6 Economic modelling of climate-change impacts

Key Messages

The monetary cost of climate change is now expected to be higher than many earlier studies suggested, because these studies tended not to include some of the most uncertain but potentially most damaging impacts.

Modelling the overall impact of climate change is a formidable challenge, involving forecasting over a century or more as the effects appear with long lags and are very long-lived. The limitations to our ability to model over such a time scale demand caution in interpreting results, but projections can illustrate the risks involved – and policy here is about the economics of risk and uncertainty.

Most formal modelling has used as a starting point 2 - 3°C warming. In this temperature range, the cost of climate change could be equivalent to around a 0 - 3% loss in global GDP from what could have been achieved in a world without climate change. Poor countries will suffer higher costs.

However, 'business as usual' (BAU) temperature increases may exceed 2 - 3°C by the end of this century. This increases the likelihood of a wider range of impacts than previously considered, more difficult to quantify, such as abrupt and large-scale climate change. With 5 - 6°C warming, models that include the risk of abrupt and large-scale climate change estimate a 5 - 10% loss in global GDP, with poor countries suffering costs in excess of 10%. The risks, however, cover a very broad range and involve the possibility of much higher losses. This underlines the importance of revisiting past estimates.

Modelling over many decades, regions and possible outcomes demands that we make distributional and ethical judgements systematically and explicitly. Attaching little weight to the future, simply because it is in the future ('pure time discounting'), would produce low estimates of cost – but if you care little for the future you will not wish to take action on climate change.

Using an Integrated Assessment Model, and with due caution about the ability to model, we estimate the total cost of BAU climate change to equate to an average reduction in global per-capita consumption of 5%, at a minimum, now and forever.

The cost of BAU would increase still further, were the model to take account of three important factors:

- First, including direct impacts on the environment and human health ('non-market' impacts) increases the total cost of BAU climate change from 5% to 11%, although valuations here raise difficult ethical and measurement issues. But this does not fully include 'socially contingent' impacts such as social and political instability, which are very difficult to measure in monetary terms;
- Second, some recent scientific evidence indicates that the climate system may be more responsive to greenhouse gas emissions than previously thought, because of the existence of amplifying feedbacks in the climate system. Our estimates indicate that the potential scale of the climate response could increase the cost of BAU climate change from 5% to 7%, or from 11% to 14% if non-market impacts are included. In fact, these may be only modest estimates of the bigger risks – the science here is still developing and broader risks are plausible;
- Third, a disproportionate burden of climate change impacts fall on poor regions of the world. Based on existing studies, giving this burden stronger relative weight could increase the cost of BAU by more than one quarter.

Putting these three additional factors together would increase the total cost of BAU climate change to the equivalent of around a 20% reduction in current per-capita consumption, now and forever. Distributional judgements, a concern with living standards beyond those elements reflected in GDP, and modern approaches to uncertainty all suggest that the appropriate estimate of damages may well lie in the upper part of the range 5 – 20%. Much, but not all, of that loss could be avoided through a strong mitigation policy. We argue in Part III that this can be achieved at a far lower cost.

6.1 Introduction

The cost of climate change is now expected to be larger than many earlier studies suggested.

This Chapter brings together estimates from formal models of the monetary cost of climate change, including evidence on how these costs rise with increasing temperatures. It builds on and complements the evidence presented in Chapters 3, 4 and 5, which set out the effects of climate change in detail and separately considered its consequences for key indicators of development: income, health and the environment.

In estimating the costs of climate change, we build on the very valuable first round of integrated climate-change models that have come out over the past fifteen years or so. We use a model that is able to summarise cost simulations across a wide range of possible impacts – taking account of new scientific evidence – based on a theoretical framework that can deal effectively with large and uncertain climate risks many years in the future (see Section 6.4). Thus our focus is firmly on the economics of risk and uncertainty.

Our estimate of the total cost of 'business as usual' (BAU) climate change over the next two centuries equates to an average welfare loss equivalent to at least 5% of the value of global per-capita consumption, now and forever. That is a minimum in the context of this model, and there are a number of omitted features that would add substantially to this estimate. Thus the cost is shown to be higher if recent scientific findings about the responsiveness of the climate system to greenhouse gas (GHG) emissions turn out to be correct and if direct impacts on the environment and human health are taken into account. Were the model also to reflect the importance of the disproportionate burden of climate-change impacts on poor regions of the world, the cost would be higher still. Putting all these together, the cost could be equivalent to up to around 20%, now and forever.

The large uncertainties in this type of modelling and calculation should not be ignored. The model we use, although it is able to build on and go beyond previous models, nonetheless shares most of their limitations. In particular, it must rely on sparse or non-existent observational data at high temperatures and from developing regions. The possibilities of very high temperatures and abrupt and large-scale changes in the climate system are the greatest risks we face in terms of their potential impact, yet these are precisely the areas we know least about, both scientifically and economically – hence the uncertainty about the shape of the probability distributions for temperature and impacts, in particular at their upper end. Also, if the model is to quantify the full range of effects, it must place monetary values on health and the environment, which is conceptually, ethically and empirically very difficult. But, given these caveats, even at the optimistic end of the 5 – 20% range, 'business as usual' climate change implies the equivalent of a permanent reduction in consumption that is strikingly large.

In interpreting these results, economic models that look out over just a few years are insufficient.[1] The impacts of GHGs emitted today will still be felt well over a century from now. Uncertainty about both scientific and economic possibilities is very large and any model must be seen as illustrative. Nevertheless, getting to grips with the analysis in a serious way does require us to look forward explicitly. These models should be seen as one contribution to that discussion. They should be treated with great circumspection. There is a danger that, because they are quantitative, they will be taken too literally. They should not be. They are only one part of an argument. But they can, and do, help us to gain some understanding of the size of the risks involved, an issue that is at the heart of the economics of climate change.

Although this Review is based on a multi-dimensional view of economic and social goals, rather than a narrowly monetary one, models that can measure climate-change damage in monetary terms have an important role.

A multi-dimensional approach to development is crucial, as our discussions in Part II make clear and as is embodied, for example, in the Millennium Development Goals (MDGs). In this Chapter, we focus on three dimensions most affected by climate change: income/consumption, health, and the

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[1] Cline (1992)

environment. Chapters 3 to 5 have laid out how these dimensions are affected individually. Here we consider how they might be combined in a single metric of damage[2].

Our preference is to consider the multiple dimensions of the cost of climate change separately, examining each on its own terms. A toll in terms of lives lost gains little in eloquence when it is converted into dollars; but it loses something, from an ethical perspective, by distancing us from the human cost of climate change.

Nevertheless, in this chapter the Review does engage with formal models of the monetary cost of climate change. Such models produce useful insights into the global cost of climate change. In making an analytical assessment in terms of the formal economics of risk and uncertainty, our models incorporate, systematically and transparently, the high risks that climate change is now thought to pose. Estimating those costs is essential for taking action (although we have emphasised strongly the dangers of taking them too literally). Once the aggregate cost of climate change is expressed in monetary terms, it is possible to compare this cost with the anticipated cost of mitigating and adapting to climate change. This is covered in Chapter 13, where the Review also considers other ways, beyond this modelling, of examining the case for action.

6.2 What existing models calculate and include

Modelling the monetary impacts of climate change globally is very challenging: it requires quantitative analysis of a very broad range of environmental, economic and social issues. Integrated Assessment Models (IAMs), though limited, provide a useful tool.

IAMs simulate the process of human-induced climate change, from emissions of GHGs to the socio-economic impacts of climate change (Figure 6.1). We focus on the handful of models specially designed to provide monetary estimates of climate impacts. Although the monetary cost of climate change can be presented in a number of ways, the basis is the difference between income growth with and without climate change impacts. To do this, the part of the model that simulates the impacts of climate change is in effect ‘switched off’ in the ‘no climate change’ scenario.

Income in the ‘no climate change’ scenario is conventionally measured in terms of GDP – the value of economic output. The difficulty is that some of the negative effects of climate change will actually lead to increases in expenditure, which increase economic output. Examples are increasing expenditure on air conditioning and flood defences. But it is correct to subtract these from GDP in the ‘no climate change’ scenario, because such expenditures are a cost of climate change. As a result, the measure of the monetary cost of climate change that we derive is really a measure of income loss, rather than output loss as conventionally measured by GDP.

Making such estimates is a formidable task in many ways (discussed below). It is also a computationally demanding exercise, with the result that such models must make drastic, often heroic, simplifications along all stages of the climate-change chain. What is more, large uncertainties are associated with each element in the cycle. Nevertheless, the IAMs remain the best tool available for estimating aggregate quantitative global costs and risks of climate change.

The initial focus of IAMs is on economic sectors for which prices exist or can be imputed relatively straightforwardly. These ‘market’ sectors include agriculture, energy use and forestry. But this market-sector approach fails to capture most direct impacts on the environment and human health, because they are not priced in markets. These important impacts – together with some other effects in agriculture and forestry that are not covered by market prices – are often described as ‘non-market’.

Economists have developed a range of techniques for calculating prices and costing non-market impacts, but the resulting estimates are problematic in terms of concept, ethical framework, and practicalities. Many would argue that it is better to present costs in human lives and environmental quality side-by-side with income and consumption, rather than trying to summarise them in monetary terms. That is indeed the approach taken across most of the Review. Nevertheless, modellers have

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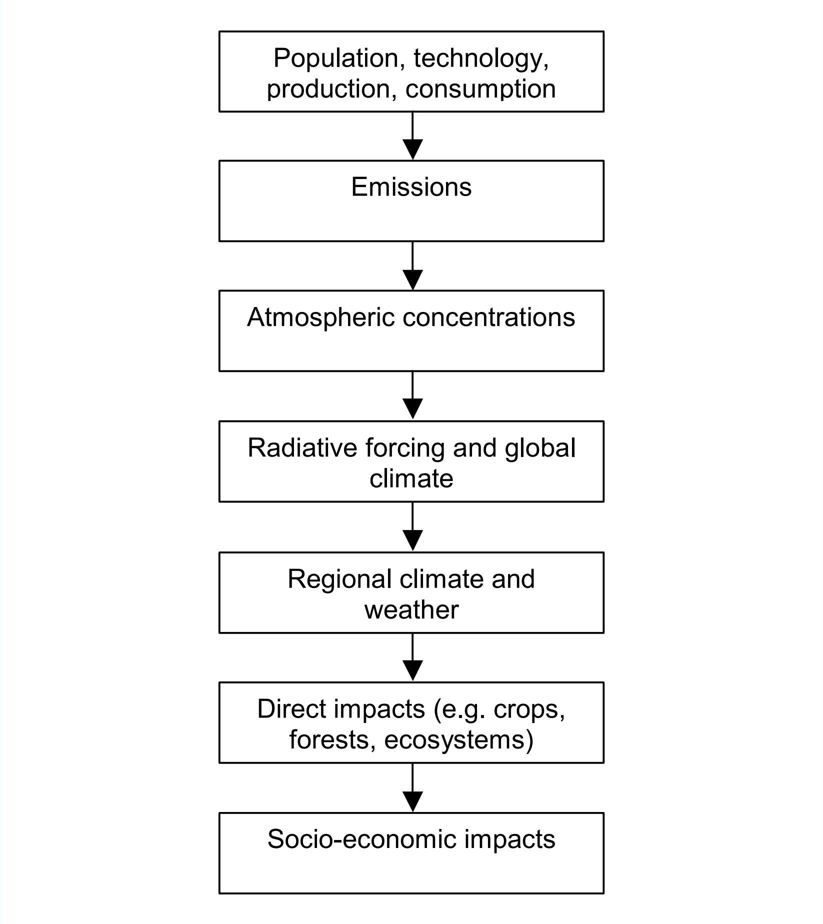
[2] Ethical perspectives other than those embodied in the models below – such as the approaches based on rights and liberties, intergenerational responsibilities, and environmental stewardship discussed in Chapter 2 – also point towards focusing on the costs of climate change in terms of income/consumption, health, and environment.

tried to do their best to assess the full costs of climate change and the costs of avoiding it on a comparable basis, and thus make their best efforts to include 'non-market' impacts.

Figure 6.1 Modelling climate change from emissions to impacts.

This figure describes a simple unidirectional chain. This is a simplification as, in the real climate-human system, there will be feedbacks between many links in the chain.



Source: Hope (2005).

Estimates from the first round of IAMs laid an important foundation for later work, and their results are still valuable for informing policy. However, they were limited to snapshots of climate change at temperatures now likely to be exceeded by the end of this century.

The first round of estimates from a wide range of IAMs, presented in the IPCC's 1996 *Second Assessment Report*,[3] were based on a snapshot increase in global mean temperature. The models estimated the effects of a doubling of atmospheric CO_2 concentrations from pre-industrial levels, which was believed likely to lead to a 2.5°C mean temperature increase from pre-industrial levels. The costs of such an increase were estimated at 1.5 - 2.0% of world GDP, 1.0 - 1.5% of GDP in developed countries, and 2 - 9% in developing countries.

Because they took a snapshot of climate change at 2.5°C warming, these early IAM-based studies did not consider the risks associated with higher temperatures. Since then, a smaller number of models have traced the costs of climate change as temperatures increase, although their parameters are still largely calibrated on estimates of impacts with a doubling of atmospheric CO_2. These models have also covered new sectors and have looked more carefully at adaptation to climate change.

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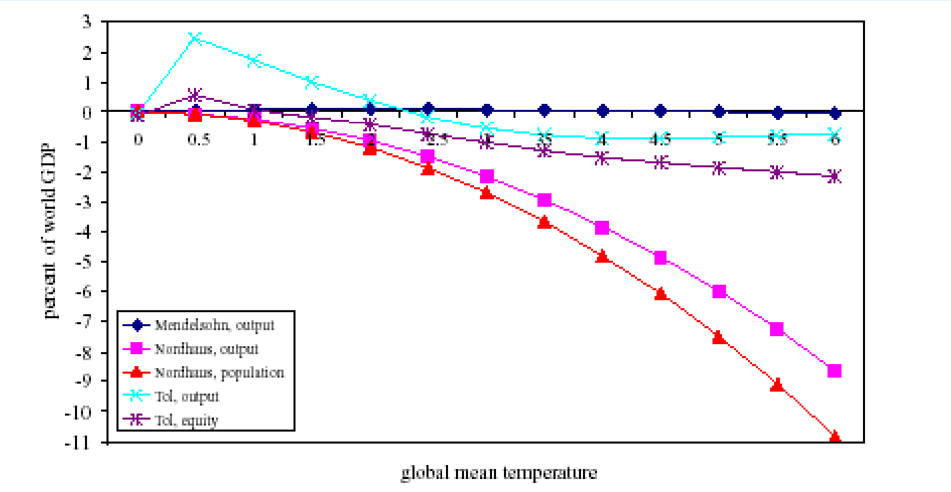
[3] Pearce *et al*. (1996)

Figure 6.2 Estimates of the global impacts of climate change, as a function of global mean temperature, considered by the 2001 IPCC *Third Assessment Report*.

The figure below traces the global monetary cost of climate change with increases in global mean temperature above pre-industrial levels (shown on the x-axis), according to three models:

- 'Mendelsohn, output' traces the estimates of Mendelsohn *et al*. (1998), with regional monetary impact estimates aggregated to world impacts without weighting;
- 'Nordhaus, output' traces the estimates of Nordhaus and Boyer (2000), with regional monetary impact estimates aggregated to world impacts without weighting;
- 'Nordhaus, population' also traces the estimates of Nordhaus and Boyer (2000), with regional monetary impact estimates aggregated to world impacts based on regional population;
- 'Tol, output' traces the estimates of Tol (2002), with regional monetary impact estimates aggregated without weighting;
- 'Tol, equity' also traces the estimates of Tol (2002), with regional monetary impacts aggregated to world impacts weighting by the ratio of global average per-capita income to regional average per-capita income.



Source: Smith et al. (2001).

Figure 6.2 illustrates the results of three important models (whose assumptions are reported in detail in Warren *et al*. (2006)) at different global mean temperature rises:

- **The 'Mendelsohn' model**[4] estimates impacts only for five 'market' sectors: agriculture, forestry, energy, water and coastal zones. The global impact of climate change is calculated to be very small (virtually indistinguishable from the horizontal axis) and is positive for increases in global mean temperature up to about 4°C above pre-industrial levels.

- **The 'Tol' model**[5] estimates impacts for a wider range of market and non-market sectors: agriculture, forestry, water, energy, coastal zones and ecosystems, as well as mortality from vector-borne diseases, heat stress and cold stress. Costs are weighted either by output or by equity-weighted output (see below). The model estimates that initial increases in global mean temperature would actually yield net global benefits. Since these benefits accrue primarily to rich countries, the method of aggregation across countries matters for the size of the global benefits. According to the output-weighted results, global benefits peak at around 2.5% of global GDP at a warming of 0.5°C above pre-industrial. But, according to the equity-weighted results, global benefits peak at only 0.5% of global GDP (also for a 0.5°C temperature increase). Global impacts become negative beyond 1°C (equity-weighted) or 2 - 2.5°C

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[4] Mendelsohn *et al*. (1998)

[5] Tol (2002)

(output-weighted), and they reach 0.5 - 2% of global GDP for higher increases in global mean temperature.

- **The 'Nordhaus' model**[6] includes a range of market and non-market impact sectors: agriculture, forestry, energy, water, construction, fisheries, outdoor recreation, coastal zones, mortality from climate-related diseases and pollution, and ecosystems. It also includes what were at the time pioneering estimates of the economic cost of catastrophic climate impacts (the small probability of losses in GDP running into tens of percentage points – see below). These catastrophic impacts drive much of the larger costs of climate change at high levels of warming. At 6°C warming, the 'Nordhaus' model estimates a global cost of between around 9 - 11% of global GDP, depending on whether regional impacts are aggregated by output (lower) or population (higher). The Nordhaus model also predicts that the cost of climate change will increase faster than global mean temperature, so that the aggregate loss in global GDP almost doubles as global mean temperature increases from 4°C to 6°C above pre-industrial levels. As Section 6.3 explains, this reflects the fact that higher temperatures will increase the chance of triggering abrupt and large-scale changes, such as sudden shifts in regional weather patterns like the monsoons or the El Niño phenomenon (and see Chapter 3 for a discussion of increasing marginal damages).

Models differ on whether low levels of global warming would have positive or negative global effects. But all agreed that the effects of warming above 2 - 3°C would reduce global welfare, and that even mild warming would harm poor countries.

These results are quite difficult to compare, because of the many differences between the models and the inputs they use, but some key points can be made:

- ***Up to around 2 - 3°C warming,*** there is disagreement about whether the global impact of climate change will be positive or negative. But, even at these levels of warming, it is clear that any benefits are temporary and confined to rich countries, with poor countries suffering significant costs. For example, Tol estimates a cost to Africa of 4.1% of GDP for 2.5°C warming, very close to Nordhaus and Boyer's estimate of 3.9%.

- ***For warming beyond 2 - 3°C***, the models agree that climate change will reduce global consumption. However, they disagree on the size of this cost, ranging from a very small fraction of global GDP to 10% or more. In this range too, the models agree that poor countries will suffer the highest costs, although in the Nordhaus model the estimated cost to Western Europe of 6°C warming is second only to the cost to Africa.[7]

These results depend on key modelling decisions, including how each model values the costs to poor regions and what it assumed about societies' ability to reduce costs by adapting to climate change.

Each model's results depend heavily on how it aggregates the impacts across regions, and in particular how it values costs in poor regions relative to those in rich ones. The prices of marketed goods and services, as well as the hypothetical values assigned to health and the environment, are typically higher in rich countries than in poor countries. Thus, in these models, a 10% loss in the volume of production of an economic sector is worth more in a rich country than in a poor country. Similarly, a 5% increase in mortality, if 'values of life' are based on willingness to pay, is worth more in purely monetary terms in a rich country than a poor country, because incomes are higher in the former. Many ethical observers would reject both of these statements. Thus some of the authors have used welfare or 'equity' weighting. Explicit functions to capture distributional judgements are also used in this Review – see Chapter 2 and Appendix. In summary, if aggregation is done purely on the basis of adding incomes or GDP, then very large physical impacts in poor countries will tend to be overshadowed by small impacts in rich countries.

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[6] Nordhaus and Boyer (2000)

[7] The European result is driven in large part by Europe's expected willingness to pay to reduce the risk of a catastrophic event such as a significant weakening of the Atlantic thermohaline circulation – part of which keeps Western Europe warmer than its latitude would otherwise imply.

Nordhaus and Boyer and Tol both adopt equity-weighting approaches, a step which in our view is supported by the type of ethical considerations discussed in Chapter 2 and its Appendix, as well as empirical observations of the attitudes that people actually hold towards inequality in wealth.[8][9] Mendelsohn does not use equity weights.

Adaptation to climate change is another important factor in these models, because it has the capacity to reduce the cost of BAU climate change. The key questions are how much adaptation can be assumed without extra stimulus from policy (financial, legal and otherwise), how much will it cost, because the costs of adaptation themselves are part of the cost of climate change, and what would it achieve? Again, it is difficult to compare the models, because each treats adaptation in a different manner. In general, the models do assume that households and businesses do what they can to adapt, without extra stimulus from policy.

The 'Mendelsohn' model is most optimistic about adaptation, and – not coincidentally – it estimates the lowest cost of climate change.[10] In their method, future responses to climate change are calibrated against the relationship between output and climate that can be seen from region to region today, or that can be determined from laboratory experiments.[11] The former method models adaptation most completely. In effect, as temperatures increase, and controlling for other climate and non-climate variables, environmental and economic conditions migrate from the equator towards the poles. High-latitude regions climb a hill of rising productivity for a time as temperatures make conditions easier (e.g. for agriculture), while low-latitude regions fall further into more difficult conditions. This method encompasses a variety of ways a region can adapt, because regions can be assumed to be well adapted to their current climates. Its major drawback, however, is that it makes no provision for the costs and difficulties of transition from one climate to another or the potential movement of people. Whether these are small or large, it is, on balance, an underestimate of the cost of climate change.

A final point to keep in mind is that all three models are based on scientific evidence up to the mid- to late 1990s. Since then, new evidence has come to light, most importantly on the possibilities of higher and more rapidly increasing temperatures than envisaged then, as well as possibilities of abrupt and large-scale changes to the climate system. Section 6.3 explores the consequences of these risks at greater length.

6.3 Do the existing models fully capture the likely cost of climate change?

Existing estimates of the monetary cost of climate change, although very useful, leave many questions unanswered and omit potentially very important impacts. Taking omitted impacts into account will increase cost estimates, and probably strongly.

Understanding of the science and economics of climate change is constantly improving to overcome substantial gaps, but many remain. This is particularly true of the existing crop of IAMs, due in part to the demands of modelling and in part to their reliance on knowledge from other active areas of research. Indeed, the knowledge base on which the cost of climate change is calibrated – specialised studies of impacts on agriculture, ecosystems and so on – is particularly patchy at high temperatures.[12] In principle, the gaps that remain may lead to underestimates or overestimates of global impacts. In practice, however, most of the unresolved issues will increase damage estimates.

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[8] Stern (1977), Pearce and Ulph (1999)

[9] Equity weights should reflect the choice of social welfare function – sometimes called the 'objective' function. This aggregates the consumption of individuals over space and time, reflecting judgements about the value of consumption enjoyed by individuals in different regions at different times (see the Appendix to Chapter 2). Here we focus on how this weighting should be carried out across regions within the present generation when considering the aggregation of small changes. The first step in calculating a weighted average change is to calculate the proportional impact of climate change on the representative individual in each region. If the utility function for an individual has constant marginal utility, the proportional impacts on per capita consumption can then be aggregated to give the proportional impact on overall social welfare by weighting them by the share of each individual's consumption in total consumption. At the regional level, this means weighting the impact on the representative individual by the region's share in global consumption (i.e. regional per-capita consumption multiplied by regional population, as a share of total global consumption). With a utility function given by the log of individual consumption, the proportional impacts on individuals should simply be added up; thus, at the regional level, the proportional impact on the representative consumer is weighted by the region's population.

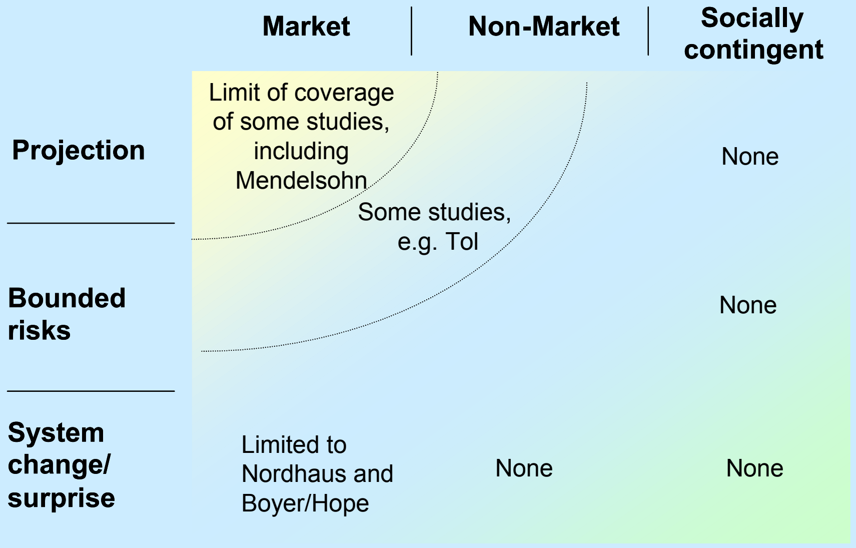
[10] There are several reasons why the 'Mendelsohn' model estimates the lowest cost of climate change. Adaptation is likely to be one, its omission of non-market impacts and the risk of catastrophe another.

[11] That is, they estimate the relationship between production in their five market sectors and climate based on how production varies across current world climates, and control for other important determining factors.

[12] See Hitz and Smith (2004)

Existing models omit many possible impacts. Watkiss *et al.*[13] have developed a 'risk matrix' of uncertainty in projecting climate change and its impacts to illustrate the limitations of existing studies in capturing potentially important effects. Figure 6.3 presents this matrix and locates the existing models on it.

Figure 6.3 Coverage of existing integrated assessment studies.



Source: Watkiss, Downing *et al*. (2005).

Figure 6.3 summarises which impacts existing estimates of the monetary cost of climate change cover (by reference to the authors of the various studies) and which impacts are omitted.

The vertical axis captures uncertainty in predicting climate change, with uncertainty increasing as we go down. There are three categories:

- Projection – high confidence on the direction of these changes and bounds can be placed around their magnitude (i.e. temperature change and sea-level rise);
- Bounded risks – more uncertainty about the direction and magnitude of these changes, though reasonable bounds can be placed around them (i.e. precipitation, extreme events);
- System change and surprises – large uncertainty about the potential trigger and timing of these changes (e.g. weakening of the thermohaline circulation, collapse of the West Antarctic Ice Sheet). However, evidence on the risk of such changes is building (see Chapters 1 and 3).

The horizontal axis captures uncertainty in the economic measurement of impacts, with uncertainty increasing as we go from left to right. There are again three categories:

- 'Market' impacts – where prices exist and a valuation can be made relatively easily, such as in agriculture, energy use and forestry;
- 'Non-market' impacts – directly on human health and the environment, where market prices tend not to exist and methods are required to create them;
- 'Socially contingent' responses – large-scale, 'second-round' socio-economic responses to the impacts of climate change, such as conflict, migration and the flight of capital investment.

As the figure shows, most existing studies are confined to the top left part of the matrix and are thus limited to a small subset of the most well understood, but least damaging, impacts (for example, the 'Mendelsohn' model, which is also most optimistic about adaptation: see previous section). By contrast, because the impacts in the bottom right corner of the matrix are surrounded by the greatest

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[13] Watkiss *et al*. (2005)

scientific uncertainty, they have not been incorporated into IAMs. Yet it is also these paths that have the potential to inflict the greatest damage.

Extreme weather events are not fully captured in most existing IAMs;[14] the latest science suggests that extreme events will increase in frequency and severity with climate change.

Chapters 1 and 3 laid out the newer evidence that climate change will spur an increase in extreme weather events – notably floods, droughts, and storms. Experience of weather disasters in many parts of the world demonstrates that the more extreme events can have lasting economic effects, especially when they fall on an economy weakened by previous weather disasters or other shocks, or if they fall on an economy that finds it difficult to adjust quickly.[15] Thus it is very important to consider the economic impacts of variations in weather around mean trends in climate change.

However, it is at least as important to consider the climatic changes and impacts that will occur if GHG emissions lead to very substantial warming, with global mean temperatures 5 - 6°C above pre-industrial levels or more. High temperatures are likely to generate a hostile and extreme environment for human activity in many parts of the world. Some models capture aspects of this, because costs both in market and non-market sectors accelerate as temperatures increase.[16] At 5 - 6°C above pre-industrial levels, the cost of climate change on, for example, agriculture can be very high.

Further, Chapter 1 detailed emerging evidence of risks that higher temperatures will trigger massive system ‘surprises’, such as the melting and collapse of ice sheets and sudden shifts in regional weather patterns like the monsoons. Thus there is a danger that feedbacks could generate abrupt and large-scale changes in the climate and still further losses.

Existing IAMs largely omit these system-change effects; including them is likely to increase cost estimates significantly. Although many factors can produce differences in results from model to model, it is nevertheless intuitive that the Nordhaus estimates[17], produced by the only model to include catastrophic ‘system change/surprise’, were the highest among the existing IAMs. For increases in global mean temperature of 5 - 6°C above pre-industrial levels or more, costs were estimated to approach and even exceed 10% of global GDP.

The Nordhaus method is based on polling a number of experts on the probability that a very large loss of 25% of global GDP, roughly equivalent to the effect of the Great Depression, will result from increases in global mean temperature of 3°C by 2090, 6°C by 2175 and 6°C by 2090. Taking account of estimated differences in regional vulnerability to catastrophic climate change, the model uses survey data to estimate people’s willingness to pay to avoid the resulting risk. This approach is simple, but it takes us some way towards capturing the economic importance of complex, severe responses of the climate system.

Most existing IAMs also omit other potentially important factors – such as social and political instability and cross-sectoral impacts. And they have not yet incorporated the newest evidence on damaging warming effects.

One factor omitted at least in part from most models is ‘socially contingent’ responses – the possibility that climate change will not only increase the immediate costs of climate change, but also affect investment decisions, labour supply and productivity, and even social and political stability.

On the one hand, these knock-on effects could dampen the negative effect of climate change, if the economic response is to adapt, for example, by shifting production from the most climate-sensitive sectors into less climate-sensitive sectors. As mentioned, recent models have taken adaptation more fully into account.

On the other hand, knock-on effects could amplify the future consequences of today’s climate change, for example if they reduce investment. This possibility has yet to be taken fully into account. In some models, baseline income is taken from outside the model, so that the impacts in any one time period do not affect growth in future periods. In other models, such as that employed by Nordhaus and

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[14] Warren *et al*. (2006)

[15] Hallegatte and Hourcade (2005) and Chapter 4.

[16] Although this depends on how rapidly costs increase in proportion to temperature.

[17] Nordhaus and Boyer (2000)

Boyer,[18] the economy makes investment and saving decisions based on the level of income it starts off with and on expectations of how that income will grow in the future. Climate change reduces investment and saving, as the income available to invest and the returns to saving fall.[19]

How important might these effects be? Fankhauser and Tol[20] unpack the 'Nordhaus' estimates to show that the knock-on cost of depressed investment on the total, long-run cost of 3°C warming is at least an additional 90% over and above the immediate cost. Furthermore, substituting for a more powerful model of economic growth that is better able to explain past and present growth trends, world GDP losses are almost twice as high as they are for immediate impacts alone. These dynamic effects may be especially strong in some developing regions, where the further effect of climate change may be to precipitate instability, conflict and migration (see Chapters 3 and 4).

A second omitted factor is possible interactions between impacts in one sector and impacts in another, which past IAMs have not generally taken into account. Climate damage in one sector could multiply damage in another – for example, if water-sector impacts amplify the impacts of climate change on agriculture. The reasons for excluding these effects have to do with the modelling approach: in the basic IAM method, impacts are characteristically enumerated on a sector-by-sector basis, and then added up to arrive at the overall economy-wide impact.

Finally, even in market sectors that the IAMs do cover well, the latest specialised impact studies suggest that IAM-based estimates may be too optimistic.[21] The underlying impacts literature on which the IAMs are based dates primarily from 2000 or earlier. Since then, many of the predictions of this literature have become more pessimistic, for example, on the possible boost from CO_2 fertilisation to agriculture (Chapter 3).

The building of the IAMs has been a valuable contribution to our understanding of possible effects. Any model must necessarily leave out much that is important and can use only the information available at the time of construction. The science has moved quickly and the economic analysis and modelling can move with it.

6.4 Calculating the global cost of climate change: an 'expected-utility' analysis

Modelling the global cost of climate change presents many challenges, including how to take account of risks of very damaging impacts, as well as uncertain changes that occur over very long periods.

A model of the monetary cost of climate change ideally should provide:

- Cost simulations across the widest range of possible impacts, taking into account the risks of the more damaging impacts that new scientific evidence suggests are possible.
- A theoretical framework that is fit for the purpose of analysing changes to economies and societies that are large, uncertain, unevenly distributed and that occur over a very long period of time.

This section begins with the first challenge, illustrating the consequences of BAU climate change in a framework that explicitly brings out risk. The second challenge is addressed later in the chapter, allowing consideration of how to value risks with different consequences, particularly the risks, however small, of very severe climate impacts.

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[18] Nordhaus and Boyer (2000)

[19] Because the Nordhaus and Boyer model simplifies the economy to one sector, it ignores the possibility that productivity will increase if production is shifted from low productivity/highly climate-sensitive sectors to high productivity/low sensitivity sectors. But a multi-sector study for the USA (Jorgensen *et al*., 2005) indicates that such processes are negligible, at least in that region.

[20] Fankhauser and Tol (2003)

[21] Warren *et al.* (2006)

The model we use – the PAGE2002 IAM[22] – can take account of the range of risks by allowing outcomes to vary probabilistically across many model runs, with the probabilities calibrated to the latest scientific quantitative evidence on particular risks.

The first challenge points strongly to the need for a modelling approach based on probabilities (that is, a 'stochastic' approach). The PAGE2002 (Policy Analysis of the Greenhouse Effect 2002) IAM meets this requirement by producing estimates based on 'Monte Carlo' simulation. This means that it runs each scenario many times (e.g. 1000 times), each time choosing a set of uncertain parameters randomly from pre-determined ranges of possible values. In this way, the model generates a probability distribution of results rather than just a single point estimate. Specifically, it yields a probability distribution of future income under climate change, where climate-driven damage and the cost of adapting to climate change are subtracted from a baseline GDP growth projection[23].

The parameter ranges used as model inputs are calibrated to the scientific and economic literatures on climate change, so that PAGE2002 in effect summarises the range of underlying research studies. So, for example, the probability distribution for the climate sensitivity parameter – which represents how temperatures will respond in equilibrium to a doubling of atmospheric carbon dioxide concentrations – captures the range of estimates across a number of peer-reviewed scientific studies. Thus, the model has in the past produced mean estimates of the global cost of climate change that are close to the centre of a range of peer-reviewed studies, including other IAMs, while also being capable of incorporating results from a wider range of studies.[24] This is a very valuable feature of the model and a key reason for its use in this study.

PAGE2002 has a number of further desirable features. It is flexible enough to include market impacts (for example, on agriculture, energy and coastal zones) and non-market impacts (direct impacts on the environment and human mortality), as well as the possibility of catastrophic climate impacts. Catastrophic impacts are modelled in a manner similar to the approach used by Nordhaus and Boyer.[25] When global mean temperature rises to high levels (an average of 5°C above pre-industrial levels), the chance of large losses in regional GDP in the range of 5 - 20% begins to appear. This chance increases by an average of 10% per ºC rise in global mean temperature beyond 5°C.

At the same time, PAGE2002 shares many of the limitations of other formal models. It must rely on sparse or non-existent data and understanding at high temperatures and in developing regions, and it faces difficulties in valuing direct impacts on health and the environment. Moreover, like the models depicted in Figure 6.3, the PAGE2002 model does not fully cover the 'socially contingent' impacts. As a result, the estimates of catastrophic impacts may be conservative, given the damage likely at temperatures as high as 6 - 8°C above pre-industrial levels. Thus the results presented below should be viewed as indicative only and interpreted with great caution. Given what is excluded, they should be regarded as rather conservative estimates of costs, relative to the ability of these models to produce reliable guidance.

We present results based on different assumptions along two dimensions: first, of how fast global temperatures increase in response to GHG emissions and, second, different categories of economic impact.

To reflect the considerable uncertainty about likely probability distributions and difficulties in measuring different effects, we examine models that differ along two dimensions:

- **Response of the climate to GHG emissions.** We run the model under two different assumed levels of climatic response. The 'baseline climate' scenario is designed to give outputs consistent with the IPCC *Third Assessment Report* (TAR)[26]. The 'high climate' scenario adds to this a risk of there being amplifying natural feedbacks in the climate system. This is based on recent studies showing that there is a real risk of additional feedbacks, such as weakening carbon sinks and natural methane releases from wetlands and thawing

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[22] Hope (2003)

[23] We follow PAGE2002 in referring to 'GDP' but, as remarked above, it is preferable to think of a broader income concept in interpreting some of the results.

[24] Tol (2005)

[25] Nordhaus and Boyer (2000)

[26] IPCC (2001)

permafrost. This scenario gives a higher probability of larger temperature changes. These scenarios are discussed in more detail in Box 6.1. Both climate scenarios give temperature outputs that are roughly consistent with other studies.

Box 6.1 The PAGE2002 climate scenarios.

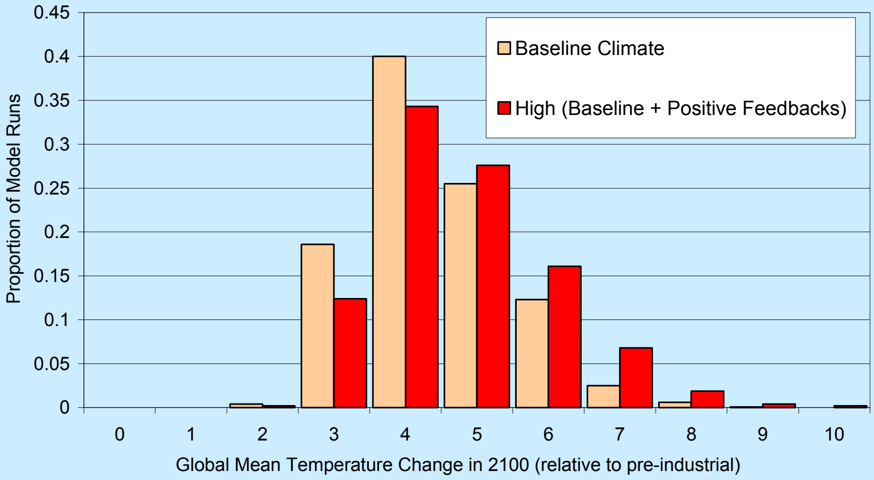
Baseline Climate: This is designed to give outputs consistent with the range of assumptions presented in the IPCC *Third Assessment Report* (TAR). The scenario produces a mean warming of 3.9°C relative to pre-industrial in 2100 and a 90% confidence interval of 2.4 – 5.8°C (see figure below) for the A2 emissions scenario used in this exercise. This is in line with the mean projection of 4.1°C given by the IPCC TAR. The IPCC does not give a probability range of temperatures. It does quote a range across several models of 3.0 – 5.3°C. The wider range of temperatures produced by PAGE2002 mainly reflects the wider combinations of parameters explored by the model.

High Climate: This is designed to explore the impacts that may be seen if the level of temperature change is pushed to higher levels through the action of amplifying feedbacks in the climate system. Scientists are only just beginning to quantify these effects, but these preliminary studies suggest that they will form an important part of the climate system's response to GHG emissions. No studies have yet combined ranges of climate sensitivity and feedbacks in this way, so these results should be treated as only indicative of the possible potential scale of response. The scenario includes recent estimates of two types of amplifying feedback: a weakening of natural carbon absorption and increased natural methane releases from, for example, thawing permafrost.

- **Weakened carbon sinks:** As temperatures increase, plant and soil respiration increases. Recent evidence suggests that these extra natural emissions will offset any increase in natural sink capacity due to carbon fertilisation, so that carbon sinks will be weakened overall (discussed in Chapter 1). Weakening of carbon sinks is modelled as a function of temperature, based on Friedlingstein et al. (2006).

- **Increased natural methane releases:** Natural methane currently locked in wetlands and permafrost is released as temperatures rise. This is simulated using a probability distribution based on recent studies (Box 1.3)[27].

In this exercise, these feedbacks push the mean temperature change up by around 0.4°C and give a higher probability of larger temperature increases. Accordingly, the 90% confidence interval increases to 2.6 - 6.5°C. There is little effect on the lower bound of temperature changes, as, at this level, temperatures are not large enough to initiate a significant feedback effect from the carbon cycle. The increase in the mean and upper bound are consistent with recent studies (chapter 1).



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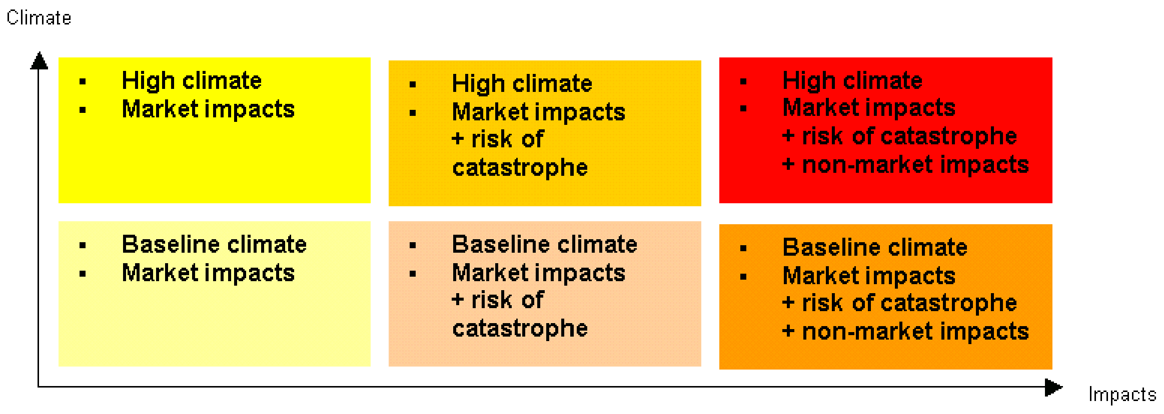
[27] For example, the central value is based on Gedney *et al.* (2004) assuming 4.5°C temperature rise in 2100

- **Categories of economic impact.** Our analyses also vary in the comprehensiveness with which they measure the impacts of climate change on the economy and on welfare. The first set of estimates includes only the impacts of 'gradual climate change' on market sectors of the economy. In other words, it takes no account of the possibility of catastrophic events that we now know may occur. The second set also includes the risk of catastrophic climate impacts at higher temperatures. Figure 6.3 illustrated that these also fall on market sectors of the economy, but are much more uncertain. Finally, the third set includes market impacts, the risk of catastrophe *and* direct, non-market impacts on human health and the environment. This chapter shall argue that attention should be focused on the second and third cases here, since there is very good reason to believe that both are relevant.

These dimensions combine to produce a 2x3 matrix of scenarios (Figure 6.4). For example, the lowest cost estimates would be expected to come from the scenario that (i) uses the baseline-climate scenario and (ii) considers only those impacts from gradual climate change on market sectors.

Figure 6.4 A 2x3 matrix of scenarios.



▪ High climate ▪ Market impacts	▪ High climate ▪ Market impacts + risk of catastrophe	▪ High climate ▪ Market impacts + risk of catastrophe + non-market impacts
▪ Baseline climate ▪ Market impacts	▪ Baseline climate ▪ Market impacts + risk of catastrophe	▪ Baseline climate ▪ Market impacts + risk of catastrophe + non-market impacts

Preliminary estimates of average losses in global per-capita GDP in 2200 range from 5.3 to 13.8%, depending on the size of climate-system feedbacks and what estimates of 'non-market impacts' are included.

Estimates of losses in per-capita income over time are benchmarked against projected GDP growth in a world without climate change. The baseline-climate/market-impacts scenario generates the smallest losses, where climate change reduces global per-capita GDP by, on average, 2.2% in 2200. However, as discussed in the previous section, the omission of the very real risk of abrupt and large-scale changes at high temperatures creates an unrealistic negative bias in estimates.

Figure 6.5 shows the results of scenarios including a risk of 'catastrophe'. The lower-bound estimate of the global cost of climate change in Figure 6.5 uses the baseline climate and includes both market impacts and the risk of catastrophic changes to the climate system (Figure 6.5a). In this scenario, the mean loss in global per-capita GDP is 0.2% in 2060. By 2100, it rises to 0.9%, but by 2200 it rises steeply to 5.3%.

There is a substantial dispersion of possible outcomes around the mean and, in particular, a serious risk of very high damage. The grey-shaded areas in Figure 6.5 give the range of estimates in each year taken from the 5th and 95th percentile damage estimates over the 1000 runs of the model. For the lower-bound estimate in 2100, the range is a 0.1 - 3 % loss in global GDP per capita. By 2200, this rises to 0.6 – 13.4%.

Figures 6.5b to d demonstrate the loss in global GDP per capita when first, the risk of more feedbacks in the climate system is included (the high-climate scenario), and second, estimates of non-market impacts of climate change are included.
In the high-climate scenario, the losses in 2100 and 2200 are increased by around 35%. In 2200, the range of losses is increased to between 0.9% and 17.9%.

The inclusion of non-market impacts increases these estimates further still. In this Review, non-market impacts, on health and the environment, are generally considered separately to market impacts. However, if the goal is to compare the cost of climate change in monetary terms with the equivalent cost of mitigation, then excluding non-market costs is misleading. For the high-climate scenario with non-market impacts (Figure 6.5c), the mean total losses are 2.9% in 2100 and 13.8% in 2200. In 2200, the 5th and 95th percentiles increase significantly, to 2.9% to 35.2%.

These estimates still do not capture the full range of impacts. The costs of climate change could be greater still. For example, recent studies demonstrate that the climate sensitivity could be greater than the range used in the PAGE2002 climate scenarios (Chapter 1). Were this to be the case, costs would rise again. The potential impacts of higher climate sensitivity are explored speculatively in Box 6.2.

Box 6.2 Exploring the consequences of high climate sensitivity.

The climate scenarios described in Box 6.1 are based on a climate sensitivity (the equilibrium temperature increase following a doubling in atmospheric carbon dioxide concentrations) range of 1.5 - 4.5°C, as outlined in the IPCC TAR[28]. However, studies since the TAR have shown up to a 20% chance that the climate sensitivity could be greater than 5°C.

In order to explore the possible consequences of recent scientific evidence on a higher climate sensitivity, we develop a 'high+' climate scenario that combines the amplifying natural feedbacks explained in Box 6.1 with a higher probability distribution for the climate sensitivity parameter. We use the climate sensitivity distribution estimated by Murphy *et al*. (2004). This is has a 5 - 95% range of 2.4 - 5.4°C, and a mode of 3.5, with a loglogistic distribution (Box 1.2).

This scenario is particularly speculative, but we cannot rule out that this is the direction that further evidence might take us. Combining the high+ scenario with market impacts and the risk of catastrophe, the mean loss in global per-capita GDP is 0.4% in 2060. In 2100, it rises to 2.7%, but by 2200 it rises to 12.9%. Adding non-market impacts, the mean loss is 1.3% in 2060, 5.9% in 2100 and 24.4% in 2200.

In addition, these results reflect the aggregation of costs across the world, but aggregating simply by adding GDP across countries or regions masks the value of impacts in poor regions. A given absolute loss is more damaging for a person on lower incomes. Nordhaus and Boyer[29] and Tol[30] demonstrate that giving more weight to impacts in poor regions increases the global cost of climate change. Nordhaus and Boyer estimate that the global cost increases from 6% to 8% of GDP for 5°C warming, one quarter higher. Tol estimates that the global cost is almost twice as high for 5°C warming, if he uses welfare weights (see Section 6.2).

Only a small portion of the cost of climate change between now and 2050 can be realistically avoided, because of inertia in the climate system.

Past emissions of GHGs have already committed the world to much of the loss in global GDP per capita over the next few decades. Over this period, market impacts are likely to be relatively small. This is, in large part, because the risk of catastrophic, large-scale changes to the climate system, as well as amplifying natural feedbacks (which boost the temperature response to GHG emissions), become a bigger factor later. Non-market impacts are significant in the period to 2050, reaching around 0.5% of per-capita global GDP in 2050 in both the baseline and high-climate scenarios.

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[28] IPCC (2001)
[29] Nordhaus and Boyer (2000)
[30] Tol (2002)

Figure 6.5 a. Baseline-climate scenario, with market impacts and the risk of catastrophe.

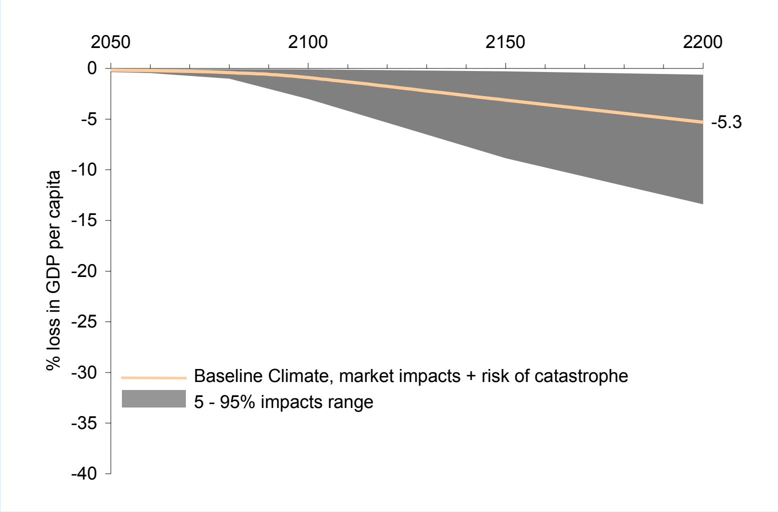


Figure 6.5b. High-climate scenario, with market impacts and the risk of catastrophe.

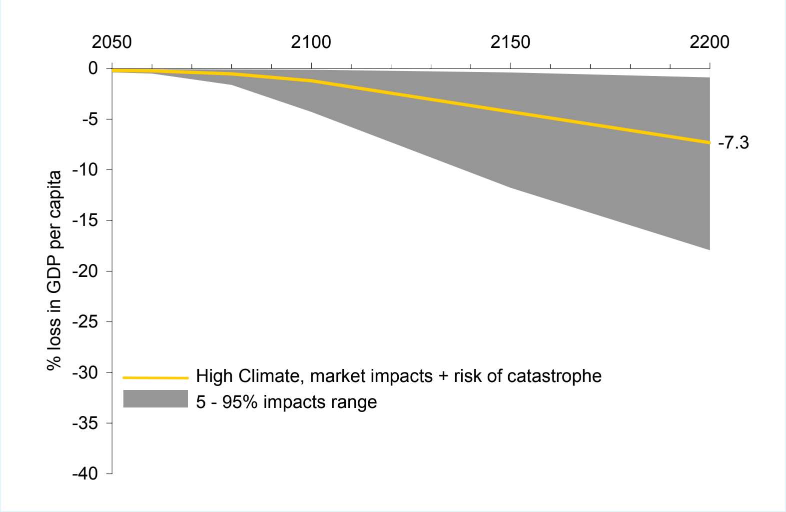


Figure 6.5c. High-climate scenario, with market impacts, the risk of catastrophe and non-market impacts.

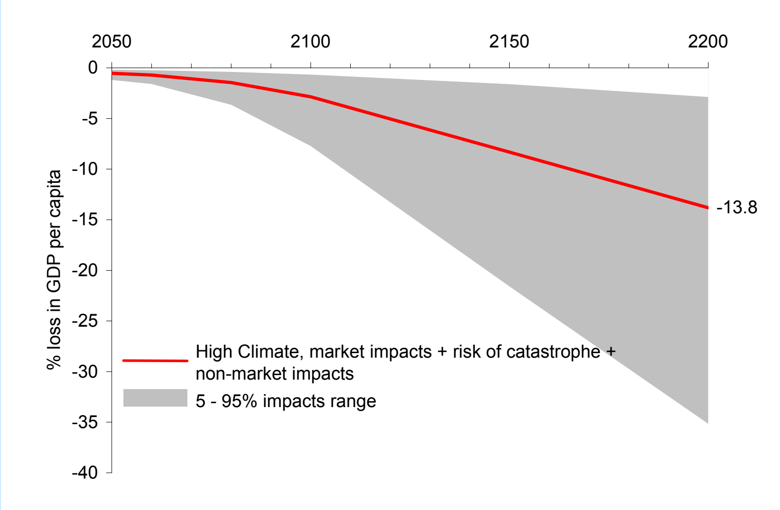


Figure 6.5d. Combined scenarios.

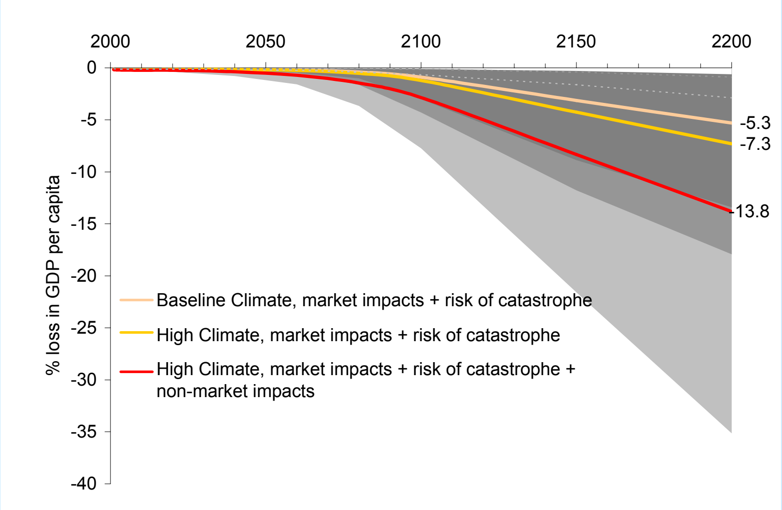


Figure 6.5a-d traces losses in income per capita due to climate change over the next 200 years, according to three of our main scenarios of climate change and economic impacts. The mean loss is shown in a colour matching the scenarios of Figure 6.4. The range of estimates from the 5th to the 95th percentile is shaded grey.

In all scenarios, the highest impacts are in Africa and the Middle East, and India and South-East Asia.

For example, in the baseline-climate scenario with all three categories of economic impact, the mean cost to India and South-East Asia is around 6% of regional GDP by 2100, compared with a global average of 2.6%.

In all scenarios, the consequences of climate change will become disproportionately more severe with increased warming.

Figure 6.6 examines the relationship between mean losses in per-capita GDP and average increases in global mean temperature produced by the baseline and high-climate scenarios. The figure makes two important points graphically:

- The first is that the climatic effects suggested by the newer scientific evidence have the potential to nudge global temperatures, and therefore impacts, to higher levels than those suggested by the IPCC TAR report. In the high scenario, global mean temperature rises to an average of nearly 4.3°C above pre-industrial levels by 2100, compared with an average of 3.9°C above pre-industrial levels in the baseline scenario. The difference between the two scenarios increases beyond 2100, because the effect of the amplifying natural feedbacks becomes more marked at higher temperatures. By 2200, the rise in global mean temperature increases to 8.6°C in the high-climate scenario, while the baseline reaches only 7.4°C. These numbers should be treated as indicative, as climate models have not yet been used to explore the high temperatures that are likely to be realised beyond 2100. They do demonstrate that, if emissions continue unabated, the climate is very likely to enter unknown territory with the potential to cause severe impacts.

- Second, scenarios that include the risk of catastrophe and non-market impacts project higher costs of climate change at any given temperature. The figure makes an additional point that the incremental cost associated with including these non-market and catastrophic impacts increases as temperatures rise, so that the wedge between the economic scenarios becomes more and more substantial.

Estimates of income effects and distribution of risks can also be used to calculate the overall welfare cost of climate change.

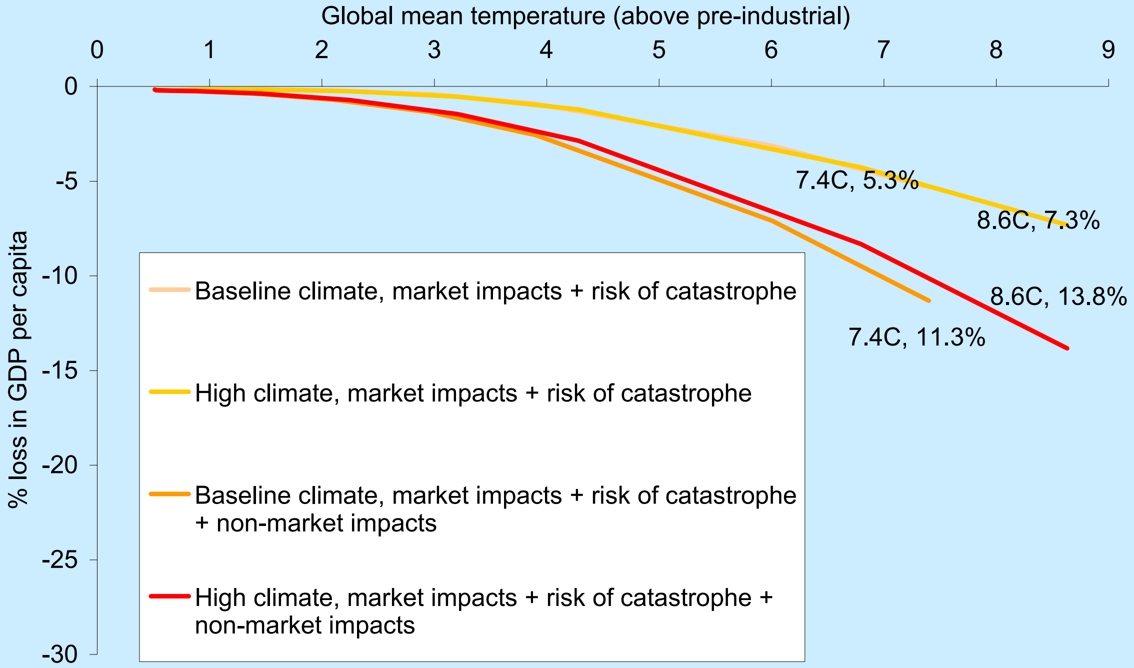
Whereas the first part of Section 6.4 estimated how BAU climate change would affect income, the remainder of the section tackles a still more important challenge: estimating the global welfare costs of climate change, taking explicitly into account the risks involved. Because the forecast changes are large, uncertain, and unevenly distributed, and because they occur over a very long period of time, this exercise must take on the problem of aggregating across different possible outcomes (risk), over different points in time (inter-temporal distribution), and over groups with different incomes (intra-temporal distribution). It should carry out these three types of aggregation consistently. At this stage of the analysis, we have not incorporated intra-temporal distribution.

First, the analysis requires evaluation of the significance of severe climate risks that would result in very low levels of global GDP relative to the world without climate change. In the high-climate scenario with market impacts, the risk of catastrophe and non-market impacts, for example, the 95th percentile estimate is a 35.2% loss in global per-capita GDP by 2200. This is not the statistical mean, but it is nevertheless a risk that few would want to ignore. As discussed below, such risks have a disproportionate effect on welfare calculations, because they reduce income to levels where every marginal dollar or pound has greater value. That is indeed how risk is generally treated in economics.

Second, it requires deciding how to express the future costs of BAU climate change in terms that can be compared with current levels of well-being: we have to evaluate costs occurring at different times on a common basis. The process of warming builds over many decades. In the baseline-climate scenario, 5°C warming is not predicted to occur until some time between 2100 and 2150. By then, growth in GDP will have made the world considerably richer than it is now.

Figure 6.6 Mean losses in income per capita from four scenarios of climate change and economic impacts, plotted against average increases in global mean temperature (above pre-industrial levels).

This figure traces mean losses in per-capita GDP due to climate change as a function of increasing global mean temperature, according to four of the scenarios of climate change and economic impacts. Losses are compared to baseline growth in per-capita GDP without climate change. Because temperature is one of the probabilistic outputs of the PAGE2002 model, increases in temperature in each scenario are averaged across all 1000 runs.



To make these calculations, the model uses the standard tools of applied welfare economics, as described in Chapter 2 and its Appendix.

In these highly aggregated models, the basic approach has to be simple, but it does depend on key assumptions. It is important to lay them out transparently. First, in applying this basic welfare-economics theory to the PAGE2002 model, we follow many other studies in calculating overall social welfare (or global 'utility', to use the standard economic term) as the sum of social utilities of consumption of all individuals in the world. In practice, for this exercise, this means that we convert per-capita global GDP at each point in time into consumption[31], and then calculate the social utility of per-capita consumption. This is then multiplied by global population (Box 6.3).

An approach that would better reflect the consequences of climate change on different world regions would take regional per-capita utility (e.g. for India and South-East Asia) and multiply by regional population to get 'regional utility'. Global utility would then be the sum of regional utilities[32]. Doing so was beyond the scope of this exercise, given the limited time available for analysis, but it is possible to provide some assessment of the bias from this omission. 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.

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[31] In these calculations, we assume that some fixed proportion of income is saved for future consumption. A more sophisticated model would vary the rate of saving as a result of prospects for future consumption, as determined by the model itself.

[32] As in Nordhaus and Boyer (2000)

Second, we use the assumption of diminishing marginal utility as we evaluate risks and future welfare. This standard assumption in economics, generally supported by empirical evidence on behaviour and preferences, holds that the extra utility produced by additional consumption falls as the level of consumption rises. That is, an extra dollar or pound is worth more to a poor person than it is to a rich person. This assumption plays an important role in the welfare calculations, in that it places greater weight on:

- Near-term consumption than on consumption in the distant future, because even with climate change, the world will be richer in the future as a result of economic growth; and

- The most severe climate impacts, because they reduce consumption to such low levels (see Chapter 2 and its Appendix for the underlying welfare economics).

Third, consumption growth is allowed to vary in the future in systematic ways. Traditionally, economic appraisal of projects and policies has taken a simplified approach to this basic welfare-economics framework. Consumption is simply assumed to grow at a certain rate in the future, with uncertainty entering the projection only to the extent that there will be perturbations around this assumed path. In our case, however, climate change could substantially reduce consumption growth in the future, and so two probabilistic model runs with different climate impacts produce different growth rates. So the simplified approach will not work here. Instead, we have to go back to the underlying theory, which implies that consumption paths must be valued separately along each of the model's many (1000, say) runs.

Fourth, in carrying out the expected-utility valuation process, we use a pure rate of time preference (or 'utility discount rate') to weight (or value) the utility of consumption at each point in the future. Thus utility in the future has a different weight simply because it is in the future.[33] This assumption is difficult to justify on ethical grounds, as discussed in Chapter 2 and its Appendix, except where we take into account the probability that individuals will be alive in the future to enjoy the projected consumption stream. In other words, if we know a future generation will be present (that is, apart from discounting for the small chance of global annihilation), we suppose that it has the same claim on our ethical attention as the current one.

Putting all this together, we can:

- Calculate the aggregate utility of the different paths over the future by adding utilities over time, as described, and then;
- Average utility across all 1000 runs to calculate the expected utility under each scenario.

Finally, we need to decide in what terms to express the loss in expected future welfare due to climate change. If the result is to guide policy, it must be easily understandable. When we calculate social utility and aggregate over time for risk, the resulting measure might most immediately be expressed in expected 'utils', but this would not be easily understood. Instead, we introduce the idea of a 'Balanced Growth Equivalent' (hereafter BGE)[34] to calibrate welfare along a path. The BGE essentially measures the utility generated by a consumption path in terms of the consumption now that, if it grew at a constant rate, would generate the same utility.[35]

Taking the difference between the BGE of a single consumption path with climate damage and a consumption path without it gives the costs of climate change, measured in terms of a permanent loss of consumption, now and forever. One can think of the costs measured in this way as like a tax levied on consumption now and forever, the proceeds of which are simply poured away.

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[33] We are not considering here the discounting of extra units of consumption in the future because consumption itself may be higher then.

[34] Proposed by Mirrlees and Stern (1972)

[35] Formally, the change in the BGE is a natural commodity measure of welfare that expresses changes in future consumption due to policy in terms of the percentage increase in consumption (along a steady-state growth path), now and forever, that is equal to the changes that are forecast to follow from the policy change being examined. In a one-sector growth model with natural growth α and consumption C at time t, we want to calibrate welfare from the path $[C(t)]$. If this is equivalent, in welfare terms, to the balanced growth path yielding consumption $\gamma e^{\alpha t}$, then γ is the BGE of $[C(t)]$.

Box 6.3 'Expected-utility' analysis of the global cost of climate change.

PAGE2002 takes baseline GDP growth from an exogenous scenario[36] and produces 1000 runs of global GDP, less the cost of climate change damage and adaptation to climate change, from 2001 to 2200. Thus we obtain a probability distribution of global income pathways net of climate change damage and adaptation costs.

We first transform this probability distribution into GDP per capita, dividing through each run by a population scenario determined exogenously.[37] Then we transform each run into global consumption per capita, taking an arbitrary, exogenous rate of saving of 20%.

We transform consumption per capita into utility:

$$U(t) = \frac{C^{1-\eta}}{1-\eta} \tag{1}$$

where *U* is utility, *C* is consumption per capita, *t* is the year[38] and η is the elasticity of the marginal utility of consumption (see the Appendix to Chapter 2). In our main case, we take η to be 1, in line with recent empirical estimates.[39] Further work would investigate a broader range of η, including higher values.[40] Where η is 1, the utility function is a special case:

$$U(t) = \ln C(t) \tag{2}$$

Then discounted utility (with constant population) is given by:

$$W = \int_{t=1}^{\infty} U(t)e^{-\delta t}dt \tag{3}$$

where *W* is social welfare and δ is the utility discount rate. The value of δ is taken to be 0.1% per annum, so that the probability of surviving beyond time *T* is described by a Poisson process $e^{-\delta T}$, where δ is the annual risk of catastrophe eliminating society, here 0.1%. So the probability of surviving beyond, say, 2106 is $e^{-0.001*100}$, which is 90.5%. The Appendix to Chapter 2 discusses the implications of this choice in more detail.

Where population varies exogenously over time, we would automatically weight by population. In the case of just one region (i.e. the world), this means that we integrate global utility weighted by global population over time:

$$W = \int_{t=1}^{\infty} N(t)U(t)e^{-\delta t}dt \tag{4}$$

where *N* is global population. Where global income data can be disaggregated, regional utility should be evaluated for consistency using similar utility functions to that used in (4).[41] For endogenous population growth, some difficult ethical issues are involved and we cannot automatically apply this criterion (see Chapter 2 and appendix).

In the PAGE2002 modelling horizon – 2001 to 2200 – we can calculate total discounted utility as the sum of discounted utility in each individual year:

$$W = \sum_{t=1}^{2200} U(t)e^{-\delta t} \tag{5}$$

We approximate utility from 2200 to infinity based on an assumed, arbitrary rate of per-capita consumption growth *g*, which is achieved by all paths, as well as assessing constant population. We use 1.3% per annum, which is the annual average projection from 2001 to 2200 in PAGE2002's baseline world without climate change. In other words, as a simplification, in each run the world

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[36] An extrapolated version of the IPCC's A2 scenario (IPCC, 2000), characterised by annual average GDP growth of about 1.9%.

[37] Also extrapolated from the IPCC's A2 scenario. Annual average population growth is about 0.6%.

[38] In fact, the model is restricted to a subset of uneven time steps. Thus we interpolate linearly between time steps to produce an annual time series.

[39] See Pearce and Ulph (1999).

[40] Pearce and Ulph (1999) and Stern (1977).

[41] Nordhaus and Boyer (2000).

instantaneously overcomes the problems of climate change in the year 2200 (zero damages and zero adaptation) and all runs grow at an arbitrary 1.3% into the far-off future. In this sense there is an underestimate of the costs of climate change. Again, a special case arises where the elasticity of the marginal utility of consumption is 1:

$$W = \sum_{t=1}^{2200} N(t)\ln C(t)e^{-\delta t} + \left(\frac{N_T \ln C_T}{\delta} + \frac{N_T g}{\delta^2}\right)e^{-\delta T} \qquad (6)$$

Expected utility is given by the mean of total discounted utility from 2001 to infinity along all 1000 runs.

Finally, we can find the balanced growth equivalent (BGE) of the discounted consumption path described in 6. This is the current level of consumption per capita (i.e. in 2001), which, growing at a constant rate *g* set again to 1.3% per annum, delivers the same amount of utility as in (6) for the case of $\eta = 1$.

$$W = \sum_{t=1}^{2200} N(t)\left(\frac{C_{BGE}^{1-\eta}}{1-\eta} + gt\right)e^{-\delta t} + \left(\frac{N(t)\left(\frac{(C_{BGE}+200g)^{1-\eta}}{1-\eta}\right)}{\delta - g(1-\eta)}\right)e^{-\delta T} \qquad (7)$$

We have to go beyond the simple BGE generated in this way to take account of uncertainty. Thus the BGEs calculated here calibrate the expected utility in a particular scenario (with many possible paths) in terms of the definite or certain consumption that, if it grew at a constant rate, would generate the same expected utility. One can, therefore, think of the BGE measure of climate-change costs not as a tax but as the maximum insurance premium society would be prepared to pay, on a permanent basis, to avoid the risk of climate change (if society shared the policy-maker's ethical judgements). In practice, as we shall see, society will not in fact have to pay as much as this. Thus the BGE here combines the growth idea of Mirrlees and Stern[42] with the certainty equivalence ideas in, say, Rothschild and Stiglitz[43]. The next step, if intra-temporal income distribution is taken into account explicitly, would be to combine it with the 'equally distributed equivalent' income of Atkinson[44]. Box 6.3 outlines our calculations in more detail.

The welfare costs of BAU climate change are very high. Climate change is projected to reduce average global welfare by an amount equivalent to a permanent cut in per-capita consumption of a minimum of 5%.

Table 6.1 presents results in terms of Balanced Growth Equivalents (BGEs), based on defensible values for the utility discount rate (0.1% per annum) and for the elasticity of the marginal utility of consumption (1.0) (see Chapter 2 and its Appendix for an explanation and justification). For each of our six scenarios of climate change and economic impacts, we calculate three BGEs:

- For mean total discounted utility;
- For total discounted utility along the 5th percentile run;
- For total discounted utility along the 95th percentile run.

Table 6.1 shows the results. In each case, we quote the difference between the BGEs with and without climate change – the cost of climate change – in percentage terms. These are our headline results from the modelling. The numbers express the cost of 'business as usual' (BAU) climate change over the next two centuries in terms of present per-capita consumption for each scenario as a whole and for specific paths with impacts at the low and high end of the underlying probability distributions.

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[42] Mirrlees Stern (1972)

[43] Rothschild and Stiglitz (1970)

[44] Atkinson (1970)

Table 6.1 Losses in current per-capita consumption from six scenarios of climate change and economic impacts*.

Scenario		**Balanced growth equivalents: % loss in current consumption due to climate change**		
Climate	**Economic**	**Mean**	**5th percentile**	**95th percentile**
Baseline climate	**Market impacts**	2.1	0.3	5.9
	Market impacts + risk of catastrophe	5.0	0.6	12.3
	Market impacts + risk of catastrophe + non-market impacts	10.9	2.2	27.4
High climate	**Market impacts**	2.5	0.3	7.5
	Market impacts + risk of catastrophe	6.9	0.9	16.5
	Market impacts + risk of catastrophe + non-market impacts	14.4	2.7	32.6

*Utility discount rate = 0.1% per annum; elasticity of marginal utility of consumption = 1.0.

The results under the different scenarios range greatly, but virtually all project that BAU climate change will have very significant costs. In our lower-bound scenario, comprising the baseline climate scenario and including both market impacts and the risk of catastrophe, the BGE of the mean outcome is 5% below the equivalent BGE without climate change, meaning that the expected welfare cost of BAU climate change between 2001 and 2200 is equivalent to a 5% loss in per-capita consumption, now and forever. The BGE of the 95th percentile run amounts to a 12.3% loss in consumption now and forever, while the BGE of the 5th percentile run amounts to a 0.6% loss.

Climate change will reduce welfare even more if non-market impacts are included, if the climatic response to rising GHG emissions takes account of feedbacks, and if regional costs are weighted using value judgements consistent with those for risk and time. Putting these three factors together would probably increase the cost of climate change to the equivalent of a 20% cut in per-capita consumption, now and forever.

- Adding the possibility of the feedbacks involved in the high-climate scenario reduces the BGE of mean total discounted utility to 6.9% below the equivalent BGE without climate change. The BGE of the 95th percentile run is 16.5% below, while the BGE of the 5th percentile run is just 0.9% below.

- In the high-climate scenario and with all three categories of economic impact (that is, adding the non-market impact), the BGE of the mean outcome is reduced to 14.4% below the equivalent BGE without climate change. The BGE of the 95th percentile run is 32.6% below, while the BGE of the 5th percentile run is 2.7% below. If the possibility of still higher climate sensitivities is taken into account, the incremental cost might be higher still.

- Calculating the BGE cost of climate change after including value judgements for regional distribution is beyond the scope of this Review, given our limited time. But if we take as an indication of how much estimates might increase the results of Nordhaus and Boyer[45], then estimates might be one quarter higher. In addition, because their deterministic approach could not take into account the valuation of risk, there is good reason to believe that the weighting would in our model increase estimates still further (see the Appendix to Chapter 2). In total, the global cost of climate change would probably be equivalent to around a 20% reduction in the BGE compared with a world without climate change.

Finally, we should discuss where one might place the evaluation of the losses from climate change between the 5 and 20% figures. There are two types of issue. The first is the inclusion of relevant effects and the second is the presence of different possible probability distributions.

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[45] Nordhaus and Boyer (2000)

On the first, it is reasonable to include what we consider to be relevant effects. This means catastrophic events, non-market effects and distribution of impacts within a generation. We have calculated the first two of these. However, we have conceptual, ethical and practical reservations about how non-market impacts should be included, although there is no doubt they are important. We have yet to calculate the distributional effects – that is for further work – but, based on previous studies, we can hazard a guess.

The second type of issue concerns the fact that we are unsure of which probability distribution to use. This takes us back to the distinction between risk and uncertainty discussed in Chapter 2 and the Appendix. We argued there that we now have some theory to guide us. Essentially, it points to taking a weighted average of the best and worst expected utility.

The first type of issue would take the evaluation towards an overall loss in the region of 13-15% (using the 10.9% figure of Table 6.1 and scaling up by one-quarter or more for distribution). The second type of issue would lead to taking a weighted average somewhere between this figure (13 or 14%) and 20%. The weights would depend on crude judgements about likelihoods of different kinds of probability distributions, on judgements about the severity of losses in this context, and on the basic degree of cautiousness on the part of the policy-maker. Together, they would make up the 'aversion to ambiguity' discussed in Chapter 2 and the Appendix.

This discussion points to areas for further work in the context of this particular model: distribution within a generation and explaining different distributional judgements. Of course, there is much more to do in terms of considering different economic models – we have investigated just one – and exploring different probability distributions.

6.5 Conclusion

This Chapter has presented global cost estimates of the losses from 'business as usual' climate change. They have been expressed in terms of their equivalent permanent percentage loss in consumption. They are averages over time and risk and can be compared with percentage costs, similarly averaged over time, of mitigation – that is the subject of Part III of this Review. In the final chapter of that part, we include a discussion of how much of the losses estimated in this Chapter could be saved by mitigation. The loss estimates of this Chapter should be viewed as complementary to the discussions of the scale of the separate impacts on consumption, health, and environment that were presented in Chapters 3 to 5.

What have we learned from this exercise? Notwithstanding the limitations inherent in formal integrated models, there can be no doubt that the economic risks of a 'business as usual' approach are very severe – and probably more severe than suggested by past models. Relying on the scientific knowledge that informed the IPCC's TAR, the cost of BAU climate change over the next two centuries is equivalent to a loss of at least 5% of global per-capita consumption, now and forever. More worrying still, when the model incorporates non-market impacts and more recent scientific findings on natural feedbacks, this total average cost is pushed to 14.4%.

Cost estimates 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, there may be greater risks to the climate from dynamic feedbacks and from heightened climate sensitivity beyond those included here. If these are included, the total cost would be likely to be around 20% of current per-capita consumption, now and forever.

Further, there are potentially worrying 'social contingent' impacts such as migration and conflict, which have not been quantified explicitly here. If the world's physical geography is changed, so too will be its human geography.

Finally, we must close with the warning about over-literal interpretation of these results with which we began this chapter. The estimates have arisen from an attempt to add two things to the previous literature on IAM models. The first is use of recent scientific estimates of probabilities and the second is putting these probabilities to work using the economics of risk and uncertainty. The most worrying possible impacts are also among the most uncertain, given that so little is known about the risks of very high temperatures and potential dynamic instability. The exercise allows us to see what the implications of the risks, as we currently understand them, might be. The answer is that they would imply very large estimates of potential losses from climate change. They give an indication of the stakes involved in making policy on climate change. The analysis of this Chapter shows the inevitable difficulties of all these models in extrapolating over very long periods of time. We therefore urge the reader to avoid an over-literal interpretation of these results. Nevertheless, we think that they illustrate a very important point: the risks involved in a 'business as usual' approach to climate change are very large.

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Successive IPCC assessments of the IAM literature can be found in Pearce *et al.* (1996) and Smith *et al*. (2001). Hitz and Smith (2004) provide a more recent summary, focussing on the nature of the relationship between rising temperatures and the cost of climate change. William Cline's 1992 book *The Economics of Global Warming* and William Nordhaus and Joseph Boyer's 2000 book *Warming the World* provide an important and well-structured discussion of the issues, while Hope (2005) explains Integrated Assessment Modelling in detail. Watkiss *et al*. (2005) is a valuable discussion of the uncertainties around estimating the monetary cost of climate change, while Warren et al. (2006) subject the damage functions in IAMs to critical scrutiny.

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