High Stakes

Designing emissions pathways to reduce the risk of dangerous climate change

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Acknowledgements

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About the authors

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Foreword

'To tackle climate change', said Tony Blair in 2006, 'we now need to begin to agree a framework for after 2012 that includes a long-term goal that will stabilise the climate at a safe level' (Blair 2006a). This, he argued, 'would be the best stimulus to the action needed to reduce emissions and create the right incentives for investment in clean technology' (Blair 2006b).

With the first phase of the Kyoto Protocol due to end in 2012, it is critically important that a shared understanding is reached rapidly on what level of action is needed to avoid dangerous climate change and to shape the next phase of international commitments to be negotiated and long-term investment decisions taken by business.

The Institute for Public Policy Research (ippr) commissioned the research presented in this report to find out what that goal and the intermediary steps needed to meet it should be. It builds on previous work that ippr undertook for the International Climate Change Taskforce (Retallack 2005), created to provide advice on making progress on climate change at the international level during the UK's presidencies of the G8 and EU in 2005.

The authors of this research were commissioned to develop estimates of emissions pathways that have a high likelihood of keeping the rise in the world's average surface temperature above pre-industrial levels to below 2°C.

The 2°C target, long advocated by European governments, businesses and civil society groups alike, is far from perfect. Severe impacts and feedback mechanisms that amplify the problem are already occurring at relatively low temperature increases. Nevertheless, the importance of the 2°C objective cannot be overstated. Beyond that threshold, the extent and magnitude of impacts are likely to increase in a way that may widely be considered as being dangerous, and in some cases irreversible.

The likely impacts for a rise of between 2 and 3°C include an increase in the number of people affected by water scarcity to two billion; agricultural losses extending to the world's largest exporters of food; the loss of the world's most bio-diverse ecosystems including most of the coral reefs, and irreversible damage to the Amazon rainforest, which could result in its collapse. Particularly worrying is the likely transformation of the planet's soils and forests into a net source of carbon, causing an additional 2 to 3°C rise in temperature, and an increase in the likelihood of other abrupt changes in climate, such as the slowing-down of the Gulf Stream and the loss of the Greenland and West Antarctic ice sheets, which together would raise sea levels by 12 metres (ibid).

The stakes are clearly extremely high – high enough to merit seeking strategies that would have a high chance of avoiding such impacts. In identifying pathways to achieve that, the research published here goes several steps further than ippr's previous work in this area.

It does so by incorporating a rigorous quantitative treatment, using a standard method of risk analysis, of each of the key uncertainties in the chain of 'cause and effect' between emissions and average temperature increase. These include climate sensitivity (the long-term effect of doubling atmospheric carbon dioxide), ocean heat uptake, land use emissions (from deforestation and other activities), the carbon sink (the carbon absorbed by oceans, plants and soils) and aerosols (small solid or liquid particles from burning fossil fuels and biomass thought to have a cooling effect).

The results of this modelling are explosive, blowing away the dominant view about the scale and speed of action necessary.

The research concludes, based on a reasonable set of assumptions, that to have a 'very low to low risk' (calculated as a nine to 32 per cent chance) of exceeding the 2°C threshold, global emissions of carbon dioxide (CO_2) would need to peak between 2010 and 2013, achieve a maximum annual rate of decline of four to five per cent by 2015-2020, and fall to about 70 to 80 per cent below 1990 levels by the middle of the century. This would need to be matched by similarly stringent reductions in the other greenhouse gases.

These calculations are based on scenarios in which atmospheric concentrations of CO_2, which stand at 380 parts per million (ppm) today, peak at between 410-421ppm mid century, before falling to between 355-366ppm by 2100. This in turn is based on the understanding that CO_2 concentrations can be reduced by lowering annual emissions below the level of CO_2 which is absorbed by global carbon sinks, which currently take up approximately half of the CO_2 emitted annually by human activity.

These conclusions go further than the Stern Review, which proposes a long-term goal to stabilise greenhouse gases at between the equivalent of 450 and 550 ppm CO_2. That range has a medium to high risk of exceeding a 2°C rise in temperature.

Our modelling calculated that scenarios in which CO_2 stabilised at 450ppm had a 46 to 86 per cent chance; 500ppm had a 70 to 95 per cent chance; and 550ppm had a 78 to 99 per cent chance of exceeding 2°C. Even more troublingly, these scenarios had an 11 to 24 per cent, 18 to 47 per cent and 28 to 71 per cent chance respectively of exceeding a 3°C rise in global average temperature.

These are not freak, isolated results. This may be the most explicit examination yet of emissions trajectories oriented towards the precautionary 2°C threshold, but very similar results are beginning to appear from other researchers.

The conclusions will be daunting and deeply unpalatable for policymakers. Given that global emissions trajectories are currently heading in the opposite direction, the level of effort required to bend the global emissions curve in time is Herculean. Particularly when it might reasonably be assumed that developed countries will need to make deeper reductions in emissions than developing ones, to allow for a greater degree of equity in levels of per capita emissions over time. For countries such as the UK, that could essentially mean preparing to build a zero-carbon economy by 2050.

Ultimately, it is up to policymakers to decide what level of risk is tolerable. But given what is at stake for billions of people, precaution would surely dictate that as low a level of risk as possible should be aimed for. If we took the opposite stance – deciding today that it was acceptable to take a significant chance of exceeding 2°C – and that ended up, for example, melting the polar ice sheets, future generations would condemn us as being grossly irresponsible.

If we accept that conclusion, it places us in a new mitigation paradigm, requiring a crash programme to reduce emissions on a far deeper and more rapid scale than envisaged. It will also necessitate a step change in adaptation to climate change.

This is not a counsel of despair. The technology exists to meet this challenge: we know how to achieve substantial increases in energy efficiency, generate energy without fossil fuels, and reduce emissions from the destruction of forests and soils. The challenge for governments is to adopt the policies and direct the level of resources necessary to do this in time.

It is the timetable for action, above all, that our research shows we urgently need to rethink. We do not have decades in which to bend the global CO_2 curve: we have less than ten years. What we do now at the global level will be of critical importance.

The United States, the world's largest greenhouse gas emitter, can no longer sit on the fence: it needs to adopt a national cap on its emissions without further delay. While the developed world will need to continue to do the most, the highest emitting developing countries such as China will also need to be engaged far more substantially and far sooner than previously thought, with developed countries almost certainly needing to prepare to pay for the bulk of climate mitigation efforts there.

All of this of course is likely to be enormously difficult and will be characterised as unrealistic in the current political environment. The gap between what is necessary and what seems feasible clearly looms large. But if we want to avoid significant risks of appalling global harm, we will need to re-imagine what is feasible.

If at the end of the day we conclude that the challenge is simply too great, we should at the very least be honest about the risks we are incurring and imposing on others.

Simon Retallack
Head of the Climate Change Team, ippr

Executive summary

As increasingly alarming reports of current impacts from human-caused climate change hit the news, policymakers are paying greater attention to the challenge of setting long-term climate objectives and the short- to medium-term policies needed to achieve them. In doing so, they quite reasonably ask what policies – what stabilisation targets for atmospheric levels of greenhouse gases (GHGs) and ultimately what emissions targets – would offer assurance of avoiding intolerable impacts.

It is clear that policymakers are dependent on scientists to know the likely impacts from any level of temperature increase and, similarly, the likely temperature consequences of any emissions reductions policies. And indeed, as we try to do here, scientists can usefully estimate – though necessarily imprecisely – the emissions policies necessary to reduce temperature and impacts risks to any chosen level.

What science alone cannot tell us is what should be considered 'acceptable risk', or alternatively, in the language of the United Nations Framework Convention on Climate Change (UNFCCC), what is 'dangerous anthropogenic interference with the climate system'. Such a choice demands not just scientific reasoning, but also ethical and political judgment. Until now, the most widespread interpretation of 'dangerous climate change' (we blur for the moment any distinction between this and 'dangerous anthropogenic interference') has been the definition of the '2°C threshold'. The goal of holding global average temperature increase to less than 2°C above the pre-industrial level (compared with the current increase of roughly 0.7°C) has been a stated objective of the European Union, including the UK government, for a number of years.

A discussion of the justification of the 2°C threshold would take us far beyond the scope of this paper, but based on earlier work (Baer 2005, Retallack 2005) we suggest that the likely and possible consequences of exceeding the 2°C threshold warrant seeking a *high to very high likelihood of staying below it*. We interpret this quantitatively as requiring in the order of no more than a 10 to 25 per cent likelihood of exceeding the threshold. We choose this range, however, not because we are comfortable with such a risk, but because these are reasonable numbers that quite starkly show the urgency of our situation. Moreover, the methods we demonstrate are independent of any policy prescriptions about levels of acceptable risk.

Recent research has robustly shown that a high likelihood of keeping the long-term warming below the 2°C threshold requires the stabilisation of the net 'effective' concentration of GHGs (including the offsetting effects of aerosols, small airborne particles or droplets which reflect sunlight) below the level equivalent to 400 parts per million (ppm) of carbon dioxide (CO_2) (Meinshausen 2006, Baer 2005). For reasons we discuss in the text, this net level of CO_2-equivalent (CO_2-e) is very likely to be exceeded in the coming decades.

However, because of the time lag between the increase in GHG concentrations and the increase in temperature – what we call 'thermal inertia' – the atmosphere need never reach the maximum level of temperature 'implied' by the GHG concentration peak (the long-term temperature that would be reached if CO_2-equivalent concentrations were held at that peak level indefinitely). The faster and further that GHG concentrations can be lowered below their peak, the lower will be the peak temperature increase that is eventually reached.

Our primary focus in this study, then, is to develop estimates of emissions pathways that lead to a 'peak and decline' in both CO_2 concentrations and in the net equivalent CO_2 concentration (including other GHGs) and that have a high likelihood of keeping the average surface temperature below the 2°C threshold. This requires us to be able to estimate the likely temperature pathway of any emissions scenario, using a method that reflects the many uncertainties in the chain of cause and effect between emissions and average temperature increase. To produce these estimates of likely temperature increase, we use a standard method of risk analysis called 'Monte Carlo modelling'. However, because none of the important uncertainties can be quantified precisely, the risk estimates that are the output of the model must necessarily be presented as ranges.

Although our focus is on 'peak and decline' scenarios, we include here an example of a calculation of risk associated with a more familiar stabilisation scenario that is a common focus of the policy debate, in which CO_2 concentrations reach 450 ppm and are held at that level indefinitely. In this example, in which other non-CO_2 GHGs are counted separately (but in fact held to rather optimistically low levels) we calculate the following estimated risks for the likelihood of exceeding various temperature thresholds in the next 200 years:

- Risk of exceeding 2°C: between 46 and 85 per cent

- Risk of exceeding 2.5°C: between 21 and 55 per cent

- Risk of exceeding 3°C: between 11 and 24 per cent

- Risk of exceeding 3.5°C: between 4 and 11 per cent

Scenarios in which CO_2 concentrations reach 500 or 550 ppm have a correspondingly greater risk of exceeding 2°C: 70-95 per cent and 78-99 per cent respectively.

Why the range? Why can we not give a more precise estimate of the likely temperature increase?

To explain this requires us also to explain something very important about this kind of risk modelling. Put simply, what a Monte Carlo model does is calculate an estimate of the likely value of some 'output variable' (such as temperature in 2100) on the basis of assumptions about the likely values of several uncertain 'input variables' (such as the climate sensitivity, defined as the estimated long-term increase in global average temperature in response to a doubling of atmospheric CO_2). Generating a single result requires making specific assumptions about how to quantify the uncertainty in each input variable. But for variables such as the climate sensitivity, there is a variety of reasonable assumptions about how best to quantify its uncertainty. Therefore the *range* of calculated output will reflect the range of reasonable input assumptions.

What do we mean by 'reasonable assumptions'? Roughly speaking, an assumption is reasonable if one knowledgeable scientist would not consider another to be crazy or dishonest for using it in their calculations. What follows from this is that, while there may be disagreement about the borders between reasonable and unreasonable, there is in any field enough background agreement to fix some assumptions to be 'clearly reasonable' and others 'clearly unreasonable'.

We will return briefly below, and in much greater detail in the text, to the importance of the idea of 'a range of reasonable assumptions'. First, however, having explained very briefly what 'a result' looks like and why it is described as a range, we turn to our key results.

The central results of our risk analysis are temperature projections for a set of stringent emissions mitigations scenarios, again expressed as a range of likelihood of exceeding various temperature thresholds. In the text, we discuss six indicative scenarios in which CO_2 concentrations peak between about 410 and 430 ppm (versus today's 380 ppm) and then decline to between about 350 and 400 ppm. This requires a very rapid peak in global CO_2 emissions, as well as very steep subsequent reductions.

In the six scenarios we model, global emissions peak between 2010 and 2014, and the maximum annual rate of emissions reductions – between three and five per cent (depending on the scenario) – are reached between 2015 and 2020. (We discuss the modelling of non-CO_2 GHGs and aerosols in the text.) Here we show the results for the highest and lowest of the scenarios and one in between. The results for global CO_2 emissions are sobering:

- Peak in 2014, three per cent maximum annual rate of decline, 48 per cent reduction below 1990 levels by 2050: 20-49 per cent risk of exceeding 2°C.

- Peak in 2010, three per cent maximum annual rate of decline, 57 per cent reduction below 1990 levels by 2050: 16-43 per cent risk of exceeding 2°C.

- Peak in 2010, five per cent maximum annual rate of decline, 81 per cent reduction below 1990 levels by 2050: 9-26 per cent risk of exceeding 2°C.

More details are given in Table 4.1 on page 24. However, the message should already be clear: while very rapid reductions can greatly reduce the level of risk, it nevertheless remains the case that, even with the strictest measures we model, the risk of exceeding the 2°C threshold is in the order of 10 to 25 per cent.

What these calculations show is that, if the 2°C threshold is taken seriously, our situation is indeed very urgent. Clearly, accepting 'stabilisation at 450 ppm CO_2' as the best that can be hoped for is to accept a significant, even high, likelihood of exceeding 2°C, with a corresponding likelihood of severe consequences. Yet just as clearly, the effort required to reduce the risk of exceeding the 2°C threshold to low levels requires action that starts sooner and moves more quickly than would be characterised as practical in today's political climate.

In this paper we attempt to show, for both technical and non-technical readers, how our results are

calculated, how they should be interpreted, and why we believe they are robust. To repeat the point that we made above, the estimates of risk we calculate are reported as ranges that reflect the range of reasonable assumptions about the uncertainty in our input variables. Another team using a different model and a different set of assumptions about quantifying uncertainty will come up with a different number (actually, a different range of numbers), but our claim is that our assumptions are reasonable and that, therefore, other reasonable ranges must overlap ours.

In addition to our modelling of global emissions scenarios, we also make estimates of the allowable emissions for the UK under our peak-and-decline scenarios. Assuming that global per capita emissions of CO_2 converge no later than 2050, we calculate that the UK's fair global allocation in 2050 would be in the order of 88 to 94 per cent below 1990 levels, compared with the 60 per cent cuts that have been proposed by the UK government.

Finally, we suggest that *it is now critical to decide how urgent the problem is.* If we are correct, then a precautionary approach requires near immediate efforts to 'bend the curve' of global emissions, and much steeper reductions than are currently contemplated.

Thus policymakers and scientists alike will have to decide quickly whether the assumptions we have made are reasonable. Our own conclusion is that further resolution of uncertainty is in effect policy-irrelevant, and that we do not have time to wait for more precise estimates of risk.

1. Introduction

At the time that the United Nations Framework Convention on Climate Change (UNFCCC) was adopted in 1992, there was little research available to suggest what might be considered, in the famous words of the UNFCCC's Article 2, 'dangerous anthropogenic interference with the climate system'. Some made arguments that an increase in temperature of more than 2°C above pre-industrial levels would move us beyond the 'normal range of long-term variation', and thus should be avoided (Nordhaus 1979, cited in Oppenheimer and Petsonk 2005). On the basis of this and other plausible but preliminary lines of argument, the EU, the British government and a variety of other institutions adopted 2°C above pre-industrial as a temperature threshold to be avoided.

However, this was largely a 'placeholder', as little serious effort was made to estimate emissions pathways likely to keep below this level, or even to specify in any fashion how important it might be to do so in terms of avoided impacts. Furthermore, in the late 1990s and until fairly recently, policymakers' attention was focused on the negotiation and ratification of the Kyoto Protocol, and the question of long-term objectives was relegated to the back burner.

This is now changing. Evidence of current impacts from climate change is accumulating, as is evidence of risks of severe impacts at relatively low temperature increases and of possible feedback mechanisms that amplify the problem (Schellnhuber *et al* 2006). It is increasingly recognised among scientists and others that limiting temperature increase to 2°C will not necessarily avoid severe regional, and possibly global, impacts, including:

- damage to vulnerable ecosystems such as coral reefs, arctic and montane regions (the high-altitude slopes of mountains)

- the possibility of triggering partial deglaciation of the Greenland or West Antarctic ice sheets, leading to potentially significant sea level rise

- serious harm, particularly in developing countries, from increased intensity of storms, floods and droughts

- the possible release of stored carbon from forests or peat bogs that might cause a significant increase in greenhouse gas (GHG) concentrations in the atmosphere.

There is also growing evidence that, independent of the effects on climate, simply increasing the atmospheric concentration of CO_2 may cause enough acidification of the oceans to have serious impacts on ocean food webs.

Furthermore, the policy context has also changed. The Kyoto Protocol is in force and formal negotiating steps towards a post-2012 agreement are underway. The UK government has begun to address long-term objectives in a variety of ways, including commissioning the recently published Stern Review, a significant internal review of impacts and mitigation costs (see www.sternreview.org.uk). Broadly speaking, a new phase of action is on the table, and it is increasingly clear that the timeframe for response is shorter than previously recognised.

Recent policy analyses based on current scientific knowledge of the *climate sensitivity* – defined as the long-run warming expected from a doubling of CO_2 concentration from its pre-industrial level (see Appendix for additional explanation) – have concluded that keeping the risk of exceeding an eventual increase of 2°C to even 20 per cent requires stabilisation of GHG concentrations (and other contributors to climate change) at a net level at or below the equivalent of 400 ppm CO_2.

Yet the current atmospheric concentration of long-lived GHGs – CO_2, CH_4 (methane) N_2O (nitrous oxide), CFCs (chloroflurocarbons) – is already equivalent to about 450 ppm of CO_2, while the overall net level of all the agents affecting temperature is estimated still to be below the equivalent of 400 ppm of CO_2, only due to masking from aerosols (very fine airborne particles and droplets largely arising from burning fossil fuels and biomass).[1] Thus it is almost certain that we will reach CO_2-equivalent levels well above 400 ppm in the coming decades.

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1. The Intergovernmental Panel on Climate Change's Third Assessment Report (the TAR) (Houghton *et al* 2001) declined to provide an explicit estimate of net radiative forcing, but summarised evidence suggesting that net forcing was about 370 ppm CO_2-equivalent, and all the included modelling studies which estimated future temperature increase began from about this level. The forthcoming Fourth Assessment Report ('AR4') is likely to make this judgment explicit.

The overall impact on the atmosphere of GHGs and other contributors to climate change is summarised by the concept of *radiative forcing*, defined as the change in the energy balance of the planet and measured in Watts per square metre (Wm^{-2}). Positive radiative forcing (as from GHGs) causes overall warming near the earth's surface, while negative radiative forcing (as from sulphate aerosols) causes cooling near the earth's surface.

As described above, the net contribution to radiative forcing from various GHGs and other factors (for example, changes such as the conversion of forests to cropland that add 'negative forcing' by increasing the reflectivity of the planet's surface) can be mathematically converted to an equivalent concentration of CO_2 (measured in ppm CO_2-equivalent, or CO_2-e). And as we will show in the remainder of this study, it is our ability to control the pathway of net radiative forcing – and our uncertainties about both its current level and future behaviour – that will determine the level and rate of warming that we experience.

Even though net radiative forcing is likely to exceed 400 ppm CO_2-equivalent this century, it is still possible to achieve lower long-term levels through peak and decline pathways for CO_2 concentrations and net radiative forcing. CO_2 concentrations themselves can be reduced by lowering annual emissions below the level of CO_2 that is absorbed by global 'carbon sinks' (oceans, plants and soils), which currently take up approximately half of the CO_2 emitted annually by human activity.

While there is uncertainty about the future uptake of carbon sinks (particularly if the global temperature increase is large or rapid), reasonable assumptions, as made in this study, suggest that the reduction of CO_2 concentrations is feasible even without strategies that create effective 'negative emissions' (such as sequestering the CO_2 from biomass combustion).

Furthermore, some of the other contributors to warming – particularly methane, soot and tropospheric ozone[2] – have short atmospheric lifetimes, and their concentrations and thus their warming impact can be reduced quickly by reducing annual emissions. But because of the existing levels of GHGs and the various 'locked in' increases in radiative forcing, assuring stabilisation below 400 ppm CO_2-equivalent will almost certainly require a substantial drawdown of CO_2 below peak concentration levels, with emissions being held well below the rate of uptake by carbon sinks for many decades.

In this context, there is now an urgent need to define precautionary emissions pathways in quantitative terms. It is not our task here to justify the 2°C target in any detail. We have instead taken it as our scope of work to begin from this point, and to identify emissions pathways that have a high likelihood – which we characterise as in the order of 80 to 90 per cent – of keeping the peak in global mean temperature below that level. For while we cannot practically have certainty of staying below 2°C in the short run, the higher and longer that temperatures exceed 2°C, the greater the impacts will be and the greater the likely difficulty of subsequently reducing GHG concentrations and temperature.

We briefly discuss in Section 2 our methods and their interpretation. In Section 3 we discuss our model in slightly greater detail, and in particular we give an overview of each of the key uncertainties we incorporate. Readers who are less interested in the structure of the model can skip ahead to Section 4, in which we present our key results. Section 5 translates the results into consequences for the UK. Section 6 concludes with a more detailed discussion of the interpretation of the results and their implications for policymaking. Technical details of the model are available separately.

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2. Tropospheric or 'ground level' ozone is both a major 'conventional' air pollutant and a significant contributor to global warming.

2. Methods and interpretation

Sources of uncertainty

Any analysis that connects CO_2 emissions to temperature increase must address a complex causal chain in which the key elements, while now well understood qualitatively, are subject to substantial quantitative uncertainty.

In this study we focus on incorporating a rigorous quantitative treatment of uncertainty in five key subsystems of the overall climate system: climate sensitivity, thermal inertia, current land use emissions, the carbon sink and current aerosol forcing. We briefly discuss these subsystems (see Section 3 and the Appendix for further discussion of each component). In all cases the authoritative sources are the reports of the Intergovernmental Panel on Climate Change's (IPCC) Working Group One.

Climate sensitivity

As mentioned above, the climate sensitivity is defined as the long-term response of global average temperature to an increase in radiative forcing equivalent to a doubling of atmospheric CO_2. This is one of the most important sources of uncertainty in projections of future global warming. The IPCC has, historically, stated only that the climate sensitivity is likely to be between 1.5°C and 4.5°C, with no quantification of the likelihood that it is outside that range. Recently a variety of estimates of the climate sensitivity have calculated that there is anywhere from a three to a 48 per cent likelihood that the climate sensitivity is greater than 4.5°C (see Appendix).

Thermal inertia

The long-term temperature increase in response to a specified increase in radiative forcing is defined by the climate sensitivity. However, the rate at which the actual surface temperature will increase towards that long-run equilibrium is a consequence of the thermal inertia of the system – that is, how long it takes the system to heat up with a given increase in energy, just as, for a particular size of flame under a pot of water, the time the water takes to boil depends on how much is in the pot. The rate at which the atmosphere warms up in response to an increase in radiative forcing is determined primarily by the rate at which heat is transferred into the ocean, a process which is difficult either to measure or to model.

Current land use emissions

Emissions from deforestation and other land use activities (for example, the continued tilling of existing agricultural land) are a significant component – between perhaps 15 and 30 per cent – of annual global CO_2 emissions. The large uncertainty in this component has a variety of consequences for projected CO_2 concentrations and thus projected temperature increase. Uncertainty in current emissions implies an uncertainty in total emissions over time if reductions are defined, as in this study, in annual percentage terms. Furthermore, our best estimates of the amount of carbon currently being absorbed by plants, soils and the oceans depend on this estimate of human land use emissions (see next section).

The carbon sink

Only about half of the CO_2 emitted by humans every year remains in the atmosphere, the rest is reabsorbed into the oceans, plants (which take it up through photosynthesis) and soils (as plants and their leaves and other parts decompose). These pools of carbon and the annual flows of carbon into them are called 'carbon sinks', and in the aggregate is known as 'the carbon sink' or 'the global carbon sink'. (Note that one can also refer to the carbon that remains in the atmosphere as the 'atmospheric sink'.)

Put simply, as long as annual emissions are greater than the annual global carbon sink, atmospheric CO_2 concentrations will increase. Today the best estimates are that annual CO_2 emissions are about eight gigatonnes of carbon (GtC) (1 GtC $=10^9$ – or one billion – tonnes of carbon[3]), plus or minus about one gigatonne, and the global carbon sink is about 4 GtC, again plus or minus about one gigatonne. Thus,

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3. This measures the amount of carbon in the CO_2 emitted. Sometimes emissions are reported in tonnes or gigatonnes of CO_2, including the mass of the oxygen atoms – the conversion factor is 44/12, or 3.67. Measured this way, annual global emissions are about 30 billion tonnes (30 Gt) of CO_2.

straightforwardly, the stabilisation of atmospheric CO_2 concentrations requires emissions to be reduced to 4 GtC, a reduction of about 50 per cent from today's emissions.

Again, the level or 'size' of the global carbon sink today isn't precisely known, nor is it clear exactly how it will respond in the future. Increasing CO_2 concentrations are presumed to be the main reason why the oceans and biosphere are storing increasing amounts of carbon, and thus the continued increase in CO_2 should, if anything, make the annual sink larger. But it is widely recognised that global warming itself is likely to lead to a reduction in the size of the carbon sink (as, for example, rising temperatures cause forests to dry out and die), and the point at which these two effects might offset each other is not known.

Current aerosol radiative forcing

As described above, the small solid or liquid particles known as aerosols are believed to make a substantial net negative contribution to radiative forcing, masking or offsetting the warming from CO_2 and other greenhouse gases. The dominant direct effect of these aerosols is the reflection of sunlight, hence their effective cooling. Some aerosols (such as soot) do however absorb sunlight, producing a warming like that from GHGs, and reducing the overall negative effect.

A second consequence is a change in the behaviour of clouds, which both reflect sunlight and trap heat at the surface. As aerosols form the nuclei around which water condenses to form clouds, increases in aerosol concentrations change the amount and longevity of clouds. These so-called 'indirect' effects are very uncertain, but they are believed to add as much or more to the negative forcing from aerosols as the direct effects.

Monte Carlo models and probability distributions

The results presented in this analysis come from a simple computer model which incorporates mathematically the uncertainty in each of the five system components described above. The model uses Monte Carlo analysis, so-called because the results are based on many (typically hundreds or thousands) of runs of the same scenario, with a random number generator producing a different value for each of the uncertain parameters in each run, and with the odds (in the form of probability distributions, or probability density functions (PDFs)[4]) for each variable determining how likely any given value is to be picked each time. PDFs are numerical representations of our estimate of the likelihood of some event occurring, or of a quantity having some particular value. An introduction to probability distributions is given in Box 2.1.

Box 2.1 Probability distributions

We are all familiar with probability distributions in gambling, as we understand that rolling one fair die produces an equal chance of each face coming up, while rolling two fair dice has the highest probability of turning up seven, and the lowest chance of turning up two or twelve. A graphical representation of the probability distribution of the outcome of rolling two fair dice is shown in Figure 2.1.

Figure 2.1 Probability distribution of outcome of rolling two fair dice
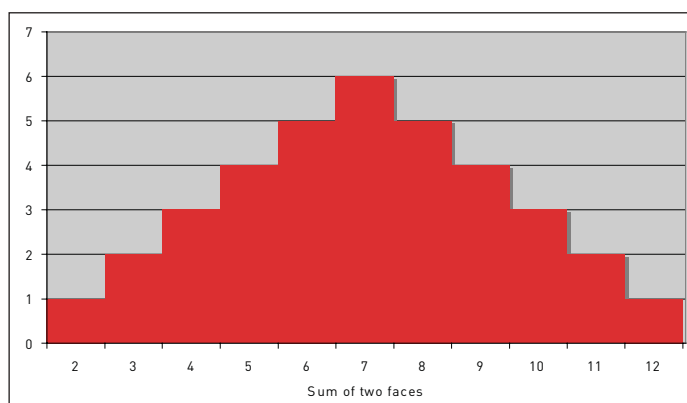
In computer modelling, two common probability distributions or PDFs used to represent uncertain quantities are the *uniform distribution*, in which the variable is equally likely to take on any value between its minimum and maximum, and the *normal distribution*, the familiar bell curve, in which the central value is most likely, and the tails are symmetrical and can be anywhere from very wide to very narrow. In Figure 2.2, we show two examples of probability distributions that might be used to represent the historical characterisation of the climate sensitivity as 'likely to be between 1.5 and 4.5ºC'.

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4. PDF – probability density function – is a technical term that is, for practical purposes, interchangeable with probability distribution, and is commonly used for brevity, a convention we will adopt.

Box 2.1 cont.

Figure 2.2 Example of uniform and normal probability distributions that match the IPCC range for the climate sensitivity. Normal distribution has a mean of 3.0ºC and a standard deviation of 0.75
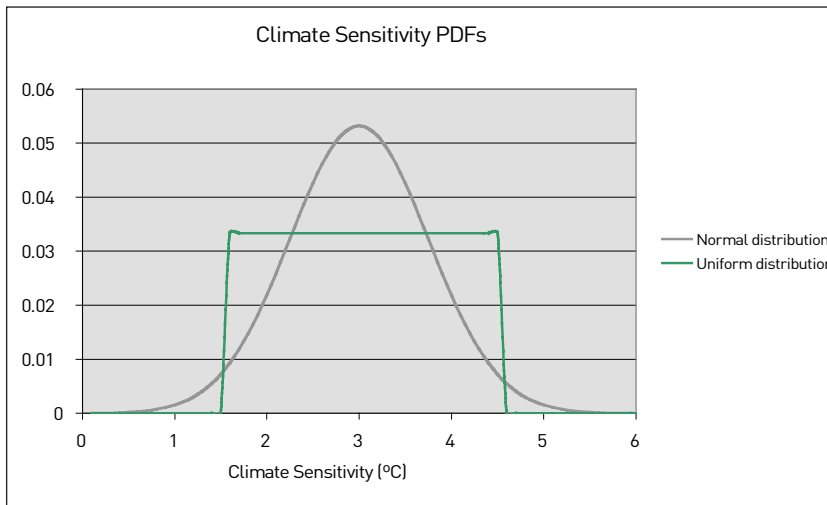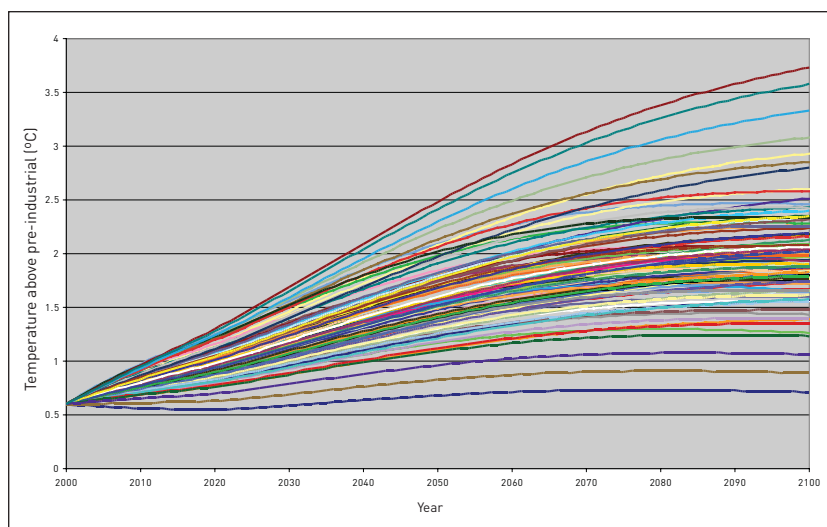

Climate Sensitivity PDFs

Normal distribution
Uniform distribution

Figure 2.3 Example of a probability envelope for temperature from 100 runs of our Monte Carlo model

As we noted above, normal distributions are symmetrical, with the central value defined by the mean (average), and the width of the tails defined by the *standard deviation*, such that about 68 per cent of the distribution is within plus or minus one standard deviation of the mean, about 95 per cent of the distribution is within plus or minus two standard deviations from the mean, and about 99.7 per cent of the distribution is within plus or minus three standard deviations from the mean. In the example given in Figure 2.2, the mean is 3ºC and the standard deviation is 0.75, so that the 1.5ºC and 4.5ºC limits of the IPCC range are exactly plus and minus two standard deviations. Thus about five per cent of the distribution is in the two 'tails' that extend beyond the 1.5º and 4.5º limits.

Just as a probability distribution, or PDF, represents the uncertainty in a specific quantity, we coin the term 'probability envelope' for the uncertainty in a time series such as the pathway of temperature in the 21st century.

Figure 2.3 shows a probability envelope for the increase in global mean surface temperature for our reference scenario, given a particular set of input PDFs. For each of the 100 runs displayed, different values of each of the uncertain input parameters were selected by a random number generator; the colours serve only arbitrarily to indicate the different runs. The density of lines at any level of temperature increase is an indication of the likelihood, as calculated by the model, of reaching that temperature. Thus we can see that the most likely value of temperature in 2100 is about 2ºC above pre-industrial, with a small possibility that it is over 3ºC and an even smaller possibility that it is under 1ºC.

For reasons that need not concern us here, the estimates of probability at the tails of a distribution in a modelling result of this kind are particularly unreliable. Therefore, even though it is clear that only one of the paths is under 1ºC in 2100, it wouldn't be appropriate to say 'the likelihood of the temperature increase being under 1ºC in 2100 is one per cent'.

Also, it is important to realise that in a complex model of this kind, many of the individual temperature pathways that are calculated will cross over each other. Thus there is no straightforward definition of the median pathway (the median of a distribution is the value for which exactly half are higher and half are lower, and is often the best indicator of the central tendency of a distribution). The value of this graphical representation, however, is that it allows us quickly to see how the median and spread change over time, which would otherwise require us to report the distribution separately at several different time steps, either numerically or graphically.

Using this terminology, our Monte Carlo model calculates an estimate of the likelihood of a given temperature response by specifying the input PDFs for each of the parameters (variables) treated as uncertain, and then running the model many hundreds of times. The results of these multiple runs are then aggregated to form an output PDF, which is interpreted as a measure of risk of the consequences of the given policy. For example, 500 runs of the model using a particular emissions reduction scenario might result in 50 runs in which the temperature exceeds 2°C during the 21st century. This can be interpreted as meaning that, for the particular assumptions used in the 500 runs, there is a 10 per cent risk of exceeding the 2°C threshold.

We will discuss the interpretation of our results in greater detail in Section 4. However, there are two crucial points that cannot be overemphasised. The first is that all of the input and output PDFs represent *subjective probability* – that is to say, they represent judgment about likelihood, rather than some objective property of the world. When we say 'the likelihood that the climate sensitivity is over 4.5°C is 10 per cent', we do not mean that one out of every ten times we double atmospheric CO_2 the result will be a warming greater than 4.5°, or that on one in every ten earthlike planets the climate sensitivity is over 4.5°.

There *is* a 'fact of the matter', we are just uncertain what it is due to the limits of our knowledge. Quantifying this uncertainty as, say, a 10 per cent probability, is a way of saying that 'based on the evidence, we think it is about as likely the climate sensitivity is over 4.5°C as is that we will roll a 10 on the next roll of a 10-sided die'. And when we say that there is a 10 to 20 per cent chance that a given emissions policy will exceed some threshold, we are not quantifying what the risk or likelihood of some event *is*; we are quantifying what it is reasonable to believe – and to act as if we believe.

This may seem like an irrelevant distinction, but it helps to understand the decision-making problem we face and the consequences of the many sources of uncertainty in the climate system. We cannot ask 'yes, but what is the "true" probability distribution?', because there is no such thing, as a subjective probability distribution is, by definition, a representation of the uncertainty in one person's beliefs. And, because of the complexity of the system, there is a wide range of reasonable[5] estimates of the likely probability distributions for the climate sensitivity and other parameters such as current aerosol forcing, and so different scientists will (and do) interpret the evidence differently.

The second point is that since different input probability distributions will lead to different model outputs, there is also a range of reasonable estimates of the risks associated with any policy scenario. For example, there have been at least nine PDFs for the climate sensitivity published in the last few years (see Appendix). Using more than one of these PDFs will result in different estimates of the likely temperature consequences of an emissions trajectory, and thus *the risk estimates must be presented as ranges*.

For example, if a given policy scenario is run with three different PDFs for the climate sensitivity (as we do in this study), the calculated likelihood of exceeding 2°C in the 21st century might be eight per cent with one PDF, 12 per cent with another, and 15 per cent with a third. We will therefore typically state results in a form such as, 'the likelihood of exceeding the 2°C threshold is between eight and 15 per cent'. However, this is not the same as saying that the 'true' probability lies in this range because, at the risk of labouring the point, there is no true probability, only more or less reasonable estimates.

To make this more concrete, we demonstrate below the risk calculations for a single emissions reduction scenario. We will use what we somewhat arbitrarily define to be our reference case, in which the growth of CO_2 emissions (fossil fuel and land use emissions considered together) begins to decline in 2010 from its current growth rate (estimated at 1.75 per cent annually) and annual emissions reach their peak in 2014 and then begin to fall. The annual rate of reduction steadily increases until 2020, when emissions are dropping by four per cent , and continue to decrease at that rate throughout the 21st century.[6]

Current land use emissions have a substantial uncertainty, with most estimates ranging between about 1 and 2 GtC annually, but with lower or higher values not excluded (DeFries *et al* 2002, Houghton 2003). In panel A of Figure 2.4, we show the single emissions trajectory calculated by our reference case policy scenario if land use emissions in 2000 are specified as precisely known as 1.5 GtC annually. Panel B shows 50 model runs in which land use emissions vary in each run, producing what we call a probability

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Figure 2.4 CO$_2$ emissions in reference case: emissions rise at 1.75 per cent annually until 2010, then make a gradual transition to four per cent rate of decline by 2020, continuing through to 2100

A

Panel A: Land use emissions specified as 1.5 GtC in 2000.

B

Panel B: Probability envelope generated by 50 model runs with land use emissions defined by a normal distribution with mean 1.5 GtC and standard deviation 0.25 (see Box 2.1).
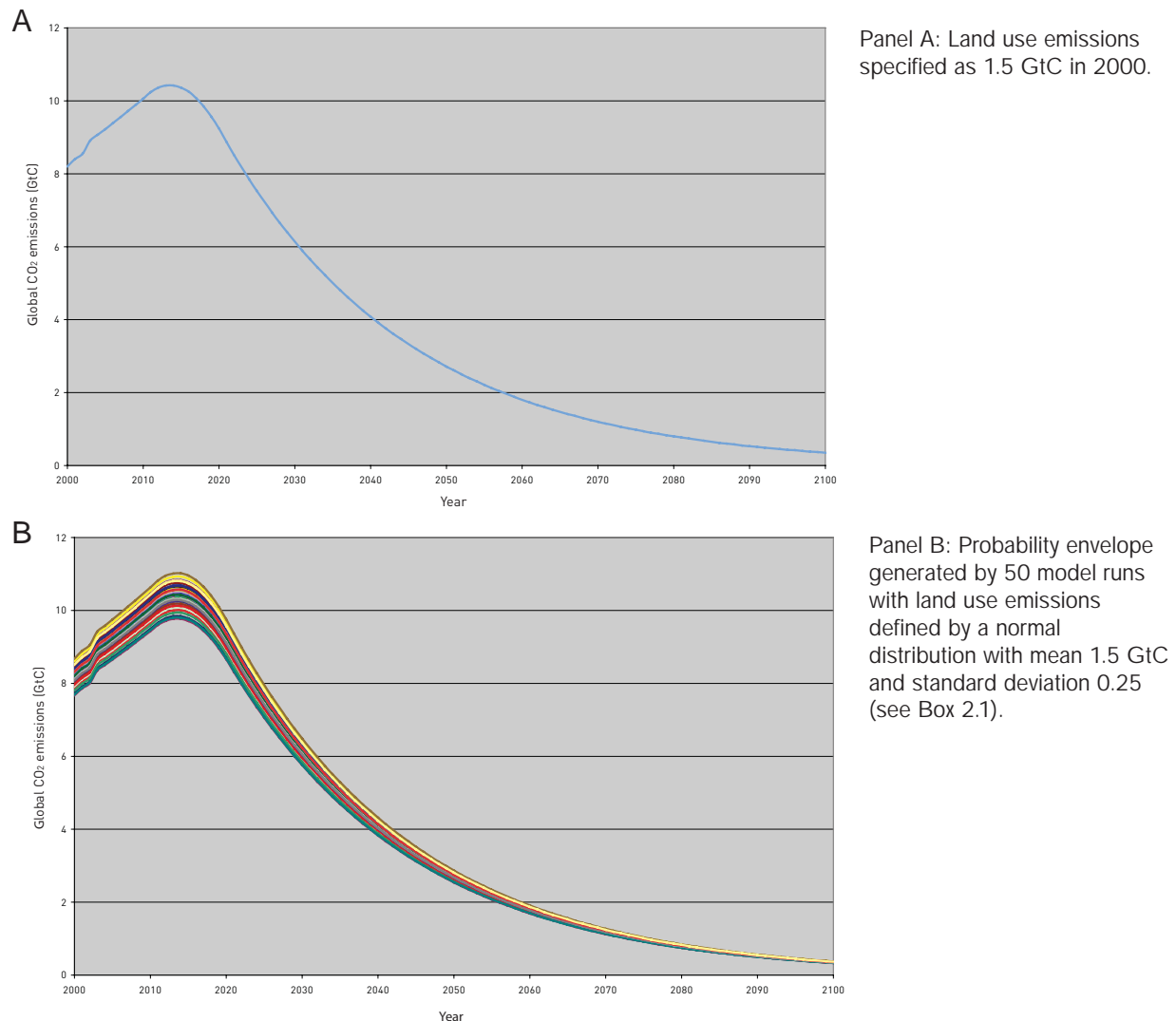
envelope (see Box 2.1). In the fixed case, cumulative CO$_2$ emissions are 415 GtC over the 21st century, in the probabilistic case, the average is 415 GtC, with a minimum and maximum of 385 and 455 GtC respectively and a fifth to ninety-fifth percentile range[7] of 395 to 436 GtC.

In Section 3, we go step by step through the treatment of each uncertainty that must be taken into account in generating a probability envelope for the global mean temperature increase for any scenario. In Figure 2.5, we skip over this complexity and show the probability envelope for temperature generated using our full Monte Carlo analysis, in which probability distributions are used for the five parameters discussed above: climate sensitivity, thermal inertia, current land use emissions, the carbon sink and current aerosol forcing. Non-CO$_2$ GHGs and other sources of radiative forcing besides aerosols (such as land cover change and solar variability) are considered to add 1 Wm^{-2} in 2000 (equal to around 80 ppm CO$_2$-equivalent[8]), and to drop to 50 per cent of that level between 2010 and 2040.

Panel A shows the probability envelope for temperature using a more optimistic PDF for the climate sensitivity, while panel B shows the probability envelope using a more pessimistic PDF (see Section 3). The

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7. The fifth percentile of a distribution is the number for which only five per cent of the values in the distribution are below it, and the 95th percentile is the number for which only five per cent are above it.

8. One of the most annoying little 'facts' about basic climate science is that there is no uniform conversion between an increment of radiative forcing when measured in units of Wm^{-2} and when measured in ppm of CO$_2$-equivalent. For example, if you add 1 Wm^{-2} of 'other' GHGs to 400 ppm of CO$_2$, you get 485 ppm CO$_2$-equivalent, but if you add 1 Wm^{-2} to 500 ppm of CO$_2$, you get 607 ppm CO$_2$-equivalent. See Appendix for further discussion.

Figure 2.5 Probability envelopes for global mean temperature generated by reference case emissions scenario described in Figure 2.4

A

Panel A: optimistic climate sensitivity PDF (based on Wigley and Raper 2001.)

B

Panel B: pessimistic climate sensitivity PDF (based on Murphy *et al* 2004). Note that the colours have no meaning other than distinguishing the different trajectories generated by the Monte Carlo model.

Note the different scale on the y-axis in Panels A and B.
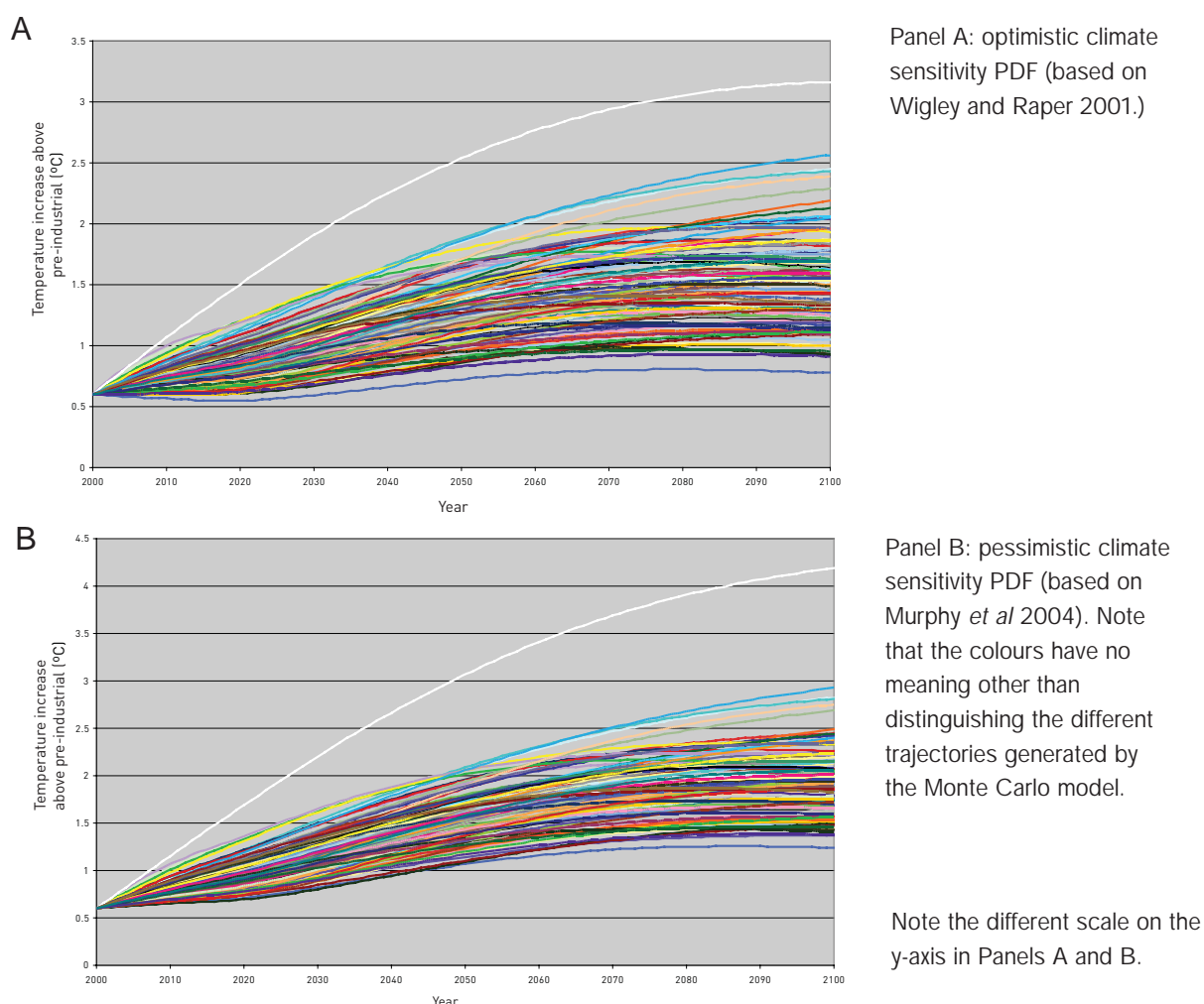
latter is visibly skewed towards higher temperatures and shows greater variability (a wider spread).

The graphs in Figure 2.5 show only 100 runs, enough to represent visually the shape of the probability envelope. To generate a statistical output distribution closer to the 'true' characteristics of the model, we need a larger number of model runs. Table 2.1 thus shows a description of the results from running the model 500 times using the two PDFs used in Figure 2.5 as well as an intermediate PDF based on Annan and Hargreaves (2006) (see Figure 3.4). These three PDFs for the climate sensitivity represent optimistic, moderate and pessimistic estimates, but not the most extreme optimistic or pessimistic possibilities.

Considering the results shown in Figure 2.5 and Table 2.1 allows us to draw two key conclusions. First, the possible temperature consequences of a given emissions scenario span a very wide range. Second, even for

Table 2.1 Statistical summary of output distribution from 500 model runs for reference case emissions scenario, using three different PDFs for the climate sensitivity

Climate sensitivity PDF	Temp increase to 2100 (ºC above pre-industrial)				Percentage of runs exceeding specified temperature threshold		
	Mean	Stand. dev.	Max	95th percentile	>2ºC	>2.25ºC	>2.5ºC
Wigley and Raper (2001)	1.5	0.5	3.2	2.4	16%	9%	3%
Annan and Hargreaves (2006)	1.7	0.4	3.2	2.5	26%	11%	4%
Murphy *et al* (2004)	2.0	0.4	4.1	2.8	43%	22%	11%

our reference case emissions scenario, which has quite rapid reductions and a peak CO_2 concentration around 425 ppm, there is still a significant likelihood of exceeding a 2°C increase in the 21st century – between 16 and 43 per cent – given our model assumptions and using different PDFs for the climate sensitivity.

It is important at this point to reiterate our main message regarding the interpretation of these results. First, none of these results represents the 'true' probability of a given temperature increase, because there simply is no such thing. The ranges reported in Table 2.1 are the consequences of a variety of reasonable alternative assumptions. Other assumptions about the climate sensitivity PDF or any of the other components would produce different ranges, and if our uncertainty about some parameters is reduced in the future, the range of reasonable probabilities may be narrowed.

But, as we hope to demonstrate in the remainder of this report, the assumptions we have made are in fact reasonable, and thus the ranges of projections produced by other models must significantly overlap ours. Indeed, related work has produced similar results (see for example Harvey in press-a, in press-b, Meinshausen 2006) but, partly because PDFs for the expected behaviour of the global carbon sinks or many other system parameters have not yet been published, there have been few similarly comprehensive attempts to integrate the full range of uncertainty.[9]

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9. Wigley and Raper (2001) and Webster *et al* (2003) have published papers that have attempted to incorporate as many of the uncertainties, but neither applies their techniques to very low emissions scenarios.

3. Incorporation of critical uncertainties

In the previous section, we gave an overview of the methods we used in this study, and very brief definitions of the key components of the climate system we include in our model. We also defined and illustrated the key concepts of probability distributions, subjective probability, probability envelopes and probability ranges. We then used those concepts to describe and interpret the results generated by the modelling of a particular emissions scenario, and explained how those results were sensitive to variations in the estimated probability distribution for one particularly important parameter, the climate sensitivity.

Readers who are not interested in the technical details but are prepared to accept our modelling methods and assumptions are encouraged to skip ahead to our results in Section 4. But for those with sufficient technical background and/or curiosity, we will in this section step briefly through the ways in which key climate uncertainties were incorporated in our model. This will, for many of our more technical readers, answer the obvious questions, 'How did they...?' and thus 'How confident should I be in their results?'. Most of the equations and discussions of model calibration will be left for supplemental materials[10] but we cannot avoid using some technical terms. The key point is to satisfy those readers who care to judge for themselves whether our assumptions, and thus our results, are reasonable.

Uncertainties in radiative forcing

The carbon sink and atmospheric CO_2 concentrations

The first step in generating a temperature envelope from an emissions pathway is to calculate atmospheric CO_2 concentrations by estimating the carbon sink over the 21st century. Predicting the future behaviour of the carbon cycle is currently a major research project of the climate science community, but there has been little effort systematically to quantify its uncertainty as a probability distribution.

Briefly, we use an extremely simple model to represent the carbon cycle. First, the carbon sink in 2000 is assumed to be directly proportional to the increase from pre-industrial CO_2 concentrations. For example, if we assume that the carbon sink in 2000 took up 4 GtC annually, and the increase of CO_2 has been around 100 ppm, we would predict that if the CO_2 concentration increased by another 50 ppm, the sink would increase 50 per cent to 6GtC annually.

Next, to account for the likelihood that, for many reasons, the annual CO_2 uptake of the oceans and biosphere would be expected to fall over time for a specified (fixed) CO_2, concentration (see Appendix), the calculated constant of proportionality decreases over the century. So, for example, if CO_2 concentration were held fixed at today's level by adjusting annual emissions to match the carbon sink, in our model the annual uptake by the carbon sink would be projected to fall by between 40 and 80 per cent by 2100. We rather imprecisely call the variable that determines this rate of decrease the 'feedback parameter' because, among other things, it simulates the feedback between temperature and the carbon cycle.[11] However, as we discuss in the Appendix, we make the decrease in the carbon sink a simple function of time, not temperature.[12]

In Figure 3.1, we show the consequences of modelling the carbon sink this way. Panel A shows the time path of CO_2 concentration for our reference case (see Figure 2.4) when land use emissions are specified as 1.5 GtC annually (as in Figure 2.4, panel A) and the feedback parameter is set to its median value. In this case CO_2 concentrations peak at 425 ppm and drop to 378 ppm in 2100, with the carbon sink averaging about 4 GtC annually over the century. Panel B shows the probability envelope for CO_2 concentration from 50 model runs when the feedback parameter is varied according to a normal distribution. In this case the peak CO_2 concentration (around the years 2030-2040) ranges from 422 to 432 ppm and CO_2 concentration in 2100 ranges from 355 to 423 ppm.

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10. Contact Paul Baer at pbaer@ecoequity.org for the most up-to-date model documentation.

11. 'Feedback' occurs when one variable – like such as the CO_2 concentration of the atmosphere – both affects, and is affected by, another variable – like such as temperature. If the response of the second variable to an increase in the first variable is an additional increase in the first variable, it is called positive feedback; if the response of the second variable to an increase in the first variable is subsequent decrease in the first variable, it is called negative feedback.

12. The probability distribution used for this feedback parameter is set to a normal distribution, which roughly reproduces the variability of the results from the Coupled Climate Carbon-Cycle Model Intercomparison Program (C[4]MIP) (Friedlingstein *et al* 2006).

Figure 3.1 Atmospheric CO_2 concentration for emissions reference scenario (see Figure 2.5)

A

CO₂ concentration (ppm)

Panel A: Fixed land use emissions, carbon cycle feedback parameter is set to its median value.

B

Panel B: Variable land use emissions, carbon cycle feedback parameter varies according to PDF with normal distribution.
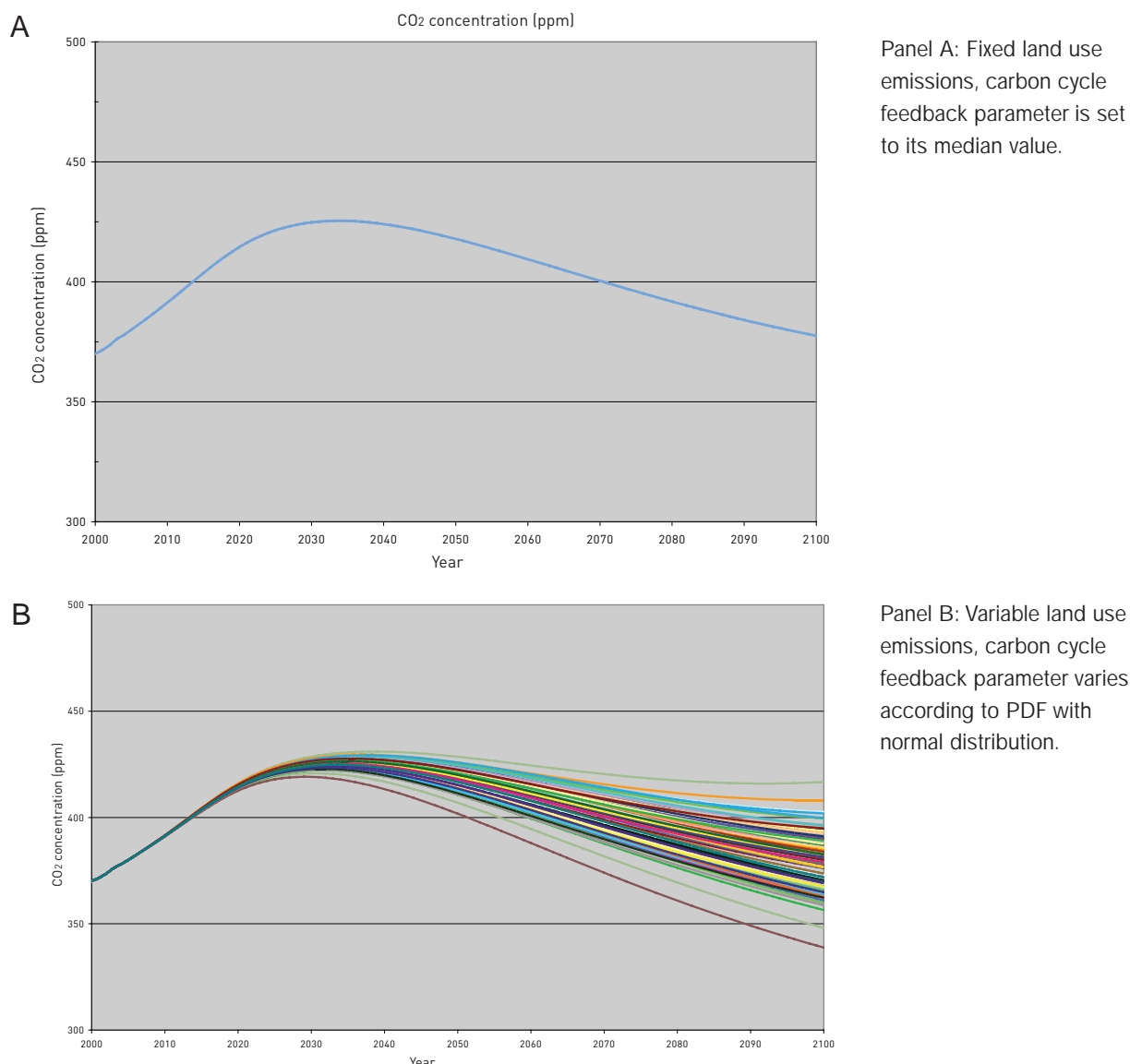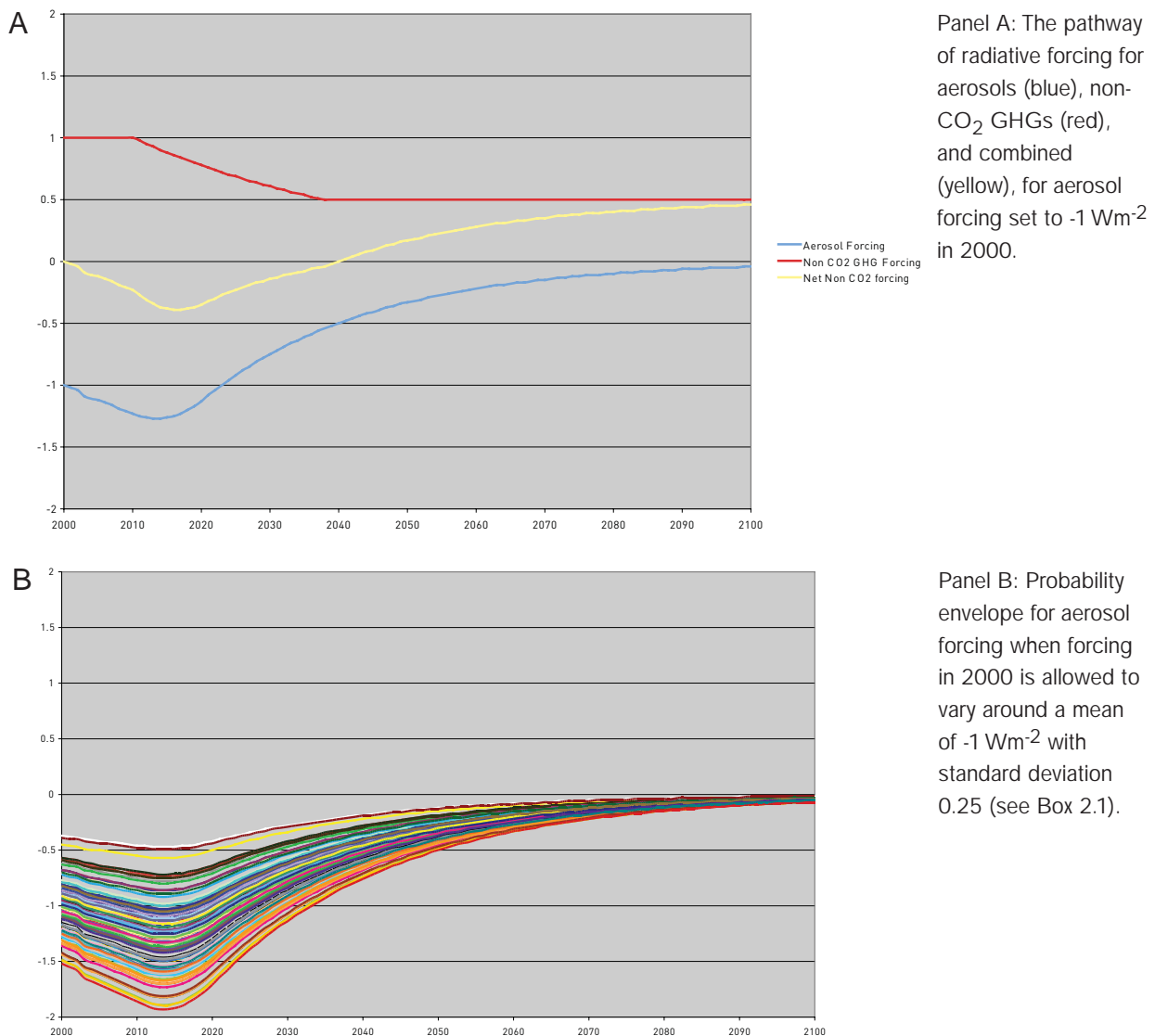
Non-CO_2 sources of radiative forcing

The next step in the calculation is the inclusion of non-CO_2 sources of radiative forcing. These include other long-lived GHGs such as CH_4, N_2O and CFCs, short-lived GHGs such as tropospheric ozone, aerosols (both cooling and warming), changes in land surface albedo (reflectivity) and solar variability. Briefly, we divide them into two components: aerosols, which are uncertain today but are treated as if they are perfectly correlated with CO_2 emissions, and the rest, which we will for simplicity call non-CO_2 GHGs, and which are treated as if they are certain today and can be precisely reduced by policy intervention.

We assume in our model that non-CO_2 GHGs add a total of 1 Wm^{-2} of radiative forcing in 2000 (equivalent to about 80 ppm of CO_2 – see footnote 7). This sum is reduced by 2.5 per cent annually, starting the same year in which GHGs begin to decline, until it reaches a 'floor' set at 50 per cent of the 2000 level, at which point it is held fixed for the remainder of the century. This pathway, shown by the red line in Figure 3.2, represents an aggressive and perhaps optimistic policy scenario, but one which we consider reasonable given the sources and atmospheric lifetimes (or other characteristics) of the agents in question, particularly in the context of rapid CO_2 reductions (see Appendix for further discussion).

Aerosols are considered to add a forcing of -1 Wm^{-2} in 2000 (effectively offsetting the 80 ppm CO_2-equivalent of non-CO_2 GHGs), with uncertainty that is normally distributed around this value with a standard deviation of 0.25 (see Box 2.1). Again, to restate our key theme, there is no 'correct' representation of this uncertainty, but this is well within the range of reasonable PDFs for aerosols as discussed in a recent

Figure 3.2 Non-CO$_2$ forcings

A

Panel A: The pathway of radiative forcing for aerosols (blue), non-CO$_2$ GHGs (red), and combined (yellow), for aerosol forcing set to -1 Wm^{-2} in 2000.

Legend:
Aerosol Forcing
Non CO2 GHG Forcing
Net Non CO2 forcing

B

Panel B: Probability envelope for aerosol forcing when forcing in 2000 is allowed to vary around a mean of -1 Wm^{-2} with standard deviation 0.25 (see Box 2.1).

expert survey (Morgan *et al* 2005). Crucially, because aerosols have very short atmospheric lifetimes and most aerosols (except dust) are highly correlated with either fossil fuel or biomass combustion, aerosol forcing is projected to grow and then decline in direct proportion to CO$_2$ emissions.[13]
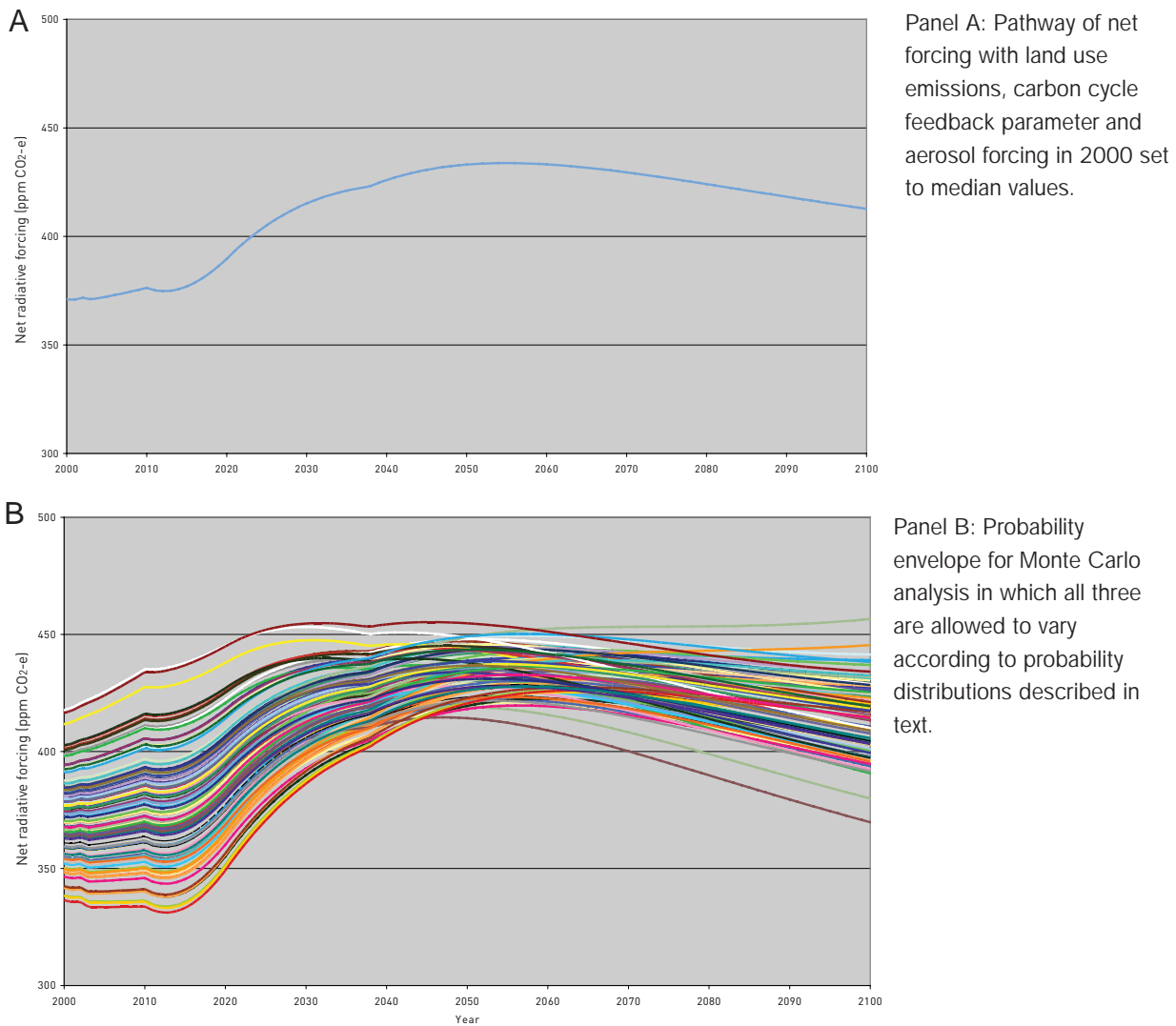
The consequences of these assumptions are shown in Figures 3.2 and 3.3. In Figure 3.2, panel A shows, for aerosol forcing set to -1 Wm^{-2} in 2000, the pathway of radiative forcing for aerosols (in blue), non-CO$_2$ GHGs (in red), and combined (in black). It shows that, in this median case, the total non-CO$_2$ forcing from aerosols and non-CO$_2$ GHGs (black) is zero in 2000, becomes slightly negative, and then rises to almost 0.5 Wm^{-2} as the negative aerosol forcing goes away over time (a consequence of its being correlated with the sharply reduced emissions of CO$_2$ in the reference scenario).

Where panel A shows the consequences of specific mid-range assumptions for each of its components, panel B shows the probability envelope, in this case just for aerosol forcing when it is allowed to vary as specified above. The level of forcing varies widely early in the century, but in all cases approaches zero as CO$_2$ emissions are reduced later in the century.

In Figure 3.3, these non-CO$_2$ forcings are combined with our reference case CO$_2$ forcing. Panel A shows the case where all variables are set to their median values. Panel B shows the complete probability envelope for

13. This method follows Wigley (1991). The general problem of the removal of negative aerosol forcings either as CO$_2$ emissions are reduced, or even sooner as nations act to reduce acid rain and particulate emissions, is also discussed in Anderson *et al* (2003), Crutzen and Ramanathan (2003) and Andreae *et al* (2005).

Figure 3.3 Net radiative forcing for reference scenario

Panel A: Pathway of net forcing with land use emissions, carbon cycle feedback parameter and aerosol forcing in 2000 set to median values.

Panel B: Probability envelope for Monte Carlo analysis in which all three are allowed to vary according to probability distributions described in text.

radiative forcing, given the uncertainty in land use emissions, the global carbon sink, and aerosols (note that the y-axis in Figure 3.2 is in Wm^{-2}, while the y-axis in Figure 3.3 is in ppm CO_2-equivalent).

Figure 3.3 panel B is particularly important, because it demonstrates the large uncertainty in radiative forcing associated with even a well-specified reduction pathway for CO_2 and non-CO_2 GHGs. These uncertainties come from both the carbon cycle and aerosol forcings, and they are, quite frankly, unlikely to be reduced significantly in the very near future. Thus, realistic emissions policies must take account of them explicitly. We will return to this later when we integrate uncertain forcing pathways with an uncertain climate response.

Uncertainties in temperature response to radiative forcing

The preceding section documents the uncertainty in radiative forcing associated with a specified emissions policy, separate from the uncertainty in the climate response. In this section, we discuss the very simple model we use to calculate the climate response (specifically the increase in global mean surface temperature) from a radiative forcing pathway.

For practical purposes, the response of the climate system to a specified level of radiative forcing can be described by two characteristics: the equilibrium response (after many centuries) to that forcing, and the rate at which the system approaches that equilibrium. The former is typically represented by the climate sensitivity, defined as the equilibrium response to an increase in forcing equivalent to a doubling of CO_2. The rate at which the system approaches that equilibrium, which we characterised previously as the system's thermal inertia, is to a first order (i.e. close enough) governed by the rate of uptake of heat by the ocean, which is in turn a consequence of ocean circulation, This is because the surface waters of the ocean –

Figure 3.4 Three climate sensitivity PDFs used in this study, from Murphy *et al* (2004), Wigley and Raper (2001), and Annan and Hargreaves (2006)
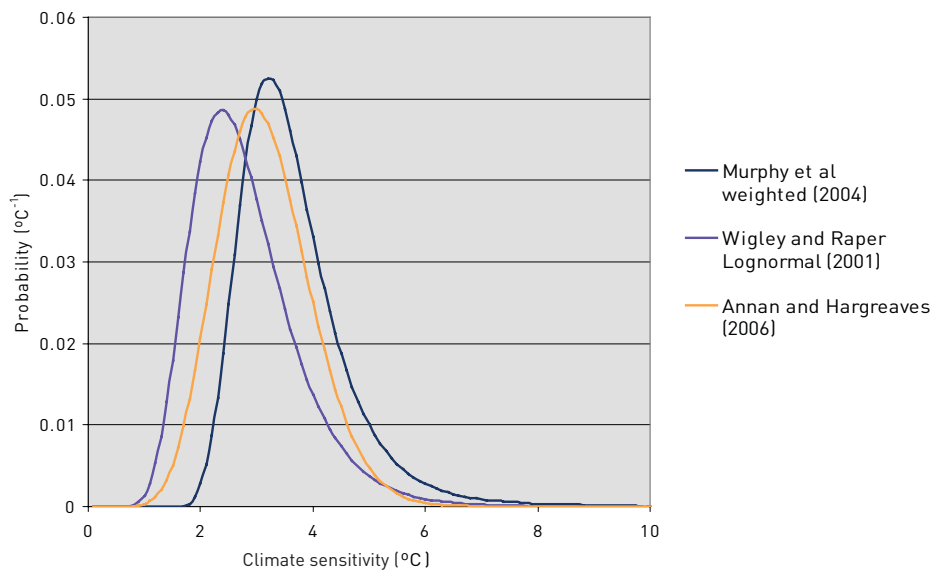
the so-called 'mixed layer' – come into temperature equilibrium with the atmosphere relatively quickly (see Appendix).

Climate sensitivity

The climate sensitivity is the most uncertain component of the climate system. The IPCC and its predecessors have, for 25 years, repeated the judgment that it is likely to be between 1.5 and 4.5ºC, with no quantification of the meaning of 'likely'.[14] In the last few years a variety of research teams have published probability distributions for the climate sensitivity, using different methods and producing quite a wide range of results. What matters for our purposes is simply that there is quite a wide range of reasonable PDFs, and thus any risk analysis must somehow incorporate that range in its methods. In this analysis we use three PDFs, ranging from 'more optimistic' to 'more pessimistic', as shown in Figure 3.4. (A discussion of these and other PDFs for the climate sensitivity is included in the Appendix.)

Thermal inertia/ocean heat uptake

There is no single parameter like the climate sensitivity that straightforwardly characterises the thermal inertia of the system and defines the transient response of temperature to forcing.[15] Our approach to the problem, following Richels *et al* (2004), is to simplify the system as much as possible, and to represent the rate of convergence to equilibrium temperature by a single parameter, a time constant, which we call tau.
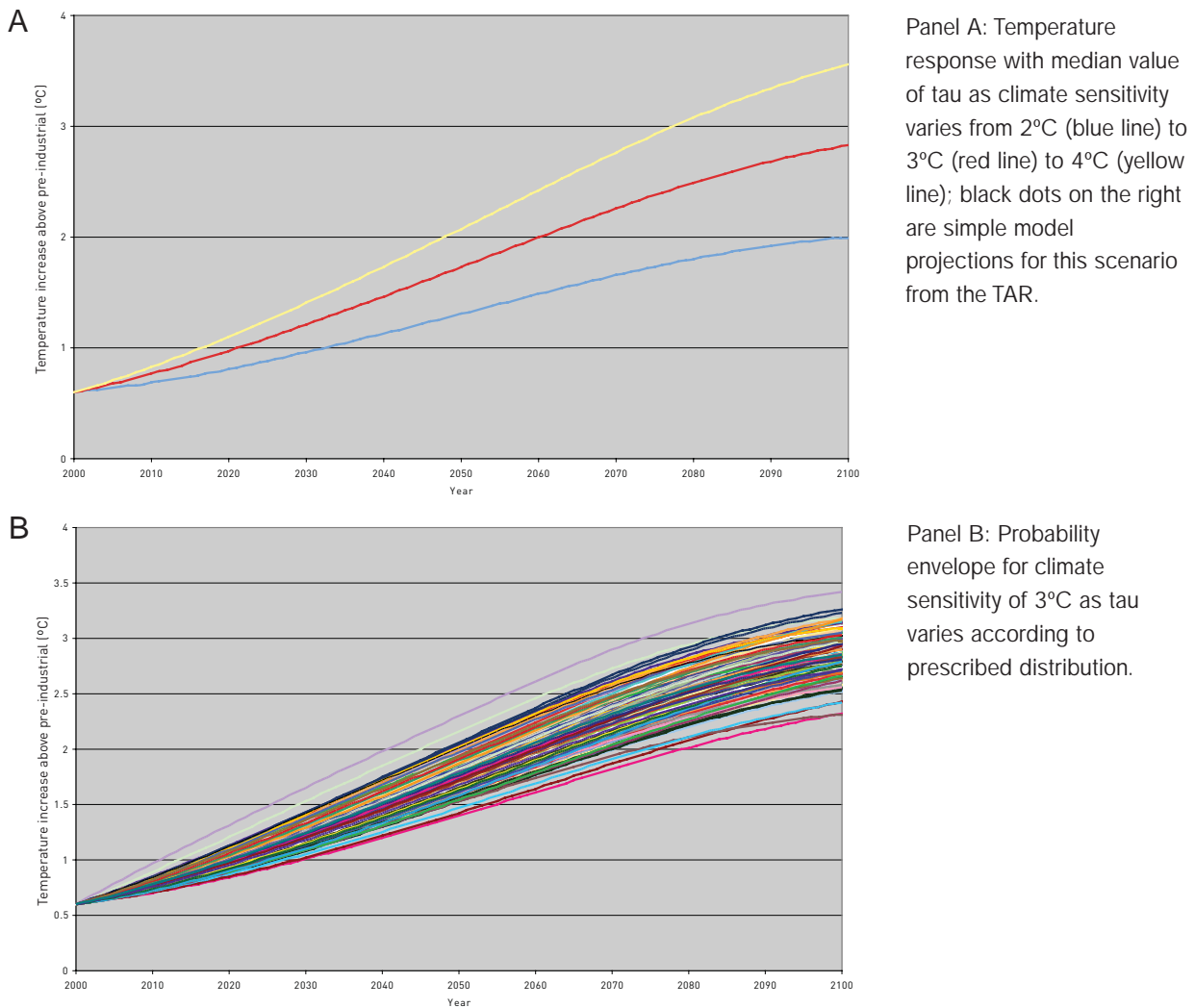
Tau determines the rate of convergence between the current surface temperature and what we call the 'implied equilibrium temperature' (IET) – the expected equilibrium temperature if forcing were held constant at the value specified at a given time. For any tau, there is a fixed annual percentage convergence between current temperature and IET. If tau is large, the rate of convergence is slow; if tau is small, the rate of convergence is high.

We give a more detailed justification for this choice, and a description of our calibration methodology, in the model documentation available from the authors, but its essential virtue is its ability to reproduce both the similarity and variations between general circulation models (GCMs) of the climate system in their relationship of climate sensitivity with effective thermal inertia. Central to this relationship is the fact that, in general, climate models with higher climate sensitivity converge to equilibrium more slowly. Therefore,

---

14. The first appearance of the 1.5-4.5ºC range was in the first published assessment of climate science, the so-called Charney Report (National Academy of Sciences 1979). For a discussion of the history of this range through the IPCC's Second Assessment Report, see van der Sluijs *et al* (1998). For additional considerations about the interpretation of this uncertainty, see Baer (2005).

15. More technical readers will note that 'effective diffusivity' as a measure of ocean heat uptake serves this purpose in many models (see the Appendix for a discussion of this and the so-called transient climate response).

Figure 3.5 Temperature response to forcing from SRES B1 marker scenario

A

Panel A: Temperature response with median value of tau as climate sensitivity varies from 2ºC (blue line) to 3ºC (red line) to 4ºC (yellow line); black dots on the right are simple model projections for this scenario from the TAR.

B

Panel B: Probability envelope for climate sensitivity of 3ºC as tau varies according to prescribed distribution.

in our representation, if the climate sensitivity is higher in a particular run of the Monte Carlo model, tau will on average have a higher value.

The characteristics of this model are shown in Figure 3.5. Panel A shows the temperature response to the forcing from the SRES B1 marker scenario[16] (Cubasch and Meehl 2001) as climate sensitivity varies from 2ºC to 4ºC. Panel B shows the temperature response for a climate sensitivity of 3ºC as tau is allowed to vary according to the distribution we describe in the Appendix. As we detail in the Appendix, these temperature pathways are consistent with recent GCM simulations and the simple climate model used by the IPCC.

Another important point about this representation is that it produces the expected behaviour if radiative forcing begins to drop – that is, temperature will increase more and more slowly as forcing drops below its peak, until the point at which radiative forcing and temperature are in effective equilibrium. Then if radiative forcing continues to fall, the modelled temperature will also begin to fall. Frankly, there is as yet little evidence from GCMs or other sources about exactly how the earth system will behave under these conditions, but we suggest that our model provides a good rough approximation of both the expected behaviour and the uncertainties involved.

16. SRES scenarios are a group of emissions scenarios published by the IPCC in its 2000 Special Report on Emissions Scenarios and used for climate projections in its Third (and upcoming Fourth) Assessment Reports. In the B1 marker scenario, CO_2 concentrations reach about 550 ppm in 2100 and CO_2-equivalent concentrations reach about 610 ppm.

4. Results

Scenarios in which CO$_2$ concentrations peak and decline

In the previous section, we discussed all the uncertainties that are included in our model. These are the steps that create the mathematical linkage between a specified emissions scenario and the probability envelope (or, more accurately, the range of probability envelopes) for global mean temperature, as demonstrated in Figures 2.1 and 2.2. We will now address our primary research question: taking into account the full range of uncertainties, what rate of emissions reductions is necessary to have a high probability of keeping transient temperature increase below 2ºC?

To explore this question we have run our model on six emissions scenarios, divided into two groups in which CO$_2$ concentrations peak mid-century and then decline.

In the first group, 'immediate reductions', the rate of growth of CO$_2$ emissions begins to decline in 2007, the peak level of emissions is reached in 2010, and the maximum rate of emissions reductions is reached in 2015 and continues through the century. In the second group, 'delayed reductions', the rate of growth of CO$_2$ emissions begins to decline in 2010, the peak rate of emissions is reached in 2013 or 2014, and the maximum rate of emissions reductions is reached in 2020. In both cases, we have run the model with a maximum annual rate of reductions of three per cent, four per cent, and five per cent. The scenarios are therefore named, for example, I3 (immediate reductions, three per cent maximum rate of decline) or D5 (delayed reductions, five per cent maximum rate of decline). The results are shown in Table 4.1.

Table 4.1 Results of two central scenario groups – 'immediate reductions' (I3-I5) and 'delayed reductions' (D3-D5)									
	Decl start yr	E peak yr	Max decl yr	Max decl rt	Cum CO$_2$ (GtC)	Peak CO$_2$ (ppm)	CO$_2$ in 2100 (ppm)	Peak CO$_2$e (ppm)	Pct > 2.0º	Pct > 2.5º
I3	2007	2010	2015	3%	426	419	388	429	17-41%	3-11%
I4	2007	2010	2015	4%	357	413	367	423	12-31%	2-5%
I5	2007	2010	2015	5%	309	410	355	421	9-26%	2-5%
D3	2010	2014	2020	3%	488	431	402	441	20-49%	5-13%
D4	2010	2014	2020	4%	415	425	380	435	16-43%	3-11%
D5	2010	2013	2020	5%	365	421	366	432	12-32%	2-10%

Notes: each run 500 times with three climate sensitivity PDFs. The first five columns specify the reduction scenario (see text), the sixth column shows the mean value of cumulative emissions over the 21st century, the seventh and eighth columns show the mean value of the peak CO$_2$ concentration and CO$_2$ concentration in 2100, the ninth column shows the mean value of peak radiative forcing (in ppm CO$_2$-equivalent), and the last two columns show the range (for the three climate sensitivity PDFs) of the fraction of 500 runs exceeding 2ºC or 2.5ºC.

The important results in the last two columns of Table 4.1 are ranges describing the percentage of 500 runs in which temperature exceeds 2ºC or 2.5ºC, for simulations using the three climate sensitivity PDFs. For practical purposes they can be read as 'the likelihood that temperature will exceed X, given these assumptions'. Again, and crucially, these are fundamentally statements about the model, and about the stylised world that the model represents. They are calculations of the consequences of our assumptions, not objective statements about the probability that something will actually happen in the world. Nevertheless, as we suggested above and will discuss further in the conclusion, this is one of the few ways we have of reasoning quantitatively about risk, so statements of this type are a crucial input to policy deliberations.

These results are sobering. Simply put, for a set of very reasonable assumptions about the probability distributions of key climate parameters, even a very quick transition from current rates of emissions growth to rapid rates of emissions reductions yields likelihoods of exceeding 2ºC in the order of 25 to 30 per cent, or higher. Again, the interpretation of these results is not at all straightforward, because none represents the 'true' risk. But, as we have tried to show, these ranges are in a meaningful sense robust – all assumptions that underlie them are transparent and defensible, and thus any comparable study is likely to produce

closely overlapping ranges. Thus, policy debates that are serious about reducing the risk of severe climate impacts must be based on these types of risk estimates.

Table 4.2 shows another view of the same scenarios shown in Table 4.1, this time grouped subjectively by their risk level. The first three scenarios, with the lowest emissions, we classify as 'very low to low risk' of exceeding the 2°C threshold. The second category, which we call 'low to moderate risk', has two scenarios, and the third category of 'moderate risk' has just one scenario. The data reported are for exactly the same model runs shown in Table 4.1. However, we also show an additional indicator of the stringency of the target – the level of CO_2 emissions in 2050 as a percentage of 1990 emissions (a common policy indicator) – as well as the data for the percentage of runs exceeding the 2°C threshold using the intermediate PDF for the climate sensitivity (Annan and Hargreaves 2006).

Table 4.2 Summary of emissions scenario by risk category

Risk of exceeding 2°C	Scenario	CO_2 in 2050 as % of 1990	Cumulative CO_2 emissions to 2100	% of model runs exceeding 2°C – by climate sensitivity PDF		
				Wigley and Raper (2001)	Annan and Hargreaves (2006)	Murphy et al (2004)
Very low to low risk	I4, I5, D5	19-29%	309-365	9-12%	14-22%	26-32%
Low to medium risk	I3, D4	36-43%	415-436	16-17%	23-26%	41-43%
Medium risk	D3	52%	488	20%	31%	49%

Note: Scenario labels refer to Table 4.1

Because the data are based on a limited number of scenarios, each one of which was run for a single batch of 500 runs, and because we report the specific results of these calculations, the data show a somewhat false precision. Nonetheless, the information can be summarised with a certain amount of subjective rounding.

For example, it is possible to say that, for each climate sensitivity PDF, the lowest range of risk comes from scenarios I4, I5 and D5,[17] in which CO_2 emissions in 2050 are reduced to 19-30 per cent of 1990 levels, and cumulative emissions over the century are between 300 and 400 GtC. A slightly higher level of risk comes from scenarios I3 and D4, with reductions to between 35 and 45 per cent of 1990 levels in 2050 and cumulative emissions between 400 and 450 GtC CO_2. The highest level of risk – which we call 'medium risk', as the likelihood of exceeding 2°C is between 20 and 40 per cent, depending on climate sensitivity PDF – is for scenario D3, with reductions to about 50 per cent of 1990 levels in 2050 and cumulative emissions of slightly under 500 GtC.

CO_2 stabilisation scenarios

Because the rates of emissions reductions associated with a high probability of staying below the 2°C threshold are quite high and will, to many, seem to be politically unrealistic, we have for comparison calculated transient temperature projections for some more gradual emissions reductions. In Table 4.3 we show the same types of results as we did for our rapid reduction scenarios, in which both CO_2 and CO_2-equivalent levels peak and decline, but this time for scenarios designed to *stabilise* CO_2 concentrations (not net radiative forcing) at 450, 500, and 550 ppm CO_2.

This reflects the common focus of the policy debate on CO_2 stabilisation, although we suggest that this focus is misplaced, for at least three reasons: first because the uncertainty in the carbon sinks means that the emissions necessary to stabilise concentrations are very uncertain; second because it is the net radiative forcing, not merely CO_2, that is the effective driver of climate change; and third because if it were possible to achieve emissions reductions adequate for stabilisation, there would be no obvious reason not to continue reductions and reduce CO_2 below its peak level (similar arguments are made in Frame *et al* 2006). Nonetheless, we consider these scenarios to be instructive from the perspective of risk analysis.

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17. Recall that for example 'I4' stands for 'Immediate reductions' (rate of growth starts to decline in 2007) and a 4 per cent annual rate of reductions, and 'D4' stands for 'Delayed reductions' (rate of growth starts to decline in 2010).

Because in these cases temperature will typically still be rising in 2100, we have run the scenarios out until 2200. Also, in order for the scenarios to produce a stable CO_2 concentration, we have set land use emissions in 2000 and the carbon sink feedback parameter to their median values. Thus only the climate sensitivity, tau (the thermal inertia parameter) and the level of negative aerosol forcings are contributing to the uncertainty in the temperature projections.

It should also be pointed out that our reference case treatment of non-CO_2 GHGs – a 50 per cent decline from 2000 levels and then stabilisation – becomes increasingly unrealistic as higher CO_2 concentrations are specified, and as the timeframe increases. However, we have kept this the same in these scenarios for the purposes of apples-with-apples comparison. Note that the combination of these large reductions in non-CO_2 GHGs and the larger aerosol forcing that remains with higher emissions levels mean that net forcing is, on average, not much above the level of CO_2 alone.

Table 4.3 Results of CO_2 stabilisation runs					
CO_2 stabilisation level	Maximum radiative forcing (ppm CO_2-e) mean (5th-95th)	Pct > 2.0º	Pct >2.5º	Pct >3.0º	Pct >3.5º
450	467 (454-480)	46-85%	21-55%	11-24%	4-11%
500	502 (481-522)	70-95%	36-77%	18-47%	11-24%
550	551 (528-575)	78-99%	55-88%	28-71%	17-39%

Notes: Column 2 shows the mean of the maximum radiative forcing in CO_2-equivalent in 300 runs, as well as the 5th and 95th percentile values. Columns 3-6 show the percentage of 300 runs in which temperature exceeds the specified threshold some time during the period 2000-2200

Table 4.3 shows that, except for the most optimistic climate sensitivity PDF, stabilisation at 450 ppm CO_2 is more likely than not to lead to temperatures exceeding the 2ºC threshold in the next 200 years, and has a likelihood in the order of 10-25 per cent of exceeding a 3ºC temperature increase. For stabilisation at 500 ppm CO_2, even with net non-CO_2 forcing that averages close to zero, the likelihood of exceeding 3ºC is in the order of 20-50 per cent, and for stabilisation at 550 ppm CO_2, there is a likelihood in the order of 30-70 per cent of exceeding 3.0ºC.

Again, just as we chose not to argue in detail about the justification for the 2ºC threshold, we will not discuss here the likely consequences of temperature increases that approach 3ºC or even 4ºC, or the implications of taking significant risks of temperatures reaching that level. However, we feel confident in saying that *prima facie* it would not be consistent with the UNFCCC explicitly to choose to allow CO_2 concentrations to reach these levels.

5. Implications for the UK

The consequences for the UK of the global adoption of an emissions trajectory like those described above depend on at least two factors – the specific global emissions reduction target and the allocation of the global budget between countries. We explore this question by selecting two of the six emissions scenarios shown in Table 4.1 and considering variants on the well-known 'Contraction and Convergence' (C&C) formula for the allocation of tradable emissions permits developed by the Global Commons Institute (see www.gci.org.uk). Under C&C, total global emissions *contract* from today's level to a level consistent with a global precautionary target, while the per capita emissions of every country converge to equality over a fixed timeframe (30 to 50 years in most examples).

In our calculations, we show the results in terms of the UK's allowable percentage of 1990 emissions, for comparison with the non-binding goal of a 60 per cent reduction below 1990 levels in 2050 recommended by the Royal Commission on Environmental Pollution (RCEP) (RCEP 2000) and adopted in the Department of Trade and Industry's 2003 Energy White Paper (DTI 2003).

It is important to recognise that in any such exercise based on a global cap-and-trade system such as C&C, there is a complicated and ambiguous relationship between the allocation of emissions permits between countries and the actual location of emissions reductions. Indeed, the entire point of such a system is to decouple allocation of permits from the location of reductions, and thus allow the reductions to take place where they are economically most advantageous. Thus, on the one hand, a country would not have to reduce its actual domestic emissions at the same rate at which its emissions allocation is reduced. On the other hand, the cost to an individual country will still be proportional to the rate at which permit allocations are reduced, with steeper rates of reductions of allocations leading to higher costs.

In addition, the exact allocations calculated will depend on a variety of details, including assumptions about the level and inclusion of land use emissions and the success of countries in achieving their Kyoto targets (or, in the case of the UK, its declared CO_2 reduction goal of 20 per cent below 1990 levels in 2010).

Some of the complications that arise in the cases we consider stem from the fact that, in some cases, the global emissions trajectory begins to decline as early as 2007, and in other cases no later than 2010. We have assumed for the sake of simplicity that convergence begins in the year (either 2007 or 2010) in which global emissions start to decline from their assumed default growth, with each country's share of global emissions in that year being the starting point of the convergence to equal per capita allocations in the specified year of convergence. Of course many other implementations would be possible which take account of countries' Kyoto targets and performance in different ways.

For the sake of comparison we have selected scenarios I5 and D4 from Table 4.1. These are, respectively, the most rapid reduction, and the most gradual reduction scenario that still achieves a low to medium risk of exceeding the 2°C threshold for global temperature increase. In Table 5.1 we show, for both scenarios, the annual total emissions, the UK permit allocation, the percentage of 1990 emissions, the per capita rate of emissions and the five-year average rate of reduction for the UK, using a global convergence year of 2050. We assume in this case that the UK's rate of reductions between 2004 and either 2007 or 2010 was such that it would have met its Kyoto goal in 2010 (a 1.7 per cent annual rate of reduction from 2004). Incorporating the UK's 20 per cent below 1990 goal would, using our simple allocation algorithm, result in a smaller permit allocation.

Table 5.1 shows that either scenario requires more rapid reductions (or more precisely, allocates fewer permits to the UK) than the RCEP target of 60 per cent below 1990 levels in 2050. Indeed, due to the requirement of the UK and other nations with above global average per capita emissions to converge towards the global average, the rate of reductions is, necessarily, steeper than the maximum global rate of decline. In scenario I5, which has a five per cent maximum global annual rate of reductions, the five-year average for the UK reaches eight per cent in 2040. In scenario D4, with a four per cent maximum global annual rate of reduction, the five-year average is almost seven per cent.

The differences between scenarios I5 and D4 for the UK are substantial. However, scenario I5 has almost 25 per cent lower cumulative emissions than D4, a mean level of peak forcing that is 15 ppm lower, and around half the risk of exceeding 2°C (or any higher threshold) (see Table 4.1).

Table 5.2 shows the consequences, for scenario D4, of changing the convergence year from 2050 to 2035 or 2020. Again, the differences are substantial, with the UK's permit allocation in 2020 ranging from 49 per

Table 5.1: Global and UK-specific emissions data for scenarios I5 and D3 from Table 4.1. Note that before 2050 rows show every five years, and after 2050, every 10 years

Year	Global emissions (MtC) I5	D4	UK permit allocation (MtC) I5	D4	UK emissions - % of 1990 I5	D4	UK per capita allocation (tC) I5	D4	UK average five-year rate of reduction (%) I5	D4
2000	8,005	8,005	149	149	95%	95%	2.5	2.5	..	..
2005	9,141	9,141	150	150	96%	96%	2.5	2.5	0.1	0.1
2010	9,723	9,969	133	136	85%	87%	2.2	2.2	-2.4	-2.0
2015	8,577	10,270	110	131	70%	83%	1.8	2.1	-3.8	-0.7
2020	6,637	9,152	79	108	50%	69%	1.3	1.8	-6.7	-3.8
2025	5,135	7,463	56	81	36%	52%	0.9	1.3	-6.9	-5.9
2030	3,974	6,085	39	59	25%	38%	0.6	1.0	-7.2	-6.2
2035	3,075	4,961	27	43	17%	27%	0.4	0.7	-7.6	-6.5
2040	2,379	4,045	18	30	11%	19%	0.3	0.5	-8.0	-6.9
2045	1,841	3,299	14	24	9%	15%	0.2	0.4	-5.5	-4.4
2050	1,425	2,690	10	20	6%	12%	0.2	0.3	-5.4	-4.3
2060	853	1,788	6	13	4%	8%	0.1	0.2	-5.0	-4.0
2070	511	1,189	4	9	3%	6%	0.1	0.1	-5.0	-4.0
2080	306	790	2	6	1%	4%	<0.1	0.1	-5.0	-4.0
2090	183	525	1	4	1%	3%	<0.1	0.1	-5.0	-4.0
2100	110	349	1	3	1%	2%	<0.1	<0.1	-5.0	-4.0

Table 5.2 Comparison of UK emissions allocations for scenario D4 (see Table 4.1) with three different convergence years

Year	Convergence 2020 UK allocation (MtC)	UK % of 1990	Convergence 2035 UK allocation (MtC)	UK % of 1990	Convergence 2050 UK allocation (MtC)	UK % of 1990
2000	149	95%	149	95%	149	95%
2005	150	96%	150	96%	150	96%
2010	136	86%	136	86%	136	86%
2015	114	73%	129	82%	133	85%
2020	76	49%	105	67%	112	72%
2025	60	38%	77	49%	86	55%
2030	48	30%	55	35%	65	42%
2035	38	24%	38	24%	49	31%
2040	30	19%	30	19%	37	23%
2045	24	15%	24	15%	27	17%
2050	20	12%	20	12%	20	12%

cent of 1990 levels in the case with 2020 convergence to 72 per cent of 1990 levels in the case with convergence in 2050.

These sharp differences and the additional costs they imply might suggest that C&C is only viable if the convergence date is relatively far in the future. However, this perspective, based on the costs to Annex I (industrialised) countries, ignores the perspective of developing countries, which must also agree to any global regime and which, under C&C, are never compensated for the historical disproportionate use of the atmosphere by developed countries.

As shown in Figure 5.1, under the steep reductions of scenario D4, even with the most favourable allocation to developing countries, their per capita emissions can never exceed about 1.25 tC annually, far below the levels that fuelled the development of the industrialised North.[18] Under allocations that converge in 2035 or 2050, per capita emissions peak at just over 1 tC annually and must begin to drop, while emissions from the developed world are still close to three times as high, and developing countries will still be far below the level of per capita income of the developed countries today.

Figure 5.1 Per capita CO$_2$ emissions globally and for three convergence years (2020, 2035, 2050) for Annex I (developed) and Non-annex I (developing) countries

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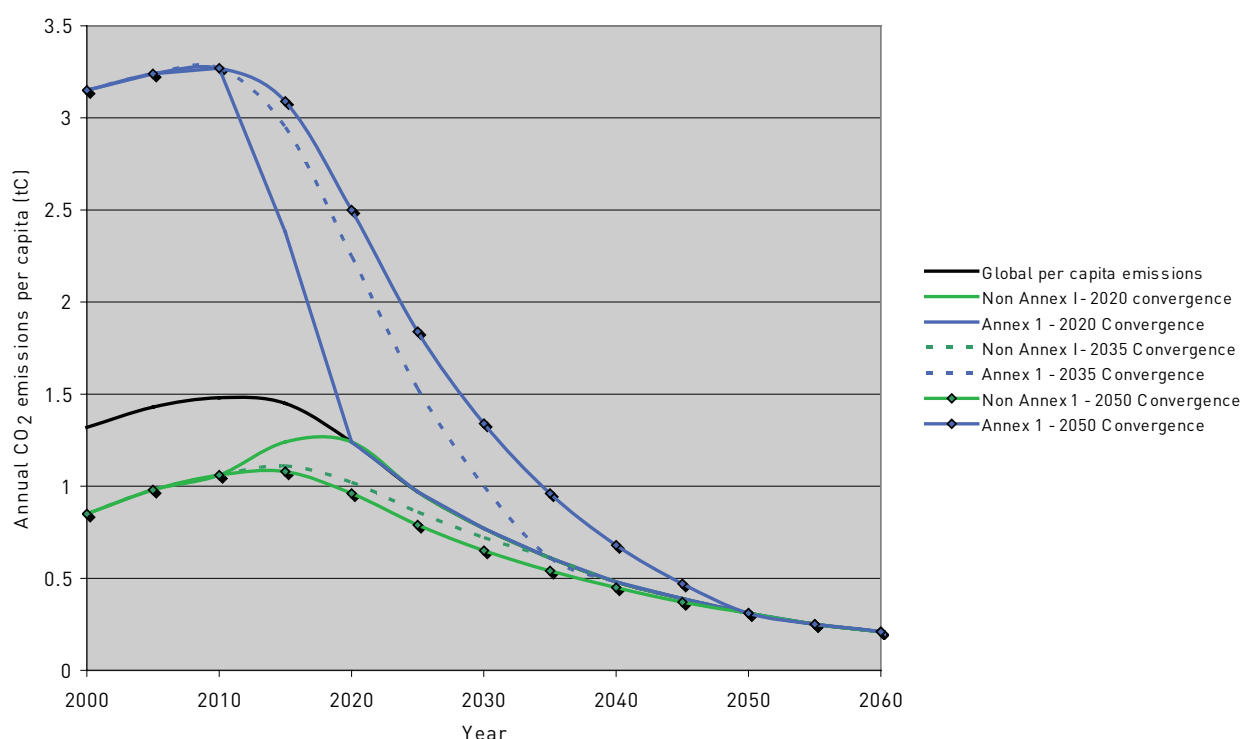
18. Note that in these calculations, Annex I emissions includes the US, whose emissions are assumed to grow at 1.4 per cent annually until the point at which the global reductions begin (for example, 2007 in scenario I5 or 2010 in scenario D4). Annex 1 per capita emissions excluding the US are considerably lower. Note, also, that these calculations assume global population stabilises by 2050 at a little under nine billion, a mid-range estimate.

6. Conclusions

We have demonstrated, using a model that is simple by climate modelling standards but nevertheless quite complex, that very steep emissions reductions are necessary in order to have a high probability of keeping global temperature increase below 2°C above pre-industrial levels. We believe that our calculations are robust; that is to say, anyone else who attempts the same sort of risk analysis will come up with solutions and calculations that are close to ours. Indeed, we suggest that they must literally overlap ours.

And, in fact, while this may be the most explicit examination yet of emissions trajectories oriented towards the precautionary 2°C threshold, very similar results are beginning to appear from other researchers. Using related probabilistic methods, geographer Danny Harvey of the University of Toronto recently demonstrated in a pair of important papers that, with a reasonable definition of 'dangerous climate change' (consistent with the arguments from supporters of the 2°C threshold), we are already causing 'dangerous anthropogenic interference' (Harvey, in press-a). In this case, no possible rate of emission reductions could be too steep, ignoring cost considerations – which of course cannot be ignored.

Harvey also showed that the rapid short-term reductions consistent with high possible estimates of the climate sensitivity would turn out to be desirable under any but the 'luckiest' (and thus very unlikely) 'answer' (Harvey, in press-b). Similarly, work by Malte Meinshausen (2006) showed, using one fairly optimistic PDF for the climate sensitivity, that a pathway with radiative forcing that peaks at 475 ppm CO_2-equivalent and then returns to 400 ppm CO_2-equivalent has roughly a 15 to 33 per cent chance of exceeding the 2°C threshold.[19]

This work and ours does not prove that our results are 'true'. But suppose that we actually are right. What follows?

First, it needs to be acknowledged that the situation is indeed extraordinarily urgent. If one accepts, as we do, the evidence that human-caused climate change is already causing serious harm, and that severe impacts cannot be ruled out at even just 2°C of warming then, clearly, very rapid and stringent emissions reductions are warranted. Furthermore, we will have to take much more seriously the need for adaptation to climate change that cannot be avoided.

Second, anyone who suspects but is undecided about whether we are right needs to decide what would be necessary to quickly convince them that we are either wrong or 'right enough'. This recommendation – directed particularly at policymakers in a position to commission additional research – is an unusual one to make in a scientific report, but it is a fundamental one in a situation where uncertain scientific facts are at the centre of urgent policy disputes with very high stakes,[20] and in which the very concept of uncertainty has been repeatedly used as a justification for inaction. Simply put, if the situation is this urgent, then we have very little time to spend waiting for stronger proof. This implies a critical need to demonstrate that these kinds of results are the best estimates of risk and uncertainty that we can expect anytime soon.

Finally, if we are right, then the important questions concern the policies necessary to avoid or at least greatly reduce these risks, and what political strategies might make those policies – which are perceived to be unrealistic in today's political environment – possible, and quickly. In this context, it is worth noting the lack of any serious proposal by which global emissions actually begin to drop in the near future, a lack that is in turn rooted in the assumption that poor countries' emissions must continue to grow in order for them to meet their development and poverty alleviation goals. Clearly, neither these goals nor the goal of preventing dangerous climate change through stringent mitigation can be compromised; thus a way forward must be found that integrates both.[21]

And what of the US? Under any reasonable global accord, the US – both the world's largest economy and the world's largest GHG emitter – would have the greatest share of the global mitigation burden. Yet it is still governed, for at least two more years, by an administration that has yet to consider significant

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19. Meinshausen uses the same 'lognormal' PDF from Wigley and Raper (2001) that we use as our 'optimistic" PDF. The risk numbers are from our interpretation of his Figure 28.7.

20. Some might recognise these conditions as those that philosophers of science Sylvio Funtowicz and Jerry Ravetz have called 'post-normal science'. This overall analysis owes much to them. See for example Funtowicz and Ravetz (1994), a critique of cost-benefit analysis of climate change.

21. For a new framework based on the concept of 'greenhouse development rights', see Athanasiou *et al* 2006 and Kartha *et al* 2005, available at www.ecoequity.org/GDRs

mitigation policy. Thus, while there is plenty of activity brewing at local, state and regional levels, the challenge of bringing the US back into the global regime remains formidable.

The gap between what is necessary and what seems possible looms wide. But we cannot allow that to justify ignoring results such as these. Surely that is what precaution requires.

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Appendix: Extended definitions

Climate sensitivity

The basic definition of the climate sensitivity is simple: the equilibrium increase in the earth's surface temperature (measured as a global average) in response to an equivalent doubling of atmospheric CO_2. However, the fact that it is defined relative to doubling is ultimately quite arbitrary, as will be shown by a more detailed explanation.

It is important to realise that the climate sensitivity is not a quantity that can be straightforwardly measured, rather it is a simplified representation of an emergent property of the climate system. By emergent property we mean one that is a consequence of the complex interaction of 'lower level' components. What it describes is the way in which components of the 'climate system', such as ice, clouds and water vapour, interact in response to an initial change in the system's energy balance – that is, to radiative forcing.

The underlying mechanism of the so-called greenhouse effect, which warms the planet, is a consequence of basic thermodynamics. Put simply, an object that is absorbing energy, as the earth does from the sun, will warm until it is radiating as much energy as it is absorbing. This is the 'energy balance' we refer to. If something changes the energy balance – like increasing greenhouse gases, which traps heat – the system's temperature must change (in this case, increase) until the incoming and outgoing radiation are again in balance (as the radiation from an object increases with its temperature).

If the earth's climate were a very simple system, basic physics could be used to predict the warming from a given increase in CO_2 in the atmosphere. However, the climate system is anything but simple, and a change in one factor, like CO_2 concentration, can lead to a whole series of effects – called 'feedbacks', for reasons we will discuss below – such as changes in ice, snow, water vapour and clouds, which contribute to additional changes in temperature. It is our inability to measure or predict these feedbacks accurately that is the fundamental source of uncertainty in the climate sensitivity, and in the rate and extent of climate change more generally.

A feedback occurs when a change in one component of a system leads to a change in a second component, which in turn leads to a further change in the first component. For example, a warming due to increased CO_2 may lead to less seasonal ice cover, which in turn leads to more warming. This is called 'positive' feedback, not because it is good, but because it adds to the initial effect. If the change in the second component subtracts from the initial effect, it is called 'negative' feedback.

Estimates of the climate sensitivity come from a variety of sources. Historically the most important has been from climate models, measuring the model response to the experiment of doubling CO_2. Other ways of estimating the climate sensitivity, which always involve components of modelling, involve comparisons of past changes in atmospheric composition with past temperature change, either the recent past or sometimes as far back as the last ice age and beyond.

The first modern assessment of the climate sensitivity, in 1979, estimated that it was in the range 1.5 to 4.5°C, with no quantification of the likelihood that it was outside that range (National Academy of Sciences 1979: 1634). This estimate persisted through the IPCC's Third Assessment Report in 2001, and rumours suggest it will change only very slightly, if at all, (and only at the lower bound) in the forthcoming Fourth Assessment Report.

Although the IPCC has never further quantified the uncertainty beyond this simple estimate of the range, a variety of researchers have used different methods to quantify it more precisely, typically in the form of probability distributions, or PDFs (see Box 2.1). The methods used vary quite widely, as do the results. A sample of nine recently published PDFs is shown in Figure A.1, below.

How could one tell which, if any, of these PDFs is correct? This is a trick question, because there is no such thing as a 'correct' PDF when estimating the uncertainty of the prediction of a unique event. To repeat what we said in the text, if we say there is a 10 per cent chance the climate sensitivity is over 4.5°C, we do not mean that one out of every ten times we double atmospheric CO_2 the result will be a warming greater than 4.5°, or that on one in every ten earthlike planets the climate sensitivity is over 4.5°. For practical purposes,

Figure A.1 Nine published PDFs (probability density functions) for the climate sensitivity
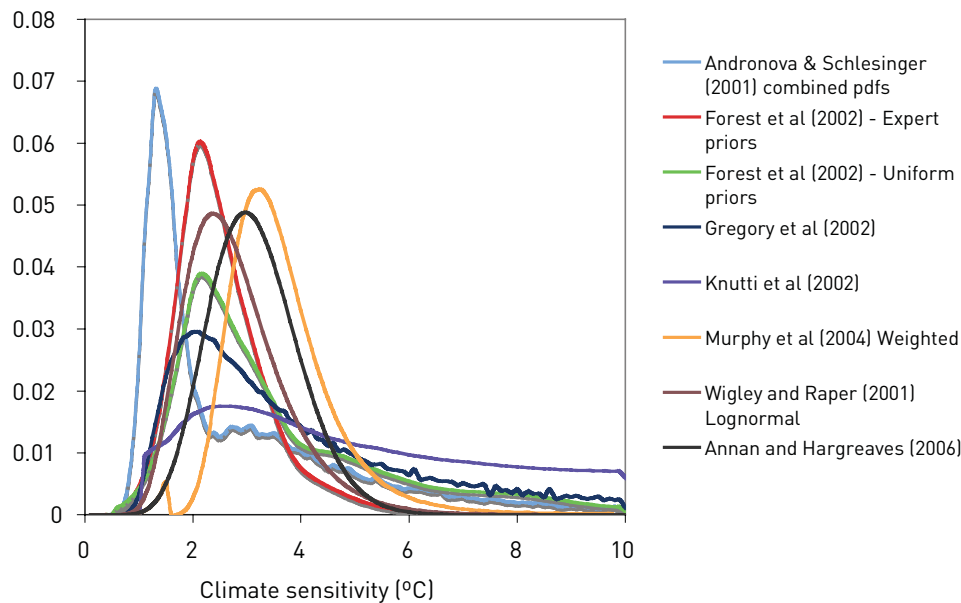
there is just one 'true' climate sensitivity,[22] and if we ran the experiment, we would find out what it is. If it turned out that the climate sensitivity was in fact 4.5ºC, it wouldn't mean that a PDF that put the likelihood of it being that high at only five or ten per cent was in any simple sense wrong.

This does not mean that all PDFs for the climate sensitivity are equally plausible. To give a particularly controversial example, several of the PDFs that have been published (for example Andronova and Schlesinger 2001, Knutti *et al* 2002) have very 'fat tails' – that is, much of the distribution is higher than 4.5º (including a significant likelihood of values of 6ºC or above). This is in part because these studies are based on measurements or estimates of radiative forcing, ocean heat uptake and temperature increase, and we do not have an accurate enough measurement of radiative forcing to rule out the possibility that forcing is on the low side and climate sensitivity is on the high side.

On the other hand, a variety of other sources of information, such as the estimated forcing and temperature response at the last ice age and the response to volcanic eruptions, suggest that a very high climate sensitivity is quite unlikely (Annan 2006: 1909). However, we are trying to estimate the response of the system as it becomes warmer than it has been during any of the past for which we have evidence, and there are no guarantees that it will behave as it has in the past, particularly since the source of the climate sensitivity is the interaction of atmospheric and ocean circulation with land and ice, all of which will be changing.

For our study, we have chosen to use three PDFs that span the range from moderately optimistic to moderately pessimistic. Our model is very sensitive to the PDF used for the climate sensitivity (as would be expected of any model that runs for 100 years), and thus the exact ranges we report as results are a consequence of these choices. Using a different set of PDFs would produce different ranges. However, our argument is that, while these PDFs span more optimistic to more pessimistic assumptions, they are all *reasonable*, in that one climate scientist would not judge another crazy or dishonest to be using any of them. It is this fact, that any range of reasonable PDFs must overlap our selection, which gives us confidence in the robustness of our results.

Radiative forcing

The simple technical definition of radiative forcing is a change in the balance between radiation entering the earth's atmosphere and the energy going out. Radiative forcing is measured in Watts per square metre

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22. Of course this is only an approximation. While there might be only one 'true' climate sensitivity in response to a perfect doubling of CO_2 concentrations from a pristine pre-industrial environment, in reality what we really want to know is the additional temperature increase expected from an incremental radiative forcing, and for many reasons this can be expected to vary with the actual state of the climate system.

(Wm^{-2}), a measure of energy per unit area. This is the same unit in which the solar energy falling on the earth's surface is measured. Indeed, positive radiative forcing, which warms the planet, has the same general effect at the surface as an increase in solar radiation, while negative radiative forcing is generally equivalent at the surface to a decrease in solar radiation.

Different gases and other forcing agents cause changes in different ways. CO_2 and other greenhouse gases absorb long-wave (heat) radiation that is being re-radiated towards space, increasing the temperature near the surface – hence the frequent reference to GHGs as 'heat-trapping gases'. Aerosols – small particles or droplets that are suspended in the atmosphere – can either reflect incoming sunlight (a negative forcing) or (for dark aerosols like soot) absorb heat and sunlight (positive radiative forcing). Changes in land use (such as conversion of forests to crop land) that increase the albedo (reflectivity) of the earth's surface are classified as negative forcing agents.

Radiative forcing is a relative measure. One common use is to define the total change in the energy balance of the planet since the beginning of the industrial era. Combined with the climate sensitivity (see below). This allows us to make an estimate of the expected future warming from anthropogenic changes in greenhouse gases and other effects. (A small increase in solar radiation is typically included in the total measure of radiative forcing since the pre-industrial period.) Radiative forcing can also measure the change due any increase or decrease in GHGs compared with the present.

A doubling of CO_2 is estimated to cause a radiative forcing of about 3.7 Wm^{-2}, with an uncertainty of about ±10 per cent. For a variety of reasons it is common to convert the radiative forcing of non-CO_2 gases and other forcing agents into parts per million (ppm) of CO_2-equivalent. This works because, to a first order (that is, close enough), the climate consequences of 1 Wm^{-2} of forcing are independent of what causes it. Thus one can take all the positive and negative forcing agents and add them together, get a sum measured in Wm^{-2}, and convert that number to ppm CO_2-equivalent. Difficulties arise because the conversion between ppm of CO_2 and radiative forcing is not linear. Put simply, an additional ppm of CO_2 added to a low existing level of CO_2 causes more additional warming (more radiative forcing) than an additional ppm added to a higher level of CO_2. For the mathematically inclined, this relationship is logarithmic – thus one ppm of CO_2 added to 275 ppm causes twice the additional warming of one ppm of CO_2 added to 550 ppm.

The unfortunate consequence is that one can't specify the radiative forcing of any specific increment of a non-CO_2 GHG in ppm CO_2-equivalent. It is common to speak of non-CO_2 gases as adding 'about 80-100

Table A.1 Radiative forcing of major sources or 'forcing agents', as reported in the IPCC's Third Assessment Report

Forcing agent	Radiative forcing (Wm^{-2})	Uncertainty	CO_2-equivalent (ppm)
CO_2	1.46	10%	
Methane	0.48	10%	
N_2O	0.15	10%	
Halocarbons (CFCs etc.)	0.34	10%	
Subtotal: well-mixed GHGs	*2.43*		*438*
Tropospheric ozone	0.35	40%	
Solar	0.3	67%	
Stratospheric H20	0.2		
Subtotal	*0.85*		
Total positive	**3.28**		**513**
Aerosols – direct	-0.6		
Aerosols – indirect	-1	0 to -2	
Stratospheric ozone	-0.15	67%	
Land use	-0.2		
Total negative	**-1.95**		
Net forcing	**1.33**		**356**

ppm CO_2 equivalent' to the effective concentration of GHGs, but this is true only relative to the amount of CO_2 currently in the atmosphere.

Measuring the radiative forcing of various gases and other forcing agents is another whole can of worms. Particularly because some agents – such as aerosols – work through a variety of direct (reflecting or absorbing sunlight) and indirect (changing the amount and properties of clouds, which in turn absorb or reflect sunlight) mechanisms, accurate estimates are difficult, and large uncertainties have persisted for many years. Table A.1 gives best estimates from the IPCC's Third Assessment Report of the major sources of radiative forcing as of 1998. We use these, with very slight modifications, as the basis for our modelling of non-CO_2 gases.

The carbon cycle and carbon budget: carbon sinks and land use emissions

The carbon cycle is the name given to the set of processes by which carbon, in the form of CO_2, organic molecules and other compounds, moves back and forth between the atmosphere, oceans, plants, soils, and geologic reservoirs including fossil fuels and carbon-containing rocks. Among the key processes are photosynthesis and respiration, which in biology refers not to breathing, but to the release of energy from organic molecules in cells, which creates CO_2.

The simplest model of the carbon cycle – as modified by humans – involves four boxes: fossil carbon, terrestrial carbon, atmospheric carbon and ocean carbon. On longer timescales, the geological carbon in rocks is also important (particularly the storage of carbon in ocean sediments and the release from weathering of rocks and soils).

For obvious conservation reasons, carbon can only move from one box to another. Straightforwardly, carbon released from fossil fuels through combustion immediately enters the atmosphere. At the end of any arbitrary period, some fraction will remain in the atmosphere as CO_2, some will enter the ocean through well understood chemical processes, and some will enter the terrestrial biosphere through photosynthesis. This conservation condition can be expressed in the following equation:

> fossil fuel emissions + land use emissions =
> atmospheric accumulation + uptake by oceans + uptake by terrestrial biosphere

Fossil fuel emissions are considered to be known fairly precisely (say, ± five per cent), and are typically treated as if they were in fact known precisely. The annual increment of CO_2 in the atmosphere is also known fairly precisely, perhaps with even less than five per cent error. Land use emissions, as we noted above, are very uncertain, known only perhaps to a factor of two (i.e., somewhere in the range from 1 to 2 GtC annually, with neither smaller nor larger values ruled out). The annual uptake by the ocean is now believed to be, in the terms of the trade, 'fairly well constrained' – that is, the uncertainty is relatively small, though still in the order of ±10 to 20 per cent, with uptake by the terrestrial biosphere somewhat more

Table A.2 Two consistent interpretations of the global carbon budget, based on rounded approximations of 2000 values

	Low land use emissions	High land use emissions
Fossil fuel emissions	6	6
Land use emissions	1	2
Atmospheric accumulation	4	4
Ocean sink uptake	2	2
Terrestrial sink uptake	1	2
Total sink uptake	3	4

Note: Note that total emissions = atmospheric accumulation + total sinks. All figures are in GtC (billions of tonnes of carbon)

uncertain than uptake by the ocean.

The overall balance of the system gives us some important information. Put simply, we know that what we're emitting is going into the atmosphere or into the carbon sink, considering the oceans and terrestrial biosphere together. We don't really know how much is being emitted from land use change, but whatever assumption we make about it specifies how much must be going into the combined sinks. An example of two consistent interpretations of the global carbon budget, using rounded approximations of 2000 data, is shown in Table A.4. Again, it shows that if land use emissions are larger, the total sink must be assumed to be larger.

Obviously, if the carbon sinks were not taking up as much CO_2 as they are, atmospheric CO_2 concentrations would be growing even more rapidly and, all other things being equal, we would be experiencing more rapid warming and greater eventual warming. Thus the amount we can expect the ocean and land sinks to take up in the coming decades matters a great deal to our prospects for limiting climate change. This in turn requires us to understand the processes by which they are currently taking up CO_2.

The basic processes by which CO_2 moves from the atmosphere into the ocean are well understood. As the concentration of CO_2 in the atmosphere increases, more will enter the surface layer of the ocean, although due to the circulation of the ocean, which takes water 'enriched' with CO_2 away from the surface, it will take literally thousands of years before a new equilibrium is reached. The rate of the flow into the surface layer is controlled by factors including temperature (warmer water holds less CO_2), winds and both chemical and biological processes that transform CO_2 into other carbon-containing molecules. As uptake will increase with increasing CO_2 in the atmosphere and decrease with increasing temperature, the balance of these effects and the other chemical and biological impacts of climate change will govern the long-term behaviour of the ocean sink, and for many reasons the combined effects are difficult to predict.

The processes that store carbon from the atmosphere in plants and soils are also well understood qualitatively, but poorly understood quantitatively. There are longstanding debates about the extent to which the increased rate of CO_2 uptake reflects 'CO_2 fertilisation' (the enhancement of photosynthesis by increased CO_2 concentrations, an effect that is well demonstrated in laboratories but whose effect in the world is hard to measure), the re-growth of forests on land previously cleared, or other factors such as increased fertilisation from nitrogen (introduced by humans in the form of fertilisers or air pollution).

Furthermore, the net uptake by plants and soils represents a comparatively small difference between total photosynthesis and total respiration (the conversion of sugars and other organic molecules back into CO_2 and water to provide the energy for life), which means that small variations of these two processes make the net rate vary greatly. And because both processes will be affected by changes in temperature and water availability, which will interact with changes in vegetation types, the end result is great uncertainty in the future rate of CO_2 uptake by the terrestrial sink.