute to full forcing but were outside the scope of this study. Further model development and comparison on these issues would be valuable to the design of climate change strategies, as well as evaluation of linkages between air pollution and climate policy.

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