When could global warming reach 4°C?

Hadley Centre technical note 80

Richard A. Betts, Matthew Collins, Deborah L. Hemming, Chris D. Jones, Jason A. Lowe and Michael Sanderson

December 2009

When could global warming reach 4°C?

Richard A. Betts, Matthew Collins, Deborah L. Hemming, Chris D. Jones, Jason A. Lowe and Michael Sanderson

Summary

The 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 1.4°C and 6.9°C by the end of the 21st Century, relative to pre-industrial. While much political attention is focussed 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 21st 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 (A1FI) was not examined with complex general circulation models (GCMs) in 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 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.

This report 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 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 2060.

1. Introduction

The Working Group 1 (WG1) volume of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4; IPCC 2007a) assessed the global climate change projected to result from 6 scenarios of greenhouse gas emissions, taken from a larger set of scenarios from the IPCC Special Report on Emissions Scenario (SRES; Nakićenović et al. 2000). These 6 SRES "marker scenarios" are identified as A1FI, A1B, A1T, A2, B1 and B2, and are discussed in more detail in Section 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 21st Century, the lowest cumulative emissions are projected by the B1 scenario, and the highest by A1FI. All 6 scenarios were considered by IPCC to be equally sound; no scenario was considered to be more or less likely than any others (IPCC 2007a).

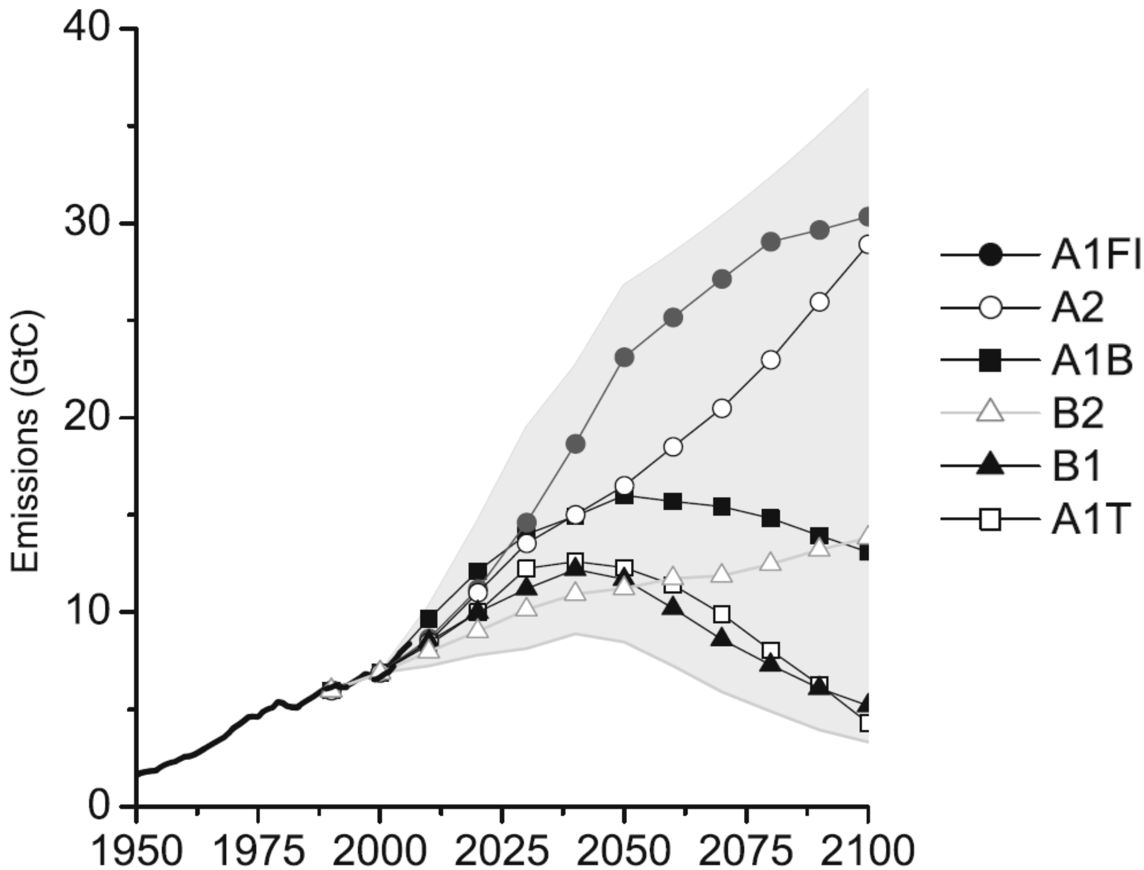

Figure 1. Emissions of CO_2 from fossil fuel in the 6 SRES marker scenarios (black curves) and the full range of SRES scenarios (grey plume). The SRES scenarios also include emissions of non-CO_2 greenhouse gases, aerosols, and emissions from land use change, which are not included in this figure. Reproduced from Van Vuuren and Riahi, 2008. Copyright Springer Science + Business Media B.V. 2008

IPCC WG1 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 (Meehl et al, 2007). The conclusion was that under the 6 SRES marker scenarios, global mean temperatures are likely to increase by between 1.1°C and 6.4°C by the end of the 21st 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 (IPCC 2007b). 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.

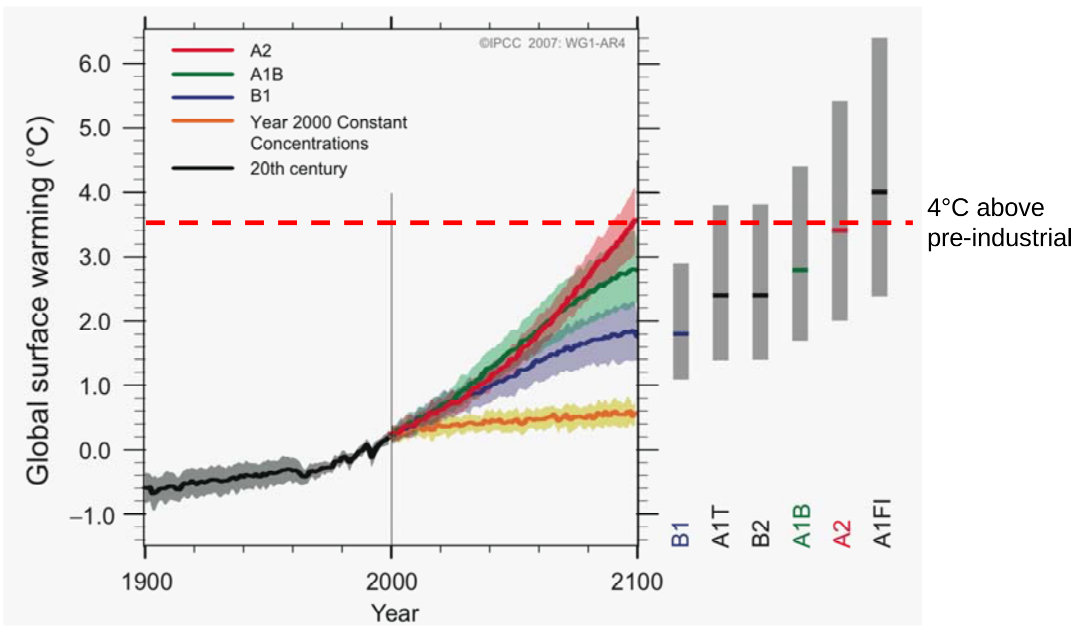

Figure 2. Past changes in global mean temperature (black curve), and projected future changes resulting from the IPCC SRES marker scenarios of greenhouse gas and aerosol emissions (coloured curves and grey bars), relative to the 1980-2000 mean (Meehl et al, 2007). Climate changes under the A2, A1B and 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 simple climate models. Grey bars show the "likely range" of warming for each scenario, from expert assessment based on all available evidence from GCMs, simple climate models.and observational constraints. The red dashed line marks warming of 3.5°C relative to 1980-2000, which represents 4°C relative to pre-industrial (IPCC 2007b) Copyright IPCC, 2007.

Although the 6 scenarios were all considered by IPCC to be equally sound as representations of a world that does not implement policies to mitigate climate change, not all the scenarios were examined to the same depth. 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 general circulation models (GCMs) from all the participating modelling groups[1]. Simple climate models 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 AR4 the highest emissions scenario (A1FI) was examined only with simple climate models and not directly with complex ocean-atmosphere GCMs (Meehl et al, 2007). .

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 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°C to 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 the speed with which this is reached. When assessing the warming of the full set of 6 SRES marker scenarios, Meehl et al (2007) focussed largely on the magnitude of warming by the end of the 21st Century. Discussion of uncertainties in warming rates earlier in the century to the scenarios was centred more on the GCMs (B1, A1B and A2). 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 report assesses the dates at which 4°C could be reached. We use a similar "expert assessment" approach to that used in 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 simple climate model 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

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

consequences of the A1FI scenario for the projected magnitude of global warming by the end of the 21st Century, and the times by which a global warming of 4°C is projected to be reached.

2. SRES marker scenarios and comparison with recent emissions

A key factor for future climate change will be the quantity of emissions of GHGs 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 GHG 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 climate models assessed in AR4 used scenarios from the Special Report on Emissions Scenarios (SRES; Nakićenović et al. 2000). These scenarios were grounded in plausible storylines of the human socioeconomic future, with differences in economy, technology, and population but no explicit inclusion of emissions reductions policies. A large number of scenarios were developed using a number of Integrated Assessment Models (IAMs), and 6 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 include a reduction in emissions through climate policy. The A1FI storyline describes a future world of very rapid economic growth, global population that peaks in 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 toward 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, due 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. In 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.

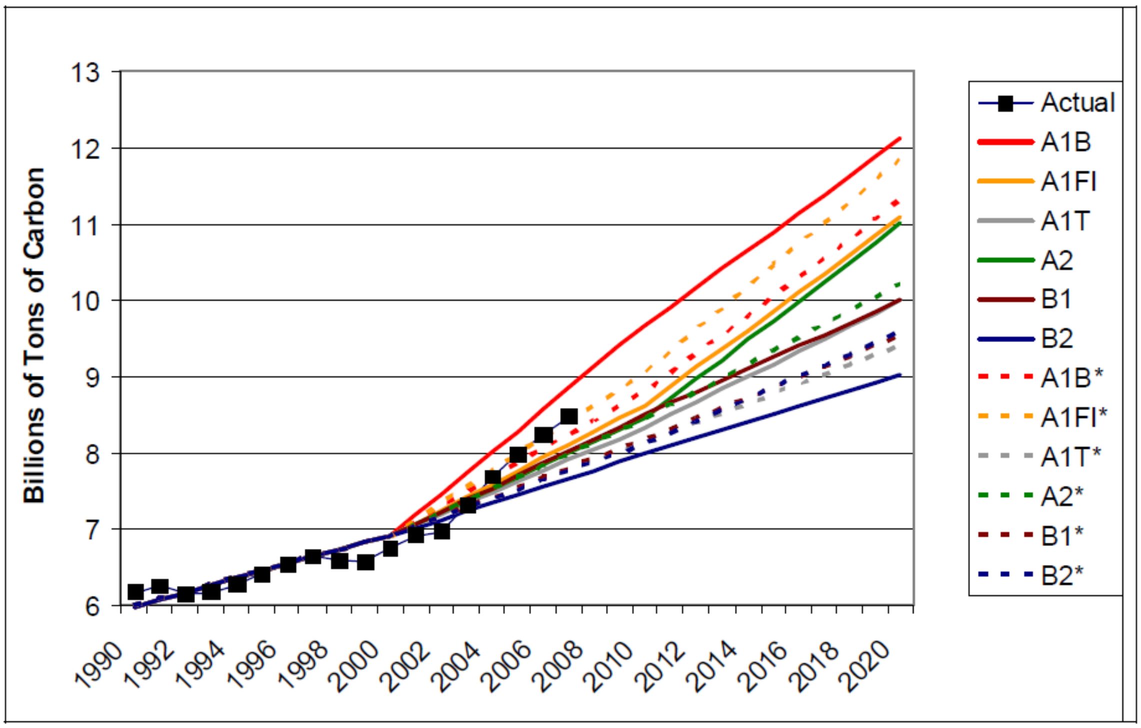

Figure 3. Comparison of actual fossil fuel CO_2 emissions from 1990 to 2007 with SRES emissions scenarios. Dashed lines show mean emissions from all IAMs for each SRES storyline, solid lines show the emissions from the SRES marker scenarios as used in IPCC climate projections (Figures 1 and 2). Observed 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] Reproduced from Leggett and Logan (2008)

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 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 (Le Quéré et al, 2009). On the basis of a projected decrease in GDP of 1.1%, it is predicted that emissions will decrease by 2.8% in 2009 (Le Quéré et al, 2009) (Figure 4).

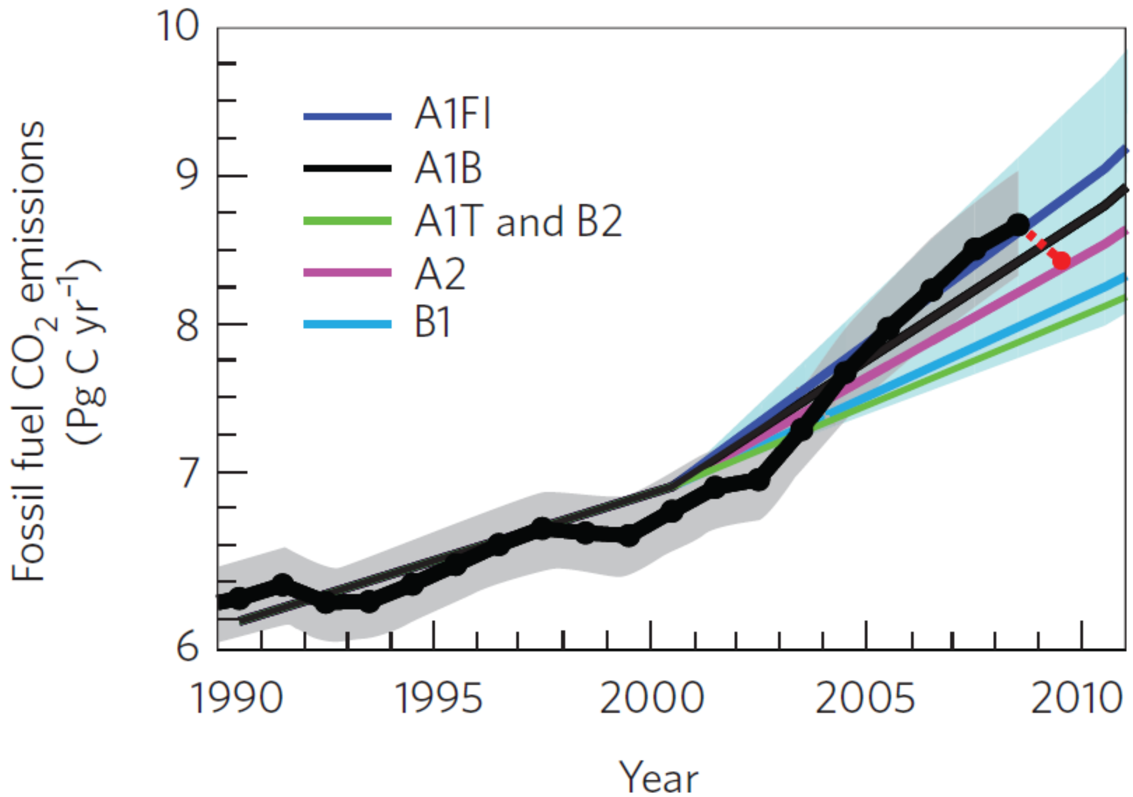

Figure 4. Updated comparison of SRES scenarios of fossil fuel CO_2 emissions with actual emissions up to 2008 (thick black line with solid circles) and projected emissions for 2009 (dashed red line and solid circle). Data on actual emissions were from the Carbon Dioxide Information Analysis Centre (CDIAC). Note that the emissions scenarios shown here are the means of the SRES scenario families from all IAMs (dashed lines in Figure 3), not the SRES marker scenarios as used in IPCC climate projections (Figures 1 and 2). The blue plume shows the range of SRES projections. Reproduced from (Le Quéré et al, 2009).

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 (Raupach et al., 2007; 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 (Van Vuuren and Riahi, 2008; Leggett and Logan, 2008; Le Quéré et al, 2009). 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 (Leggett and Logan, 2008).

3. The 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 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 "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 (Cox et al, 2000; Cramer et al, 2001; Friedlingstein et al, 2006; Denman et al, 2007). The airborne fraction is currently approximately 40 ± 14% (Jones and Cox, 2005), and interpretations vary on whether the airborne fraction is already increasing significantly. Le Quéré et al (2009) suggest a trend of increasing airborne fraction of 0.3 ± 0.2 % y^{-1} between 1959 and 2008, whereas Knorr (2009) suggests an insignificant trend of 0.07 ± 0.14% y^{-1} since 1850.

The Coupled Climate-Carbon Cycle Model Intercomparison Project (C4MIP) used a number of coupled climate-carbon cycle models to examine uncertainties in the strength of feedbacks between climate change and the carbon cycle. C4MIP included some models based on GCMs (including several which were closely aligned to those used for the main projections in IPCC), and also Earth-system models of intermediate complexity (EMICs). The C4MIP models were driven by observed 20th 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 0.38% to 0.56% in the absence of climate change effects, and importantly, none of the models simulated a significant increase in the airborne fraction from 1960-2006 even when climate change effects were

[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 GHGs). In climate projections driven by time-dependent scenarios of GHG 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").

included; indeed many of the models simulate a decrease in the airborne fraction over (Figure 4). The lack of increase in the airborne fraction over the 20th Century can be explained by the strong dependency on previous emissions (Jones et al, 2007). Although the C4MIP models simulate a weaker land carbon sink over the 20th 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.

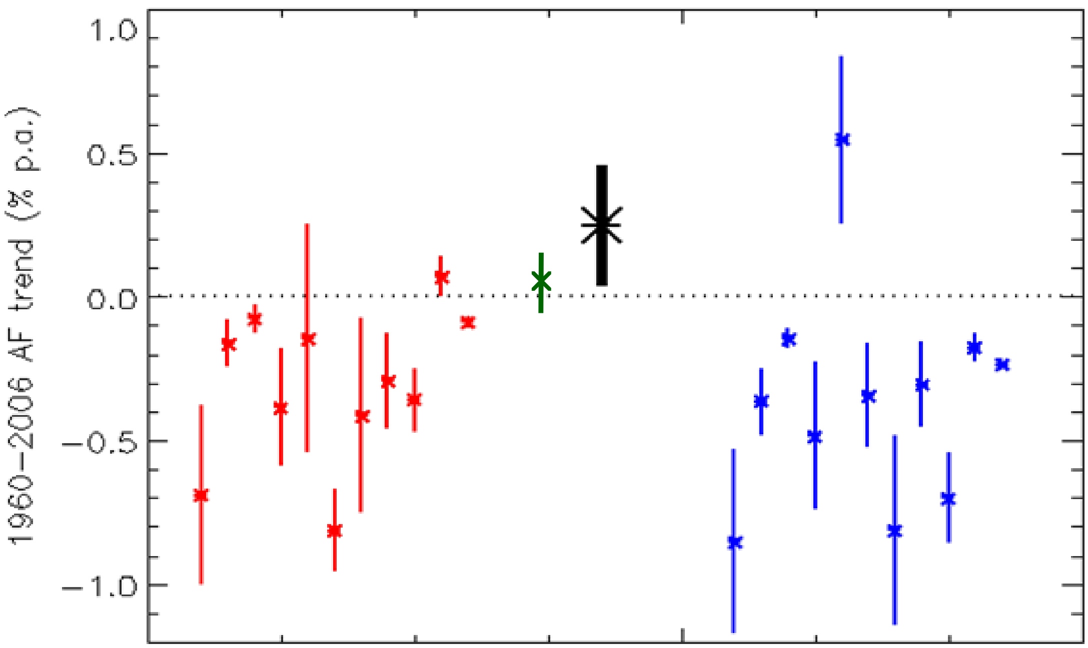

Figure 4. Trends in the airborne fraction of CO_2 emissions (fossil fuel and deforestation) from 1960-2006, estimated from observations by Canadell et al (2007) (black, with a similar estimate to Le Quéré et al, 2009) and Knorr (2009) (green), compared with the airborne fraction trend simulated by the C4MIP models with climate-carbon cycle feedbacks (red) and without climate-carbon cycle feedbacks (blue). Reproduced from Jones et al (2007)

In the projections of 21st 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 21st Century (Friedlingstein et al, 2006). While there were shown to be large uncertainties in the strength of the climate-carbon cycle feedback 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 will lead to an acceleration of the rise in CO_2 levels (Figure 5). 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). This uncertainty mainly affects the upper end of the range of warming, due to the model consensus that the feedback is positive. Therefore, 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).

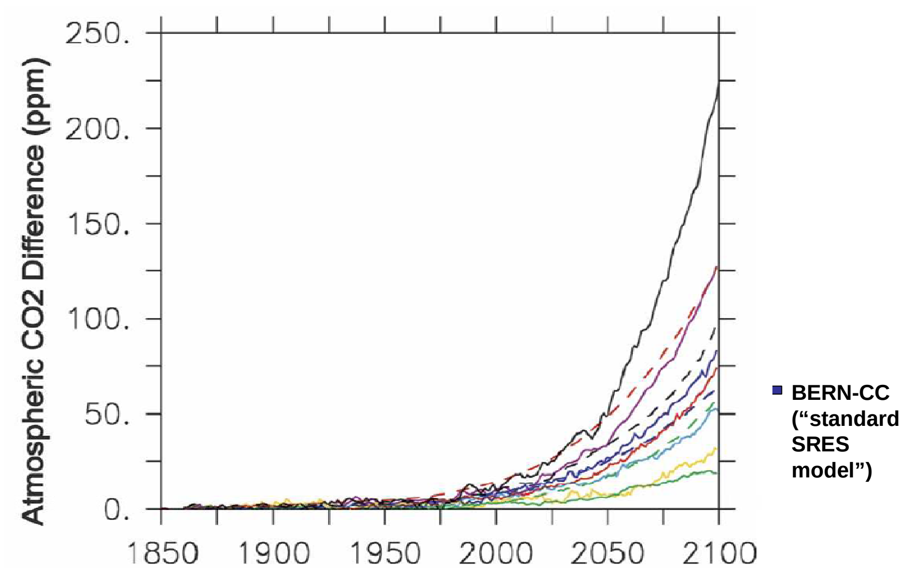

Figure 5. Effect of climate-carbon cycle feedbacks on the rate of rise of atmospheric CO_2 from the A2 emissions scenario, from the C4MIP models. Each line shows, for each model, the difference in CO_2 projected with and without climate-carbon cycle feedbacks. The model previously used to generate the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

.

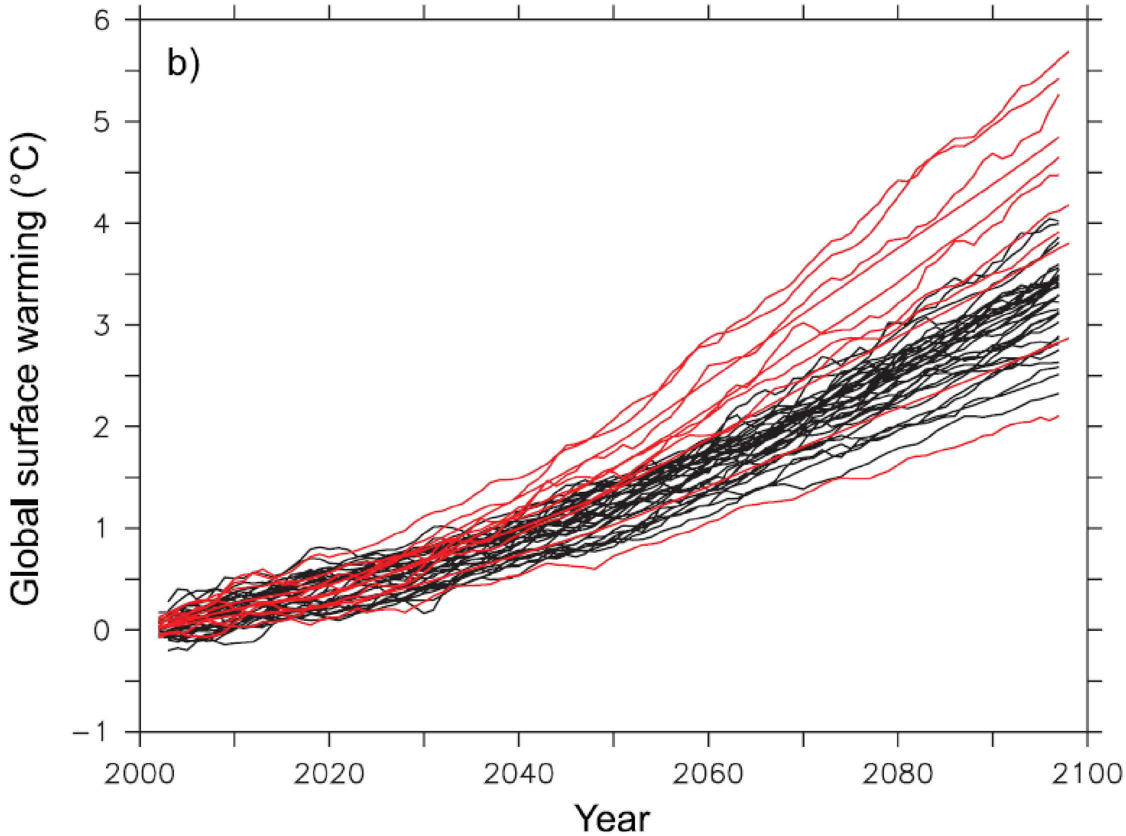

Figure 6. Projections of global mean temperature over the 21st Century using the SRES A2 scenario, from the standard AR4 model ensemble driven by standard concentration scenarios (black lines) and the C4MIP ensemble of coupled climate-carbon cycle models driven by CO_2 emissions (red lines). The C4MIP projections were driven by CO_2 alone (Friedlingstein et al, 2006), and these purposes were then scaled with a simple model to account for the radiative forcing of non-CO_2 GHGs and aerosols (Reproduced from Meehl et al, 2007. Copyright IPCC, 2007).

Although the IPCC assessed the feedbacks between climate change and the carbon cycle using a range of both simple and complex models, it had not been 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 AR4. Following previous standard practice, the GCM simulations for AR4 were instead driven by standard scenarios of CO_2 concentrations which were derived from the SRES emissions scenarios with an EMIC, in this case the Bern climate-carbon cycle model (BERN-CC; Joos et al., 2001). In this model, the strength of climate-carbon cycle feedbacks is below the average of the C4MIP ensemble (Friedlingstein et al, 2006 – see also Figure 5). In this report, we follow Meehl et al (2007) in referring to these concentrations 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 6 marker scenarios including climate-carbon cycle feedbacks, the IPCC used simple climate models (SCMs) designed to capture the global aspects of the more complex models with less computational expense. The SCM "Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC) (Wigley and Raper 2001) 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.

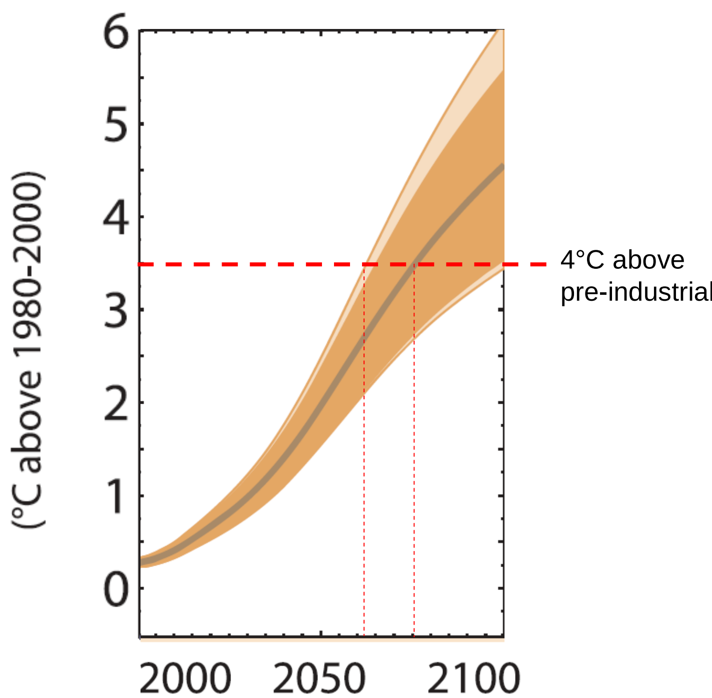

Figure 7. Projections of global warming relative to pre-industrial for the A1FI emissions scenario, using an ensemble of simulations with the MAGICC simple climate model tuned against the AR4 GCMs and C4MIP coupled climate-carbon cycle models. The horizontal red dashed line marks warming of 3.5°C relative to 1980-2000, which represents 4°C relative to pre-industrial (IPCC 2007b) (Reproduced from Meehl et al, 2007). Copyright IPCC, 2007.

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.

4. New projections of climate change under the A1FI scenario

4.1 Overview of methodology

The scenario with the highest emissions (A1FI) was not examined with GCMs in 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 impacts outcomes.

This section aims to provide more complete information regarding the upper end of the range of global warming, focussing 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 simple climate models 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[3]" scenario. This expert-assessment approach is compatible with the approach used by 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 (Gordon et al, 2000; Collins et al. 2009) to project possible climate changes over the 21st Century following the A1FI scenario (which gives the highest emissions of the 6 SRES marker scenarios). We refer to this set of variants of HadCM3 as HadCM3-QUMP ("Quantifying Uncertainties in Model Projections": Murphy et al, 2004). 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 (Murphy et al 2004, Collins et al, 2006; Collins et al, *submitted*). The parameter perturbations are designed to allow the ensemble to cover a wide range of behaviours of the model (Webb et al., 2006), 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 IPCC AR4 (commonly referred to as the AR4 ensemble) (Meehl et al, 2007). This used 23 GCMs[4] from climate modelling centres worldwide. The AR4 ensemble was not applied to the

---

[3] 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.
[4] 24 GCMs are shown in AR4, but one was later withdrawn from the model data archive.

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.

A small number of un-calibrated ensemble members such as 17 or 23 is 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 emission scenarios (Murphy et al., 2007; 2009). It has not been possible to produce such probabilistic estimates for this report, 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.

4.2. 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[5] of global warming in response to this scenario, the mean, median and minimum of the HadCM3-QUMP ensemble projections were approximately 25% higher than those projected by the AR4 ensemble, and the maximum was 8% higher (Table 1).

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.

Ensemble	No. of members	Projected warming by 2090s relative to 1861-1890 (°C)			
		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

[5] 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. 21 of the 23 AR4 simulations projected warming between the minimum and maximum projected by the full set of 17 HadCM3-QUMP simulations.

4.3 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 (see Figure 2 and Table 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 IPCC AR4, Meehl et al (2007) used a simple climate model 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 section 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 which are outliers in the distribution and hence we caution against attaching too high a likelihood to the ensemble member which 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 the next section.

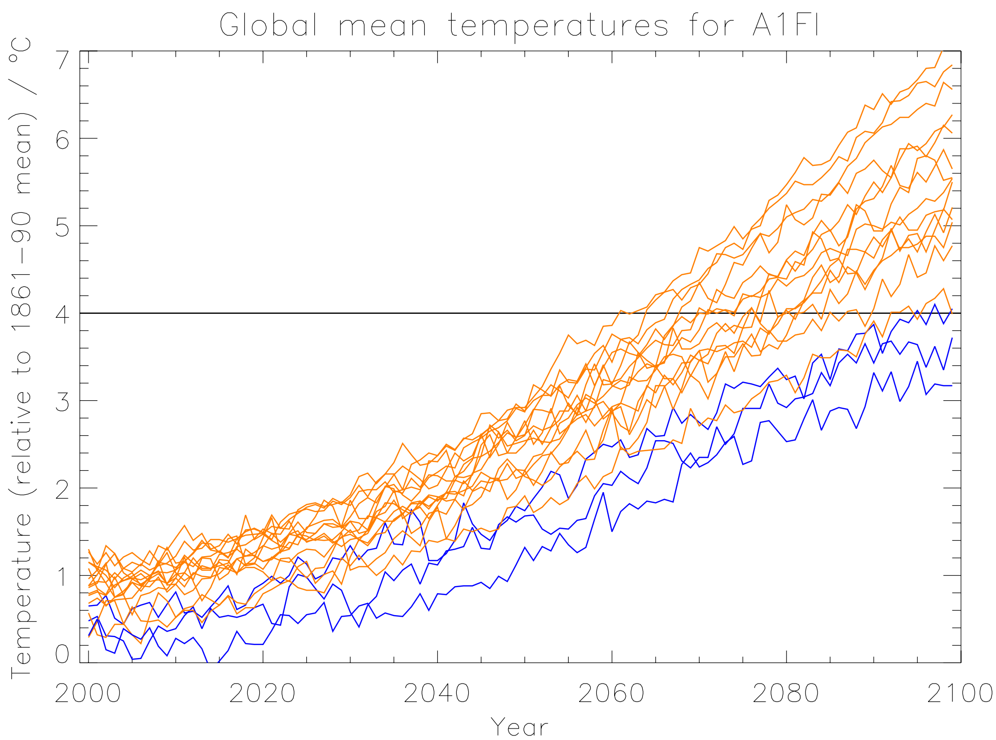

Figure 8. Projections of global mean temperature rise relative to 1861-1890 with the HadCM3-QUMP perturbed physics GCM ensemble driven by the standard A1FI concentration scenario. Ensemble members which project a warming of 4°C or more by the 2090s are shown in orange, and the remainder are shown in 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 4.0°C greater than the mean of 1861-1890.

HadCM3 Qump A1FI			
Year @ 4ºC	T 2090s / ºC	Year @ 4ºC	T 2090s / ºC
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

4.4. Projected warming including uncertainties in atmospheric response and carbon cycle feedbacks: an estimate using a simple climate model

Although a number of GCM-based coupled climate-carbon cycle models now exist, these have not yet been used to project climate change resulting from the A1FI scenario. 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 IPCC AR4 by Meehl et al (2007) but with the climate sensitivity tuned against the HadCM3-QUMP GCM ensemble. Following Meehl et al (2007), we tuned MAGICC against the C4MIP models to represent of strengths of carbon cycle. We carried out an ensemble of 729 simulations with MAGICC-tuned in this way, and excluded the highest and lowest 10% 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 the 2090s, with 4°C being reached at approximately 2070. The 10th and 90th percentiles encompassed a range of warming of 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 (2007) with MAGICC tuned against the AR4 ensemble. The best estimate for reaching 4°C global warming relative to pre-industrial is approximately 5 years earlier in our ensemble, consistent with HadCM3-QUMP ensemble exhibiting a systematically higher climate sensitivity than the AR4 ensemble as demonstrated with our comparison using the A1B scenario.

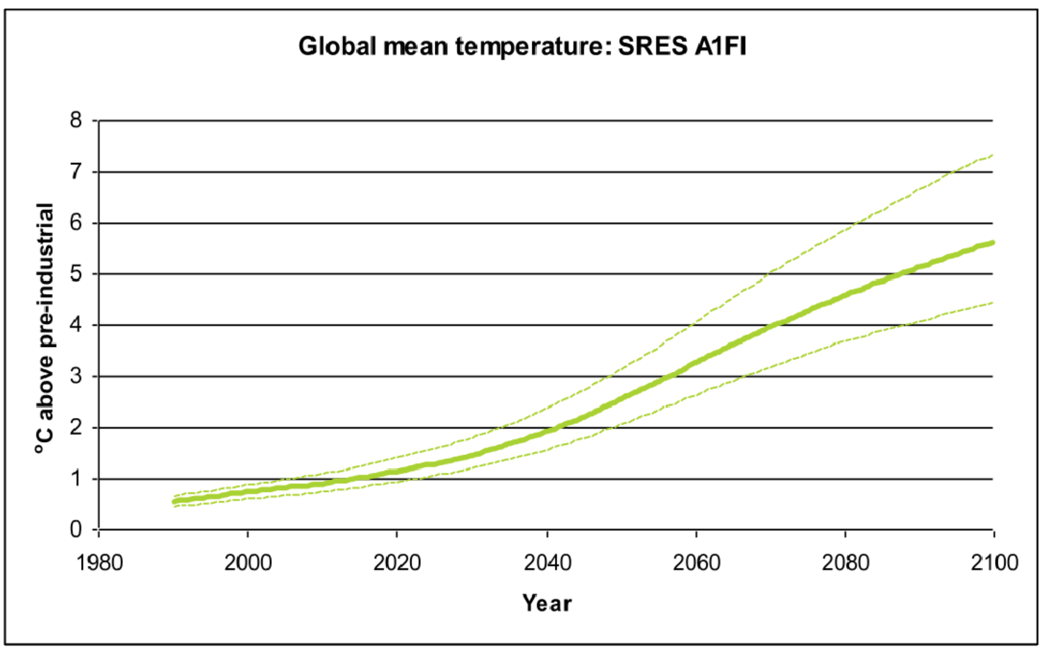

Figure 9. Global mean temperature change over the 21st Century relative to pre-industrial, under the A1FI emissions scenario, projected with an ensemble of 729 simulations with the MAGICC simple climate model tuned against the HadCM3-QUMP and C4MIP ensembles. The central thick green line shows the median projection, and the two dashed green lines show the 10th and 90th percentiles of the frequency distribution of the 729 MAGICC experiments.

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 GHG 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 simple climate model, along with existing results presented in 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 (Table 3). A temperature rise of 4°C could be reached in the 2070s as a best estimate, with the earliest plausible date for reaching 4°C being approximately 2060 if carbon cycle feedbacks are strong.

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 which is consistent with that used in assessment reports such as the IPCC AR4. A further step that needs to be undertaken is to quantify the uncertainty using statistical techniques which take into account all the available modelling, understanding and observational evidence for climate change (e.g. Murphy et al., 2009).

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 at 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.

Source	Warming by 2090s	Warming by 2090s (range)	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 standard deviation)	2075	2065 – 2100 (±1 standard deviation)
IPCC AR4 expert assessment	4.5 (GCM mean)	2.9 – 6.9 (Likely range)	Not reported	Not reported
HadCM3-QUMP	5.1 (mean)	3.1 – 6.6 (full range)	2076	2061 – after 2100 (full range)
MAGICC tuned to HadCM3 and C4MIP	5.5 (median)	4.3 – 7.2 (10^{th} – 90^{th} %)	2070	2058 – 2088 (10^{th} – 90^{th} %)

References

Collins, M., Booth, B.B.B., Harris, G.R., Murphy, J.M., Sexton, D.M.H. and Webb, M.J. (2006). Towards quantifying uncertainty in transient climate change. *Clim. Dyn.*, 27, 127-147.

Collins, M., Booth, B.B.B., Bhaskaran, B., Harris, G., Murphy, J.M., Sexton, D.M.H., Webb, M.J. (2009). A comparison of perturbed physics and multi-model ensembles: Model errors, feedbacks and forcings. *Climate Dynamics*, submitted.

Cox, P.M., R.A.Betts, C.D.Jones, S.A.Spall and I.J.Totterdell (2000) Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model. *Nature*, 408, 184-187.

Cramer, W., A. Bondeau, F.I. Woodward, I.C. Prentice, R.A. Betts, V. Brovkin, P.M. Cox, V. Fisher, J.A. Foley, A.D. Friend, C. Kucharik, M.R. Lomas, N. Ramankutty, S. Stitch, B. Smith, A. White, and C. Young-Molling (2001) Global response of terrestrial ecosystem structure and function to CO_2 and climate change: Results from six dynamic global vegetation models. *Global Change Biol*., 7(4), 357-374.

Denman, K.L., G. Brasseur, A. Chidthaisong, P. Ciais, P.M. Cox, R.E. Dickinson, D. Hauglustaine, C. Heinze, E. Holland, D. Jacob, U. Lohmann, S Ramachandran, P.L. da Silva Dias, S.C. Wofsy and X. Zhang (2007). Couplings Between Changes in the Climate System and Biogeochemistry. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Friedlingstein P., Cox P. M., Betts R. A., Bopp L., von Bloh W., Brovkin V., Cadule P., Doney S., Eby M., Fung I., Bala G., John J., Jones C. D., Joos F., Kato T., Kawamiya M., Knorr W., Lindsay K., Matthews H. D., Raddatz T., Rayner P., Reick C., Roeckner E., Schnitzler K. G., Schnur R., Strassmann K., Weaver A. J., Yoshikawa C. and Zeng N., 2006. Climate carbon-cycle feedback analysis: results from the C4MIP model intercomparison, J. Climate, 19 (14), 3337-3353

Gordon, C., C.Cooper, C.A.Senior, H.Banks, J.M.Gregory, T.C.Johns, J.F.B.Mitchell and R.A.Wood (2000) The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Clim. Dyn*., 16, 147-168

IPCC (2007a) *Climate change 2007: The physical science basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, et al., eds. Cambridge, UK, and New York: Cambridge University Press. www.ipcc.ch.

IPCC (2007b) *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* [Core writing team, Pachauri, R.K. and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.

.

Jones, C.D. and P.M. Cox (2005) On the significance of atmospheric CO2 growth rate anomalies in 2002-2003, *Geophys. Res. Lett.,* 32, LI14816, doi:10.1029/2005GL023027

Jones, C.D., P.M. Cox and C. Huntingford (2007) The atmospheric CO2 airborne fraction and carbon cycle feedbacks. Conference proceedings from The 50th Anniversary of the Global Carbon Dioxide Record Symposium, Kona, Hawaii, Novermber 2007

Joos, F., I. C. Prentice, S. Sitch, R. Meyer, G. Hooss, G.-K. Plattner, S. Gerber, and K. Hasselmann, 2001: Global warming feedbacks on terrestrial carbon uptake under the Intergovernmental Panel on Climate Change (IPCC) emission scenarios. *Global Biogeochem. Cycles,* 15**,** 891–907

Knorr, W (2009) Is the airborne fraction of anthropogenic CO_2 emissions increasing? *Geophys. Res. Lett.* 36, L21710, doi: 10.1029/2009GL040613

Le Quéré, C., M. Raupach, J.G. Canadell, G. Marland, L. Bopp, P. Ciais, T.J. Conway, S.C. Doney, R.A. Feely, P. Foster, P. Friedlingstein, K. Gurney, R.A., Houghton, J.I. House, C. Huntingford, P.E. Levy, M.R. Lomas, J. Majkut, N. Metzl, J.P. Ometto, G.P. Peters, I.C. Prentice, J.T. Randerson, S.W. Running, J.L. Sarmiento, U. Schuster, S. Sitch, T. Takahashi, N. Viovy, G. van der Werf and F.I. Woodward. (2009) Trends in the sources and sinks of carbon dioxide. *Nature Geoscience*, 2, doi:10.1038/NGEO689

Leggett, J.A. and Logan, J. (2008) Are Carbon Dioxide Emissions Rising More Rapidly Than Expected?" CRS Report RS22970, Congressional Research Service, Washington DC (October 17 2008 version).

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver and Z.-C. Zhao, 2007: Global Climate Projections. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Murphy, J.M., D.M.H. Sexton, D.N. Barnett, G.S. Jones, M.J. Webb, M. Collins, D.A. Stainforth (2004) Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature*, 430, 768-772

Murphy, JM, Booth, BBB, Collins, M, Harris, GR, Sexton, D and Webb, M. (2007). A methodology for probabilistic predictions of regional climate change from perturbed physics ensembles. *Phil. Trans. Roy. Soc. A*, 365 (1857), 1993-2028.

Murphy, J.M. Sexton, D., Jenkins, G., Boorman, P., Booth, B., Brown, K., Clark, R., Collins, M., Harris, G. and, Kendon, E. (2009). UKCP09 Climate change projections. ISBN 978-1-906360-02-3.

Nakićenović N., Alcamo J., Davis G., de Vries B., Fenhann J., Gaffin S., Gregory K., Grübler A., Jung T. Y., Kram T., La Rovere E. L., Michaelis L., Mori S., Morita T., Pepper W., Pitcher H., Price L., Riahi K., Roehrl A., Rogner H.-H., Sankovski A., Schlesinger M., Shukla P., Smith S., Swart R., van Rooijen S., Nadejda V., Dadi, Z., 2000. IPCC Special report on emissions scenarios. Cambridge University Press, Cambridge, United Kingdom, and New York, NY. www.ipcc.ch.

van Vuuren, D., and K. Riahi. (2008). Do recent emission trends imply higher emissions forever? *Clim. Change*, 91, 237-248.

Webb, M. J., C. A. Senior, D. M. H. Sexton, W. J. Ingram, K. D. Williams, M. A. Ringer, B. J. McAvaney, R. Colman, B. J. Soden, R. Gudgel, T. Knutson, S. Emori, T. Ogura, Y. Tsushima, N. Andronova, B. Li, I. Musat, S. Bony, K. E. Taylor (2006). On the contribution of local feedback mechanisms to the range of climate sensitivity in two GCM ensembles. *Clim. Dyn.*. 27, 17–38.

Wigley, T.M.L., and S.C.B. Raper (2001). Interpretation of high projections for global-mean warming. *Science*, 293, 451–454.