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After the Stern Review: reflections and responses

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STERN review ON THE ECONOMICS OF CLIMATE CHANGE

PAPER A:

‘The case for action to reduce the risks of climate change’

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The case for action to reduce the risks of climate change

A basic conclusion of the Stern Review is that the costs of strong and urgent action on climate change will be less than the costs thereby avoided of the impacts of climate change under business as usual.

A number of critiques of the Review have challenged elements of the analysis that lead to this conclusion. This paper, inter alia, sets out our response to these critiques and takes the opportunity to further the discussion. It demonstrates that the conclusions of the Review are robust, and do not rest on any one particular modelling approach or assumption. The economics of climate change has the economics of risk and uncertainty at its core. The unmitigated accumulation of greenhouse gases in the atmosphere poses ever-greater risks, and the policy challenge is to find the most cost-effective, efficient and equitable way to reduce the risks. It is worth re-emphasising that the problem is not going to be solved without international collective action: there is no laissez-faire solution.

The first half of the Review considered three broad elements that together supported our overall conclusion. First, we reviewed the physical science base on which any economic analysis must rest. Second, we considered the risks of damage from future climate change, and the human and economic costs associated with that damage. Third, we looked at the costs of action to mitigate climate change. We brought this analysis together in Chapter 13, which considered how economic analysis could help to identify specific goals for climate policy, and explored the concept of the social cost of carbon, including how it might act as a guide to policymakers or operate as a policy instrument.

In this paper we will briefly recap our approach and key conclusions, drawing attention to areas where misunderstandings have arisen. We will also present some sensitivity analysis for the formal economic modelling of the impacts of climate change, demonstrating that while there are a number of factors that influence the specific results, the estimates presented in the Review are in the middle of a plausible range. This process also helps highlight areas of potential further research, for example in moving beyond the sensitivity of aggregated model towards more detailed regional studies.

A1 The scientific basis for the economics of climate change

The Stern Review was commissioned in July 2005 and required to report in the autumn of 2006, ahead of the IPCC's Fourth Assessment Report (AR4). It was clear during the writing of the Review that the science had moved on since the IPCC's Third Assessment Report (TAR), and that the economic literature had not yet fully reflected the scientific advances. The first chapter of the Review therefore set out our own understanding of the key findings and directions from the IPCC TAR and from more recent peer-reviewed scientific literature.

The IPCC's Working Group on the science of climate change has now published its Summary for Policymakers[1]. The IPCC has confirmed that there is now very high confidence that human activity is warming the climate, and that human influences are likely to have been at least five times greater than those due to solar variations[2]. There is now very little justification for believing that the scientific understanding of climate change is fundamentally flawed, or that the remaining areas of uncertainty imply that current knowledge is inadequate as a basis for drawing conclusions for policy. **The fact that the IPCC 4AR drew similar conclusions to us was no surprise as we drew on the same body of evidence and consulted the same experts in the field**. In similar vein, the latest IEA Global Energy Outlook explains that the two integrated reports on science and costs have been fully in line with our assessment of the costs of mitigation[3].

The findings of the IPCC are consistent with the scientific evidence summarised in the Stern Review for projected temperature rise, the impacts on patterns of precipitation, and the incidence of extreme events.

The IPCC reports a wide range of possible outcomes for temperature rise. This range reflects (1) six alternative scenarios for social and economic development and therefore for emissions of greenhouse gases during the next 100 years and (2) the 66% confidence interval of the implications of each of those scenarios. This confidence interval represents the uncertainty in our current understanding of the climate system, including for example,

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[1] IPCC Working Group 1 Summary for Policy Makers www.ipcc.ch

[2] The IPCC WG1 SPM also notes that urban heat islands have only a negligible effect on global average temperatures and that certain discrepancies reported in the TAR have now been resolved. These conclusions are in line with the findings reported in SRCh1.

[3] Claude Mandil, Executive Director of the International Energy Agency, is quoted as saying that conclusion that the benefits of strong, early action on climate change outweigh the costs is one that the International Energy Agency fully endorses

uncertainties in the sensitivity of the climate to greenhouse gas concentrations and the feedbacks between climate and the carbon cycle. For the purposes of comparison, it is important to point out that temperate increases in the Review are expressed relative to pre-industrial levels, so equivalent increases will be 0.7% higher than in the IPCC. We also refer to eventual temperature increases under various stabilisation paths rather than 2100 temperatures.

Table A1 IPCC emissions scenarios: projections of temperature increase for 2100

IPCC scenario	CO2e concentration 2100, ppm	IPCC SPM temperature estimates in 2100 compared with 1980-1999
A1F1	1550	4.0 [2.4-6.3]
A2	1250	3.2 [1.9-5.1]
A1B	850	2.7 [1.6-4.3]
B2	800	2.4 [1.4-3.8]
A1T	700	2.4 [1.4-3.8]
B1	600	1.7 [1.0-2.7]

The IPCC states that all six scenarios are to be regarded as equally valid. This does not mean that they are all equally likely. They are all coherent and based on explicit and plausible (if not equally plausible) assumptions. But some of them invoke social and technological changes that are hard to describe as 'business as usual' (BAU). It is important for policymakers to understand the assumptions in each one and to come to their own conclusions about the likelihood of each scenario developing in the absence of any policy intervention. In Chapter 7 of the Review, we examined recent evidence on emissions growth. If annual emissions were stabilised at 2000 levels, and maintained at that level throughout the century, concentrations would reach at least 650ppm CO2e by 2100.

However, this is a conservative estimate. Emissions are extremely unlikely to remain at 2000 levels. By 2003, global emissions from fossil fuel burning had already increased by 7%. The stocks of hydrocarbons that are profitable to extract under current conditions are more than enough to take the world to 750ppm CO2e and beyond. Emissions are growing rapidly, driven by a new wave of investment in fossil-fuel based infrastructure, including in both rich and poor countries.

The emission projections used in the Stern Review are broadly consistent with the IPCC A2 scenario. For example, in 2050, A2 estimates 60.4 GtCO2 (carbon only). The BAU emission projections presented in chapter 7 (derived from IEA and other highly reputable data sources) in 2050 are 58 GtCO2. The BAU emission projections underlying Dennis Anderson's resource cost estimates in chapter 9 lead to emissions of 60.9 GtCO2 in 2050[4]. The Stern and IEA projection for all greenhouse gas emissions of 84 GtCO2e by 2050 most closely matches with the A2 estimate (83 GtCO2e).

Policymakers have no room for complacency when assessing the range of plausible outcomes for atmospheric concentrations of greenhouse gases in the absence of interventions that specifically target emissions reductions.

The Stern Review drew attention to the risks and economic implications of increases in global average temperature up to and beyond 5°C *relative to pre-industrial levels* over the next 200 years, and some people have suggested that this was biased or alarmist. The IPCC report shows that there is real cause for concern. Three of the six scenarios lead to at least a small risk that temperature change on this scale will be seen *by the end of this century*, and for the scenario with the highest emissions, 4°C of temperature increase by 2100 represents the central estimate, with a likely (66%) range of 2.4 – 6.4°C.

The upper bound of the IPCC range has been driven higher than in the Third Assessment Report by the inclusion of positive feedbacks from the carbon cycle. This feedback amplifies warming through weakening the amount of natural carbon uptake by forests, vegetation and soils as areas become warmer and drier. Our modelling in Chapter 6 included a simple representation of this feedback within the “high” climate scenario. In this modelling scenario, we also introduced a second type of feedback, where methane is released from melting permafrost . The effect of both of these feedbacks in our model pushed up the 90th percentile warming by only 0.7°C. This is slightly smaller than that projected in the IPCC report.

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[4] See Chapter 9 and also Anderson's paper “Cost and Finance of Carbon Abatement in the Energy Sector” published on the Review website www.sternreview.org.uk.

A2 Understanding the impacts of climate change

We looked at climate change impacts in two ways:

(i) an analysis of the physical impacts around the world - temperature, water cycle, extreme weather events (in Chapters 3, 4 and 5 of the Review);

(ii) an analysis of the way in which formal economic modelling tries to account for those impacts (in Chapter 6).

It is important to consider the evidence from the two approaches together. **The formal economic modelling in Chapter 6 represents a highly aggregated attempt to capture these impacts and express them in terms of GDP costs.** Models require specific ethical frameworks and value judgements to be adopted, and can be used to illustrate and explore the effect of different assumptions. **But decision-makers require a richer understanding of the scale and nature of the risks involved in climate change.** Different people will attach different weights to the different types of impacts. This is a question of different ethical systems, and not just cost-benefit economics. So all attempts to model aggregate impacts should be accompanied by an analysis of specific, regional and sectoral impacts (with probabilities attached). This and other modelling issues are discussed in more detail below.

A3 What are the implications of the disaggregated analysis of impacts?

The majority of the scientific and economic literature currently explores the implications of relatively moderate and gradual increases in temperature.

At 1-2°C of temperature rise, there will be some winners and some losers. Longer growing seasons in northern latitudes, and reduced mortality from winter cold snaps, will create economic gains in some areas and opportunities for new activities including in the agriculture, energy and tourism sectors in some regions.

But **even at low levels of warming, there are already significant impacts on vulnerable communities.** Rapid warming is causing serious challenges for indigenous communities in the Arctic Circle, and some low-lying tropical islands have already been evacuated. And even the small changes in global average temperature that the world has experienced to date have led to discernible increases in extreme weather events and in the intensity of drought across an increasing area[5]. Ecosystems, particularly for example coral reefs, are highly vulnerable to climate changes, with many systems already showing signs of significant changes.

For those parts of the world that are adversely affected by low levels of global average warming, the impacts are not trivial. Adaptation to the changes will require complex and costly measures, including programmes to resettle people and replace infrastructure – for example, hundreds of thousands of kilometres of railways and road surfaces that have not been designed to cope with very high temperatures.

How does this picture compare with a world where global average temperatures could increase by 5-6°C or more, and where sea levels are rising further and faster than under more moderate scenarios? Five degrees Celsius is the distance between now and the last Ice Age. A further 5°C would transform the physical geography and thus the human geography of the world. It involves great risks of major shifts in climate, economic and social disruption, migration and conflict.

The Review summarised a range of impacts of climate change for which it is reasonable to assume that the damages rise more strongly as temperatures increase (ref to Chapter 3). A recent paper by Nordhaus[6] suggested a ninth power relationship between hurricane wind speed and damages. In addition to the gradual change of global average temperatures, the risks of abrupt changes, and of major shifts that are irreversible on all but geological timescales, are an essential part of the challenge of climate change. The paleoclimatic record suggests that climate change has not taken place in a linear, gradual way. Significant changes to the global climate have occurred within only a couple of decades. Regional events that could bring severe disruption with little advance warning include a strengthening of El Nino or widespread forest fires in Siberia or in the Amazon. These could trigger an abrupt failure in monsoon rains and a significant fall in agricultural yields in key areas of Asia, Australia or Latin America, with implications for the global trade in

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[5] IPCC SPM

[6] The Economics of Hurricanes in the United States, William Nordhaus, 20 September 2006, see http://www.som.yale.edu/faculty/nok4/files/seminar/nordhaus.pdf

commodities such as wheat and soya as well as risks of human misery, social instability, and migration in densely populated regions of the world. These events do not depend on crossing a critical threshold of global average temperature, but become ever more likely as global temperatures rise.

In retrospect we might have emphasised still more strongly the risks of these abrupt changes and the risks of very large increases in temperatures, where the literature is still sparse but the likelihood of strong damages is great. The disaggregated analysis points to a very strong risk of serious disruption and dislocation in the global economy as temperatures continue to rise. The biggest costs in the world are likely to be where climate change interacts with other vulnerabilities and tensions to create movements of people and conflict. Analogies might be drawn with the dislocation that accompanied the Great Depression, with the very large human cost and long-lasting impacts that accompanied the mass movement of people as borders were re-drawing in South Asia, and with the global impact of the World Wars. The socio-economic impacts of climate change are already starting to be felt, even with a 0.7°C warming relative to pre-industrial - climate change and associated water stress has arguably been a contributory factor to the conflict in Darfur.

The existing economic literature has not begun to come to grips with changes on this magnitude. The scientific basis for understanding the changes is not complete, but the IPCC's latest report demonstrates that the risks cannot be ignored. **It is essential that policymakers include the risks of adverse outcomes from climate change in their decision-making. And the evidence base for doing this is increasingly robust.**

A4 What can formal economic modelling tell us about these risks?

Chapter 6 of the Stern Review examined the role of formal estimates of the monetary cost of climate change. Our conclusions have attracted a wide range of responses from both the scientific and economic research communities. Some have pointed out that our estimates are higher than previously published studies and go on to argue that they are too high. Others have encouraged us to consider whether our estimates might in fact be lower than some of the scientific evidence suggests.

Aggregated models are in many ways a clumsy tool to express the value of a variety of outcomes ranging from economic activity, human health, lifestyles, the environment and ecosystems. One must avoid over-literal interpretation. Moreover, **projecting so far ahead is bound to be fraught with uncertainty, which is why we put analysis of risk and uncertainty at the heart of our assessment**. Any aggregate numbers pertaining to definitively quantify the impacts of climate change must be treated with great circumspection. The modelling of Chapter 6 is only a supplementary argument to the main argument of why it is urgent to take strong action and what the broad goals of stabilisation should be. These are discussed in Chapters 1, 3, 4, 5, 8, 13 without formal modelling. Aggregate estimates suppress much or most of what is interesting and troubling about climate change.

Nevertheless, aggregate assessments do afford us a highly abbreviated snapshot of the likely magnitude of the damages associated with climate change. It is for this reason that such estimates attract public attention in a way that a long list of likely disaggregated impacts never could. **It is therefore very important that these aggregated estimates are treated with great care in their formulation, presentation and interpretation.**

Outputs are driven by inputs, behavioural assumptions and value judgements, so the choice of plausible inputs and parameters is crucial. With sensible characteristics, however, the numbers models generate should accord with an informed assessments of the dangers of climate change. In addition, **an important question is whether aggregated model projections match our assessment of the likely disaggregated impacts under business as usual, including our ability to cope with the outcomes and our willingness to risk catastrophic events?** This question will be addressed below, but first in order to understand the derivation of some of these highly uncertain predictions, it is important to be clear on precisely what choice of assumptions underlay our model outputs. **The following section examines three key modelling issues, to which overall damage estimates are highly sensitive**. In doing so, we repeat, and build on, arguments and evidence outlined in the Postscript to the Review, and its Technical Annex. The three issues are:

- **Discounting and intergenerational equity.** We adopt lower pure time discount rates than some earlier literature so that the analysis gives future generations equal ethical weight. How one specifies the relationship between rising consumption and welfare or 'utility' also matters for discounting, as does the combination of these two factors (a detailed account of our approach to discounting can be found in Paper B "Value judgements, welfare weights and discount rates: issues and evidence" on our website)

- **Treatment of risk and uncertainty.** Climate change is all about risk and uncertainty and in Chapter 6 we invoke the economics of risk directly, explicitly building in aversion to the risk of highly damaging climate-change scenarios in an expected-utility framework. Although there have been notable exceptions,[7] most previous studies have relied on simpler approaches. We also respond to progress in the scientific literature taking advantage of the latest probabilistic assessments. One reason why our estimates of the cost of climate change are higher than some previously published studies is that we make use of recent scientific evidence on the probabilities of temperature increase, although we did not incorporate the risks of higher climate sensitivity.

- **Treatment of the damage function and catastrophic risk.** Climate change impacts are expected to rise more than proportionately with temperatures. In the Review two separate effects model this explicitly. The first relationship is captured by the exponent applied to the damage function (see Annex to Postscript) and reflects the fact that the cost of damages in any particular sector rise more than proportionately with temperature[8]. The second, separable effect is given by the risk of catastrophic damages as thresholds are passed and discontinuities initiated. As temperatures rise, the risk of major, irreversible changes in the climate system increase sharply[9]. These impacts are represented in the model by a simple probabilistic mechanism, so that when global mean temperature rises above certain levels the chance of large losses in regional GDP begins to appear.

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[7] e.g. Tol (1999).

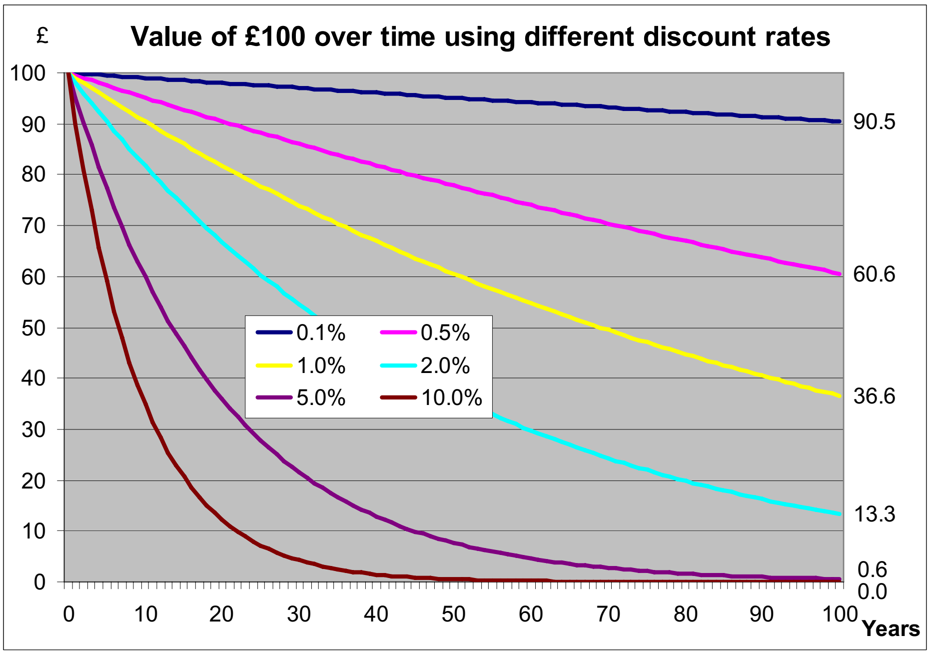
[8] As an intuitive example consider the following illustrative escalation of costs relative to temperature: at between zero and two degrees warming, agricultural output can be adapted and crops can change; some regions will see higher yields and longer growing seasons, levies can be strengthened and irrigation projects enhanced; between two and four degrees warming, new agricultural plant and processes may be required, levies and barriers must be rebuilt and new irrigation sources found; between four and six degrees some coastal areas must be abandoned and populations moved and former agricultural land must be left for arid. It is clear that the costs and impact are highly disproportionate - convex – to the linear change in temperature.

[9] Such risks include ice-sheets melting (for example in Greenland and West Antarctica), oceanic flows being diverted (such as the collapse of the Atlantic thermohaline circulation) and temperature-induced greenhouse gas releases (such as methane releases from melting permafrost) – see Chapter 3.

In the technical appendix to this paper, we investigate the importance of each of these three broad factors in estimating the monetary cost of climate change. Through a variety of empirical investigations, we have demonstrated that **the estimated cost of climate change is highly sensitive to all three factors**, but that the range of estimates presented in Chapter 6 fall within the centre of a range of plausible results.

Discounting has been the subject of much attention since publication of the Review, and rightly so, since it is clear and was very strongly emphasised in the Review, that a very low weight on the future will simply downplay the risks that occur 50, 100 or 150 years from now (see Chapters 2 and 6). In the Review it was argued that the most straightforward ethical approach to understanding the pure time discount rate was through the probability of existence of the world. Otherwise, discrimination by date of birth is difficult to justify on ethical grounds. For example, a discount rate of 3% would give individuals existing at the end of this century roughly one tenth of the ethical weight of the current generation and only a 1% weight by 2200. With such a high discount factor, it becomes easy to see why climate change, which results in significant impacts in the future gets a relatively low ethical weight: this choice of discount factor says little more than “if you don't care much about the future, you won't care much about climate change” (see Paper B)

Chart A.1: comparative discount factors



But discounting is not the only factor driving the case for climate change. Our sensitivity analysis demonstrates that the treatment of risk and uncertainty and the extent to which the model responds to progress in the scientific literature are of roughly equal importance[10].

Table A2 outlines seven plausible dimensions for model structure (those regarding the damage exponent, emissions assumptions, growth assumptions, terminal conditions and the treatment of uncertainty and irreversibilities and the rise in the relative value of environmental goods). The precise methodology is outlined in the appendix to this paper, but leading alternative treatments of these key factors suggest a range of possible outcomes relative to our central estimate of the damages – some higher and some lower than we project. **Overall, there seems to be little justification for us to change our view that our central estimate of climate change impacts equivalent to 11% of GDP (under a balanced growth equivalent measure) is anything other than in the middle of a plausible range**.

For example, the choice of a lower emissions scenario in the baseline, or higher discounting would lower the assessment of the damages. On the other hand, a higher exponent on the damage function, a more comprehensive treatment of uncertainty or allowance for a wider income distribution – all of which are plausible - would raise the projected impacts potentially quite significantly. In fact it is notable that the convexity of the damage function perhaps more than anything else drives the aggregated results. The impact of different baseline growth assumptions is ambiguous; stronger growth will raise emissions from economic activity, and thus accelerate the impacts of climate change, but at the same time it will also augment discounting on account of the fact that future generations will be richer.

In each case, a large change is considered under in the "variation" column, but reasonable people will obviously differ on the magnitude. Table A2 summarises the results qualitatively.

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[10] This can be demonstrated by looking at the sensitivity of estimates to different modelling strategies that incorporate and value risk and uncertainty to different degrees. It can also be demonstrated by comparing our baseline-climate scenario with our high-climate scenario, and by analysing the importance of modelling convexities in the damage function describing impacts with rising temperatures, as well as the risk of catastrophic climate impacts – see appendix.

Table A2 Variation in damages in terms of BGE for different assumptions

Model structure	*Variation*	*Magnitude of variation*	*Method of estimation*	*Approximate change in BGE damages in terms of % of consumption*
	1. Increasing the damage function exponent (γ)	**Stochastic - 3**	**A**	**+20**
	2. Emissions scenario (population)	40% lower	B	-4
	3. Growth	1% higher	B	+
	4. Terminal conditions	Continued growth post-2200 or decline	B	High sensitivity ++
	5. Further incorporation and valuation of risk and uncertainty	More parameter & baseline uncertainty	B	+3
	6. Accounting for aversion to irreversibilities		B	+
	7. The rise in price of environmental goods relative to consumption goods	Expressing equivalent loss in consumption	B	+2
Value judgements	8. Increasing the value of elasticity of marginal utility of consumption (inequality and risk aversion	1- 2	A	-7
	9. Increasing the pure rate of time preference	0.1-1.5%	A	-8
	10. Accounting for intra-generational income distribution/ regional equity weighting	Including regional distribution	B	+6

A = direct calculation; B = ‘back of the envelope’ or other studies[11].

Similar sensitivity analyses to those we have conducted on PAGE have been undertaken using alternative models and these show very similar results to those we present in PAGE.

For example, Ackerman and Finlayson (2007 forthcoming) re-run DICE but with assumptions similar to those used in the Review: zero pure rate of time preference; latest

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[11] Notes to ‘back of envelope’ calculations (B) in table A2. Row 2: for any change in underlying population, the damages can be scaled by η(ΔN/N). Row 3: a change in growth will produce an ambiguous result. For example, 1% higher growth would raise the stock of greenhouse gases by a factor of 3 or 4 by early next century probably quadrupling the damages by then. On the other hand the discount factor could also quadruple as future generations become richer. The effect is likely to be finely balanced at first, but the non-linearity of the damage function at high temperatures dominates over the longer term. Row 4: the Review assumes that emissions fall instantly towards 5GTCO2 post-2200 allowing the impacts to stabilise and the stock greenhouse gases to rise very slowly. A more realistic emissions profile is likely to bias up the impacts, though this will be limited to the extent that fossil fuels are assumed to become anachronisms in the very long term even in the absence of policy. Row 5: based on Appendix table A3. Row 6: we do not account explicitly for aversion to having to make irreversible decisions – the number of such decisions are likely to increase in line with the stock of greenhouse gases adding an further element to the costs. Row 7: to the extent that the sharp rise in the price of environmental goods is not captured in the utility estimates (expressed using consumption as the numerair) the damage impacts are likely to be underestimated see Appendix 2A.2. Row 10: inferred from other model studies (see section 6.4).

science; different assumptions on the benefits of warming. On the basis of modest alterations to reflect these assumptions, **the DICE model generates results that are comparable to those presented in the Review, suggesting a much stronger case for early action than in the original model runs**.[12] This is an interesting result, as DICE does not in general allow for parameter uncertainty. The technical appendix to this paper shows the importance of the fact that PAGE is stochastic, while other IAMs are in general not, an appropriately treating the presence of uncertainty. Ackerman et. al (forthcoming) significantly increase the DICE estimate of the damages even though they still don't undertake an expected-utility analysis. Similarly, the PAGE model was able to fully replicate many of the impacts from previous studies by adapting assumptions[13] Further sensitivity analyses and investigations of underlying parameters as well the explicit modelling of risks using models other than PAGE are likely to prove highly informative and are strongly encouraged.

The Review notes that the PAGE model was the most well-suited to assessing the impact of risks and uncertainties by taking explicit account of uncertainty across models. However, **model uncertainty is only one of many uncertainties that underlie damage projections**. Only Nordhaus and Boyer allow for parameter uncertainty within their model, by expressing stochastic results in terms of a certainty-equivalent mean. Tol and Yohe (2006) argue that inclusion of this result in our PAGE study amounted to double counting. In fact, to the extent that parameter uncertainty has not be accounted for in some of the other studies, our results are likely to understate the true cost of the full range of uncertainties. As models evolve, more and more are likely to express stochastic rather than deterministic projections, and allow for a more plausible account to be taken of uncertainties surrounding climate change impacts. As this happens, estimate of the damages are likely to rise.

Given that we would argue that the assumptions underlying our model are plausible and well-founded, the question is often asked **why our results show a higher valuation of the impacts of climate change under business as usual when compared with previous studies?** The answer should by this stage be clear:

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[12] Mastrandrea and Schneider (2004) put three different climate sensitivities into DICE and show that the projected impacts vary significantly. Ceronsky et al. design rapid climate change into Tol's FUND model and get very high social costs of carbon.

[13] For example, it was able to effectively replicate the mean social cost of carbon from Richard Tol’s review in 2005

1) Our study takes on the latest science including a probabilistic assessment of high climate change impacts.
2) We have explicitly accounted for the economics of risk: risks and uncertainties are at the heart of concerns about climate change, but have hitherto been mostly ignored.
3) We have investigated ethical judgements about the valuation of future generations that are time-consistent and that do not discriminate on the arbitrary basis of birth dates.

The question remains whether the model results match our assessment of the likely disaggregated impacts under business as usual, including our ability to cope with the outcomes and our willingness to risk catastrophic events? Do our projection of damages in a range equivalent to 5-20% loss in annual consumption once risks and uncertainties are appropriately accounted for accord with what we would expect from a disaggregated assessment of the list of likely social, economic and environmental damages from continuing along our present emissions path under BAU? We feel that they do[14]. Indeed, some have argued that such aggregate models fail to embody the kind of very large disruptions that are possible.

Having assessed the model properties and characteristics and compared the results with the disaggregated impacts associated with a business as usual emissions path, we remain confident that our estimates are very much in the centre of any plausible range of model projections.

A5 Costs of mitigation

Having assessed the damages under business as usual, the Review went on to analyse the costs through time of adhering to a plausible stabilisation corridor – keeping atmospheric concentrations below 550ppm CO2e in order substantially to reduce the risks of the highest increases in temperature.

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[14] It should be noted that even at the 20% upper-end loss, society would still be projected to be around 175 times richer in 2200 than it is today.

Our assessment was based primarily on the latest literature covering model estimates of the cost of mitigation. Our central estimate of an annual cost of 1% of GDP to meet a 550ppm CO2e stabilisation pathway applies through to the end of this century (with a range of +/-3% points by 2050). This is based on a very wide range of international model estimates and does not stem from the use of one particular approach[15].

The Stern review also commissioned a simple and transparent cost-assessment exercise designed to cross-check the wide-ranging model estimates. In order to assess the likely costs of mitigation in a world where behaviour remained unchanged, a probabilistic projection of the evolution of low carbon technologies and of fossil fuel prices was used[16].

The study corroborated the more complex behavioural modelling exercises and showed that under a feasible technology mix, substituting carbon-intensive energy generation and transportation with low-carbon technologies to meet an emissions corridor consistent with stabilisation at 550ppm CO2e[17] could be attained with a mean cost of approximately 1% of GDP by mid-century. The uncertainty around this mean amounted to around +/-3% points of GDP, reflecting in particular uncertainty in technological innovation and the evolution of fossil fuel costs. Unlike the behavioural models whose results are driven by detailed assumptions and parameters, this approach offered a very simple and transparent way of assessing a first approximation of the likely cost of decarbonising economic activity.[18]

There has been some debate about the estimates presented in the Review for the costs of mitigation and it is important to try and clarify some simple misunderstandings.

First, this estimate is *not* materially affected by the choice of discounting assumptions, as the mean cost estimate of 1% of GDP is relatively constant throughout the

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[15] The following studies were investigated: Stanford University's Energy Modelling Forum (EMF-16, EMF19 and supporting multi-gas estimates for EMF-21); the meta-analysis study by Fischer and Morgenstern (Resources For the Future (2005)); the International Energy Agency accelerated technology scenarios; the IPCC survey of modelling results; the Innovation Modelling Comparison Project (IMCP); the draft US CCSP Synthesis and Assessment of "Scenarios of Greenhouse-Gas Emissions and Atmospheric Concentrations and Review of Integrated Scenario Development and Application" (June 2006).

[16] See Chapter 9 and also Anderson's paper "Cost and Finance of Carbon Abatement in the Energy Sector" published on the Review website www.sternreview.org.uk.

[17] Relative to a baseline path consistent with the IPCC A2 path used to estimate the damages.

[18] It should be noted that marginal costs are not falling through time in the Anderson study, they are rising. Average costs are falling. Some commentators, for example Tol and Yohe (2006), have confused average with marginal costs. Box 9.6 points out that although marginal costs are likely to rise through time, in line with a rising social cost of carbon, average costs may rise, fall or stay the same, depending on the rate of technological progress. This is fully in line with the academic literature on the evolution of costs.

medium-term and so is invariant to a discount rate when expressed in present value terms[19]. It is designed to be consistent with our approach in expressing likely climate-change impacts using 'balanced growth equivalent' paths. **Both approaches to measuring impacts and mitigation costs express costs as a percentage of real income and are directly comparable.**

Second, a more interesting question concerns the validity of attempts to compare near-term costs and long-term damages, and the issue of whether 1% of GDP represents a trivial investment. **There is no inconsistency in comparing costs over the next 100 years with impacts occurring in the more distant future[20].** As we argued, the decision on whether to act now hinges on the question of irreversible outcomes and risks. Decisions taken today will have potentially large and irreversible consequences in terms of climate change impacts; this is not true to the same extent of mitigation costs[21]. Moreover, policymakers can keep cost estimates under review and revise policy in the light of new information. By contrast, the impact from global warming will become increasingly costly to reverse. In part this reflects the fact that damages are caused by the stock of GHGs (and not the annual flow) but it also reflects the risks associated with irreversible thresholds and discontinuities.

The Review therefore asks the question: what are the relatively certain and reversible costs we must incur in the short term in order to avoid potentially large, uncertain and irreversible damages in the future.

Some have argued that our estimate of the costs is unrealistically low. Firstly, this seems intuitively odd. For one thing, primary energy costs in most developed economies amount to around 3-4% of GDP (a little higher in some industrialising countries). This means that anything less than a 25% increase in primary fuel costs is unlikely to raise costs above a maximum 1% of GDP. In practice, opportunities for energy efficiency and substitution to alternate processes and technologies are likely to keep the cost associated with such a rise in energy prices much lower than that (see Chapter 11). It was no surprise that our

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[19] There is a range of projection for mitigation costs beyond 2050. By 2100, some fell reflecting greater efficiencies from induced technological innovation while others rose sharply, reflecting the greater uncertainty about the costs of seeking out successive new mitigation options.

[20] In any case, the evidence suggests that a one percent annual cost of mitigation is a reasonable estimate of the flow of costs into the long term.

[21] The length of the irreversibility of mitigation cost would be dictated primarily by the lifetimes of capital equipment, infrastructure and networks. There is no reason to believe that inertia in endogenous factors such as knowledge resulting say from a switch to alternative energies will yield long-term net costs to society or inhibit long-term growth.

estimates of costs were precisely reaffirmed by the IEA in their World Energy outlook 2006 published after our Review. Secondly, it is worth re-emphasising that **1% of GDP is not a trivial amount**. It represents a very significant change in the patterns of energy investment, in line with the replacement cycles for capital stock, towards low-carbon energy technology.

Finally, it is important to understand precisely what the 1% of GDP cost estimate refers to. Many of the criticisms that costs could be higher in a world of poorly applied or coordinated policy are not inconsistent with our assessment.

This cost estimate we present applies to costs in an efficient world where early action is taken. It reflects the likely costs under a flexible, global policy, employing a variety of economic instruments in cost-effective ways to control emissions of a broad range of greenhouse gases. It would require clear long-term price signals and policy frameworks that encourage technological innovation. In the absence of these factors, or were action to be delayed or restricted to a limited number of countries, the costs would be significantly higher. By contrast, many of the **higher cost estimates are generated through pessimistic assumptions about technological innovation and/or little substitution** across production, inputs and technologies. This means that sectors continue to supply output at ever increasing costs as mitigation intensifies - an assumption that seems entirely out of line with human experience.

Studies that estimate costs under inappropriate policy in a particular country, or without the possibility of substitution across sectors, or which omit to model learning and innovation will tend to estimate higher costs. This is so particularly later in the century when the tightest emissions reductions require tackling some of the more technologically complex sectors such as transport and ensuring very widespread deployment of zero emissions power technologies for which are likely to require early investment in research, development and innovation.

More than $70bn (£36bn) of new money was invested globally in clean or renewable energy or clean technology last year. That constitutes a 43 per cent increase on the year before with considerable investments in solar, wind and biofuels. Goldman Sachs alone has invested $1.5bn in alternative energy in the past year. Financial market estimates suggests that the solar market will grow 20-30% a year globally in next few years. This sector currently provides 4GW worldwide, and it is expected that California alone will produce 3GW of energy from solar in next 10 years. By 2010 maybe 10-20% of this could be "thin film", a technology that drastically cuts the amount of silicon needed (making it in some cases silicon-free) and so has the potential to substantially reduce cost. Companies investing in this include First Solar, Mitsubishi Heavy Industries, and Shell. There is now the very real prospect of rapid advances in solar technologies (using new materials), nano-battery storage and celluloic biofuels.

Model estimates of global mitigation costs do not provide information on the incidence or distribution of these of costs. Potential costs are likely to be higher in economies that are energy intensive, and lower in those which are less energy intensive or happen to be endowed with viable low carbon alternatives. **Since emissions are a global problem, there will need to be transfers to ensure that the lowest cost mitigation strategies are pursued across the globe**.

A6 Stabilisation

In the Review, we argued that the economics of climate change points to a stabilisation range of between 450ppm CO2e and 550ppm CO2e[22]. Anything lower than 450ppm CO2e, and the incremental costs of reducing a tonne of emissions would clearly exceed the discounted benefits. Anything higher than 550ppm CO2e and the damages caused by not cutting a tonne of emissions clearly exceeds the cost of the mitigation itself. Stabilising in this range will eliminate more than 90% of the damages relative to BAU.

However, this range is not static. Because the stock of greenhouse gases continues to grow, the cost of attaining a given stabilisation path increases with time. For example, chart A2 shows that the world currently emits over 40 GtCO2e of greenhouse gasses each year. This is enough to raise the stock of greenhouse gasses, which currently stands at about 425ppm CO2e, by about 2-2.5ppm a year. In order to stabilise the stock of atmospheric greenhouse gasses, annual emissions must be brought down towards 5 GtCO2e; this represents the earth's natural capacity to absorb greenhouse gases in any one year.

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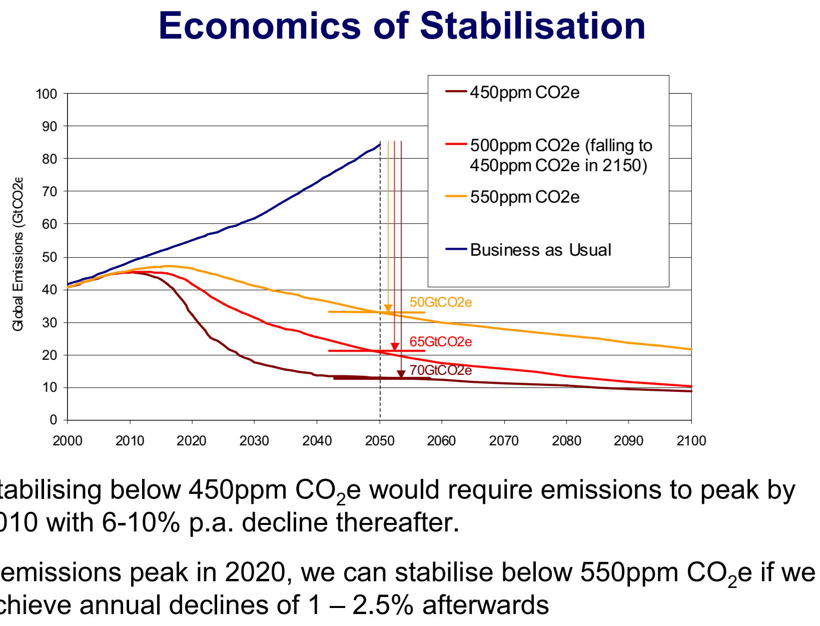
[22] See sections 13.6 and 13.7.

Chart A2. Emission corridors to stabilisation



Economics of Stabilisation

Stabilising below 450ppm CO_2e would require emissions to peak by 2010 with 6-10% p.a. decline thereafter.

If emissions peak in 2020, we can stabilise below 550ppm CO_2e if we achieve annual declines of 1 – 2.5% afterwards

It is still possible to adopt a path to stabilise at 550ppm CO2e. This is shown in chart A2; emissions can peak in the next twenty years with a smooth decline of 1-2½% annual reduction thereafter. Ten or twenty years ago, a similarly smooth and affordable path might have been available for a stabilisation corridor consistent with stabilising below 450ppm CO2e. But it is now too late – the kind if retrenchment required to meet a stabilisation corridor for 450ppm CO2e and below would be extremely costly. It would require early scrapping of functional capital and the premature use of expensive technologies (whose costs will not have benefited from learning and experience). This is why 450pmm CO2e currently marks the lower bound of our target range.

If action is delayed for another ten or twenty years, stabilisation at 550ppm CO2e – and all the unpleasant consequences associated with it[23] - will slip out of our reach. There is a now a compelling case for strong, urgent and international action on climate change.

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[23] At 550ppm CO2e there is a 50/50 chance of temperatures exceeding 3?C relative to pre-industrial by the next century up to 60% more people at risk from hunger, with half the increase in Africa and West Asia, more than 1 billion people may suffer water shortages, many in Africa, ecosystems will be destroyed and between 20 – 50% of species face extinction, serious droughts in Europe and California could occur as often as once every 10 years and the risk of abrupt and major events such as the onset of irreversible melting of the Greenland ice sheet increase dramatically.

A7 The social cost of carbon

The Stern Review makes the case for strong action in three ways: **a 'bottom-up' approach**, comparing estimates of the heterogeneous damages from unrestrained climate change with the costs of specific mitigation strategies; **a 'model-based' approach** taking account of interactions in the climate system and the global economy; and **a 'price-based' approach**, comparing the marginal costs of abatement with the social cost of carbon. The concept of the social cost of carbon is elaborated in Chapter 13. Essentially, it is a measure of the impact of emitting an extra unit of carbon at any particular time on the present value (at that time) of expected well-being or utility, expressed in terms of a numeraire such as current per capita consumption.[24]

The concept is useful in three ways. First, it conveys the message that each and every emission of greenhouse gases imposes a cost on society. Second, it can give a guide to policy-makers as to the price that should be charged to those who emit greenhouse gases. Third, by comparing it with the marginal cost of reducing carbon emissions, it can help to demonstrate that there are net benefits of action to stop climate change. **Chapter 13 concludes that the social cost of carbon today, if the world continues to travel along a 'business as usual' path, is much higher than the very low (and possibly zero) marginal costs of undertaking the cheapest forms of mitigation now.** This is because the very cheapest mitigation options, including energy efficiency measures and reduced deforestation, can be most productively undertaken first. Once mitigation efforts intensify, and the social cost of carbon increases, more expensive marginal technologies and processes will need to be applied raising average costs towards 1% of GDP.

However, the concept of the social cost of carbon has its limitations. First, in this analysis, it is path dependent. That is to say, the value of the marginal cost of carbon today depends on what happens to the stock of greenhouse gases in the future, for as long as the gas emitted today stays in the atmosphere. This is because the damage done by greenhouse gases is a function of the stock at any particular time. As damages are expected to rise more rapidly than the stock (the damages function is 'convex' in the

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[24] Thus a social cost of, say, £20 per tonne means that emitting an extra tonne of carbon today has the same impact on society's expected welfare as reducing a representative consumer's consumption by £20 today.

relevant region), a tonne of carbon emitted today will have a worse impact over time if there is no emissions abatement in future.

But if tough climate-change policies are adopted, its impact will not be as bad, and its social cost will be lower. To take a view about what the social cost of carbon is today means taking a view about the path of greenhouse gas emissions in the future, which depends on what policies are adopted and how the many uncertainties about the damages from climate change are resolved. Thus, **from the point of view of policy-makers responsible for tackling climate change, the social cost of carbon follows from the stabilisation goal adopted** (and, to a lesser extent, the precise path of emissions, and hence the stock of greenhouse gases, on the way to stabilising the stock).

Chapter 13 rehearses a general economic approach to choosing a stabilisation goal. The economist wants a goal such that the marginal costs of abatement along the path to the goal are just equal to the social cost of carbon. **As the social cost rises with time, so more costly marginal abatement opportunities become viable and the mitigation effort will gradually increase.** For a goal that is too high, that is, insufficiently demanding, some abatement would be carried out but, at the margin, the costs of doing a little extra would be below the social cost of carbon, so more action would be efficient. If the goal were set too low, the trajectory of the social cost of carbon over time would be lower, but the marginal costs of bringing about the necessary abatement would be above that trajectory.

The second limitation is to do with the relationship between the social cost of carbon as defined here and the carbon prices (or tax rates) that would be necessary to bring about the behaviour by households and firms that would reduce emissions and lead to the stabilisation goal. As the Review explains in Chapters 2 and 14, in some circumstances, setting a tax rate or price of a pollutant equal to its social cost ensures that the most desirable degree of abatement is obtained.[25] The anti-pollution policy can successfully be 'decentralised' – brought about by the actions of lots of different individuals without any further co-ordination being required. People undertake abatement activities (such as investing in zero-carbon electricity generation or economising on car journeys) up to the point where their marginal costs equal the tax or carbon price set. If the goal set is too lax, so that the social cost of carbon is on the high side, a tax or carbon price set equal to the

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[25] See Chapter 14

social cost of carbon will bring about 'too much' abatement in relation to that goal. If the goal set is too demanding, the tax/price set will not bring about enough abatement to achieve it. The appropriate goal from the point of view of the economist is the one which generates a social cost of carbon and hence a tax/price that is just sufficient to bring about exactly the amount of abatement necessary to attain the stabilisation goal.

The problem is that strong assumptions are needed to conclude that policy-makers should bring about a price of carbon equal to the social cost of carbon. This is because carbon pricing may induce other changes in behaviour as well as reducing the extent of emissions-creating activities. **The tax or carbon price may interact with other aspects of the economy, such as market structure – e.g. the competitive structure of the energy sector – natural resource rents and externalities in the process of innovation**.

Here are three examples:

- **Setting a carbon tax or price may lead to a fall in the prices of hydrocarbon energy sources, as the scarcity rents of the exhaustible natural resources are reduced.** This endogenous response of energy prices is sometimes ignored in the analysis of climate change, but could help to undermine the effectiveness of climate-change policies, as pointed out in Chapter 7 of the Review. Sinclair[26] shows how in some circumstances this might mean that the carbon price should be set high and then fall over time, even though the conventional social cost of carbon was rising.

- **Setting a carbon tax or price may change the incentives to undertake research and deploy new technologies.** Otto et al (2006)[27] develop a model of the economy in which, because of technology externalities, carbon-intensive sectors of the economy should bear relatively more of the abatement burden and hence should face a higher price for carbon than other sectors.

- **The calculation of a social cost of carbon entails choosing how to discount uncertain future climate-change damages.** If the policy-maker uses lower discount factors than the households and firms making decentralised decisions, then the latter will

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[26] Sinclair (1994)

[27] Otto, VM, Loschel, A, and J Reilly (2006): 'Directed technical change and climate policy', Report 134, April, MIT Global Change Joint Program, Cambridge, Massachusetts

not undertake as much investment in carbon abatement capital as the policy-maker would were s/he responsible for the investment decision. As the Review discusses, it is quite plausible that the policy-maker would discount less heavily than private individuals. S/he may make the ethical judgement that future generations should be given the same ethical weight as the current one, while private individuals care less about what happens after they die. And the policy-maker does not have to reflect in his or her decision-making capital market imperfections that push up market interest rates. One way of getting more investment over time – a profile more like the one the policy-maker would choose him or herself – would be to subsidise the interest payments on carbon-abatement investments. But if that were not possible or desirable, the policy-maker could set a carbon tax or price that rose more rapidly than the social cost of carbon over time (but which started lower).[28]

It is plain, therefore, that there is no short cut to setting a carbon tax or price. First, it cannot be calculated without taking a view about the path of emissions over the future, so it does not absolve the policy-maker from choosing a stabilisation goal and assessing the likely quantitative implications of climate-change policies on the emissions path to it. In fact it requires it.

Second, the carbon tax or price that is sufficient to bring about the amount of abatement needed on the chosen emissions trajectory may not be equal to the value of the social cost of carbon from current attempts to estimate it; the policy-maker needs to know more about how the economy will react to the chosen policy instrument. The social cost of carbon is still a key part of the assessment, so it can still be a useful guide to the magnitude of the appropriate carbon tax or price, but it is not the whole story.[29]

What are the implications of this for practical policy-making? This analysis reinforces the case made in the Stern Review for a pragmatic approach. **First, international**

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[28] This would still distort the choice between current spending on immediate abatement and investment in future abatement, so would not generate as cost-effective a path for abatement as the first-best option of bringing the private discount factor into line with the policy-maker's.

[29] This is also relevant for the use of the social cost of carbon in cost-benefit analysis of projects. First, those evaluating projects have to take a view as to how strong future climate-change policy will be. One could argue that, within the public sector, that view should be consistent with the view taken by the government. But outside the public sector, that is not so obvious, and some sensitivity analysis with respect to different values of the social cost of carbon is likely to be necessary, particularly while global climate-change policy is barely off the drawing board. Second, the social cost of carbon that should be used is not necessarily the carbon price, as the latter may diverge from the true social cost of carbon.

consensus on a stabilisation goal provides essential context for climate change policy. That cannot be determined by economics alone, because of the ethical issues and uncertainties involved. Choosing a goal requires having taken a view about the likely cost-effective emissions path. So **the second stage is to choose policy instrument settings** – taxes or emissions quotas – thought likely to keep the world's emissions within a corridor around that path, while also tackling the other problems in the global economy likely to impede cost-effective abatement (such as under-investment in R&D, imperfect information, asymmetries between the incentives for energy efficiency facing landlords and tenants, etc.).[30] The choice between using tradable quotas and a tax is not clear-cut. It is likely that there is greater variability in marginal abatement costs than in the social cost of carbon in the short run, which points towards the benefits of a tax-like instrument.[31]

But the uncertainty about the interactions of the carbon price with the rest of the global economy points towards starting with some sort of quantity constraint; that at least can ensure that the emissions path starts out within the original corridor implied by the initial stabilisation goal[32]. And the fact that there is already an international quota-based framework in place also provides a pragmatic argument for quotas, based on the benefits of adapting existing institutions that have been shown to work. In some sectors, direct regulation is often the most effective policy for example in building standards, the efficiency of white goods and car emissions. In these sectors pricing mechanisms are often less effective and market failures in research and development and energy efficiency are greatest.

Third, the policy instrument settings need to be reviewed at regular intervals as progress towards the stabilisation goal is monitored. **Fourth, the goal itself needs to be reviewed as knowledge accumulates** about climate-change damages and abatement costs. Any regime has to allow for changes in the level of carbon prices/trajectory for emissions in the light of improving knowledge, but the basic nature of the regime needs to be long-lasting: 'long, loud and legal'. **Fifth, excess volatility in the carbon price needs to be avoided**, so banking and borrowing, financial derivatives and/or price caps and floors are

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[30] See Chapters 16 and 17, as well as 12 on energy efficiency and Box 9.4 on learning energy technologies

[31] See Box 14.1

[32] For example, as shown by Weitzman where the marginal damage curve is steeper than the marginal abatement curve for a long-run trade-off, setting the wrong prince can lead to abatement efforts significantly off the mark relative to the optimal stabilisation target.

worth considering. In addition, the more countries and sectors in emissions trading, the less volatile the price is likely to be.

A8 Conclusion

Climate change presents a very complex challenge with a very large number of dimensions, and with interactions and dynamic feedbacks between separate impacts. It is important for policymakers to find the right way to think about the problem. It is essential to describe the impacts, including impacts on human health, ecosystems and patterns of migration and human settlement that are not adequately captured in formal economic modelling.

No-one can predict specific effects of climate change 50, 100, 150 years in the future with certainty, but scientists and economists are providing policymakers with informed judgements about the likely direction and scale of the changes. It is reasonable to ask policymakers to take a strategic view of these threats, and to consider whether it is acceptable to incur certain costs now to reduce the risks. This approach is commonplace in considering defence expenditure, and applies to some extent to preparations for pandemics and other health emergencies as well as guarding against financial panics and crises. Of course, it is not worth incurring any cost to reduce small risks, or to make only a small reduction in the probability of very large risks. So policymakers must make a judgement as to the likely costs and the cost-effectiveness of measures to reduce risk.

If we follow this route, what advice would we give to policymakers on the risks of climate change? We argue that the costs of inaction far exceed the costs of action and that a sensible stabilisation range is in the region 450-550ppmCo2e. Anything higher than 550ppmCO2e is a very dangerous place to be, and the most severe damages can be avoided at affordable cost; anything lower than 450ppmCO2e is simply too expensive to realistically attain under current technologies and would not justify the damages avoided. Because the stock of greenhouse gases is growing rapidly, the costs of meeting these targets rise for every year that action is delayed. This augurs for urgent, strong and international action.

Since the publication of the Review, expert opinion has strongly endorsed our position. In particular, the IPCC Fourth Assessment Report reaffirmed our projections on the science behind global warming (hardly surprising as we used the same expert base), while the IEA 2006 World Energy Outlook supported our emissions projections and estimates of the likely costs of mitigation.

In order to assess the broad impacts of climate change, and the costs of stabilising emissions, we have drawn on ideas and techniques from most of the important areas of economics and ethics, including many recent advances. We have taken explicit account of risks and uncertainties, which are at the heart of concerns about global warming. We have measured environmental degradation and the possibility of extreme events, which scientists tell us are more probable at high temperatures. We value human life in a way that avoids discounting arbitrarily on the basis of birth dates and allows us to take a long-term view commensurate with the challenge that climate change presents. In short, we have moved closer than any previous study to measuring what counts. In the process, we have sparked a lively and welcome debate on the assessment and choice of value judgements. Such judgements form an integral part of trying to assess the impact of climate change on people of different incomes and vulnerabilities living in different times and are the subject of a separate paper "Value judgements, welfare weights and discount rates: issues and evidence" on our website.

The output of any aggregated assessment should not be taken literally. Nevertheless, the costs we present accord with list of disaggregated impacts and risks. As more studies account explicitly for risks and uncertainties, assess a broad range of impacts and use up-to-date science, a more accurate assessment of the true costs of climate change is likely to emerge. Failure to do so has been the reason for some of the implausibly low estimated costs of climate change. In addition, we strongly urge further research on disaggregated regional impacts that offer a richer and more well-founded understanding of the true impacts of climate change than the broader aggregate snapshots.

Our conclusion that costs under flexible, global policy could be in the range around 1% of GDP +/-3% is based on a broad consensus of modelling studies. The Review also considered expert opinion on technological possibilities and innovation and economic analysis on behavioural responses to relative price movements and likely input and product substitution. Higher estimates are usually based on undue pessimism over policy or technological innovation, combined with historically unprecedented assumptions about lack of substitute between products, inputs and technologies.

We have shown that climate change could have very serious impacts on growth and development. The costs of stabilising the climate are significant but manageable. There is still time to avoid the worst impacts of climate change, if we take strong action now[33], but delay could significantly increase the dangers and the costs.

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[33] Our assessment of the key policy principles that should underlie an international collective response are outlined in the second half of the Review and expanded further in “Building an effective international response to climate change”.

Technical Appendix

This Technical Appendix presents detailed analysis on the issues raised by the formal economic modelling presented in Chapter 6 of the Review, in particular:

1. the role of discounting;
2. the treatment of risk, uncertainty and recent scientific evidence;
3. modelling climate impacts at high temperatures.

Through a variety of empirical investigations, we demonstrate that the estimated cost of climate change is highly sensitive to all three factors:

- Discounting has been the subject of much attention since publication of the Review, and rightly so, since it is clear that the valuation of the future is of substantial importance in explaining the damages that occur from climate change;
- Treatment of risk and uncertainty and responding to progress in the scientific literature are of roughly equal importance. This can be demonstrated by looking at the sensitivity of estimates to different modelling strategies that incorporate and value risk and uncertainty to different degrees;
- It can also be demonstrated by comparing our baseline-climate scenario with our high-climate scenario, and by analysing the importance of modelling convexities in the damage function describing impacts with rising temperatures, as well as the risk of catastrophic climate impacts;
- The necessity to model risk, uncertainty and 'dangerous' climate change makes interactions with risk and uncertainty important. The more averse we are to risk, the more sensitive estimates are to these factors in general.

Discounting

The way in which the future costs of climate change are discounted in the analysis of Chapter 6 has been a particular focus for comment by the economics community (see Appendix 2A.2). The discount factors calculated in Chapter 6 depend on two parameters:

1. **The elasticity of marginal utility of consumption (*η* for convenience)**, which takes into account the marginal value of increments in consumption as initial consumption rises. Evidence from a variety of empirical sources tends to suggest that extra consumption is worth less, the richer we are (the more initial consumption we enjoy). The value of a dollar of consumption to someone earning a dollar a day is likely to be far higher than the value of a dollar of consumption to a millionaire. This means that we discount the future, if we assume economic growth makes future generations richer. Overall, the economic scenarios we apply in Chapter 6 make this assumption and deliver consumption growth, even after the impacts of climate change are deducted. But, in the simple framework we apply[34], the relationship between consumption and utility – the elasticity of marginal utility of consumption – also completely describes our attitude to risk. Assuming diminishing marginal utility with respect to consumption, we place greater weight on future scenarios of severe climate-change impacts, because consumption is lower. We are averse to risk. (This is examined at length in the Review, the Appendix to the Postscript and the paper on value judgements on our website).

2. **Pure time preference (*δ* for convenience)**, which is the extent to which we discount the future simply because it is the future. The Review suggests a value for δ such that future generations are afforded equal moral standing in today's decisions, subject only to the risk that they will not exist to enjoy consumption. We set this rate equal to 0.1% per annum. An alternative ethical stance that places more weight on the empirical observation that the current generation displays impatience for consumption would set δ to a higher value. This is based on observations of the impatience that we ourselves experience given that we will not be alive to enjoy consumption in the far-off future and which we therefore factor into our private decision-making. This individual impatience is of course much higher than the same risk facing our whole generation, and in turn facing humankind.

As section 2A.2 sets out, η and δ, together with projected growth in per-capita consumption g, give the social discount rate[35]:

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[34] Formally, an iso-elastic utility function.

[35] The constancy of η and δ are not obviously appropriate and one fruitful research avenue would be to seek alternate variants.

$$r \equiv \eta g + \delta \qquad (1)$$

In Tables A1 and A2 below, we illustrate the sensitivity of our summary estimate of the total cost of BAU climate change to increases in *η* and *δ*, for both the baseline-climate and high-climate scenarios. Our summary estimate compares the 'balanced growth equivalent' or BGE of consumption without climate change to the BGE of consumption after climate-change damage and adaptation costs have been deducted. It summarises simulated losses over time, regions of the world and possible scenarios in terms of a permanent loss of global mean per-capita consumption today. Some elements of this analysis are presented in the Postscript to the Review and its Technical Annex, but here we extend the analysis to include simultaneous variation of the two parameters.

We test values of *δ* in the range 0.1% to 1.5% per annum. 0.1% is the value taken in the Review and follows from a strong ethical stance. 1.5% per annum corresponds to some 'descriptive' estimate of the pure rate of time preference that would follow from the preferences of those currently alive for valuations over at most the few decades of their remaining lifetimes.[36] Note that some studies have used still higher values[37], but it is doubtful whether such values are consistent with more direct empirical evidence. Such studies tend to solve for the pure time discount rate as the difference between the product of consumption growth and η on the one hand, and observed discount rates used in public-sector or even private-sector projects on the other.

For η, we take a range of 1 to 3. The Review applied a value of 1, which is quite well supported by recent empirical evidence.[38] However, the combination of δ=0.1 with η=1 does place a lot of weight on impacts in the far-off future[39]. **Some commentators have raised concerns that such low discounting is inconsistent with observed saving behaviour on aggregate. This is a 'descriptive' approach, as explained in 'Value judgements, welfare weights and discounting: issues and evidence', and contrasts with a 'prescriptive' approach.** While such arguments are not at all straightforward, resting importantly on definitions of income and sources of economic growth (see above), they

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[36] Pearce and Ulph (1999).

[37] E.g. Nordhaus and Boyer (2000).

[38] Cowell and Gardiner (1999); Pearce and Ulph (1999).

[39] A derivative of this is that it comes close to leading to the net present value of expected utility being unbounded, reflected in the mathematical problem of the utility integral not converging - see Dasgupta (2006) and Nordhaus (2006a). Technically, if consumption per head eventually grows at rate g and population is eventually constant, then convergence of the utility integral requires $(1-\eta)g-\delta<0$. Thus for η=1 and δ>0, we have convergence but it is close to the borderline.

warrant sensitivity analysis with higher elasticities. Because of the increasing complexity of the analysis, we restrict ourselves to consideration of one economic scenario modelled in our review: that which includes market impacts, the risk of catastrophic impacts, and non-market impacts.[40]

Throughout this analysis, it should also be noted that there is no ‘equity weighting’ of impacts in poor regions of the world. In reality, the assumption of diminishing marginal utility of consumption would lead us not only to weight impacts in the future lower, since economic growth makes us richer, but also to weight impacts in poor regions of the world higher. Since these same regions are widely expected to bear the highest relative cost of climate change, equity weighting in this way increases total cost estimates.[41] It was beyond the limited time of the Review to incorporate regional weighting formally in its modelling, so Chapter 6 roughly estimated the increase based on previous studies. Equity-weighted estimates are typically one quarter/one third higher or more, all else equal.[42] **Indeed, because such approaches tend not to value risk systematically (see below), there is good reason to believe that the weighting would in our model increase estimates still further than we have accounted for** (see Appendix to Chapter 2), as, again, the worst-case scenarios imply especially severe impacts in poor regions.

Table A1. Sensitivity to pure rate of time preference and elasticity of marginal utility (baseline-climate scenario)

(Total discounted cost of climate change under BAU - mean BGE loss, 5-95% confidence interval).

		Consumption elasticity of marginal utility (η)				
		1.0	*1.5*	*2.0*	*2.5*	*3.0*
Pure rate of time preference (δ)	*0.1*	11.1 (2.4-27.7)	6.5 (1.7-16.5)	3.6 (1.1-9.4)	2.1 (0.6-5.5)	1.3 (1.8-4.6)
	0.5	8.1 (1.7-20.4)	4.5 (1.2-11.7)	2.6 (0.8-6.7)	1.5 (0.6-4.0)	1.0 (0.4-2.4)
	1.0	5.2 (1.2-13.2)	2.9 (0.8-7.5)	1.6 (0.5-4.3)	1.1 (0.5-2.6)	0.7 (0.3-1.6)
	1.5	3.3 (0.7-8.5)	1.9 (0.6-4.9)	1.1 (0.4-2.9)	0.8 (0.4-1.8)	0.7 (0.3-1.3)

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[40] We have set out reasons why ‘non-market’ impacts on ecosystems and human health might be excluded from such analysis, when undertaken in parallel with disaggregated assessments of ecosystem and health impacts in metrics other than money. However, for the purposes of a stand-alone sensitivity analysis, excluding such impacts may give a misleading indication that such impacts are in effect of no value.

[41] e.g. Fankhauser et al. (1997).

[42] Nordhaus and Boyer (2000).

Table A2. Sensitivity to pure rate of time preference and elasticity of marginal utility (high-climate scenario)

(Total discounted cost of climate change under BAU - mean BGE loss, 5-95% confidence interval).

		Consumption elasticity of marginal utility (η)				
		1.0	*1.5*	*2.0*	*2.5*	*3.0*
Pure rate of time preference (δ)	*0.1*	*14.7* *(2.7-33.0)*	*10.2* *(2.0-20)*	*7.4* *(1.1-12.2)*	*8.1* *(0.7-6.9)*	*13.2* *(1.8-5.3)*
	0.5	*10.6* *(2.0-24.4)*	*6.5* *(1.4-15.2)*	*4.7* *(0.9-8.5)*	*5.0* *(0.6-4.9)*	*7.8* *(0.5-2.9)*
	1.0	*6.7* *(1.3-16.0)*	*4.0* *(1.0-9.6)*	*2.7* *(0.5-5.4)*	*2.7* *(0.5-3.1)*	*3.9* *(0.3-1.9)*
	1.5	*4.2* *(0.8-10.1)*	*2.5* *(0.7-6.0)*	*1.7* *(0.5-3.4)*	*1.6* *(0.4-2.2)*	*2.1* *(0.3-1.4)*

Comparing both Tables, we can see that increases in the pure time discount rate significantly reduce estimates of the total cost of business-as-usual (BAU) climate change. This matches our intuition, because the impacts of climate change increase over time, as time correlates with temperature. Increasing δ reduces the importance of future climate-change costs in present-day decisions. In the baseline-climate scenario, for example, increasing δ from 0.1% p.a. to 1.5% p.a. reduces the mean total cost of BAU climate change from 11.1% to 3.3%, where η is 1. In the equivalent column for the high-climate scenario, the mean estimate falls from 14.7% to 4.2%.

Increasing η has more complex effects, because it increases both discount rates and risk aversion, so the valuation of scenarios with severe climate-change impacts can carry more weight. In the baseline-climate scenario, increasing η from 1 to 3 reduces the mean total cost of BAU climate change from 11.1% to 1.3%, where δ is 0.1% p.a. In the high-climate scenario, initial increases in η from 1 to 2 reduce the mean total cost of climate change (from 14.7% to 7.4% where δ is 0.1% p.a.). But further increases in η from 2 to 3 actually drive the equivalent estimates back upwards again, from 7.4% to 13.2%. **This means that, while in most instances increases in η have a greater positive effect on discount rates than they do on risk aversion, the opposite is true when upper-bound values of η are applied to the high-climate scenario.** This is also intuitive, since the high-climate scenario realises the highest global temperatures, which work through to produce the highest damage and the lowest consumption. Scenarios that produce very low consumption receive very high marginal valuation when η lies in the range 2.5-3. Compare the mean total cost of climate change with the corresponding 5-95% confidence interval.

When η lies in the range 2.5-3, the mean lies below even the 95th percentile, because consumption is very low in scenarios that are less than 5% likely, and this feeds through to extremely low utility.

The different outcomes illustrate the impact of assumptions about the range of values for the pure time discount rate and for the consumption elasticity of marginal utility. Increasing δ reduces the cost of BAU climate change. This reinforces the conclusion, simply put, that if you do not care much for the future you will not care much about climate change. High pure rates of time preference trivialise what are, with significant likelihood, severe impacts on economies, societies and natural systems at high temperatures. While the reasons for higher values of δ cannot be dismissed out of hand – economics tells us to consider carefully the consistency of our choices with other areas of policy and economic behaviour more generally – counter-arguments are not easily made and the ethics of the decision are compelling. Among the many thought experiments we can undertake to aid this choice is the following: can we accept an outcome where catastrophic losses in income and welfare in the far-off future are discounted away? We believe that most would answer ‘no’.

Increasing η also reduces the cost of BAU climate change on the baseline-climate scenario and initially on the high-climate scenario, but for higher-bound values it increases the cost of climate change on the high-climate scenario. Where η equals 2, the range of cost estimates across the two climate scenarios is 3.6% to 7.4% (δ=0.1% p.a.). Higher values of η are less well supported by revealed behaviour with respect to individual saving and social redistribution, though some have argued that it better approximates aversion to risk.[43] This illustrates the restrictive nature of a simple utility function, in which η must at the same time capture inequality aversion and risk aversion. Values in the range of 2 to 3 will at least ensure the utility integral converges quite comfortably. Where η equals 3, the range of cost estimates across the two climate scenarios is 1.3% to 13.2% (δ=0.1% p.a.). This is a more complex decision and we must think carefully about how to evaluate two discrete probability distributions, where the overall probabilities that one or other distribution is ‘true’ are unknown. Theory tells us that a similar form of risk aversion can be applied to such situations, such that we would place greater relative weight on the high-climate scenario, depending on the relative probabilities of the two scenarios. Coupled with equity weighting, these considerations would push us away from the lower-bound estimate

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[43] Gollier (2006).

towards the higher-bound estimate. **The sensitivity analysis suggests that the original conclusions of the Review remain robust**.

Risk, uncertainty and recent scientific evidence

Although discounting is a very important parameter in estimating the monetary cost of climate change, we must not lose sight of the importance of taking (1) the economics of risk and uncertainty and (2) the latest scientific findings into account, when we do formal modelling. In this section we discuss both issues together, since a discussion of the effects of taking risk and uncertainty into account cannot take place without considering recent evidence, which points to increased risks of higher impacts and wider confidence intervals overall. **We demonstrate that the effect of taking risk and uncertainty into account is of a comparable magnitude to variations in discounting.**

In Chapter 6, we took account of recent evidence of increased risks from climate change, incorporating this into our modelling in two ways. **First, the probabilities of temperature increase we estimate in our baseline-climate scenario span a broader interval than has typically been entertained in previous Integrated Assessment Modelling studies** (see below). In particular, this interval incorporates temperature increases that were considered to be high, but possible, by the IPCC in its 2001 TAR. The AR4 has confirmed this possibility, in fact increasing it. But many previous economic modelling studies in effect ignore this possibility (see below). **Second, the balance of recent scientific evidence has pointed to the possibility of still higher temperature increases**. We take this into account by specifying a high-climate scenario, which is calibrated on published studies investigating the likelihood of positive natural feedbacks in the climate system, specifically the weakening of carbon sinks and methane released from a melting permafrost.[44] The contribution of these feedbacks to warming this century is also in line with summary estimates from AR4.

All the links in the chain between emissions of greenhouse gases and the economic and social impacts of climate change – each of which needs to be parameterised in an integrated assessment model (IAM) – are subject to uncertainty. Uncertainty about

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[44] Friedlingstein (2006); Gedney et al. (2004).

warming is but one, albeit important, link. We chose to use the PAGE2002[45] IAM, because it is a flexible, stochastic model and can thus take account of such uncertainties. PAGE2002 has a deterministic, fixed structure, in terms of the equations on which it is built and how each equation relates to another. But the parameters that describe the equations are stochastic. In particular, the model produces estimates based on 'Monte Carlo' simulation, which means that it runs each scenario many times (e.g. 1000 times), each time sampling a set of 31 uncertain parameters randomly from pre-determined ranges of possible values. And although its results depend, as they do in any model, on its structure, it has the additional advantage of being calibrated on the underlying scientific and economic literatures, so it is set up to capture a broad sweep of results.

Insufficient treatment of uncertainty could cause misleading results. We can test this proposition by using PAGE2002 to simulate a range of modelling strategies, each of which takes risk into account to a different degree. Table A3 presents estimates from four modelling approaches.

1. **'All modes'.** The first is to set all stochastic parameters in PAGE2002 to their mode values. This simulates a modelling strategy in which best guesses are made about the value of all parameters, 'best' in the sense of being most likely. This strategy is very common in the literature.
2. **'All means'.** The second is to set all stochastic parameters in PAGE2002 to their mean values. This also simulates a deterministic strategy, but the mean of any distribution will be different from the mode, if the probability distribution that it summarises is asymmetric. This is important in modelling the impacts of climate change, because the overall distribution of impacts is acknowledged to have a 'fat tail' of severe impacts with a low probability.
3. **'Expected consumption'.** The third utilises the standard stochastic specification of PAGE2002, but instead of carrying out full expected-utility analysis as in Tables A1 and A2 and in Chapter 6 of the Review, we calculate the BGE for expected consumption, the mean path of global consumption per capita net of climate-change impacts and adaptation costs. In essence, we make use of a stochastic modelling strategy, but we fail to follow it through to a systematic valuation of risks, because we collapse uncertainty in consumption, before converting it to utility.

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[45] Comprehensively described in Hope (2006).

4. **'Expected utility'.** The fourth reproduces the analysis in Tables A1 and A2, solving for the BGE equivalent to the expected utility of consumption. The difference between an 'expected consumption' strategy and an 'expected utility' strategy is, very broadly, that the latter allows us to fully build in risk aversion.

Table A3. Estimated cost of BAU climate change under different modelling strategies
(Total discounted costs where δ=0.1% p.a., η=1.0)

Modelling strategy	*Baseline climate (%pt BGE loss)*	*High climate (%pt BGE loss)*
All modes	3.5	4.6
All means	8.0	11.0
Expected consumption	10.4	12.7
Expected utility (mean loss)	11.1	14.7

From Table A3 it is clear that a modelling strategy based on taking mode values for all parameters – equivalent to a best-guess strategy – leads to a significant underestimate of the total discounted cost of climate change, relative to an expected-utility approach. In the baseline-climate scenario, this strategy yields an estimate of the BGE loss that is 3.5% of present global mean consumption per capita, relative to a mean of 11.1% when expected-utility analysis is applied. In the high-climate scenario, the 'all modes' strategy performs even worse, estimating a 4.6% BGE loss, compared to 14.7% using expected-utility analysis. Moving to an 'all means' strategy reduces the shortfall significantly, although it is still 3.1 percentage points below at 8% in the baseline-climate scenario. Similarly, it is 3.7 percentage points below at 11% in the high-climate scenario.

Calculating the utility of expected consumption brings the estimates much closer. In the baseline-climate scenario, it is 10.4%, which is just 0.7 percentage points below the expected-utility estimate, a shortfall of 6.3% relative to the benchmark expected-utility estimate. However, the expected-consumption strategy does perform worse in the high-climate scenario, falling short by 2 percentage points or 13.6%. As before, the higher temperatures estimated by the high-climate scenario produce a slightly higher likelihood of scenarios in which the impacts of climate change are very severe indeed. Even with relatively modest risk aversion (recall that in Table A3, η=1), the need to value these risks systematically is clear.

This last point indicates that **a useful extension to the analysis would be to consider how the expected-consumption strategy performs relative to the expected-utility strategy for higher values of *η*.** Table A4 presents this analysis for *η*=1,2 and 3. In the baseline-climate scenario, increases in *η* reduce the absolute shortfall between the expected-consumption estimate and the expected-utility estimate, from 0.7 percentage points where *η* is 1 to 0.2 percentage points where *η* is 3. However, the relative shortfall is in fact rising, from 6.3% as a share of the expected-utility estimate where *η* is 1, to 15.4% where *η* is 3. Even in the baseline-climate scenario, which attains lower temperatures and lower impacts on average than the high-climate scenario, **the significance of failing to value risk systematically rises with rising risk aversion**.

This result is magnified to a much greater extent in the high-climate scenario. When *η* is 1, the shortfall caused by taking an expected-consumption approach is 2 percentage points or 13.6%. But when *η* is 3, the shortfall is 11.9 percentage points, or 90.2% of the expected-utility estimate. One the one hand, such a result encourages us to consider the implications of high values of *η*, where strong aversion to a small number of scenarios (less than 5% likely) dominates the expected-utility estimate. On the other hand, if we do believe that this is the appropriate way to specify the consumption elasticity of utility in a simple framework, then the last result demonstrates that even an expected-consumption approach, which at least rests on stochastic modelling, understates – possibly by a large amount – the risks we face.

Table A4. Comparing expected-consumption and expected-utility approaches with different degrees of risk aversion.

Climate scenario	*Modelling strategy*	*Elasticity of marginal utility of consumption (η)*		
		1.0	*2.0*	*3.0*
Baseline	*Expected consumption*	10.4	3.3	1.1
	Expected utility (mean loss)	11.1	3.6	1.3
High	*Expected consumption*	12.7	4.0	1.3
	Expected utility (mean loss)	14.7	9.2	13.2

To summarise at this stage, Tables A3 and A4 demonstrate the proposition that inappropriate treatment of uncertainty leads to estimates of the cost of BAU climate change that are misleadingly small. Similar results have been produced by past

studies, although they have not focused on the issue in such detail.[46] Furthermore, the difference between a comprehensive, expected-utility approach and simpler approaches is often large. **Broadly, the differences revealed are of the same magnitude as those produced by different assumptions about discounting**. Moving from an 'all modes' modelling strategy to expected-utility analysis increases the mean total cost of BAU climate change by 7.6 percentage points in the baseline-climate scenario. Increasing the pure rate of time preference from 0.1% p.a. to 1.5% p.a. produces a 7.8 percentage point rise in that same scenario.

Recent scientific evidence increases the imperative to adopt an explicit analysis of risks, for example, since it has raised the possibility of very large impacts and as a result has effectively increased the confidence interval around the future consequences of climate change. The bigger differences between modelling strategies in the high-climate scenario reflect this, insofar as the high-climate scenario takes on board the possibility of higher temperature increases than does the baseline scenario. **The economics of uncertainty is at centre stage** when examining the impacts of climate change (as explained in Chapter 2 and Appendix A2.2)

And it is very likely that even PAGE2002 underestimates the uncertainty around many of its parameters, because of limitations in the data it must rely on. In many cases, the probability distributions that are estimated for its parameters are based on a range of underlying studies that give 'best guesses'. As such, PAGE2002 can encapsulate uncertainty between the best guesses of other models, but it is unlikely to adequately capture uncertainty within these models themselves. Consider the important 'climate sensitivity' parameter, which describes the equilibrium increase in global mean temperature accompanying a doubling in atmospheric carbon dioxide concentrations. In Chapter 6, we calibrated this to a minimum of 1.5ºC, a mode of 2.5ºC and a maximum of 4.5ºC, which represents the IPCC's long-standing, non-probabilistic range (stated in the *First*, *Second* and *Third Assessment Reports*). It is a non-probabilistic range, because it is drawn from the best guesses of several climate models. But recent probabilistic research in the scientific literature has begun to explore within-model uncertainty. In a survey of eleven studies that sought to estimate climate sensitivity probability distributions, Meinshausen calculates an overall range that runs from around 0.5ºC to well over 10ºC (the 90% confidence interval is

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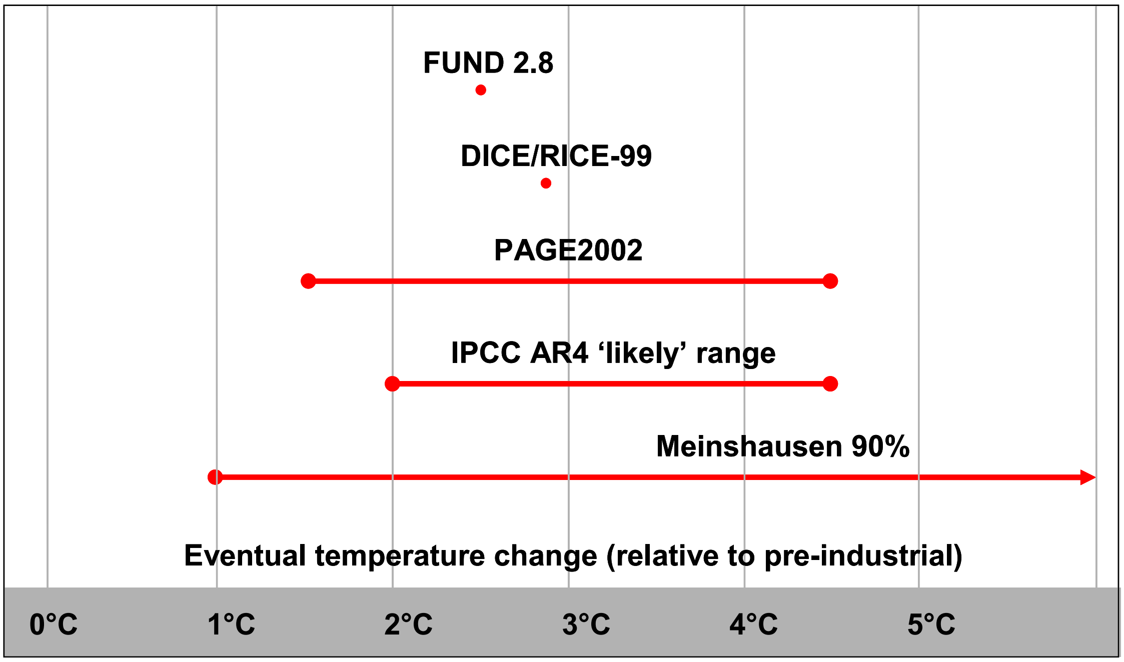
[46] e.g. Azar and Lindgren (2003), Tol (1999).

1-8ºC). This is broadly consistent with the IPCC range, insofar as the most probable values continue to lie in a narrower range around 2-3ºC, but indicates that **much higher values cannot be ruled out**. The high end of this range would produce temperature increases in excess of that predicted by our high-climate scenario.

In making overall decisions on how much mitigation to undertake, one implication of this finding is that we must take into account outcomes beyond those predicted in our formal models. But **it again drives home the inadequacy of a simple, deterministic approach to modelling, without valuation of risk**. The climate sensitivity in Nordhaus' DICE/RICE models is about 2.9ºC;[47] in Tol's FUND model it is 2.5ºC. As Figure A1 demonstrates, these are sensible 'best guesses' relative to the evidence amassed by IPCC (the likely range – 66% confidence – from IPCC AR4) and Meinshausen, but they foreclose the evaluation of the full range of estimates, especially high estimates that would command special attention in calculating expected utility, because they would give rise to severe climate impacts.

Figure A1. Comparison of climate sensitivity in three IAMs

(Using ranges estimated by IPCC AR4 and Meinshausen 2006)



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[47] Nordhaus and Boyer (2000).

Similarly, Warren *et al*. (2006) make the point that the same IAMs use a limited set of the wider literature when estimating impacts in particular sectors. Examples may be found in the agriculture and ecosystems sectors. For agriculture, the region-specific IAMs use literature that assumes strong adaptation (RICE, FUND) and/or strong carbon dioxide fertilisation (FUND) and hence smaller impacts than the overall combined literature would suggest. **While the authors of these studies may explore the consequences of their assumptions, the assumptions themselves raise very serious questions regarding:**

1) the limited or absent treatment of risk;
2) the limited treatment of climate change sensitivity;
3) the low path for baseline emissions;
4) the high pure discounting

it must also be recognised that entirely different results are possible.

Costing 'dangerous' climate change

In light of such recent evidence, it is also important to analyse how IAMs simulate the cost of very high global temperatures. As we argued in the Review, there is strong cause to believe that the impacts of climate change will increase faster than temperature, as emissions drive warming beyond the range of 2-3ºC above pre-industrial (the conventional focus of IAMs). However, although the evidence certainly points to the qualitative nature of this relationship, it is too thin to make precise, quantitative predictions. There is very little empirical evidence available for around 5ºC warming and beyond. This renders a stochastic modelling approach, as well as the task of undertaking sensitivity analysis, all the more important.

In the simple, reduced-form framework of an IAM like PAGE2002, **the broad story of 'dangerous' climate change is told through two modelling parameters**, which formally separate two causes of an overall 'convex' relationship between warming and its impacts:

1. **The amount of convexity assumed in the damage function(s):** this captures the market and non-market impacts of what we might call 'gradual' climate change. As Chapter 3 of the Review discussed, there are a number of basic biological and physical principles indicating that impacts in many sectors will become disproportionately more severe with rising temperatures. And empirical evidence

supports this intuition in several cases. For example, the relationship between the wind speed of tropical storms and consequent damage is convex, on top of the sharply increasing relationship between sea surface temperature and storm wind speed itself.[48] On the other hand, systematic empirical support for the overall convex relationship between climate-change impacts and temperature – across all impact sectors – is lacking.[49] In part this is because there is very little empirical evidence of any sort on the impacts of 5ºC warming and beyond. However, intuitive examples are easier to envisage across all sector.[50] In addition, the fact that IAMs miss interactions in the impacts between sectors becomes all the more troubling, as temperatures increase. Another interpretation of the convex damage function is as a simple minded indirect proxy for bringing in increased temperature risks from omitted feedbacks;

2. **Whether the risk of catastrophic climate change is modelled:** there is emerging evidence of the risks that higher temperatures could trigger large-scale shifts in the climate system, such as the melting and collapse of ice sheets and sudden shifts in regional weather patterns like the Indian and African monsoons. In 2001, IPCC identified the risk that such shifts could trigger impacts on the economy orders of magnitude higher than ordinary weather disasters.[51]

Focusing first on convexity, PAGE2002 represents impacts on market and non-market sectors of a regional economy by respective damage functions that depend on regional temperature increase (T_R) and the damage function exponent γ (which is common to both sectors/functions). If we normalise these functions to damages at 2.5ºC, which is the common calibration point for functions in aggregated IAMs, then the general-form equation can be described by:

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[48] IAG (2005); Nordhaus (2006b).

[49] Hitz and Smith (2004).

[50] Consider the following illustrative escalation of costs relative to temperature: at between zero and two degrees warming, agricultural output can be adapted and crops can change; some regions will see higher yields and longer growing seasons, levies can be strengthened and irrigation projects enhanced; between two and four degrees warming, new agricultural plant and processes may be required, levies and barriers must be rebuilt and new irrigation sources found; between four and six degrees some coastal areas must be abandoned and populations moved while former agricultural land must be left for arid. Water stress in some regions and coastal and delta flooding in others prompts migration. It is clear that the costs and impact are highly disproportionate - convex – to the linear change in temperature

[51] Smith et al. (2001), p947.

$$Damages \propto \left(\frac{T_R}{2.5} \right)^{\gamma}$$

(1)

Damages are defined as a loss in income in market sectors and a loss in welfare in non-market sectors. Both are normalised as a percentage of GDP. Note that actual damages also depend on assumptions about adaptation, which affect the rate and level of temperature increase 'tolerated' before impacts begin, and can 'buy down' impacts above those tolerable thresholds. For ease of exposition, we hold these assumptions constant here[52].

The damage function exponent is critical in determining the scale of the estimated impacts, especially at high temperatures. In the standard model (as used in Chapter 6, the Postscript and most of this paper), γ is defined by a triangular probability distribution, with a minimum of 1, a mode of 1.3, and a maximum of 3. A power of 1 describes a linear relationship between warming and impacts. A power of 3 describes significant convexity. This range is based on assumptions and results from several previous studies. Figure A2 demonstrates the dependence of damages at any given temperature on γ, normalised to damages at 2.5°C. At 6ºC above pre-industrial, a range of values for γ from 1 to 3 gives rise to a difference in the undiscounted mean cost of climate change that spans approximately 2.5-14% of GDP.

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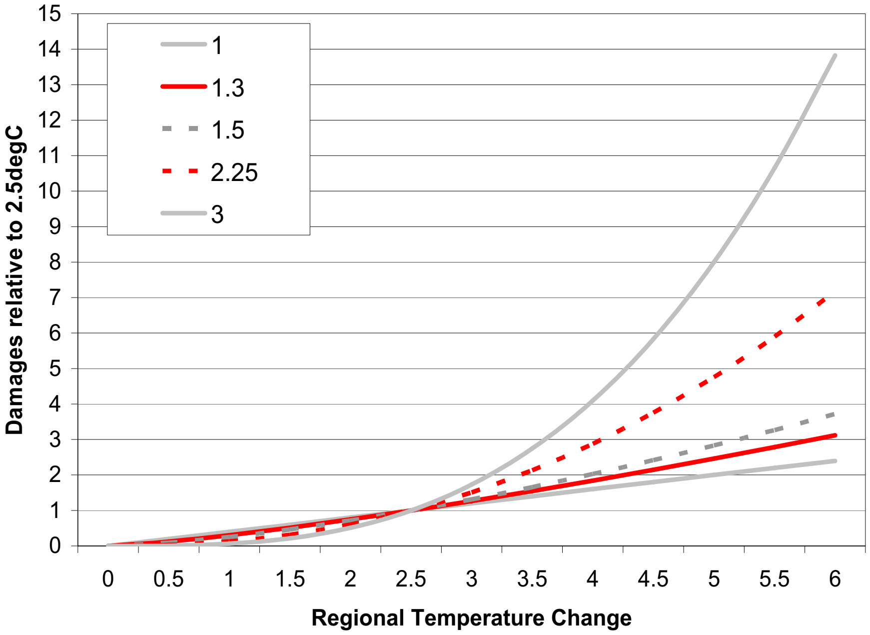
[52] PAGE assumes that 90% of the impacts are adapted to in rich countries, and 50% in poor, and this remains constant. Some have argued that adaptive capacity should increase with time, but this is open to judgement. The ability to adapt to small impacts is likely to increase as countries become richer and more technologically advanced, however, it is likely that they will become less able to cope with the more extreme events associated with higher temperatures. In addition, a large slug of the damage costs either extends beyond our ability to adapt or are not amenable to technological improvement in the same way that, say, energy generation or fighting diseases is. Vulnerability may also increase with GDP as more expensive capital is at risk and rapidly increasing populations are forced to inhabit vulnerable coastal areas.

Figure A2. PAGE2002 damage functions.



In the Postscript to the Review, we provided an initial test of the sensitivity of our summary estimate of the total cost of climate change, the BGE loss in terms of present global mean consumption per capita, to a change in the probability distribution of γ. We increased the minimum to 1.5 and the mode to 2.25. We held the maximum constant at 3. In the baseline-climate scenario, where δ=0.1% p.a. and η=1, the mean estimate of the total cost of climate change increased from 10.9% to 14.2%. In the high-climate scenario, the equivalent estimates increased from 14.4% to 21.9%.

Thus overall estimates are indeed sensitive to the damage function exponent. In this paper, we examine this sensitivity in slightly more detail. In addition, we analyse how uncertainty about the damage function exponent interacts with different degrees of risk aversion. This is likely to be an important interaction, since higher values of γ – more convexity in the damage function – increase the likelihood of very severe impacts. The discussion above demonstrates the significance of how we think about and consequently model such risks.

In Tables A5 and A6, we treat γ as deterministic, in order to assess sensitivity to its variation more systematically. In Table A5, we initially discuss results for a low range of γ from 1 to 2, and examine how that range interacts with a range of *η* – the elasticity of marginal utility of consumption, describing inequality and risk aversion – from 1 to 3. In Table A6, we go on to explore a higher range for the damage function exponent, taking in values of 2.5 and 3. In both cases, the analysis is confined to the baseline-climate scenario and holds *δ* constant at 0.1% p.a.

Table A5. Cost variations with damage function exponent and elasticity of marginal utility
(total discounted cost of BAU climate change baseline-climate scenario, *δ*=0.1% p.a.)

		Consumption elasticity of marginal utility (η)		
		1	*2*	*3*
Damage function exponent (γ)	*1*	5.4 (1.3-12.1)	1.9 (0.8-4.3)	0.9 (0.4-1.7)
	1.5	7.2 (1.7-16.6)	2.4 (0.9-5.7)	1.0 (0.4-2.1)
	2	10.4 (2.2-22.8)	3.3 (0.9-7.8)	1.1 (0.4-2.7)

Where the consumption elasticity of marginal utility, *η*, equals 1, increasing *γ* from 1 to 2 raises the mean total cost of climate change from 5.4% of present global mean consumption per capita to 10.4%, an increase of 92% in relative terms. A power of 2 produces an estimate closest to our main result, reported in Table A1. Thus where *η*=1, our summary estimate of the total cost of climate change is indeed very sensitive to the damage function exponent, as the Postscript to the Review also suggested.

However, where *η*=3, the mean total cost of climate change increases from 0.9% to just 1.1%, a rise of just 0.2 percentage points or around 22% in relative terms. We would indeed have expected all estimates to fall, since raising the consumption elasticity of marginal utility increases the discount rate. But the relative effect of changes in the damage function exponent has also fallen. This indicates that **increases in the consumption elasticity of marginal utility work to a greater extent to increase discount rates than they do to increase risk aversion, for this relatively modest range of damage function exponents**.

However, increasing *γ* beyond 2 paints a different picture for our overall evaluation. Table A6 reproduces the analysis, but for high values of *γ*, 2.5 and 3. For reference, we reproduce the corresponding evidence where *γ*=1.

Table A6. Further variations in damage function exponent and elasticity of marginal utility

(Total discounted cost of BAU climate change - baseline-climate scenario, δ=0.1% p.a.)

		Consumption elasticity of marginal utility (η)		
		1	*2*	*3*
Damage function exponent (γ)	*1*	5.4 (1.3-12.1)	1.9 (0.8-4.3)	0.9 (0.4-1.7)
	2.5	17.1 (3.3-37.5)	6.7 (1.2-12.9)	2 (0.7-5.0)
	3	34.4 (4.2-74.8)	39.6 (1.5-37.1)	59.0 (0.5-15.9)

Table A6 illustrates that estimates are much more sensitive to increases in γ when we reach the top end of the range. The mean total cost of climate change increases to 34.4% where γ=3 and η=1. Moreover, as risk aversion increases, the range of estimates increases too. Where η=3, the total cost estimate jumps to 59%, as γ increases to 3. Comparing the mean cost with the 90% confidence interval shows that, where γ=3 and η=3, the mean lies far beyond the 95th percentile estimate. This is not a misprint. What it means is that less than 5% of high-damage model runs dominate the overall calculus, by delivering utility low enough to overwhelm the calculation of expected utility. So **if we ascribe high values to *η*, perhaps based on empirical evidence on risk aversion, then assumptions about the convexity of damage become all the more important.** This raises the interesting question as to whether higher values of η might be appropriate for risk and lower values for inequality – an exciting field for future research. Disagreement about the ‘correct’ value of γ will of course persist, but the point is that high values cannot be ruled out, perhaps beyond even 3. Thus the need for an expected-utility framework is reinforced, as is the need to consider the overall model estimates against the possibility of unquantified uncertainty.

Many of the same points apply to the second method in which the PAGE2002 IAM incorporates ‘dangerous’ climate change: that is, in a separate function that describes the risk of catastrophic climate impacts. When global mean temperature rises to high levels (an average of 5°C above pre-industrial levels, a minimum of 2°C, mode of 5°C, and maximum of 8°C), the chance of large losses in regional GDP in the range of 5-20% begins to appear. This chance increases by an average of about 10 percentage points per ºC rise in global mean temperature (minimum 1, mode 10, maximum 20).

A similar approach is used by Nordhaus and Boyer in DICE[53], and it is in large part for this reason that their estimates of the undiscounted cost of climate change are higher than other models, especially when warming rises beyond 2-3ºC above pre-industrial.[54] In the Review, we reported the total discounted cost of climate change with and without the risk of catastrophic climate impacts. The difference was 2.9 percentage points (Table 6.1).

Summary

Through a variety of empirical investigations, we have demonstrated that the estimated cost of climate change is highly sensitive to three factors:

- the approach to discounting;
- the treatment of risk, uncertainty and recent scientific evidence;
- modelling climate impacts at high temperatures.

Table A7 brings together the results of the Appendix. The base case, from which deviations are reported, is our 'central' modelling case. This comprises the baseline-climate scenario, with market impacts, the risk of catastrophic climate change, and non-market impacts. The pure rate of time preference is 0.1% per annum, the elasticity of marginal utility of consumption is 1, the damage function exponent is sampled from the range 1-3 (mode=1.3), and expected-utility analysis is carried out. For each of the modelling issues we have examined, we summarise the effect on our mean estimate of the total cost of climate change when one of these parameters is varied, holding everything else constant.

Table A7. Sensitivity of mean total cost of BAU climate change

(to variations in discounting, treatment of risk, uncertainty and recent scientific evidence, and modelling climate impacts at high temperatures)

Variation	*Magnitude of variation*	*Change in mean total cost of climate change (percentage points BGE costs)*
Increasing the damage function exponent (γ)	1-3	+29
Increasing the pure rate of time preference	0.1-1.5% p.a.	-7.8

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[53] Nordhaus and Boyer (2000).

[54] Smith et al. (2001).

Not incorporating and valuing risk and uncertainty	Expected utility – all modes	-6.6
Increasing the value of elasticity of marginal utility of consumption	1-3	-9.8
Not incorporating recent science	High climate - baseline	-3.6
Exclusion of risk of catastrophe	With - without	-2.9

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