Committee on Climate Change

CHAPTER 1 TECHNICAL APPENDIX:

PROJECTING GLOBAL EMISSIONS, CONCENTRATIONS AND TEMPERATURES

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This technical appendix details the global climate modelling work described in Chapter 1 of the 2008 report by the Committee on Climate Change (CCC). It explains the overall approach taken to climate modelling, specifically discussing the model used and the greenhouse gases (GHGs) included. The methods used to design global GHG emission trajectories are discussed, both for a baseline scenario assuming no policy action and for different levels of explicit action designed to reduce emissions. Using a climate model, we then set out the changes in atmospheric concentrations and global mean temperatures that result from these trajectories.

Results show that in order to meet the global climate targets set out in the report, GHG emissions must be put on a path towards substantial reductions. The global trajectories which are most likely to meet these targets show a peak in emissions within the next decade (for Kyoto gases measured on a CO_2-equivalent basis) and reach at least a 50% reduction from current levels by 2050, followed by further reductions out to 2100.

Version changes

Version 1.1: corrected climate sensitivity text accompanying Figure 7; corrected N_2O text in section 2.3.

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1. APPROACH

The amount of global warming experienced over the coming decades will be fundamentally determined both by the level of global GHG emissions and by the sensitivity of the climate system, which is not precisely known[1]. Although there is currently no universal agreement as to what constitutes dangerous climate change, it is widely agreed that the risks of negative impacts are likely to be unacceptably high if global emissions continue to grow at current rates. Indeed, substantial emissions reductions are required in order to meet many of the global targets proposed to keep climate change within acceptable bounds[2].

Chapter 1 of the report sets out the level of climate change that should be avoided according to the judgment of the CCC. In order to set emissions targets to meet these levels, a range of emissions reduction trajectories have been created representing different levels of global effort. Here we outline the modelling methods that have been used to match emission trajectories to climate outcomes.

1.1 Model

Researchers use a range of global climate models to understand and predict climate change, and these can be ranked in a hierarchy according to their complexity. The most complex global models split the atmosphere and ocean into a three-dimensional grid and solve within each gridbox the equations that determine circulation and thermodynamics. For the atmosphere, the equations governing the movement of water are also included. For the ocean, equations governing the flow of salt are included. Many other processes occurring in the atmosphere, ocean, and on the land surfaces are represented: the models have more than 100 parameters, each of which will typically have some uncertainty attached to it. This type of model, known as an ocean-atmosphere general circulation model, typically takes several weeks on a fairly powerful computer to produce a single 200-year simulation. However, simpler climate models can be used which run much more quickly and which have been set up to emulate some basic features of the more complex models, notably the global average near surface temperature[3]. The uncertainty in the complex models can also be simulated with the simple models, but by varying a much smaller number of parameters.

[1] Solomon, S., et al. (eds.) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, Cambridge University Press.

[2] Metz, B., et al. (eds.) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, Cambridge University Press.

[3] For the MAGICC models see Solomon, S., et al. (eds.) above. For an alternative simple model (the Met Office Hadley Centre simple model) see House, J. I., et al. (2008) What do recent advances in quantifying climate and carbon cycle uncertainties mean for climate policy? *Environmental Research Letters*, 3, 1-6.

For these reasons we use a modified version of a simple climate software suite known as MAGICC 4.1 in our analysis[4, 5]. It calculates global averages of atmospheric GHG concentrations, radiative forcing and near surface temperature for an inputted emissions trajectory. Sources of uncertainty are included by varying key parameters within the simple climate model.

Whilst MAGICC is a simple climate model it has been used extensively during previous IPCC assessments to emulate the global average surface temperature response of a wide range of more complex models. We have extended the emulation to cover a greater range of climate system uncertainties. Specifics on how the uncertainties in parameters of the climate system are handled, and how the probability distributions of future atmospheric concentrations and temperatures are generated, are detailed in section 3.

1.2 Included emissions

Emissions inputs for MAGICC include the long-lived GHGs covered by the Kyoto Protocol: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and various halogen-containing compounds (PFCs, HFCs and SF_6). Our trajectories include CO_2 emissions relating to land-use. Also included are gases which have an indirect greenhouse effect through their interaction with other GHGs, namely carbon monoxide (CO), nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Finally, sulphur dioxide (SO_2) emissions can be input.

The historic trajectory of all these emissions up to 1990 is fixed in MAGICC, with the user able to define the trajectory after this point. Emissions of some other halocarbons (CFCs and HCFCs which can have a strong radiative effect but are already controlled by the Montreal Protocol) are fixed in the model for all time periods.

Chapter 1 of the report frames targets in terms of Kyoto gases, and to this end emissions and concentrations data are presented in terms of their CO_2-equivalent (CO_2e). When referring to emissions, this involves multiplying the emitted mass of each gas by its individual Global Warming Potential (GWP), with 100-year GWP values given in Table 1.

CO_2-equivalence when referring to atmospheric concentrations is the concentration of CO_2 that would give rise to the same amount of radiative forcing as a given mixture of GHGs. It is expressed in units of parts per million by volume (ppmv). GWPs are not used internally in the MAGICC model (which uses a more sophisticated treatment of radiative forcing) but are used to describe the emissions trajectories set out below.

[4] Wigley, T. M. L. & Raper, S. C. B. (2001) Interpretation of High Projections for Global-Mean Warming. *Science*, 293, 451-454.

[5] http://www.cgd.ucar.edu/cas/wigley/magicc/index.html [Accessed 14th November 2008]

Table 1. 100-year GWPs for gases included in the Kyoto Protocol, taken from http://unfccc.int/ghg_data/items/3825.php. HFCs and PFCs are families of gases, for which the range of individual GWPs are given.

Gas	Kyoto GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)	21
Nitrous oxide (N_2O)	310
Hydrofluorocarbons (HFCs)	140 – 11,700
Perfluorocarbons (PFCs)	6,500 – 9,200
Sulphur hexafluoride (SF_6)	23,900

2. GLOBAL EMISSIONS TRAJECTORIES

Global emissions are increasing, and are likely to continue to do so until a global deal is reached and takes effect. The emissions trajectories we have developed include historic changes and then present a range of future efforts to reduce emissions out to 2200.

Our trajectories are built in four stages: i) past and projected 'baseline' emissions until the peaking phase; ii) a peaking phase during which emissions move off the baseline and start to decrease; iii) a sustained reduction period, until iv) an emissions floor is reached, beyond which emissions cannot fall further on the timescales we consider here. It is important to note that this method of constructing scenarios does not aim to precisely stabilise either atmospheric concentrations of greenhouse gases or temperature during the 21st or 22nd centuries; in fact, we would expect many cases to show concentrations peaking before starting to fall to lower levels.

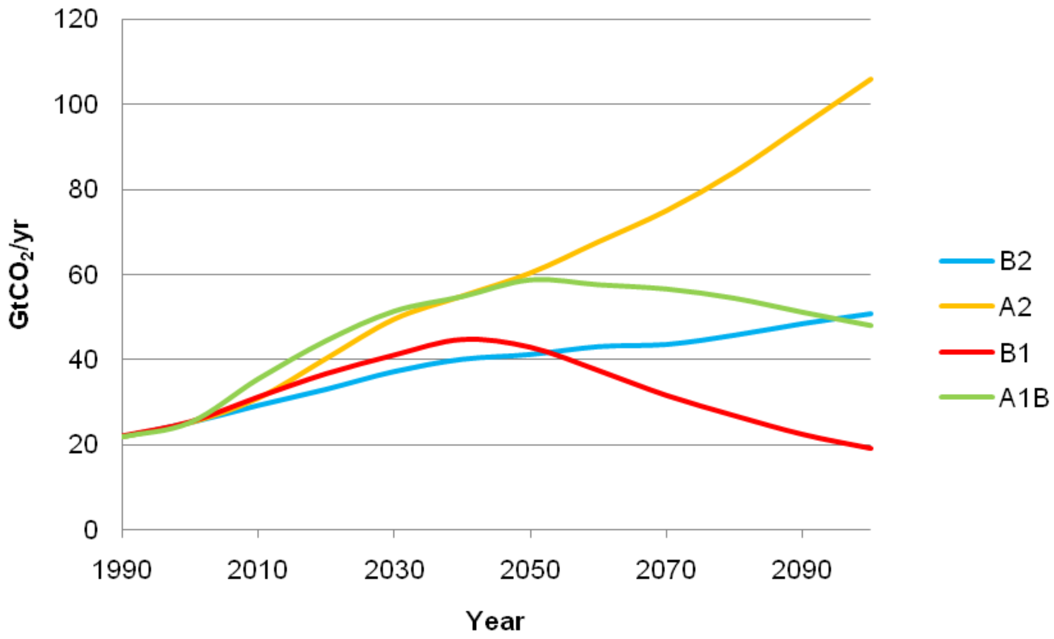
Whilst the climate targets set out in the CCC's 2008 report refer to global mean temperature change by 2100, each trajectory is extended out to 2200 in recognition of the fact that further, smaller temperature increases might be expected in the 22nd century (although this will depend on the details of the emissions trajectory and choice of model parameters). The stages in building these trajectories are detailed below.

2.1 1990 – peaking phase, and baseline emissions

During this period it is assumed that emissions follow a baseline trajectory – in effect what would happen in the absence of any specific climate policy to reduce GHG emissions. Uncertainty in this trajectory increases as it is extended further into the future, because it depends both on the socio-economic development of the world in the coming decades and on changes to GHG emitting activities that may occur (for instance advances in energy production, or changes in agriculture and forestry practices). Nonetheless, it serves an important purpose by creating the first phase of our emissions reduction trajectories. It is also used to calculate the amount of abatement that needs to be found by 2050 and to estimate the damages avoided by taking action.

The Intergovernmental Panel on Climate Change (IPCC) published a Special Report on Emissions Scenarios (SRES) in 2000[6]. This presents a range of 40 different emissions pathways, assuming no explicit climate policy action, based on four different storylines of world development from 1990 to 2100. Each is underpinned by a comprehensive analysis of emissions from different economic sectors, and by projections of future socio-economic drivers over the next century. To obtain our baseline, we narrowed down the group of scenarios from which our baseline would be selected to one of four SRES 'marker' scenarios, which have been used extensively in subsequent research (Figure 1).

Figure 1. Total global carbon dioxide emissions (including those relating to land-use) for four SRES 'marker' scenarios, measured in gigatonnes per year ($GtCO_2$/yr).



In order to select which single SRES marker scenario is most appropriate for use as a baseline we compared them to observed emissions trends since 2000, along with estimates of emissions, population and economic growth.

Data on recent CO_2 emissions from fossil fuel use and industrial activity are available on an annual basis and are the most reliable. Comparison of the SRES scenarios against these data suggests the A1B scenario accounts most closely for both the magnitude and annual growth of these emissions, especially since around 2004 (Figure 2). Furthermore, recent IEA forecasts of CO_2 emissions from fossil fuel use and industrial activity out to 2050 show closest matches to SRES scenarios A1B and A2 (Figure 3).

[6] Nakicenovic, N. & Swart, R. (eds) *Special Report on Emissions Scenarios*. *A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge, UK, Cambridge University Press.

Figure 2. Measured recent global carbon dioxide emissions (excluding those relating to land-use) compared to the SRES scenarios. Source: Global Carbon Project (http://www.globalcarbonproject.org/carbontrends/index.htm). Errors in actual emissions estimates are around 5%.

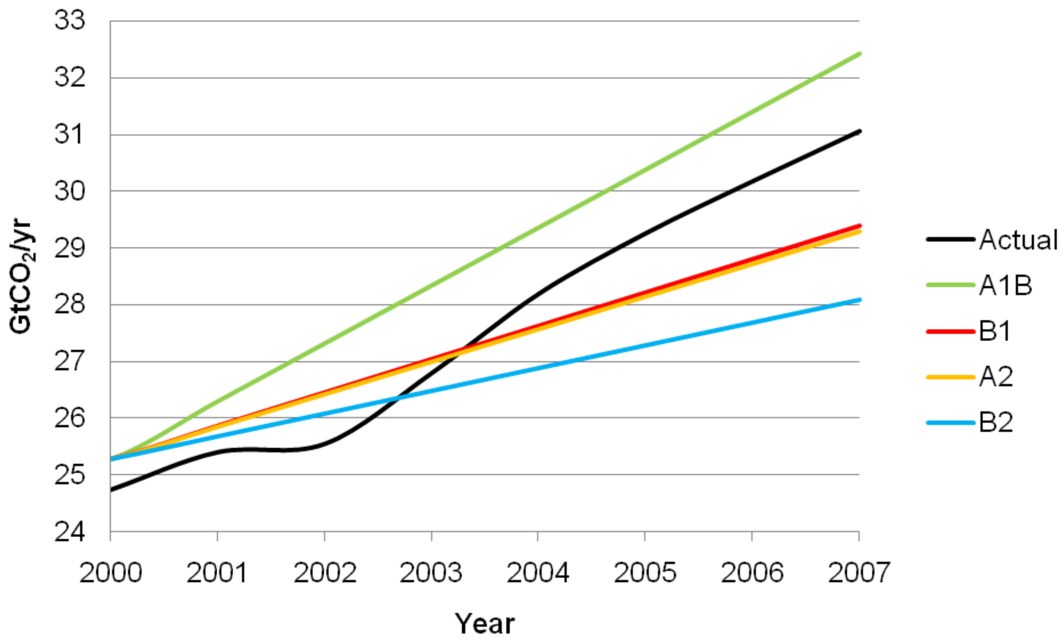
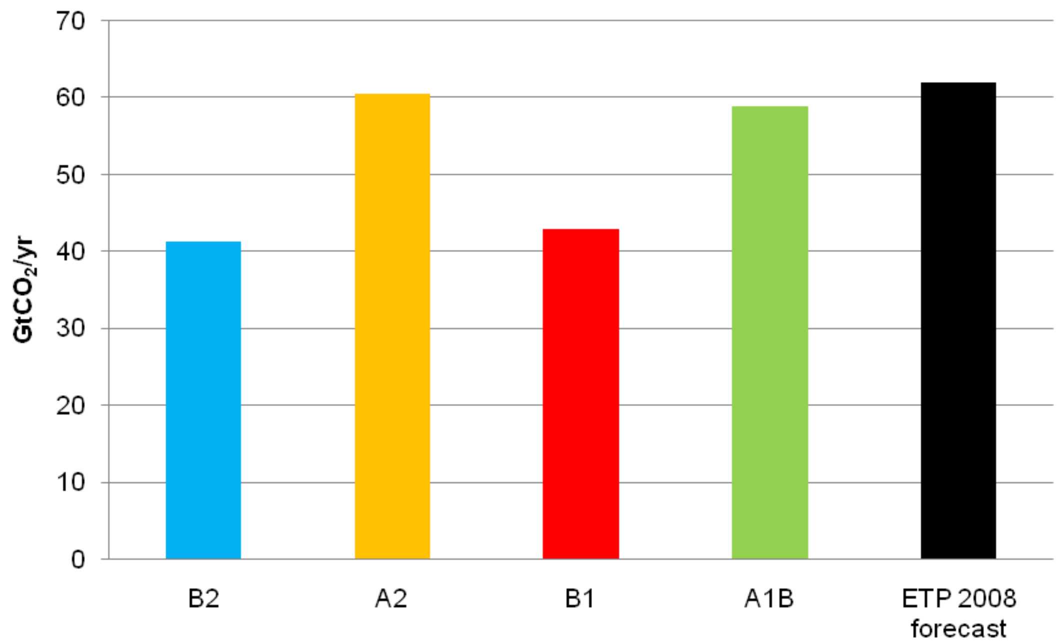


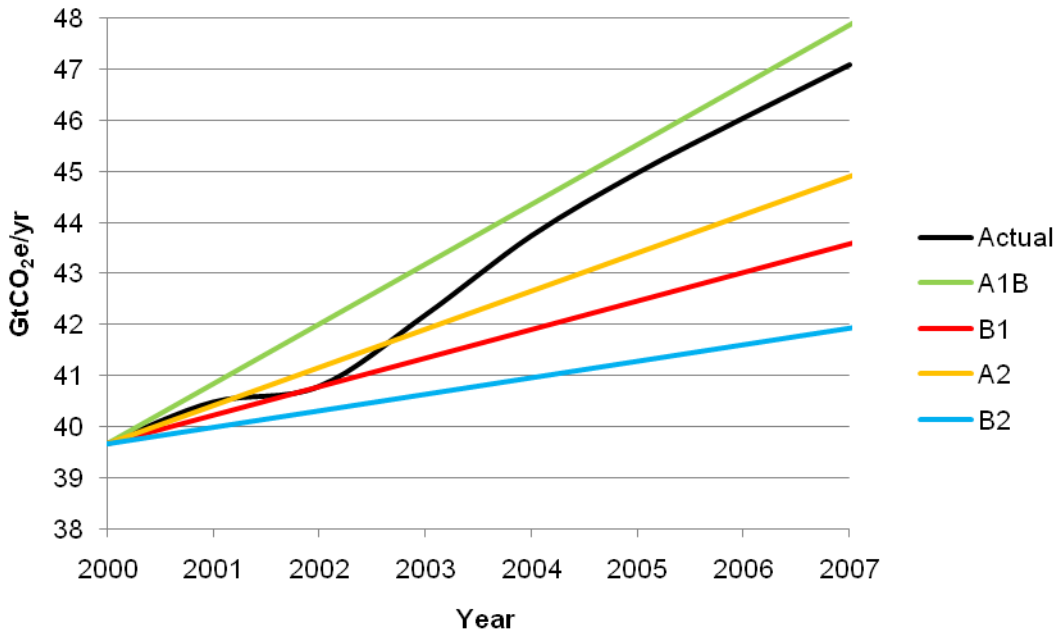
Figure 3. SRES carbon dioxide emissions from fossil fuel use in the year 2050, compared to a current forecast from the International Energy Agency[7].



[7] International Energy Agency (2008) *Energy Technology Perspectives*, OECD/IEA

Recent estimates for the full set of global Kyoto GHG emissions (including CO_2 emissions relating to land-use) are less well constrained by observations than those for fossil fuel and industrial CO_2. Using a combination of sources however, GHG emissions on a CO_2-equivalent basis can be compared to the SRES scenarios and are plotted in Figure 4. When each component of the Kyoto basket is considered individually it is evident that there are some compensating errors in all the SRES scenarios: general underestimates of land-use CO_2 emissions appear to offset overestimates of other GHG emissions. Despite this, Figure 4 shows that recent trends match A1B most closely for total emissions.

Figure 4. Measured recent global Kyoto GHG emissions (including CO_2 emissions relating to land-use) compared to the SRES scenarios. Source: Global Carbon Project, Anderson & Bows (2008)[8] for estimates of land-use CO_2 emissions, and the U.S. Environmental Protection Agency for other GHG emissions[9].



In terms of population the A1B scenario forecasts a world population in 2050 of 8.7 billion, comparing favourably to the UN's most recent medium projection of 9.2 billion (7.8 to 10.8 billion)[10]. The A1B estimate of current and projected economic growth is at the upper end of the SRES scenarios, although at an average 3% per annum between 1990 and 2100, it is similar to the annual average growth rate experienced between 1970 and 2007 of 3.1%[11].

[8] Anderson, K. & Bows, A. (2008) Reframing the climate change challenge in light of post-2000 emission trends. *Phil. Trans. R. Soc. A*, 366 (1882), 3863-3882.

[9] USA Environmental Protection Agency (2006) *Global anthropogenic non-CO2 greenhouse gas emissions: 1990-2020*, Office of Atmospheric Programs, Climate Change Division, USA Environmental Protection Agency.

[10] United Nations (2006) *World population prospects: the 2006 revision*. United Nations Population Division.

[11] http://unstats.un.org/unsd/snaama [Accessed 14th November 2008]

In view of this evidence, all of our emissions reduction trajectories follow SRES A1B up until the peaking phase. As with the other SRES scenarios, A1B data are given in 10 year intervals running from 1990 to 2100 and are broken down into four world regions: OECD nations, Central and Eastern European nations, Asia, and Africa and Latin America. For the purposes of the rest of this document, and for consistency with the UNFCCC negotiations, the Central and Eastern European and OECD regions are referred to together as 'Annex I', and the Asia, Latin America and Africa regions as 'non-Annex I'[12].

It is important to note that other studies of global Kyoto GHG emissions reduction show a range of different emissions trends during the period from 1990 to peaking. This is either due to the fact that later studies have access to more recent emissions data, or because they make different assumptions regarding the development of baseline emissions[13]. The emissions values we use fall between the highest and lowest trends currently available in the peer reviewed literature. For instance, an analysis by Meinshausen et al. (2006)[14], which investigates comparable climate targets and emissions reductions, shows growth in global Kyoto GHG emissions until they peak in 2015 at around 45 $GtCO_2e$/yr. According to Figure 4, observed emissions may have passed this value in 2005, and the SRES A1B scenario suggests emissions of 56 $GtCO_2e$/yr by 2015 and 60 $GtCO_2e$/yr by 2020. In contrast, baseline projections published by den Elzen and Höhne (2008) suggest even stronger growth with emissions potentially as high as 62 $GtCO_2e$/yr by 2020[15].

2.2 Peaking phase

The modelling of emissions reduction trajectories requires an assumption about when emissions will peak. For simplicity we have assumed two peaking years – 2016 and 2028. The former represents a case where the world community successfully commits to a global deal in Copenhagen in 2009, as set out in the "Bali Action Plan" of the United Nations Framework Convention on Climate Change[16], and the latter peaking year represents a much less optimistic world: Annex I and non-Annex I emissions both continue to follow the baseline until the world commits to action at a later date. In reality it is difficult to know for certain when global emissions will peak. A seven year period between achieving a global deal in Copenhagen and the peak in emissions does not seem unreasonable however, given that agreements will need to be ratified and policies will need to be developed and implemented.

[12] The terms 'Annex I' and 'Non-Annex I' are used because these reflect the country groupings as set out in the UN Framework Convention on Climate Change (UNFCCC).

[13] See for instance Garnaut, R. *The Garnaut Climate Change Review*. Port Melbourne, Australia, Cambridge University Press. pp53-71.

[14] Meinshausen, M., et al. (2006) Multi-gas emissions pathways for meeting climate targets. *Climatic Change*, 75 (1-2), 151-194.

[15] den Elzen and Höhne (2008) Reductions of greenhouse gas emissions in Annex I and non-Annex I countries for meeting concentration stabilisation targets. *Climatic Change*

[16] UNFCCC Decision 1/CP.13. [Online]. Available from: http://unfccc.int/documentation/decisions/items/3597.php#beg [Accessed 14th November 2008]

To estimate the speed with which global emissions could transfer onto a constant year-on-year reduction path, and to take into account current targets, assumptions were made about emissions in 2020 following a 2016 peak. We assume in this case that emissions from Annex I countries are 20% lower in 2020 relative to 1990 and non-Annex I emissions remain on the baseline until 2020. The shape of the global deal is currently under negotiation and the final outcome is difficult to predict. Our assumption is cautious: analysis by Working Group III of the IPCC suggests that, in order to stabilise concentrations at 450ppm CO_2e, a 25-40% cut by Annex I countries and a substantial deviation from the baseline by non-Annex II countries will be required relative to 1990 levels[17].

We have modelled the possibility that the world will take more ambitious action by 2020, either by further reducing Annex I emissions or through emissions reductions in non-Annex I countries. If more ambitious international action were taken then the risks of dangerous climate change could be further reduced (as is demonstrated in the accompanying spreadsheet by a trajectory named 2014:3%low+, showing a global emissions reduction by 2020 at the very top end of that considered by the IPCC).

2.3 Annual reductions and emissions floors

After the peaking phase we use constant year-on-year percentage reduction rates for CO_2 emissions. This is a simple, highly aggregated approach, however the shape of the emissions trajectory that results is credible: there are likely to be significant early reductions in the magnitude of emissions thanks to ‘easy wins’, followed by smaller reductions as abatement options become more scarce and expensive. Emissions of other direct and indirect GHGs are reduced in a consistent manner until they reach a level beyond which no further reductions are possible (the ultimate emissions floor).

A key question becomes what range of reduction rates, especially the maximum rate, is achievable at a global level? The Stern Review looked at past historical examples, concluding that it is difficult to reduce CO_2 fossil fuel emissions by more than 1% per year, except in instances of recession[18]. On the other hand, none of these historical examples involved explicit climate policies or sizeable investment in low carbon technologies. Furthermore, much greater reduction rates are used and justified in many studies aimed at limiting climate change to within perceived acceptable bounds[19].

In defining a range of annual reductions and emissions floors, we adopted the following approach for each gas:

- *All CO_2 emissions are reduced at rates from 1.5% to 4% per annum*. Our most rapid annual reduction rate leads to CO_2 emissions of around 12 Gt/yr in 2050, a reduction of 48 Gt/yr relative to baseline emissions. This is consistent with the International

[17] Metz, B., et al. (eds.) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK, Cambridge University Press. Box 13.7

[18] Stern, N., et al. (2006) *Stern Review: The Economics of Climate Change*, HM Treasury, London. p238.

[19] Including the Stern Review itself. See also den Elzen and Meinshausen: 2005 ‘Meeting the EU 2°C climate target: global and regional emission implications’

Energy Agency's (IEA) strongest mitigation scenario, which shows that a reduction of around 48 Gt/yr is possible by 2050 relative to their baseline[20] for a cost of $200-500 per tonne of CO_2. Studies suggest that there is enough energy capacity available from low carbon sources (such as renewables, nuclear power generation, and fitting of carbon capture and storage to fossil fuel power stations) to meet energy demand in 2050. It is therefore likely that energy production can be completely decarbonised in the future. Emissions from industrial processes and other sectors may prove more difficult to eliminate, although the decarbonisation of power generation opens up the possibility of decarbonising large areas of transport through the deployment of electric vehicles. Beyond 2050 further innovations which allow deeper emissions reduction are likely to be possible. *We therefore allow CO_2 emissions to fall until they reach a residual level of 5 Gt/yr for most trajectories, except for two cases where it is assumed strong efforts are made to reduce CO_2 emissions to zero*. Net emissions from land-use can be positive or negative, and could therefore be used as an additional source of CO_2 abatement.

- *Emissions of halogen-containing compounds included in the Kyoto Protocol are reduced such that their CO_2-equivalent level of emissions falls at the same rate as CO_2 emissions*. As a result, emissions of PFCs, HFCs and SF_6 are reduced to around 0.26 $GtCO_2e$/yr in 2050 under our most aggressive scenario, representing a cut of around 90% relative to the baseline. There is significant abatement available in this sector, as industrial controls preventing venting of these gases are adopted and low-GWP alternatives to commonly used HFCs are phased in. We assume that the market mechanisms that will be needed to drive a low-carbon society will also drive development of these alternatives, and high-GWP HFCs will be phased out. One study suggests that these emissions can be reduced by up to 90% in 2050 at a carbon price of around $140 per tonne of CO_2[21], with larger reductions possible in 2100.

- Other indirect GHGs (CO, NO_x, VOCs and SO_2) are linked in different ways to fossil fuel use. Through a range of existing policies many of them are already being cleaned out of the fossil fuel burning process, meaning that emissions of these species per unit fossil fuel consumption will decrease over time. This is however offset to some extent by increasing overall fossil fuel use. *We have estimated emissions of these species by looking at the ratio of their emission to fossil fuel CO_2 emissions in the SRES B1 scenario*, which is designed to represent a future world where environmental concerns are of a high priority. For a species X in year Y, we calculate the level of emissions $E_{X,Y}$ using the formula:

$$E_{X,Y} = E_{CO2,Y} \times (E^{B1}_{X,Y} / E^{B1}_{CO2,Y})$$

where $E_{CO2,Y}$ is the level of CO_2 emissions for a given trajectory in year Y (Y=2010, 2020, ... 2100), and $E^{B1}_{X,Y}$ & $E^{B1}_{CO2,Y}$ are the emissions species X and CO_2

[20] International Energy Agency (2008) *Energy Technology Perspectives*, OECD/IEA. p67.

[21] Lucas, P. L., et al. (2007) Long term reduction potential of non CO_2 greenhouse gases. *Environmental Science and Policy*, 10, 85-103.

respectively in the SRES B1 scenario for that year. Therefore emissions of each species decrease with decreasing fossil fuel combustion and also decrease as improvements in combustion technology (such as low sulphur fuel) become more prevalent across the course of the 21st century.

- CH_4 emissions are also linked to fossil fuel use through mining and production, with additional major sources from agriculture and waste. In our 4% trajectory, CH_4 emissions are 67% below baseline by 2050. For comparison, the IEA estimate that methane sources (excluding agriculture) could be reduced, relative to the baseline, by around 60% in 2050 for a carbon price of \$50 per tonne of CO_2[22]. Yet further reductions appear possible for a higher carbon price (or further in the future) both from fossil fuel mining and from waste[23]. Agricultural CH_4 emissions can also be reduced but it seems unlikely from today's vantage point that they will be completely eliminated. *In our trajectories, total CH_4 emissions are calculated using the same SRES B1 ratio formula used for indirect GHGs (see above), until a floor of 150Mt/yr (approximately 3.2 $GtCO_2e$/yr) is reached*. This floor is very similar to the level of methane emissions from agriculture in 2005[24].

- N_2O emissions come primarily from agriculture and as such are not linked directly to fossil fuel use[25]. Projections of N_2O emissions are highly uncertain and cover a wide range depending upon what is assumed about agricultural practices and methods[26]. The SRES A1B scenario assumes that fertiliser use in developing countries is nearly saturated and increased productivity comes from better management, giving it some of the lowest levels of N_2O emissions of the SRES marker scenarios. Some studies suggest a maximum reduction of up to 30-35% relative to baseline emissions by 2050[27, 28], however *we take N_2O emissions in our trajectories directly from the SRES B1 scenario*. This assumes a similar population profile to the A1B scenario but projects greater use of fertilisers. As a result, our trajectories show no significant abatement of N_2O emissions by 2050.

Having set the annual reduction rate of CO_2 emissions for a given trajectory, other emissions are reduced as outlined above until the ultimate emissions floor is reached. For all

[22] International Energy Agency (2008) Energy Technology Perspectives, OECD/IEA. p421

[23] Lucas, P. L., et al. (2007)

[24] Metz, B., et al. (eds.) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK, Cambridge University Press. p63.

[25] There are emissions of N_2O from acid production and transport but these are relatively small.

[26] Nakicenovic, N. & Swart, R. (eds) *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change.* Cambridge, UK, Cambridge University Press.

[27] Lucas, P. L., et al. (2007)

[28] van Vuuren, D. P., et al. (2007) Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*, 81, 119-159.

trajectories except two, this floor is at approximately 11 $GtCO_2e$/yr and consists of CO_2, CH_4 and N_2O emissions. The remaining two trajectories, representing strong global efforts to reduce emissions, have a floor of approximately 6 $GtCO_2e$/yr made up of CH_4 and N_2O.

Virtually all trajectories do not meet their emissions floor by 2100, meaning that uncertainties about the ultimate level do not have a large effect on global mean temperatures this century (and hence the climate targets set out in the report). They do however affect subsequent temperature change in the 22nd century and, in order to investigate this, trajectories have been extended out to 2200.

2.4 Plotting trajectories

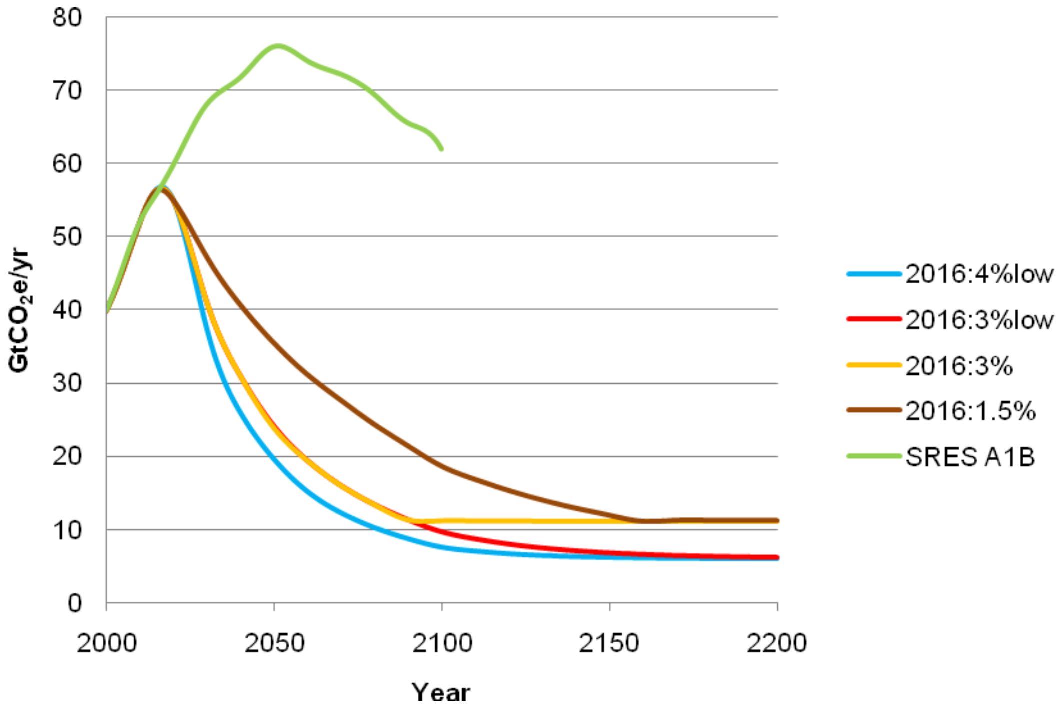
Having defined the emissions reduction trajectories at 10 year time steps out to 2200, annual emissions were interpolated between these points using a cubic spline function. This leads to very minor differences in emissions values between trajectories around the peaking phase (no more than 0.2 $GtCO_2e$/yr for the trajectories peaking in 2016). The annual emissions data are listed in the accompanying spreadsheet, and total Kyoto gas emissions for key trajectories are plotted in Figure 5.

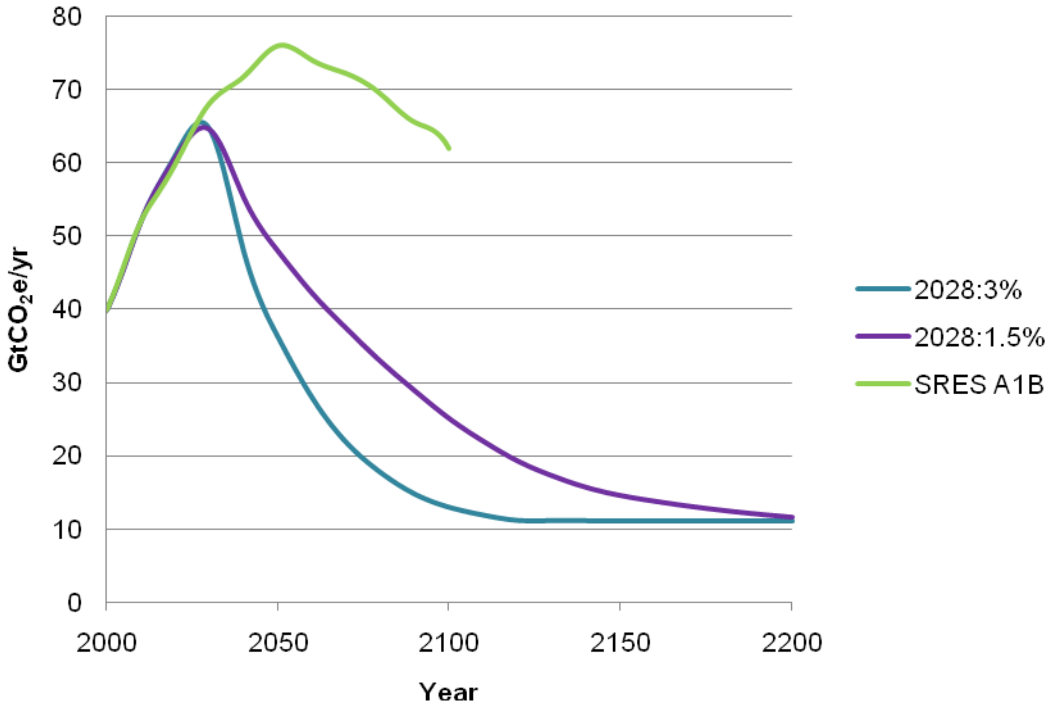
Each of the emissions reduction trajectories implies a specific level of Kyoto gas emissions in 2050, and a specific cumulative emissions budget out to 2050. These are given in Table 2.

Table 2. Kyoto gas emissions levels in 2050, their reduction relative to 1990 and 2007 levels, and cumulative emissions for the trajectories highlighted in Fig. 5.

Trajectory	Kyoto gas emissions ($GtCO_2e$/yr)			% reduction in 2050 emissions relative to		Cumulative emissions during 1990-2050 ($GtCO_2e$)
	1990	2007	2050	1990	2007	
2016:4%low	36.1	48.1	19.6	46	59	2423
2016:3%low	36.1	48.1	24.1	33	50	2536
2016:3%	36.1	48.1	23.8	34	50	2535
2016:1.5%	36.1	48.1	35.4	2	26	2757
2028:3%	36.1	48.2	36.2	0	25	3067
2028:1.5%	36.1	48.2	47.9	-33	1	3200

Figure 5. Global emissions of Kyoto greenhouse gases during the years 2000-2200 for the two sets of emissions reduction trajectories; one set peaking in 2016 (top), the other peaking in 2028 (bottom).





3. CONSEQUENCES FOR CLIMATE

To determine the climate impact of the above trajectories they were inputted into the MAGICC climate model. This section explains the modelling methods used, and then gives the results of predicted atmospheric concentrations and global mean temperatures for each trajectory.

3.1 Modelling methods

We use a version of the MAGICC 4.1 simple climate model to simulate the global average near surface warming and its uncertainty for the range of emissions trajectories defined in section 2. The specific parameters that can be varied are the climate sensitivity (defined as the equilibrium global mean temperature increase for a doubling of atmospheric carbon CO_2), the ocean mixing rate (which determines how quickly the warming at the surface is diffused throughout the ocean) and a measure of the carbon cycle strength (regulating how much carbon is emitted and absorbed naturally in response to climate change). The magnitude of aerosol forcing (how strongly sulphate aerosols act to cool the climate) can also be varied.

In order to demonstrate the reliability of MAGICC in modelling global temperature increases, the Met Office Hadley Centre has run the MAGICC model with an SRES A2 scenario for CO_2 only and emulated the results from some of the most complex models. Figure 6 shows the results, with MAGICC able to replicate the complex models to within 0.05°C in all cases.

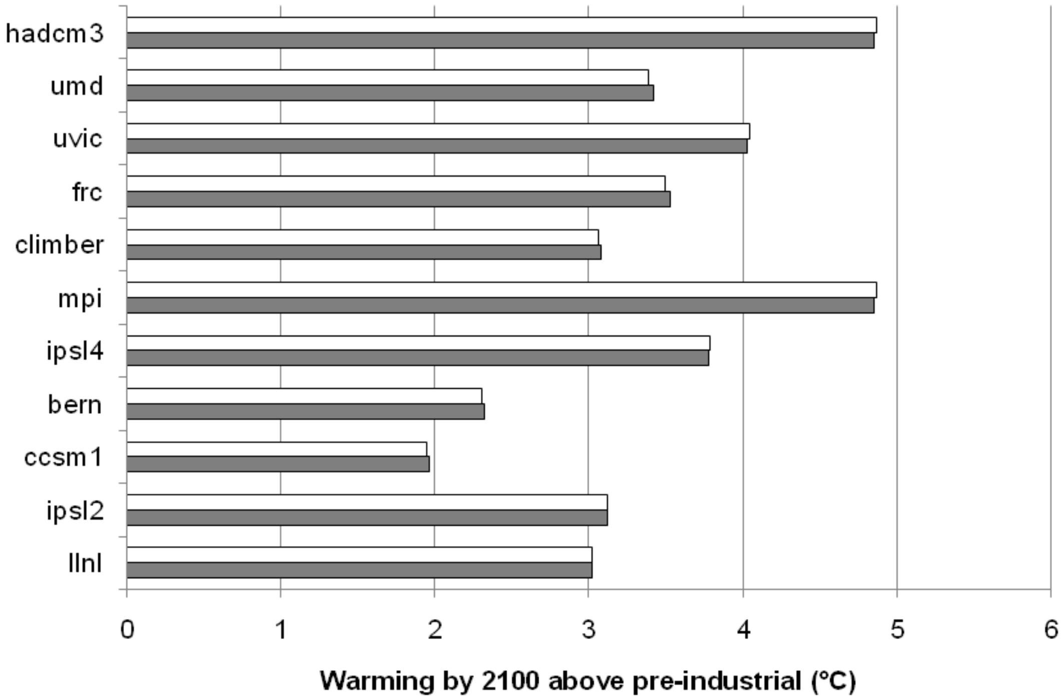
Our analysis draws on a normal distribution of carbon cycle strength parameters fitted to the behaviour of a range of fully coupled climate-carbon cycle models[29], and a lognormal distribution of ocean mixing rates fitted to the general circulation models employed by the IPCC's Third Assessment Report. We use the default MAGICC value for aerosol radiative forcing from a given unit of aerosol. A key uncertainty is the choice of climate sensitivity probability distribution. We have investigated this sensitivity using a range of different distributions available in the literature. Our investigation of this sensitivity led us to choose a distribution presented in Murphy et al. (2004)[30].

Each of the parameter distributions were divided into nine representative values, and every possible combination of these values was applied to MAGICC in analysing the individual emissions reduction trajectories. Each trajectory thus led to a range of climate outputs dependent on the combination of MAGICC parameter settings, and the likelihood of each output was determined by multiplying the probability of the individual parameter settings according to their distributions. In this way, likelihood ranges of atmospheric GHG concentrations and global mean temperature increase were produced for the trajectories.

[29] Friedlingstein, P., et al. (2006) Climate-carbon cycle feedback analysis: results from the C^4MIP model intercomparison. *Journal of Climate*, 19, 3337-3353.

[30] Murphy, J. M., et al. (2004) Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature*, 430 (7001), 768-772.

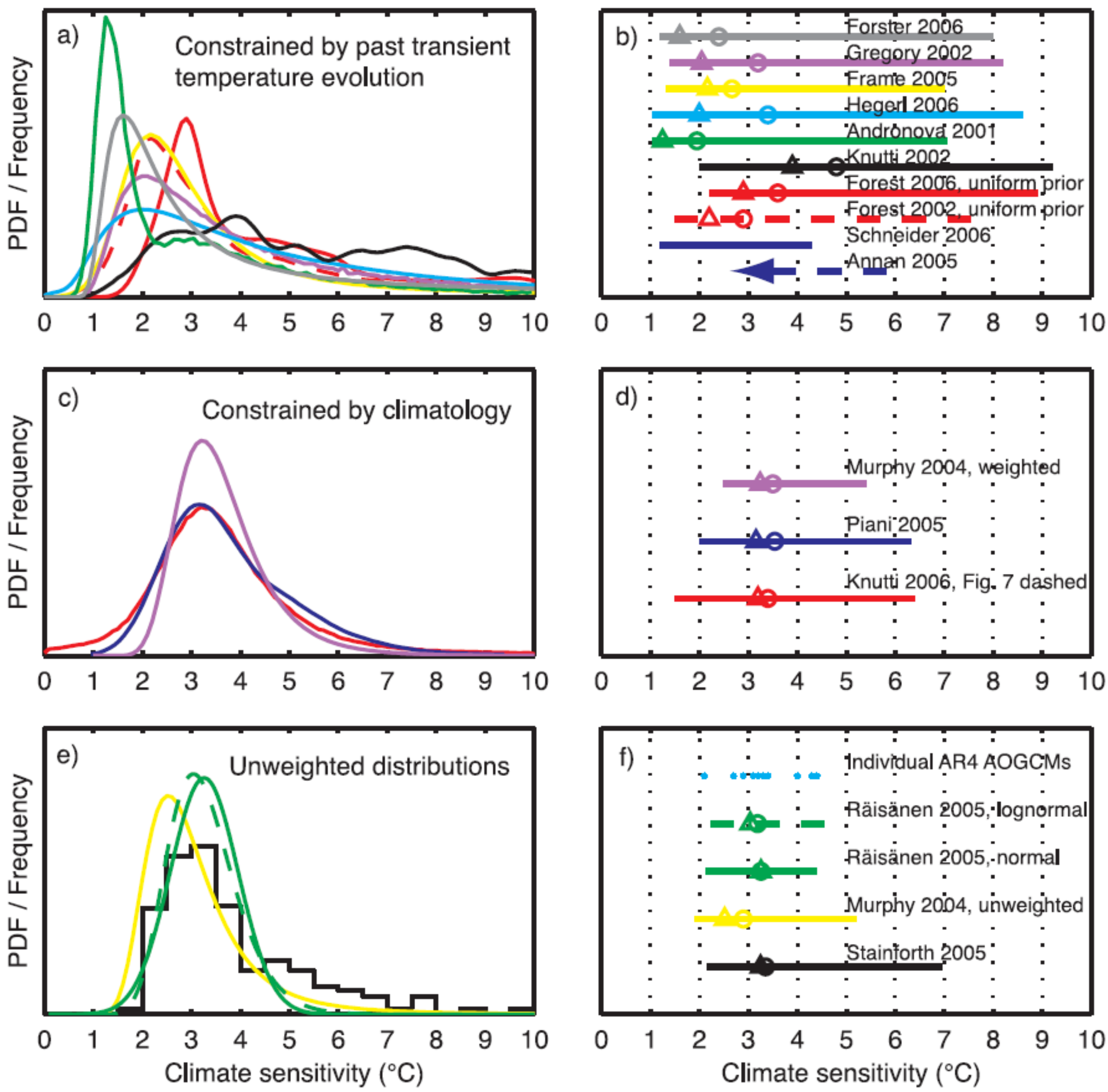
Figure 6. Global warming (above pre-industrial levels) by 2100 under a CO_2-only version of SRES A2 for models participating in the C4MIP intercomparison[31]. White bars show complex model outputs; grey bars give the MAGICC output with parameters fitted to that model.



Other distributions of probability may be attached to the range of values for each of the parameters. This is particularly notable for climate sensitivity, where many recent studies have attempted to provide a comprehensive assessment of uncertainty, some of which are shown in Figure 7. It has proved very difficult to rule out high values for this parameter, and all attempts to attach specific levels of probability to climate sensitivity values have relied on subjective *a priori* assumptions. As a result, studies show disagreements at the extreme tail of high sensitivities, although they provide better agreement for more probable values. For any particular simulation the value of climate sensitivity affects both the magnitude of eventual response and the rate of response to changes in radiative forcing.

[31] Meehl, G.A., et al. (2005) Overview of the coupled model intercomparison project. *Bull. Am. Meteorol. Soc.*, 86, 89–93.

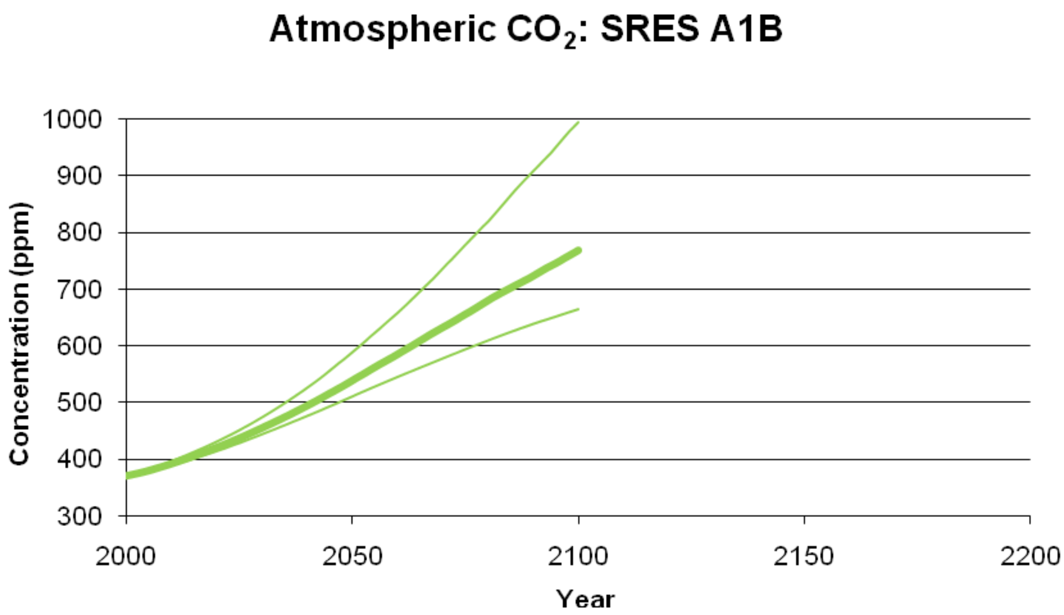
Figure 7. Probability or frequency estimates of the value of climate sensitivity from a range of studies. The results of studies using observations of past climate are shown in a), while c) and e) show results from a range of perturbed climate models. Model outputs are weighted by their ability to replicate resent-day observations in c), and unweighted in e). 5-95% ranges, medians (circles) and maximum probabilities (triangles) are shown in b), d) and f) for the distributions in a), c) and e) respectively. Our analysis uses the weighted Murphy 2004 distribution shown in c) and d). Source: IPCC WG1 AR4 Box 10.2, Figure 1.

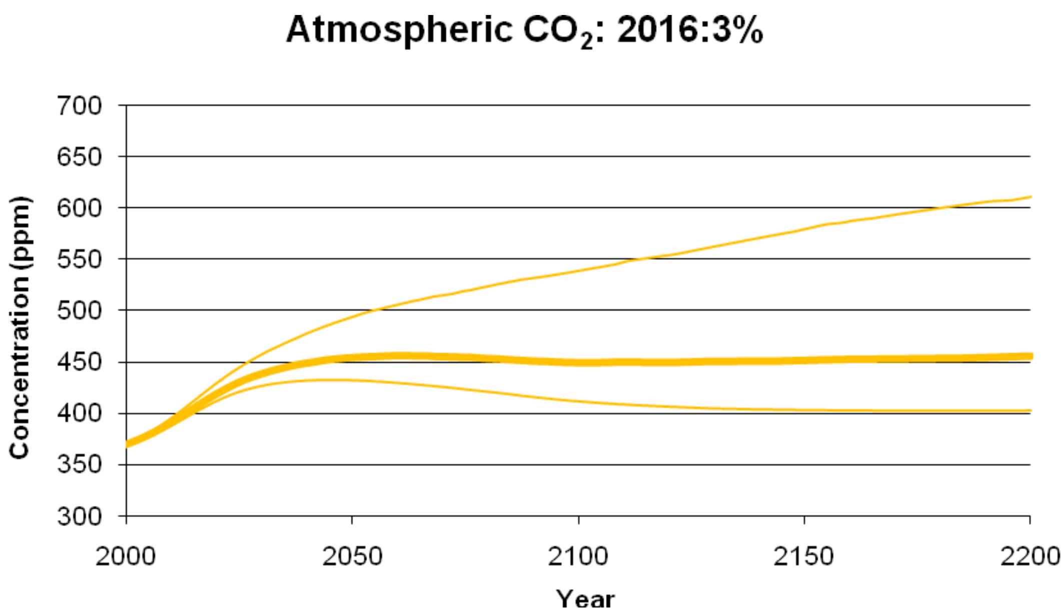


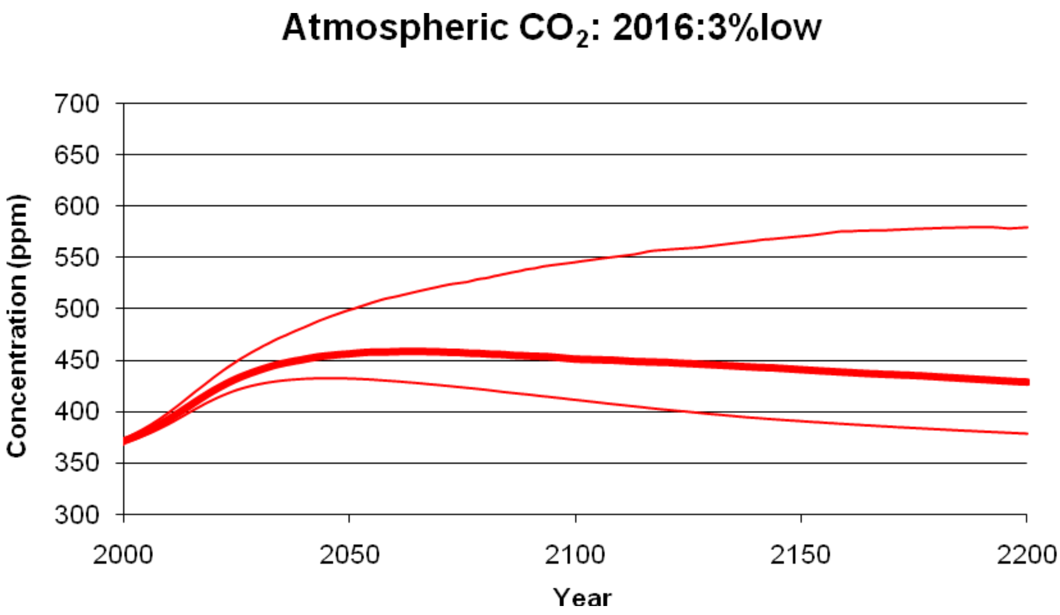
3.2 Atmospheric CO_2 concentrations

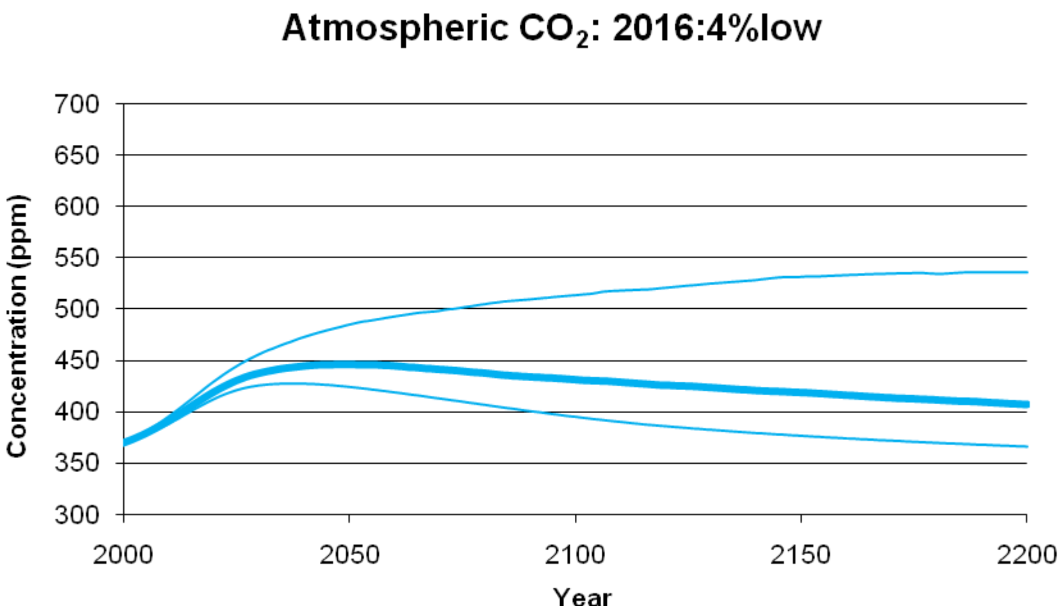
In the following sections, likelihood ranges are shown for baseline emissions and for the trajectories used in the CCC's recommendations (namely 2016:3%, 2016:3%low and 2016:4%low) purely for brevity. Complete data are given in the accompanying spreadsheet. First, the projected atmospheric concentrations of CO_2 are shown in Figure 8. Thick central lines indicate the median MAGICC output, whereas outer thin lines represent the 10^{th} – 90^{th} percentiles of outputs produced by the range of parameter settings.

Figure 8. Modelled concentrations of atmospheric CO_2 in parts per million (ppm) for the scenarios (top to bottom) SRES A1B, 2016:3%, 2016:3%low and 2016:4%low. Median MAGICC outputs are given by the thick central lines, with 10th – 90th percentile range given by the outer thin lines.





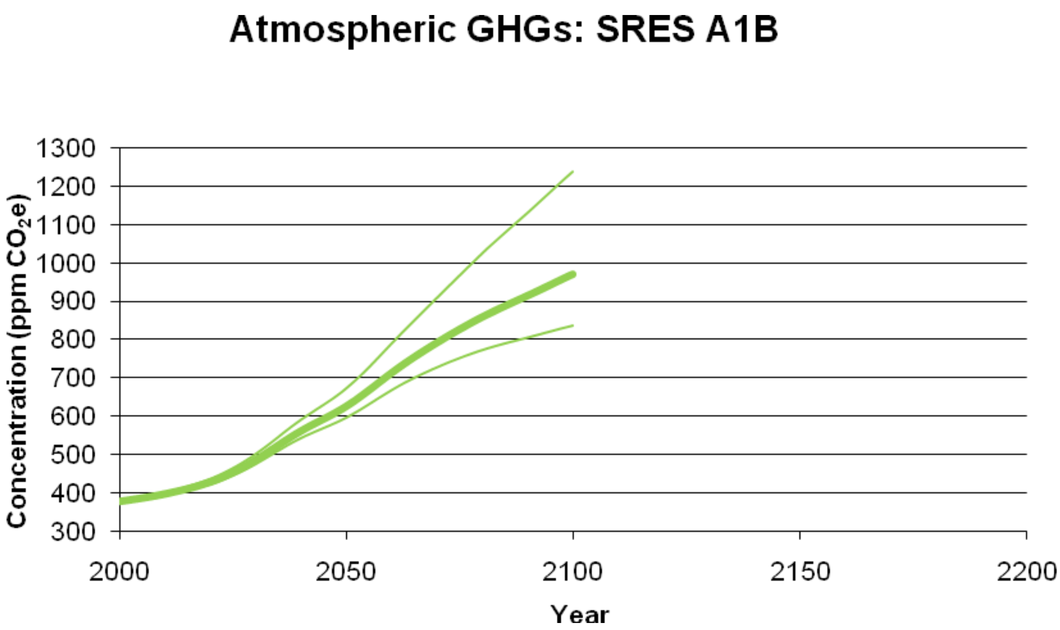


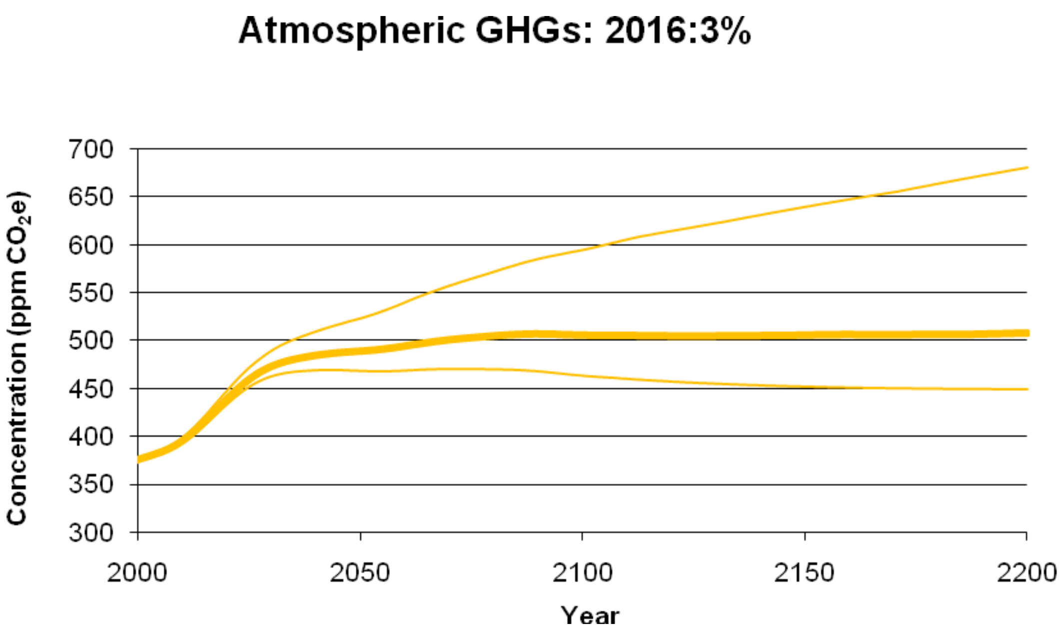


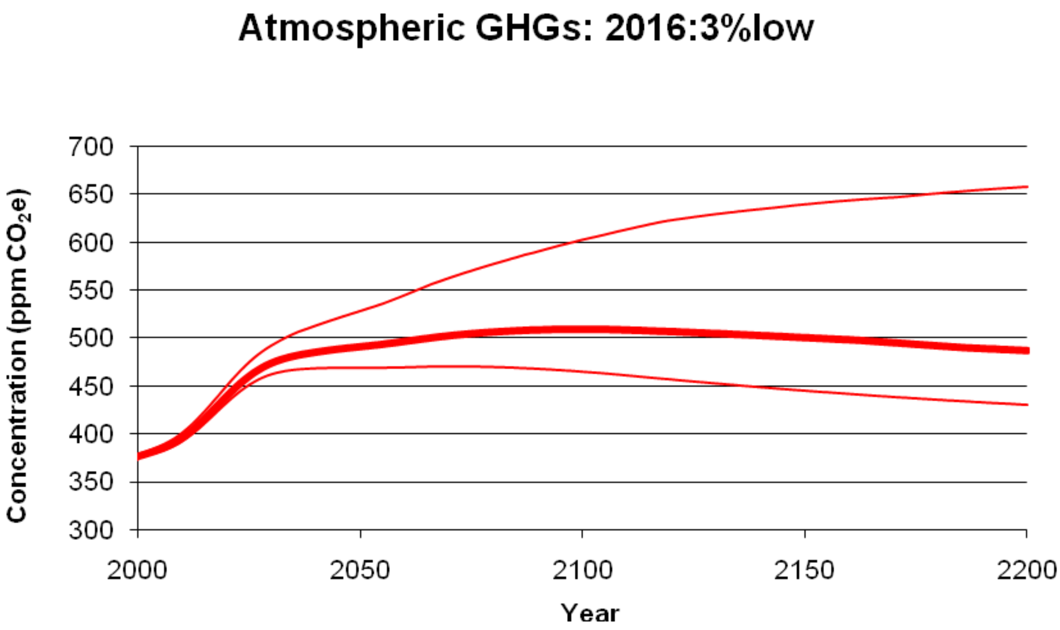
3.3 Atmospheric GHG concentrations

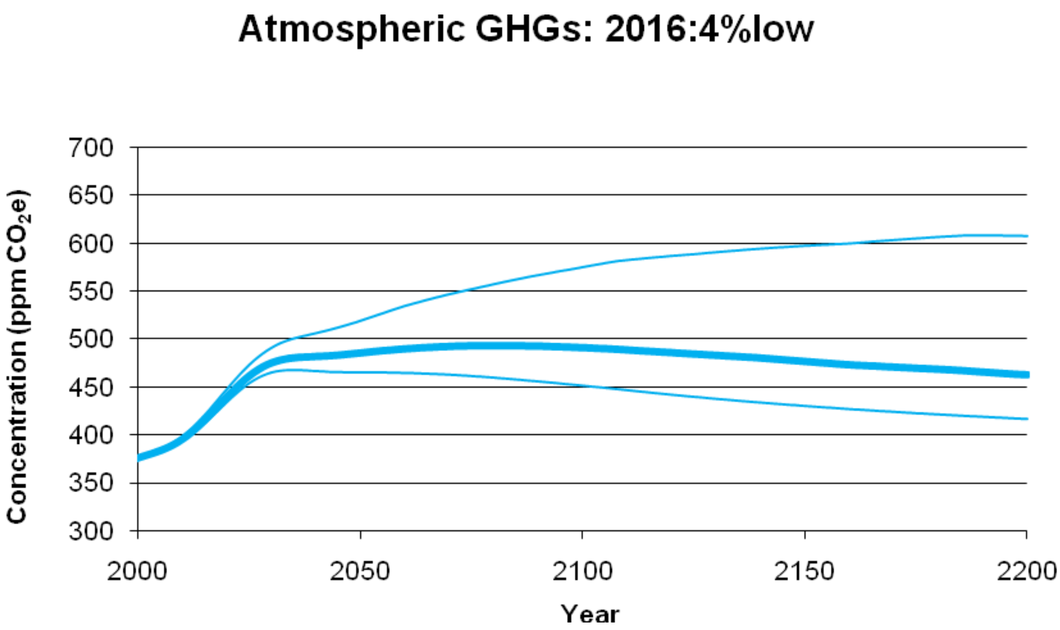
Figure 9 shows total atmospheric GHG concentrations plotted as a function of time and measured in terms of parts per million of CO_2-equivalent (ppm CO_2e). These values are calculated from the radiative forcings produced by all the species handled within the model: CO_2, CH_4, N_2O, PFCs, HFCs, CFCs, HCFCs, O_3 and sulphate aerosol.

Figure 9. Modelled concentrations of atmospheric GHGs in parts per million of CO_2-equivalent (ppm CO_2e) for the scenarios (top to bottom) SRES A1B, 2016:3%, 2016:3%low and 2016:4%low. Median MAGICC outputs are given by the thick central lines, with 10[th] – 90[th] percentile range given by the outer thin lines.





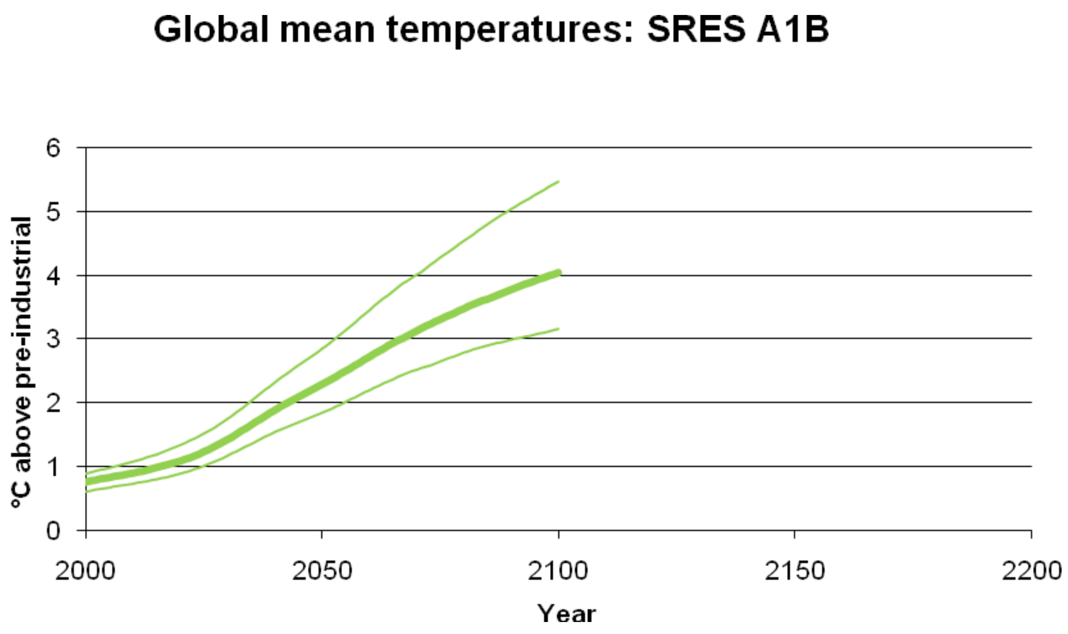


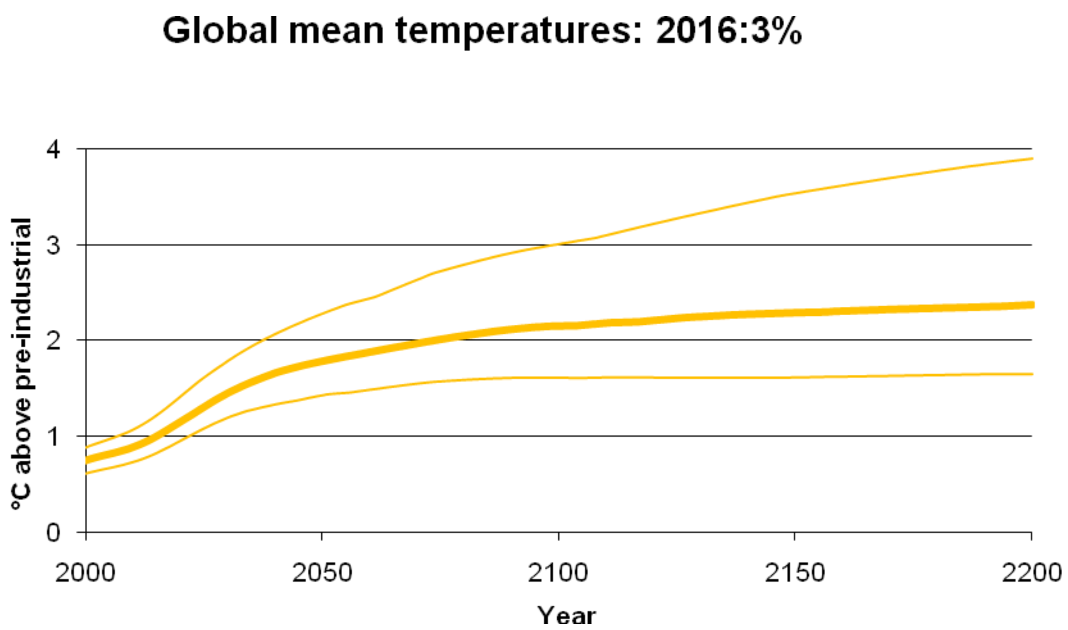


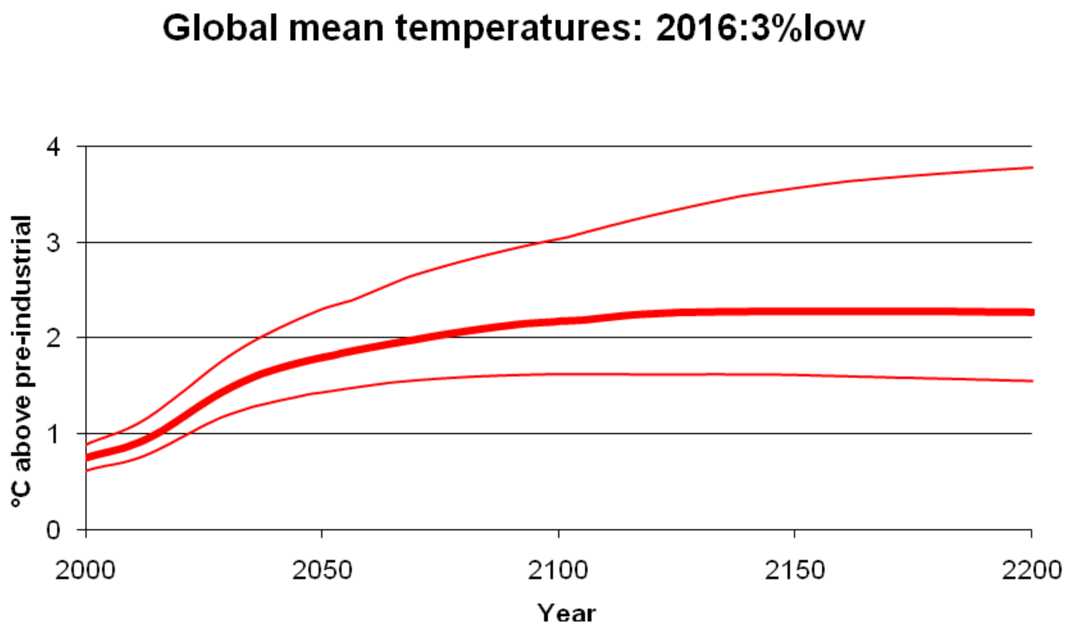
3.4 Global mean temperatures

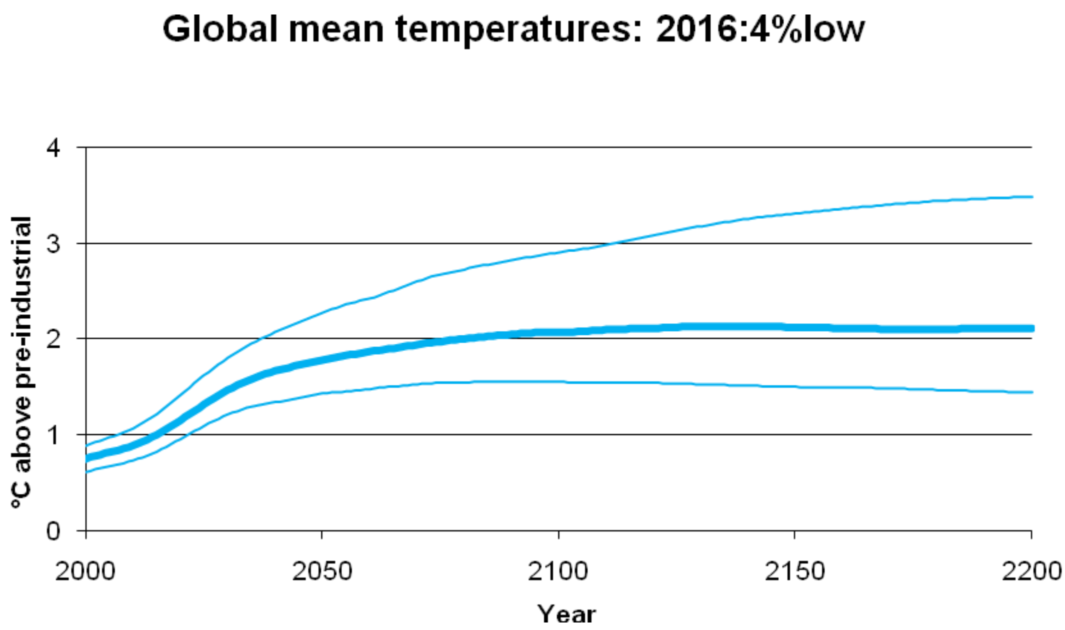
Figure 10 shows global mean temperature increase above pre-industrial levels as a function of time.

Figure 10. Modelled global mean temperature increases in degrees Celsius (°C) for the scenarios (top to bottom) SRES A1B, 2016:3%, 2016:3%low and 2016:4%low. Median MAGICC outputs are given by the thick central lines, with 10th – 90th percentile range given by the outer thin lines.









3.5 Cumulative density functions of temperature in 2100 and 2200

Probability distributions have been produced for global mean temperature increase by the years 2100 and 2200. These are plotted in the form of cumulative density functions, which represent the accumulated probability of the MAGICC outputs being below a given temperature increase, in Figures 11 & 12.

Figure 11. Cumulative density functions (cdfs) of global mean temperature increase for the year 2100. Each curve represents the range of temperature increases produced by MAGICC for each trajectory, as it samples the full range of possible climate parameter settings. Curves are shown for the family of trajectories peaking in 2016 and for SRES A1B.

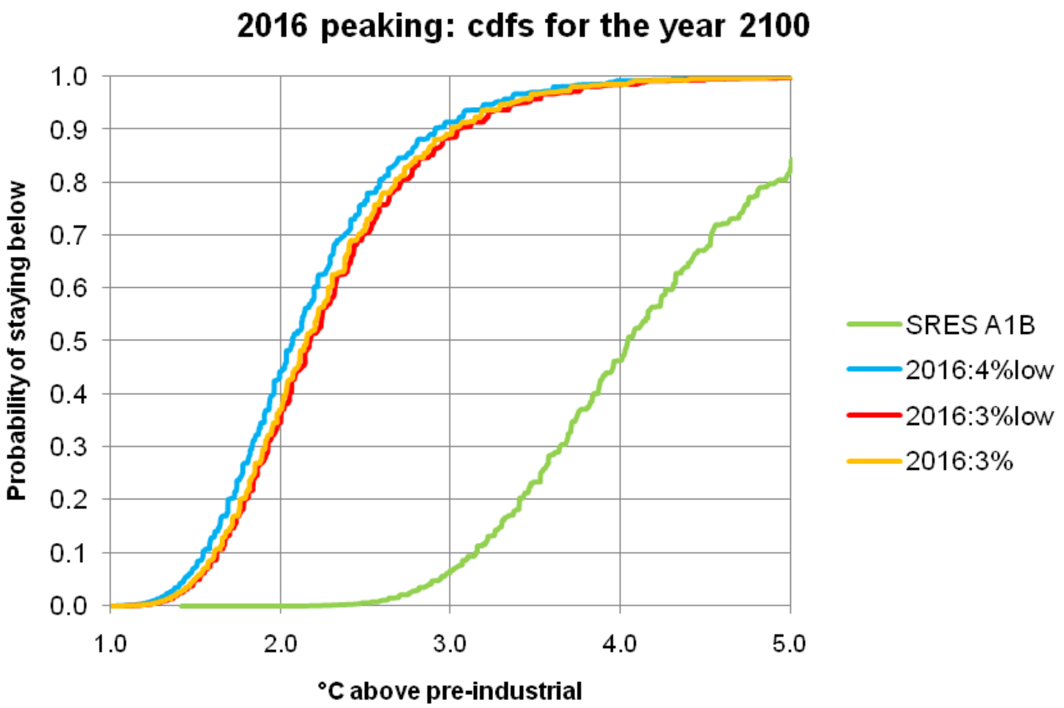
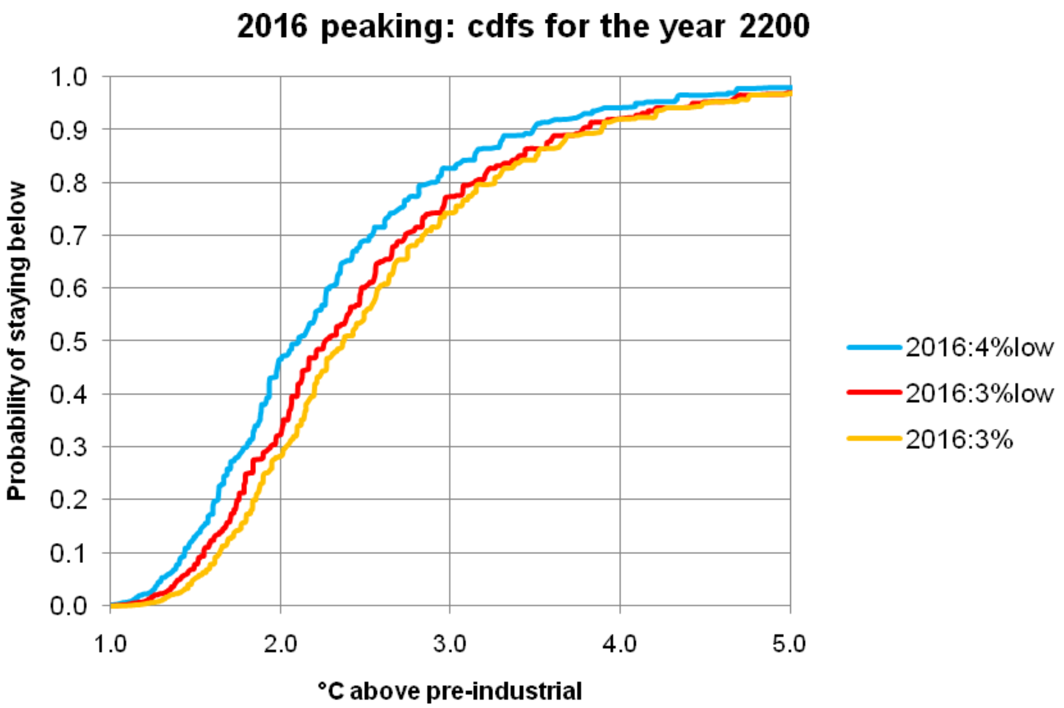


Figure 12. As in Fig. 8, but showing increases in global mean temperature for the year 2200. Curves are shown for the family of trajectories peaking in 2016 and for SRES A1B.



4. CONCLUSIONS

This technical appendix has outlined the methods used to project global GHG emissions, both for a reasonable baseline scenario and for a range of emissions reduction strategies. It has explained the approach taken to modelling the future climate effect of each emissions trajectory, and has shown summary data for those which have acted as source material for the CCC's advice in its 2008 report.

A deliberately cautious approach has been taken in many aspects of this analysis, leading to conclusions which do not overstate the effect of emissions reductions but leave room for a better climate outcome to occur. Specifically, observed GHG emissions from 2000 to the present lie slightly below our baseline; we have assumed a strong effort to reduce emissions by 2020 but more may be realised; our projected reductions in nitrous oxide emissions have been conservative; and the choice of climate sensitivity distribution yields relatively high temperature increases for our trajectories.

Estimates of global mean temperature increase have been given here as distributions of probability. These distributions allow current uncertainties in the behaviour of the climate system to be accounted for, and serve as a useful tool in a risk-based approach to setting climate targets. It is important to note however that the precise probability values are dependent on underlying assumptions, particularly regarding likely values of climate sensitivity. Whilst the central range of temperature estimates for each of the trajectories (for instance, the 10^{th} – 90^{th} percentile range) is most robust across the range of climate sensitivity distributions available in the literature, the extreme values of the distributions are likely to show more variation and should be taken as indicative.

A key area for further research will be to determine whether the climate outcomes produced here by MAGICC for very strong emissions reduction are borne out by the more complex, fully coupled models. Whilst MAGICC emulates these models well for baseline scenarios such as those produced by the IPCC, more work is required in observing and understanding how complex models respond to the type of emissions limits that are increasingly being called for.