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# Uncertainties in climate stabilization

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**Abstract** The atmospheric composition, temperature and sea level implications out to 2300 of new reference and cost-optimized stabilization emissions scenarios produced using three different Integrated Assessment (IA) models are described and assessed. Stabilization is defined in terms of radiative forcing targets for the sum of gases potentially controlled under the Kyoto Protocol. For the most stringent stabilization case ("Level 1" with $CO_2$ concentration stabilizing at about 450 ppm), peak $CO_2$ emissions occur close to today, implying (in the absence of a substantial $CO_2$ concentration overshoot) a need for immediate $CO_2$ emissions abatement if we wish to stabilize at this level. In the extended reference case, $CO_2$ stabilizes at about 1,000 ppm in 2200—but even to achieve this target requires large and rapid $CO_2$ emissions reductions over the twenty-second century. Future temperature changes for the Level 1 stabilization case differ noticeably between the IA models even when a common set of climate model parameters is used (largely a result of different assumptions for non-Kyoto gases). For the Level 1 stabilization case, there is a probability of approximately 50% that warming from pre-industrial times will be

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less than (or more than) 2°C. For one of the IA models, warming in the Level 1 case is actually greater out to 2040 than in the reference case due to the effect of decreasing $SO_2$ emissions that occur as a side effect of the policy-driven reduction in $CO_2$ emissions. This effect is less noticeable for the other stabilization cases, but still leads to policies having virtually no effect on global-mean temperatures out to around 2060. Sea level rise uncertainties are very large. For example, for the Level 1 stabilization case, increases range from 8 to 120 cm for changes over 2000 to 2300.

## 1 Introduction

In a recent exercise under the U.S. Climate Change Science Program (CCSP) three integrated assessment (IA) models were used to produce internally consistent no-climate-policy (i.e., "reference") and policy (stabilization) emissions scenarios (CCSP Synthesis and Assessment Product 2.1a; Clarke et al. 2007). Four different radiative forcing stabilization levels were considered. The modeling groups made independent choices in determining the reference emissions, and in the multi-gas mitigation policies required to achieve forcing stabilization.

The purpose of this paper is to consider the atmospheric composition, global-mean temperature and sea level implications of these scenarios within a common framework. As a unifying approach we use a single coupled gas-cycle/climate model to assess the scenarios, viz. version 5.3 of the MAGICC model, which is consistent with the IPCC Fourth Assessment Report (AR4, Meehl et al. 2007). Results were also calculated using version 4.1 of MAGICC, as used in the IPCC Third Assessment Report (TAR; Cubasch et al. 2001; Wigley and Raper 2001). The uncertainties assessed here are those arising from differences between the IA models and methods used to construct the emissions scenarios, and from parametric uncertainties in the temperature and sea level models (such as uncertainties in the climate sensitivity).

The stabilization levels were defined in terms of the combined radiative forcing for $CO_2$ and for the other gases that are potentially controlled under the Kyoto Protocol ($CH_4$, $N_2O$, HFCs, PFCs and $SF_6$)—we refer to this suite as "Kyoto gases" below. Pathways to the stabilization targets were designed to be consistent with least-cost (i.e., cost-optimized) abatement over time and across the range of Kyoto gases (see, e.g., Reilly et al. 1999; Manne and Richels 2001; Sarofim et al. 2005). Each IA modeling group, however, used somewhat different optimization approaches, in part because the model structures differed. Trajectories for other climate forcing agents (aerosols, etc.) were produced by the IA models to varying degrees, but these forcings were not part of the optimization process, nor were they considered as contributing to the forcing targets.

The stabilization targets for radiative forcing were constructed as follows. First, the $CO_2$-only forcing associated with concentrations of 450, 550, 650 and 750 ppm were defined (viz. approximately 2.58, 3.65, 4.54 and 5.31 $W/m^2$ from pre-industrial times). Then, additional radiative forcing to account for the other Kyoto gases (viz. 0.8, 1.0, 1.2 and 1.4 $W/m^2$ from pre-industrial times respectively—the forcing to 2000 for these gases is approximately 0.7 $W/m^2$) was added to obtain total Kyoto-gas forcing targets. It was assumed that higher non-$CO_2$ forcing would arise for higher $CO_2$ forcing levels in any cost-optimized scenario. The four stabilization levels are referred to as Level 1, Level 2, Level 3 and Level 4. Combining the $CO_2$ and non-$CO_2$ forcing targets, the total (Kyoto-gas) forcing targets are 3.38, 4.65, 5.74 and 6.71 W/m$^2$. The degree to which these targets are met by 2100 varies with stabilization case and IA model; see Table 1. Level 1 requires the largest reduction in radiative forcing relative to the reference case and is associated with $CO_2$ stabilization at roughly 450 ppm. When this scenario is extended out to 2300 (see below) both $CO_2$ and $CO_2$-equivalent concentrations stabilize at about 450 ppm.

The three IA models give different results for the reference and stabilization emissions scenarios, and their concentration and forcing implications. Concentration and forcing differences arise in two ways: from inter-model differences in the emissions for any given scenario; and from differences between the IA models in their gas-cycle and climate components. Here we eliminate the second factor by using a single coupled gas-cycle/climate model to assess the scenarios. Using a single gas-cycle/climate model provides a level playing field that isolates uncertainties arising solely from emissions scenario differences.

The three IA models used were EPPA (Paltsev et al. 2005), MiniCAM (Kim et al. 2006) and MERGE (Richels et al. 2007). These models have different levels of complexity in their modeling of socioeconomic, energy, industry, transport, and land-use systems. With respect to emissions, EPPA and MiniCAM are similarly comprehensive and produce output for emissions of the following: all the major greenhouse gases (including a suite of halocarbons and $SF_6$); $SO_2$; black carbon (BC) and organic carbon (OC) aerosols and their precursors; and the reactive gases CO, NOx and VOCs (which are important determinants of tropospheric ozone changes). MERGE produces emissions output for $CO_2$, $CH_4$, $N_2O$ and idealized short-lived and long-lived halocarbons (characterized by HFC134a and $SF_6$) only. To flesh out the five MERGE scenarios we have, for all five cases, used the SRES B2 scenario (Nakićenović and Swart 2000) for $SO_2$ emissions and assumed that reactive gas emissions remain constant. Further, to bring MERGE more in line with the other two IA models, we have not used the EPPA and MiniCAM BC and OC results, but assumed that total BC plus OC aerosol forcing tracks $SO_2$ emissions, i.e.:

$$Q(t) \;=\; Q(1990) \times \mathrm{ESO2}(t) \big/ \mathrm{ESO2}(1990)$$

where $Q$ is BC + OC forcing and ESO2 is $SO_2$ emissions. Results from MiniCAM, where BC and OC projections are generated internally, show that the tracking assumption provides a reasonable estimate of BC + OC forcing (which, in any event, is small).

In addition, to provide a longer timescale context, we have extended one set of scenarios out to 2300—the time horizon for the CCSP2.1a exercise was only 2100 and stabilization is not necessarily achieved by this date.

Finally, although each IA modeling group produced four stabilization scenarios, we concentrate here on the Level 1 case (approximately 450 ppm stabilization for $CO_2$). Results for the other stabilization cases are given in Appendix 1.

## 2 Emissions scenarios

Figure 1 shows emissions for fossil $CO_2$, $CH_4$, $N_2O$ and $SO_2$ for the reference and Level 1 cases. Fossil $CO_2$ combines coal, oil and gas combustion sources, cement production and gas flaring. For EPPA and MiniCAM, these emissions also

**Table 1** Kyoto-gas radiative forcing targets (from pre-industrial times; W/m$^2$) compared with actual 2100 forcing values for the three IA models

| Scenario | $CO_2$ | | | | Non-$CO_2$ | | | | Total Kyoto | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Target | MiniCAM | EPPA | MERGE | Target | MiniCAM | EPPA | MERGE | Target | MiniCAM | EPPA | MERGE |
| Ref. | | 5.300 | 6.067 | 5.383 | | 1.128 | 2.080 | 1.648 | | 6.428 | 8.147 | 7.031 |
| Level 4 | 5.31 | 5.077 | 4.760 | 5.054 | 1.4 | 1.010 | 1.125 | 1.486 | 6.71 | 6.087 | 5.885 | 6.540 |
| Level 3 | 4.54 | 4.600 | 4.189 | 4.597 | 1.2 | 0.886 | 1.040 | 1.311 | 5.74 | 5.486 | 5.229 | 5.908 |
| Level 2 | 3.65 | 3.792 | 3.418 | 3.734 | 1.0 | 0.796 | 0.950 | 1.060 | 4.65 | 4.588 | 4.368 | 4.794 |
| Level 1 | 2.58 | 2.685 | 2.668 | 2.392 | 0.8 | 0.756 | 0.852 | 0.958 | 3.38 | 3.441 | 3.520 | 3.350 |

The target values under $CO_2$ (column 2) are the forcings for the nominal $CO_2$ stabilization targets (450, 550, 650, 750 ppm). The target values under non-$CO_2$ (column 6) were specified arbitrarily in CCSP2.1a (but realistically, as the actual values show). Only the "Total Kyoto" target values (the sum of $CO_2$ and non-$CO_2$ targets; column 10) were used as forcing targets, with no constraint on when the target should be reached

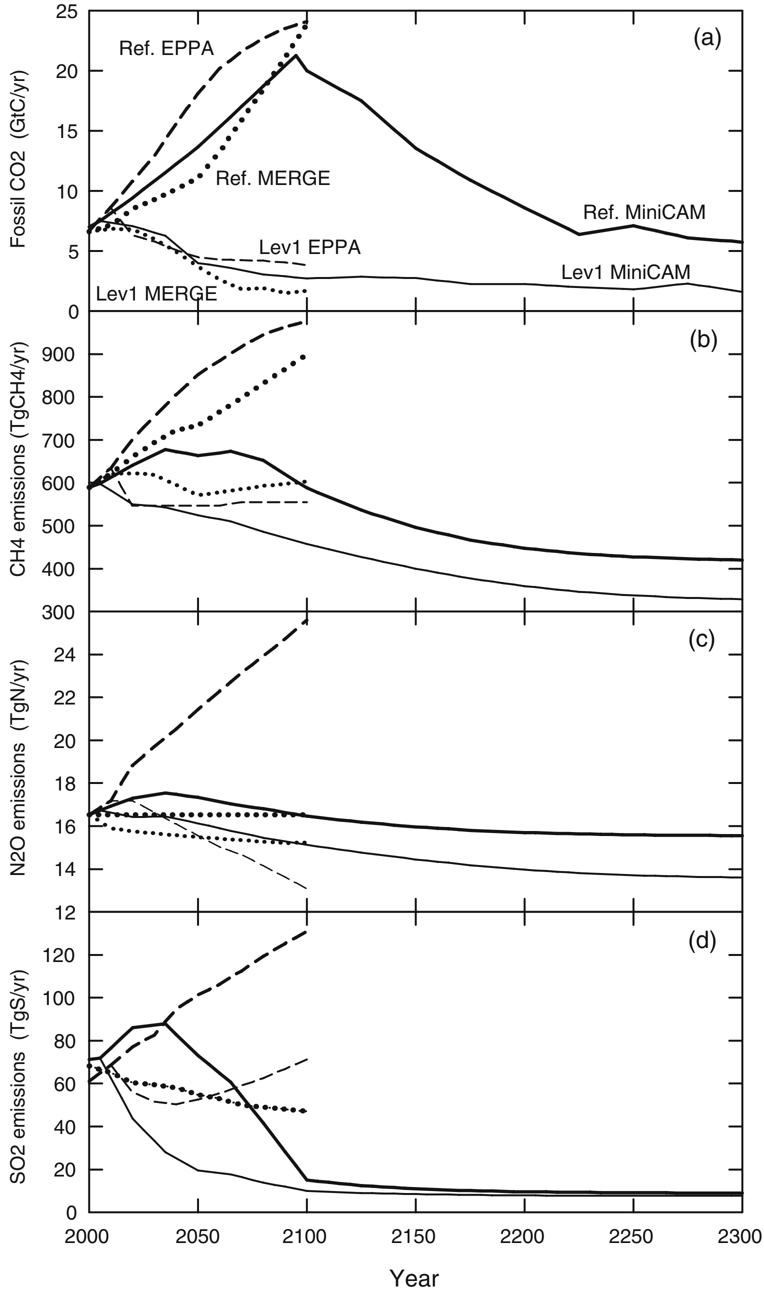



**Fig. 1** Emissions scenarios for fossil $CO_2$, $CH_4$, $N_2O$ and $SO_2$ for the reference (*bolder lines*) and Level 1 stabilization cases. EPPA results are *dashed lines*, MiniCAM results are *full lines*, and MERGE results are *dotted lines*. Note that $SO_2$ emissions for MERGE are the same for both the reference and all stabilization cases. Emissions for $CH_4$ and $N_2O$ are total emissions (natural plus anthropogenic) with the natural component obtained by budget balancing in the year 2000. It is assumed that natural emissions do not change

include contributions from oxidation of non-biogenic $CH_4$ and CO. For MERGE, the assumption of constant CO emissions means that there is no CO oxidation component. The $CH_4$ oxidation term in MERGE was calculated independently from the $CH_4$ emissions data and added to the raw fossil $CO_2$ emissions. (For MERGE, only the raw $CO_2$ emissions data are shown in Fig. 1.) Reference fossil $CO_2$ emissions are fairly consistent between the IA groups, lying approximately in the middle of the SRES range (Nakićenović and Swart 2000). Net land-use change $CO_2$ emissions ("deforestation") are discussed in Appendix 1. Both $CH_4$ and $N_2O$ emissions vary more widely than fossil $CO_2$ emissions. These differences reflect different reference-case assumptions in the different IA models, as explained in the CCSP2.1a report. (The extended MiniCAM emissions scenarios are discussed below.)

The biggest range of values is for $SO_2$ emissions. Even for the reference case, MiniCAM projects a large reduction in $SO_2$ emissions as a response to pollution concerns and the increasing ability of developing nations to respond to these concerns as their economies grow (Smith et al. 2005). The same concerns are accounted for in the SRES scenarios (and hence in MERGE, which uses SRES B2) and in the EPPA emissions scenarios, but the responses are quite different from those in MiniCAM (especially in the EPPA case). Note that these differences do not influence the stabilization calculations, which are optimized for a forcing target that considers only the Kyoto gases. In terms of climate implications, however, the range of $SO_2$ emissions has important consequences: for MiniCAM, reduced $SO_2$ emissions over the twenty-first century leads to a warming, while in EPPA, where emissions increase, there is a long-term cooling effect.

For the 450 ppm stabilization case, peak $CO_2$ emissions occur close to today, implying a need for immediate $CO_2$ emissions abatement if we wish to stabilize at this level along a pathway that avoids a substantial $CO_2$ concentration overshoot. (See Wigley et al. 2007, for more information on overshoot pathways.) The subsequent decline in emissions is similar in all three IA model results. The differences primarily reflect differences in the carbon cycle components of the IA models. For example, MERGE has no terrestrial biosphere component and assumes instead that the terrestrial biosphere is carbon neutral (see Appendix 1). The other two models have realistic terrestrial biospheres of differing complexity (more realistic in EPPA).

For $CH_4$ and $N_2O$, the reductions in emissions are similar for MiniCAM and MERGE, despite differences in their approaches to determining abatement paths. EPPA shows considerably larger reductions in large part because of the higher reference emissions levels for these gases, and because the marginal abatement cost needed to achieve $CO_2$ stabilization is greater.

For $SO_2$, since this gas is not considered in MERGE, we have used the B2 scenario for all MERGE scenarios. For the other two IA models, $SO_2$ emissions in both the reference and stabilization cases are influenced by $SO_2$-related pollution policies. In addition, $SO_2$ emissions are affected by the "knock-on" effects of policy measures implemented for other gases (largely the coupling between $SO_2$ emissions reductions and emissions reductions for $CO_2$). For example, in MiniCAM, the rapid reduction in $SO_2$ emissions in the Level 1 case relative to the reference case after 2005 arises from an assumed rapid, $CO_2$-policy driven transition away from coal-fired energy production, especially in China (Smith et al. 2005; Smith and Wigley 2006). In policy cases, substantial decoupling of $SO_2$ and $CO_2$ emissions changes occurs only when carbon capture and storage becomes a significant factor in reducing $CO_2$ emissions.

For the extended MiniCAM scenarios, the emissions of non-$CO_2$ gases were developed by Steve (S.J.) Smith. Little research has been conducted on very-long-term emissions scenarios for such gases. In order to generate a consistent set of extended emissions for the present analysis a simple heuristic approach was employed. Given that emissions of most greenhouse gases and pollutants in the MiniCAM stabilization scenarios are declining by 2100, we assume that these declines continue over the extended period, at a smoothly decreasing rate. The rates of decrease were adjusted so that emissions levels for any given gas were lower for lower stabilization targets. For the few gases in the reference case where emissions are increasing in 2100 ($CH_4$, CO, VOCs, and a few fluorinated gases), emissions were assumed to approach stabilization. Further research could refine these calculations. However, this would not have a significant effect on the results because net forcing from non-$CO_2$ gases is a relatively small portion of total forcing for these scenarios.

For the extended $CO_2$ emissions scenarios, instead of prescribing emissions and calculating concentrations from these, we prescribed concentrations directly after 2095 (this is the last year in the original CCSP2.1a scenarios for MiniCAM, which calculates emissions only at 15-year intervals). For the reference case, concentrations were assumed to approximately stabilize by 2200: concentration levels in 2100, 2200 and 2300 are 748, 1,043 and 1,061 ppm. For the Level 1 stabilization case, concentrations are approximately stable at 458 ppm after 2100. Appendix 1 gives details for the other stabilization cases. The implied post-2095 emissions for MiniCAM shown in Fig. 1 were derived from the concentration profiles using an inverse version of MAGICC. (The emissions for these extended scenarios were determined using the TAR version of MAGICC (version 4.1). With version 4.1, reference concentrations stabilize in 2200 at 1,000 ppm, while Level 1 concentrations stabilize at 450 ppm in 2150.)

The extended reference case emissions are particularly illuminating. They show that, even to stabilize at a level as high as 1,000 ppm requires very rapid emissions reductions after 2095. For the Level 1, 2, 3 and 4 scenarios, $CO_2$ emissions begin to decline well before 2100 (only Level 1 results are shown here—Fig. 1), but even in these cases emissions do not drop to zero. This is because of the very long time it takes for the atmospheric and oceanic parts of the carbon cycle to establish a new equilibrium. The atmosphere-to-ocean $CO_2$ flux declines only very slowly (Wigley 2007) so the ocean remains a sink for $CO_2$ for many centuries.

## 3 Concentration changes

The most important concentration results are those for $CO_2$ (Fig. 2). If $CO_2$ were the only factor being considered, $CO_2$ levels for the 450 ppm stabilization case should either stabilize at 450 ppm by 2100 or (since no date was prescribed for stabilization in the scenario generation exercise) be approaching this level by 2100. Since it is total Kyoto-gas forcing that is optimized, and since the contribution of $CO_2$ relative to other Kyoto gases in the optimized results will almost certainly differ from the a priori choice used to define the total forcing target, there is no need for $CO_2$ to stabilize precisely at 450 ppm.

For MiniCAM and EPPA, when using the MAGICC 5.3 carbon cycle model, the $CO_2$ trajectory overshoots the 450 ppm target slightly. In MiniCAM, concentrations

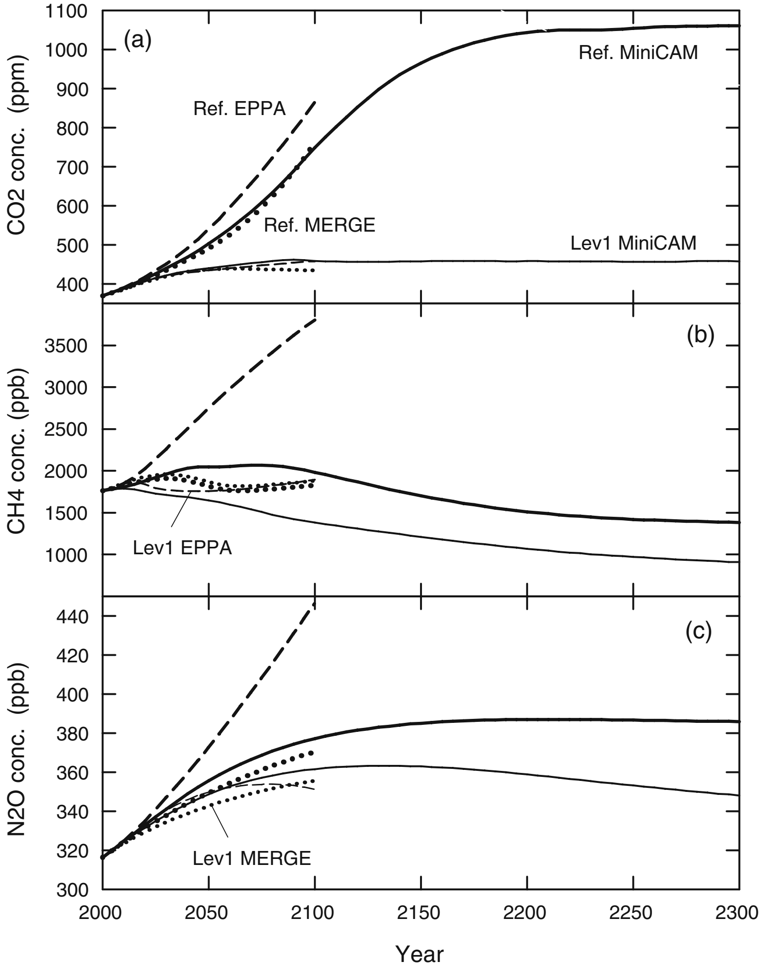



**Fig. 2** $CO_2$, $CH_4$ and $N_2O$ concentrations for the reference (*bolder lines*) and Level 1 stabilization cases. EPPA results are *dashed lines*, MiniCAM results are *full lines*, and MERGE results are *dotted lines*

peak at around 462 ppm in the late 2080s and then decline (slowly) to stabilize at around 458 ppm. This late twenty-first century $CO_2$ "surge" in the MiniCAM Level 1 concentration profile is the result of increased land-use to provide biofuels (see Appendix 1), in turn driven by fuel price changes. For MERGE, the $CO_2$ concentration is still appreciably below 450 ppm in 2100.

Concentration results for $CH_4$ and $N_2O$ (Fig. 2) show considerable differences between the IA models in the reference scenarios, particularly for $CH_4$. Part of the reason for much larger $CH_4$ concentrations with EPPA is because this model includes the effects of climate-related feedbacks on the emissions of methane. The Level 1 stabilization results for the three models are, however, more similar. EPPA shows much larger reductions in $CH_4$ and $N_2O$ concentrations than the other models for all stabilization cases (see Fig. 6 in Appendix 1). Note that, even in the extended Level

1 scenarios for MiniCAM, $CH_4$ and $N_2O$ concentrations in 2300 are still well above pre-industrial levels.

## 4 Radiative forcing

Figure 3 shows selected radiative forcing results. (Additional results are given in Appendix 1.) The top two panels compare total forcing with forcing for the Kyoto gases only, for the reference (Ref.) and Level 1 (Lev1) cases. The MiniCAM Level 1 case shows an increase in total forcing over 2080 to 2095 that requires explanation. This arises from the rapid decrease in land-use-change $CO_2$ emissions over this period (from a $CO_2$ source (deforestation) of more than 2 GtC/year in 2080 to a small $CO_2$ sink (reforestation) in 2095; see Appendix 1, Fig. 16), and the way MAGICC parameterizes aerosol forcing due to biomass burning. In MAGICC, this forcing is assumed to be linearly dependent on gross land-use-change $CO_2$ emissions, which show a large and rapid decrease over 2080 to 2095 paralleling the decrease in net land-use-change emissions. The decrease in gross land-use change leads to a decrease in biomass-burning aerosol loading and, hence, a forcing increase. While qualitatively realistic, the magnitude of this effect is quite uncertain.

Apart from this anomaly, the difference between total and Kyoto-gas forcing is due primarily to sulfate aerosols and tropospheric ozone. Total, Kyoto-gas, sulfate aerosol and tropospheric ozone forcing changes over 2000 to 2100 are shown in Table 2 for all emissions cases. Tropospheric ozone and sulfate aerosol forcings for the reference and Level 1 cases are also shown in the bottom panels of Fig. 3. It can be seen that the differences between total and Kyoto gas forcings (i.e., "non-Kyoto" forcing) vary little as one moves from the reference case to and through the stabilization scenarios. In MiniCAM and EPPA, the scenario-to-scenario changes are small because of compensating effects—aerosol forcing increases as one moves to more stringent stabilization cases, while tropospheric ozone changes decrease (see Table 2). The magnitudes of both the individual forcings and their changes, however, differ radically between MiniCAM and EPPA, with the forcings and their changes being much larger in EPPA. Note that the inter-model spread of stabilization forcings is much less for Kyoto-gas forcing (which is what was used to define the stabilization targets) than for total forcing.

A primary reason why sulfate aerosol and tropospheric ozone forcing shows large differences between MiniCAM and EPPA lies in the way they treat non-climate (i.e., pollution-related) policies. Such policies appear to have much larger effects on emissions in MiniCAM than in EPPA, with higher pollutant emissions in the EPPA reference case. A consequence of this is that it leaves more scope for climate mitigation via reactive gas emissions changes in EPPA (see, e.g., Prinn et al. 2007) than in MiniCAM—but note that this type of policy was not considered in the CCSP2.1a exercise. The inter-model differences here highlight an important area of uncertainty in emissions scenarios.

In MERGE, the aerosol and tropospheric ozone forcing changes are unrealistic due to limitations in the model structure. $SO_2$ emissions are not modeled in MERGE, so aerosol forcings do not change between scenarios. Also, since reactive gases are not considered, tropospheric ozone forcing changes are small and differences between the reference and stabilization cases arise only through the effects of the different $CH_4$ concentration projections.

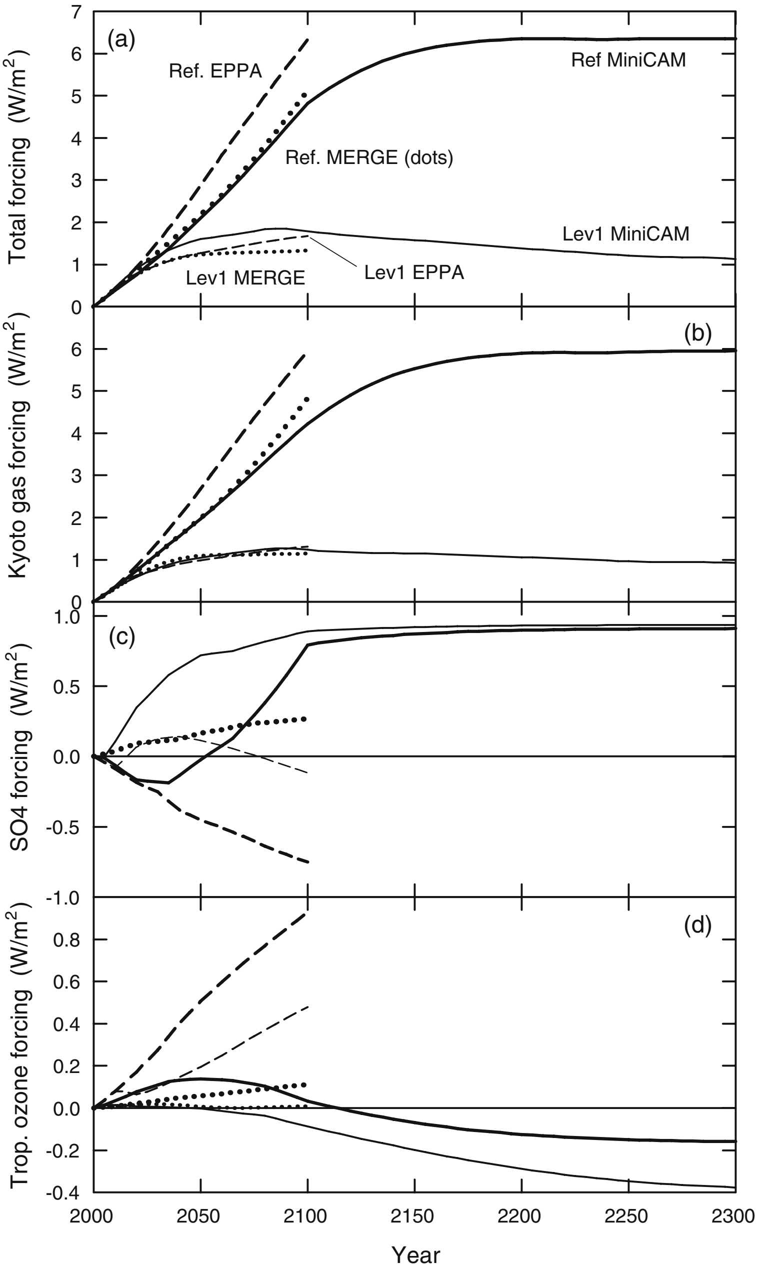
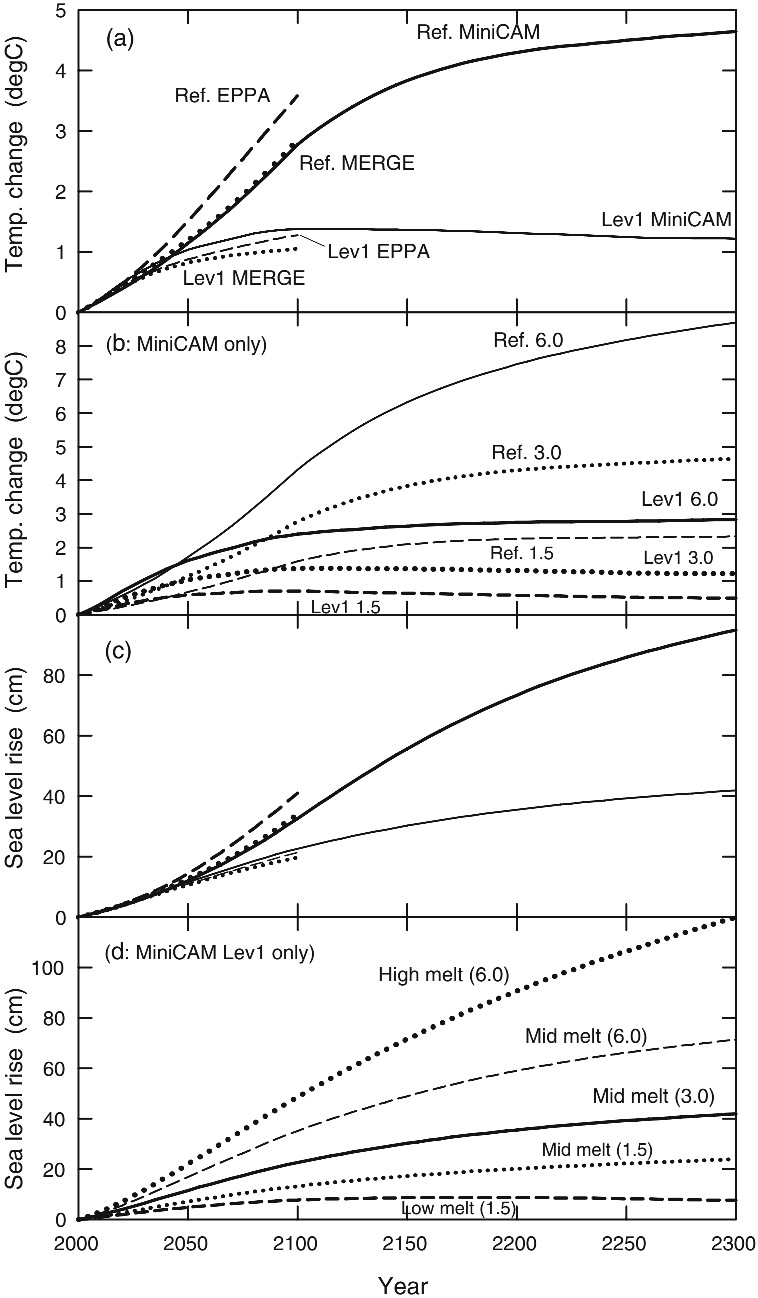



**Fig. 3** Radiative forcing results for the reference (*bolder lines*) and Level 1 stabilization cases. EPPA results are *dashed lines*, MiniCAM results are *full lines*, and MERGE results are *dotted lines*. **a** Total radiative forcing. **b** Forcing for gases potentially controlled under the Kyoto Protocol. **c** Sulfate aerosol forcing (sum of direct and indirect effects). **d** Tropospheric ozone forcing

**Table 2** 2000–2100 forcing changes (W/m$^2$)

| Model | MiniCAM | | | EPPA | | | MERGE | | | MiniCAM | | | EPPA | | | MERGE | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Total | Kyoto | Diff. | Total | Kyoto | Diff. | Total | Kyoto | Diff. | $SO_4$ | Trop. $O_3$ | Sum | $SO_4$ | Trop. $O_3$ | Sum | $SO_4$ | Trop. $O_3$ | Sum |
| Ref. | 4.82 | 4.22 | 0.60 | 6.32 | 5.94 | 0.38 | 5.13 | 4.82 | 0.30 | 0.60 | 0.03 | 0.63 | −0.51 | 0.93 | 0.42 | 0.19 | 0.11 | 0.30 |
| Level4 | 4.50 | 3.88 | 0.62 | 4.01 | 3.68 | 0.33 | 4.61 | 4.33 | 0.28 | 0.65 | 0.01 | 0.65 | −0.32 | 0.69 | 0.37 | 0.19 | 0.09 | 0.29 |
| Level3 | 3.89 | 3.28 | 0.61 | 3.37 | 3.02 | 0.35 | 3.95 | 3.70 | 0.25 | 0.68 | −0.04 | 0.63 | −0.25 | 0.63 | 0.38 | 0.19 | 0.07 | 0.26 |
| Level2 | 2.96 | 2.38 | 0.58 | 2.54 | 2.16 | 0.38 | 2.79 | 2.59 | 0.21 | 0.67 | −0.07 | 0.60 | −0.14 | 0.56 | 0.42 | 0.19 | 0.02 | 0.22 |
| Level1 | 1.79 | 1.23 | 0.56 | 1.67 | 1.31 | 0.36 | 1.32 | 1.14 | 0.18 | 0.68 | −0.09 | 0.59 | −0.08 | 0.48 | 0.39 | 0.19 | 0.01 | 0.20 |

"Total" accounts for all species, while "Kyoto" sums only those gases potentially controlled under the Kyoto Protocol. Scenario-to-scenario changes in differences (Total minus Kyoto) are due to changes in aerosol forcing and tropospheric ozone forcing. $SO_4$ refers to sulfate aerosol forcing (direct plus indirect) plus forcing from fossil carbon (soot) and organic carbon aerosols



(a)
Ref. MiniCAM
Ref. EPPA
Ref. MERGE
Lev1 MiniCAM
Lev1 EPPA
Lev1 MERGE
Temp. change (degC)
(b: MiniCAM only)
Ref. 6.0
Ref. 3.0
Lev1 6.0
Ref. 1.5
Lev1 3.0
Lev1 1.5
Temp. change (degC)
(c)
Sea level rise (cm)
(d: MiniCAM Lev1 only)
High melt (6.0)
Mid melt (6.0)
Mid melt (3.0)
Mid melt (1.5)
Low melt (1.5)
Sea level rise (cm)
Year

◀ **Fig. 4** Global-mean temperature and sea level projections for the reference (*bolder lines*) and Level 1 stabilization cases. In **a** and **c**, EPPA results are *dashed lines*, MiniCAM results are *full lines*, and MERGE results are *dotted lines*. **a** and **c** assume best-estimate climate and sea level model parameters, including a climate sensitivity ($\Delta T_{2x}$) of 3.0°C equilibrium warming for a $CO_2$ doubling. **a** Global-mean temperature. **b** Effect of climate sensitivity for the MiniCAM reference and Level 1 stabilization cases using $\Delta T_{2x}$ values of 1.5°C, 3.0°C and 6.0°C. **c** Sea level. **d** Effect of climate sensitivity and ice-melt model parameter uncertainties for sea level for the MiniCAM Level 1 stabilization case

## 5 Temperature and sea level changes

### 5.1 Temperature changes

Temperature change results for the reference and Level 1 stabilization cases are shown in Fig. 4a, with results for the other stabilization cases shown in Fig. 13 below. These results are for a central set of climate model parameters (see Appendix 2), in particular for a climate sensitivity of 3.0°C equilibrium warming for a $CO_2$ doubling. 3.0°C is the central estimate for the climate sensitivity given in the AR4.

For the extended MiniCAM forcing-stabilization scenarios, global-mean temperature virtually stabilizes by 2300. The 2300 warming levels are close to the expected equilibrium warmings for the assumed climate sensitivity. Thus, temperature could be stabilized if the emissions scenarios produced by the three IA models (and the MiniCAM extension) were followed, which in turn depends on their economic and technological feasibility. The temperature stabilization level in the extended MiniCAM Level 1 stabilization case is approximately 2°C above the pre-industrial level.

Ranges in future temperature changes arising from uncertainties in the climate sensitivity are illustrated in Fig. 4b for the MiniCAM reference and Level 1 cases. To illustrate these uncertainties we use a low sensitivity of 1.5°C and a high sensitivity of 6.0°C, estimated to be the 90% confidence interval based on the AR4 “likely” range for climate sensitivity (see Appendix 2).

For Level 1 (450 ppm), the asymptotic (i.e., equilibrium) uncertainty range for temperature changes from pre-industrial times, must, in relative terms, be the same as the climate sensitivity uncertainty range (a factor of 4 here). By 2300, the transient temperature changes have very nearly reached equilibrium, and the range of changes from pre-industrial times is, indeed, very close to a factor of four. From Fig. 4b, however, the uncertainty range for changes over 2000 to 2300 is slightly larger than four. This is because the range for transient warming in 2000 is less than the sensitivity uncertainty range.

A further consequence of the 2300 warmings being near to equilibrium and the central sensitivity warming estimate from pre-industrial times being around 2.0°C is that the probability of warming from pre-industrial times exceeding 2.0°C under the Level 1 scenario must be close to 50%. This is because, for near-equilibrium warming, the warming magnitude can depend only on the climate sensitivity. The central sensitivity (3.0°C; from AR4) is close to the median value, and has a probability of exceedence of close to 50%—so the corresponding warming must have the same probability of exceedence. 2.0°C is an important threshold politically because it is the change chosen by the European Community as the likely threshold for avoiding “dangerous anthropogenic climate change”, the UNFCCC criterion for choosing a greenhouse-gas stabilization level.

That there is a probability of about 50% of exceeding (or staying below) a warming of 2.0°C from pre-industrial times if one were to follow the MiniCAM Level 1 emissions pathway is consistent with other work, such as the analysis of Meinshausen (2006). Note also that a warming of less than 2°C would be very difficult to achieve in the absence of policies as stringent as those embodied in the Level 1 case. For example, in the MiniCAM reference case with a climate sensitivity of 1.5°C (the fifth percentile point) the warming from pre-industrial times in 2300 is 2.71°C, and the equilibrium warming is 2.96°C. A sensitivity of less than 1.1°C (corresponding to the 1-percentile point in the log-normal sensitivity distribution assumed here) is required to keep warming to 2300 below 2°C in this case.

### 5.2 $CO_2$–$SO_2$ emissions coupling

A particularly interesting and potentially important result is that, for MiniCAM Level 1, in the early decades of the twenty-first century (out to 2042), the warming is actually more than in the reference case (and the Levels 2, 3 and 4 cases). In other words, in spite of the rapid reductions in GHG emissions, there is a counter-intuitive enhanced warming. This is an effect suggested by Wigley (1991), arising as a direct result of the coupling between $CO_2$ and $SO_2$ emissions and the rapid reduction in $SO_2$ emissions in the MiniCAM Level 1 stabilization case (see above). The forcing, and hence warming response to a reduction in $SO_2$ emissions is rapid, while the response to the parallel reduction in $CO_2$ emissions is much slower due to the long response times of the carbon cycle, allowing the $SO_2$ effect to initially dominate. For further details, see Smith and Wigley (2006).

### 5.3 Sea level rise

Sea level projections (Fig. 4c, d) include the effects of thermal expansion, ice melt and other components as considered in the TAR (Church et al. 2001). The projections therefore include contributions from the Greenland Ice Sheet and Antarctica—but these components are highly uncertain. As in the AR4, they do not account for possible accelerated ice losses from Greenland and Antarctica, so the projections given here might be considered optimistically low.

The present models differ from the TAR in two ways. First, we have used an improved model for GSIC ice melt (i.e., melt from mountain Glaciers and Small Ice Caps; Wigley and Raper 2005) that allows sensible projections beyond 2100. (If applied beyond 2100, the TAR GSIC model behaves quadratically and eventually produces negative ice melt.) Second, “non-melt” contributions employed in the TAR have been set to zero, in accord with the AR4. Further details are given in Appendix 2. For GSIC melt we follow the AR4 for specifying the total available GSIC ice. As this is less than some other estimates, this is another reason for suspecting that the AR4 (and, hence, present) sea level rise projections might be optimistically low.

For sea level rise, the effect of inertia in the climate system is much more pronounced than for temperature, so that, even in the Level 1 stabilization case, sea level continues to rise steadily after forcing stabilization. This is a well-known effect (Manabe and Stouffer 1993; Wigley 1995). It has been suggested that, in the absence of far more stringent emissions controls than those considered here, the only way to stabilize sea level might be to employ some form of geoengineering strategy (Wigley 2006).

Sea level rise uncertainties are quantified in Fig. 4d for the MiniCAM Level 1 case. Uncertainties arise in two ways, from uncertainties in the temperature response and from uncertainties in the response of land-based ice for any given temperature change. We separate these effects here by first using central ice-melt parameters and changing the climate sensitivity (inner three curves in Fig. 4d) and then incorporating ice-melt uncertainties. (Ice melt parameters and their uncertainties are as given in the TAR; Church et al. 2001.) The overall uncertainty range, more than a factor of 10, is much larger than for global-mean temperature. The upper bound for Level 1 is actually greater than the central value for the reference case. Only under the most optimistic assumptions does sea level stabilize.

## 6 Conclusions

### 6.1 Emissions and forcing differences

We have considered the atmospheric composition, global-mean temperature, and sea level consequences of the reference and stabilization emissions scenarios out to 2100 produced for the CCSP2.1a report (Clarke et al. 2007), together with an extension of these emissions out to 2300. The three reference scenarios are similar for $CO_2$, but quite different for other gases. For the stabilization cases, the emissions trajectories for non-$CO_2$ gases differ considerably as a result of different economic assumptions, different choices regarding the treatment of these gases, and internal IA model differences. This leads to different total forcing trajectories. The forcing trajectories, however, are much closer when only Kyoto gases are considered—but it is total forcing that determines the climate response. An important result that is common to all three IA simulations is that, to achieve $CO_2$ stabilization at 450 ppm (the Level 1 stabilization case), peak $CO_2$ emissions occur close to today, implying, in the absence of a substantial $CO_2$ concentration overshoot, a need for immediate $CO_2$ emissions mitigation if we wish to stabilize at this level.

The extended scenarios illustrate the large inertia in the carbon cycle: continuing emissions in the absence of control policies out to 2100, as in the reference cases, would almost certainly commit us to future $CO_2$ concentrations well in excess of 1,000 ppm. Even to stabilize at 1,000 ppm would require extremely rapid emissions reductions over the twenty-second century (Fig. 1a).

### 6.2 Temperature projection uncertainties

For a climate sensitivity of 3.0°C and central values for other model parameters, global-mean temperature change over 2000–2100 for the reference cases ranges from 2.8°C to 3.5°C (see Fig. 13), and sea level rise ranges from 33 to 41 cm. For the Level 1 stabilization case, central estimate temperature changes over this period range from 1.1°C to 1.4°C, and sea level rise ranges from 20 to 23 cm. These differences reflect quite large differences in the emissions of non-Kyoto forcing agents, primarily sulfate aerosols and tropospheric ozone precursors. The non-Kyoto forcing differences in turn reflect large differences in the estimated responses to non-climate-related pollution concerns.

**Table 3** Summary of temperature and sea level changes over 2000 to 2100 and 2000 to 2300 for the extended MiniCAM Level 1 and reference scenarios

| | Year | 2100 | | | 2300 | | |
|---|---|---|---|---|---|---|---|
| | Climate sensitivity | 1.5°C | 3.0°C | 6.0°C | 1.5°C | 3.0°C | 6.0°C |
| | Ice melt | Low | Mid | High | Low | Mid | High |
| Level 1 | Temperature | 0.70 (−49%) | 1.38 | 2.40 (+74%) | 0.50 (−59%) | 1.22 | 2.84 (+133%) |
| Level 1 | Sea level | 7.7 (−66%) | 22.7 | 48.6 (+115%) | 7.5 (−82%) | 41.9 | 119.9 (+186%) |
| Reference | Temperature | 1.59 (−43%) | 2.77 | 4.32 (+56%) | 2.33 (−50%) | 4.64 | 8.70 (+76%) |
| Reference | Sea level | 13.2 (−60%) | 32.7 | 64.3 (+97%) | 23.1 (−76%) | 94.9 | 243.8 (+157%) |

Temperatures in degrees Celsius, and sea level rise in centimeters. Percentage changes relative to the central estimates are also given

Uncertainties in temperature projections due to uncertainties in the climate sensitivity have been explored using the MiniCAM reference and Level 1 scenarios (see Table 3). For changes over 2000 to 2100, the uncertainty range is −43%/+56% for the reference case (warming of 1.59°C to 4.32°C around a central estimate of 2.77°C), and −49%/+74% (warming of 0.70°C to 2.40°C around a central estimate of 1.38°C) for the Level 1 case. By 2300 the reference uncertainty is −50%/+87% (warming of 2.33°C to 8.70°C around a central estimate of 4.64°C) and the Level 1 uncertainty is −59%/+133% (warming of 0.50°C to 2.84°C around a central estimate of 1.22°C). If the assumed climate sensitivity range, 1.5°C to 6.0°C equilibrium warming for a $CO_2$ doubling, represents the 90% confidence interval (see Appendix 2), then the above transient temperature ranges would also represent 90% confidence intervals. If ocean mixing and carbon cycle feedback uncertainties were accounted for, then the uncertainty ranges could be appreciably higher—although it should be noted that the analysis of Wigley and Raper (2001) suggests that these are much smaller sources of uncertainty than the climate sensitivity.

## 6.3 Sea level projection uncertainties

For sea level, relative uncertainty ranges for changes from 2000 are larger than for temperature because of the additional uncertainties arising in estimating the ice-melt contributions to sea level rise (see Table 3). Using the MiniCAM reference and Level 1 scenarios, the uncertainty range in 2100 for the reference case is −60%/+97% (13 to 64 cm about a central estimate of 33 cm) and −66%/+115% for the Level 1 case (8 to 49 cm about a central estimate of 23 cm). By 2300 the reference uncertainty range is −76%/+157% (23 to 244 cm about a central estimate of 95 cm) and the Level 1 uncertainty range is −82%/+186% (8 to 120 cm about a central estimate of 42 cm). Even though these projections are consistent with results given in the AR4, they may well underestimate melt from land-based ice and, hence, are likely to be optimistically low.

In the upper-bound estimates (high climate sensitivity, high ice melt), sea level in 2300 is still rising at more than 50 cm/century in the MiniCAM reference case, and still rising at about 20 cm/century in the Level 1 case (Fig. 4d). At the low end, the projections are lower than might be suspected from results published in AR4 because they concatenate low model parameter results for both ice melt and climate sensitivity. As such, they must be ludged extremely unlikely.

### 6.4 The effect of $CO_2$–$SO_2$ emissions coupling

An important, but somewhat counter-intuitive result is that, for the lowest (Level 1) stabilization case, we might experience more rapid global-mean warming than for the corresponding reference case. This is the result of the strong coupling for coal combustion between $CO_2$ and $SO_2$ emissions reductions, and the more rapid (and opposite sign) response of the climate system to $SO_2$ emissions reductions relative to $CO_2$ emissions reductions (cf. Wigley 1991; Smith and Wigley 2006).

### 6.5 Dangerous interference

For the MiniCAM Level 1 stabilization case, assuming a climate sensitivity of 3.0°C, global-mean temperature stabilizes at around 2°C relative to pre-industrial times. This warming amount is often given as a threshold for avoiding dangerous

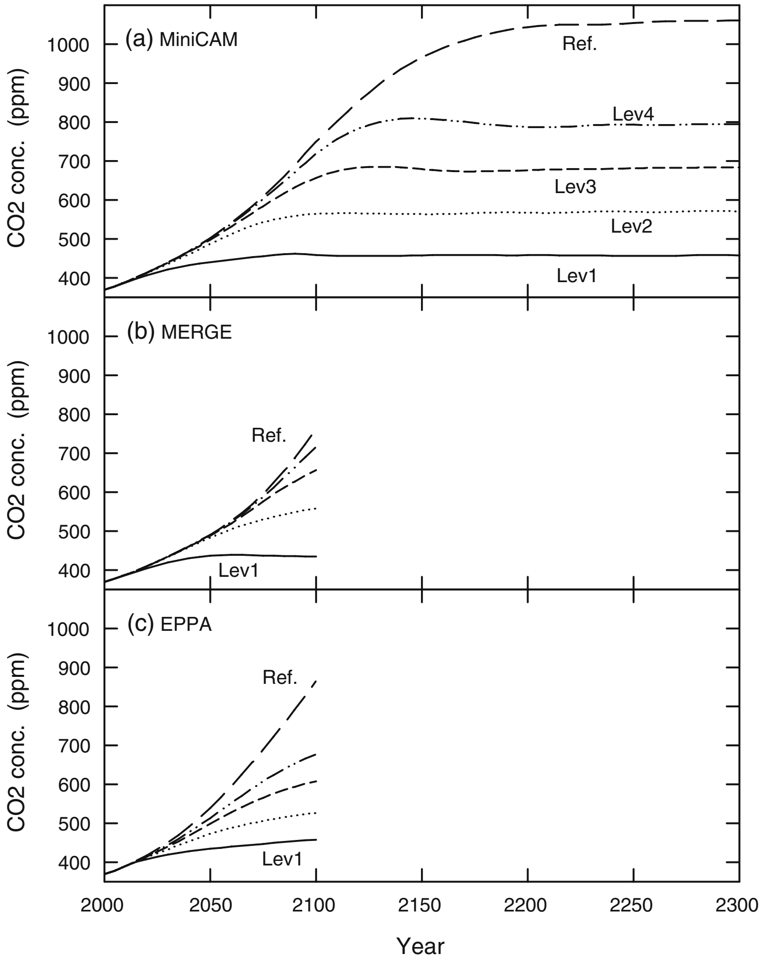



**Fig. 5** $CO_2$ concentrations for the five emissions scenarios and three integrated assessment models

interference with the climate system. Given that 3.0°C is approximately the median for estimates of the climate sensitivity's probability density function, the implication is that the probability of exceeding a 2°C warming from pre-industrial times for Level 1 (450 ppm) stabilization is around 50%. Whether Level 1 stabilization can be achieved, of course, depends on the political, economic and technological feasibility of the policies built into this stabilization scenario.

As has been noted many times, the amount of future warming that occurs even for an optimistic stabilization scenario means that significant adaptation measures will be required. Research into adaptation should therefore be afforded priority similar to that given to mitigation research. Since adaptation planning requires reliable estimates of the regional details of future climate change, it is clearly important to reduce the uncertainties in these estimates by continuing to improve state-of-the-art coupled ocean/atmosphere GCMs.

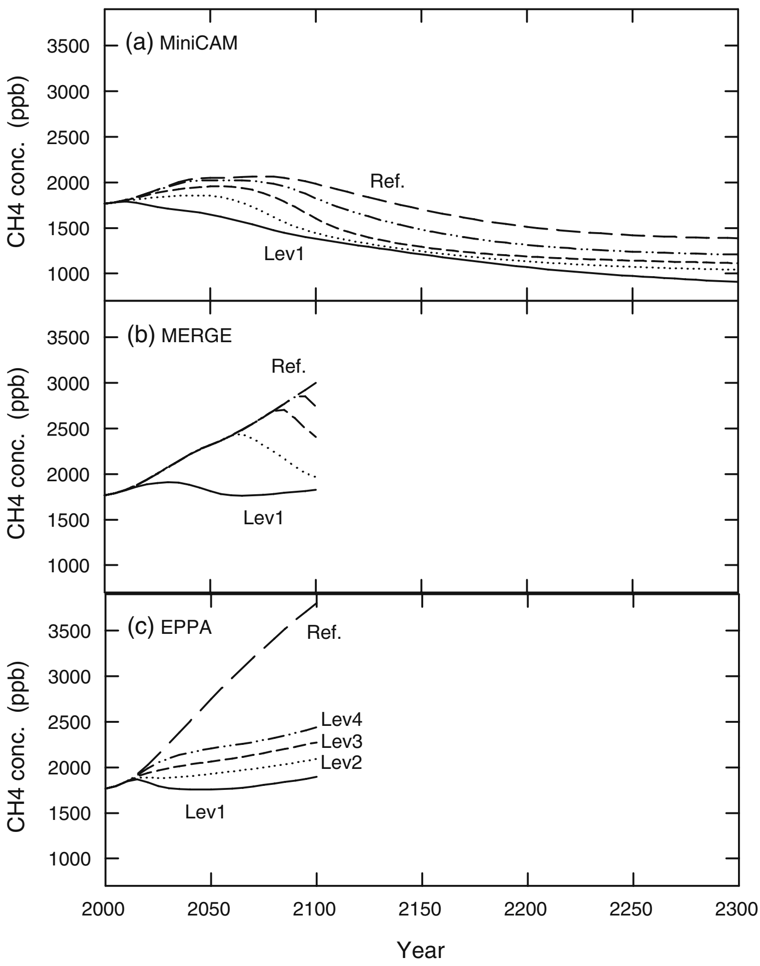



**Fig. 6** $CH_4$ concentrations for the five emissions scenarios and three integrated assessment models

## Appendix 1: Full stabilization results

The main text gave results for the reference and Level 1 case. Here we give results for the other stabilization levels.

Figures 5, 6 and 7 give concentration results. Figure 5 shows $CO_2$ concentrations. For MiniCAM, emissions were specified out to 2095, and concentrations were specified beyond this, smoothly fitted to the 2095 values and their rates of change using Padé approximants. For Levels 1, 2, 3, and 4, emissions were calculated using the inverse version of MAGICC 4.1, with $CO_2$ concentrations assumed to stabilize at 450, 550, 650 and 750 ppm in 2150, 2180, 2190 and 2200 respectively. For these emissions, concentration projections using MAGICC 5.3 are slightly higher. Figures 6 and 7 show $CH_4$ and $N_2O$ concentrations. Note that, even in the Level 1 scenarios

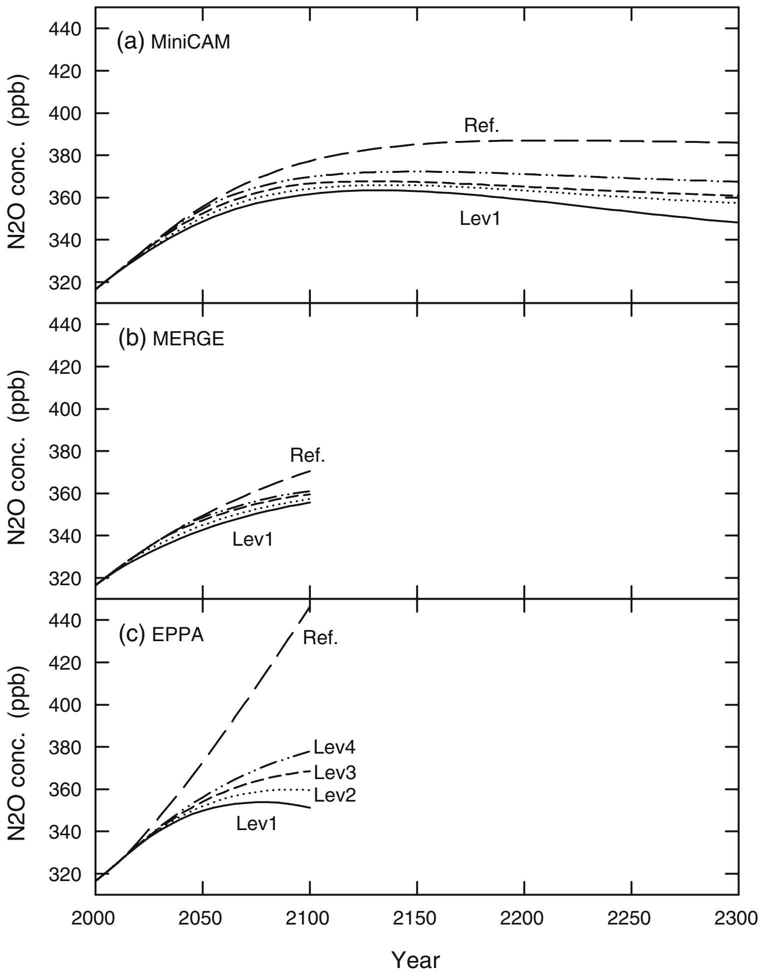



**Fig. 7** $N_2O$ concentrations for the five emissions scenarios and three integrated assessment models

for MiniCAM, $CH_4$ and $N_2O$ concentrations in 2300 are still well above pre-industrial levels.

Figures 8, 9, 10, 11 and 12 show radiative forcing results. Figure 8 shows reference scenario forcing for Kyoto gases relative to pre-industrial times (bottom panel), broken down into $CO_2$ and non-$CO_2$ components in the top two panels. $CO_2$ forcing is similar in all three IA models, but there are large relative differences for non-$CO_2$ forcings (note the different scale in the top panel).

In Fig. 9, Kyoto gas forcings are given for all models and all scenarios. These results may be compared with the total radiative forcing results in Fig. 10 (see also Fig. 3 and Table 2). The difference between total and Kyoto-gas forcing is due to aerosols and tropospheric ozone (see Figs. 3, 11 and 12 and Table 2), which, as one moves from the reference to and through the stabilization scenarios, have

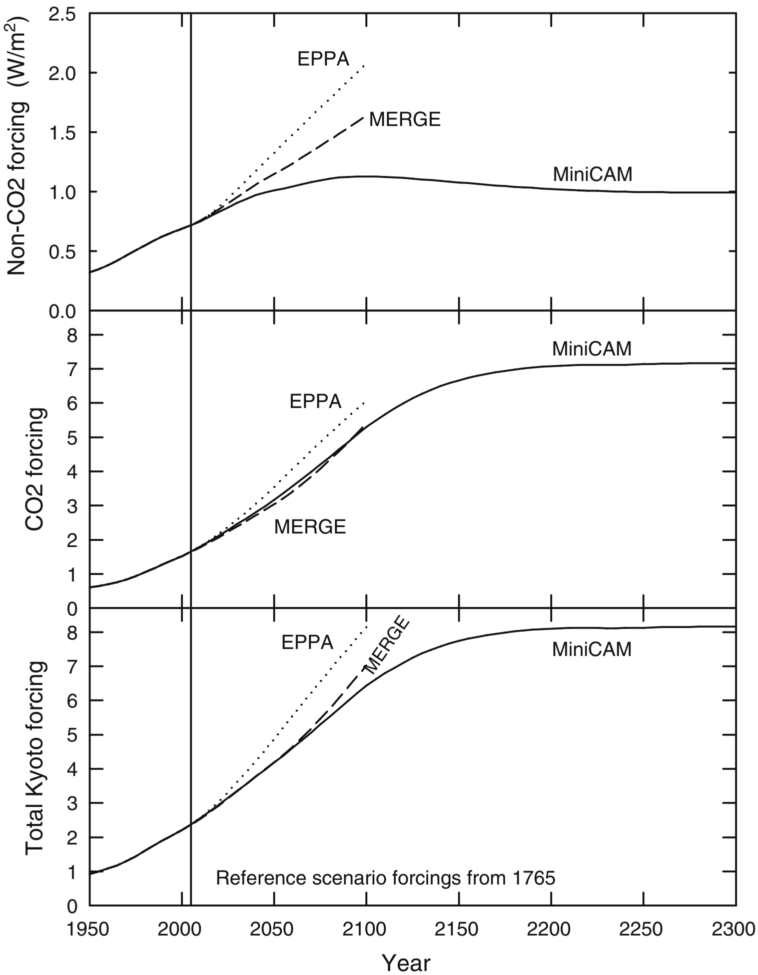



**Fig. 8** Reference-scenario Kyoto-gas radiative forcing relative to pre-industrial times for the three integrated assessment models (*bottom panel*), with breakdown into $CO_2$ and non-$CO_2$ components (the sum of forcings for $CH_4$, $N_2O$, HFCs, PFCs and $SF_6$). The *vertical line* is in 2005

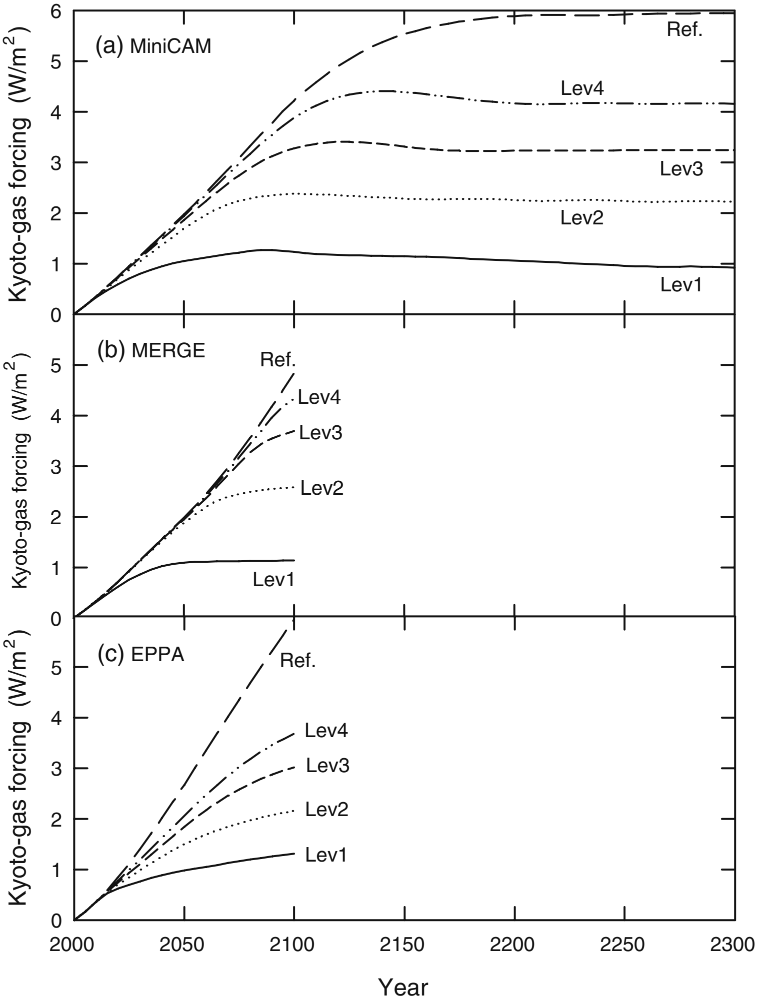



**Fig. 9** Kyoto-gas radiative forcing for the five emissions scenarios and three integrated assessment models

compensating effects. Thus, the net effects of the stabilization policies on non-Kyoto-gas forcings is small. As noted in the main text, however, there are considerable differences between the IA models in the magnitudes and changes in both aerosol and tropospheric ozone forcing, primarily as a result of inter-model differences in the effects of non-climate (pollution-related) policies. The extent to which non-climate policies influence future emissions of $SO_2$ and ozone precursors, therefore, is an important area of emissions scenario uncertainty.

Temperature change results are shown in Fig. 13 for best-estimate climate model parameter values (which include a climate sensitivity of 3.0°C equilibrium for a $CO_2$ doubling). The most striking result is that for MiniCAM, where the “knock-on” effects on $SO_2$ emissions of the Level 1 $CO_2$ emissions policies lead to additional warming that initially over-rides the direct cooling effect of the $CO_2$ policies. The

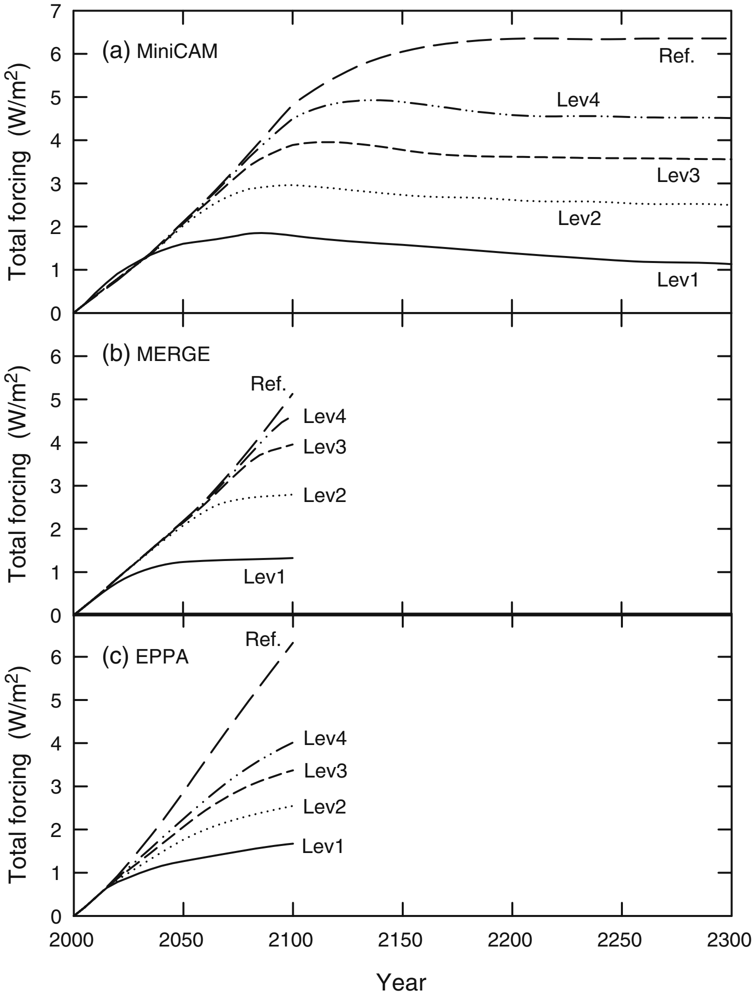



**Fig. 10** Total radiative forcing for the five emissions scenarios and three integrated assessment models

effect is similar for the other stabilization levels, albeit smaller, leading to the policies having virtually no effect on temperatures out to around 2060.

Figures 14 and 15 show thermal expansion and total sea level rise results, again using best-estimate climate and ice-melt model parameter values. Inertia in the sea level drivers leads to virtually no noticeable effect of policy on sea level out to around 2040 (slightly longer for the MiniCAM results due to the aerosol effect noted above in the case of temperature change). An important result, already stressed in the main text, is that, even in 2300, sea level is still rising in the stabilization cases.

Figure 16 shows $CO_2$ emissions from net land-use change ("net defor."). There are striking differences between MiniCAM and EPPA in terms of the effects of policy. In MiniCAM, policy effects on land-use are relatively small for Levels 2, 3 and 4.

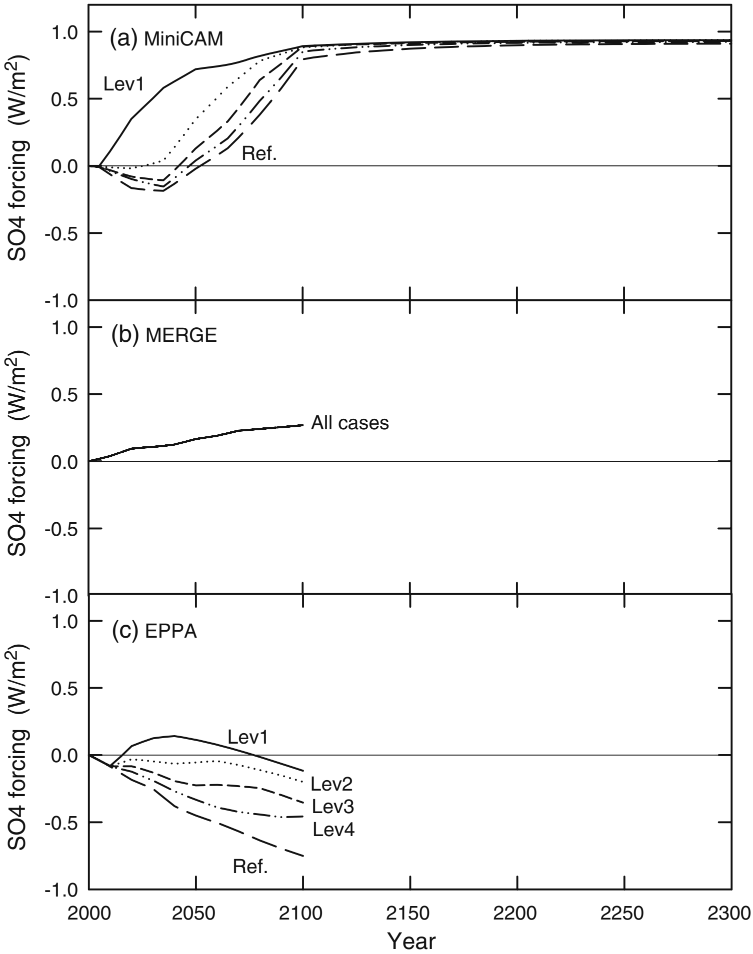



**Fig. 11** Sulfate aerosol radiative forcing (direct plus indirect) for the five emissions scenarios and three integrated assessment models

For Level 1, however, there are much larger effects that vary substantially over time. These variations arise because fuel price and land availability considerations have large but disparate effects on the use of land for biomass fuel production. The reduction in land-use emissions over 2080 to 2095 in the MiniCAM Level 1 case is sufficiently large to have a visible effect on total radiative forcing through changes in biomass-burning aerosol loading, as explained in the main text (see top panels of Figs. 3 and 10). The EPPA results, which show almost no effect of policy on land-use change, provide a striking contrast, highlighting the uncertainties surrounding such policy influences. MERGE results are not comparable with the other two models because MERGE has no terrestrial component in its carbon cycle model. Instead, MERGE assumes a "neutral biosphere" (i.e., zero net emissions, with fertilization feedbacks assumed to compensate for the sum of climate feedbacks and net land-

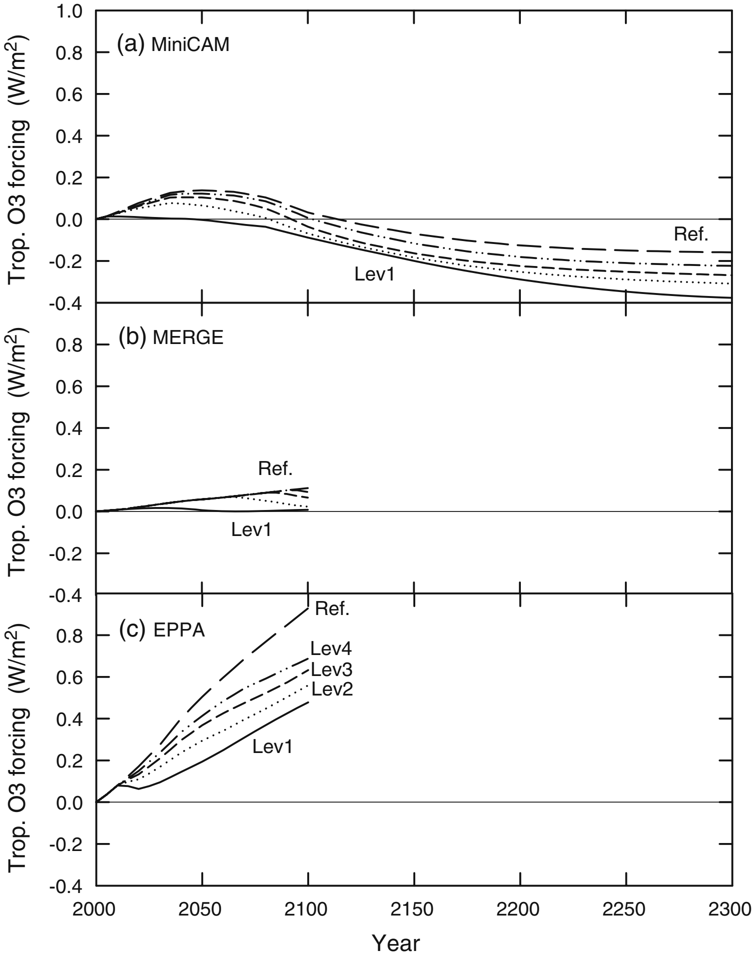



**Fig. 12** Tropospheric ozone radiative forcing for the five emissions scenarios and three integrated assessment models

use emissions). The MERGE results shown in Fig. 16 (middle panel) were obtained using inverse calculations with MAGICC 4.1.

## Appendix 2: Description of MAGICC 5.3

MAGICC is a coupled gas-cycle/climate model (*M*odel for the *A*ssessment of *G*reenhouse-gas *I*nduced *C*limate *C*hange). MAGICC has been one of the primary models used by IPCC since 1990 to produce projections of future global-mean temperature and sea level rise. The climate model in MAGICC is an upwelling-diffusion, energy-balance model that produces global- and hemispheric-mean temperature output together with results for oceanic thermal expansion. The MAGICC

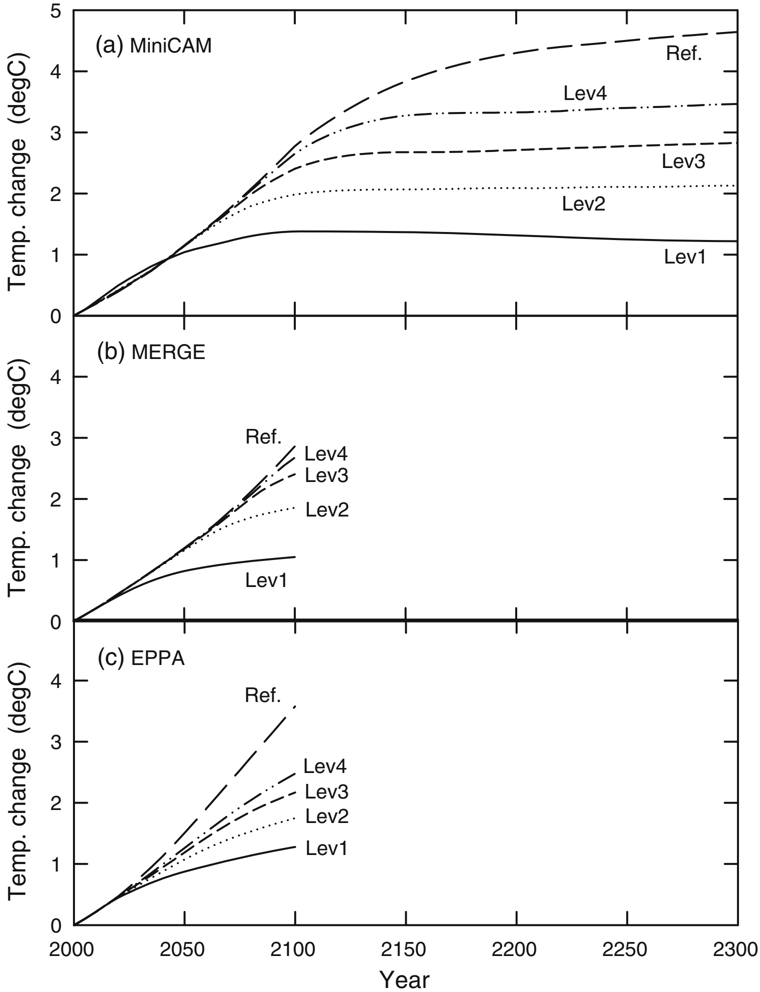



**Fig. 13** Global-mean temperature changes for the five emissions scenarios and three integrated assessment models using best-estimate gas-cycle and climate model parameters

climate model is coupled interactively with a range of gas-cycle models that give projections for the concentrations of the key greenhouse gases. Climate feedbacks on the carbon cycle are accounted for. Many of the structural elements of various versions of MAGICC are similar. Mathematical details for MAGICC 6.0 are given in Meinshausen et al. (2008a).

The 4.1 version of the software is consistent with and was used in the IPCC Third Assessment Report, Working Group 1 (TAR). The 5.3 version of the software is consistent with the IPCC Fourth Assessment Report, Working Group 1 (AR4). Consistency with the AR4 does not mean, however, that we fully endorse AR4 results. For sea level in particular, it is likely that the projected changes are underestimates.

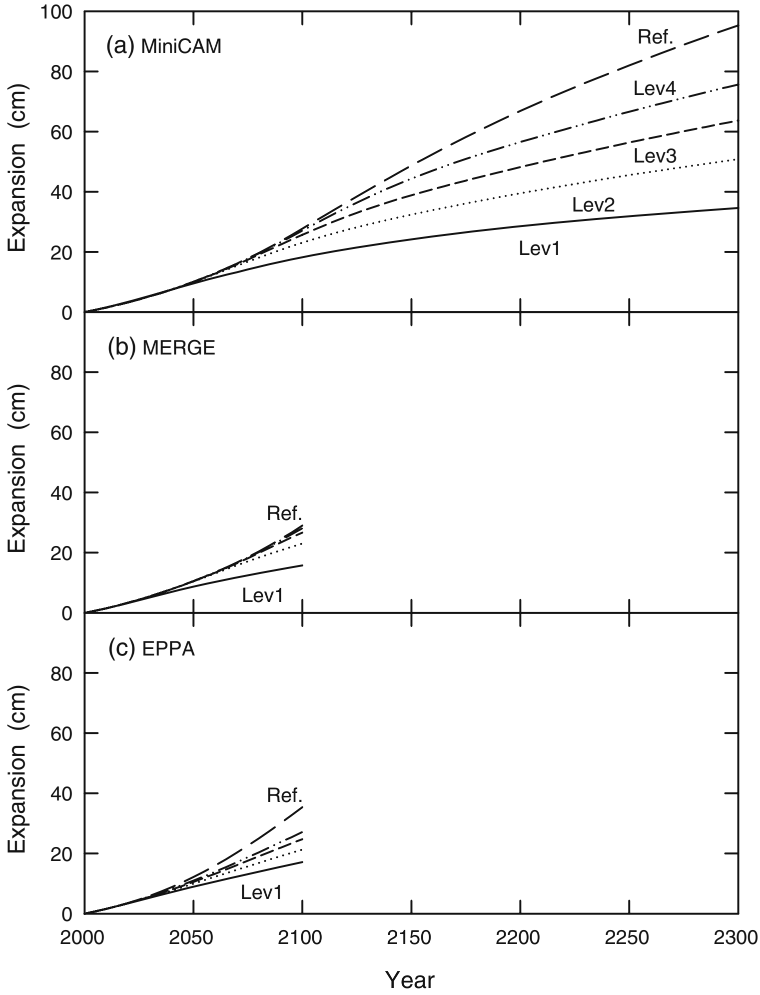



**Fig. 14** Global-mean ocean thermal expansion for the five emissions scenarios and three integrated assessment models using best-estimate gas-cycle and climate model parameters

## Forcing changes

In version 5.3, changes have been made to ensure consistency with the IPCC AR4. In version 4.1, various forcings were initialized in 1990 (or 2000 in the case of tropospheric ozone), and subsequent forcings are dependent on these initializations. The version 4.1 initialization values were consistent with best-estimate forcings given in the TAR. In AR4, new best-estimate forcings have been given for 2005. 1990 initialization values have therefore been changed slightly to give projected 2005 values consistent with these new AR4 results. As MAGICC includes historical values only to 1990 or (for $CO_2$) 2000, the 2005 values it produces depend on the chosen emissions scenario. Thus, it has not been possible to precisely emulate the AR4 2005 values. The differences, however, are very small, as shown in Table 4.

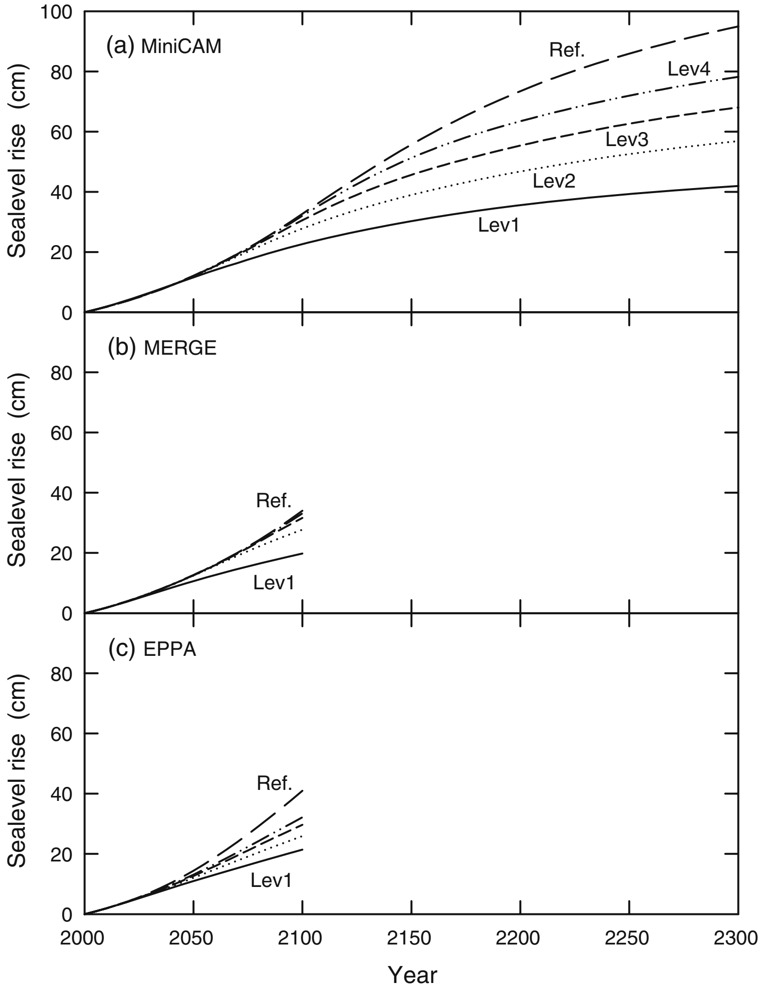



**Fig. 15** Global-mean sea level rise for the five emissions scenarios and three integrated assessment models using best-estimate gas-cycle, climate model and ice-melt model parameters

Further details are given in the MAGICC 5.3 User Manual, downloadable from http://www.cgd.ucar.edu.

## Indirect aerosol forcing

To match the AR4 2005 values, the best-estimate indirect forcing is set at $-0.7$ W/m$^2$ in 1990 (previously $-0.8$ W/m$^2$ in version 4.1). For the uncertainty range, MAGICC 5.3 uses $\pm 0.4$ W/m$^2$, the same as previously. AR4 gives a range that is asymmetrical about the central estimate, $-1.8$ to $-0.3$ W/m$^2$. Using $-1.8$ W/m$^2$ as a lower bound (1.1 W/m$^2$ below the best estimate) would lead to extremely low total historical anthropogenic forcing unless compensated by a large underestimate in some positive

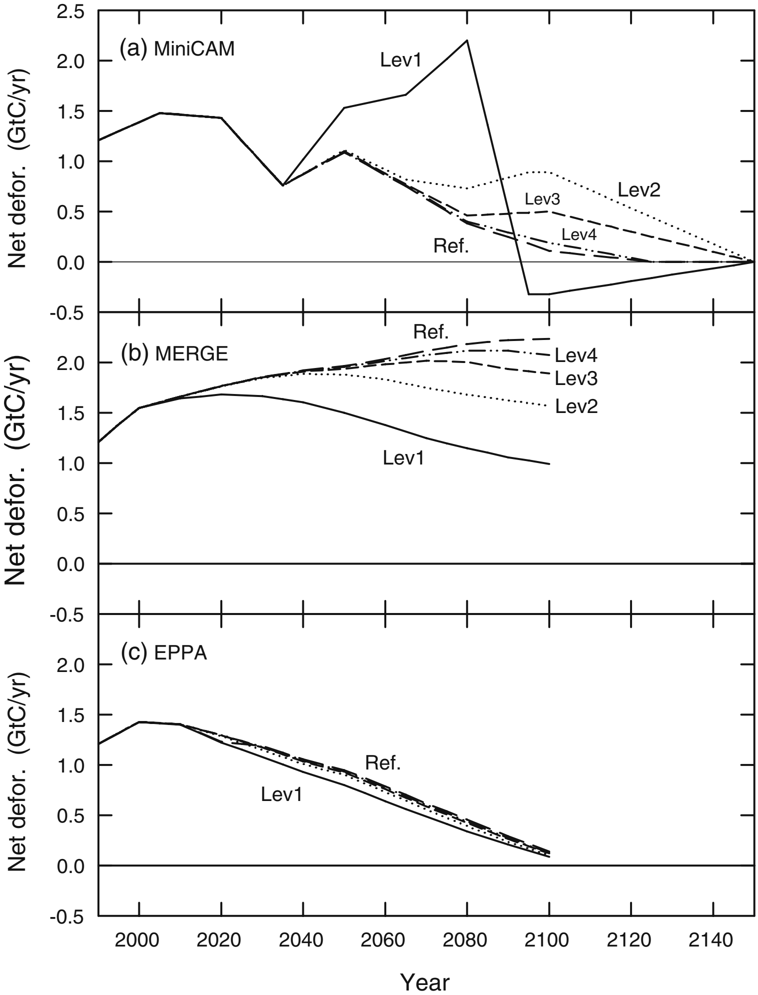



**Fig. 16** Net land-use change $CO_2$ emissions for the five emissions scenarios and three integrated assessment models. For MiniCAM the plot shows the assumed extrapolations beyond the last (2095) model-based results

forcing term, which is highly unlikely. We therefore retain ±0.4 W/m$^2$ for the uncertainty range for indirect aerosol forcing.

In support of this decision we note that a negative indirect forcing as large as −1.8 W/m$^2$ would be inconsistent with detection and attribution (D&A) studies. Such studies to date have rarely considered indirect forcing explicitly, but they do so implicitly because the response patterns of direct and indirect forcing are almost certainly similar. These studies give best-estimate values of *total* sulfate aerosol forcing ranging from −1.7 to −0.1 W/m$^2$, with a mean of about −0.8 W/m$^2$ (Hegerl et al. 2007). The lower bound here is much smaller in magnitude than the lower a priori uncertainty bound suggested by AR4. In addition, the central empirical estimate of −0.8 W/m$^2$ is noticeably smaller in magnitude than the combined best estimate

**Table 4** 2005 AR4 forcings (W/m$^2$) compared with forcings calculated for 2005 in MAGICC 5.3

| | Component | AR4, 2005[a] | MAG53, 2005 |
|---|---|---|---|
| 1 | $CO_2$ | 1.49 (1.66) 1.83 | 1.645 to 1.661 |
| 2 | $CH_4$ | 0.43 (0.48) 0.53 | |
| 2a | $CH_4$+strat. $H_2O$ | 0.55 | 0.524 to 0.528 |
| 3 | $N_2O$ | 0.14 (0.16) 0.18 | 0.165 to 0.167 |
| 4 | Halocarb. direct | 0.31 (0.34) 0.37 | 0.375 |
| 4a | 1 + 2a + 3 + 4 | 2.71 | 2.711 to 2.731 |
| 5 | Montreal gases | 0.29 (0.32) 0.35 | 0.353 |
| 6 | HFCs,PFCs,SF6 | 0.017 | 0.0216 |
| 6a | 5 + 6 | 0.337 | 0.374 |
| 7 | Trop. $O_3$ | 0.25 (0.35) 0.65 | 0.342 to 0.358 |
| 8 | Strat. $O_3$ | −0.15 (−0.05) 0.05 | −0.203 |
| 9 | $SO_4$ direct | −0.2 (−0.4) −0.6 | −0.377 to −0.440 |
| 10 | Fossil fuel organic C | −0.1 (−0.05) 0.0 | See FOC (18a) |
| 11 | Fossil fuel black C | 0.05 (0.2) 0.35 | See FOC (18a) |
| 12 | Biomass burning | −0.09 (0.03) 0.15 | 0.023 to 0.025 |
| 13 | Nitrate | −0.2 (−0.1) 0.1 | See item 14 |
| 14 | Mineral dust | −0.3 (−0.1) 0.1 | −0.2 (items 13 + 14) |
| 15 | Aerosol direct | −0.1 (−0.5) −0.9 | |
| 15a | 9 + 10 + 11 + 12 + 13 + 14 | −0.42 | |
| 16 | Aerosol indirect | −0.3 (−0.7) −1.8 | −0.674 to −0.743 |
| 17 | Land use | −0.2 | −0.2 |
| 18 | Black C on snow | 0.1 | See FOC (18a) |
| 18a | 10 + 11 + 18 (=FOC) | 0.25 | 0.230 to 0.269 |
| 19 | Contrails | 0.01 | Not included |
| 20 | Total | 0.6 (1.6) 2.4 | |
| 20a | Component sum | 1.72 | 1.596 to 1.673 |

In column 3, headed "AR4, 2005", the outer numbers give the 90% confidence interval, while the central (or sole) number gives the best estimate. In column 4, headed "MAG53, 2005", 2005 values are best estimate values and are scenario dependent. The range given is the best estimate range over the six SRES illustrative scenarios. Total forcing is given in row 20, which is the sum of 1, 2a, 3, 4, 7, 8, 15, 16, 17, 18 and 19. With AR4 best estimates, the sum of the individual components (20a) is slightly higher than the independent best estimate for the total (1.72 compared with 1.6 W/m$^2$). Similarly, the component sum (15a) differs slightly from the independent best estimate for total direct aerosol forcing (15)

[a]Ranges give the 90% confidence intervals. AR4 values assumed to be mid-year values

of direct plus indirect forcing in AR4 of −1.1 W/m$^2$ (−0.7+(−0.4)). We nevertheless retain the −1.1 value for initialization, which leads to a total historical forcing of 1.60 to 1.67 W/m$^2$ (Table 4, row 20a). The implication of D&A studies is that this value is too low, and that the AR4 estimate of the magnitude of total aerosol forcing is

**Table 5** Best-estimate total forcing in 2005 since pre-industrial times as produced by MAGICC 5.3

For comparison, the best estimate in the IPCC AR4 is 1.6 W/m$^2$

| Scenario | 2005 Total forcing ($\Delta T_{2x} = 3°C$) – W/m$^2$ |
|---|---|
| A1B | 1.596 |
| A1FI | 1.610 |
| A1T | 1.673 |
| A2 | 1.634 |
| B1 | 1.615 |
| B2 | 1.653 |
| AR4 | 1.6 |

too high. As might be expected, therefore, unless a high value of climate sensitivity is used, model estimates of historical warming are less than observed and (because aerosol forcing is larger in the Northern Hemisphere) the modeled hemispheric warming differential is greater than observed.

With these new forcing initializations, total forcing in the AR4 reference year, 2005, should be similar to the best-estimate of total forcing given in the AR4. As noted above, precise agreement is not possible as MAGICC's 2005 data are short-term projections rather than specifically defined values. MAGICC values depend on the assumed emissions scenario. Nevertheless, the MAGICC/AR4 differences are very small, as shown in Table 5. In the AR4, the best-estimate total forcing in 2005 is 1.6 W/m$^2$, with a 90% uncertainty range of 0.6 to 2.4 W/m$^2$. (Uncertainties are due primarily to uncertainties in indirect aerosol forcing.) The AR4 component sum (Table 4, row 20a) is slightly higher, 1.72 W/m$^2$, and the MAGICC 5.3 values lie between this and the best estimate total. While the MAGICC values are slightly above the AR4 best estimate total, the differences are miniscule relative to the overall forcing uncertainty and have virtually no effect on projections of temperature or sea level change.

## Carbon cycle model and $CO_2$ concentration stabilization scenarios

The carbon cycle model in MAGICC 5.3 is essentially the same as first described in Wigley (1993), a four-box terrestrial component coupled to a convolution ocean. Parameter values have been changed to give concentration projections consistent with the results from the C$^4$MIP carbon-cycle model intercomparison exercise (Friedlingstein et al. 2006). In this exercise, the SRES A2 scenario was used as a test case. MAGICC projections for A2 agree with the average of the C$^4$MIP model results, and the uncertainty range that MAGICC gives matches the 5–95% range of the C$^4$MIP data.

**Table 6** Comparison of TAR carbon cycle model concentration projections (ppm) with MAGICC 5.3 projections

| Scenario | 2050 | | | 2100 | | |
|---|---|---|---|---|---|---|
| | Bern | ISAM | MAGICC 5.3 | Bern | ISAM | MAGICC 5.3 |
| A1B | 522 | 532 | 529 | 703 | 717 | 707 |
| A1T | 496 | 501 | 497 | 575 | 582 | 569 |
| A1FI | 555 | 567 | 564 | 958 | 970 | 976 |
| A2 | 522 | 532 | 529 | 836 | 856 | 852 |
| B1 | 482 | 488 | 485 | 540 | 549 | 533 |
| B2 | 473 | 478 | 473 | 611 | 621 | 612 |
| IS92a | 499 | 508 | 505 | 703 | 723 | 714 |
| IS92a (NFB) | | | 494 | 651 | 682 | 673 |
| Feedback | | | 11 | 52 | 41 | 41 |

This is an update of results shown in Tables 7.1 and 7.2 of Wigley et al. (2007). For consistency with the TAR results, all concentrations are beginning-of-year values, and all simulations assume a climate sensitivity ($\Delta T_{2x}$) of 2.5°C. (The default climate sensitivity in MAGICC 5.3 is 3.0°C.) The models are those used in the IPCC TAR: Bern (Joos et al. 2001), and ISAM (Kheshgi and Jain 2003)

For the default case where climate feedbacks on the carbon cycle are included, the parameter changes make very little difference to the concentration projections for the six IPCC illustrative scenarios when MAGICC 5.3 is compared with MAGICC 4.1. They do, however, affect the magnitude of climate feedbacks on the carbon cycle. In MAGICC 5.3, both with-feedback and no-feedback results are consistent with the average results for the models used in the $C^4$MIP intercomparison exercise. A comparison of MAGICC 5.3 results with those of the two other carbon cycle models used in the TAR is given in Table 6.

## Sea level rise

In the IPCC Third Assessment Report (TAR; Church et al. 2001), a new method was used for projecting sea level rise from GSICs (Glaciers and Small Ice Caps). This method was only meant to be used out to 2100—if applied beyond 2100 (as, for example, in stabilization scenarios) it behaved quadratically, with sea level rise from GSIC melt rising to a maximum and then declining. Extended scenarios could therefore lead to large negative GSIC melt (i.e., a gain in GSIC ice mass relative to pre-industrial times) even when temperatures were still rising. In MAGICC 4.1, this problem was avoided simply by keeping the GSIC melt term at its maximum value once the maximum was reached. The TAR formulation constrained this maximum to a melt of 18.72 cm relative to pre-industrial times—effectively fixing the total amount of GSIC ice mass at 18.72 cm sea-level equivalent.

A more realistic, physically based formulation has been given by Wigley and Raper (2005). This gives results that are consistent with the TAR out to 2100, but allows the total GSIC ice mass to be specified externally. This new formulation produces GSIC melt that rises asymptotically towards the total available amount of GSIC ice as warming continues—i.e., eventually, almost all of the GSIC ice melts if the world becomes warm enough. MAGICC 5.3 uses this new formulation. The total GSIC ice mass ($V_0$) used here is 29 cm. This is effectively the best-estimate value given in the IPCC Fourth Assessment Report (Meehl et al. 2007). AR4 gives a best-estimate of 24 cm and scales up GSIC melt projections by 20% to account for outlet glaciers in Greenland and Antarctica. With the present GSIC model, the same effect can be achieved by scaling up $V_0$. For $V_0$ uncertainties we use the scaled-up AR4 uncertainty range, 18 to 44 cm. For timescales more than a few centuries, if warming were substantial, the Greenland/Antarctic "GSIC" contribution could be much higher than implied by the 20% $V_0$ scaling, as their total ice mass is well over 50 cm, so MAGICC 5.3 (and AR4) projections of GSIC melt are probably optimistically low.

The other change made in MAGICC5.3 is to ignore the contributions from: (1) Greenland and Antarctica due to the ongoing adjustment to past climatic change, (2) runoff from thawing of permafrost, and (3) deposition of sediment on the ocean floor. (Referred to as "non-melt" terms below and in the main text.) These terms were assumed in the TAR to contribute to sea level rise at a constant rate independent of the amount of future warming, an assumption that was not meant to be applied beyond 2100. It is now thought that these terms are small, much smaller than was assumed in the TAR, so they were not considered in the AR4 (Jonathan Gregory, personal communication). For consistency, they are ignored here.

No other changes have been made to the sea level modeling components. In the AR4 report (p. 845) it is stated that AR4 projections for the Antarctic sea level contribution “are similar to those of the TAR”, while “Greenland … projections are larger by 0.01–0.04 m” (i.e., by 2100, these projections are 1 to 4 cm larger than the TAR projections). We have not adjusted the Greenland model to account for this.

MAGICC sea level projections are very similar to those in AR4, as the Table 7 shows.

When sea level rise components are compared, MAGICC gives slightly higher expansion and slightly lower results for GSIC and Greenland contributions. The differences in these component sea level terms are, however, within their uncertainty ranges. AR4, p. 844, suggests that MAGICC gives expansion results that are biased large. AR4, p. 844, also claims that MAGICC has a slight warm bias in projections of global-mean temperature. With regard to the latter claim, the apparent temperature bias is at least partly due to forcing differences between the standard MAGICC forcings and those used in AR4 AOGCMs. This and other factors make a true like-with-like AOGCM/MAGICC comparison difficult—see Meinshausen et al. (2008a, b).

The uncertainty bounds for sea level rise in Table 7 differ from those given in the AR4. This is because we concatenate uncertainty limits for all factors that contribute to sea level rise uncertainties. It is unlikely that all of these factors would act in the same direction (although some would because they are determined by the same underlying and more fundamental uncertainties, such as those in the climate sensitivity). Thus, within the limitations of the models used, the uncertainties given by MAGICC represent extreme, low probability values. AR4 uncertainty ranges can be simulated approximately from MAGICC results by halving the differences between the MAGICC extreme and best-estimate values. AR4 uncertainties (AR4, p. 820) are stated to be “5 to 95% intervals characterizing the spread of model results”. Given that the models used do not represent the full uncertainty range (they are often referred to as an “ensemble of opportunity”), it is likely that the 5% to 95% range given in the AR4 underestimates the “true” 5% to 95% range.

It should be noted that neither the AR4 nor the TAR projections (nor MAGICC) include the possible effects of accelerated ice flow in Greenland and/or Antarctica. In the AR4 this is judged to increase the upper bound for AR4 projections to 2100

**Table 7** Sea level rise projections (cm) over 1990 to 2095 given by MAGICC 5.3

| $\Delta T_2x$ | 1.5 | 3.0 | 3.0 | 3.0 | 6.0 |
|---|---|---|---|---|---|
| Ice melt | Low | Low | Mid | High | High |
| A1B | 14 | 24 | 35 [35] | 46 | 68 |
| A1FI | 19 | 32 | 45 [43] | 59 | 86 |
| A1T | 13 | 21 | 33 [33] | 44 | 65 |
| A2 | 16 | 27 | 38 [37] | 50 | 73 |
| B1 | 10 | 17 | 26 [28] | 35 | 52 |
| B2 | 12 | 20 | 31 [31] | 41 | 61 |

In column 4, the numbers in square brackets give the results published in the AR4. AR4 numbers (Meehl et al. 2007, p. 820) are based on AOGCM results and are changes between 1980 to 1999 and 2090 to 2099 by 9 to 17 cm (AR4, p. 821). Given this, it is likely that the upper-bound sea level rise projections given here are underestimates.

## Balancing the $CH_4$ and $N_2O$ budgets

In the TAR (and in earlier IPCC reports), because of uncertainties in the present-day $CH_4$ and $N_2O$ budgets, and because emissions data produced in most scenarios give only anthropogenic emissions, it was necessary to balance the gas budgets. This was done using a simple box-model relationship: $\mathrm{d}C/\mathrm{d}t = E/\beta + C/\tau$, where $C$ is concentration, $E$ is total emissions, $\beta$ is a units conversion factor, and $\tau$ is lifetime. If $\mathrm{d}C/\mathrm{d}t$, $C$ and $\tau$ are known in some reference year, then total $E$ for that year can be calculated. If the emissions value given in the scenario is $E_0$, then a correction factor $(E - E_0)$ can be calculated and this is applied to all future emissions.

If $E_0$ is solely the anthropogenic emissions value, then the difference $E - E_0$ represents the present contribution from natural emissions sources. Applying this correction to all future emissions is based on the assumption that natural emissions will remain constant. For $CH_4$ at least, there is evidence that this has not be so in the past (Osborn and Wigley 1994; MacFarling Meure et al. 2006), and strong evidence that it will not be so in the future. Version 5.3 of MAGICC does not account for future natural emissions changes, although it is relatively easy to do this if one has information on the possible effects of global warming on natural emissions.

In MAGICC 5.3, a minor change has been made to the rate of change of methane concentration in the year 2000 that is used for balancing the initial methane budget. The small decrease, from 8.0 to 3.5 ppb/year, is in better accord with observations. This reduces the calculated natural methane emissions level in 1990 (and subsequently) from 279.0 to 266.5 $TgCH_4$/year. Consequently, future $CH_4$ concentrations are reduced relative to those calculated by version 4.1. For example, 2100 concentrations for the A1B scenario drop from 1,970 to 1,913 ppb (mid-year concentrations). The effect of this on future climate projections is negligible.

## Changes to the climate sensitivity

The only other changes are to the estimates of climate sensitivity. In accord with AR4, the best-estimate of the climate sensitivity ($\Delta T_2x$) is now 3.0°C—previously 2.6°C. The AR4 uncertainty range for sensitivity is 2.0–4.5°C, designated as the “likely” range (66% confidence interval). If the distribution is assumed to be log-normal, this corresponds to a 90% confidence interval of 1.49–6.04°C. In MAGICC 4.1, the 90% confidence interval and best estimate values were set at 1.5°C (low), 2.6°C (mid), and 4.5°C (high). These have been re-set to 1.5°C (low), 3.0°C (mid), and 6.0°C (high). The increase at the high end is substantial, and leads to noticeably higher “upper bound” projections of temperature and sea level. This increased probability of a high sensitivity value is in accord with the latest empirical estimates of the climate sensitivity. The AR4 reviews probabilistic sensitivity estimates from the recent literature in two places, in the Technical Summary (Solomon et al. 2007) and in the ”detection and attribution” chapter (Hegerl et al. 2007). In the Technical Summary (p. 65), 95th percentile results from 12 studies range from 4.4°C to 9.2°C, while the probability of a sensitivity above 6.0°C ranges from near zero to 38%. In Hegerl et al. (2007, Fig. 9.20), seven of these studies are summarized. The 95th

**Table 8** Comparison of MAGICC 4.1 and 5.3 results

| | Ref. | | | | | | Lev1 | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2050 | | 2100 | | 2300 | | 2050 | | 2100 | | 2300 | |
| Variable | 4.1 | 5.3 | 4.1 | 5.3 | 4.1 | 5.3 | 4.1 | 5.3 | 4.1 | 5.3 | 4.1 | 5.3 |
| $CO_2$ | 505 | 503 | 744 | 748 | 1,001 | 1,061 | 441 | 441 | 455 | 459 | 451 | 458 |
| $CH_4$ | 2,101 | 2,048 | 2,038 | 1,983 | 1,442 | 1,385 | 1,700 | 1,647 | 1,433 | 1,381 | 957 | 908 |
| $N_2O$ | 356 | 356 | 377 | 377 | 386 | 386 | 349 | 349 | 362 | 362 | 348 | 348 |
| Kyoto $Q$ | 1.992 | 1.971 | 4.170 | 4.219 | 5.618 | 5.949 | 1.054 | 1.050 | 1.173 | 1.233 | 0.818 | 0.919 |
| Total $Q$ | 2.103 | 2.105 | 5.088 | 4.819 | 6.501 | 6.355 | 1.738 | 1.603 | 2.076 | 1.793 | 1.504 | 1.131 |
| Total $Q$ from 1765 | 3.456 | 3.531 | 6.411 | 6.245 | 7.824 | 7.782 | 3.060 | 3.029 | 3.398 | 3.218 | 2.826 | 2.557 |
| $CO_2$,eq | 531 | 538 | 921 | 893 | 1,200 | 1,190 | 493 | 490 | 525 | 507 | 471 | 448 |
| Temp | 1.03 | 1.14 | 2.63 | 2.77 | 4.20 | 4.64 | 1.01 | 1.04 | 1.35 | 1.38 | 1.26 | 1.22 |
| Sea level | 12.6 | 12.1 | 33.7 | 32.7 | 89.9 | 94.9 | 12.6 | 11.6 | 24.6 | 22.7 | 49.3 | 41.9 |

$CO_2$ and $CO_2$,eq concentrations in ppm, $CH_4$ and $N_2O$ in ppb. "Q" denotes forcing, in W/m$^2$. Kyoto $Q$ and Total $Q$ are changes from 2000. Temperature in degrees Celsius, sea level rise in centimeters. $CO_2$-equivalent concentration is defined by $CO_2,eq = 278\exp(Q/5.35)$ where $Q$ is total forcing from pre-industrial times (1,765 here) percentile values here range from 4.3°C to 9.2°C. (The slightly different lower bound probably results from difficulties in extracting numerical values from the graphical results that are shown.) An even wider range is given in Table 9.3 (pp. 721, 722) based on a larger number of studies. Hegerl et al. note the great difficulty in constraining the upper bound from twentieth century observational data.

Comparison with MAGICC 4.1

The parameter values used in MAGICC 4.1, given the 4.1 structure, were chosen to emulate AOGCM results in the IPCC TAR—indeed, version 4.1 results were used in the TAR. For version 5.3, which involves some structural changes from 4.1 as noted above, parameter values have been chosen to emulate the IPCC AR4. The most important differences between the two versions are in the magnitude of climate feedbacks on the carbon cycle (larger in 5.3), aerosol forcing values, and the central estimates and uncertainty ranges for the climate sensitivity. For any given emissions scenario, therefore, 4.1 and 5.3 results will differ—although the differences are not large and lie well with the uncertainties surrounding projections of global-mean temperature and sea level rise.

Table 8 compares results for the two versions of MAGICC for the extended MiniCAM reference and Level 1 scenarios. Kyoto-gas forcing differences (5.3 higher than 4.1) arise primarily from $CO_2$ concentration differences, in turn due to the increase in the magnitude of climate feedbacks on the carbon cycle. Total forcing differences are in the opposite direction (5.3 less than 4.1) and arise mainly from differences in aerosol forcing estimates between the TAR and AR4. Even with lower forcing, however, warming in the reference case with 5.3 is higher than with 4.1 because 5.3 uses a higher central estimate for the climate sensitivity (3.0°C versus 2.6°C). In the Level 1 case, these two effects (forcing versus sensitivity differences) largely cancell. For sea level, there are differential effects arising from the different warmings (more warming tends to go with larger sea level rise) and from the addition of a non-melt contribution in 4.1 (which acts to give larger sea level rise), so the 4.1 versus 5.3 differences are less systematic.

For all the results presented here using MAGICC 5.3, corresponding 4.1 results are given as Electronic Supplementary Material.

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