Technical Annex to Postscript

Some commentators on the Review have focussed on particular technical issues associated with modelling the aggregated impacts of climate change.[10] Our estimates of damage from climate change derived from formal economic modelling are higher than many estimates in the literature, and there has rightly been strong interest in our underlying assumptions. This paper responds to some of the comments on the modelling we have received in the weeks since the publication of the report.

The questions concern both the model structure and the ethical judgements that are embodied in the evaluations. Investigating these questions allows us to use the models to clarify the roles of the different assumptions in a structured way. We did not present these results as part of Chapter 6, but we have subsequently carried out a sensitivity analysis in this area and the results are presented below. This Technical Annex can be seen, in part, as an annex to Chapter 6.

The role of Integrated Assessment Models (IAMs)

Integrated assessment models attempt to summarise the impacts of climate change, usually in terms of aggregate gains or damages in terms of income. These models, on the basis of their assumptions, give an idea of the magnitude of risks, their evolution over time and sensitivity to emissions. As the Review makes clear, the role of IAMs is to give an illustration of the potential effects of climate change. Modelling of the economic impacts of climate change over long time-horizons cannot give precise results and is very sensitive to assumptions. Given the difficulty of modelling so far into the future, the models must be seen as highly speculative, but they do have the advantage of exploring the logic of assumptions.

Our results using IAMs complement our analyses of the overall risks and the disaggregated impacts of climate change. In the Review, we lay stronger emphasis on the disaggregated assessment of impacts, together with overall judgements on the riskiness of very high temperatures and of unknown territory in a context where greenhouse gas (GHG) concentrations and environmental damage are very difficult to reverse. The IAM analysis illustrates these risks but should not be seen as the first or most important argument in coming to an overall judgement concerning the importance of a strong reduction in GHG emissions.

It is important to recognise the limitations of IAMs. Expressing multi-dimensional impacts in terms of aggregated income losses masks the full environmental and human implications, which can be understood only through an analysis across several dimensions. In addition, in attempting to value these impacts in relation to a common income unit, IAMs add a degree of formality and precision, which can, from some perspectives, obscure rather than illuminate an overall assessment of the impacts. Existing IAMs rely heavily on literature that, in many cases, still

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[1] The comments have reached us in various ways – via remarks at seminars, e-mails and press comments. We focus here on the most commonly expressed concerns.

[2] Discussed in Section 1.4

[3] Note that T_R in the model is actually the 'vulnerable' temperature increase, as it is assumed that most regions can adapt to some degree of temperature rise. The regional temperature increase is dependent on the global temperature increase (a linear relationship) and the regional sulphate aerosol concentration.

[4] Warren et al. (2006)

[5] This is on top of the sharply increasing relationship between sea surface temperature and hurricane wind speed.

[6] This measures how fast the value of an increment in consumption falls as consumption rises, for example when it is equal to one, an extra unit to Person A, with three times the consumption of Person B, would have one third the value to that if the extra unit went to Person B. If the elasticity were equal to two, the extra unit would have one ninth of the value.

[7] Pearce and Ulph (1999); Stern (1977).

[8] It is possible to argue that this type of risk should be embodied in the measurement of costs and benefits but it would play a similar computational role and this type of discounting and pure time preferences seems often to be combined.

[9] http://www.ft.com/cms/s/444ff4ae-783c-11db-be09-0000779e2340.html

[10] The comments have reached us in various ways – via remarks at seminars, e-mails and press comments. We focus here on the most commonly expressed concerns. We are particularly grateful to Partha Dasgupta and Bill Nordhaus for their comments.

excludes significant effects that have been explored only in the last few years, in particular the risks at high temperatures. The scientific literature has only recently been able to give probability distributions of temperatures associated with levels of greenhouse gas concentrations in the atmosphere. Crucially, this now allows more explicit analysis of the economics of risk and shows that the probability of temperature increases above 5°C under business-as-usual (BAU) may be high (above 50% in the most recent Hadley Centre estimates for some standard BAU emissions paths[11]).

The Review considers results from a range of IAMs and produces new results from one particular model: PAGE2002. The aim of this analysis was to provide an illustration of the scale of the potential impacts of climate change with an IAM that was updated to reflect recent probability estimates and incorporate the economics of risk (described below). These two features imply higher estimates than some previous literature but both are essential for a serious and up to date study of climate change. The economics is fundamentally about the economics of risk.

In addition we examined carefully the arguments for pure time discounting (see Chapter 2, its appendix, and below) and argued that whilst the growth arguments for discounting were sound (and included in the modelling) in this context, the ethical case for strong pure time discounting was weak. Lowering pure time discount rates raises estimates of losses.

Integrated Assessment Modelling in the Stern Review

In this section, we examine what shapes the outputs from the models, what innovations the Stern Review has made and what further innovations should be examined. There are four main elements: (i) the model structure; (ii) the underlying evidence; (iii) the issues being examined – here, particularly, the economics of risk; (iv) ethical judgements. We then provide a sensitivity analysis varying parameters relevant to the model structures and ethical judgements to cover issues raised with us by commentators. Finally we comment on directions for research in this area and the implications of the sensitivity analysis for the overall argument of the Review.

The model structure

The PAGE2002 model was chosen for two reasons: (i) it is particularly convenient for examining risk; and (ii) it is designed to span the range of previous models. For example, the standard damage function of the model is designed to cover the range of estimates described in the IPCC Third Assessment Report (TAR, 2001) and the climate sensitivity range is consistent with the likely range given in that report. No changes were made to the core model structure for the Stern Review analyses in Chapter 6 of the report.

Scientific and other evidence

Through assessing the full range of possible outcomes based on current scientific evidence, the results in the Review go further than the majority of previous studies in attempting to quantify the impacts of climate change. This allows us to capture more fully the risks associated with higher temperatures. The 'baseline'-climate scenario of the model is designed to be consistent with probability distributions associated with the range of projections given in the IPCC TAR. The Stern Review builds on this by considering more recent scientific evidence pointing to greater risks of high temperatures due to additional feedbacks, such as weakening carbon sinks and increased natural methane releases. This is called the 'high'-climate scenario.

In addition to the more recent estimates of probabilities of different temperatures (used for both baseline and high climate), there is also an issue of how to evaluate consequences of different temperatures. As discussed in Part II, there are uncertainties here that can only be resolved once there are sufficiently good data. The G-ECON database is one project leading the way here (see

[11] Discussed in Section 1.4 of the Review.

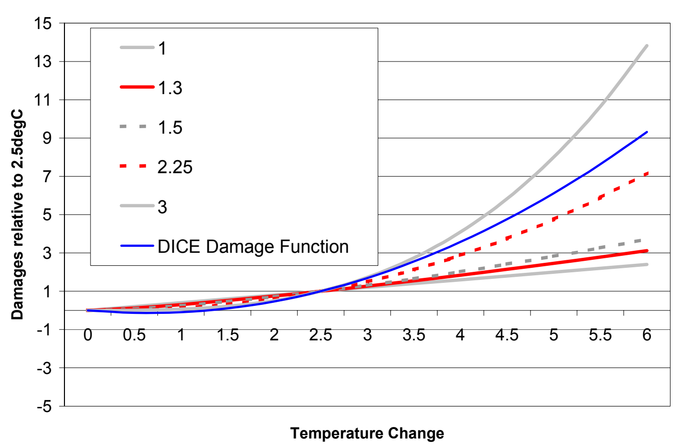
Nordhaus, 2006a). The damage function of the PAGE2002 model is designed to capture stochastically the findings of other IAMs. For lower temperatures, a wide pool of published literature informs these damage estimates. However, as temperatures rise above around 3 - 4°C above pre-industrial, information becomes scarcer. Detailed empirical assessments of impacts at high temperatures are difficult to do because they take us far outside the range of human experience. Given that under a business-as-usual trajectory there is a significant risk of temperatures exceeding 5°C, more research is required to better understand the consequences of high temperatures.

In the PAGE2002 model, impacts are represented by a damage function that takes a simple form dependent on regional temperature[12] increases (T_R) and the damage exponent γ.

$$Damages \propto \left(\frac{T_R}{2.5}\right)^{\gamma} \quad (1)$$

The damage exponent is critical in determining the scale of the estimated impacts. In the standard model (as used in Chapter 6) this is defined by a triangular probability distribution, with minimum of 1, a mode of 1.3, and a maximum of 3. This range is based on results from several previous studies discussed in the IPCC Third Assessment Report. A value of 1.0 implies that damages are a linear function of global mean temperature. A value of 1.3 implies a weak convexity and 3 implies a stronger convexity. Figure PA.1 below demonstrates the dependence of damages at a given temperature on the damage exponent, relative to the damages at 2.5°C. For comparison, the global damage function from the DICE model is shown[13].

Figure PA.1 The dependence of damages on temperature. The lines show the PAGE2002 damages, as defined by the damage function in equation 1, for damage exponents (γ) between 1 and 3.



The disaggregated impacts analysis brought together in Part II suggests that the relationship between temperature and damages will be convex. Further, there are strong reasons to consider that the scale of impacts captured by the damage exponent of 1.3, the mode of the analysis in Chapter 6, does not adequately reflect the degree of convexity of likely damages.

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[12] Note that T_R in the model is actually the 'vulnerable' temperature increase, as it is assumed that most regions can adapt to some degree of temperature rise. The regional temperature increase is dependent on the global temperature increase (a linear relationship) and the regional sulphate aerosol concentration.
[13] See Warren et al. (2006)

Damages for many individual impacts rise steeply with temperature (see, for example, Table 3.1 and Box 3.1 in the Review). As well as the strong convexity that arises from individual effects there are also aggregate convexities that arise from their interaction. For example, most previous studies look only at the effects of average climate conditions. However, a 1°C increase in mean temperatures could lead to a ten-fold increase in the frequency of severe heat waves in some regions (Chapter 1). This will have knock-on effects, heightening damages (and strengthening convexities) in areas such as agriculture and health. The convexity of the aggregate damage function is supported by Nordhaus (2006a) using the new G-ECON database. This demonstrates a powerful cross-sectional relationship between temperature and output, as well as specific examples, such as the ninth power relationship between hurricane wind speed and damages (Nordhaus 2006b)[14]. The damages associated with such interactions between impacts have not been fully incorporated into previous aggregate analyses.

In addition, there is also the risk of major, irreversible changes in the climate, ecosystems and society (Chapter 3). As temperatures rise, these risks increase sharply. Some commentators have suggested to us forcefully that the types of risk associated with high temperatures as discussed in Part 2 of the Review are not well reflected in the formal modelling of Chapter 6. This is, in our view, a suggestion that is well founded.

To test the sensitivity of the results to the damage exponent, the model is rerun with a new mode of 2.25. The lower bound of the range is increased to 1.5 and the upper bound is held constant. The range is chosen in the light of the proposed functional forms of the relationships illustrated in Box 3.1, analyses such as those just quoted, and the powerful reinforcing effect of combinations of these individual effects.

The economics of risk

Models and policy analyses are designed to investigate specific questions. In this case we have argued that the analysis of risks is crucial to the problem of climate change. Thus it is important that analyses are built around the economics of risk. For example, in the high-climate scenario with market impacts, risk of catastrophe and non-market impacts (Chapter 6), the 95th percentile estimate is a 35.2% loss in global per-capita GDP by 2200. This is not a statistical mean, but it is nevertheless a risk that few would want to ignore. Such risks can have a strong effect on welfare calculations, because they reduce consumption to levels where every marginal dollar or pound has a much greater value.

The Stern Review has adopted an expected-utility analysis, a standard tool in economics for working with risk. This is based on probability distributions of future outcomes that were not available in most previous analyses.

Ethical judgements and Discounting

In Chapter 2 and its appendix we examined a number of different ethical viewpoints. In the forward modelling of Chapter 6, with its very narrow view of outcomes in terms of monetary aggregates, we focused on a simple and standard framework in which discounted utility (as a function of consumption) of a generation is summed over time. We should also draw attention to a broader literature on sustainable development than referenced in Chapter 2 (a helpful analytical introduction and set of references is Dasgupta, 2001, and Arrow et al, 2003). We should also draw attention to an axiomatic approach to inter-temporal evaluations, which can lead to similar formulations, based on the work by Koopmans (1972). Simple aggregative modelling of the type used here usually precludes the relevant subtlety of evaluation.

Estimating the aggregate impacts of climate change requires us to consider the value of damages now compared with those in the future. For an evaluation of a marginal change of one unit at

[14] This is on top of the sharply increasing relationship between sea surface temperature and hurricane wind speed.

some time in the future, relative to a unit now, this is called the discount factor. Its rate of fall is the discount rate (see chapter 2 of the report and its appendix for a detailed discussion). Discount factors and rates depend on time and the path under examination. Discount factors and rates in the very aggregative models considered in the appendix to Chapter 2 and in Chapter 6 are shaped by two elements or questions:

1. How to take into account the fact that people are likely to be richer in the future.

2. Whether the future should be discounted simply because it is the future.

The first element appears in our modelling in a standard way. This is captured by the product of *elasticity of marginal utility of consumption*[15] (η) and the growth rate of consumption (See Chapter 2 and Appendix). Note that η has a dual role as both a parameter of inequality aversion and of relative risk aversion. In Chapter 6, we used an elasticity of marginal utility consumption of 1, in line with some empirical estimates[16]. For this case, the contribution to the discount rate at any time is equal to the rate of growth in consumption at that time on the path. Some previous studies have assumed that the discount rate at any point in time is independent of the scale of the impacts and of the path followed (the future growth trajectory). However, as climate change implies that strongly divergent paths for future growth are possible, the use of a single set of discount rates (over time) for all paths is inappropriate.

Such a value for the elasticity of marginal utility of consumption might be interpreted as implying a very high savings rate in some simple models (see Arrow, 2005, and related discussion in Section 2A.2 of the Review). However, applying this type of framework to savings rates as a central object of analysis would require more focus on issues related to savings, for example, the lifetime of capital equipment, flexibility, uncertainty, relations and responsibilities within and across generations and so on. Similarly, arguments for high η would imply stronger preference for redistribution than is reflected in policy in many countries. That does not settle any argument about η but it does indicate that application of a simple theory and model structure focused on one issue applied directly to a second issue is likely to miss out much that is important for the second. These arguments about implications for the second, while relevant, have to be handled with care. These ideas are discussed in the Appendix to Chapter 2.

The second component is captured by the *pure rate of time preference.* This requires a consideration of the ethical issues involved in comparing the incidence of costs and benefits between generations, some of which are very distant in time. We argued in the Review– in line with economists including Ramsey, Pigou, Solow and Sen – that the welfare of future generations should be treated on a par with our own. This means, for example, that we value impacts on our children and our grandchildren, which are a direct consequence of our own actions, as strongly as we value impacts on ourselves.

We argued that the primary justification for a positive rate of pure time preference in assessing the impacts of climate change is the possibility that the human race may be extinguished. As the possibility of this happening appears to be low, we assume a low rate of pure time preference of 0.1%, which corresponds with a 90% probability of humanity surviving a 100-year period, if the 'probability of existence' view of pure time discounting is invoked. Higher probabilities of survival would imply a still lower rate (see Table PA.1below).

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[15] This measures how fast the value of an increment in consumption falls as consumption rises, for example when it is equal to one, an extra unit to Person A, with three times the consumption of Person B, would have one third the value to that if the extra unit went to Person B. If the elasticity were equal to two, the extra unit would have one ninth of the value.
[16] Pearce and Ulph (1999); Stern (1977).

Table PA.1 Implication of pure time discount rate (δ) for probability of existence			
	Probability of human race surviving 50 years	Probability of human race surviving 100 years	Probability of human race surviving 150 years
δ = 0.1	0.95	0.91	0.86
0.5	0.78	0.61	0.47
1.0	0.61	0.37	0.22
1.5	0.47	0.23	0.11

Many previous studies have used higher pure rates of time preference. They have used rates similar to those often applied to the evaluation of project-based investments. However, in drawing such analogies much turns on the meaning of the uncertainty covered by the pure time discounting. In this respect, there are important differences between the kind of large-scale disinvestments in the environment involved in climate change and other types of long-term investment, e.g. a railway. In the railway example, we might think of pure time discounting as covering the possibility that the context would change in such a way that the investment would become irrelevant (e.g. the closure of the whole railway system). Or we might interpret pure time discounting as covering the possibility that the particular decision might be reversed in terms of non-renewal of the investment when it reaches the end of its life. These looser[17] but possible interpretations of pure time discounting in the project appraisal context apply to climate change only in a much weaker form. Climate change is long-term, severe and irreversible. Accumulated stocks of carbon cannot easily be reversed and we cannot opt for another planet. Thus, if these looser forms of interpretation of pure time discounting are introduced they imply stronger pure time discounting for other contexts than for climate change.

The analysis cannot avoid taking on directly the challenge of how to treat unrepresented generations. It is an ethical issue and cannot simply be derived from market behaviour. For example, Arrow (1995) and Samuelson and Nordhaus (2005) (and see references therein and in Dasgupta, 2005), rightly present the issue as 'prescriptive' rather than 'descriptive'. However, Arrow and Nordhaus come to different conclusions from those indicated here about the appropriate rate of pure time discounting. Some of those arguments were covered in the appendix to Chapter 2. See also the important discussion in Cline (1992).

The consequences of choosing a high pure time discount rate for evaluating the impacts of climate change should be very obvious and were emphasised in Chapter 2 of the Review and its appendix. They are clear from Table PA.1. For example, if the pure time discount rate is 1.5%, then benefits 50 years from now, for individuals who have exactly the same consumption, have a weight less than half that of now. In other words, a grandparent would tell a grandchild that simply because the latter's consumption flow came later (e.g. 50 years) in time than his or her own consumption flow it would be correct to assign a value of less than half to it in thinking about the consequences of actions today. In the case of climate change, this would mean that while we know the direct (stochastic) consequences of our actions today and whom they affect, we would nevertheless apply a very low weight to those consequences. Many people would find that ethical position very unattractive. It is hard to see why the logic should be any different from assessing externalities that affect members of the current generation. We must be transparent and clear. If you take little account of the interests of future generations you will care little about climate change. But ethical positions cannot be dictated by policy analysts, and sensitivity analysis of loss estimates to the rate of pure time preference is supplied below.

There are ways of thinking about the relationship between this and future generations in terms of implicit bargains rather than using an aggregate social welfare function as in Chapter 2, its Appendix and Chapter 6. We might think that future generations would willingly accept a lower

[17] It is possible to argue that this type of risk should be embodied in the measurement of costs and benefits but it would play a similar computational role and this type of discounting and pure time preferences seems often to be combined.

conventional capital stock (e.g. roads and railways) in exchange for a better climate. In that case the existing generation acting on their behalf would adjust its investment portfolio, without investing more, to invest in a better climate. These kinds of notions come in when we invoke the ideas of sustainable development (and see for example, Arrow, et al. 2003).

This formal modelling of Chapter 6 does not take into account the distribution of consumption across regions. In similar vein to a lower weighting for marginal increments to richer generations, increments in poorer regions should have a higher weighting than those in richer regions. Making such calculations was beyond the scope of this exercise, given the limited time available for analysis. Taking this regional approach would increase the climate change cost estimates, as illustrated in Section 6.2, so our decision to use a simpler global aggregation approach will bias our model toward lower cost estimates. How we might adjust for this was described in Chapter 6.

Other factors: growth rate and treatment of long time-scales

There are other aspects in the models used in the Stern Review that will affect the outcomes of the modelling exercise. We describe two briefly:

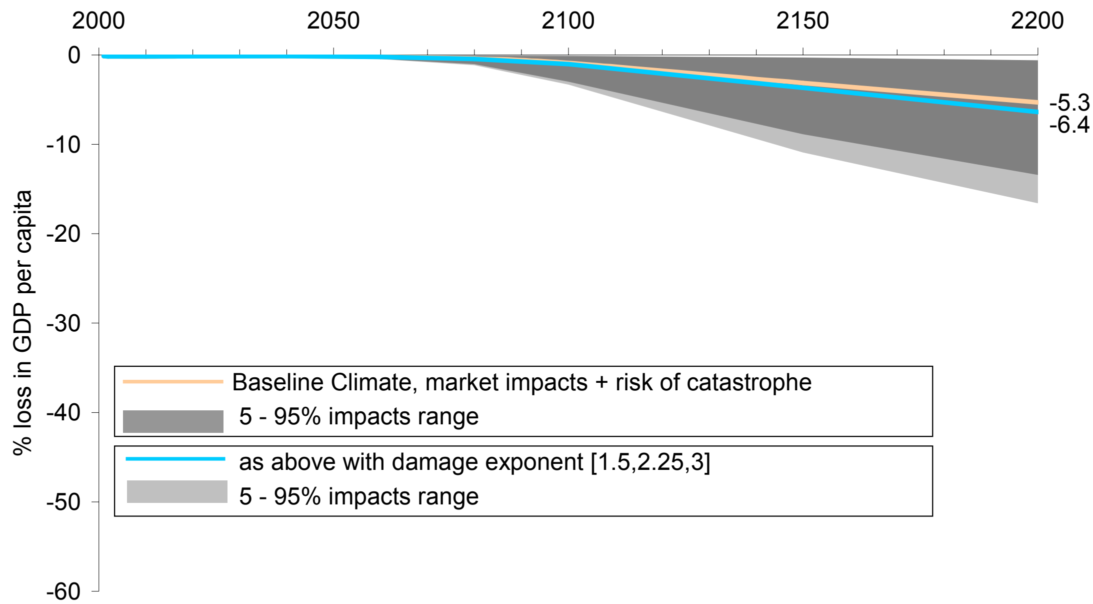
1. The baseline growth rate. A scenario with higher growth would be expected to generate greater emissions, but also have a reduced discount rate. The balance of these effects depends on the convexity of the damages function from emissions stocks and temperature change, and the elasticity of the marginal utility function.
2. The Stern Review, like other similar studies, is very conservative in its treatment of climate change after 2200. We assume that impacts post-2200 are equal to impacts in 2200. That is, we assume that the problem contains itself after this time. This assumption may lead us to underestimate the impacts of climate change.

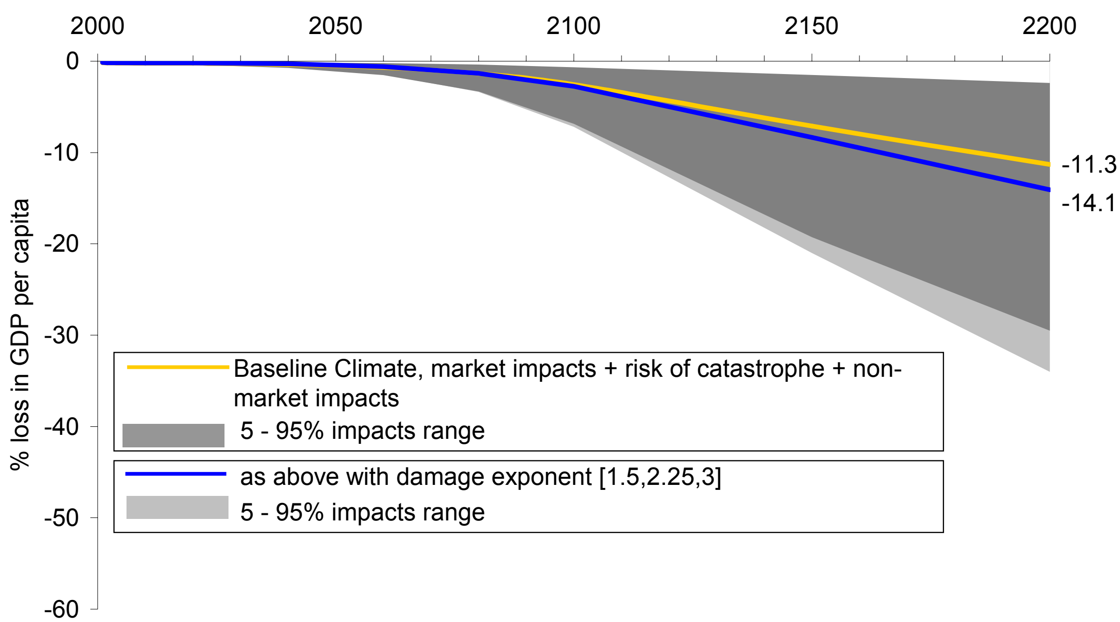
Sensitivity Analysis

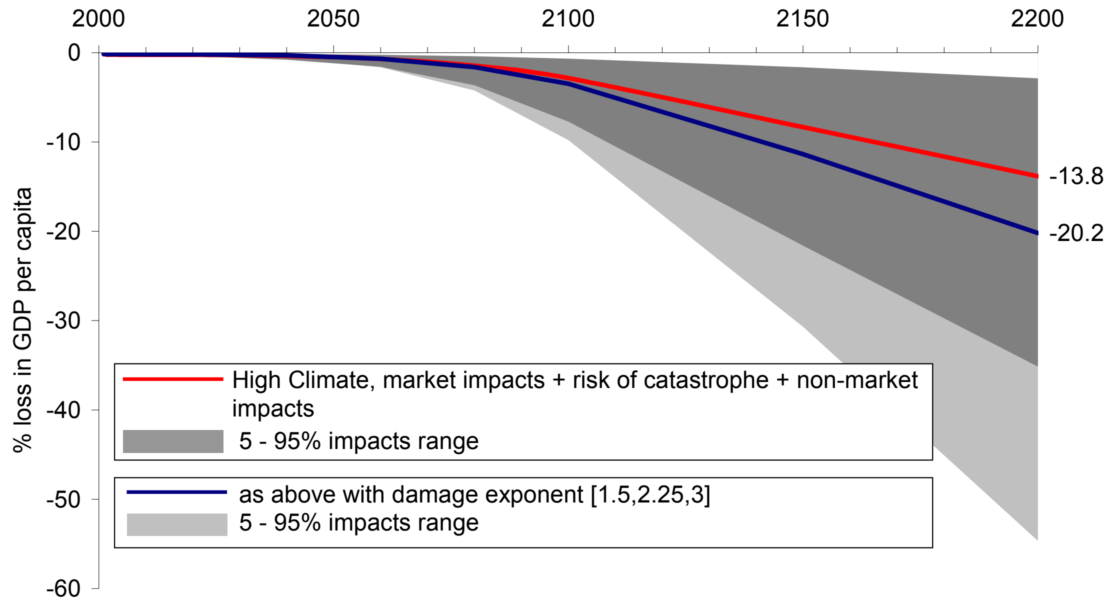
The above discussion and the comments we have received point to the importance of testing the sensitivity of the loss estimates to three key parameter choices in the model: the damage exponent γ, relevant to model structure, and the elasticity of the marginal utility of consumption, η, and the pure time discount rate, δ, relevant to ethical values.

We first consider changes in the damage exponent. Figure PA.2 shows the losses as a percentage of global GDP per capita for the scenarios above, with the standard range for the damage exponent [1, 1.3, 3] and the modified range [1.5, 2.25, 3] – see above. Note that this change to the model structure applies whichever ethical values are introduced.

Figure PA.2 Percentage losses in GDP per capita.







Next we consider the effect of changes to the ethical values. The first table looks at the implications of changing the elasticity of the marginal utility of consumption, in combination with changes to the damage exponent.

Table PA.2 presents results for three of the six scenarios originally reported in Chapter 6. They are:

1. Baseline climate; market impacts + risk of catastrophe;
2. Baseline climate; market impacts + risk of catastrophe + non-market impacts;
3. High climate; market impacts + risk of catastrophe + non-market impacts.

Table PA.2. Sensitivity analysis of estimates of the monetary cost of BAU climate change to the damage function exponent and the elasticity of the marginal utility of consumption, holding the pure time discount rate at 0.1% (*original Review estimate in italics*).

Damage function exponent	Elasticity of marginal utility of consumption	Baseline climate; market impacts + risk of catastrophe Mean (5th percentile, 95th percentile)	Baseline climate; market impacts + risk of catastrophe + non-market impacts Mean (5%, 95%)	High climate; market impacts + risk of catastrophe + non-market impacts Mean (5%, 95%)
Low range	***1.0***	*5.0 (0.6-12.4)*	*10.9 (2.2-27.4)*	*14.4 (2.7-32.6)*
	1.25	3.8 (0.6-9.6)	8.7 (2.2-21.7)	12.1 (2.7-26.0)
	1.5	2.9 (0.5-7.1)	6.5 (1.7-16.5)	10.2 (2.0-20.0)
High range	**1.0**	6.0 (0.8-15.5)	14.2 (2.8-32.2)	21.9 (3.7-51.6)
	1.25	4.6 (1.8-12.0)	11.3 (2.6-25.2)	18.2 (3.8-41.9)
	1.5	3.4 (0.3-9.0)	8.7 (1.8-19.2)	15.3 (2.8-33.1)

For a conservative scenario including baseline climate change and excluding non-market impacts on ecosystems and human health, increasing the elasticity of the marginal utility of consumption from 1.0 to 1.5 reduces the present value of the cost of BAU climate change from 5.0% to 2.9%. Using the same scenario, applying a higher probability distribution for the damage function exponent (with η constant at 1) increases the cost of BAU climate change from 5.0% to 6.0%.

We should note that higher values of η imply higher discount rates[18] via the growth effect. For example, a growth rate of 2% and an η of 1.5 would give a discount rate of 3%. And it should be noted in this modelling that we have not included declining discount rates other than through the growth rate. There is a case for such a decline (see Appendix to Chapter 2 and references therein) and this would increase the loss estimates.

Although in the Review we have argued that it is preferable to value the impacts of climate change on health and the natural environment separately from its impacts on income, a comparison of the cost of mitigating climate change to the cost of BAU climate change, excluding non-market impacts gives a misleading signal. Interpreted literally, this would imply that these impacts have zero value. That would not be a tenable position. Zero is the most implausible of assumptions even though applying specific valuations raises difficult issues. The middle and third scenarios, which include non-market impacts, have a stronger claim on our attention. Increasing the elasticity of the marginal utility of consumption from 1.0 to 1.5 reduces the estimated cost of BAU climate change from 10.9% to 6.5% (4.4 percentage points). On the other hand, applying a higher probability distribution for the damage function exponent increases the cost of BAU climate change from 10.9% to 14.2% (3.3 percentage points).

Substituting the high-climate scenario for the baseline-climate scenario, the probability distribution of the damage function exponent becomes the more important factor. Increasing this raises the cost of BAU climate change from 14.4% to 21.9% (7.5 percentage points). Increasing the elasticity of the marginal utility of consumption from 1.0 to 1.5 reduces the present value of the cost of BAU climate change from 14.4% to 10.2% (4.2 percentage points). We should note here that the elasticity of the marginal utility of consumption here plays a double role as an indication of (relative) risk aversion and of aversion to inequality. The former effect means that a high elasticity would increase damage estimates and the latter decrease them (via a stronger discounting). More sophisticated analysis could separate these effects.

Finally, we examine the sensitivity of loss estimates to the pure time discount rate, δ, presented in Table PA.3. The quantitative weighting following from different discount rates was presented in Table PA.1. The case where δ=0.1% was presented in Chapter 6 and is italicised in Table PA.3. As is intuitively clear, raising the pure time discount rate lowers loss estimates because the future is seen as less important. Nevertheless for all cases, even with the very high δ of 1.5% the loss estimates still exceed 1%, the estimated cost of strong mitigation. However, we would argue that even a pure time discount rate of 0.5% should be regarded as too high in this context, from an ethical or probability of extinction perspective (see Table PA.1 and related discussion).

[18] Note that this is the discount rate, $\eta\left(\dot{c}/c\right)+\delta$, to be applied to increments of consumption.

Table PA.3 Sensitivity analysis of estimates of the monetary cost of BAU climate change to the damage function and the pure time discount rate, holding the elasticity of the marginal utility of consumption at one (*original Review estimate in italics*).

Damage function exponent	Pure time discount rate (per cent)	Baseline climate; market impacts + risk of catastrophe Mean (5th percentile, 95th percentile)	Baseline climate; market impacts + risk of catastrophe + non-market impacts Mean (5%, 95%)	High climate; market impacts + risk of catastrophe + non-market impacts Mean (5%, 95%)
Low range	***0.1***	*5.0 (0.6-12.4)*	*10.9 (2.2-27.4)*	*14.4 (2.7-32.6)*
	0.5	3.6 (0.4-9.1)	8.1 (1.7-20.4)	10.6 (2.0-24.4)
	1.0	2.3 (0.4-5.8)	5.2 (1.2-13.2)	6.7 (1.3-16.0)
	1.5	1.4 (0.3-3.5)	3.3 (0.7-8.5)	4.2 (0.8-10.1)
High range	***0.1***	*6.0 (0.8-15.5)*	*14.2 (2.8-32.2)*	*21.9 (3.7-51.6)*
	0.5	4.3 (0.6-11.3)	10.2 (2.1-23.6)	15.8 (2.7-39.2)
	1.0	2.7 (0.4-7.2)	6.4 (1.4-15.5)	9.8 (1.7-25.6)
	1.5	1.7 (0.3-4.5)	4.0 (0.8-9.7)	5.9 (1.0-15.8)

Dr Chris Hope, the author of the PAGE2002 model, conducted a similar sensitivity analysis for the pure rate of time preference, which was published in the *Financial Times*[19] focusing on the social cost of carbon using the PAGE2002 model (baseline climate scenario with non-market impacts and the standard damage function) and $\delta = 2$. This did not include the expected utility analysis used by the Review, but provides a useful comparison. Hope found that with the higher discount rate, the social cost of carbon is reduced by just over half to $40 (for the business-as-usual path). This is roughly consistent with the reductions outlined in Table PA.3.

Conclusions from Sensitivity Analysis

Where does this sensitivity analysis leave the overall case for strong mitigation as seen from the perspective of Chapter 6? First, let us re-emphasise that our first perspective on this argument was not Chapter 6, but the disaggregated analysis together with an overall assessment of risk. Formal modelling of the very simplistic kind carried out by IAMS should not be the first claim on our attention in formulating policy. But pursuing the Chapter 6 approach, using the sensitivity analysis we can conclude that this perspective does provide a powerful argument for strong mitigation. For an analysis that takes account of non-market impacts all the calculations displayed give a loss estimate above 5% of consumption, except where the pure time discount rate is above 1%.

For the higher exponent on the damage function for temperature we find damages above the upper ranges provided in Chapter 6. Indeed even using the higher exponent on the marginal utility of consumption this statement remains true for the high climate case (for the pure time discount rate of 0.1% - see Table PA.2). We should recognise that the unitary value for the elasticity of the marginal utility of income together with δ=0.1% place stronger emphasis on later costs and benefits[20] than higher η or higher δ would imply. However, we have seen that provided δ is not extremely high (above 1%) the basic case from this approach for strong mitigation remains convincing, particularly when one takes account of higher damage exponents. And, in

[19] http://www.ft.com/cms/s/444ff4ae-783c-11db-be09-0000779e2340.html
[20] 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 $\eta = 1$ and $\delta > 0$ we have convergence but it is close to the borderline.

our view, the case for higher damage components in the context of the possibility of higher temperatures is convincing.

Many commentators have pointed to the importance of the pure time discount rate. So did the Review, clearly and strongly, and it marshalled the arguments for the level chosen. On the other hand it is quite wrong, as some have suggested, to argue that high losses from unabated climate change, relative to the costs of abatement, rest solely on this assumption. The sensitivity analysis demonstrates this clearly. Earlier authors who obtain lower damage costs do no take sufficient account of the most recent science linking probabilities of temperature increases to GHG concentration, and take insufficient account of the economics of risk.

The cost estimates presented here would increase still further if the model incorporated other important omitted effects. First, the welfare calculations fail to take into account distributional impacts, even though these impacts are potentially very important: poorer countries are likely to suffer the largest impacts. Second, the estimates here are conservative about damages post - 2200. If they continued to rise after that then cost estimates would increase. Third, there may be greater risks to the climate from dynamic feedbacks and from heightened climate sensitivity beyond those included here. During the course of the Review, we examined the possibility that some of these factors could combine to produce significantly higher probabilities of large increases in temperature. The scientific evidence is not yet available to support any conclusions in this area, and we have not included the results of this work in the conclusions presented in the Review. This is an area where further scientific investigation would be very important as a basis for future economic analysis[21].

We conclude with some brief remarks on possibilities of further research in this and related areas. We have already indicated our preference for a disaggregated approach to risk assessment in this area. Policy makers would (and probably should be) more convinced by a case which indicates the extent and seriousness of the risks involved in climate change, rather than aggregative results from speculative models that are highly sensitive to the assumptions built into them. Nevertheless these models do have a valuable supplementary role in the argument.

Thus, our first suggestion for further research is deeper investigation on the disaggregated effects of climate change. This should be oriented towards not only the 2-3°C range but also attempt to better understand the risks of 5°C and above, which we now know to be very serious possibilities under business-as-usual. This type of research would be important not only for understanding the case for strong mitigation but also be of great value in understanding what is necessary or advisable for adaptation.

This type of research would depend on high-resolution climate modeling which could provide much more detailed information on local impacts. This could and should be combined with detailed local studies, based on close local knowledge of possible implications of these climate changes.

At the same time, this type of high resolution *cum* local approach could be used, if sufficiently extensive, to inform global impact modeling. The work of Nordhaus (2006a) charts one very important line of investigation.

A second type of approach, building on the first, would be the development of the integrated assessment models to take more account of risk. Just one model was used here, chosen for convenience of use in stochastic analysis, and because it spanned a range of models. But other models should be used to develop different perspectives and in so doing test the robustness of our results.

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[21] We note that for these cases increasing η increased the loss estimates, i.e. the risk aversion effect dominated the income distribution effect.

In conclusion we should stress again that the analysis of the Review as a whole was always intended to be one contribution to a discussion. There have been, will be, and should be many more contributions.

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