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REVIEW

When could global warming reach 4°C?

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The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) assessed a range of scenarios of future greenhouse-gas emissions without policies to specifically reduce emissions, and concluded that these would lead to an increase in global mean temperatures of between 1.6°C and 6.9°C by the end of the twenty-first century, relative to pre-industrial. While much political attention is focused on the potential for global warming of 2°C relative to pre-industrial, the AR4 projections clearly suggest that much greater levels of warming are possible by the end of the twenty-first century in the absence of mitigation. The centre of the range of AR4-projected global warming was approximately 4°C. The higher end of the projected warming was associated with the higher emissions scenarios and models, which included stronger carbon-cycle feedbacks. The highest emissions scenario considered in the AR4 (scenario A1FI) was not examined with complex general circulation models (GCMs) in the AR4, and similarly the uncertainties in climate–carbon-cycle feedbacks were not included in the main set of GCMs. Consequently, the projections of warming for A1FI and/or with different strengths of carbon-cycle feedbacks are often not included in a wider discussion of the AR4 conclusions. While it is still too early to say whether any particular scenario is being tracked by current emissions, A1FI is considered to be as plausible as other non-mitigation scenarios and cannot be ruled out. (A1FI is a part of the A1 family of scenarios, with 'FI' standing for 'fossil intensive'. This is sometimes erroneously written as A1F1, with number 1 instead of letter I.) This paper presents simulations of climate change with an ensemble of GCMs driven by the A1FI scenario, and also assesses the implications of carbon-cycle feedbacks for the climate-change projections. Using these GCM projections along with simple climate-model projections, including uncertainties in carbon-cycle feedbacks, and also comparing against other model projections from the IPCC, our best estimate is that the A1FI emissions scenario would lead to a warming of 4°C relative to pre-industrial during the 2070s. If carbon-cycle feedbacks are stronger, which appears less likely but still credible, then 4°C warming could be reached by the early 2060s in projections that are consistent with the IPCC's 'likely range'.

Keywords: climate modelling; climate-change projections; 4°C; global warming; dangerous climate change

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One contribution of 13 to a Theme Issue 'Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications'.

1. Introduction

The Working Group I (WGI) volume of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; [1]) assessed the global climate change projected to result from six scenarios of greenhouse-gas aerosol emissions, taken from a larger set of scenarios from the IPCC Special Report on Emissions Scenarios (SRES; [2]). These six SRES 'marker scenarios' are identified as A1FI, A1B, A1T, A2, B1 and B2 and are discussed in more detail in §2. The scenarios represent the emissions that would be consistent with a range of plausible future trajectories of population, economic growth and technology change, without policies to specifically reduce emissions in order to address climate change. Even though the possibility of reducing emissions through climate policy was not included in these scenarios, they still project a very wide range of emissions (figure 1). Considering emissions over the entire twenty-first century, the lowest cumulative emissions are projected by the B1 scenario and the highest by A1FI. All six scenarios were considered by the IPCC to be equally sound; no scenario was considered to be more or less likely than any others [1].

The IPCC WGI assessed climate change under these scenarios from a large number of different climate models of varying levels of complexity, including ocean–atmosphere general circulation models (GCMs) and simple climate models (SCMs), with some models also including feedbacks between climate change and the carbon cycle. The IPCC used these model projections, along with observational constraints, to inform an expert assessment of the likely range of global warming that would arise from each scenario [4]. The conclusion was that under the six SRES marker scenarios, global mean temperatures are likely to increase by between 1.1°C and 6.4°C by the end of the twenty-first century, relative to the 1980–1999 average (figure 2). To present these changes relative to the usual policy-relevant baseline of pre-industrial rather than relative to 1980–1999, the IPCC recommended adding 0.5°C [5]. This implies that the likely range of global warming relative to pre-industrial under the SRES scenarios is 1.6°C and 6.9°C.

Although the six scenarios were all considered by the IPCC to be equally sound as representations of a world that does not implement policies specifically to mitigate climate change [1], not all the scenarios were examined to the same depth with climate models. Practical reasons, such as computational costs, meant that only a subset of the scenarios (A1B, A2 and B1) could be systematically examined with complex ocean–atmosphere GCMs from all the participating modelling groups.[1] SCMs were then used to estimate the warming that would have been projected by the complex models under the other scenarios (B2, A1T and A1FI). Consequently, in the AR4, the highest emissions scenario (A1FI) was examined only with SCMs and not directly with complex ocean–atmosphere GCMs [4].

The B1, A1B and A2 projections are shown in the main part of figure 2 (reproduced from the AR4) with multi-model means represented by the coloured lines and the model spread (5–95%) illustrated by the coloured plumes. The likely range of warming for these scenarios and that for the B2, A1T and A1FI projections are represented by the grey bars on the right-hand side. The best

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[1] A small number of groups had previously examined A1FI.

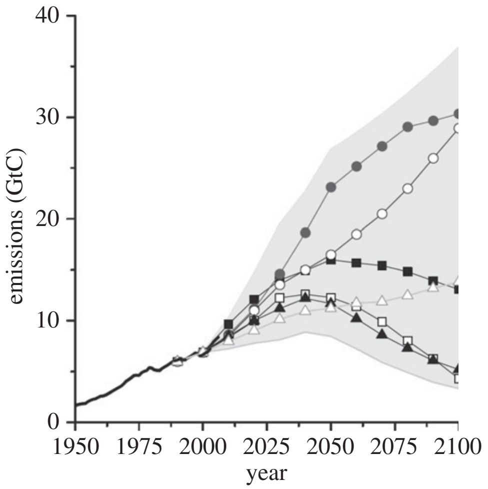

Figure 1. Emissions of CO_2 from fossil fuel in the six SRES marker scenarios (black curves) and the full range of SRES scenarios (grey plume). The SRES scenarios also include emissions of non-CO_2 greenhouse gases, aerosols and emissions from land-use change, which are not included in this figure. Filled circles, A1FI; open circles, A2; filled squares, A1B; open triangles, B2; filled triangles, B1; open squares, A1T. Reproduced with permission from van Vuuren & Riahi [3]. Copyright © Springer Science + Business Media B.V. 2008.

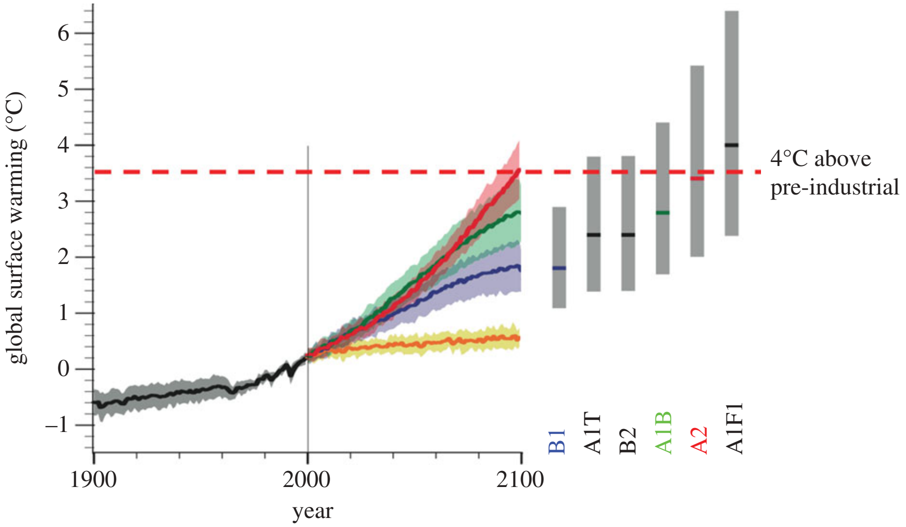

Figure 2. Past changes in global mean temperature (black curve), and projected future changes resulting from the IPCC SRES marker scenarios of greenhouse-gas and aerosol emissions (coloured curves and grey bars), relative to the 1980–1999 mean [4]. Climate changes under the A2, A1B and B1 scenarios were projected with GCMs (red, green and blue lines, with plumes showing 5–95% range of model projections without uncertainties in climate–carbon-cycle feedbacks). The full set of marker scenarios including a range of strengths of climate–carbon-cycle feedbacks were examined with SCMs. Grey bars show the likely range of warming at 2090–2099 for each scenario, from expert assessment based on all available evidence from GCMs, SCMs and observational constraints. The red dashed line marks warming of 3.5°C relative to 1980–1999, which represents 4°C relative to pre-industrial [5]. Red line, A2; green line, A1B; blue line, B1; orange line, year 2000 constant concentrations; black line, twentieth century. Copyright © IPCC, 2007.

estimates for the B2, A1T and A1FI scenarios are shown as coloured lines within the grey bars, and match the GCM-based multi-model means or the simple-model estimates. It would appear that one consequence of this form of presentation has been that often only the GCM-based projections are presented when the AR4 figure is reproduced. This can give the impression that for unmitigated emissions, a global warming of 4°C is at the very upper end of the range, particularly since the baseline in this figure is 1980–2000. However, the 'likely range' of warming for the B1, A1B and A2 scenarios is actually 1.6–5.9°C relative to pre-industrial. Moreover, when the A1FI projection is considered, the likely range extends to 6.9°C relative to pre-industrial.

The impacts of climate change would depend not only on the level of climate change, but also on the speed with which this is reached. When assessing the warming of the full set of six SRES marker scenarios, Meehl *et al.* [4] focused largely on the magnitude of warming by the end of the twenty-first century. Discussion of the warming rates earlier in the century was centred more on the GCMs and on the B1, A1B and A2 scenarios. There was no specific assessment of the projected dates at which specific levels of global warming (such as 4°C) are projected to be reached.

With concern now increasing on the possibility of global mean temperatures rising to 4°C above pre-industrial or beyond if emissions are not reduced, this paper assesses the dates at which 4°C could be reached. We use a similar 'expert-assessment' approach to that used in the IPCC, drawing in evidence from a number of available sources. We assess whether any of the SRES marker scenarios can be identified as more likely than any other, discuss the methodology for quantifying uncertainties in deriving atmospheric CO_2 concentrations from emissions scenarios and discuss the implications of observed changes in the global carbon budget for future projections of climate–carbon-cycle feedbacks. We present an ensemble of GCM simulations driven by the A1FI scenario, and a new large ensemble of SCM projections exploring the combined uncertainty in climate sensitivity and climate–carbon-cycle feedbacks in simulations driven by the A1FI scenario. We compare all these lines of evidence to assess the consequences of the A1FI scenario for the projected magnitude of global warming by the end of the twenty-first century, and the times by which a global warming of 4°C is projected to be reached.

2. Special Report on Emissions Scenario marker scenarios and comparison with recent emissions

A key factor for future climate change will be the quantity of emissions of greenhouse gases and aerosols. These will depend on the global population, their lifestyle and the way this is supported by the production of energy and the use of the land. A large population whose lifestyle demands high energy consumption and the farming of large areas of land, in a world with its main energy source being fossil-fuel consumption, will inevitably produce more greenhouse-gas emissions than a smaller population requiring less land and energy and deriving the latter from non-fossil sources. These factors could vary in a multitude of ways; the international community is already examining how energy demand and production can be modified to cause lower emissions, but the implementation of this will depend on both the international political process and the actions of individuals. Even if no specific action is taken to reduce emissions, the future rates of emissions are uncertain since the future changes in population, technology and economic state are difficult if not impossible to forecast. Therefore, rather than make predictions of future emissions, climate science examines a range of plausible scenarios in order to examine the implications of each scenario and inform decisions on reducing emissions and/or dealing with their consequences.

The SRES scenarios [2] were grounded in plausible storylines of the human socio-economic future, with differences in economy, technology and population but no explicit inclusion of emissions reductions policies. A wide range of scenarios were developed using a number of integrated assessment models (IAMs), and six particular projections of emissions based on selected storylines were selected as 'marker' scenarios to illustrate the range of futures assessed. These scenarios extend out to 2100 and vary widely in their projected emissions by that time, although none of them includes a reduction in emissions through climate policy. The A1FI storyline describes a future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, with convergence among regions and decreasing global differences in *per capita* income. New technologies are introduced rapidly, but with a continued intensive use of fossil fuels. The B1 storyline describes the same pattern of population change as A1FI, but with much greater emphasis on clean and resource-efficient technologies, with global solutions to economic, social and environmental sustainability and improved equity. The A2 storyline describes a heterogeneous world with a continuously increasing population, regionally oriented economic development and fragmented *per capita* economic growth and technological change. The B2 storyline also features ongoing population growth but at a lower rate than A2, and with less rapid and more diverse technological change than A1FI and B1. As with B1, B2 is oriented towards environmental protection and social equity, but focuses on local and regional levels.

It is important to note that different IAMs project different emissions even for any single storyline, owing to different assumptions and methods within the IAMs. The SRES marker scenarios used different IAMs for different storylines, so each marker scenario is to some extent dependent on the IAM used as well as the underlying storyline of socio-economic change. A particular consequence of this is that the early stages of the emissions scenarios overlap considerably when all IAMs are taken into account; for example, considering the mean of all the IAM projections for each storyline, A1FI produces the highest emissions in early years just as in the long term. By contrast, when the marker scenarios based on individual IAMs are considered, A1B gives higher emissions than A1FI in the early years (figure 3). This illustrates the uncertainties in translating socio-economic factors into emissions.

Another important point is that all storylines (and hence emissions scenarios) are intended to represent long-term evolution of the driving forces of emissions as opposed to capturing short-term variations in the global economy. From 2000 to 2007, fossil-fuel CO_2 emissions grew by 3.6 per cent per year, driven largely by world gross domestic product (GDP; but growth in emissions slowed to 2% in 2008 in association with the global financial crisis) [6]. Global emissions fell by approximately 1 per cent in 2009—emissions from Organization for Economic

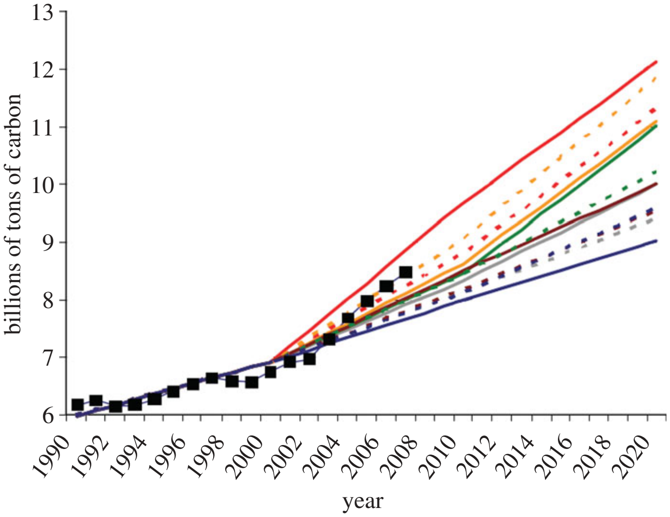

Figure 3. Comparison of actual fossil-fuel CO_2 emissions from 1990 to 2007 with SRES emissions scenarios. Dashed lines show mean emissions from all IAMs for each SRES storyline, and solid lines show the emissions from the SRES marker scenarios as used in the IPCC climate projections (figures 1 and 2). Observed emissions (published October 2008) are from Carbon Dioxide Information and Analysis Center, 'Latest Published Global Estimates' and '2006–2007 Global and National Estimates by Extrapolation' (http://cdiac.ornl.gov/trends/emis/meth_reg.html). Filled squares, actual; red line, A1B; orange line, A1FI; grey line, A1T; green line, A2; brown line, B1; blue line, B2; red dashed line, A1B*; orange dashed line, A1FI*; grey dashed line, A1T*; green dashed line, A2*; brown dashed line, B1*; blue dashed line, B2*. Adapted from Leggett & Logan [9].

Cooperation and Development (OECD) countries and Russia fell by 7 per cent owing to the economic situation, but this was almost balanced by an increase in emissions from China and India [7].

Suggestions that actual emissions have been above the upper limit of the IPCC SRES range are erroneous, and appear to be based on comparisons with the averages of different versions of the scenarios from different IAMs ([8]; dashed lines in figure 3) rather than with the individual scenarios that were actually used in climate models. Actual emissions have been within the range of the marker scenarios [3,6,9]. Given the uncertainties in the emissions scenarios themselves, and their aim of capturing long-term trends rather than short-term variations, it is still considered too early to reliably assess whether any particular SRES marker scenario is more plausible than any other [9].

3. Airborne fraction of CO_2 emissions: projections and recent observations

In the AR4, it was noted that projections of climate change should consider not only the uncertainties in the response of global temperature to a given change in CO_2 concentration ('climate sensitivity'[2]), but also the uncertainties

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[2] Climate sensitivity is the equilibrium response of global mean temperature to a doubling of atmospheric CO_2 concentration (or CO_2 equivalent of other greenhouse gases). In climate projections driven by time-dependent scenarios of greenhouse-gas concentrations, in which temperature change lags the change in forcing, a related measure is the temperature change at the time of CO_2 doubling ('transient climate response').

in translating emissions scenarios into concentrations. The ratio between the rate of rise of atmospheric CO_2 concentrations and the rate of emissions is termed the future ‘airborne fraction’. There is now a large body of evidence suggesting that the airborne fraction can be expected to be greater with climate change than without, particularly as land carbon sinks are projected to become weaker as a consequence of climate change [10–13]. The airborne fraction is currently approximately $40 \pm 14\%$ [14], and interpretations vary on whether the airborne fraction is already increasing significantly. Le Quéré *et al.* [6] suggest a trend of increasing airborne fraction of $0.3 \pm 0.2\%\,\mathrm{yr}^{-1}$ between 1959 and 2008, whereas Knorr [16] suggests an insignificant trend of $0.07 \pm 0.14\%\,\mathrm{yr}^{-1}$ since 1850. Uncertainties, particularly in CO_2 emissions from land-use change, make a precise determination of any trend difficult.

The Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP; [12]) used a number of coupled climate–carbon-cycle models to examine uncertainties in the strength of feedbacks between climate change and the carbon cycle. The C4MIP included some models based on GCMs (including several that were closely aligned to those used for the main projections in the IPCC), and also Earth System Models of Intermediate Complexity (EMIC). The C4MIP models were driven by observed twentieth century emissions and the SRES A2 scenario of future emissions, and simulated the resulting carbon-cycle processes, including changes in land and ocean carbon sinks and in atmospheric CO_2 concentrations. The models were used in two modes: (i) changes in atmospheric CO_2 affecting the climate through changes in the greenhouse effect, to allow for climate change to affect the carbon cycle and (ii) ‘switching off’ the greenhouse contribution of additional CO_2, to isolate the behaviour of the carbon cycle in the absence of feedbacks from climate change. The different projections of atmospheric CO_2 concentration between (i) and (ii), therefore, showed the magnitude of the climate–carbon-cycle feedback.

The C4MIP models simulated airborne fractions of 38–56% in the absence of climate-change effects, and importantly, none of the models simulated a significant increase in the airborne fraction from 1960 to 2006, even when climate-change effects were included; indeed many of the models simulate a decrease in the airborne fraction (figure 4). The lack of increase in the airborne fraction over the twentieth century can be explained by the strong dependency on previous emissions [17]. Although the C4MIP models simulate a weaker land carbon sink over the twentieth century when climate-change effects are included, this does not translate into an increase in the airborne fraction at that time because previous emissions are still the dominant factor.

In the projections of twenty-first century CO_2 rise and climate change under the SRES A2 emissions scenario, all C4MIP models simulated a faster CO_2 rise and increasing airborne fraction when climate-change effects were included over the twenty-first century [12]. While there were shown to be large uncertainties in the strength of the climate–carbon-cycle feedback [18] and the consequent impact on the rate of rise in atmospheric CO_2 concentrations, there was unanimous agreement between the C4MIP models that this feedback is positive in sign and hence is expected to lead to an acceleration of the rise in CO_2 levels (figure 5). Recent simulations with coupled climate–carbon-cycle models now including

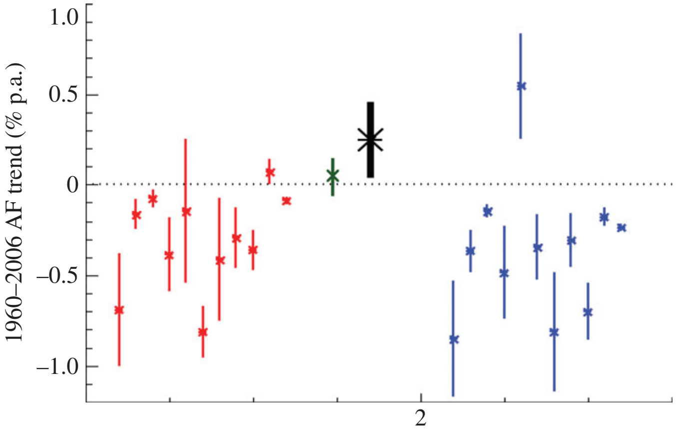

Figure 4. Trends in the airborne fraction (AF) of CO_2 emissions (fossil fuel and deforestation) from 1960 to 2006, estimated from observations by Canadell *et al.* [15] (black, with a similar estimate to Le Quéré *et al.* [6]) and Knorr [16] (green), compared with the airborne fraction trend simulated by the C4MIP models with climate–carbon-cycle feedbacks (red) and without climate–carbon-cycle feedbacks (blue).

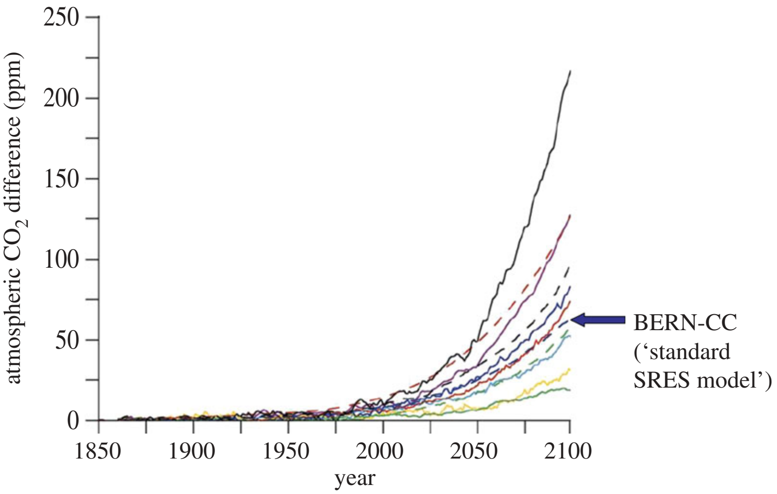

Figure 5. Effect of climate–carbon-cycle feedbacks on the rate of rise of atmospheric CO_2 from the A2 emissions scenario, from the C4MIP models. Each line shows, for each model, the difference in CO_2 projected with and without climate–carbon-cycle feedbacks. The model previously used to generate the CO_2 concentrations from the SRES scenarios as input to the GCMs used in the AR4 was the Bern climate–carbon-cycle model (BERN-CC) model; the projection of this model in the C4MIP study is highlighted here and labelled 'standard SRES model'. In this paper, we refer to the CO_2 concentrations generated by the BERN-CC model as the 'standard concentration scenario' for any given SRES scenario. Adapted from Friedlingstein *et al.* [12]. Copyright © American Meteorological Society, 2006.

nutrient cycles suggest that nitrogen limitation may reduce the climate–carbon-cycle feedback, but would still increase the airborne fraction through reduced CO_2 fertilization [19,20].

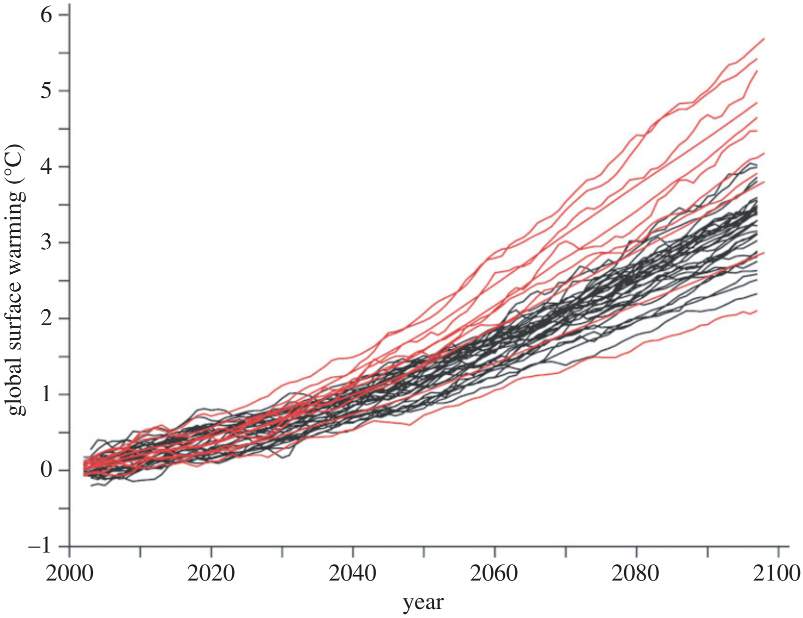

Figure 6. Projections of global mean temperature over the twenty-first century using the SRES A2 scenario, from the standard AR4 model ensemble driven by standard concentration scenarios (black lines) and the C4MIP ensemble of coupled climate–carbon-cycle models driven by CO_2 emissions (red lines). The C4MIP projections were driven by CO_2 alone [12], and for these purposes, were then scaled with a simple model to account for the radiative forcing of non-CO_2 greenhouse gases and aerosols. Adapted from Meehl *et al.* [4]. Copyright © IPCC, 2007.

The uncertainty in the strength of the climate–carbon-cycle feedback leads to increased uncertainty in the rate of global warming arising from a given emissions scenario (figure 6). Frank *et al.* [21] compare the strength of the climate–carbon-cycle feedback from temperature and CO_2 reconstructions of the Little Ice Age, but conclude that this constraint is unable to rule out any of the C4MIP models. The C4MIP study also showed that the climate–carbon-cycle feedback can increase nonlinearly in strength for greater levels of climate change, implying that the carbon-cycle feedback could be stronger under 4° of warming than previously observed during the Little Ice Age. This uncertainty mainly affects the upper end of the range of warming, owing to the model consensus that the feedback is positive. Therefore, the consideration of climate–carbon-cycle feedbacks raises the upper limit of the projected range of temperature responses, but does not significantly affect the lower limit (figure 6).

Although the IPCC assessed the feedbacks between climate change and the carbon cycle using a range of both simple and complex models, it was not possible to include this feedback mechanism in the GCMs used for the systematic projection of climate change because too few groups possessed operational carbon-cycle components of their GCMs at the time when the systematic climate-change projections were begun for the AR4. Following previous standard practice, the GCM simulations for the AR4 were instead driven by standard scenarios of CO_2 concentrations that were derived from the SRES emissions scenarios with an

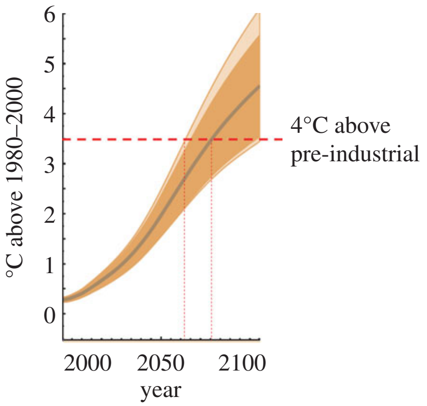

Figure 7. Projections of global warming relative to pre-industrial for the A1FI emissions scenario, using an ensemble of simulations with the MAGICC SCM tuned against the AR4 GCMs and C4MIP-coupled climate–carbon-cycle models. Dark shading shows the mean ±1 s.d. for the tunings to 19 AR4 GCMs, and the light shading shows the change in the uncertainty range when uncertainties in climate–carbon-cycle feedbacks from C4MIP are included. The horizontal red dashed line marks warming of 3.5°C relative to 1980–2000, which represents 4°C relative to pre-industrial [5]. Adapted from Meehl *et al.* [4]. Copyright © IPCC, 2007.

EMIC, in this case the Bern climate–carbon-cycle model (BERN-CC; [22]). In this model, the strength of climate–carbon-cycle feedbacks is below the average of the C4MIP ensemble ([12]; see also figure 5). In this paper, we follow Meehl *et al.* [4] in referring to these concentration scenarios as the standard SRES concentration scenarios, as distinct from the C4MIP-based ensemble projections of CO_2 concentrations, which explore uncertainty in climate–carbon-cycle feedbacks.

In order to assess the implications of the full set of six marker scenarios including climate–carbon-cycle feedbacks, the IPCC used SCMs designed to capture the global aspects of the more complex models with less computational expense and analytical complexity than GCMs and EMICs.[3] The SCM ‘Model for the Assessment of Greenhouse-gas Induced Climate Change’ (MAGICC) [23] was calibrated (‘tuned’) against the AR4 models to represent the range of atmospheric responses, and against the C4MIP models to represent the strengths of carbon-cycle feedbacks. The projections of climate change for the A1FI emissions scenario are shown in figure 7.

While this technique was used to estimate the likely range of warming for each scenario, including uncertainties in climate–carbon-cycle feedbacks, the ‘best estimate’ of warming from each scenario was based on projections using the standard SRES CO_2 concentrations, which is lower than the central estimate of CO_2 concentrations from C4MIP. The best estimate for B1, A1B and A2 used the mean of all GCM projections using the standard concentrations, and that for B2, A1T and A1FI used the MAGICC estimation of this GCM-based mean, again using the standard concentrations.

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[3] For further information on GCM-based Earth System Models, EMICs and SCMs, see Meehl *et al.* [4].

4. New projections of climate change under the A1FI scenario

(*a*) *Overview of methodology*

The scenario with the highest emissions (A1FI) was not examined with GCMs in the AR4, but with global emissions generally continuing to increase, there is an increasing need to improve our understanding of the full range of potential consequences of ongoing emissions. In particular, with the impacts of high levels of climate changes expected to be severe, it is important to assess the likelihood of reaching such high levels of change and the timing of when this might be expected to occur. While these issues are subject to considerable uncertainty, a responsible risk assessment requires a range of plausible outcomes to be examined, including not only the most likely outcomes but also the less likely but potentially higher impact outcomes.

Section 4 aims to provide more complete information regarding the upper end of the range of global warming, focusing on the high-emissions scenario and a range of strengths of climate–carbon-cycle feedbacks. We assess a more comprehensive set of models, including both GCMs and SCMs, to estimate when the high-emissions scenario would give rise to a global warming of 4°C relative to pre-industrial. We provide expert-derived estimates of both a ‘best guess’ and ‘plausible worst-case’[4] scenario. This expert-assessment approach is compatible with the approach used by the IPCC in assessing the magnitude of future climate change.

We used a perturbed physics ensemble of 17 simulations with variants of the HadCM3-coupled ocean–atmosphere GCM [24,25] to project possible climate changes over the twenty-first century following the A1FI scenario (which gives the highest emissions of the six SRES marker scenarios). We refer to this set of variants of HadCM3 as HadCM3-QUMP (‘Quantifying Uncertainties in Model Projections’; [26]). The perturbed physics approach is designed to begin to quantify uncertainty in climate projections, and involves generating a number of variants of the model, which differ according to the settings of certain key parameters [25–27]. The parameter perturbations are designed to allow the ensemble to cover a wide range of behaviours of the model [28], although this is still limited by the number of simulations that can be carried out with available in-house computing resources. Here, the perturbed physics approach was used to explore a range of possible responses of the global atmospheric state to a given scenario of greenhouse-gas concentrations.

Since these simulations have been performed with variants of a single climate model, there may be an imprint of the underlying model structure. Therefore, we also compare the HadCM3-QUMP ensemble with the multi-model ensemble assessed in the IPCC AR4 (commonly referred to as the AR4 ensemble; [4]). This used 23 GCMs[5] from climate-modelling centres worldwide. The AR4 ensemble was not applied to the A1FI scenario; however, both the AR4 and HadCM3-QUMP ensembles were applied to the A1B scenario, so we use these sets of simulations to compare the climate projections from the two ensembles under a common emissions scenario.

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[4] We consider the plausible worst case to be the most rapid projection of climate change within a reasonable range of uncertainty, discarding the outliers. A quantitative definition is given below.

[5] Twenty-four GCMs are shown in the AR4, but one was later withdrawn from the model-data archive.

Table 1. Comparison of projections of global warming by the 2090s for the A1B scenario, projected by the HadCM3-QUMP and IPCC AR4 GCM ensembles.

		projected warming by 2090s relative to 1861–1890 (°C)			
ensemble	number of members	mean	median	minimum	maximum
HadCM3-QUMP	17	4.0	4.0	2.4	5.3
AR4 GCMs	23	3.2	3.2	1.9	4.9

A small number of uncalibrated ensemble members such as 17 or 23 are not considered sufficient to assign probabilities to different projections of climate change, and indeed there is a danger of outlying ensemble members being interpreted as representing relatively high probability outcomes. In order to estimate the relative likelihood of different projections and include estimates of uncertainties in climate–carbon-cycle feedbacks as well as uncertainties in atmospheric responses, we used the MAGICC model calibrated to represent the range of atmospheric responses of the HadCM3-QUMP ensemble and range of carbon-cycle feedback strengths in C4MIP. The ultimate aim of the QUMP project is to produce projections of global and regional climate change in the form of probability distribution functions (PDFs), conditioned on different emissions scenarios [29,30]. It has not been possible to produce such probabilistic estimates for this paper, including performing all the steps to test the robustness of such projections to methodological assumptions and compare the PDFs with other estimates. This we leave to future research.

(*b*) *Comparison of the HadCM3-QUMP and AR4 ensembles*

We compared the climate projections of the HadCM3-QUMP and AR4 ensembles driven by the standard A1B concentration scenario, i.e. with climate–carbon-cycle feedbacks specified using the BERN-CC model. Atmospheric CO_2 concentrations in the A1B scenario are projected to rise to 674 ppm by the 2090s. While the two ensembles project overlapping ranges[6] of global warming in response to this scenario, the mean, median and minimum of the HadCM3-QUMP ensemble projections were approximately 25 per cent higher than those projected by the AR4 ensemble, and the maximum was 8 per cent higher (table 1).

(*c*) *Climate change projected under the standard A1FI concentration scenario*

For this study, the HadCM3-QUMP ensemble is driven by the standard concentration scenario derived from the A1FI emissions in which CO_2 concentrations rise to 872 ppm by the 2080s. The ensemble mean warming by the 2090s is 5.1°C relative to 1861–1890, with the individual members projecting warming between 3.2°C and 6.7°C (figure 8 and table 2).

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[6] Considering changes projected by the 2090s relative to pre-industrial for the A1B scenario, 15 of the 17 HADCM3-QUMP simulations projected warming between the minimum and maximum projected by the full set of 23 AR4 simulations. Twenty-one of the 23 AR4 simulations projected warming between the minimum and maximum projected by the full set of 17 HadCM3-QUMP simulations.

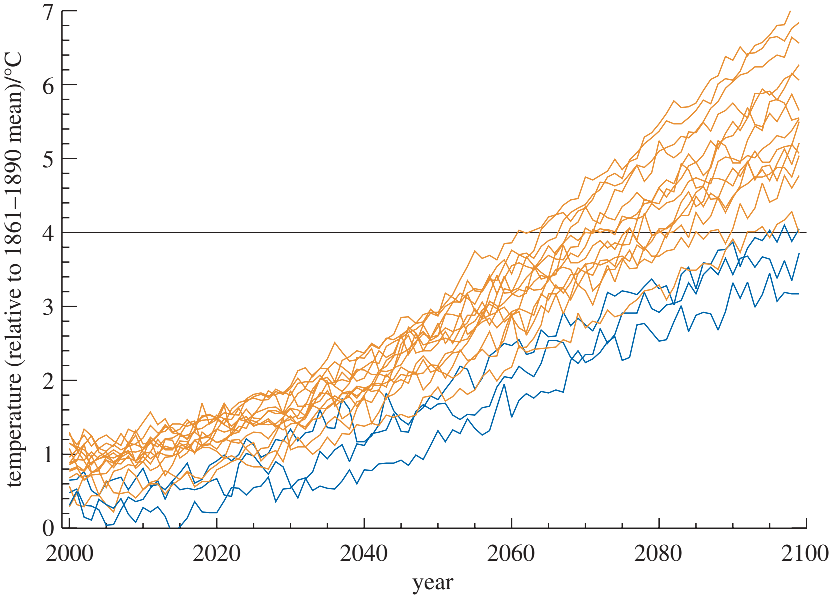

Figure 8. Projections of global mean temperature rise relative to 1861–1890 with the HadCM3-QUMP-perturbed physics GCM ensemble driven by the standard A1FI concentration scenario. Ensemble members that project a warming of 4°C or more by the 2090s are shown in orange, and the remainder are shown in blue.

Table 2. Global temperature rise by the 2090s relative to 1861–1890 projected by the 17 simulations in the HadCM3-QUMP-perturbed physics ensemble driven by the standard A1FI concentration scenario, and dates at which 4°C warming is projected to be reached. For any given simulation, the year of reaching 4°C warming is the first year in which the annual mean temperature of that year and all subsequent years is at least 4°C greater than the mean of 1861–1890.

HadCM3-QUMP A1FI			
year at 4°C	temperature 2090s (°C)	year at 4°C	temperature 2090s (°C)
2061	6.7	2076	5.1
2064	6.3	2077	5.4
2067	6.5	2079	4.9
2068	5.9	2081	4.8
2070	5.8	2085	4.5
2070	5.6	2092	4.0
2071	5.2	2095	3.9
2075	4.8	after 2100	3.6
		after 2100	3.2

Of the 17 members in the ensemble, 14 project warming above 4°C by the 2090s. The central members of the ensemble project 4°C to be reached in the 2070s, although the earliest date of reaching 4°C is 2061.

Although GCMs were not used to project climate change under A1FI for the IPCC AR4, Meehl *et al.* [4] used an SCM to scale the results of the AR4 ensemble from other scenarios to estimate what the GCMs would have projected under A1FI. They estimated that the multi-model mean warming would have been approximately 4°C by the 2090s relative to 1980–1999, implying a warming of approximately 4.5°C relative to pre-industrial. As seen in §3 for the comparison of HadCM3-QUMP and AR4 ensembles under A1B, the estimated AR4-projected warming for A1FI is lower than that projected by HadCM3-QUMP.

It is unwise to rely on simulations that are outliers in the distribution—indeed the most extreme members of the ensemble simulated warming of 1°C or above by 2000, while warming observed between 1850–1899 and 2001–2005 was between 0.57°C and 0.95°C, with a best estimate of 0.76°C [1]. Hence, we caution against attaching too high a likelihood to the ensemble member that reaches 4°C by 2061 in response to the standard A1FI concentration scenario as represented here (in which no uncertainty in carbon-cycle feedbacks is taken into account). The extent to which this may need to be adjusted to account for carbon-cycle feedbacks is discussed in §4*d*.

(*d*) *Projected warming including uncertainties in atmospheric response and carbon-cycle feedbacks: an estimate using a simple climate model*

To estimate the climate changes that the HadCM3-perturbed physics ensemble would project with climate–carbon-cycle feedbacks included and driven by the A1FI emissions scenario, we followed the approach used in the IPCC AR4 by Meehl *et al.* [4], but with the climate sensitivity tuned against the HadCM3-QUMP GCM ensemble. Following Meehl *et al.* [4], we tuned MAGICC against the C4MIP models to represent the strengths of the carbon cycle. We carried out an ensemble of 729 simulations with MAGICC tuned in this way [31], and excluded the highest and lowest 10 per cent of projected rates of global warming from our judgement of 'plausible' climate changes (figure 9). Under A1FI, this ensemble projected a median warming of 5.6°C by 2100, with 4°C being reached at approximately 2070. The 10th and 90th percentiles encompassed a range of warming from 4.4°C to 7.3°C by the 2090s, with 4°C being reached between 2058 and 2088. This is broadly consistent with the results of Meehl *et al.* [4], with MAGICC tuned against the AR4 ensemble (table 3). The best estimate for reaching 4°C global warming relative to pre-industrial is approximately 5 years earlier in our ensemble, consistent with the HadCM3-QUMP ensemble exhibiting a systematically higher climate sensitivity than the AR4 ensemble as demonstrated with our comparison using the A1B scenario.

A key question is whether any statement of likelihood can be attached to our results. The IPCC AR4 [4] used a number of lines of modelling evidence and expert judgement to define a likely range of warming projections for the 2090s, with 'likely' being defined as a greater than 66 per cent probability of occurrence. The previous results from MAGICC tuned to the AR4 ensemble and C4MIP (figure 7) gave a warming of up to 6.5°C by the 2090s (below the upper limit of the IPCC's likely range) and reached 4°C in the early 2060s in the upper uncertainty bound. Therefore, a projection of global warming of 4°C relative to pre-industrial by the early 2060s would appear to be consistent with the IPCC's likely range for the A1FI scenario. More systematic probabilistic

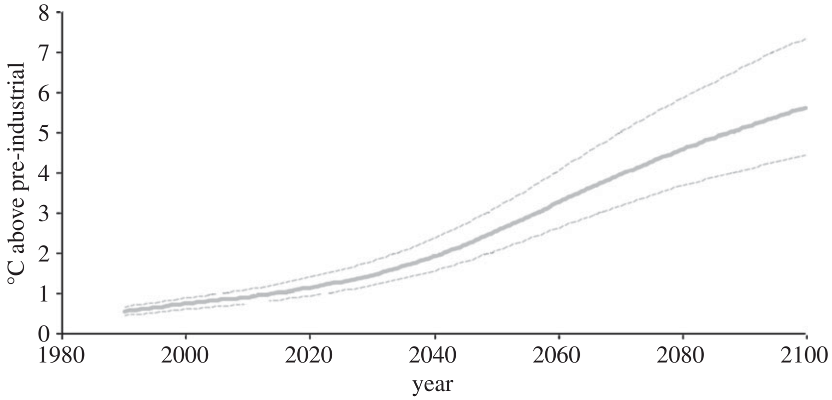

Figure 9. Global mean temperature change over the twenty-first century relative to pre-industrial, under the A1FI emissions scenario, projected with an ensemble of 729 simulations with the MAGICC SCM tuned against the HadCM3-QUMP and C4MIP ensembles. The central thick line shows the median projection, and the two dashed lines show the 10th and 90th percentiles of the frequency distribution of the 729 MAGICC experiments.

Table 3. Comparison of global warming projections by the 2090s for the A1FI scenario, from the HadCM3-QUMP ensemble, IPCC AR4 expert-assessment and MAGICC SCM ensembles tuned to AR4 + C4MIP and HadCM3-QUMP + C4MIP. The date of reaching 4°C is also given where this information is available. AR4 expert-assessment figures were originally given relative to 1980–1999. Here, we add 0.5°C warming to give warming relative to 1861–1990, as recommended in the IPCC AR4 synthesis report. (Note that the 'date of reaching 4°C' depends to some extent on inter-annual variability—for HadCM3-QUMP, we defined this date as the first year in which the annual mean temperature of that year and all subsequent years is at least 4°C greater than the mean of 1861–1890, but MAGICC does not represent inter-annual variability, so the date of reaching 4°C may be more representative of a long-term mean global temperature passing this threshold. Further details of AR4 simulations and expert assessment can be found in Meehl *et al.* [4].)

source	warming by 2090s (°C)	warming by 2090s (°C)	date reaching 4°C (best estimate)	date reaching 4°C (range)
MAGICC tuned to AR4 and C4MIP	4.9 (mean)	3.7–6.5 (±1 s.d.)	2075 (mean)	2065–2100 (±1 s.d.)
IPCC AR4 expert assessment	4.5 (scaled GCM mean)	2.9–6.9 (likely range)	not reported	not reported
HadCM3-QUMP	5.1 (median)	3.1–6.6 (full range)	2076 (median)	2061–after 2100 (full range)
MAGICC tuned to HadCM3 and C4MIP	5.5 (median)	4.3–7.2 (10th–90th%)	2070 (median)	2058–2088 (10th–90th%)

climate projections have previously been made for the UK using a complex, lengthy and systematic methodology bringing in as much of the available evidence as possible [30], but this methodology has not yet been applied to this specific problem. Our own MAGICC ensemble is designed to sample the uncertainty more completely than the HadCM3-QUMP ensemble, but nevertheless is still limited. The 90th percentile of our MAGICC ensemble projects a warming of 4°C by 2058. The IPCC [1] consider a probability of less than 10 per cent as 'very unlikely', so *if* our model results were interpreted as an indicator of probability, then this could be taken to indicate that it is very unlikely that 4°C would be reached before 2058 under the A1FI scenario. However, more complete sampling of uncertainty must be made before reliable estimates of likelihood can be made.

5. Conclusions

The A1FI emissions scenario is considered by the IPCC to be one of a number of equally plausible projections of future greenhouse-gas emissions from a global society that does not implement policies to limit anthropogenic influence on climate. Previously, this scenario has received less attention than other scenarios with generally lower rates of emissions. However, there is no evidence from actual emissions data to suggest that the A1FI scenario is implausible if action is not taken to reduce greenhouse gas emissions, and hence it deserves closer attention than has previously been given.

The evidence available from new simulations with the HadCM3 GCM and the MAGICC SCM, along with existing results presented in the IPCC AR4, suggests that the A1FI emissions scenario would lead to a rise in global mean temperature of between approximately 3°C and 7°C by the 2090s relative to pre-industrial, with best estimates being around 5°C. Our best estimate is that a temperature rise of 4°C would be reached in the 2070s, and if carbon-cycle feedbacks are strong, then 4°C could be reached in the early 2060s—this latter projection appears to be consistent with the upper end of the IPCC's likely range of warming for the A1FI scenario.

The above are estimates from our expert assessment and based on the current understanding of climate and carbon-cycle feedbacks derived from the model experiments described above. To that end, they are derived using an approach that is consistent with that used in assessment reports such as the IPCC AR4.

The natural next step that needs to be undertaken is to quantify the uncertainty and express climate projections in terms of PDFs. While we cannot comment in this paper on the ability to sample the PDF of possible human-induced emissions of greenhouse gases and other forcing agents, it is possible to explore modelling uncertainties in a systematic way. For example, Murphy *et al.* [30] describe an algorithm for sampling uncertainties in both physical and biological feedbacks using a single modelling structure with perturbations to key parameters. Model versions can be constrained by up-weighting those model versions that best reproduce observed aspects of climate and down-weight those that have the worst reproduction of the observations. Structural uncertainties may be further sampled using the international archive of climate-model output. The resulting PDFs can potentially be used to assess the degree of risk of dangerous climate change at both global and regional scales and for irreversible changes conditioned on different emissions pathways.

Such approaches use formal Bayesian statistical theories that are widely used in other prediction problems, but that are difficult to implement when using complex climate models. Climate model ensemble sizes are severely limited by available computing power, observational constraints are multi-variate and formal estimates of observational uncertainties are not readily available. There is a potential degree of subjectivity in implementing the Bayesian approach, which needs to be tested by sensitivity analysis. Nevertheless, this is an emerging area and we expect to see a number of probabilistic estimates of the risk of 4° warming (conditioned on emissions) and other dangerous climate change in the future, and these should be considered carefully in mitigation policy.

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