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Scenarios with MIT integrated global systems model: significant global warming regardless of different approaches

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Abstract A wide variety of scenarios for future development have played significant roles in climate policy discussions. This paper presents projections of greenhouse gas (GHG) concentrations, sea level rise due to thermal expansion and glacial melt, oceanic acidity, and global mean temperature increases computed with the MIT Integrated Global Systems Model (IGSM) using scenarios for twenty-first century emissions developed by three different groups: intergovernmental (represented by the Intergovernmental Panel on Climate Change), government (represented by the U.S. government Climate Change Science Program) and industry (represented by Royal Dutch Shell plc). In all these scenarios the climate system undergoes substantial changes. By 2100, the CO_2 concentration ranges from 470 to 1020 ppm compared to a 2000 level of 365 ppm, the CO_2-equivalent concentration of all greenhouse gases ranges from 550 to 1780 ppm in comparison to a 2000 level of 415 ppm, oceanic acidity changes from a current pH of around 8 to a range from 7.63 to 7.91, in comparison to a pH change from a preindustrial level by 0.1 unit. The global mean temperature increases by 1.8 to 7.0°C relative to 2000. Such increases will require considerable adaptation of many human systems and will leave some aspects of the earth's environment irreversibly changed. Thus, the remarkable aspect of these different approaches to scenario development is not the differences in detail and philosophy but rather the similar picture they paint of a world at risk from climate change even if there is substantial effort to reduce emissions.

1 Introduction

The literature on future greenhouse gas (GHG) emissions and resultant climate changes is populated by hundreds of scenarios of future development. These

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scenarios are dependent on many underlying assumptions about future human activity, the pace and shape of political and technological change, and the availability of natural resources. Some scenarios are developed simply as “storylines”, where no attempt is made to assign the likelihood of a particular scenario occurring. Other scenarios try to assign probabilities to specific outcomes. To project the development of human systems for a hundred years is a heroic exercise, but it is a desirable task for informing climate-related decisions.

The purpose of this paper is to compare the scenarios developed by three different groups: intergovernmental, government, and industry. The chosen scenarios are analyzed using the same climate model in order to assess the range of outcomes in terms of CO_2 concentrations, concentrations of all greenhouse gases expressed as CO_2-equivalents, ocean acidity, and global mean surface temperature.

For the intergovernmental scenarios we have chosen the scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on Emissions Scenarios (SRES, Nakicenovic et al. 2000). As an example of scenarios developed under a government sponsored study, we have chosen the U.S. Climate Change Science Program report on greenhouse gas scenarios (US CCSP 2007). Industrial scenarios are represented by the recently released Shell energy scenarios (Shell 2008). Our choice of scenarios is based on their relative independence from each other. There are many other emissions scenarios, mostly led by national and international organizations, but a majority of them are directly driven by SRES scenarios or IPCC results. US CCSP scenarios are in turn became a basis for the new IPCC scenarios for its next assessment report, AR5 (Moss et al. 2008), where “representative concentration pathways” (RCP) are proposed. Van Vuuren et al. (2008) provide an assessment of climate impacts using a range of scenarios from different models. The value added from the current study is in a consistent use of a specific integrated climate model to test the climate outcomes from the scenarios developed by different groups. Even thought the SRES scenarios are now quite dated much work in the literature is based on them. It is therefore useful to understand the differences between the older SRES scenarios and the US CCSP scenarios that are the basis for several of the new RCP scenarios

To explore climate response we use the MIT Integrated Global System Model (IGSM) Version 2.2 which has several improvements over Version 1 (Prinn et al. 1999) as described in detail in Sokolov et al. (2005). The IGSM 2.2 couples sub-models of human activity and emissions, the Emissions Prediction and Policy Analysis (EPPA) model, atmospheric dynamics, physics and chemistry (including separate treatment of urban regions), oceanic heat uptake, sea ice and carbon cycling, and land system processes described by the coupled Terrestrial Ecosystem Model (TEM), Natural Emissions Model (NEM), and Community Land Model (CLM).

The paper is organized in the following way. Section 2 briefly describes the three representative types of scenario exercises. In Section 3, we compare the emission profiles for CO_2 and other GHGs for each scenario. Section 4 presents the results for the atmospheric concentrations of CO_2 and all GHGs combined for the US CCSP and Shell scenarios. For the SRES scenarios, the atmospheric concentrations are not computed but simply input to the IGSM based on the numbers reported in the IPCC Third Assessment Report (IPCC 2001). Section 5 shows the results for oceanic acidity. In Section 6, we present changes in the global mean surface temperature. Section 7 notes the uncertainty of the climate results and summarizes our findings.

2 Climate scenarios

2.1 Intergovernmental: SRES

The Special Report on Emissions Scenarios (SRES, Nakicenovic et al. 2000) was prepared for the Third Assessment Report of the IPCC. There are four main "storylines" (denoted as A1, A2, B1, and B2) defined in the report. These storylines are further divided into 40 scenarios developed by six modeling teams. It is claimed that all 40 scenarios are equally valid, with no assigned probabilities of occurrence. While some scenarios assume more environmentally friendly development of the world than others, the SRES scenarios do not include any explicit climate policies.

The scenarios under the storylines are further divided into six groups: one group each in the A2, B1 and B2 storylines, and three groups in the A1 storyline, characterizing alternative developments of energy technologies: A1FI (fossil intensive), A1T (predominantly non-fossil) and A1B (balanced across energy sources). Then illustrative scenarios were selected by the IPCC to represent each of the six scenario groups.

We focus here on four illustrative SRES scenarios: A1FI (represented in the SRES projections by the MiniCAM model), A1B (represented by the AIM model), A2 (represented by the ASF model), and B1 (represented by the IMAGE model). As the SRES does not provide all information necessary for driving the full MIT IGSM, we have used the anthropogenic and net land use emissions reported in IPCC (2001).

2.2 Governmental: US CCSP

The United States Climate Change Science Program (US CCSP) was established in 2002 as a coordinating body for U.S government activities on climate change. The CCSP strategic plan calls for the creation of a series of more than 20 assessment reports. The emissions scenarios are presented in the CCSP Synthesis and Assessment Product 2.1.a (US CCSP 2007). They were developed using three integrated assessment models (IAMs). Each modeling group first produced a reference scenario under assumptions that no climate policies are imposed. Then each group produced four additional stabilization scenarios framed as departures from its reference scenario achieved with specific policy instruments, notably a global cap and trade system with emissions trading among all regions beginning in 2015. The stabilization levels are defined in terms of the total long-term effect on the Earth's heat balance of the combined influence of all GHGs.

The stabilization scenarios were chosen so that the associated CO_2 concentrations would be roughly 750, 650, 550, and 450 ppm, although the study also formulated the targets as radiative forcing levels that allowed some additional increases in the other greenhouse gases. Obviously, the CO_2-equivalent concentrations including the radiative forcing from the other greenhouse gases are higher than the above CO_2 concentrations. They are 910, 800, 660, and 550 ppm, respectively.

The MIT IGSM was one of the three models utilized in the CCSP scenario development. Anthropogenic emission profiles were created by the economic (EPPA) component of the IGSM (Paltsev et al. 2005), where an idealized cap-and-trade system was implemented in which the whole world participated. In the CCSP scenarios run by MIT IGSM, the F-gases prices are tied to the price of CO_2 using the GWPs of the gases. For CH_4 and N_2O independent emissions stabilization levels were set for each gas as GWPs poorly represent the full effects (Sarofim et al. 2005; US CCSP 2007).

The climate component of the IGSM has evolved since the CCSP exercise. Hence we run the emissions profiles from the above CCSP 2.1.a exercise through this modified IGSM, so that the climate and carbon cycle results reported here are somewhat different from the IGSM results reported in US CCSP (2007).

2.3 Industry: shell

A number of private companies have also formulated their own scenarios for future development. For example, Shell (*Royal Dutch Shell plc*) reports the results of several different scenario exercises on its website (www.shell.com/scenarios). We have used the recently released Shell energy scenarios up to 2050 (Shell 2008). Shell describes two scenarios: *Scramble* and *Blueprints*, where *Blueprints* is more technology and environmentally optimistic. These scenarios attempt to capture how the world might actually develop and so they include, implicitly at least, a wide mix of economic incentives and policy measures that vary by country but that are motivated specifically by concerns about climate change. It is assumed for example that carbon capture and storage (CCS) technology is economic and fully available in the *Blueprints* scenario. Shell also considers a variation on *Blueprints* where CCS is not available. The results for this scenario are labeled as "*Blue_excl_CCS*" in the figures and tables of this report.

The Shell scenarios do not provide projections of non-energy related emissions of GHGs and other pollutant emissions that are needed to run the IGSM. We fill in this missing data by constraining the EPPA model to match the Shell fossil CO_2 emission profiles while providing similar constraints for the non-energy CO_2 emissions and other non-CO_2 GHGs. In this way, we project the full suite of emissions of climate related substances that are consistent with the Shell energy scenarios.

For assessing climate results, we were interested in extending the Shell projections beyond their 2050 horizon and we communicated with Shell to develop some relatively simple extrapolations (private communication, 2008). Shell notes that in the *Scramble* scenario late (i.e., mid-century) actions are assumed, and if this were the beginning of a continued strong effort, the reductions might accelerate more rapidly than in our simple extrapolation. If so we might see less climate change than the version of the *Scramble* scenario portrayed in this paper. Regardless of this, we expect the climate consequences of the *Scramble* scenario to be greater than in the *Blueprints* case which benefits from earlier actions.

3 Greenhouse gas emissions

3.1 Fossil and other industrial CO_2 emissions

The sums of the fossil and other industrial CO_2 emissions for each scenario are presented in Fig. 1. We use the following coloring scheme to better illustrate the scenarios: SRES scenarios are shown in blue, US CCSP scenarios are in green, and Shell scenarios are in red. The US CCSP reference scenario (i.e., with no climate

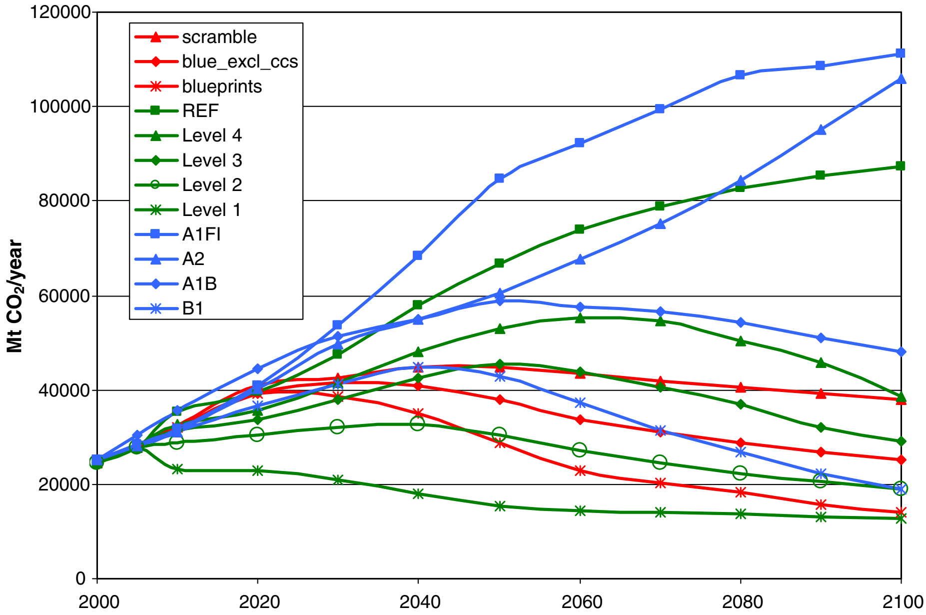

Fig. 1 Fossil and other industrial CO_2 emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of CO_2 per year

policy) is similar in cumulative emissions to the SRES *A*2 scenario and lower than the SRES *A1FI* scenario. The US CCSP *Level 1* stabilization scenario has the lowest emissions profile.

3.2 Anthropogenic terrestrial vegetation CO_2 emissions and sinks

In general, there is less certainty about net anthropogenic CO_2 emissions from terrestrial vegetation (from deforestation, sequestration through reforestation, and other land use changes) compared to the fossil and other industrial emissions and so estimates of year 2000 emissions among the different groups differ (Fig. 2). Sabine et al. (2004) provide a summary of uncertainty estimates in the land use change component.

The SRES *A1FI* scenario has the highest fossil and other industrial CO_2 emissions and the highest terrestrial sink. The US CCSP and Shell numbers reported here are derived from EPPA under the assumption that current land use emissions directly related to anthropogenic activities are gradually eliminated (through some combination of reduced deforestation and offsetting reforestation).

3.3 Non-CO_2 GHG emissions

Among the non-CO_2 greenhouse gas emissions are methane, CH_4; nitrous oxide, N_2O; hydrofluorocarbons, HFCs; perfluorocarbons, PFCs; and sulphur hexafluoride, SF_6.They are reported here in CO_2-equivalents based on their 100-year Global Warming Potentials (GWPs) (Fig. 3). Again, uncertainties lead to different estimates

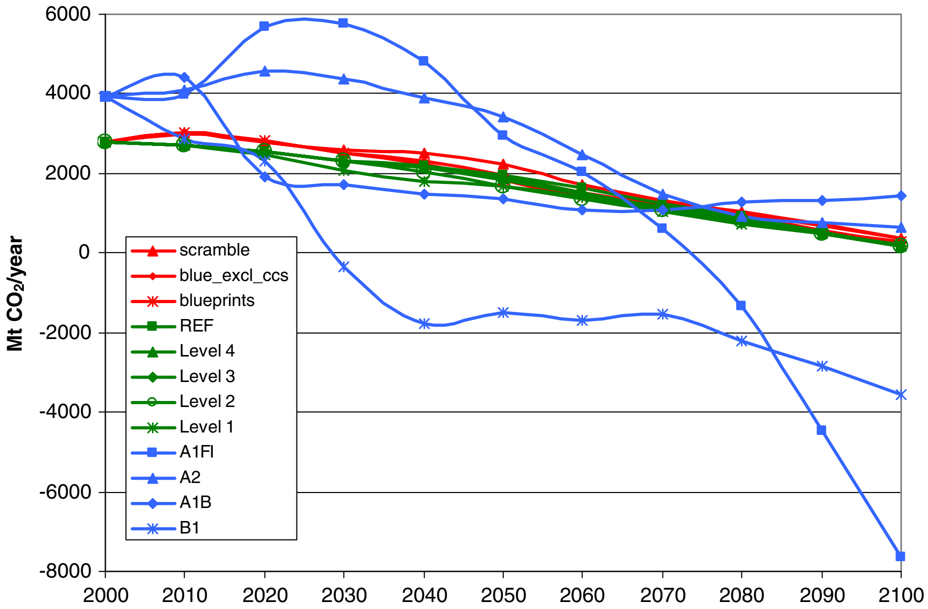

Fig. 2 Anthropogenic Net Terrestrial CO_2 emissions (*negative numbers* represent a net sink; Shell in *red*, CCSP in *green*, SRES in *blue*)

of emissions in the year 2000. The US CCSP *Reference*, Shell *Scramble*, SRES *A1FI* and SRES *A2* scenarios all assume a substantial increase in non-CO_2 GHGs. Most of the US CCSP stabilization scenarios and the two Shell *Blueprints* scenarios have

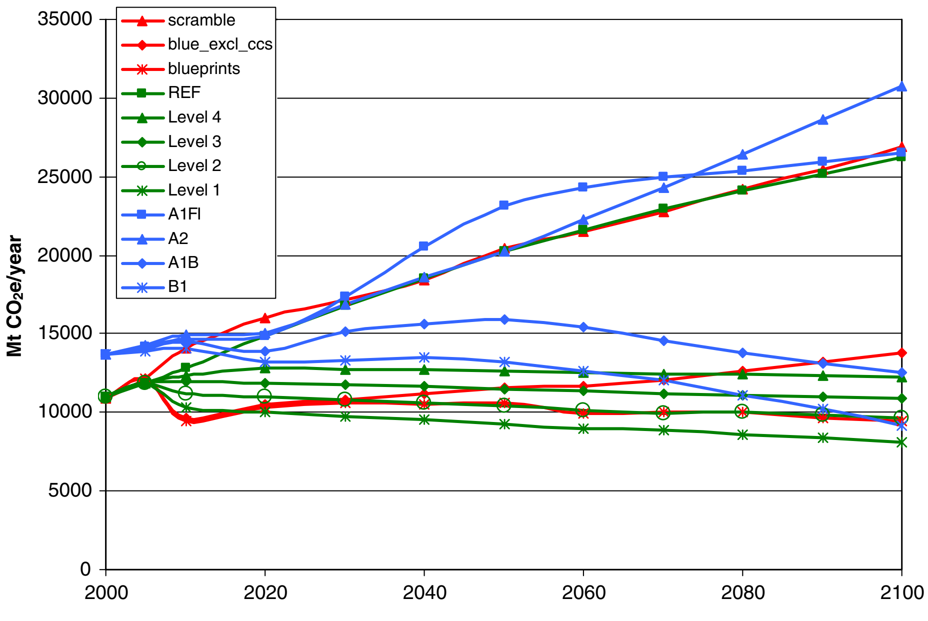

Fig. 3 Anthropogenic non-CO_2 GHG emissions (Shell in *red*, CCSP in *green*, SRES in *blue*)

Table 1 Non-CO_2 gas emissions as a percentage of total GHG emissions

	Shell				CCSP				SRES			
	Scramble	Blue_excl_ccs	Blue-prints	REF	Level 1	Level 2	Level 3	Level 4	B1	A1B	A2	A1FI
2000	29	29	29	29	29	29	29	29	32	32	32	32
2010	29	22	21	27	28	27	27	27	29	27	30	29
2020	27	20	20	26	28	25	25	25	25	23	25	24
2030	28	20	20	25	30	24	23	23	25	22	24	23
2040	28	21	22	24	32	23	21	20	24	22	24	22
2050	30	23	26	23	35	24	20	19	24	21	24	21
2060	32	25	29	22	36	26	20	18	26	21	24	20
2070	35	27	32	22	37	28	21	18	29	20	24	20
2080	37	30	34	22	37	30	23	19	31	20	24	19
2090	39	32	37	23	38	32	25	21	34	20	23	20
2100	41	35	40	23	39	34	27	24	37	20	22	20

these emissions relatively stable or slightly decreasing. The SRES scenarios have higher numbers for current non-CO_2 GHGs. This difference originates mainly in the projection of HFCs. IPCC (2001) provides supplementary data to (SRES 2000) for HFCs, as the data contained in the (SRES 2000) report was not sufficient to break down the individual contributions to HFCs, PFCs, and SF_6. The SRES emissions are also available at the CIESIN (Center for International Earth Science Information

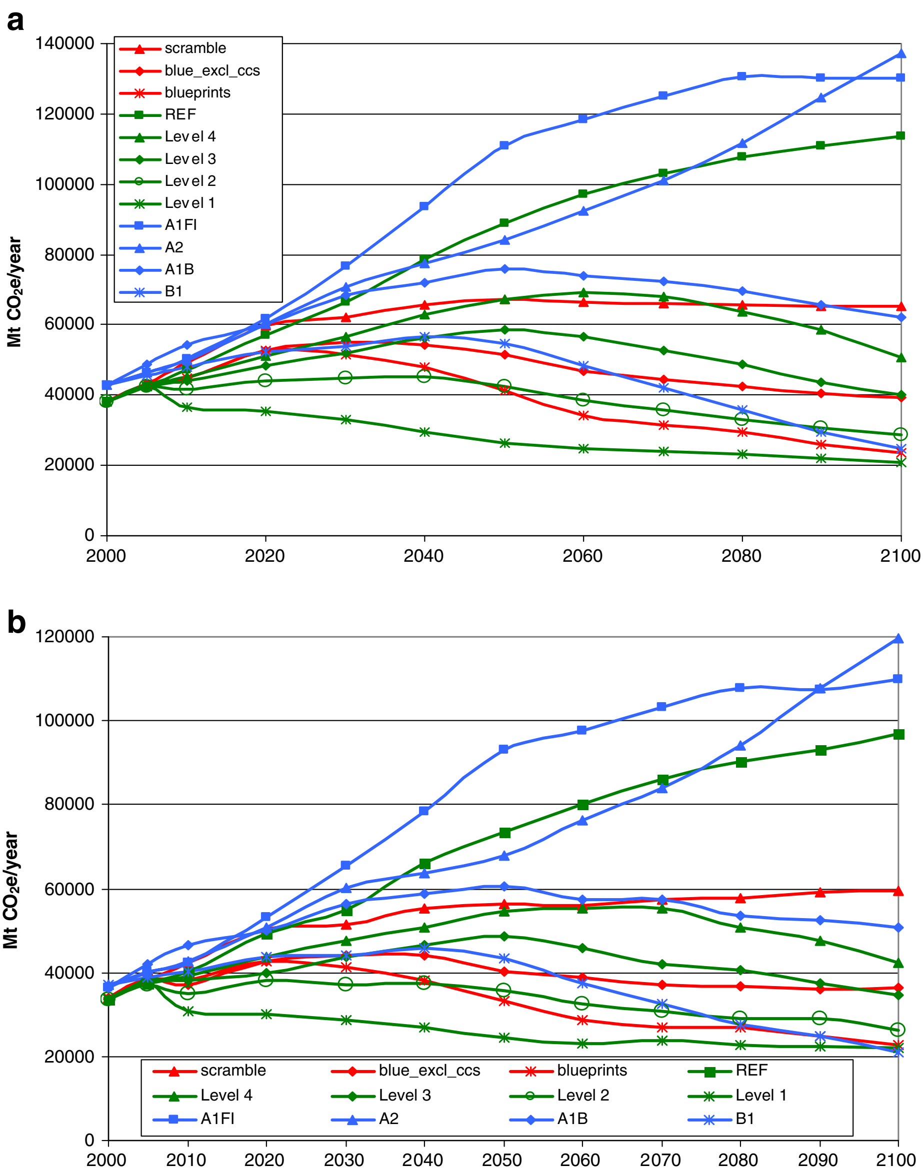

Fig. 4 **a** Total anthropogenic GHG Emissions in CO_2 equivalents (Shell in *red*, CCSP in *green*, SRES in *blue*). **b** Total natural and anthropogenic GHG Emissions in CO_2 equivalents (Shell in *red*, CCSP in *green*, SRES in *blue*)

Network) website (http://sres.ciesin.columbia.edu/final_data.html), where HFCs are combined with CFCs and HCFCs. In the IGSM structure CFCs and HCFCs are phased out (Asadoorian et al. 2006). In the SRES *A*1*B* and *B*1 scenarios the non-CO_2 emissions gradually decline approaching 2100.

Table 1 presents the non-CO_2 emissions as a percentage of the total GHG emissions. The Shell Scramble scenario assumes no policy restricting non-CO_2 GHG emissions. The US CCSP percentages are higher in the stabilization scenarios as it is harder to eliminate or to drastically reduce CH_4 and N_2O. The SRES scenarios assume no explicit climate policy as noted earlier. The emissions of the individual non-CO_2 greenhouse gases covered by the Kyoto Protocol, and of aerosols (black carbon, BC; organic carbon, OC) aerosol precursors (SO_2, NO_X, NH_3), and ozone precursors (CO, VOC, NO_x) are provided in an Appendix.

3.4 Total GHG emissions

Figure 4a presents total anthropogenic GHG emissions. As with fossil and other industrial CO_2 emissions, the SRES *A1FI* emissions are the highest. The SRES *A*2 does not have the decline by 2100 seen in the US CCSP reference scenario, but the cumulative emissions are comparable. The US CCSP *Level 2* stabilization and Shell *Blueprints* are comparable and the US CCSP *Level 1* again is the lowest emission scenario, reflecting the specific long term radiative forcing goal that was part of the CCSP exercise.

In addition to anthropogenic emissions reported in Fig. 4a, there are natural emissions of CH_4 and N_2O computed in the NEM sub-model of IGSM, uptake of CO_2 by terrestrial ecosystems (land sink) computed in TEM, and uptake by oceans treated in the ocean model. Figure 4b shows the net GHG emissions when these additional flows are included.

4 Concentrations

4.1 CO_2 concentrations

As mentioned in Section 2.1, we used the emissions profiles, derived using the EPPA model for the US CCSP and Shell scenarios, to drive the climate component of the IGSM. For the SRES scenarios we have driven the IGSM climate component using emissions reported by the (SRES 2000) and IPCC (2001). As discussed by Sokolov et al. (2005, 2009) the IGSM characteristics affecting model's response to GHG emissions, such as climate sensitivity, rate of heat and carbon uptake by the deep ocean and so on, can be varied by changing model's parameters. In this study we use mean values of the parameters distributions from Forest et al. (2008) and Sokolov et al. (2009), in particular the effective climate sensitivity is set at 2.9°C. Figure 5 presents the resultant CO_2 concentrations. The SRES *A1FI* scenario results in the highest concentration (around 1020 ppm). The SRES *A*2 and US CCSP *Reference* scenarios are comparable in terms of their CO_2 emissions and their resulting CO_2 concentrations (around 890–900 ppm by 2100). The SRES *A*1*B* case has higher concentrations than the US CCSP *Level 4* scenario as the *A*1*B* emissions profile is always higher than the *Level 4* scenario. The SRES *B*1 and Shell *Blueprints without*

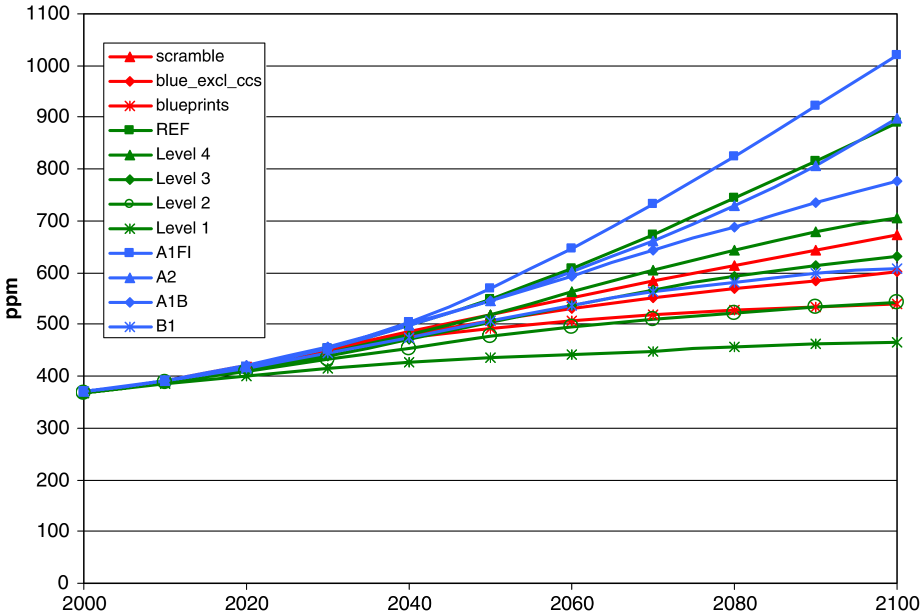

Fig. 5 CO_2 concentrations (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are molecules of CO_2 per million molecules of air

CCS scenarios lead to almost the same CO_2 concentrations of around 600 ppm by 2100. The US CCSP *Level 2* and *Blueprints* cases have different curvatures in their CO_2 emissions but yield similar cumulative emissions and CO_2.concentrations of around 540 ppm. These cases have higher CO_2 emissions and concentrations than the *Level 1* scenario whose emissions and resultant concentrations are again the lowest.

In contrast to most of the existing terrestrial carbon models, the TEM sub-model of the IGSM takes into account an effect of nitrogen limitation on carbon uptake by terrestrial ecosystems. Because of that, the MIT IGSM computes smaller carbon uptake by terrestrial ecosystems than other models (Plattner et al. 2008; Sokolov et al. 2008). As a result, the CO_2 concentrations projected by the MIT IGSM for the SRES scenarios are close to the concentrations produced by the ISAM model for the low uptake case (IPCC 2001). At the same time they are noticeably lower than concentrations simulated by the Bern-CC model with low uptake (IPCC 2001).

4.2 CO_2 equivalent concentrations of GHGs

Figure 6 shows the CO_2-equivalent concentrations, where the CO_2-equivalent is that level of CO_2 that would produce the same radiative forcing as that from all GHGs (excluding radiative forcing from ozone and aerosols). The various scenarios have profiles similar to their CO_2-only concentrations with the exception of the Shell *Scramble* scenario, which does not control the non-CO_2 GHGs. As a result *Scramble* is closer to SRES *A1B* and higher than the US CCSP *Level 4* concentrations (recall that *Scramble* was lower than the *Level 4* scenario in its CO_2-only concentrations).

The differences between the equivalent CO_2 concentrations for the SRES scenarios simulated by the MIT IGSM and those calculated from GHGs concentrations

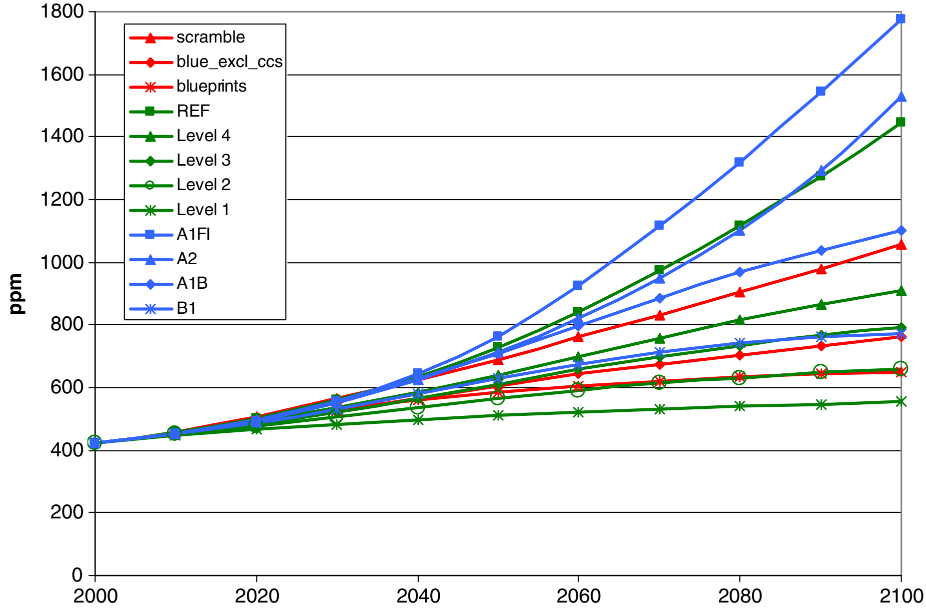

Fig. 6 Total (in CO_2 equivalents) concentrations of GHGs (Shell in *red*, CCSP in *green*, SRES in *blue*)

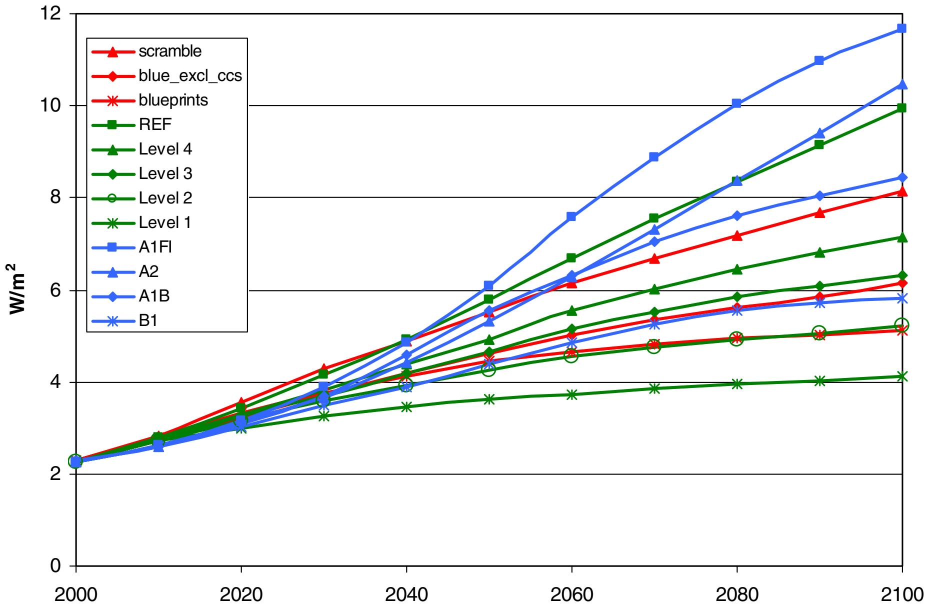

Fig. 7 Net radiative forcing due to all long-lived GHGs, sulfate and black carbon aerosols, and ozone (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are watts per square meter

reported by the IPCC (2001) are larger than their differences in CO_2-only concentrations because the MIT IGSM also produces higher CH_4 and N_2O concentrations. The primary reason for these differences is the increase of natural CH_4 and N_2O calculated by the NEM sub-model of the IGSM. In IPCC (2001), natural emissions of CH_4 and N_2O are fixed at a constant level.

4.3 Total radiative forcing

In addition to the GHGs, the MIT IGSM takes into account the radiative effects of sulfate and black carbon aerosol and ozone. Magnitudes and, most importantly, temporal patterns of SO_2 and BC emissions (see Figs. 15 and 16 in Appendix) for the SRES scenarios are very different from those in the other scenarios. The SRES scenarios have much higher sulfate aerosol levels in the first half of the twenty-first century. As a result, total radiative forcing for SRES *A*2 scenario (Fig. 7) is smaller than that for the US CCSP *Reference* up to year 2080 even though emissions and concentrations of GHGs are higher.

5 Oceanic acidity

Rising CO_2 leads to ocean acidification that alters seawater chemical speciation and biochemical cycles of many elements (Doney et al. 2009). Figure 8 shows the changes in oceanic acidity on the pH scale (a decrease of 1 in this scale corresponds to a factor

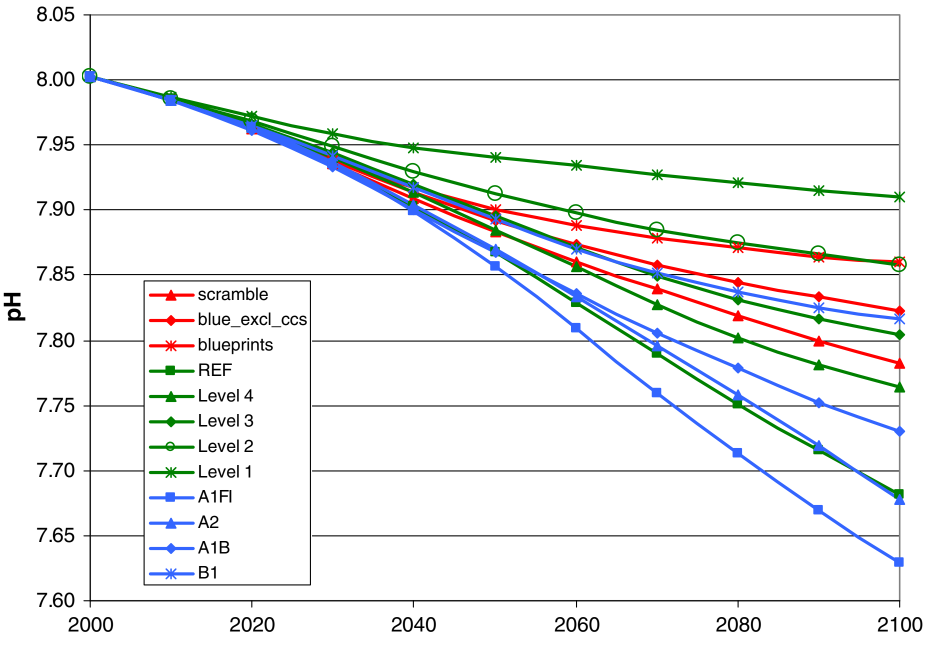

Fig. 8 Oceanic acidity or hydrogen ion concentration $[H^+]$ expressed on the pH scale ($= -\log_{10} [H^+]$) (Shell in *red*, CCSP in *green*, SRES in *blue*)

of 10 increase in acidity). The *Level 2* and *Blueprints* cases have pH changes that are quite close. The SRES *A1FI* scenario shows a decrease in oceanic pH from 8 to 7.63 (which would significantly impact all calcareous phytoplankton that are the base of the oceanic food chain), while the *Level 1* stabilization scenario reduces the oceanic pH only to 7.91 (a much smaller impact).

To put these changes into perspective, the average surface water pH has fallen by approximately 0.1 since preindustrial times (Royal Society 2005) and IPCC AR4 reports that since the 1980s the average pH measurements in Eastern Atlantic have decreased by approximately 0.02 per decade (Solomon et al. 2007).

6 Global mean temperature

Figure 9 presents the results for the global mean temperature increases relative to 2000. With some minor exceptions, these temperatures follow the net radiative forcing for each scenario (Fig. 7). Note that the temperature increases are not very different among the scenarios up to 2040. However, by 2100 the SRES *A1FI* scenario shows the highest increase in temperature (about 7.0°C), as it was also the highest in CO_2-equivalent concentrations. The SRES *A*2 scenario is close to the US CCSP *Reference* with 5.8°C increase by the end of the century, even though the net radiative forcing (Fig. 7) is slightly higher than that for the US CCSP *Reference* case in 2100. Also note that CO_2-equivalent concentrations in these two scenarios are comparable up to 2090, but the SRES *A*2 temperature increase is lower up to 2090 due to stronger negative aerosol forcing.

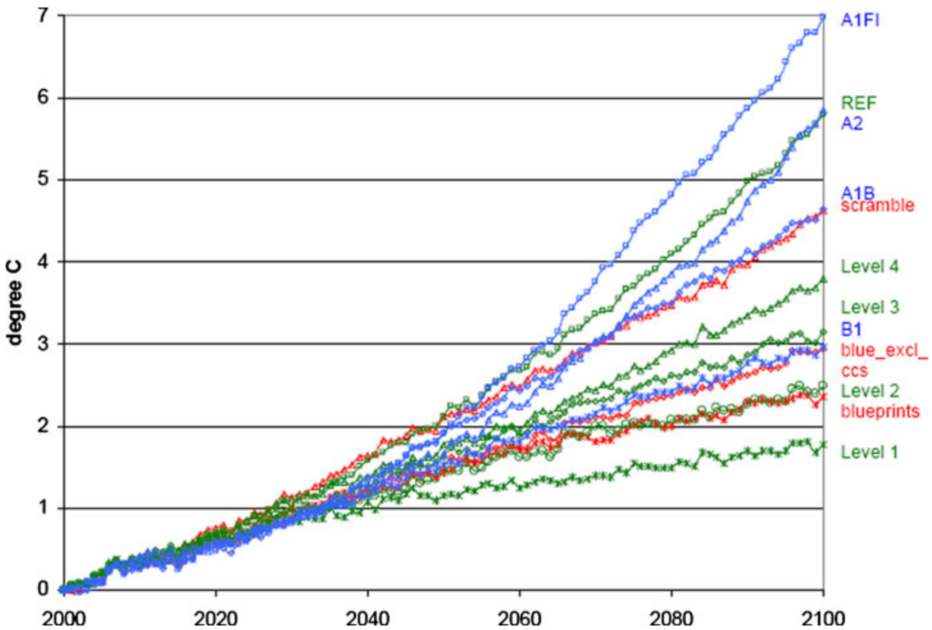

Fig. 9 Increase in the Global Mean Temperature in degrees Centigrade (relative to 2000; Shell in *red*, CCSP in *green*, SRES in *blue*)

The SRES *A*1*B* and Shell *Scramble* scenarios are quite close in their temperature increases by 2100 (around 4.6°C increase). Note that while the SRES *A*1*B* net radiative forcing (Fig. 7) is higher by 2100, it is lower than Shell *Scramble* before 2050. The US CCSP *Level 4* case results in around 3.8°C increase in temperature. The *Level 3* scenario ends up with a 3.15°C increase and SRES *B*1 and *Blueprints without CCS* scenario are quite close with 2.95–2.97°C increases. The *Level 2* and *Blueprints* are also close to each other (around 2.35–2.5°C increase by 2100 relative to 2000). The US CCSP *Level 1* stabilization scenario is again the lowest with only 1.8°C increase in temperature.

Surface warming simulated by the MIT IGSM for the SRES scenarios is noticeably larger than the results based on the simulations with the IPCC AR4 AOGCM climate models (Meehl et al. 2007). Specifically, surface temperatures averaged over the last decade of the twenty-first century are higher than the 1981–2000 averages by 2.9, 4.5, 5.4 and 6.6°C in the MIT IGSM simulations compared to the AR4 values of 1.8, 2.8, 3.4 and 4.0°C for the *B*1, *A*1*B*, *A*2 and *A1FI* SRES scenarios respectively. One source of these differences are higher GHG concentrations in the MIT IGSM simulation because of differences in the representation of GHG cycles; for example positive feedbacks from increases in the natural sources of CH_4 and N_2O. If we force the MIT IGSM by the concentrations from the IPCC, then the corresponding temperature increases are 2.5, 3.8, 4.6 and 5.6°C. The rest of the differences between IGSM results and IPCC AR4 are explained by the fact that the rates of the heat uptake by the deep ocean in most of the AR4 AOGCMs are larger than the median of the distribution obtained by Forest et al. (2008) that are used in the simulations described in this paper, and lead to faster warming in the IGSM.

7 Conclusions

Different groups employ different philosophies and methodologies to produce emissions scenarios. The IPCC SRES exercise generated a range of storylines where some involved a strong commitment to the environment and rapid improvement in low carbon technologies (e.g., *B*1) even though there were no explicit climate policies. The CCSP structured the exercise to include explicitly a case where there was no climate policy and then four cases with explicit long term targets for the world that were met. The Shell exercise included neither a reference scenario without climate policy nor explicit long term policy targets but simply imagined different ways that energy and climate policy might evolve nationally and internationally, along with other forces shaping the energy markets.

The CCSP and the SRES exercises created the widest range of future emissions projections, with the CCSP range being overall somewhat lower in terms of emissions. This difference is influenced by the fact that the CCSP scenarios were designed to meet explicit long term policy targets. It is not surprising that the Shell scenario range is somewhat narrower as their philosophy was to extend from the current situation to what seems likely or possible in terms of energy and climate policy. Taking account of the strong concerns about climate change and mounting evidence on the dangers of unabated emissions growth a world with no abatement seems unlikely, and so the reference CCSP is useful in illustrating the dangers of unabated emissions growth, and thus in helping the world to see the great risks in this path before proceeding much farther along it. At the same time, it seems politically unlikely that the dramatic near-term world-wide actions envisioned in the low end CCSP scenarios can be put in place in just a few years. While it is interesting to see the implications of such a low end scenario, it seems increasingly unlikely that it is achievable.

The broader implication of these scenarios is that all see substantial continued increases in temperature that would create serious environmental concerns. If we rule out the highest (*A1FI*, *A*2, and *Reference*) as unthinkable and the lowest (*Level 1*) as possibly unachievable we arrive at a scenario-dependant temperature increase ranging from about 2.5 to 4.5° compared to present. Such increases will require considerable adaptation of many human systems and will leave some aspects of the earth's environment irreversibly changed. Particularly at risk are the polar regions where warming is amplified. Changes there will bring potentially large disruptions to coastal regions due to sea level rise as significant amounts of the land ice sheets melt. This was the case in the last interglacial period (Eemian) when temperatures were no higher than these projected levels. Thus, the remarkable aspect of these different approaches to scenario development drawn from industry, a national government sponsored study, and an intergovernmental process is not the differences in detail and philosophy but rather the similar picture they paint of a world at risk from climate change even if there is substantial effort to reduce emissions from reference conditions.

Finally, we emphasize that each of these climate projections has significant uncertainties that can span the differences among some of them (see Sokolov et al. 2009, Webster et al. 2009). However, our consistent use of a specific version of the MIT IGSM in this study means that the relative ordering (if not the magnitudes) of the impacts projected for each scenario should be fairly reliable.

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Appendix

Emissions of the major non-CO_2 gases (in CO_2 equivalents assuming a 100-year time horizon), the major primary aerosols (black carbon, BC and organic carbon, OC), aerosol precursors (NO_x, SO_2, NH_3) and ozone precursors (NO_x, volatile organic carbon (VOC), CO) are provided below. These influence the radiative forcing in each scenario causing differences among them in addition to those caused simply by their differing CO_2 emissions.

Figures 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21.

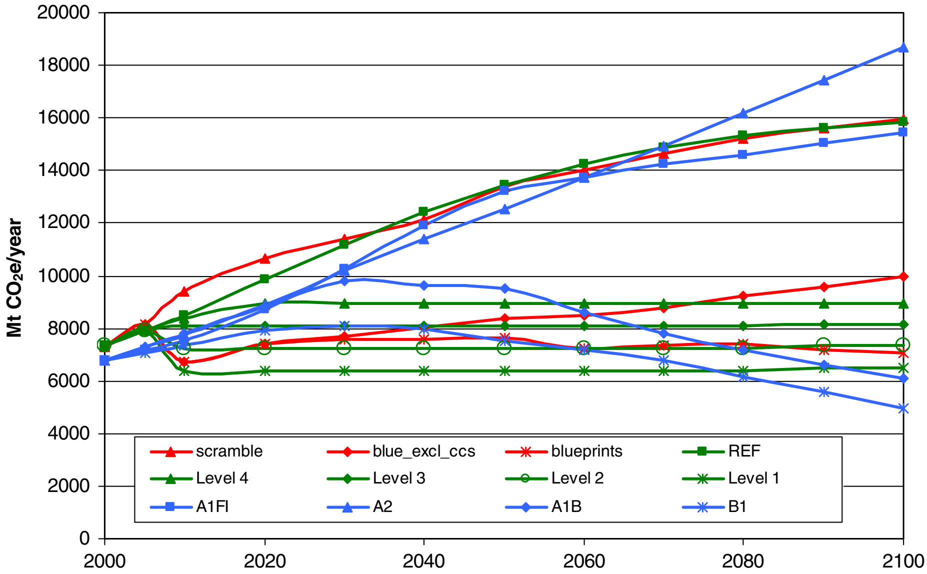

Fig. 10 CH_4 emissions (Shell in *red*, CCSP in *green*, SRES in *blue*)

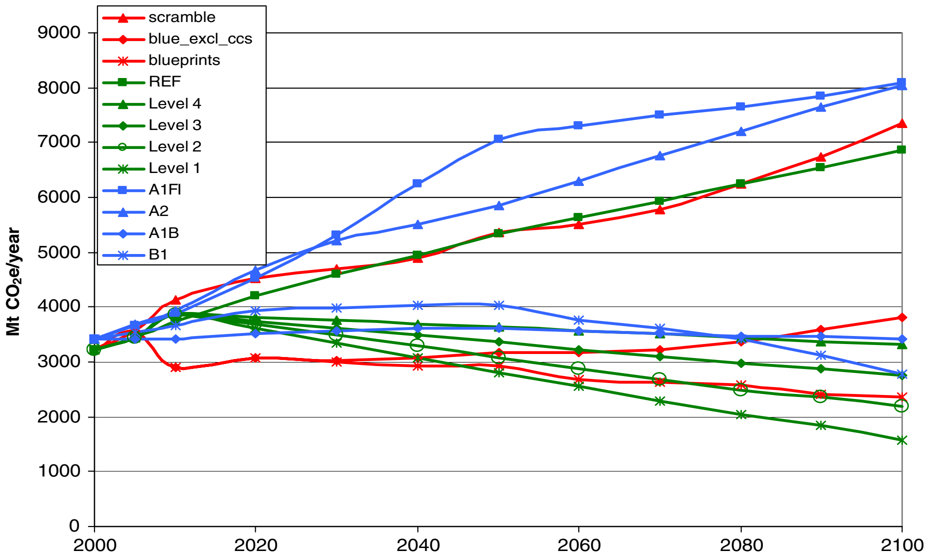

Fig. 11 N_2O emissions (Shell in *red*, CCSP in *green*, SRES in *blue*)

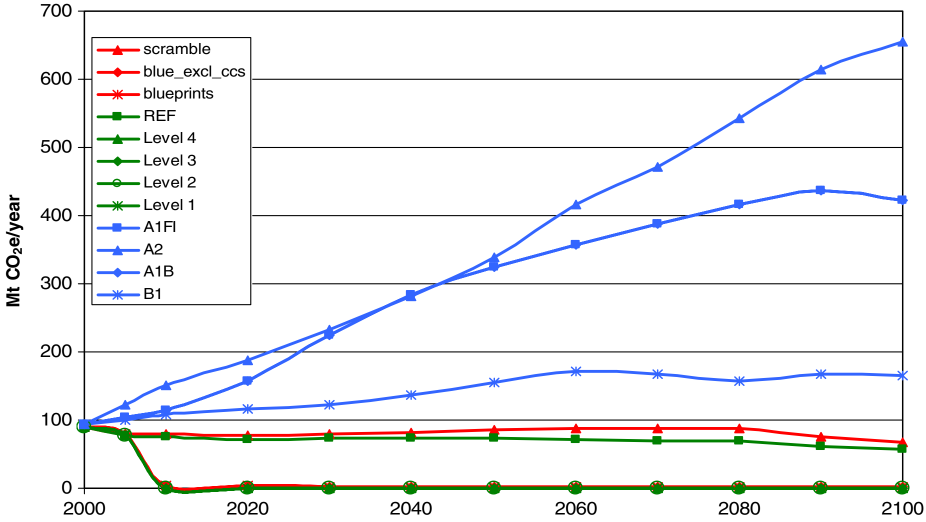

Fig. 12 Perfluorocarbon (PFC) emissions (A1B and A1FI are the same). In CCSP and Shell (except for REF and scramble), all emissions go to almost zero in the policy cases (Shell in *red*, CCSP in *green*, SRES in *blue*)

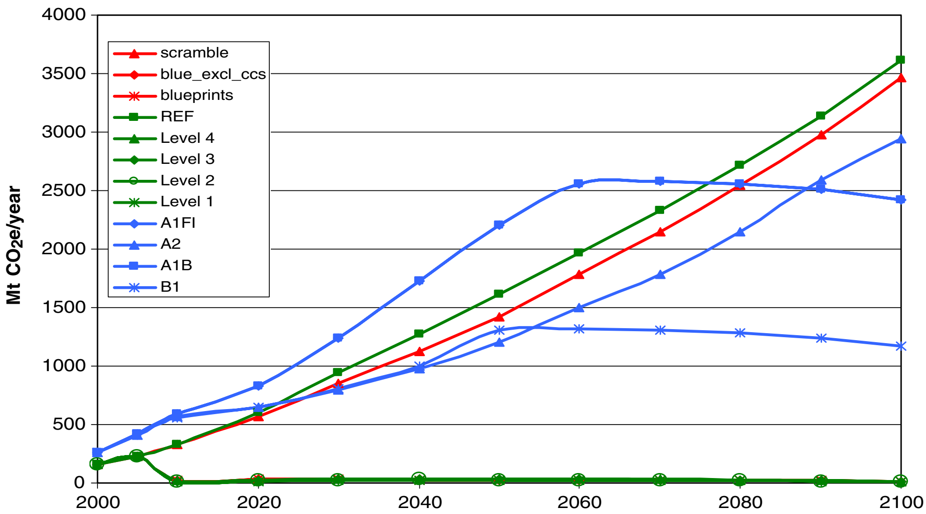

Fig. 13 Hydrofluorocarbon (HFC) emissions (A1B and A1FI are identical). CCSP and Shell (except for REF and scramble) are near zero in the policy cases (Shell in *red*, CCSP in *green*, SRES in *blue*)

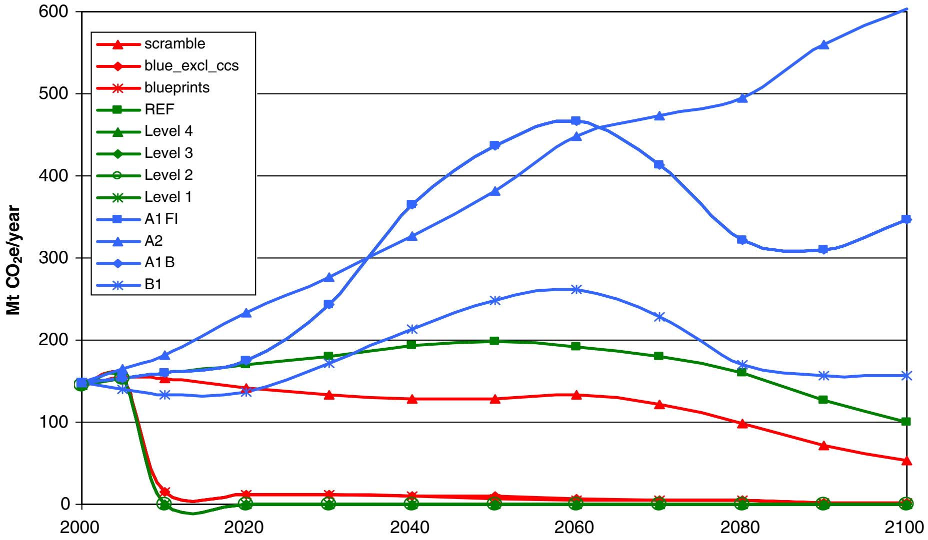

Fig. 14 SF_6 emissions (A1B and A1FI are identical). CCSP and Shell (except for REF and scramble) are near zero in the policy cases (Shell in *red*, CCSP in *green*, SRES in *blue*)

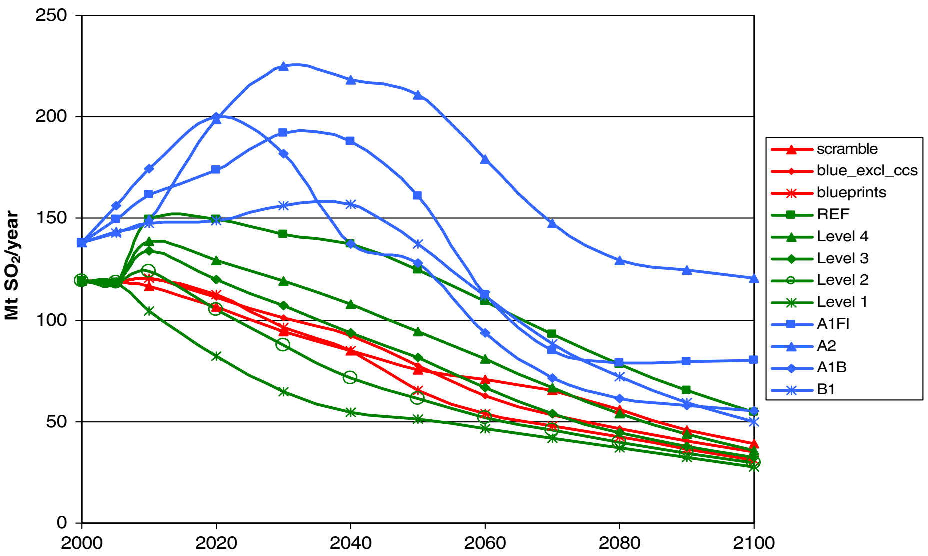

Fig. 15 SO_2 emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of SO_2 per year

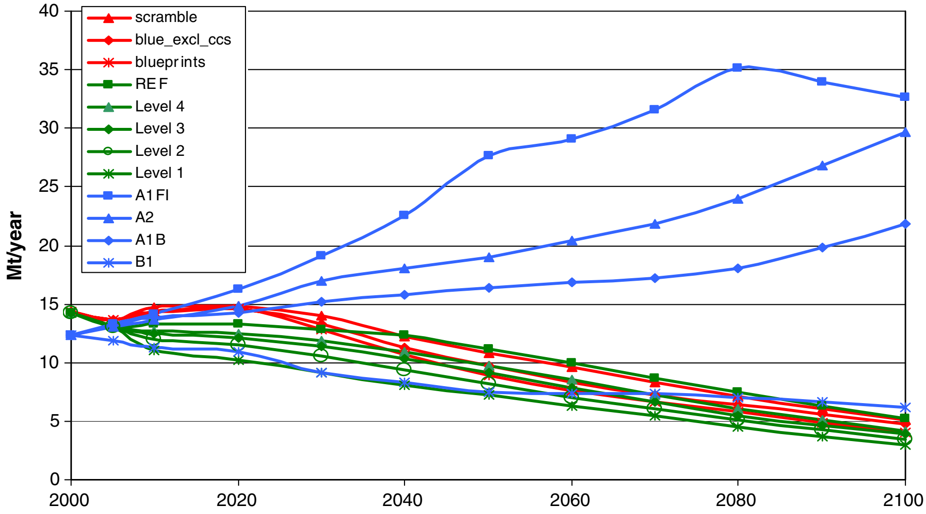

Fig. 16 Black Carbon (BC) emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of C per year

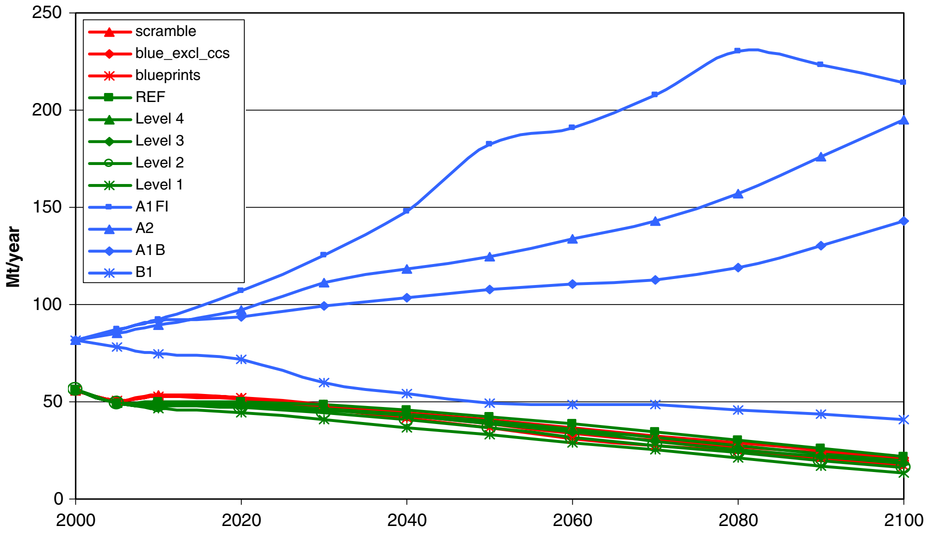

Fig. 17 Organic Carbon (OC) emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of organic matter per year

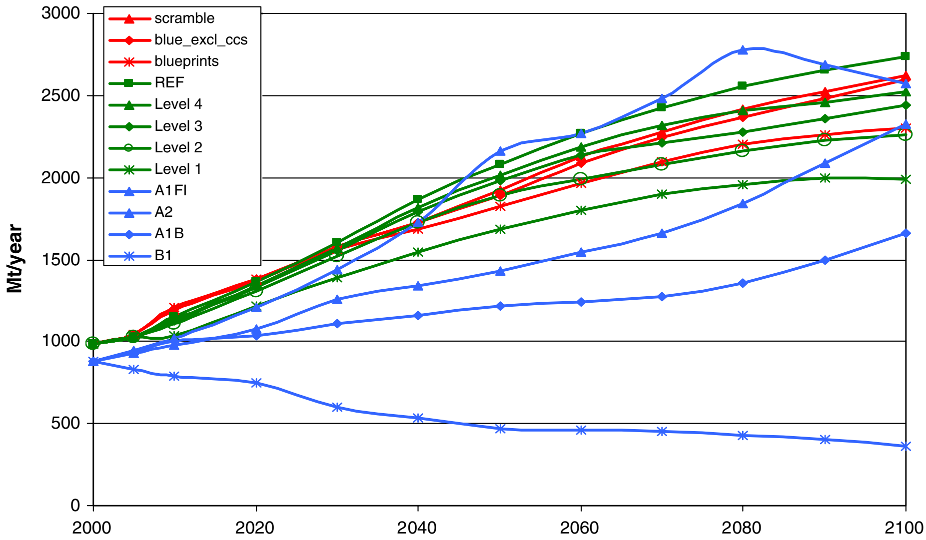

Fig. 18 CO emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of CO per year

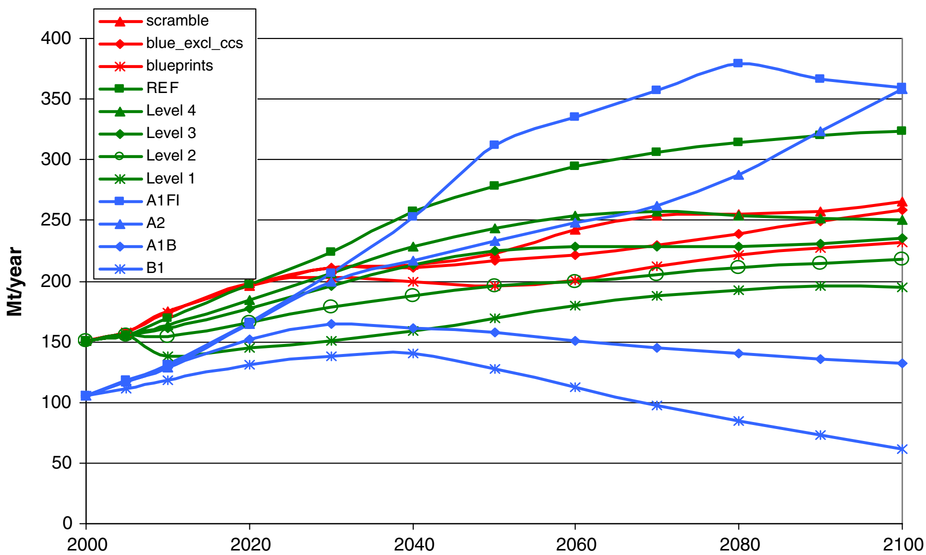

Fig. 19 NO_x emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of NO and NO_2 per year

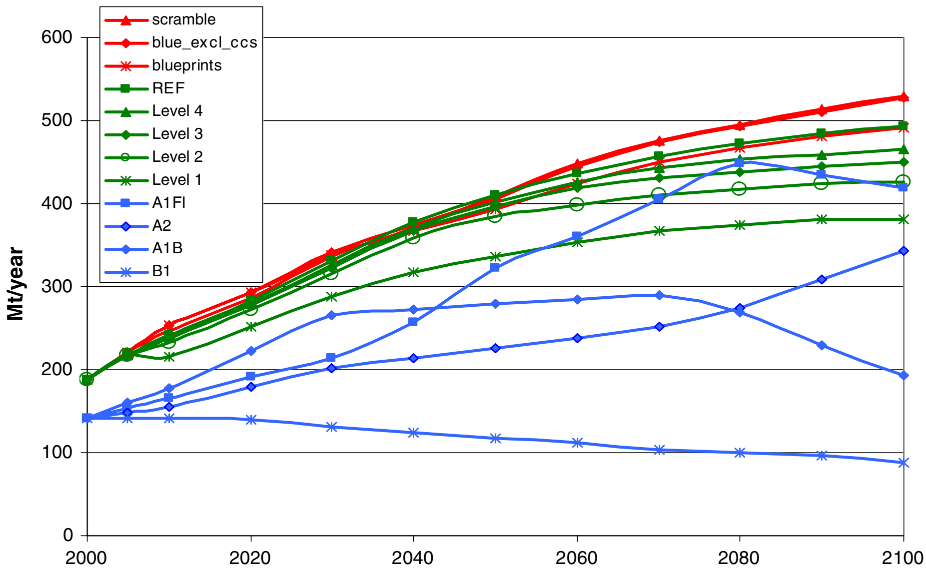

Fig. 20 Volatile organic carbon (VOC) emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of volatile organic material per year

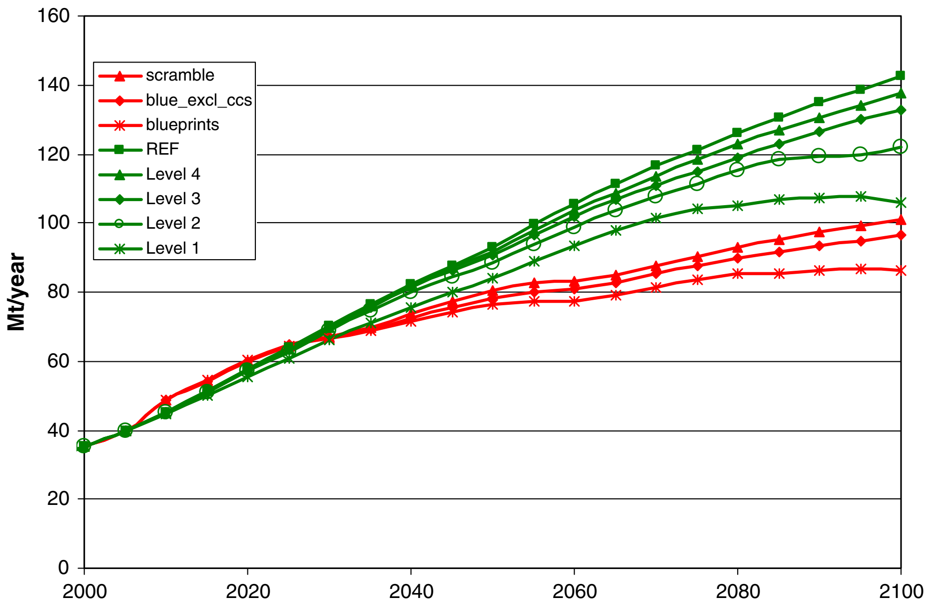

Fig. 21 NH_3 emissions (Shell in *red*, CCSP in *green*, SRES in *blue*). Units are megatons (10^{12} gm) of NH_3 per year

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