

# How well do integrated assessment models represent non-CO<sub>2</sub> radiative forcing?

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**Abstract** This study aims to create insight in how Integrated Assessment Models (IAMs) perform in describing the climate forcing by non-CO<sub>2</sub> gases and aerosols. The simple climate models (SCMs) included in IAMs have been run with the same prescribed anthropogenic emission pathways and compared to analyses with complex earth system models (ESMs) in terms of concentration and radiative forcing levels. In our comparison, particular attention was given to the short-lived forcers' climate effects. In general, SCMs show forcing levels within the expert model ranges. However, the more simple SCMs seem to underestimate forcing differences between baseline and mitigation scenarios because of omission of ozone, black carbon and/or indirect methane forcing effects. Above all, results also show that among IAMs there is a significant spread (0.74 W/m<sup>2</sup> in 2100) in non-CO<sub>2</sub> forcing projections for a 2.6 W/

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m<sup>2</sup> mitigation scenario, mainly due to uncertainties in the indirect effects of aerosols. This has large implications for determining optimal mitigation strategies among IAMs with regard to required CO<sub>2</sub> forcing targets and policy costs.

## 1 Introduction

Integrated assessment models (IAMs) are important tools to inform policy-makers about different aspects of climate policy by providing an integrated view on topics like technology development, mitigation costs and functioning of the earth system. Given the complexity involved in integrating these different topics, these models need to represent the relevant aspects in a simplified way. This implies, for instance, that the earth system is represented by simplified equations often derived from results of simulations with state-of-the-art earth system models. The way IAMs represent the earth system can have a considerable impacts on their results regarding optimal emission strategies and related policy costs (Hof et al. 2012).

Van Vuuren et al. (2011b) presented a detailed comparison of the representation of the carbon cycle and climate system in different IAMs. It was concluded that the representations of the carbon cycle in IAMs mostly lie within the range of earth system models (referred to as “expert models”). Yet, it was also shown that the representation of these factors leads to very different results across IAMs.

In this study, we present a similar diagnostic analysis, but now focusing on the non-CO<sub>2</sub> representation. It has been shown in various studies that using a multigas response strategy (including non-CO<sub>2</sub> greenhouse gas emissions) leads to considerably lower mitigation policy costs than a CO<sub>2</sub> only strategy to achieve a set radiative forcing target (Rao and Riahi 2006; Van Vuuren et al. 2006; Weyant et al. 2006). Differences between models in the representation of non-CO<sub>2</sub> forcing therefore can be very relevant for the projected mitigation costs.

The central question of this study is: “*How do the representations of different non-CO<sub>2</sub> climate parameters in IAMs compare to those of expert models?* “. In answering this question, we look at the concentration and forcing representation of simple climate models (SCMs) included in IAMs regarding CH<sub>4</sub>, N<sub>2</sub>O, ozone and aerosols and compared the outcomes of SCMs to state-of-the-art atmospheric chemistry models (expert models). The research entails running prescribed emissions scenarios with the SCMs and by recording the concentration and forcing outcomes. The prescribed scenarios (Representative Concentration Pathways (RCPs)(Van Vuuren et al. 2011a) and scenarios describing short-lived climate forcers (UNEP and WMO 2011)) were selected to allow comparison with relevant outcomes of the expert models from the literature.

## 2 Methods

### 2.1 Models

In order to understand how different IAMs perform in describing the forcing representation of non-CO<sub>2</sub> gases, the outcomes of these IAMs have been compared to those of state-of-the-art atmospheric chemistry models. Note that projections from these expert models are also uncertain, but can be considered the most reliable source of information. We have looked into the representation of multiple IAMs: MERGE\_ETL, MERGE5.1, FUND3.7, PAGE09 and

DICE2013R. Since the concentration and forcing equations within these models are relatively simple, they are referred to as simple climate models (SCMs). We also included MAGICC, a much more complex stand-alone SCM used by most, more detailed IAMs (e.g. MESSAGE, REMIND, IMAGE, WITCH and AIM), which form a vital source of information for international climate policy. For this study we made a distinction between the two latest versions; MAGICC5.3 and MAGICC6.3 (see Table 1 for a description of the participating models).

The equations for deriving concentrations of non-CO<sub>2</sub> gases in most of the SCMs are based on a single or double box model representation of the global atmosphere. They are based on an incoming flow (emissions) and an outgoing flow (removal, often represented by a simple atmospheric decay function). MAGICC forms an exception in this respect with non-linear relationships between concentration levels and removal as well as temperature impacts on atmospheric chemistry. For most radiative forcing calculations, a linear or logarithmic relationship is used based on concentrations, while forcing of aerosols is scaled with emissions. Sulphate forcing is represented by an exogenous (scenario-independent) variable in DICE, MERGE and FUND. For sulphate aerosols in MAGICC and PAGE, a linear relationship is assumed for the direct forcing and a logarithmic relationship for indirect forcing. Aerosols other than sulphate (black carbon (BC), organic carbon (OC) and nitrate), tropospheric ozone and several indirect forcing effects are only represented in MAGICC. Unlike MAGICC5.3, MAGICC6.3 has the option of generating efficacy-adjusted radiative forcing (EARF) values. These are radiative forcing values corrected for differences in geographical and vertical distributions of forcing agents that influence the surface temperature response, e.g. via cloud forming and surface ice albedo effects. Although uncertain, with the correction factor (or “efficacy”), EARF is found to be a better estimator of the global climate response (Hansen et al. 2005; Joshi et al. 2003). Particularly, for the comparison of short-lived climate forcers with an uneven global distribution this concept is useful, and is therefore used here for the analysis of aerosol forcings.

## 2.2 Approach

In order to ensure a fair comparison, all models have been run with prescribed anthropogenic emission pathways and with equal concentration levels in the start year 2000. As output, projected concentrations and radiative forcing (RF) levels have been recorded. A key question is how these simple representations of non-CO<sub>2</sub> gas and aerosol behaviour included in IAMs compare to the complex behaviour of atmospheric chemistry models (also referred to as expert models here). Therefore, we ran experiments that have also been run by such expert models.

- **RCPs:** The first experiment constitutes the RCP2.6 and RCP8.5 emission scenarios between 2000 and 2100 (See Fig. 1 and the [Supplementary Material](#) for the emission pathways used in the models)(Van Vuuren et al. 2011a). The atmospheric-climatic effects of the RCP scenarios have been thoroughly analysed in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP) by 16 complex atmospheric chemistry models (Lamarque et al. 2013; Shindell et al. 2013). With respect to RF, ACCMIP is particularly detailed in analysing aerosol effects of which uncertainties are generally high. Since model differences in the spatial pattern of forcing by well-mixed greenhouse gases (WMGHGs) are small, the WMGHG forcing pattern projections relied on two expert models (NCAR-CAM3.5 and GISS-E2-R). Their average forcing pattern was scaled to the total WMGHG RF as originally determined for the RCPs, based on MAGICC6.

**Table 1** Participating climate models with description of underlying emissions-concentration- forcing relations. For radiative forcing, a distinction is made between well mixed greenhouse gases (WMGHGs) and short-lived, unevenly distributed forcing agents ( $O_3$  and aerosols) (See [Supplementary Material](#) for additional information)

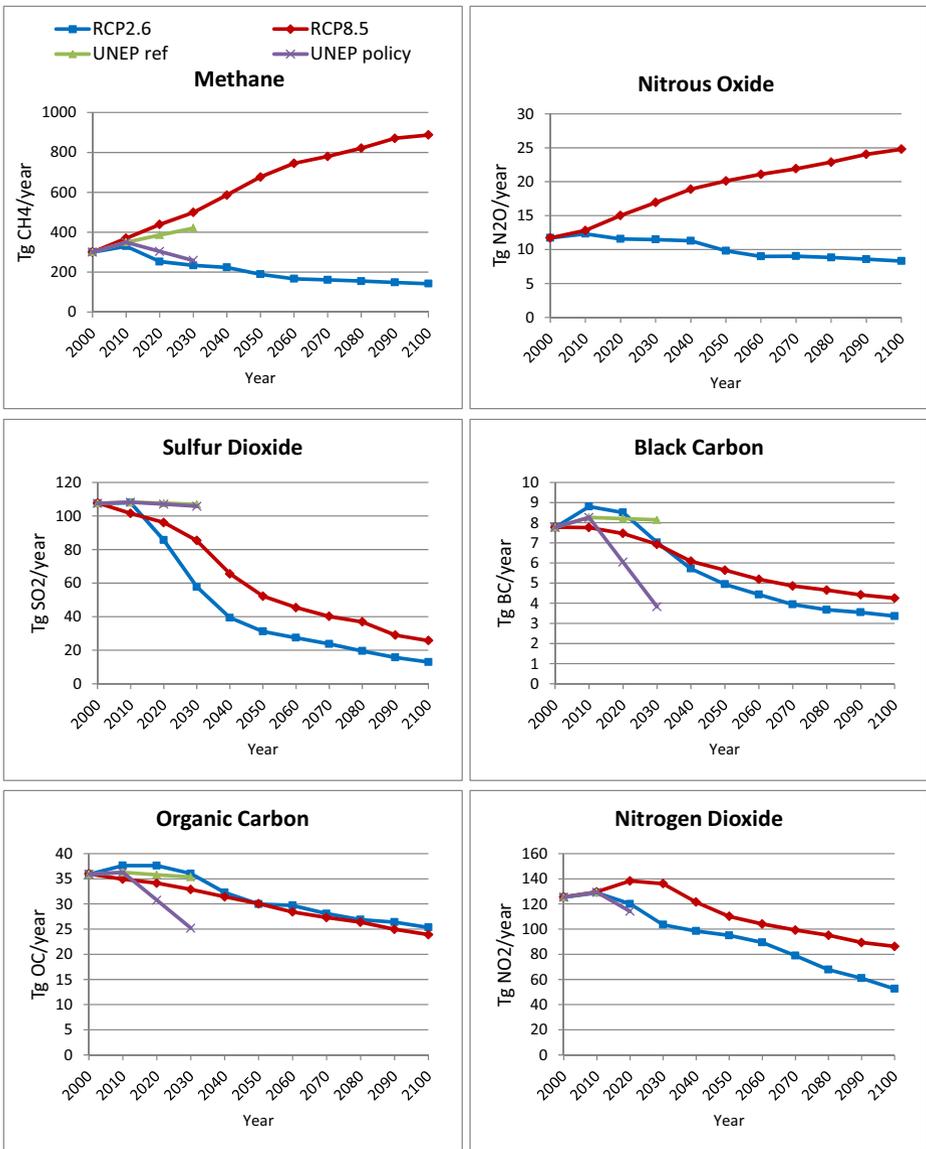
Concentrations		Radiative Forcing		Main Reference	
MAGICC 6.3	<p><math>CO_2</math> (Carbon cycle)</p> <p>Mass balance model based on fluxes between 6 global reservoirs calibrated to C4MIP. Includes updates such as temperature feedback on <math>CO_2</math> fertilization.</p>	<p>Non-<math>CO_2</math></p> <p>Updated concentration equations based on (Ehhalt et al. 2001)</p>	<p>WMGHGs</p> <p><math>CO_2</math>, <math>CH_4</math>, <math>N_2O</math> and 28 halogenated gases (mostly F-gases). Calculations based on IPCC AR4. Includes oxidizing effect <math>CH_4</math> to <math>CO_2</math>.</p>	<p><math>O_3</math>/Aerosols</p> <p><math>O_3</math> forcing derived from precursor concentrations via (Ehhalt et al. 2001)</p> <p>Aerosols: sulphate, BC, OC, nitrate. Direct aerosol forcing scaled with emissions.</p> <p>Patterns based on (Hansen et al. 2005). Includes indirect aerosol effects.</p>	<p><a href="http://www.magicc.org/">http://www.magicc.org/</a> (Meinshausen et al. 2011)</p>
MAGICC 5.3 <sup>a</sup>	<p>See MAGICC 6.3, minus temperature feedback update.</p>	<p>Same as MAGICC6.3</p>	<p>See MAGICC 6.3, minus <math>CH_4</math> oxidizing effect.</p>	<p>Same as MAGICC6.3<sup>a</sup></p>	<p><a href="http://www.magicc.org/">http://www.magicc.org/</a> (Wigley 2008)</p>
MERGE-ETL	<p>5 integrals based on emission pulse-response function (Maier-Reimer and Hasselmann 1987).</p>	<p>Single box representations with decay functions.</p>	<p><math>CO_2</math>, <math>CH_4</math>, <math>N_2O</math>, F-gases (based on SF6 and HFC 143a emissions). Function of concentration (linear and logarithmic) based on TAR (IPCC 2001)</p>	<p><math>O_3</math> not included.</p> <p>Sulphate forcing exogenous, and scenario dependent</p>	<p><a href="http://www.psi.ch/eem/methods-and-tools">http://www.psi.ch/eem/methods-and-tools</a></p>
MERGE 5.1 <sup>b</sup>	<p>Same as MERGE-ETL</p>	<p>Same as MERGE-ETL</p>	<p>Same as MERGE-ETL, but with simplified interaction term between <math>CH_4</math> and <math>N_2O</math></p>	<p><math>O_3</math> not included.</p> <p>Sulphate (exogenous)</p>	<p><a href="http://www.stanford.edu/group/MERGE/GERAD1.pdf">http://www.stanford.edu/group/MERGE/GERAD1.pdf</a></p>
DICE 2013R	<p>Box description of in/out flows of three reservoirs: atmosphere, upper oceans and deep oceans.</p>	<p>Not modelled.</p>	<p><math>CO_2</math> forcing: logarithmic function based on benchmark with several Earth System Models (ESMs)</p> <p>Total non-<math>CO_2</math> forcing exogenously modelled (scenario independent and linearly increasing towards 2100).</p>	<p>Not included. See WMGHGs.</p>	<p><a href="http://dicemodel.net">http://dicemodel.net</a></p>

**Table 1** (continued)

	Concentrations	Radiative Forcing	Main Reference
PAGE09	Pulse-response function (one exponential decay time)	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O, F-gases (latter represented by one variable). Function of concentration (linear, square root and logarithmic) based on TAR (Meinshausen et al. 2011)	O <sub>3</sub> not included. Sulphate forcing scaled with emissions (including indirect effect) <a href="http://www.jbs.cam.ac.uk/fileadmin/user_upload/research/workingpapers/wp1104.pdf">http://www.jbs.cam.ac.uk/fileadmin/user_upload/research/workingpapers/wp1104.pdf</a> (Hope 2006, 2013)
FUND 3.7	Pulse-response function (based on (Maier-Reimer and Hasselmann 1987))	CO <sub>2</sub> , CH <sub>4</sub> , N <sub>2</sub> O, F-gases (exogenous). Linear and logarithmic relations based on TAR (Meinshausen et al. 2011). Including indirect CH <sub>4</sub> effect.	O <sub>3</sub> not included. Sulphate (exogenous)

<sup>a</sup> This MAGICC 5.3 version is used by MESSAGE and has been upgraded to specify BC and OC emissions explicitly (based on: (Smith and Bond 2014)). In the original version BC and OC emissions are generally scaled with CO emissions

<sup>b</sup> One change in MERGE 5.1 was made to take into account a N<sub>2</sub>O related correction included in the latest MERGE versions. Information on the latest MERGE versions can be found in (Blanford et al. 2013; Rose et al. 2013)



**Fig. 1** Emission pathways of CH<sub>4</sub>, N<sub>2</sub>O, aerosols/aerosol precursors and ozone precursors in RCP2.6, RCP8.5, the UNEP reference and policy scenarios (see [Supplementary Material](#) for all emissions used)

- UNEP Integrated Assessment of Black Carbon and Tropospheric Ozone:** In a second experiment, we used the emission pathways up to 2030 from the UNEP Integrated Assessment of Black Carbon and Tropospheric Ozone report (Shindell et al. 2012; UNEP and WMO 2011). By implementing the reference and mitigation policy emission scenarios from the report in SCMs, we assessed to what extent the SCMs produce results similar to those presented in the UNEP report. The latter is based on the expert models ECHAM5-HAMMOZ and GISS-PUCCINI.

Wherever possible we have looked at the forcing levels for separate components. The SCMs differ in the number of included gases and aerosols as well as in the complexity and number of forcing effects. For CH<sub>4</sub>, N<sub>2</sub>O and sulphate, most models could be compared. For ozone (O<sub>3</sub>) only projections from MAGICC could be compared with those in ACCMIP. In DICE, an exogenous scenario-independent variable is used to account for all non-CO<sub>2</sub> effects, so the model has no outcomes for individual species. While several models (FUND, DICE, PAGE) can be run stochastically, in this analysis all models other than PAGE were run using mean values without probabilistic distributions in reproduced versions based on the models' source code. Uncertainty ranges are shown for PAGE.

### 3 Results

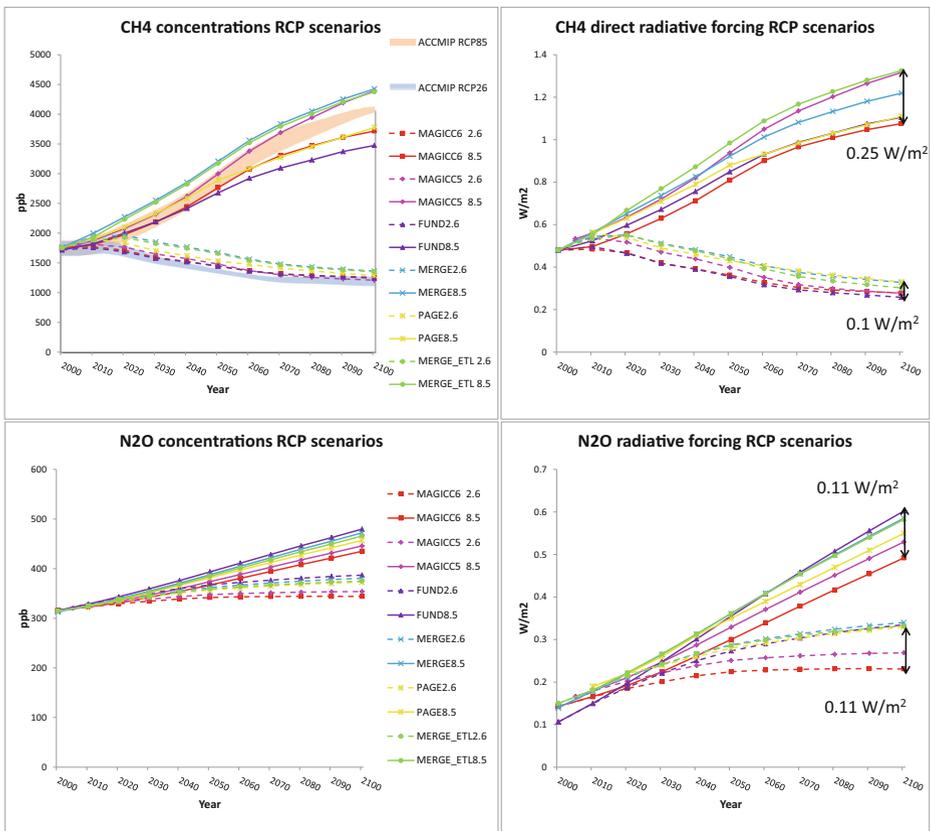
#### 3.1 Representation of CH<sub>4</sub> concentration and radiative forcing

The CH<sub>4</sub> emissions from RCP2.6 and 8.5 are shown in Fig. 1. By using these emissions as input, the SCMs somewhat diverge in terms of the concentrations in 2100 – especially for the RCP8.5 scenario (see Fig. 2, upper left panel). Overall, the SCM results seem to be consistent with those projected by the expert models in ACCMIP. Note however, that the ACCMIP range is defined by only two models that recorded a long-term projection (LMDzORINCA and GISS-E2-R), and should only serve as an indication of the trend. This projection corresponds with a study of future uncertainties in methane abundance, which concludes that the methane concentration in 2100 in RCP8.5 is  $3990 \pm 330$  ppb (Holmes et al. 2013). Compared to this range, the projections of MERGE, MERGE\_ETL and MAGICC5.3 are slightly high and those of FUND slightly low. MERGE and MERGE\_ETL also show high concentrations for RCP2.6. In contrast, the FUND concentration levels are relatively low for RCP8.5. This can be attributed to the use of a lower atmospheric lifetime of CH<sub>4</sub> than the estimated perturbation lifetime of approximately 12 years (IPCC 2013)(Ch.6). For RCP2.6 in general, the difference between models is smaller than for RCP8.5 because of the much smaller relative influence of anthropogenic emissions. This leads to concentration levels closer to the more certain background concentration of CH<sub>4</sub> (approximately 790 ppb).

All models use a very similar way to translate concentration into forcing, which leads to a very similar picture (Fig. 2, upper right panel) (see [Supplementary Material](#) for a visualisation of this relation for CH<sub>4</sub> and N<sub>2</sub>O). For RCP8.5 this results in a difference across models of 0.25 W/m<sup>2</sup>. For RCP2.6 this value is 0.1 W/m<sup>2</sup>.

#### 3.2 Representation N<sub>2</sub>O concentration and radiative forcing

For N<sub>2</sub>O (Fig. 2, lower left panel), the differences across models for reported concentration levels are similar for both scenarios, varying between 435 and 480 ppb in 2100 in RCP8.5 and between 344 and 387 ppb in RCP2.6. In general, N<sub>2</sub>O concentration projections for MAGICC (particularly MAGICC6.3) are relatively low compared to the other SCMs. Unlike the other models, MAGICC includes natural N<sub>2</sub>O emissions, derived from historical time series of N<sub>2</sub>O concentration profiles. In the model, atmospheric decay is applied to the complete atmospheric burden of N<sub>2</sub>O, not merely to the anthropogenic part. With the current calibration, the decay of the natural background concentration is larger than the influx by natural emissions. As such, this could lead to an overestimation of the decay of N<sub>2</sub>O, in turn resulting in lower atmospheric



**Fig. 2** Projected concentration and radiative forcing levels for CH<sub>4</sub> (upper panels) and N<sub>2</sub>O (lower panels) in RCP2.6 and RCP8.5. The ACCMIP expert model ranges for CH<sub>4</sub> concentration are based on two models and are used as an indicative benchmark

concentrations. This should be verified in further studies, since unfortunately, there is no information from the expert models available to compare the results to.

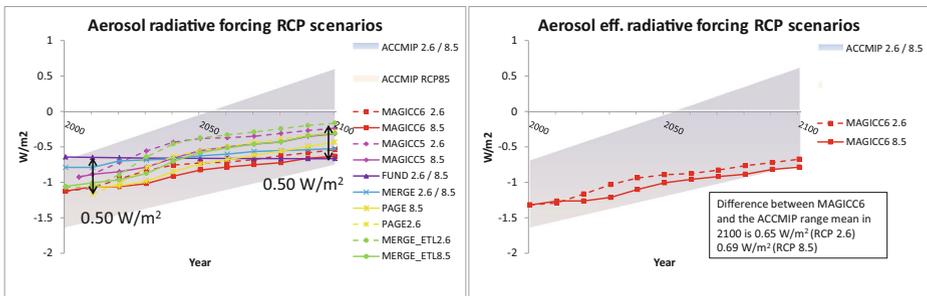
As with CH<sub>4</sub>, all models use a rather similar way to translate N<sub>2</sub>O concentration into forcing, and therefore both panels (Fig. 2, lower two) show comparable results. The overall spread in forcing outcomes across the models in 2100 is 0.11 W/m<sup>2</sup> for both scenarios, much smaller than for methane in RCP8.5 and slightly larger in RCP2.6.

### 3.3 Representation aerosol radiative forcing

As for other physical and chemical processes, the representation of aerosols is considerably more simplified in SCMs than in the ACCMIP models. In fact, only MAGICC explicitly describes aerosol forcing other than sulphate (BC, OC and nitrate). All models except FUND and DICE make an explicit distinction between direct (scattering and absorbing) and indirect (cloud forming) effects of aerosols. FUND and MERGE (unlike MERGE\_ETL) make use of scenario-independent forcing pathways. This means that they do not respond to differences in emission pathways. Although these models use only simplified approximations of aerosol RF, this is the only aerosol related input they use as a basis for further economic analysis.

Therefore, it is relevant to compare these RF projections within one aggregate aerosol category.

Figure 3 shows the aerosol forcing projections of the different models. The SCM projections in the left panel are the combined total of *direct and indirect aerosol forcing*. The right panel shows *effective aerosol forcing* (aerosol ERF) in which MAGICC6.3 is compared with ACCMIP. For both categories, the SCMs fall within the present day ACCMIP range. For total aerosol forcing, there is a wide spread in RF projections (0.50 W/m<sup>2</sup> in 2010 and 2100 for RCP2.6) compared to CH<sub>4</sub> or N<sub>2</sub>O and compared to the total forcing of 2.6 W/m<sup>2</sup>. The ACCMIP range shown in both panels of Fig. 3 is the aerosol ERF projection, and is strictly speaking not an exact comparison for the SCM RF projections. Yet both are used as a comparable input for modelling temperature response in the different models. Aerosol ERF as used in ACCMIP is also slightly different from EARF as calculated by MAGICC6.3 (see [Supplementary Material](#)). Also here the comparison is relevant as both concepts are used as inputs proportional to the global temperature response. The depicted (stylized) aerosol ERF range in ACCMIP is based on the uncertainty ranges in 2000 and 2100 for RCP8.5. Because of large similarities in aerosol precursor global emissions between the scenarios, ACCMIP RCP8.5 results were also used for RCP2.6, but with a larger assumed uncertainty range. For the 2100 projection, five expert models were used of which three reached values close to -0.3 W/m<sup>2</sup> and two were distinct, possibly questionable, outliers (0.55 W/m<sup>2</sup> and -0.76 W/m<sup>2</sup>). The aerosol ERF mean in 2100 as used in ACCMIP is -0.12 W/m<sup>2</sup> and was derived by using multi-model averages for the total effect in 2000 and the change in ERF towards 2100. This relatively small value can be attributed to a general decline in anthropogenic aerosol emissions, but also to a change in the relative influence of specific aerosols. As sulphate determines most of the negative indirect forcing in ACCMIP, the decreasing sulphate emissions lead to a change in total indirect cloud forcing in 2100 to a value near zero or even positive in all ACCMIP models and both RCP scenarios. Much uncertainty remains surrounding ERF values attributable to specific aerosol types, leading to a wide range forcing projections (IPCC 2013; Shindell et al. 2013; Smith and Bond 2014). In ACCMIP, for example nitrate forcing is very uncertain and potentially quite significant to total aerosol forcing. Yet, the observation that negative forcing will strongly decline driven by reduction in specific aerosol emissions seems robust. Moreover, a recent study indicates that anthropogenic aerosols are likely to be a minor contributor to RF by the end of the century (Smith and Bond 2014).



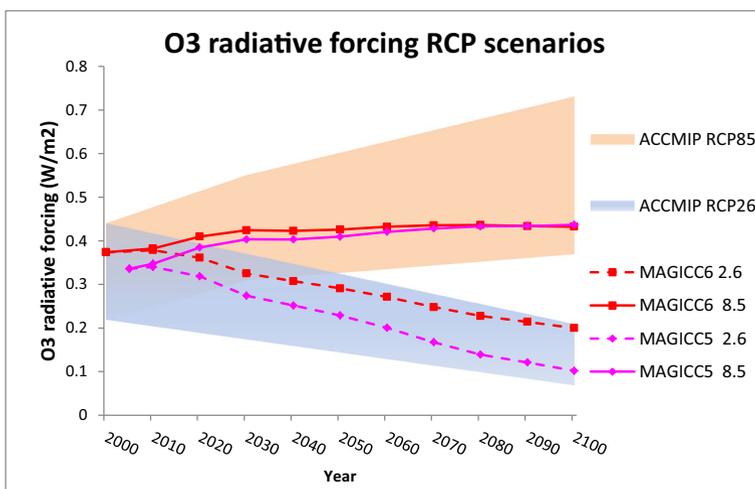
**Fig. 3** Projected aerosol radiative forcing levels for RCP2.6 and RCP8.5. Left: total direct and indirect aerosol forcing. Right: Aerosol effective radiative forcing. The two frames show the ACCMIP ERF range as a benchmark (stylized, based on the 2000 and 2100 uncertainty). The by arrow indicated spread between SCMs is given for the RCP 2.6 values in 2010 and 2100 (Uncertainty range PAGE in 2100 in W/m<sup>2</sup>:RCP2.6: -0.12 to -0.46 RCP8.5: -0.18 to -0.69)

With that in mind, the SCMs seem to have too large negative forcing projections (exceptions being MAGICC5.3, PAGE and MERGE\_ETL which are relatively close to the ACCMIP mean), and could likely improve their aerosol forcing representations. Notably, MAGICC6.3 shows a very large negative forcing effect, because of strong indirect forcing. For MAGICC5.3, forcing levels are less negative, as in this model indirect aerosol forcing is mainly defined by sulphate emissions. When considering ERF values, the negative effect in MAGICC6.3 is even more profound. The right panel shows that the differences between MAGICC6.3 and the mean of the ACCMIP range are 0.65 W/m<sup>2</sup> (RCP2.6) and 0.69 W/m<sup>2</sup> (RCP8.5) in 2100. On average, ACCMIP models project less negative aerosol ERF than direct aerosol forcing in 2100 (the latter not shown here). This means that the combination of all indirect effects and the effect of uneven global dispersion is likely to lead to positive forcing in that year. For MAGICC this is not the case, since both aerosol indirect effects and uneven aerosol distribution add to negative forcing. Improvements for MAGICC could lie in attributing different indirect forcing factors to specific aerosols (see [Supplementary Material](#) for further explanation).

### 3.4 Representation of tropospheric ozone radiative forcing

Figure 4 shows the ozone (O<sub>3</sub>) forcing projections in the two MAGICC versions compared to the range from 6 ACCMIP models (the other SCMs do not explicitly report O<sub>3</sub> forcing). Both the ACCMIP models as well as MAGICC use the same data on anthropogenic precursor emissions in the RCPs (CO, NO<sub>x</sub>, VOCs and CH<sub>4</sub>), although natural emissions vary between the models. Results are within the uncertainty range of ACCMIP, but show a relatively small difference between RCP2.6 and RCP8.5, particularly MAGICC6.3. Both MAGICC versions result in O<sub>3</sub> forcing levels that are low in the RCP8.5.

ACCMIP range. Effects not included in MAGICC that may account for this include temperature feedbacks and, particularly in RCP8.5, enhanced stratospheric-tropospheric ozone exchange (Kawase et al. 2011; Lamarque et al. 2011). The fact that other SCMs do not include



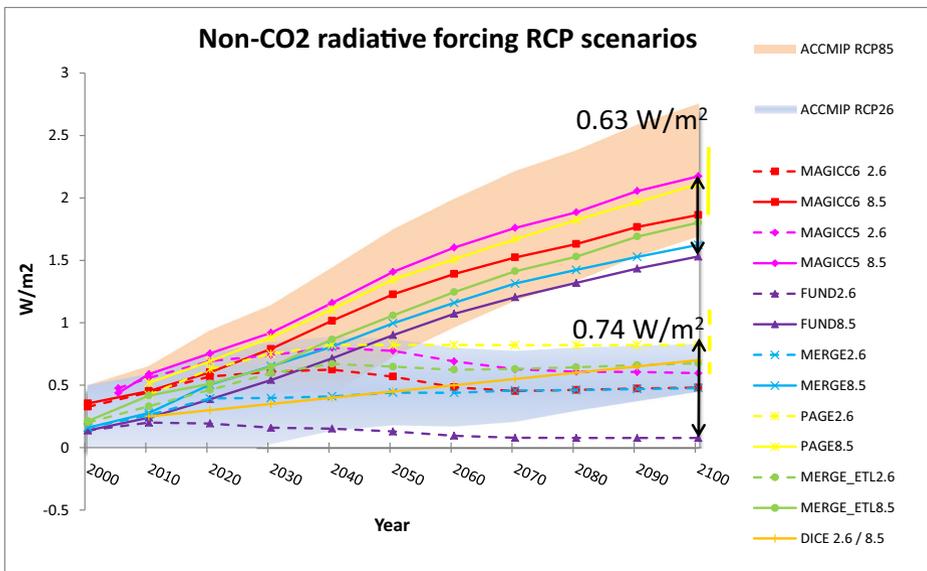
**Fig. 4** O<sub>3</sub> radiative forcing levels for RCP2.6 and RCP8.5 projected by MAGICC. The ACCMIP expert model ranges from 6 models are used as a benchmark

the forcing effects of O<sub>3</sub> results in higher forcing levels in MAGICC and the expert models by approximately 0.1–0.5 W/m<sup>2</sup> in 2100.

### 3.5 Representation all non-CO<sub>2</sub> forcers

Figure 5 gives an overview of the combined forcing effect of all non-CO<sub>2</sub> gases and aerosols, using only the forcing components included in each model. In general, most IAMs (except FUND in both scenarios and DICE and MERGE in RCP8.5) are within the ACCMIP expert model range. The ACCMIP range includes all relevant forcing effects, except indirect stratospheric water vapour from CH<sub>4</sub> (see also Table 2). This is a positive forcing effect in a 0.1 W/m<sup>2</sup> order of magnitude (Hansen et al. 2005). As most SCMs do not include land use albedo change, a negative forcing effect of similar size as indirect stratospheric water vapour, total non-CO<sub>2</sub> RF from ACCMIP is a good comparison for most SCMs. Only MAGICC6.3 includes both effects, implying that MAGICC6.3 results should be considered slightly lower than what is shown, in order to have a more accurate comparison with ACCMIP.

As can be seen, MAGICC5.3 lies very well within the ACCMIP range for both scenarios. MAGICC6.3 is slightly low, particularly for RCP2.6 where it is just inside the range in 2100, especially when considering indirect CH<sub>4</sub> effects. Reducing the negative indirect forcing from aerosols in MAGICC would lead to an overall projection that is more consistent with the ACCMIP mean. FUND shows a very low overall non-CO<sub>2</sub> forcing for both scenarios. For FUND, similar to MAGICC6.3, strong negative aerosol forcing is also the main cause for the low projection. The exogenous, scenario-independent non-CO<sub>2</sub> forcing time-series in DICE falls well within the RCP2.6 range, but is not suited for a baseline scenario such as RCP8.5. PAGE is within the ACCMIP model range, considering its own uncertainty range (shown with



**Fig. 5** Projected total non-CO<sub>2</sub> radiative forcing levels for RCP2.6 and RCP8.5. The ACCMIP expert model ranges are used as a benchmark for the other models. Vertical yellow lines in 2100 show the uncertainty range of PAGE. The two numerical values represent the spread of IAM outcomes in 2100 for the two scenarios (DICE not included for the RCP8.5 scenario). Land use albedo changes are not included

**Table 2** RCP2.6 and RCP8.5 radiative forcing components in 2100. Only mean values shown for the SCMs that have probabilistic outputs, land use albedo change not included ( $W/m^2$ ). Grey shaded cells indicate components that are not included in the model

RCP 2.6									
	ACCMIP	MAGICC6.3	MAGICC5.3	MERGE_ETL	MERGE5.1	FUND3.7	PAGE09	DICE 2013R	
CO <sub>2</sub>	2.83(+/- 0.28)	2.24	2.02	2.15	2.38	2.43	2.31	2.20	
CH <sub>4</sub>		0.28	0.28	0.30	0.33	0.26	0.33	0.70	
N <sub>2</sub> O		0.23	0.27	0.33	0.34	0.33	0.33		
Halogenated gases		0.22	0.19	0.09	0.33	0.05	0.32 <sup>3</sup>		
Cloud indirect total	-0.12(+/- 0.10) <sup>4</sup>	-0.40	-0.13	-0.12	-0.14 <sup>3</sup>	-0.67 <sup>3</sup>	-0.25		
SOx direct		-0.06	-0.04	-0.05	-0.38 <sup>3</sup>		-0.04		
BC/OC direct		0.10	0.03	0.12			0.13		
Nitrate direct		-0.18	-0.10						
BC snow		0.04							
Trop. O <sub>3</sub>	0.14(+/- 0.12)	0.20	0.10			0.10			
Strat. H <sub>2</sub> O from CH <sub>4</sub>		0.05							
Total <sup>1</sup>	2.86(+/- 0.32)	2.72	2.62	2.83	2.86	2.50	3.13	2.90	
Total non-CO <sub>2</sub> RCP2.6 <sup>2</sup>	<b>0.63(+/- 0.19)</b>	<b>0.48</b>	<b>0.60</b>	<b>0.68</b>	<b>0.48</b>	<b>0.08</b>	<b>0.82</b>	<b>0.70</b>	
RCP 8.5									
	ACCMIP	MAGICC6.3	MAGICC5.3	MERGE_ETL	MERGE5.1	FUND3.7	PAGE09	DICE 2013R	
CO <sub>2</sub>	8.27(+/- 0.83)	6.53	6.73	6.50	6.38	6.30	6.16	6.50	
CH <sub>4</sub>		1.08	1.32	1.33	1.22	1.11	1.11	0.70	
N <sub>2</sub> O		0.49	0.53	0.58	0.59	0.60	0.55		
Halogenated gases		0.29	0.21	0.09	0.34	0.05	0.32 <sup>3</sup>		
Cloud indirect total	-0.12(+/- 0.05) <sup>4</sup>	-0.46	-0.23	-0.22	-0.14 <sup>3</sup>	-0.67 <sup>3</sup>	-0.37		
SOx direct		-0.11	-0.09	-0.09	-0.38 <sup>3</sup>		-0.06		
BC/OC direct		0.18	0.10	0.12			0.57		
Nitrate direct		-0.24	-0.10						
BC snow		0.05							

**Table 2** (continued)

Trop. O <sub>3</sub>	0.55(+/-0.30)	0.43	0.44							
Strat. H <sub>2</sub> O from CH <sub>4</sub>		0.18					0.44			
Total <sup>1</sup>	8.71(+/-0.88)	8.43	8.90	8.31	8.00		7.83	8.27		7.20
Non-CO <sub>2</sub> RCP8.5 <sup>2</sup>	<b>2.21(+/-0.53)</b>	<b>1.90</b>	<b>2.17</b>	<b>1.81</b>	<b>1.62</b>		<b>1.53</b>	<b>2.11</b>		<b>0.70</b>
Totals: well mixed greenhouse gases (WMGHGs), aerosols, and other forcing agents										
RCP8.5	ACCMIP	MAG/CC6.3	MAG/CC5.3	MERGE_ETL	MERGE5.1	FUNDS.7	PAGE09	DICE 2013R		
WMGHGs (excl CO <sub>2</sub> )	1.78	1.86	2.05	2.00	2.15	1.76	1.98	0		
Aerosols	-0.12	-0.58	-0.32	-0.31	-0.52	-0.67	-0.43	0		
Other	0.55	0.62	0.44	0.12	0	0.44	0.57	0.70		
Total non-CO <sub>2</sub> <sup>2</sup>	<b>2.21</b>	<b>1.90</b>	<b>2.17</b>	<b>1.81</b>	<b>1.62</b>	<b>1.53</b>	<b>2.11</b>	<b>0.70</b>		
RCP2.6										
WMGHGs (excl CO <sub>2</sub> )	0.61	0.73	0.73	0.72	1.00	0.64	0.98	0		
Aerosols	-0.12	-0.50	-0.24	-0.17	-0.52	-0.67	-0.29	0		
Other	0.14	0.25	0.10	0.12	0	0.10	0.13	0.70		
Total non-CO <sub>2</sub> <sup>2</sup>	<b>0.63</b>	<b>0.48</b>	<b>0.60</b>	<b>0.68</b>	<b>0.48</b>	<b>0.08</b>	<b>0.82</b>	<b>0.70</b>		
Difference 8.5/2.6										
WMGHGs (excl CO <sub>2</sub> )	1.17	1.13	1.32	1.27	1.15	1.11	1.00	0		
Aerosols	0	-0.08	-0.08	-0.15	0	0	-0.15	0		
Other	0.41	0.37	0.33	0	0	0.34	0.43	0		
Total non-CO <sub>2</sub>	<b>1.58</b>	<b>1.42</b>	<b>1.58</b>	<b>1.13</b>	<b>1.15</b>	<b>1.45</b>	<b>1.29</b>	<b>0</b>		

<sup>1</sup> = To calculate the total non-CO<sub>2</sub> forcing for ACCMIP, the RCP CO<sub>2</sub> forcing is assumed and deducted from WMGHG forcing

<sup>2</sup> = PAGE uncertainty range total non-CO<sub>2</sub> forcing: RCP2.6-5 %: 0.65 W/m<sup>2</sup>, 95 % 0.99 W/m<sup>2</sup>, RCP8.5-5 %: 1.86 W/m<sup>2</sup>, 95 % 2.36 W/m<sup>2</sup>

<sup>3</sup> = Scenario independent, exogenous radiative forcing levels for individual components

<sup>4</sup> = Max range aerosol RF: -0.76-0.58 W/m<sup>2</sup>

the vertical yellow bar). The high projection in RCP2.6 can be attributed to a combination of a relatively high forcing value for halogenated gases and an exogenous forcing factor of  $0.13 \text{ W/m}^2$  that compensates for missing components (see Table 2).

All SCMs show somewhat low projections for RCP8.5. Furthermore, PAGE, MERGE, and MERGE\_ETL display relatively small differences in non-CO<sub>2</sub> forcing between RCP2.6 and RCP8.5. This indicates that they are less sensitive to emission changes, which could lead to a bias towards higher projected mitigation policy costs.

Another important result is that differences in outcomes are largest in the mitigation scenario. The spread in total non-CO<sub>2</sub> forcing in the RCP2.6 scenario is very large:  $0.74 \text{ W/m}^2$  compared to an overall forcing in the order of  $2.6 \text{ W/m}^2$ . The outliers can be attributed to strong negative aerosol forcing (FUND) and a high exogenous forcing factor (PAGE). Much of this spread in model outcomes already exists in the base year (see [Supplementary Material](#)). In 2010, the spread between models in RCP2.6 is  $0.36 \text{ W/m}^2$  (range determined by MAGICC5.3 and FUND). The representation of non-CO<sub>2</sub> in the SCMs seems to have important implications for determining the optimal mitigation strategy: a  $2.6 \text{ W/m}^2$  mitigation scenario (RCP2.6) could require CO<sub>2</sub> forcing targets of only  $1.8 \text{ W/m}^2$  up to  $2.5 \text{ W/m}^2$  depending on the model (range determined by the outliers). This, in turn, has a very large effect on the resulting carbon budgets, which can vary between approximately 950 and 1400 MtCO<sub>2</sub> given this range (the range is 1029 to 1177 MtCO<sub>2</sub> when excluding the outliers PAGE and FUND) (see [Supplementary Material](#)). Obviously, this has large consequences for projected optimal mitigation strategies and policy costs.

Table 2 shows the forcing components as projected by the models in the two RCP scenarios for 2100 (only mean figures are presented for the SCMs. PAGE does have an uncertainty range for CO<sub>2</sub> and total forcing levels). Below, the RF sum of all WMGHGs, aerosols and other forcings as well as the difference between the two scenarios are shown.

For both MAGICC model versions and FUND, the difference in total non-CO<sub>2</sub> forcing levels between RCP2.6 and RCP8.5 is comparable to the difference between the mean values in ACCMIP, while for the other SCMs the difference is smaller. One of the reasons for this small difference is that the SCMs, with the exception of MAGICC, do not capture RF from O<sub>3</sub>. The larger difference in FUND can be attributed to taking into account the effects of stratospheric water vapour due to CH<sub>4</sub>. This compensates for excluding O<sub>3</sub> forcing. By also including this effect, MAGICC6.3 slightly compensates for larger negative aerosol effects in RCP8.5.

The totals suggest that all SCMs have relatively high outcomes for the forcing of non-CO<sub>2</sub> WMGHGs, but there is no basis for such a conclusion. For these parameters, ACCMIP results are based on RF in the RCPs, which was originally determined by an early MAGICC6 version (Van Vuuren et al. 2011a). Therefore, further analyses with expert models are needed. The forcing from WMGHGs is a combined effect of the different non-CO<sub>2</sub> forcings: N<sub>2</sub>O, CH<sub>4</sub> and halogenated gases (with a spread of  $0.28\text{--}0.29 \text{ W/m}^2$  for halogenated gases in both scenarios, shown in the [Supplementary Material](#)). Although these individual forcing effects differ considerably across models, the effect is largely cancelled out when only comparing total forcing from WMGHGs. Still, MERGE and PAGE have considerably larger non-CO<sub>2</sub> WMGHG forcing values than the other SCMs in RCP2.6. At the same time, all models consistently show higher negative aerosol forcing levels than the ACCMIP mean. This might therefore offer an important area for improvement.

The [Supplementary Material](#) also provides an analysis of what causes differences between expert models and SCMs: either missing forcing components or differently modelled forcing effects. Although the causes for large deviations differ per model and scenario, it can be stated

that in RCP2.6 most of the difference is explained by differently modelled components and that in RCP8.5 most of the difference is explained by missing components (notably O<sub>3</sub> and indirect CH<sub>4</sub>).

### 3.6 Effect of non-CO<sub>2</sub> climate system representation on projected forcing of short-lived climate forcers

To further assess the climate system representation of short-lived climate forcers, the SCMs have been run with prescribed emission pathways as used in the UNEP Integrated Assessment of Black Carbon and Tropospheric Ozone study (UNEP and WMO 2011) (see Fig. 1 and the [Supplementary Material](#)). The relevance of this experiment is twofold: 1) There are large aerosol and O<sub>3</sub> related differences between models, which are more thoroughly analysed with these scenarios, and 2) The conclusions of the UNEP study are highly policy relevant. They indicate that a large short-term radiative forcing reduction might be possible by intensifying the mitigation of short-lived forcers. It is important to assess if this can also be concluded when using commonly used SCMs.

The mitigation scenario from the UNEP report describes a situation where CH<sub>4</sub>, BC, OC and O<sub>3</sub> precursor emissions are strongly reduced. Since GISS-PUCCINI was the only expert model in the UNEP study that included all forcing effects, it is used here as the main comparison for the SCM model outcomes. The model took part in ACCMIP in combination with an ocean-coupled climate model as GISS-E2-R. ECHAM5\_HAMMOZ, the second expert model used in the study, functions as a comparison for CH<sub>4</sub>, O<sub>3</sub> and direct forcing effects. Note that the two model projections in the UNEP report cannot fully serve as a basis for validation of the SCMs, since individual expert models differ considerably in aerosol forcing estimates (See Fig. 3). Table 3 shows the RF difference between the reference and mitigation policy scenarios as projected by the models for 2030 (a comparison of the forcing profiles until 2030 is difficult as the models show considerable differences in present day forcing levels (See [Supplement](#))). Interestingly, the SCMs project forcing responses of less than half the expert model mean value. For models other than MAGICC this is partly the result of not including O<sub>3</sub> and BC. Particularly for MAGICC the result is remarkable, given the RCP results presented earlier with ACCMIP as a benchmark, although an earlier analysis with MAGICC5.3 already indicated a smaller response (Smith and Mizrahi 2013). Unlike many of the other ACCMIP models, GISS-E2-R diagnoses indirect RF attributed to specific aerosols, and produces a substantial positive cloud forcing for BC. In MAGICC this is in fact a negative effect, hence causing a clear difference between the models. The reason that this difference does not occur in the RCP experiments is that there the change in BC emissions is smaller. When including ERF values from MAGICC6.3 the difference is even larger, as the negative indirect aerosol forcing is stronger. A similar effect occurs when the same efficacies are applied to MAGICC5.3 results (not shown). Note that the differences between models are relatively small for the direct effects that have been modelled by ECHAM5\_HAMMOZ. Different modelling of indirect forcing effects explains a much larger part of the differences. Note that the full uncertainty range of GISS-PUCCINI can be considered larger than the 0.05 W/m<sup>2</sup> depicted here. The reason is that the uncertainty includes only the internal variability in the model's meteorology, and not any uncertainty in physical processes that define RF of aerosol components. The latter has a large effect on projected cloud indirect effects (Boucher et al. 2013; Shindell et al. 2013), which is in line with the large projected uncertainty range for BC in Bond et al. (Bond et al. 2013).

**Table 3** Difference between projected radiative forcing levels in 2030 in reference and a policy mitigation scenario based on prescribed emission pathways of short-lived forcers as used in the UNEP Integrated Assessment of Black Carbon and Tropospheric Ozone (UNEP, WMO 2011). Grey shaded cells indicate components that are not included in the model

	<i>ECHAM5-HAMMOZ</i>	<i>GISS-PUCCINI</i>	<i>MAGICC6.3</i>	<i>MAGICC5.3</i>	
			<i>RF</i>	<i>ERF</i>	
CH4 direct + indirect	0.20	0.18	0.14	0.15	0.14
O3	0.10	0.19	0.09	0.07	0.12
BC	0.15	0.22	0.30	0.25	0.21
OC		-0.07	-0.05	-0.04	
SOx		0.02	-0.004	-0.003	-0.004
Nitrate		-0.01	-0.06	-0.05	0.00
Aerosols indirect/clouds		0.16	-0.09	-0.13	-0.01
BC albedo		0.09	0.05	0.08	
Total	<b>n.a.</b>	<b>0.77<sup>1</sup></b>	<b>0.37</b>	<b>0.32</b>	<b>0.46</b>
	<i>MERGE_ETL</i>	<i>MERGE5.1</i>	<i>FUND3.7</i>	<i>PAGE09</i>	<i>DICE 2013R</i>
CH4 direct + indirect	0.14	0.10	0.19	0.11	
O3					
BC					
OC					
SOx	-0.01				
Nitrate					
Aerosols indirect/clouds					
BC albedo					
Total	<b>0.13</b>	<b>0.10</b>	<b>0.19</b>	<b>0.11</b>	<b>0.00</b>

<sup>1</sup> uncertainly range total radiative forcing difference due to internal variability GISS-PUCCINI's meteorology: +/- 0.05 W/m<sup>2</sup>

The representation of the short-lived forcers in the other SCMs than MAGICC show an even smaller forcing difference between the two scenarios and, thus, compared to MAGICC and the GISS-PUCCINI results underestimate the effect of reducing emissions of short-lived forcers. The main reason for this is the omission of BC in determining climate effects (this effect is 0.31 W/m<sup>2</sup> for GISS-PUCCINI and 0.25 W/m<sup>2</sup> for MAGICC). To a lesser extent the same is true for the exclusion of O<sub>3</sub> with projected differences of 0.19 W/m<sup>2</sup> and 0.09 W/m<sup>2</sup>, respectively, and a projected difference of 0.1 W/m<sup>2</sup> by ECHAM5-HAMMOZ.

In any case, the effect of reducing short-lived forcers as assessed in the UNEP report would be much smaller if done using the SCMs discussed here.

## 4 Conclusions

From the non-CO<sub>2</sub> climate system representation analyses, it can be concluded that the overall behaviour of non-CO<sub>2</sub> gases and aerosols seems to be reasonably captured by most models, given that most overall non-CO<sub>2</sub> radiative forcing projections are found within the expert model range. For the baseline scenario RCP8.5, this means that models project a non-CO<sub>2</sub> forcing (mean value) between 1.69 and 2.75 W/m<sup>2</sup> in 2100. DICE, with a scenario-

independent non-CO<sub>2</sub> projection, is below this range with 0.7 W/m<sup>2</sup>. FUND is also slightly below the range with 1.53 W/m<sup>2</sup>. For the strong mitigation scenario RCP2.6, all models except FUND (with 0.23 W/m<sup>2</sup>) are within the expert model range of 0.45 W/m<sup>2</sup> to 0.83 W/m<sup>2</sup>.

There is a very large spread between the SCMs for the same emission-driven mitigation scenario (0.74 W/m<sup>2</sup> for RCP2.6). This implies that the choice of a climate model has large implications for determining the mitigation strategies in terms of CO<sub>2</sub> reduction and associated policy costs. In that sense, models may want to move closer to the median of the expert model range. Much of the differences in model projections are a consequence of uncertainty in scientific understanding. Differences in aerosol assumptions (notably indirect, cloud forming effects) account for the large spread in forcing projections. Variations in N<sub>2</sub>O, halogenated gas and exogenous forcing assumptions also play a large role in the spread in forcing outcomes. For N<sub>2</sub>O as well as for CH<sub>4</sub>, model differences mainly occur in calculation of emission to concentrations while models show consistency in deriving forcing levels from concentrations.

Compared to expert models, many IAMs seem to show a less rapid decline of negative aerosol forcing. MAGICC6.3 has a particularly negative forcing projection in 2100 compared to the expert model range. Future improvements could potentially lie in accounting for the sign of individual indirect forcing effects of specific aerosols. For well-mixed greenhouse gases further comparison with expert models is needed.

Because most SCMs (other than MAGICC) generally do not include important forcings such as O<sub>3</sub>, BC and stratospheric vapour from CH<sub>4</sub>, they run the risk of underestimating forcing differences between baseline and mitigation scenarios. This is the case when considering all non-CO<sub>2</sub> gases and aerosols, as well as in the specific case of reducing only short-lived forcings. Obviously, this has clear consequences for the evaluation of specific strategies by IAMs using these SCMs.

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