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Variation in the climatic response to SRES emissions scenarios in integrated assessment models

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Abstract Integrated assessment models (IAMs) have commonly been used to understand the relationship between the economy, the earth's climate system and climate impacts. We compare the IPCC simulations of CO_2 concentration, radiative forcing, and global mean temperature changes associated with five SRES 'marker' emissions scenarios with the responses of three IAMs—DICE, FUND and PAGE—to these same emission scenarios. We also compare differences in simulated temperature increase resulting from moving from a high to a low emissions scenario. These IAMs offer a range of climate outcomes, some of which are inconsistent with those of IPCC, due to differing treatments of the carbon cycle and of the temperature response to radiative forcing. In particular, in FUND temperatures up until 2100 are relatively similar for the four emissions scenarios, and temperature reductions upon switching to lower emissions scenarios are small. PAGE incorporates strong carbon cycle feedbacks, leading to higher CO_2 concentrations in the twenty-second century than other models. Such IAMs are frequently applied to determine 'optimal' climate policy in a cost–benefit approach. Models such as FUND which show smaller temperature responses to reducing emissions than IPCC simulations on comparable timescales will underestimate the benefits of emission reductions and hence the calculated 'optimal' level of investment in mitigation.

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1 Introduction

Integrated assessment models have commonly been used to understand the relationship between the economy, the earth's climate system and climate impacts. Goodess et al. (2003) presents a detailed review of these models, categorizing them into models of the 'cost–benefit' type, which contain a detailed treatment of economics and relatively simple representations of climate and impacts, and biophysical impact models which have much more detailed information about physical climate changes and impacts and a relatively simple representation of the economic system, often without any economic valuation of impacts. All of these integrated models, and particularly those of the cost–benefit type, necessarily contain a simplified representation of the climate system. To ensure that policy advice coming from these models incorporates current knowledge about climate change science, it is important that these simplified representations adequately reflect the behaviour of more complex climate models (GCMs). In this paper we compare how three well known and broadly used examples of these integrated models simulate the carbon dioxide concentration, radiative forcing, and global mean temperature change resulting from emissions trajectories corresponding to five SRES marker scenarios (Nakicenovich et al. 2000). In doing so we have isolated the climate and carbon cycle components of the models in order to drive them with a consistent set of SRES emissions scenarios. We focus on two models of the cost–benefit type (DICE, FUND) because these have frequently been applied in the literature to recommend 'optimal' climate policies (e.g. Nordhaus 1991, 2006; Nordhaus and Boyer 2000; Tol 1999). We also include in our study the PAGE model (Plambeck and Hope 1997; Hope 2006) because of its application in the Stern review (Stern 2007). PAGE has also more recently been used in optimization applications (e.g., Hope 2009). We compare the climate outcomes of these models with the summaries of GCM outputs contained in Solomon et al. (2007) (hereafter referred to as IPCC AR4) and Houghton et al. (2001) (hereafter refereed to as IPCC TAR), which detail the likely range of climatic responses to the five SRES emissions scenarios. These are based on a multi-model ensemble (of 21 models in IPCC AR4) of simulations, which are combined into an unweighted multi-model mean and likely range. 'Likely' in the IPCC context means, "with a probability greater than 66%". In carrying out the study, the latest versions of model code available at the time were used, specifically DICE2007, PAGE2002, and FUND2.8, in addition to an older version of DICE (DICE99).

2 Overview of carbon cycle and climate representations in the models

The modeled response of the climate system to reductions in greenhouse gas emissions is a key determinant of the benefits of climate policies explored in the three models. Here we provide an overview of how this response is calculated in the three models. We provide here a summary of (i) representation of equilibrium climate sensitivity, i.e. the long term temperature increase associated with an increase in greenhouse gas concentrations in the atmosphere (ii) what affects the rate at which temperatures reach this level (iii) model structure including the representation of feedbacks between climate change and the carbon cycle, which affects the fraction of emissions from human activities that remains in the atmosphere and (iv) treatment of non-CO_2 greenhouse gases and aerosols.

(i) *Equilibrium climate sensitivity*. IPCC AR4 presented a "likely" range for climate sensitivity (i.e. estimated a 66% probability that climate sensitivity lies in this range) of 2–4.5°C, with a best estimate of 3°C. In DICE, one value for climate sensitivity is specified under standard assumptions (3°C in DICE2007, increased from 2.91°C in previous versions). In PAGE, a triangular probability distribution is specified with a minimum value of 1.5°C, a most likely value of 2.5°C, and a maximum value of 5°C, yielding a mean of 3°C. In FUND, a single value for climate sensitivity of 2.5°C is used. Tol (2005) explores the implications of uncertainties in the sectoral impacts of climate damages in FUND, but does not explore uncertainties in the model's representation of the climate system itself. Thus, model values fall within the IPCC range. However, uncertainty is better captured by the PAGE distribution.

(ii) *Transient temperature response.* This is influenced by equilibrium climate sensitivity, but also by other factors, and different models take different approaches. FUND and PAGE employ a "half-life" term that governs the rate of temperature increase towards its equilibrium level (determined by radiative forcing). In FUND it is set to 50 years, whilst in PAGE the most likely value is 50 years with a minimum value of 25 years and a maximum of 75 years. DICE employs a simple representation of heat uptake by the ocean that affects the rate of atmospheric temperature increase.

(iii) *Structure and representation of carbon cycle feedbacks.* Since around half of CO_2 emissions from human activities are rapidly removed from the atmosphere by oceans and terrestrial ecosystems, the representation of these key components of the carbon cycle in the models is important. Modelling studies have projected a weakening of these natural carbon sinks over time in response to climate change but the strength of this feedback is uncertain (Friedlingstein et al. 2006). This process is termed the carbon cycle feedback.

In the DICE99 and DICE2007 models the major reservoirs (or 'boxes') of carbon in the climate system are represented by a two-box model (representing the atmosphere/upper ocean and the deep ocean, based on Schneider and Thompson (1981)). The carbon cycle itself is represented by a three-reservoir model representing the atmosphere, the upper ocean and biosphere, and the deep ocean, with flows between reservoirs calibrated to existing carbon-cycle models (Nordhaus and Boyer 2000; Nordhaus 2008). However, carbon cycle feedback processes are not included, and so there are fixed rates of flow of carbon between the ocean, atmosphere and biosphere.

In FUND, the time evolution of CO_2 follows a 5 box model taken from Maier-Reimer and Hasselmann (1987), with parameters set as in Hammitt et al. (1992). This is based on a linear impulse–response function for CO_2, parameterized to include ocean sinks, but not the terrestrial carbon sink or any climate-change induced modification of the carbon cycle. 13% of total emissions remain forever in the atmosphere, while 10% is—on average—removed in 2 years. Again, carbon cycle feedback processes are not included.

The PAGE model is not based upon a box-model formulation, but it does explicitly represent atmospheric carbon. A constant fraction of emissions is removed from the atmosphere immediately, and another fraction is removed

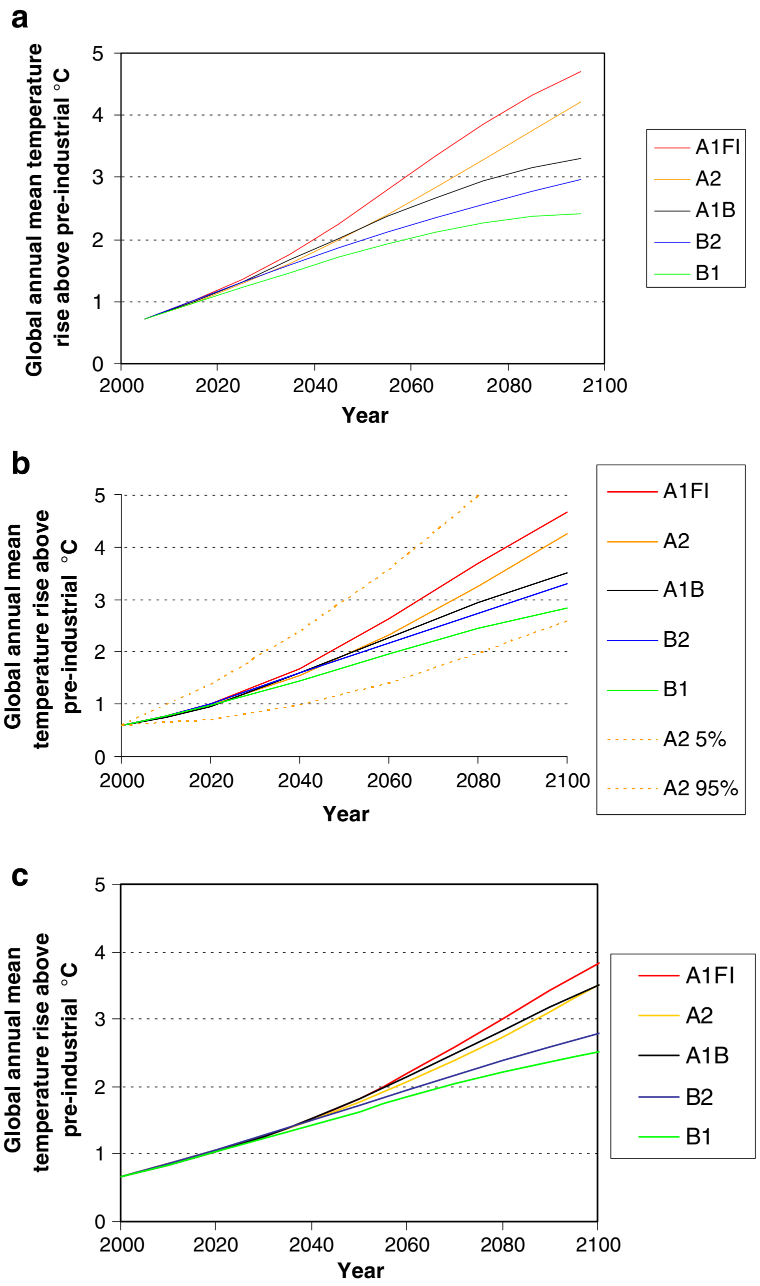


Fig. 1 Annual global mean temperature rise relative to pre-industrial in SRES marker scenarios in **a** DICE2007 simulations, **b** PAGE simulations (mean values only, except for A2 where 5–95% range is shown), **c** FUND simulations

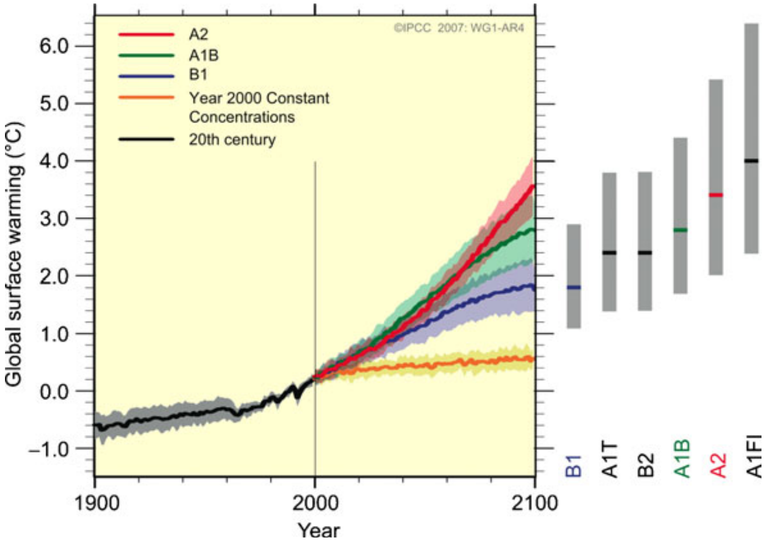


Fig. 2 Taken from Solomon et al. (2007). Figure SPM.5. *Solid lines* are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the twentieth century simulations. *Shading* denotes the ±1 standard deviation range of individual model annual averages. The *orange line* is for the experiment where concentrations were held constant at year 2000 values. The *grey bars* at right indicate the best estimate (*solid line within each bar*) and the likely range assessed for the six SRES marker scenarios. The assessment of the best estimate and likely ranges in the *grey bars* includes the AOGCMs in the *left part* of the figure, as well as results from a hierarchy of independent models and observational constraints

at an exponential rate similar to that used in FUND. PAGE also includes a ‘natural emissions’ term that increases as a function of temperature, to represent carbon cycle feedbacks. PAGE is set up in a probabilistic spreadsheet format which enables the user to find the sensitivity of outputs to the input assumptions. Regional temperature rise is calculated by a simple formulation of radiative forcing, sulphate aerosol forcing and carbon cycle feedback which

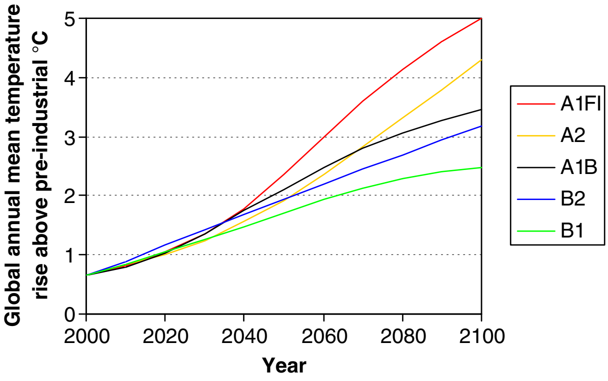
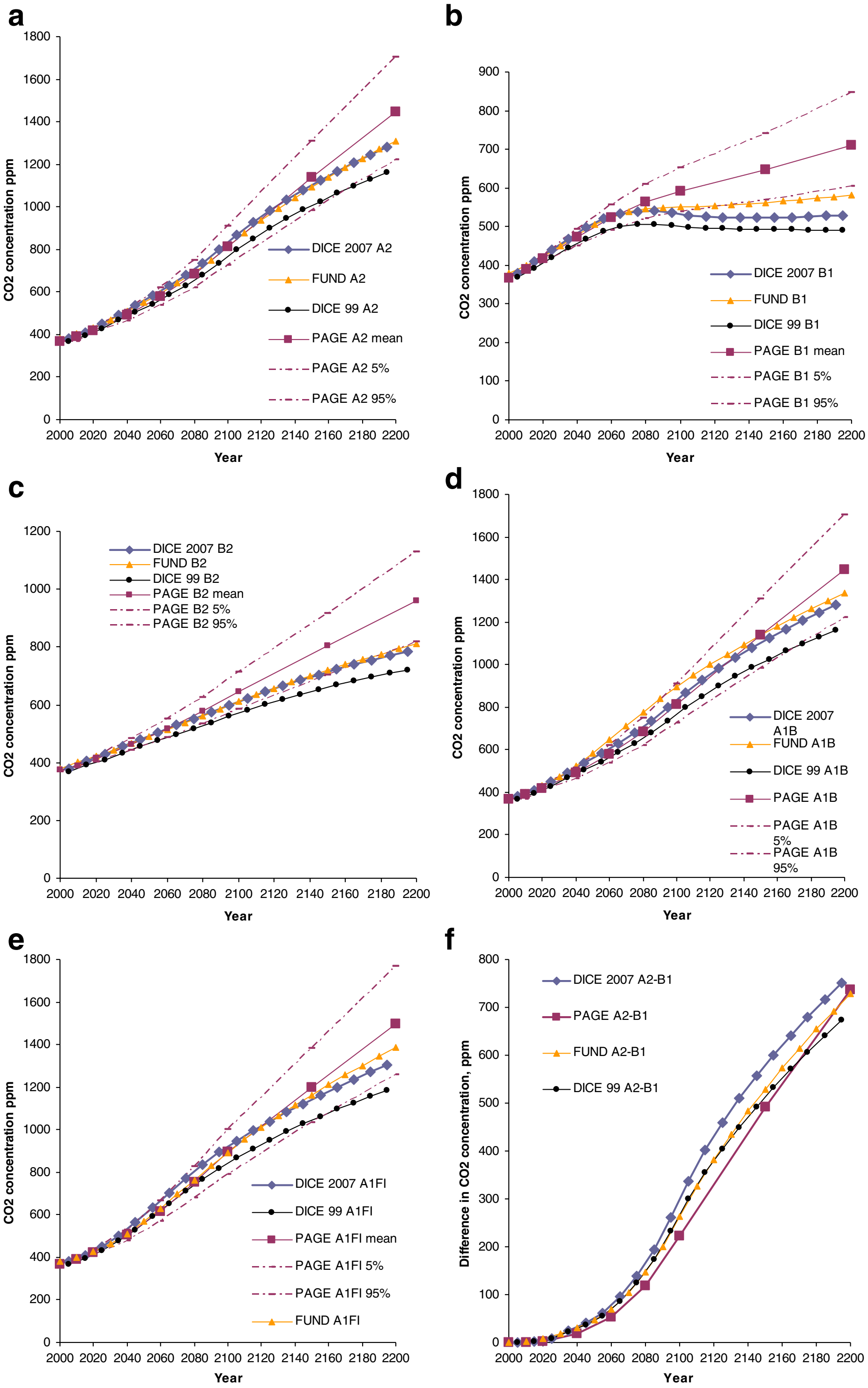


Fig. 3 Global annual mean temperature response to the emissions of the SRES scenarios as simulated in IPCC TAR (Houghton et al. 2001) Re-plotted from data provided by the University of East Anglia


a
CO2 concentration ppm
0
200
400
600
800
1000
1200
1400
1600
1800
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
DICE 2007 A2
FUND A2
DICE 99 A2
PAGE A2 mean
PAGE A2 5%
PAGE A2 95%
b
CO2 concentration ppm
0
100
200
300
400
500
600
700
800
900
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
DICE 2007 B1
FUND B1
DICE 99 B1
PAGE B1 mean
PAGE B1 5%
PAGE B1 95%
c
CO2 concentration ppm
0
200
400
600
800
1000
1200
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
DICE 2007 B2
FUND B2
DICE 99 B2
PAGE B2 mean
PAGE B2 5%
PAGE B2 95%
d
CO2 concentration ppm
0
200
400
600
800
1000
1200
1400
1600
1800
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
DICE 2007 A1B
FUND A1B
DICE 99 A1B
PAGE A1B
PAGE A1B 5%
PAGE A1B 95%
e
CO2 concentration ppm
0
200
400
600
800
1000
1200
1400
1600
1800
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
DICE 2007 A1FI
DICE 99 A1FI
PAGE A1FI mean
PAGE A1FI 5%
PAGE A1FI 95%
FUND A1FI
f
Difference in CO2 concentration, ppm
0
100
200
300
400
500
600
700
800
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
DICE 2007 A2-B1
PAGE A2-B1
FUND A2-B1
DICE 99 A2-B1

◀ **Fig. 4** **a** CO_2 concentration trajectories in the A2 scenario across the three models. **b** CO_2 concentration trajectories in the B1 scenario across the three models. **c** CO_2 concentration trajectories in the B2 scenario across the three models. **d** CO_2 concentration trajectories in the A1B scenario across the three models. **e** CO_2 concentration trajectories in the A1FI scenario across the three models. **f** CO_2 concentration differences between the A2 and B1 scenarios as a function of time across the three models

has uncertain parameters that are varied strongly in the model to allow for uncertainties.

(iv) *Treatment of non-CO_2greenhouse gases*. In DICE99 and DICE2007, radiative forcing from CO_2 is endogenously calculated in the model, with radiative forcing from other GHGs specified exogenously. In FUND, methane and nitrous oxide emissions are specified exogenously, sulphur hexafluoride depend on GDP and GDP per capita, and sulphur dioxide emissions depend on population growth, per capita income and the level of decarbonisation. These gases (apart from sulphur dioxide, for which emissions are used) are taken up in the atmosphere, and then geometrically depleted, with radiative forcing described as in Shine et al. (1990). PAGE takes (a) exogenously specified emissions of CO_2, methane, and SF6 with forcing from other gases defined exogenously, and simulates (b) the resultant increase in radiative forcing (c) cooling from sulphate aerosols (d) regional temperature changes. Detailed model equations may be found in Hope (2006).

3 Comparison of model outputs

The models were all driven using the standard emission data for the SRES marker scenarios (available at http://sres.ciesin.org/final_data.html), and then extending the scenarios to 2200 assuming that emissions remain constant after 2100. Amongst the models studied here, DICE uniquely treats radiative forcing from all non-CO_2 greenhouse gas emissions as exogenous. Hence to ensure consistency in our cross-model comparison we drove both versions of DICE with the SRES CO_2 emissions and an additional forcing for the non-CO_2 gases. We obtained this additional forcing from the non-CO_2 radiative forcing figures output by the PAGE model in our study. The FUND model is designed to initialize in the year 1950, and we ran it in this manner in these scenarios, but also utilized the PAGE non-CO_2 forcings from the year 2000 onwards.[1] Thus any intermodel differences that we find are due to differing representations of the carbon cycle and/or the relationship between radiative forcing and temperature, rather than due to any difference in CO_2 emissions or radiative forcing of non-CO_2 gases. In making comparisons of temperature outcomes it was necessary to correct for the use of different baselines. We assumed a temperature

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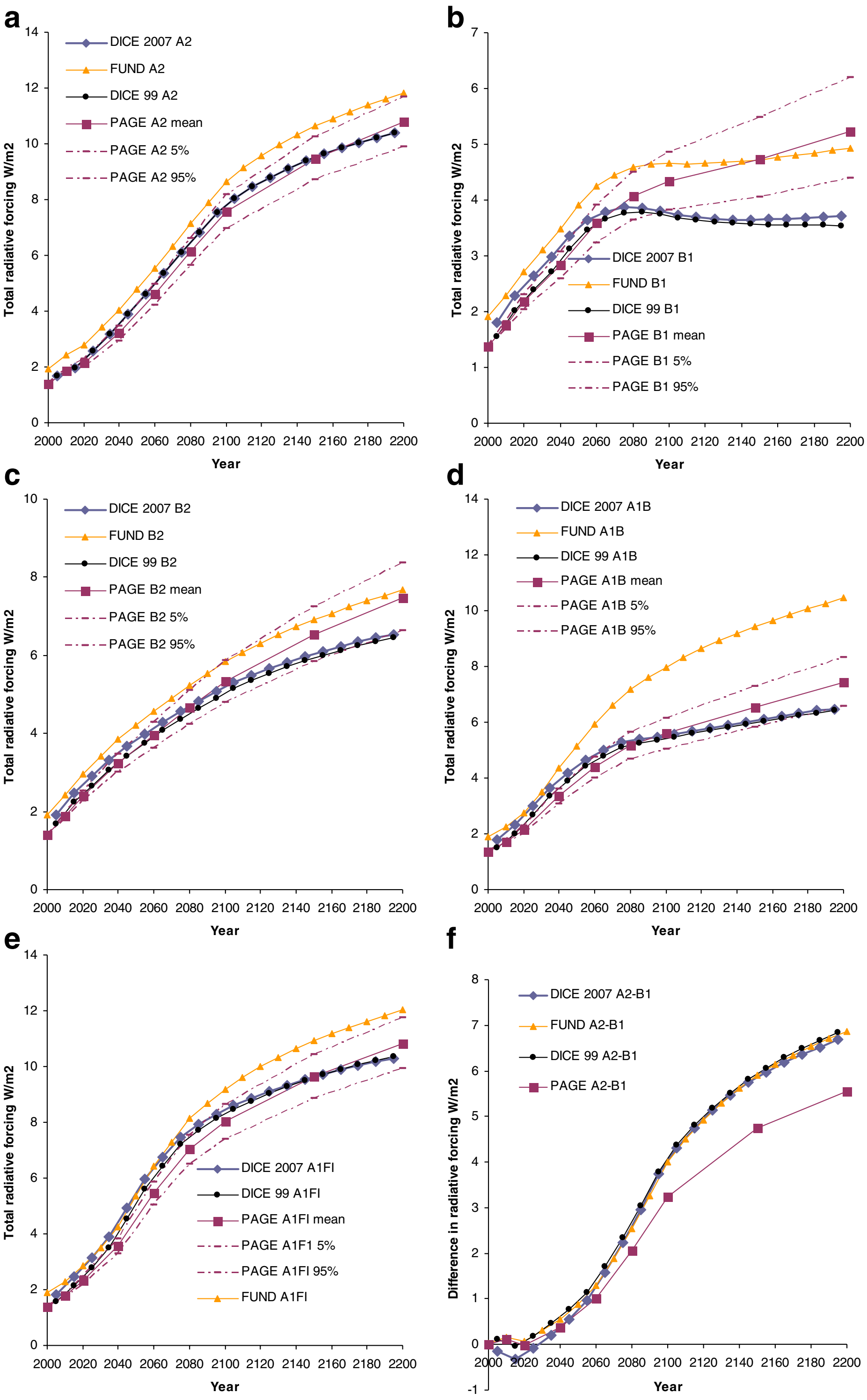
[1] Since FUND requires the forcing of sulphates to be relative to that of 1950, we subtracted this forcing from the PAGE values before use. In FUND, when anthropogenic emissions of SO_2 are zero the (negative) forcing from sulphate was 0.73 W/m^2, thus providing the figure to correct the PAGE forcings by.


a
DICE 2007 A2
FUND A2
DICE 99 A2
PAGE A2 mean
PAGE A2 5%
PAGE A2 95%
Total radiative forcing W/m2
0
2
4
6
8
10
12
14
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
b
DICE 2007 B1
FUND B1
DICE 99 B1
PAGE B1 mean
PAGE B1 5%
PAGE B1 95%
Total radiative forcing W/m2
0
1
2
3
4
5
6
7
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
c
DICE 2007 B2
FUND B2
DICE 99 B2
PAGE B2 mean
PAGE B2 5%
PAGE B2 95%
Total radiative forcing W/m2
0
2
4
6
8
10
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
d
DICE 2007 A1B
FUND A1B
DICE 99 A1B
PAGE A1B mean
PAGE A1B 5%
PAGE A1B 95%
Total radiative forcing W/m2
0
2
4
6
8
10
12
14
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
e
DICE 2007 A1FI
DICE 99 A1FI
PAGE A1FI mean
PAGE A1F1 5%
PAGE A1FI 95%
FUND A1FI
Total radiative forcing W/m2
0
2
4
6
8
10
12
14
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year
f
DICE 2007 A2-B1
FUND A2-B1
DICE 99 A2-B1
PAGE A2-B1
Difference in radiative forcing W/m2
-1
0
1
2
3
4
5
6
7
8
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200
Year

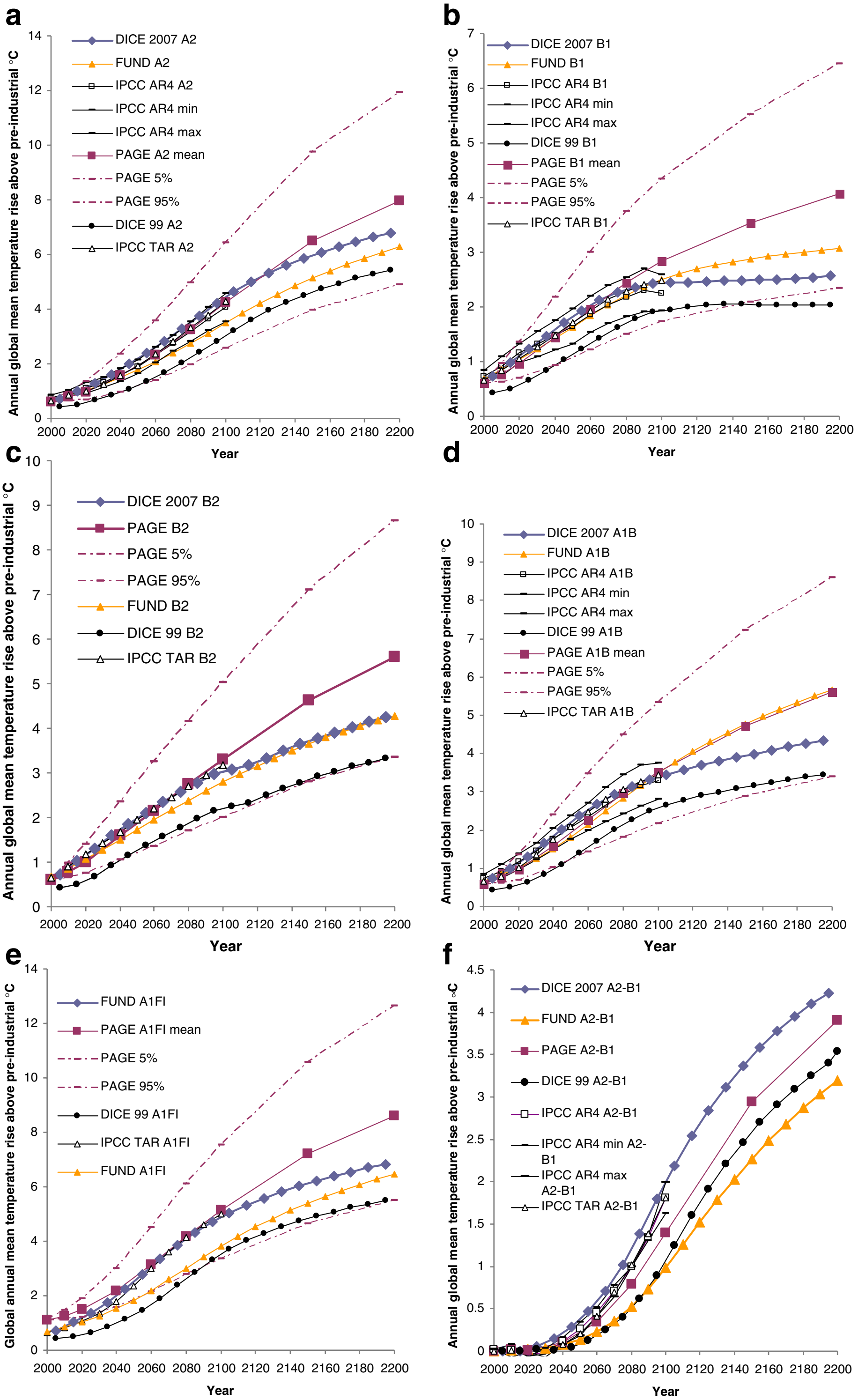
◀ **Fig. 5** **a** Radiative forcing trajectories in the A2 scenario across the three models, showing 5–95% ranges from PAGE. **b** Radiative forcing trajectories in the B1 scenario across the three models. **c** Radiative forcing trajectories in the B2 scenario across the three models. **d** Radiative forcing trajectories in the A1B scenario across the three models. **e** Radiative forcing trajectories in the A1FI scenario across the three models. **f** Radiative forcing differences between the A2 and B1 scenarios as a function of time across the three models

change of 0.5C between pre-industrial times and the mean 1980–2000 (i.e. 1990) climate (Solomon et al. 2007). We also corrected the FUND radiative forcing outputs to a pre-industrial baseline by utilizing the SO_2 forcing in 1950.

In the case of DICE, the code is freely available and the DICE delta version 8 (DICE2007) of the code was used for this study (http://www.econ.yale.edu/~nordhaus/DICE2007_programs/). We also included in the comparison the previous version, DICE99 (Nordhaus and Boyer 2000). The standard version 1.4 of PAGE2002 was used (Hope 2006).

FUND2.8 may be downloaded from http://www.fnu.zmaw.de/FUND.5679.0.html. The climate and carbon cycle representations in FUND 2.8 are the same as those in version 1.6, described in Tol (1999, 2001, 2002). The climate and carbon cycle code was isolated from the FUND model by extracting all the relevant climate and carbon cycle functions to a spreadsheet. To test the spreadsheet version of the FUND climate and carbon cycle code, concentrations, radiative forcing and temperature outcomes from the spreadsheet version were compared with an original FUND run (using TurboPascal 7.0), using the same emissions as input. In addition a spreadsheet version of FUND corresponding to version 2.8, was provided by the code author, Prof. Tol, for which we are grateful, and used for supplementary testing. It should be noted that after completion of our study a new version FUND3.5 (Anthoff and Tol 2009; Tol 2009) became available with updated climate and carbon cycle modules. In this version, the half-life term has been changed to a triangular distribution with a mean of 75 years and a minimum and maximum of 25 and 125 years, respectively. Furthermore, the calculation of radiative forcing has been revised according to the IPCC TAR (Ramaswamy et al. 2001), and a gamma distribution for climate sensitivity is used, which has a mean of 2.85°C and a most likely value of 2.5°C. Finally, a representation carbon cycle feedbacks from terrestrial ecosystems have also been included. See Tol (2009) for further information.

Figure 1a–c shows the simulations of evolving temperature relative to pre-industrial times across the five SRES scenarios in each of the three integrated assessment models (DICE2007, PAGE's mean values, and FUND2.8). These may be compared with Figs. 2 and 3 which show the IPCC AR4 and IPCC TAR simulations respectively (note that IPCC AR4 results do not include simulations for A1FI or B2 scenarios). Comparing now across models for each of five SRES scenarios, Fig. 4a to e compare the concentration projections, Fig. 5a to e the radiative forcing projections, and Fig. 6a to e the global mean temperature change projections relative to pre-industrial times. PAGE is the only one of the three models which takes a probabilistic approach to the projection of climate change, and hence mean, 5 and 95% ile ranges of outputs from PAGE are shown. Figure 6a to d include also temperature projections from the IPCC TAR and AR4 (mean and likely minimum and maximum).


a
Annual global mean temperature rise above pre-industrial °C
Year
DICE 2007 A2
FUND A2
IPCC AR4 A2
IPCC AR4 min
IPCC AR4 max
PAGE A2 mean
PAGE 5%
PAGE 95%
DICE 99 A2
IPCC TAR A2
b
Annual global mean temperature rise above pre-industrial °C
Year
DICE 2007 B1
FUND B1
IPCC AR4 B1
IPCC AR4 min
IPCC AR4 max
DICE 99 B1
PAGE B1 mean
PAGE 5%
PAGE 95%
IPCC TAR B1
c
Annual global mean temperature rise above pre-industrial °C
Year
DICE 2007 B2
PAGE B2
PAGE 5%
PAGE 95%
FUND B2
DICE 99 B2
IPCC TAR B2
d
Annual global mean temperature rise above pre-industrial °C
Year
DICE 2007 A1B
FUND A1B
IPCC AR4 A1B
IPCC AR4 min
IPCC AR4 max
DICE 99 A1B
PAGE A1B mean
PAGE 5%
PAGE 95%
IPCC TAR A1B
e
Global annual mean temperature rise above pre-industrial °C
Year
FUND A1FI
PAGE A1FI mean
PAGE 5%
PAGE 95%
DICE 99 A1FI
IPCC TAR A1FI
FUND A1FI
f
Annual global mean temperature rise above pre-industrial °C
Year
DICE 2007 A2-B1
FUND A2-B1
PAGE A2-B1
DICE 99 A2-B1
IPCC AR4 A2-B1
IPCC AR4 min A2-B1
IPCC AR4 max A2-B1
IPCC TAR A2-B1
2000 2020 2040 2060 2080 2100 2120 2140 2160 2180 2200

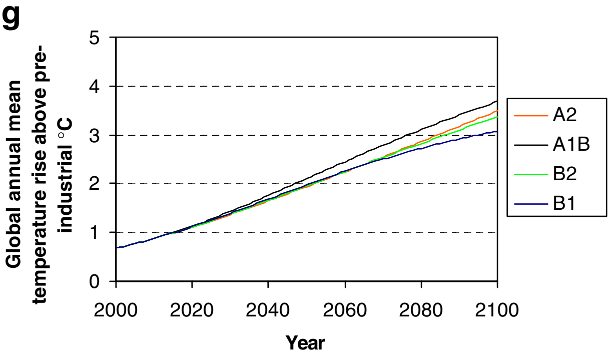
◀ **Fig. 6** **a** Temperature trajectories in the A2 scenario across the three models, showing AR4 trajectories for comparison (minimum and maximum IPCC AR4 ranges are shown, together with 5–95% ranges from the PAGE model). **b** Temperature trajectories in the B1 scenario across the three models. **c** Temperature trajectories in the B2 scenario across the three models. **d** Temperature trajectories in the A1B scenario across the three models. **e** Temperature trajectories in the A1FI scenario across the three models. **f** Temperature differences between the A2 and B1 scenarios as a function of time across the three models, showing AR4 trajectories for comparison. **g** Annual global mean temperature rise relative to pre-industrial in SRES emissions scenarios simulated by the FUND spreadsheet model

4 Discussion

Temperature profiles for the five SRES scenarios in DICE2007, PAGE (mean output), and FUND2.8 (Fig. 1a to c), show that the SRES scenarios provide a range of outputs in terms of radiative forcing, concentration and temperature trajectories. They show the same trends as the IPCC simulations shown in Figs. 2 and 3, with scenarios B1, A1B and A2 resulting in progressively larger changes in global mean temperature, with a large range in possible temperatures by 2100 spanning about 2.5°C.. However, over the twenty-first century and in 2100 the temperature profiles for the five SRES scenarios in FUND2.8 (Fig. 1c) lie significantly closer together than in the other models or in either of the IPCC simulations, with a range in 2100 of only 1.3°C compared with 2.3–2.5°C for the other models (mean values), and approximately 2.2–2.5°C for AR4 and TAR mean values (see also Fig. 7). In FUND2.8, the temperature rise under A1B exceeds that for A2 until 2100, in contrast to the other two models and the IPCC mean results in Figs. 2 and 3, where the outcomes are similar only up until to around 2065, after which greater temperature increases occur in the A2 scenario than the A1B scenario.

Figures 4a–e, 5a–e and 6a–e compare the CO_2 concentration, radiative forcing and temperature outcomes of the various models and where available also show the mean and range of the IPCC and PAGE simulations for the SRES scenarios A1B, B1 and B2. It is clear that the DICE99 model underestimates CO_2 concentrations, radiative forcing and temperature rise compared with the other models, including the DICE2007 model. This is to be expected since the DICE2007 model improves upon

Fig. 6 (continued)



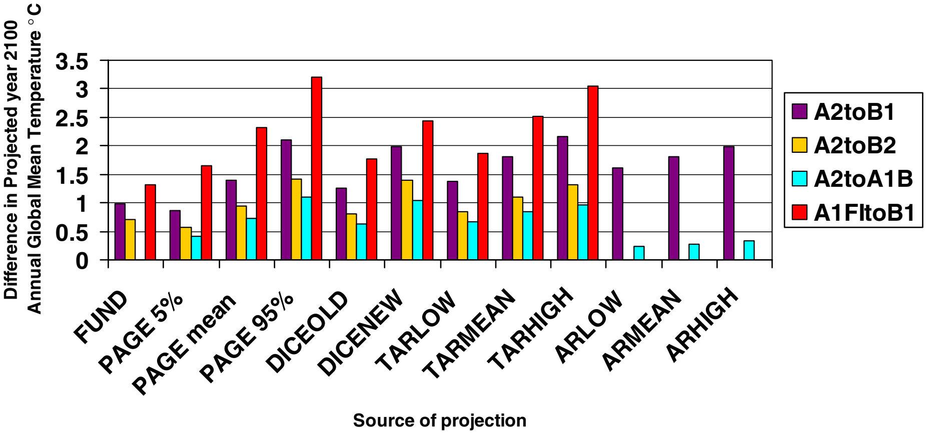


Fig. 7 Year 2100 comparison of inter-scenario differences as simulated by the three models, compared with IPCC TAR and IPCC AR4

the DICE99 climate and carbon cycle model components as outlined in (Nordhaus 2008), mainly through updating the value of climate sensitivity to a higher figure and by tuning the carbon cycle to match the MAGICC model as used in IPCC TAR (Houghton et al. 2001, Ch 10).

Considering firstly CO_2 concentrations (Fig. 4a–e), the models diverge after 2100, with PAGE mean value showing higher CO_2 concentrations than the other models, except in the A1B scenario where early in the twenty-second century, FUND2.8 has higher values. These high concentrations in PAGE after 2100 are due to the model's representation of the carbon cycle which takes into account feedback processes. The standard PAGE2002 model contains an estimate of the extra natural emissions of CO_2 that will occur as the temperature rises (an approximation for a decrease in absorption in the ocean and possibly a loss of soil carbon (Houghton et al. 2001, p218), with the effect the same as an increase in emissions). The DICE models assume a static carbon cycle (i.e. one in which the transfers between land, atmosphere and ocean are governed by fixed percentages that do not change over time), whilst in FUND2.8 the carbon cycle is based on an impulse–response model that does not include feedback processes. In the twenty-second century, in the B1 and B2 scenarios the DICE and FUND2.8 outputs for CO_2 concentration lie below or close to the edge of the PAGE 5–95% ile range. For the A1B, A2 and A1FI scenarios this is only so for DICE99 near 2200. This reflects the very different treatments of the carbon cycle in the various models. When comparing two SRES scenarios with very different emissions, A2 and B1 (Fig. 4f), the models' CO_2 concentration outputs respond similarly in their sensitivity to this change in emissions, although DICE2007 responds more strongly than most and the mean result from PAGE the least.

Considering secondly radiative forcing (Fig. 5a–e), as time evolves the model simulations diverge increasingly in all the SRES scenarios. FUND2.8's radiative forcing generally increases faster than in the other models, lying outside the PAGE 95% ile values in all scenarios in twenty-first century, and in the A1B, A1FI and (particularly) A2 scenarios in the twenty-second century. FUND2.8 simulates a CO_2 forcing of 2.0 W/m2 in 2000, compared to the other models' 1.5 W/m2. DICE's forcing outputs tend to level out during the twenty-second century in contrast to the other models. However, when two scenarios with very different emissions are compared (A2 and B1 in Fig. 5f) the mean result from PAGE responds less strongly to the change in emissions than any of the other models, particularly in the twenty-second century. This to be expected due to the inclusion of strong climate feedbacks in this model.

Considering thirdly global mean temperature rise (Fig. 6a–e), temperatures are consistent at the start of the century in all SRES scenarios, but as time evolves the model simulations diverge with the mean PAGE values giving much higher temperatures than DICE and FUND2.8 in 2200 (except under A1B where FUND2.8's temperatures are similar). However, most of the model outputs (except for DICE99 in the initial decades of the twenty-first century) lie outside the PAGE 5–95% range. In the B2 scenario, ignoring the now-revised DICE99 model, divergence does not occur till after 2100, (IPCC AR4 estimates are not available) whereas in the other emission scenarios significant differences already appear in the twenty-first century. For example, the temperature response of FUND2.8 to the A2 and A1FI emissions scenarios (Fig. 6a, e) are lower than the other model simulations and for A2, at the extreme low end of the IPCC AR4 range, in spite of the fact that radiative forcing estimates for FUND2.8 A2 are slightly higher than in other models (Fig. 5a), suggesting an inter-model difference in the relationship between radiative forcing and temperature response. Hence when the models' global temperature responses to a change of emission scenario from A2 to B1 are compared (Fig. 6f), FUND2.8 simulates much smaller temperature reductions in 2100 (of 1°C) than do the mean result of PAGE and DICE2007 (1.4–2°C), and than are implied by the ranges of IPCC TAR and AR4 results (1.4–2.2°C).

For comparison, the spreadsheet FUND model was also used to simulate the four SRES scenarios, and in this case the temperature outcomes for the scenarios were clustered between 3.0–3.7°C in 2100 (Fig. 6g). These values are of course also affected by the internal calculation of SRES emissions in FUND, which might differ significantly from the SRES marker emission scenarios. Furthermore, emissions in 2000 for SO_2 were 9.55 TgS in FUND as compared with 74 TgS in the EDGAR database. [Note, we did not use these emissions in the main simulations reported here, since we applied the nonCO_2 forcings from the PAGE model from 2000 onwards].

These model differences can be summarized by their widely differing estimates of the change in temperature upon moving from high to low SRES emission trajectories (Fig. 7). The PAGE mean and 95%ile estimates, and the DICE 2007 estimates, generally lie close to the mean estimate from AR4, whilst the FUND2.8 model simulates dramatically smaller ones, which tend to be more similar to those simulated by the DICE 99 model or by the 5% percentile of the PAGE range. Similar trends are found when comparing other pairs of low/high emission scenarios such as A1B and B1, and A2 and B2, also shown in Fig. 7.

5 Conclusions

The integrated models offer a range of climate outcomes not entirely consistent with those of IPCC. In particular, the outcome for the FUND2.8 model is particularly unusual in that temperatures up until 2100 are more similar for the four different emissions scenarios than in other models, and are particularly low for high emission scenarios. PAGE2002 is the only model studied here which incorporates strong carbon cycle feedbacks in the twenty-second century, and this leads to higher CO_2 concentrations than the other models in the twenty-second century, particularly for low emission scenarios. Models which do not include carbon cycle feedbacks might underestimate climate changes, but the scale of the feedbacks is still an open question. The model comparison suggests that differences between the models and also between the models and the IPCC simulations are due to both the differing treatments of the carbon cycle, and also differing treatments of the relationship between radiative forcing and temperature. For example, FUND2.8's radiative forcing is based on Shine et al. (1990), which formed part of the Second Assessment Report of the IPCC. Whilst a brief overview of the representation of these processes in the various models has been given here, further investigation is warranted to fully understand the reasons for the discrepancies.

Since these models are frequently applied to determine 'optimal' climate policy in a cost–benefit approach, inconsistency with IPCC AR4 in terms of the global temperature response to emission reductions implies that such calculations need to be investigated and understood, rather than accepted at face value. Models such as FUND2.8 which show smaller temperature responses to reducing emissions than IPCC AR4 simulations on comparable timescales will underestimate the benefits of emission reduction and postpone the benefits of emission reduction to a date farther into the future, at which time they will be more strongly discounted. Hence the calculated optimal level of investment in mitigation implied by the IPCC AR4 results will be underestimated by FUND2.8.

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